COMPASS news on TMD observables

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Trieste University & INFN

on behalf of the **COMPASS Collaboration**

2nd Workshop on Probing Strangeness in Hard Processes
Frascati National Laboratories, 11-13 November 2013

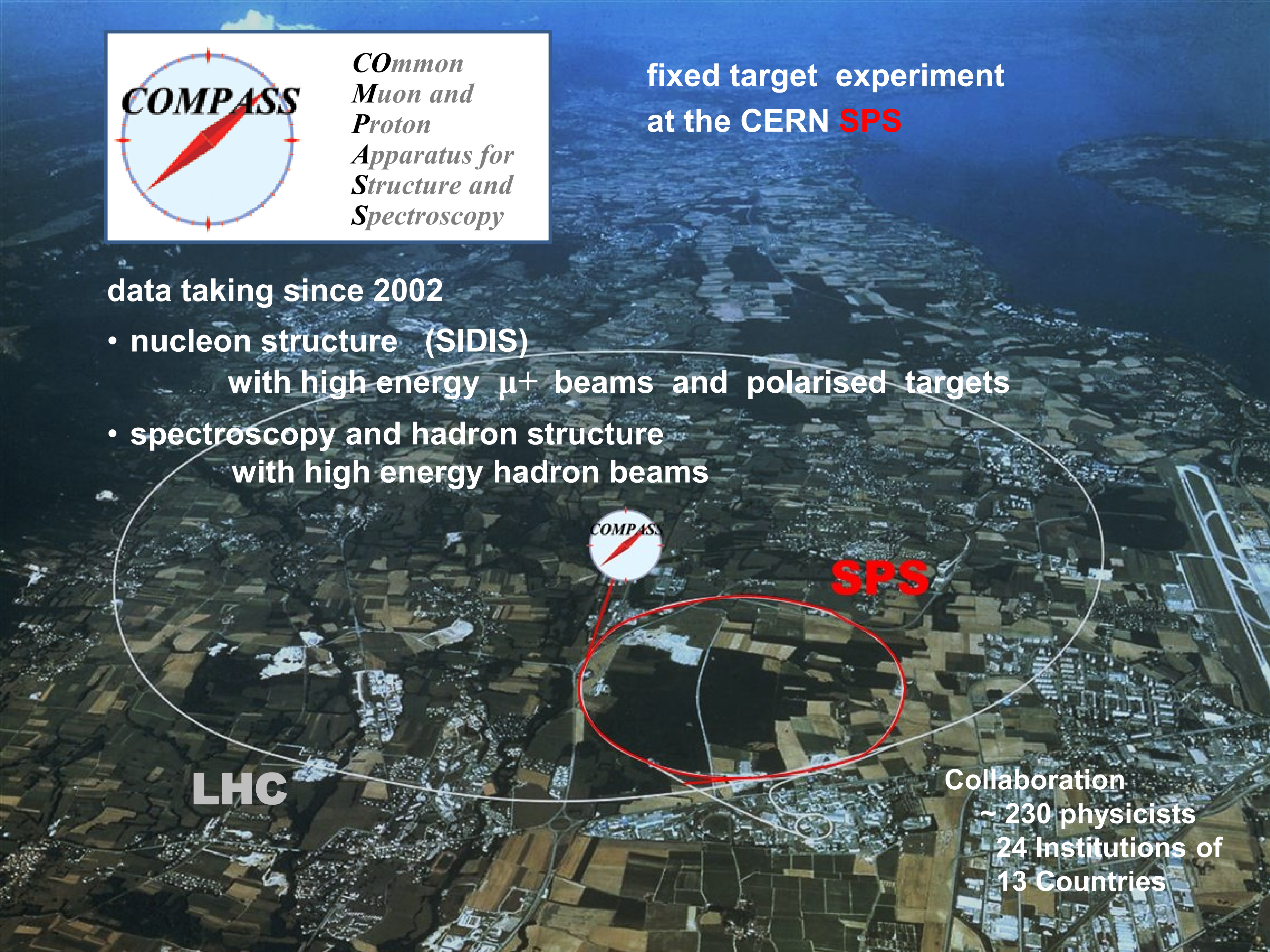
COMPASS

*CO*mmon
*M*uon and
*P*roton
*A*pparatus for
*S*tructure and
*S*pectroscopy

fixed target experiment
at the CERN SPS

data taking since 2002

- nucleon structure (SIDIS)
  with high energy μ+ beams and polarised targets
- spectroscopy and hadron structure
  with high energy hadron beams



Collaboration
~ 230 physicists
24 Institutions of
13 Countries

COMPASS data taking

longitudinally polarised μ^+ beam - nucleon structure

160 GeV/c

deuteron (^{6}LiD)	**L & T polarisation**	**2002 – 2004**
	L polarisation	**2006**
proton (NH_3)	**L & T polarisation**	**2007**
	T polarisation	**2010**

190 GeV/c

proton (NH_3)	**L polarisation**	**2011**

hadron spectroscopy	**2008 – 2009**	→ Drell-Yan test run
Primakoff	**2012**	→ DVCS test run

near future: Drell-Yan, DVCS & SIDIS 2014-2017

COMPASS data taking

longitudinally polarised μ^+ beam - nucleon structure

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	L	**polarisation**	**2006**
proton (NH_3)	**L & T**	**polarisation**	**2007**
	T	**polarisation**	**2010**

⇨ **SIDIS results on TMDs**

190 GeV/c

proton (NH_3)	**L**	**polarisation**	**2011**

hadron spectroscopy	**2008 – 2009**	→ Drell-Yan test run
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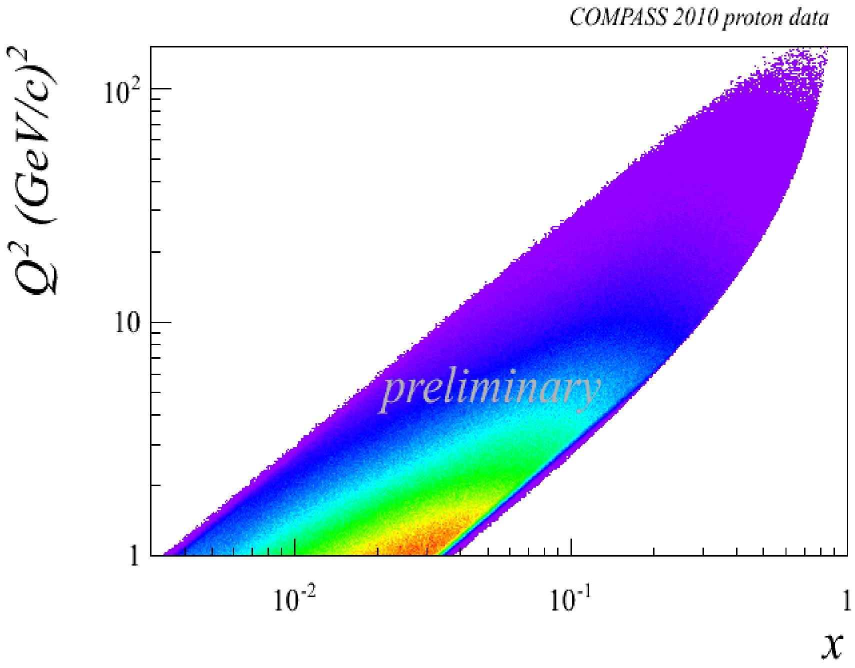
near future: Drell-Yan, DVCS & SIDIS 2014-2017

SIDIS at COMPASS

$p_\mu = 160$ GeV/c

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

h± selection: $p_t^h > 0.1$ GeV/c
$z > 0.2$ + low y low z



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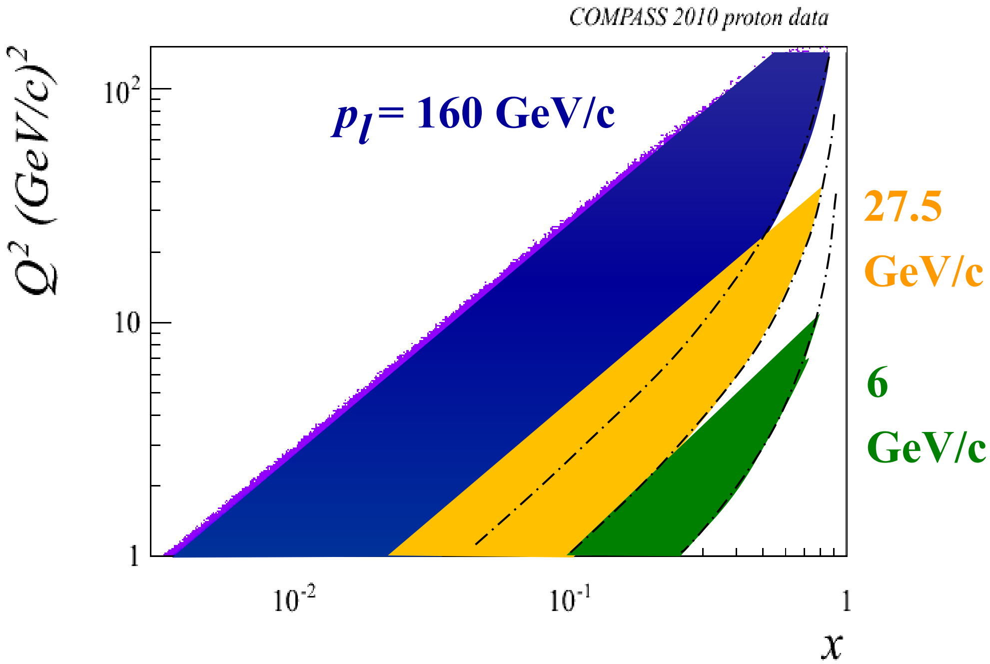

complemetary to
HERMES, Jlab, JLab12

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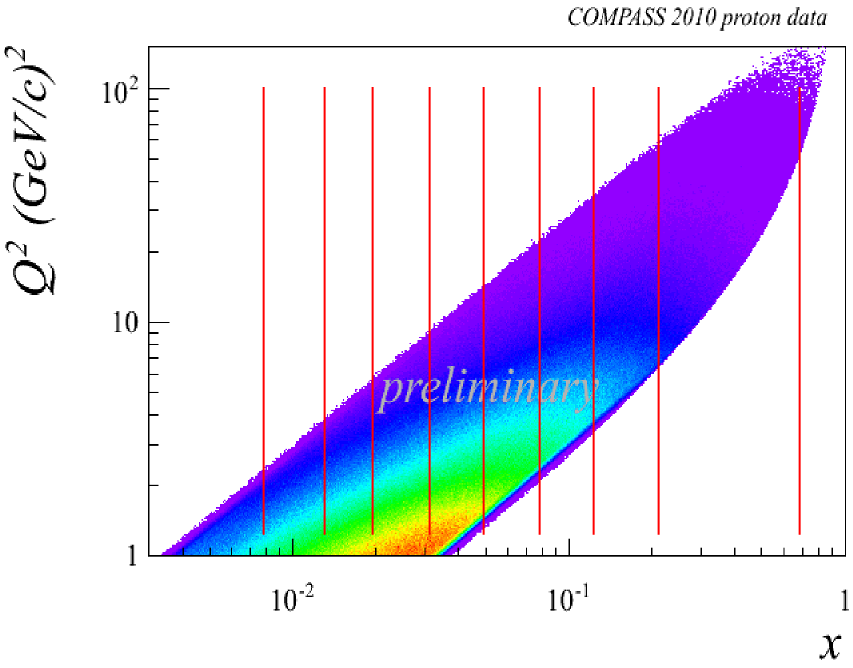

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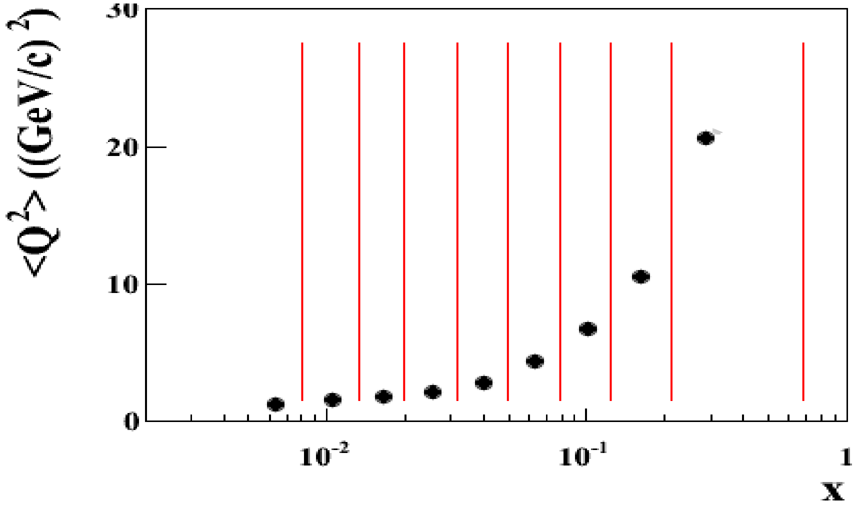
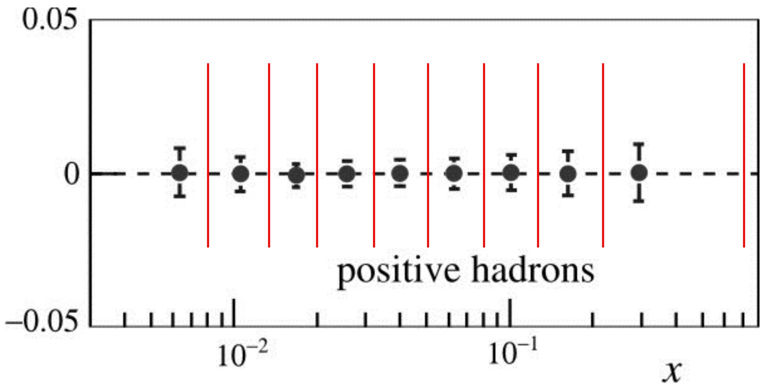
HERMES, Jlab, JLab12



statistical error (raw asymmetry corrected for f)
6 months of data taking (June-November 2010)



SIDIS at COMPASS

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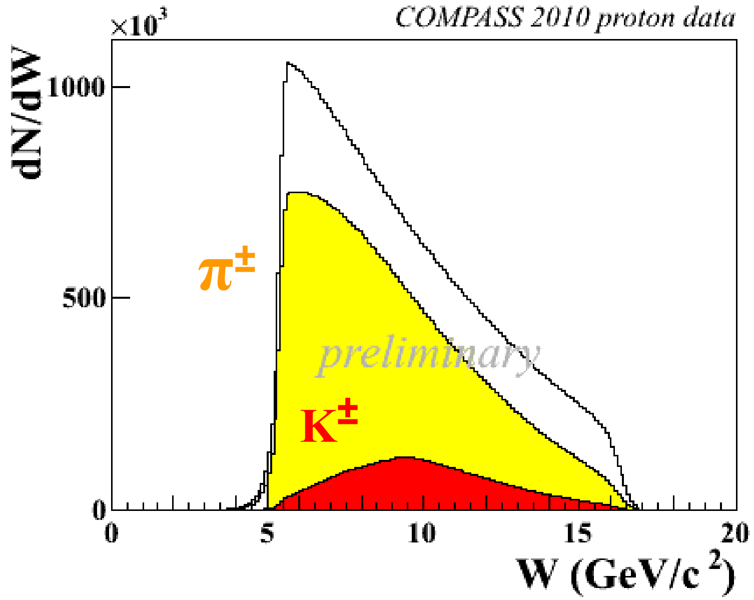
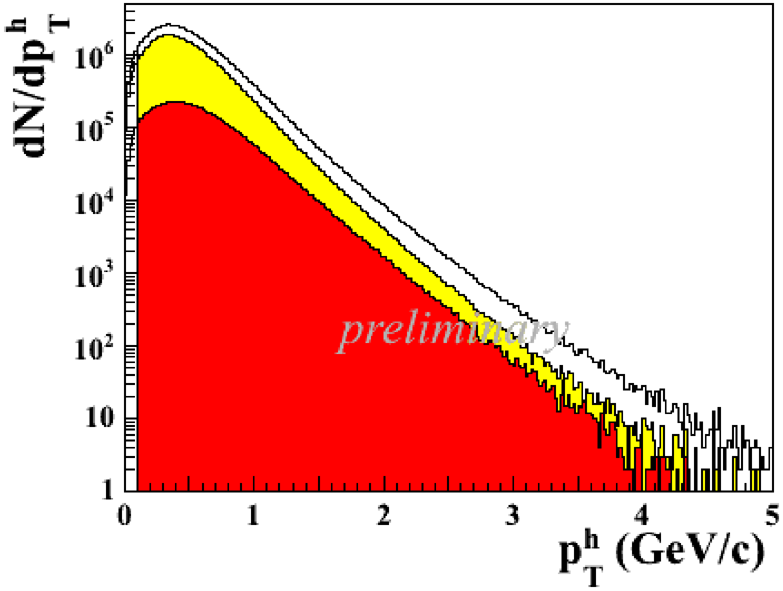
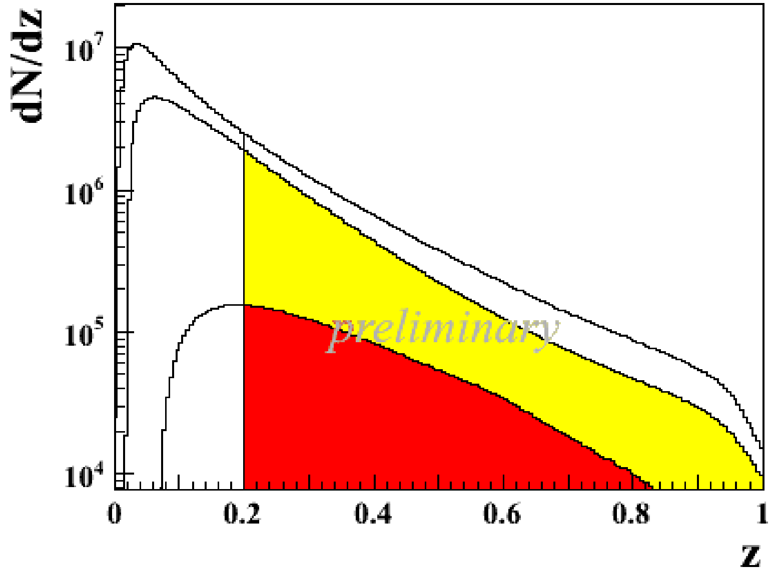
$z > 0.2$ + low y low z

PID: $1.5 < p^\pi < 50$ GeV/c
$9.5 < p^K < 50$ GeV/c







results

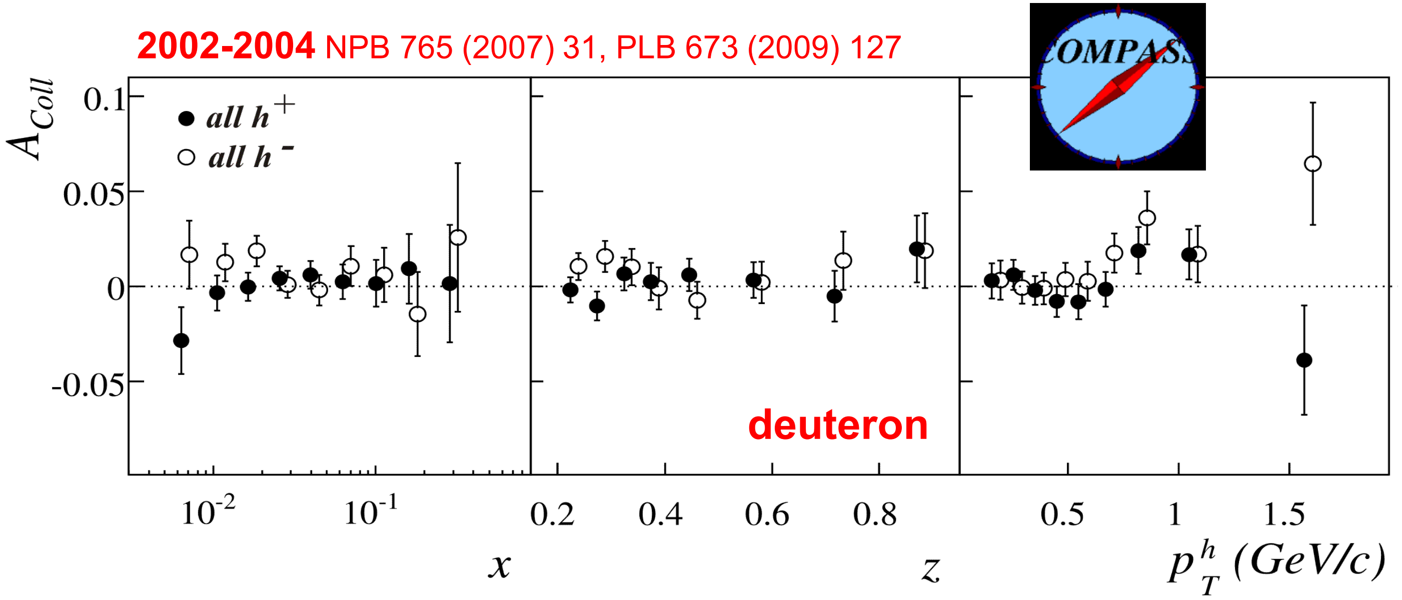
Transversity

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

Collins asymmetry

- **clear non-zero effects first seen by HERMES on p in 2005**
- **~ zero asymmetries measured by COMPASS on d**

