Recent Key Measurements for Accessing the Transverse Spin and Momentum Structure of the Nucleon

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content

- **introduction on TMDs in SIDIS**
- **review of recent results**

apologies

for the many plots I will show

mainly to give an idea of the amount and precision of the data

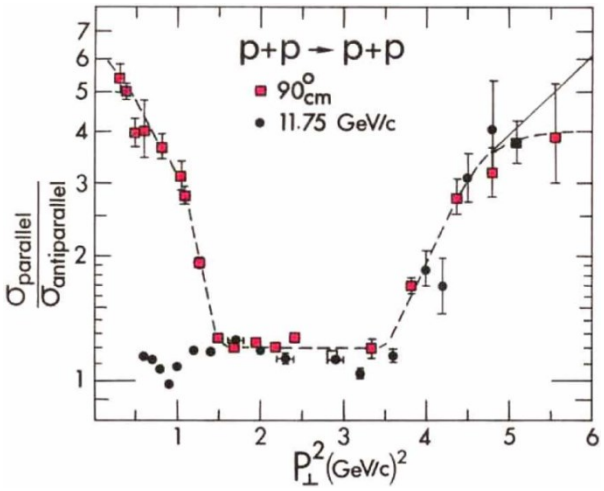
and for the many plots and results I will not be able to show

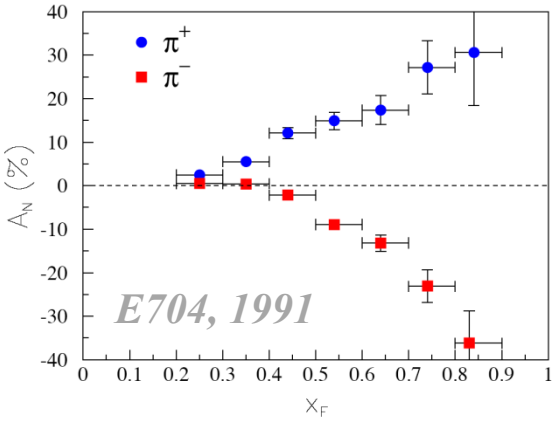
Transverse Spin and Momentum Structure of the Nucleon

manifests itself in many phenomena, some of those known since a long time

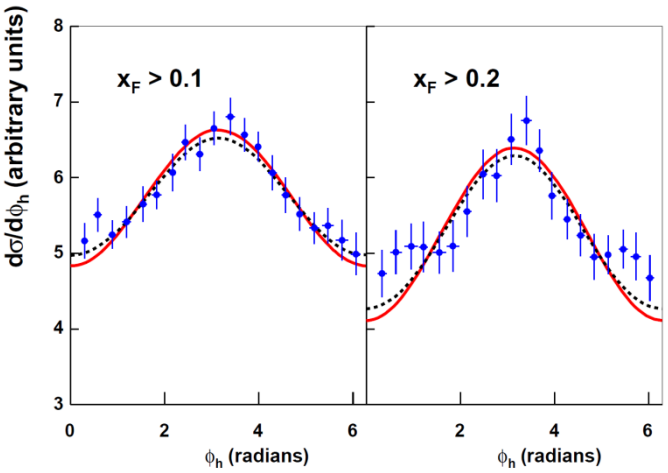
- Λ polarisation
- LR asymmetries in $pp \to \pi^{\pm} X$
- azimuthal asymmetries in Drell-Yan and SIDIS
- elastic pp scattering ….

Argonne, ZGS, 1977





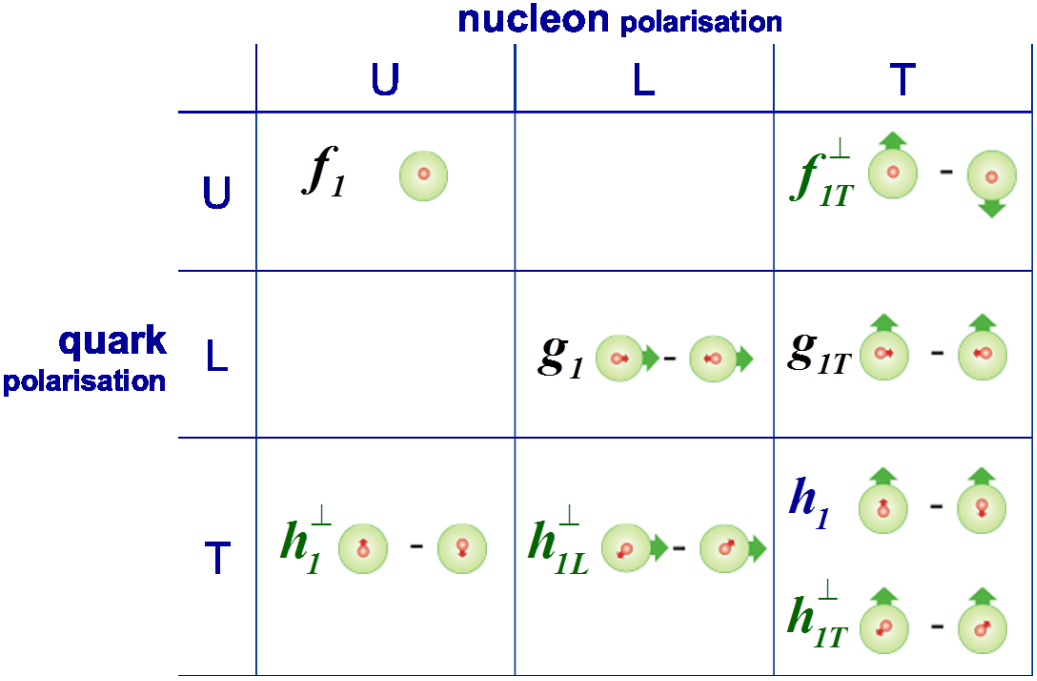
EMC, 1987



Transverse Spin and Momentum Structure of the Nucleon

today the information is encoded in the **TMD PDFs** which describe the correlations between: - nucleon spin and quark spin
- nucleon spin and quark transverse momentum
- quark transverse momentum and spin

8 at twist 2



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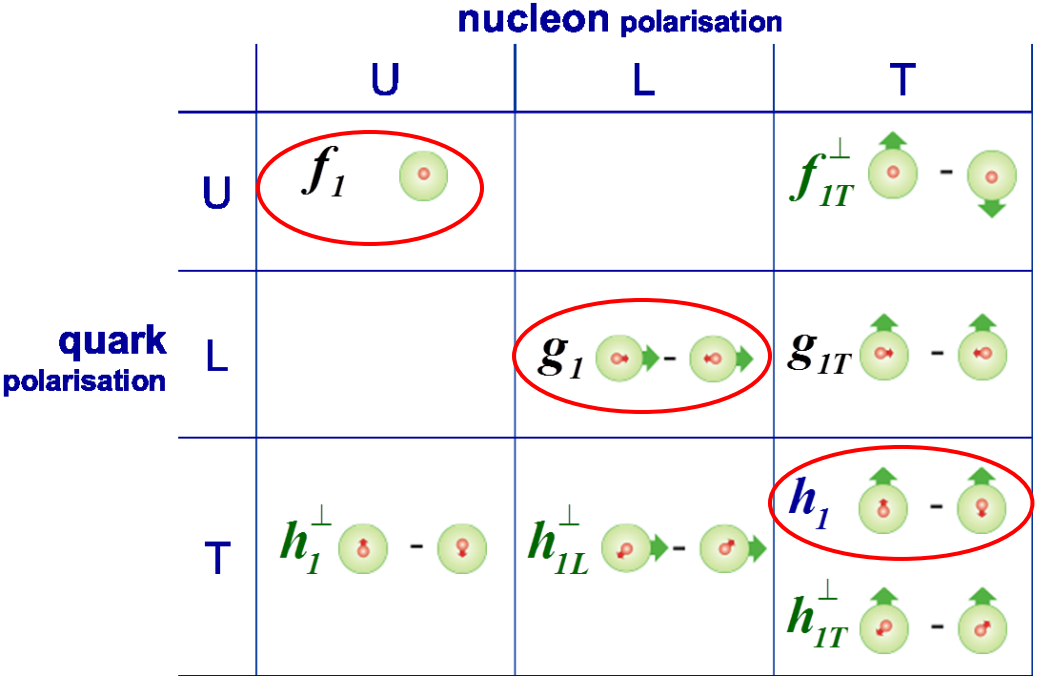

only 3 of them survive after integration over transverse momenta

- **number density** f_1^q
  well known
- **helicity** g_1^q
  known
- **transversity** h_1^q
  chiral-odd
  completely unknown till 2005
  → SIDIS plus e+e-

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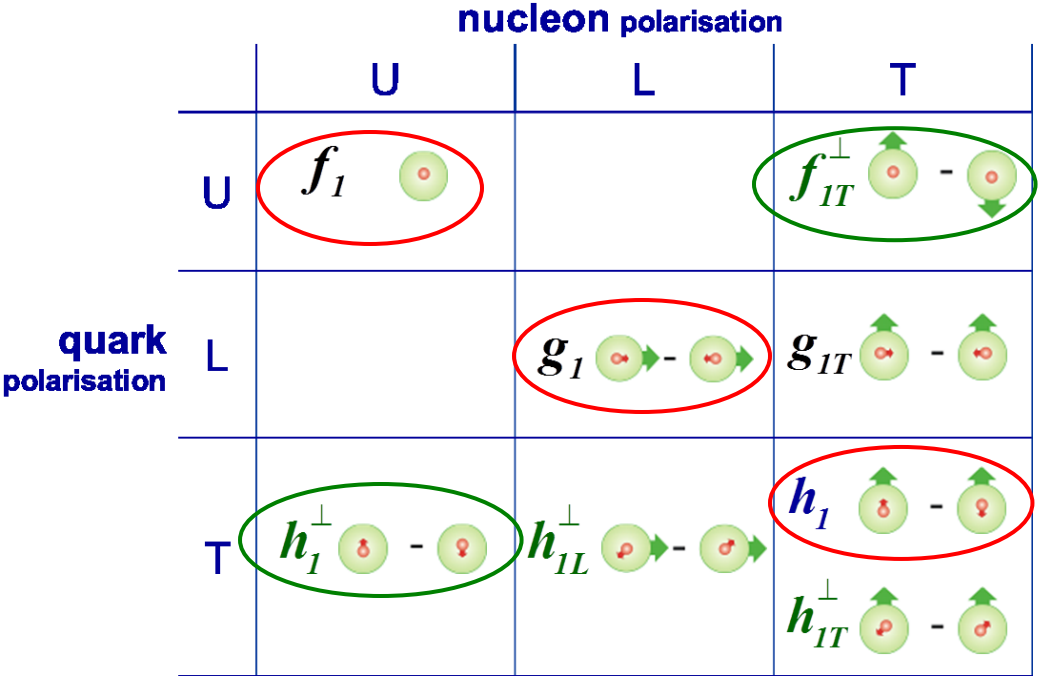


two of them are T-odd

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

nucleon transverse spin ↔ parton transverse momentum

Boer-Mulders $h_1^{\perp}$

parton transverse spin ↔ parton transverse momentum

…

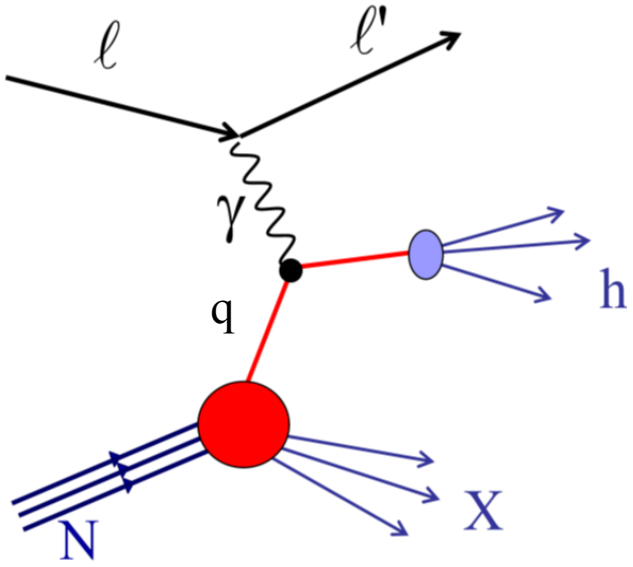
all of great interest

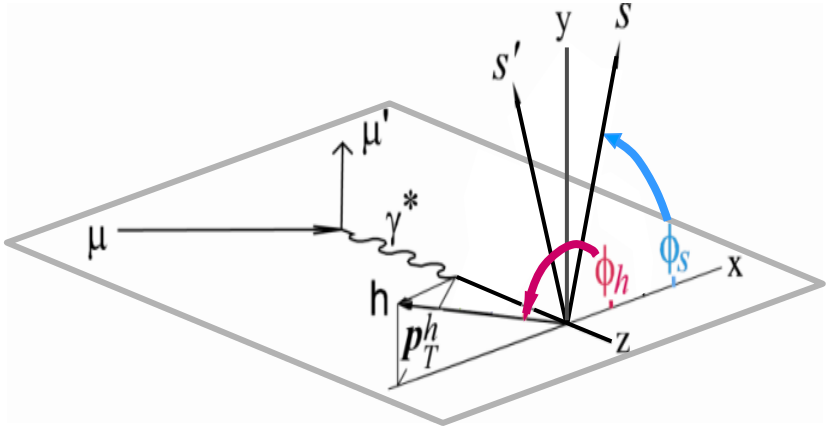
and almost unknown

Transverse Spin and Momentum Structure of the Nucleon

studied in different processes *SIDIS, Drell-Yan, pp reactions*

today most of the knowledge on TMD PDFs comes from SIDIS





$$d\sigma^{\ell p\to \ell h X} \sim \sum_q f_q(x,\boldsymbol{k}_\perp;Q^2)\otimes d\sigma^{\ell q\to \ell q}\otimes D_q^h(z,\boldsymbol{p}_T;Q^2)$$

SIDIS cross-section

14 azimuthal modulations
14 azimuthal asymmetries

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\Big\{1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}$$

2+1

$$+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\varphi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\varphi_h)A_{UL}^{\sin(2\phi_h)}\right]$$

2+1

$$+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\varphi_h A_{LL}^{\cos\phi_h}\right]$$

$$+S_T\Big[\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)$$

$$+\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)\Big]$$

5+3

$$+S_T\lambda\Big[\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)$$

$$+\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)\Big]\Big\}$$

$$\boxed{A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}}}$$

$$\varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\qquad \gamma=\frac{2Mx}{Q}$$

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$$+\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)\Big]$$

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azimuthal asymmetries in SIDIS (U,T: 11→10)

$$A_{UU}^{\cos\phi_h} \propto Q^{-1}\left(f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + Q^{-1}\left(f_1^q \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

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$$A_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

leading twist

$$A_{UT}^{\sin(\phi_s)} \propto Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

$$A_{UT}^{\sin(2\phi_h - \phi_s)} \propto Q^{-1}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

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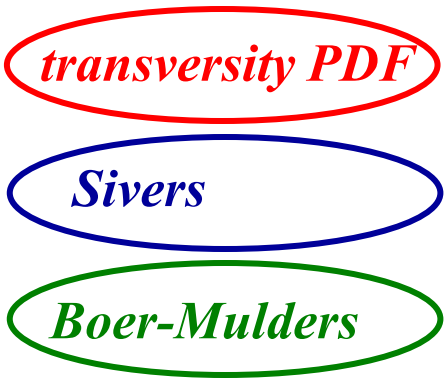

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transversity PDF

Sivers

Boer-Mulders

Collins FF

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transversity PDF

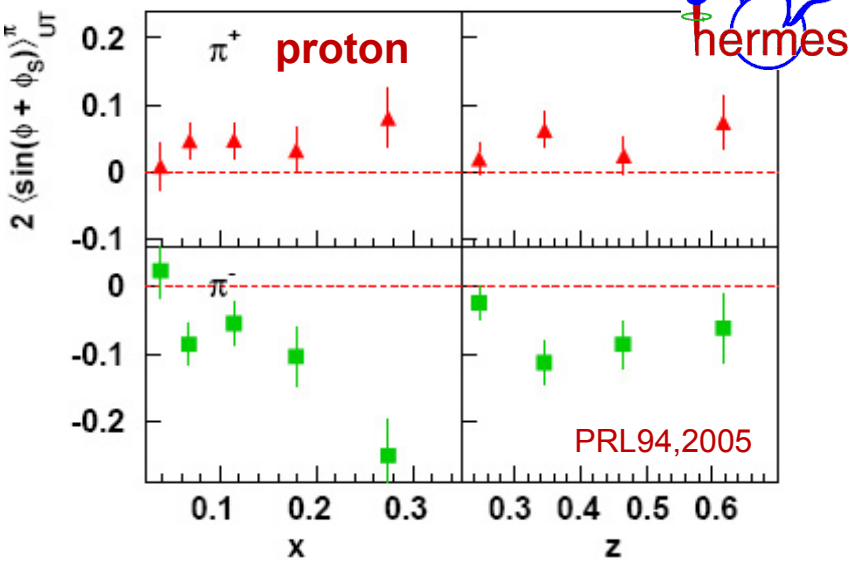
Sivers

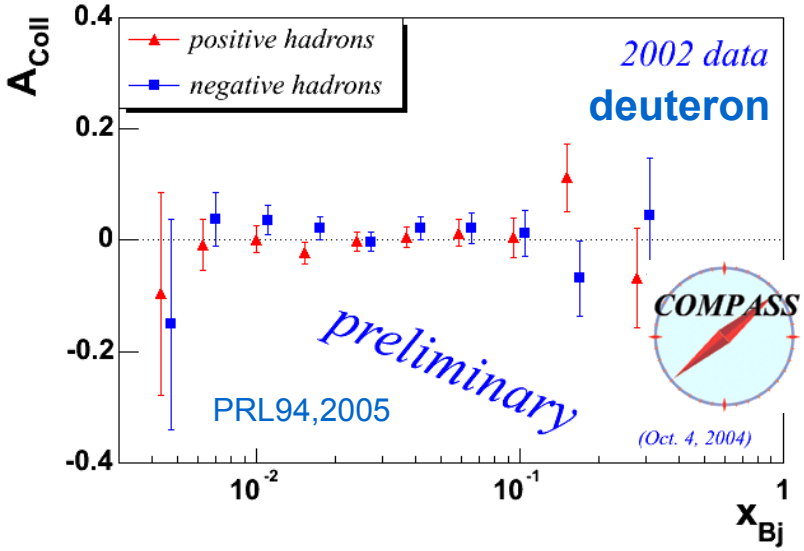
Boer-Mulders

Collins FF

first information on these new objects came in 2004, with the measurements of the Collins and Sivers asymmetries

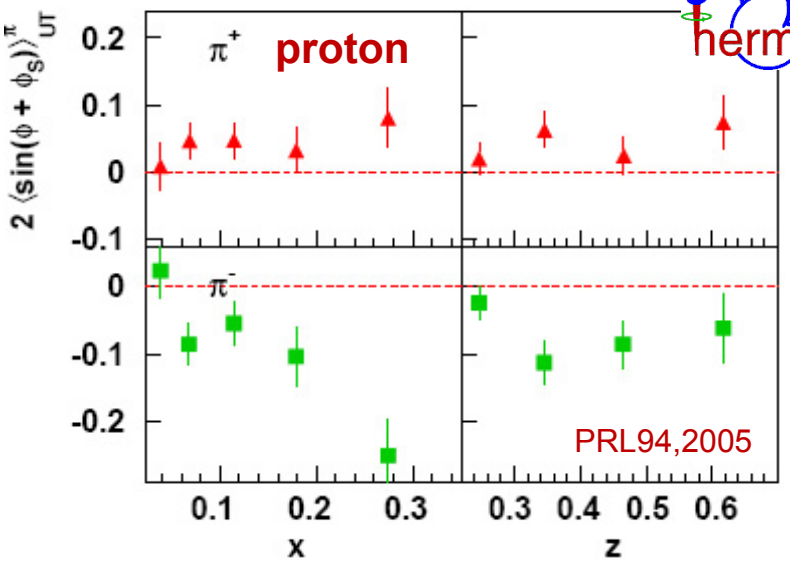
Collins asymmetry

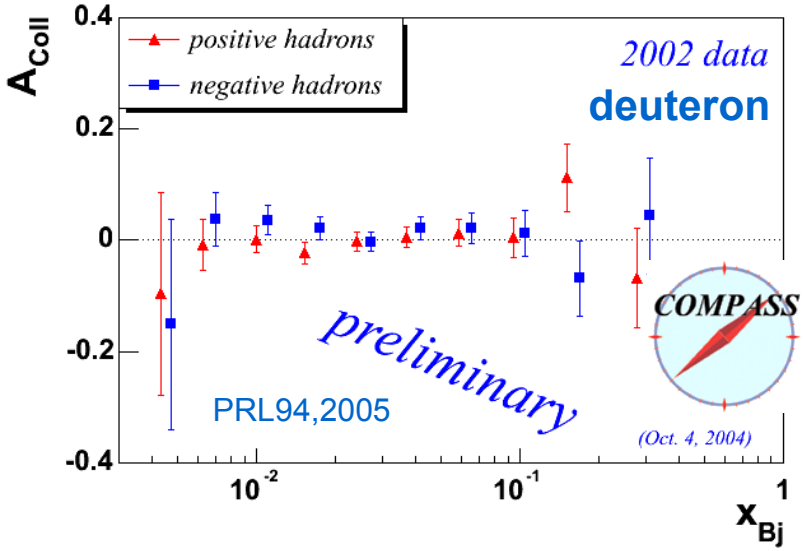




first evidence for
non-zero u-quark transversity
and Collins FF
~ opposite u- d- quark contributions

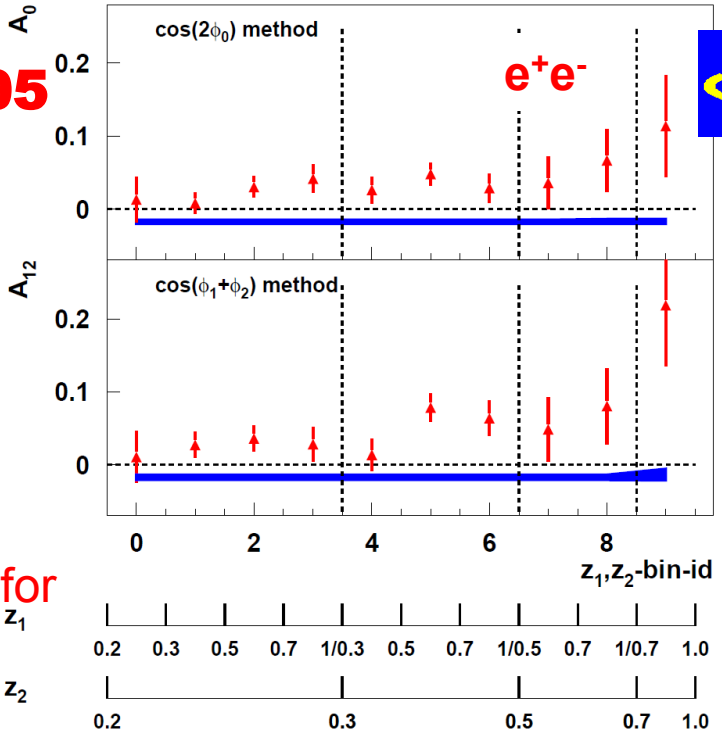
Collins asymmetry





DIS2005

PRL96,2006



first evidence for
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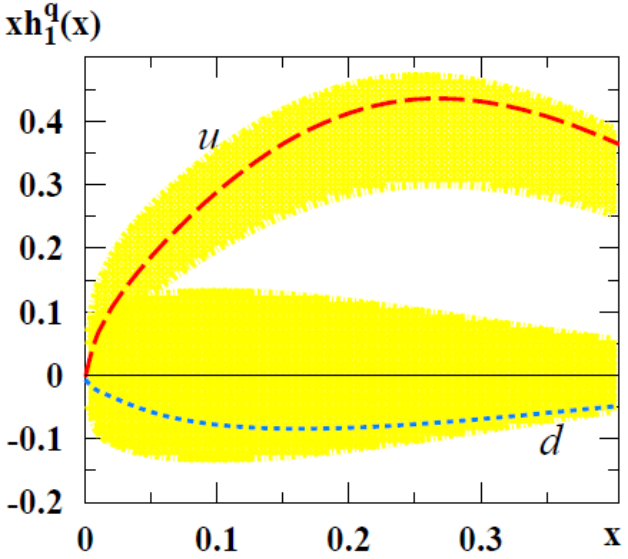
independent evidence for
non-zero Collins FF

