# Transverse Spin and Transverse Momentum Structure of the Nucleon

## from the COMPASS Experiment

**Franco Bradamante**

*Trieste University*

on behalf of the
**COMPASS Collaboration**

# TRANSVERSITY

## one of the main goals of COMPASS

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

$q(x)$ : number density or unpolarised distribution — $f_1^q(x)$

$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$ : longitudinal polarization or helicity distribution — $g_1^q(x)$

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

**ALL OF EQUAL IMPORTANCE !**

# Transversity

- **proposed in '77** (Ralston & Soper)
- **different properties than helicity, more difficult to measure**
- **convincing evidence that it is non zero only recently in SIDIS from the HERMES and the COMPASS experiments**

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

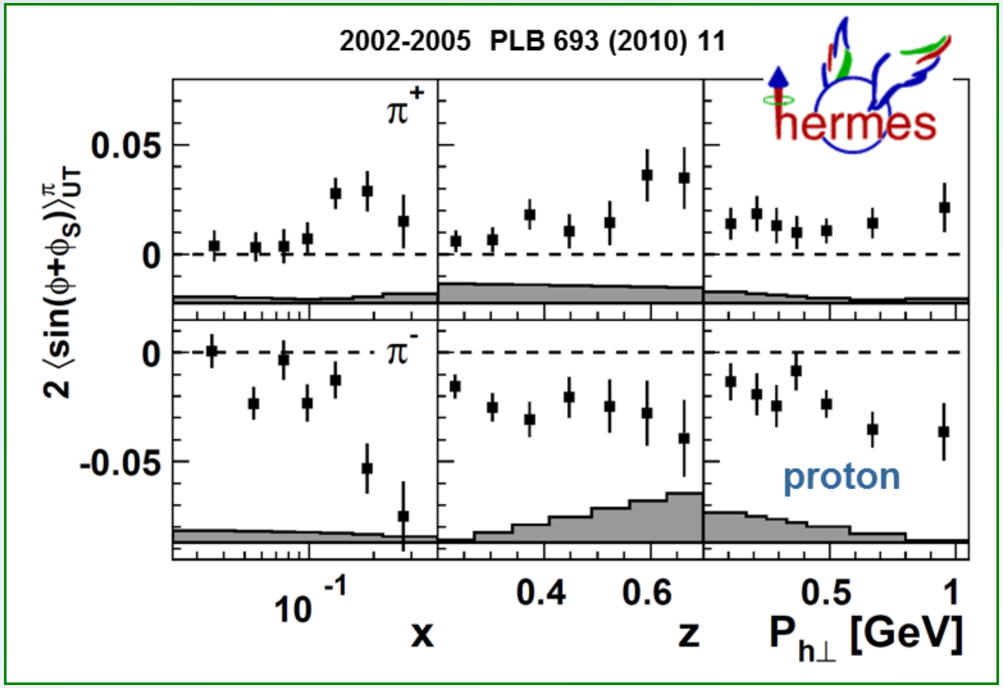
**"Collins FF"**
left-right asymmetry in the hadronization of a transversely polarized quark

$$A_{Coll} \approx \frac{\sum_q e_q^2 \;\; h_1^q \otimes H_1^{\perp q}}{\sum_q e_q^2 \; f_1 \otimes D_1^q}$$

# Transversity

## SIDIS results

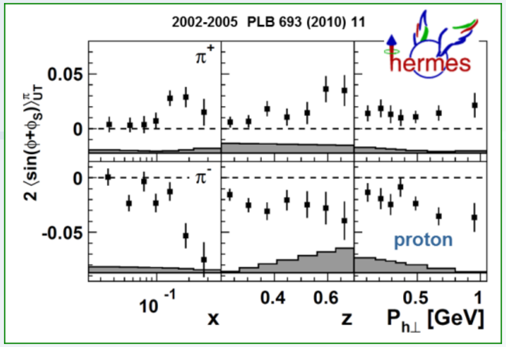
- clear non-zero effects first seen by HERMES on p

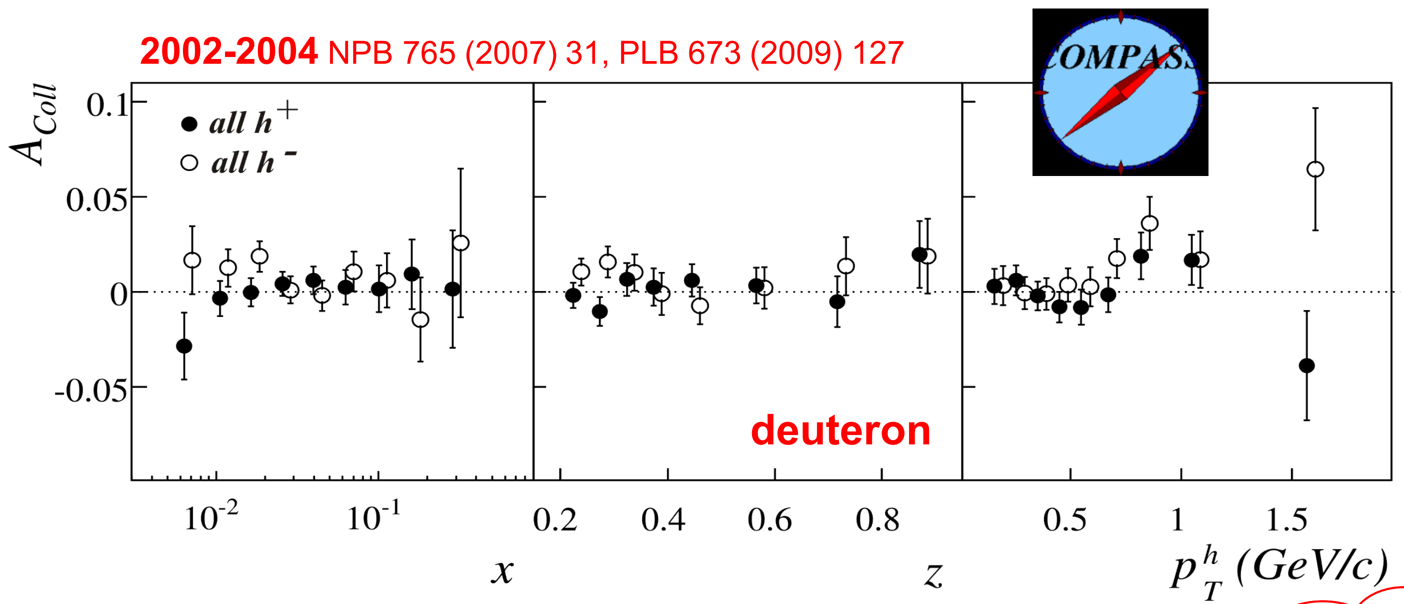


# Transversity

## SIDIS results

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




still only measurements on d !

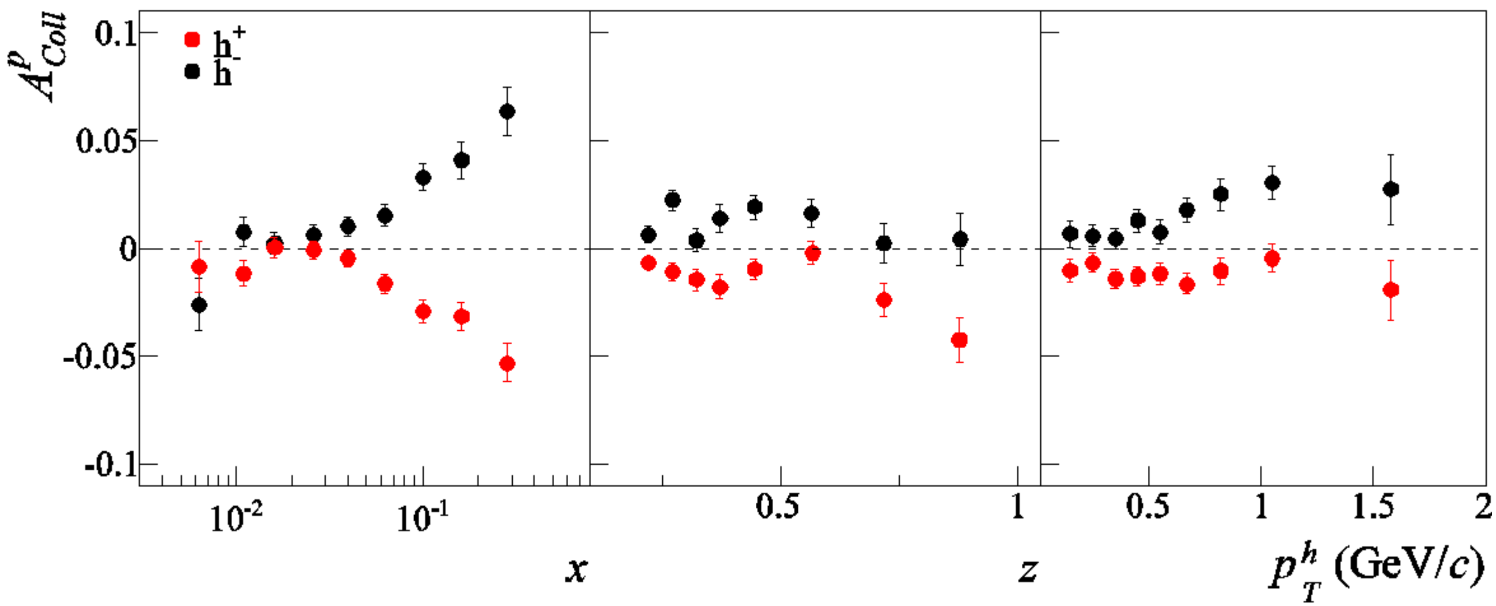
and understood as u – d cancellation

→ $\boxed{h_1^u \approx -h_1^d}$ $\boxed{H_1^{\perp fav} \approx -H_1^{\perp unf}}$

# Transversity

## COMPASS results on proton target (2007, 2010 data)

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

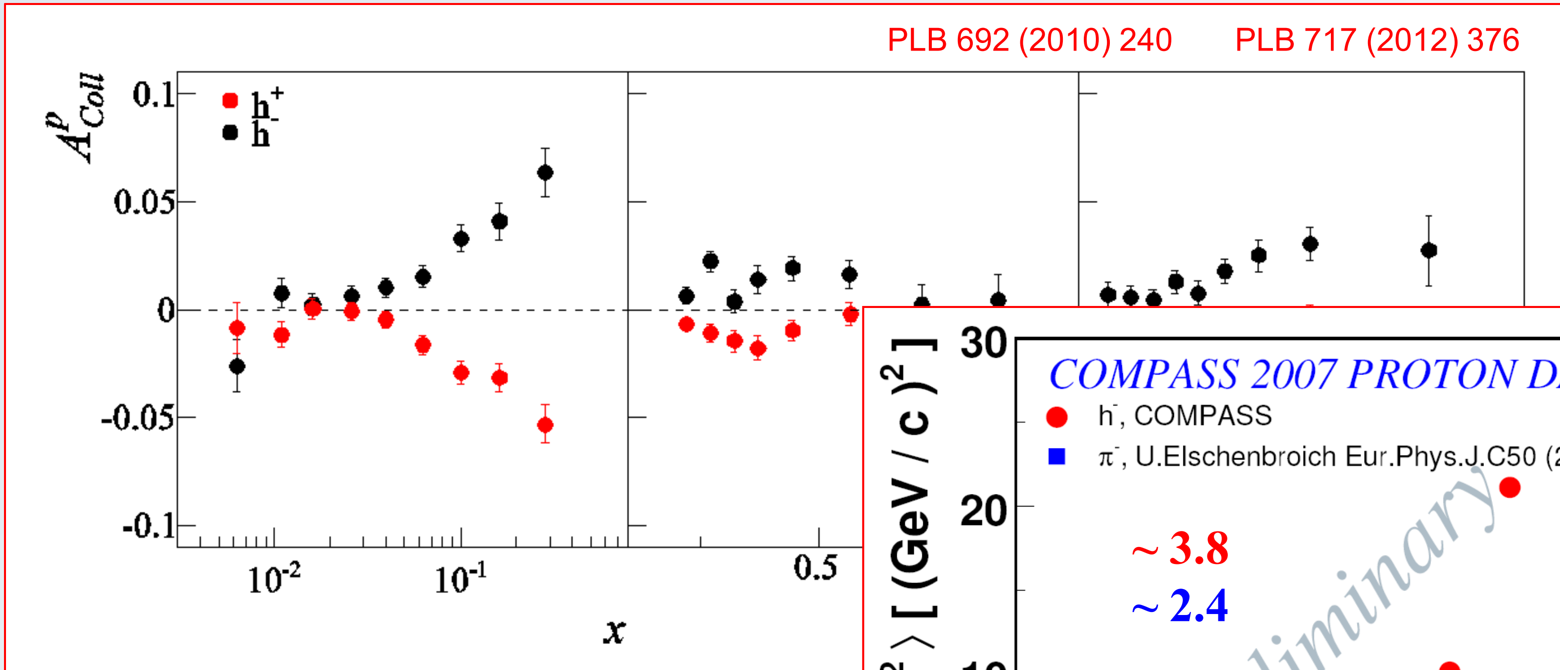


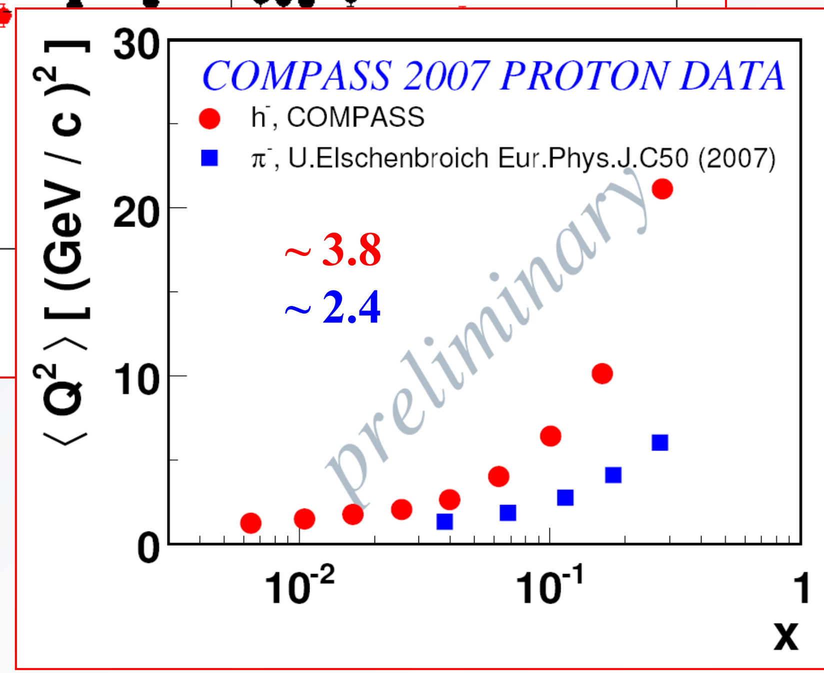

- **good agreement with HERMES in the $x$ overlap region**

  ***same for pions and kaons***

# Transversity

## COMPASS results on proton target  (2007, 2010 data)




- good agreement with HERMES in the $x$ overlap region

- quite different $Q^2$ and W ranges
  → information on Q2 evolution

# Transversity

**conclusion:**

**transversity is different from zero and**

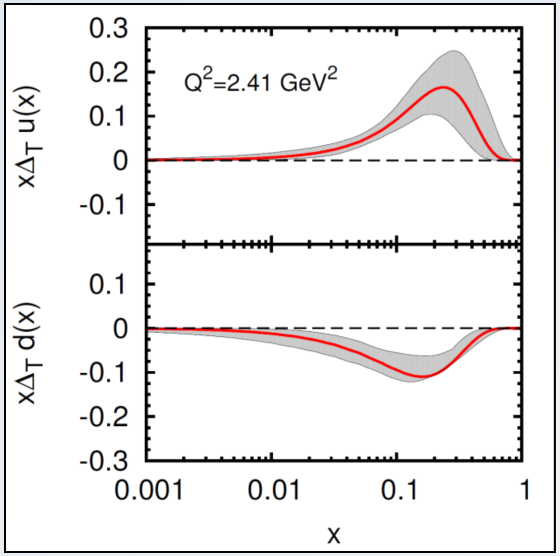
**can be measured in SIDIS thanks to the “Collins effect”**