2002-2004 NPB 765 (2007) 31, PLB 673 (2009) 127



explained with

$$\boxed{h_1^u \approx -h_1^d}$$

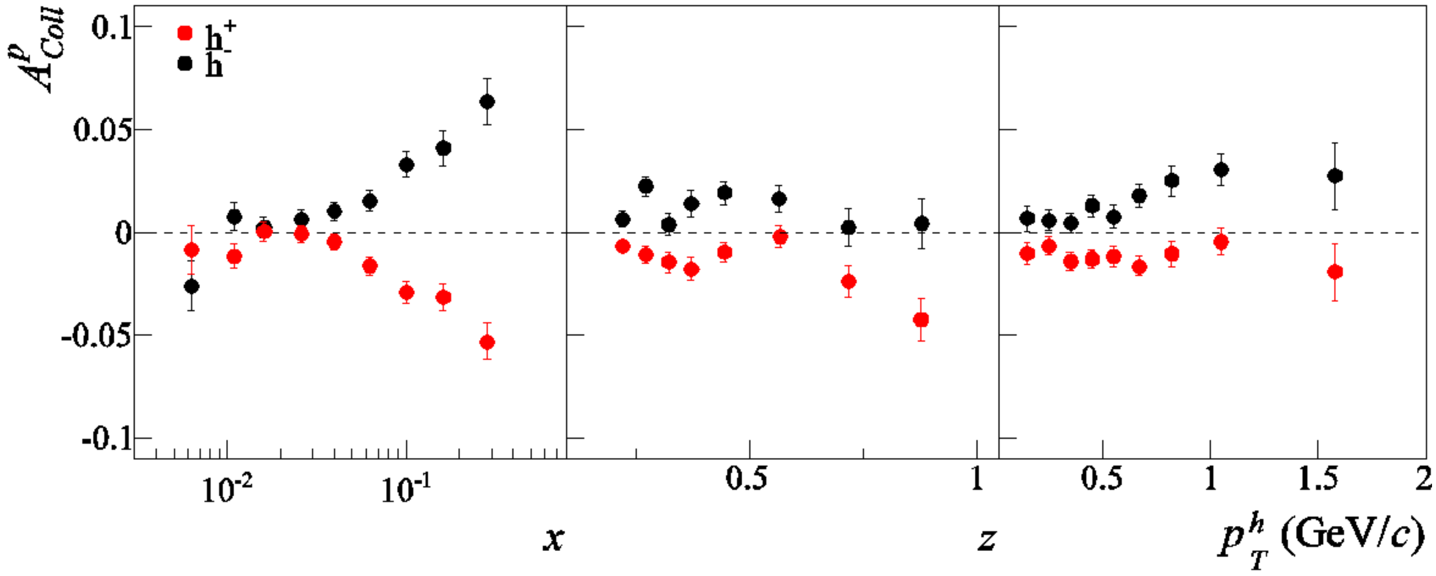
$$\boxed{H_1^{\perp fav} \approx -H_1^{\perp unf}}$$

still only measurements on d

Collins asymmetry

COMPASS results on proton target (2007, 2010 data)

PLB 692 (2010) 240 PLB 717 (2012) 376



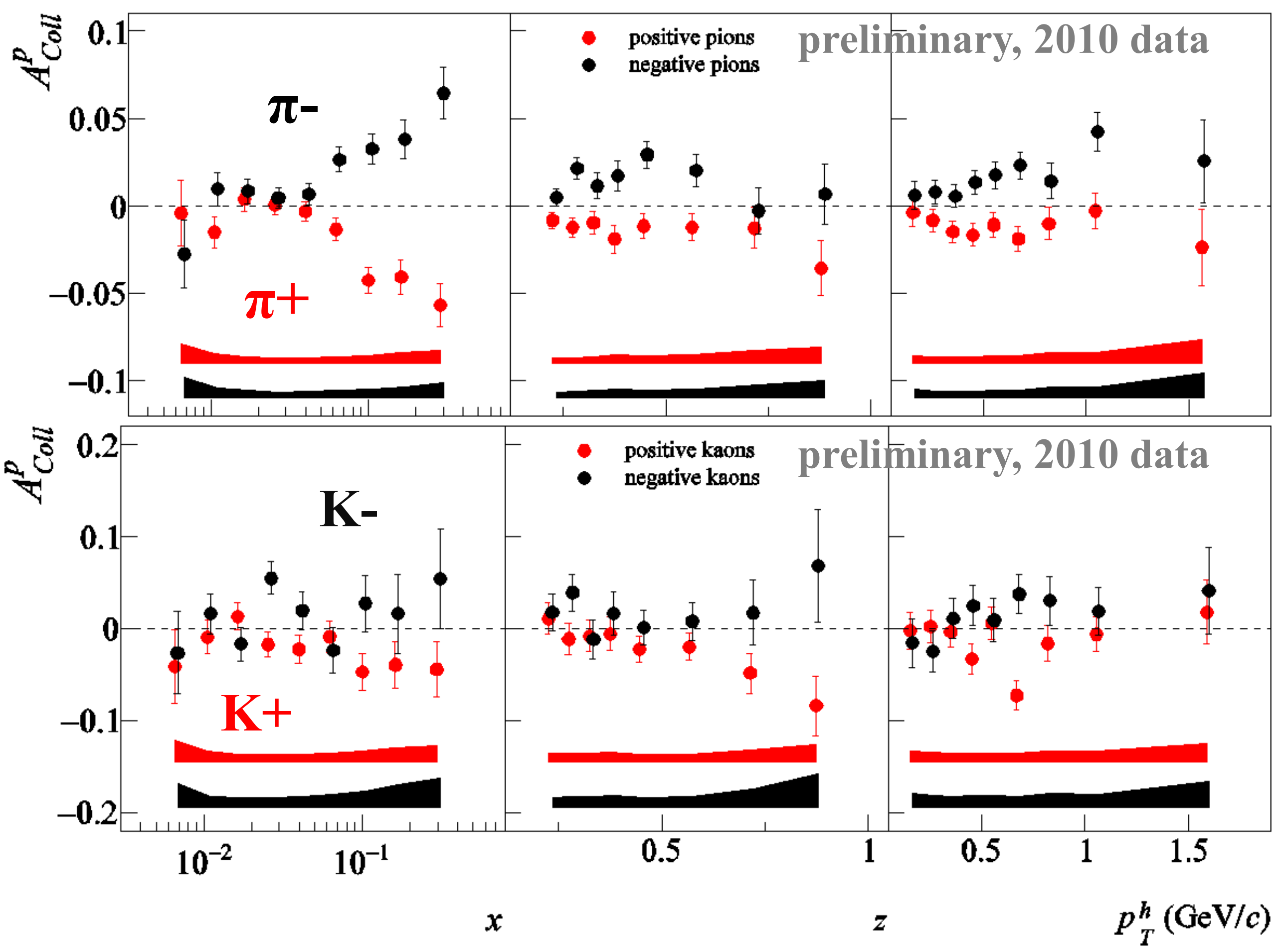
good agreement with HERMES in the x overlap region

same for pions

Collins asymmetry

COMPASS results on proton target

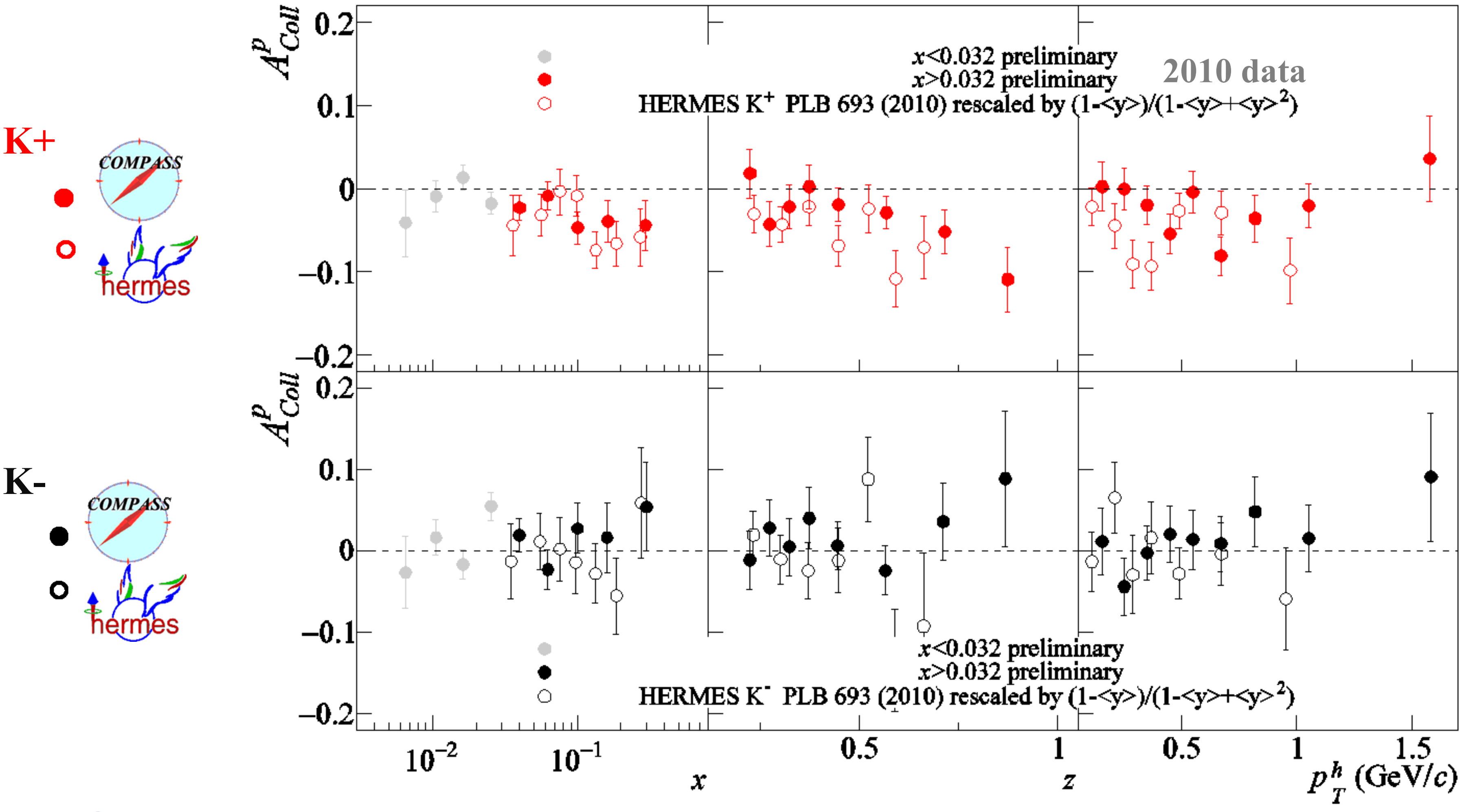
charged pions and kaons *(2007 data – SPIN2010, 2010 data – SPIN 2012)*



Collins asymmetry

results on proton

charged kaons



Collins asymmetry

results on proton

charged pions

π+

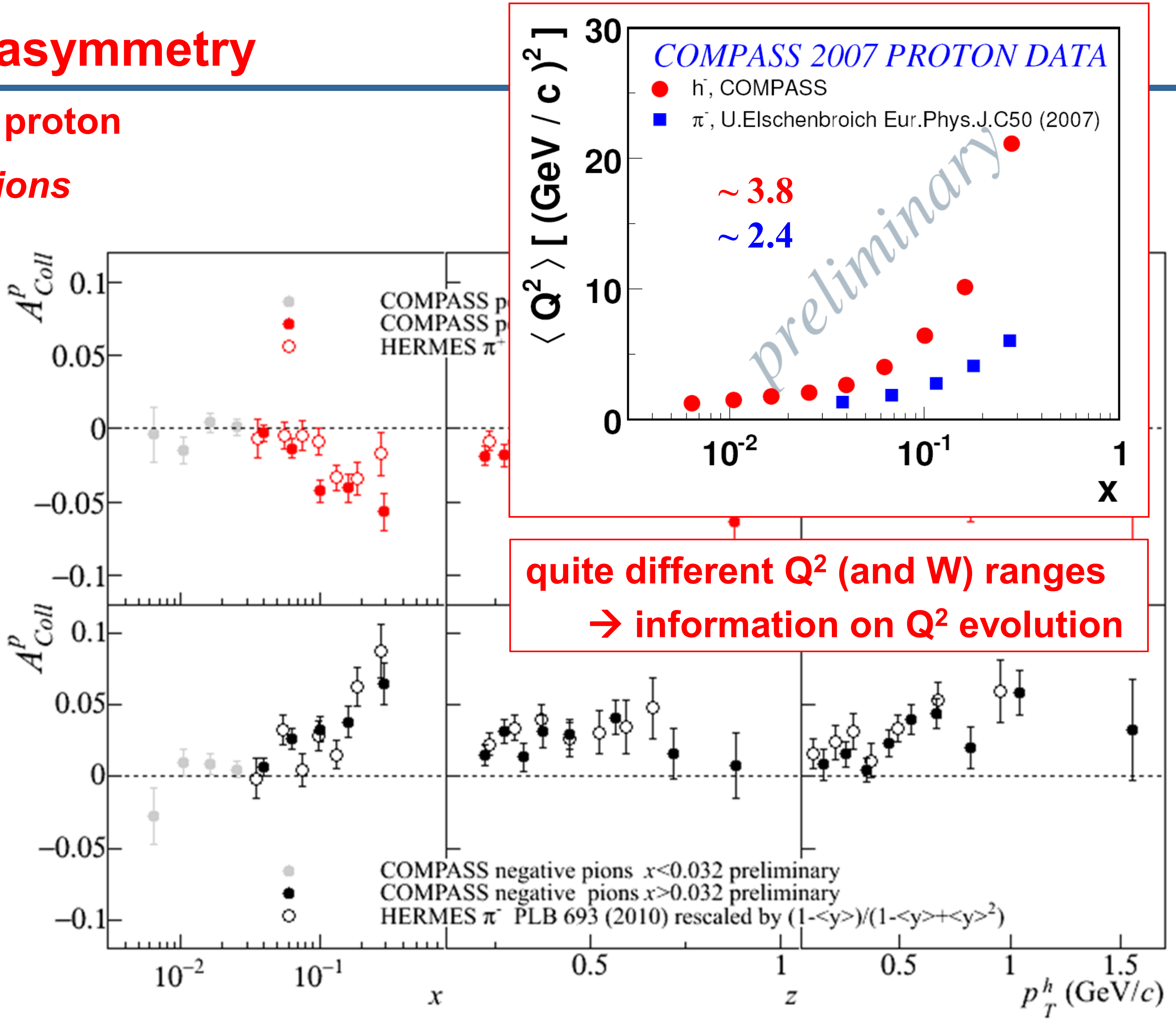
● COMPASS

○ hermes

π-

● COMPASS

○ hermes



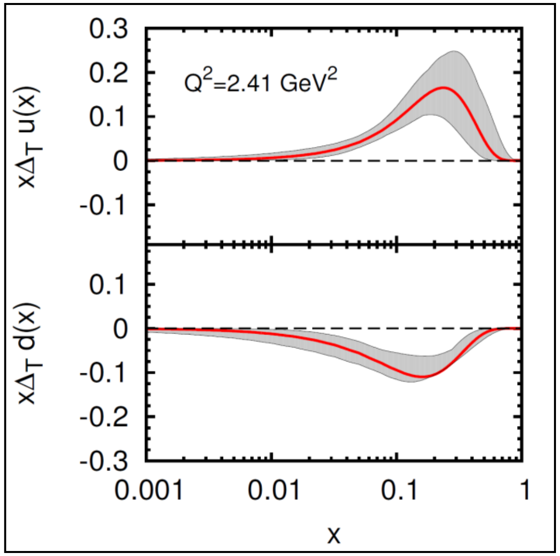
quite different Q^2 (and W) ranges

→ information on Q^2 evolution

Transversity

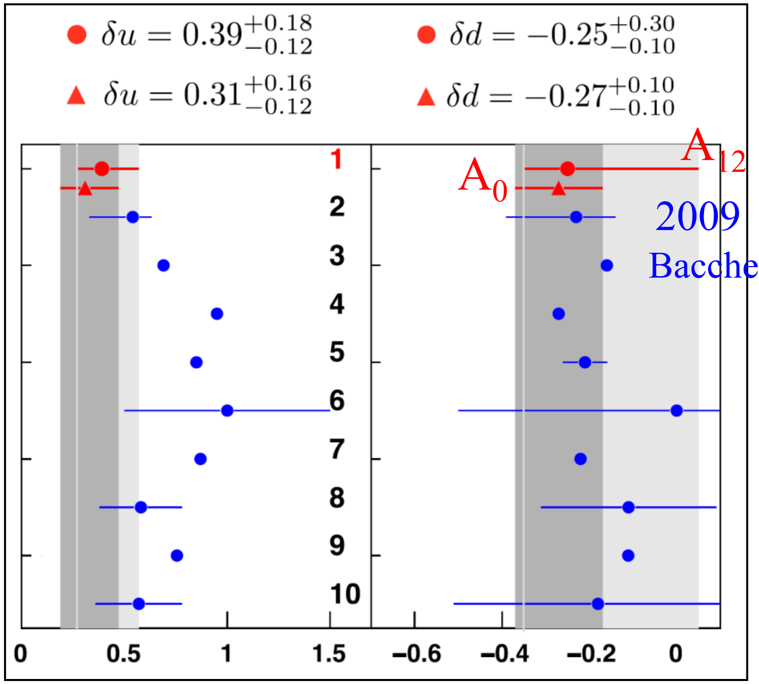
transversity is different from zero and

can be measured in SIDIS thanks to the "Collins effect"



M. Anselmino et al., PRD87 (2013) 094019
simultaneous fit of
HERMES p, COMPASS p & d, and Belle data
very good χ^2

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



2009

Bacchetta et al, 2012

model calculations

more data

large and small x, p & d / n, PID

are needed

dihadron asymmetry

→ Christopher Braun talk

independent channel to access transversity

dihadron asymmetry

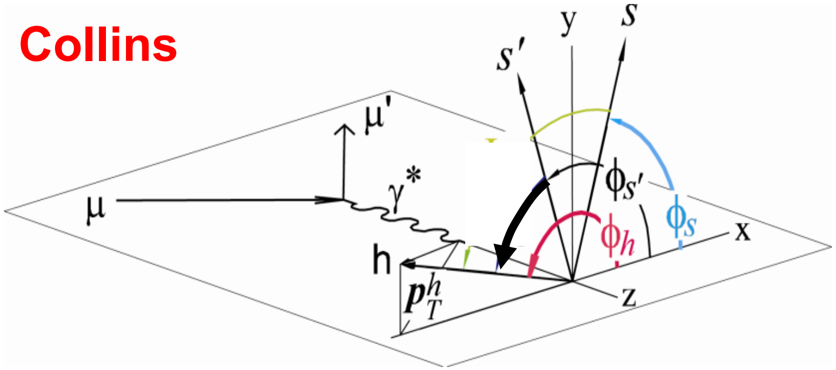
independent channel to access transversity

$$\boxed{\phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi}$$

$$\phi_h = \frac{(\vec{q}\times\vec{l})\cdot\vec{p}_T^{\,h}}{|(\vec{q}\times\vec{l})\cdot\vec{p}_T^{\,h}|}\arccos\left(\frac{(\vec{q}\times\vec{l})\cdot(\vec{q}\times\vec{p}_T^{\,h})}{|\vec{q}\times\vec{l}\,||\vec{q}\times\vec{p}_T^{\,h}|}\right)$$

$$\boxed{N(\phi_C) = N^0\cdot\{1 + f\,P_T D\cdot A_{Coll}\cdot\sin\phi_C\}}$$

Collins



$$\boxed{\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi}$$

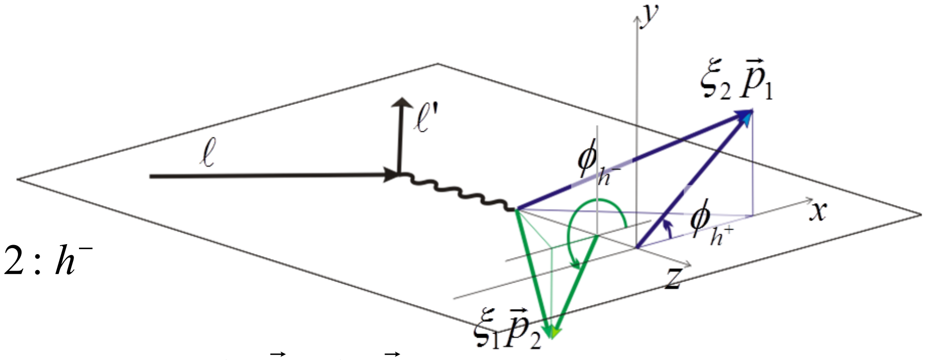
$$\phi_R = \frac{(\vec{q}\times\vec{l})\cdot\vec{R}}{|(\vec{q}\times\vec{l})\cdot\vec{R}|}\arccos\left(\frac{(\vec{q}\times\vec{l})\cdot(\vec{q}\times\vec{R})}{|\vec{q}\times\vec{l}\,||\vec{q}\times\vec{R}|}\right)$$

$$\vec{R} = \frac{z_2\vec{p}_1 - z_1\vec{p}_2}{z_1 + z_2} =: \xi_2\vec{p}_1 - \xi_1\vec{p}_2$$