Transversity

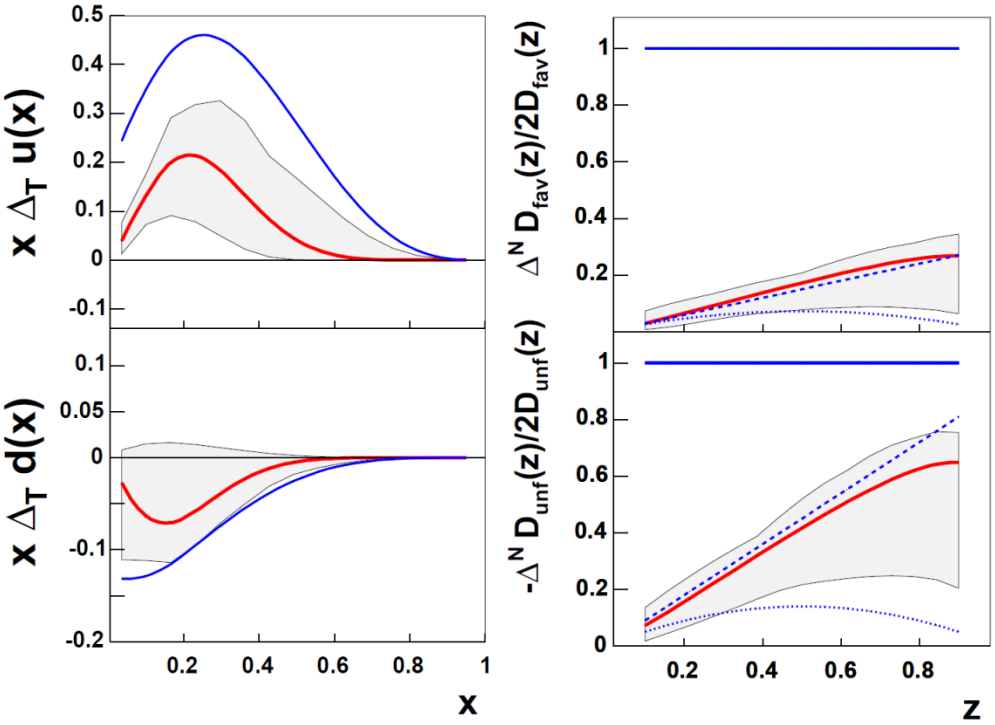
HERMES p, COMPASS d, Belle data well described by theory

first extraction of transversity and Collins FF

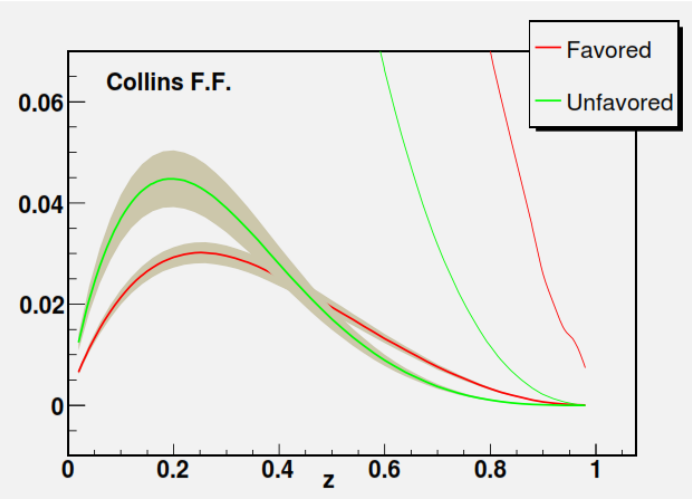
Efremov, Goeke, Schweitzer PRD73, 2006



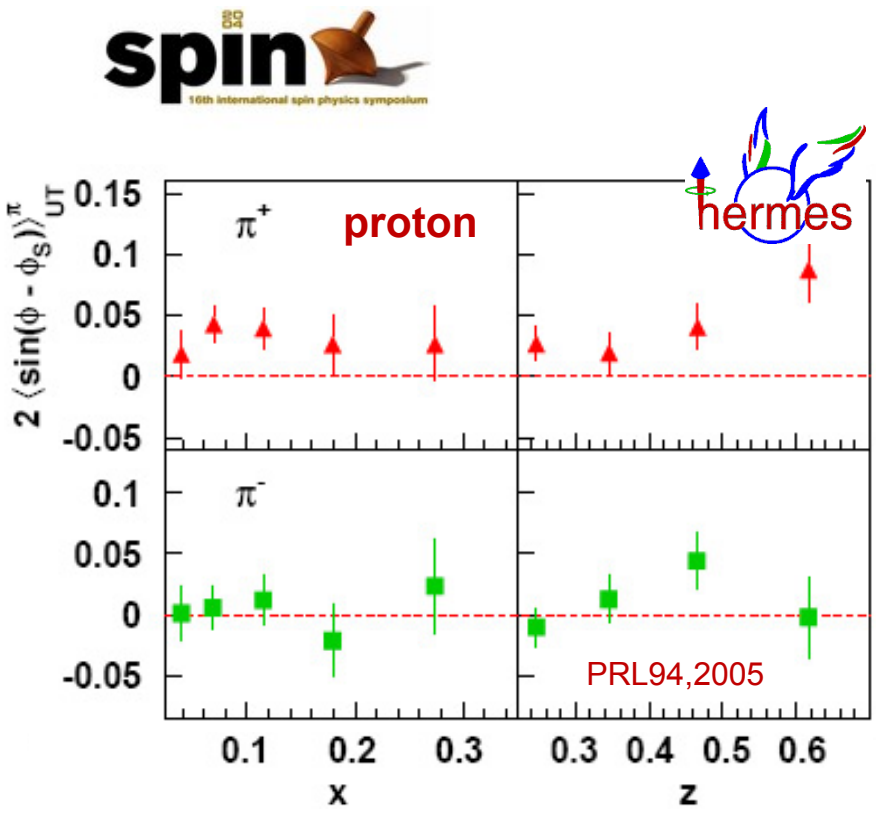
Anselmino et al PRD73, 2006



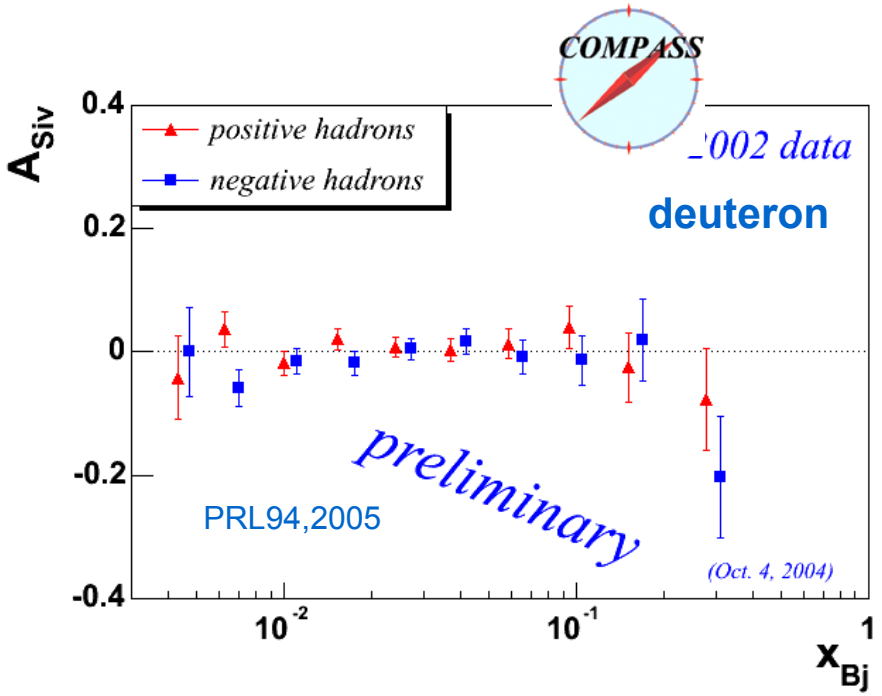
Vogelsang, Yuan PRD72, 2005



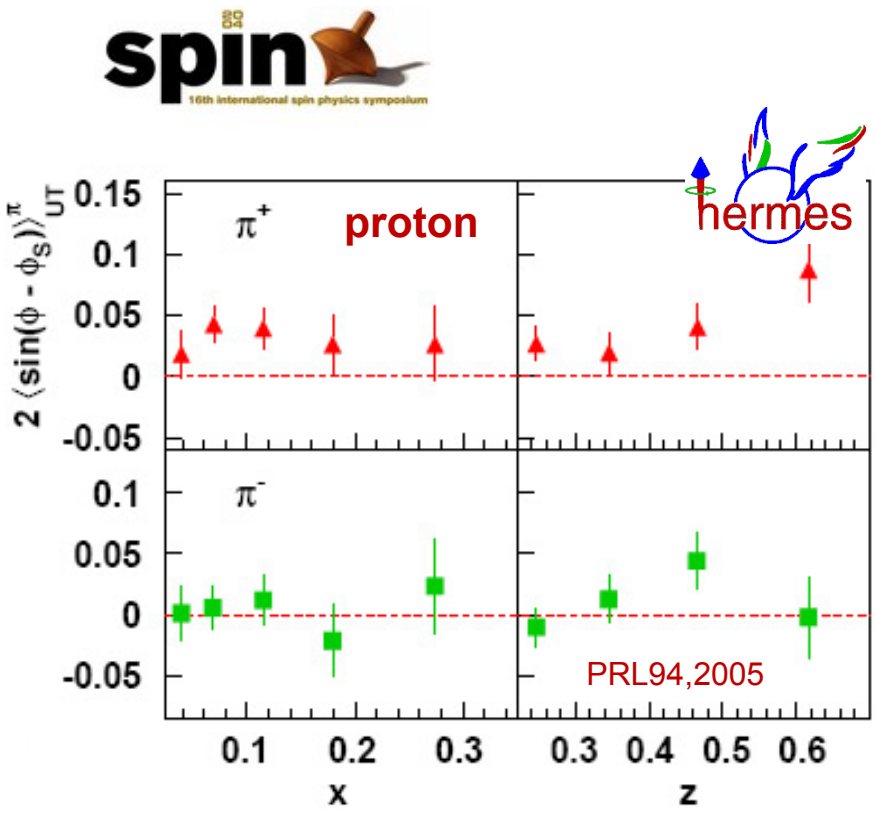
Sivers asymmetry



first evidence for
non-zero Sivers function
~ opposite u- d- quark contributions



Sivers asymmetry



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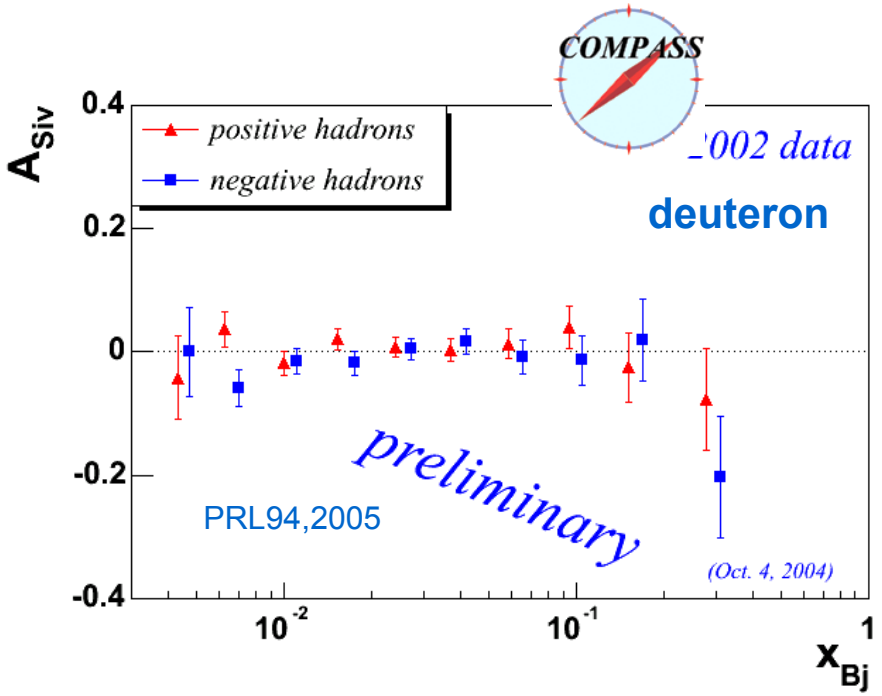


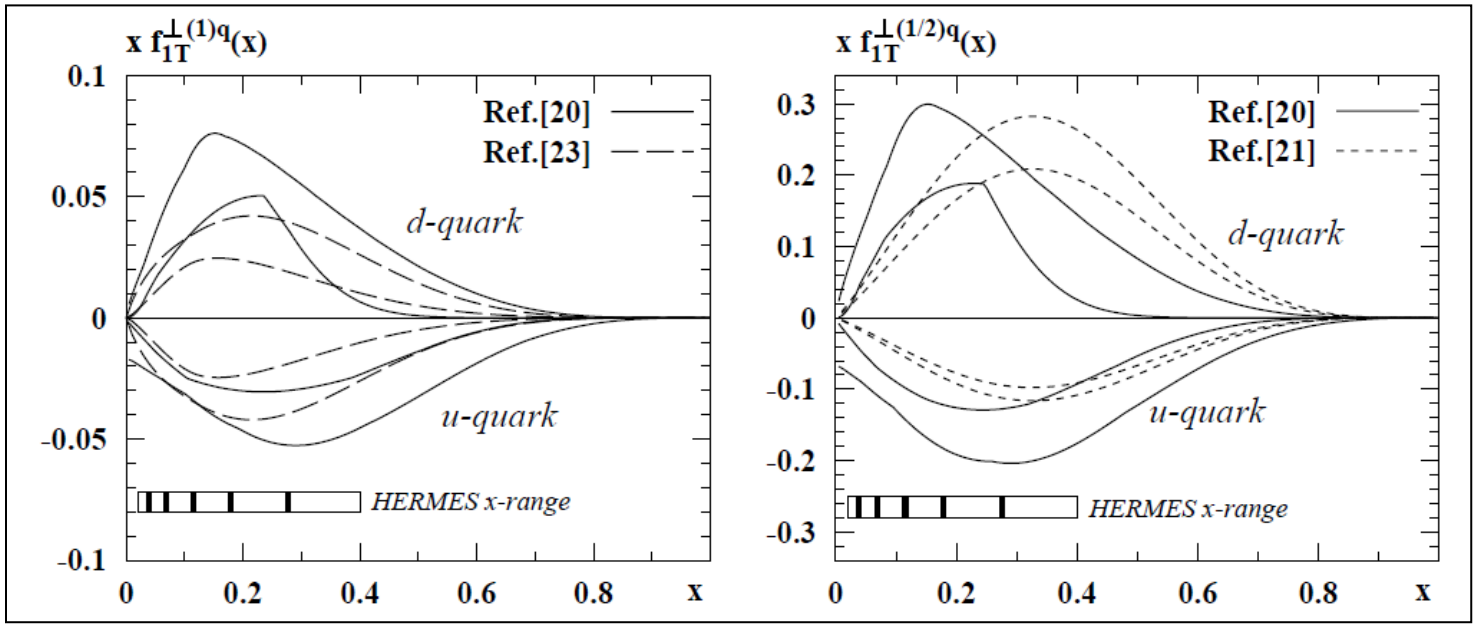
HERMES p and COMPASS d
data well described by theory

first extraction of Sivers function

Sivers function

M. ANSELMINO[1], M. BOGLIONE[1], J. C. COLLINS[2], U. D'ALESIO[3],
A. V. EFREMOV[4], K. GOEKE[5], A. KOTZINIAN[1], S. MENZEL[5], A. METZ[5],
F. MURGIA[3], A. PROKUDIN[1], P. SCHWEITZER[5], W. VOGELSANG[6,7], F. YUAN[7]

proceedings of Transversity2005 hep-ph/0511017



Sivers function

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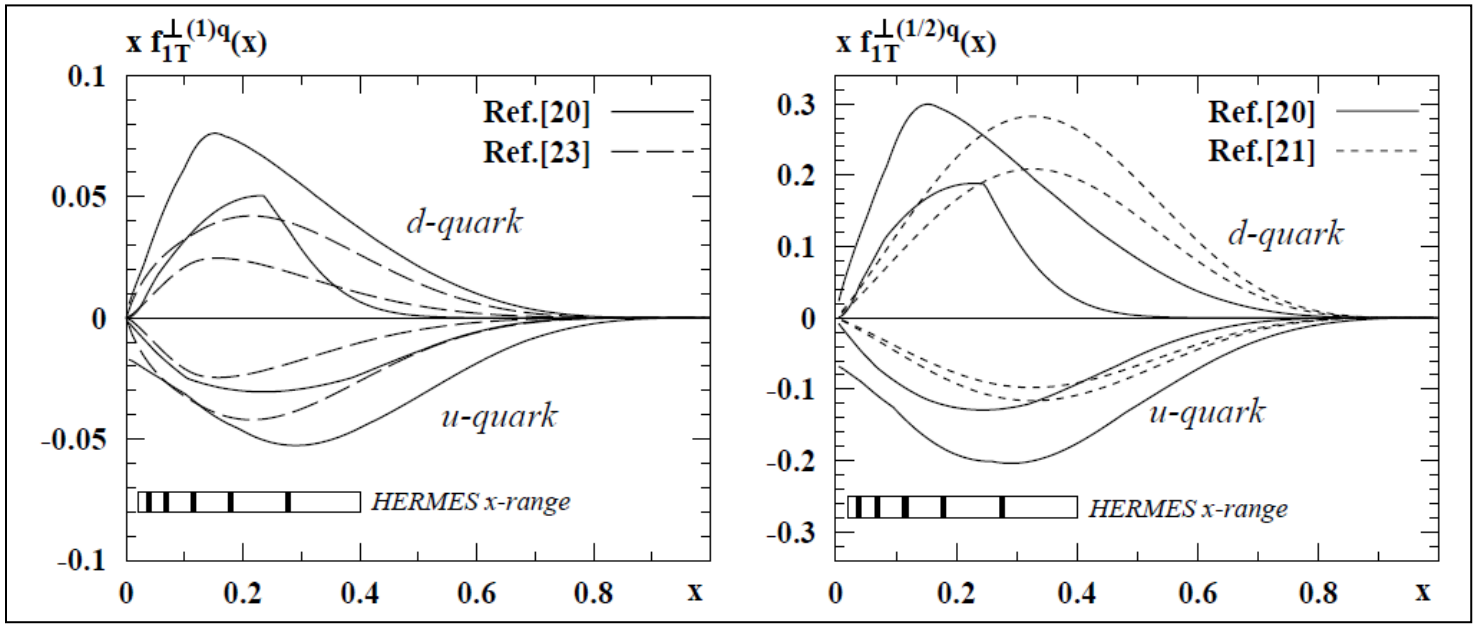
A. V. EFREMOV[4], K. GOEKE[5], A. KOTZINIAN[1], S. MENZEL[5], A. METZ[5],
F. MURGIA[3], A. PROKUDIN[1], P. SCHWEITZER[5], W. VOGELSANG[6,7], F. YUAN[7]

proceedings of Transversity2005 hep-ph/0511017



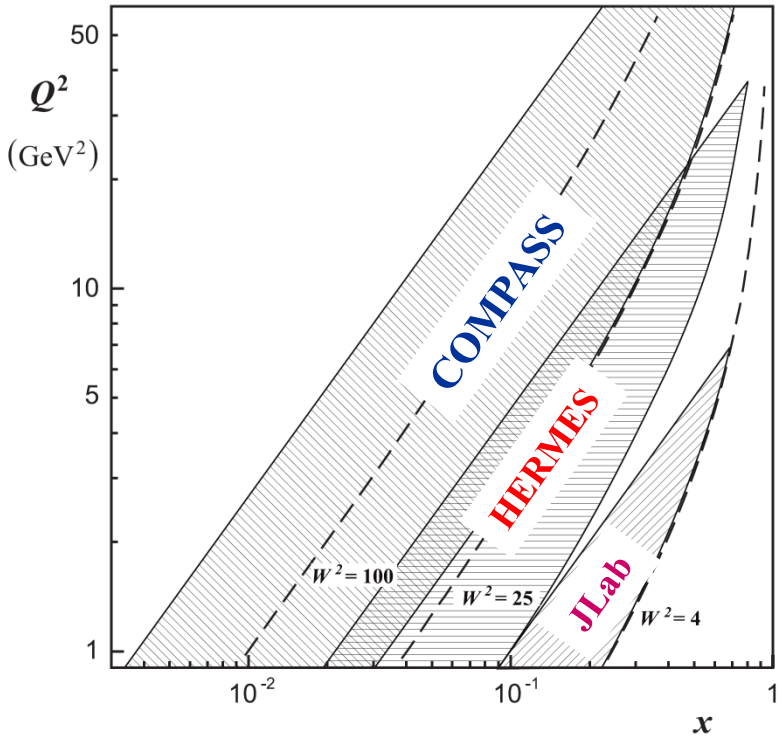
very positive conclusion from 2004-2005 data:
transversity and Sivers PDFs different from zero !
all data fit well in the TMDs framework

still ….

Collins and Sivers asymmetries

evidence from HERMES only

zero asymmetries from COMPASS due to isoscalar target or to higher Q^2?



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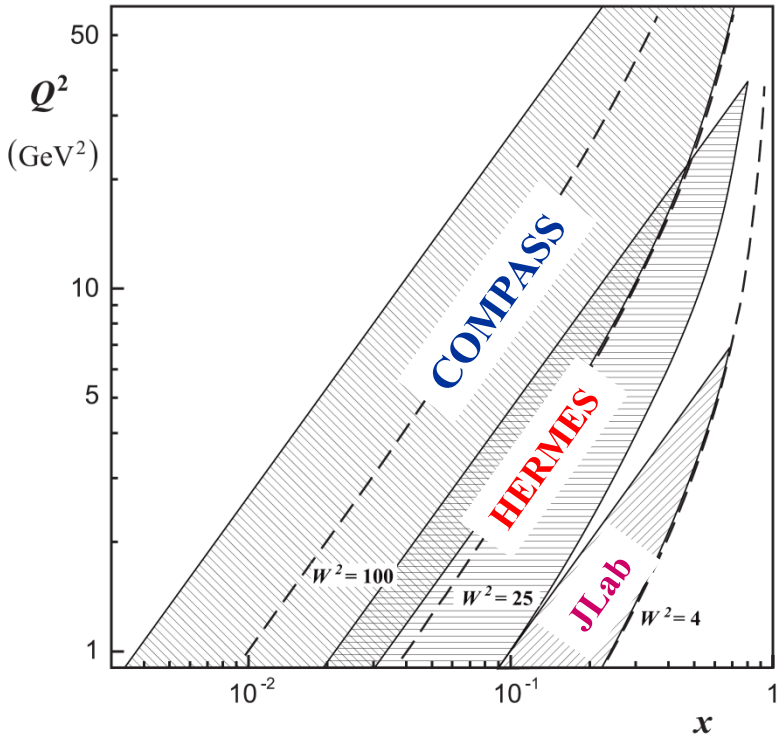
COMPASS took data
with p↑ in 2007 and 2010:
an important step forward!



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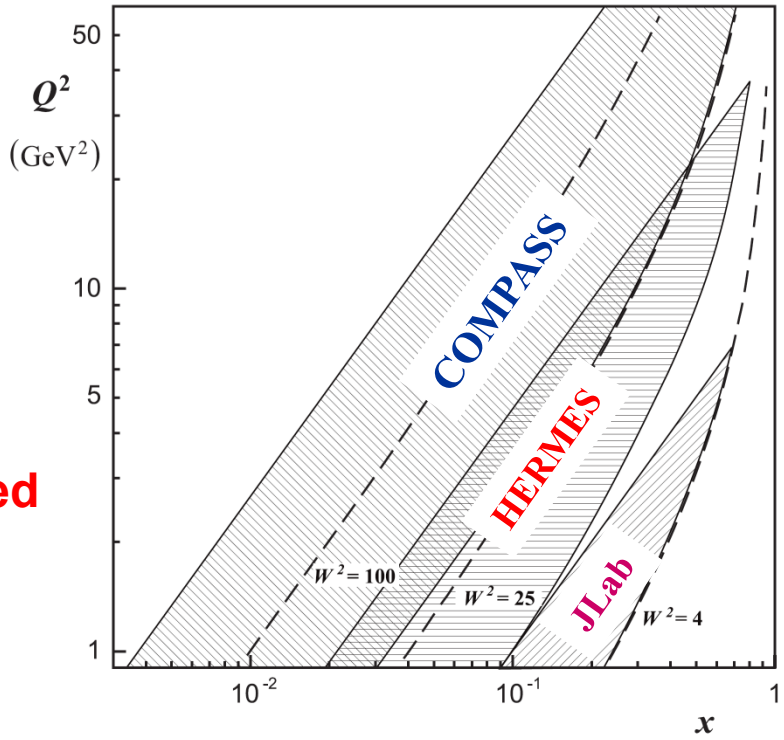


in the last years a lot has been learn on TMDs thanks to the new SIDIS results which have been produced by HERMES, COMPASS, JLab on

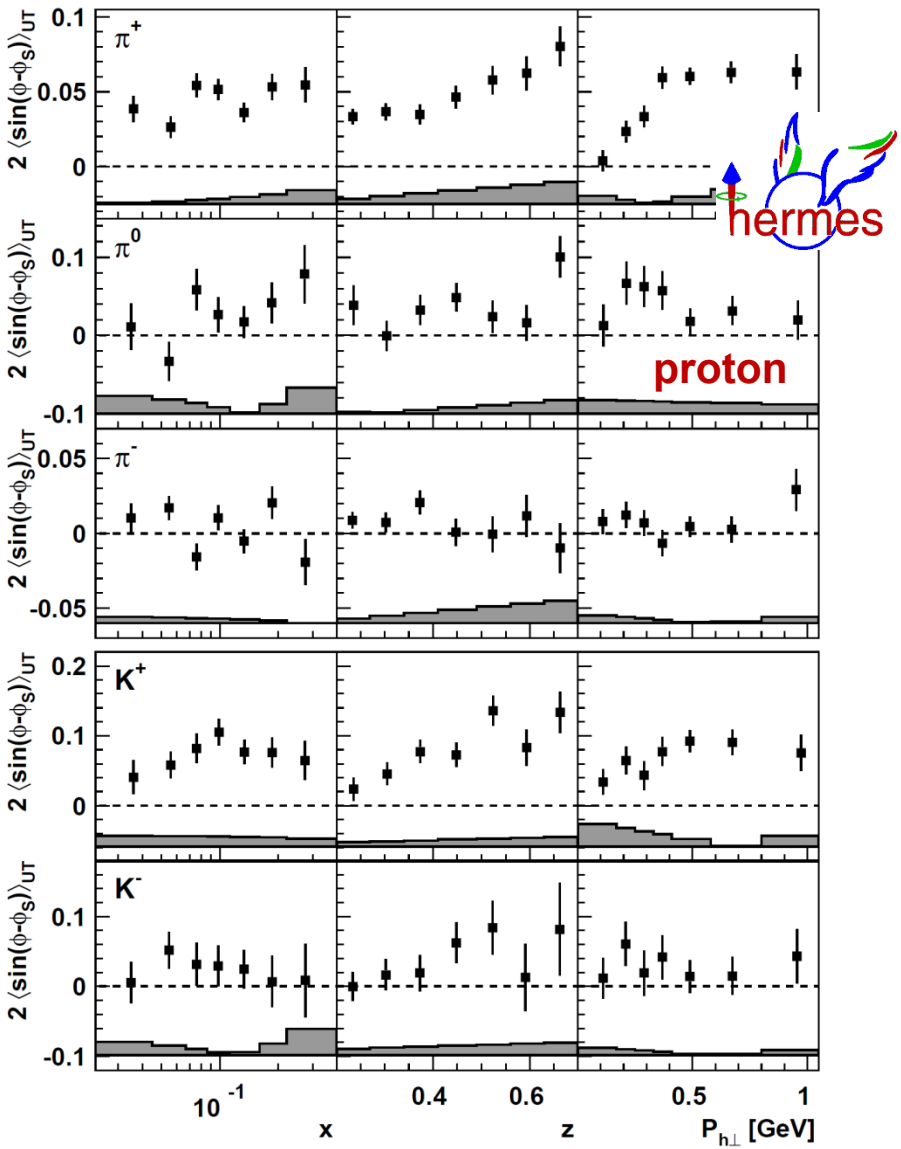
- Sivers asymmetry
- Collins and di-hadron asymmetries
- other TSA
- unpolarised asymmetries

many of them are key results !

