Measurement of TMD observables at COMPASS

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COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
28 institutions
12 countries

fixed target experiment at the CERN SPS

COmmon
Muon and
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Apparatus for
Structure and
Spectroscopy

wide physics program carried on using both **muon** and hadron beam

luminosity: $\sim 5 \cdot 10^{32}$ cm^{-2} s^{-1}

beam intensity: $2 \cdot 10^{8}$ μ^{+}/spill (4.8s/16.2s)

beam momentum: 160 GeV/*c*

longitudinally polarized muon beam

deuteron (^{6}LID) polarized target	2002	L/T
	2003	
	2004	
proton (NH_3) polarized target	2006	L
	2007	L/T
	2010	T
	2011	L
H_2 target	2012	

hadron beam

nuclear targets	2004
LH target	2008
	2009
	2012

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longitudinally polarized muon beam

- **deuteron (^{6}LID)** polarized target
- **proton (NH_3)** polarized target
- H_2 target

in this talk
the results on the
TMDs measured from SIDIS
are presented

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

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

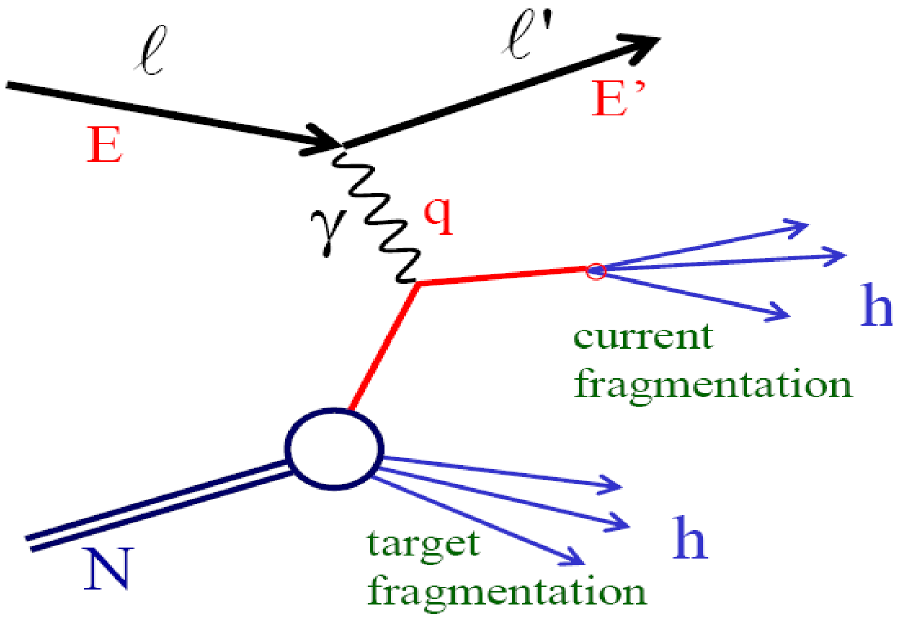
$$q = \ell - \ell'$$

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

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

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

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



at least one hadron is detected in the final state

(information on the struck quark)

The complete ***SIDIS cross section*** *(one photon exchange approximation)*

14 ***independent modulations*** *in the* ***azimuthal angle***
of the ***spin*** φ_S
and of the ***hadron*** φ_h
(around the virtual photon direction)

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

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

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

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

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

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

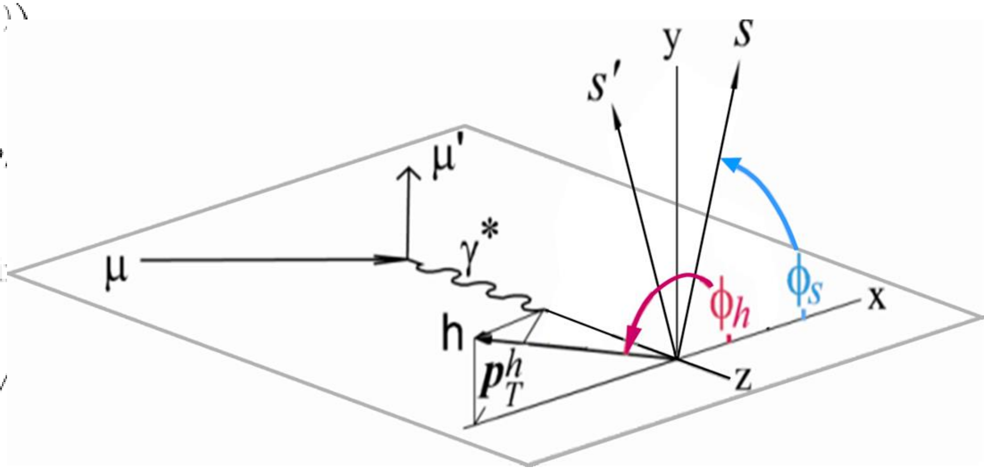
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\,\mathrm{si}\ldots$$

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

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

target nucleon polarisation

beam polarisation



transverse momentum of the hadron $\boldsymbol{p}_T{}^h$

*The complete **SIDIS cross section** (one photon exchange approximation)*

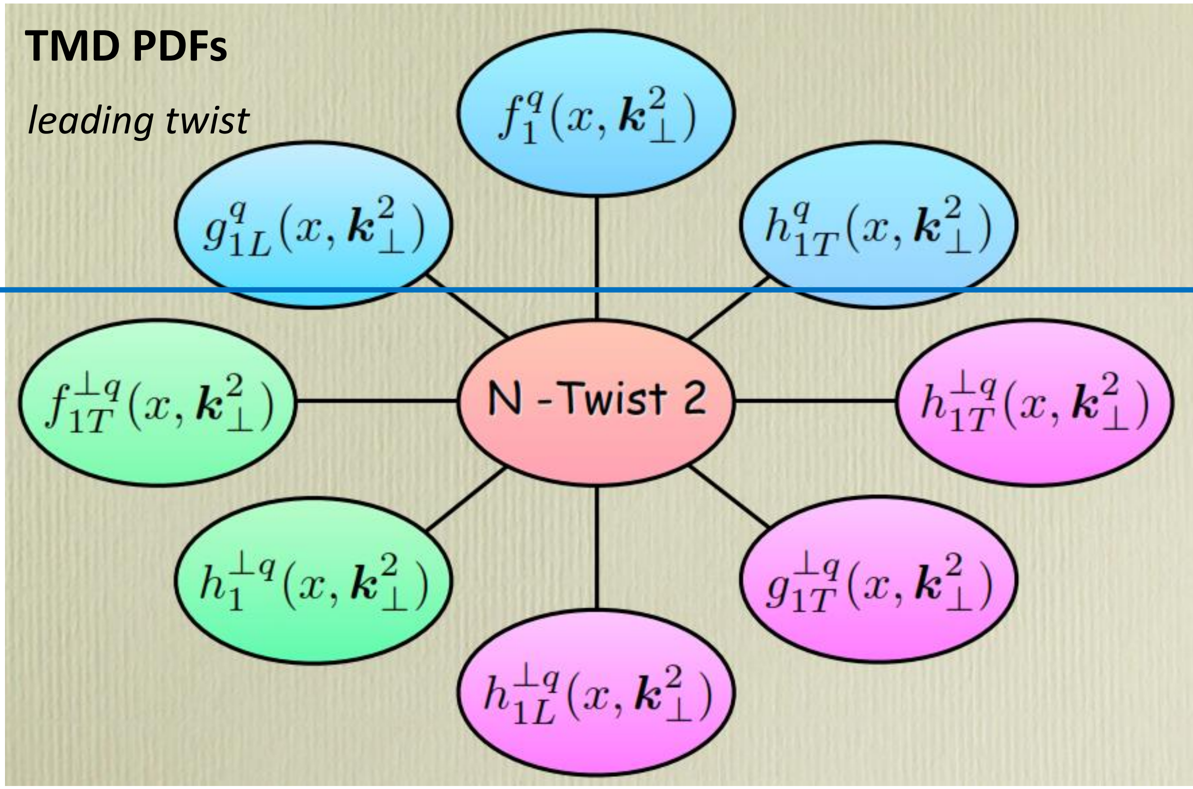
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = {} & \\
\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,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