$1:\ h^+,\ 2:\ h^-$

$$\boxed{N(\phi_{RS}) = N^0\cdot\{1 + f\,P_T D\cdot A_{RS}\cdot\sin\phi_{RS}\}}$$

dihadron



$\vec{q}\times\vec{R} \equiv \vec{q}\times\vec{R}_T$

dihadron asymmetry

independent channel to access transversity

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

“Interference / Di-hadron FF”

Belle Babar

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

“spin independent di-hadron FF”

being measured at COMPASS

dihadron asymmetry

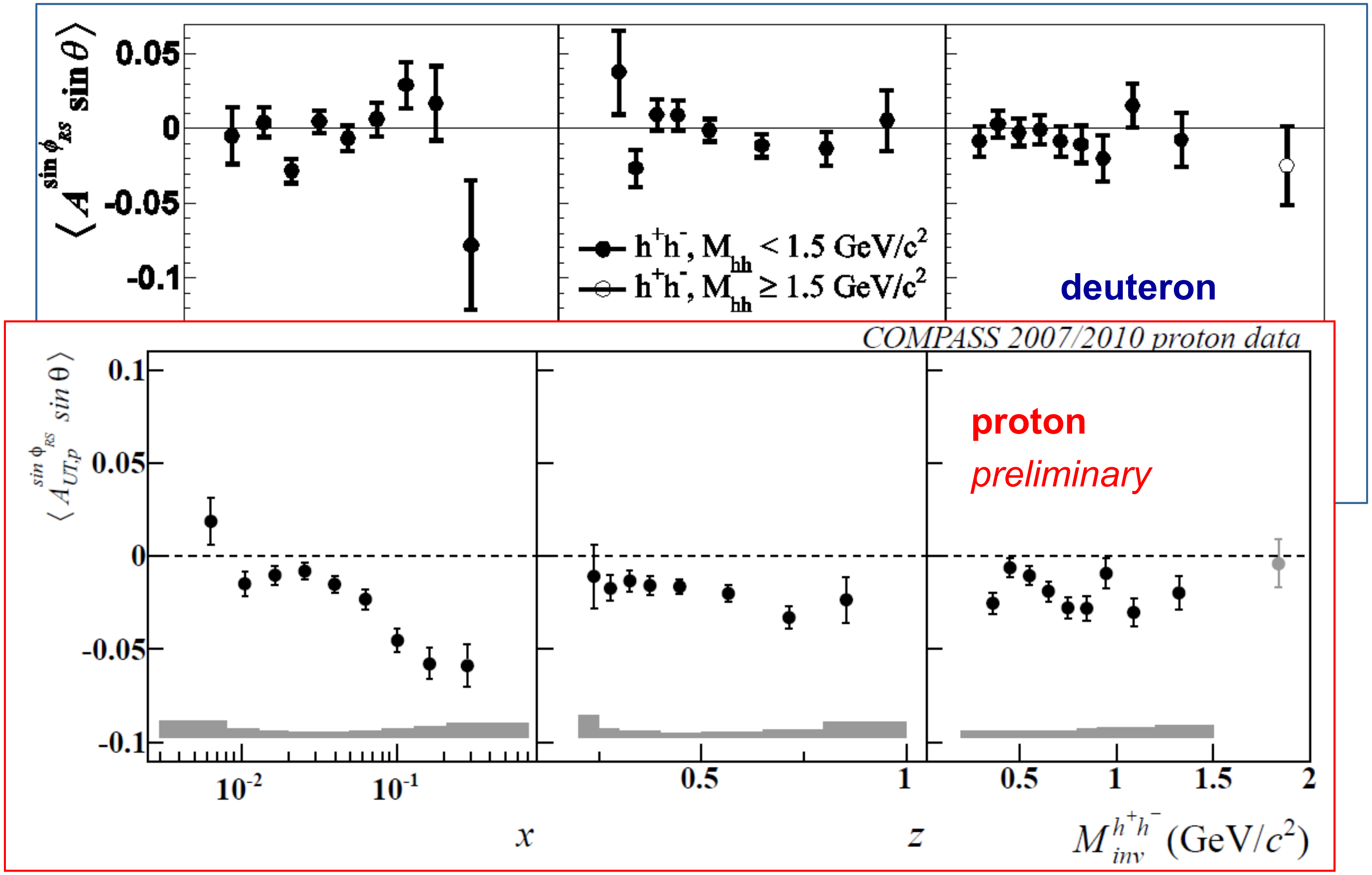
all d data

PLB 713 (2012) 10

h+ h-

all p data

PLB 713 (2012) 10
& Transversity 2011



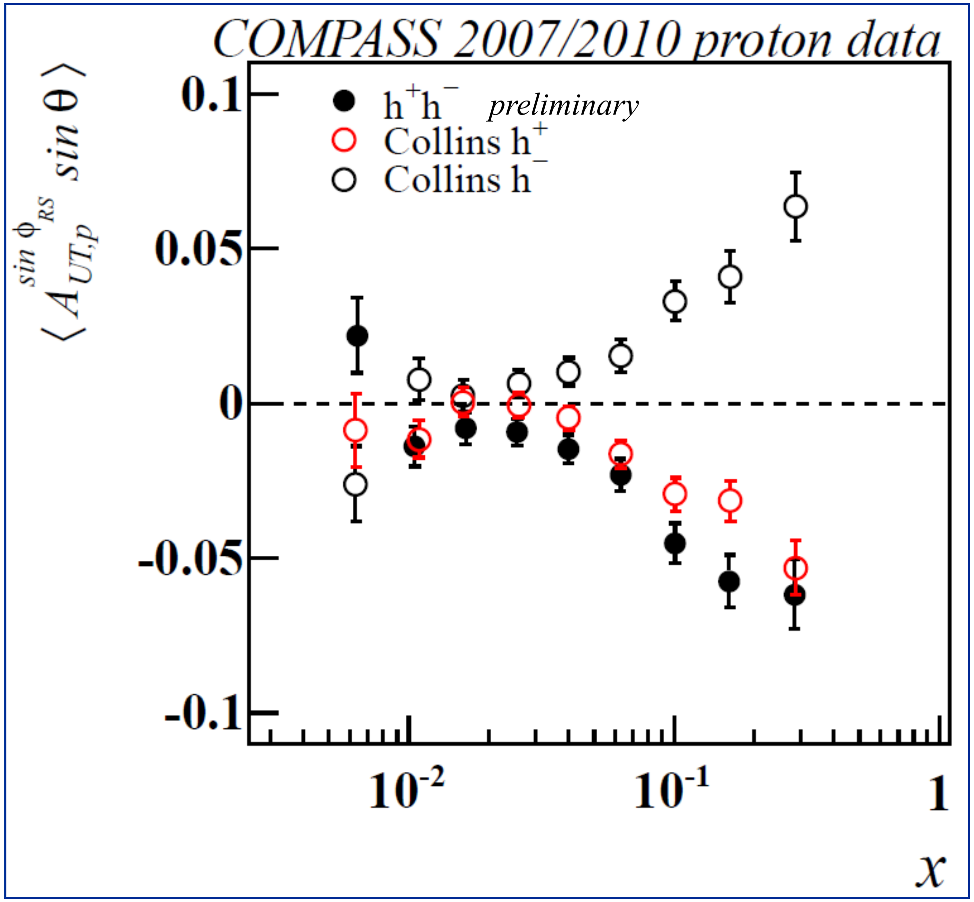
high statistics over a wide x range

dihadron asymmetry and Collins asymmetries

remarkable similarity between

- **Collins asymmetry for h+ and Collins asymmetry for h-**
  "mirror symmetry": similar absolute values, opposite sign
- **dihadron asymmetry and Collins asymmetries**
  same sign as Collins h+, only somewhat larger than the mean of Collins h+ and – Collins h- (as expected)

  here measured on different hadron samples, ~ the same on the "common" hadron sample



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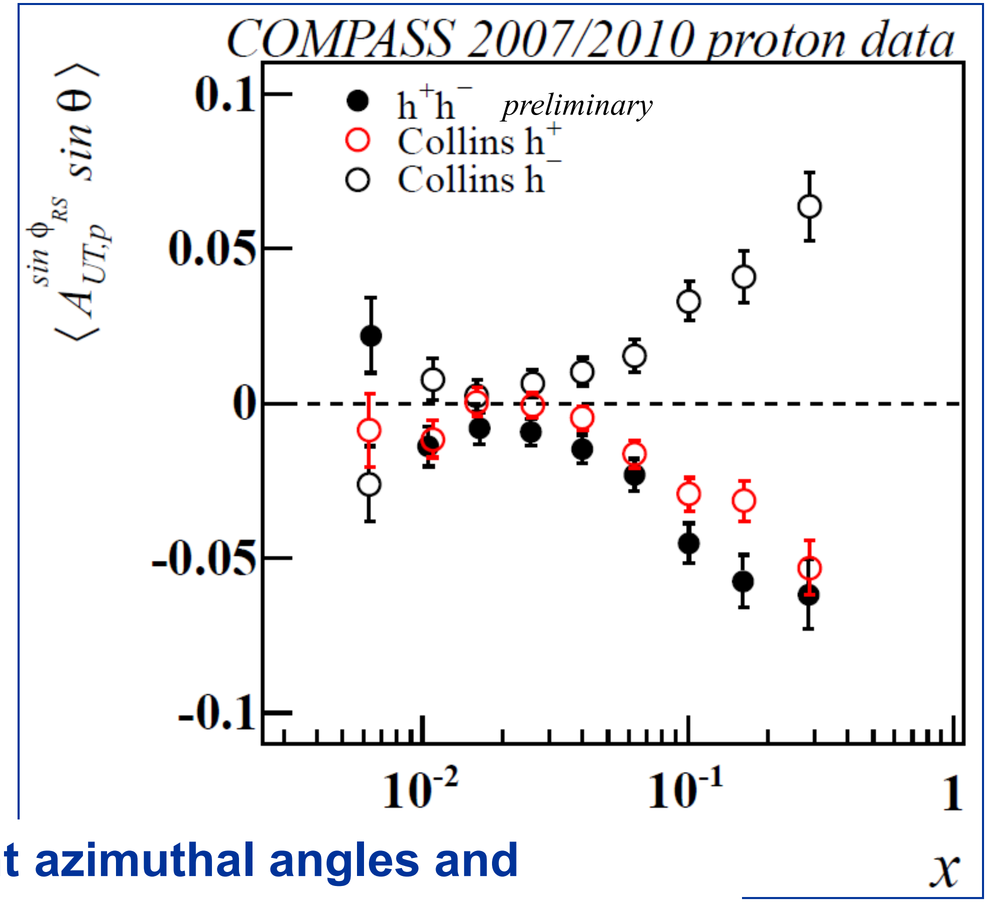


first investigation:

correlations between the relevant azimuthal angles and the corresponding asymmetries

→ information on the nature of the fragmentation

Collins vs 2h interference mechanisms

dihadron asymmetry and Collins asymmetries

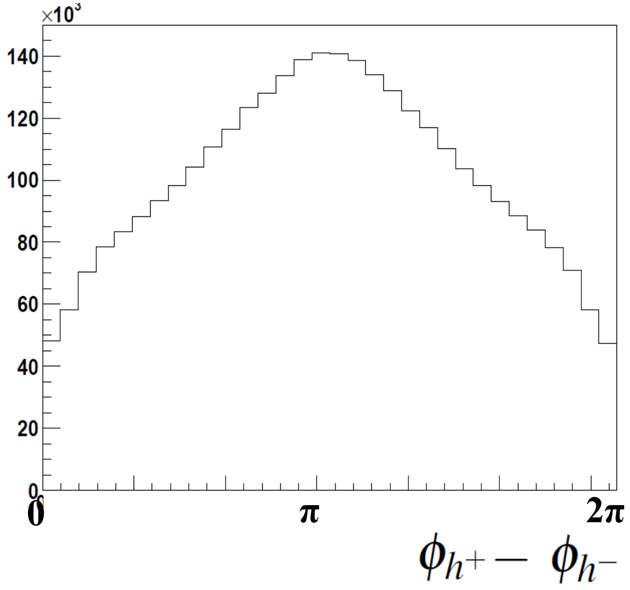
correlations between the relevant azimuthal angles

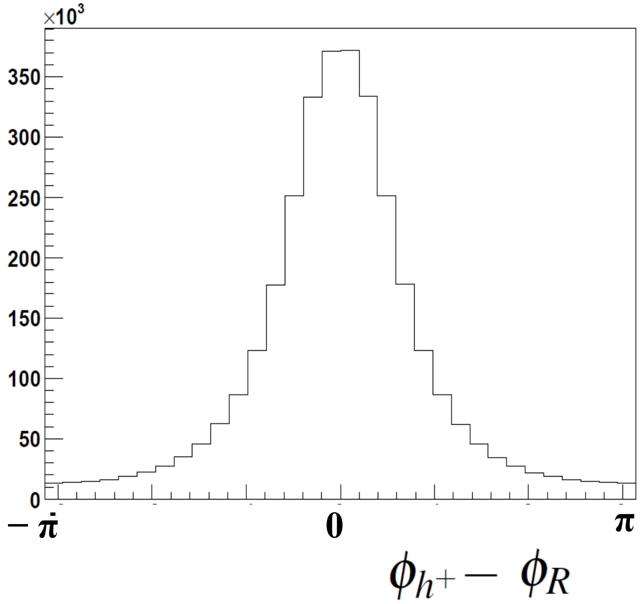
the mirror symmetry in the Collins asymmetry

amplitude of $\sin\phi_C$ *with* $\phi_C = \phi_h + \phi_S - \pi$

suggests that $\phi_{h^+} - \phi_{h^-} \approx \pi$

i.e. that positive and negative hadrons produced in the fragmentation of transversely polarised quarks have antiparallel transverse momenta





flat if

independent

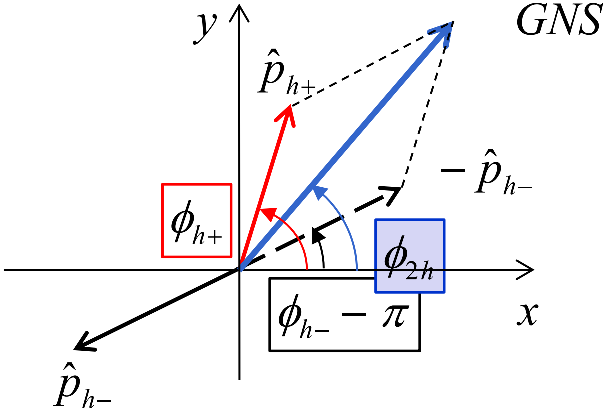
same with unpolarised Lepto

dihadron asymmetry and Collins asymmetries

correlations between the relevant azimuthal angles

if this is true, one can introduce as azimuthal angle of the hadron pair the “mean” of the azimuthal angles of the two hadrons

$$\boxed{\phi_{2h} = \frac{\phi_{h^+} + (\phi_{h^-} - \pi)}{2}}$$



$$\phi_{C^\pm} = \phi_{h^\pm} - \phi_{S'} = \phi_{h^\pm} + \phi_S - \pi$$

$$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$$

$$\phi_{C2h} = \phi_{2h} - \phi_{S'} = [\phi_{h^+} - \phi_{S'} + (\phi_{h^-} - \phi_{S'} - \pi)]/2$$

$$= [\phi_{C+} + (\phi_{C-} - \pi)]/2$$

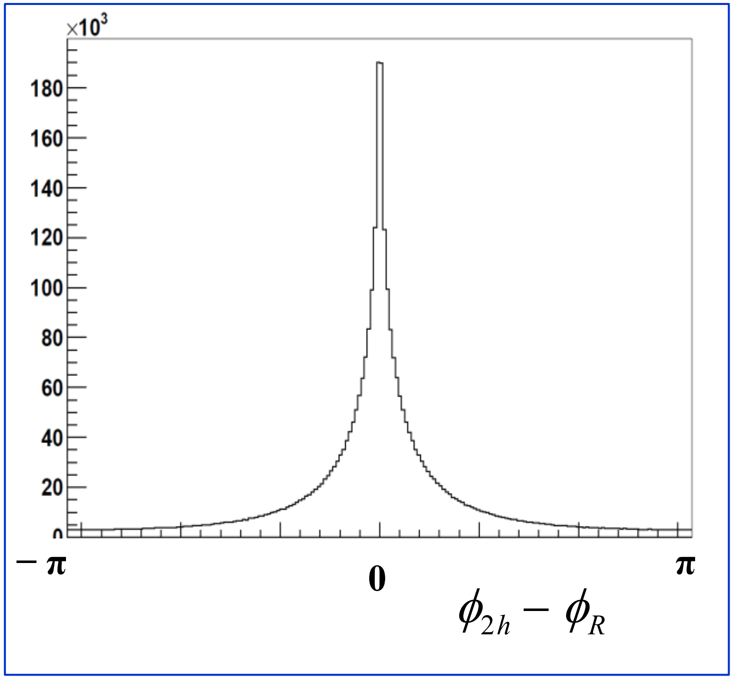
“mean” of the Collins angles of h+ and h-

dihadron asymmetry and Collins asymmetries

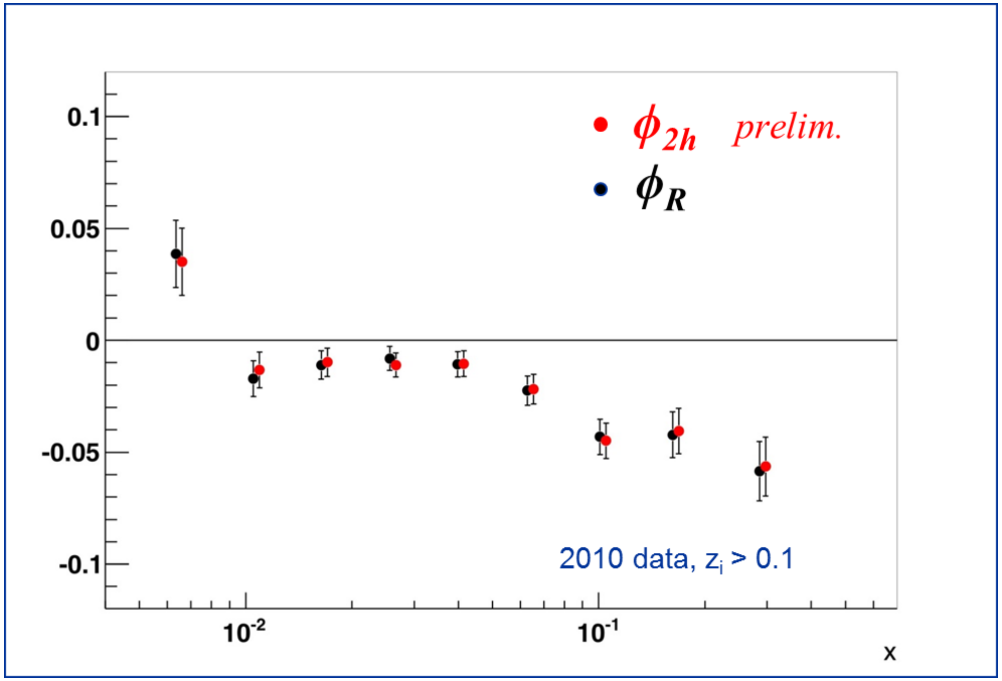
correlations between the relevant azimuthal angles and asymmetries

strong correlation

between ϕ_{2h} and ϕ_R



asymmetries



the asymmetries are very close,
hinting at a common physical origin for the Collins mechanism
and the di-hadron fragmentation function

Sivers function

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

Sivers function

in SIDIS on transversely polarized nucleons it can be accessed via the “Sivers asymmetry”