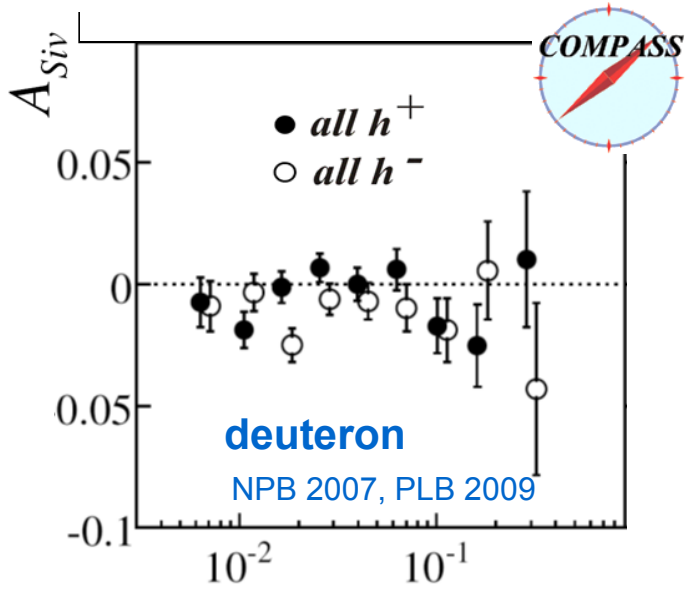
in the following, some of the SIDIS results on

- Sivers asymmetry
- Collins asymmetry
- di-hadron asymmetry
- other TSA
- unpolarised asymmetries

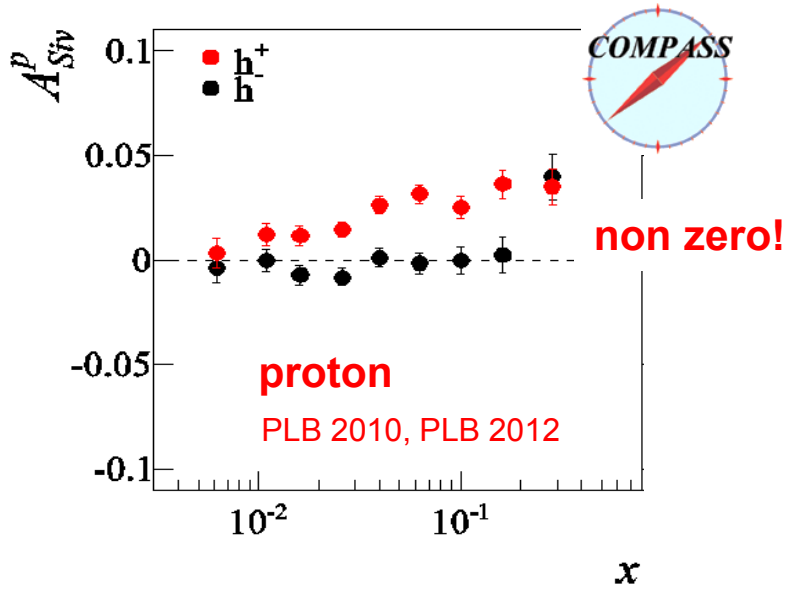
Sivers asymmetry – final results



PR103, 2009

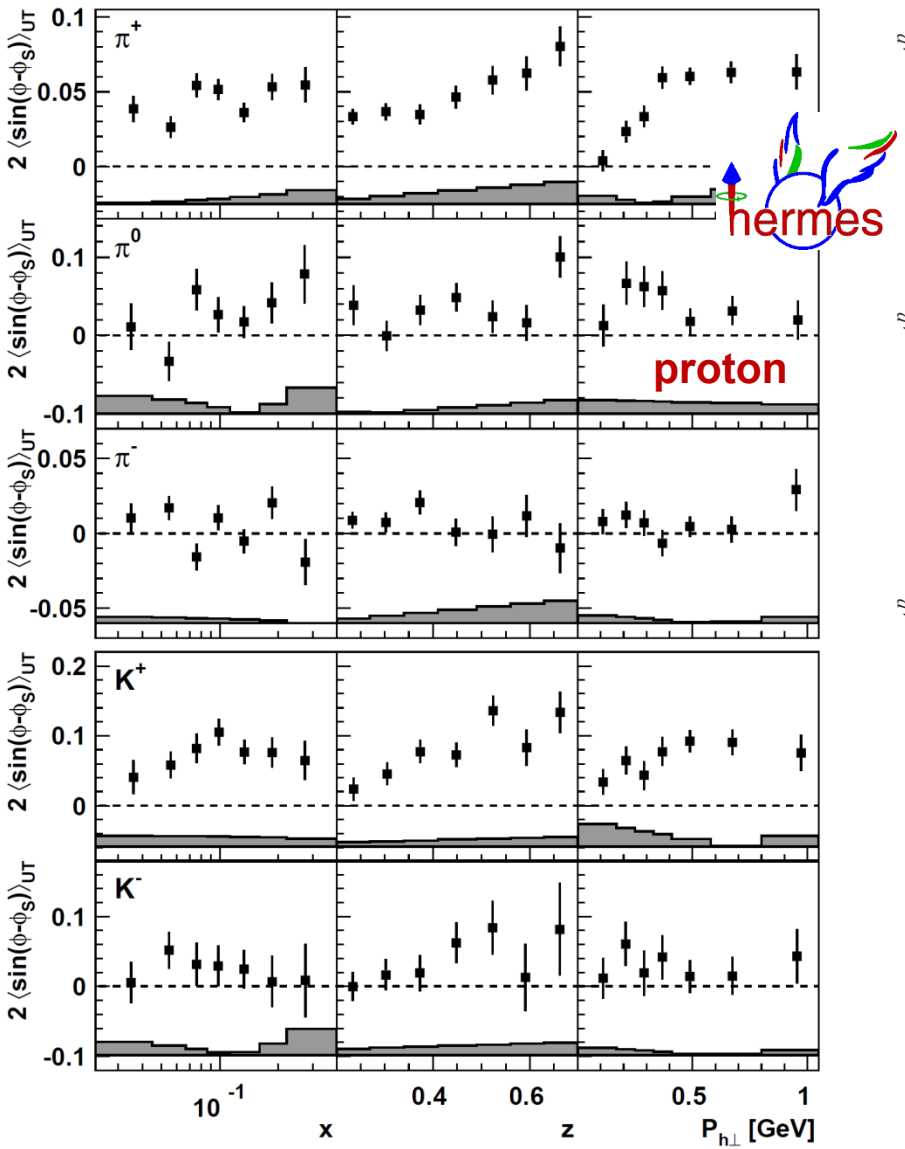


NPB 2007, PLB 2009



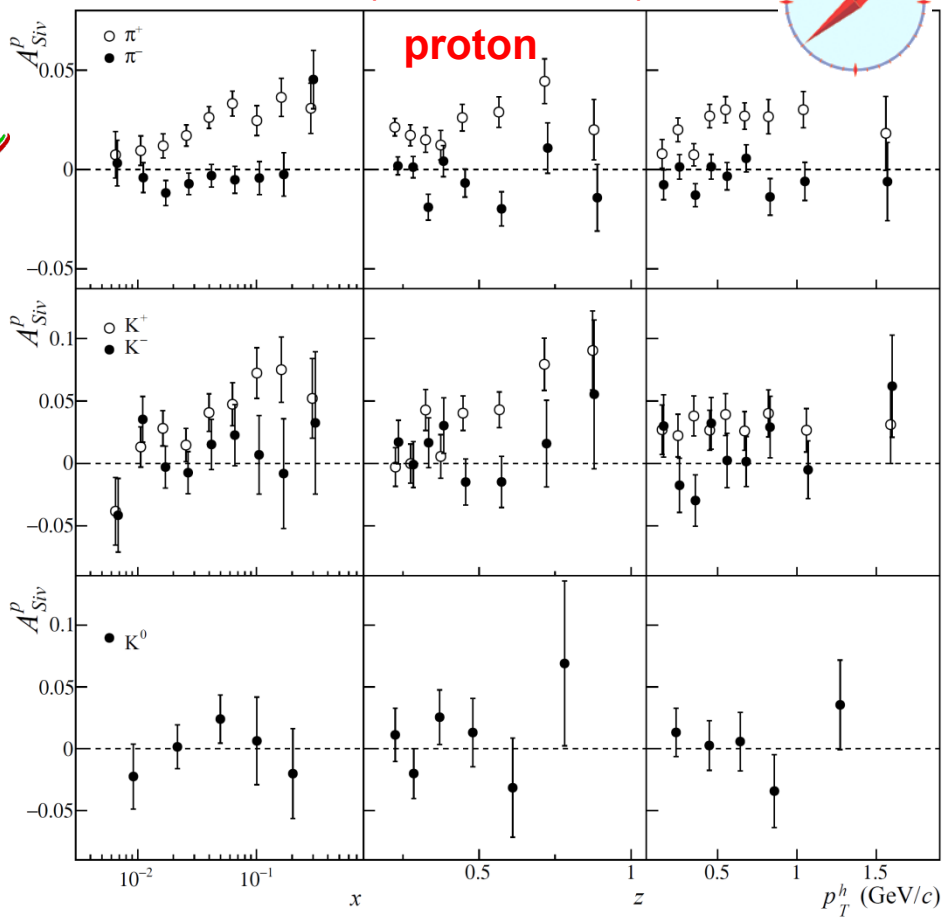
PLB 2010, PLB 2012

Sivers asymmetry – final results

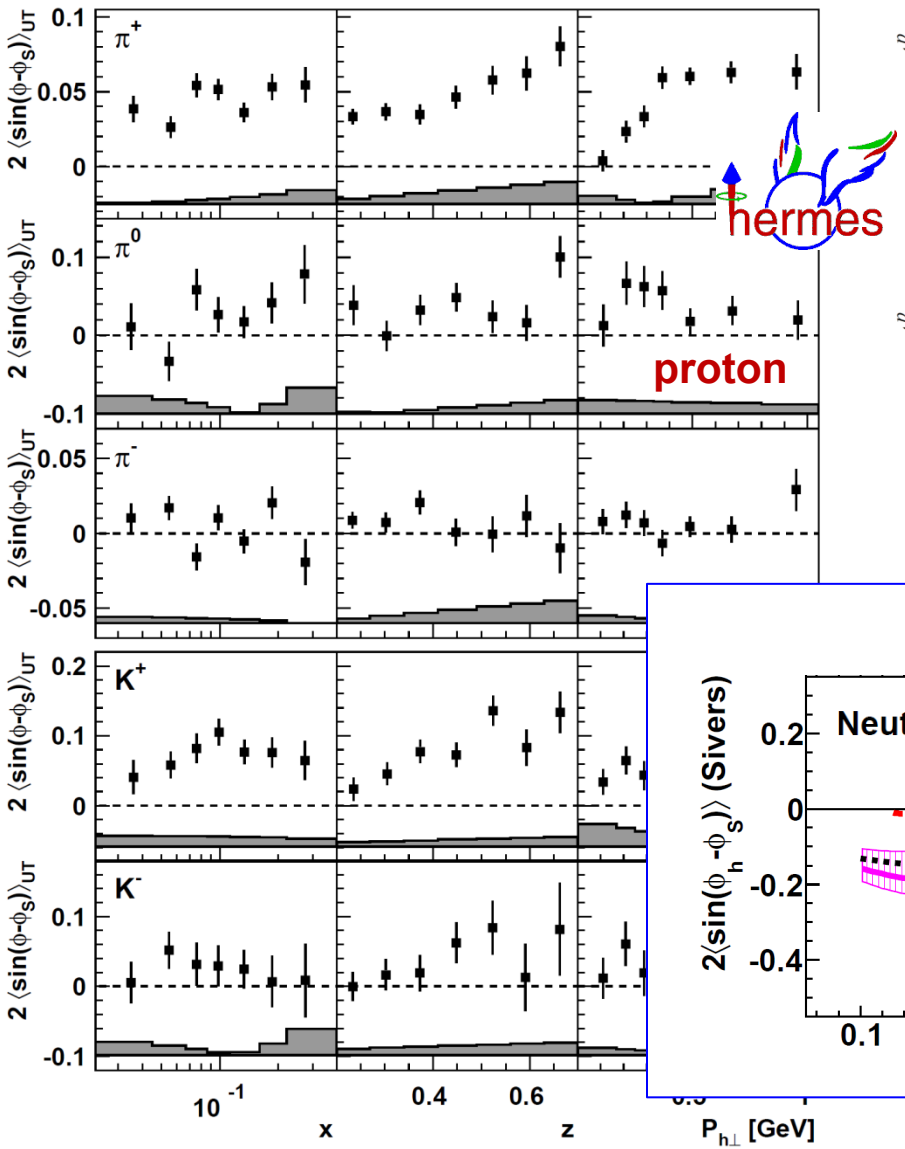


PR103, 2009

hep-ex/1408.4405 sfp

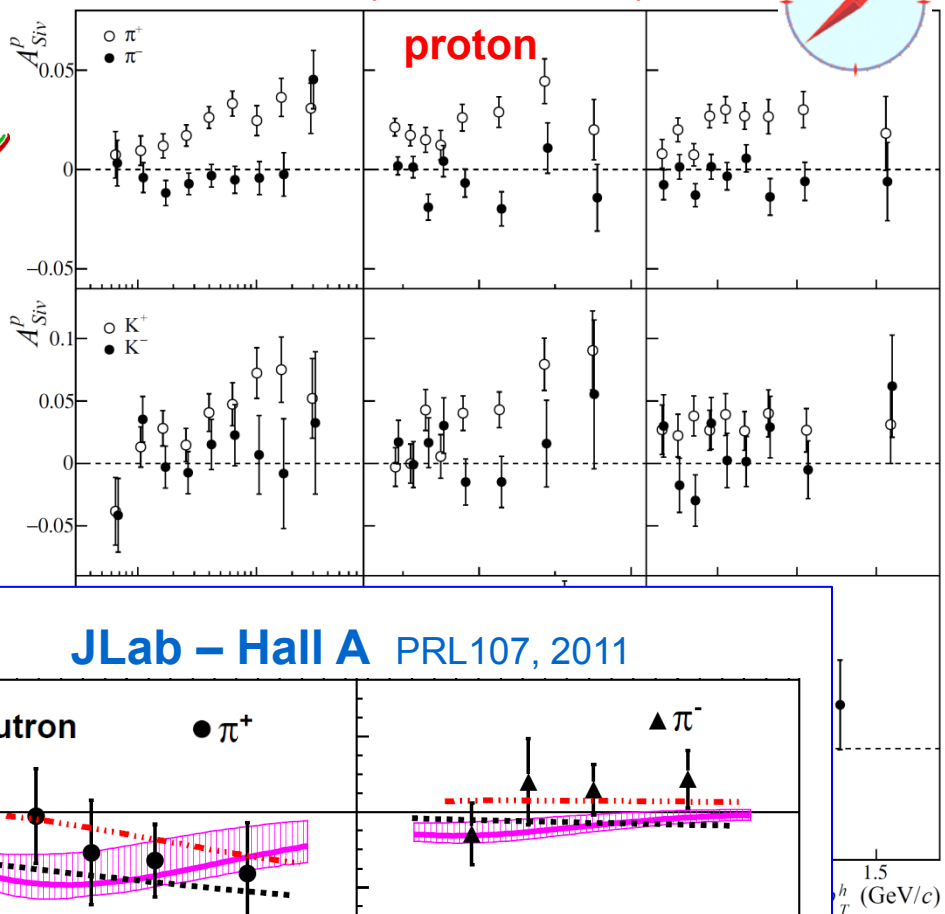


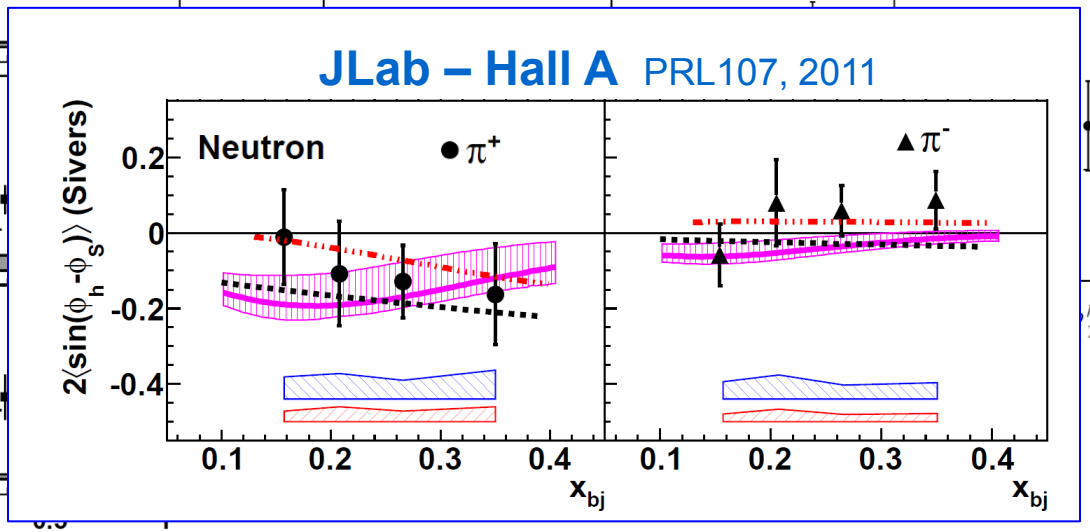
Sivers asymmetry – final results



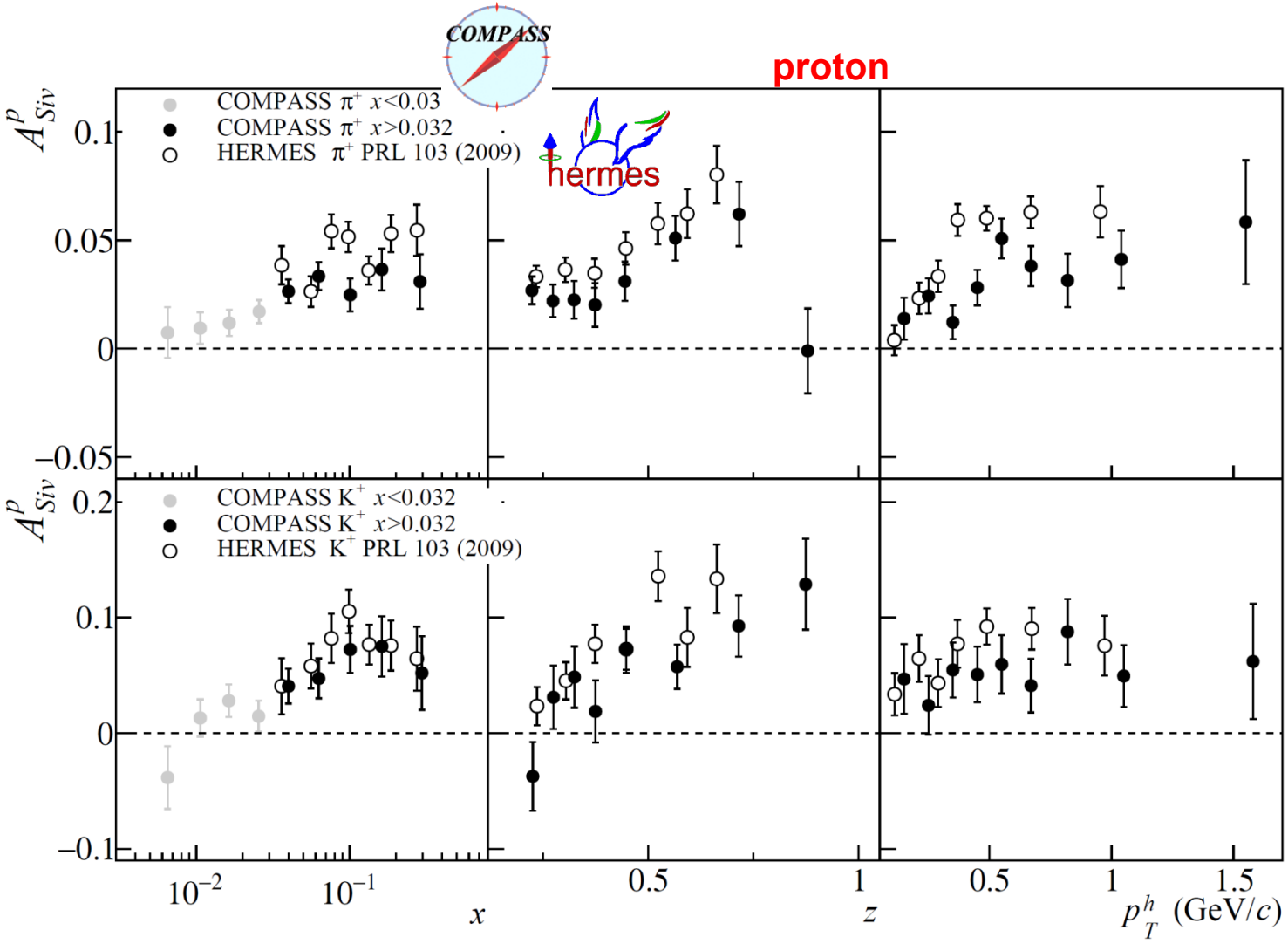
PR103, 2009

hep-ex/1408.4405 sfp



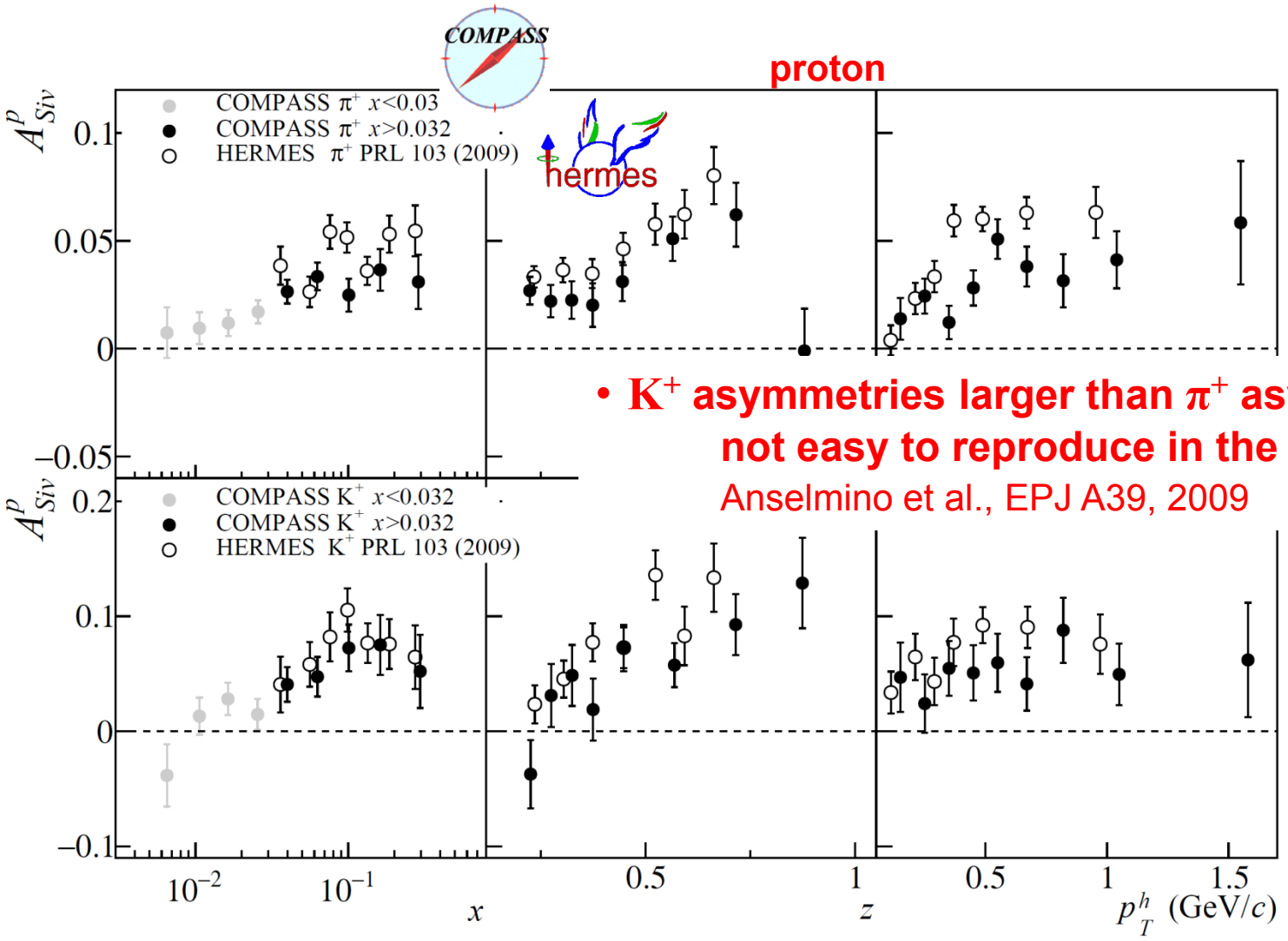


Sivers asymmetry – final results



PR103, 2009

Sivers asymmetry – final results

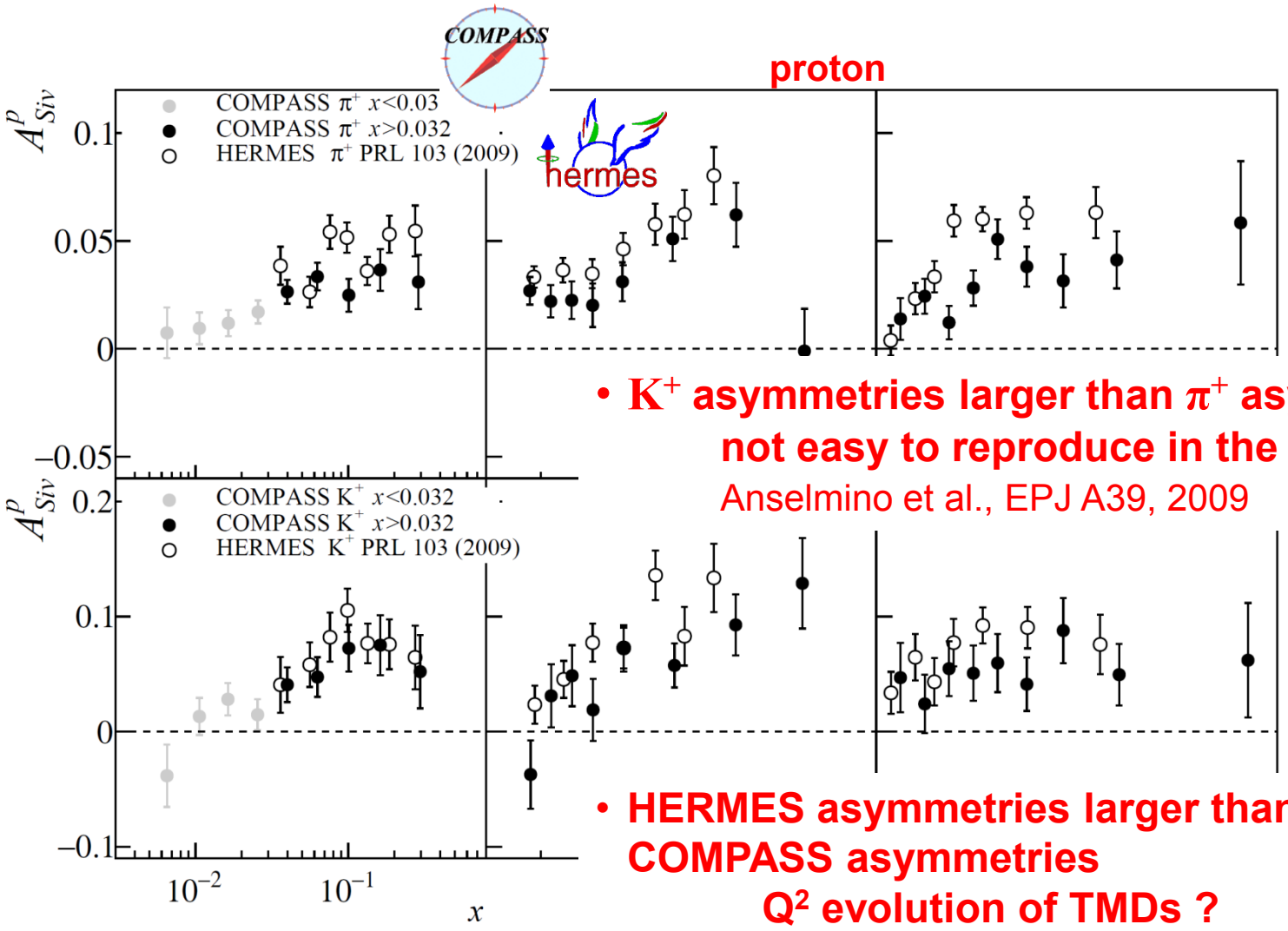


- K^+ asymmetries larger than π^+ asymmetries not easy to reproduce in the fits

  Anselmino et al., EPJ A39, 2009

PR103, 2009

Sivers asymmetry – final results



- **K^+ asymmetries larger than π^+ asymmetries not easy to reproduce in the fits**

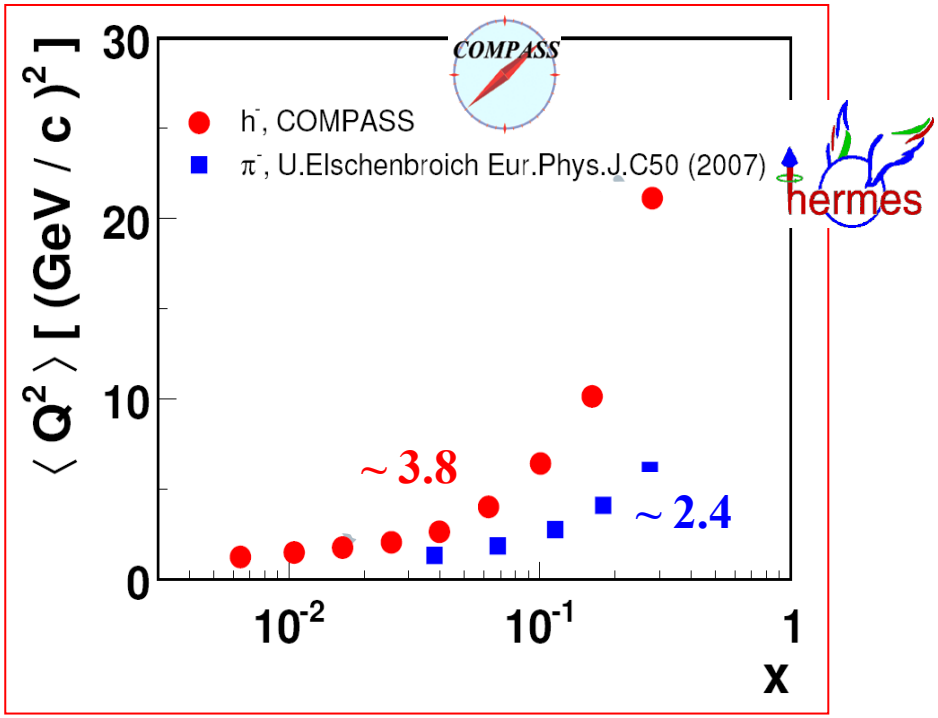
  Anselmino et al., EPJ A39, 2009

- **HERMES asymmetries larger than COMPASS asymmetries**

  Q^2 evolution of TMDs ?