*14 **independent modulations***
*in the **azimuthal angle***
*of the **spin φ_S***
*and of the **hadron φ_h***
(around the virtual photon direction)

each **modulation** is coupled with a **Structure Function F**

The Structure Function F is the convolution over the ***transverse momenta*** of a PDF and a FF → *describing the fragmentation of the quark in an unpolarised hadron*

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



survive after integration over $k_\perp$

correlation between spin and transverse momentum

all** of the **amplitudes** of the azimuthal modulations of the polarised SIDIS cross section have been **measured at COMPASS

the COMPASS spectrometer

- high energy beams
- large angular acceptance
- broad kinematical range

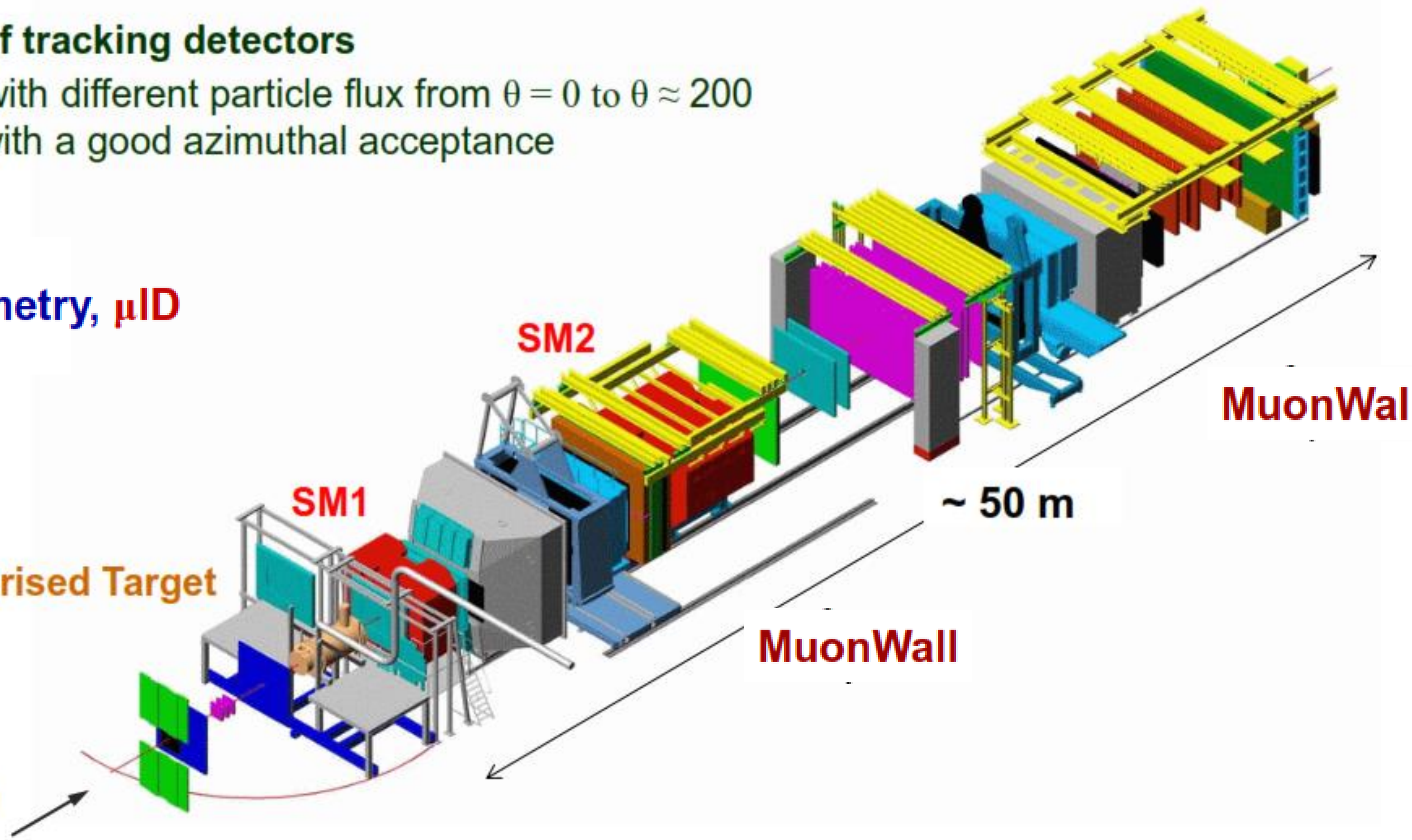
two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance



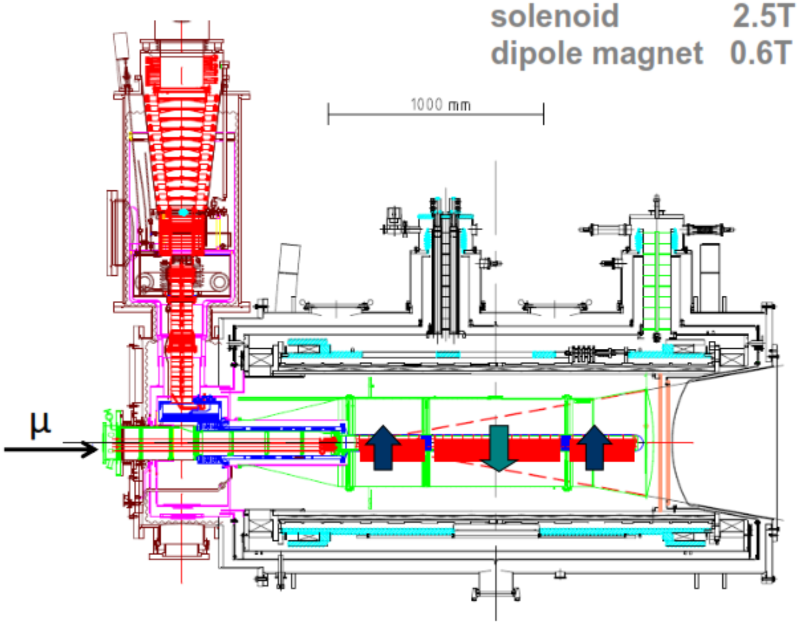
polarized target system (>2005)

solid state target operating in frozen spin mode

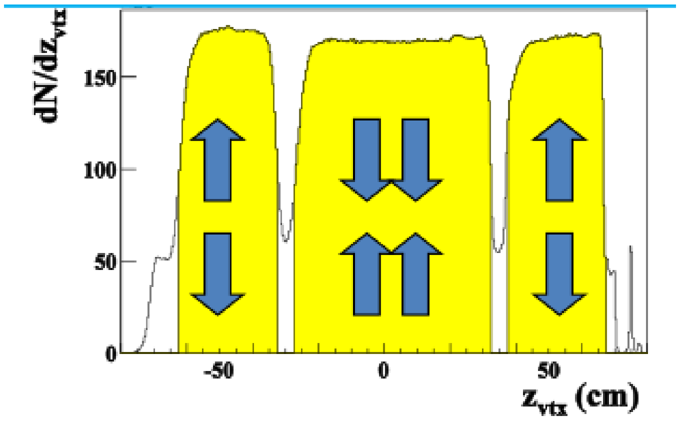
	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