# Transversity

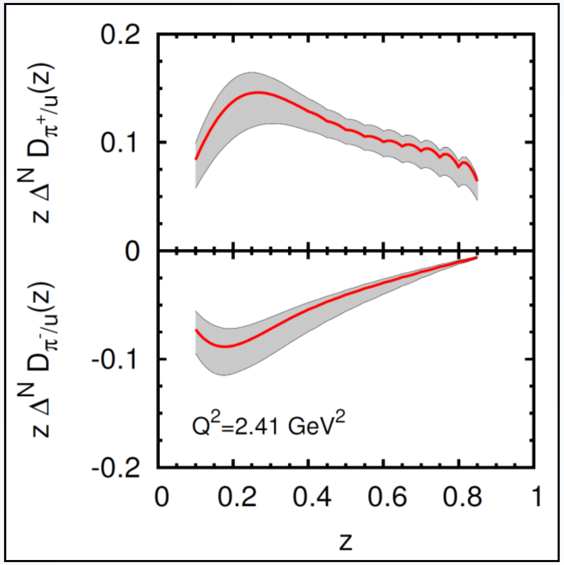
**conclusion:**

**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 $A_0$ data** **very good $\chi^2$**

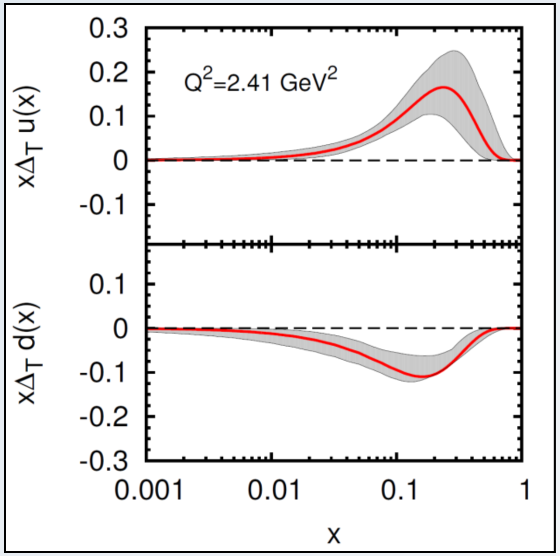


# Transversity

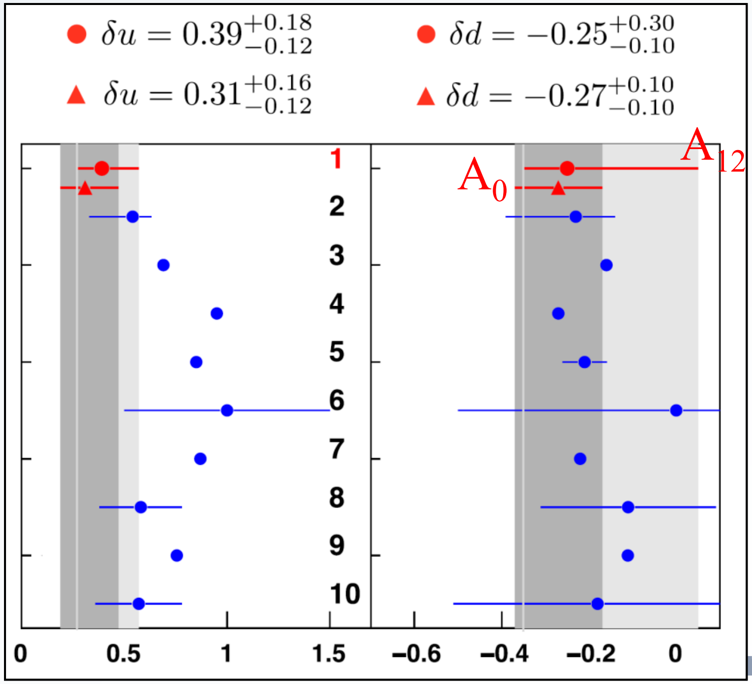
**conclusion:**

**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 $A_0$ data** **very good $\chi^2$**




2009

Bacchetta et al, 2012

model calculations

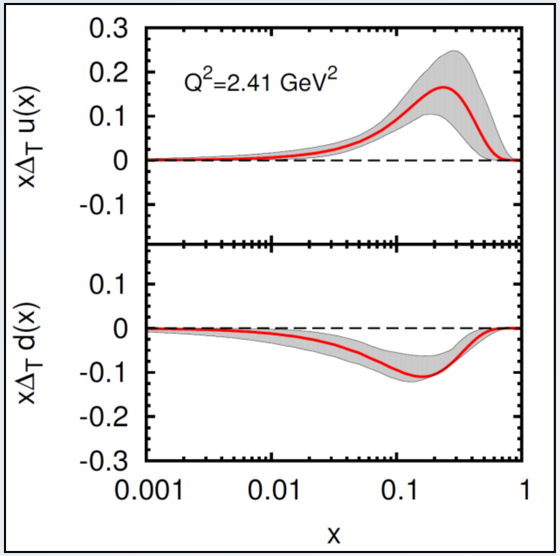
**the work has started !**

# Transversity

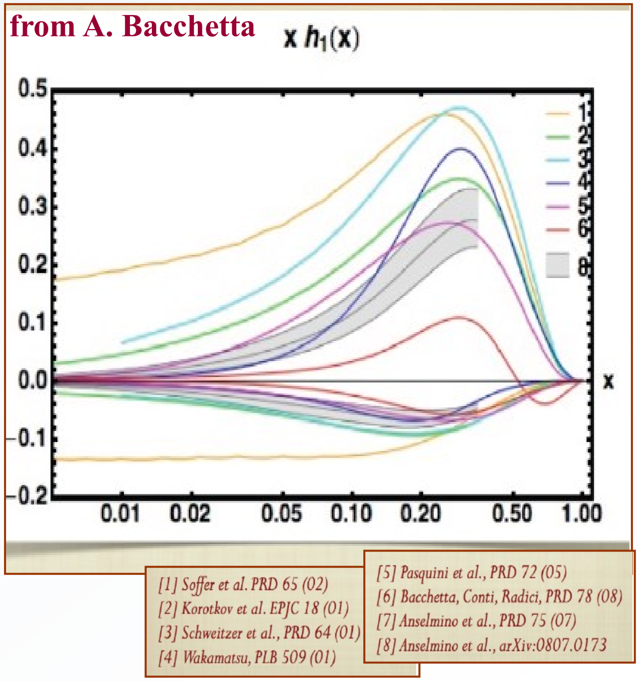
**conclusion:**

**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 $A_0$ data** **very good $\chi^2$**




**more data - large and small $x$, p & d / n -**
**are needed to map the**
**$Q^2$, $z$ and $p_T$ dependence**

# Two-hadron asymmetry

## independent channel to access transversity

# Two-hadron asymmetry

## independent channel to access transversity

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

$$\boxed{N^{\pm}(\phi_{RS}) = N^0 \cdot \{1 \pm A \cdot \sin\phi_{RS}\}}$$

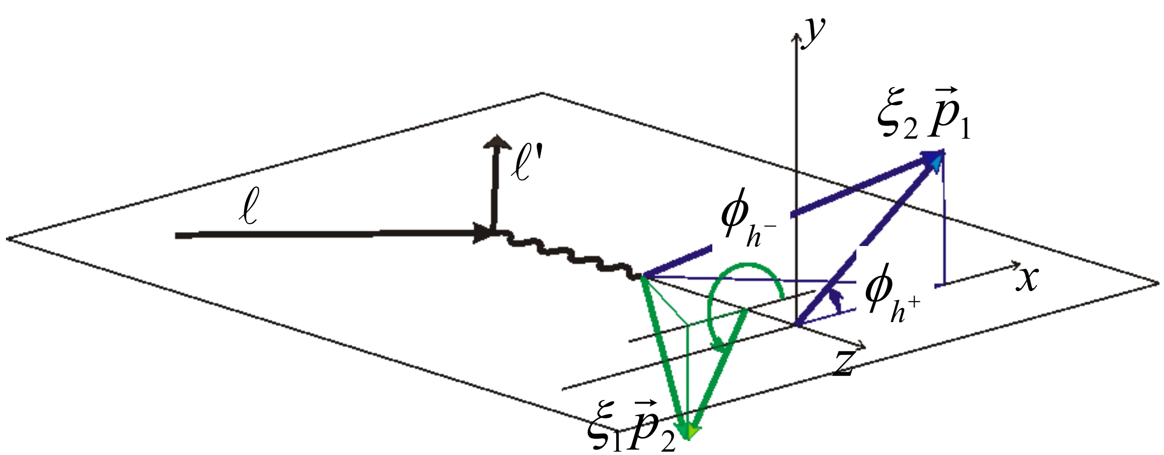
$$\boldsymbol{R} = \frac{z_2 \boldsymbol{p_1} - z_1 \boldsymbol{p_2}}{z_1 + z_2} =: \xi_2 \boldsymbol{p_1} - \xi_1 \boldsymbol{p_2}$$

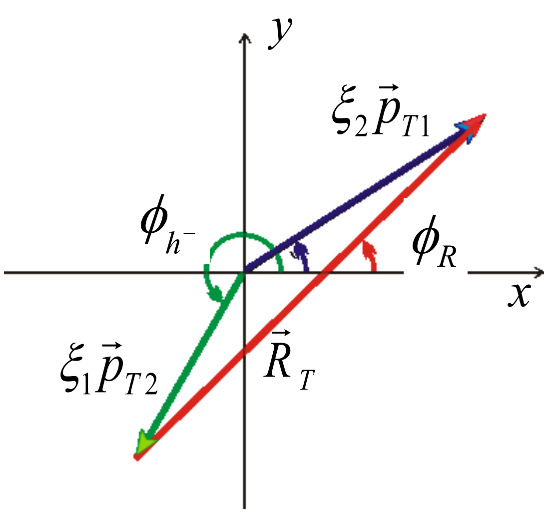
$$\phi_R = \frac{(\boldsymbol{q} \times \boldsymbol{l}) \cdot \boldsymbol{R}}{|(\boldsymbol{q} \times \boldsymbol{l}) \cdot \boldsymbol{R}|} \arccos\left(\frac{(\boldsymbol{q} \times \boldsymbol{l}) \cdot (\boldsymbol{q} \times \boldsymbol{R})}{|\boldsymbol{q} \times \boldsymbol{l}||\boldsymbol{q} \times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

note: $\boldsymbol{q}$ x $\boldsymbol{R}$ → the same as $\boldsymbol{q}$ x $\boldsymbol{R_T}$

*A. Bacchetta, M. Radici, hep-ph/0407345*

*X. Artru, hep-ph/0207309*



# Two-hadron asymmetry

## independent channel to access transversity

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

$$N^{\pm}(\phi_{RS}) = N^0 \cdot \{1 \pm A \cdot \sin\phi_{RS}\}$$

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

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

note: $\boldsymbol{q} \times \boldsymbol{R}$ → the same as $\boldsymbol{q} \times \boldsymbol{R}_T$

*A. Bacchetta, M. Radici, hep-ph/0407345*

*X. Artru, hep-ph/0207309*

**"Interference / Di-hadron FF"**

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

from Belle and Babar

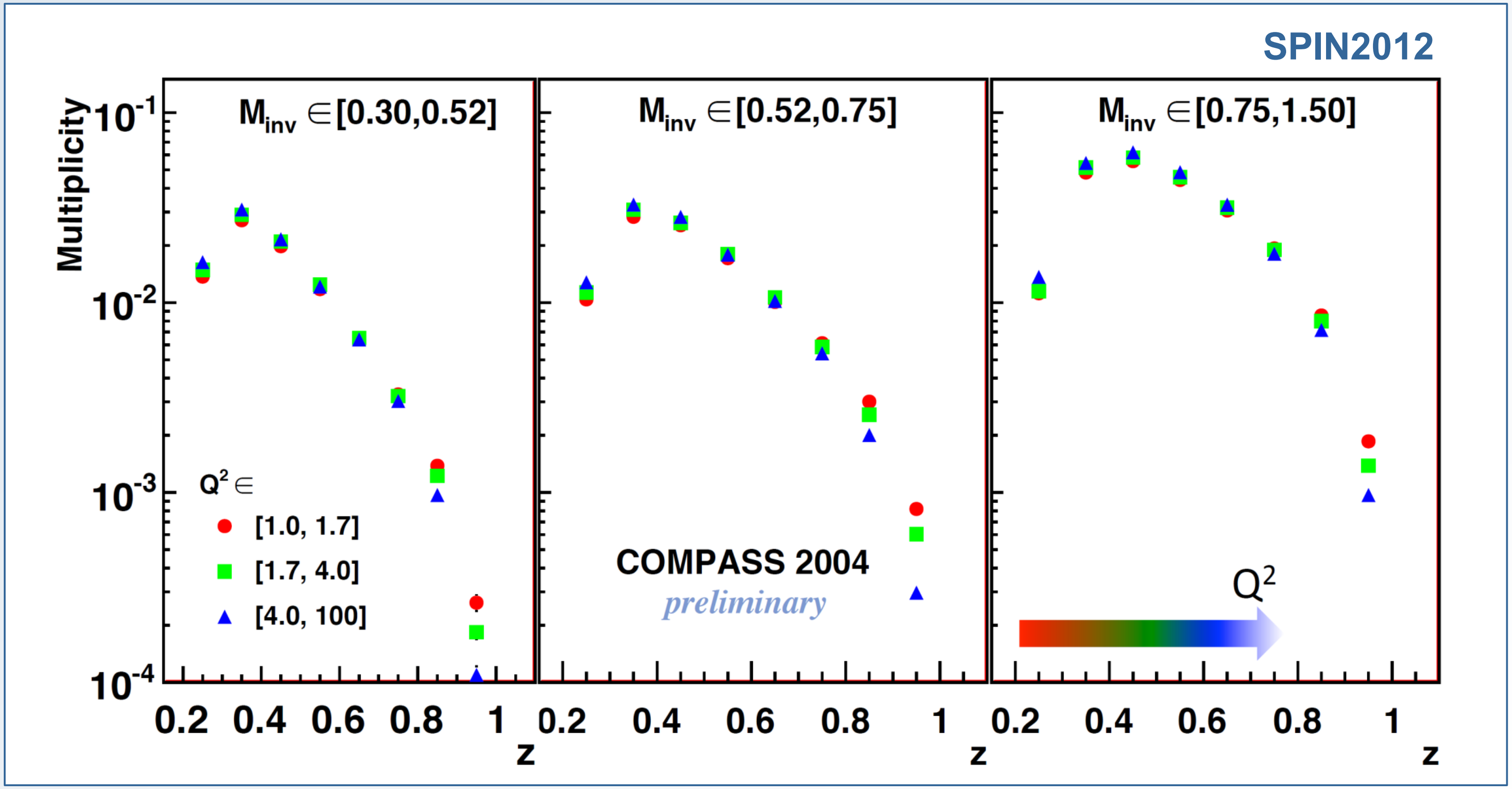
from Belle and Babar

**being measured at COMPASS**

# hadron multiplicities in SIDIS

## hadron pair multiplicities

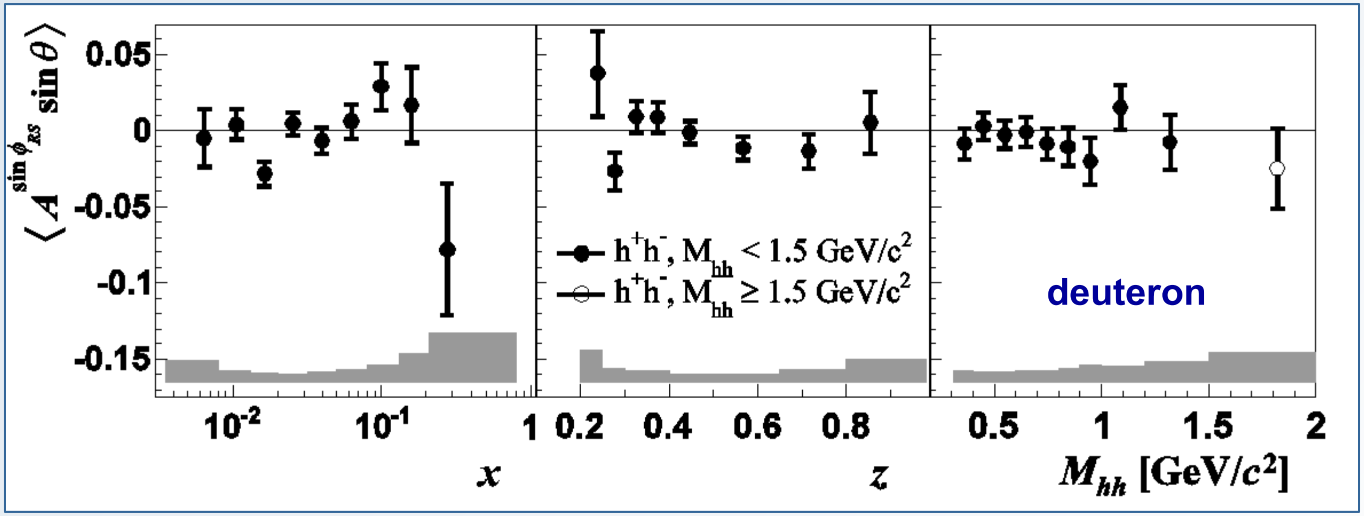
## in $M_{inv}$, $z=z_1+z_2$, $Q^2$ bins



