Azimuthal asymmetries in the unpolarized SIDIS mu-D cross section at COMPASS

Giulio Sbrizzai Trieste University and INFN

on behalf of the COMPASS collaboration

SPIN2010 - Juelich

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

NA58

Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia

Bielefeld, Bochum, Bonn, Calcutta, CERN,

Dubna, Erlangen, Freiburg, Lisbon,

Mainz, Moscow, Munich, Prague, Protvino,

Saclay, Tel Aviv, Torino, Trieste, Warsaw,Yamagata

29 Institutes, ~230 physicists

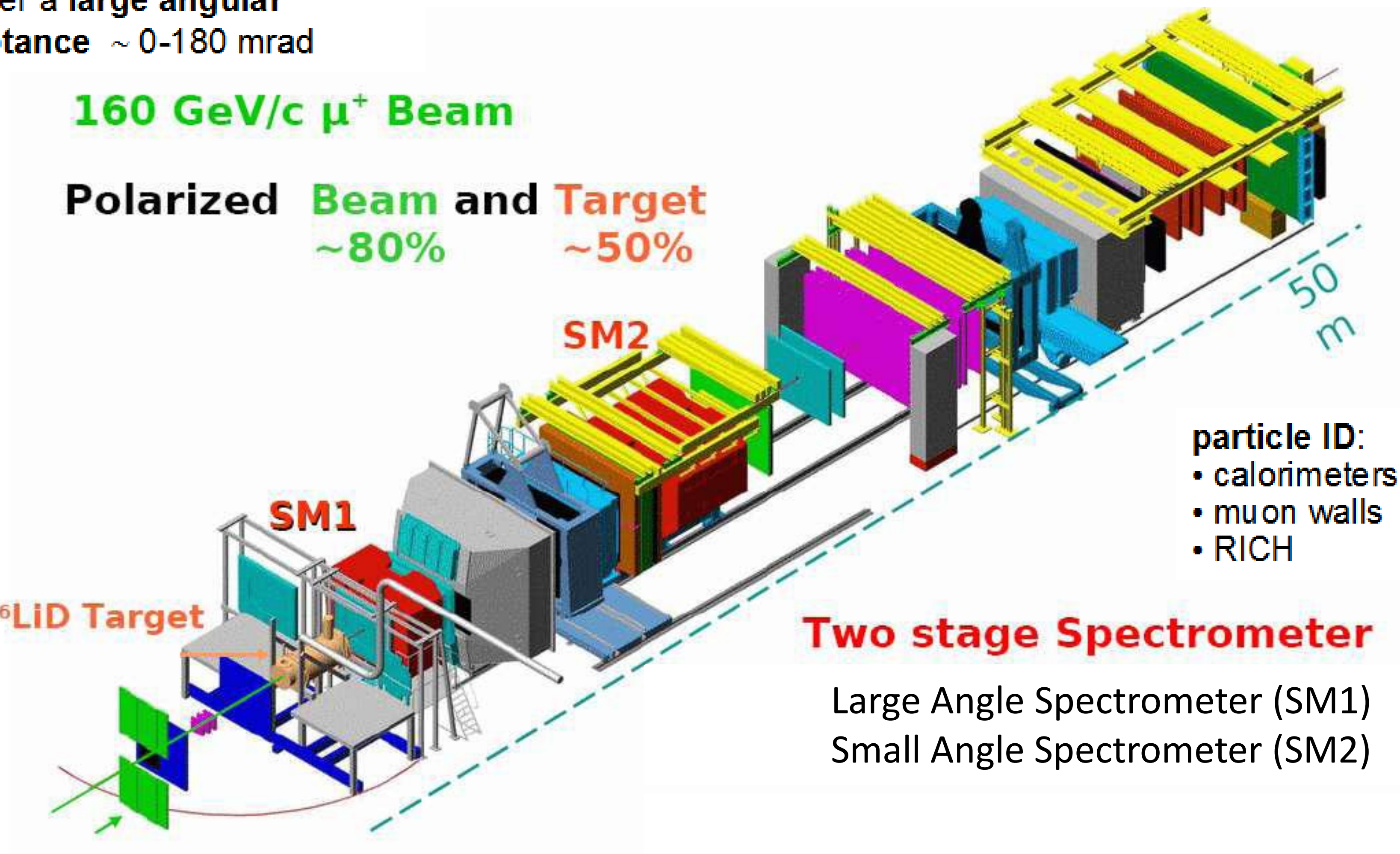

muon beam
deuteron (^{6}LID) polarized target
2002
2003
2004
2006
proton (NH_3) polarized target
2007
2010
hadron beam
LH target
2008
2009
luminosity: ~5 · 10^{32} cm^{-2} s^{-1}
beam intensity: 2·10^8 μ^+/spill (4.8s/16.2s)
beam momentum: 160 GeV/c
COMPASS
LHC
SPS
N

This talk will focus on the results extracted from the 2004 data (longitudinally pol. muon beam, transversely pol. deuteron target)

The COMPASS experiment (2004 setup)

several tracking detectors of different type

- to cope with **high particle rates**
- to cover a **large angular acceptance** ~ 0-180 mrad



Large Angle Spectrometer (SM1)
Small Angle Spectrometer (SM2)

OUTLINE

- Introduction
- The Analysis
  - asymmetries extraction
  - MC description
  - acceptance studies
  - systematic errors
- Final results
- Conclusions

SIDIS: a key process to investigate the structure of the nucleon

lepton interacts with a **single constituent** of the nucleon ($Q^2 > 1 GeV^2/c^2$)

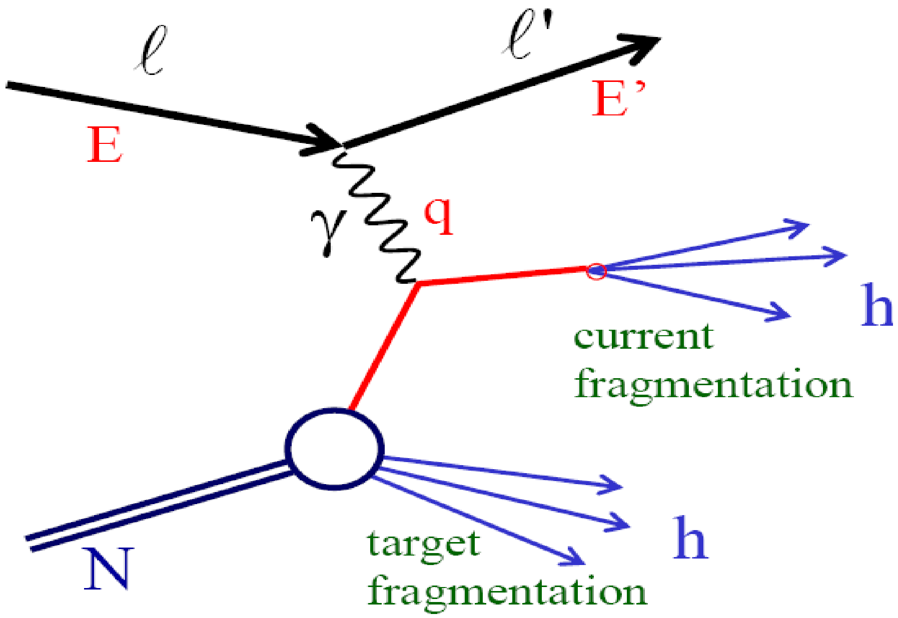
$$q = \ell - \ell'$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$x = \frac{Q^2}{2P \cdot q}$$ *Bjorken scaling variable*

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

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



at least one hadron is detected in the final state
(information on the struck quark)

The SIDIS cross section (one photon exchange approximation)

From A. Bacchetta et al., JHEP 0702:093,2007.

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

unpolarized

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

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

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

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

nucleon long. pol.

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

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

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

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

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

nucleon transv. pol.

independent modulations in the azimuthal angle of the spin ϕ_S and of the hadron ϕ_h

(around the virtual photon direction)

coupled with different Structure Functions related to the:

- nucleon and quark polarization
- quark transverse momentum

...

The SIDIS cross section (one photon exchange approximation)

From A. Bacchetta et al., JHEP 0702:093,2007.

nucleon polarization

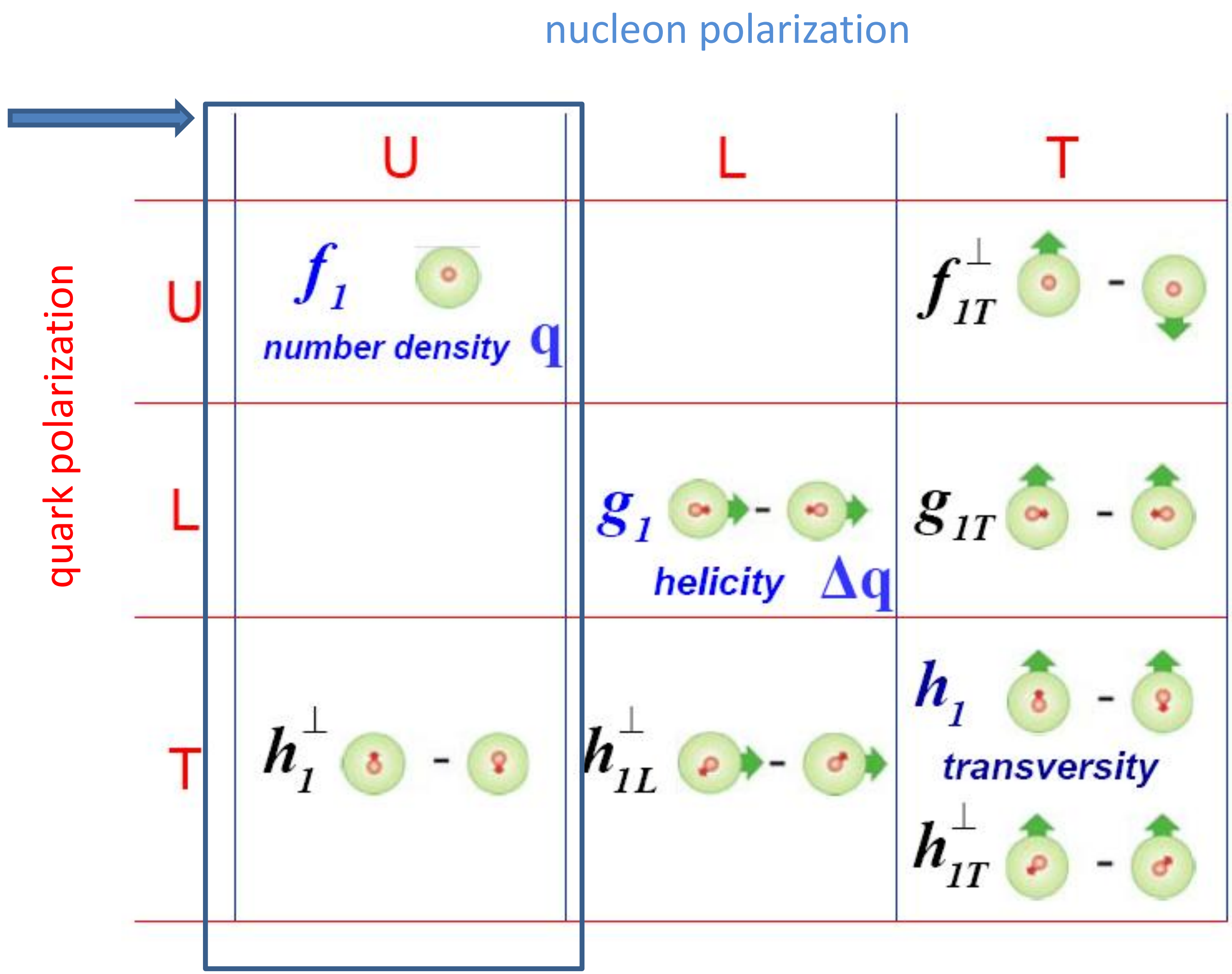
quark polarization	U	L	T
U	f_1 number density q		$f_{1T}^{\perp}$
L		g_1 helicity Δq	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 transversity $h_{1T}^{\perp}$

... allow to measure
the **Parton Distribution Functions (PDF)**
which describe
the nucleon at leading order

The SIDIS cross section (one photon exchange approximation)

From A. Bacchetta et al., JHEP 0702:093,2007.