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

solenoid 2.5T
dipole magnet 0.6T



3 cells target with opposite polarizations

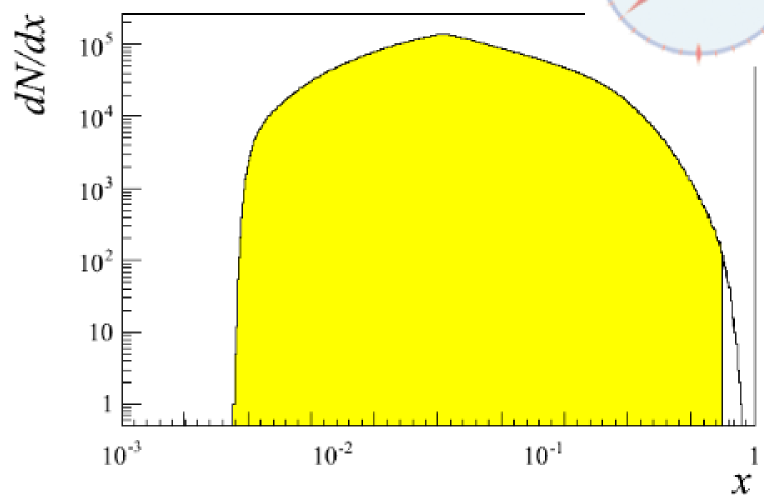


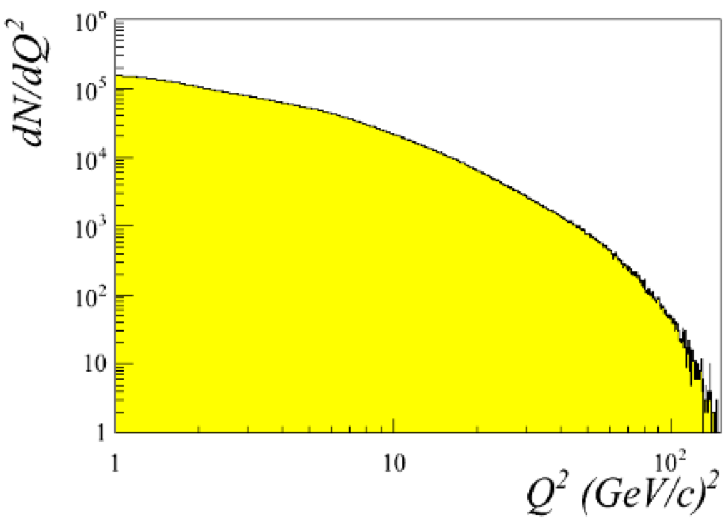
2 configurations:
polarisation reversed each week
to minimize possible systematic errors

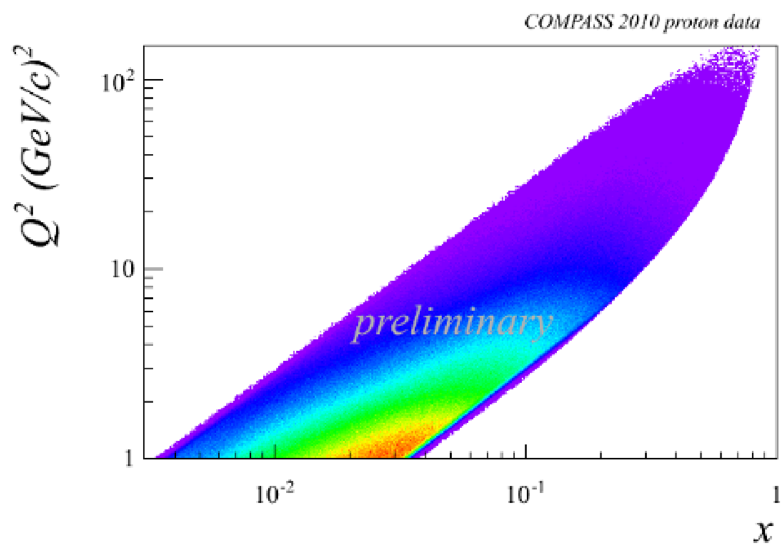
SIDIS event selection

p_μ = 160 GeV/c

DIS cuts: $Q^2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W > 5\ GeV/c^2$



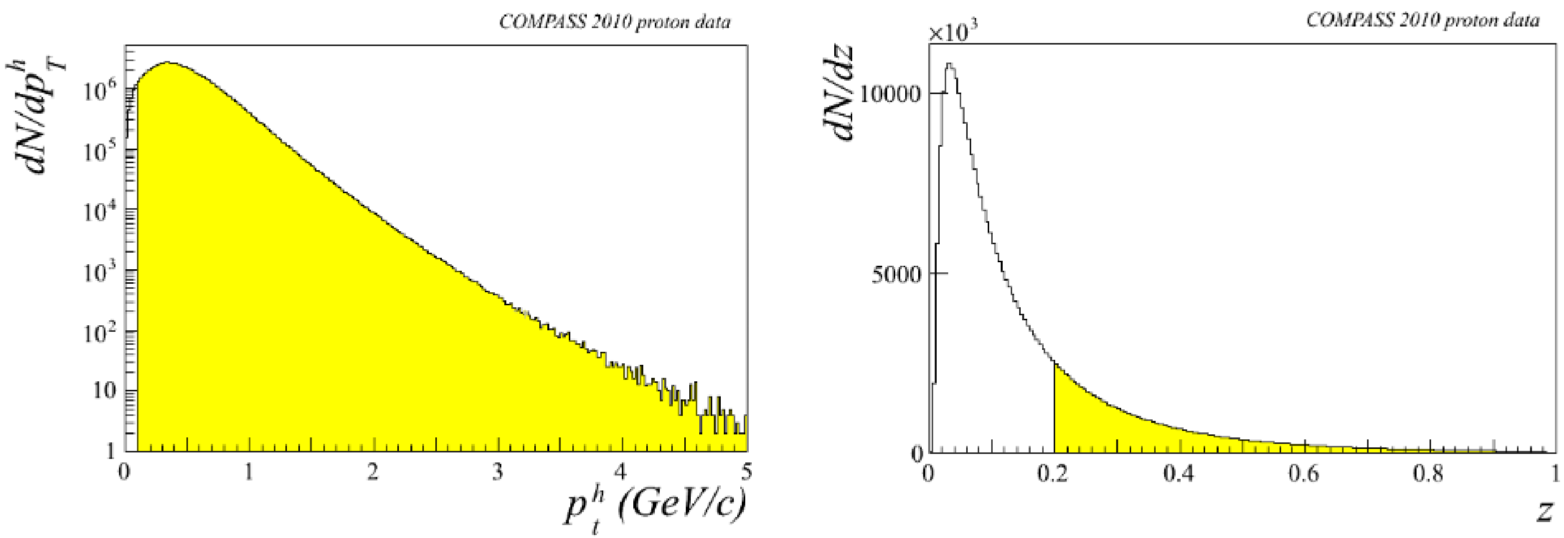




SIDIS event selection p_μ = 160 GeV/c

DIS cuts: $Q^2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W > 5\ GeV/c^2$