# Two-hadron asymmetry

**all d data**

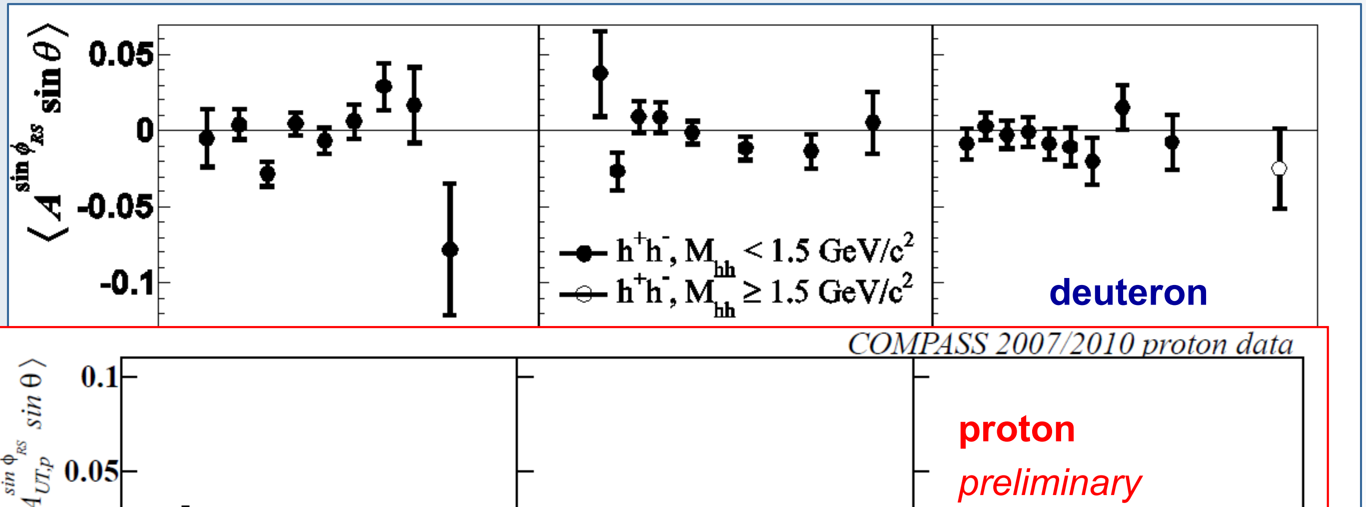
PLB 713 (2012) 10



# Two-hadron asymmetry

**all d data**

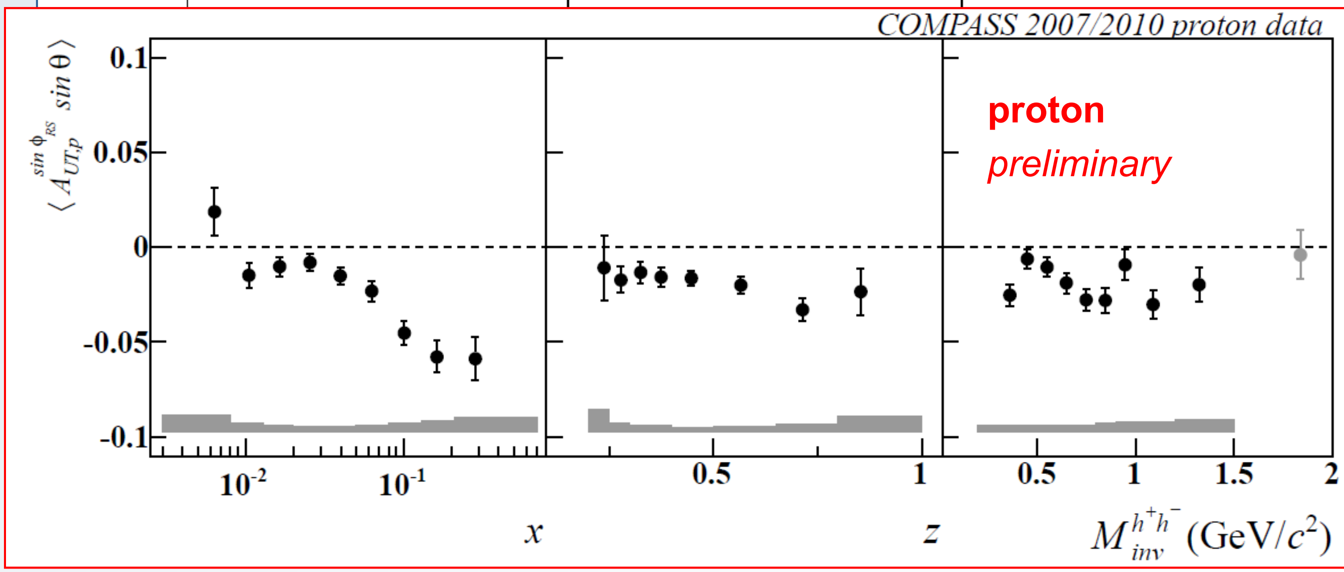
PLB 713 (2012) 10




**all p data**

PLB 713 (2012) 10

Transversity 2011

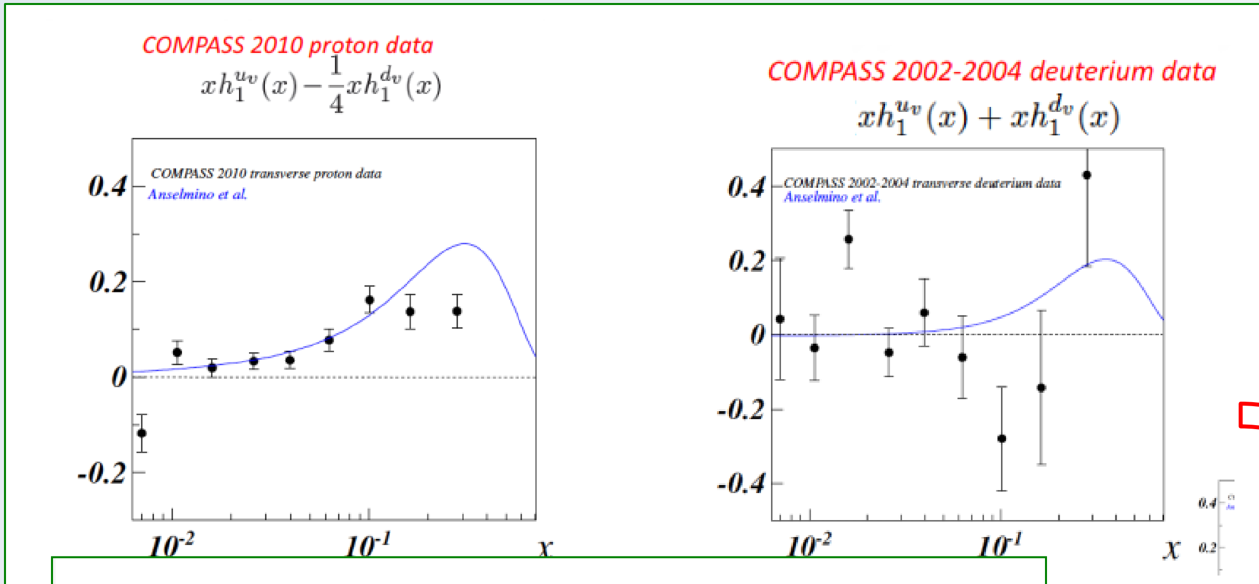


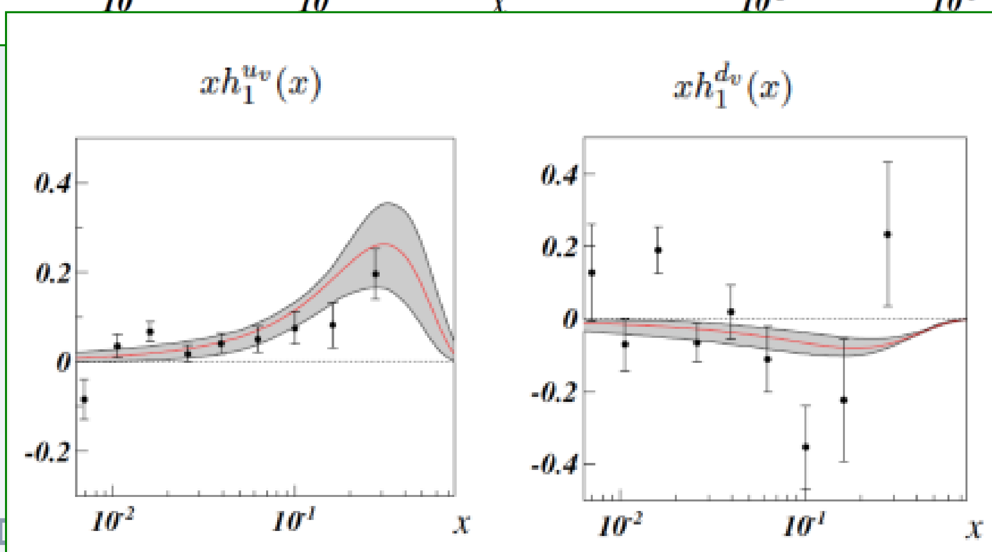

**high statistics over a wide x range**

**p & d data → extraction of transversity for u & d**

# 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

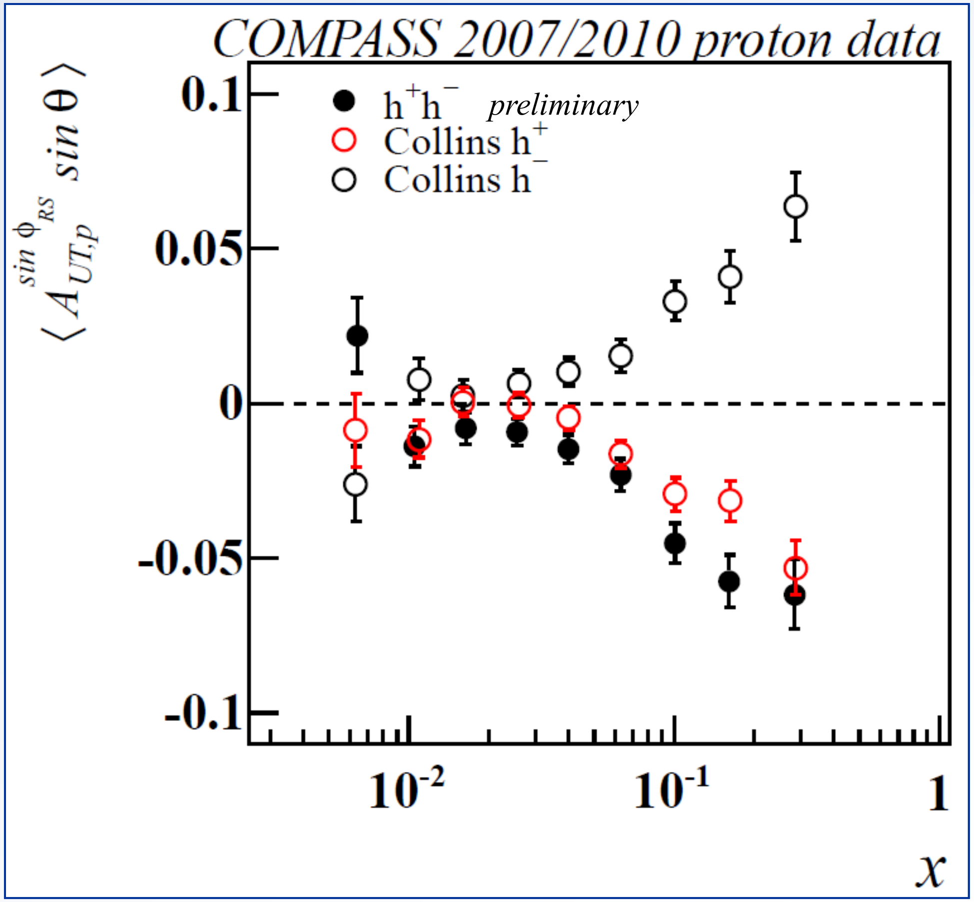
# Interplay between

# Collins and two-hadron asymmetries

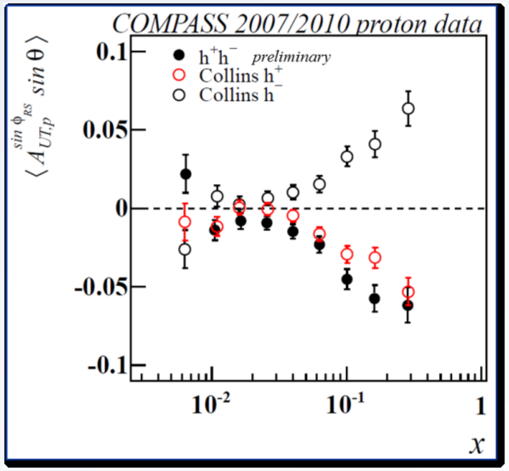
# Interplay between

# Collins and two-hadron asymmetries

remakable similarity among
Collins asymmetry for h+,
Collins asymmetry for h-
and hadron pair asymmetry



# Interplay between
# Collins and two-hadron asymmetries




first investigations

1. correlations between
   the relevant azimuthal angles and
   the corresponding asymmetries
   → information on the nature of the fragmentation
   Collins vs 2h interference mechanisms

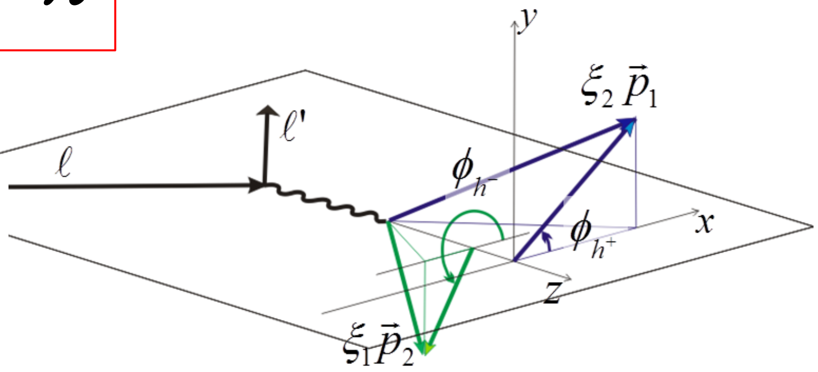
2. Collins and two-hadron asymmetries from the same hadron sample
   → information on the ratio of the analysing powers
   convolution over transvers moment and Collins FF vs IFF

# relevant angles

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

$$\boldsymbol{R} = \frac{z_2 \boldsymbol{p_1} - z_1 \boldsymbol{p_2}}{z_1 + z_2} =: \xi_2 \boldsymbol{p_1} - \xi_1 \boldsymbol{p_2}$$

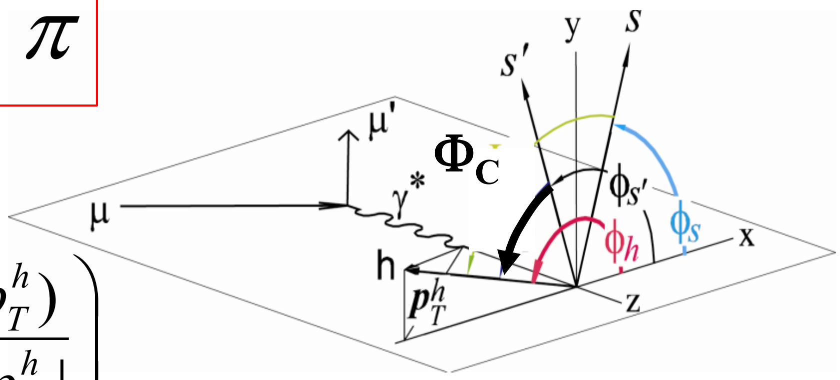
$$\phi_R = \frac{(\boldsymbol{q} \times \boldsymbol{l}) \cdot \boldsymbol{R}}{|(\boldsymbol{q} \times \boldsymbol{l}) \cdot \boldsymbol{R}|} \arccos\left(\frac{(\boldsymbol{q} \times \boldsymbol{l}) \cdot (\boldsymbol{q} \times \boldsymbol{R})}{|\boldsymbol{q} \times \boldsymbol{l}||\boldsymbol{q} \times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




note: $\boldsymbol{q}$ x $\boldsymbol{R}$ → the same as $\boldsymbol{q}$ x $\boldsymbol{R_T}$