PRL103, 2009

Sivers asymmetry – final results

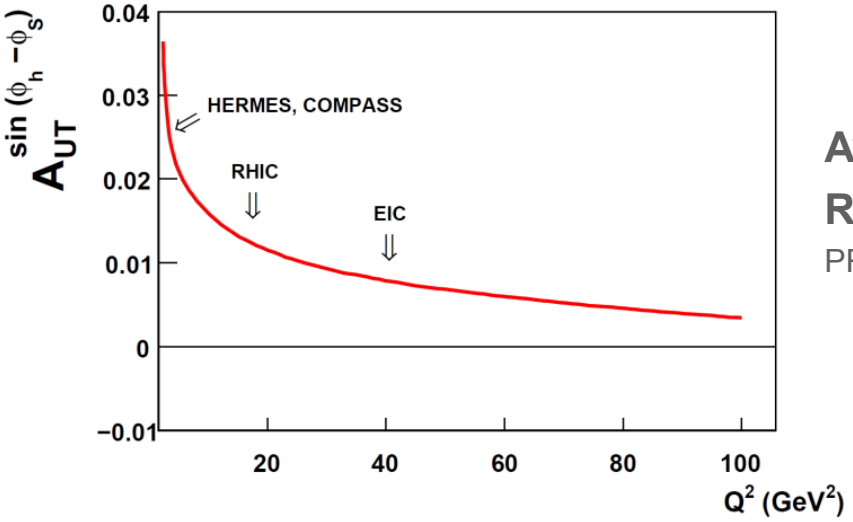


- **HERMES asymmetries larger than COMPASS asymmetries**
  Q^2 evolution of TMDs ?

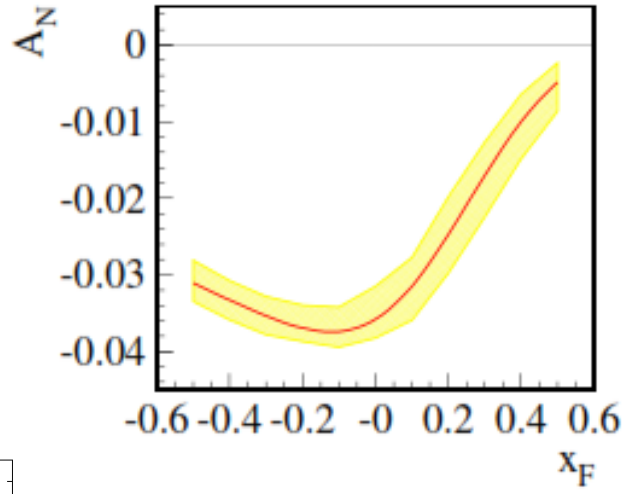
TMDs evolution

a lot of work in the last years, progressing fast
from very strong to weak

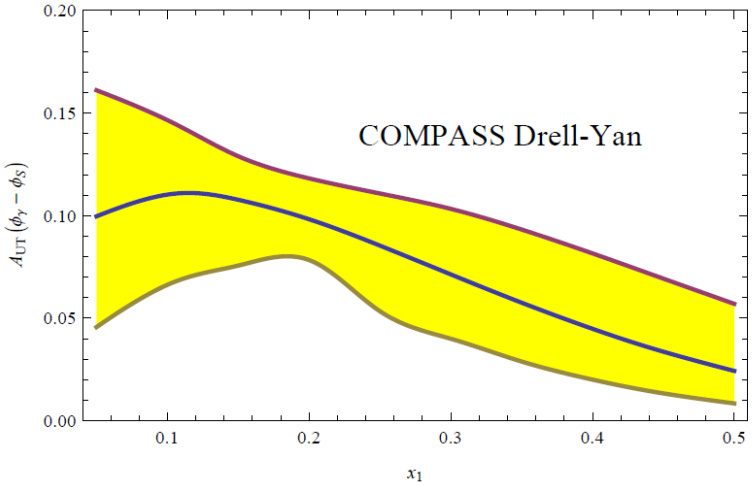
several papers with fits of SIDIS data and predictions for DY at COMPASS



Aybat Prokudin
Rogers
PRL108 2012



Echevarria et al
PRD89 2014



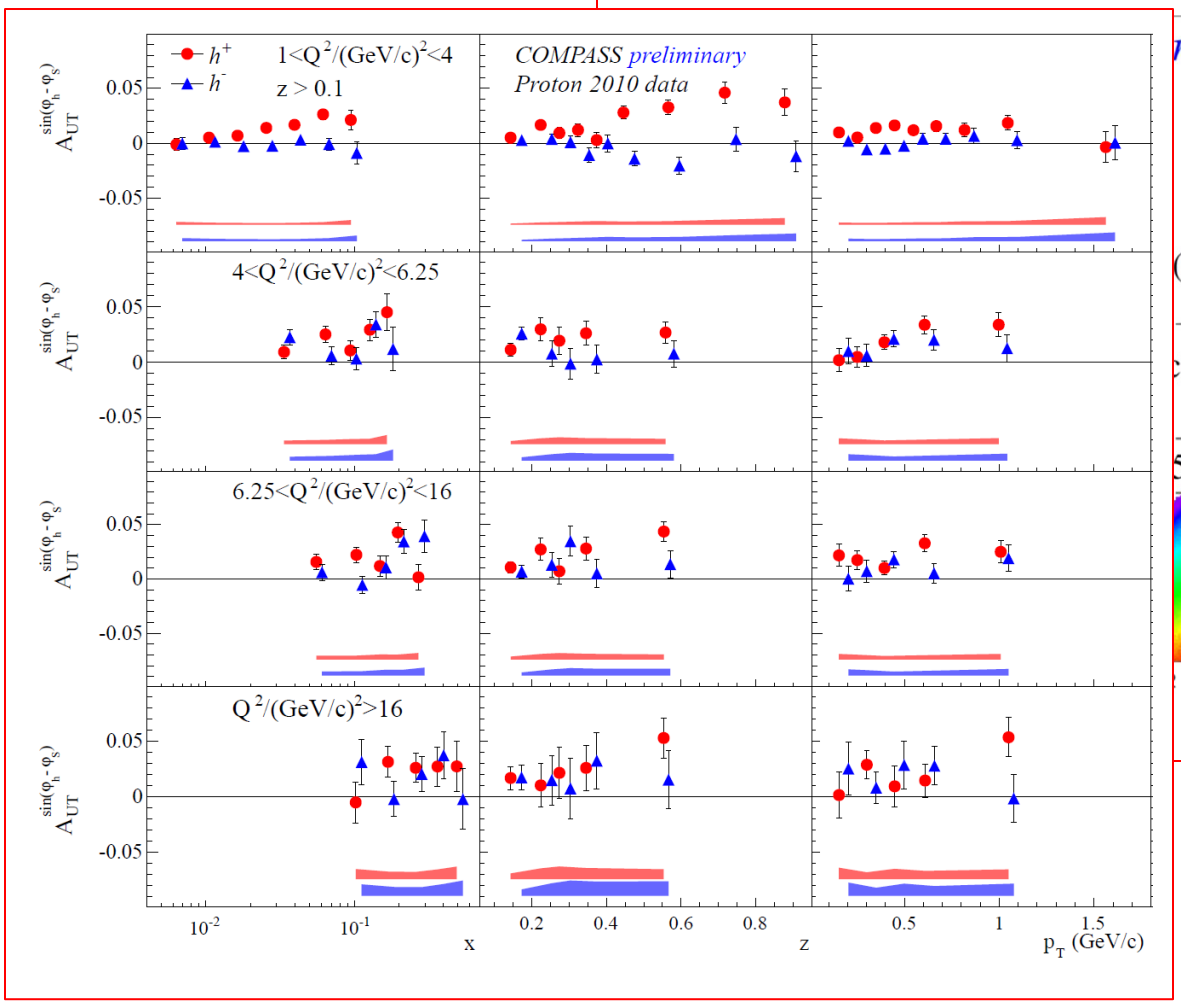
Sun, Yuan
PRD88 2013

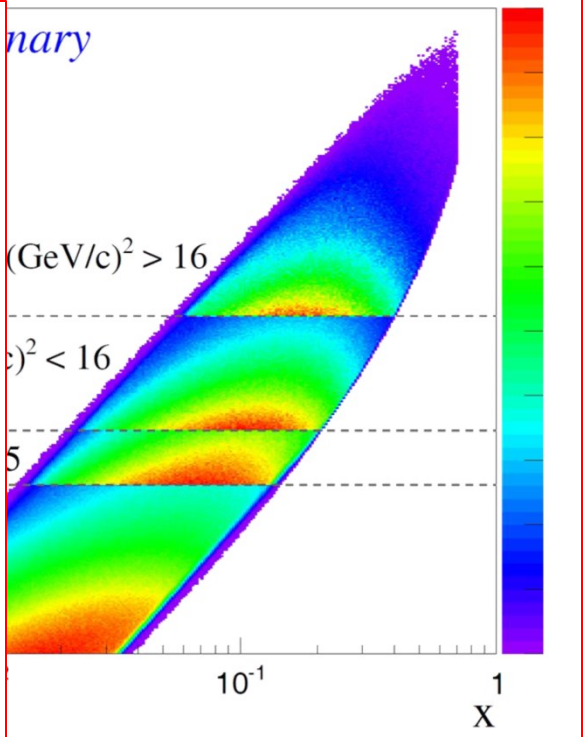
PR103, 2009

TMDs evolution c1 – high Q^2

COMPASS has measured the TSA in the Q^2 "golden" range of the Drell-Yan measurement of COMPASS

B. Parsamyan, Transversity 2014





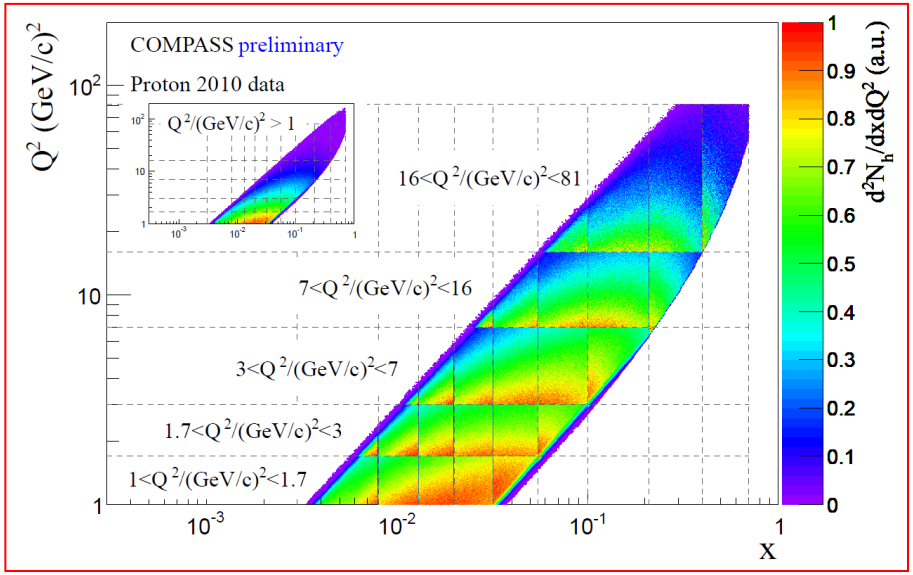
clearly positive:

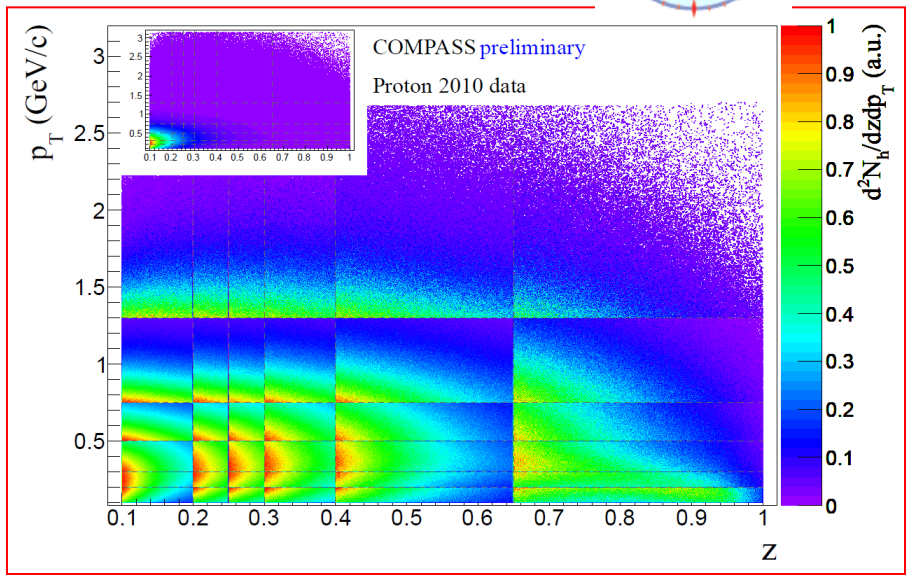
test of change of sign ok!

TMDs evolution c1 – high Q^2

new: multidimensional measurement of TSA at COMPASS

→ B. Parsamyan, today





TMDs evolution c1 – high Q^2

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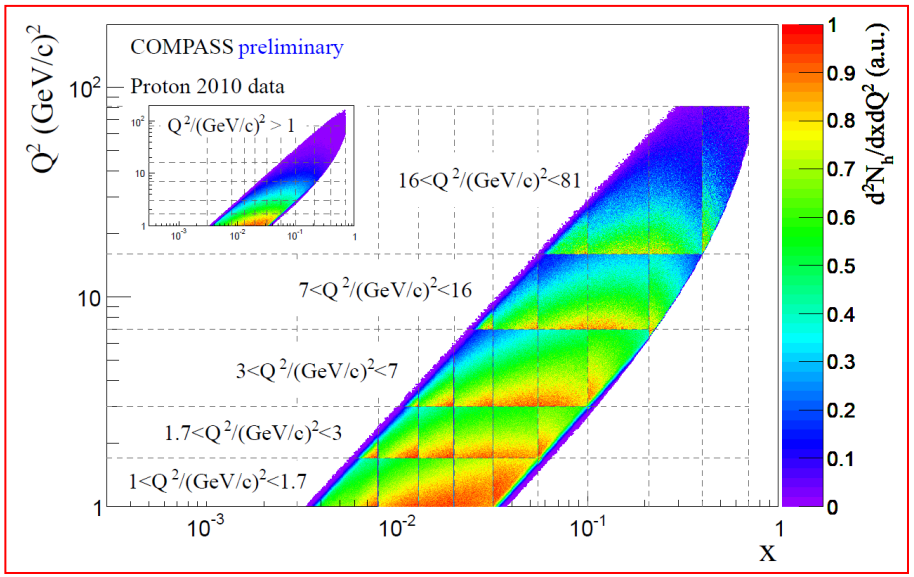

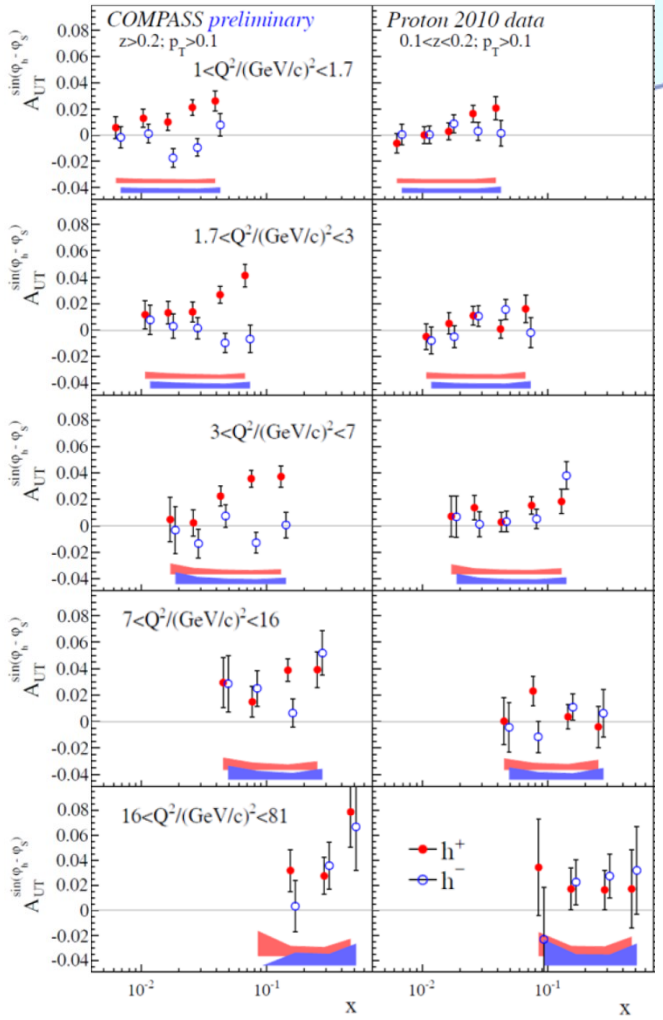

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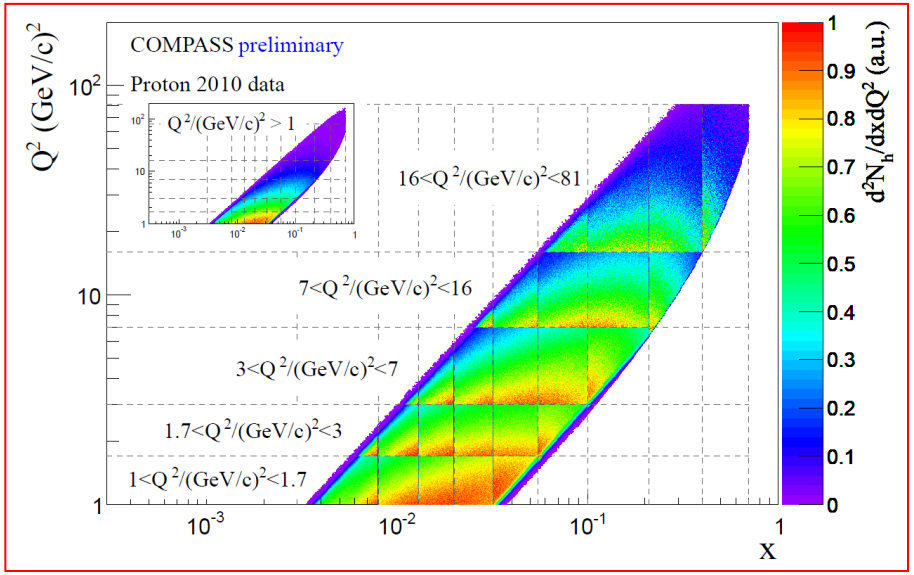
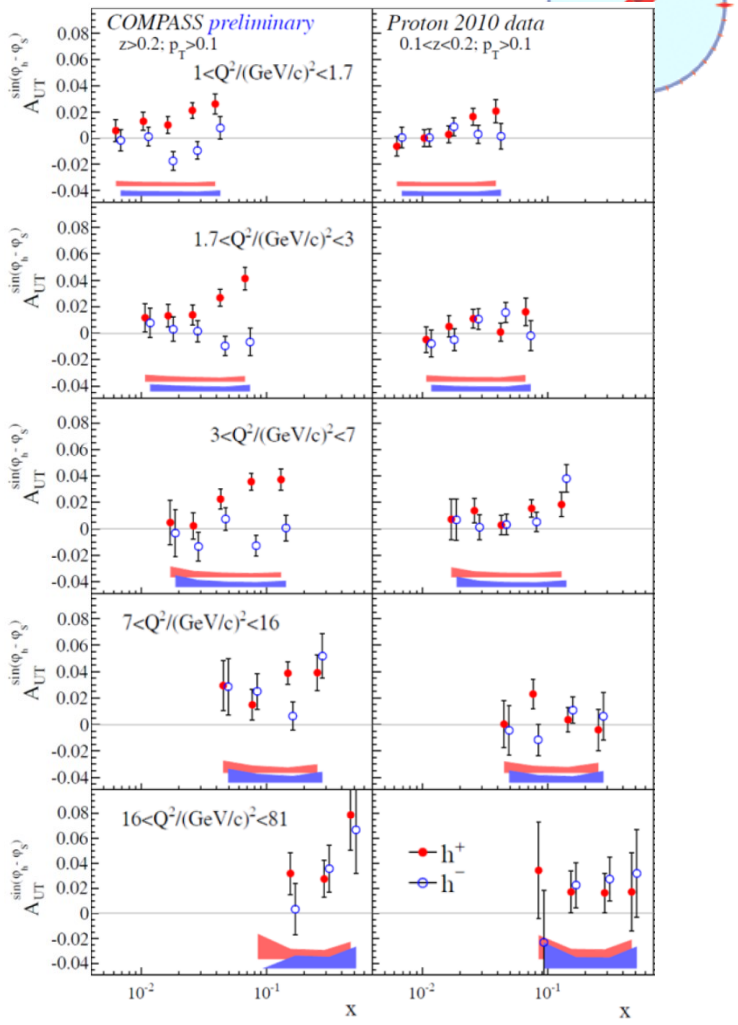




new: similar analysis by HERMES

A. Rostomyan, yesterday

TMDs evolution c2 – $< k_T^2 >$

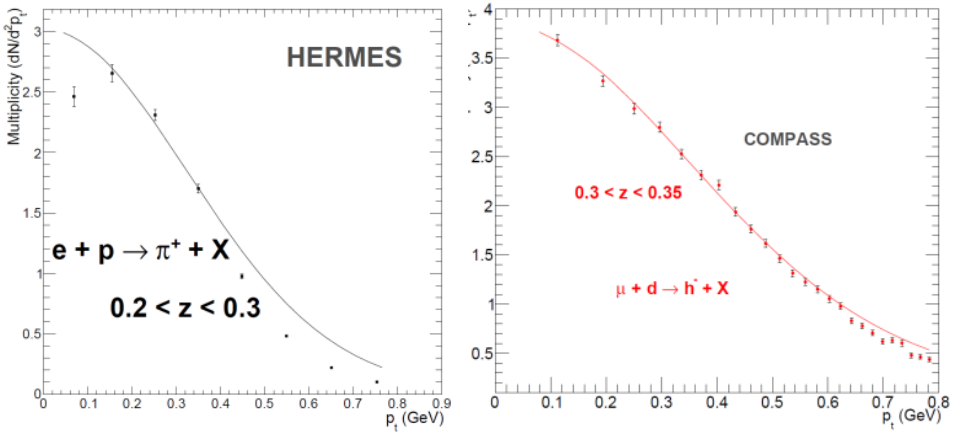
P_T^2 distributions are a hot topic: needed for Q^2 evolution, PDF extraction, …

the published data have been used by several groups

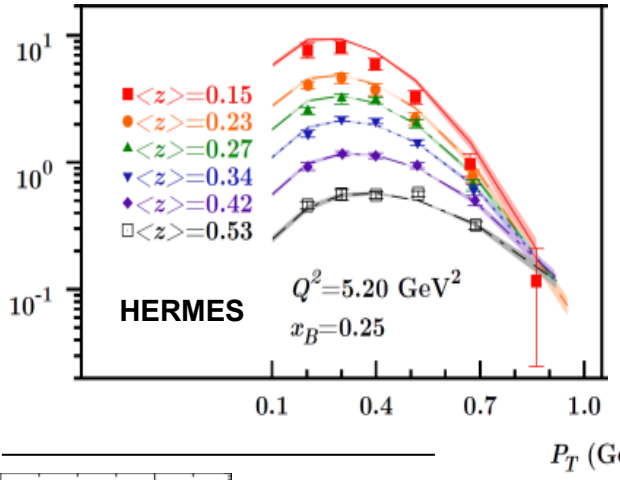
TMDs evolution c2 – $< k_T^2 >$

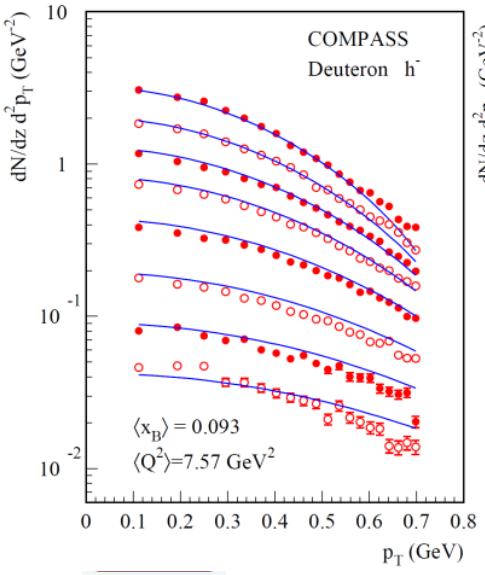
P_T^2 distributions are a hot topic: needed for Q^2 evolution, PDF extraction, …