PDF which appear in an unpolarized nucleon
(balancing data taken with different target polarization)



3 independent azimuthal modulations *expected in the*
in the **azimuthal hadrons distribution**
if the Transverse Momentum (TM) of the quarks $\neq 0$

$$N(\phi_h) \propto N_0 \cdot \left(1 + \varepsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \varepsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h + \lambda_l \varepsilon_3 A^{LU}_{\sin\phi_h} \sin\phi_h\right)$$

$$\sum_q PDF_q(x) \otimes FF_q^h(z)$$

convolution on the TM of the quark

interesting terms: TMD PDFs , FFs

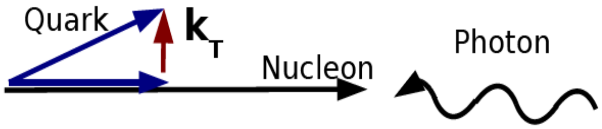
kinematical factors

$$\varepsilon_1 = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \qquad \varepsilon_2 = \frac{2(1-y)}{1+(1-y)^2} \qquad \varepsilon_3 = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

λ_l beam polarization

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

mainly **Cahn** effect: **kinematical effect** proportional to the **quark transverse momentum**



$$d\sigma^{lq\to lq} \propto \hat{s}^2 + \hat{u}^2 \propto \left(1 + \varepsilon_1 \frac{k_\perp}{Q}\cos\varphi\right)$$

pQCD negligible for P^h_T < 1 GeV/c

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

Boer-Mulders (*T-odd !*) function, one of the most famous **TMD PDF**, convoluted with the **Collins FF**

also Cahn effect contribution $\propto \left(\frac{k_\perp}{Q}\right)^2$

pQCD negligible for P^h_T < 1 GeV/c

the **Boer-Mulders function correlates** the **quark transverse momentum** and the **quark spin** in an **unpolarized nucleon**

$A^{LU}_{\sin\phi_h}$

twist 3 effect due to beam polarization

The **amplitudes of the 3 azimuthal modulations** have been **measured at COMPASS** separately for **positive and negative hadrons**, as functions of the kinematical variables **x,z** and $\mathbf{P^h_T}$ (transv. mom. of the hadron w.r.t. the virtual photon)

Basic idea of the method

- To measure those amplitudes from experimental data
the **apparatus acceptance is needed** (unlike transverse spin asymmetries measurement)

- **for each bin** (k) in **x, z** and $\mathbf{P_T^h}$

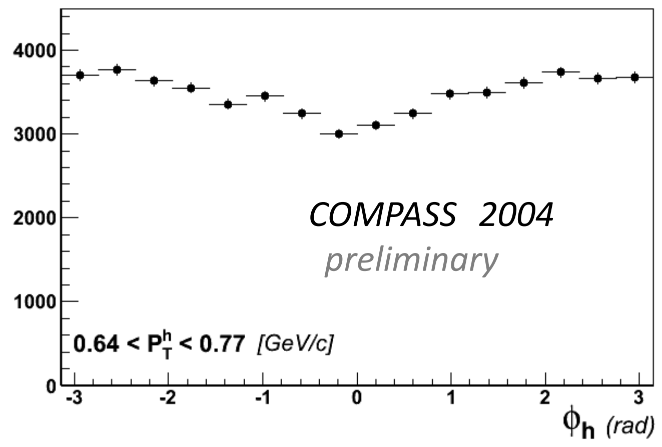
  - The **measured azimuthal distributions** need to be **corrected** for the **apparatus acceptance** which may depend on ϕ_h

$$N_k^{corr}(\phi_h) = \frac{N_k(\phi_h)}{Acc_k(\phi_h)}$$

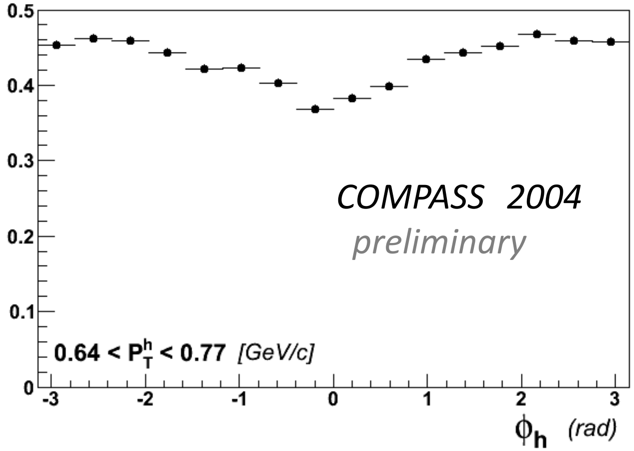
  - Azimuthal acceptance calculated from **dedicated MC simulations**

$$Acc_k(\phi_h) = \frac{R_k^{mc}(\phi_h)}{G_k^{mc}(\phi_h)}$$

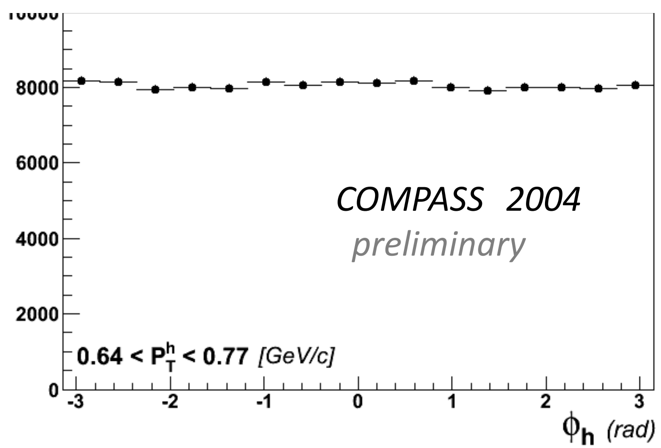
MC rec. azimuthal distribution



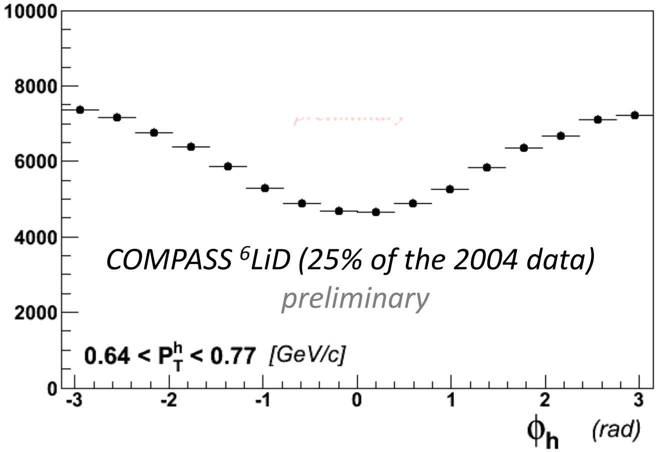
azimuthal acceptance



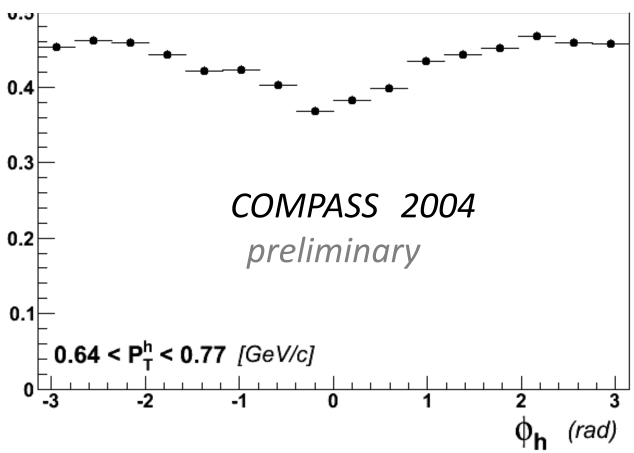
MC gen. azimuthal distribution



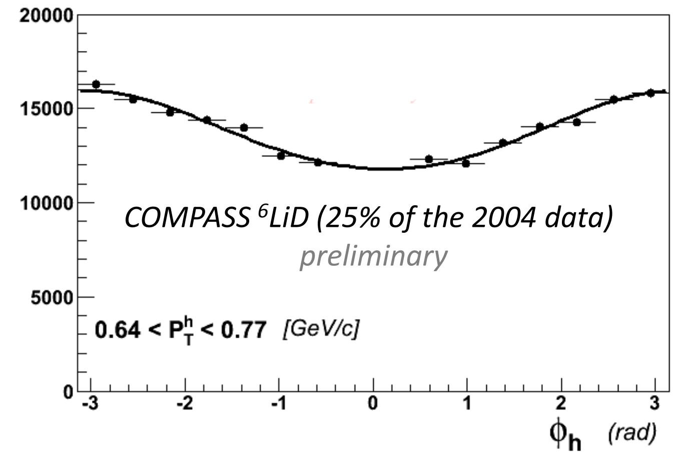
measured azimuthal distribution



azimuthal acceptance



measured azimuthal distributions corrected by the acceptance



amplitudes extracted with a fit:

$$p_0 \cdot (1 + p_1 \cdot \cos\phi_h + p_2 \cdot \cos 2\phi_h + p_3 \cdot \sin\phi_h)$$

ACCEPTANCE STUDIES

Full MC chain to reproduce apparatus acceptance:

- LEPTO (generator, CTEQ5L PDF)
- COMGEANT (dedicated software to simulate the spectrometer)
- CORAL (same software used for the event reconstruction)

SIDIS cuts applied

$Q^2 > 1\ (GeV/c)^2$

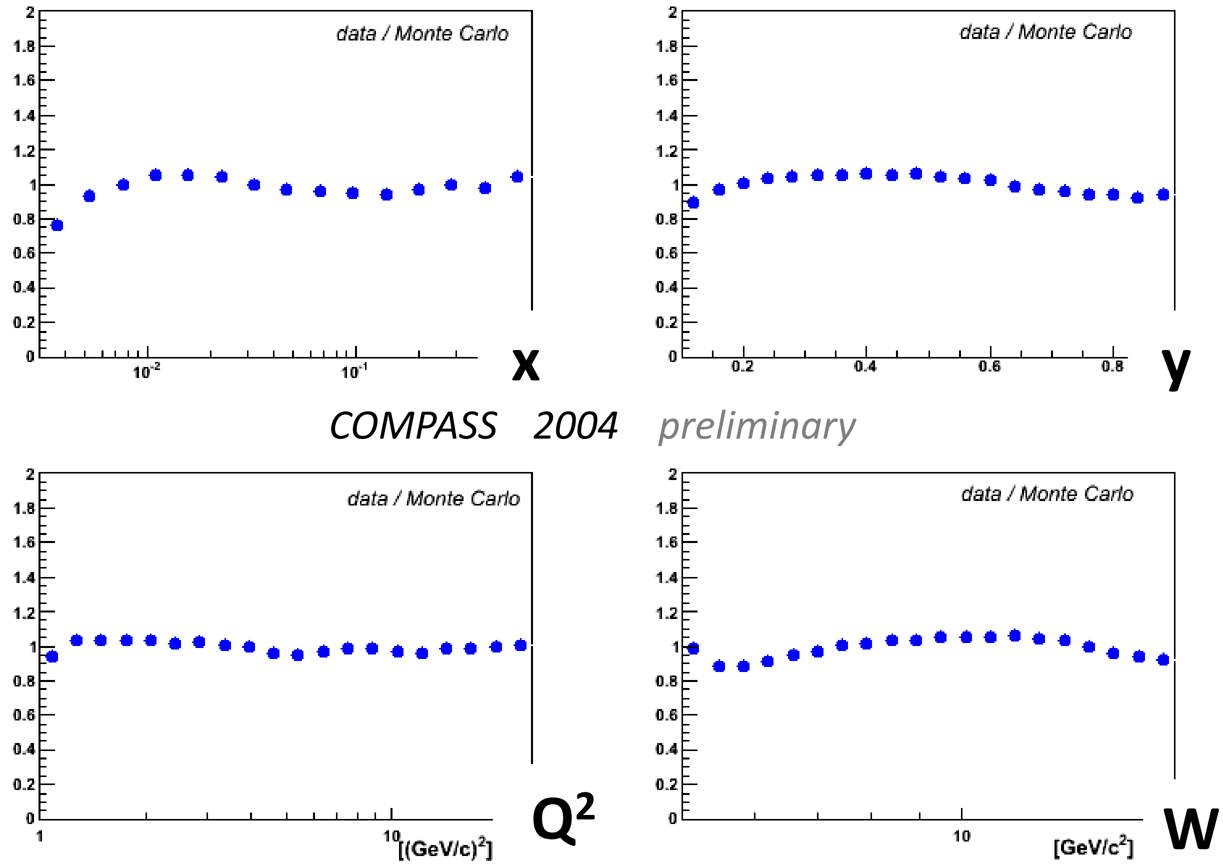
$0.1 < y < 0.9$

$W > 5\ GeV/c^2$

$0.2 < z < 0.85$

$P^T_h > 0.1\ GeV/c$

DATA / MONTE CARLO   DIS variables



overall good agreement between real data and MC is a check on the reliability of the MC description (no absolute normalization needed)