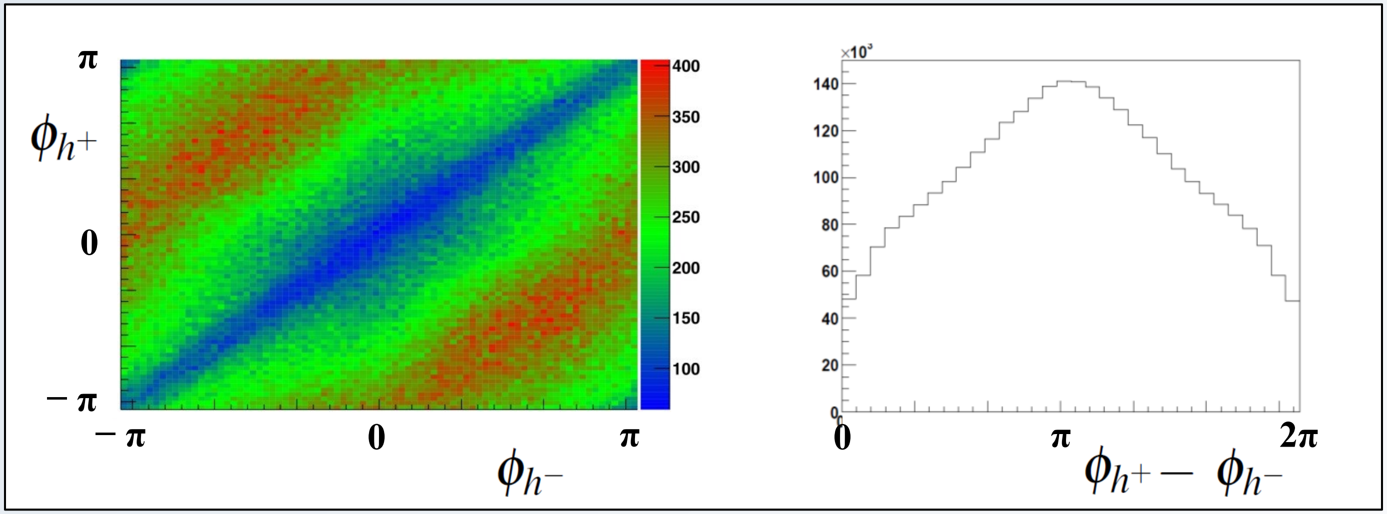
$$\boxed{\phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi}$$

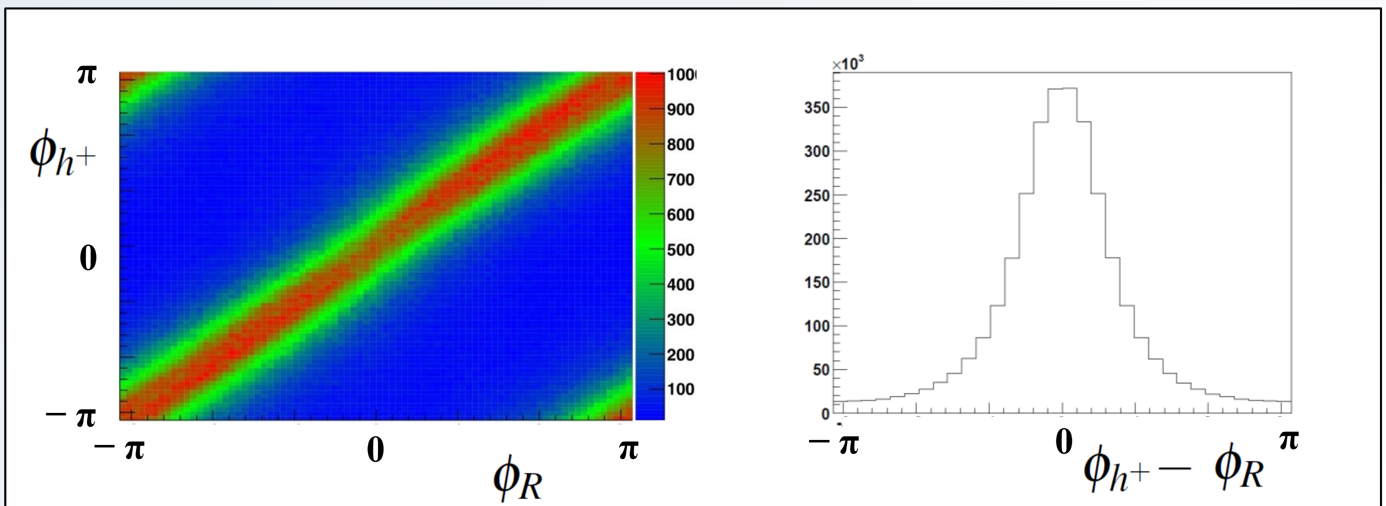
$$\phi_h = \frac{(q \times l) \cdot p_T^h}{|(q \times l) \cdot p_T^h|} \arccos\left(\frac{(q \times l) \cdot (q \times p_T^h)}{|(q \times l)||q \times p_T^h|}\right)$$



# Collins and two-hadron asymmetries

## 1. correlations between the relevant azimuthal angles




**same with unpolarised Lepto**

# Collins and two-hadron asymmetries

## 1. correlations between the relevant azimuthal angles

interesting because

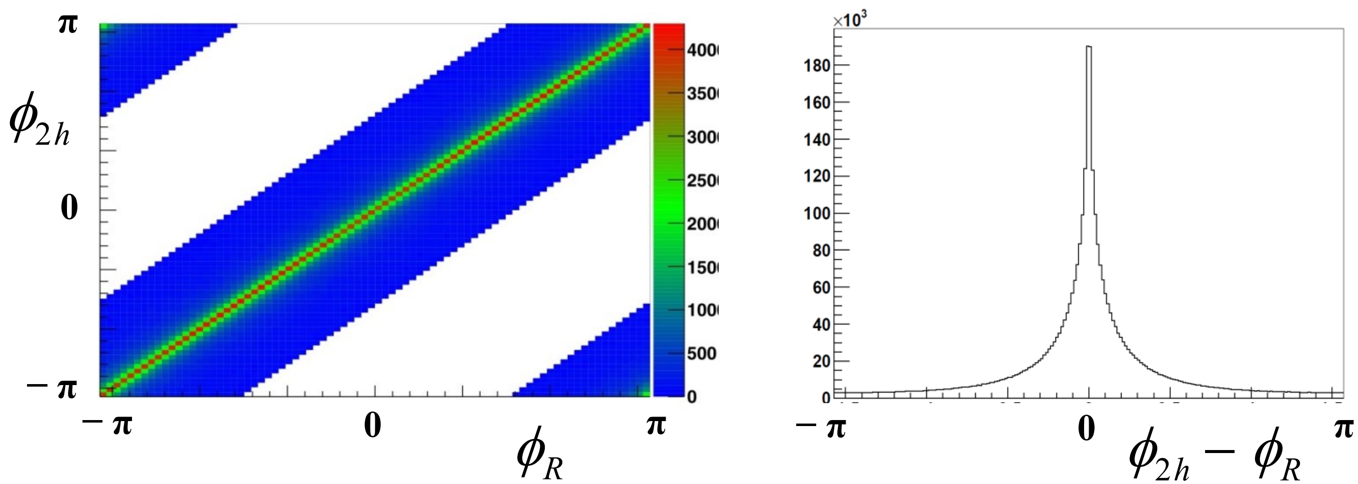
$$\phi_{2h} = \frac{\phi_{h^+} + (\phi_{h^-} - \pi)}{2}$$

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

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

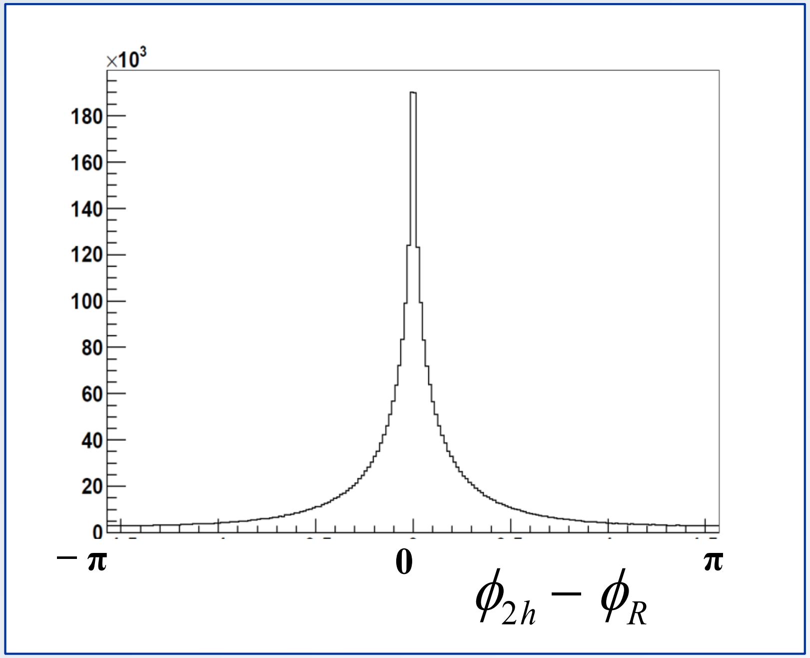
$$\phi_{2h} - \phi_{S'} = [\phi_{h^+} - \phi_{S'} + (\phi_{h^-} - \phi_{S'} - \pi)]/2$$
$$= [\phi_{C+} + (\phi_{C-} - \pi)]/2 = \phi_{C2h}$$

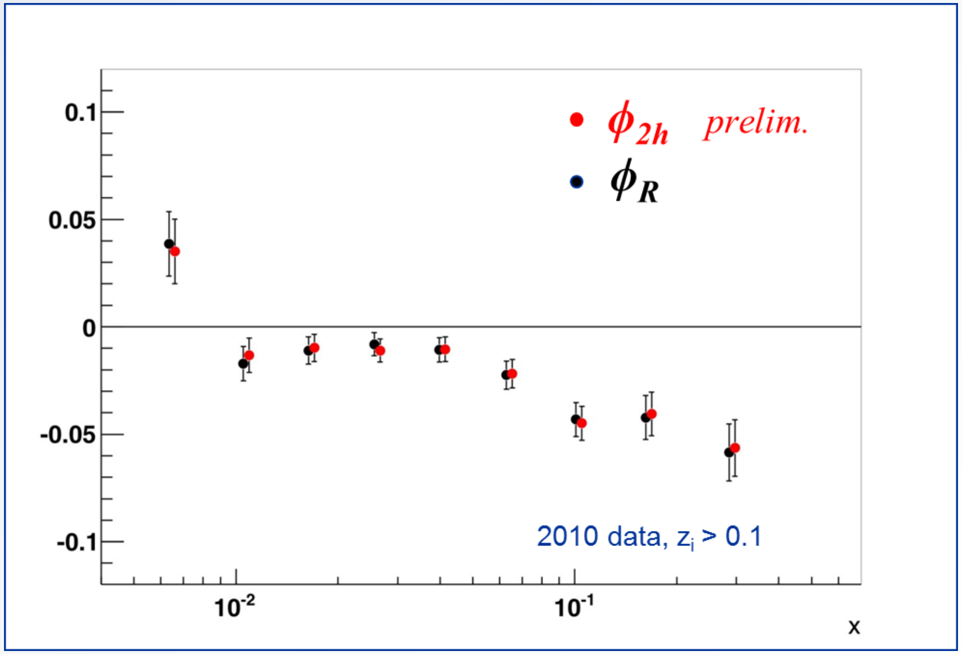
very simple !



# 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)

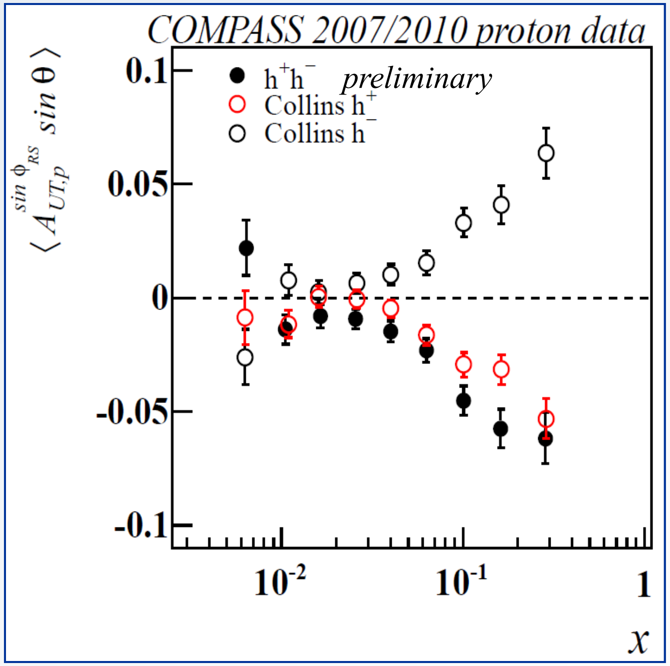
# Collins and two-hadron asymmetries

## 2. Collins and two-hadron asymmetries from the same hadron sample

remakable similarity among Collins asymmetry for h+, Collins asymmetry for h- and hadron pair asymmetry

but

the used data samples are different



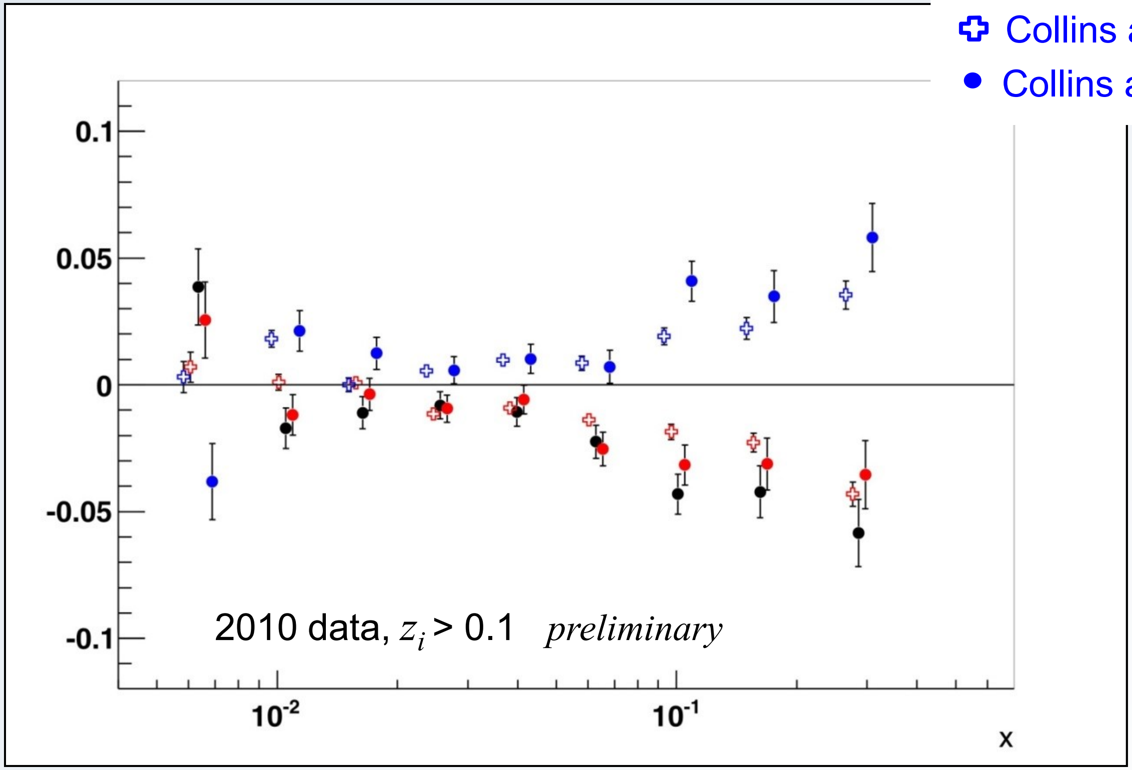

→ identification of common hadron samples for Collins and two-hadron analysis,

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)