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

the most famous of the TMD PDFs

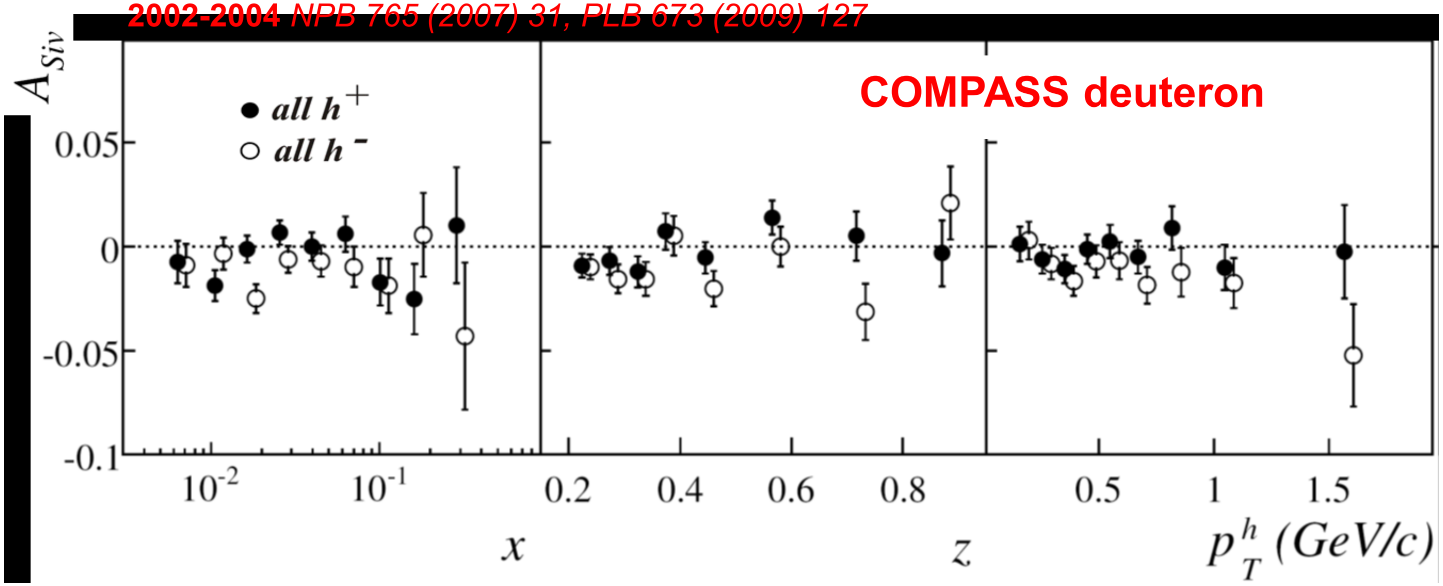
correlation between the transverse spin of the nucleon and the transverse momentum of the quark

sensitive to orbital angular momentum

change of sign from SIDIS to Drell - Yan

Sivers asymmetry

- strong signal seen by HERMES in π^+ production on p in 2005
- no signal seen by COMPASS on d



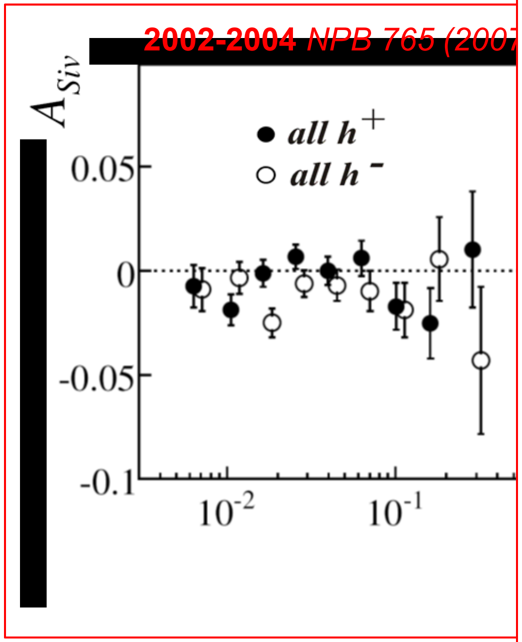
2002-2004 *NPB 765 (2007) 31, PLB 673 (2009) 127*

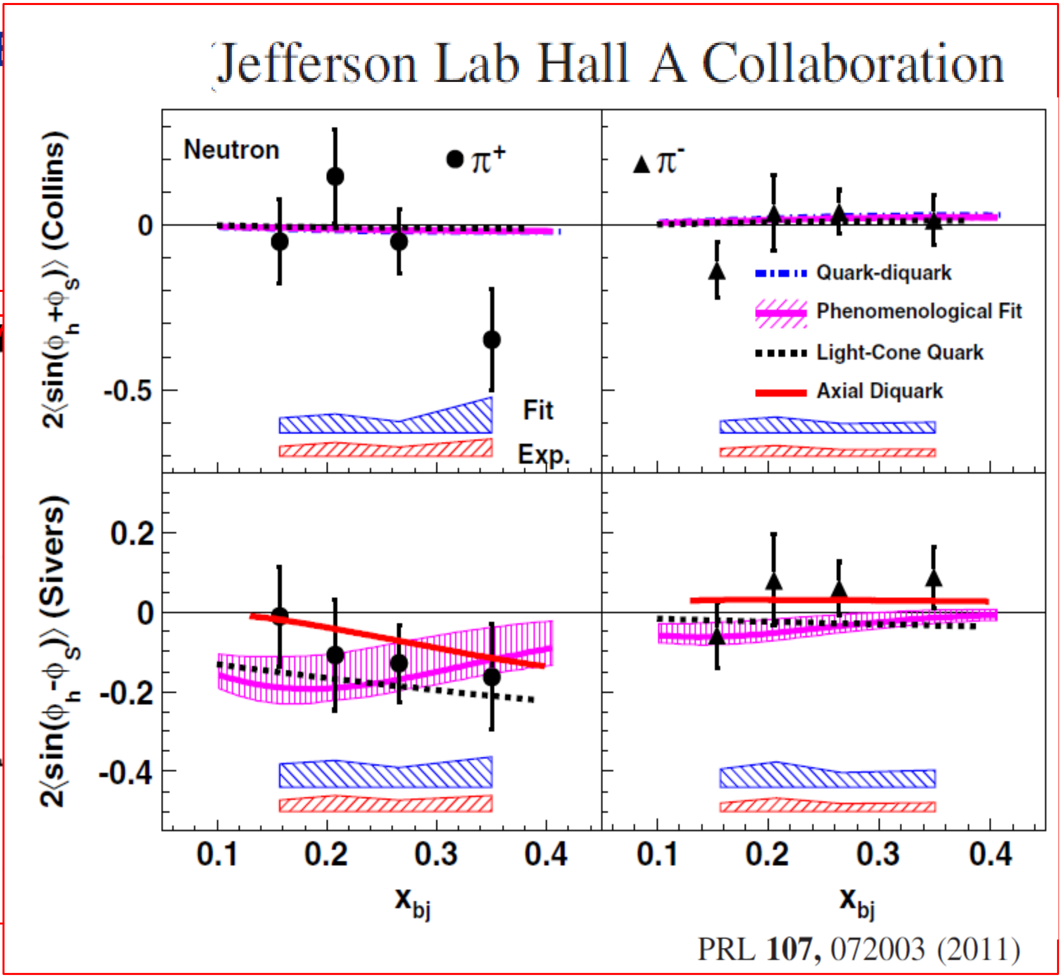
COMPASS deuteron

still only measurements on d

Sivers asymmetry

- **strong signal seen by HERME**
- **no signal seen by COMPASS**




Jefferson Lab Hall A Collaboration

PRL **107**, 072003 (2011)

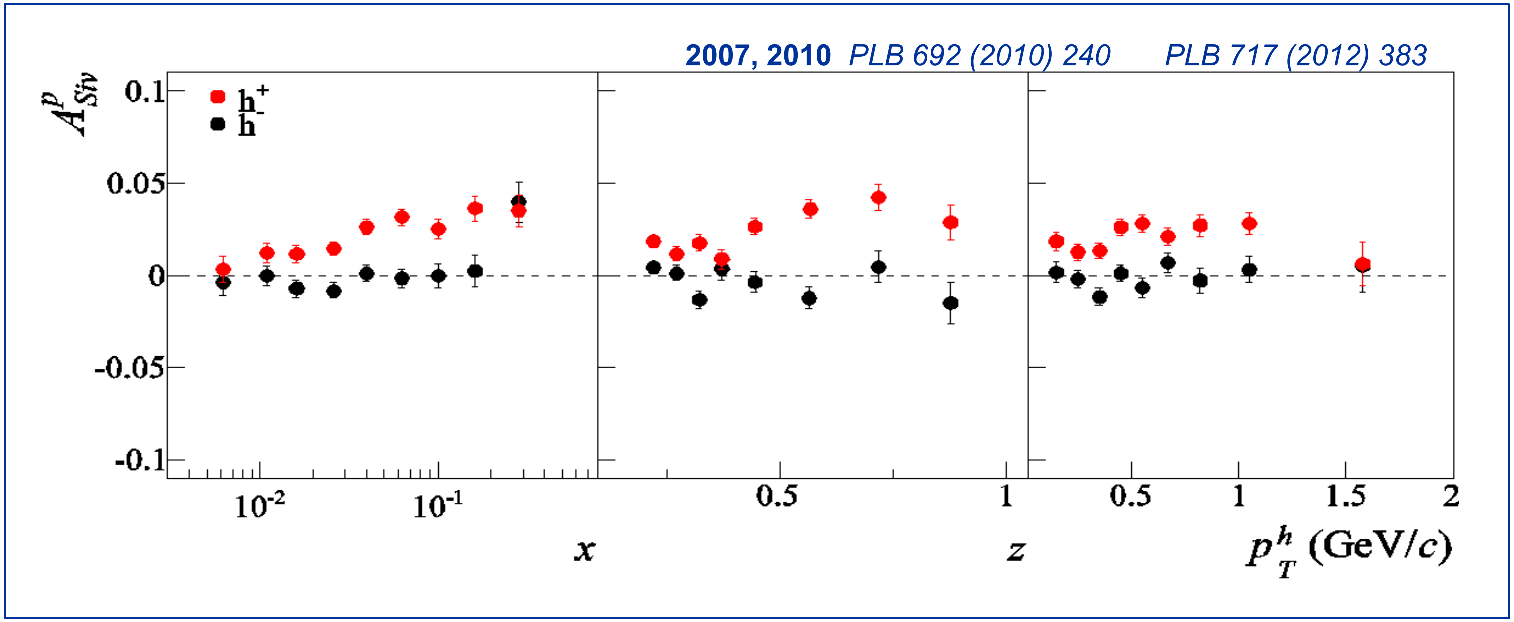
still only measurements on d

Sivers asymmetry

- strong signal seen by HERMES in π^+ production on p in 2005
- no signal seen by COMPASS on d
- COMPASS results on proton:

  clear signal for h+

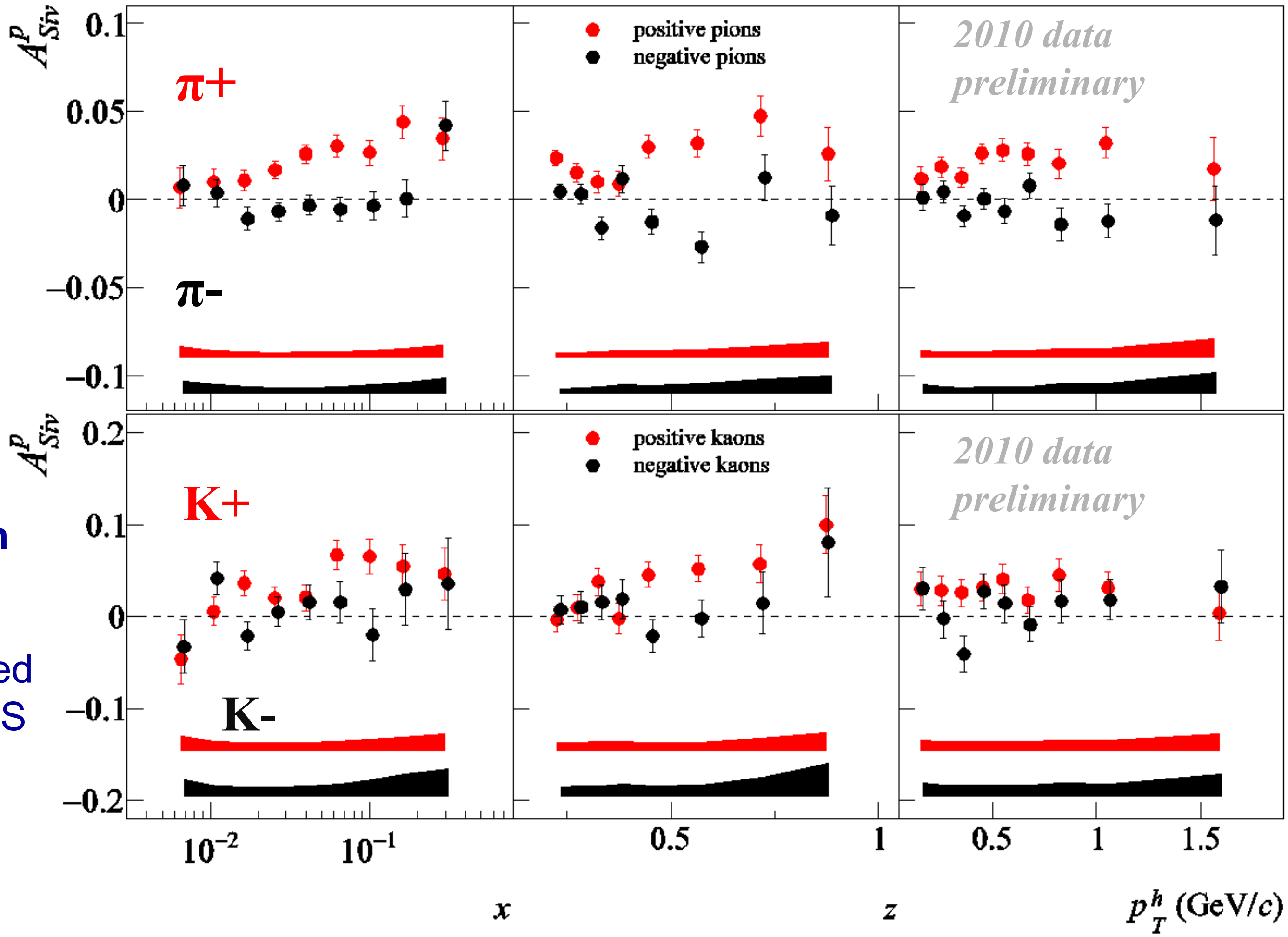
  down to low x, in the previously unmeasured region



Sivers asymmetry

COMPASS results on p for pions and kaons

similar
to h+ h-



larger than
for pions

as measured
by HERMES

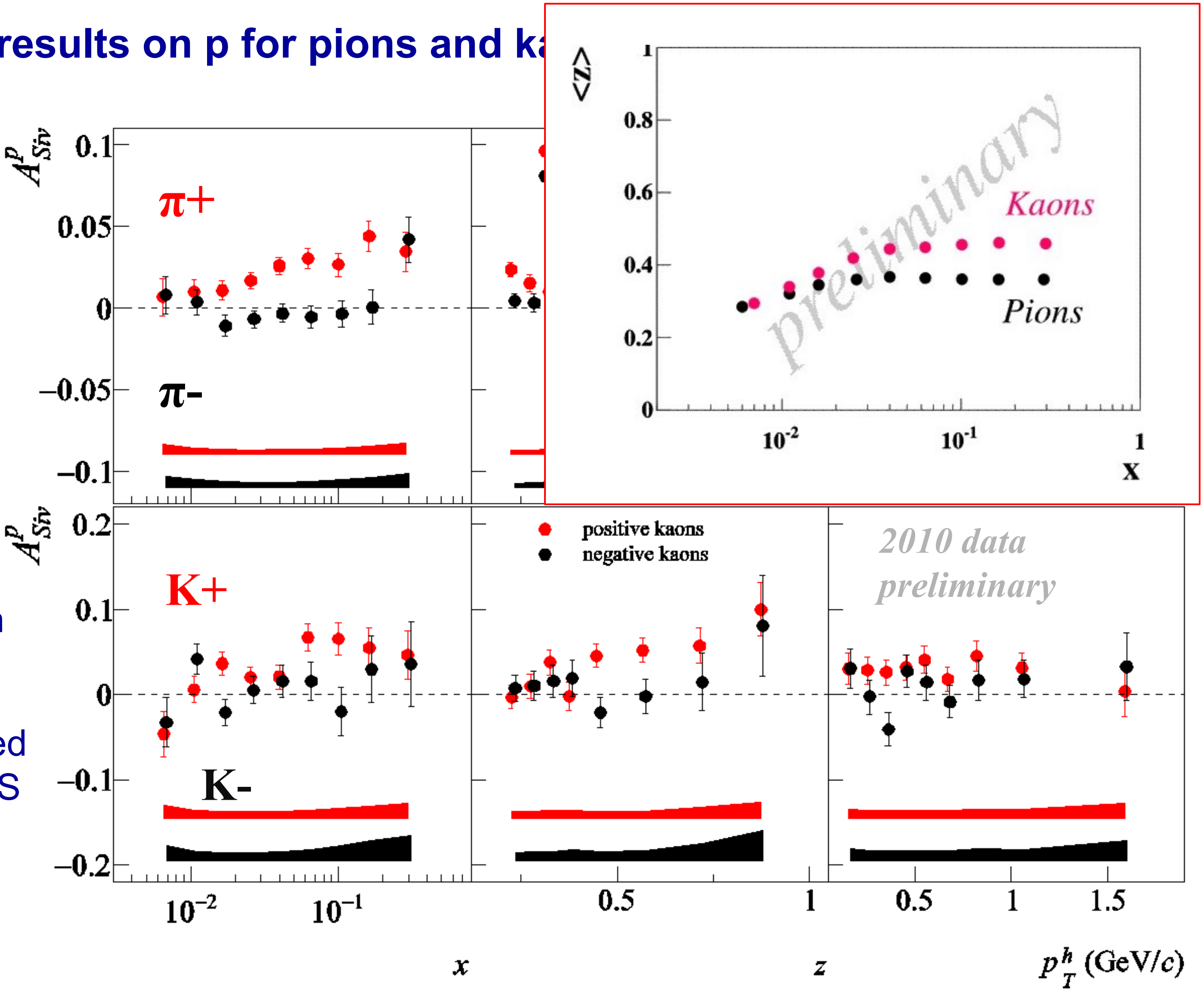
Sivers asymmetry

COMPASS results on p for pions and ka

similar
to h+ h-

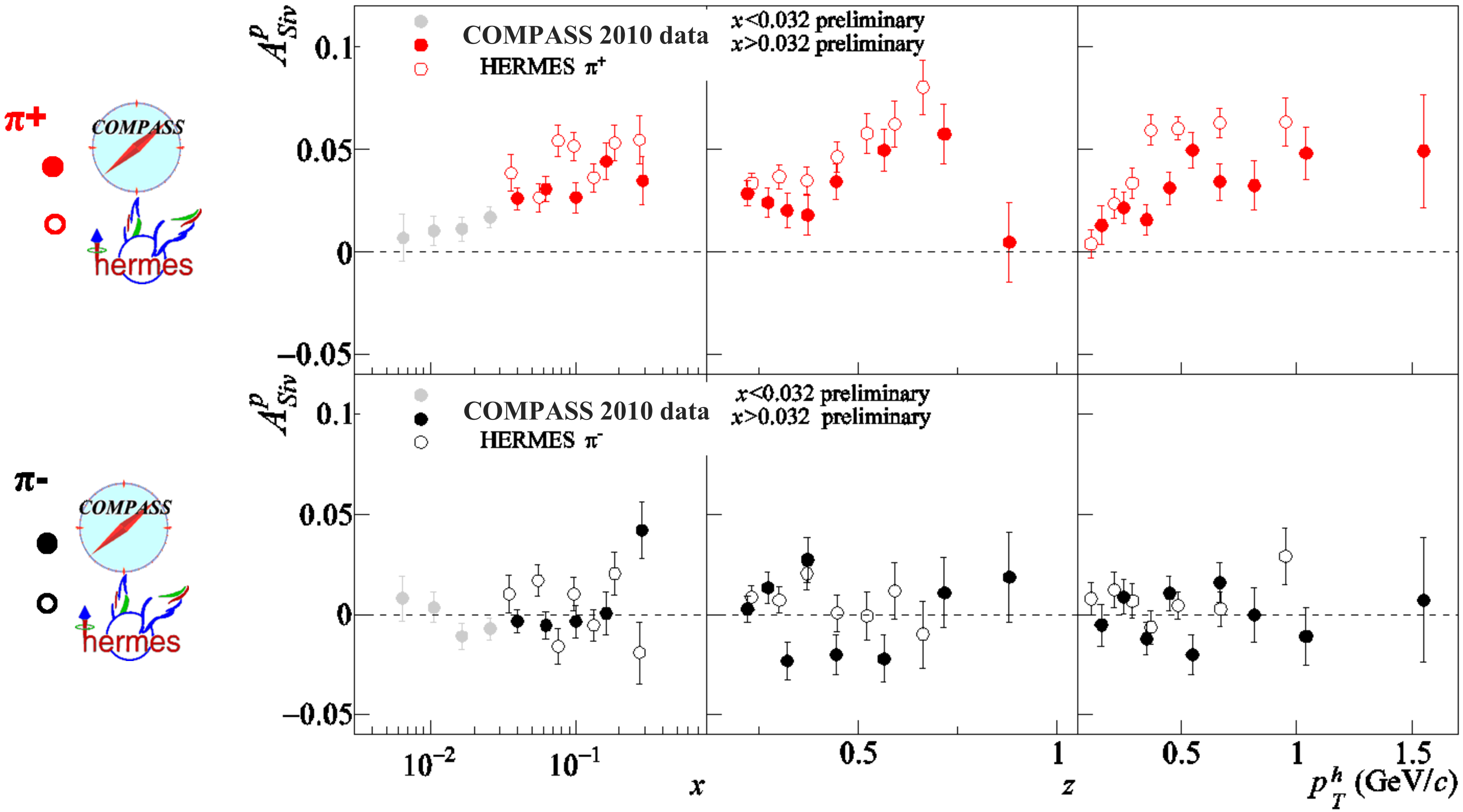
larger than
for pions

as measured
by HERMES



Sivers asymmetry

results on proton for pions



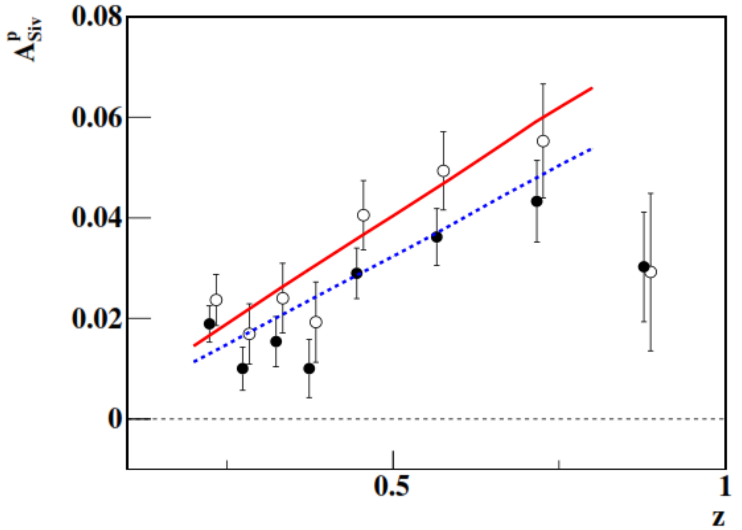
in the overlap x range, agreement with HERMES, but clear indication that the strength decreases