DATA / MONTE CARLO

Hadron variables

SIDIS cuts applied

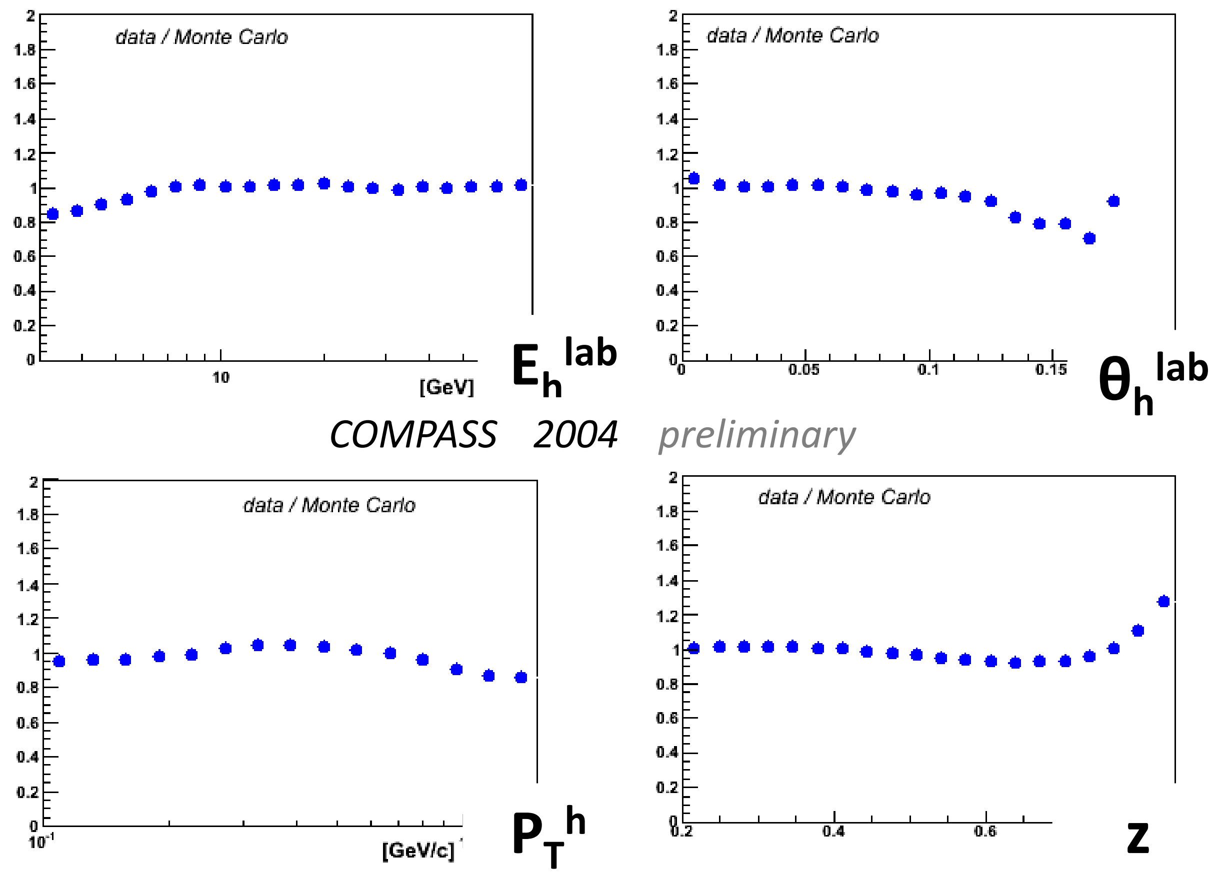
$Q^2 > 1\ (GeV/c)^2$

$0.1 < y < 0.9$

$W > 5\ GeV/c^2$

$0.2 < z < 0.85$

$P^T_h > 0.1\ GeV/c$



The apparatus azimuthal acceptance *as a function of the event kinematics has been* ***studied*** *at length* ***in order to exclude*** *the regions giving rise to* ***large azimuthal modulations in the acceptance*** *(above 50% for some bin)*

→ **new cuts have been tuned:**

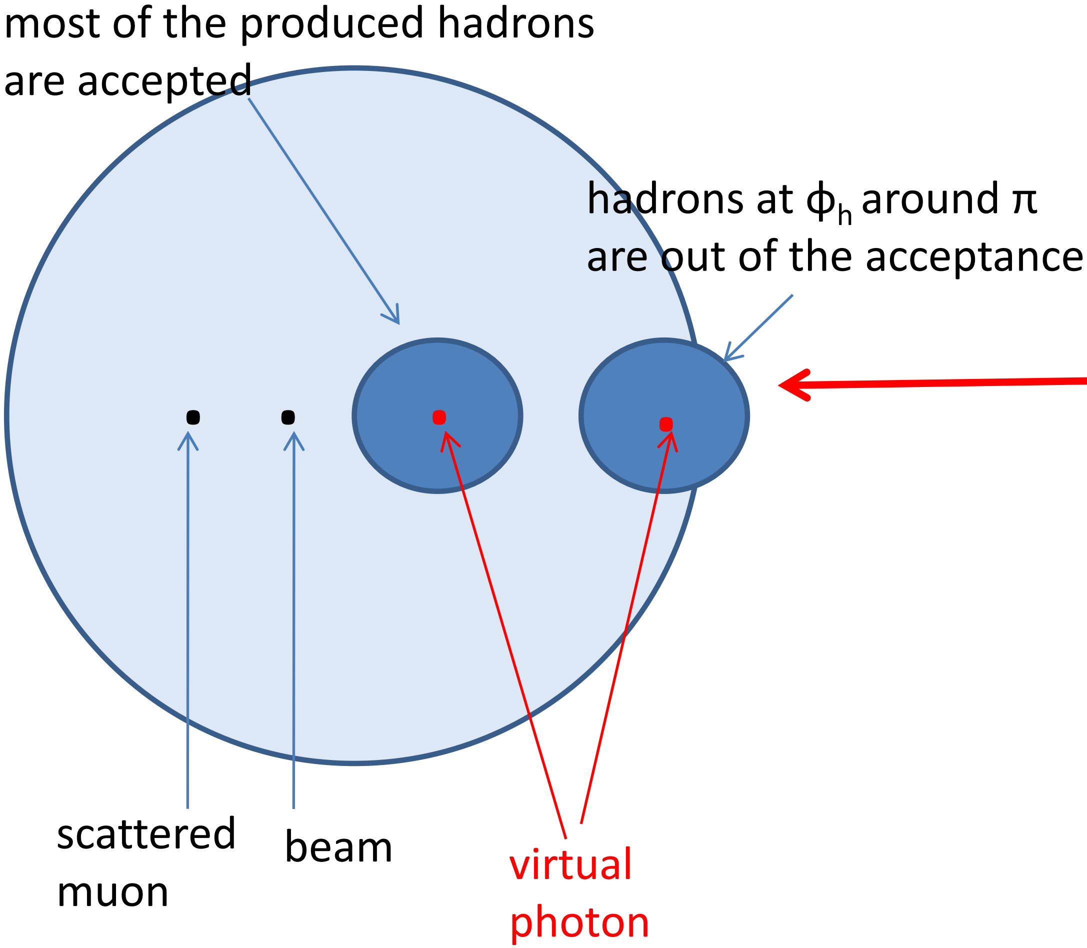
$Q^2 > 1\ (\text{GeV}/c)^2$

$< y < 0.9$

$W > 5\ \text{GeV}/c^2$

$0.2 < z < 0.85$

$0.1 < P^T_h \quad \text{GeV}/c$



$Q^2 > 1$ (GeV/c)^2

$\theta_\gamma^{lab} < 0.06$

$0.003 < x < 0.13$

$0.2 < y < 0.9$

$W > 5$ GeV/c^2

$0.2 < z < 0.85$

$0.1 < P^T_h < 1$ GeV/c

the **large corrections** given by the acceptance **disappeared**

- the dependence of the **acceptance** from all the ϕ_h dependent terms turned out to be **flat** over the kinematical range

↓

checked by extracting the acceptance in one more dimension (x in the example)

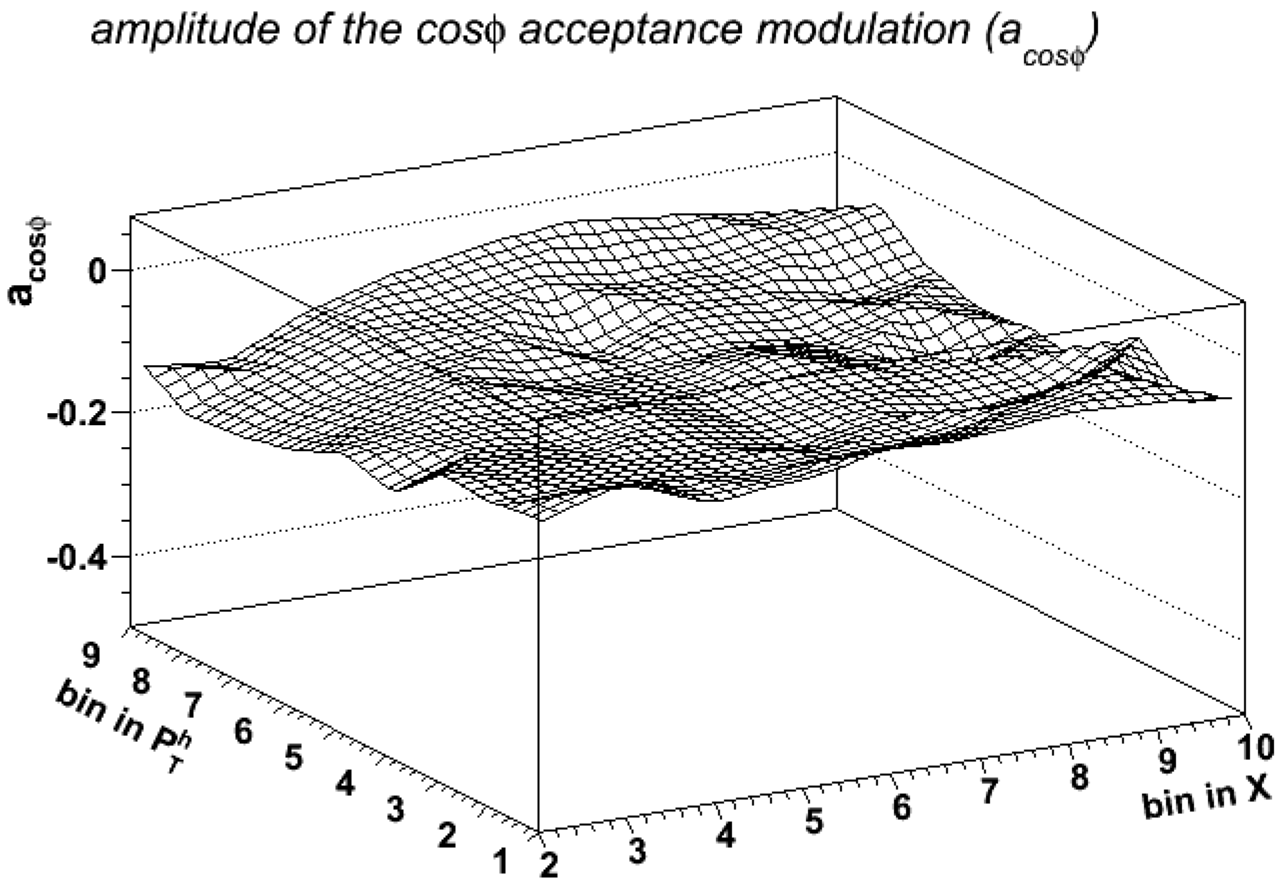
$$Acc_k(\phi_h, x) = \frac{R_k^{mc}(\phi_h, x)}{G_k^{mc}(\phi_h, x)}$$

←

$$Acc_k(\phi_h) = \frac{R_k^{mc}(\phi_h)}{G_k^{mc}(\phi_h)}$$

$$Acc_k(\phi, x) = a_0^k(x) \cdot (1 + a_1^k(x)\cos\phi + a_2^k(x)\cos 2\phi + a_3^k(x)\sin\phi + \ldots)$$

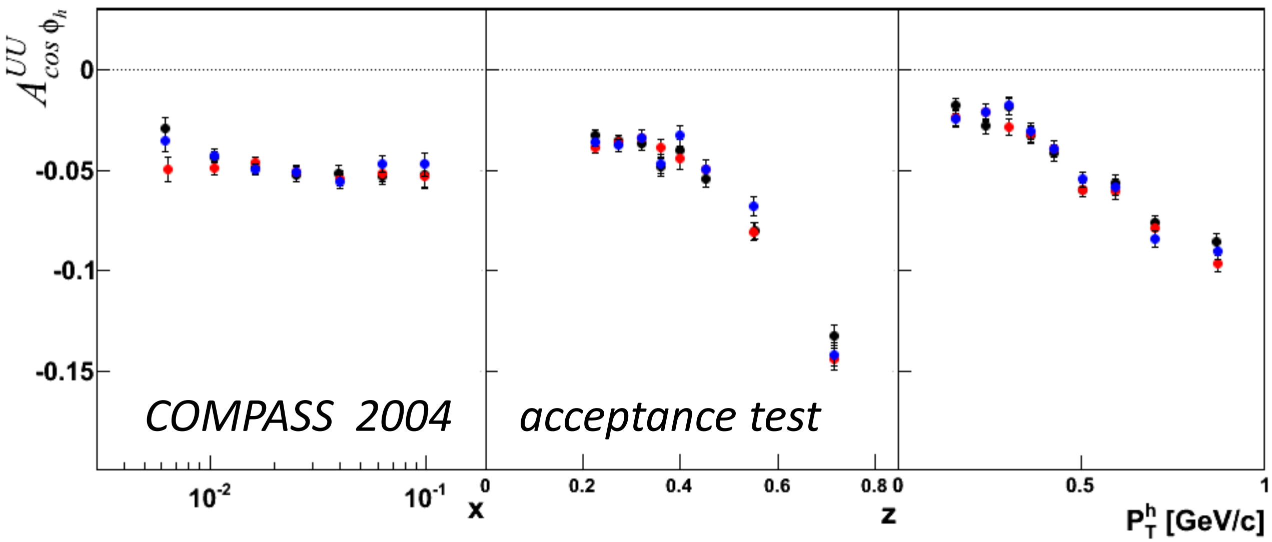
- the dependence of the **acceptance** from all the ϕ_h dependent terms turned out to be **flat** over the kinematical range