# Collins and two-hadron asymmetries

## 2. Collins and two-hadron asymmetries from the same hadron sample




h-

- ✚ Collins asymmetry "standard sample"
- ● Collins asymmetry "common sample"

h+

- ✚ Collins asymmetry "standard sample"
- ● Collins asymmetry "common sample"

h+h-

- ● two-hadron asymmetry "common sample"

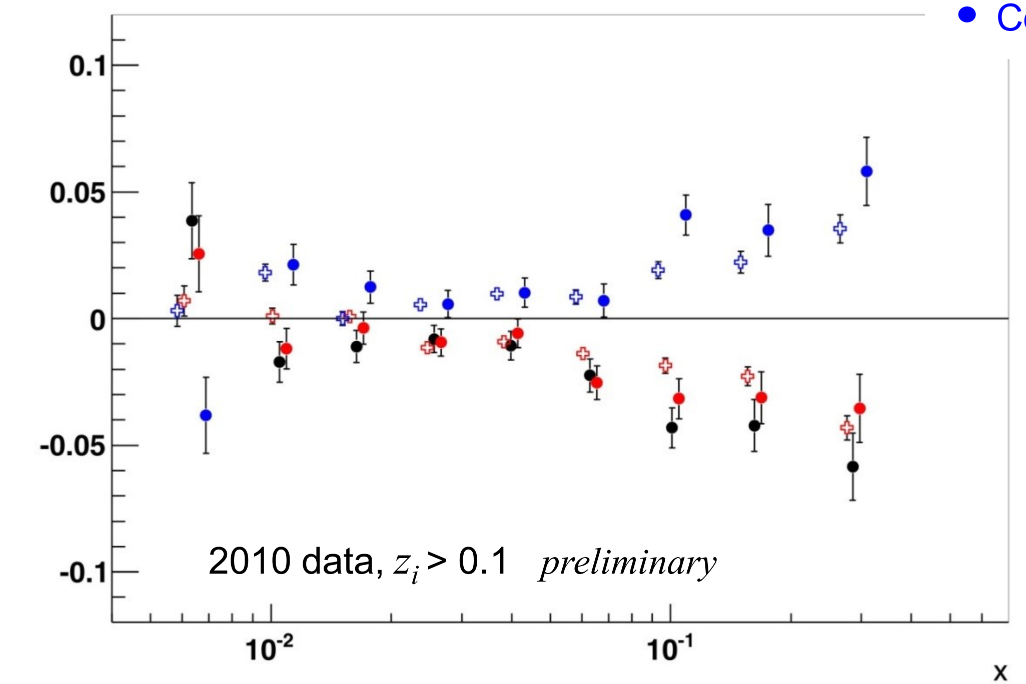
somehow larger, as expected

… each emitted gluon changes the quark direction, introducing a random error on $p_T$. At high $Q^2$ the one-particle Collins effect becomes blurred. One can avoid this blurring by considering the relative Collins effect between two fast particles of the jet. ….

(X. Artru, arXiv:hep-ph/0207309)

# Collins and two-hadron asymmetries

## 2. Collins and two-hadron asymmetries from the same hadron sample




h-

- Collins asymmetry "standard sample"
- Collins asymmetry "common sample"

h+

- Collins asymmetry "standard sample"
- Collins asymmetry "common sample"

h+h-

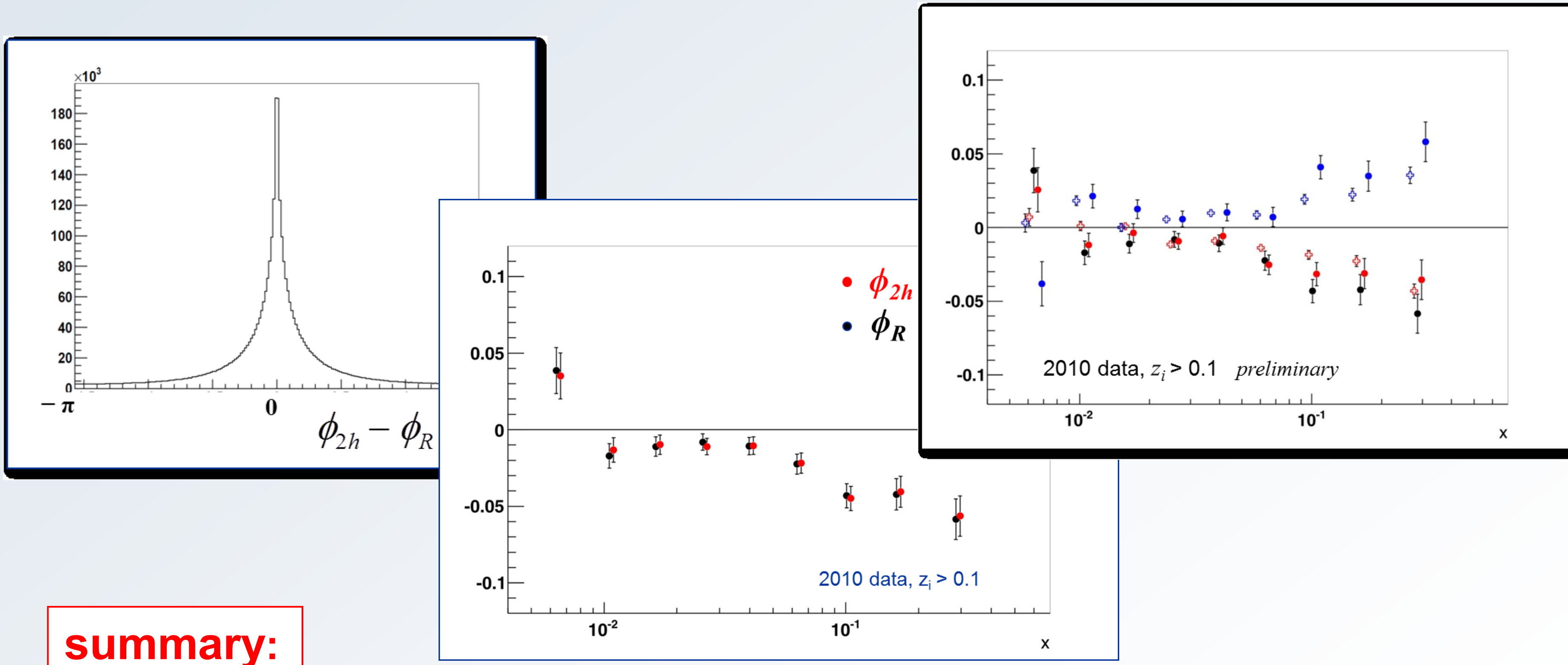
- two-hadron asymmetry "common sample"

somehow larger, as expected

from the comparison of the asymmetries
→ information on the contribution of the intrinsic transverse momentum,
or on the relative analysig powers

# Interplay between

# Collins and two-hadron asymmetries




**summary:**

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

# Nucleon Structure

**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*<br>$h_{1T}^{\perp}$ - |

**SIDIS**

*interesting properties*

*at twist-3 more TMD PDF's*

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

# SIDIS cross-section

## leading order

Collins asymmetry

$$d^6\sigma \approx \frac{4\pi\alpha^2 sx}{Q^4}\cdot$$

$$[1+(1-y)^2]\{\sum_q e_q^2 f_1^q \otimes D_1^q$$

$$+(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h)\sum_q e_q^2 h_1^{\perp q} \otimes H_1^{\perp q}$$

unpol

$$-|S_L|(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h)\sum_q e_q^2 h_{1L}^{\perp q} \otimes H_1^{\perp q}$$

L pol. target

$$+|S_T|(1-y)\frac{p_{h\perp}}{zM_h}\sin(\phi_h+\phi_S)\sum_q e_q^2 h_1^q \otimes H_1^{\perp q}$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{p_{h\perp}}{zM_N}\sin(\phi_h-\phi_S)\sum_q e_q^2 f_{1T}^{\perp q} \otimes D_1^q$$

$$+|S_T|(1-y)\frac{p_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h-\phi_S)\sum_q e_q^2 h_{1T}^{\perp q} \otimes H_1^{\perp q}$$

T pol. target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_q e_q^2 g_1^q \otimes D_1^q$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{p_{h\perp}}{zM_N}\cos(\phi_h-\phi_S)\sum_q e_q^2 g_{1T}^q \otimes D_1^q\}$$

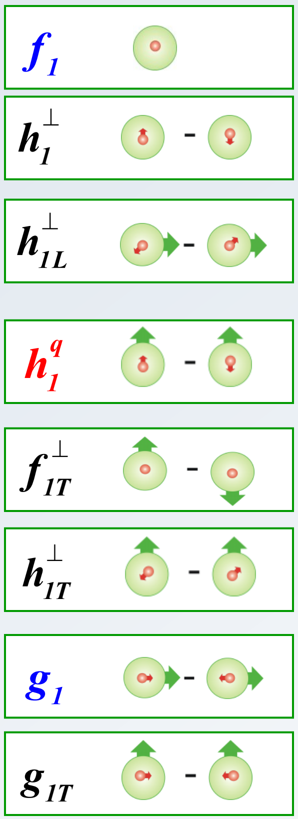
pol. beam & target

$h_1^q$ 

$S_L$ and $S_T$: target polarizations; $\lambda_e$: beam polarization

# SIDIS cross-section

## leading order




$$
\begin{aligned}
d^6\sigma \approx \frac{4\pi\alpha^2 sx}{Q^4}\cdot
&\Big\{[1+(1-y)^2]\sum_q e_q^2 f_1^q \otimes D_1^q \\
&+(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h)\sum_q e_q^2 h_1^{\perp q}\otimes H_1^{\perp q} \qquad \text{unpol} \\
&-|S_L|(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h)\sum_q e_q^2 h_{1L}^{\perp q}\otimes H_1^{\perp q} \qquad \text{L pol. target} \\
&+|S_T|(1-y)\frac{p_{h\perp}}{zM_h}\sin(\phi_h+\phi_S)\sum_q e_q^2 h_1^q\otimes H_1^{\perp q} \\
&+|S_T|(1-y+\frac{1}{2}y^2)\frac{p_{h\perp}}{zM_N}\sin(\phi_h-\phi_S)\sum_q e_q^2 f_{1T}^{\perp q}\otimes D_1^q \qquad \text{T pol. target} \\
&+|S_T|(1-y)\frac{p_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h-\phi_S)\sum_q e_q^2 h_{1T}^{\perp q}\otimes H_1^{\perp q} \\
&+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_q e_q^2 g_1^q\otimes D_1^q \\
&+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{p_{h\perp}}{zM_N}\cos(\phi_h-\phi_S)\sum_q e_q^2 g_{1T}^q\otimes D_1^q\Big\} \qquad \text{pol. beam \& target}
\end{aligned}
$$

$S_L$ and $S_T$: target polarizations; $\lambda_e$: beam polarization

# SIDIS cross-section

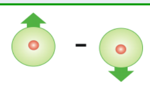
## presently, the most “famous” TMD PDFs are:

- **the Boer-Mulders PDF**

$h_1^{\perp}$  

correlates the quark transverse spin and the quark $k_t$ (unpol. N)

- **the Sivers PDF**

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

correlates the nucleon spin and the quark $k_t$ (tr. pol. N)

- **and the Pretzolosity PDF**

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

which correlates the quark transverse spin and the quark $k_t$ (tr. pol. N)

**all important for assessing the orbital angular momentum of the quarks**

$$d^6\sigma \approx \frac{4\pi\alpha^2 sx}{Q^4}\cdot$$

unpol

$$[1+(1-y)^2]\{\sum_q e_q^2 f_1^q \otimes D_1^q$$

$$+(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h)\sum_q e_q^2 h_1^{\perp q}\otimes H_1^{\perp q}$$

L pol. target

$$-|S_L|(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h)\sum_q e_q^2 h_{1L}^{\perp q}\otimes H_1^{\perp q}$$

T pol. target

$$+|S_T|(1-y)\frac{p_{h\perp}}{zM_h}\sin(\phi_h+\phi_S)\sum_q e_q^2 h_1^q \otimes H_1^{\perp q}$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{p_{h\perp}}{zM_N}\sin(\phi_h-\phi_S)\sum_q e_q^2 f_{1T}^{\perp q}\otimes D_1^q$$

$$+|S_T|(1-y)\frac{p_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h-\phi_S)\sum_q e_q^2 h_{1T}^{\perp q}\otimes H_1^{\perp q}$$

pol. beam & target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_q e_q^2 g_1^q \otimes D_1^q$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{p_{h\perp}}{zM_N}\cos(\phi_h-\phi_S)\sum_q e_q^2 g_{1T}^q \otimes D_1^q\}$$

# Sivers function

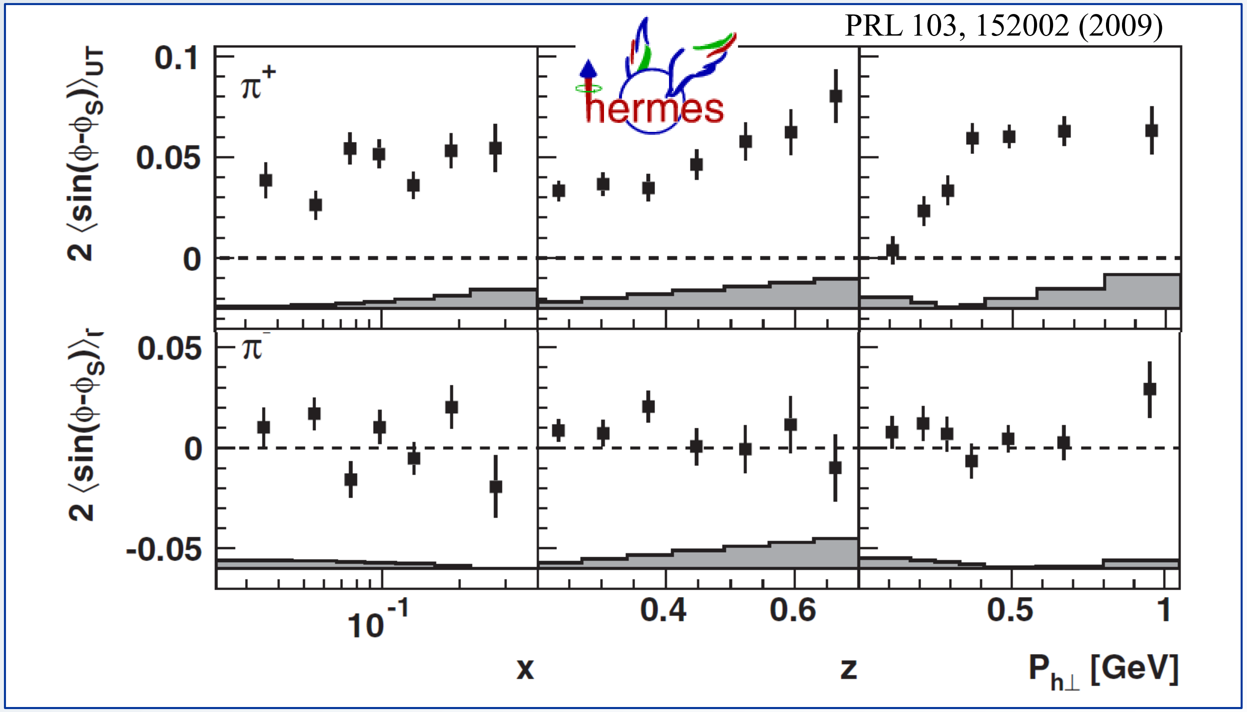
- proposed in 1990
- initially thought to be zero (Collins, 1993)
- resurrected in 2002 (Brodsky, Hwang, Schmitt) – *FSI, gauge link …*
- related to the "Sivers asymmetry" in SIDIS on transversely polarized targets

