Recent Measurements of Transverse Spin Asymmetries

Anna Martin

Trieste University & INFN

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Transverse Structure of the Nucleon

Transverse Structure of the Nucleon

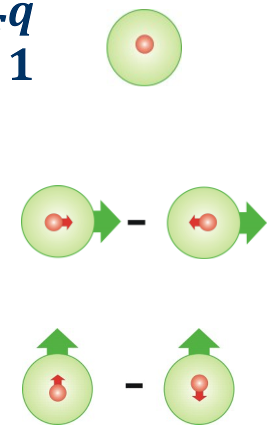
in the GPM the information is encoded in the **TMD PDFs** which describe the correlations between transverse momentum and spin of quarks and nucleon spin

8 at twist 2 for each q

quark \ nucleon	U	L	T	
U	f_1		$f_{1T}^{\perp}$	
L		g_1	g_{1L}	
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1	$h_{1T}^{\perp}$

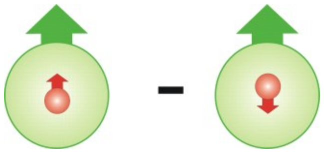
3 of them survive after integration over transverse momenta *collinear*

- **number density** f_1^q — q, well known
- **helicity** g_1^q — Δq, known
- **transversity** h_1^q — $\Delta_T q$, **new**



ALL OF EQUAL IMPORTANCE !

Transversity PDF



- **proposed in ’77** (Ralston & Soper)
- **different properties than helicity**
    - **chiral-odd, cannot be measured in inclusive DIS**
    - **no contribution from the gluons**
    - **first moment: tensor charge**
- **first ideas on possible measurements in the 90s (Collins, …)**
- **first measurements in 2005**

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L		g_1	g_{1L}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

other **5 new PDFs** which vanish when integrating over transverse momentum:

all of great interest and ~ unknown

two of them are T-odd

Boer-Mulders $h_1^{\perp}$

parton transverse spin ↔ parton transverse momentum

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

nucleon transverse spin ↔ parton transverse momentum

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

nucleon transverse spin $\leftrightarrow$ parton transverse momentum

- 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,
new experiments

Transverse Structure of the Nucleon

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8 at twist 2 for each q

quark \ nucleon	U	L	T
U	f_1		$f_{1T}^{\perp}$
L		g_1	g_{1L}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

how to measure these new PDFs?

either chiral-odd

or vanishing when integrating over transverse momentum

→ **not in DIS**

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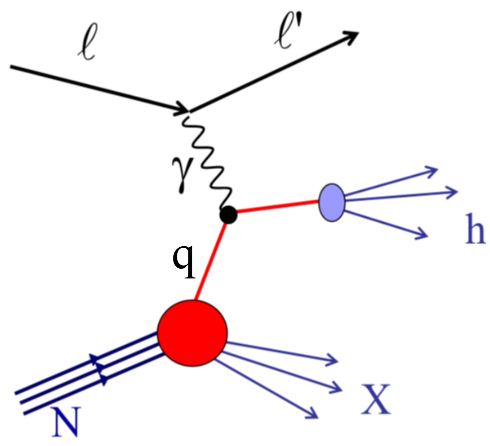
accessing transversity and TMD PDFs

they can be accessed through different processes

SIDIS



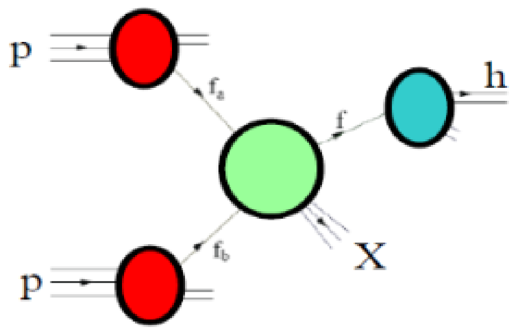
HERMES

COMPASS

Jefferson Lab

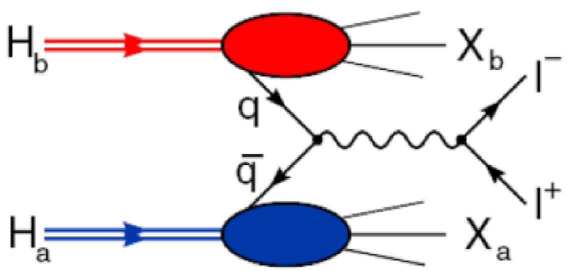
what we know today comes from these measurements

hard polarised pp scattering



RHIC

not easy to disentangle different effects

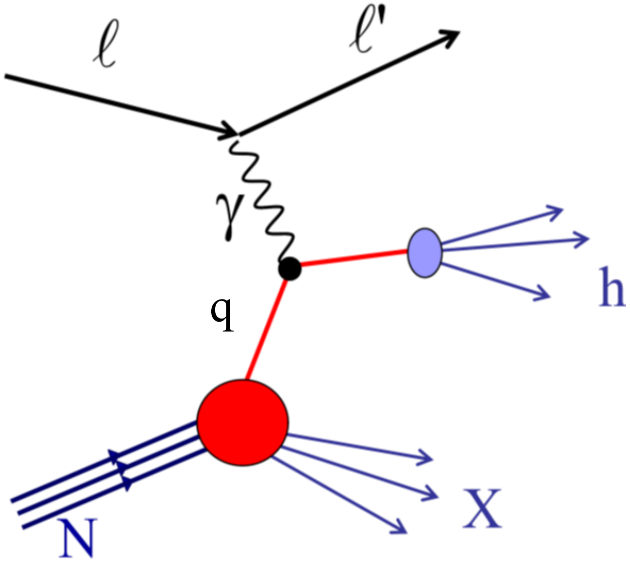


Drell-Yan

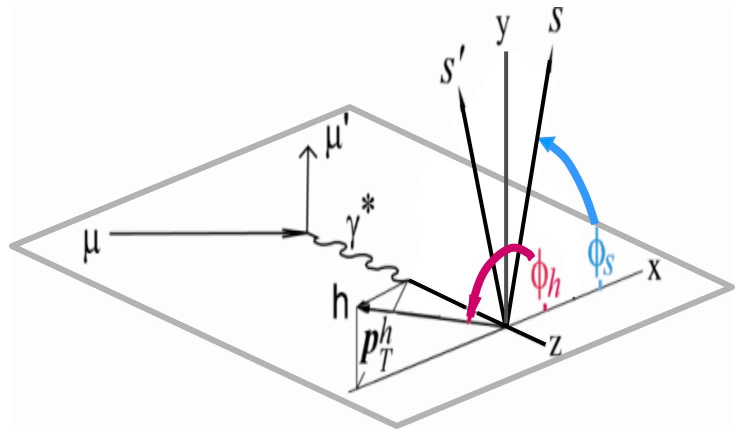
no polarised data (yet !)

why SIDIS

a simple process, a special tool



$x,\ Q^2;\qquad z,\ P_T^h,\qquad \phi_h,\ \phi_S$

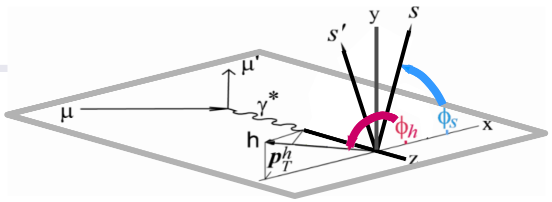


$$d\sigma^{\ell p\to\ell hX} \sim \sum_q e_q^2 f_q(x,\boldsymbol{k}_\perp)\cdot d\sigma^{\ell q\to\ell q}\cdot D_q^h(z,\boldsymbol{p}_T)$$

p, n, d targets , final state particle identification
→ flavor separation

all the TMD PDFs appear in the cross-section and the different effects can be disentangled

why SIDIS



cross-section

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

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

$h_1^\perp H_1^\perp$

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

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

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

$f_{1T}^\perp D_1$

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

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

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

$h_1 H_1^\perp$

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

$g_{1T} D_1$

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

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

18 structure functions

14 azimuthal modulations

A Bacchetta et al., 2006

azimuthal asymmetries

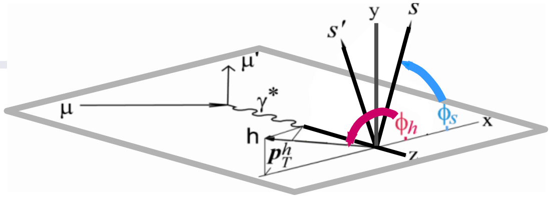
fi Sivers

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

- the Fragmentation Functions must be well known
- convolutions on transverse momenta

crucial to know them!

why SIDIS



cross-section

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

$f_{1T}^{\perp} D_1$ — $\sin(\phi_h - \phi_S)$

$h_{1T}^{\perp} H_1^{\perp}$ — $\sin(3\phi_h - \phi_S)$

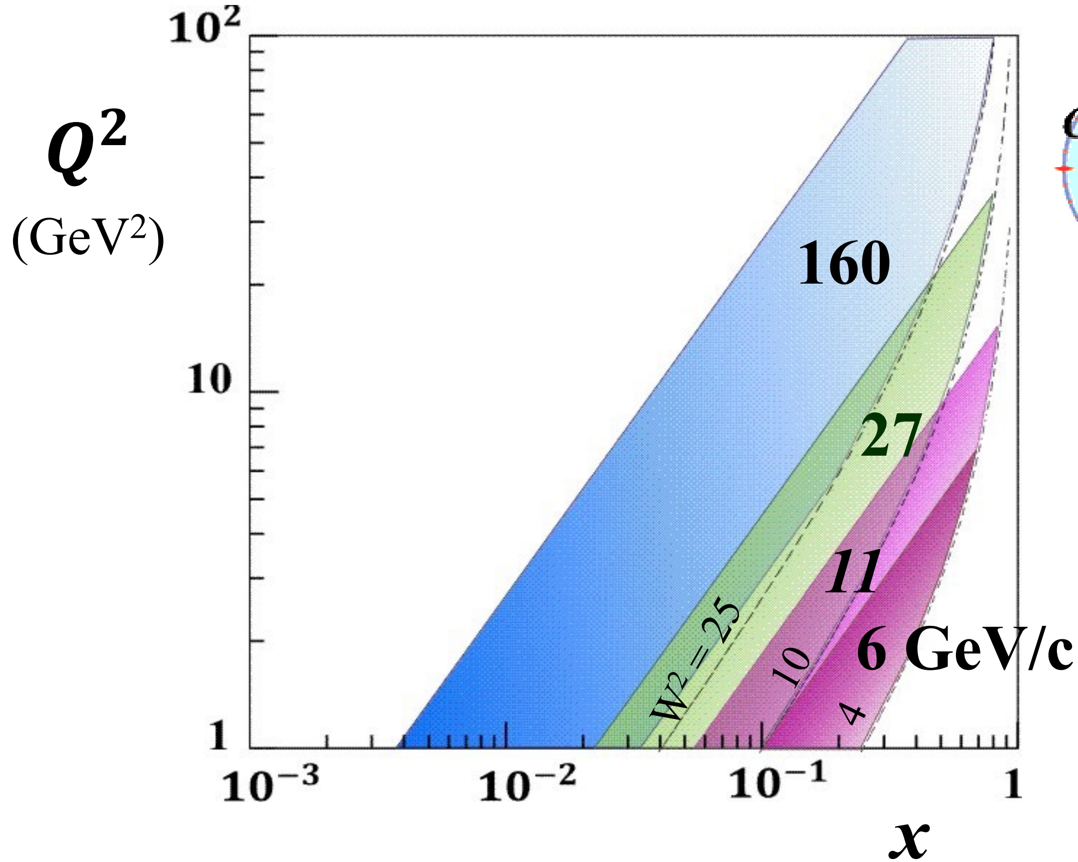
$h_1 H_1^{\perp}$ — $\sin(\phi_h + \phi_S)$

$g_{1T} D_1$ — $\cos(\phi_h - \phi_S)$

A Bacchetta et al., 2006

results

from HERMES, COMPASS and Jefferson Lab experiments



COMPASS hermes Jefferson Lab

some selected results only …

Sivers asymmetry

amplitude of the modulation in $\phi_h - \phi_S$ $A_{UT}^{\sin(\phi_h - \phi_S)}$

2004: first evidence for non-zero values on proton

compatible with zero on deuteron

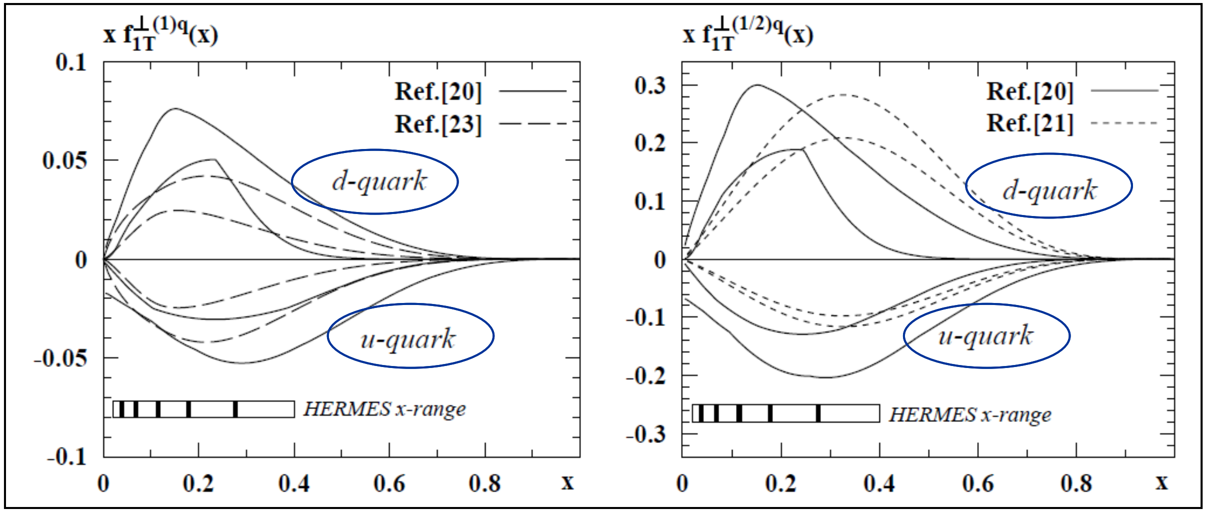
data well described by theory

first extractions of the 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

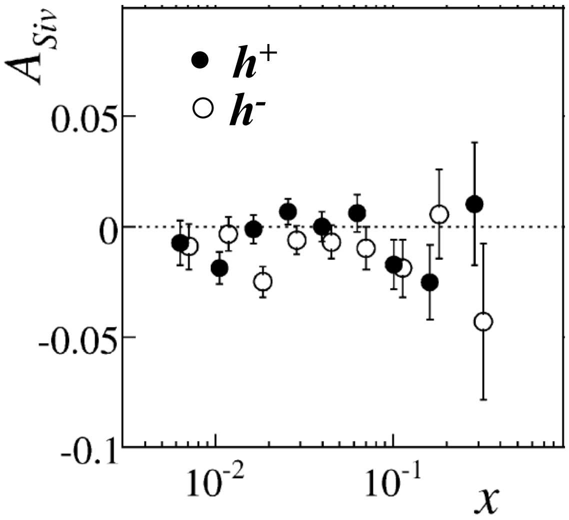
~ opposite u- d- quark contributions

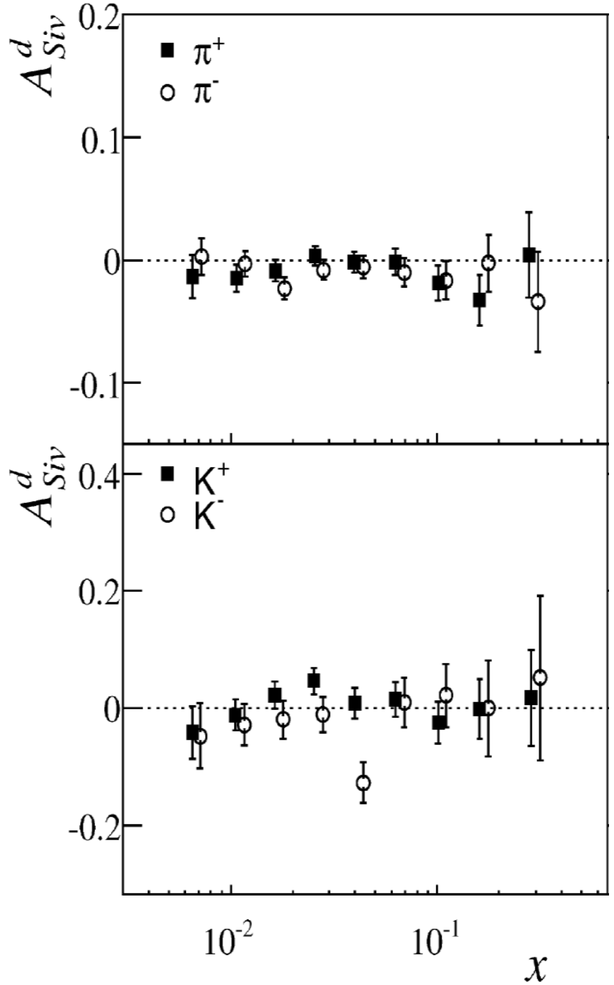


Sivers asymmetry

final results on
deuteron

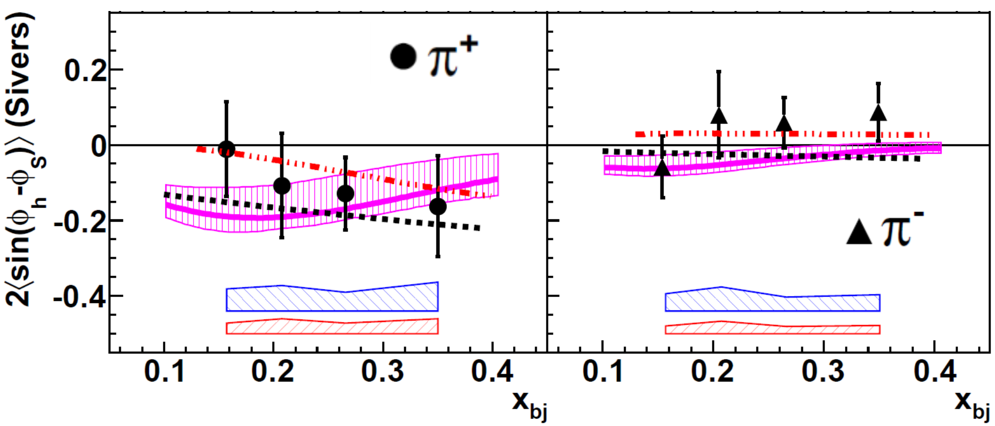
2002-2004 data
NPB765 2007, PLB673 2009





and **neutron**

Hall A PRL107, 2011



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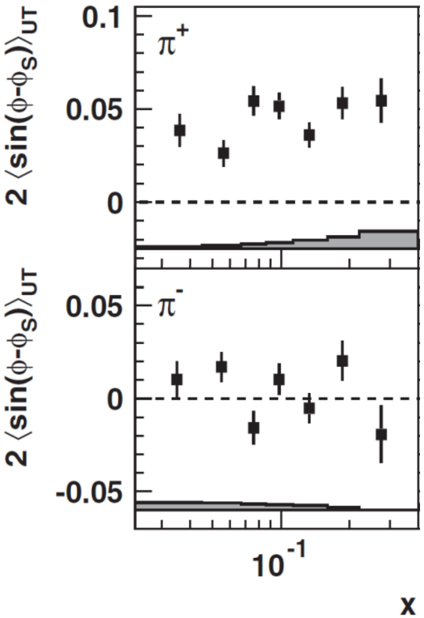
Sivers asymmetry

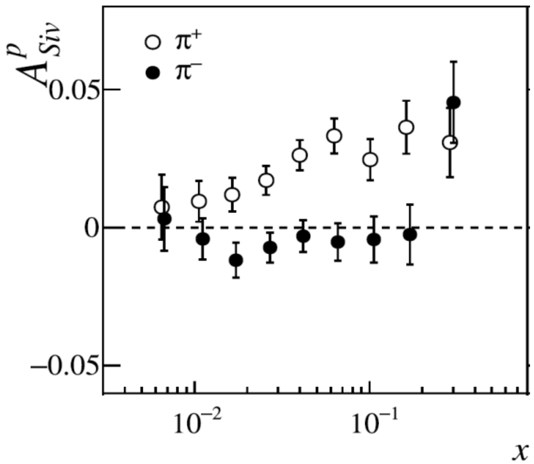
PRL103 2009



1D final results on **proton**

$z > 0.2$

PLB744 2015



- **clearly positive for π^+ down to $x \sim 10^{-2}$**

Sivers asymmetry

already published:

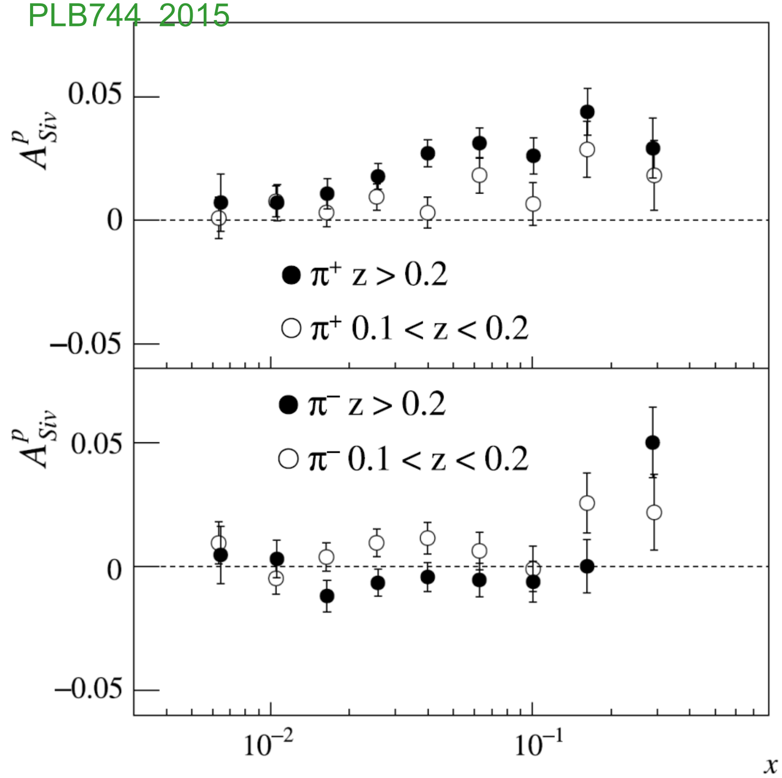
TSA vs z and p_T in different x ranges
vs x and p_T in different z ranges
vs x and z in different p_T ranges

or in extended kinematical ranges

low z / low y

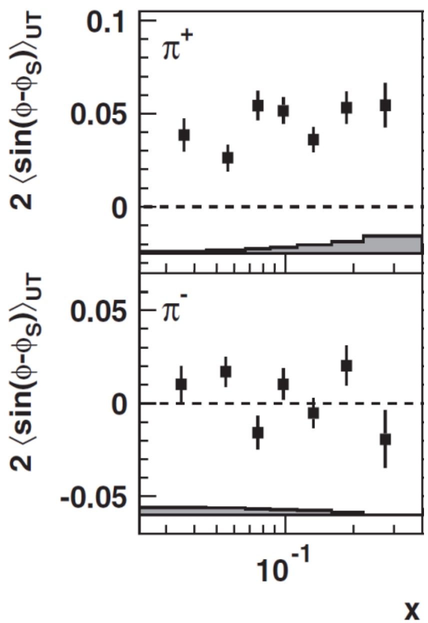
COMPASS

PLB744 2015



Sivers asymmetry

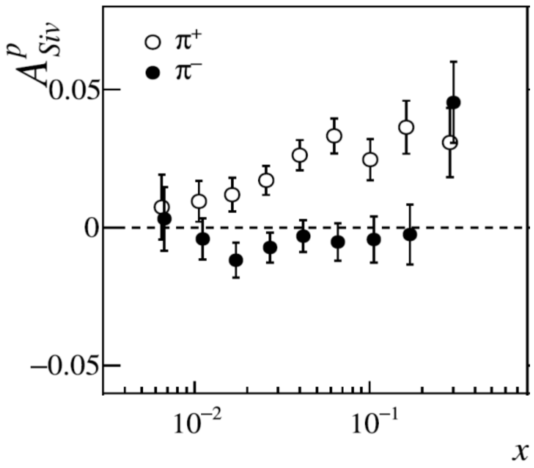
PRL103 2009



final results on **proton**

$z > 0.2$

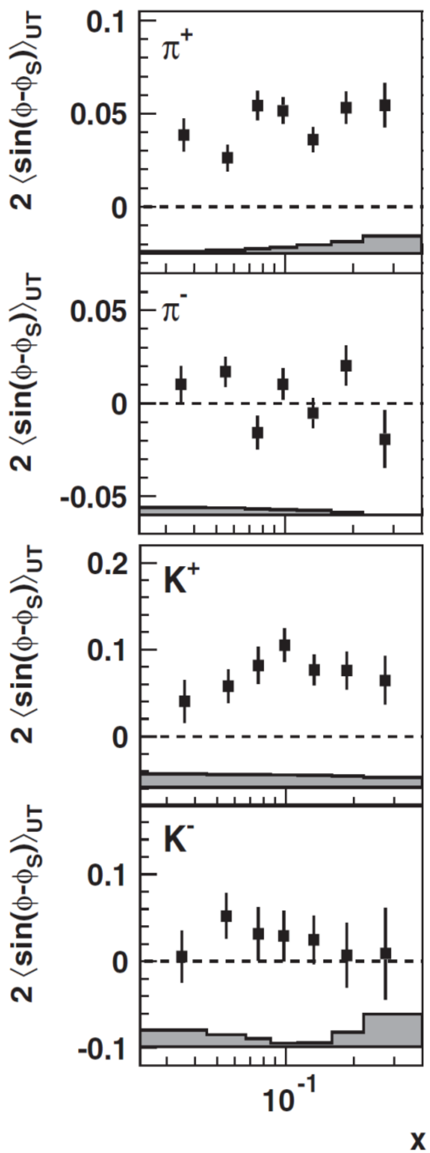
PLB744 2015



- **clearly positive for π^+ down to $x \sim 10^{-2}$**

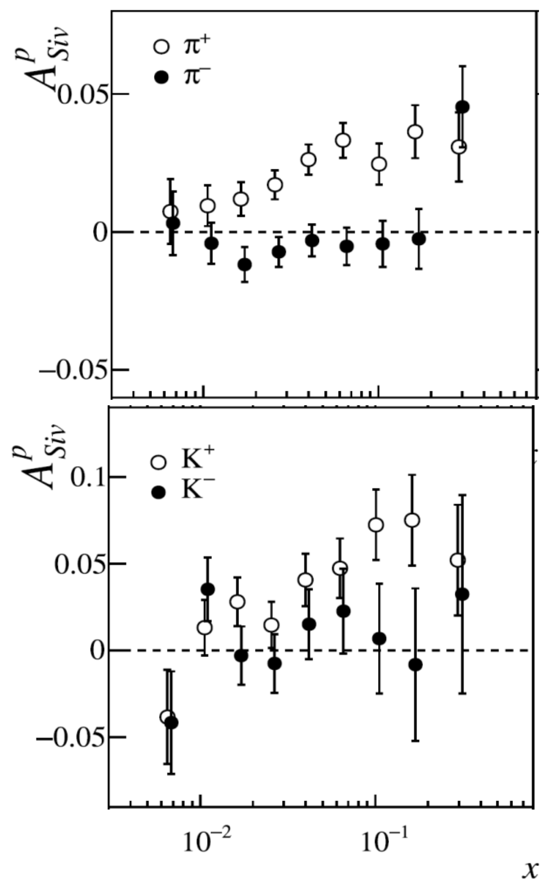
Sivers asymmetry

PRL103 2009



final results on **proton**

PLB744 2015

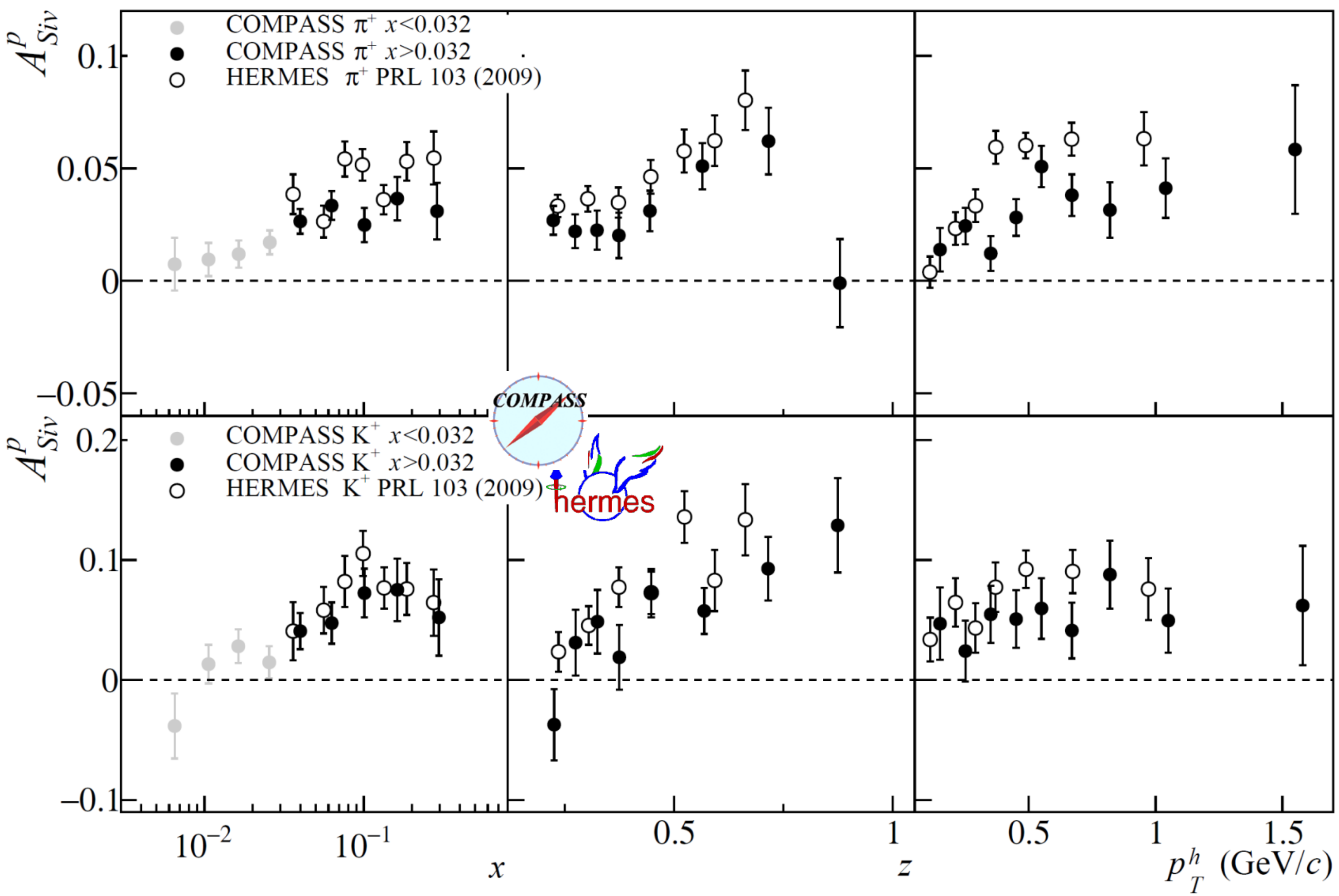


$z > 0.2$

- **clearly positive for π^+ down to $x \sim 10^{-2}$**
- **K^+ asymmetries larger than π^+ asymmetries**

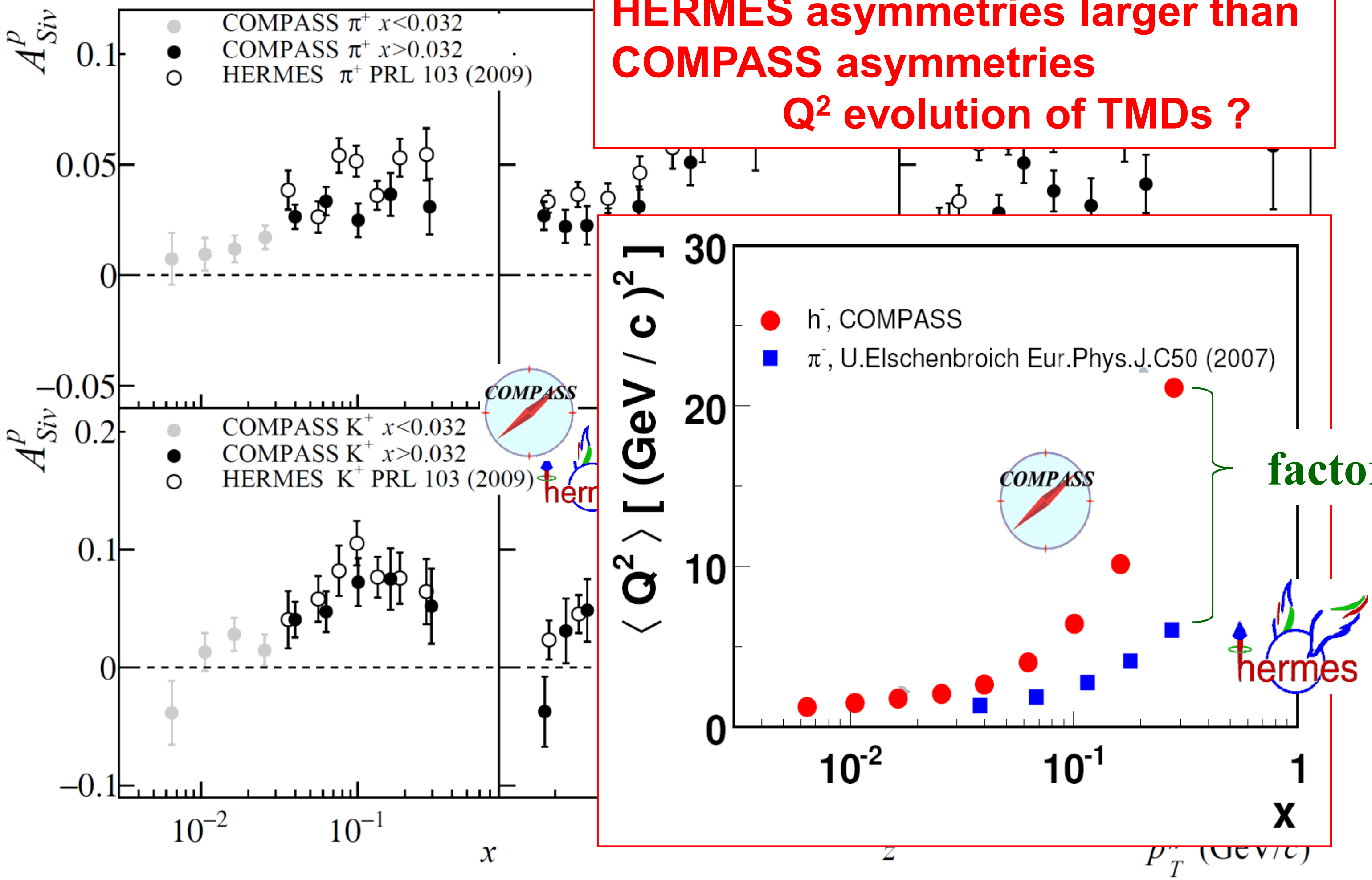
Sivers asymmetry

final results on **proton** for **positive** particles vs



Sivers asymmetry

final results on **proton** for **positive** particles hermes vs COMPASS



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

TMDs evolution

a lot of work in the last few years
still ongoing

new extractions from existing SIDIS data
and predictions for SIDIS experiments at different energies
and polarised Drell-Yan experiments

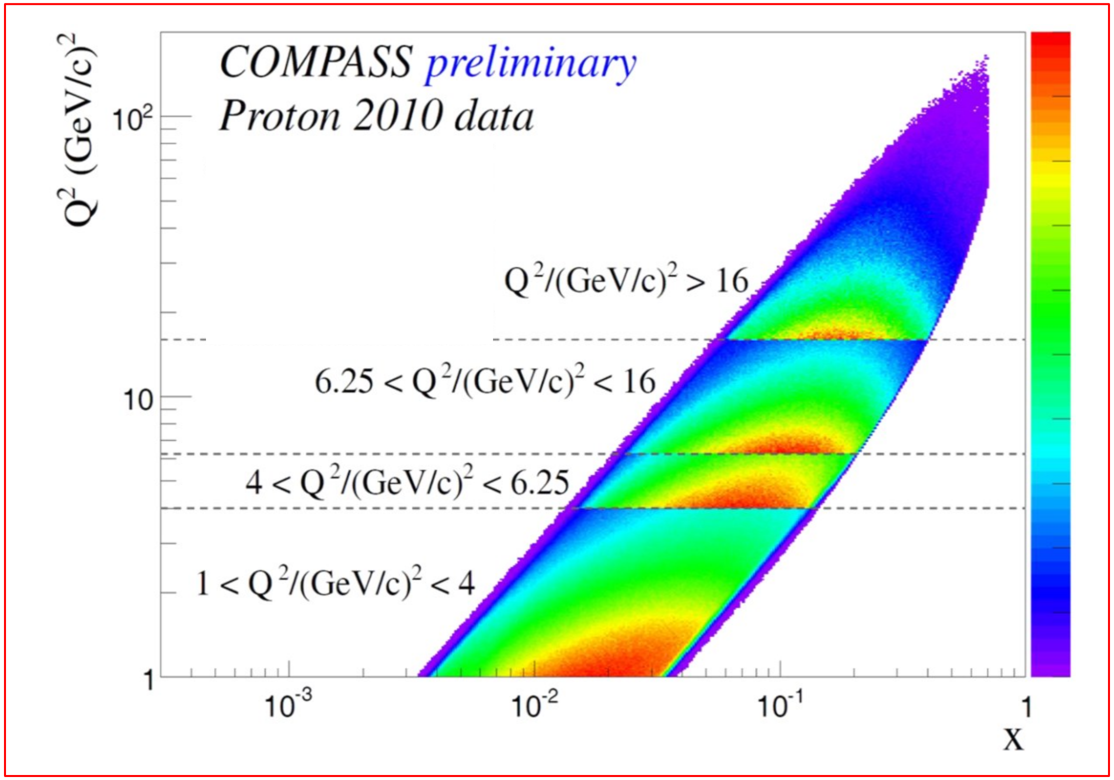
from small to very large Q^2 dependence

multidimensional analysis

Sivers asymmetry

COMPASS has measured the TSA in the 4 Q^2 ranges of the “future” Drell-Yan experiment

Transversity 2014

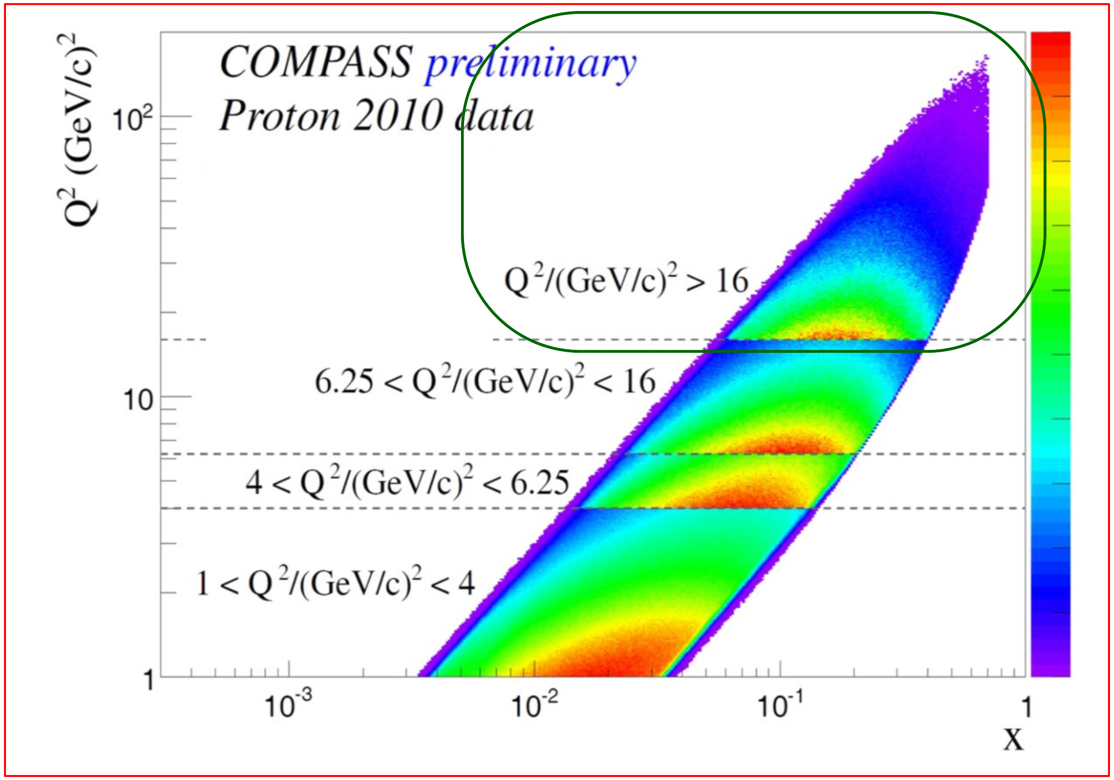


Sivers asymmetry

COMPASS has measured the TSA in the 4 Q^2 ranges of the "future" Drell-Yan experiment