$h^\pm$ selection: $p_t^h > 0.1$ GeV/c
$z > 0.2$



TM effects measurements

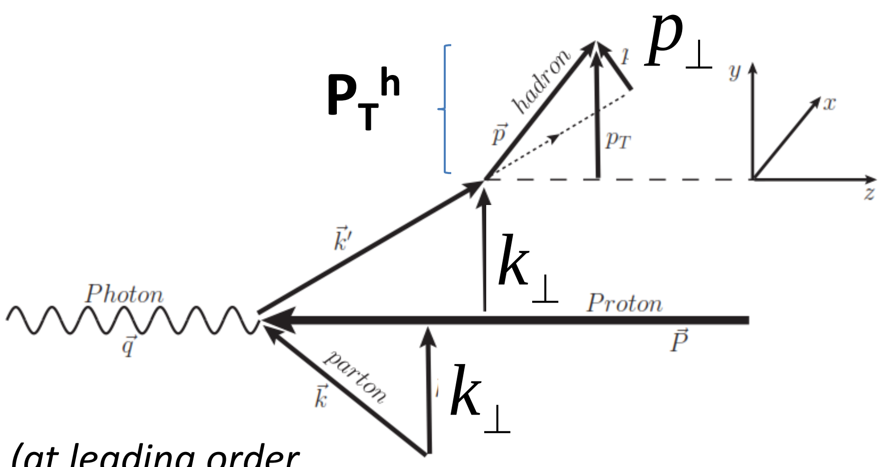
shown in this presentation

- hadron multiplicities in SIDIS off unpolarised target

- azimuthal asymmetries in SIDIS off unpolarised target

- azimuthal asymmetries in SIDIS off transversely polarised target

hadron multiplicities as function of $(P_T^h)^2$



(at leading order valid for small P_T^h values)

the $\mathbf{P_T^h}$ of the detected hadron is given by the intrinsic TM of the quark inside the nucleon $k_\perp$ and the TM of the quark in the fragmentation $p_\perp$

differential SIDIS cross-section / differential DIS cross-section

$$\frac{d^2 n^{h\pm}(x,Q^2,z,p_T^{h^2})}{dz dp_T^{h^2}} \approx \frac{\Delta^4 N^{h\pm}(x,Q^2,z,p_T^{h^2})/(\Delta x \Delta Q^2 \Delta z \Delta p_T^{h^2})}{\Delta^2 N^{DIS}(x,Q^2)/(\Delta x \Delta Q^2)}$$

hadron multiplicities as function of $(P_T^h)^2$

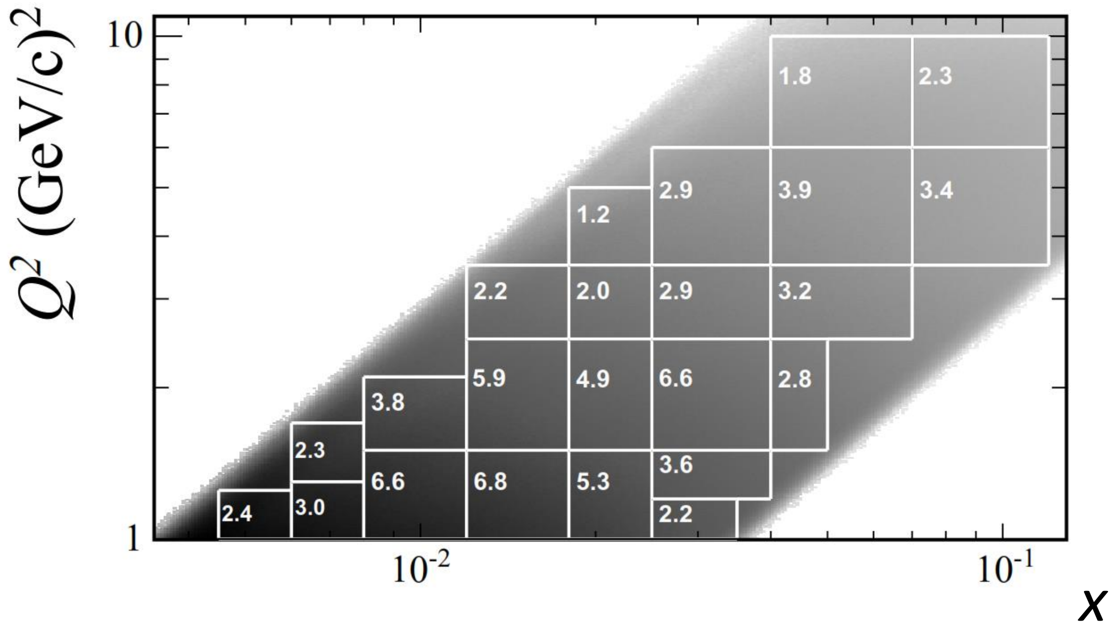
SIDIS events from 2004 ^{6}LiD data

multiplicities measured
in *4 dimensions*:

23 x, Q^2 intervals
$1 < Q^2 < 10$ $(GeV/c)^2$
$0.004 < x < 0.12$

8x40
z and P_T^h
intervals

45.8×10^6 DIS events

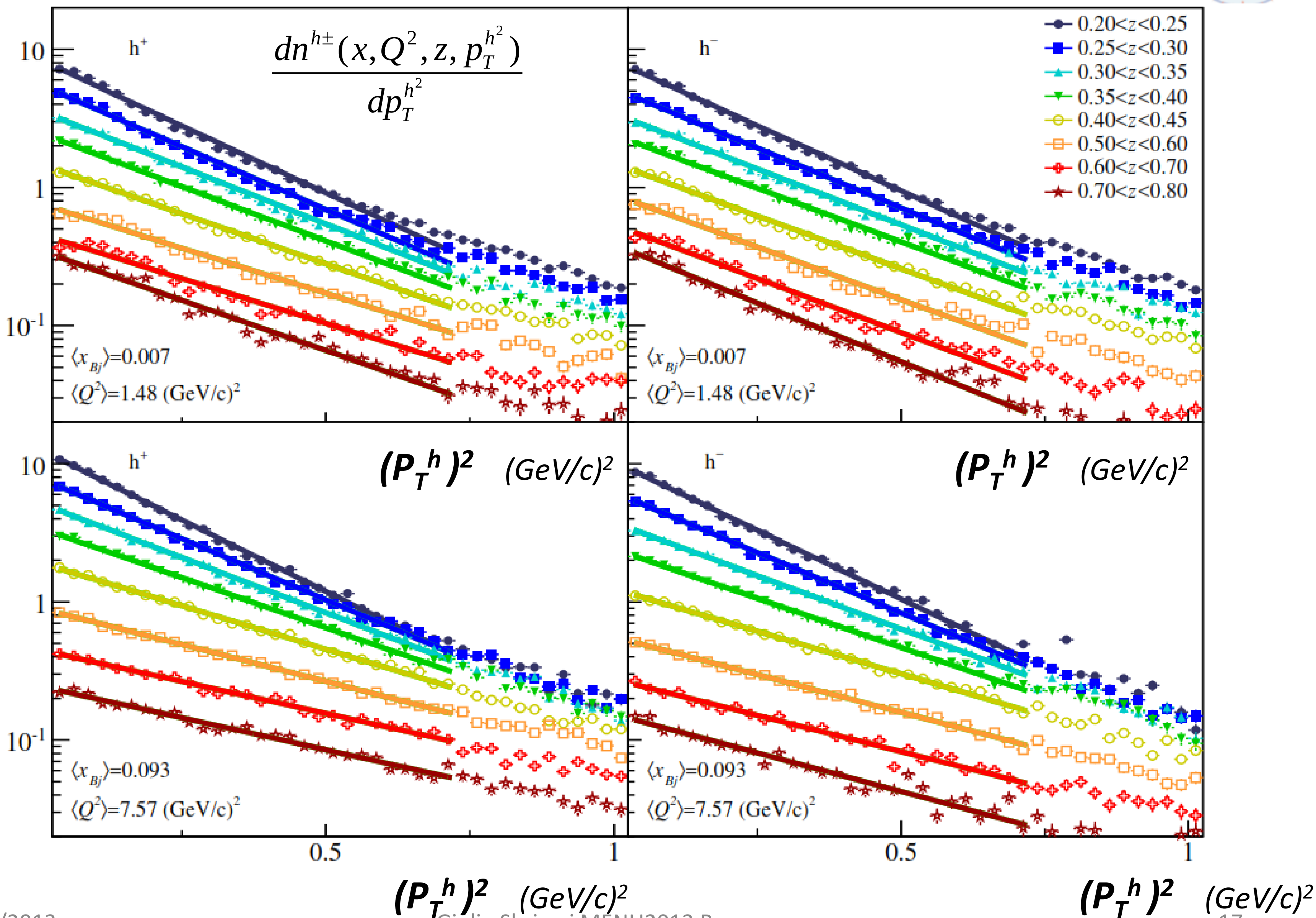


separately for h+ and h-

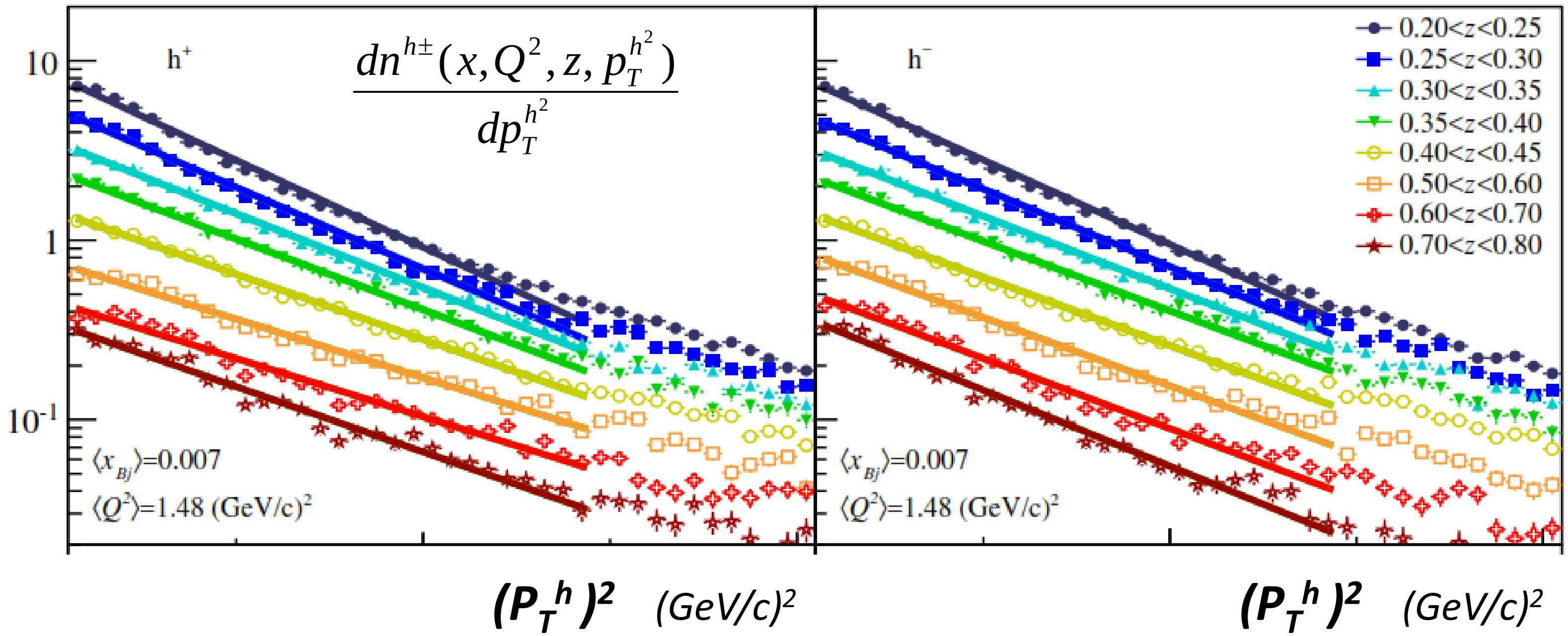
for each bin the "raw" multiplicity is **corrected for the acceptance** calculated using **Monte Carlo simulations**