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

# Sivers function

## SIDIS results

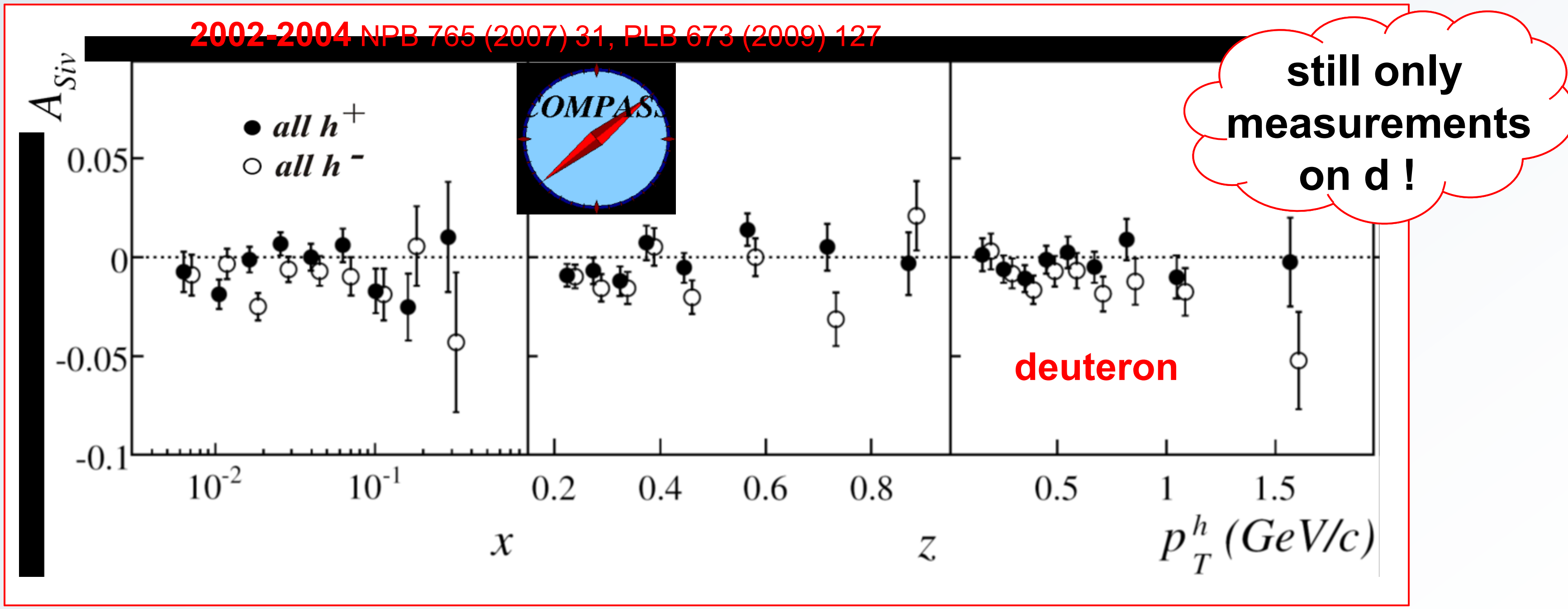
• strong signal seen by HERMES in $\pi^+$ production on p



# Sivers function

## SIDIS results

- strong signal seen by HERMES in $\pi^+$ production on p
- no signal seen by COMPASS on d




and understood as u – d cancellation (as for the Collins asymmetry)

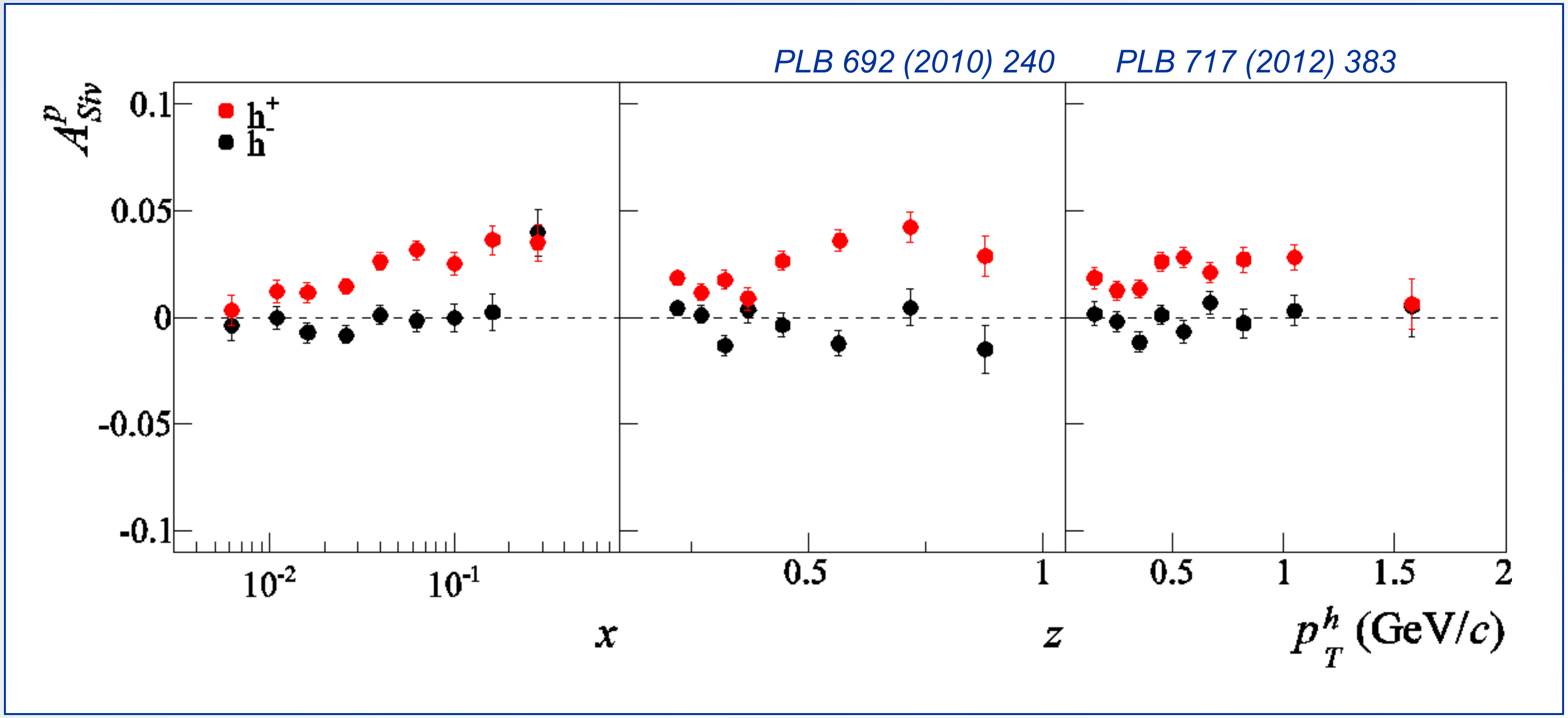
→ $\boxed{f_{1T}^{\perp u} \approx - f_{1T}^{\perp d}}$

