# Measurements of unpolarized azimuthal asymmetries in SIDIS at COMPASS

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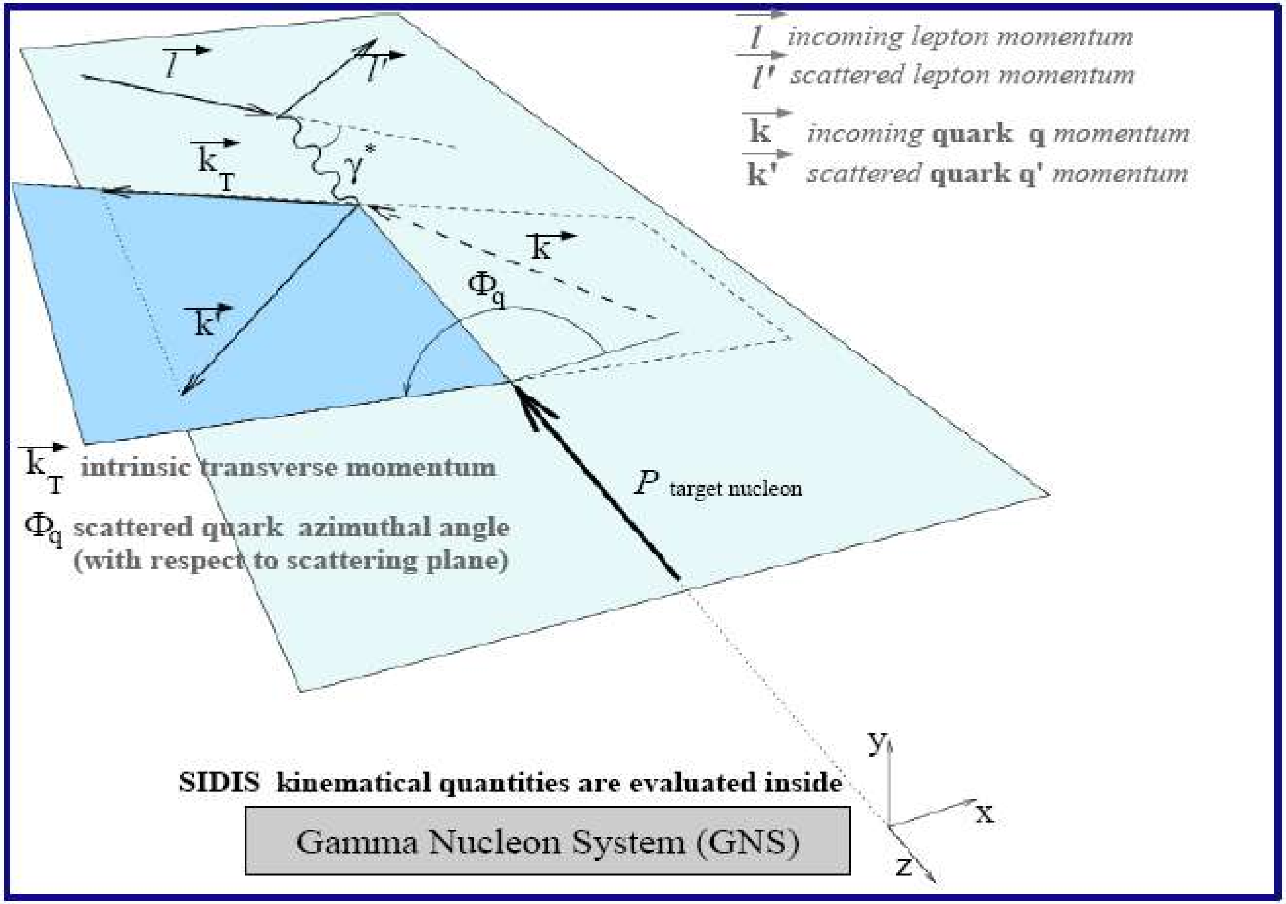
*on behalf of the COMPASS Collaboration*

# Measurements of unpolarized azimuthal asymmetries in SIDIS at COMPASS

## Outlook

- **Introduction**
- **The COMPASS experiment**
- **Asymmetries extraction**
- **Results**

- *for completeness, also a look at Collins and Sivers asymmetries from 2007 polarized proton data*



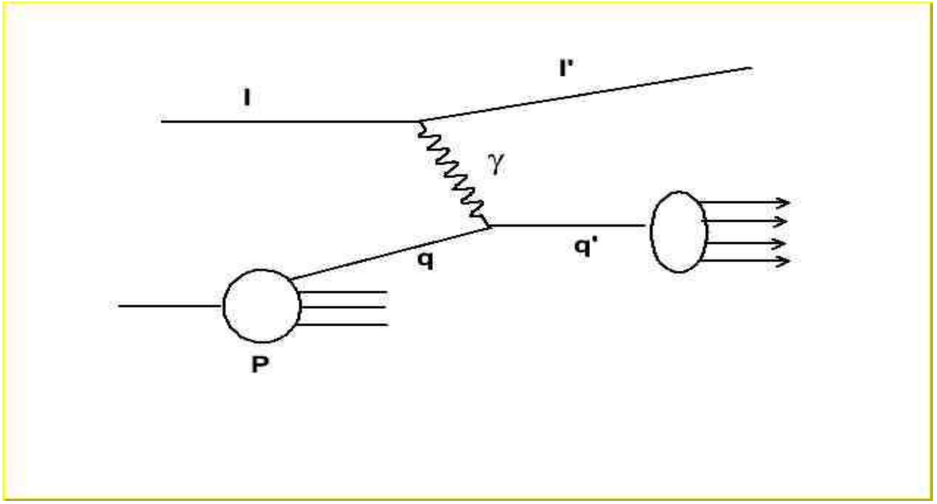

$$Q^2 = -(l - l')^2$$

$$x = \frac{Q^2}{2M\nu}$$

$$y = \frac{P\,(l - l')}{P \cdot l}$$

$$\nu = \frac{P \cdot (l - l')}{M}$$

SIDIS $\quad l\,n \rightarrow l'\,h'\,X$




Giulio Sbrizzai

# Present experimental status

$l\ n \rightarrow l'\ h'\ X$

- **EMC** PL B 130 (1983) 118; ZP C34(1987) 277
- **E665** PR D48 (1993) 5057

**→ large cos $\phi_h$ effect (up to 40% amplitude), cos $2\phi_h$ small (~5%)**

  - **no charge separation so far!**

$l\ n \rightarrow l'\ h'\ X$

- **Zeus (pQCD region)** PL B481 (2000) 199
- **sin$\phi_h$ ~ 3% (CLAS)** PR D69 (2004) 112

## Unpolarized target SIDIS cross section

(*model independent, Bacchetta et al. 2006*)

$$d\sigma \propto F_{UU} + F_{UU}^{\cos\phi}\epsilon_1 \cos(\phi_h) + F_{UU}^{\cos 2\phi}\epsilon_2 \cos(2\phi_h) + \lambda_l F_{LU}^{\sin\phi}\epsilon_3 \sin(\phi_h)$$

kine factors:

$$\epsilon_1 = \frac{(2-y)\cdot 2\cdot\sqrt{1-y}}{1+(1-y)^2} \quad \epsilon_2 = \frac{(1-y)\cdot 2\cdot\sqrt{1-y}}{1+(1-y)^2} \quad \epsilon_3 = \frac{y\cdot 2\cdot\sqrt{1-y}}{1+(1-y)^2}$$

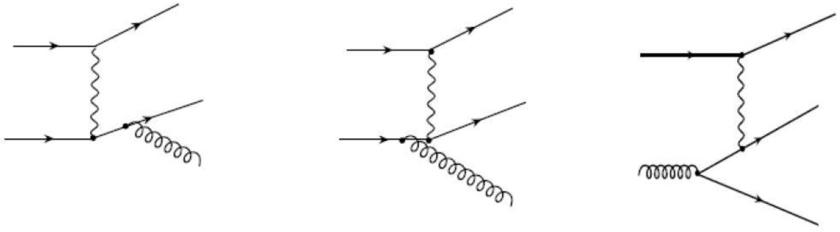
- **3 independent modulations in the hadron azimuthal distribution**

beam polarization

Cahn effect, Boer-Mulder, pQCD

# The origin of the azimuthal asymmetries

- *First measurements were proposed as test for perturbative QCD azimuthal asymmetry due to gluon radiation (Georgi-Politzer, 1978)*
  - **pQCD contributions expected to be important at $p_T$ > 1 GeV/c**



$\mathcal{O}(\alpha_s^1)$:

H. Georgi and H. D. Politzer. PRL 40 (1978) 3-6

A. Mendez. NP B145 (1978) 199-220.

$\mathcal{O}(\alpha_s^2)$:

A. Daleo, D. de Florian, and R. Sassot. PR D71 (2005) 034013.

## The origin of the azimuthal asymmetries

- *First measurements were proposed as test for perturbative QCD azimuthal asymmetry due to gluon radiation (Georgi-Politzer, 1978)*

- *Alternative hypothesis*
  *azimuthal asymmetry due to* **quark intrinsic transverse momentum**
  *inside nucleon, kinematical effect (Cahn 1978)*

# Cahn effect

- **Kinematical effect**
- Leading order QED with non null quark transverse momentum (quark-lepton scattering)

**QPM**

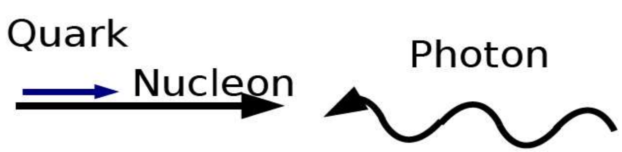
$$d\sigma^{l\,h \to l'\,h\,X} \propto \sum_i f_i \cdot d\sigma^{q_i\,l \to q_i'\,l'} \cdot D_i^h$$

$$d\sigma^{q\,l \to q'\,l'} \propto \hat{s}^2 + \hat{u}^2$$

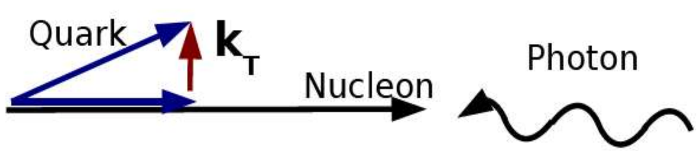
$$\hat{s} = (l + k)^2$$

$$\hat{u} = (l - k')^2$$

- $\vec{k}_t = 0$




- $\vec{k}_t \neq 0$




→ **Additional physics**

(modulations in the azimuthal distributions of the hadrons)

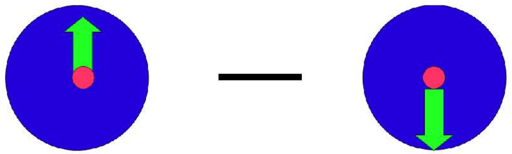
$$\cos(\phi)\ ;\ \cos(2\phi)$$

# The origin of the azimuthal asymmetries

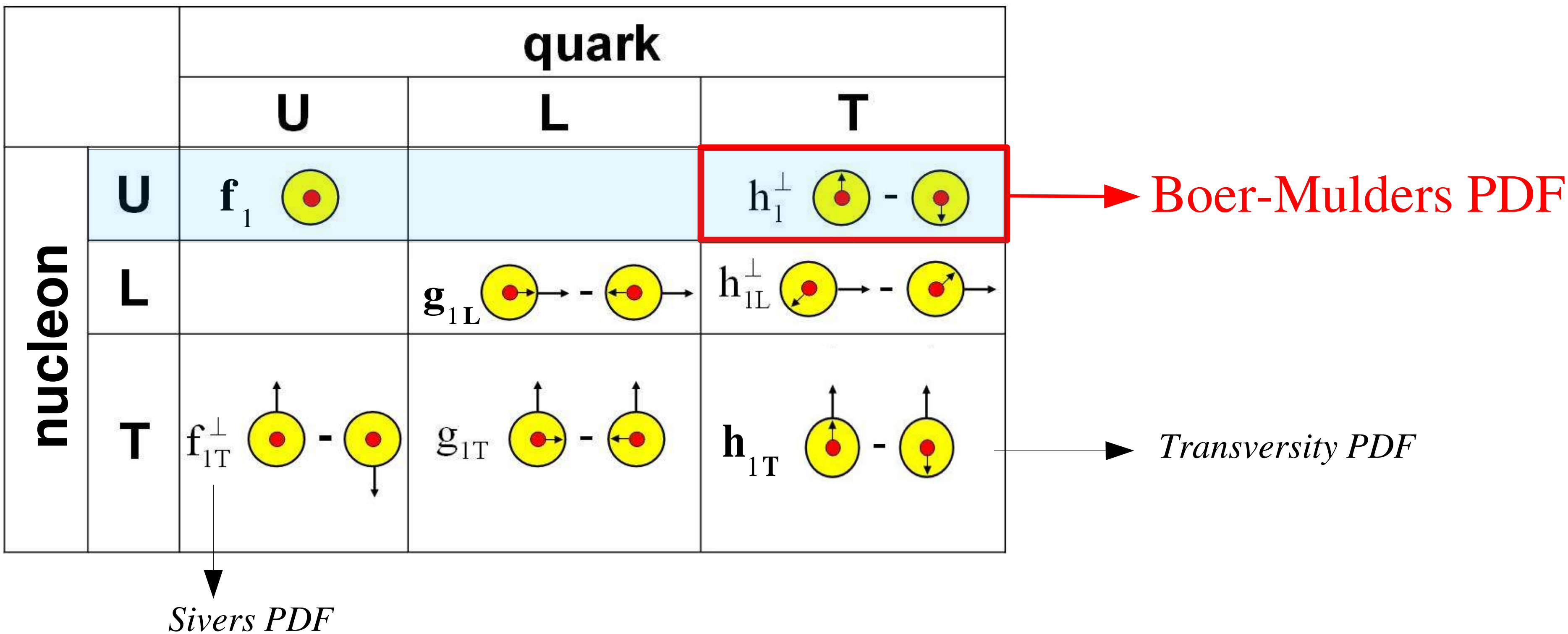
- *First measurements were proposed as test for perturbative QCD azimuthal asymmetry due to gluon radiation (Georgi-Politzer, 1978)*

- *Alternative hypothesis azimuthal asymmetry due to* **quark intrinsic transverse momentum** *inside nucleon, kinematical effect (Cahn 1978)*

- *Recently, interest is renewed because they can give further informations on Boer-Mulders TMD PDF (Boer-Mulders 1998)*
  - leading order PDF
  - correlation between quark intrinsic transverse momentum and transverse polarization in an unpolarized nucleon



## (TMD) **PDF**


quark
U
L
T
nucleon
U
$f_1$
$h_1^\perp$
Boer-Mulders PDF
L
$g_{1L}$
$h_{1L}^\perp$
T
$f_{1T}^\perp$
$g_{1T}$
$h_{1T}$
Transversity PDF
Sivers PDF

## (TMD) **PDF**

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

$h_1^\perp$ → Boer-Mulders PDF

$h_{1T}$ → *Transversity PDF*

$f_{1T}^\perp$ → *Sivers PDF*

## (TMD) **FF**

| | | hadron |
|---|---|---|
| | | U |
| quark | U | $D_1$ |
| | T | $H_1^\perp$ |

$H_1^\perp$ → Collins FF

# (TMD) **PDF**

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

$h_1^{\perp}$ → Boer-Mulders PDF

$h_{1T}$ → *Transversity PDF*

$f_{1T}^{\perp}$ → *Sivers PDF*

# (TMD) **FF**

| | | hadron |
|---|---|---|
| | | U |
| **quark** | U | $D_1$ |
| | T | $H_1^{\perp}$ |