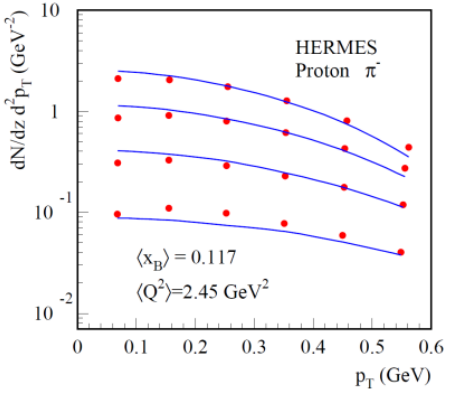
Sun, Yuan PRD88 2013



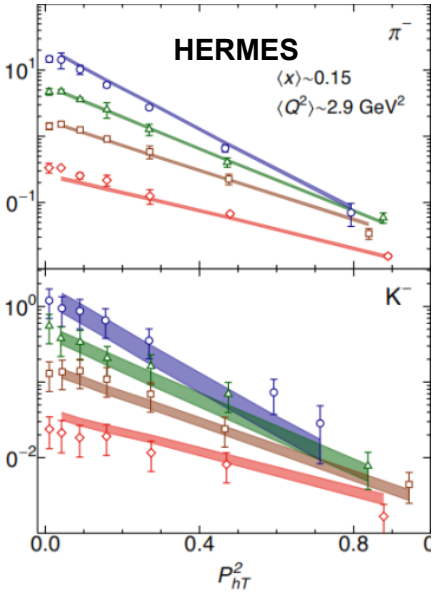
Anselmino et al JHEP 1404 2014







Echevarria et al
PRD89 2014

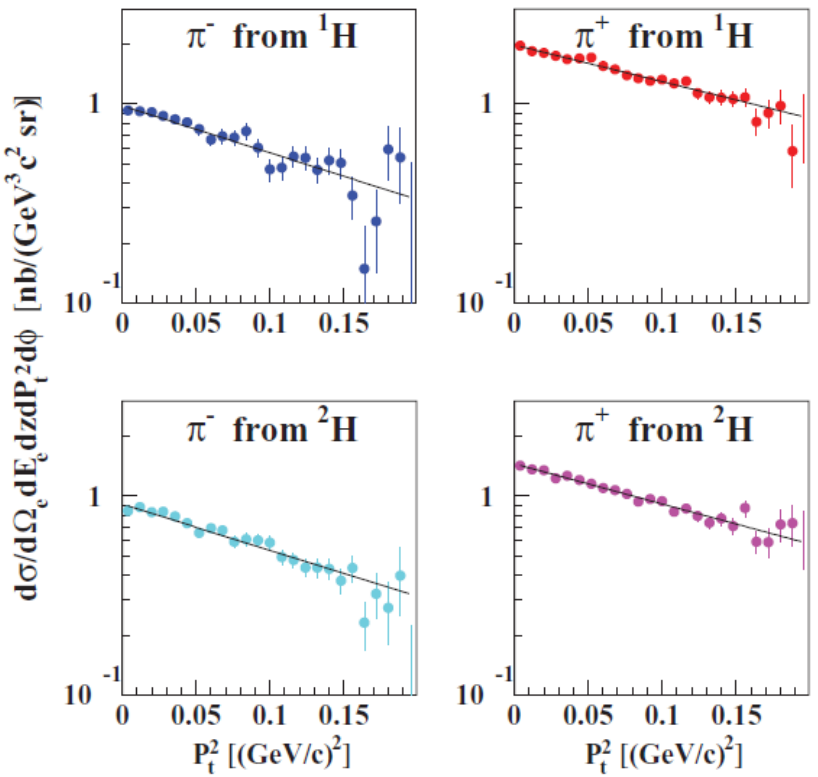


Signori et al
JHEP1311 2013

TMDs evolution c2 – $< k_T^2 >$

P_T^2 distributions are a hot topic: needed for Q^2 evolution, PDF extraction, …

many interesting results from JLab



Asaturyan et al. PRC85 2012

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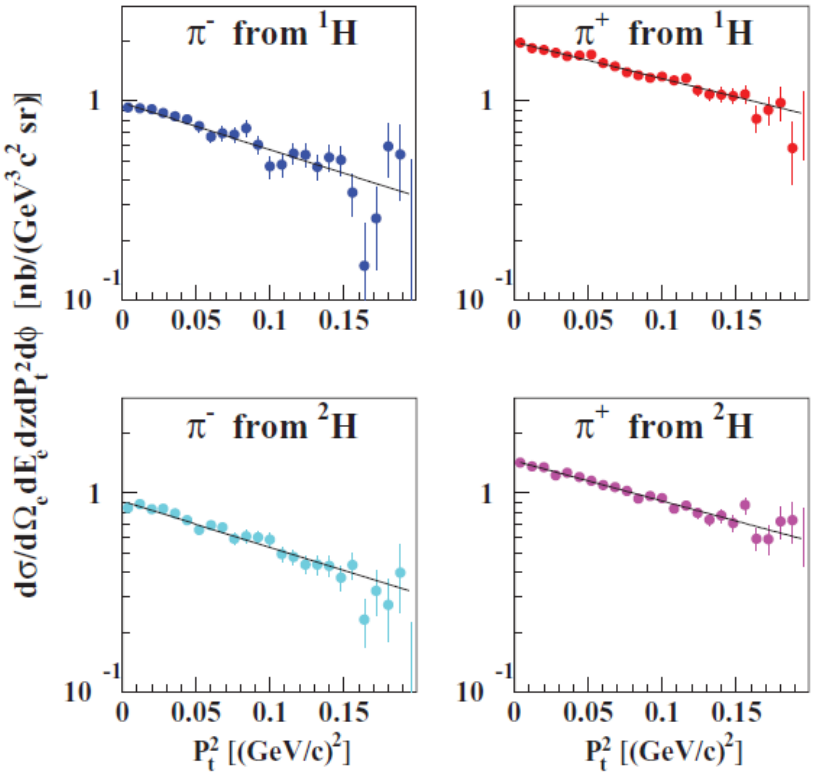
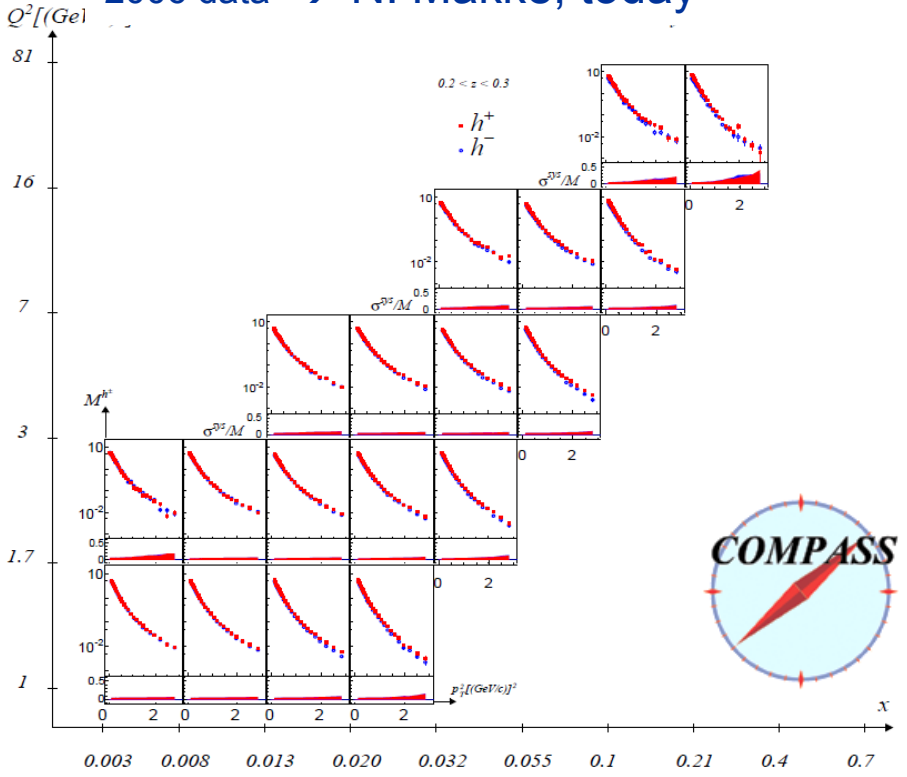


Asaturyan et al. PRC85 2012

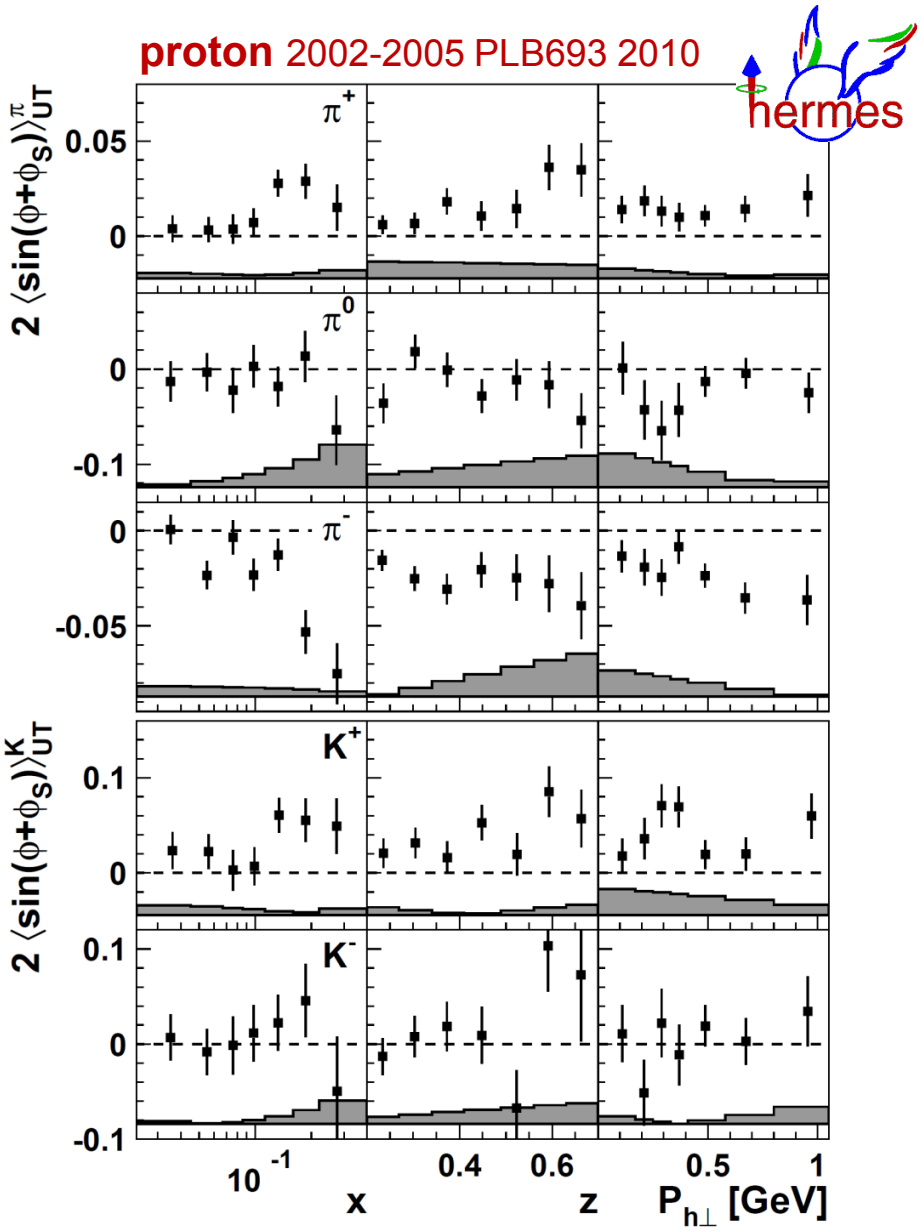
new: results from COMPASS

2006 data → N. Makke, today

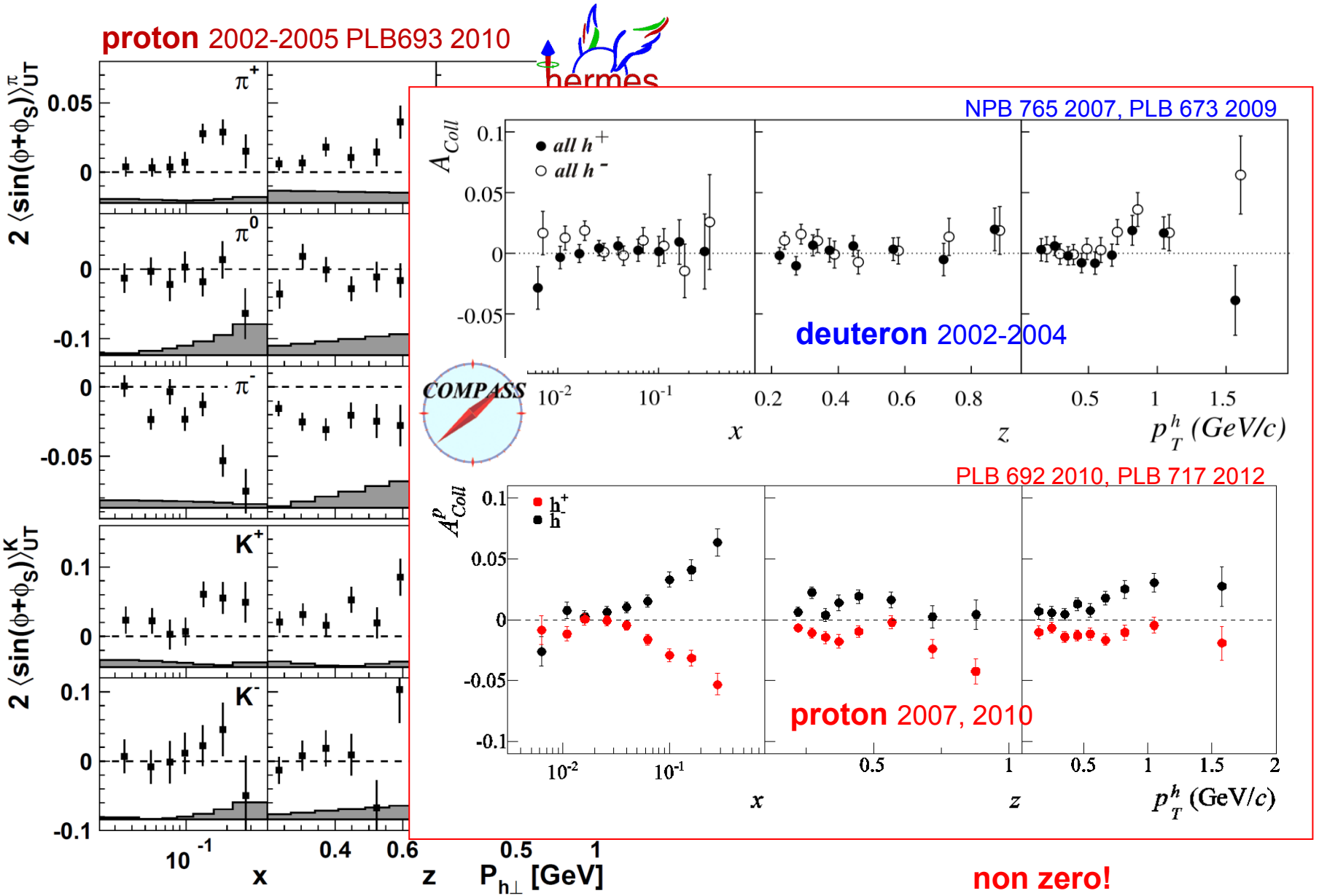


- Sivers asymmetry
- **Collins asymmetry**
- di-hadron asymmetry
- other TSA
- unpolarised asymmetries

Collins asymmetry – final results

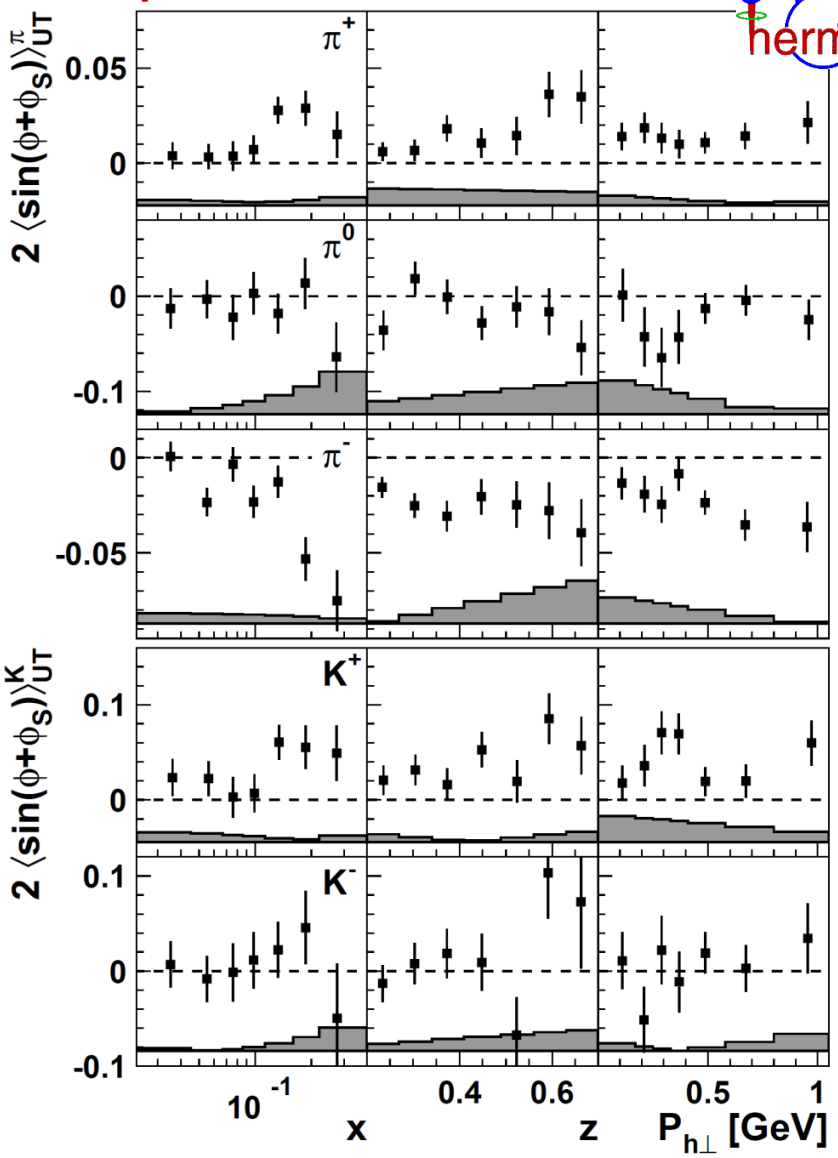


Collins asymmetry – final results

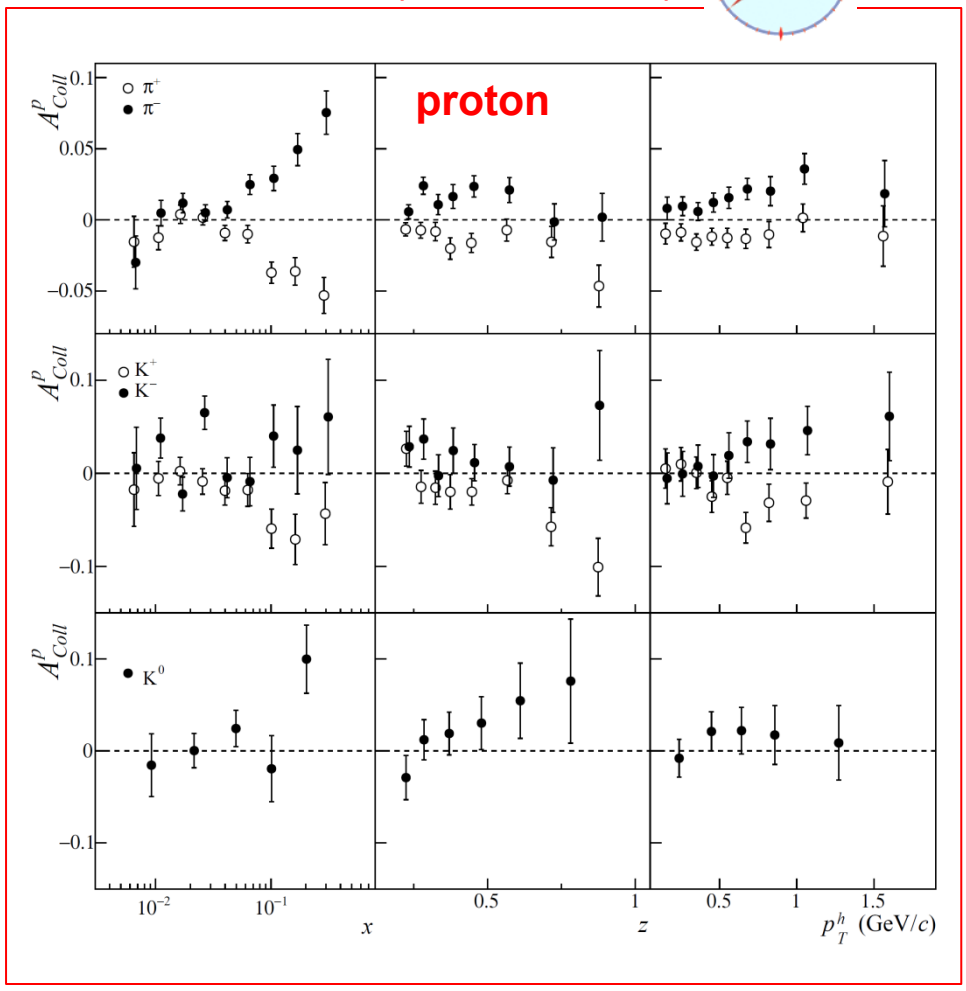


Collins asymmetry – final results

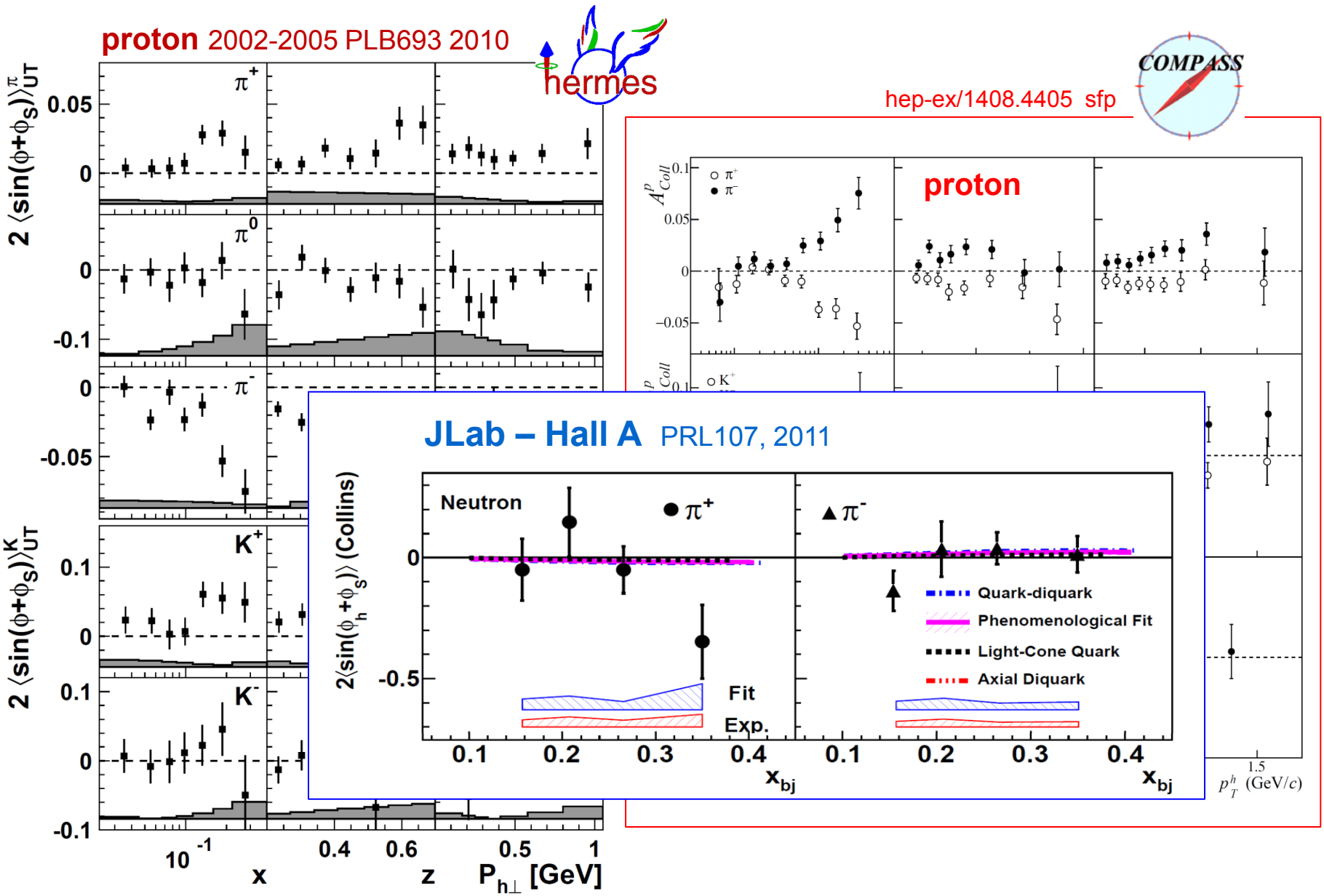
proton 2002-2005 PLB693 2010



hep-ex/1408.4405 sfp



Collins asymmetry – final results

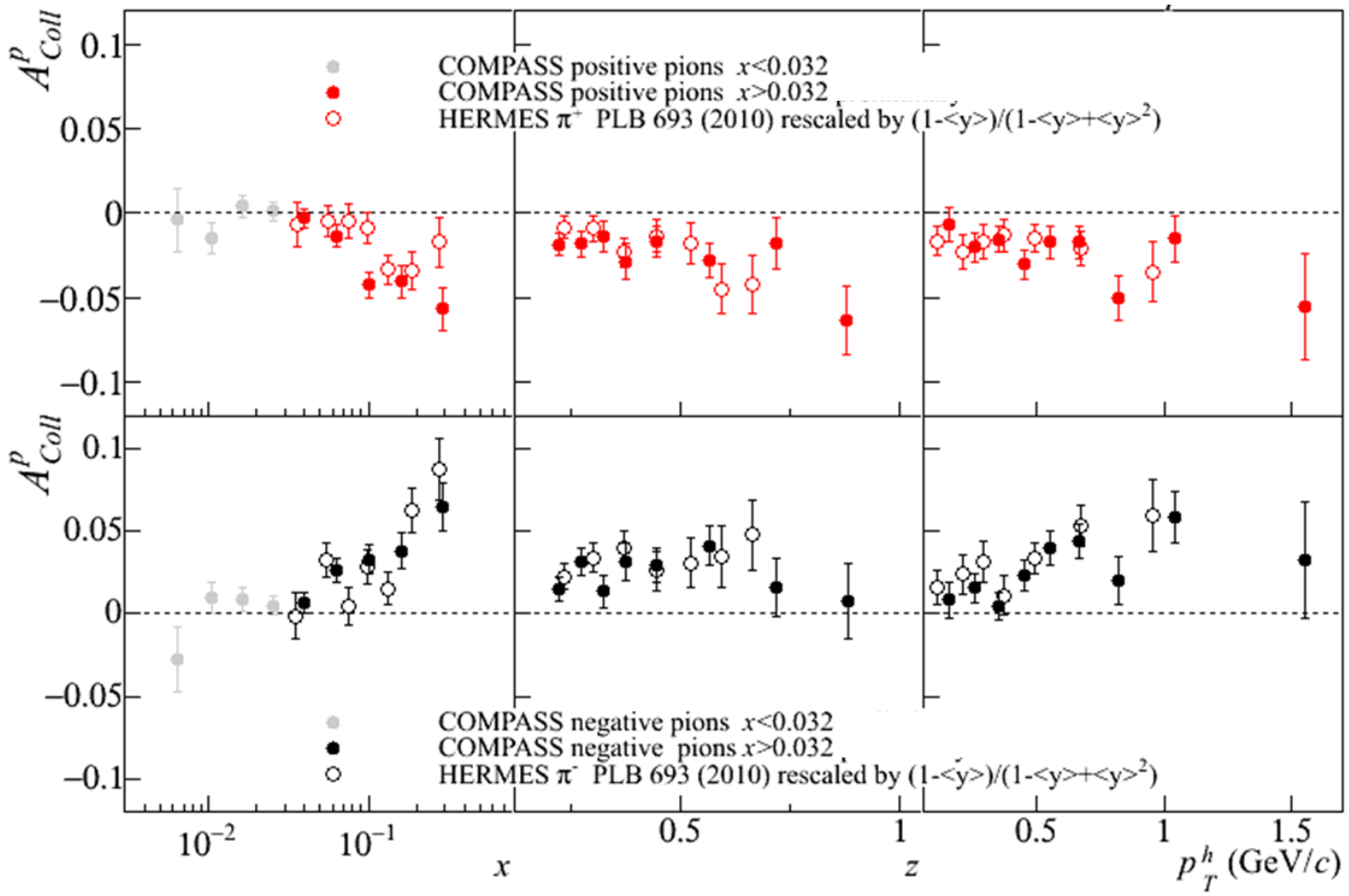


Collins asymmetry – final results

charged pions

π+ ● ○

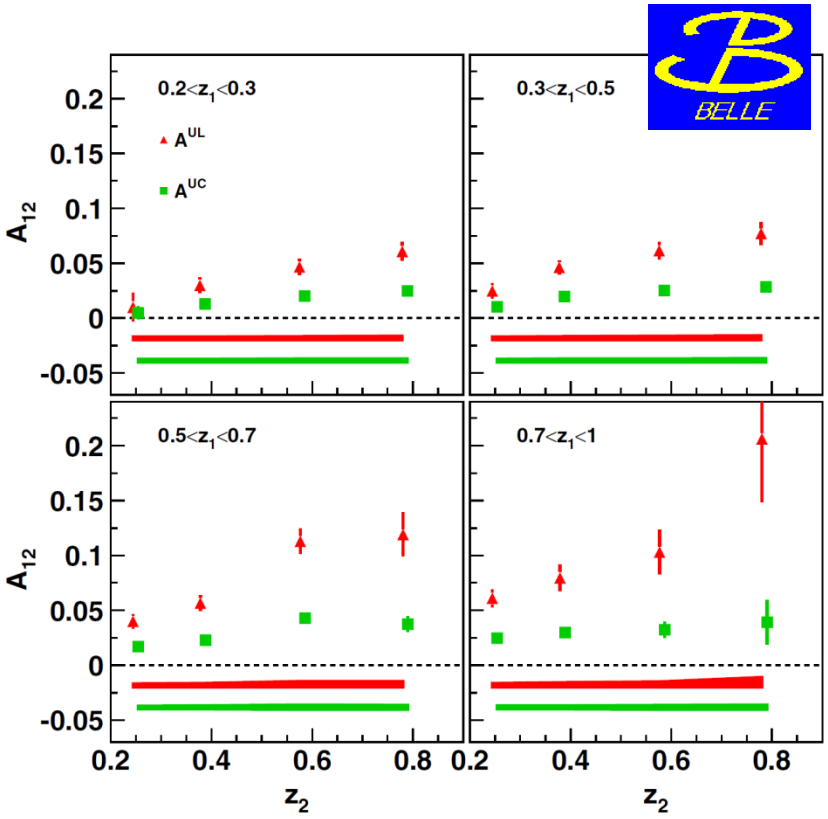
π- ● ○



Q^2 evolution of Collins FF?