first extraction from HERMES p and COMPASS d data in 2005

# Sivers function

## COMPASS results on proton target

## combined 2007 – 2010 results:



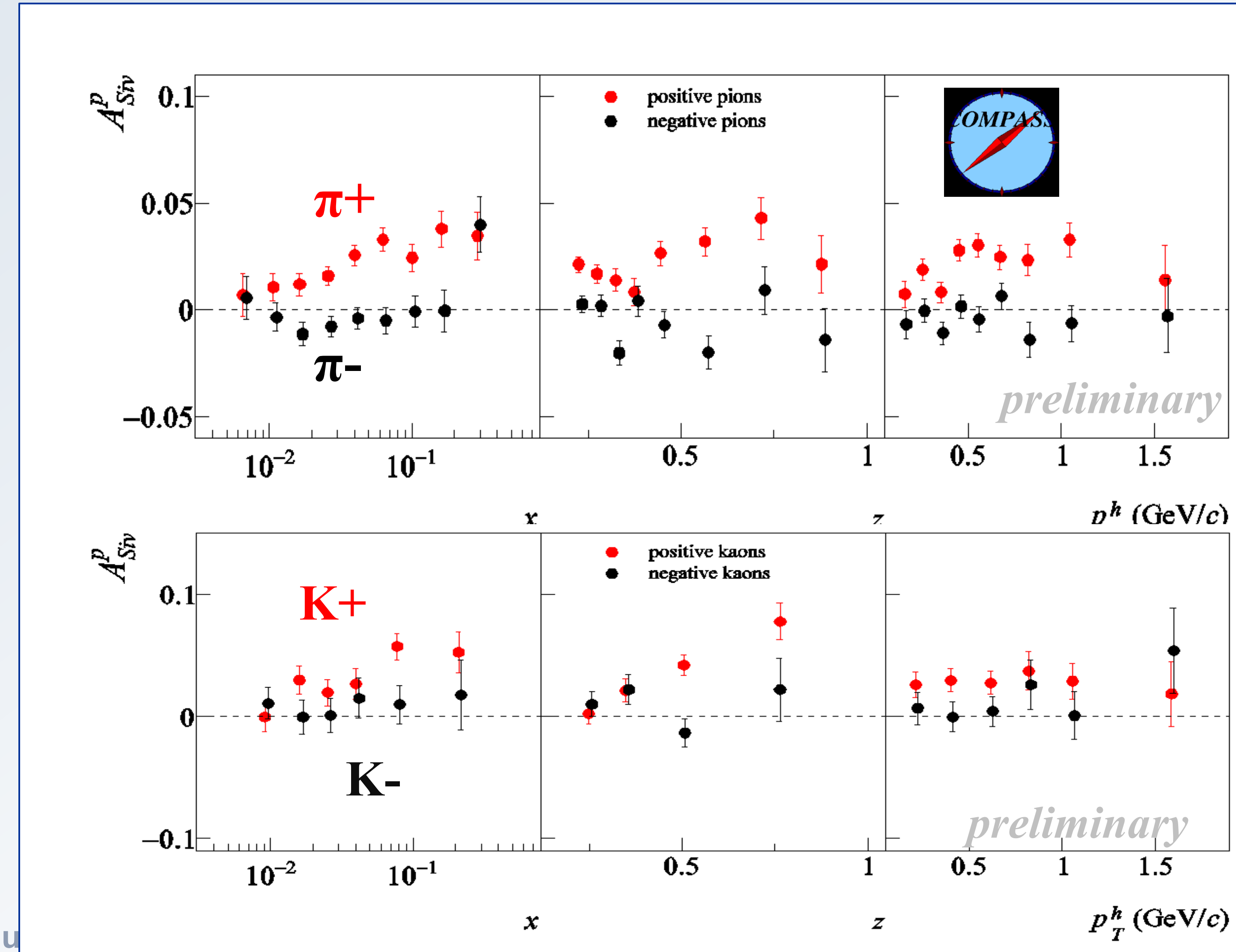

**h+ : clear signal down to low x, in the previously unmeasured region**

# Sivers function

## COMPASS results on proton target combined 2007 – 2010 results

~ h+ / h-

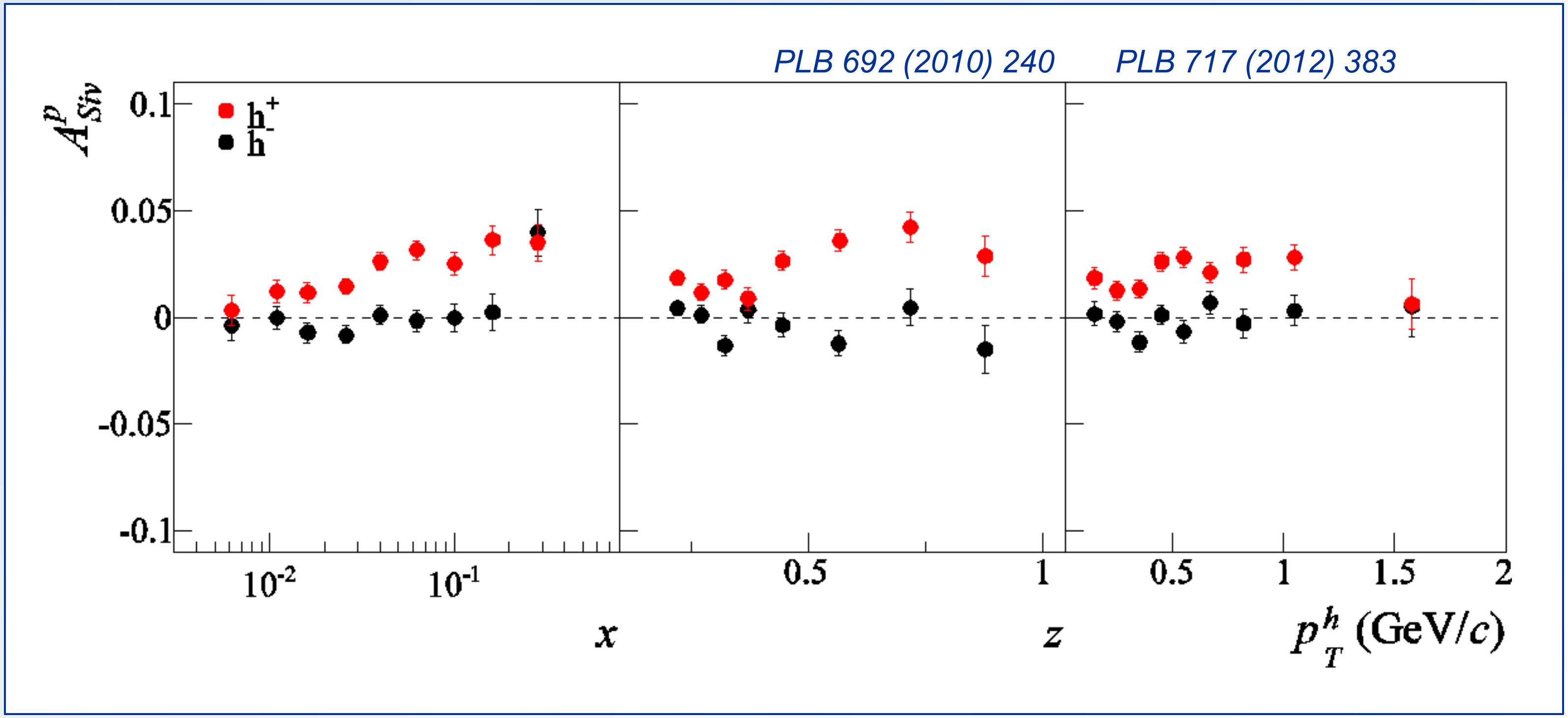
larger than for π+



# Sivers function

## COMPASS results on proton target

## combined 2007 – 2010 results:



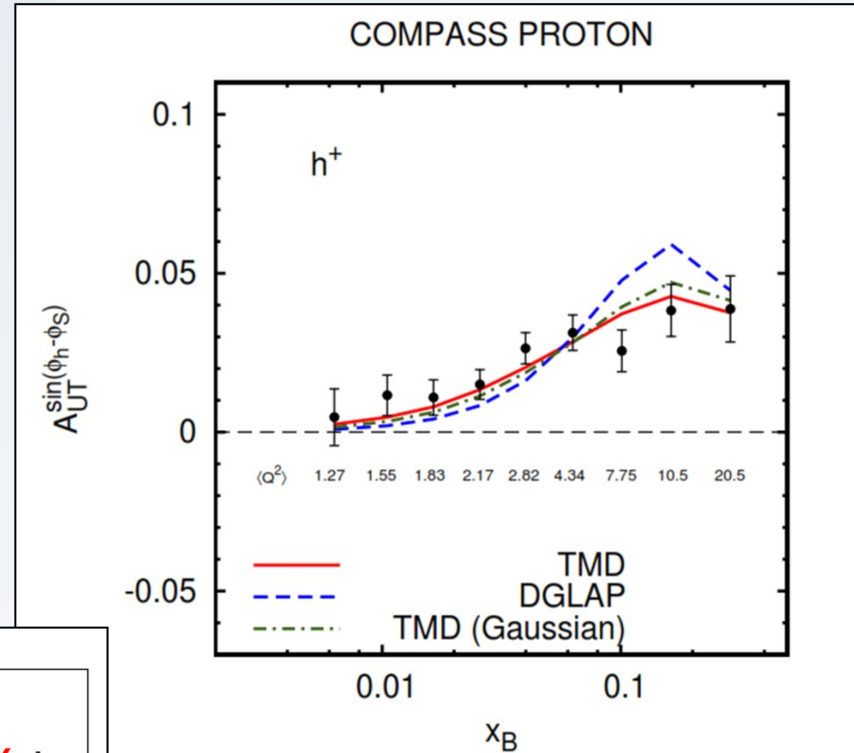

h+ : clear signal down to low x, in the previously unmeasured region

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

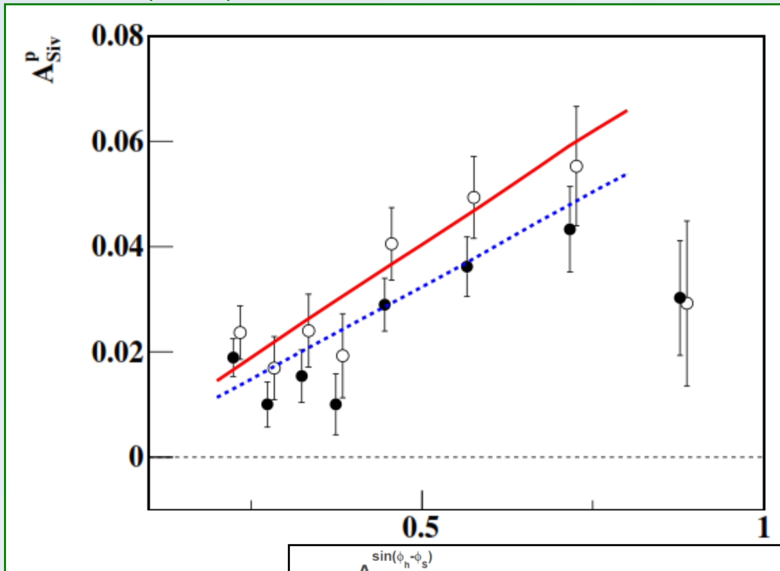
# Sivers function

## new extractions and Q² evolution

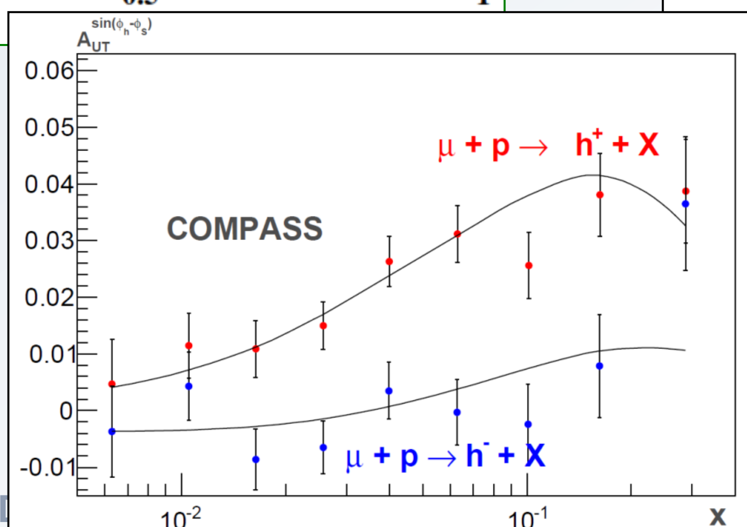
**Anselmino, Boglione, Melis**
PRD86 (2012) 014028




**Aybat, Prokudin, Rogers**
PRL 108 (2012) 242003




**Sun, Yuan**
arXiv:1308.2993
[hep-ph]



# SIDIS cross-section

## leading order

all amplitudes measured in COMPASS

$$d^6\sigma \approx \frac{4\pi\alpha^2 sx}{Q^4}\cdot$$

unpol

$$[1+(1-y)^2]\{ \sum_q e_q^2 f_1^q \otimes D_1^q$$

$$+(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h} \cos(2\phi_h) \sum_q e_q^2 h_1^{\perp q} \otimes H_1^{\perp q}$$

L pol. target

$$-|S_L|(1-y)\frac{p_{h\perp}^2}{4z^2 M_N M_h} \sin(2\phi_h) \sum_q e_q^2 h_{1L}^{\perp q} \otimes H_1^{\perp q}$$

T pol. target

$$+|S_T|(1-y)\frac{p_{h\perp}}{zM_h} \sin(\phi_h+\phi_S) \sum_q e_q^2 h_1^q \otimes H_1^{\perp q}$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{p_{h\perp}}{zM_N} \sin(\phi_h-\phi_S) \sum_q e_q^2 f_{1T}^{\perp q} \otimes D_1^q$$

$$+|S_T|(1-y)\frac{p_{h\perp}^3}{6z^3 M_N^2 M_h} \sin(3\phi_h-\phi_S) \sum_q e_q^2 h_{1T}^{\perp q} \otimes H_1^{\perp q}$$

pol. beam & target

$$+\lambda_e |S_L| y(1-\frac{1}{2}y)\sum_q e_q^2 g_1^q \otimes D_1^q$$

$$+\lambda_e |S_T| y(1-\frac{1}{2}y)\frac{p_{h\perp}}{zM_N} \cos(\phi_h-\phi_S) \sum_q e_q^2 g_{1T}^q \otimes D_1^q \}$$

# SIDIS cross-section

**all amplitudes measured in COMPASS**

*A.Kotzinian, Nucl. Phys. B441, 234 (1995). Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).*

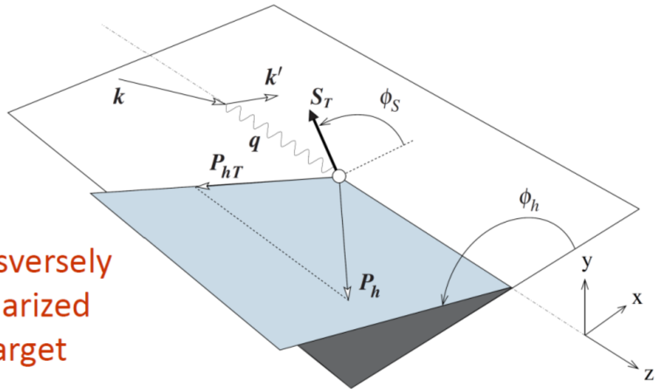
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$\left\{\begin{array}{l}
1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\\
S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+\\
S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+\\
S_T\left[\begin{array}{l}
\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\
\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\\
\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\\
\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+\\
\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)
\end{array}\right]+\\
S_T\lambda\left[\begin{array}{l}
\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+\\
\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+\\
\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array}\right]
\end{array}\right\}$$