$H_1^{\perp}$ → Collins FF

in **cross section: PDF ⊗ FF**

$$h_1^{\perp} \otimes H_1^{\perp}$$

# The COMPASS experiment

# COMPASS

fixed target experiment
at the CERN SPS
broad physics programme

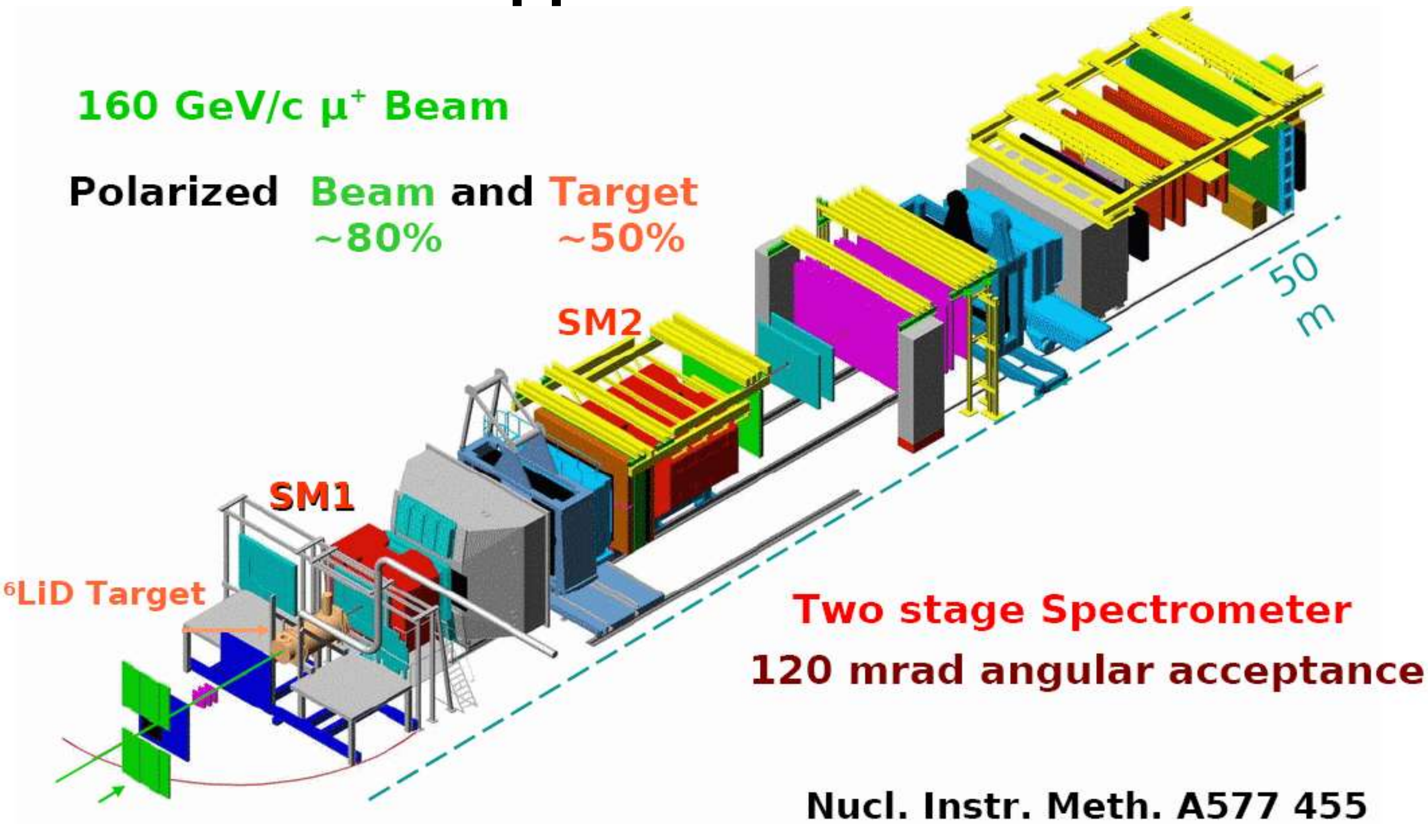

Data taking since 2002:

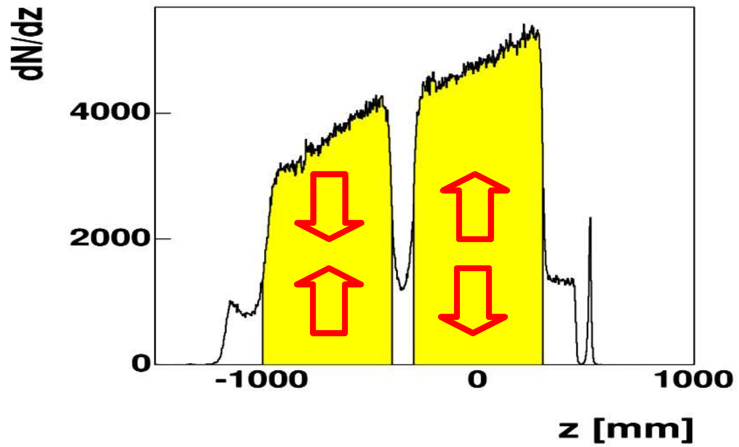
| | | | |
|---|---|---|---|
| muon beam | deuteron ($^6$LiD) polarised target | 2002<br>2003<br>2004 | L/T target polarisation 4:1 |
| | | 2006 | L target polarisation only |
| | proton ($NH_3$) polarised target | 2007 | L /T target polarisation 1:1 |
| hadron beam | LH target | 2008 | |

2004 → used in this analysis

muon beam: 160 GeV/c
longitudinal polarization -80%
intensity 2*10^8 $\mu$+ / spill (4.8s/16.2s)

# 2004 COMPASS apparatus




2002-2004: $^6$LiD (polarised deuteron)
dilution factor f = 0.38
polarization $P_T$ = 50%

## data sample: (for this analysis)

- part of the 2004 data collected with longitudinal (L) and transverse (T) polarization

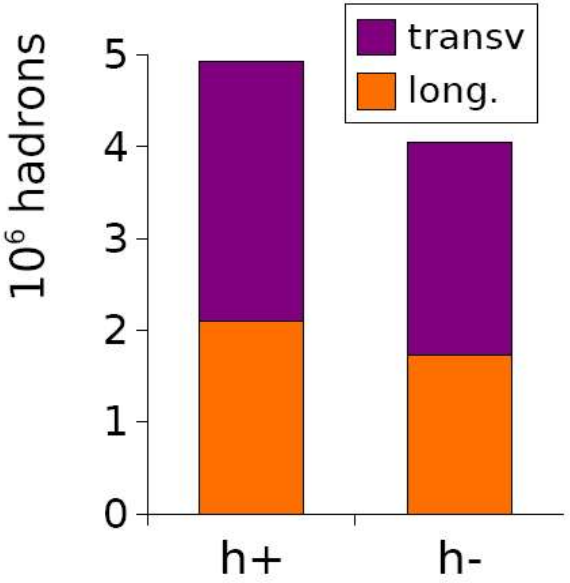
- with both target orientation configurations to cancel possible polarization effects

## event selection: (for this analysis)

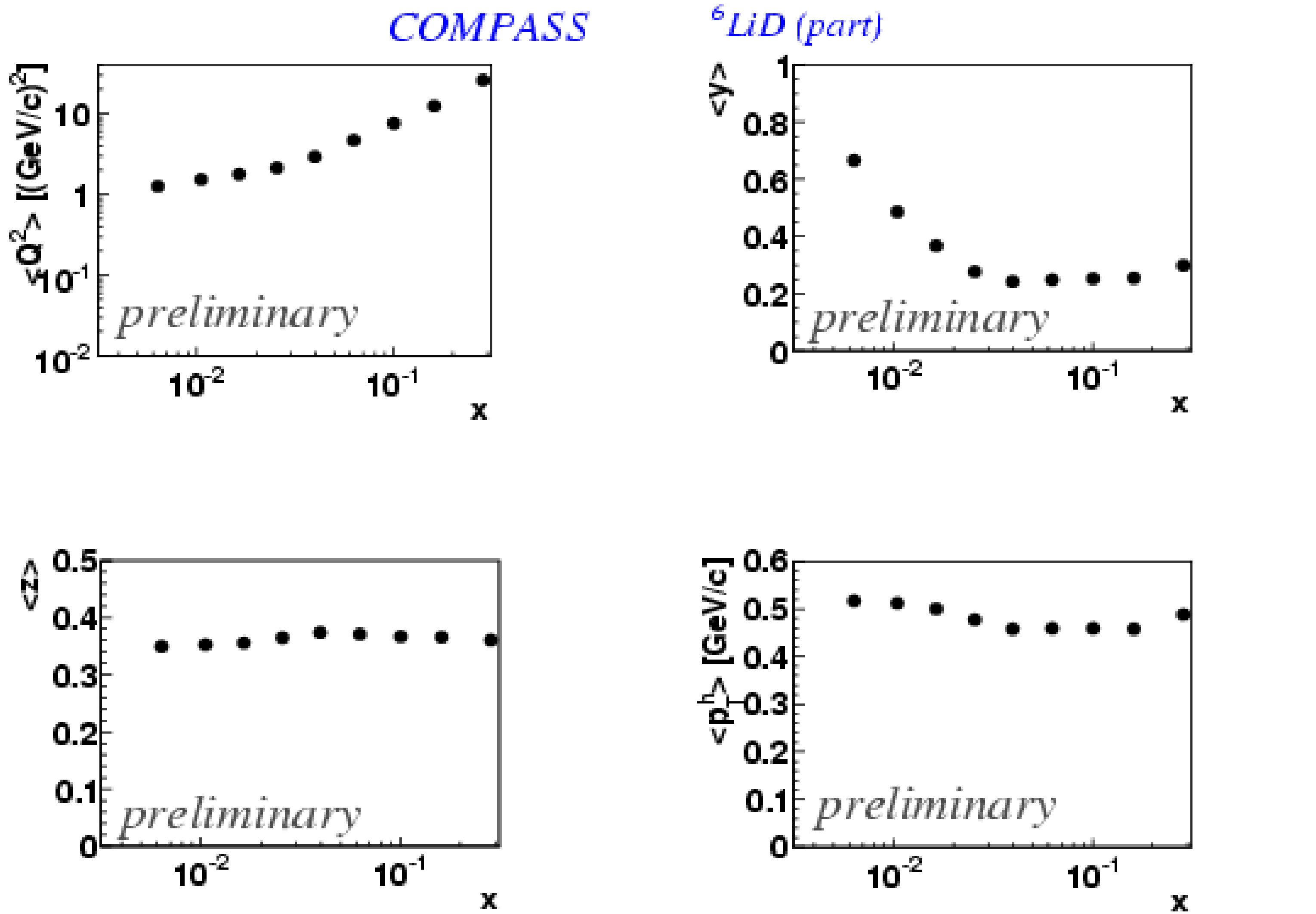
- $Q^2 > 1 \ (GeV/c)^2$
- $0.1 < y < 0.9$
- $W > 5 \, GeV/c^2$