"golden" range: Q^2 >16 GeV^2

Transversity 2014



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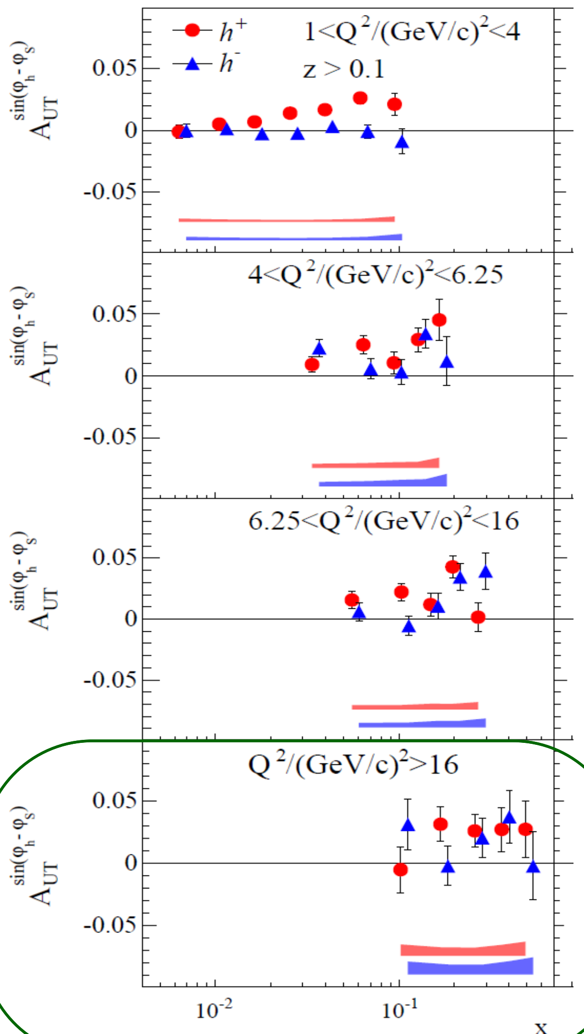

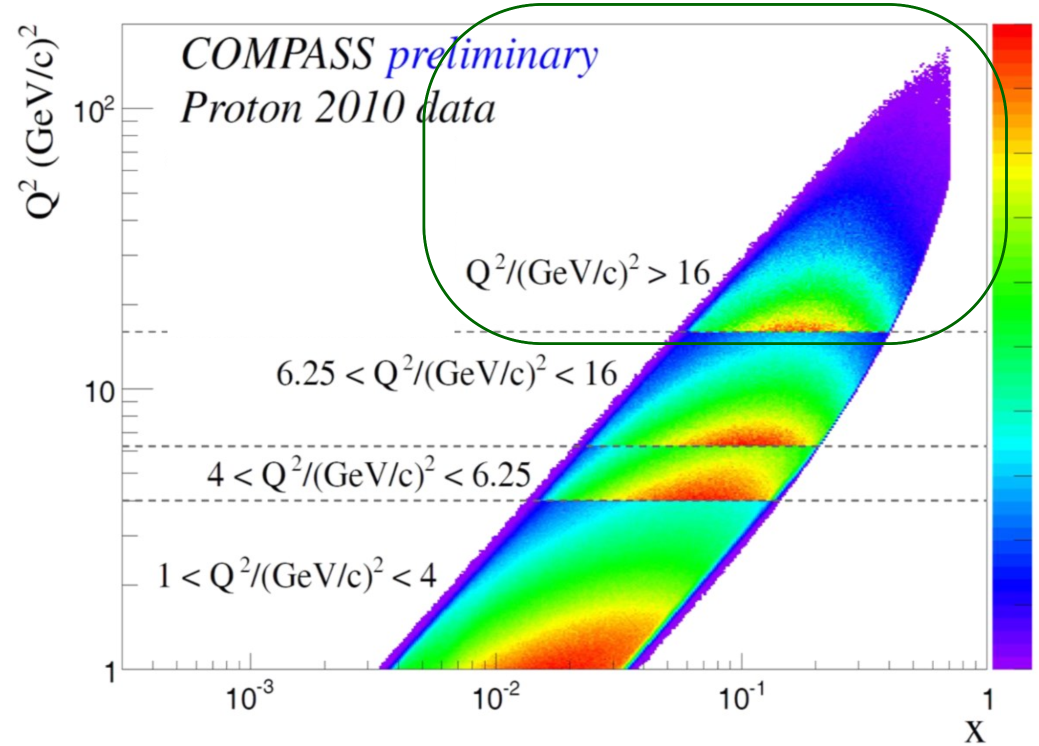

clearly positive
test of change of sign feasible

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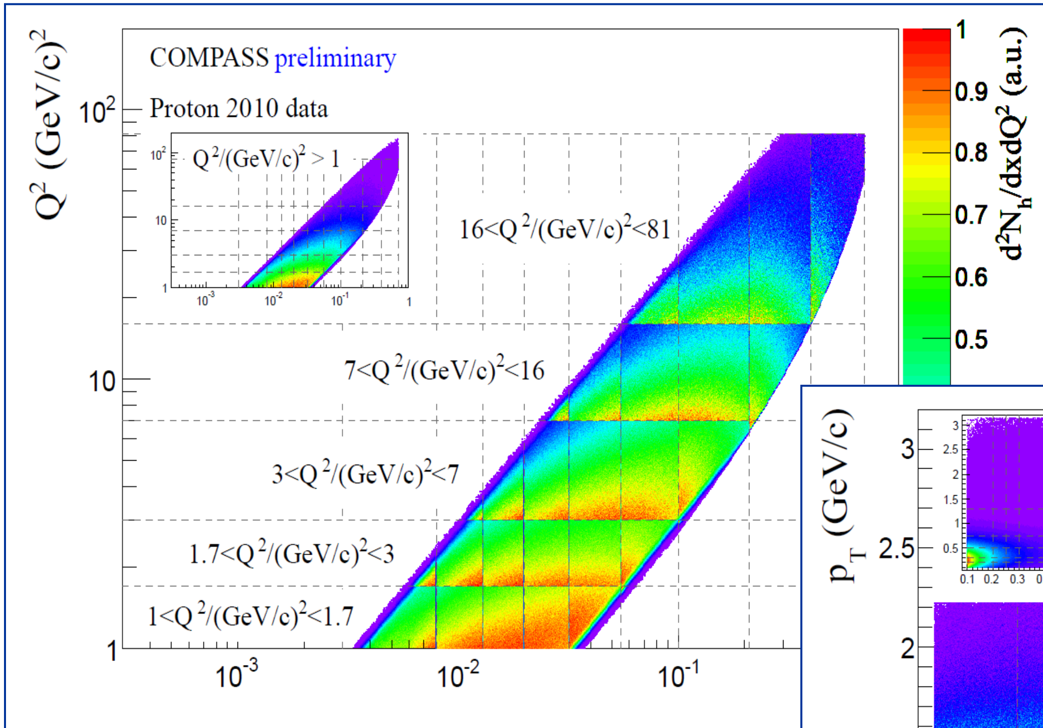
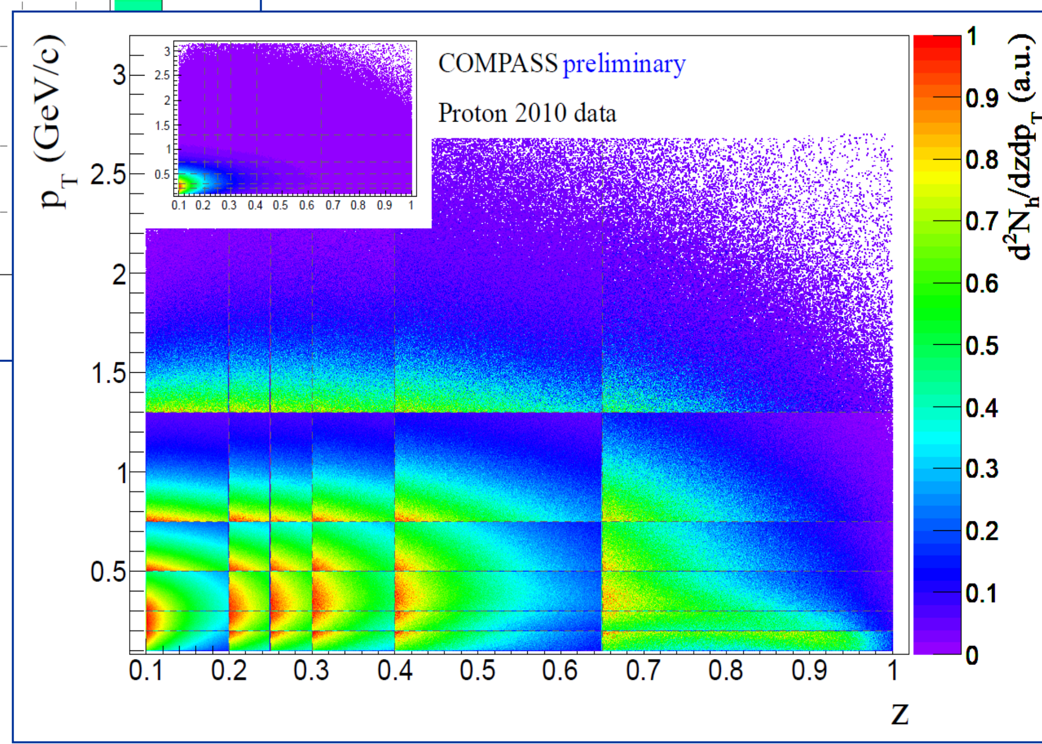
Sivers asymmetry

complete multidimensional measurements

SPIN2014





optimised x-Q^2

z-p_T binning

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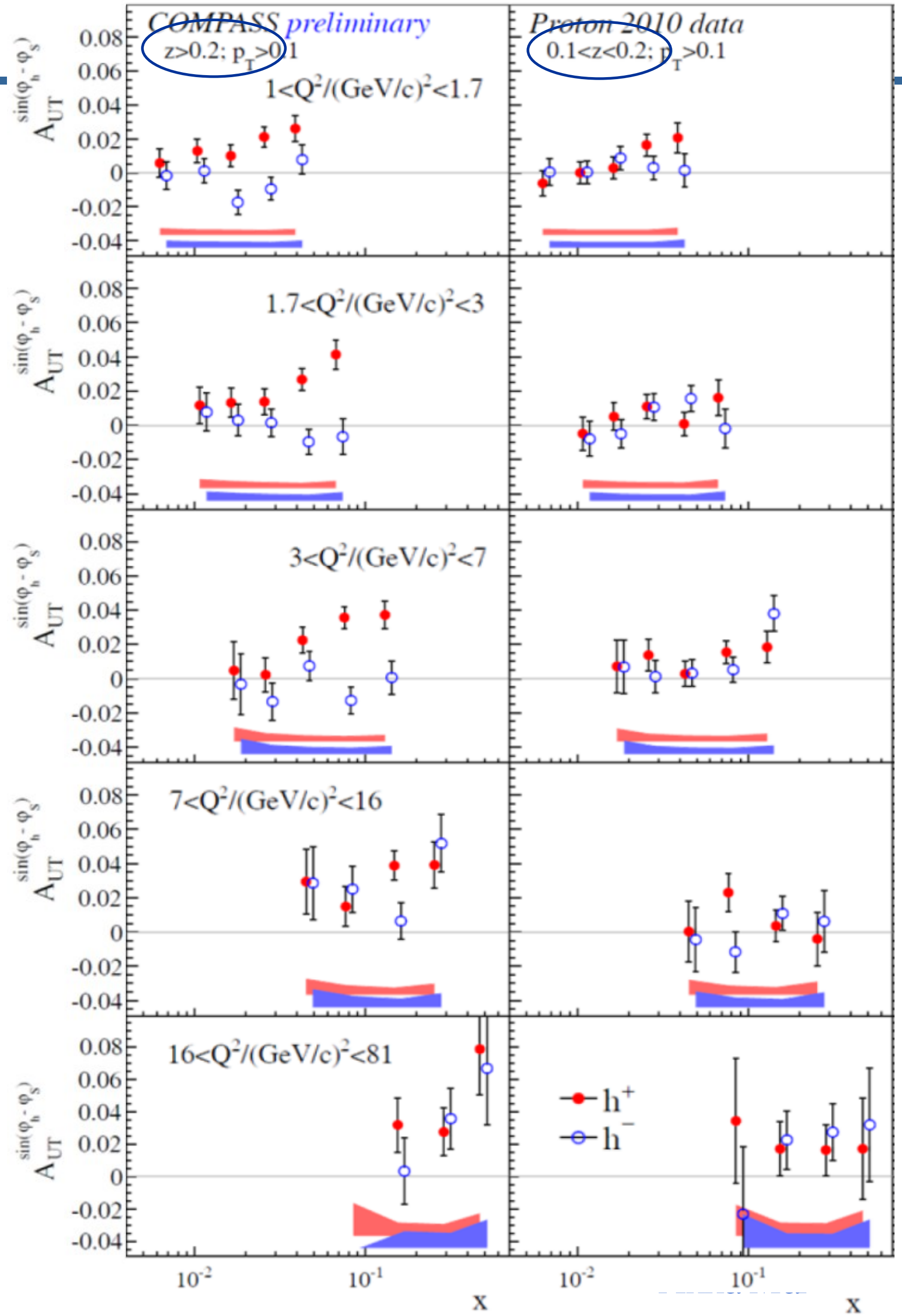
Sivers asymmetry

complete multidimensional measurements



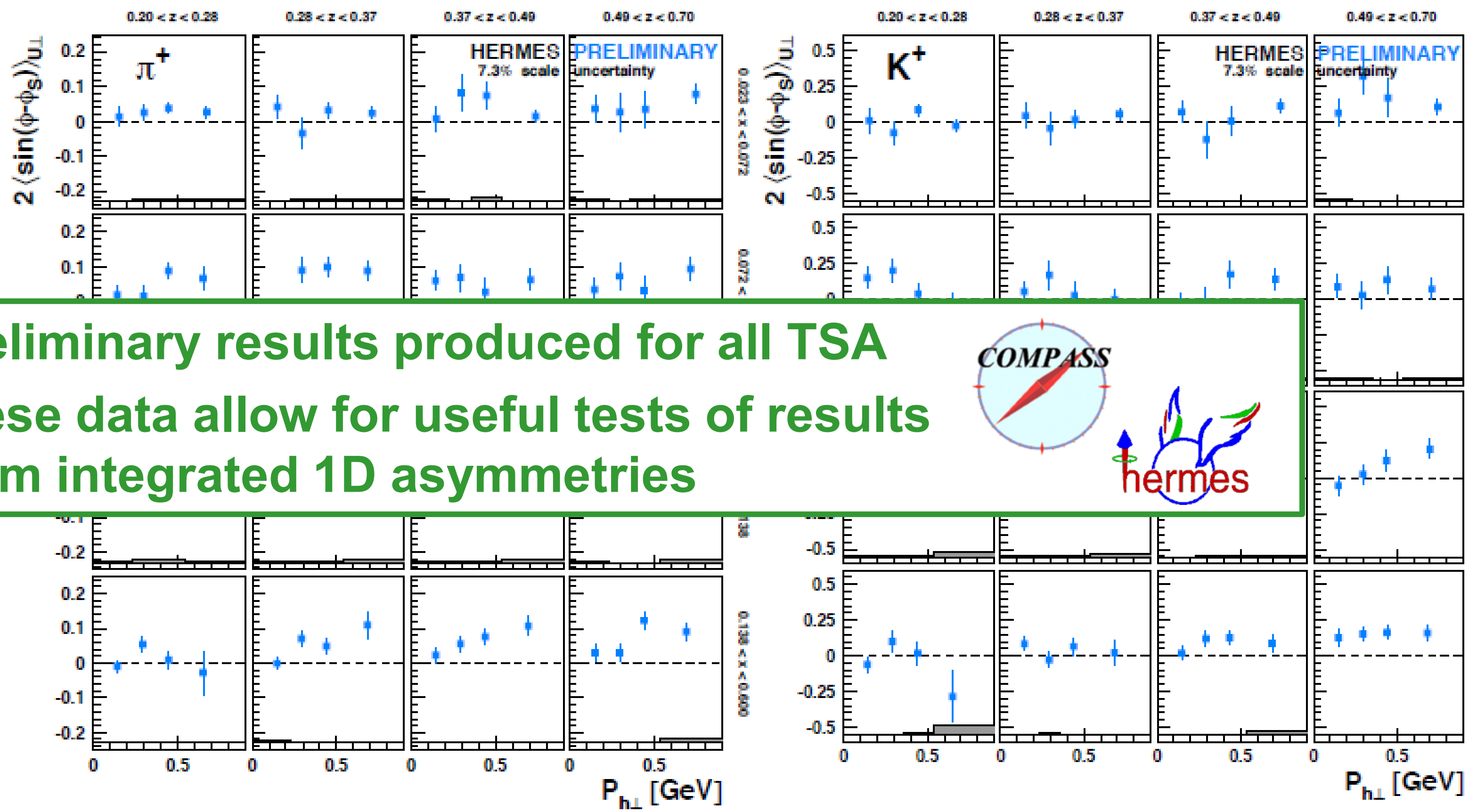
SPIN2014

Sivers asymmetry

Sivers asymmetries: 3D

NEW

$\sigma_{UT} \propto f_{1T}^{\perp q} \otimes D_1^q$



- preliminary results produced for all TSA
- these data allow for useful tests of results from integrated 1D asymmetries

> K^+ amplitudes are larger than π^+ in most kinematic regions
>
> ➡ role of sea quarks

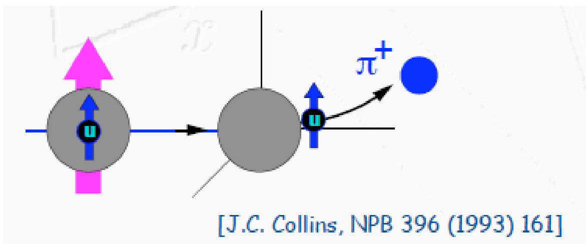
Collins asymmetry

Collins asymmetry

amplitude of the modulation in $\phi_h + \phi_S - \pi$

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

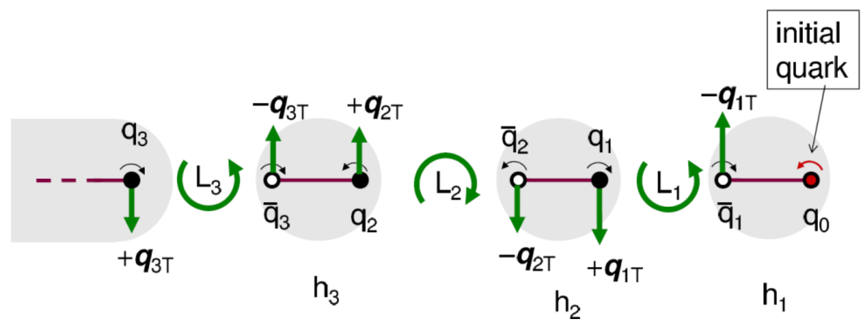
convolution of transversity with the chiral-odd Collins FF



G. Schnell

correlation between
transverse spin of the fragmenting quark
and
transverse momentum of hadrons