Sivers function

new extractions and Q^2 evolution

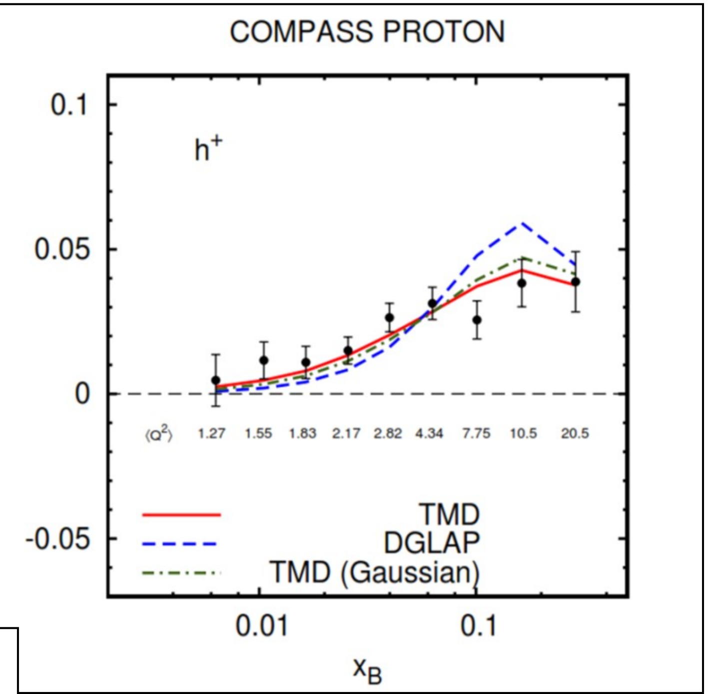
Aybat, Prokudin, Rogers

PRL 108 (2012) 242003



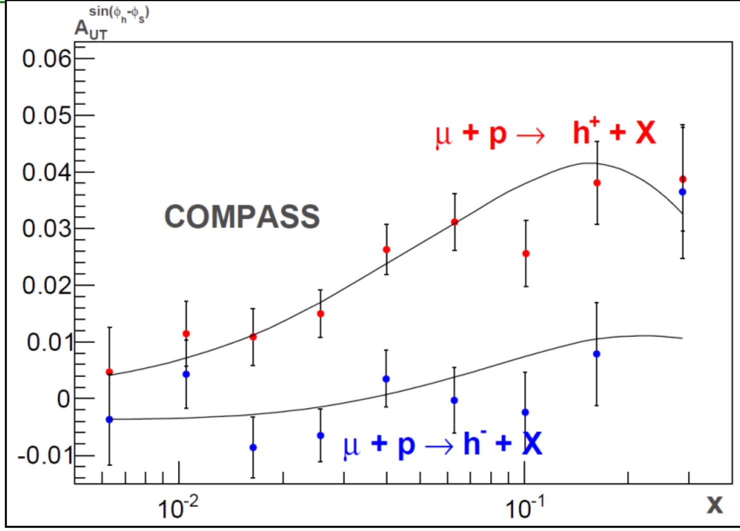
Anselmino, Boglione, Melis

PRD86 (2012) 014028



Sun, Yuan

arXiv:1308.2993 [hep-ph]



other transverse spin asymmetries

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

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

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

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

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

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

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

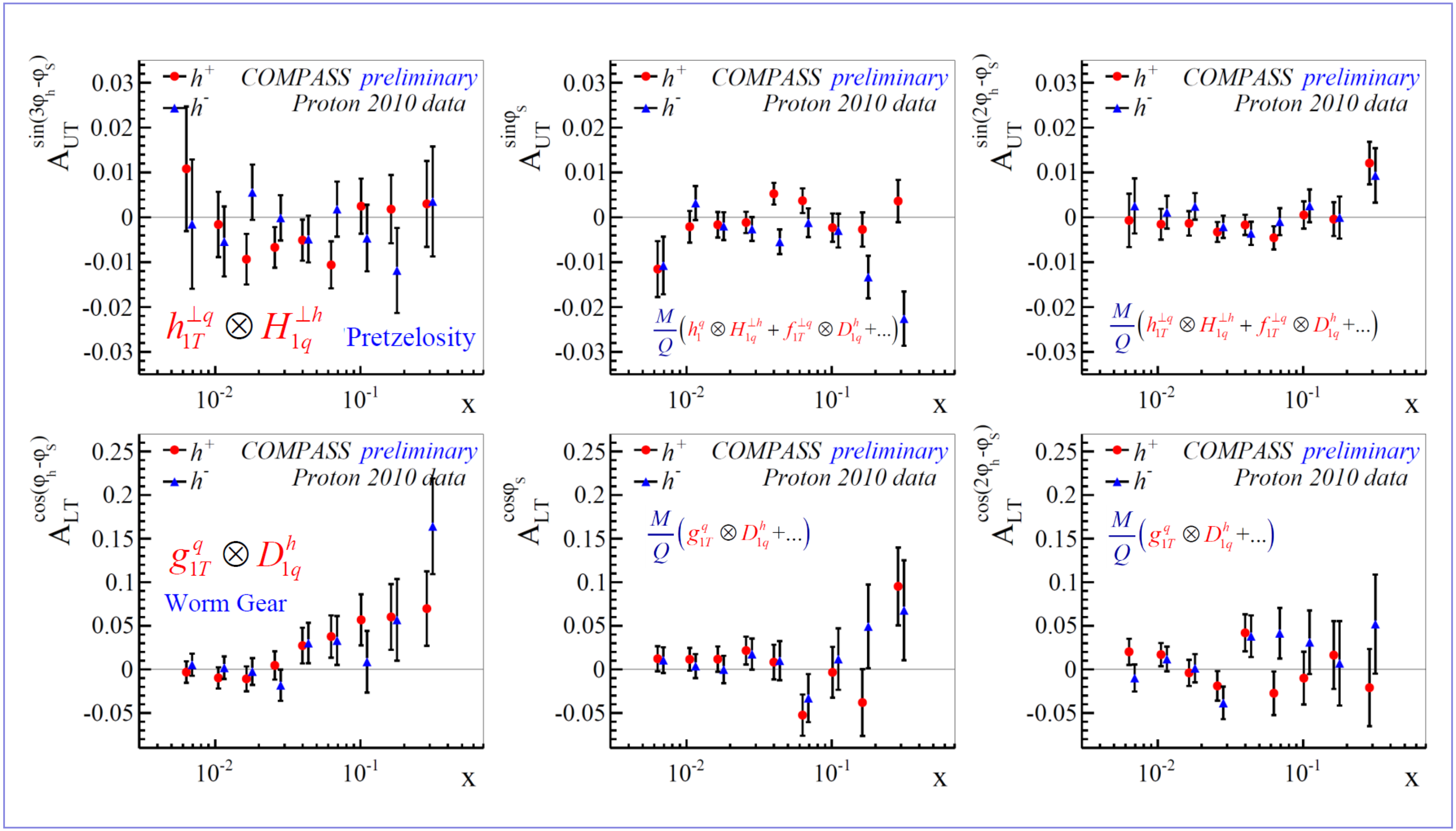
$$+\boxed{|\boldsymbol{S}_\perp|\lambda_e}\Big[\sqrt{1-\varepsilon^2}\,\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\cos\phi_S}\,F_{LT}^{\cos\phi_S}$$

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

all measured
on p and d
in COMPASS

compatible with
zero on d

other transverse spin asymmetries on p

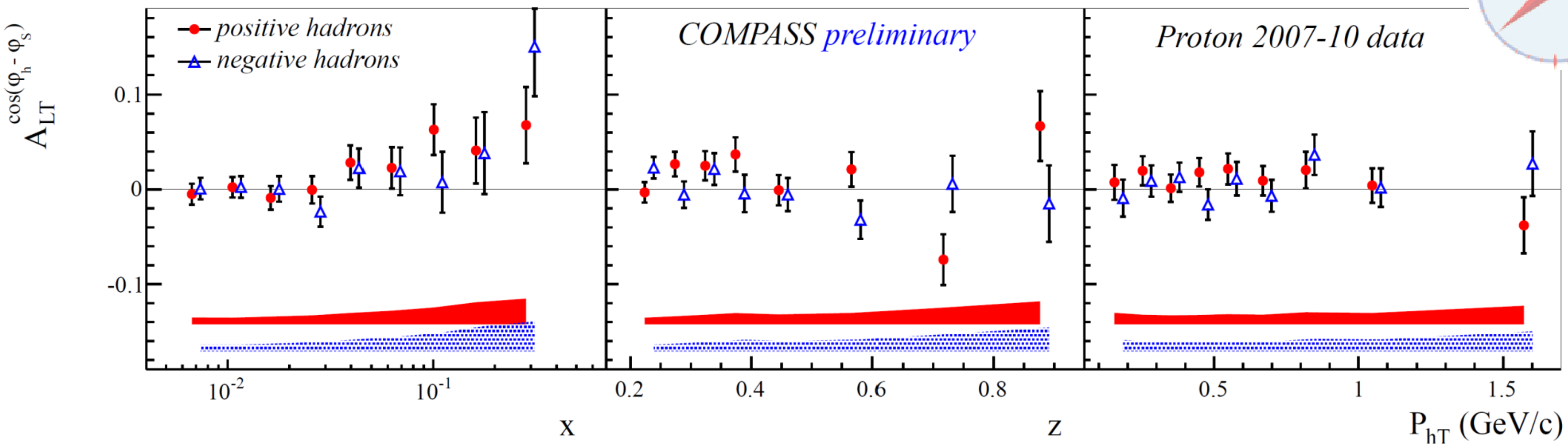


different factors D(y)

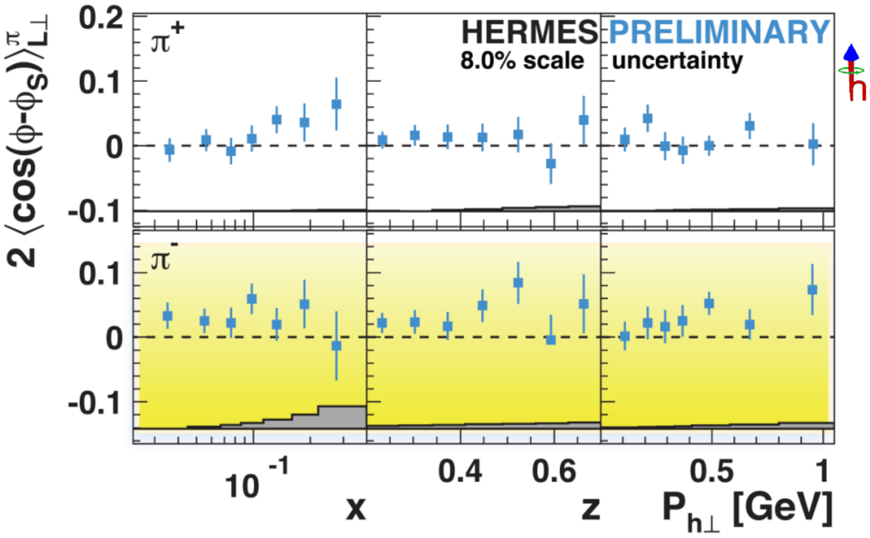
→ different statistical errors

other transverse spin asymmetries on p

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

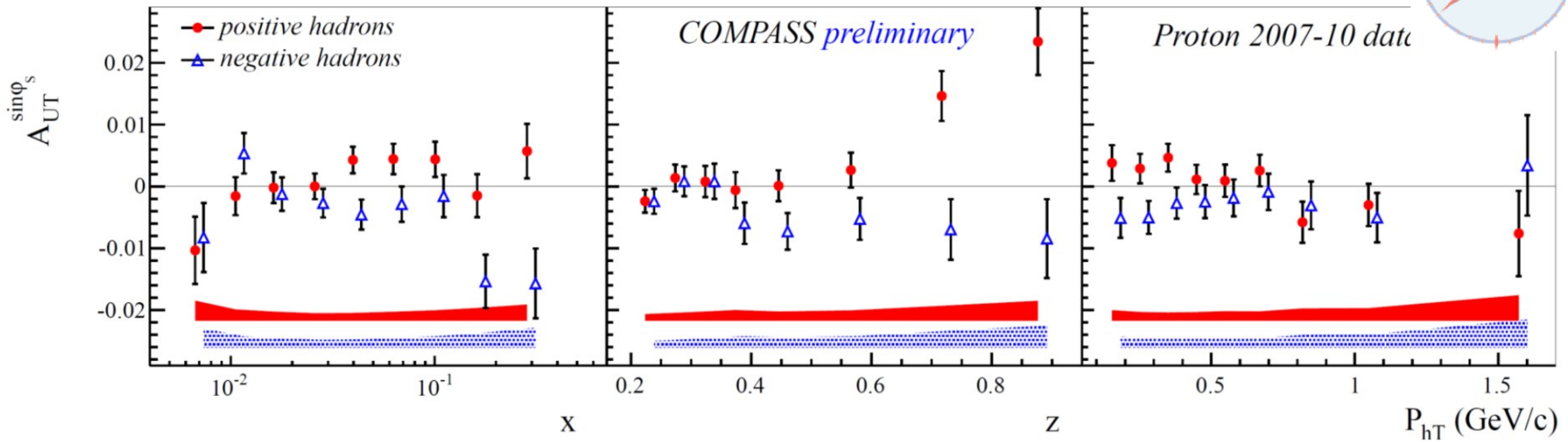


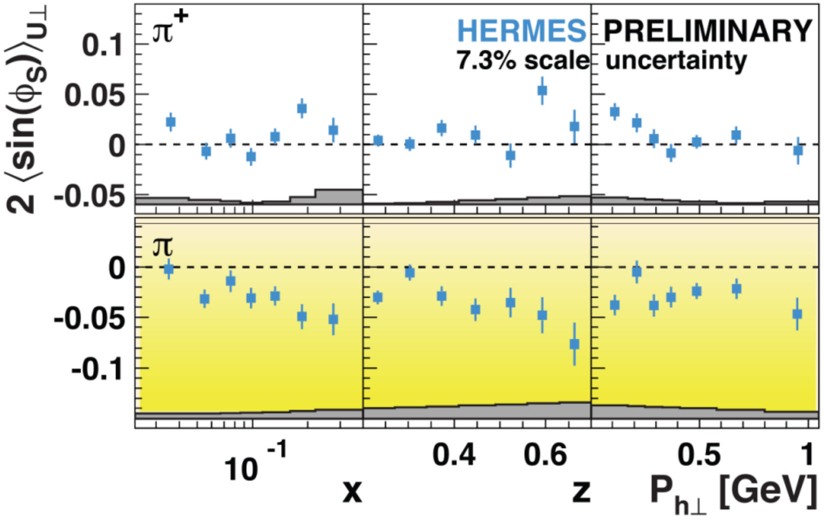
same trend



other transverse spin asymmetries on p

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





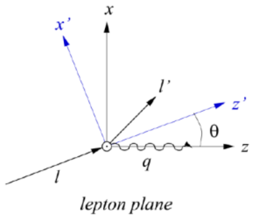
same trends, but
considerably larger at HERMES

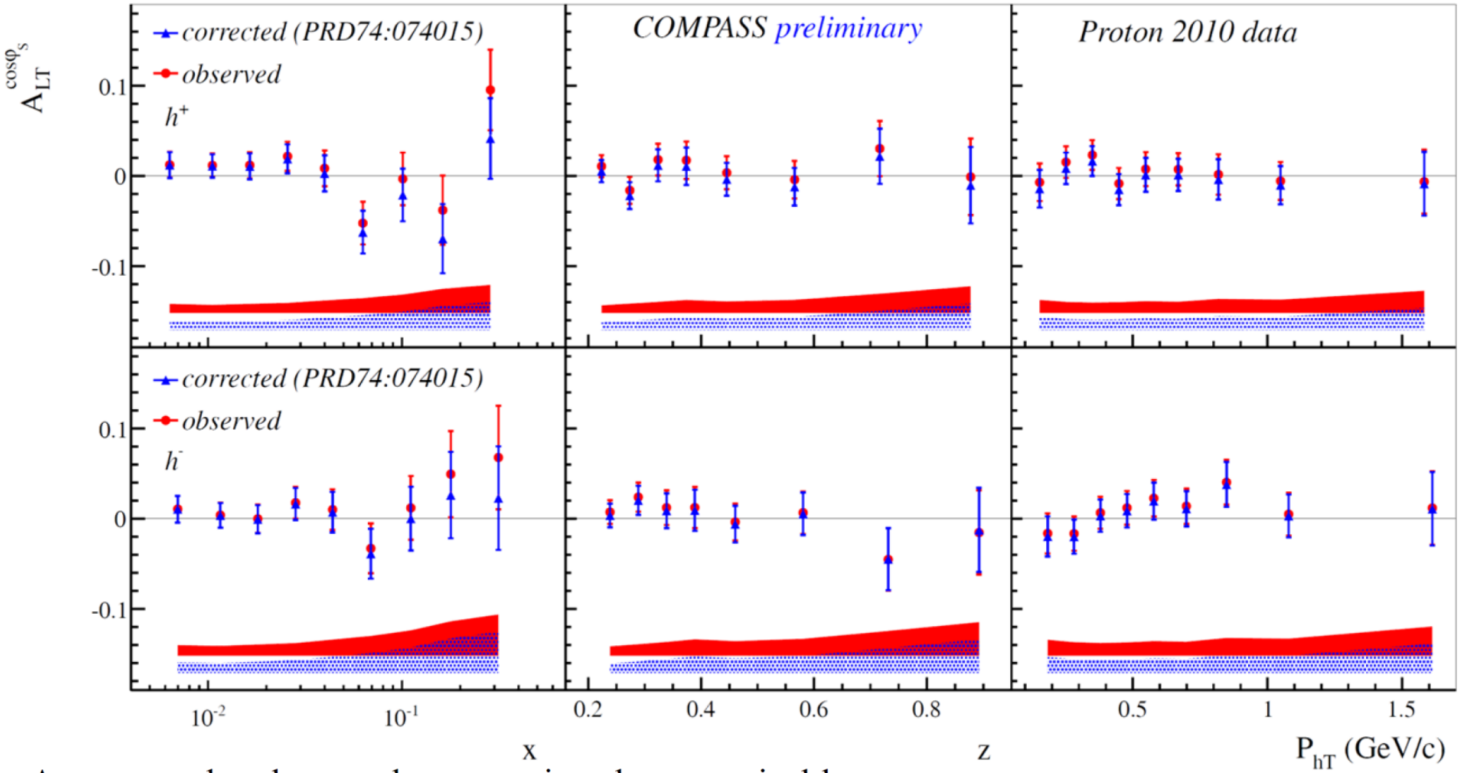
as expected

other transverse spin asymmetries on p

$$A_{LT}^{\cos\phi_s} \propto \frac{M}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \ldots\right)$$

$$A_{LT}^{\cos\varphi_S'} \approx \left(\cos\theta\, A_{LT}^{\cos\varphi_S} - \sin\theta \frac{\sqrt{\left(1-\varepsilon^2\right)}}{\sqrt{2\varepsilon\left(1-\varepsilon\right)}} A_{LL}\right)$$





due to the small value of θ at COMPASS, this is the only asymmetry which needs to be corrected for the longitudinal component of the nucleon spin

longitudinal spin azimuthal asymmetries

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

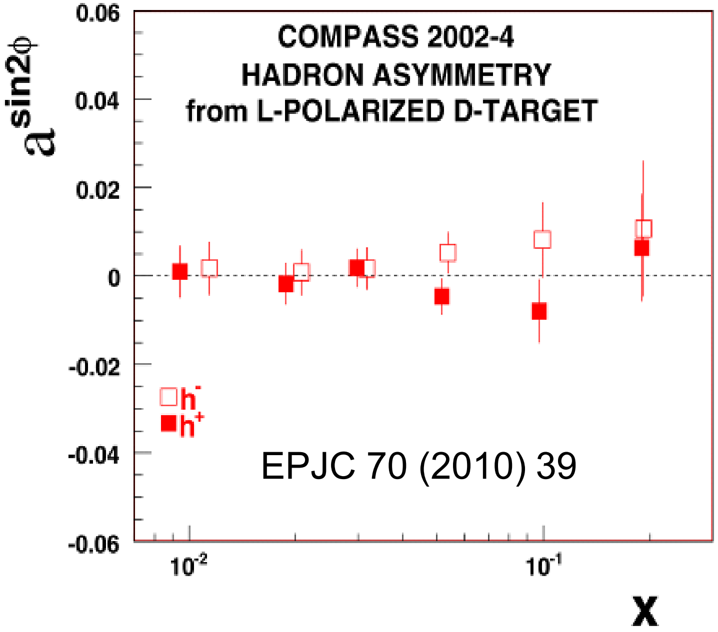
longitudinal spin azimuthal asymmetries

first measurement on d 2004 data: all compatible with zero

$$F_{UL}^{sin2\phi_h} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

"worm gear" PDF

$\otimes$ Collins FF



EPJC 70 (2010) 39

being measured with better statistics on d and on p

SIDIS off unpolarised deuteron

combining data taken with oppositely polarised ^{6}LiD target

COMPASS has measured

- azimuthal asymmetries

information on $k_{\perp}$ and $p_{\perp}$

- hadron multiplicities

SIDIS off unpolarised deuteron

combining data taken with oppositely polarised ^{6}LiD target
COMPASS has measured