- $0.2 < z < 0.85$
- $0.1 < p_T < 1.5 \, GeV/c$

## final statistics: (for this analysis)



# Mean values of kinematical variables



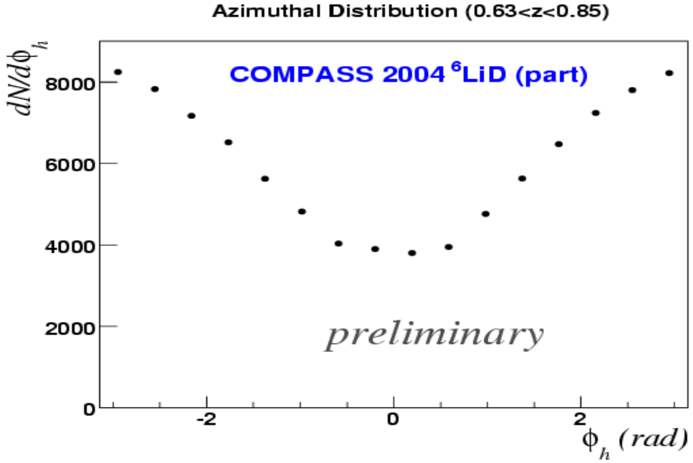
# Asymmetries extraction

**To extract the asymmetries:**

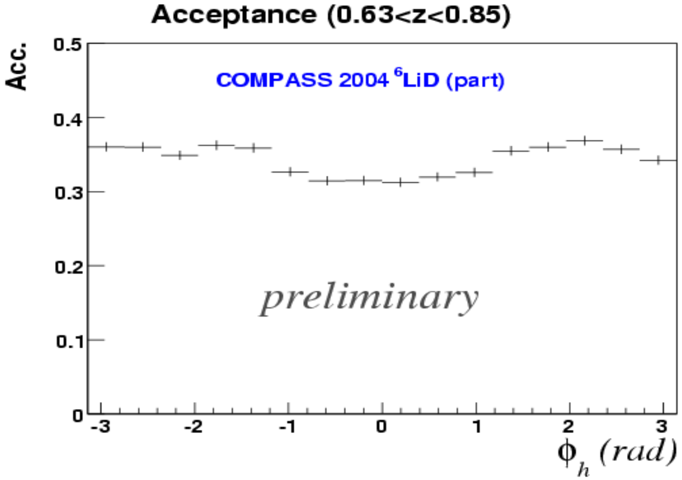
the azimuthal distributions have to be **corrected by the apparatus acceptance**

➔ **dedicated MC simulations** for L and T target polarization data

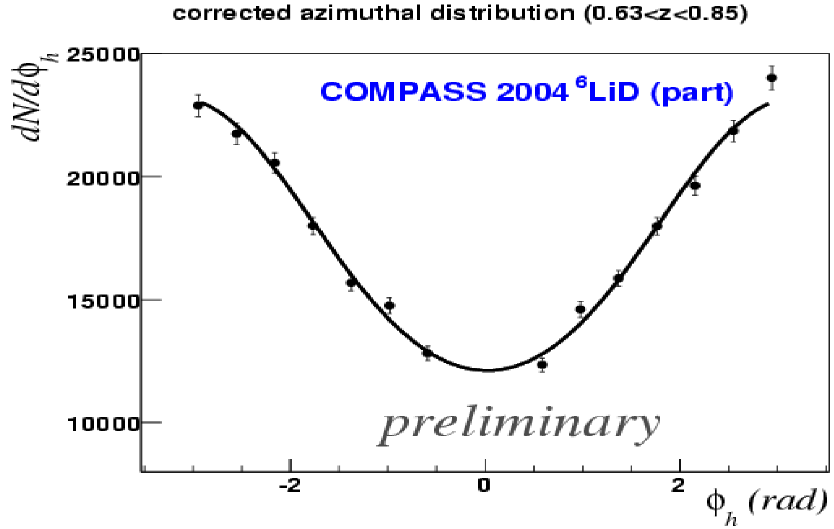
***initial az. distribution***




***acceptance***




***final az. distribution***



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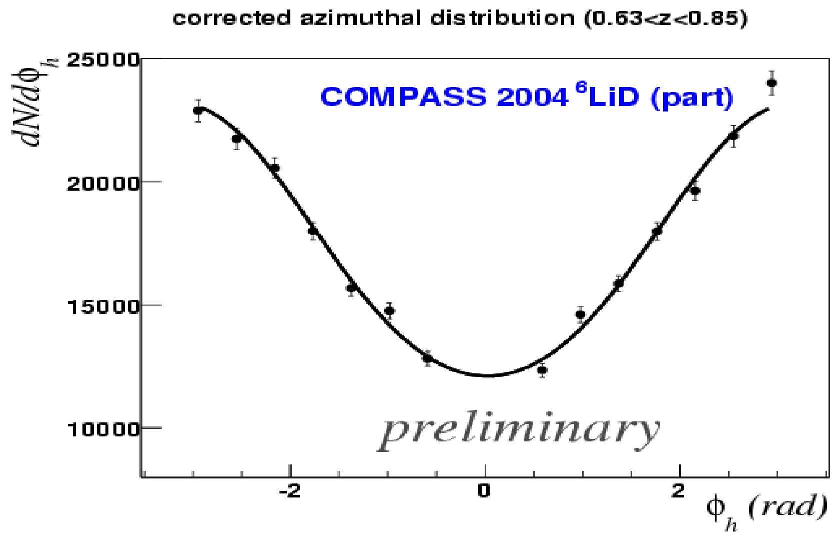
***final az. distribution***




***the final azimuthal distributions are fitted with the function:***

$$N_{corr}(\phi) = N_0 \cdot \left\{ 1 + A_{\cos\phi} \cdot \cos(\phi) + A_{\cos 2\phi} \cdot \cos(2\phi) + A_{\sin\phi} \cdot \sin(\phi) \right\}$$

## systematic errors evaluated from:

- **compatibility of results with L and T target polarization (different experimental conditions, different MCs)**

- **comparison of results obtained using two different MCs with different settings for each data set (LEPTO default, standard COMPASS high pt; ~extreme cases)**

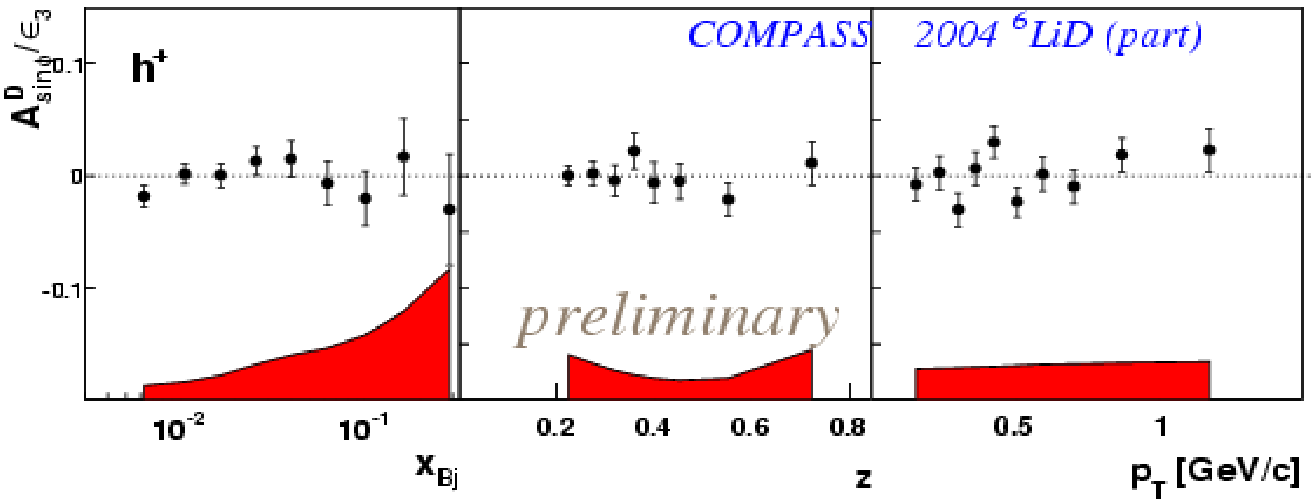
- **compatibility of results from subsamples corresponding to**
  - different periods
  - different geometrical regions for the scattered muon