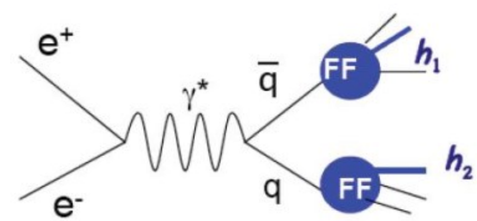
Classical *String* + $^3P_0$
mechanism
of Collins effect
Artru, Czyzewski, Yabuki ZP C73 1997



can be (has been) accessed in

$$e^+e^- \rightarrow q\,\bar{q} \rightarrow h_1\,h_2\,X$$

Collins FF ⊗ Collins FF



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Collins asymmetry

amplitude of the modulation in $\phi_h + \phi_S - \pi$

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

2004: non-zero values on proton hermes

compatible with zero on deuteron COMPASS

first evidence that both h_1 and Collins FF different from zero

first e+e- measurements from Belle

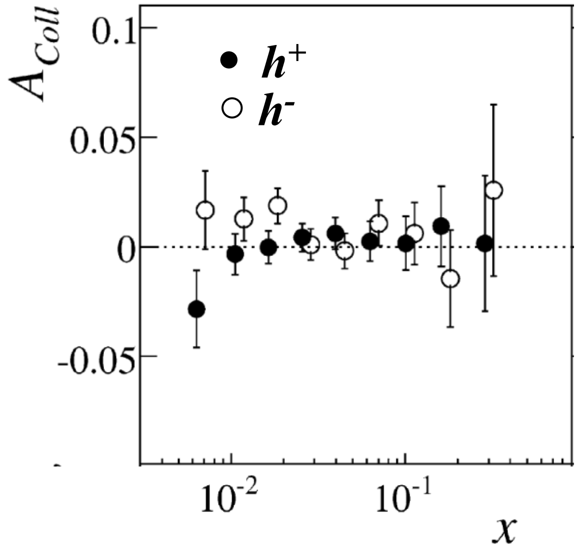
“global” fits

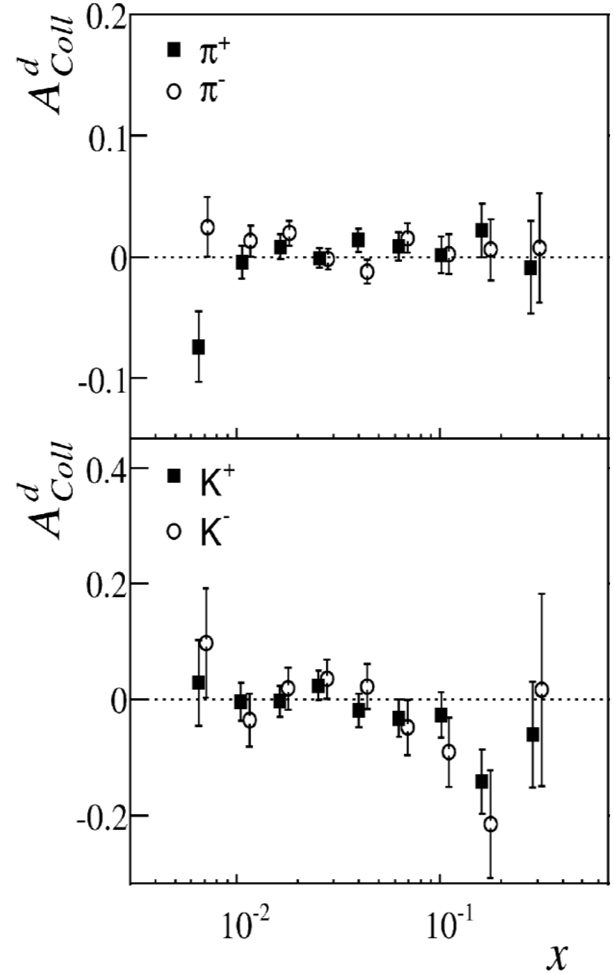
→ first extractions of h_1 and Collins FF

Collins asymmetry

final results on
deuteron

2002-2004 data
NPB765 2007, PLB673 2009

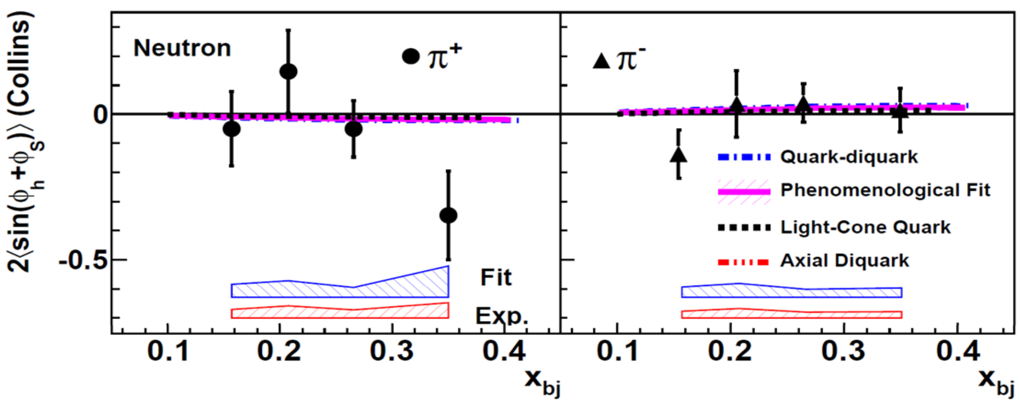




and **neutron**

Jefferson Lab

Hall A PRL107, 2011



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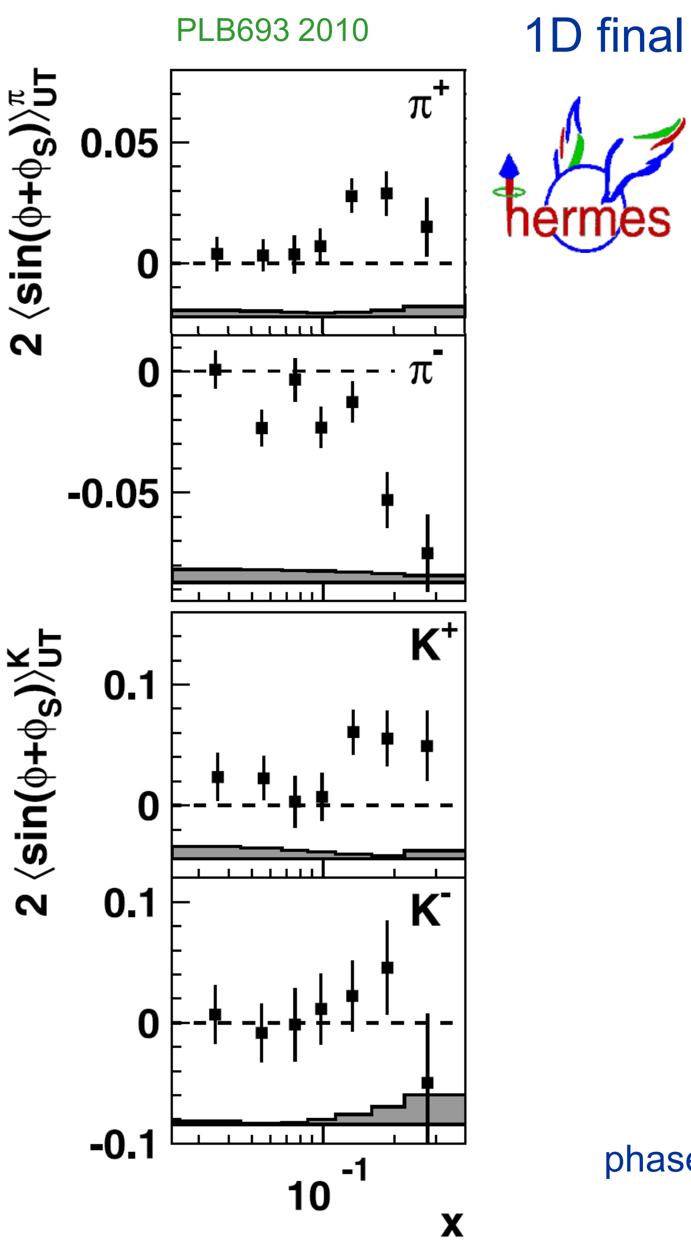
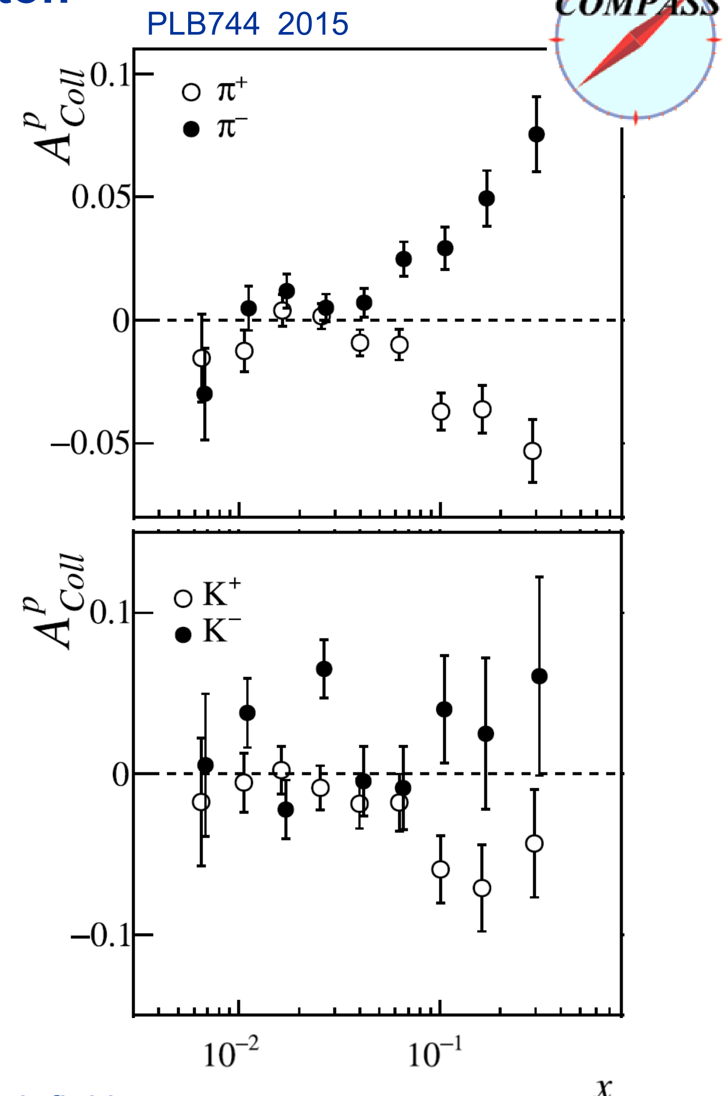
Collins asymmetry

1D final results on **proton**





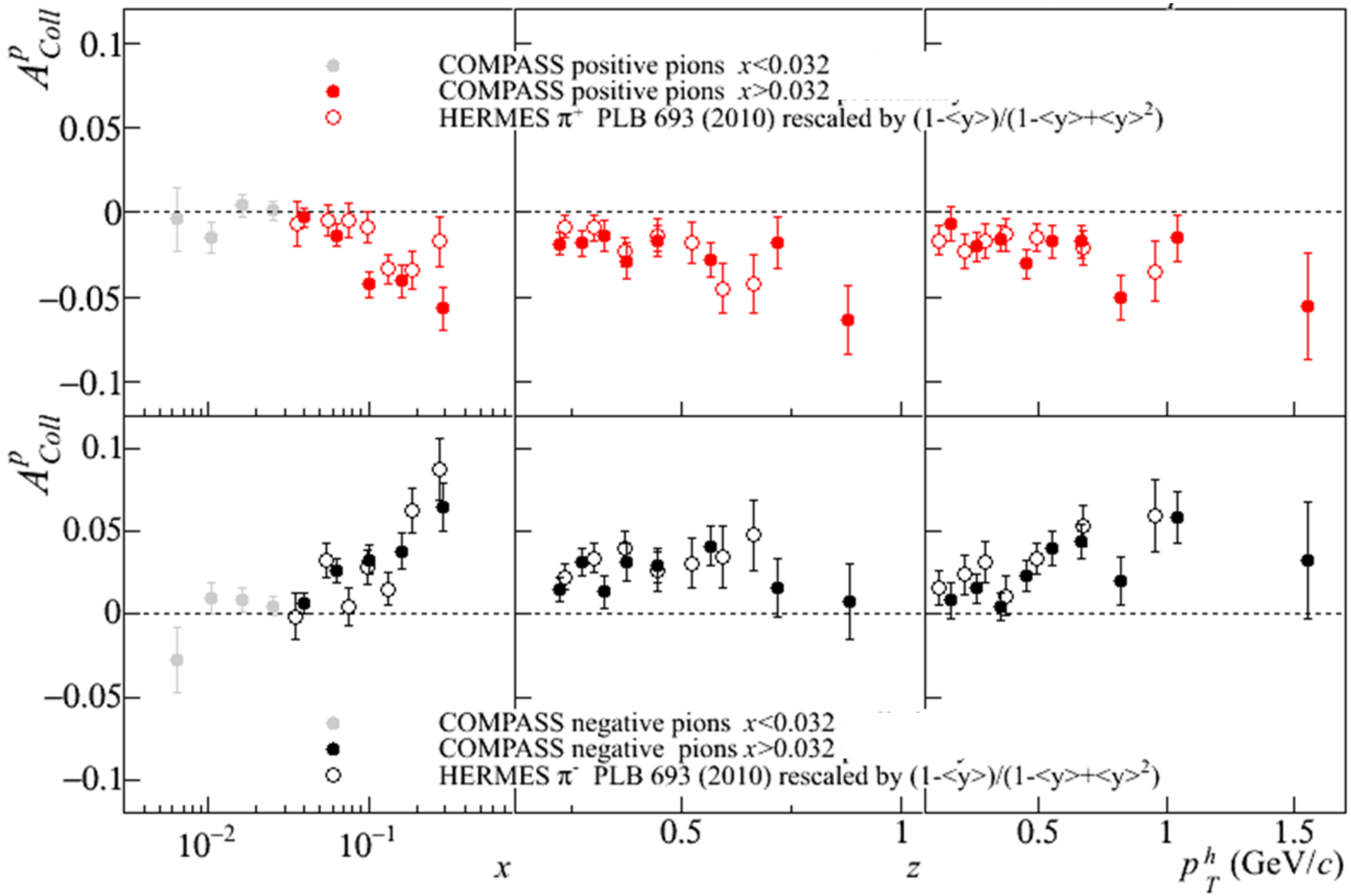
phase π in Collins angle definition

Collins asymmetry

charged pions

π+

π-

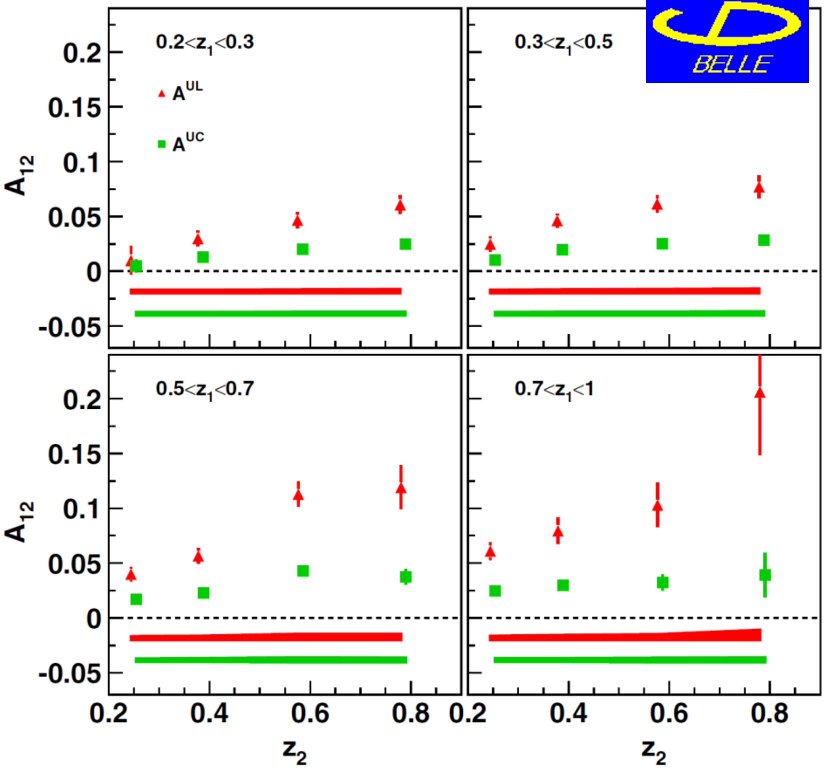


Q^2 evolution of Collins FF?

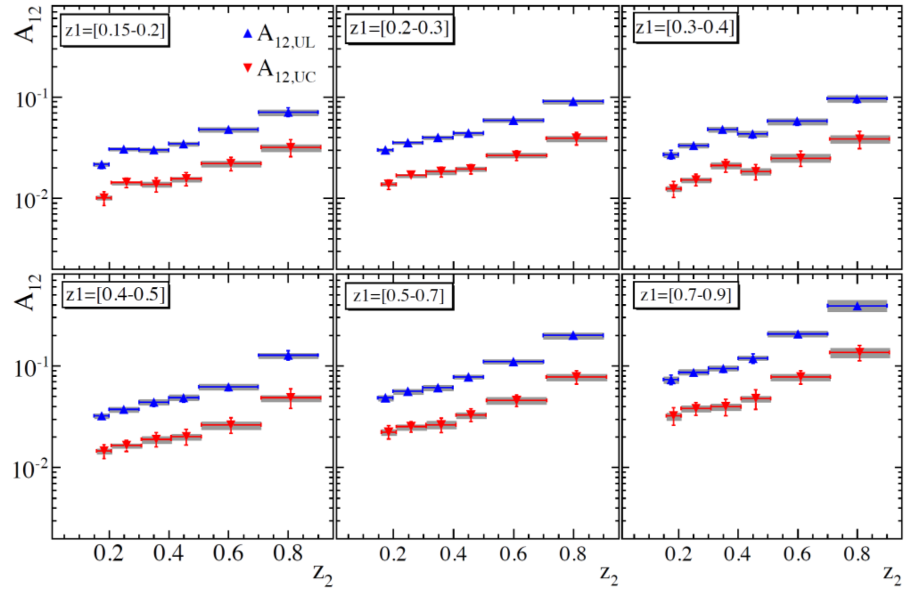
Collins FF

Collins FF

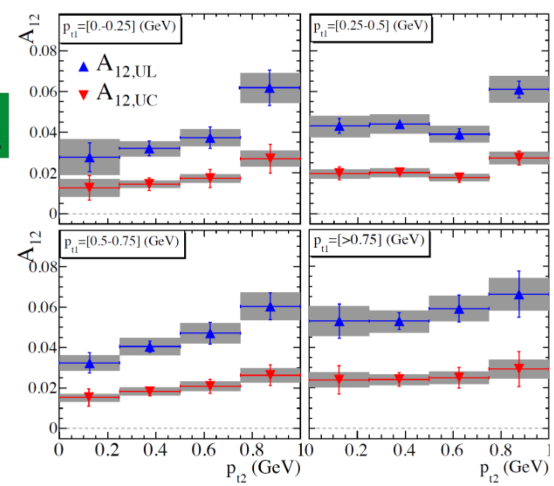
PRD78, 2008 PRD86, 2012



PRD90 2014



(z_1,z_2,p_{t1},p_{p2})