- **azimuthal asymmetries**
- **hadron multiplicities**

Cahn effect

Boer-Mulders PDF

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

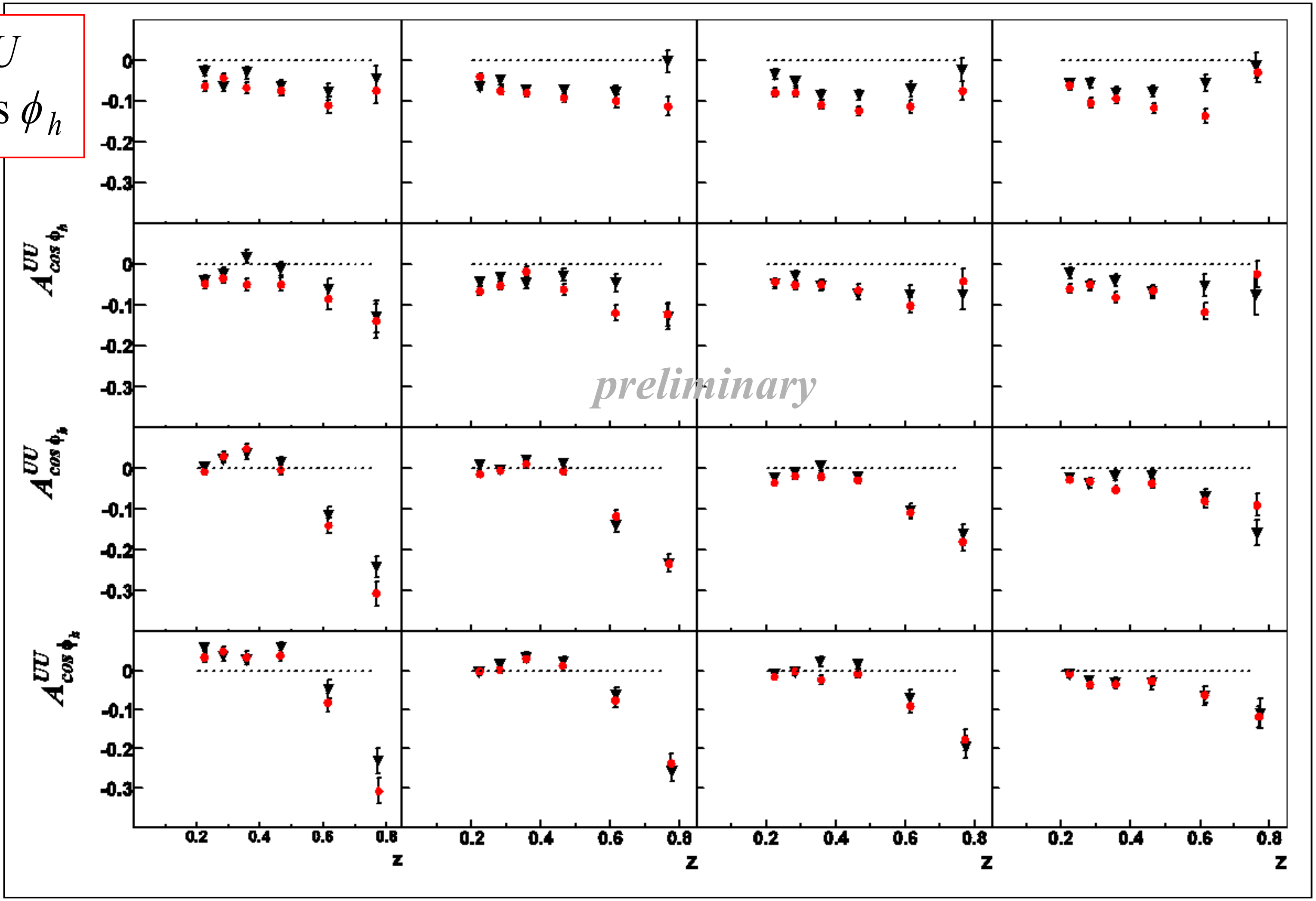
$$+\,\varepsilon\,\boxed{\cos(2\phi_h)}\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\boxed{\sin\phi_h}\,F_{LU}^{\sin\phi_h}+\dots$$

twist3

Boer-Mulders PDF x Collins FF
+ Cahn effect (twist 4, 1/Q^2)

unpolarised deuteron - azimuthal asymmetries

$A^{UU}_{\cos\phi_h}$



▼ **h-**

● **h+**

$sys \approx 2 \cdot stat$

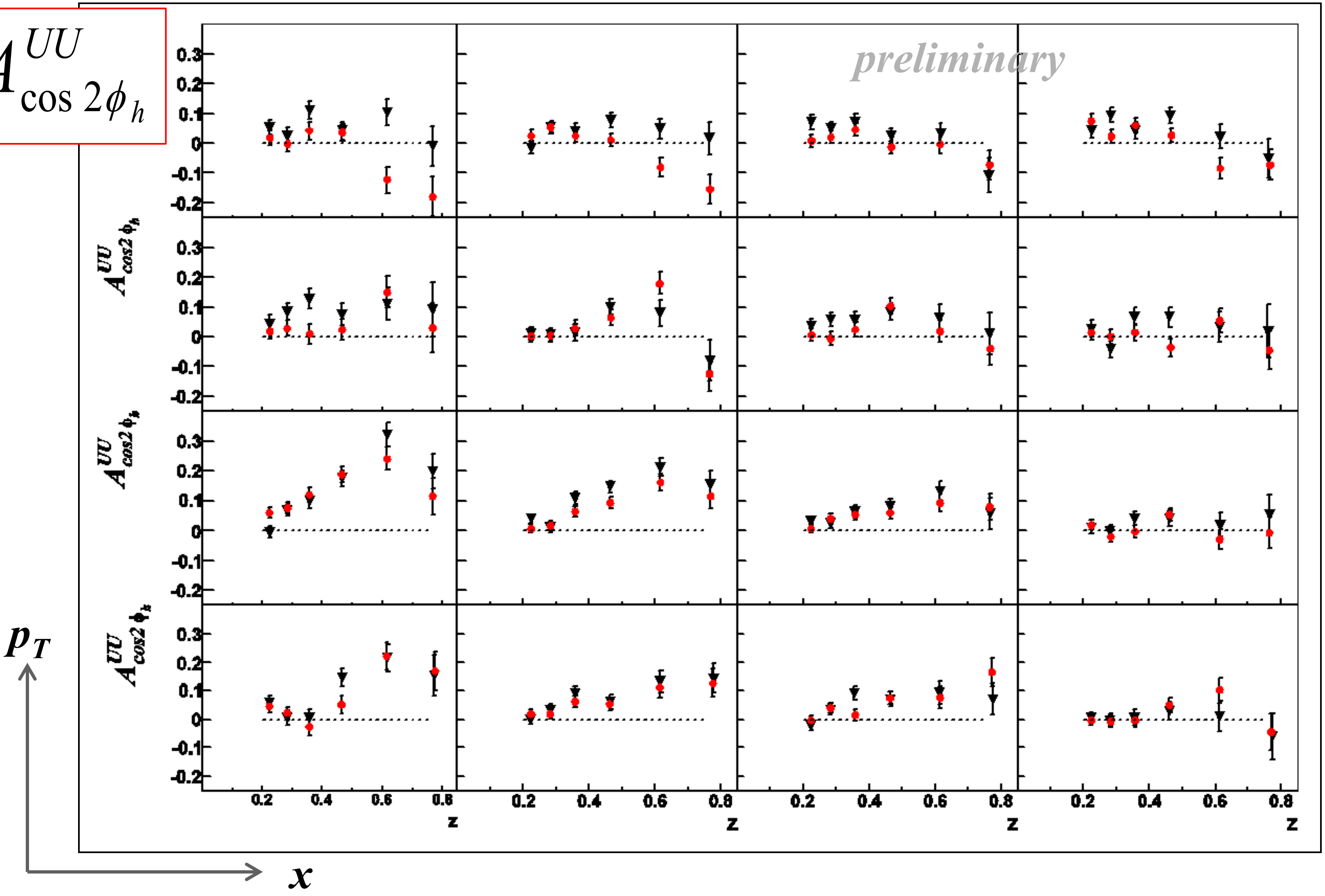
p_T

x

strong z dependence mainly at small x and small p_T

unpolarised deuteron - azimuthal asymmetries

$$A^{UU}_{\cos 2\phi_h}$$

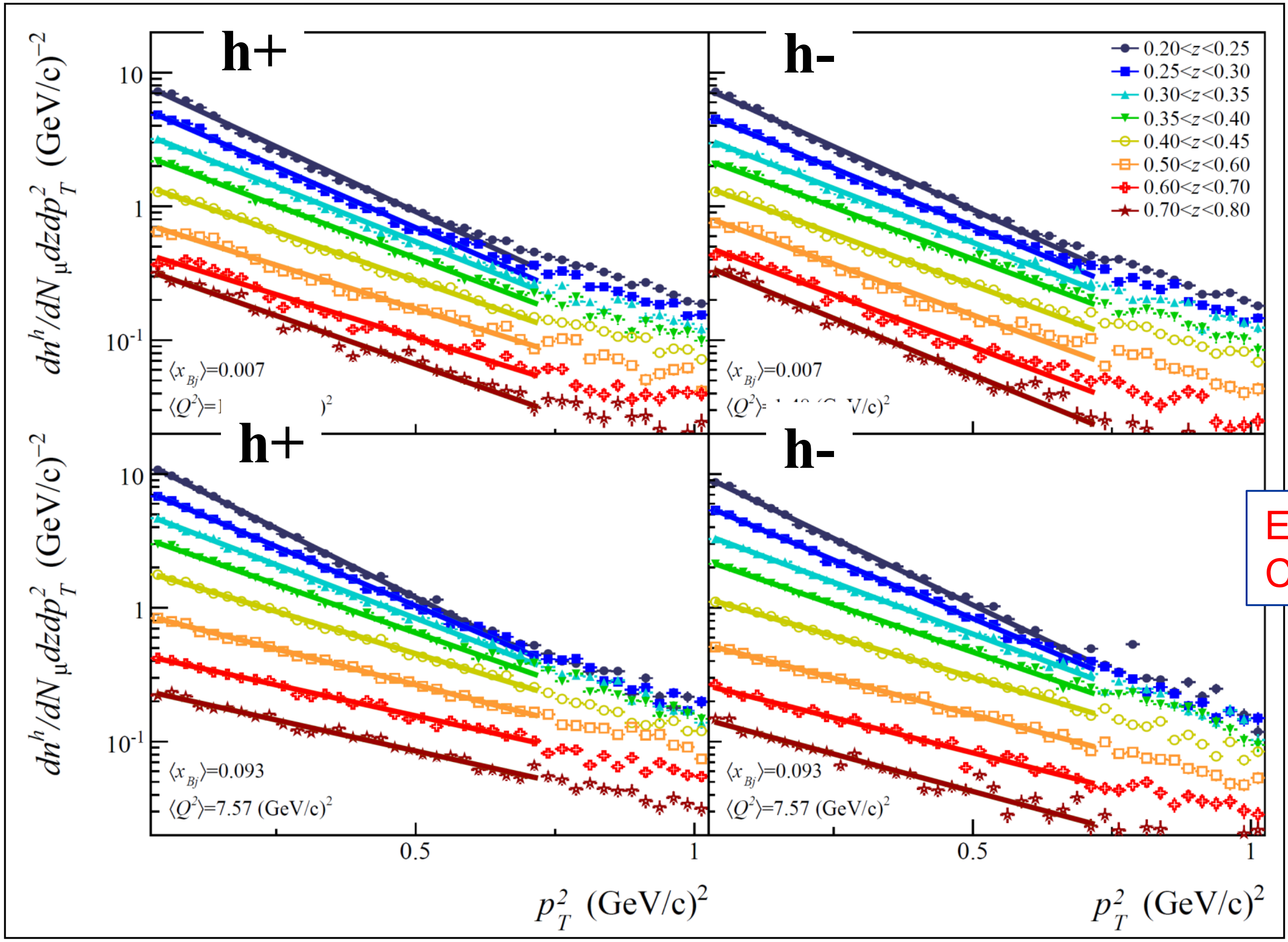


▼ h-

● h+

$sys \approx 2 \cdot stat$

unpolarised deuteron hadron multiplicities vs p_T^2



Eur.Phys.J.
C73 (2013) 2531

unpolarised deuteron

hadron multiplicities vs p_T^2

$\langle x \rangle$

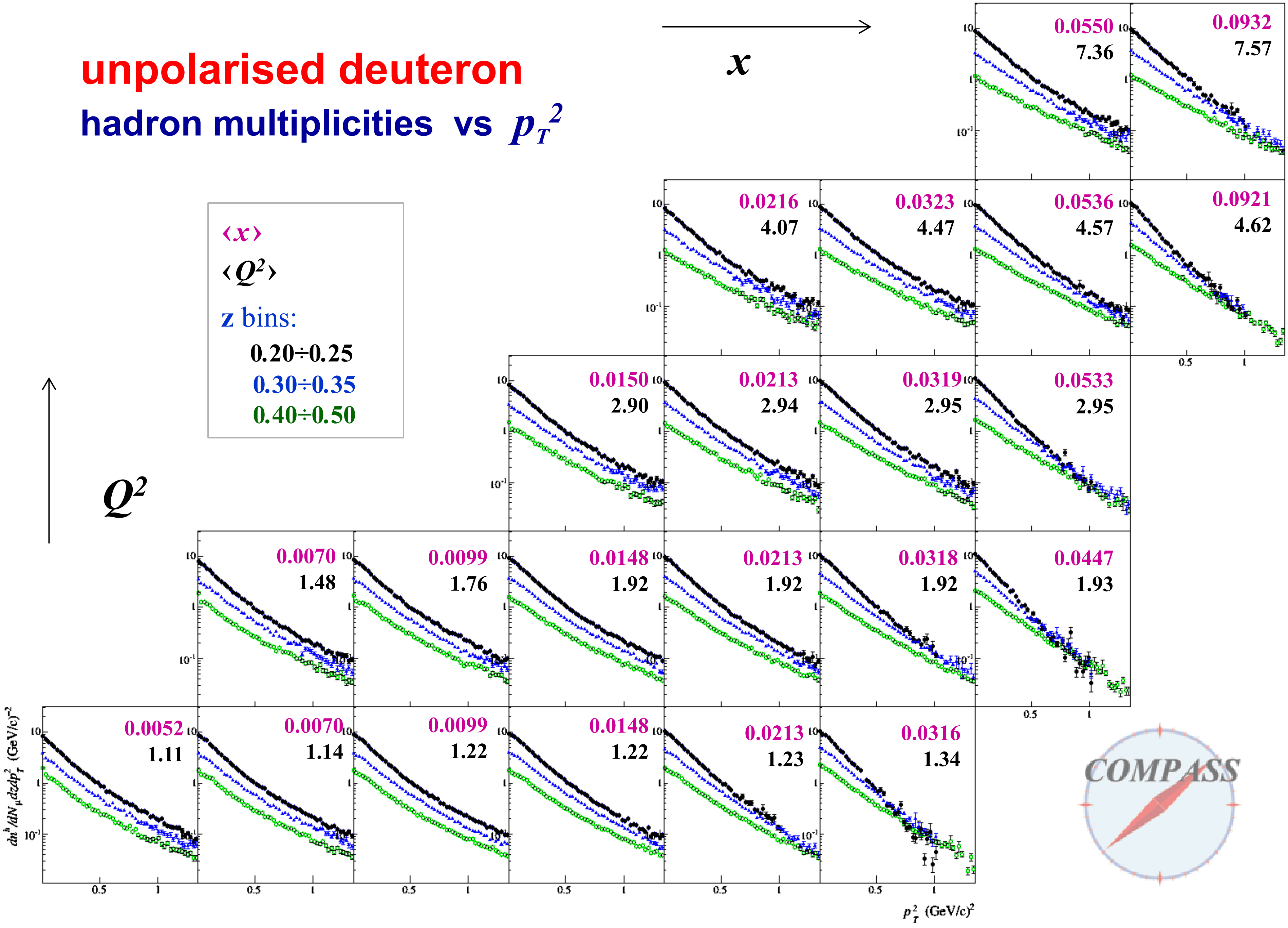
$\langle Q^2 \rangle$

z bins:

0.20÷0.25

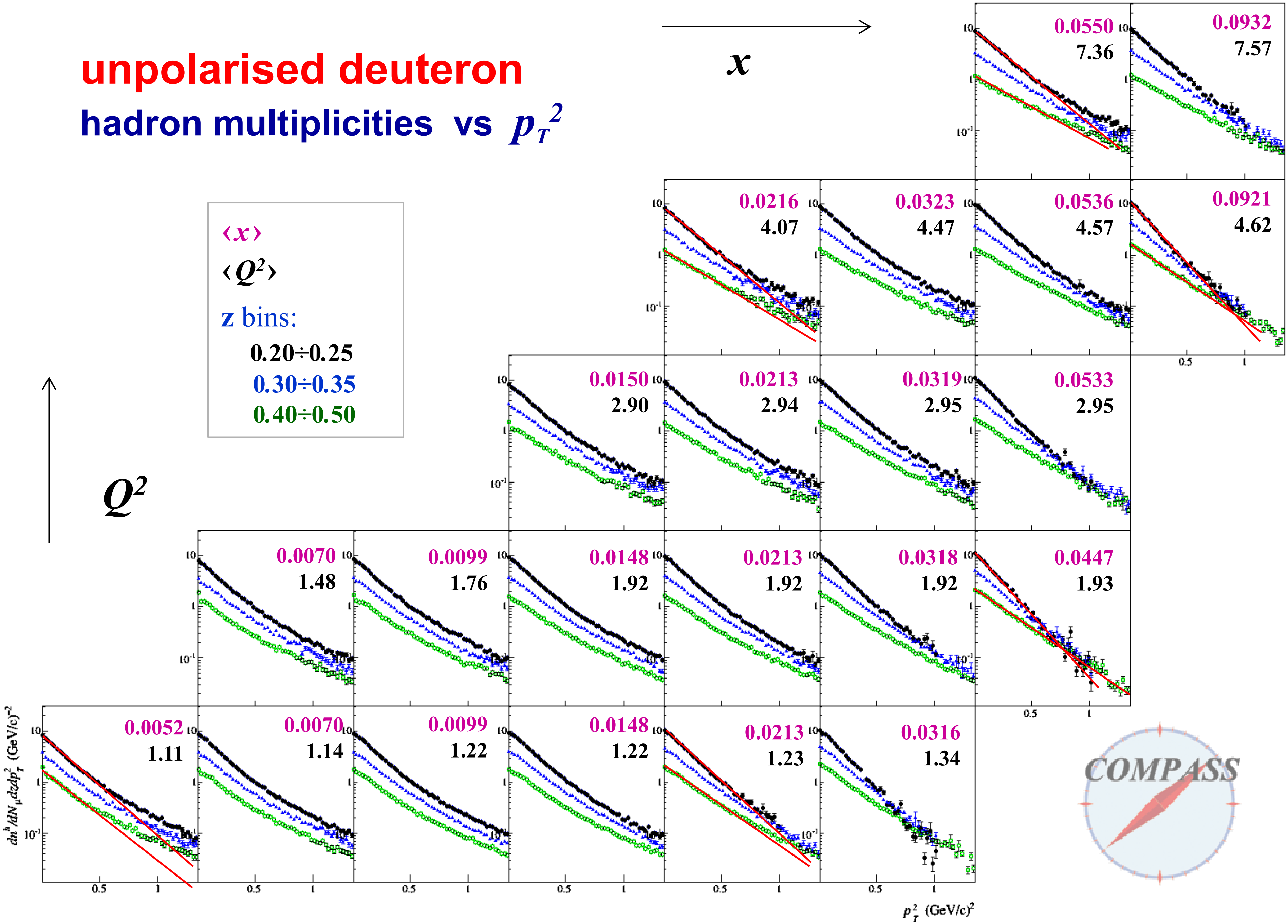
0.30÷0.35

0.40÷0.50



unpolarised deuteron

hadron multiplicities vs p_T^2



$\langle x \rangle$

$\langle Q^2 \rangle$

z bins:

0.20÷0.25

0.30÷0.35

0.40÷0.50

future COMPASS contribution to TMDs

SIDIS

coming soon, from existing data:

- further investigation of single hadron and dihadron asymmetries
- multidimensional analysis of transverse spin asymmetries
  Collins, Sivers, …
- more d and p results on longitudinal spin azimuthal asymmetries
- more results on azimuthal asymmetries and multiplicities from unpolarised d data (PID)

2016-2017 runs

- measurements in parallel with DVCS – LH_2 target

2015, …

DY process: pion beam, T polarised target

change of sign of the Sivers function

later on

more SIDIS data on transversely polarised d and p ?