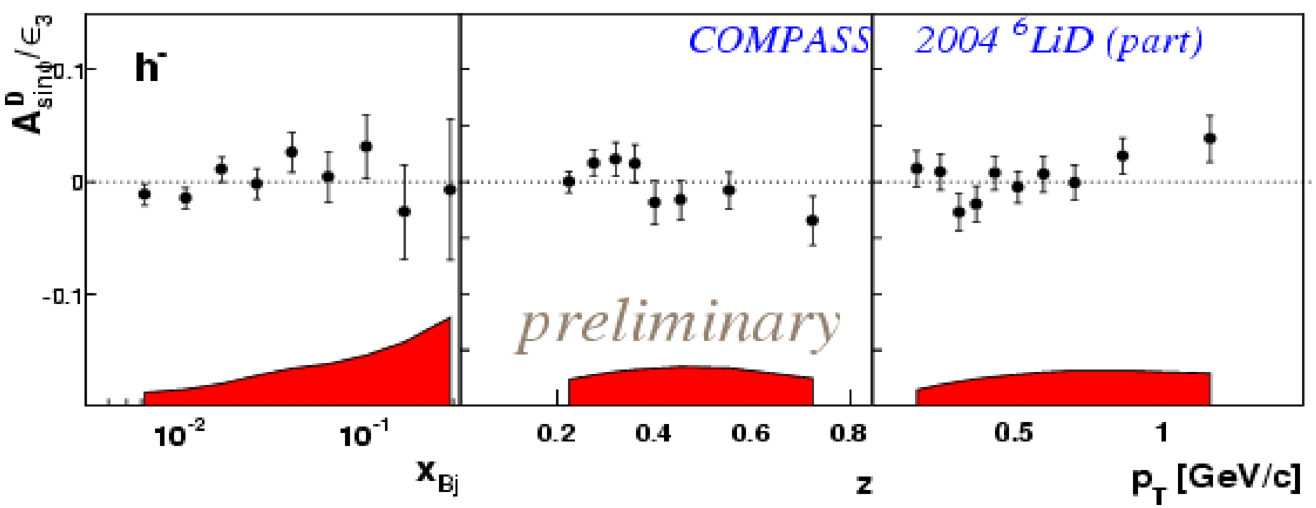
# Results

# sin$\Phi$ modulation

$$\frac{A_{\sin\phi}}{\epsilon_3}$$

$$\epsilon_3 = \frac{y \cdot 2 \cdot \sqrt{1-y}}{1+(1-y)^2} \cdot |\lambda_l|$$



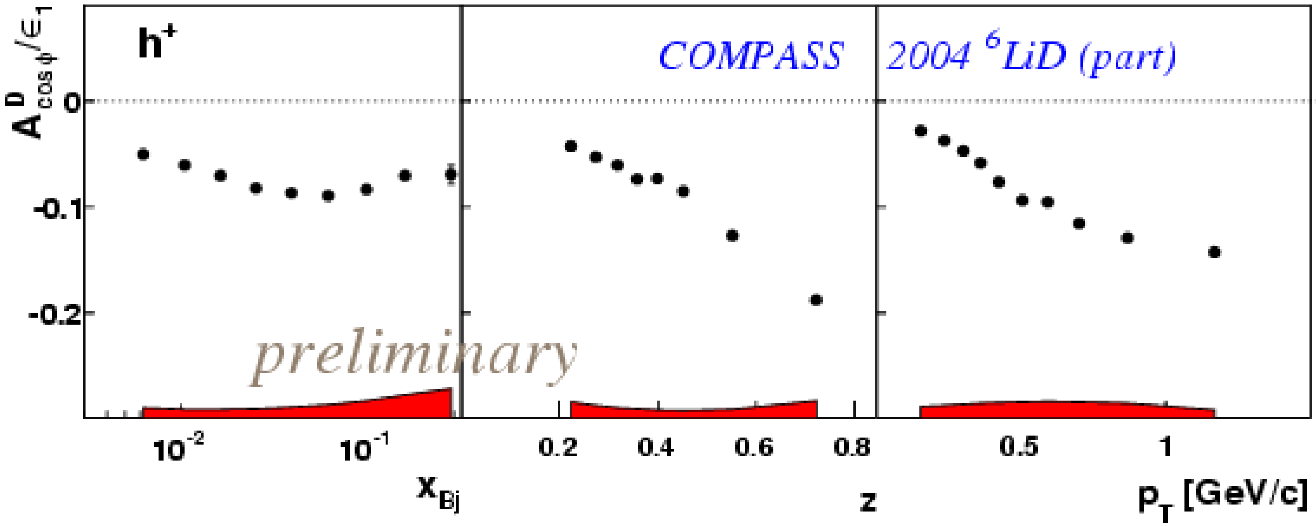

**error bars: statistical errors**

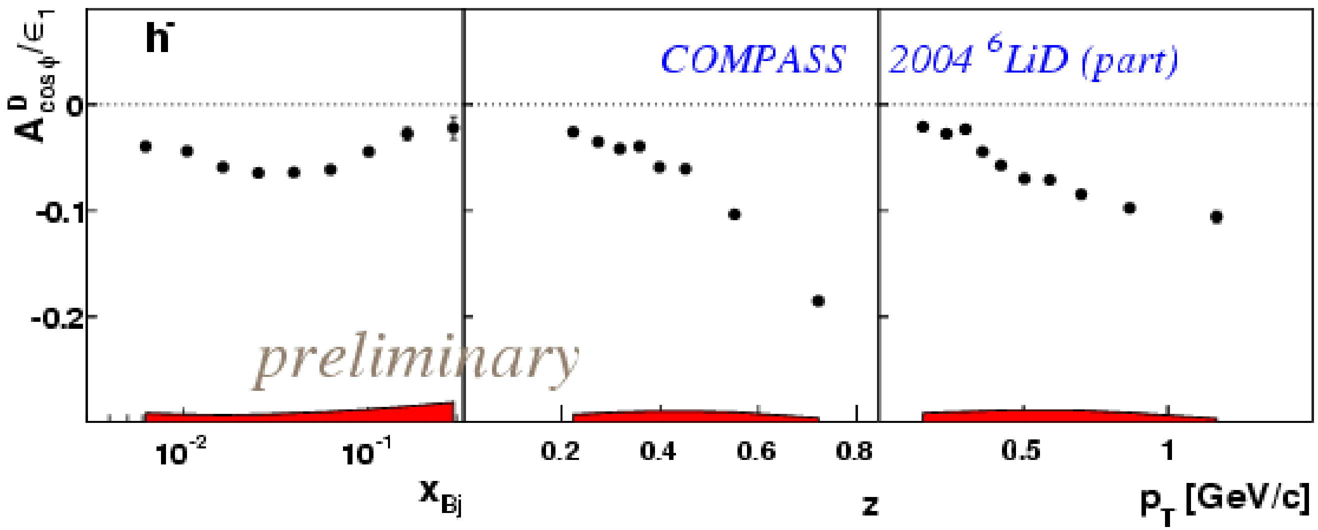
**red bands: systematical errors**

# cosΦ modulation

$$\frac{A_{\cos\phi}}{\epsilon_1}$$

$$\epsilon_1 = \frac{(2-y)\cdot 2\cdot\sqrt{1-y}}{1+(1-y)^2}$$



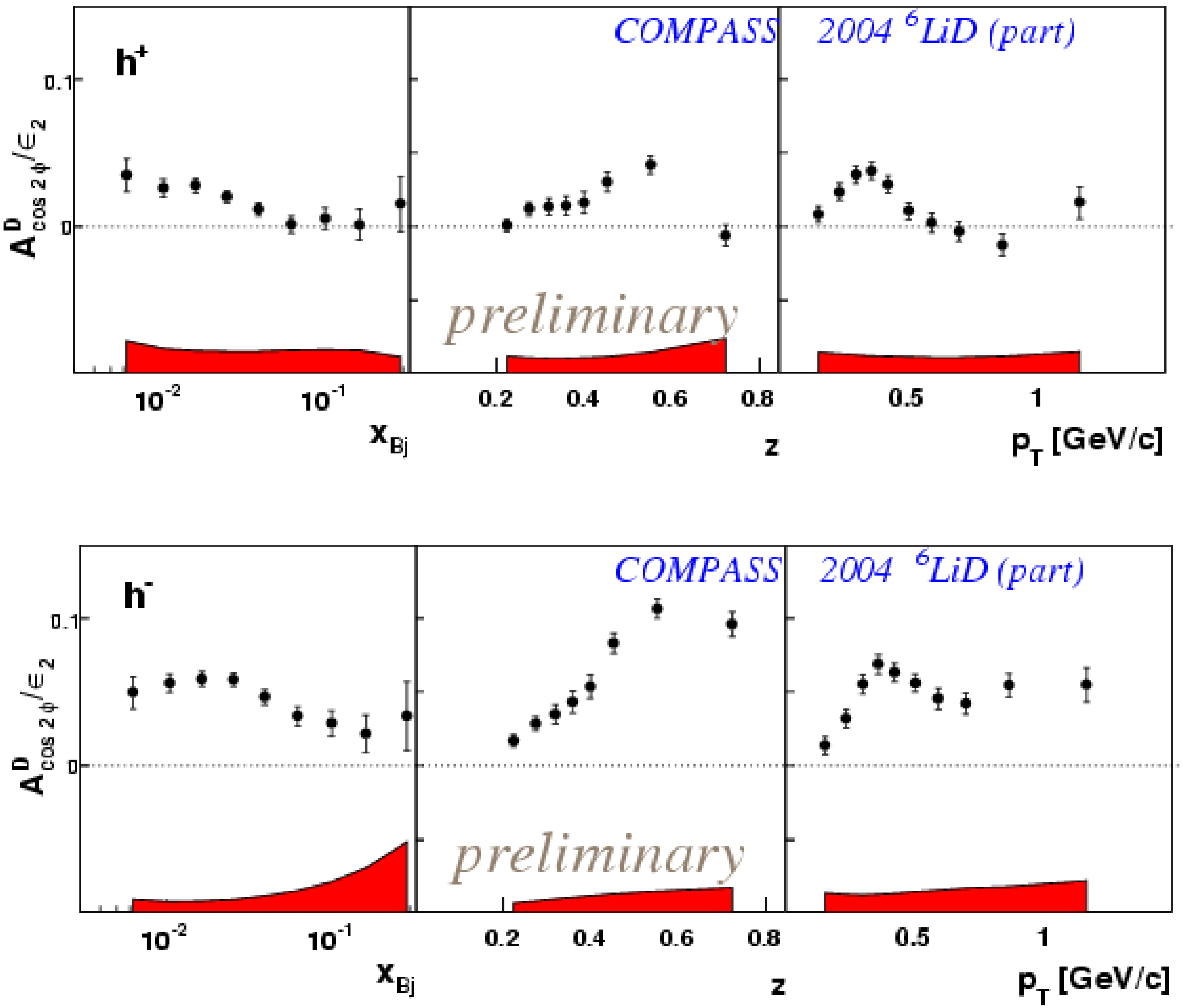

**error bars: statistical errors**

**red bands: systematical errors**

# cos2$\Phi$ modulation

$$\frac{A_{\cos 2\phi}}{\epsilon_2}$$

$$\epsilon_2 = \frac{(1-y)\cdot 2\cdot\sqrt{1-y}}{1+(1-y)^2}$$



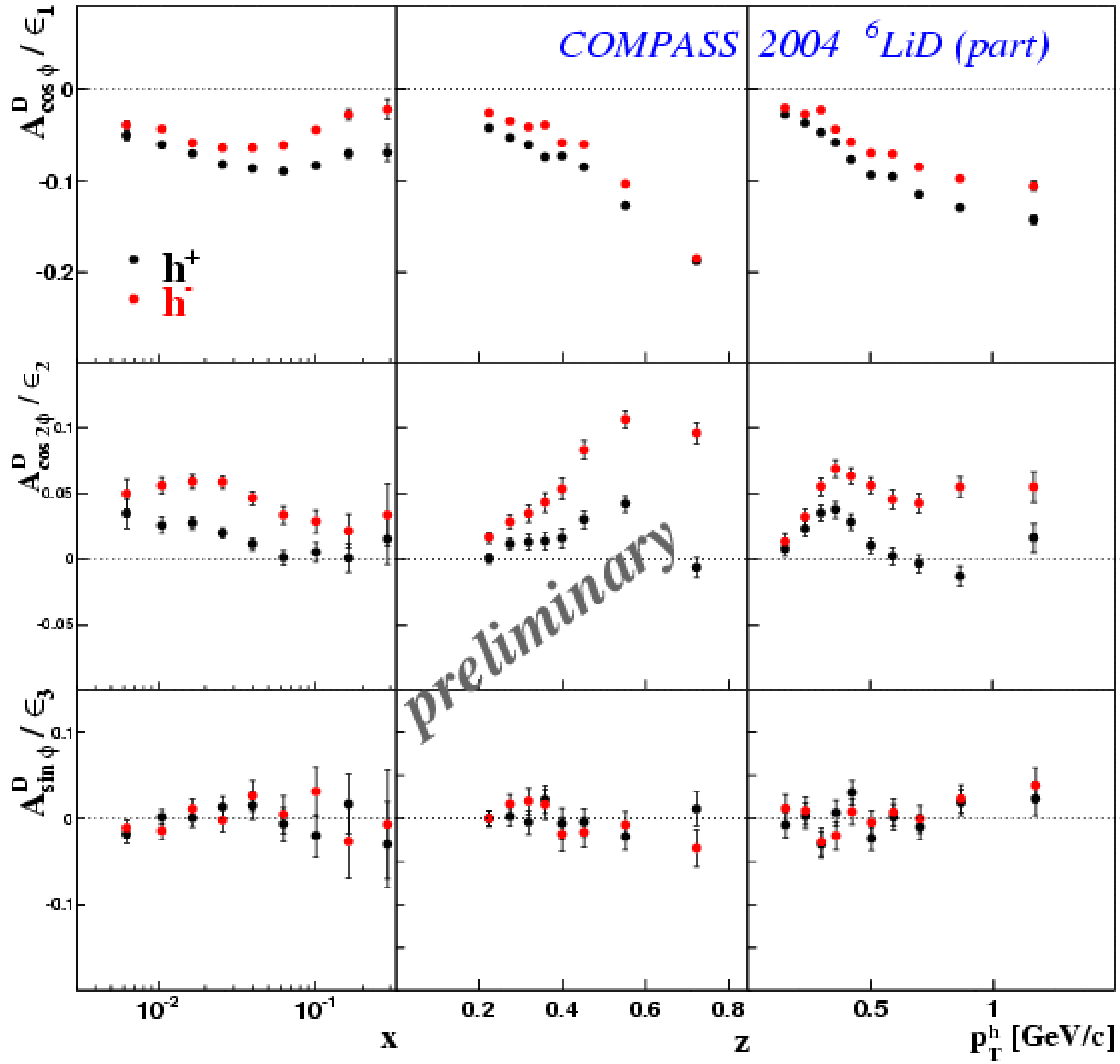

**error bars: statistical errors**

**red bands: systematical errors**

# summary:

**positive hadrons**

**negative hadrons**

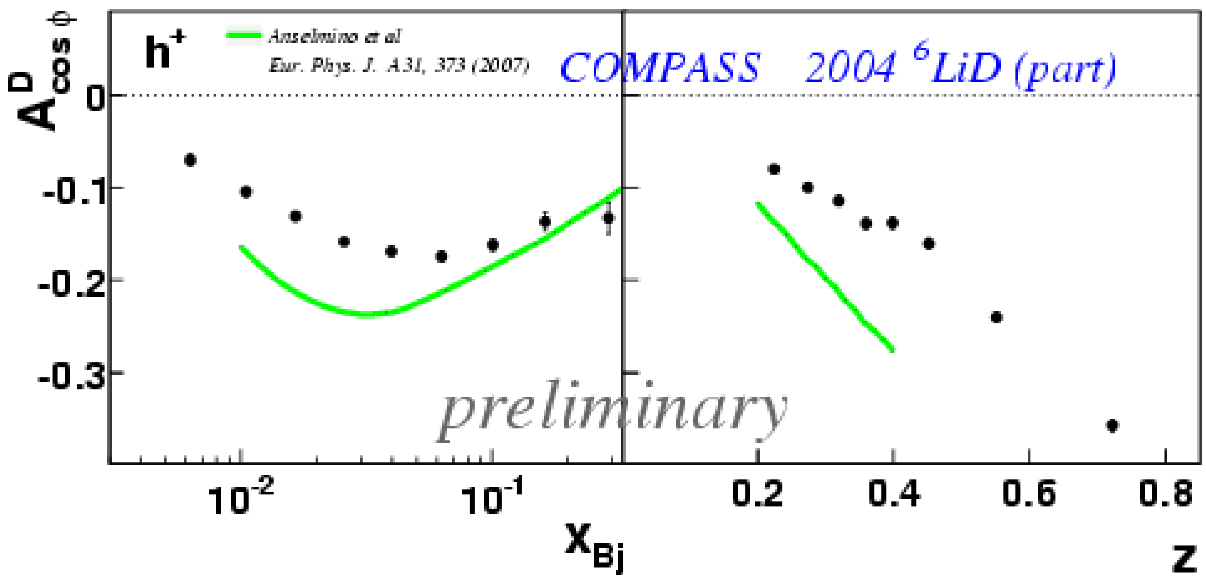