Unlike-sign couples / Like-sign couples

Unlike-sign couples / All charges

$\sqrt{s}$=10.58 GeV

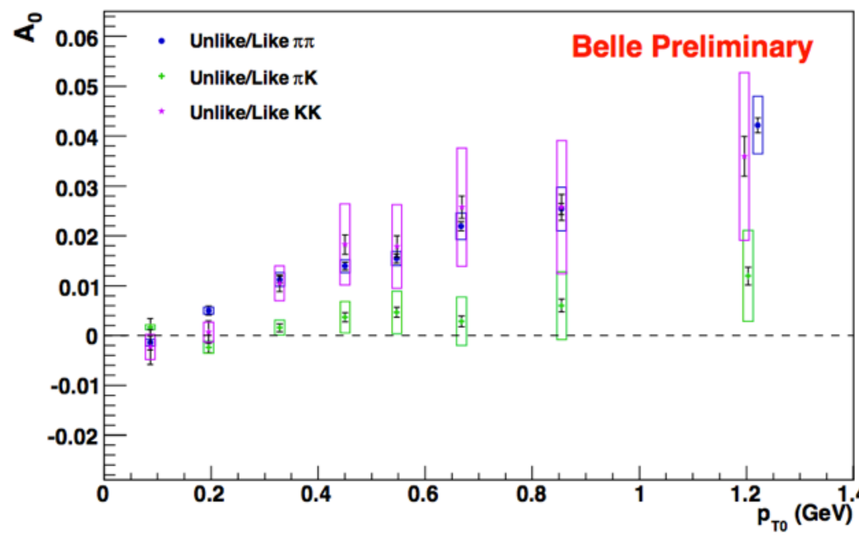
Collins FF

$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

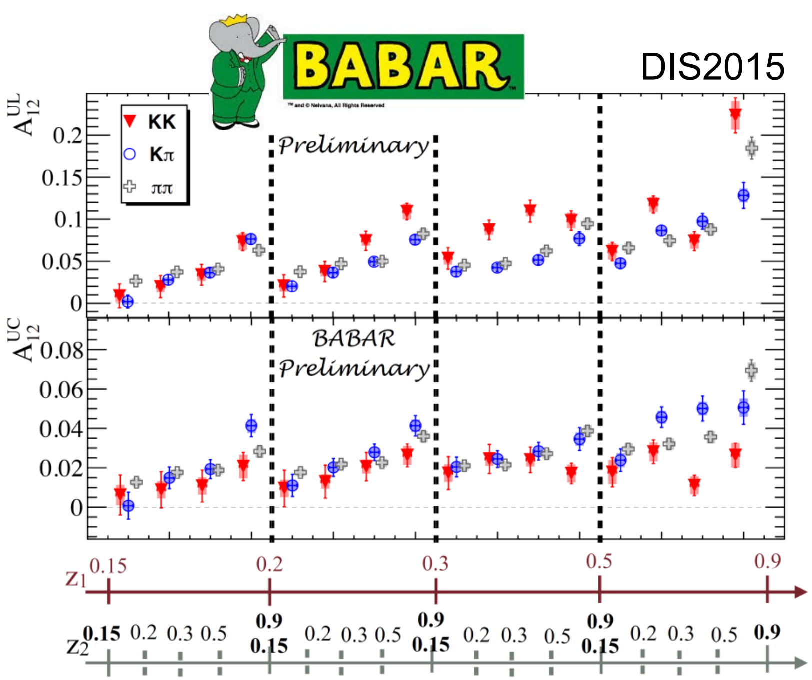
πK => asymmetries compatible with zero

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

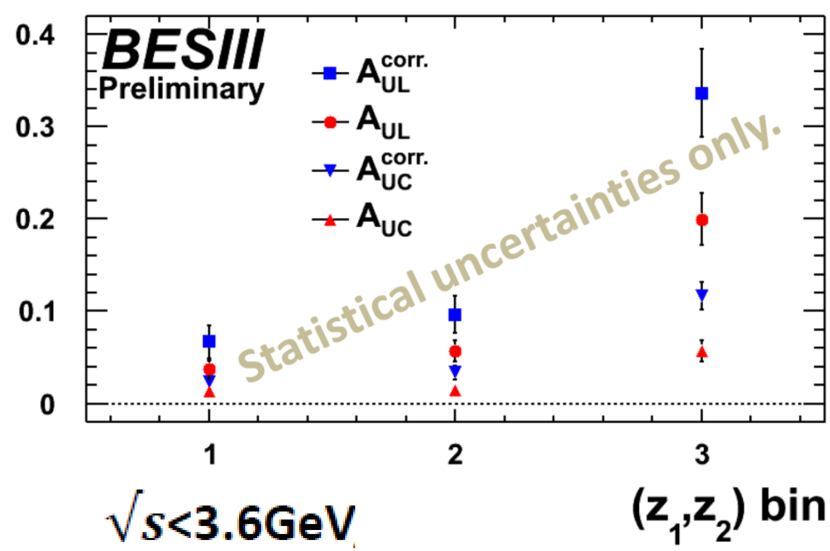
Transversity2014



DIS2015



DIS2015



Transversity

simultaneous fit of HERMES p, COMPASS p & d, and Belle data

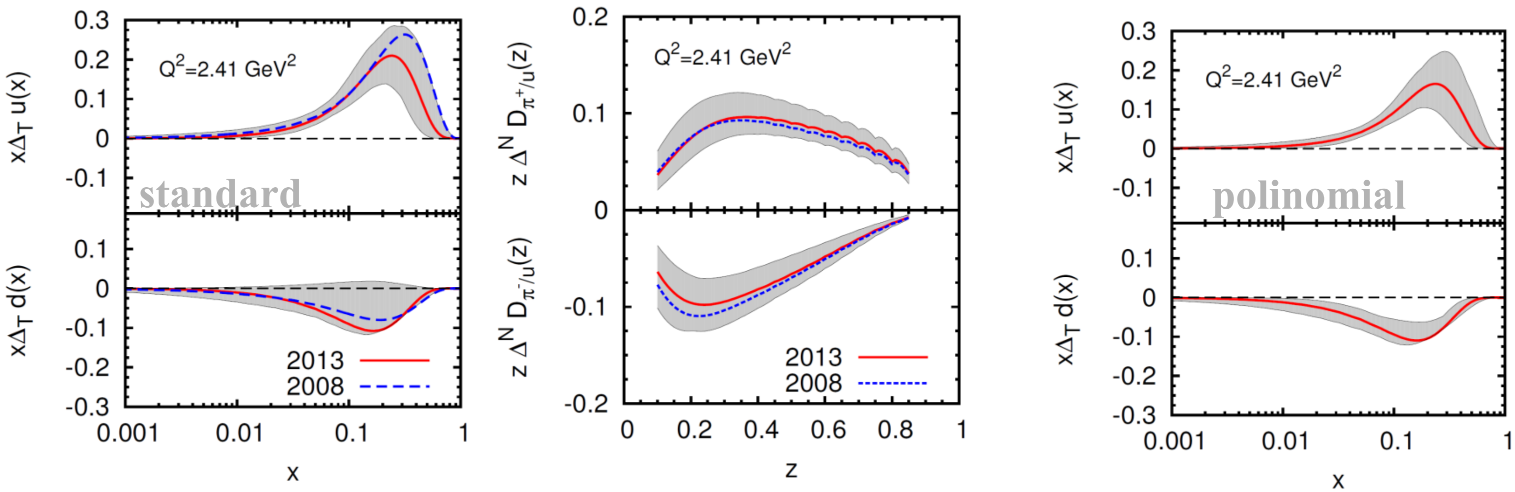
parametrisations of Transversity and Collins functions

very good χ^2

Transversity

simultaneous fit of HERMES p, COMPASS p & d, and Belle data
parametrisations of Transversity and Collins functions very good χ^2

Anselmino et al., PRD87 2013



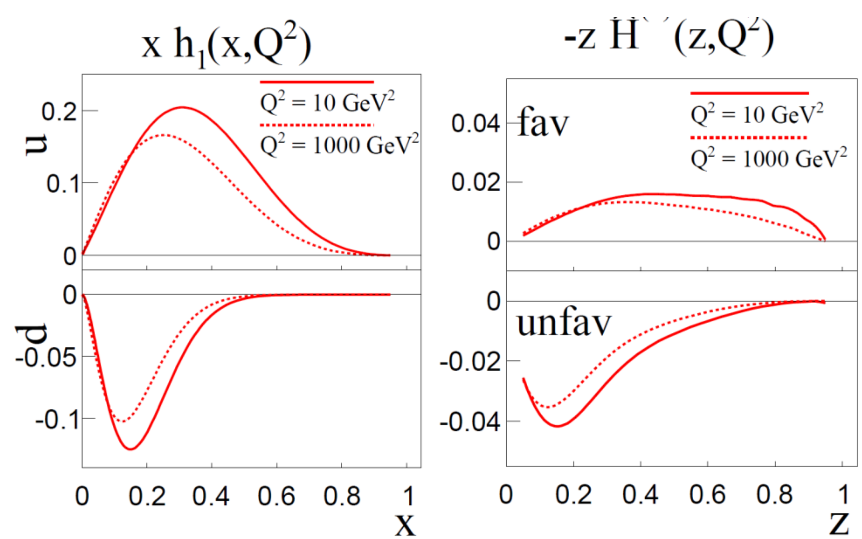
$\delta u = 0.39^{+0.18}_{-0.12}$ $\delta d = -0.25^{+0.30}_{-0.10}$

$\delta u = 0.31^{+0.16}_{-0.12}$ $\delta d = -0.27^{+0.10}_{-0.10}$

Kang et al, PRD91 2015

$$\delta u^{[0.0065,0.35]} = +0.30^{+0.12}_{-0.08}$$
$$\delta d^{[0.0065,0.35]} = -0.20^{+0.28}_{-0.11}$$

higher order corrections, x z

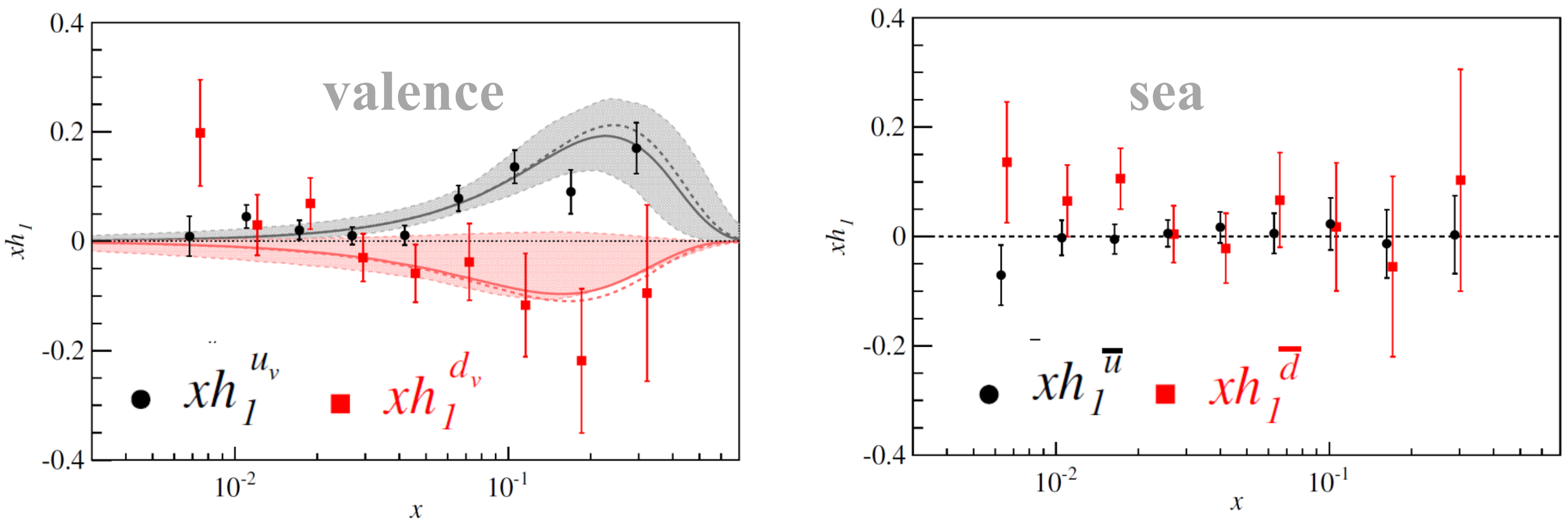


Transversity

from **COMPASS p & d** and **Belle** data, **point by point extraction**

- evolution: the same for Collins and unpolarised FF
- convolution on k_T neglected

Martin Bradamante Barone PRD91 2015



curves
from Anselmino et al.,
PRD87 2013

Transversity

alternative channels to access transversity in SIDIS

- **Λ production**, measurement of transverse polarisation
  difficult: low statistics (see COMPASS d)

- **hadron pair production**, measurement of the di-hadron asymmetry
  easier / done

dihadron asymmetry

independent channel to access transversity in SIDIS off transversely polarised nucleons

Collins

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

"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"

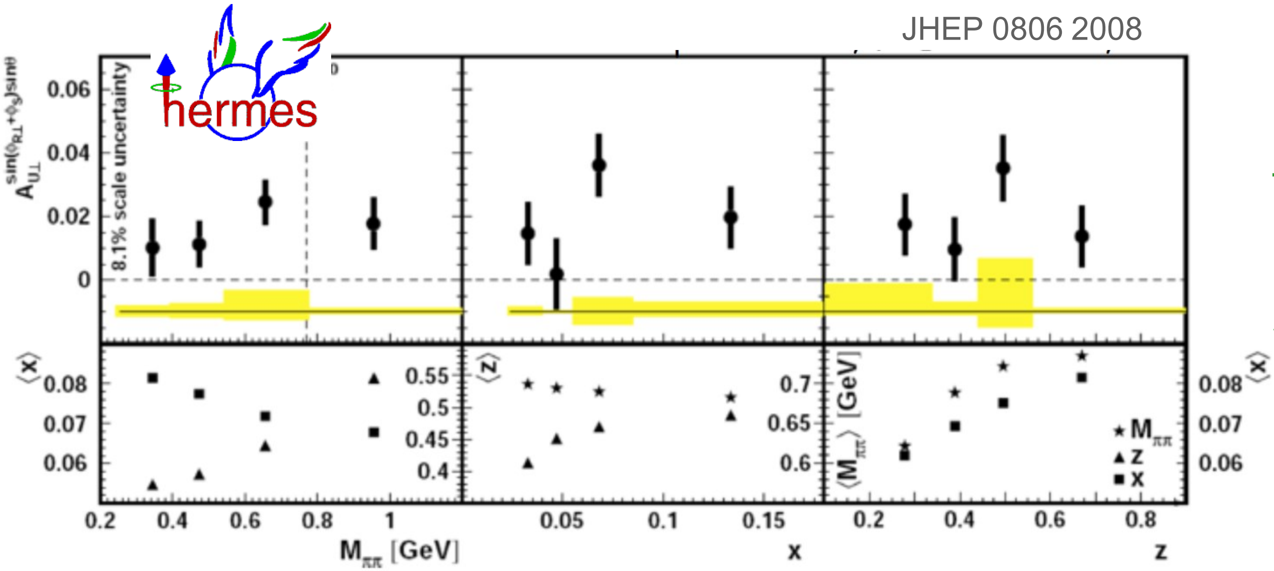
Belle Babar

"spin independent di-hadron FF"

being measured at Belle Babar COMPASS

dihadron asymmetry

JHEP 0806 2008



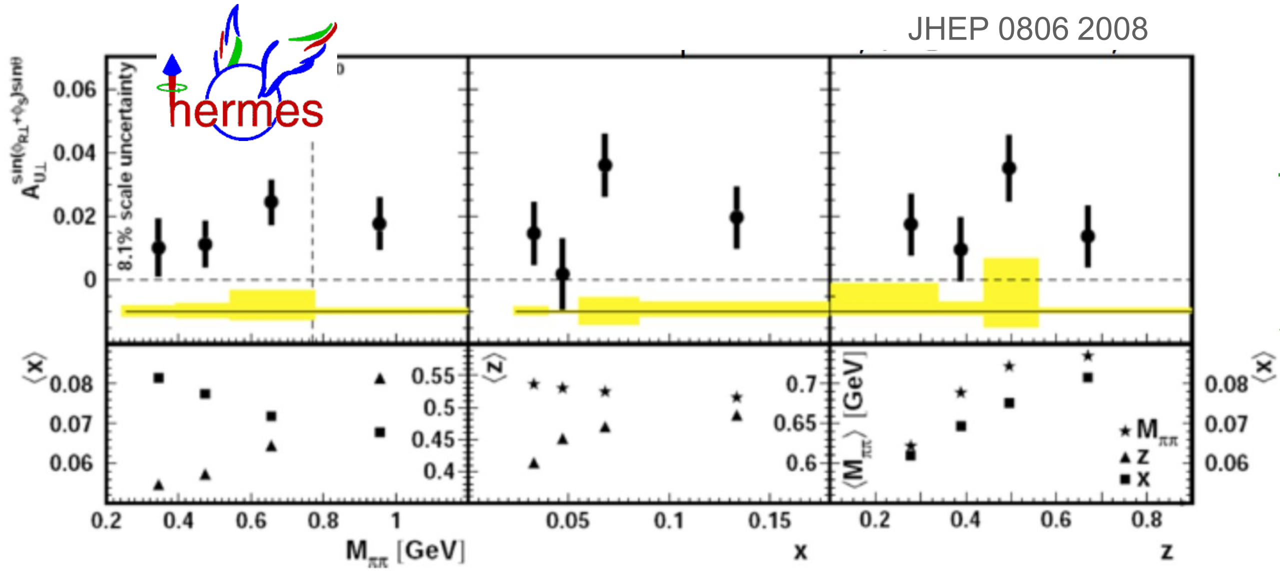
HERMES proton

first evidence for non-zero dihadron FF,

same sign of Collins asymmetry for π^+

dihadron asymmetry

JHEP 0806 2008



HERMES proton

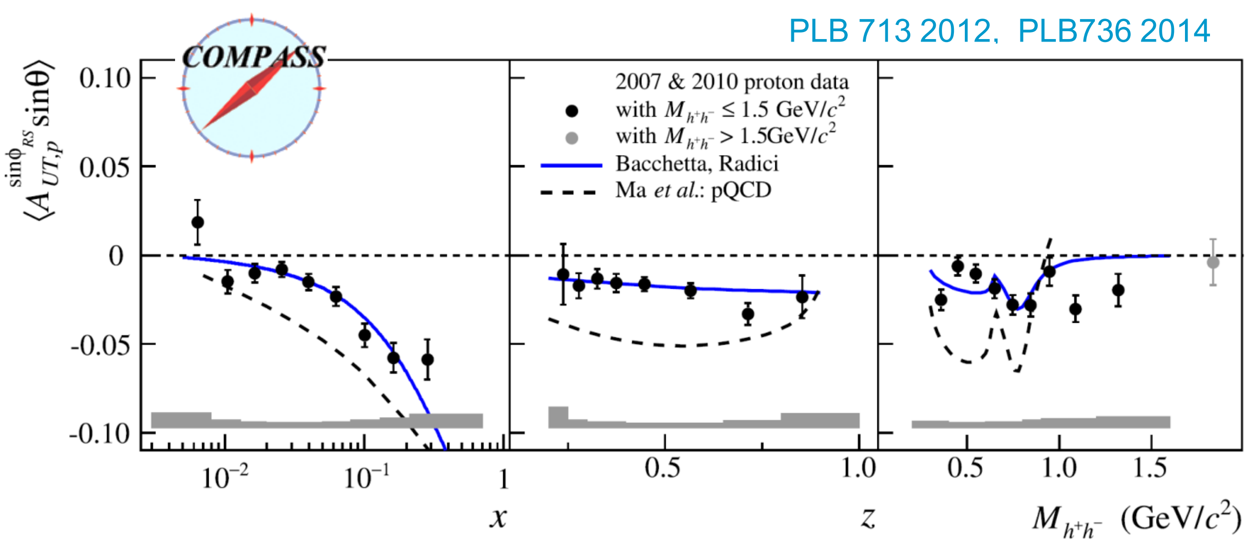
first evidence for

non-zero dihadron FF,

same sign of Collins

asymmetry for π^+

PLB 713 2012, PLB736 2014



COMPASS

deuteron:

compatible with zero

proton:

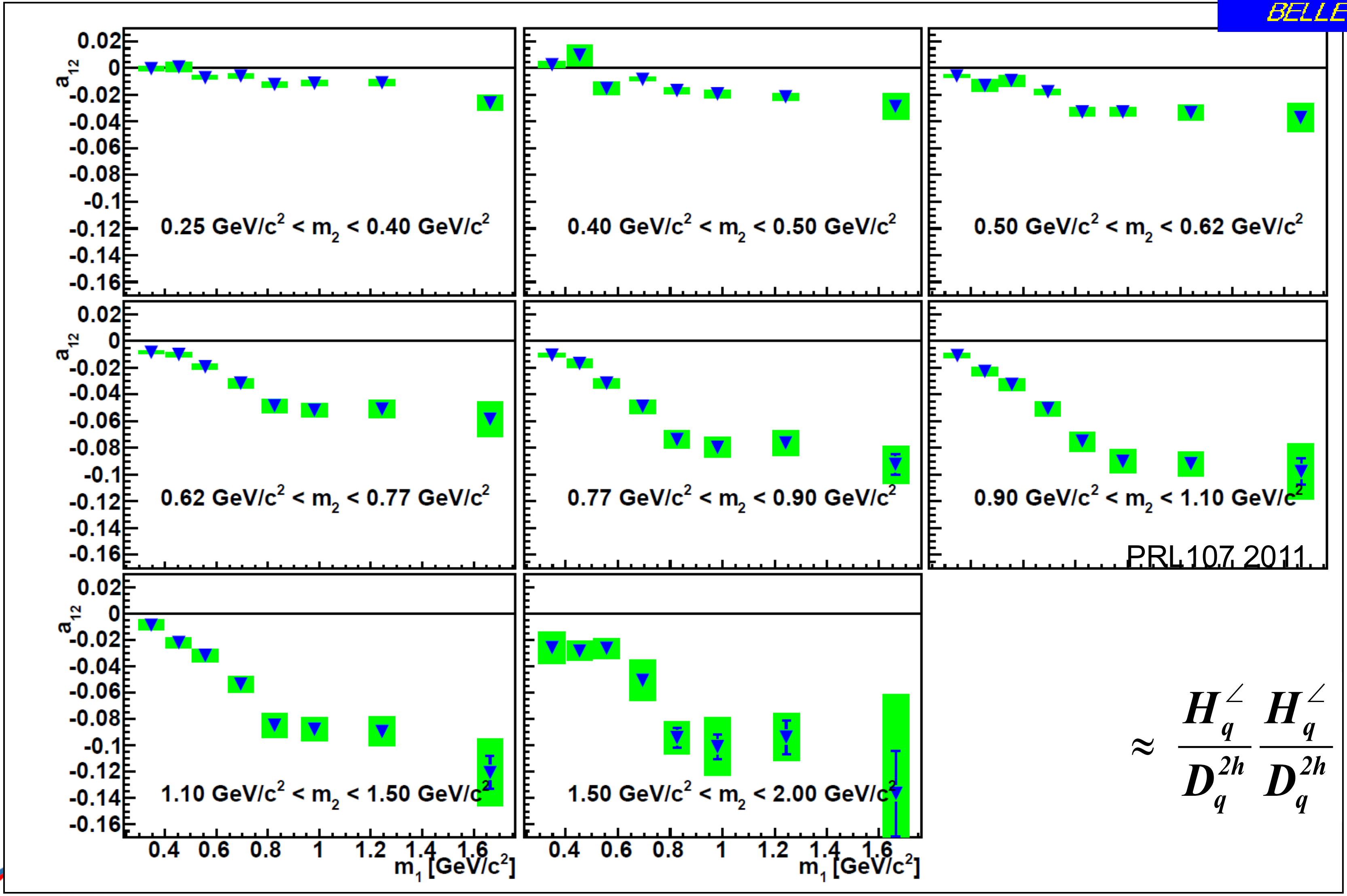
same sign and shape

slightly higher

than Collins asymmetry

for h^+

dihadron FF



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

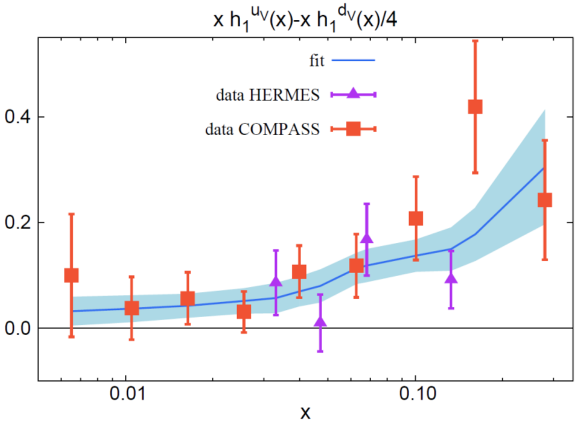
Transversity from 2h asymmetries

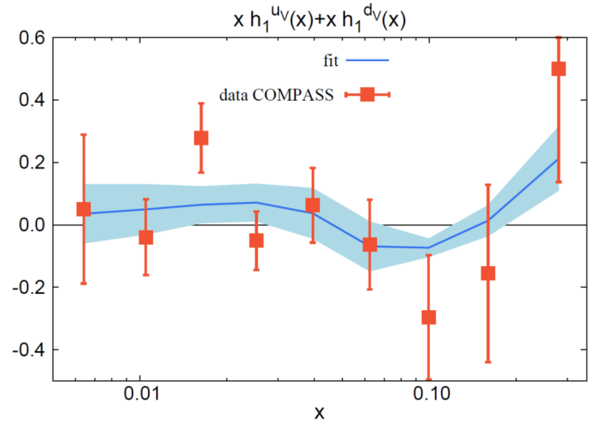
Bacchetta Courtoy Radici JHEP 1303 2013

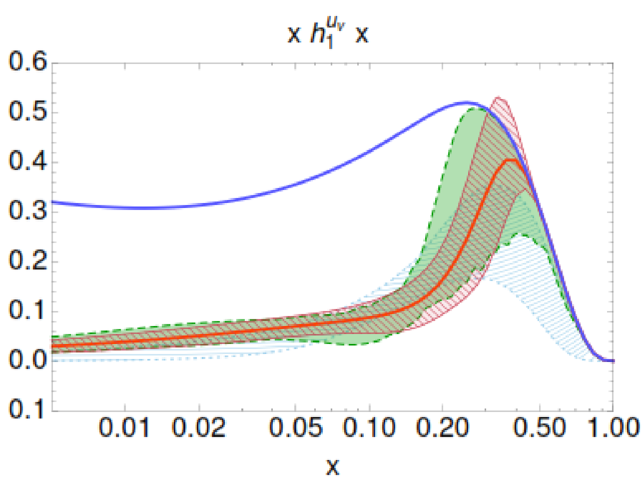
D_q^{2h} from PYTHIA HERMES p, COMPASS p and d, Belle data

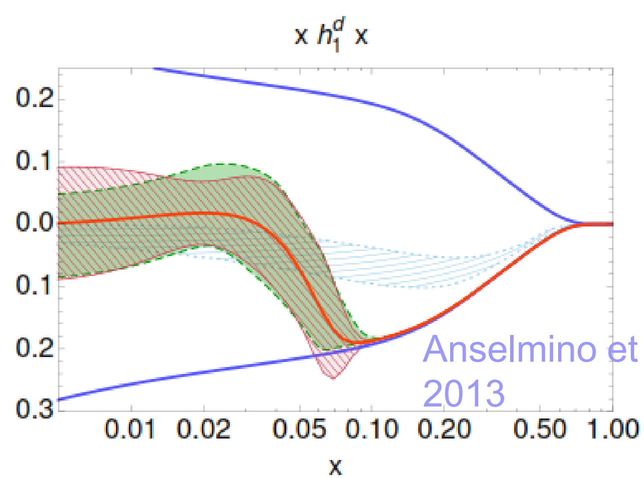
→ linear combinations of transversity for u and d valence quark

fit with parametrisations → transversity PDFs









Anselmino et al 2013

flexible

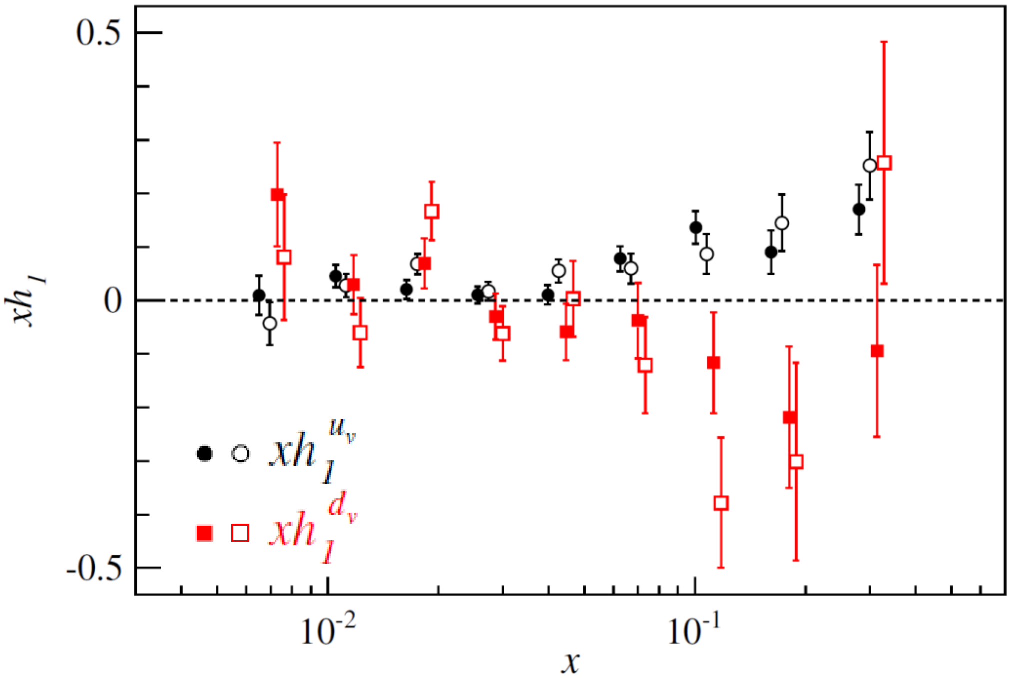
Transversity from 2h asymmetries

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

one can use directly the COMPASS p and d data, and the Belle data (plus some "reasonable" assumptions) to evaluate the analysing power

advantages:

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



open points: dihadron

closed points: Collins

further confirmation that k_T is not so relevant in this case

Martin Bradamante Barone
PRD91 2015

dihadron asymmetry - new ideas

dihadron asymmetry - new ideas

Gliske, Bacchetta, Radici PRD90 2014, P.R.D91 2015

new partial wave expansion for fragmentation functions

- it gives a consistent framework for fragmentation into final states of any polarization
- shows that the two-hadron SIDIS cross sections, at any twist, can be derived from single-hadron SIDIS cross section
- two-hadron SIDIS cross section is given up to subleading twist, including the dependence upon the transverse momentum of involved particles

$$D_1 = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta)\cos\left(m(\phi_{R_\perp} - \phi_p)\right) \times D_1^{|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|),$$

$$H_1^\perp = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} P_{\ell,m}(\cos\vartheta) e^{im(\phi_{R_\perp} - \phi_p)} \times H_1^{\perp|\ell,m\rangle}(z, M_h, |\boldsymbol{p}_T|),$$

not easy …

→ HERMES

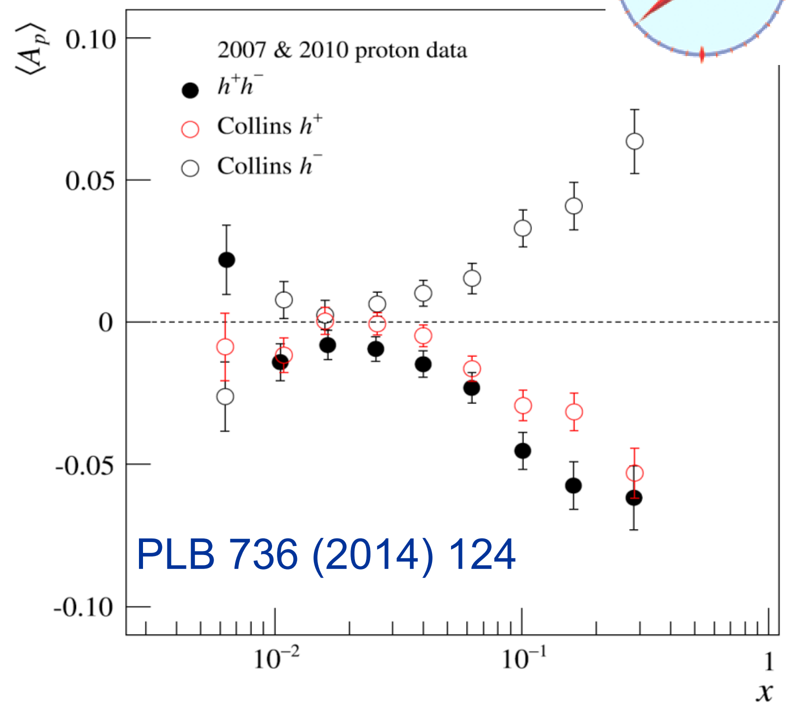
dihadron asymmetry - new ideas

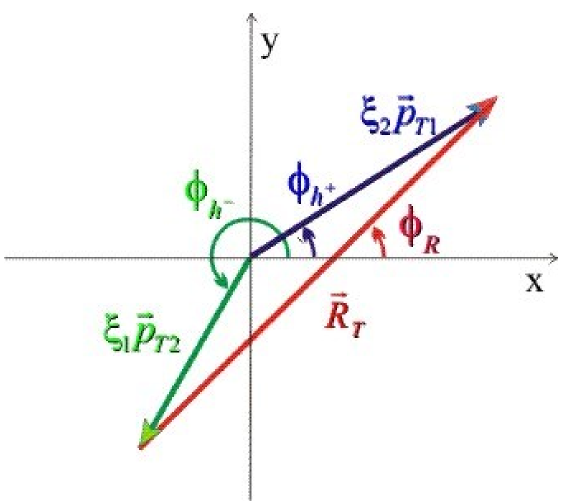
interplay between dihadron and single hadron asymmetries

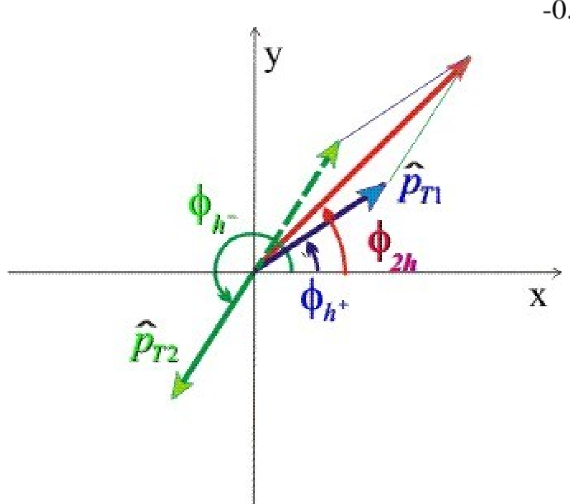
known intriguing results

- Collins asymmetry for h+ and for h-
  "mirror symmetry"
- dihadron asymmetry
  only somewhat larger than h+ Collins

→ first studies of the correlations between the relevant azimuthal angles and the corresponding asymmetries $\phi_R \sim \phi_{2h}$







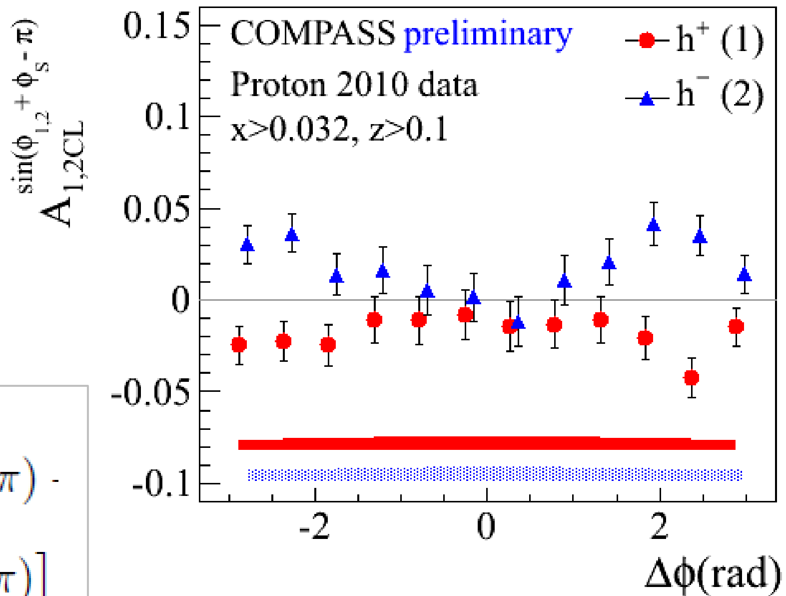
hints for a common origin of the Collins FF and DiFF

Como 2013, DSpin2013, PLB736 2014

interplay between single hadron and dihadron asymmetries

new: Collins like and di-hadron asymmetries vs $\Delta\phi = \phi_1 - \phi_2$
using the events with at least 2 oppositely charged hadrons (2h sample):
Trannsversity2014, SPIN2014

the asymmetries are expected to be specular and maximum at $\Delta\phi \simeq \pi$



analytical calculations:
A. Kotzionian, PRD91 2015

$$\frac{d\sigma^{h_1h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U^{h_1h_2} + S_T\left[\sigma_{C1}^{h_1h_2}\sin(\phi_1+\phi_S-\pi)\cdot + \sigma_{C2}^{h_1h_2}\sin(\phi_2+\phi_S-\pi)\right]$$

$$A_{CL1}^{\sin(\phi_1+\phi_S-\pi)} = \frac{1}{D_{NN}}\frac{\sigma_{C1}^{h_1h_2}+\sigma_{C2}^{h_1h_2}\cos\Delta\phi}{\sigma_U^{h_1h_2}}$$

$$A_{CL2}^{\sin(\phi_2+\phi_S-\pi)} = \frac{1}{D_{NN}}\frac{\sigma_{C2}^{h_1h_2}+\sigma_{C1}^{h_1h_2}\cos\Delta\phi}{\sigma_U^{h_1h_2}}$$

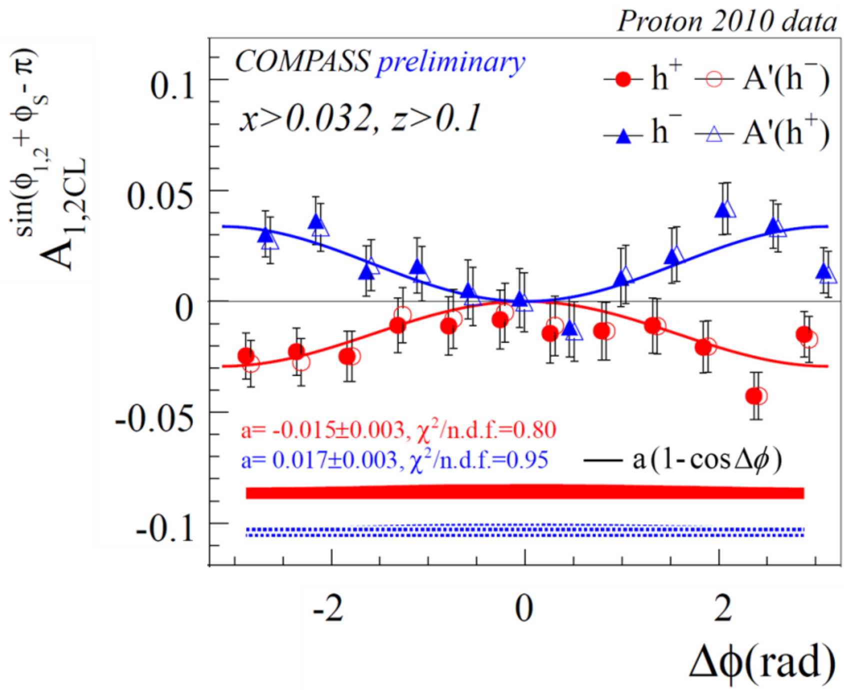
good agreement with data if

$$\sigma_{C1}^{h_1h_2} = -\sigma_{C2}^{h_1h_2}$$

interplay between single hadron and dihadron asymmetries

$$\sigma_{C1}^{h_1h_2} = -\sigma_{C2}^{h_1h_2} \Rightarrow \begin{cases} A_{CL1}^{\sin(\phi_1+\phi_S-\pi)} = \dfrac{1}{D_{NN}} \dfrac{\sigma_{C1}^{h_1h_2}}{\sigma_U^{h_1h_2}} \cdot (1-\cos\Delta\phi) \\ A_{CL2}^{\sin(\phi_2+\phi_S-\pi)} = - A_{CL1}^{\sin(\phi_1+\phi_S-\pi)} \end{cases}$$

mirror symmetry



interplay between single hadron and dihadron asymmetries

$$\sigma_{C1}^{h_1 h_2} = -\sigma_{C2}^{h_1 h_2}$$

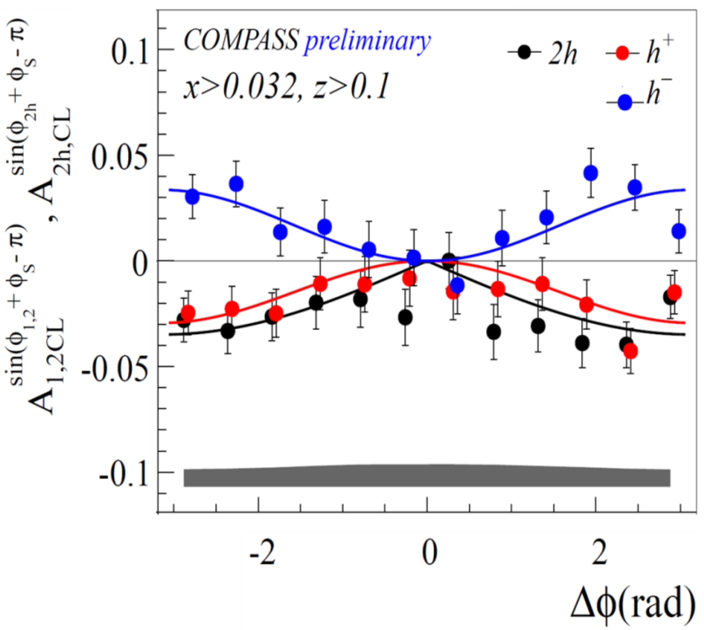
$$\begin{cases} A_{CL1}^{\sin(\phi_1+\phi_S-\pi)} = \dfrac{1}{D_{NN}} \dfrac{\sigma_{C1}^{h_1h_2}}{\sigma_U^{h_1h_2}} \cdot (1-\cos\Delta\phi) \\ A_{CL2}^{\sin(\phi_2+\phi_S-\pi)} = -\ A_{CL1}^{\sin(\phi_1+\phi_S-\pi)} \end{cases}$$

mirror symmetry

rewriting the cross-section in terms of ϕ_{2h} and $\Delta\phi$ one easily obtains

$$A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)} = \frac{1}{D_{NN}} \frac{\sigma_{C1}^{h_1h_2}}{\sigma_U^{h_1h_2}} \cdot \sqrt{2(1-\cos\Delta\phi)}$$

a very **simple relationship** between dihadron and single hadron asymmetries in the 2h sample



in agreement with data

ratio of the integrals: $4/\pi$

slightly larger than h^+

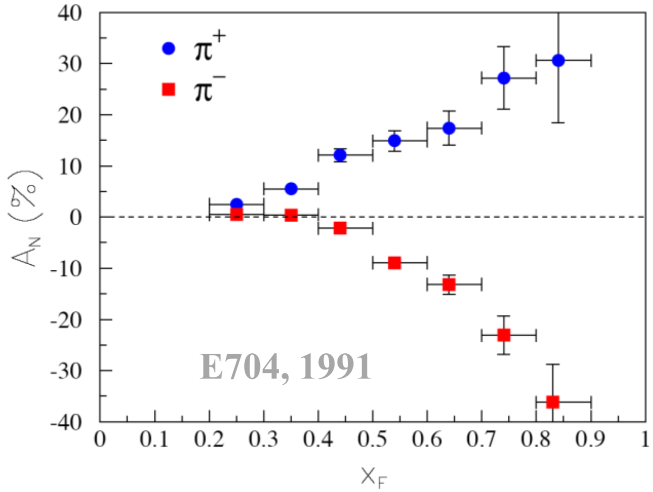
it would be interesting to perform the corresponding studies in e^+e^-