Thank you

the COMPASS spectrometer

- high energy beams
- large angular acceptance (0 – 200 mrad)
- broad kinematical range

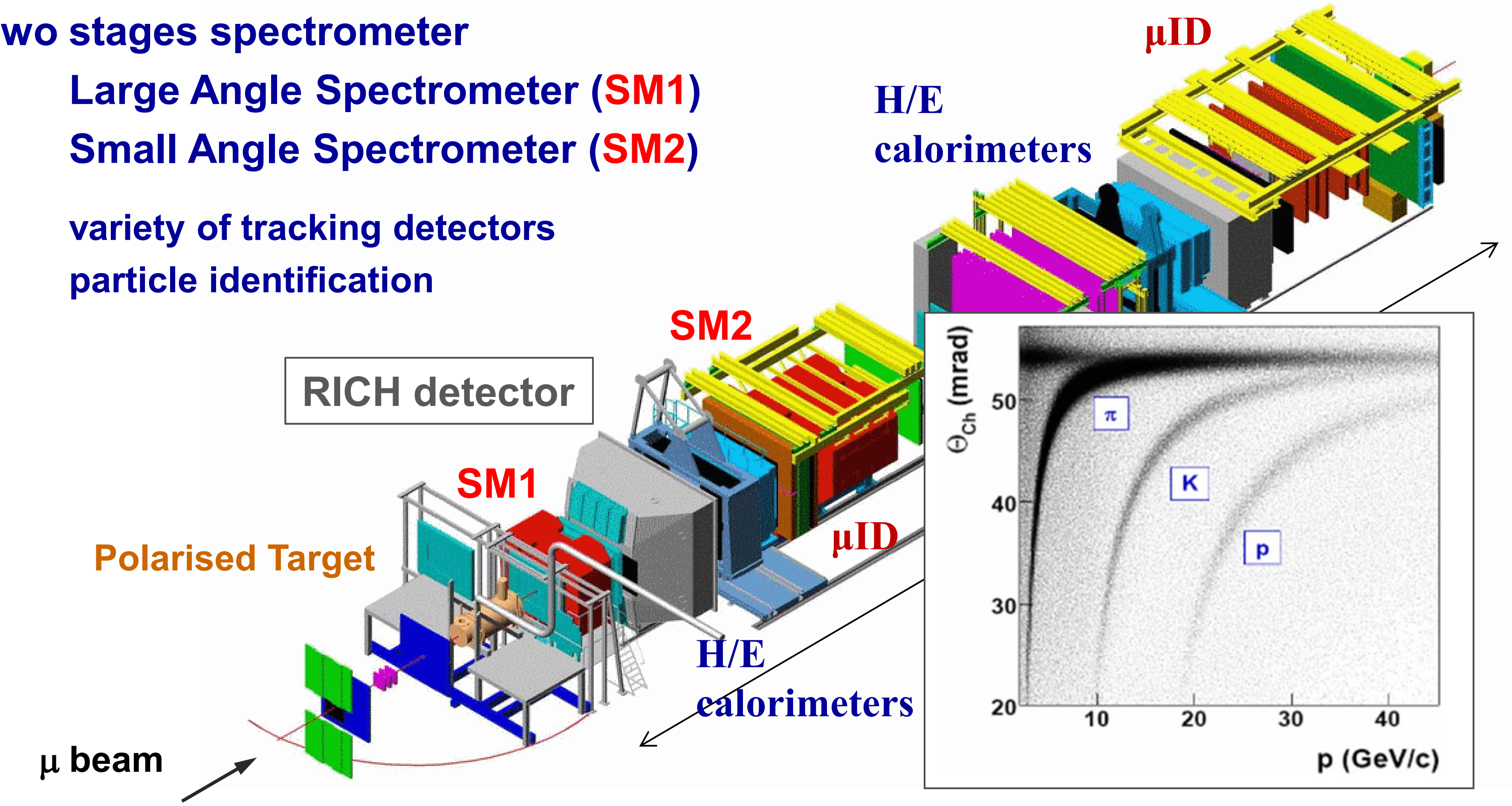
two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

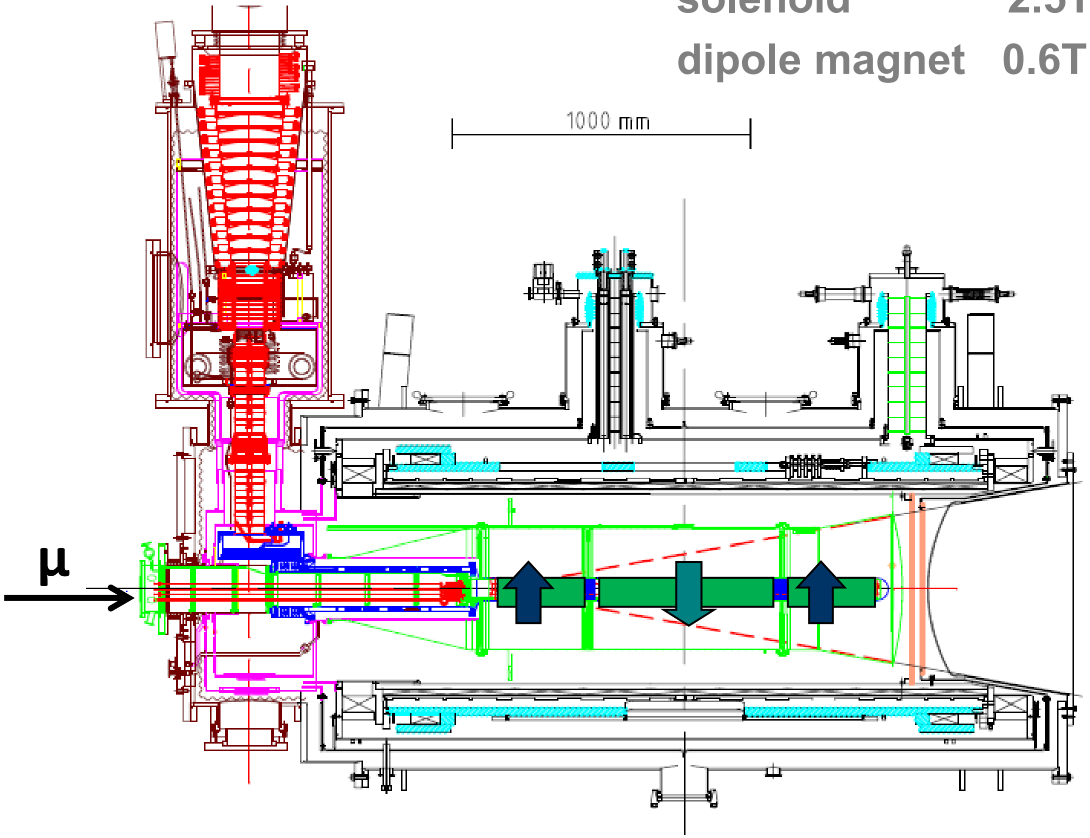
particle identification



the polarized target system (>2005)

^{3}He – ^{4}He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

3 target cells

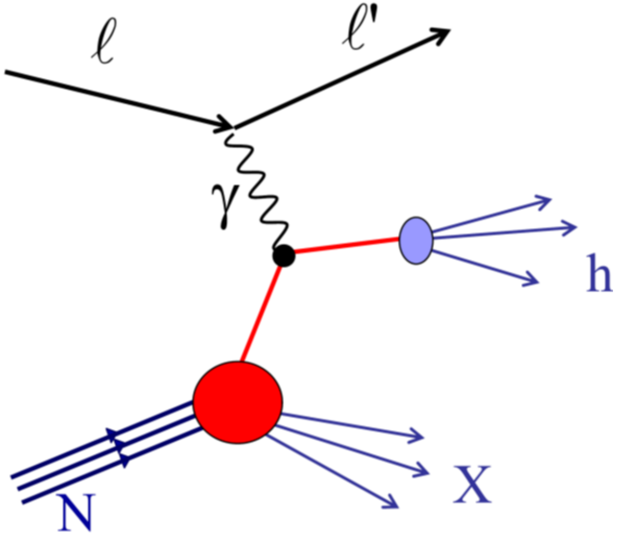
30, 60, and 30 cm long

opposite L or T polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

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

Semi-Inclusive Deep Inelastic Scattering



$$x = \frac{Q^2}{2P\cdot q}$$

$$Q^2 = -q^2$$

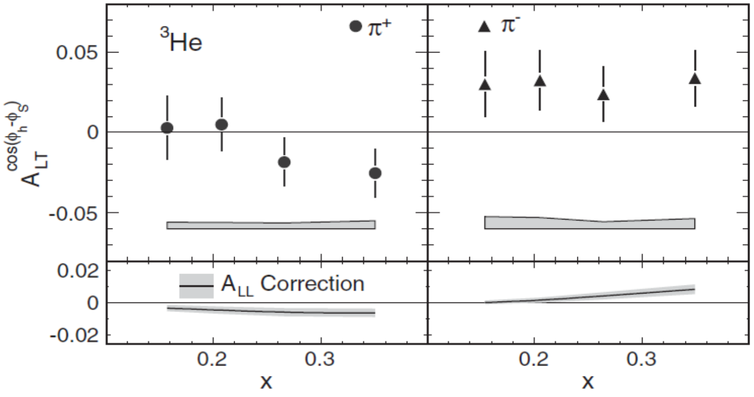
$$y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

$$W^2 = (P+q)^2$$

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

p_T^h ϕ_h

JLab E06-010 PRL **108,** 052001 (2012)

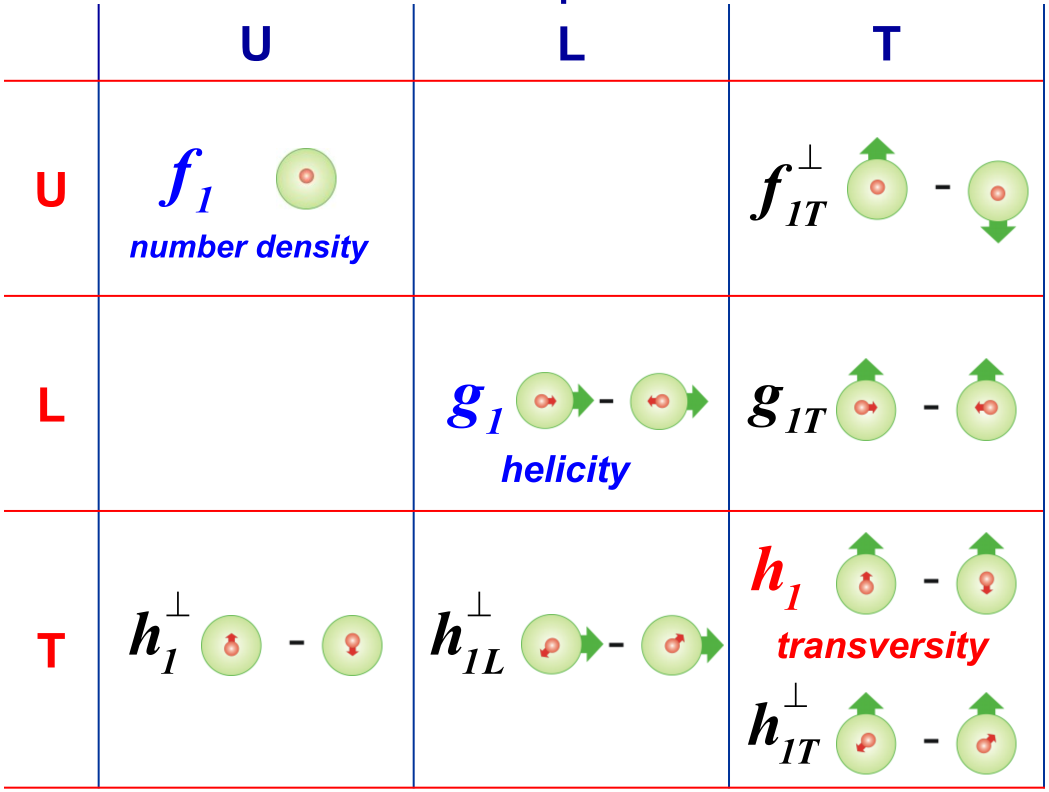


an essential tool to investigate

Nucleon Structure

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

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



nucleon **polarization**

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

SIDIS

interesting properties

correlations between nucleon spin and quark spin and transverse momentum

at twist-3 more TMD PDF's

not all have a simple interpretation in the framework of the QPM

Semi-Inclusive Deep Inelastic Scattering

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

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

$$+\,\varepsilon\;\text{[redacted]}\;F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon}\;\text{[redacted]}\;F_{LU}^{\sin\phi_h}$$

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

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

$$+\,\varepsilon\;\text{[redacted]}\;F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\;\text{[redacted]}\;F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

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

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

14 independent azimuthal modulations

amplitudes of the modulations

→ TMD PDFs

all the amplitudes
– azimuthal asymmetries –
have been measured in COMPASS

TRANSVERSITY

one of the main goals of COMPASS

$h_1^q(x)$ $\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transverse polarization or **transversity distribution**

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

different properties than helicity

tensor charge of the N

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

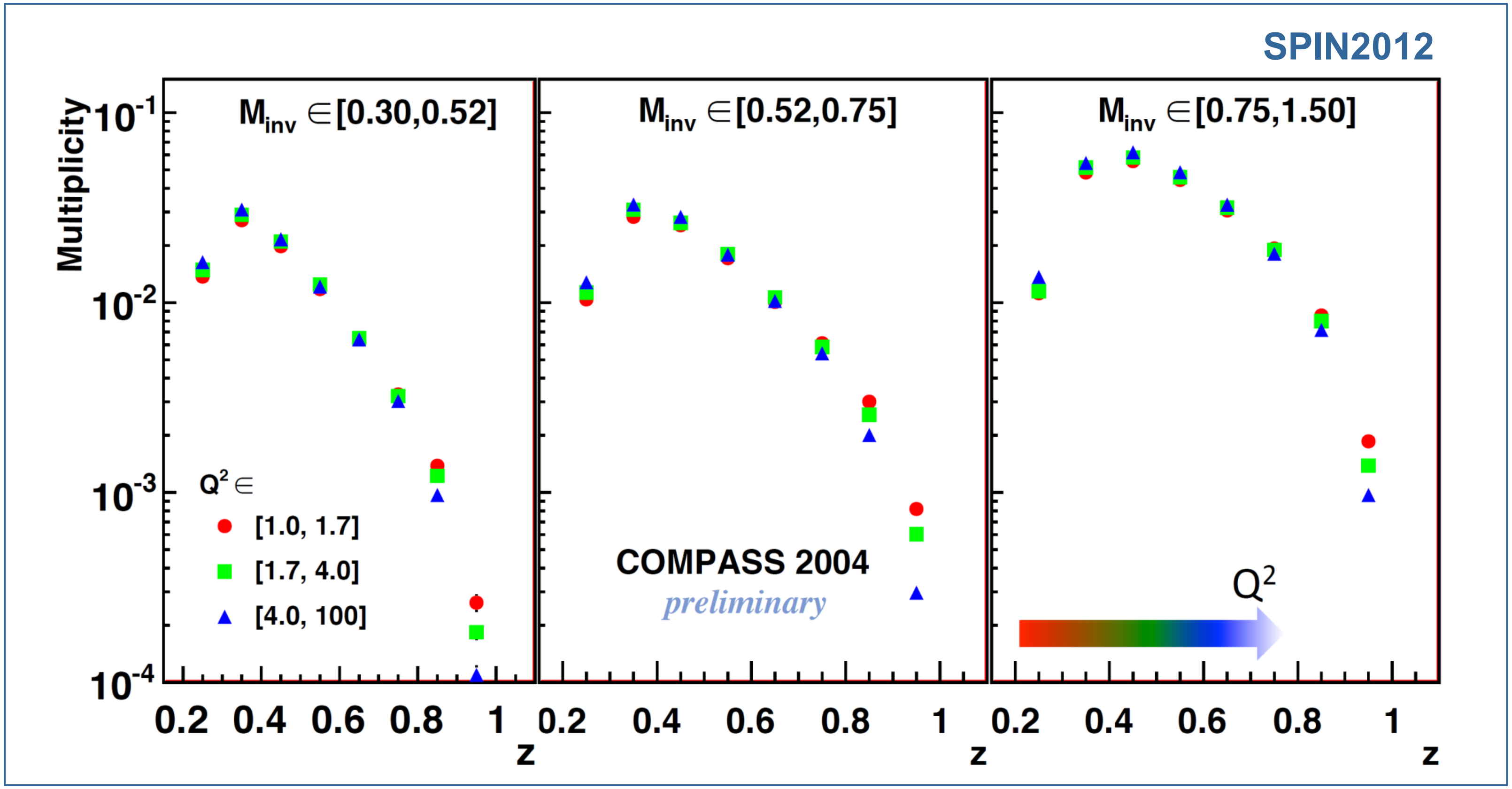
more difficult to measure

- **proposed in ’77** (Ralston & Soper)
- **convincing evidence that it is non zero only recently in SIDIS from the HERMES and the COMPASS experiments**