**error bars:**

**statistical only**

$\cos\Phi$

# comparison with theory




**predictions by:**

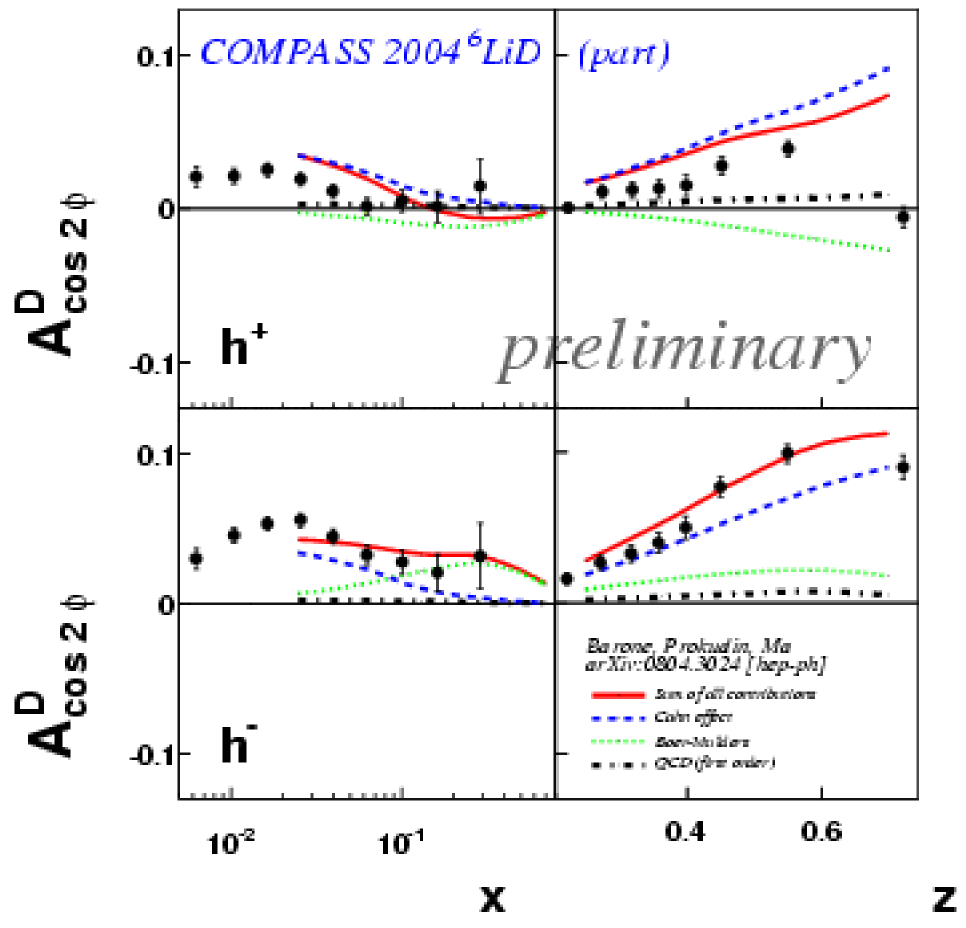
M. Anselmino, M. Boglione, A. Prokudin, C. Turk

Eur. Phys. J. A 31, 373-381 (2007)

**does not include Boer-Mulders contribution**

cos2$\Phi$

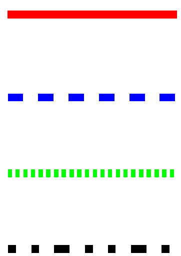
# comparison with theory




**predictions by:**

V. Barone, A. Prokudin, B.Q. Ma

arXiv:0804.3024 [hep-ph]



sum of all contributions

Cahn effect

Boer-Mulders

QCD (first order)

# Conclusions (I)

## First results on unpolarized asymmetries from COMPASS

- **sin$\Phi$ compatible with zero**
- **cos$\Phi$ stronger effect (up to 40%), cos2$\Phi$ up to 10%**
  **(good general agreement with predictions)**
- **Differences between asymmetries from positive and negative hadrons (cos$\Phi$ and cos2$\Phi$) --> hint of B-M PDF**
- **new input for theoretical work and the better understanding of the nucleon structure**