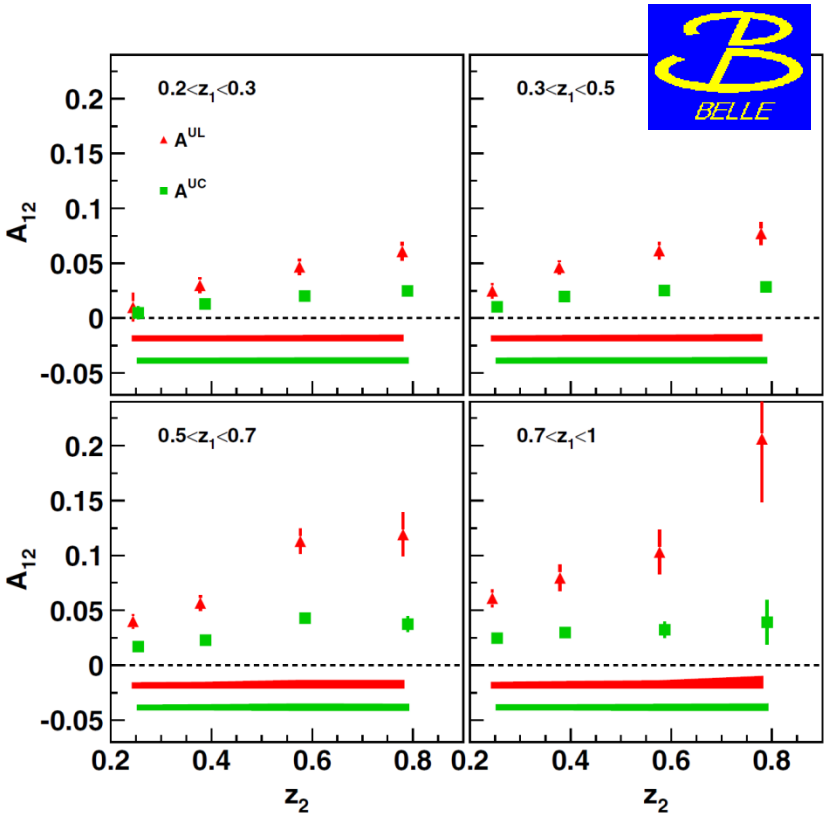
ratio ~3

Collins FF

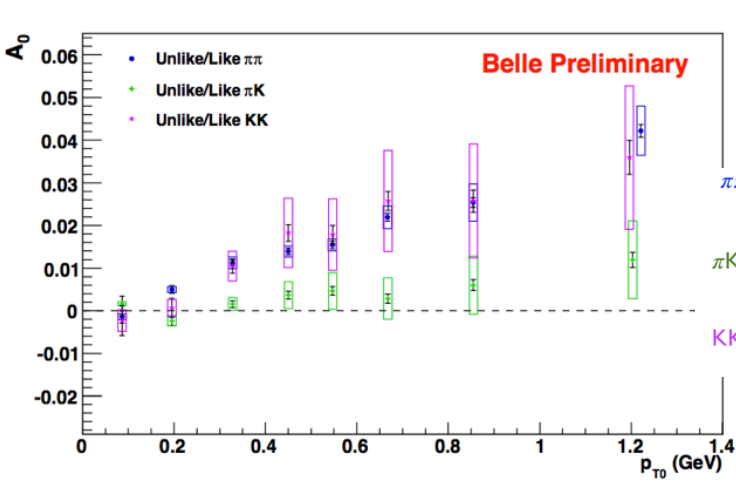


PRD78, 2008 PRD86, 2012

Collins FF



PRD78, 2008 PRD86, 2012

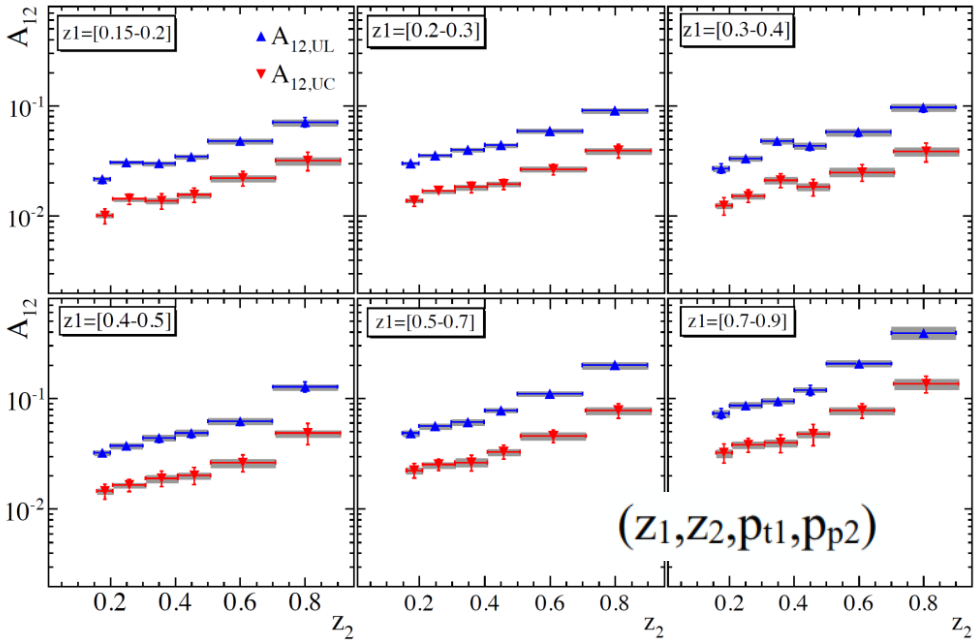


ππ => non-zero asymmetries, increase with z_1, z_2

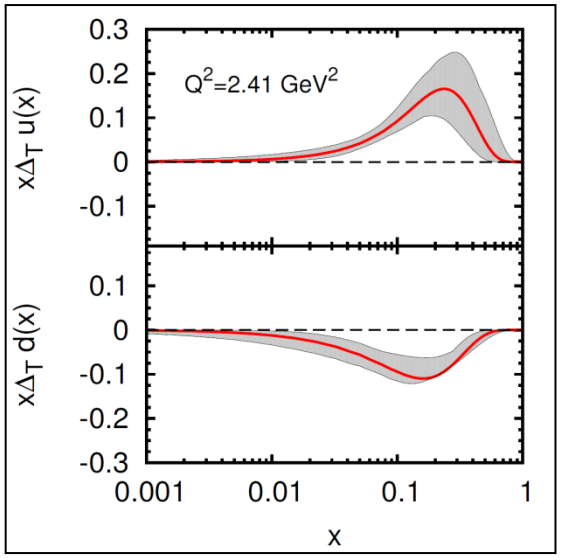
πK => asymmetries compatible with zero

KK => non-zero asymmetries, increase with z_1,z_2

BABAR PRD90 2014

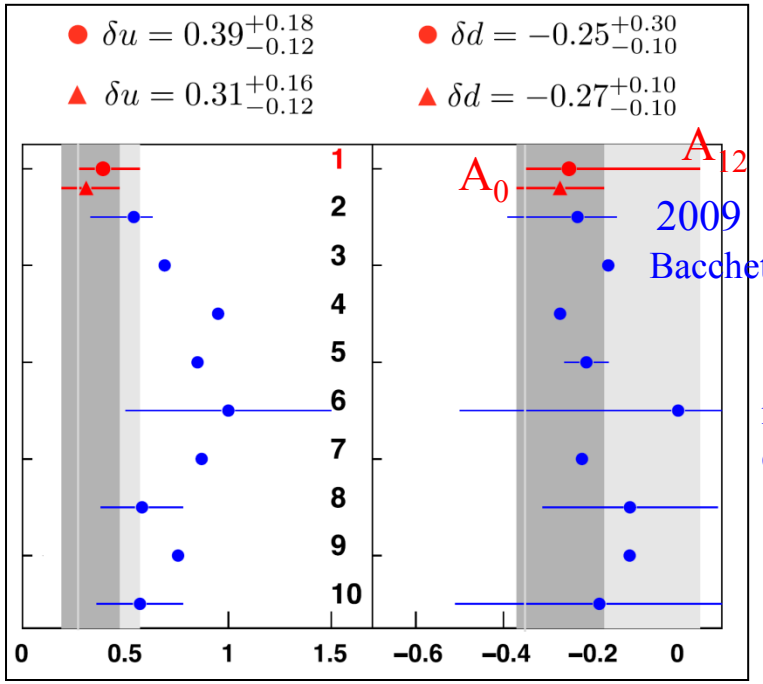


Transversity



Anselmino et al., PRD87 2013
simultaneous fit of
HERMES p, COMPASS p & d, and Belle data
very good χ^2

$$\int_0^1 dx[h_1^q(x) - \bar{h}_1^q(x)] = \delta q.$$



2009
Bacchetta et al, 2012

model calculations

more data
large and small x, p & d / n, PID are needed

- Sivers asymmetry
- Collins asymmetry
- **di-hadron asymmetry**
- other TSA
- unpolarised asymmetries

dihadron asymmetry

independent channel to access transversity in SIDIS on transversely polarised nucleons

Collins

$$A_{Coll} \approx \frac{\sum_q e_q^2 \; h_1^q \otimes H_1^{\perp q}}{\sum_q e_q^2 \; f_1^q \otimes D_q}$$

"Collins FF"

Belle Babar

dihadron

$$A_{RS} \approx \frac{\sum_q e_q^2 \; h_1^q \cdot H_q^{\angle}}{\sum_q e_q^2 \; f_1^q \cdot D_q^{2h}}$$

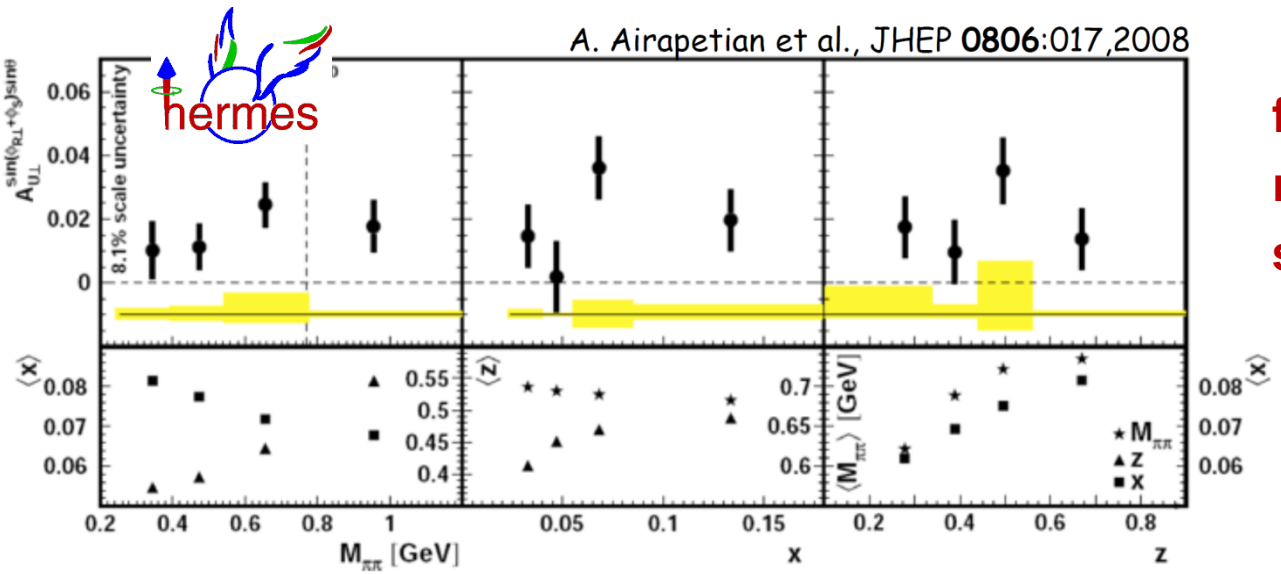
"Interference / Di-hadron FF"

Belle Babar

"spin independent di-hadron FF"

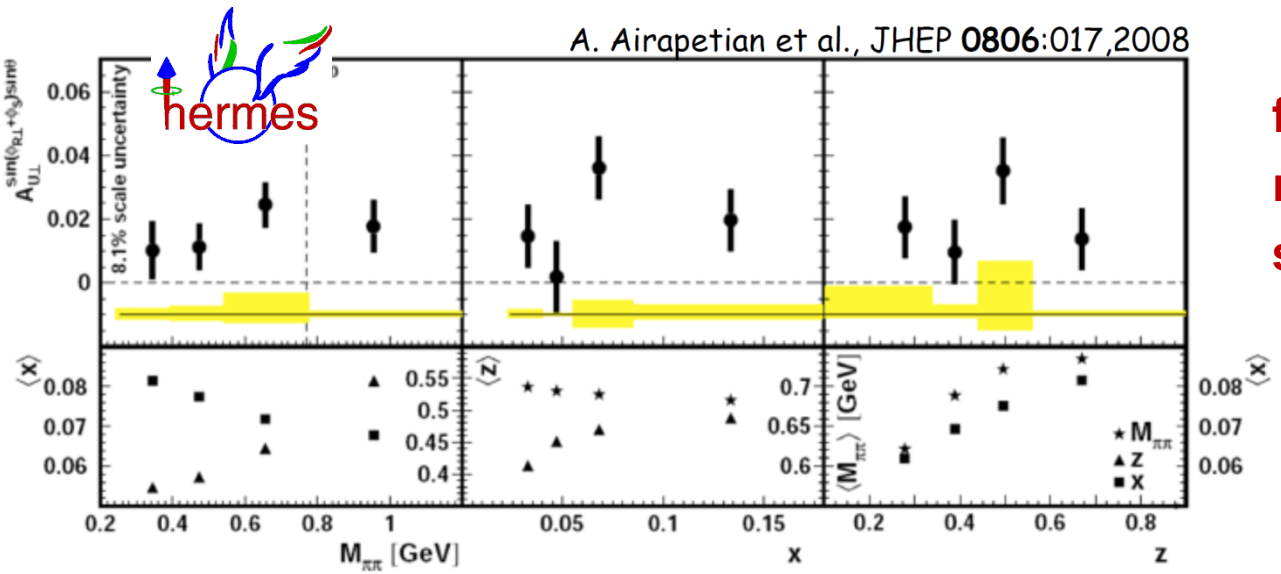
being measured at COMPASS

dihadron asymmetry – final results



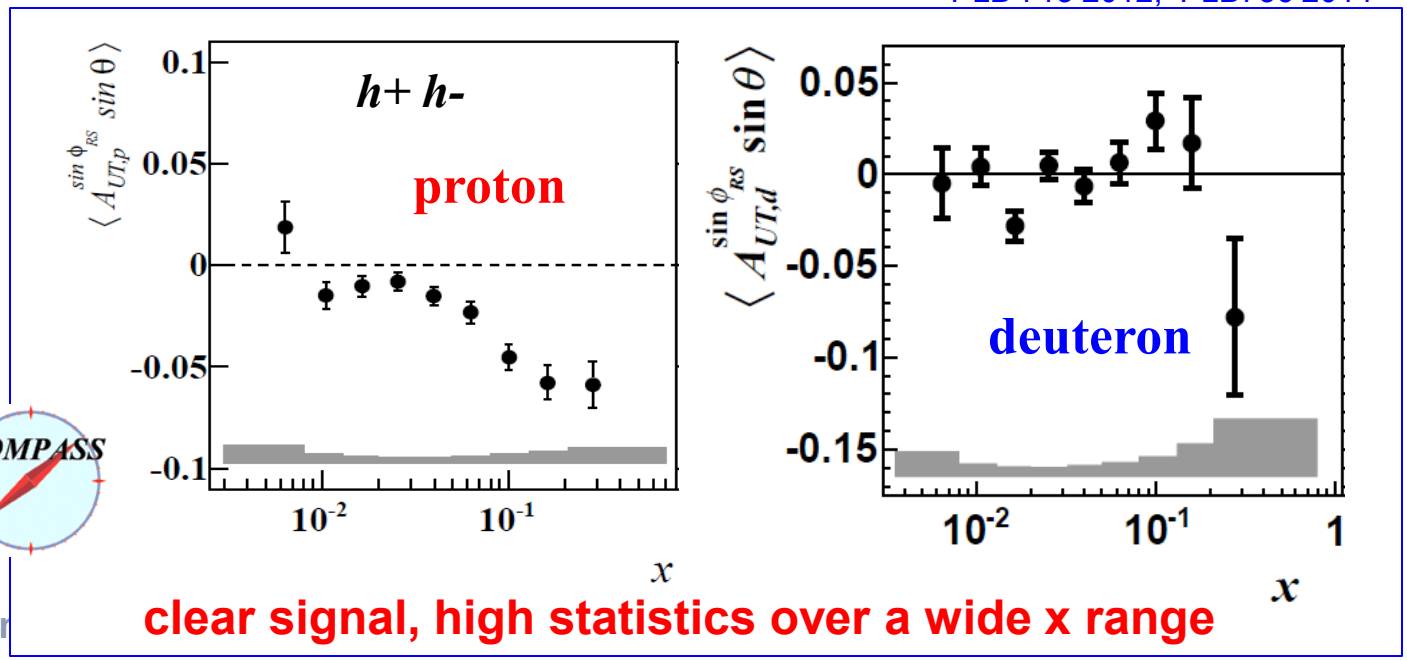
first evidence for non-zero dihadron FF, same sign of Collins FF

dihadron asymmetry – final results



first evidence for non-zero dihadron FF, same sign of Collins FF

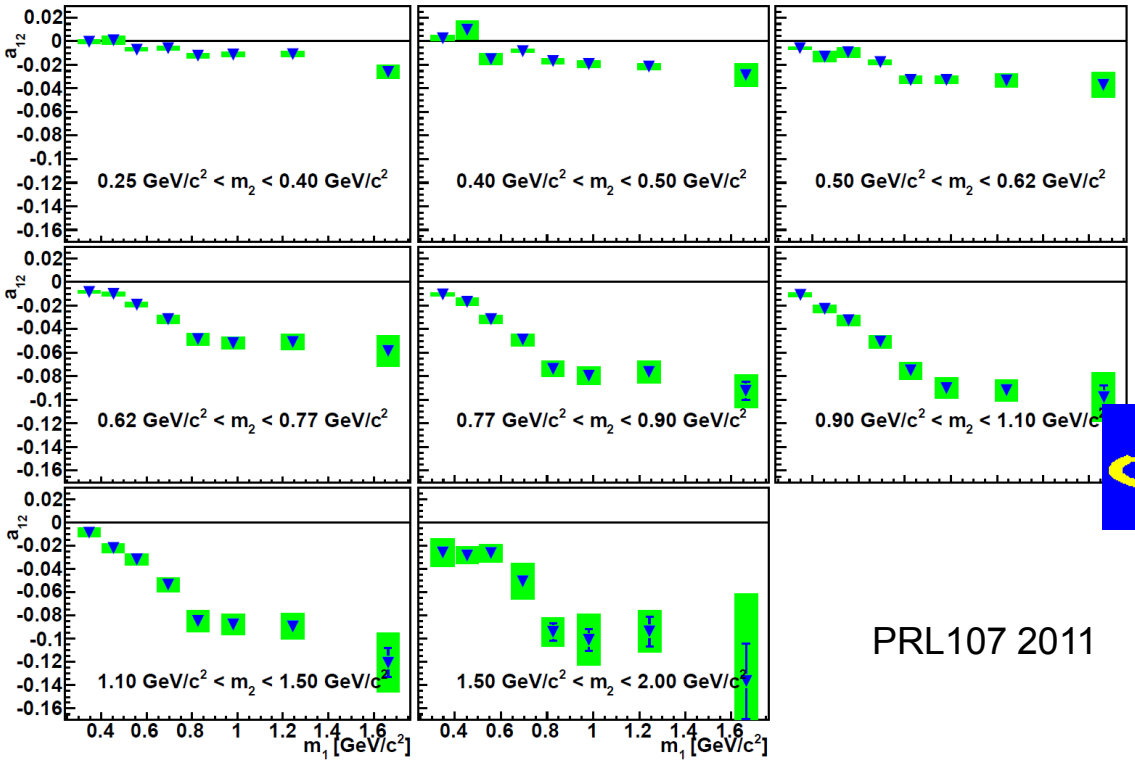
PLB 713 2012, PLB736 2014



clear signal, high statistics over a wide x range

dihadron FF

$$\approx \frac{H_q^{\angle}}{D_q^{2h}} \frac{H_q^{\angle}}{D_q^{2h}}$$



PRL107 2011

D_q^{2h} **still unknown: ongoing work at Belle, Babar, COMPASS** (SPIN2012)

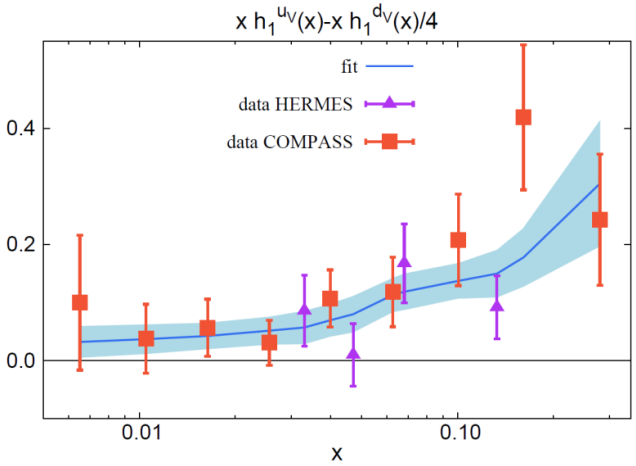
Transversity from 2h asymmetries 1

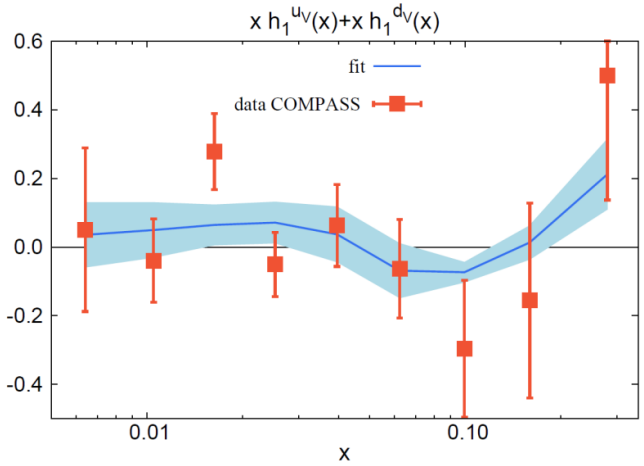
Bacchetta Courtoy Radici JHEP 1303 2013

D_q^{2h} from PYTHIA plus HERMES p, COMPASS p and d (2h), Belle data

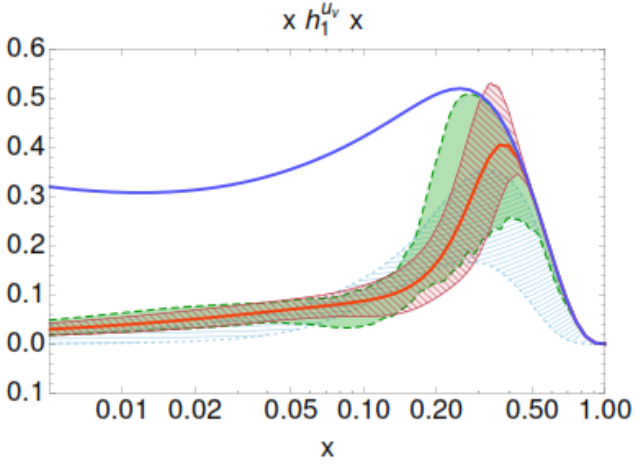
→ linear combinations of transversity for u and d valence quark

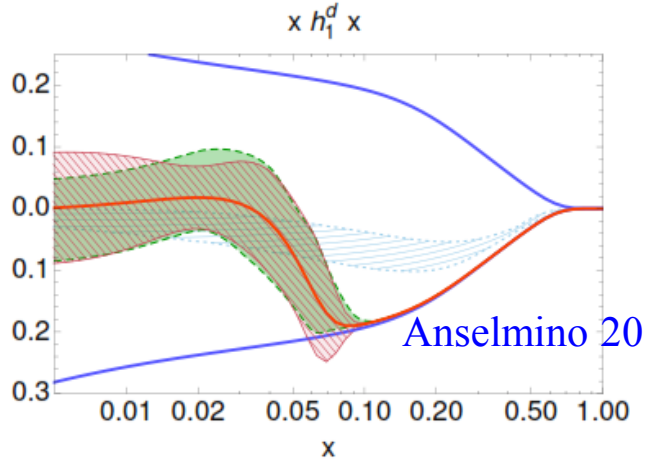
fit with parametrisations → transversity PDFs





flexible





Anselmino 2013

Transversity from 2h asymmetries 2

also possible: **point-to-point extraction**

using

- the “analysing power” from Pavia group
- the COMPASS p and d results (same x-bins)

one can **extract in each x-bin the transversity PDF**

(new charged pion results, DIS2014)

results → G. Sbrizzai, this Session

Transversity from 2h asymmetries 2

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or one can use directly the Belle data (and some "reasonable" assumptions) to evaluate the analysing power

advantages:

- no MC nor parametrisation is needed
- the same technique can be used for the Collins asymmetries

→ F. Bradamante, today

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→ F. Bradamante, today

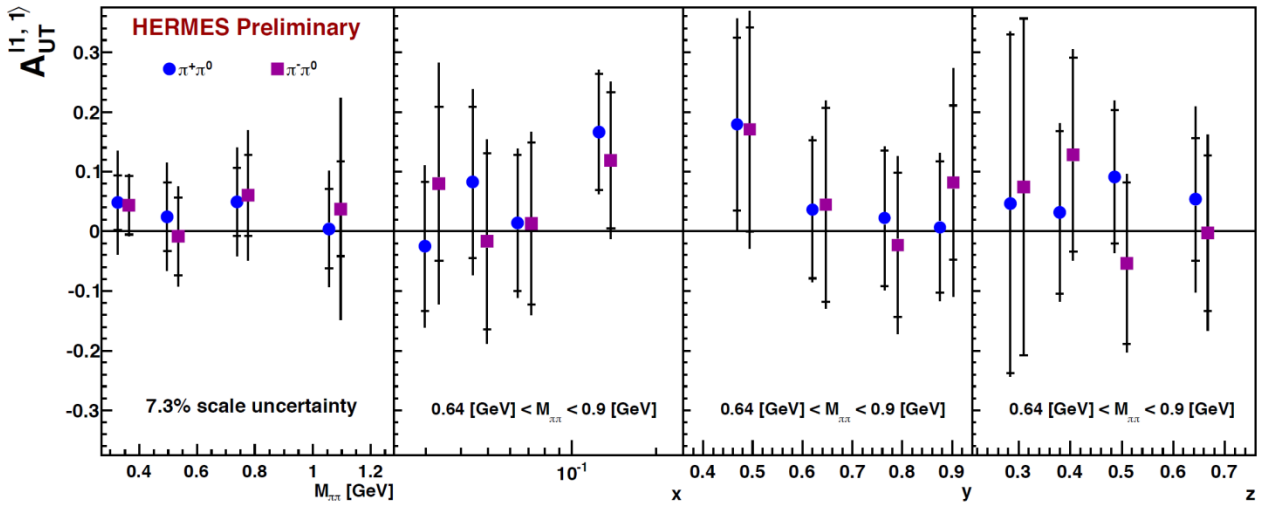
there are other new ideas on the extraction of information on transversity from SIDIS and e+e- data only

and new ideas on data analysis

dihadron asymmetry - new ideas

Partial Wave expansion

$|1,1>$ Collins moments for $\pi\pi$



van Hulse, Transversity 2014

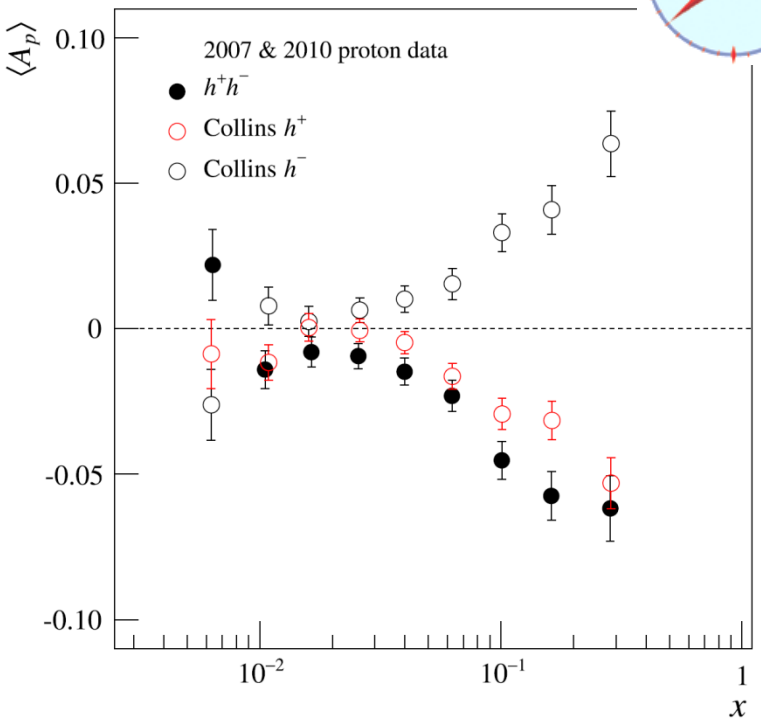
Gliske Bacchetta Radici arXiv:1408.5721

dihadron asymmetry - new ideas

interplay between dihadron and single hadron asymmetries

intriguing results

- Collins asymmetry for h+ and for h- *"mirror symmetry"*
- dihadron asymmetry vs Collins asymm. *only somewhat larger*



this motivated the study of the correlations between the relevant azimuthal angles and the corresponding asymmetries