5% systematic uncertainties

hadron multiplicities as function of $(P_T^h)^2$



hadron multiplicities as function of $(P_T^h)^2$



$$\frac{dn^{h\pm}(x,Q^2,z,p_T^{h^2})}{dp_T^{h^2}}$$

for each bin in **x, Q²** and **z**

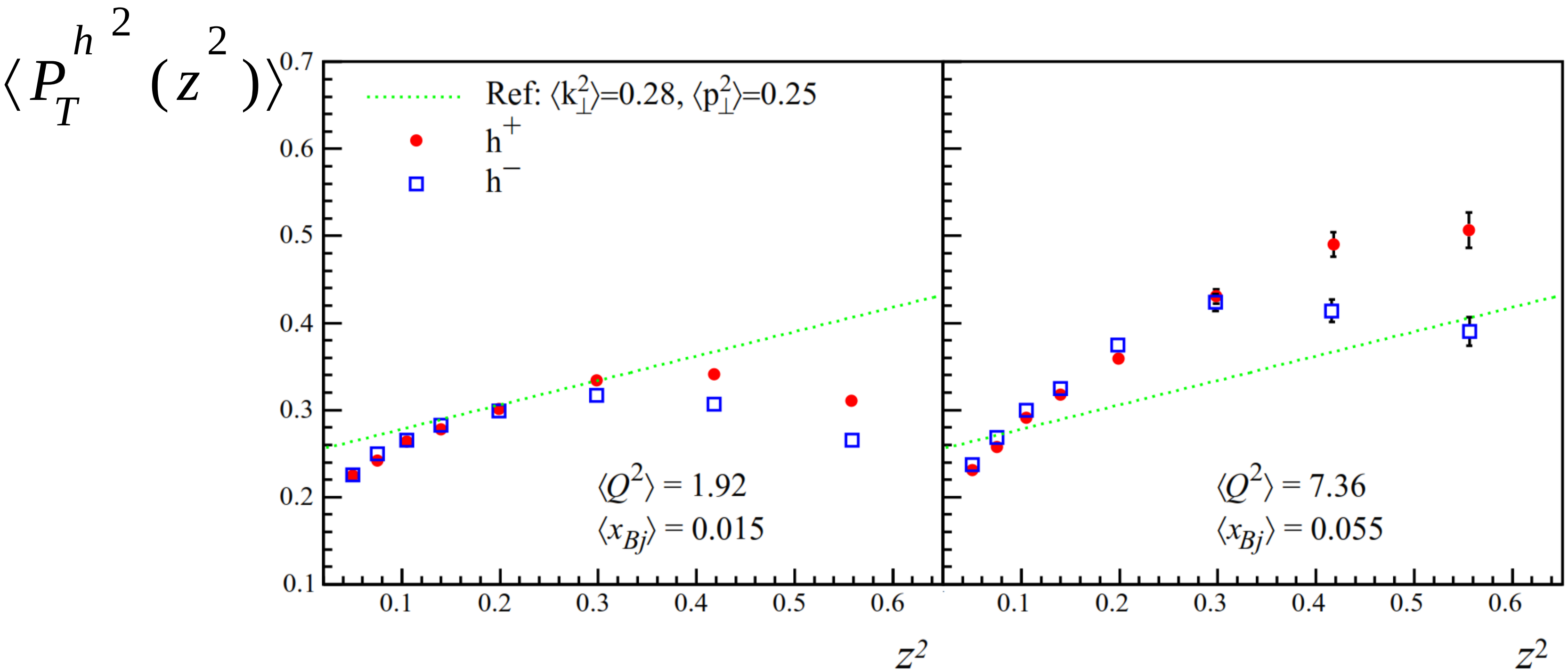
fit using $$A\cdot e^{-P_T^{h^2}/\langle P_T^{h^2}\rangle}$$

→ extract

$$\boxed{\langle P_T^{h\,2}\rangle} = \langle P_\perp^2\rangle + z^2\langle k_\perp^2\rangle$$

for P_T^h < 0.85 GeV/c to stay away from the region where transverse momentum effects related to gluon radiation become relevant

z dependence



$$\langle P_T^{h\,2}(z)\rangle = \langle P_\perp^2(z)\rangle + z^2\langle k_\perp^2\rangle$$

this term should be calculated from DIS generator
using the best knowledge on jet fragmentation

not so easy to reproduce the results…

- hadron multiplicities in SIDIS off unpolarised target

- azimuthal asymmetries in SIDIS off unpolarised target

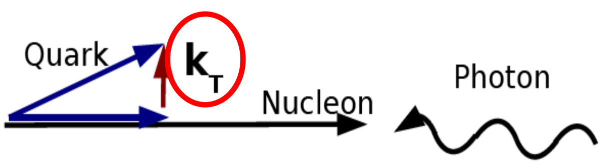
- azimuthal asymmetries in SIDIS off transversely polarised target

The azimuthal hadron distribution for the unpolarised target is:

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

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

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



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

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

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

fundamental prediction pQCD
sign change between B-M TMD as measured in SIDIS and in Drell-Yan

higher twist effect proportional to beam polarization λ_l

no clear interpretation in terms of PM

The azimuthal hadron distribution for the unpolarised target is:

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

(SIDIS events from 2004 ^{6}LiD data)

$Q^2 > 1$ (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

separately for h+ and h-
in **each bin** of x, z and P_T^h :

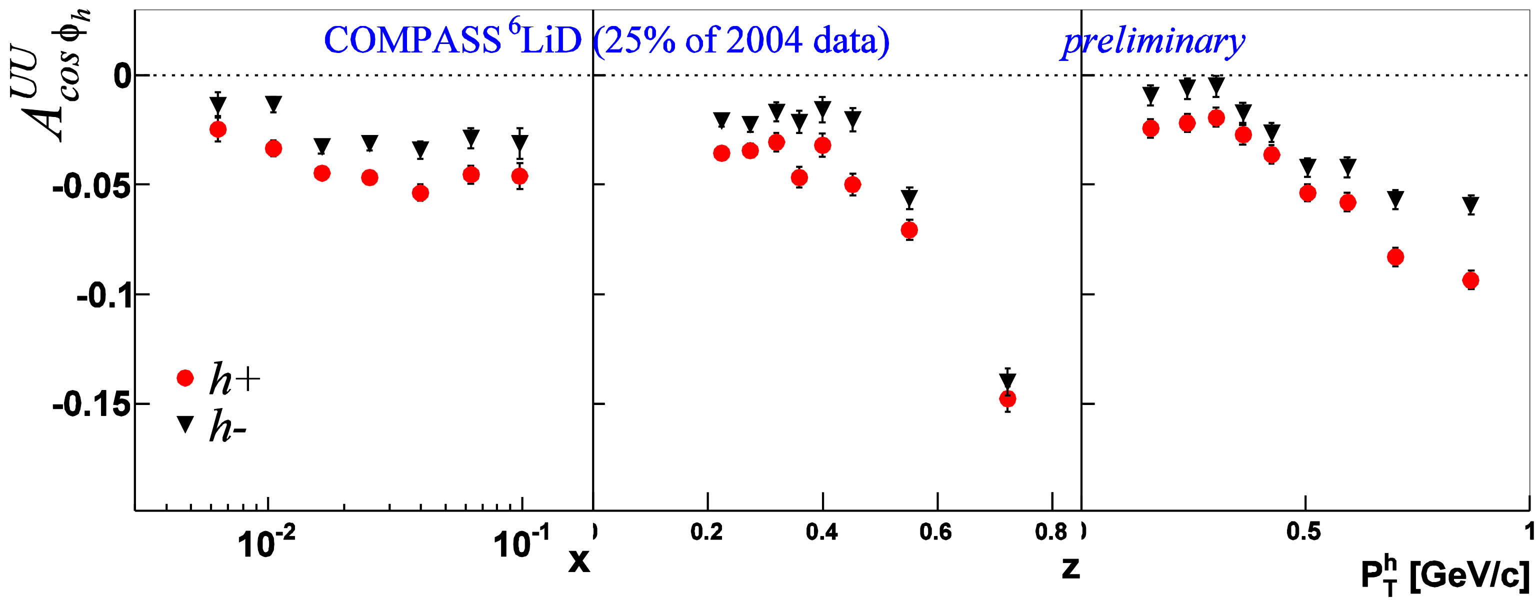
the **acceptance is calculated**, using **Monte Carlo** simulations

the “raw” **azimuthal distribution** is **corrected for** the apparatus **azimuthal acceptance**

$$A^{UU}_{\cos\phi_h}, \quad A^{UU}_{\cos 2\phi_h}, \quad A^{LU}_{\sin\phi_h}$$

are **extracted fitting the hadron distribution in ϕ_h**

Results extracted binning alternatively in x, z and P_T^h



$$A^{UU}_{\cos\phi_h} = \frac{1}{Q}\,\mathrm{Cahn} + \frac{1}{Q}\,\mathrm{BM}$$

sys ≈ 2 · stat

strong z dependence, for z > 0.5

to better understand the interesting and unexpected kinematical dependencies found