# COMPASS results on transverse spin and transverse momentum effects

**on deuteron (2002-2004)**

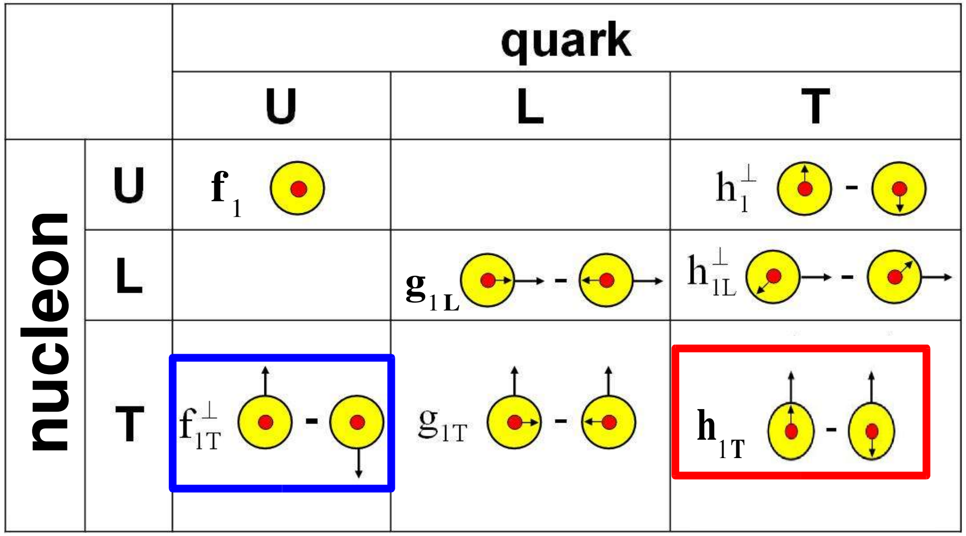
- Transversity DF
  - Collins asymmetry — charged only, identified hadrons
  - Two hadron asymmetries — charged only, identified hadrons
  - $\Lambda$ polarization
- Sivers DF
  - single hadron asymmetries — charged only, identified hadrons
- Other transverse spin dependent PDF
  - single hadron asymmetries — charged only, identified hadrons

**2007 proton data ...**

**just a flash:**

**Collins and Sivers asymmetries extracted from proton data (2007)**

new COMPASS results shown at Transversity 2008 (Ferrara-Italy)
on transverse spin and transverse momentum effects




| | | hadron |
|---|---|---|
| | | U |
| quark | U | $D_1$ |
| | T | $H_1^{\perp}$ |

$f_{1T}^{\perp} \otimes D_1$ **Sivers asymmetries**

Sivers PDF

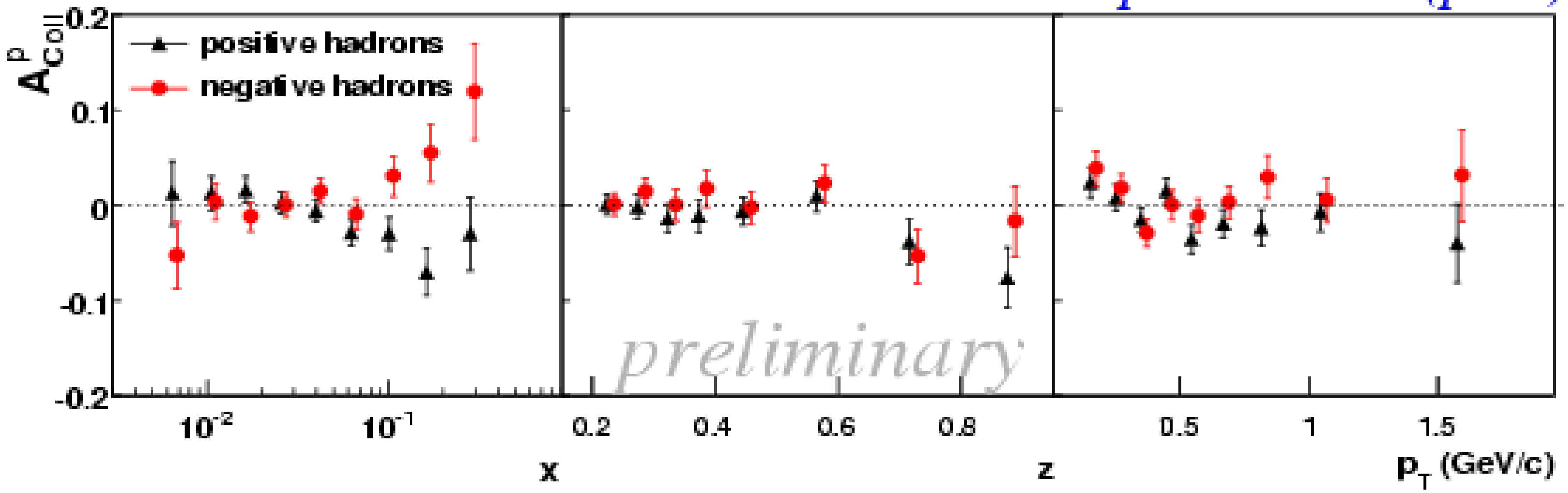
**Collins asymmetries** $h_{1T} \otimes H_1^{\perp}$