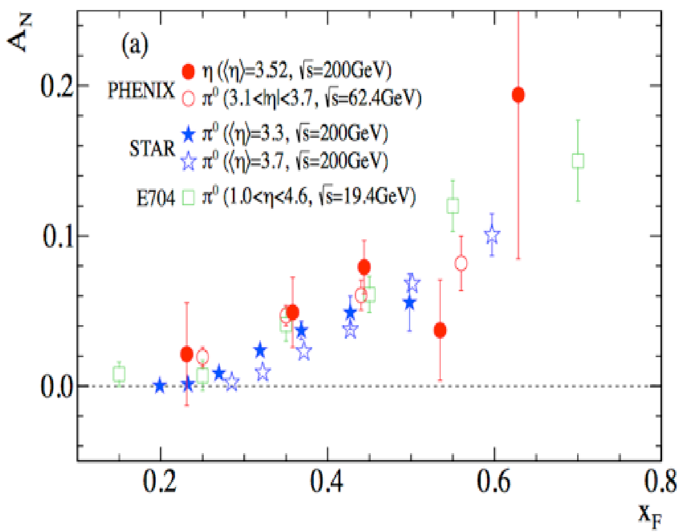
Transversity in pp

Transversity in pp

inclusive pion production $p^{\uparrow}p \longrightarrow \pi X$

one of the most famous measurements
and one of the motivations for the last 20 years of studies of transverse spin effects





large spin effects confirmed at RHIC
still not clear how large is the contribution of transversity

Drell-Yan:

convolution of u and $\bar{u}$ (d and $\bar{d}$) transversity distributions → difficult

still …

Suzdal 2015 iwhss

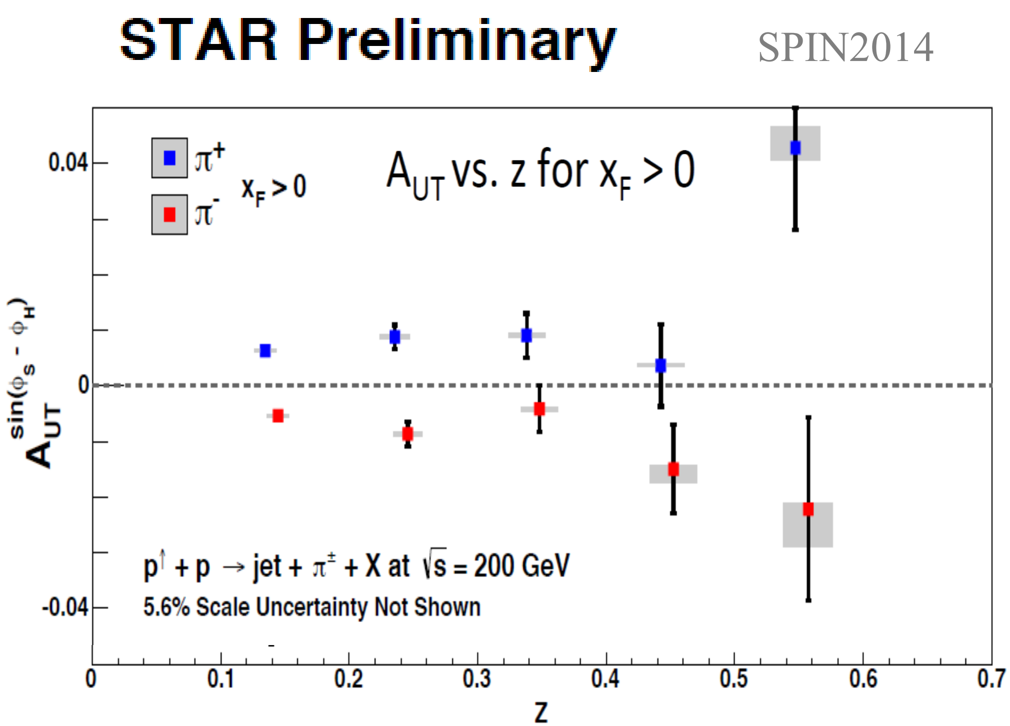
Anna Martin

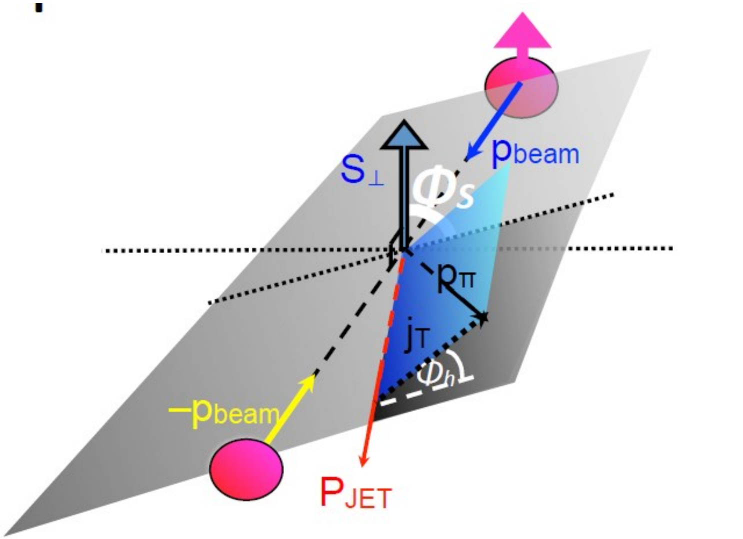
Transversity in pp

hadrons inside a jet

Collins asymmetry

$$\phi_C = \phi_S - \phi_H$$

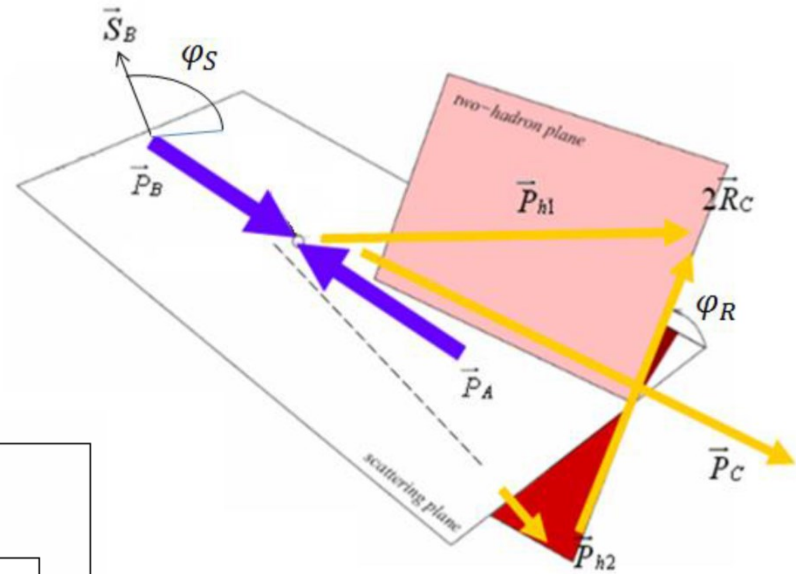




" the first statistically significant non-zero Collins asymmetries measured in hadronic collisions "

Transversity in pp

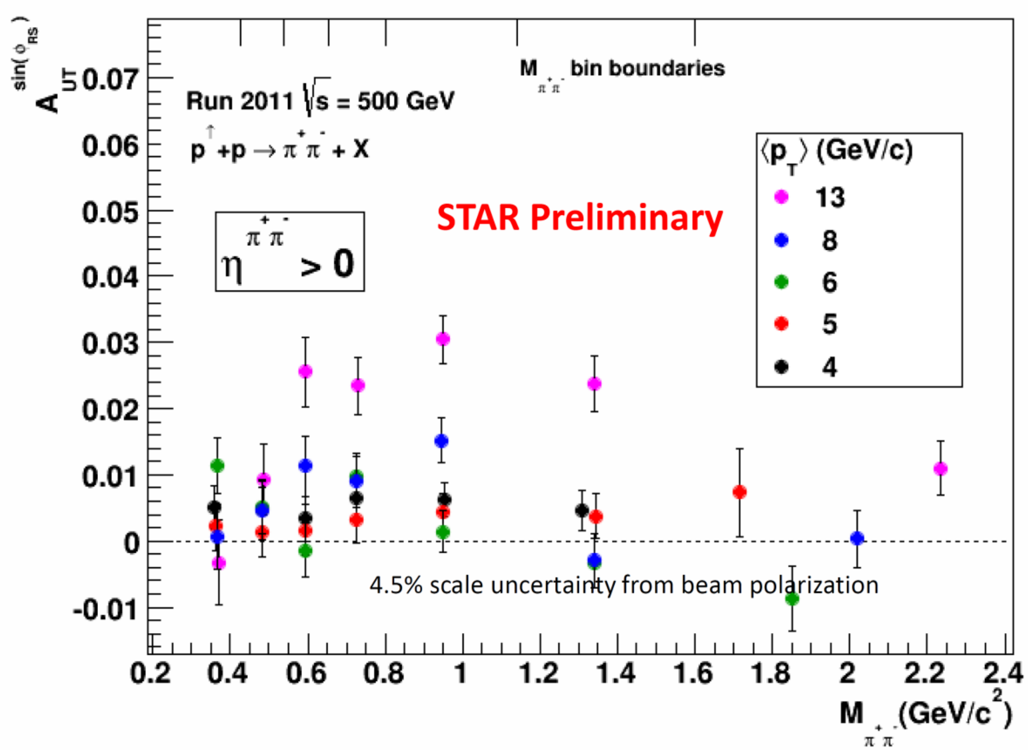
hadrons inside a jet



di-hadron asymmetry

$$\varphi_{RS} = \varphi_S - \varphi_R$$

SPIN2014



"results are at much higher Q^2 and sample a different mixture of quark flavors than SIDIS"

complementary input

other SIDIS transverse spin asymmetries

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

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

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

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

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

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

$h_1 H_1^{\perp}$

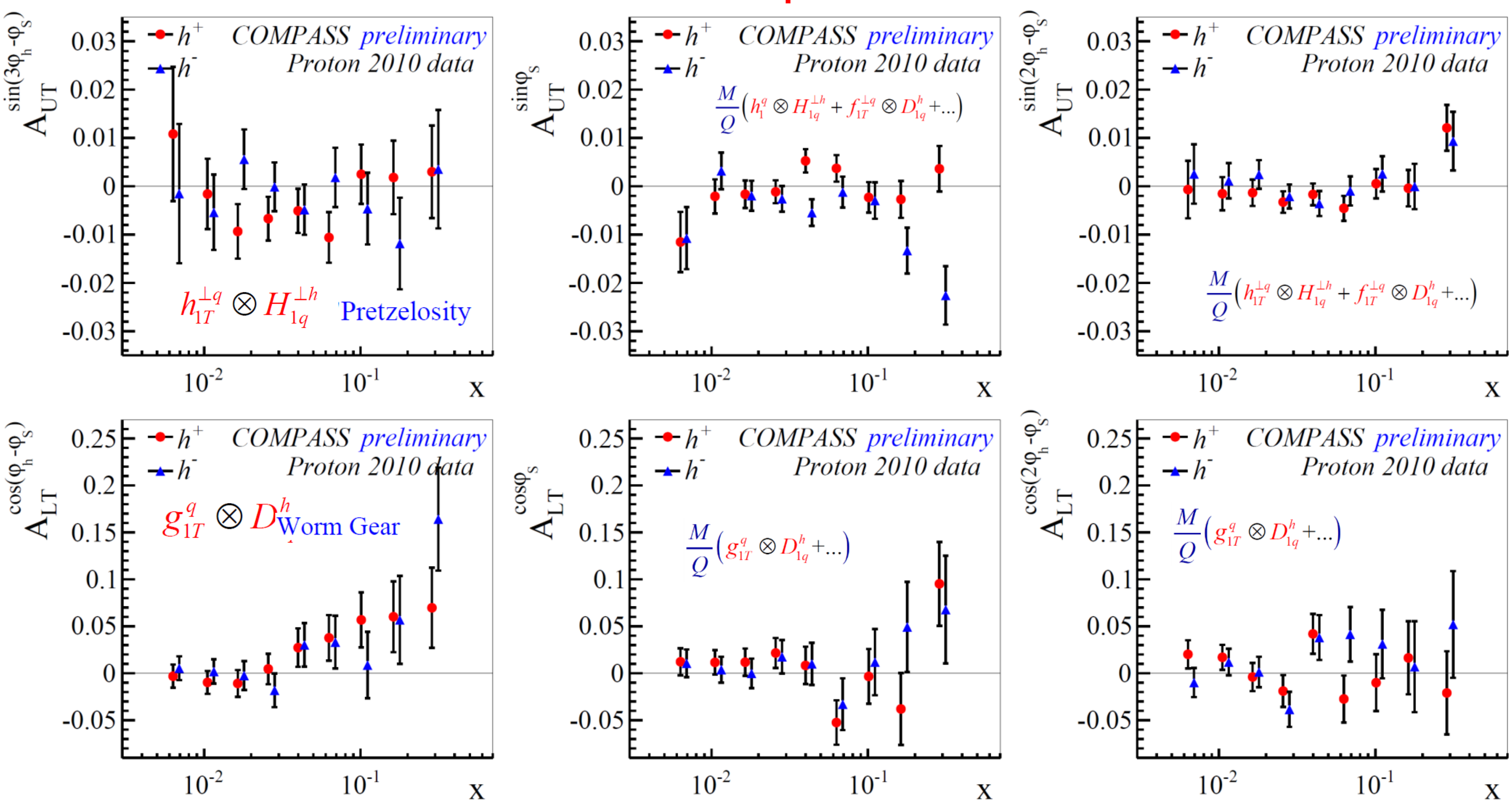
all of them (and more …) have been measured on p / d / n by COMPASS, HERMES, JLab

preliminary results for multidimensional analysis also produced at COMPASS and HERMES (SPIN2014)

other SIDIS transverse spin asymmetries

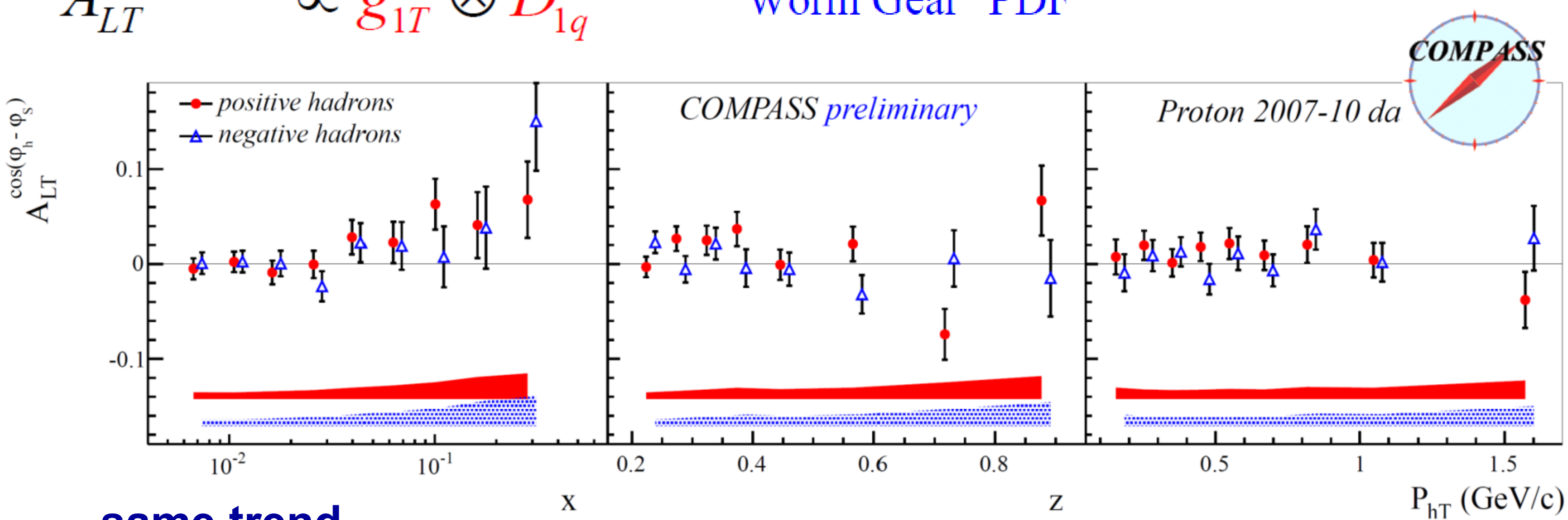
measured on p (HERMES, COMPASS)
d (COMPASS) and n (JLab)