transversely polarized target

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

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

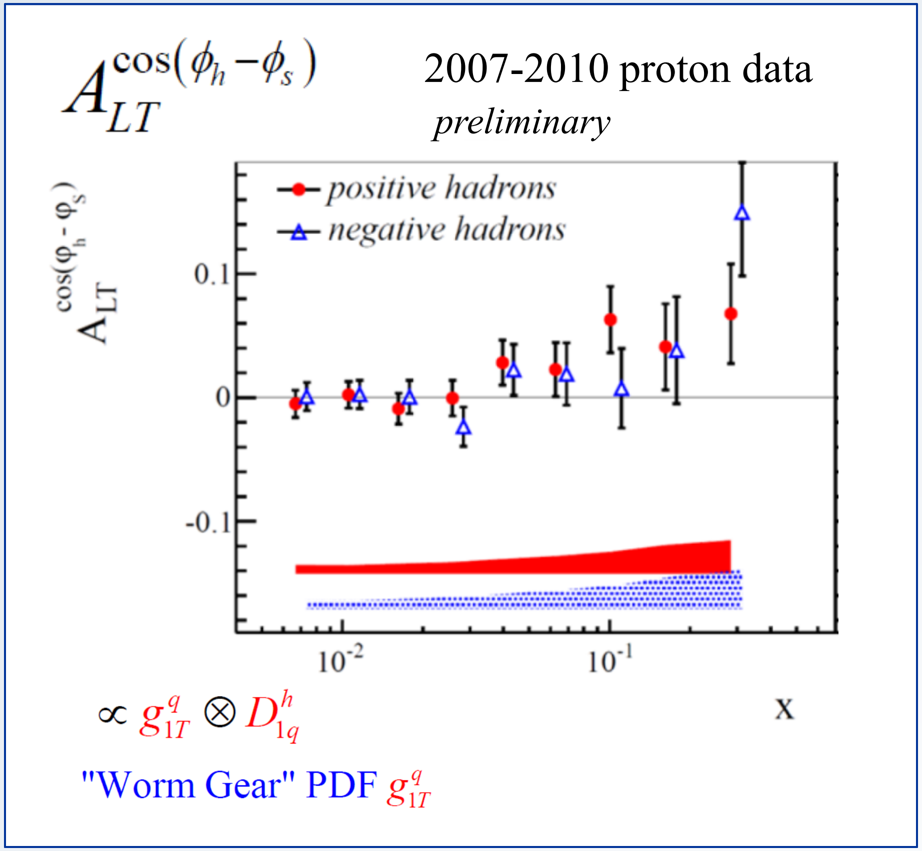



Bakur Parsamyan

# Other Transverse Spin Azimuthal Asymmetries

**almost all compatible with zero,**

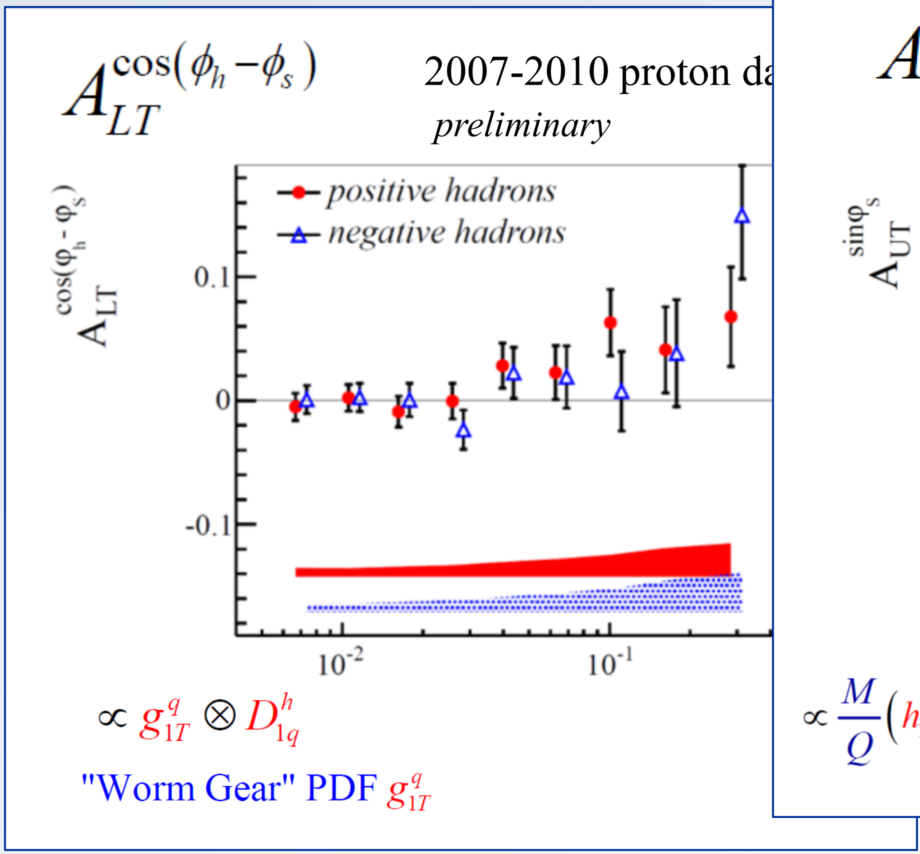
**both on p and d** but

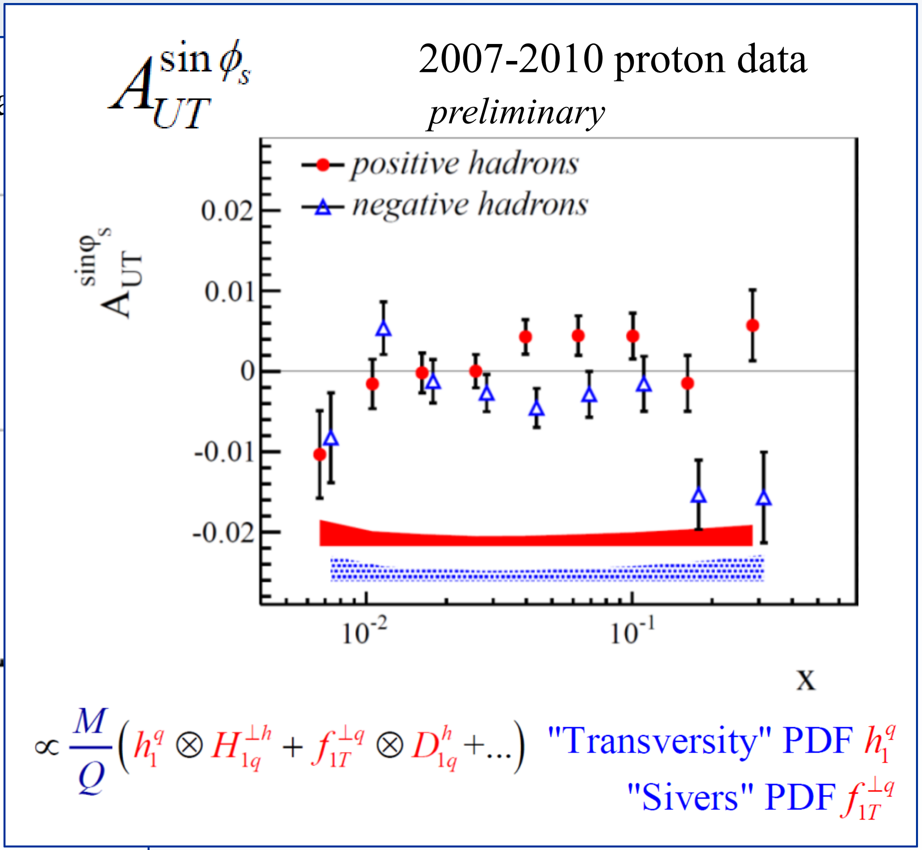


# Other Transverse Spin Azimuthal Asymmetries

**almost all compatible with zero,**

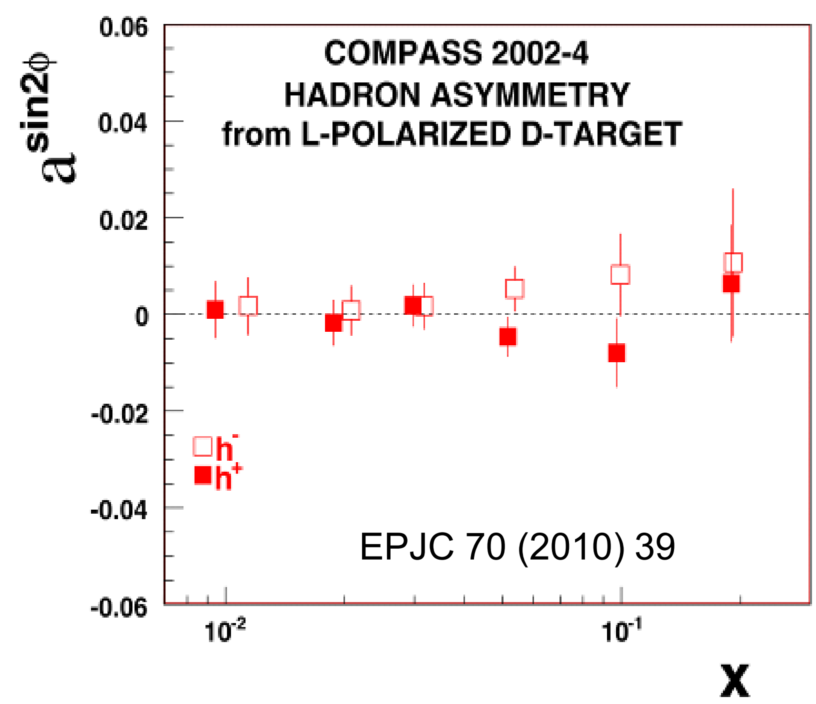
**both on p and d** but



# Longitudinal Spin Azimuthal Asymmetries

first measurement on d: all compatible with zero




$$F_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

"worm gear" PDF
$\otimes$ Collins FF

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**

- **hadron multiplicities**

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

- **azimuthal asymmetries**

# SIDIS off unpolarised deuteron

**combining data taken with oppositely polarised $^6$LiD target**
**COMPASS has measured**

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

**Cahn effect**

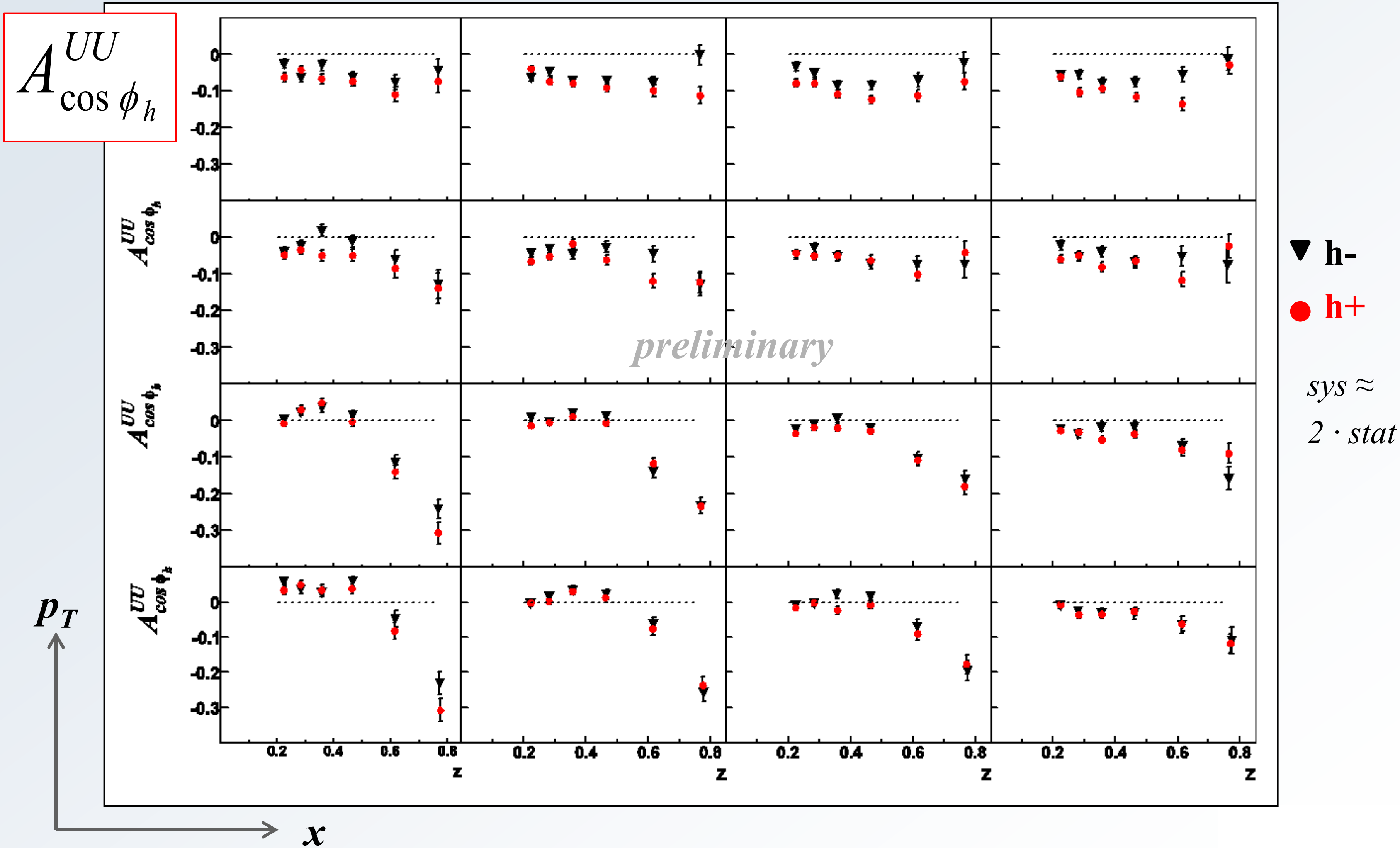
Boer-Mulders PDF

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

**twist3**

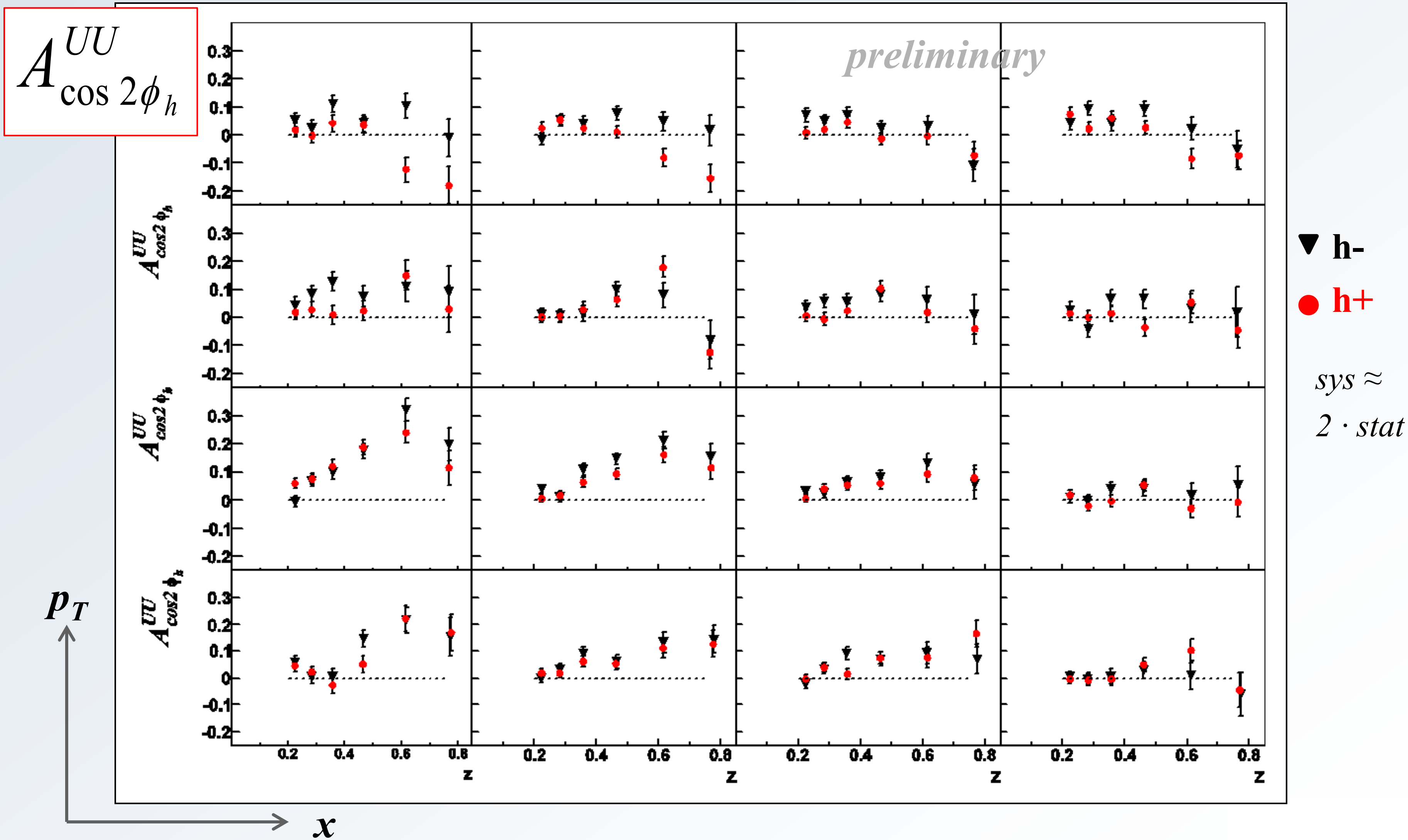
**Boer-Mulders PDF** x Collins FF
+ Cahn effect (twist 4, 1/$Q^2$)

# SIDIS off unpolarised deuteron



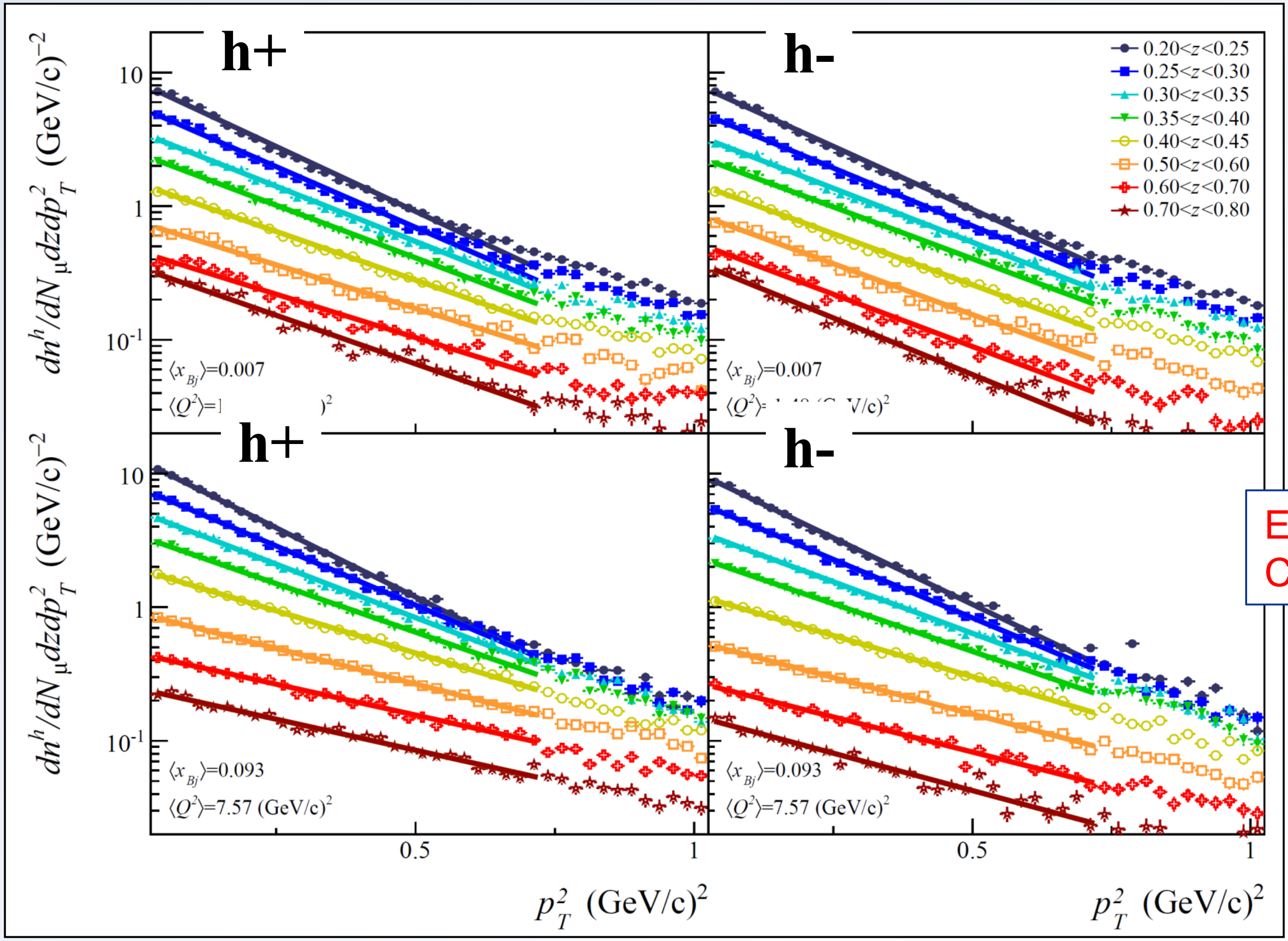

strong $z$ dependence mainly at small $x$ and small $p_T$

# SIDIS off unpolarised deuteron



# SIDIS off unpolarised deuteron

## hadron multiplicities vs $p_T^2$




Eur.Phys.J.
C73 (2013) 2531

# future COMPASS contribution to TMDs from SIDIS

coming soon

- T: interplay
- T: multidimensional analysis C&S
- L: more d and p results
- U: more results from d

later on

- U: SIDIS measurements in parallel with DVCS – $LH_2$ target (2016-2017)
- DY with T polarised target (2015, …)

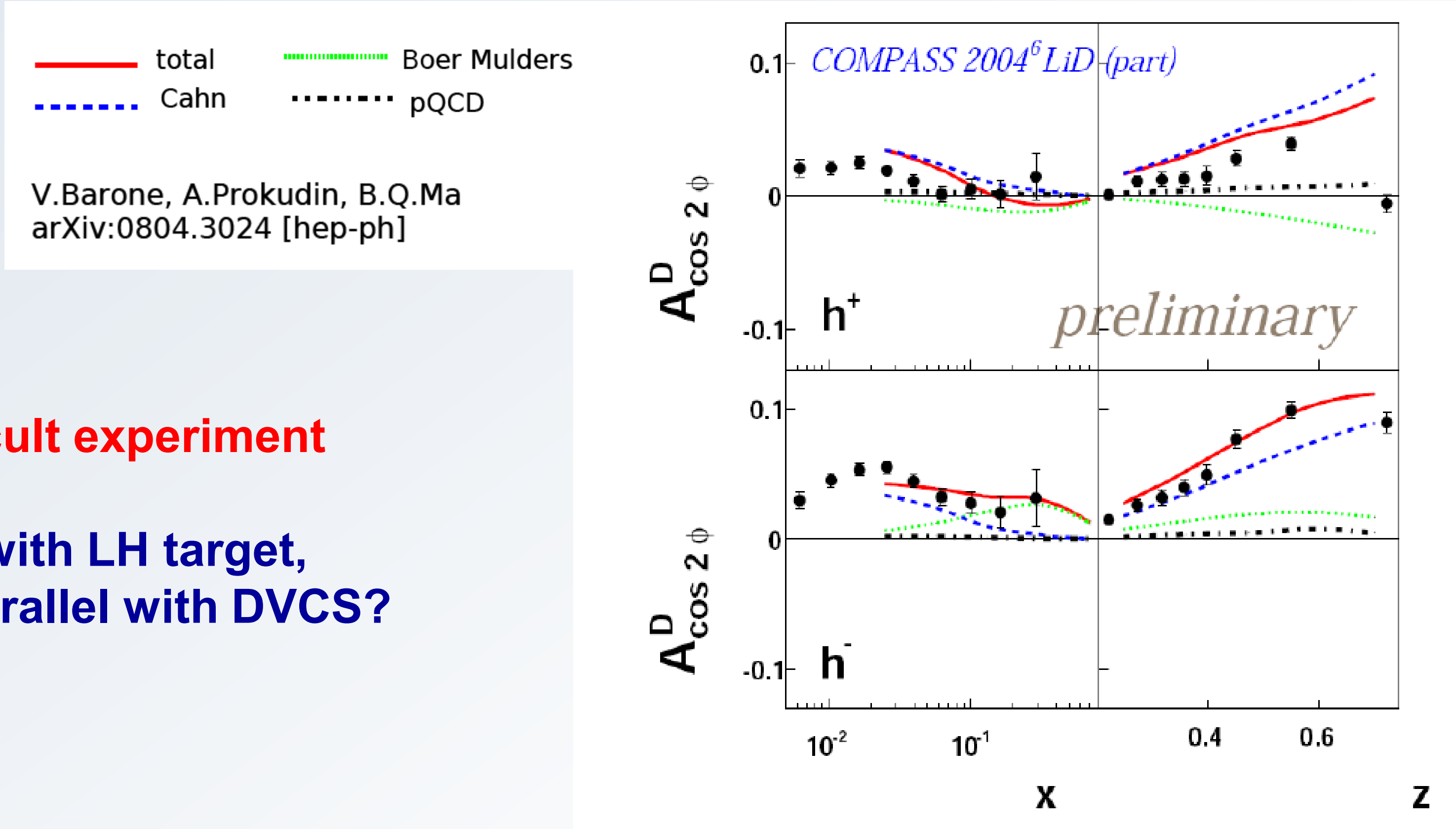
and after that

- T: more data on d and p ?

**Thank you !**

# Boer-Mulders function

**in principle can be extracted by the *cos* $2\phi_h$ modulation of the unpolarized SIDIS cross-section**




**difficult experiment**

**run with LH target,**
**in parallel with DVCS?**

# SIDIS on transversely polarized targets

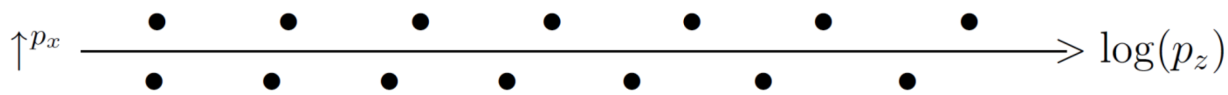
## WHY MEASURE @ CERN ?

- the existing COMPASS spectrometer with its long Polarized Target can be used as such

- the high energy beam ensures the hardness of the process
  - large W
    *current jet and target fragmentation well separated*
  - small x
    *parameterization*
    *spin sum rule, tensor charge*
  - large $Q^2$ coverage

complementary kinematic range to JLab12

# Collins and two-hadron asymmetries




*sheared* one-particle fragmentation function

$\mathbf{k}$ 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

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

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

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

# Collins and two-hadron asymmetries

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