↓

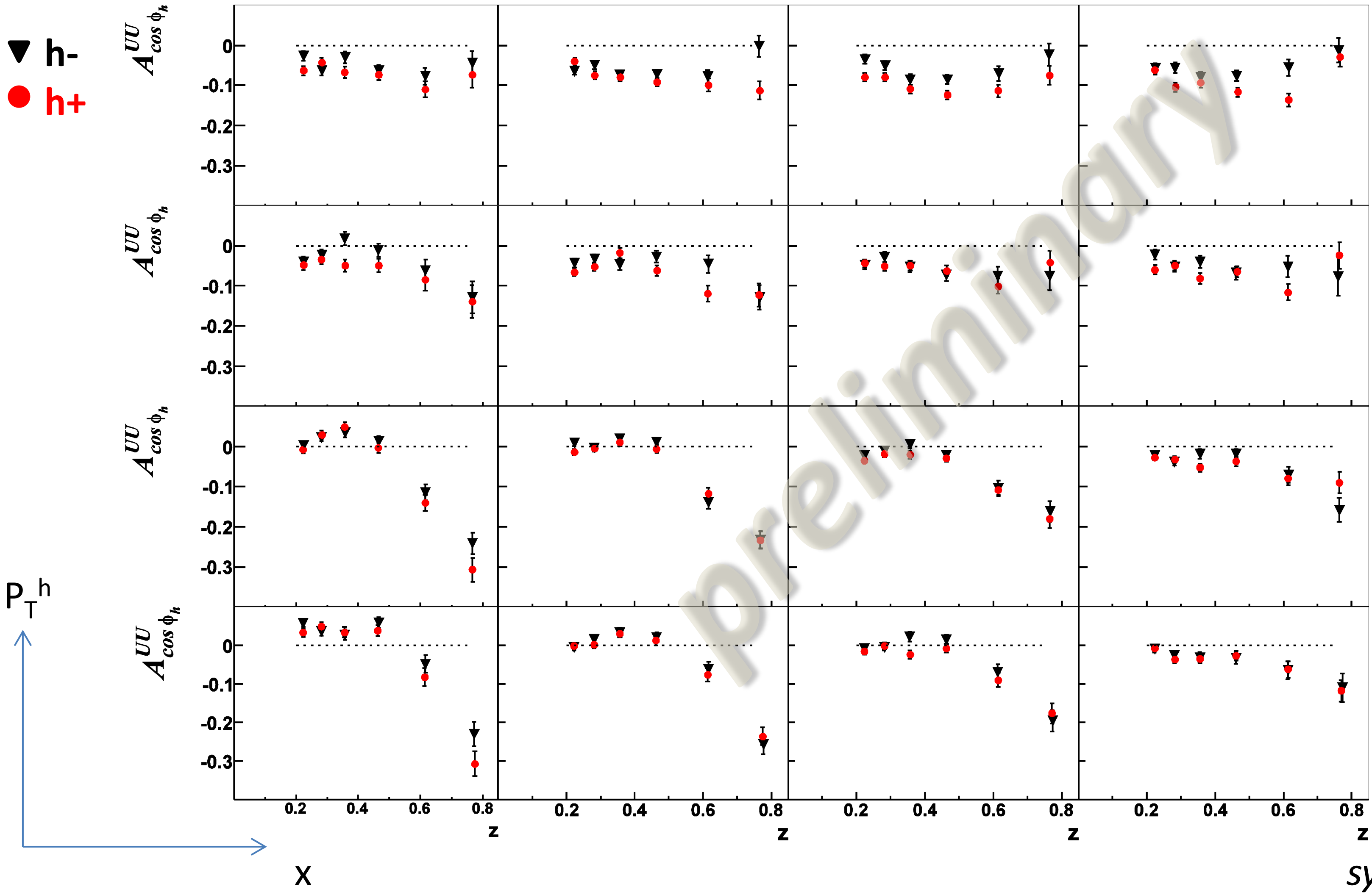
a multi dimensional analysis has been done

binning simultaneously in x, z and P_T^h

x	P_T^h	z
0.003 - 0.012	0.1 - 0.3	0.2 - 0.25
0.012 - 0.02	0.3 - 0.5	0.25 - 0.32
0.02 - 0.038	0.5 - 0.64	0.32 - 0.40
0.038 - 0.13	0.64 - 1.0	0.40 - 0.55
		0.55 - 0.70
		0.70 - 0.85

results shown at SPIN2012 in Dubna

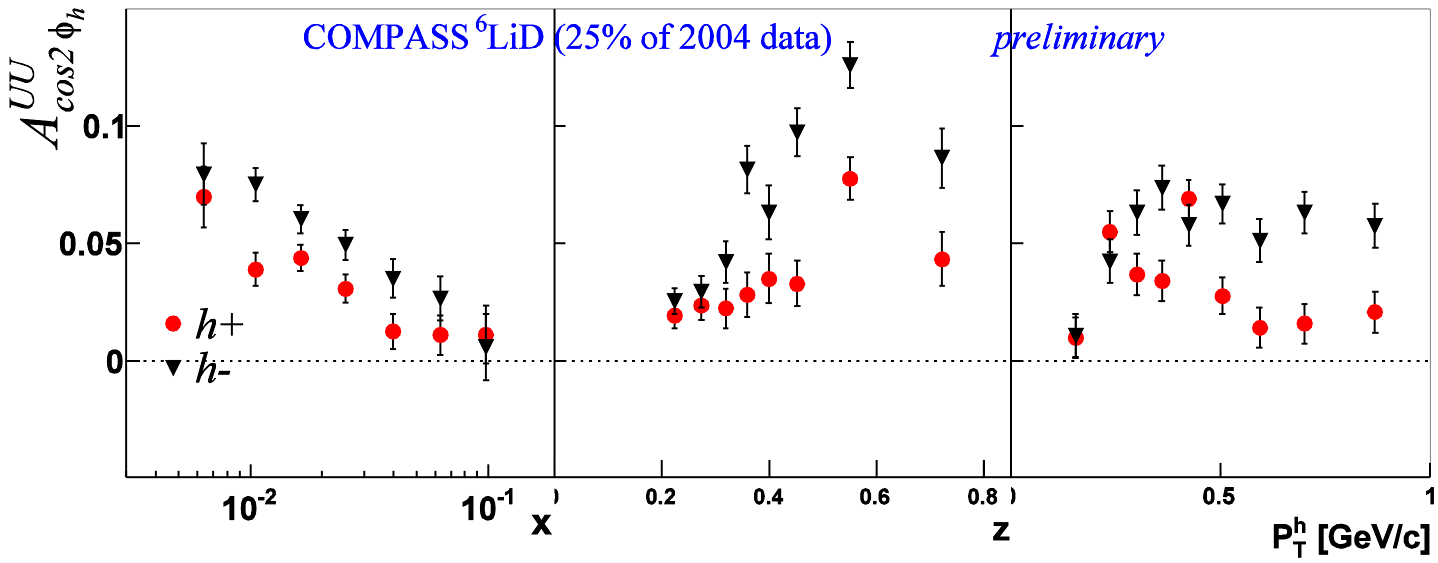
COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