SYSTEMATIC ERROR

the sources of the systematic error which have been checked and included in the evaluation are the following:

- differences between amplitudes of the azimuthal modulations extracted using 3 different MC samples
  (obtained by changing PDFs and FF parameters)



the differences are small as expected if

$$Acc_k(\phi_h) = \frac{R_k^{mc}(\phi_h)}{G_k^{mc}(\phi_h)} = \frac{\int G_k^{mc}(\phi_h, x) \cdot Acc_k(\phi_h, x) dx}{G_k^{mc}(\phi_h)}$$

SYSTEMATIC ERROR

the sources of the systematic error which have been checked and included in the evaluation are the following:

- differences between amplitudes of the azimuthal modulations extracted using the 3 different MC samples

- differences between amplitudes of the azimuthal modulations extracted from transverse and longitudinal data (different apparatus setup → 2 different MC descriptions)

- estimation of possible azimuthal effects from unknown inefficiencies of detectors in low redundancies region

the different contributions calculated in each kinematical bin have been summed in quadrature :

$$\sigma_{sys} = 2 \cdot \sigma_{stat}$$

other studies ...

- a first calculation of the possible effects of radiative corrections have been performed using RADGEN and have been found to be relatively small

- more amplitudes have been added in the fitting function to the ones expected from the unpolarized cross section → compatible with zero

... not included in the systematic errors

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

have been extracted from the 2004 COMPASS data on the ^{6}LiD transversely polarized target

$Q^2 > 1\ (GeV/c)^2$

$0.003 < x < 0.13$

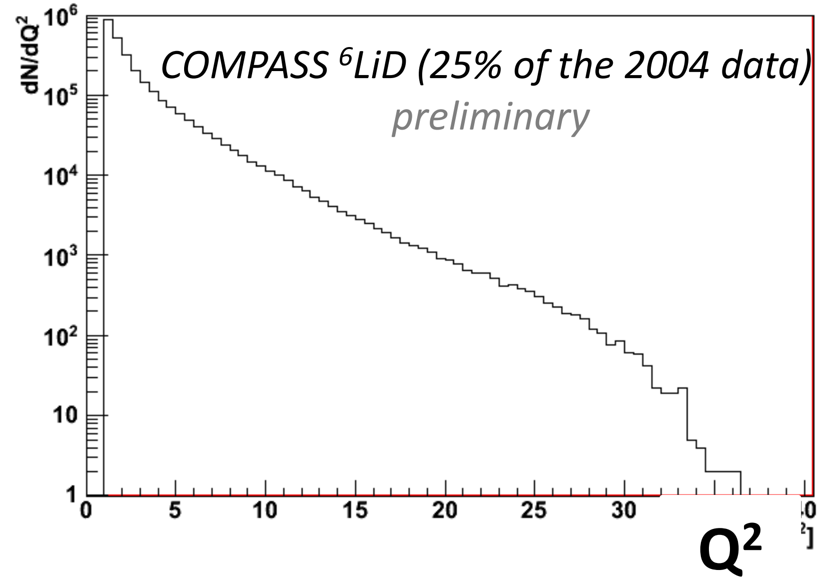
$0.2 < y < 0.9$

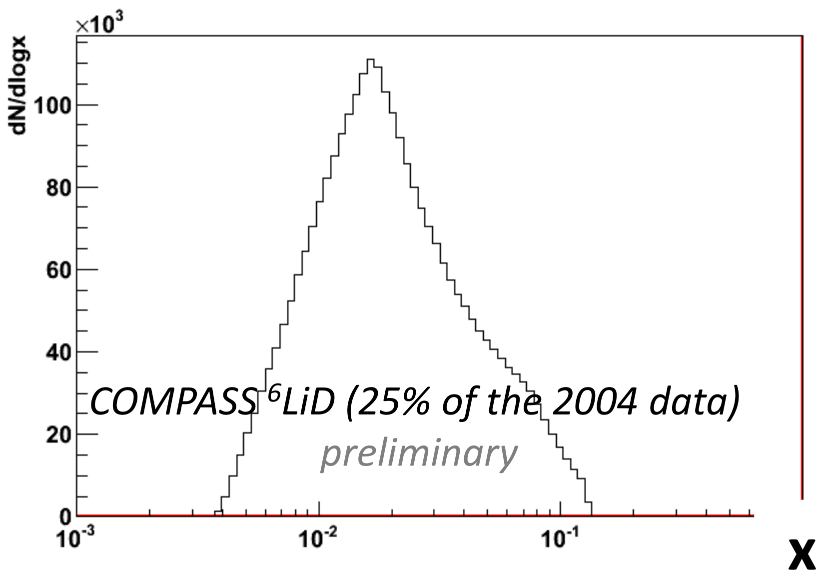
$W > 5\ GeV/c^2$

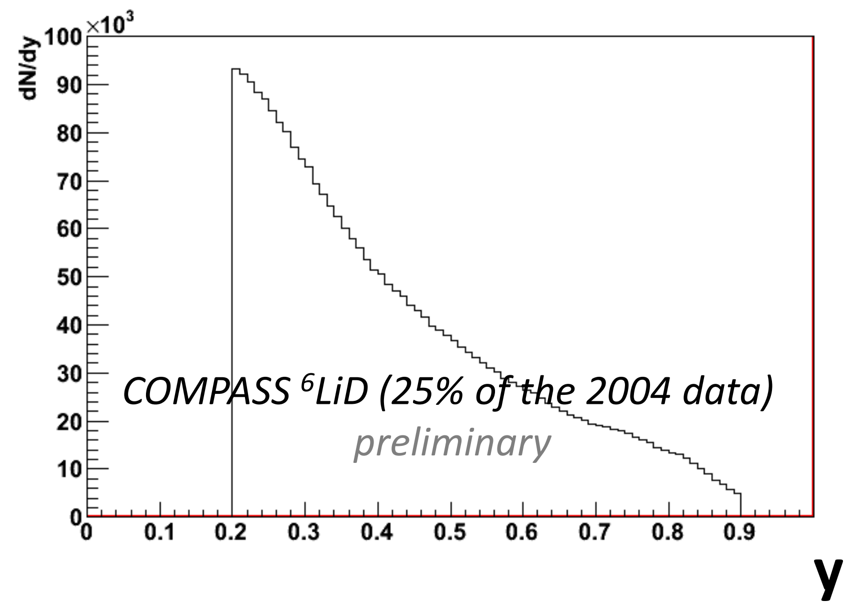
$0.2 < z < 0.85$

$0.1 < P^T_h < 1\ GeV/c$

kinematical distributions

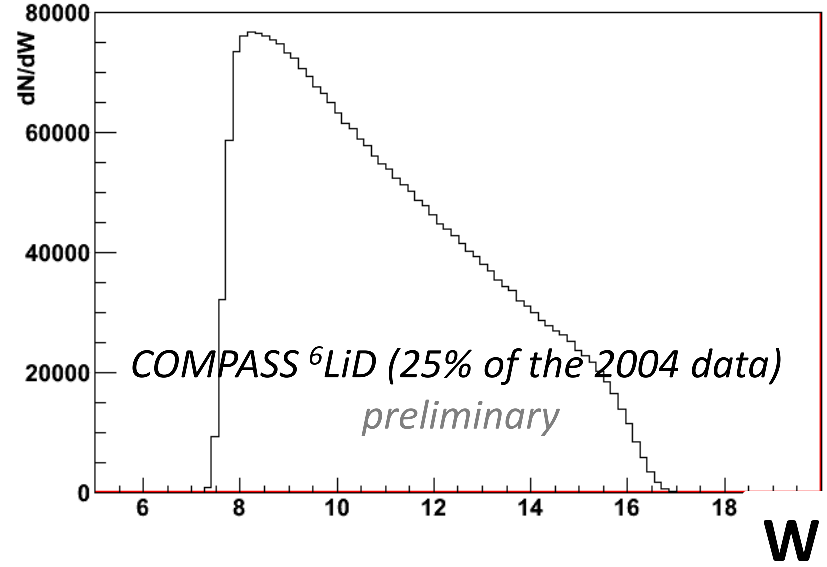


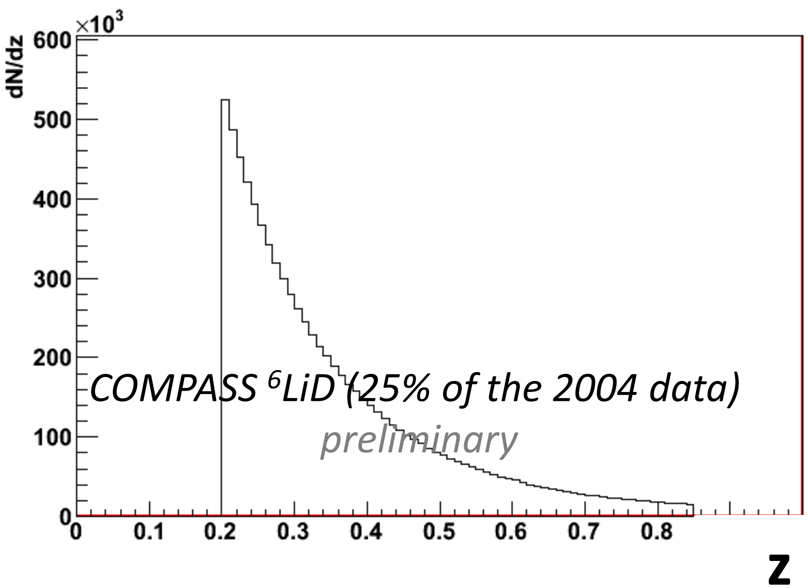


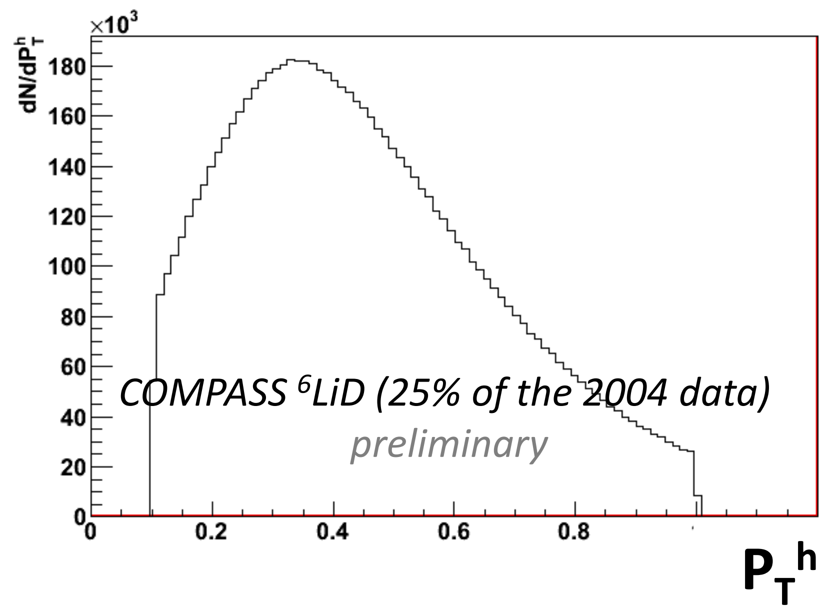


$Q^2 > 1\ (GeV/c)^2$
$0.003 < x < 0.13$
$0.2 < y < 0.9$
$W > 5\ GeV/c^2$
$0.2 < z < 0.85$
$0.1 < P^T_h < 1\ GeV/c$