proton

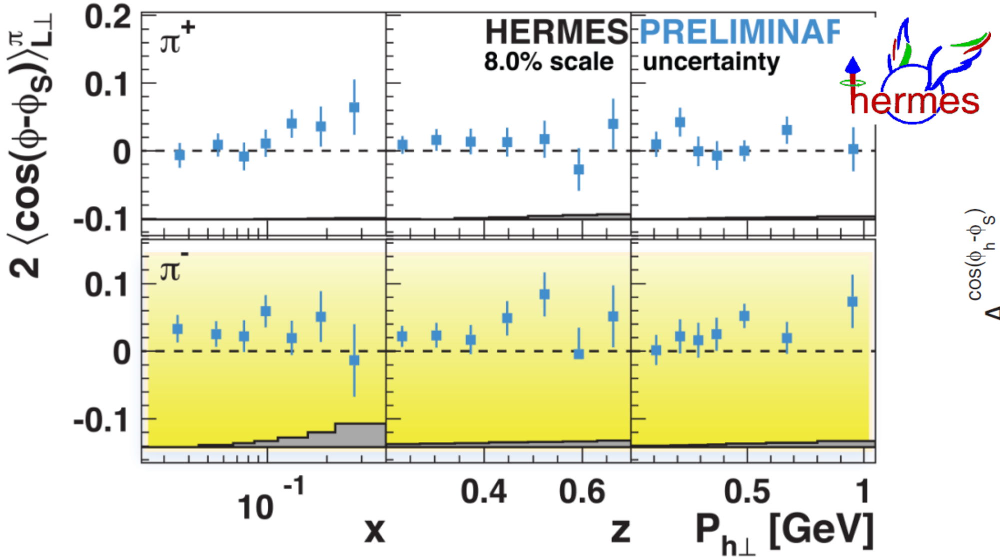


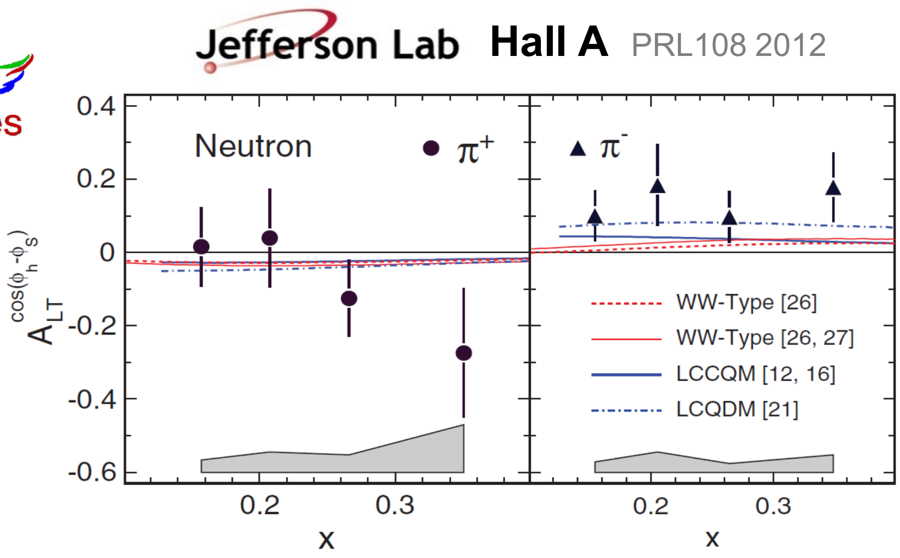
other SIDIS transverse spin asymmetries

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



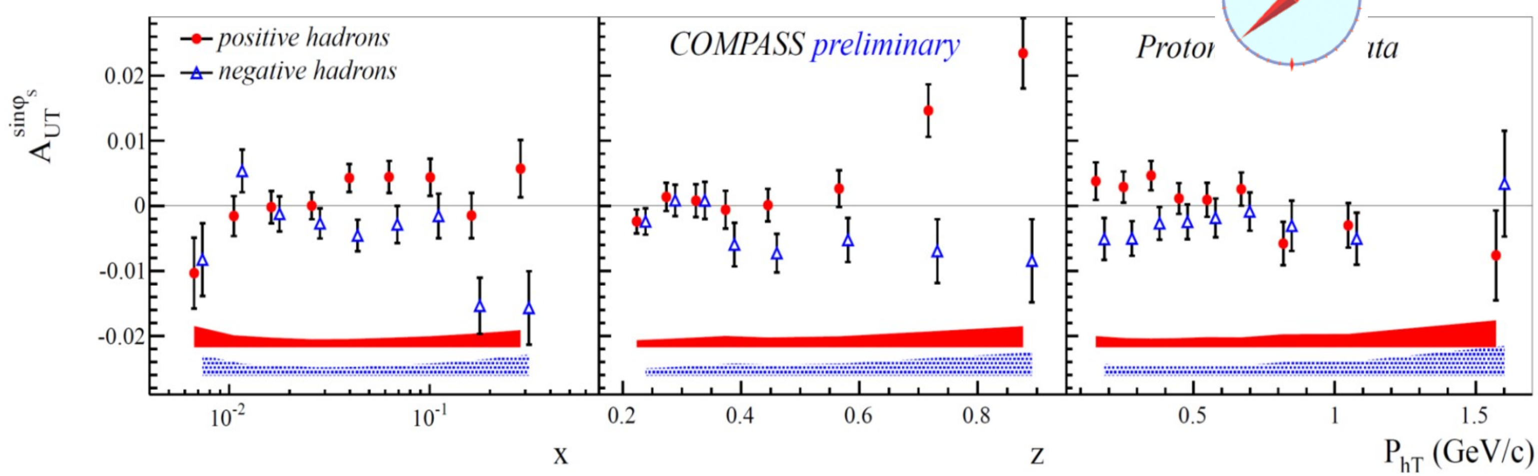
same trend

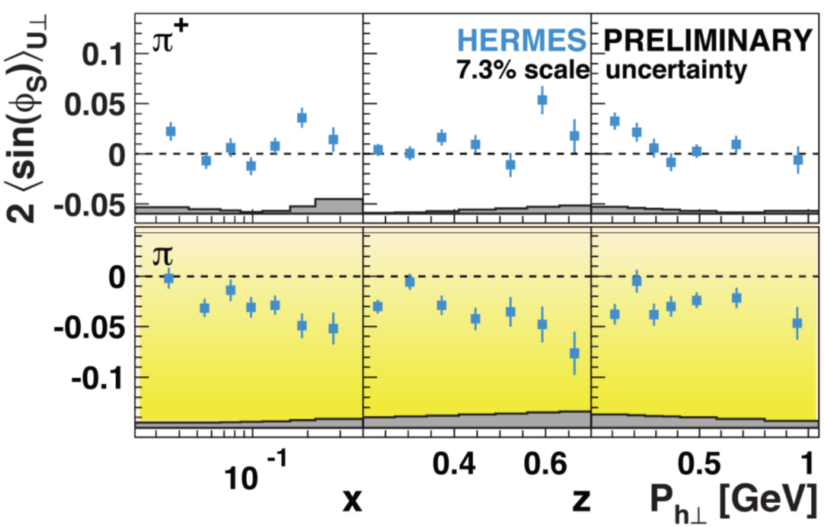




other SIDIS transverse spin asymmetries

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





considerably larger at HERMES

as expected

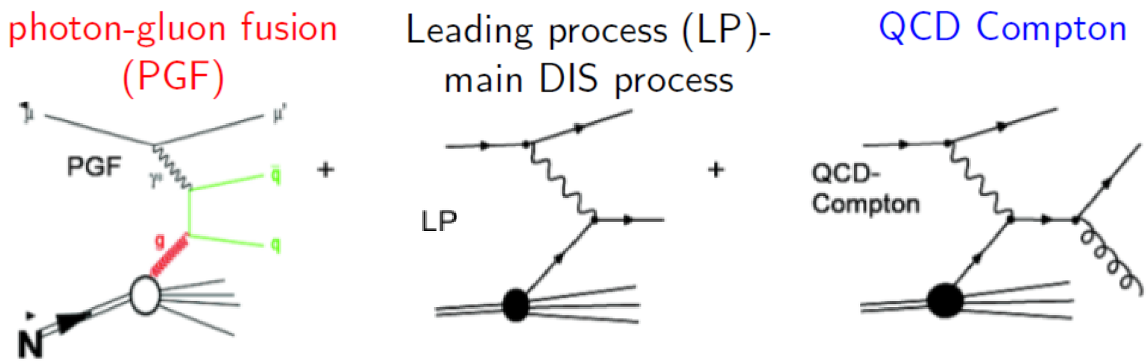
Gluon Sivers function

Gluon Sivers function

1. measurement of the "Sivers" asymmetry in $lp \rightarrow l'hh\,X$

$$\phi_P - \phi_S, \quad P = p_1 + p_2$$

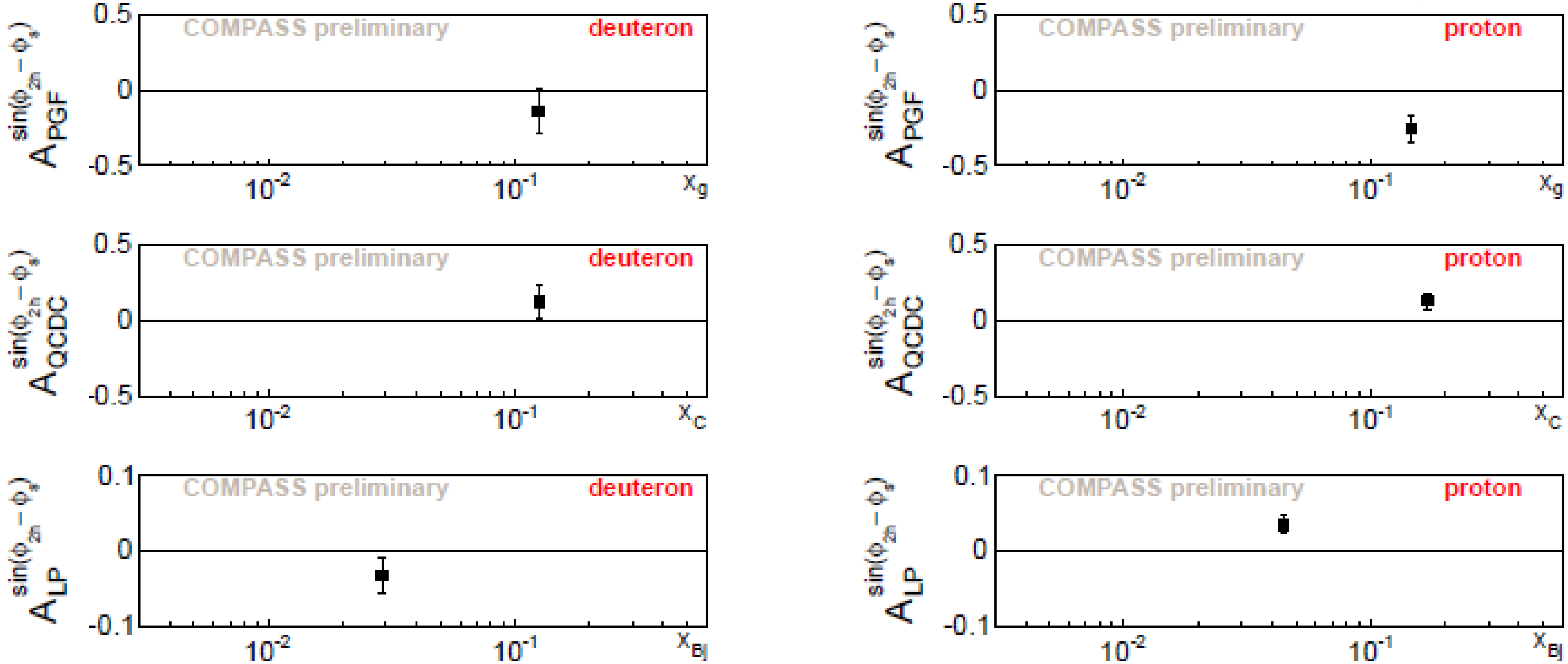
2. extraction of the asymmetries for **Photon-Gluon Fusion, Leading Process** and **QCD Compton** using NN trained on MC data



the sample with PGF events is enhanced by selecting DIS events with at least 2 hadrons with large p_T $(p_{T1} > 0.7, \; p_{T2} > 0.4 \text{ GeV/c})$

Gluon Sivers function

QNP2015



deuteron $A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.14 \pm 0.15(stat.) \pm 0.06(syst.)$ $\langle x_G \rangle = 0.13$

proton $A_{PGF}^{\sin(\phi_{2h}-\phi_s)} = -0.26 \pm 0.09(stat.) \pm 0.08(syst.)$ $\langle x_G \rangle = 0.15$

PHENIX results from proton-proton collisions with $\sqrt{s} = 200\text{GeV}$ for the observable A_N sensitive to the gluon Sivers function give values compatible with zero.

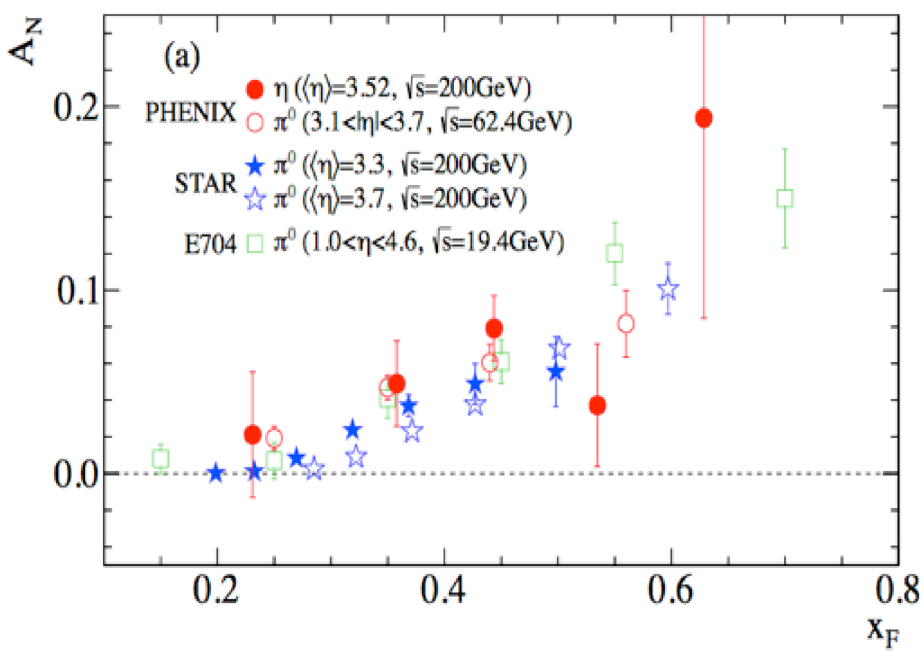
TSA A_N in $lp \rightarrow hX$ processes

TSA A_N in $lp \to hX$ processes

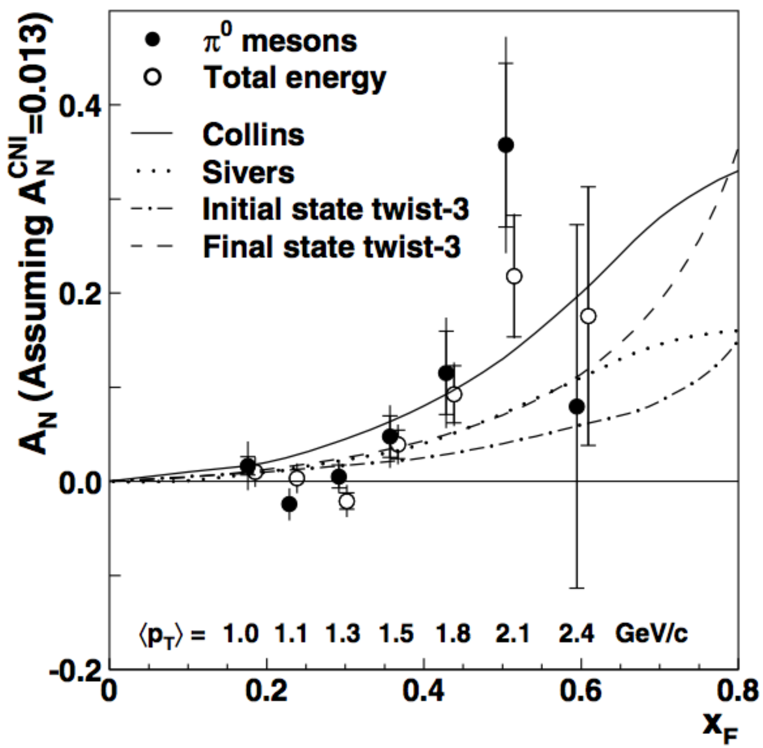
motivation:

direct test of the validity of the TMD factorization in $lp \to hX$

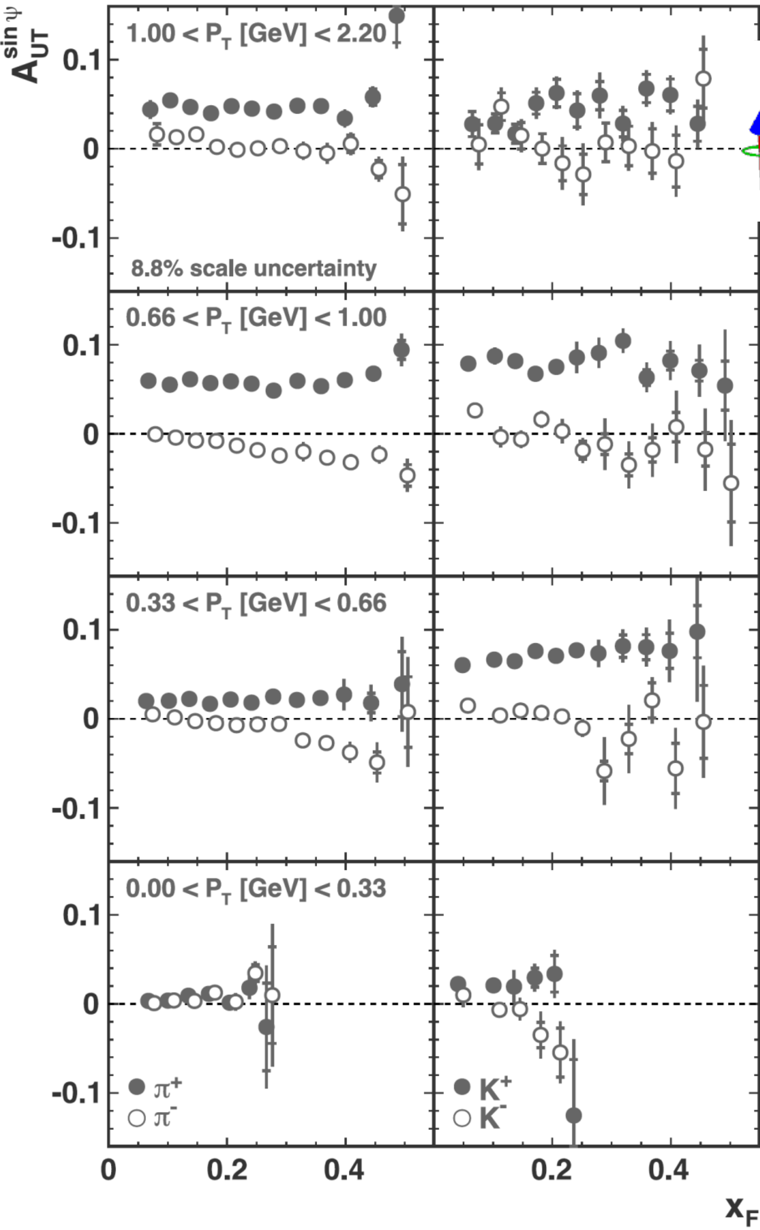
→ understanding TSA in $pp^{\uparrow} \longrightarrow hX$ M. Anselmino et al PRD 81 2010



PRL 92 2004



TSA A_N in $lp \to hX$ processes



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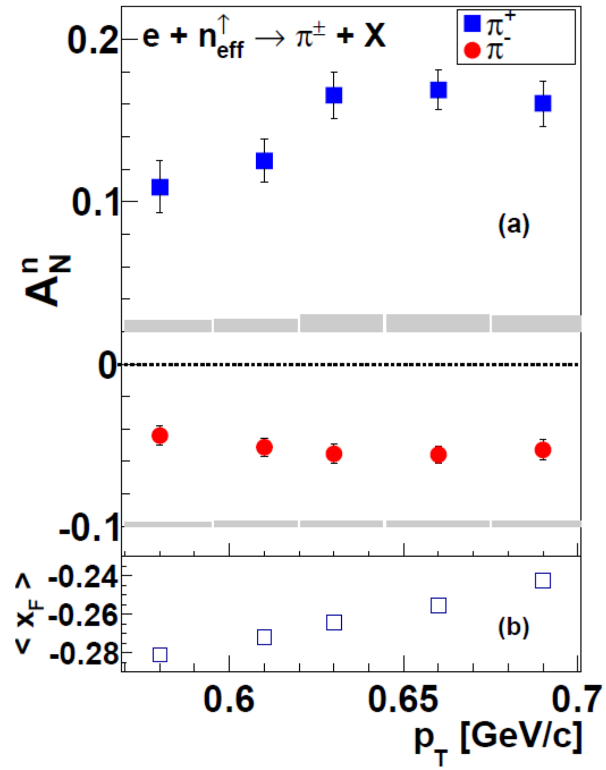

phenomenological interpretation in progress

summary

many new SIDIS results, not all easy to explain

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

more information is still hidden in the data and has to be extracted

from SIDIS at COMPASS, HERMES, JLab experiments
pp at RHIC
e^+e^- at Belle / Babar / BES

while waiting for the results of the new complementary mesaurements and experiments

at COMPASS too!