[F. Bradamante , Como2013, D-SPIN2013]

conclusion:

hints for a common physical origin for the Collins mechanism and the polarised dihadron FF

[PLB 736 (2014) 124]

dihadron asymmetry - new ideas

interplay between dihadron and single hadron asymmetries

new developments:

dependence of the asymmetries on $\Delta\phi = \phi_{h+} - \phi_{h-}$

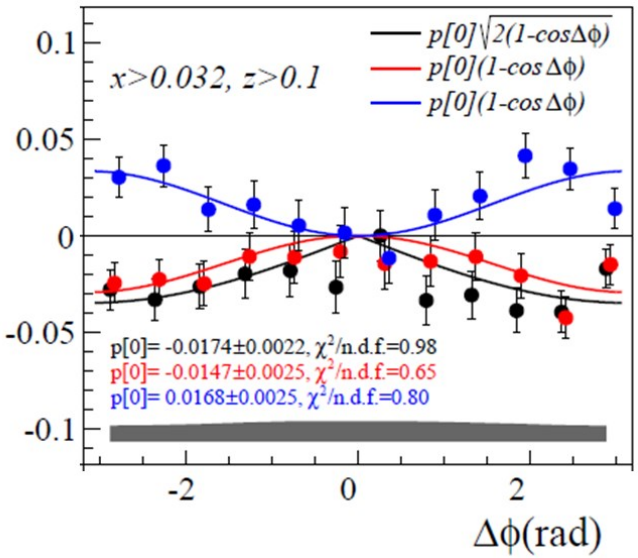
first results: Transversity2014

presently a consistent description of the h+ and h- Collins asymmetries and of the dihadron asymmetries

$A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}$

$A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}$

$A_{2h,CL}^{\sin(\phi_{R'}+\phi_S-\pi)}$



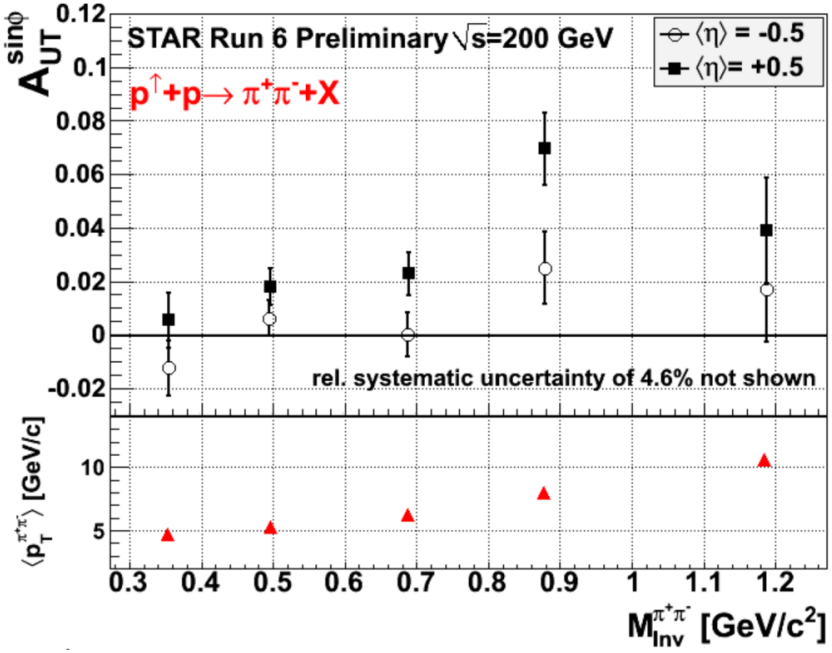
→ F. Bradamante, this Session

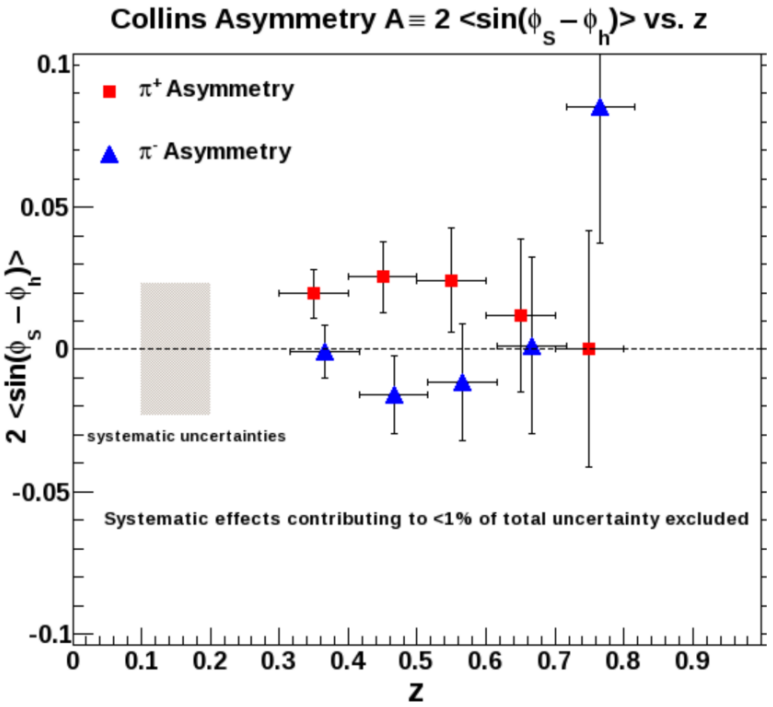
accessing Transversity at RHIC

news from

dihadron correlation

$$A_{UT} \propto h_1 \cdot H_1^{\sphericalangle}$$





"Collins" asymmetry

$$A^{\sin(\phi S-\phi h)} \propto h_1 \otimes H_1$$

$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f^N_{a/A\uparrow} \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulder•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$

A. Vossen, Transversity2014

accessing Transversity at RHIC

news from STAR

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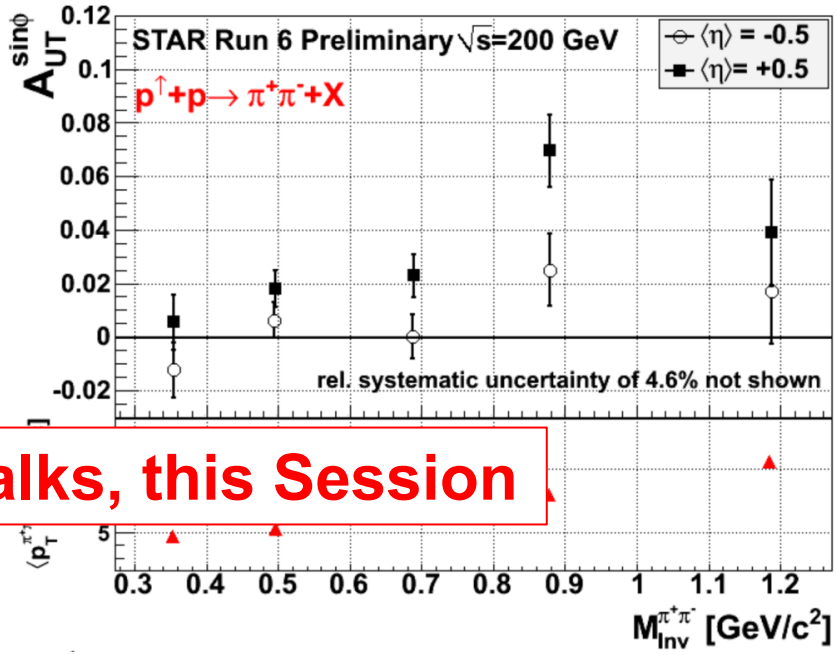
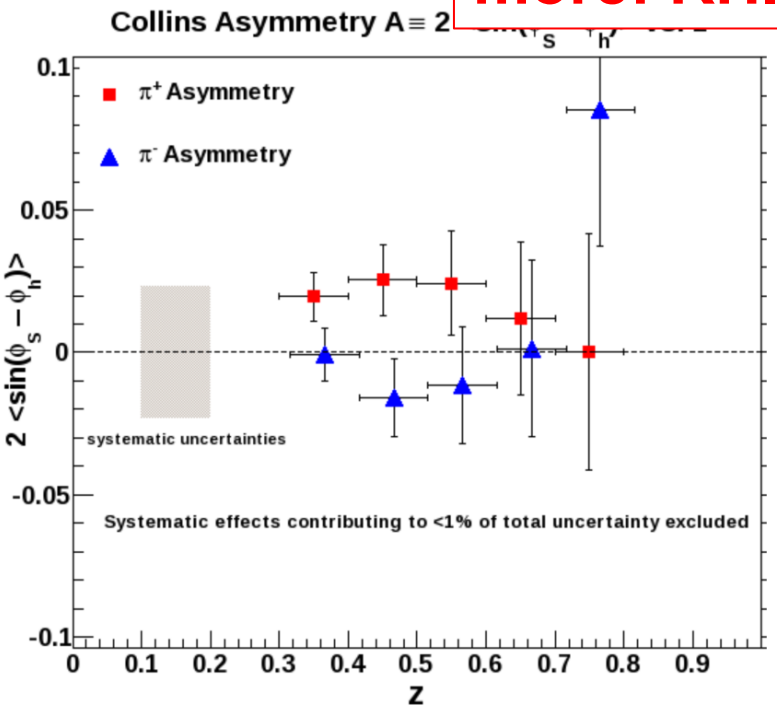


more: RHIC talks, this Session



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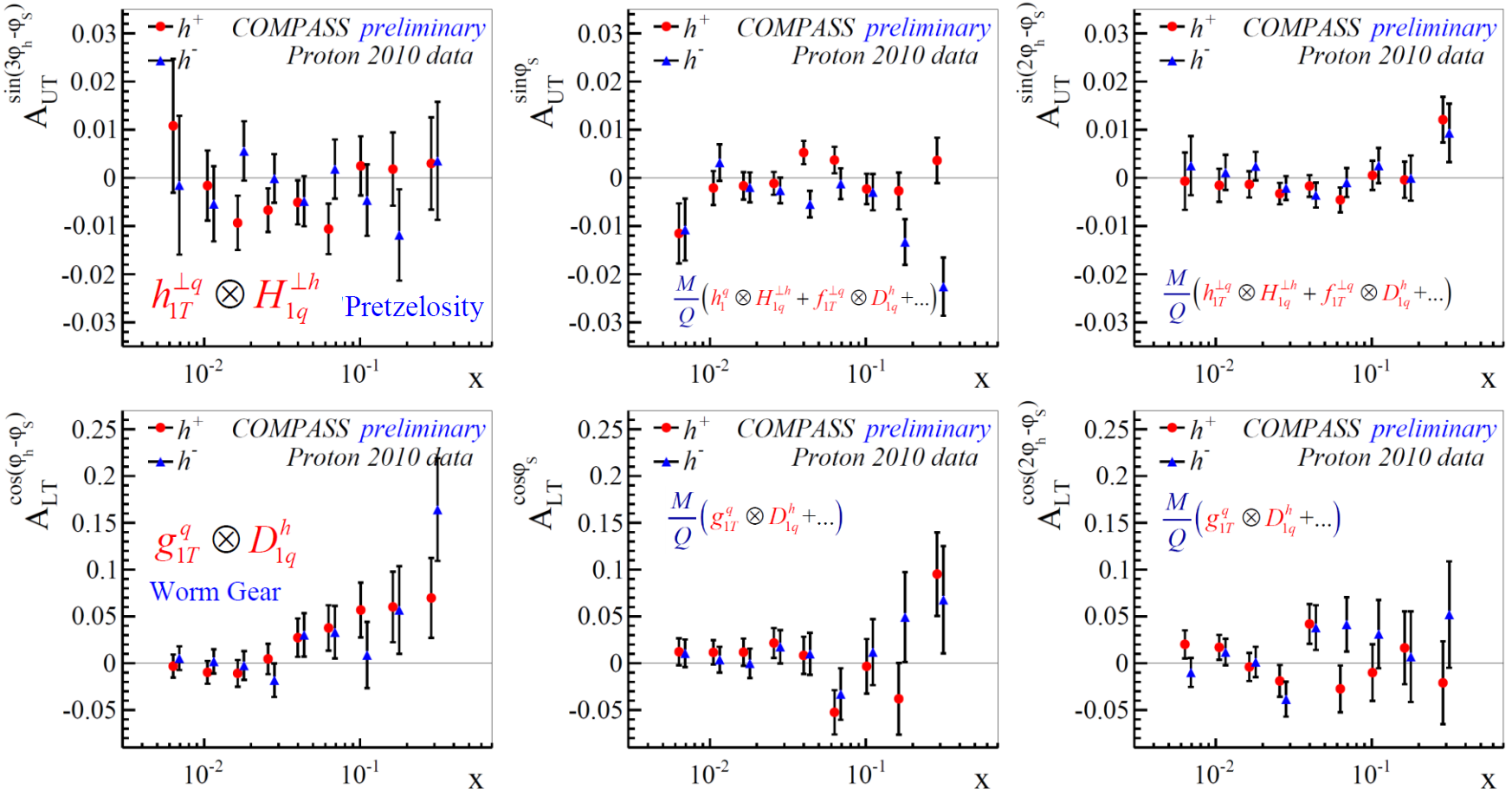
A. Vossen, Transversity2014

- Sivers asymmetry
- Collins asymmetry
- di-hadron asymmetry
- **other TSA**
- unpolarised asymmetries in SIDIS

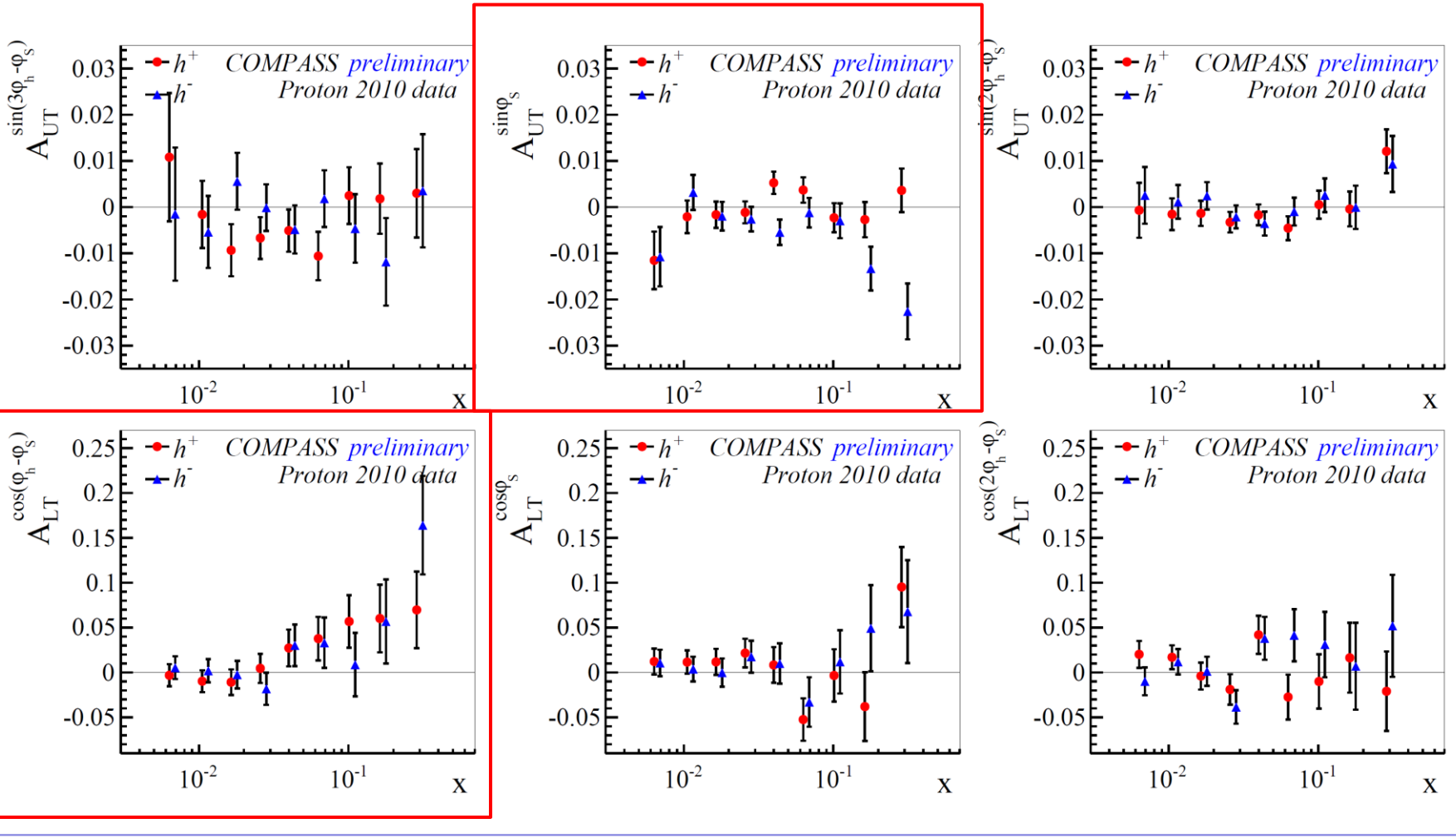
other SIDIS TMD transverse spin asymmetries

proton



all measured on p (HERMES, COMPASS) and d (COMPASS)

other SIDIS TMD transverse spin asymmetries

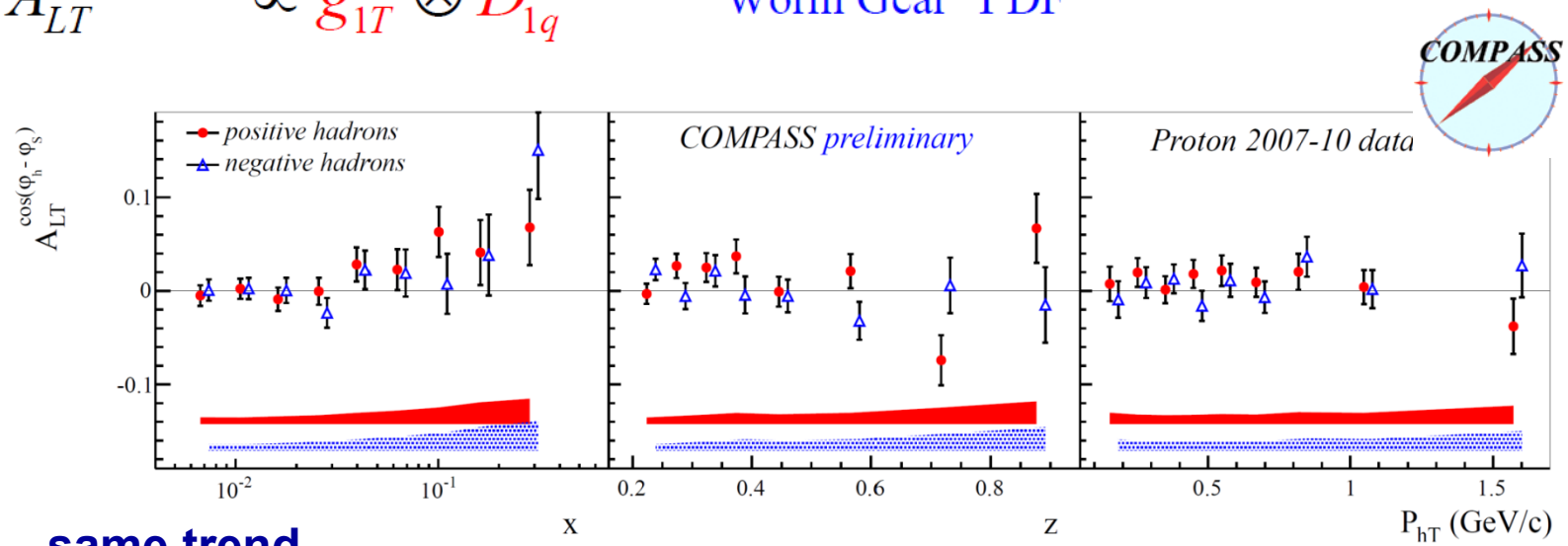


all measured on p (HERMES, COMPASS) and d (COMPASS)

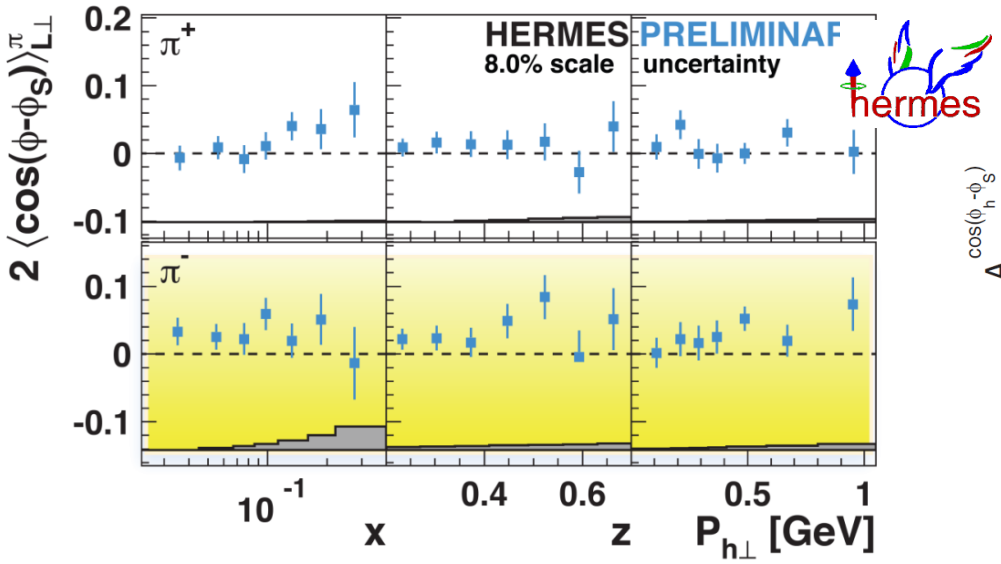
other SIDIS TMD transverse spin asymmetries

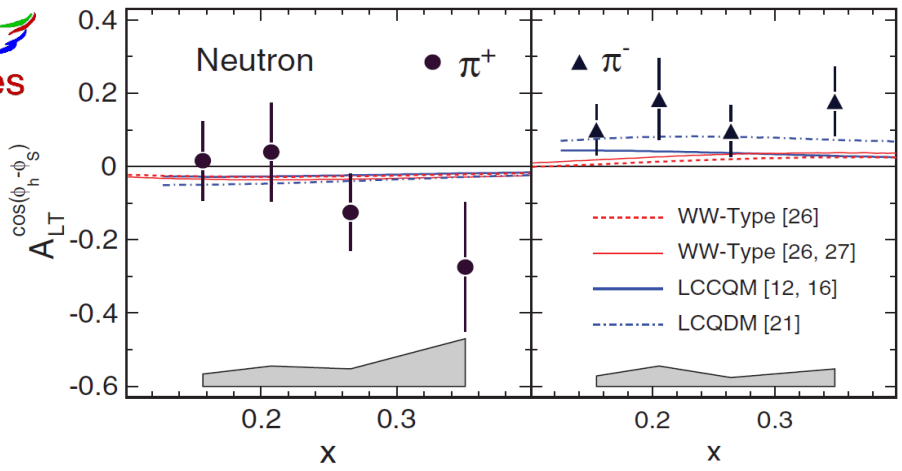
$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

"Worm Gear" PDF



same trend

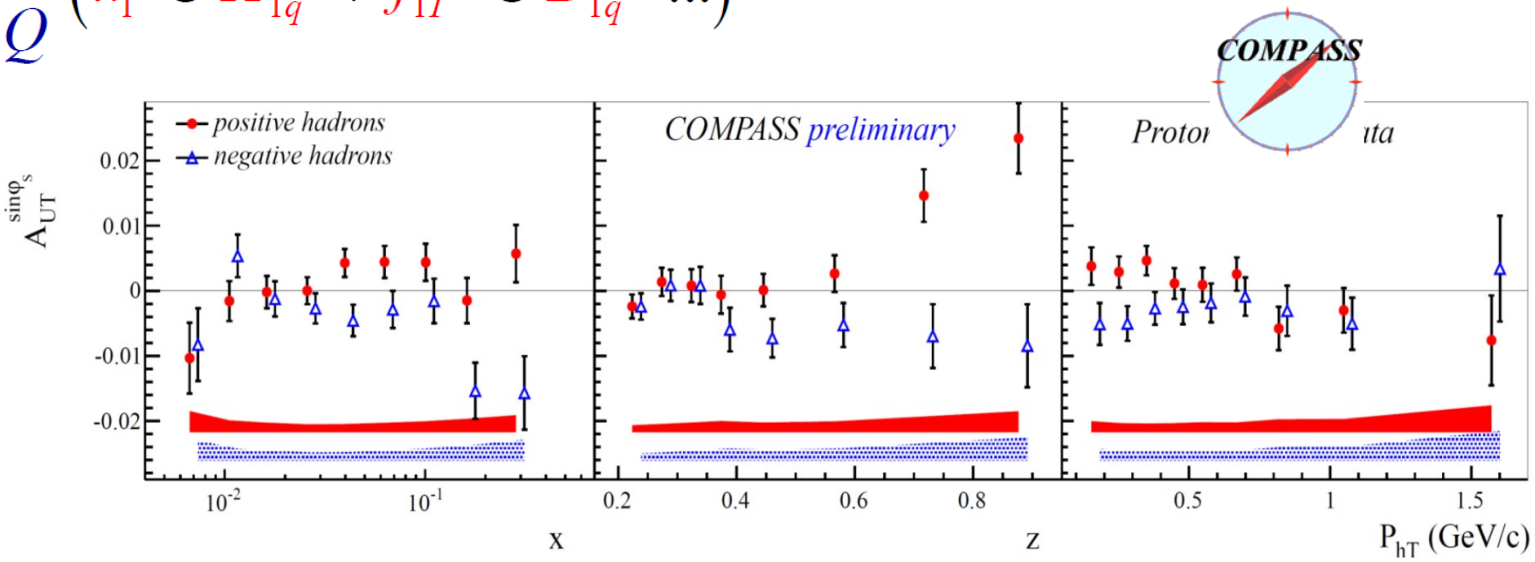


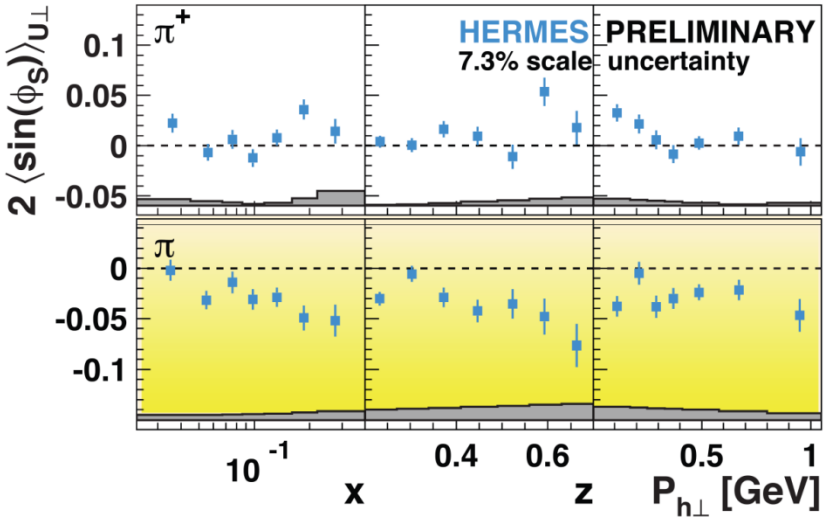


Hall A PRL108 2012

other SIDIS TMD transverse spin asymmetries

$$A_{UT}^{\sin\phi_s} \propto \frac{M}{Q}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \ldots \right)$$