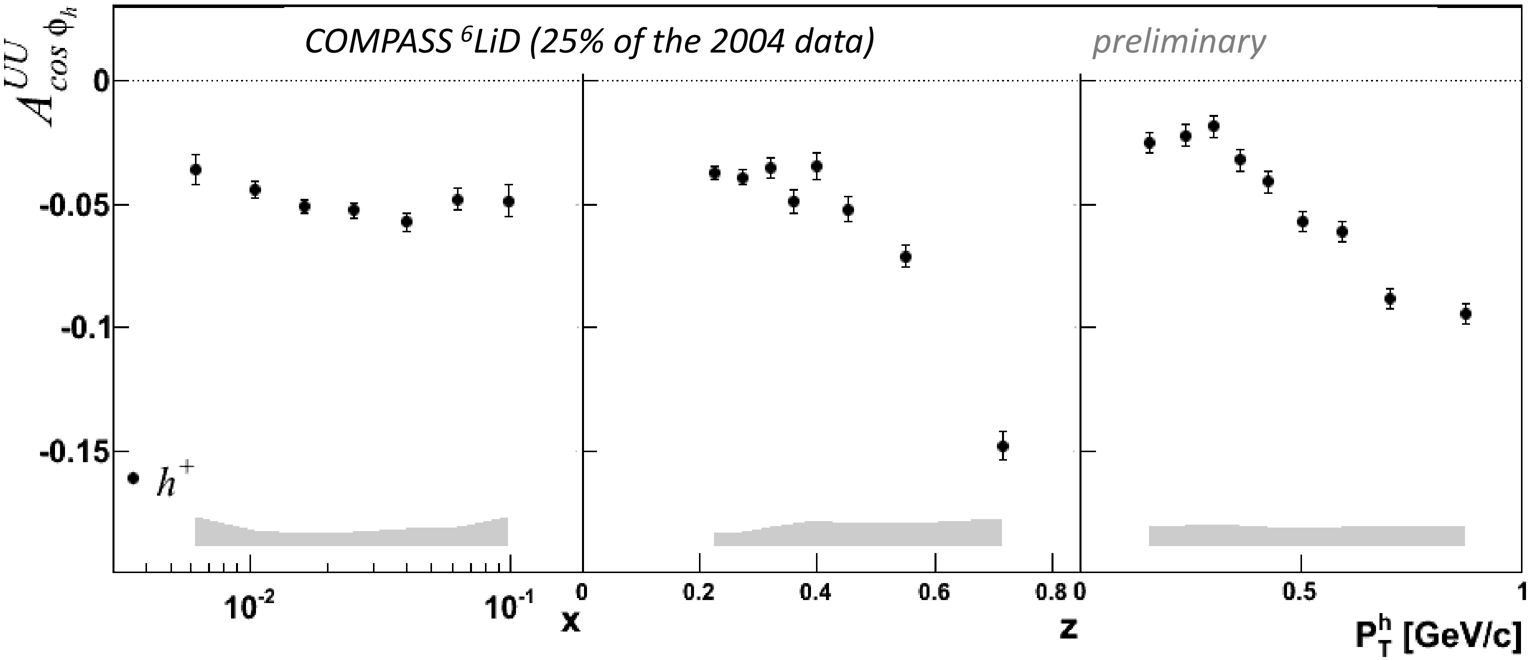
kinematical distributions



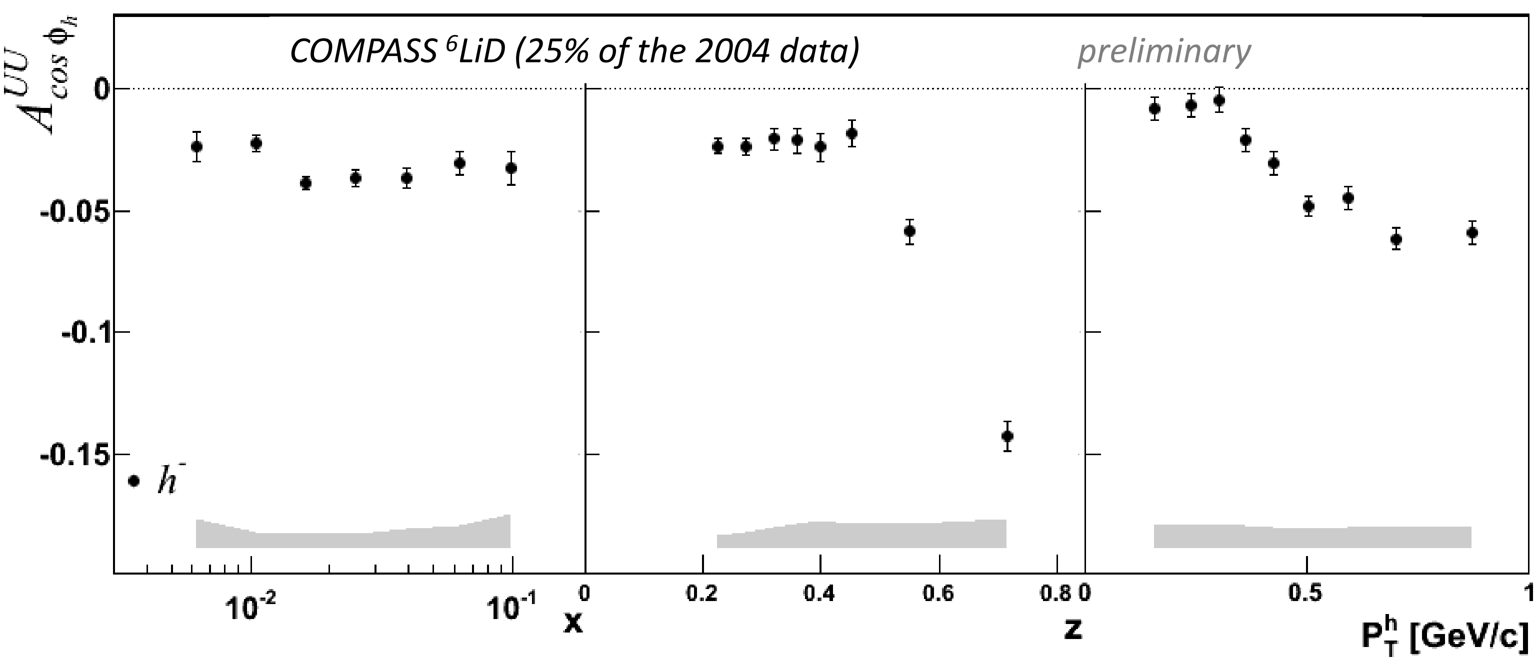




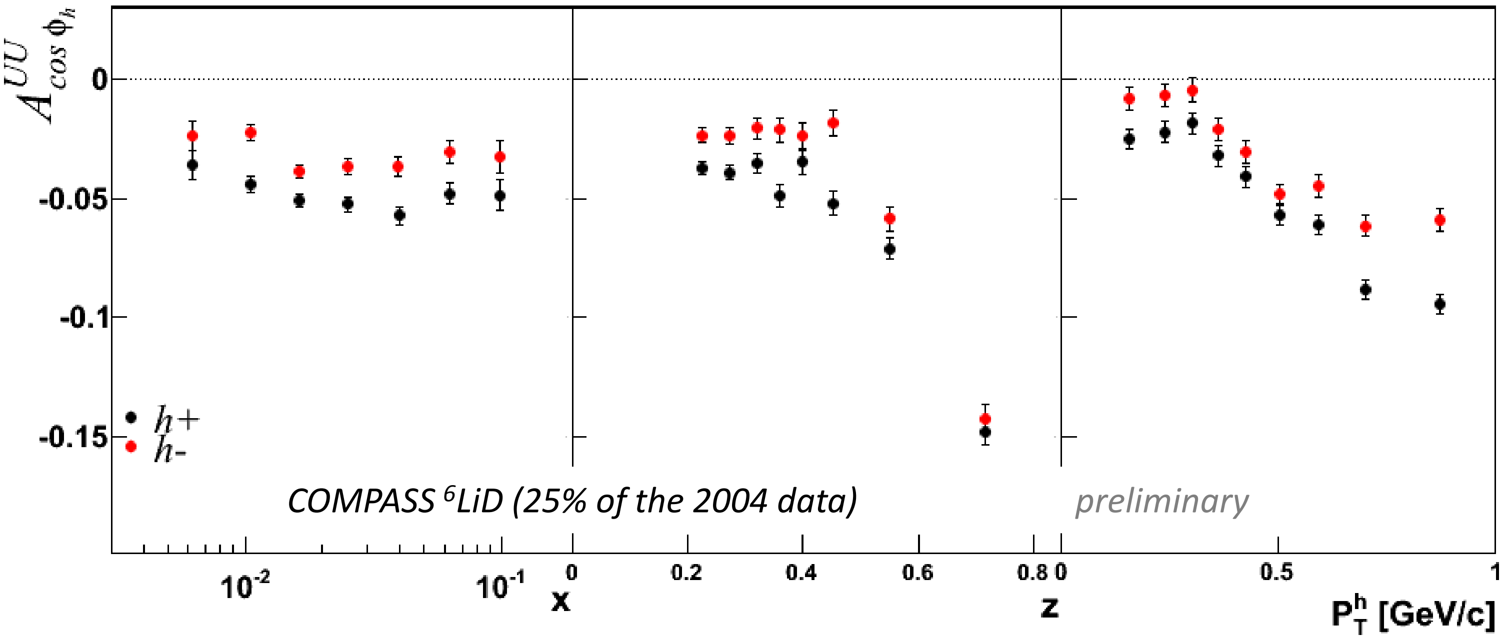
$$A_{\cos\phi_h}^{UU}$$



COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
$A^{UU}_{cos\,\phi_h}$
0
-0.05
-0.1
-0.15
h^+
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P^h_T [GeV/c]



COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
$A^{UU}_{cos\,\phi_h}$
0
-0.05
-0.1
-0.15
h^-
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P^h_T [GeV/c]



different results for positive and negative hadrons

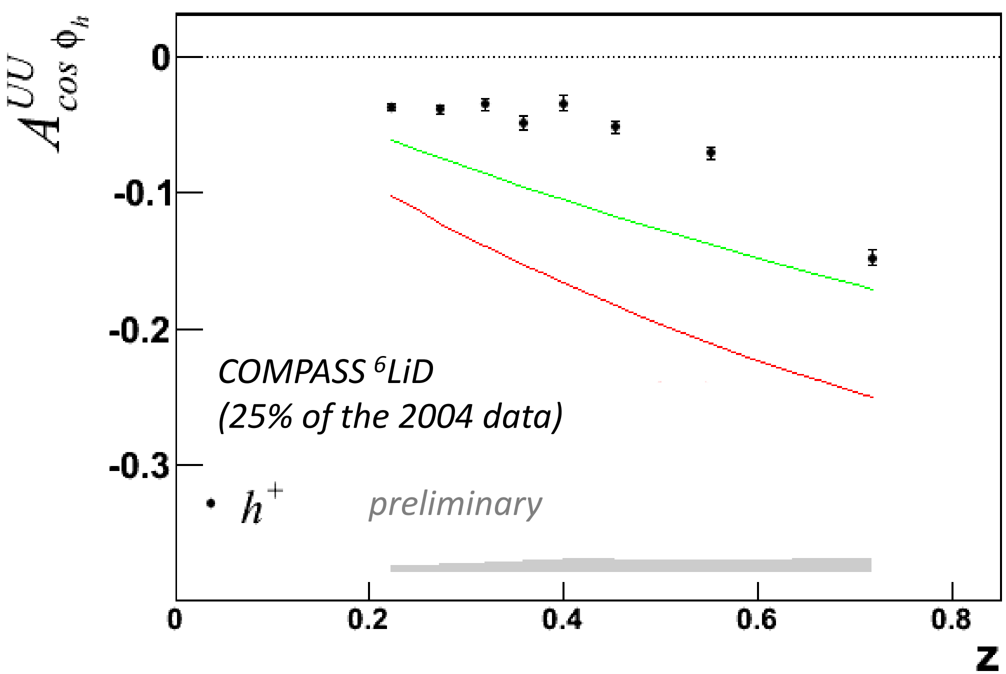
- **different transverse momentum for the u and d quarks**
- **Boer-Mulders TMD PDF (higher twist)**

considering only the Cahn effect one expects: *Schweitzer at al.*

$$A^{UU}_{\cos\phi_h}(z) = \frac{z < k_\perp^2 > \sqrt{\pi}}{2 < Q > \sqrt{z^2 < k_\perp^2 > + < p_\perp^2 >}}$$

$k_\perp$ *quark transverse momentum of w.r.t. the direction of the virtual photon*

$p_\perp$ *hadron transverse momentum w.r.t. the direction of the fragmenting quark*