hadron multiplicities in SIDIS

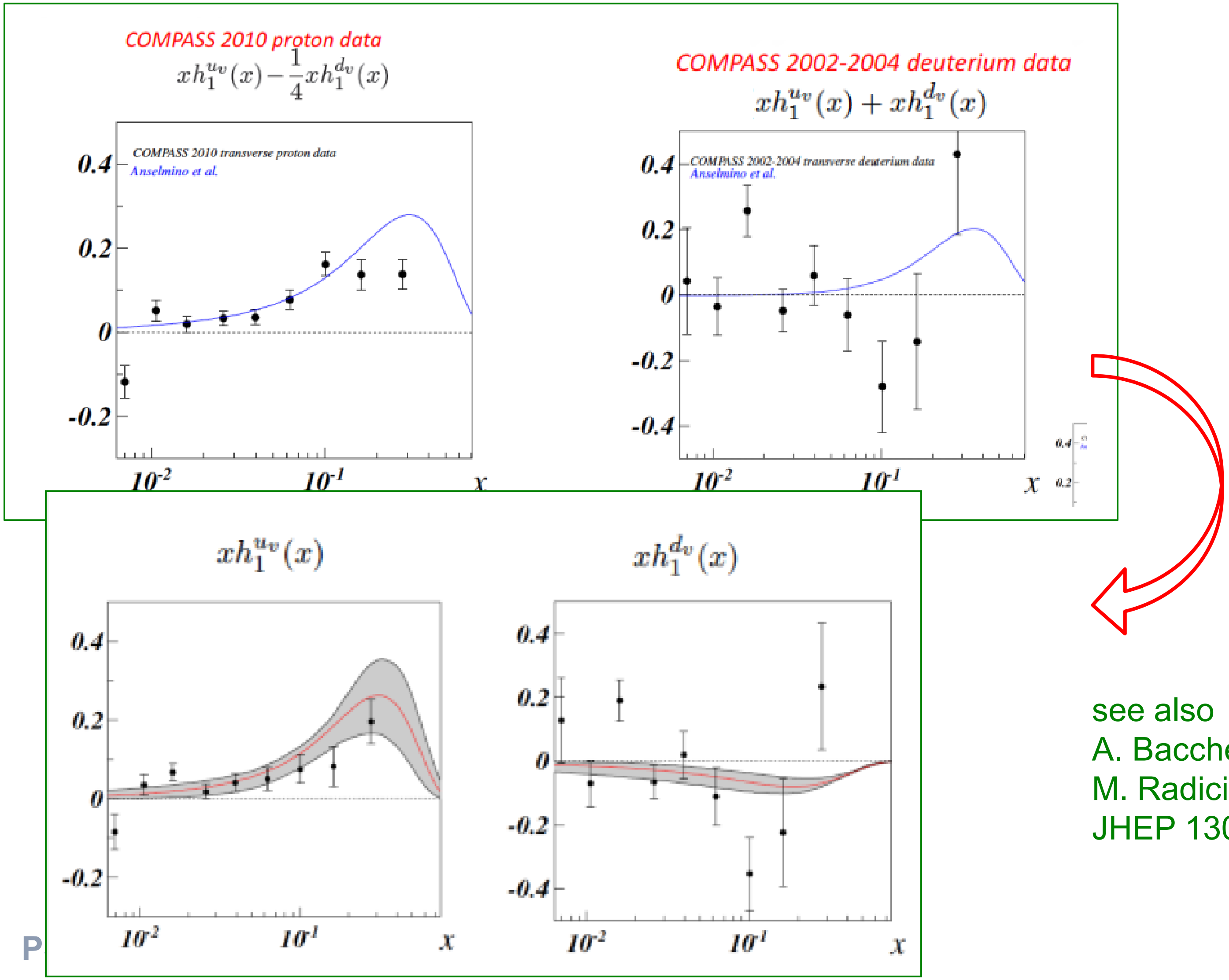
hadron pair multiplicities

in M_{inv}, $z=z_1+z_2$, Q^2 bins



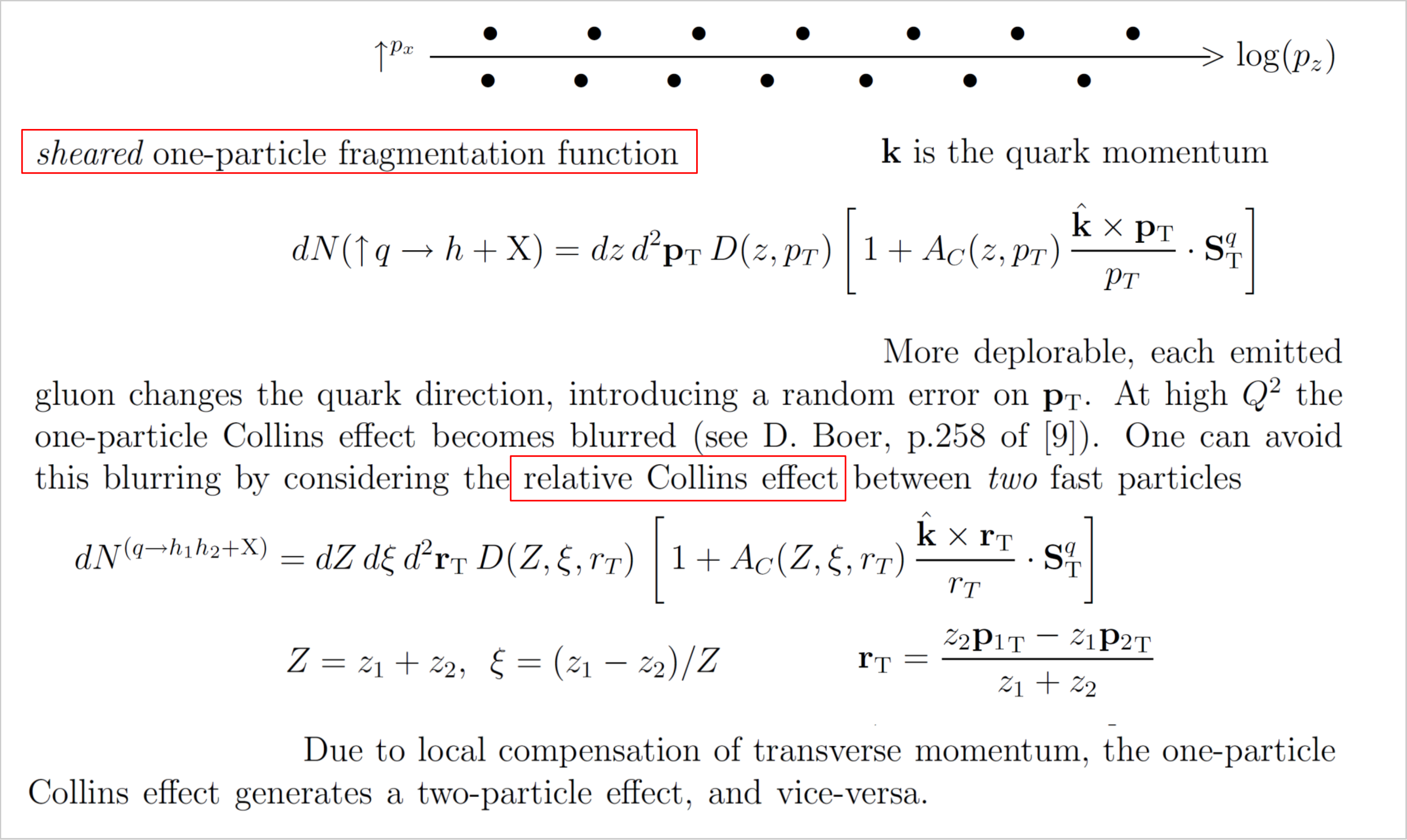
Two-hadron asymmetry

from C. Elia PhD thesis (2012), following A. Bacchetta, A. Courtoy, M. Radici PRL 107 (2011) 012001



see also
A. Bacchetta, A. Courtoy,
M. Radici
JHEP 1303 (2013) 119

Collins and two-hadron asymmetries



$\uparrow p_x$ $\longrightarrow \log(p_z)$

sheared one-particle fragmentation function

k is the quark momentum

$$dN(\uparrow q \to h + \mathrm{X}) = dz\, d^2\mathbf{p}_\mathrm{T}\, D(z, p_T) \left[1 + A_C(z, p_T) \frac{\hat{\mathbf{k}} \times \mathbf{p}_\mathrm{T}}{p_T} \cdot \mathbf{S}^q_\mathrm{T} \right]$$

More deplorable, each emitted gluon changes the quark direction, introducing a random error on $\mathbf{p}_\mathrm{T}$. At high Q^2 the one-particle Collins effect becomes blurred (see D. Boer, p.258 of [9]). One can avoid this blurring by considering the relative Collins effect between *two* fast particles

$$dN^{(q \to h_1 h_2 + \mathrm{X})} = dZ\, d\xi\, d^2\mathbf{r}_\mathrm{T}\, D(Z, \xi, r_T) \left[1 + A_C(Z, \xi, r_T) \frac{\hat{\mathbf{k}} \times \mathbf{r}_\mathrm{T}}{r_T} \cdot \mathbf{S}^q_\mathrm{T} \right]$$

$$Z = z_1 + z_2, \quad \xi = (z_1 - z_2)/Z \qquad \mathbf{r}_\mathrm{T} = \frac{z_2 \mathbf{p}_{1\mathrm{T}} - z_1 \mathbf{p}_{2\mathrm{T}}}{z_1 + z_2}$$

Due to local compensation of transverse momentum, the one-particle Collins effect generates a two-particle effect, and vice-versa.

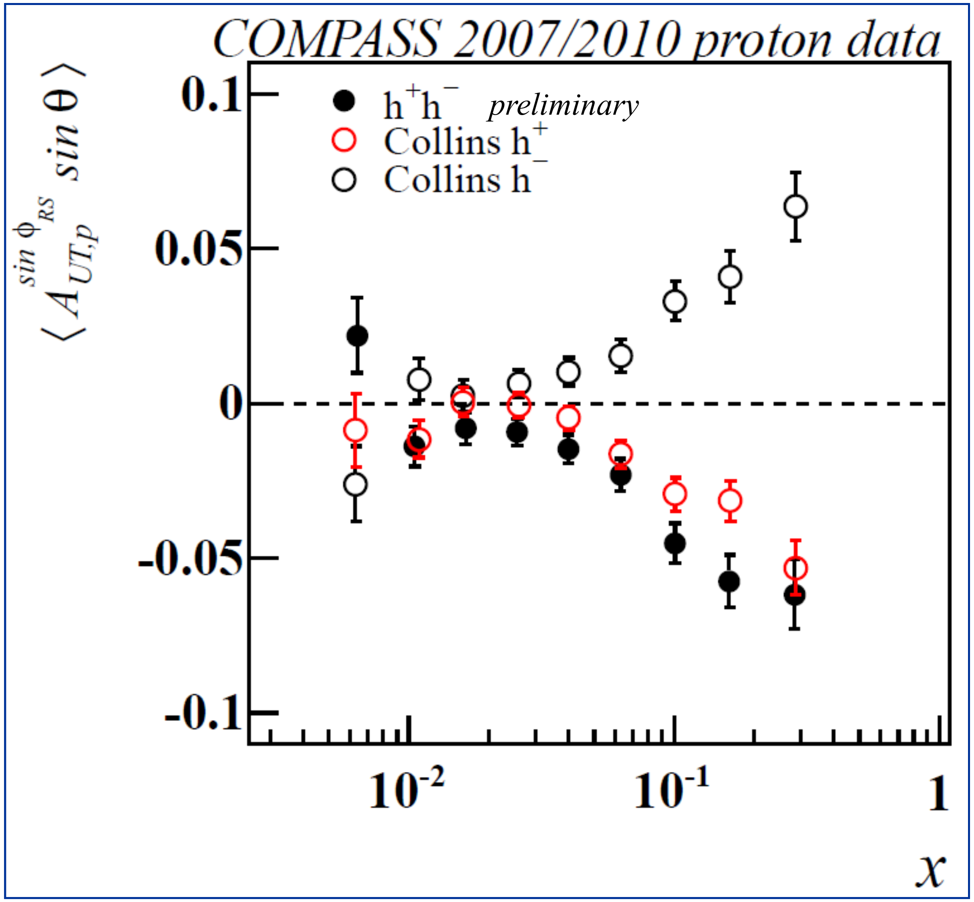
X. Artru, arXiv:hep-ph/0207309

dihadron asymmetry and Collins asymmetries

remarkable similarity between

- **Collins asymmetry for h+ and Collins asymmetry for h-**
  "mirror symmetry": similar absolute values, opposite sign
- **dihadron asymmetry and Collins asymmetries**
  same sign as Collins h+, only somewhat larger than the mean of Collins h+ and – Collins h- (as expected)

  here measured on different hadron samples, ~ the same on the "common" hadron sample



dihadron asymmetry and Collins asymmetries

remarkable similarity between dihadron asymmetry and Collins asymmetries

stays ~ the same when the asymmetries are evaluated on

a common hadron sample

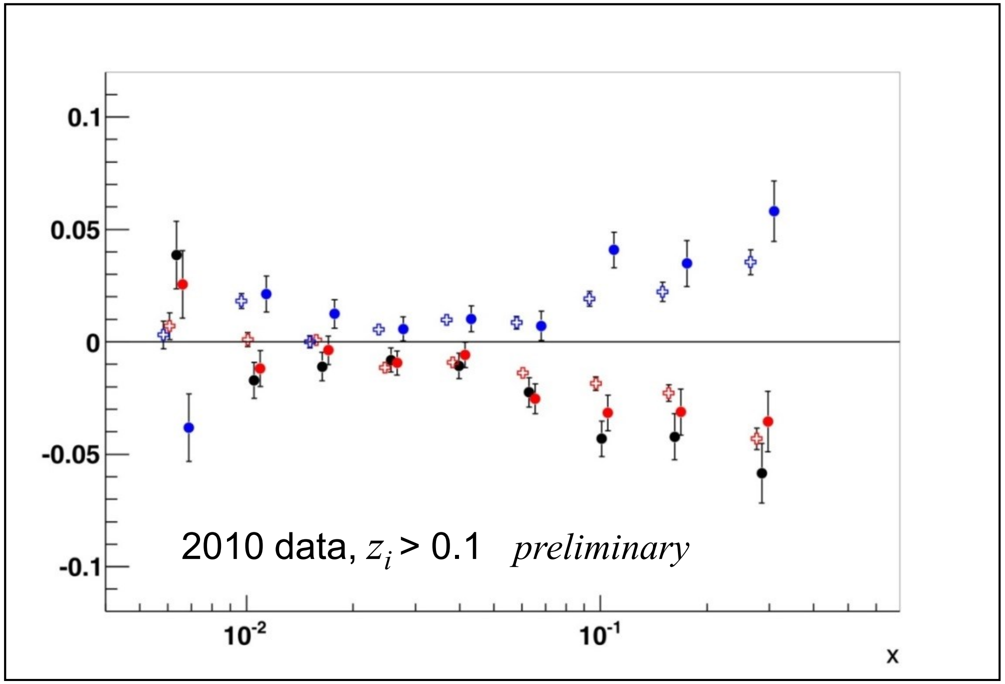
i.e.

- events which contain at least one positive hadron and at least one negative hadron
- for each event the number of hadrons is the number of h+h− pairs, as defined in the two-hadron analysis
- $p^h{}_T$ > 0.1 GeV/c and R_T > 0.07 GeV/c
- same z_i cut (two sets of data: z_i > 0.1 and z_i > 0.2)

dihadron asymmetry and Collins asymmetries

remarkable similarity between dihadron asymmetry and Collins asymmetries

stays ~ the same when the asymmetries are evaluated on a common hadron sample



h+ / h-

✚ ✚ Collins asymmetry "standard sample"

● ● Collins asymmetry "common sample"

h+h-

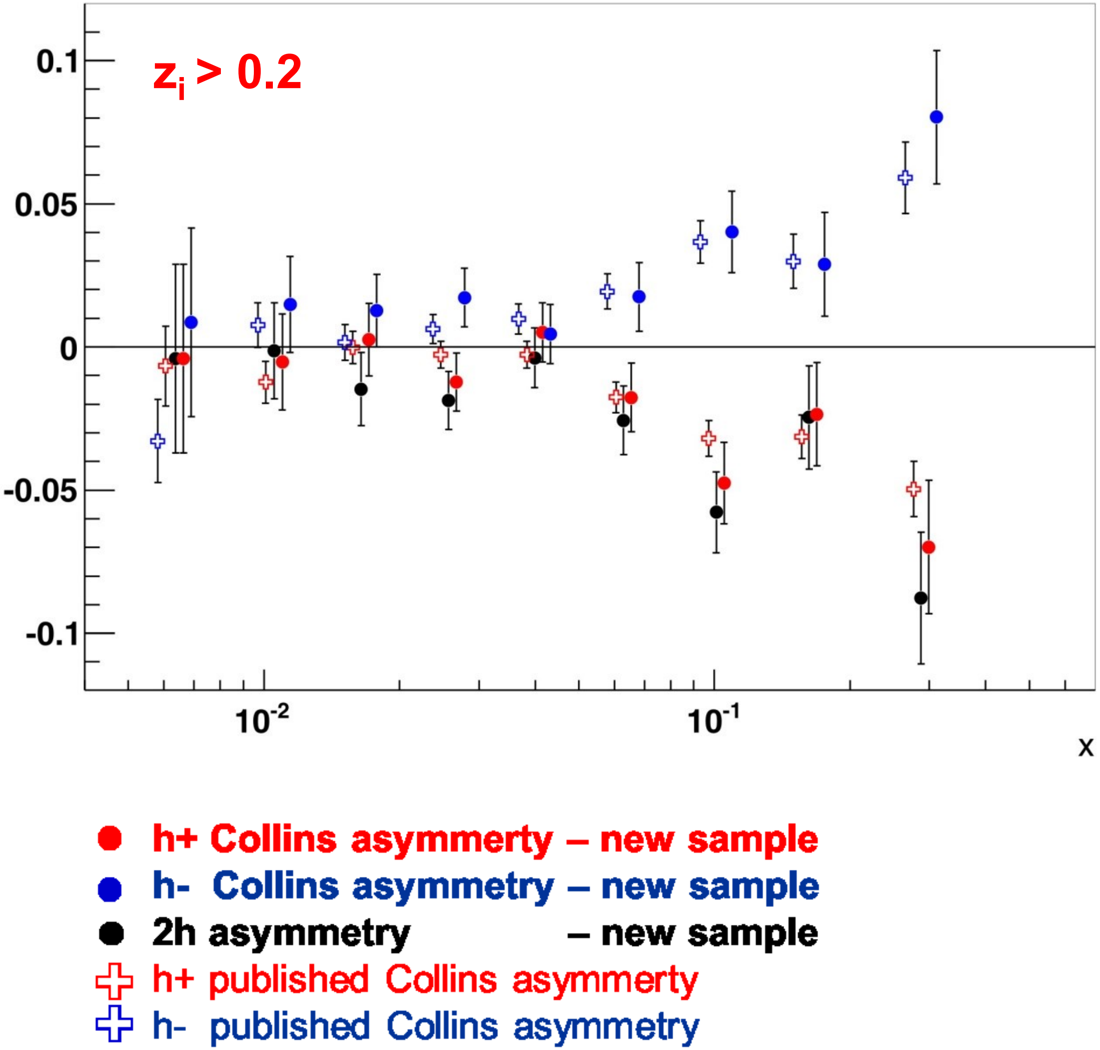
● dihadron asymmetry "common sample"

somehow larger, as expected

also, from the comparison of the asymmetries
→ information on the relative value of the two analyzing powers

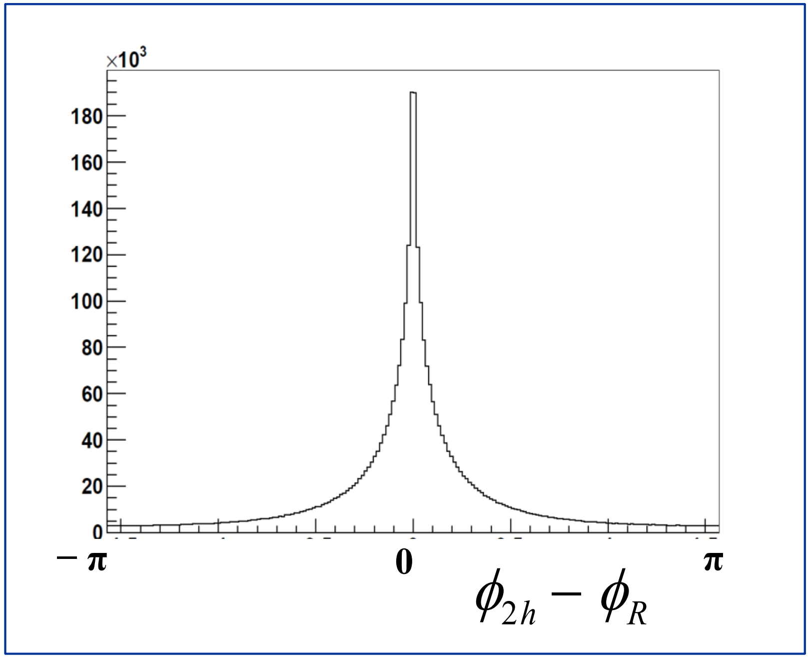
Collins and two-hadron asymmetries

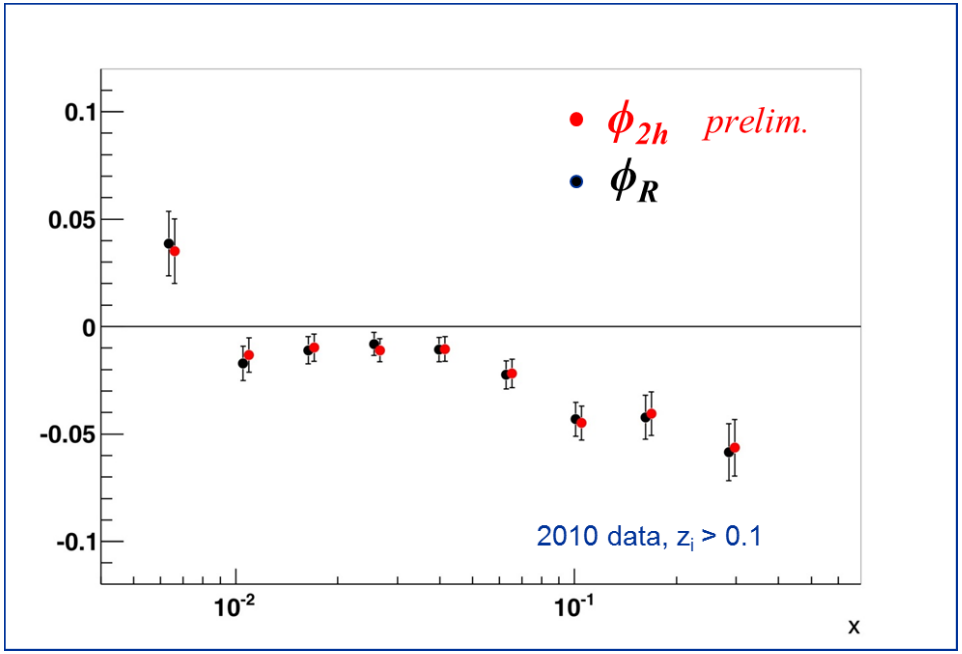
2. Collins and 2h asymmetries from the same hadron sample



Collins and two-hadron asymmetries

1. correlations between the relevant azimuthal angles and the corresponding asymmetries





… Due to local compensation of transverse momentum, the one-particle Collins effect generates a two-particle effect, and viceversa. … (X. Artru, arXiv:hep-ph/0207309)