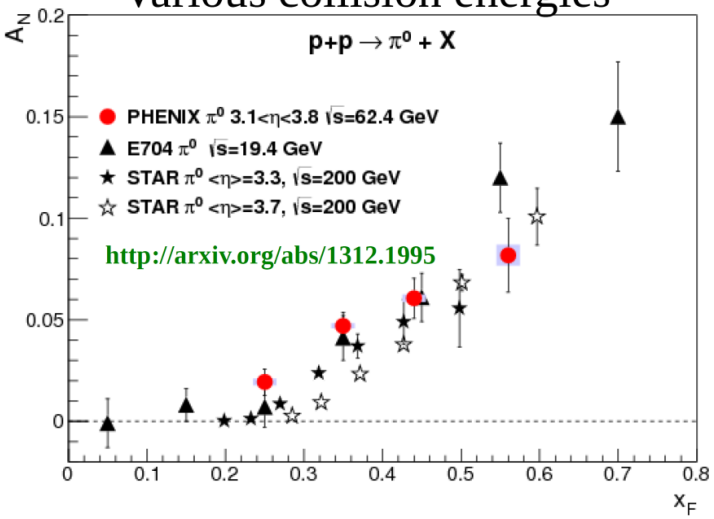


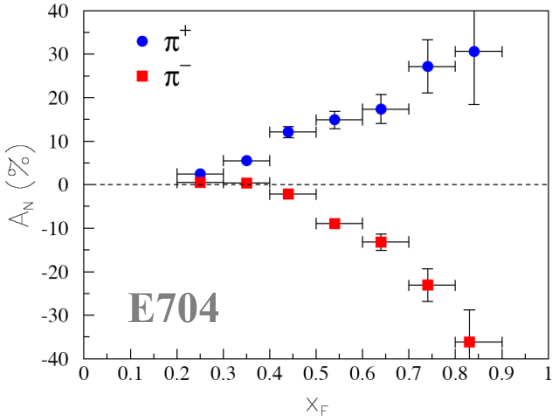
considerably larger at HERMES

as expected

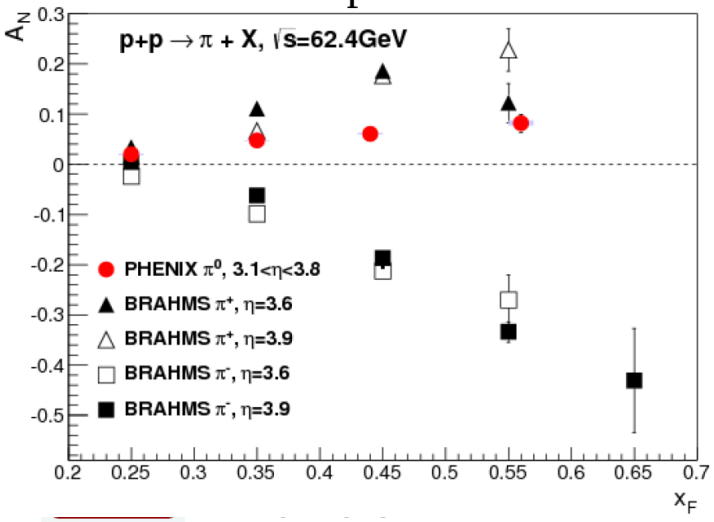
A_N in pp collisions

Various collision energies





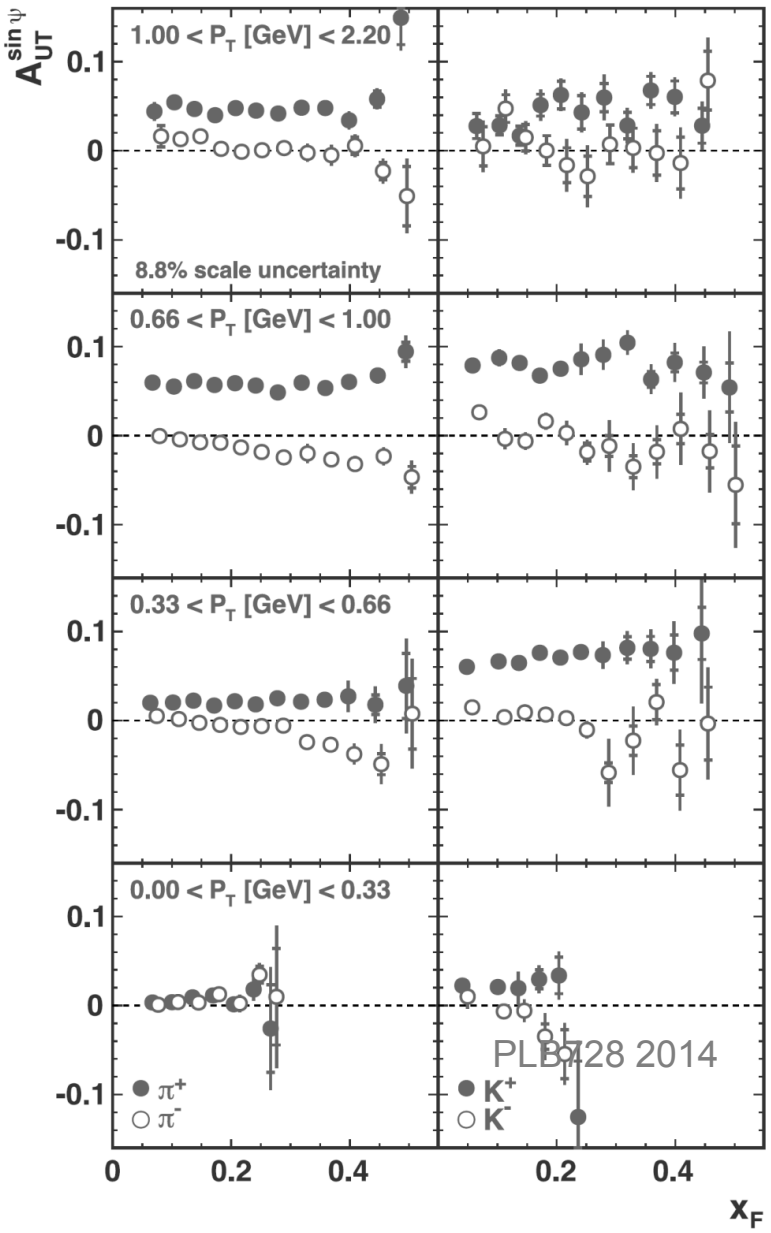
Various particles



origin not yet clear

to understand it, measurement of A_N in $\ell N^{\uparrow} \rightarrow \pi X$

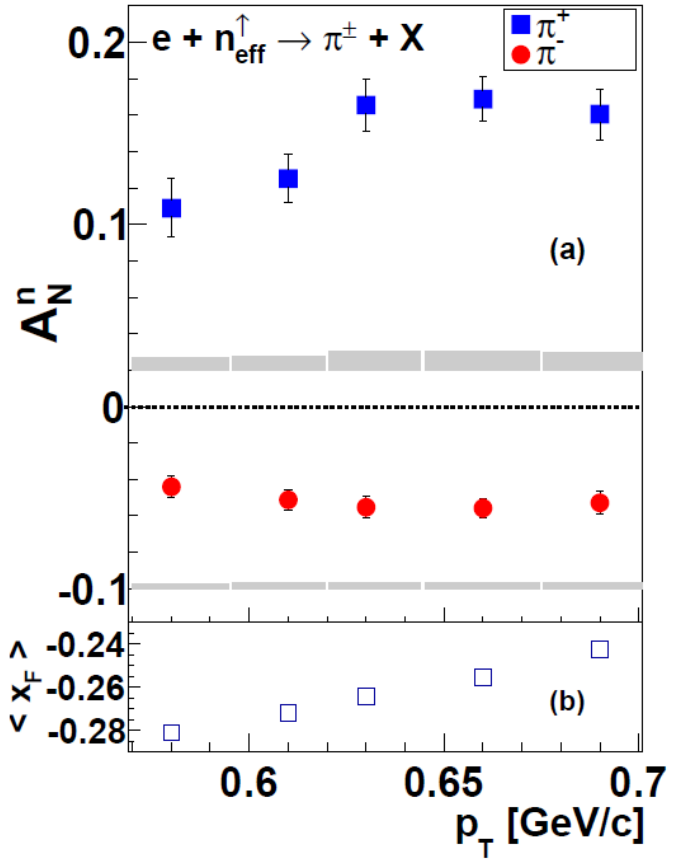
A_N in lepton nucleon collinsion



PLB728 2014

JLab Hall A

PRC 2014



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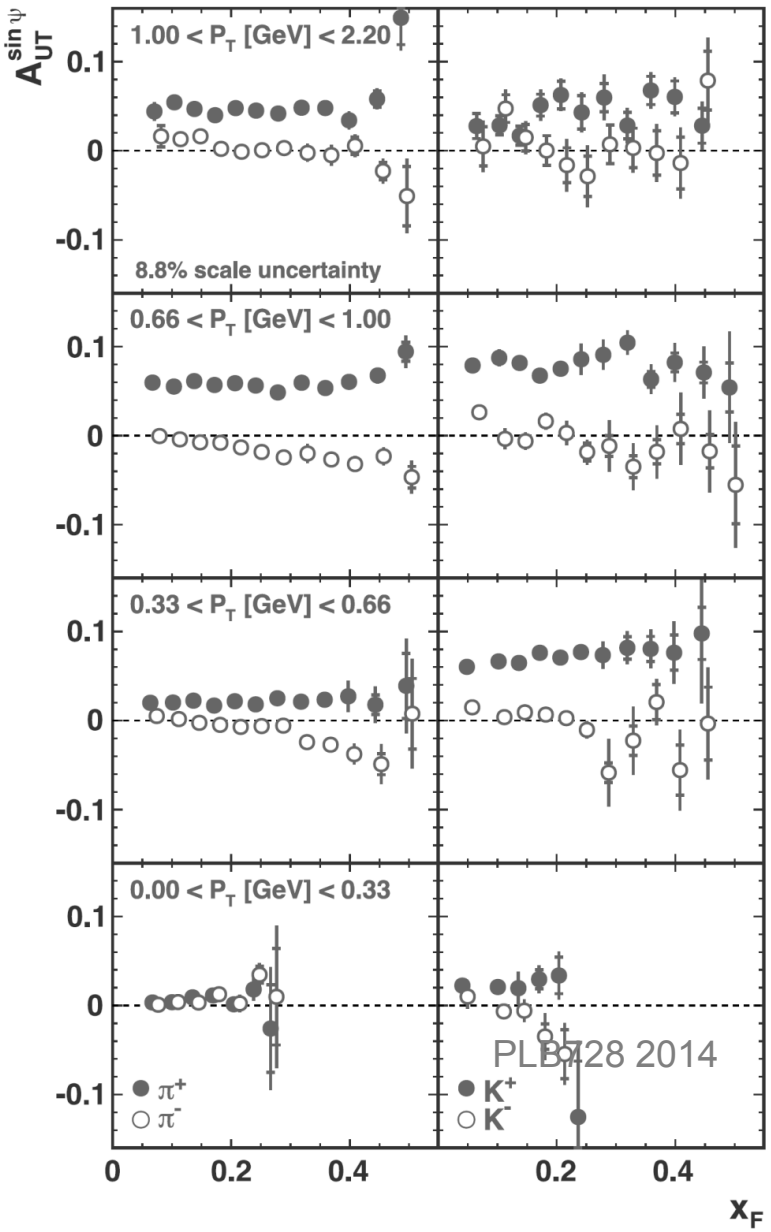
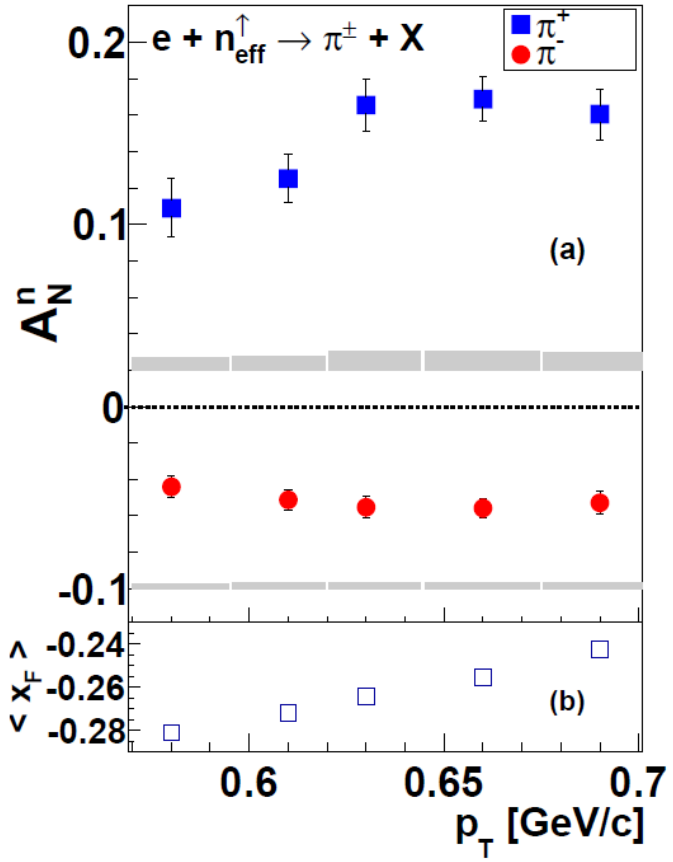


PLB 728 2014

hermes

JLab Hall A

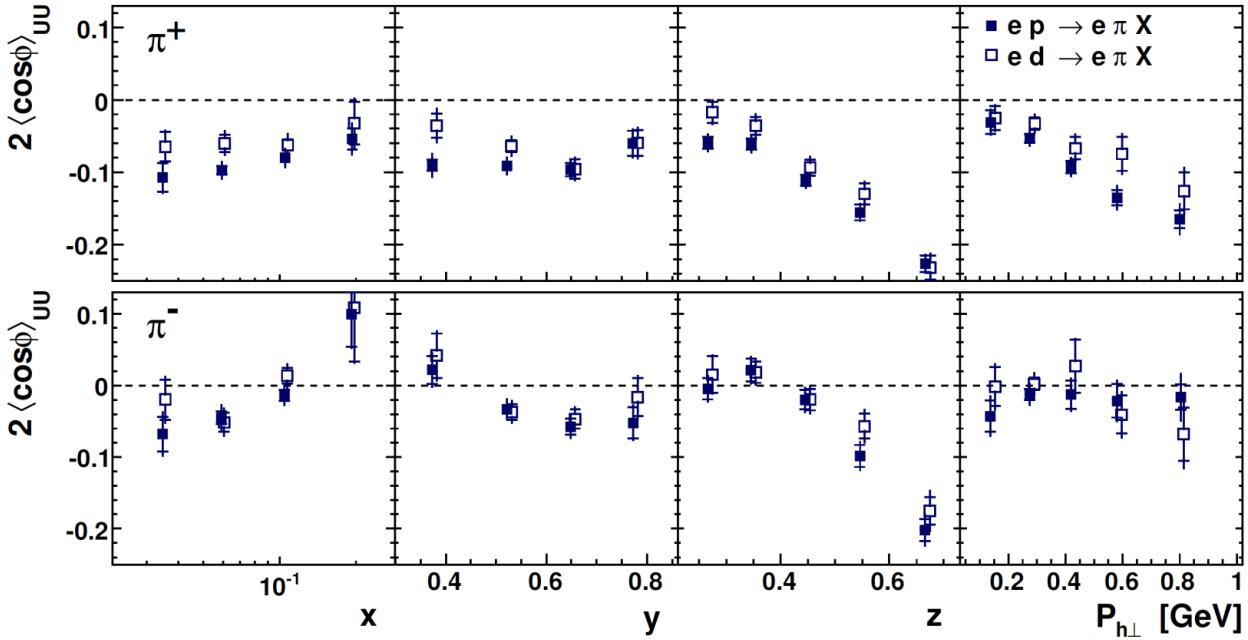
PRC 2014



phenomenological interpretation in progress

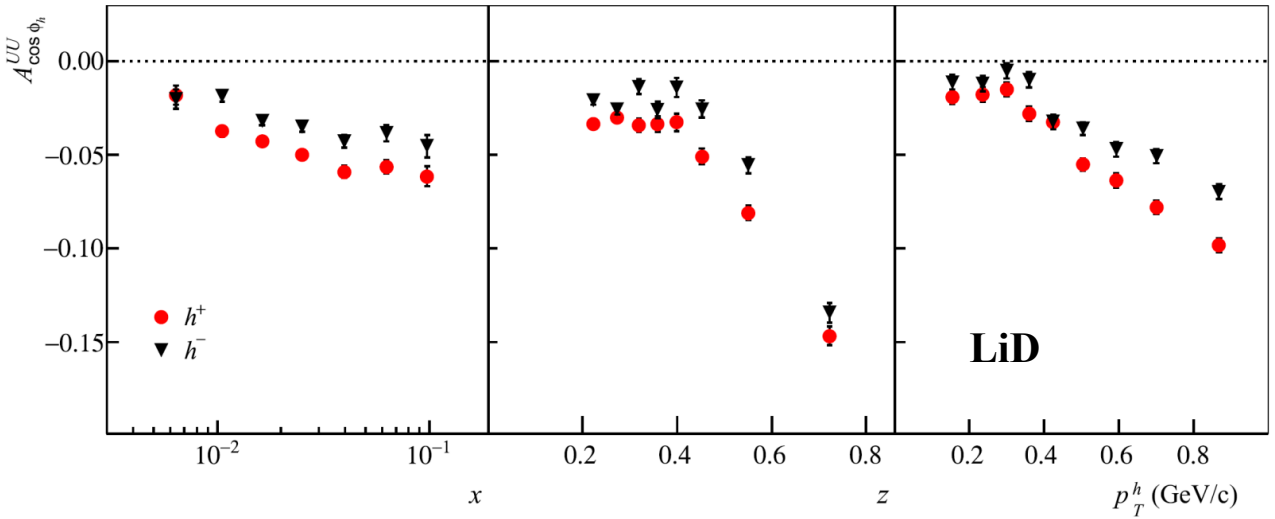
- Sivers asymmetry
- Collins asymmetry
- di-hadron asymmetry
- other TSA
- **unpolarised asymmetries in SIDIS**

unpolarisd azimuthal asymmetries - reminder



PRD87 2013

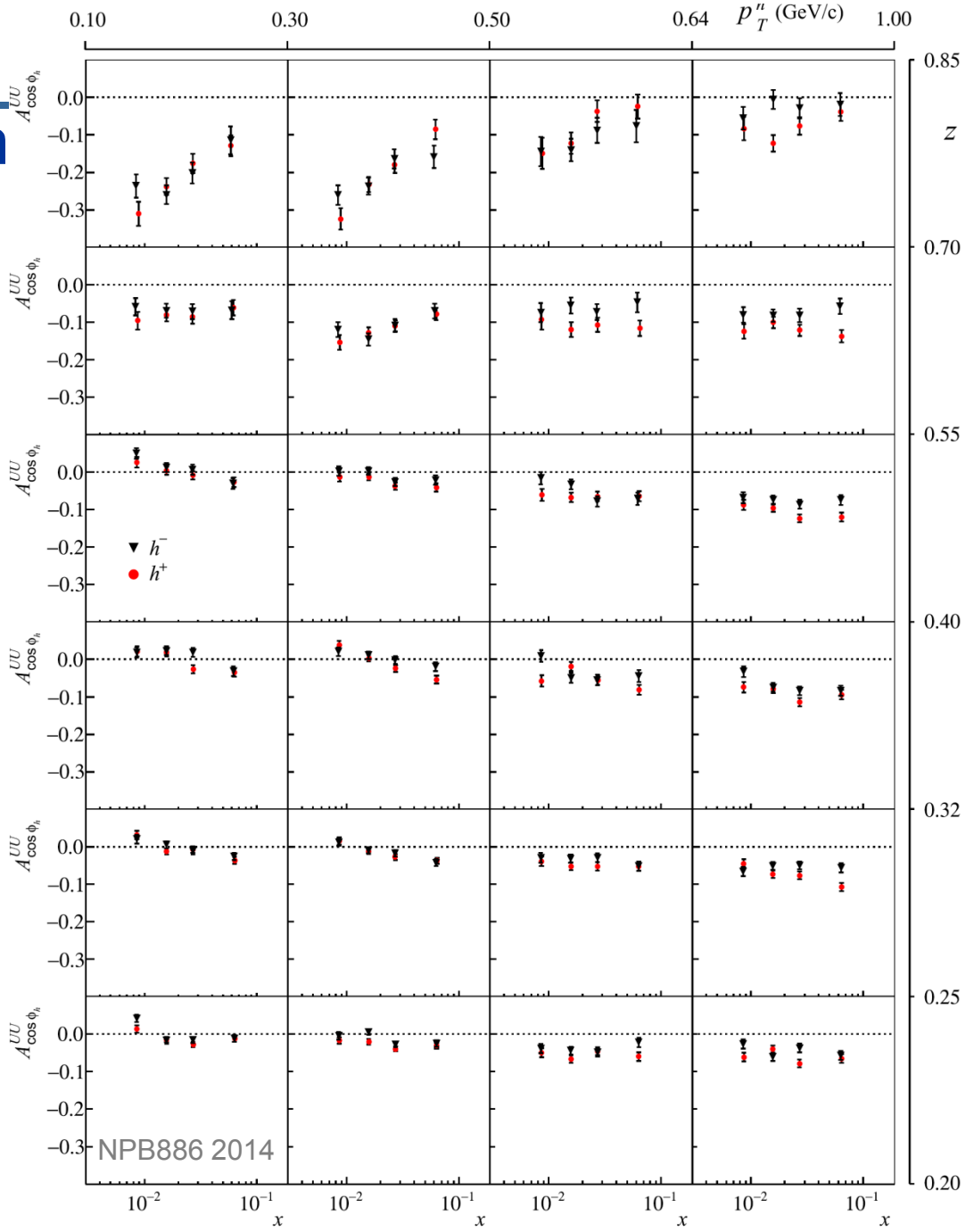
NPB886 2014



unpolarised azimuthal asymm

not easy as expected!

- $< k_T^2 >$ ~ x (1-x) ?
- **Boer-Mulders PDF still ~ unknown**



COMPASS

unpolarised azimuthal asymm

not easy as expected!

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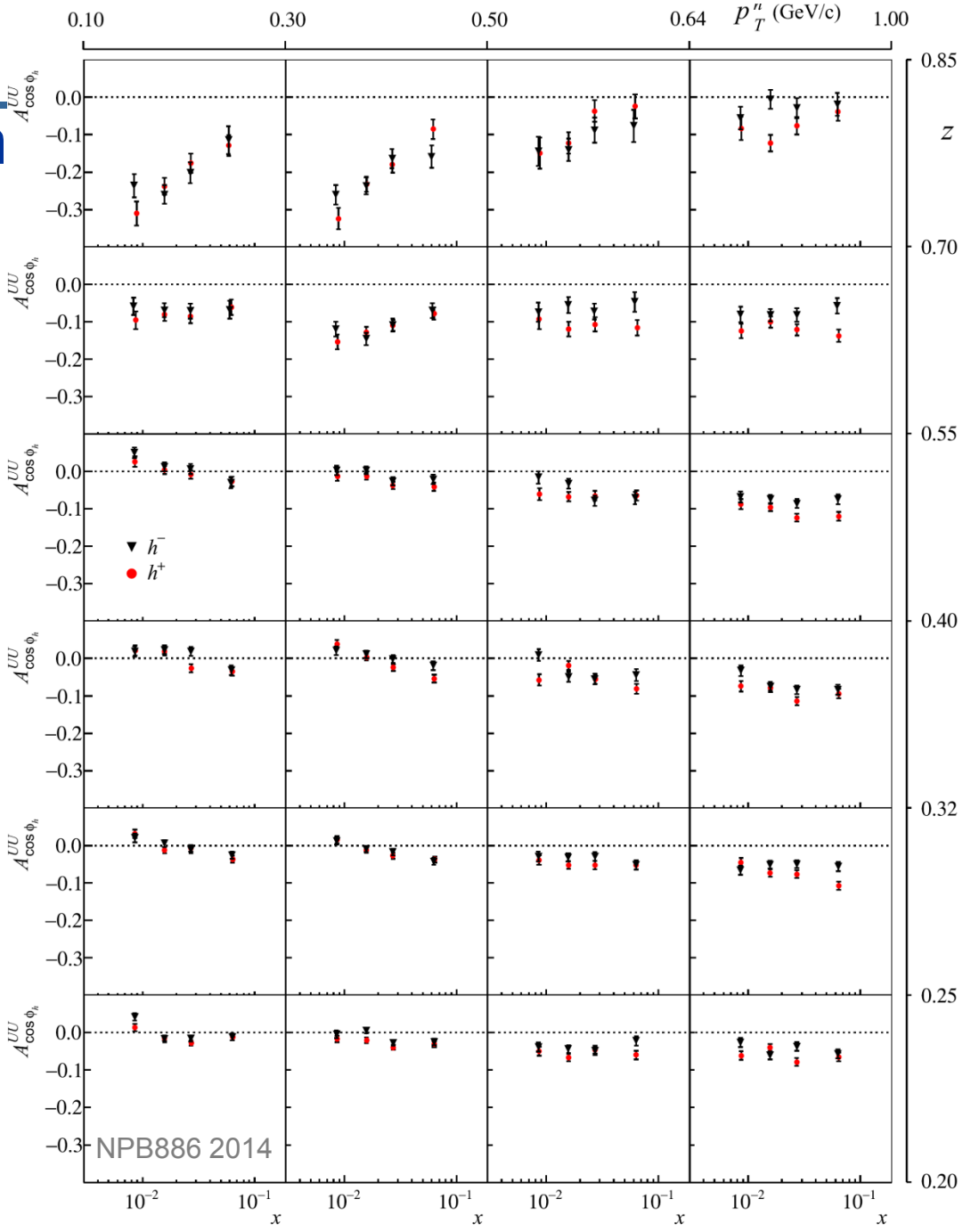
future:

- **2006 data**
- **SIDIS run with LH2 in 2016-2017 (DVCS)**



summary

many new results, not all easy to explain; a lot of work ongoing …

- **the SIDIS data collected in so far are unique**
- **the analysis are not yet over**

  more multidimensional measurements,
  gluon Sivers from high pT and J/Ψ → K. Kurek
  interplay 1h-2h,
  weighted asymmetries, ….

- **new interesting results on transversity and TMD observables will come soon** from

  SIDIS at JLab, HERMES, COMPASS

  pp at RHIC

  e^+e^- at Belle / Babar

  while waiting for the results of the new experiments

  Drell-Yan measurements

  JLab12, eN Collider, high energy ep experiments

Thank you