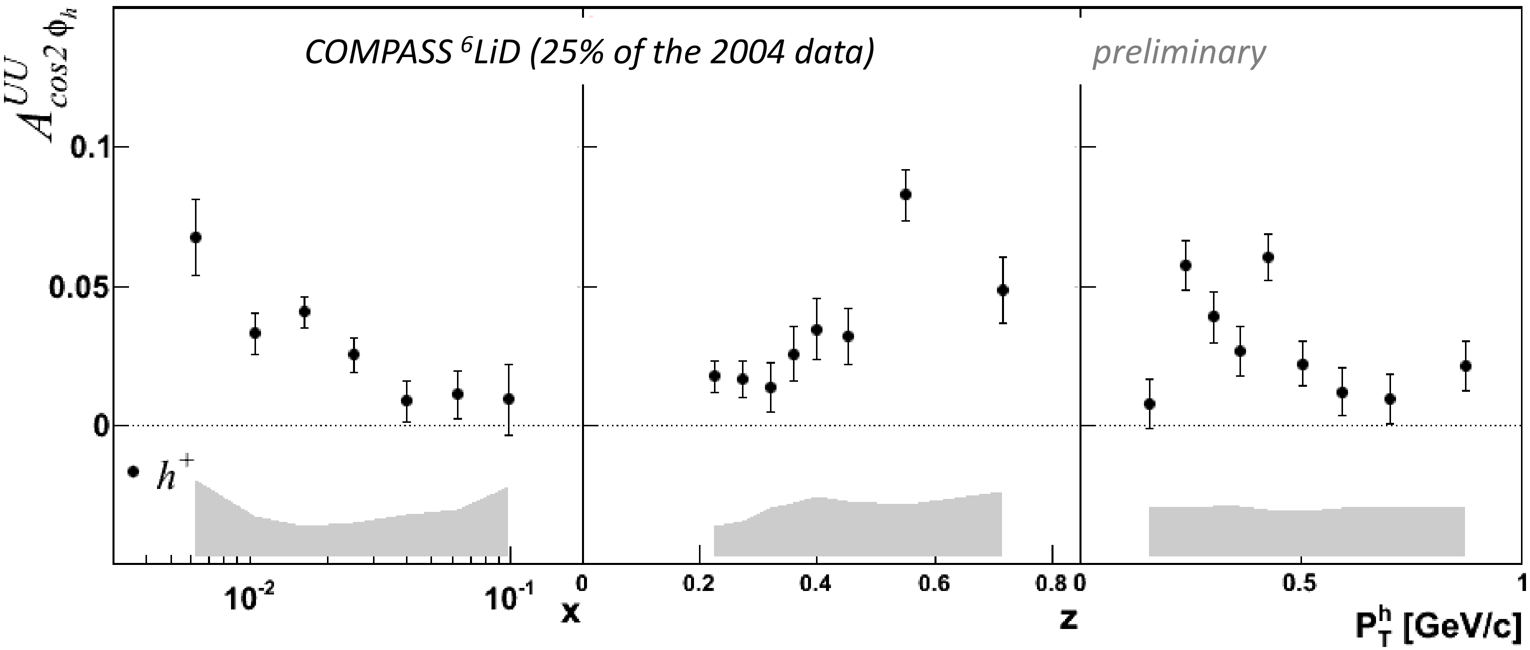
expected curve with:

$< k_\perp^2 >$, $< p_\perp^2 >$ (GeV/c)^2

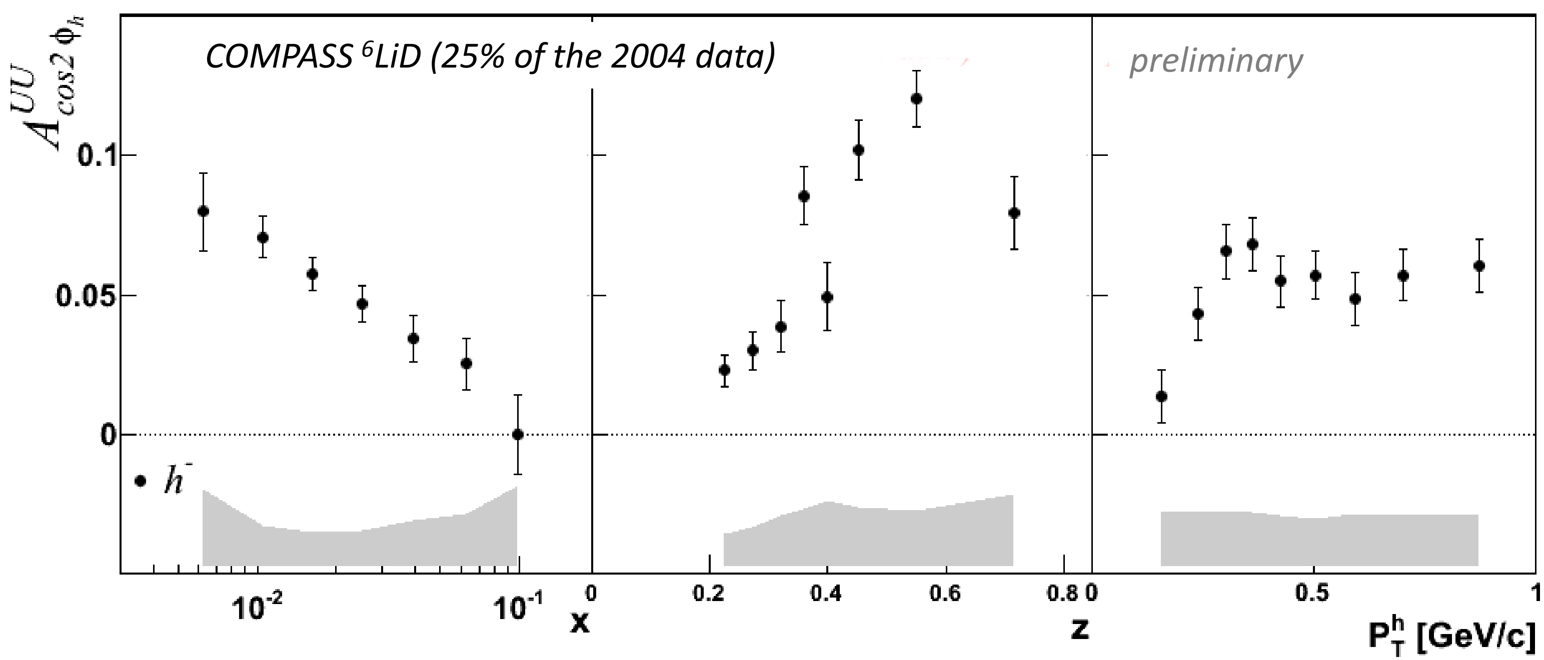
0.25, 0.20 *Anselmino et al. (EMC data)*

0.38, 0.16 *Schweitzer et al. (HERMES data)*

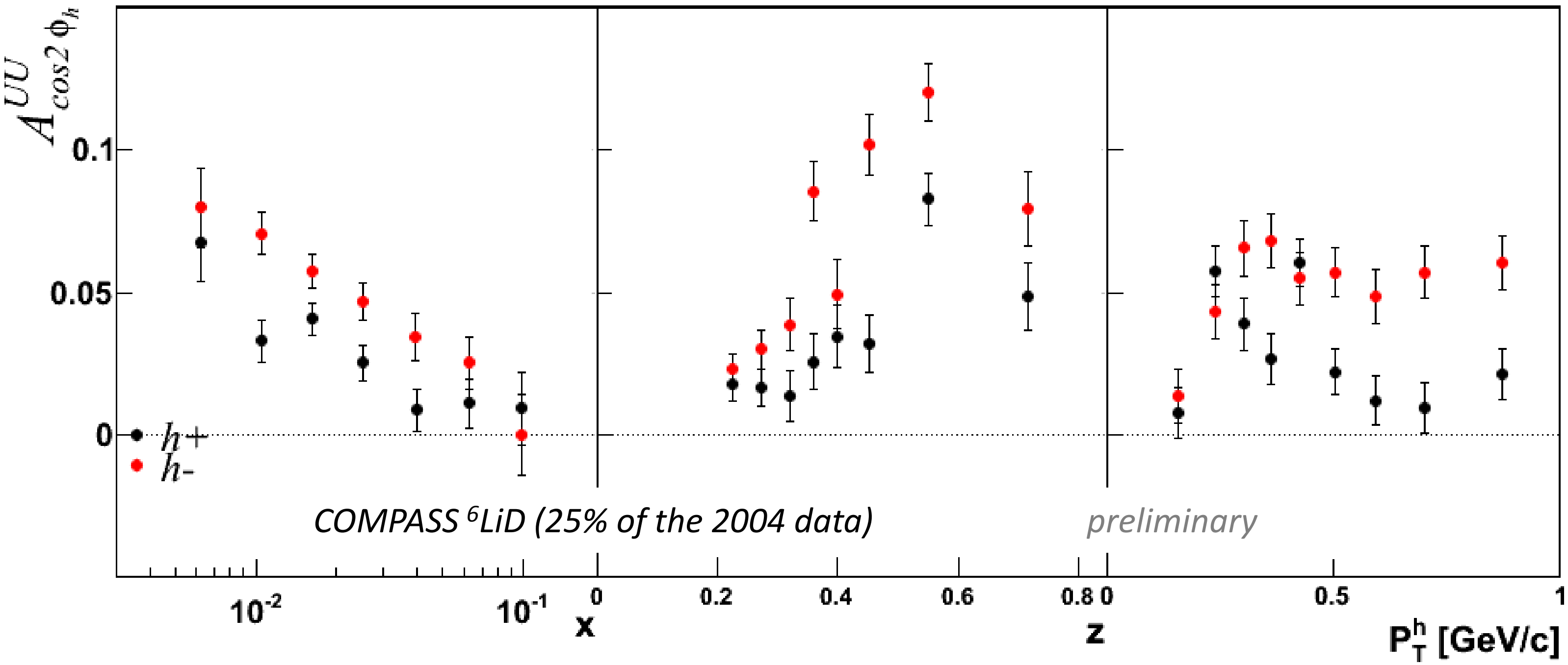
$$A^{UU}_{\cos 2\phi_h}$$



COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
$A^{UU}_{cos2\phi_h}$
0.1
0.05
0
h^+
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P_T^h [GeV/c]



COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
$A^{UU}_{cos2\phi_h}$
0.1
0.05
0
h^-
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P_T^h [GeV/c]



Different results for positive and negative hadrons

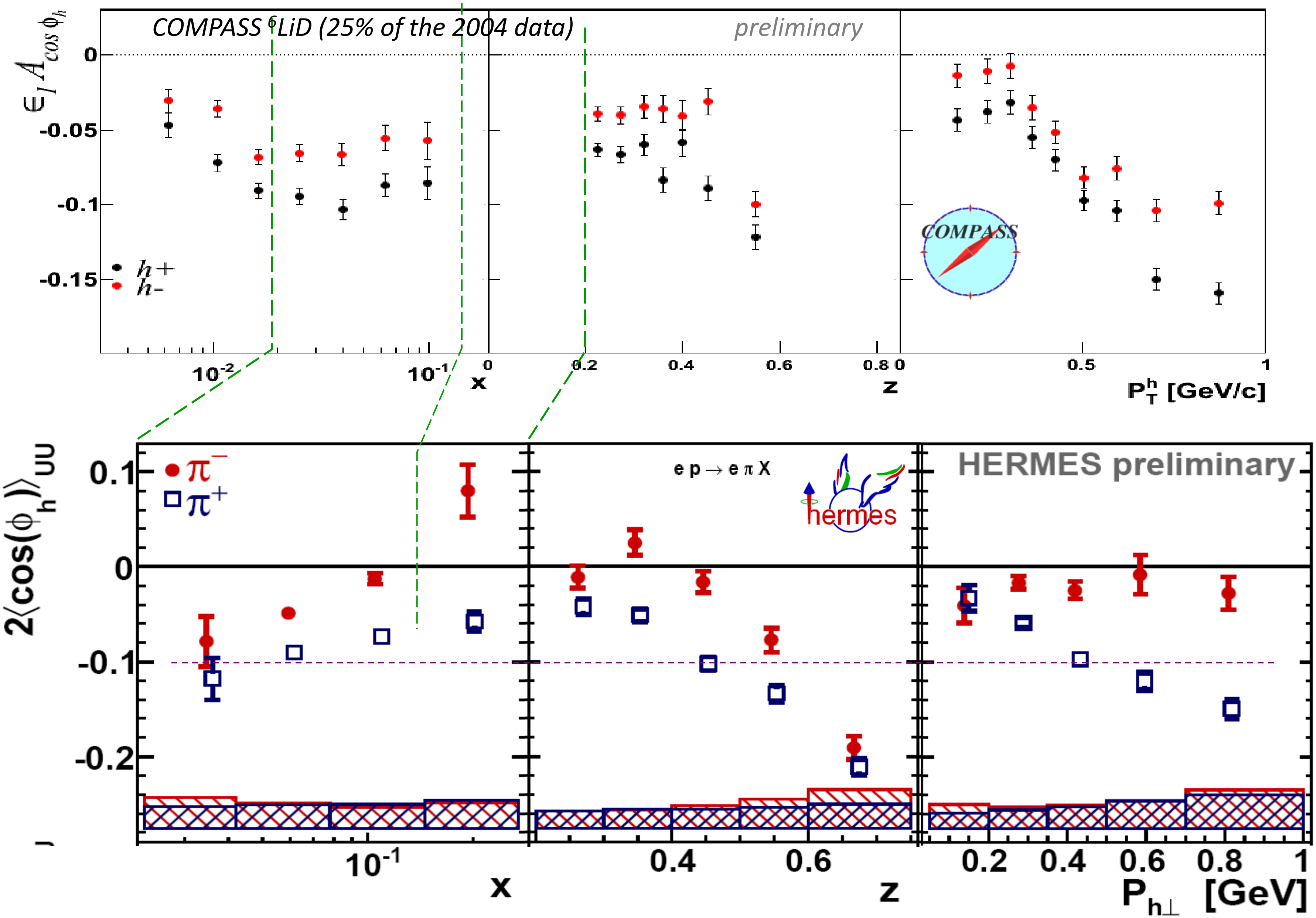
→ Boer-Mulders TMD PDF (flavour dependent)