transversity Collins FF

two independent
azimuthal modulation in hadrons distributions

# Collins asymmetry

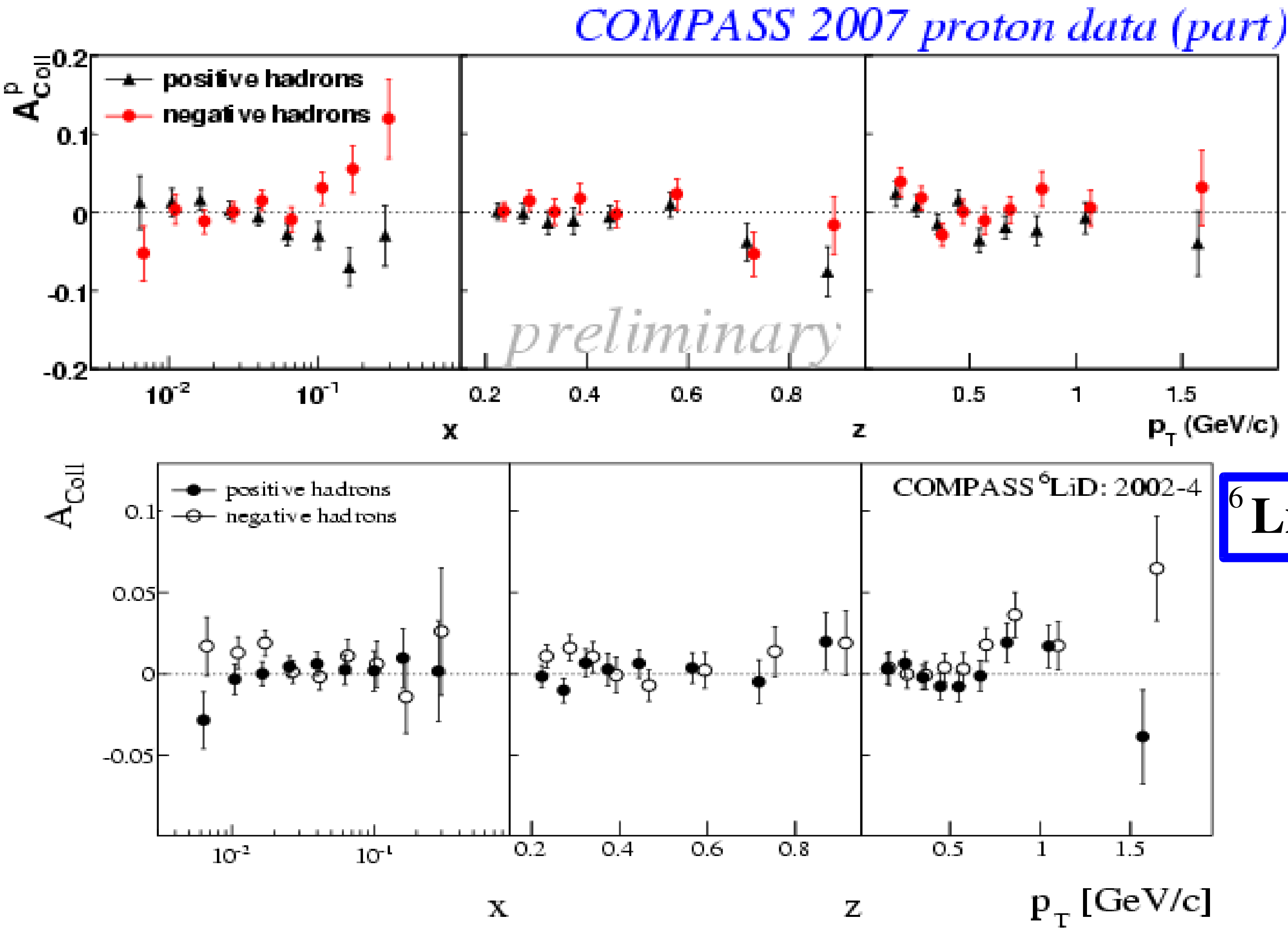
COMPASS 2007 proton data (part)




statistical errors only; systematic errors ~0.3 $\sigma_{stat}$

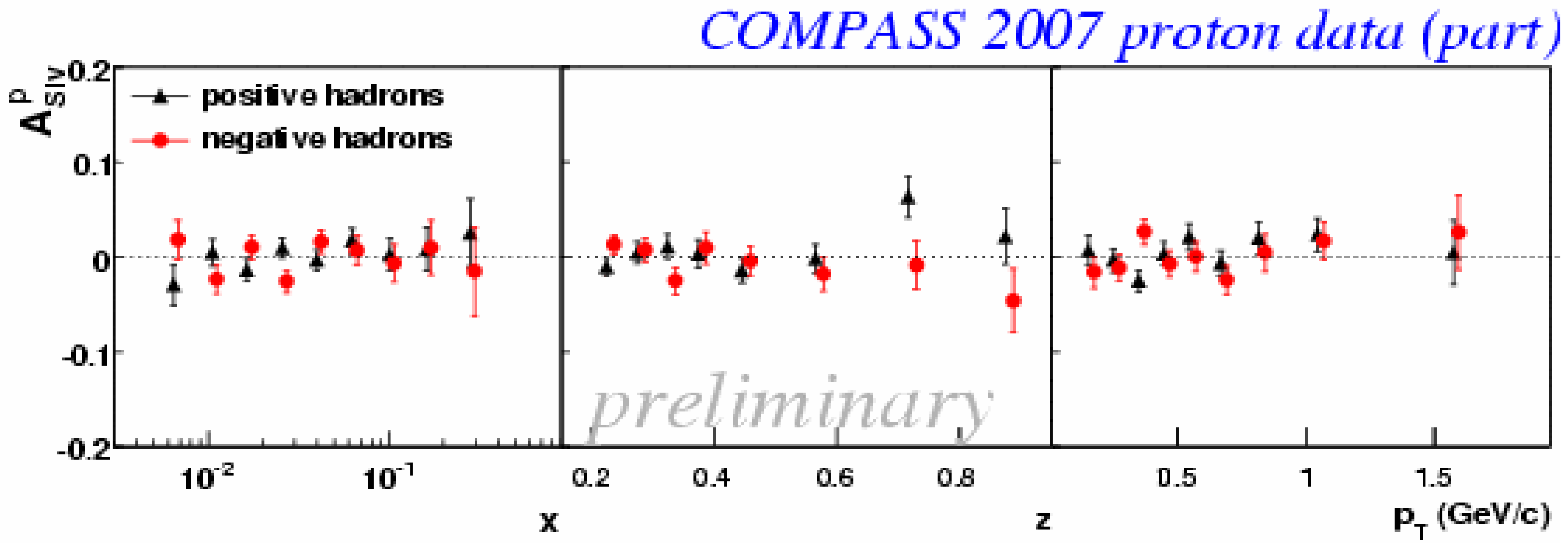
at small x the asymmetries are compatible with zero
in the valence region the asymmetries are different from zero, of opposite sign for positive and negative hadrons, and have the same strength and sign as HERMES

# Collins asymmetry




$^6$LiD target

# Sivers asymmetry




statistical errors only; systematic errors ~0.5 $\sigma_{stat}$

the measured asymmetries are small, compatible with zero

# Conclusions (II)

## Collins and Sivers asymmetries for protons

- **Collins asymmetry on proton target is different from zero**
  **the effect is there at COMPASS energies**
  **(transversity PDF and Collins FF different from zero)**

- **Sivers asymmetries smaller, compatible with zero**
  **these results suggest small effect at COMPASS energies**
  **to be understood**