Cahn effect $\propto \left(\frac{k_\perp}{Q}\right)^2$

comparison with HERMES results for $\cos\phi_h$ and $\cos 2\phi_h$
(shown at TMD 2010 – ECT ,Trento)

different kinematics (lower Q^2 and W)
→ needs to be taken into account for a comparison

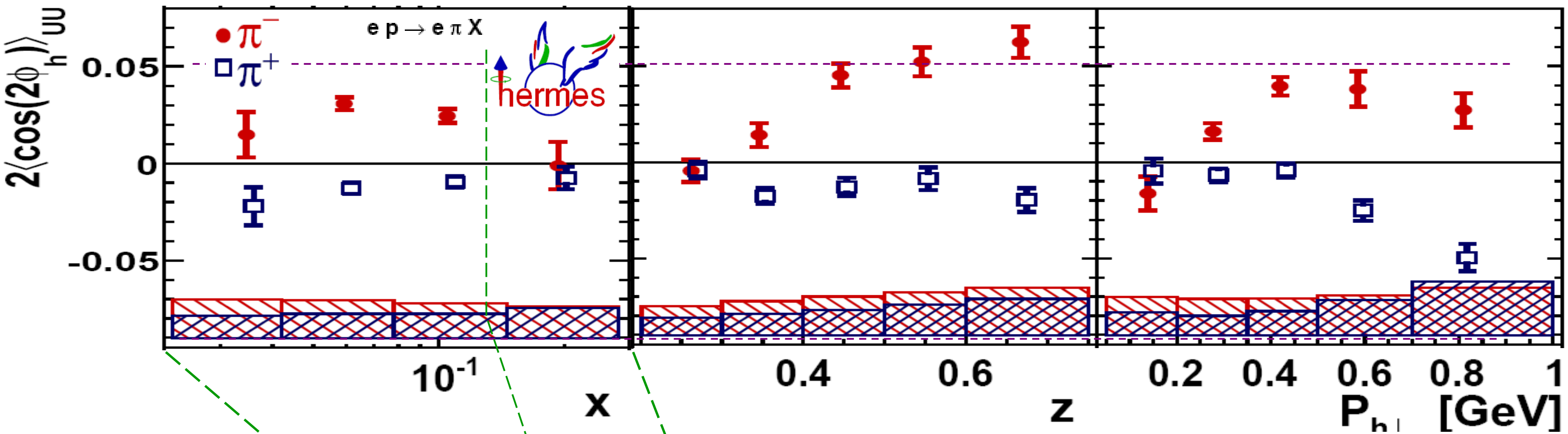
$$\varepsilon_1 A^{UU}_{\cos\phi_h}$$

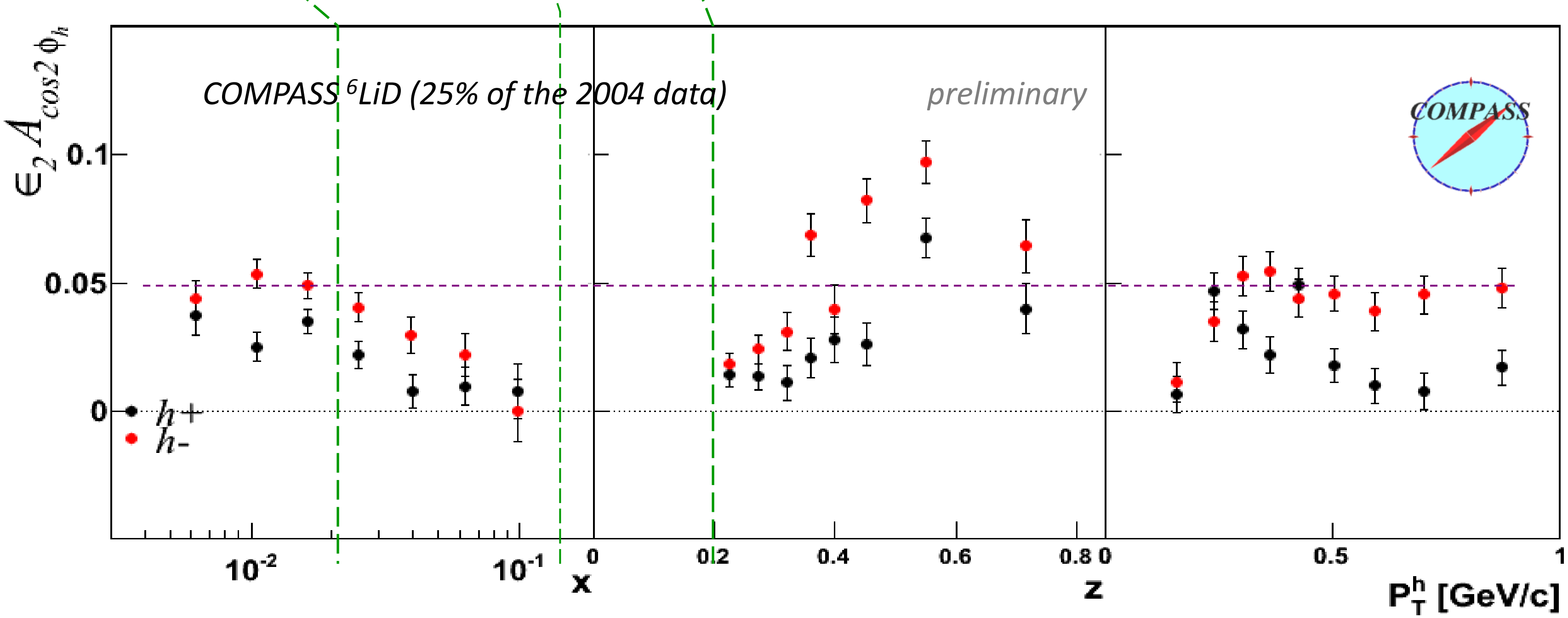


HERMES results shown by A.Rostomyan - TMD2010, Trento

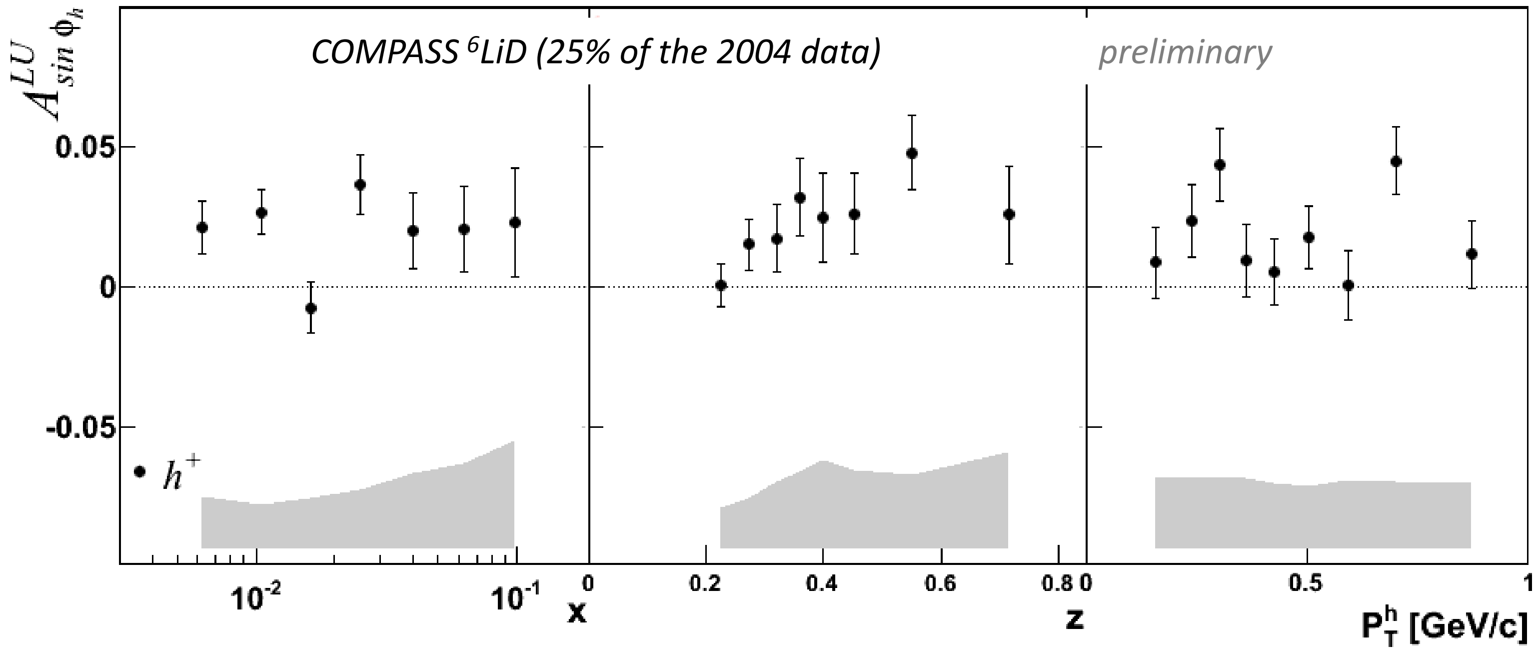
$\varepsilon_2 A^{UU}_{\cos 2\phi_h}$

HERMES results shown by A.Rostomyan - TMD2010, Trento

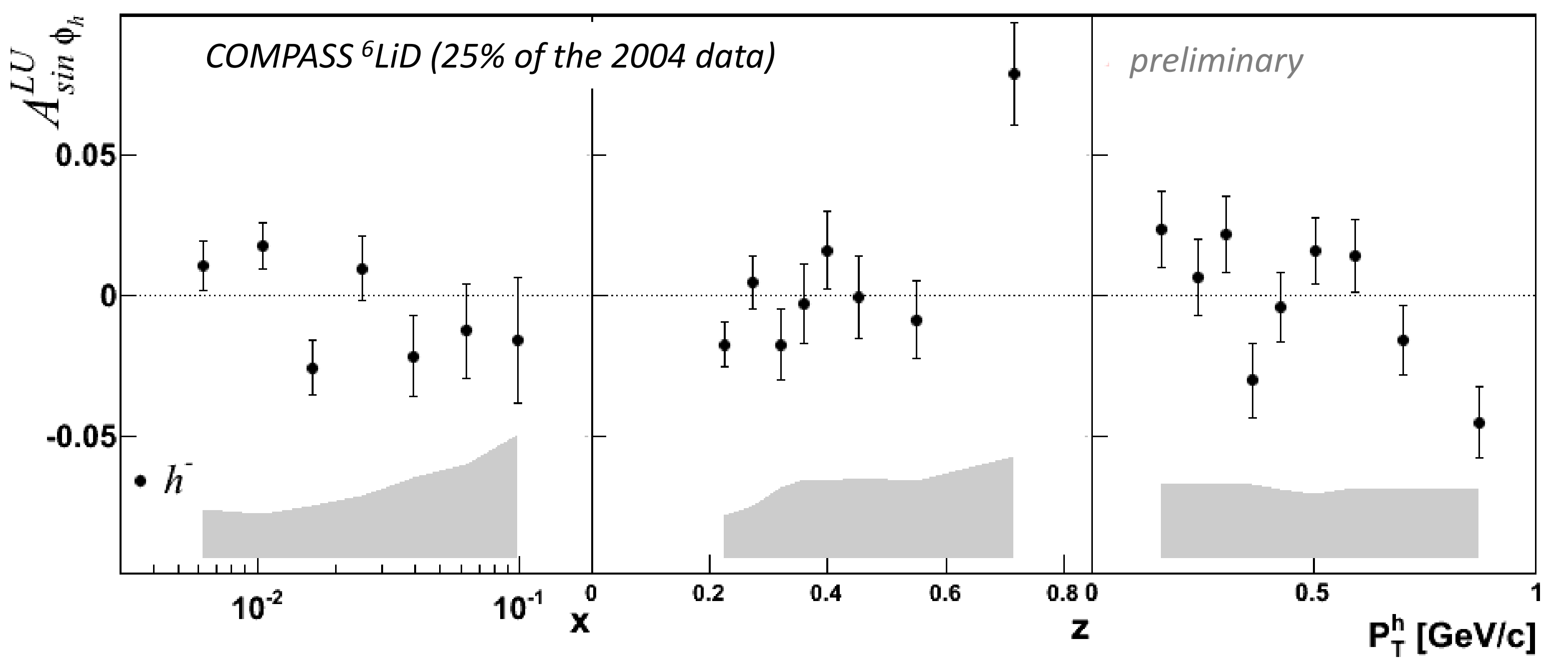




$$A^{UU}_{\sin\phi_h}$$

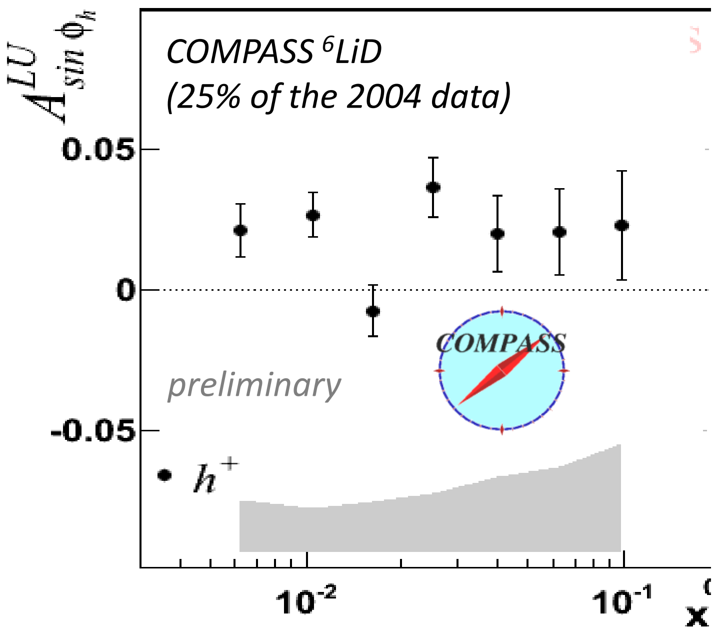


$A^{LU}_{sin\,\phi_h}$
COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
0.05
0
-0.05
h^+
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P_T^h [GeV/c]

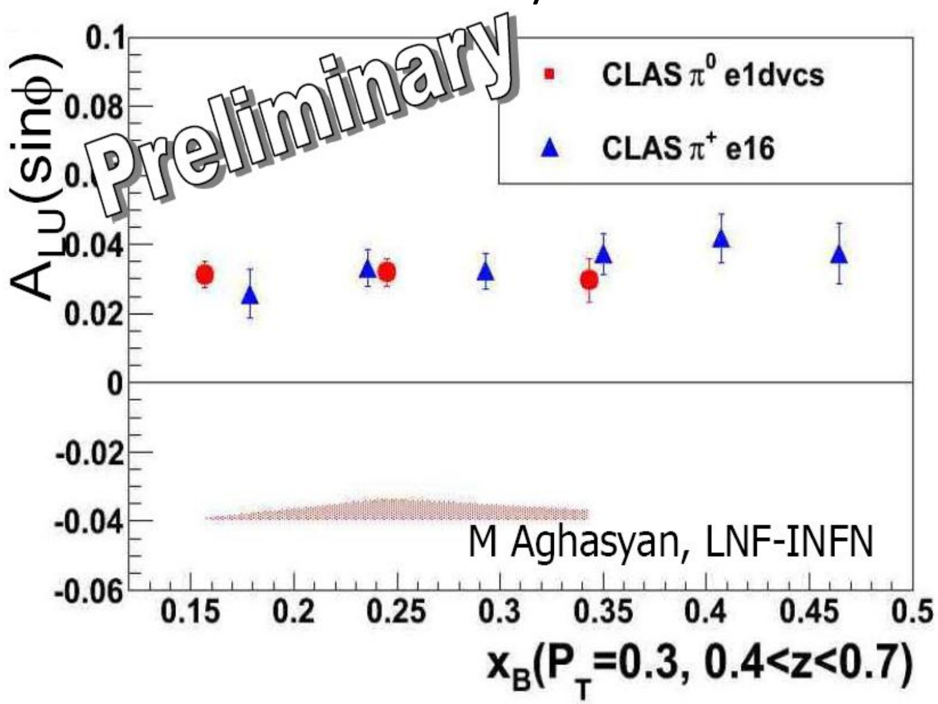


$A^{LU}_{sin\,\phi_h}$
COMPASS ^{6}LiD (25% of the 2004 data)
preliminary
0.05
0
-0.05
h^-
10^{-2}
10^{-1}
x
0
0.2
0.4
0.6
0.8
z
0
0.5
1
P_T^h [GeV/c]

comparison with JLab results (beam energy 6 GeV)
(shown at TMD 2010 – ECT ,Trento)



CLAS results shown by H.Avakian - TMD2010, Trento



positive signal for positive hadrons found in both experiments

CONCLUSIONS:

results on the unpolarized SIDIS azimuthal asymmetries
from the COMPASS data (6LiD) have been produced
as functions of the kinematical variables **x**, **z** and $\mathbf{P_T^h}$
for positive and negative hadrons

the measured amplitude of the $\cos\phi_h$ modulation shows a clear negative signal
(up to 15%)

the measured amplitude of the $\cos2\phi_h$ modulation shows a positive signal
of the order of 5%

the difference between the results for positive and negative hadrons could
be interpreted as
flavour dependent intrinsic TM
Boer-Mulders TMD PDF

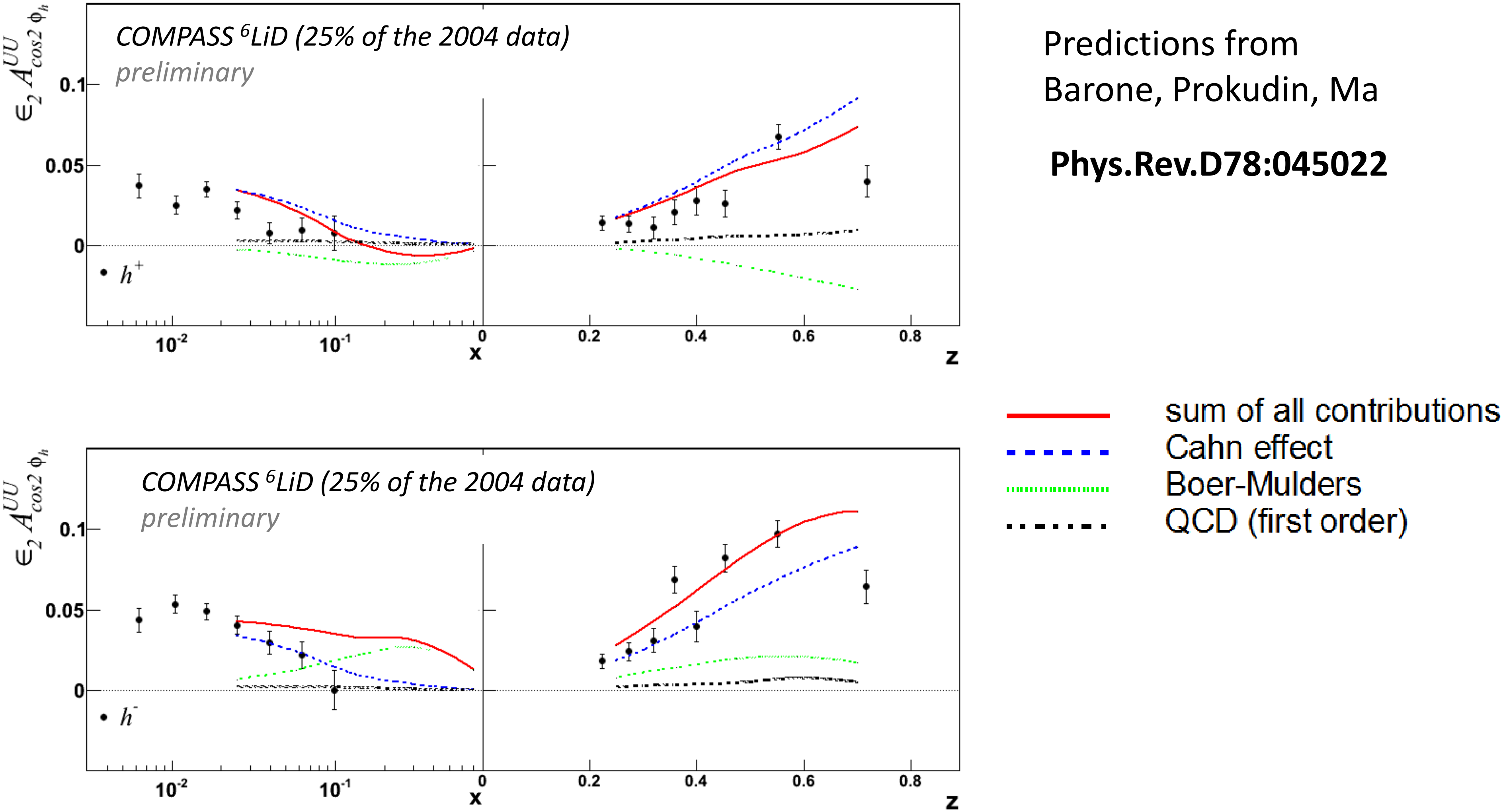
interesting input for theoretical work and global analysis

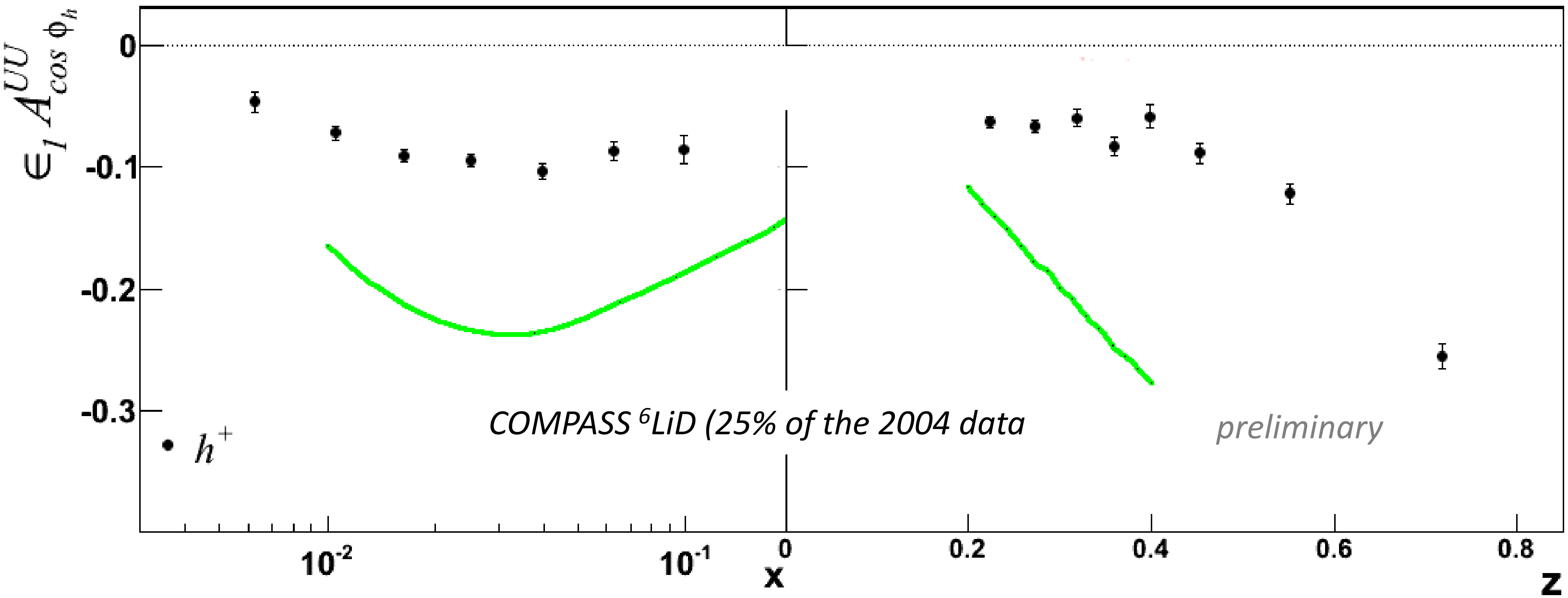
THANKS

backup

Predictions from
Barone, Prokudin, Ma

Phys.Rev.D78:045022





comparison with predictions from Anselmino et al. (**Eur.Phys.J.A31:373-381,2007**)
only Cahn effect
no dependence on the quark flavour

based on EMC, E665 data

Tuning of the LEPTO parameters

transverse momentum of the hadron in the fragmentation:

- PARJ(21): 0.34 GeV/c
- PARJ(23): 0.04
- PARJ(24): 2.8

LUND FF parameters:

- PARJ(41): 0.025
- PARJ(42): 0.075 GeV-2