z strong dependence more evident at small x and small P_T^h

Results extracted binning alternatively in x, z and P_T^h

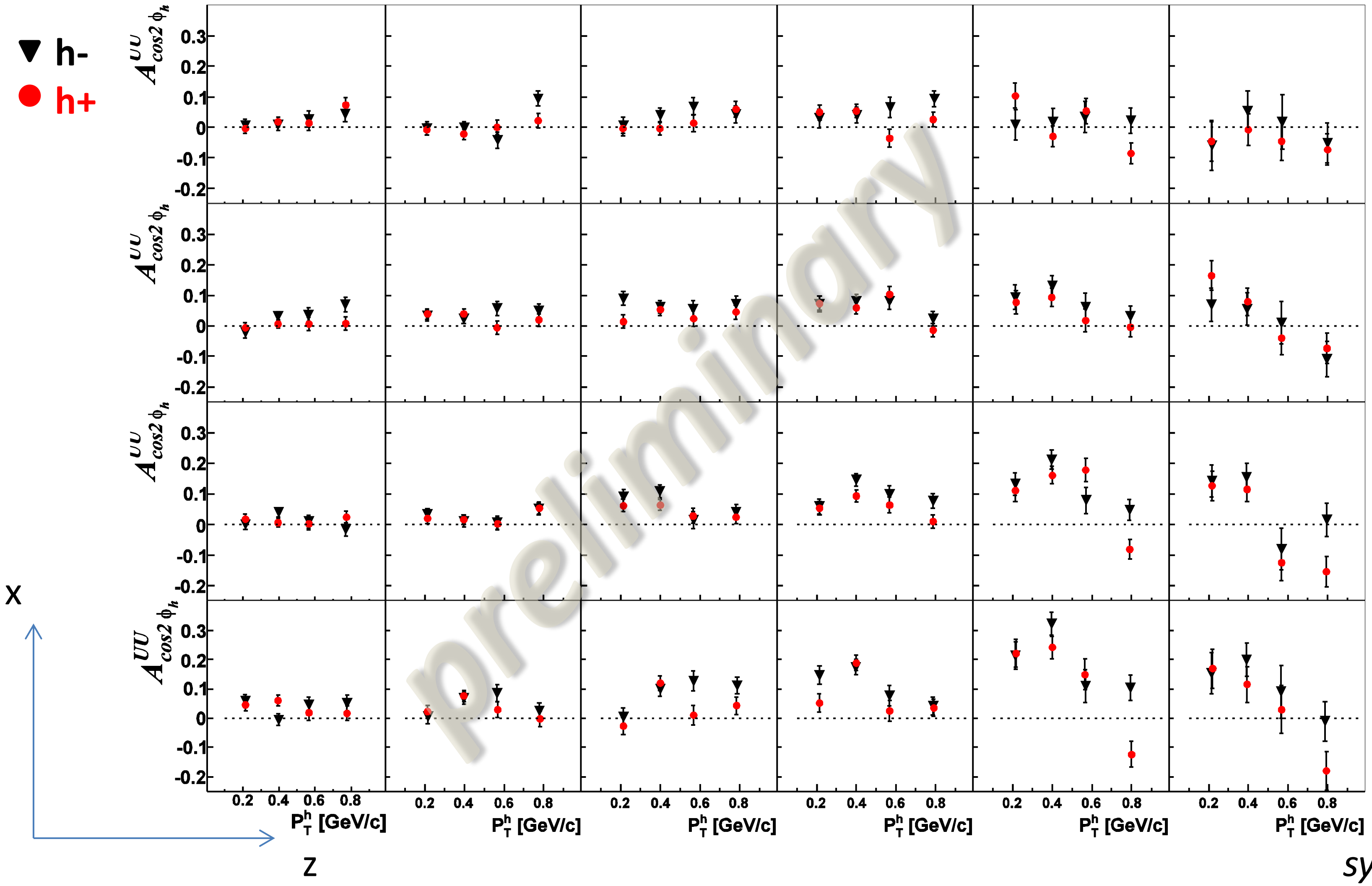


sys ≈ 2 · stat

$$A^{UU}_{\cos 2\phi_h} = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

P_T^h dependence difficult to be reproduced (PRD81, Barone,Melis,Prokudin)

COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

the P_T^h trend difficult to be reproduced by calculations is there for large z and low x

increasing interest for unpolarised SIDIS: theoretical work in progress…

- hadron multiplicities in SIDIS off unpolarised target

- azimuthal asymmetries in SIDIS off unpolarised target

- azimuthal asymmetries in SIDIS off transversely polarised target

Azimuthal hadrons distribution on transversely polarised target

direction of the polarization

kinematical factors $D_{NN} = \frac{1-y}{1-y-\frac{y^2}{2}}$

$$N_h^{\pm}(\phi_h,\phi_S) = N_h^0(\phi_h)\left[1 \pm fP_T D_{NN} A_{Coll} \sin(\phi_h + \phi_S + \pi) \pm fP_T A_{Siv} \sin(\phi_h - \phi_S) \pm \ldots\right]$$

target polarisation P_T

dilution factor f

Collins angle

Sivers angle

amplitudes of the azimuthal modulations **extracted**

fitting the azimuthal distribution in ϕ_h and ϕ_S

in the different bins of ***x***, ***z*** and p_T^h

Azimuthal hadrons distribution on transversely polarised target

there are also **other 6 modulations related to different TMDs**
they all have been measured at COMPASS

$$
\begin{aligned}
&+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big) \\
&\quad + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big] \\
&+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)} \cos\phi_S\, F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},
\end{aligned}
$$

sivers
collins

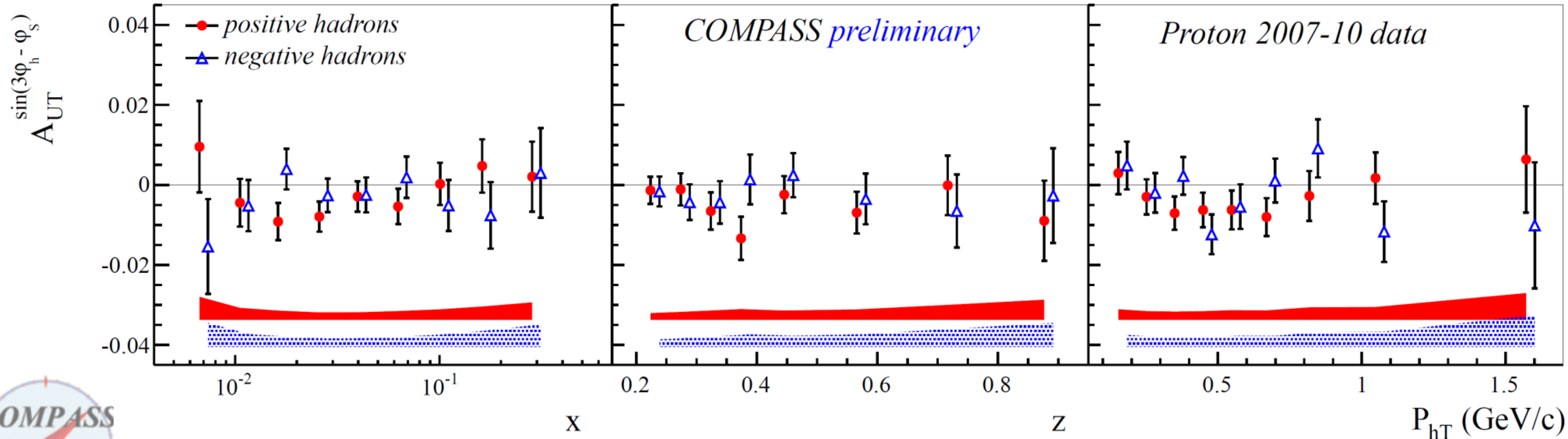
pretzelosity

worm-gear

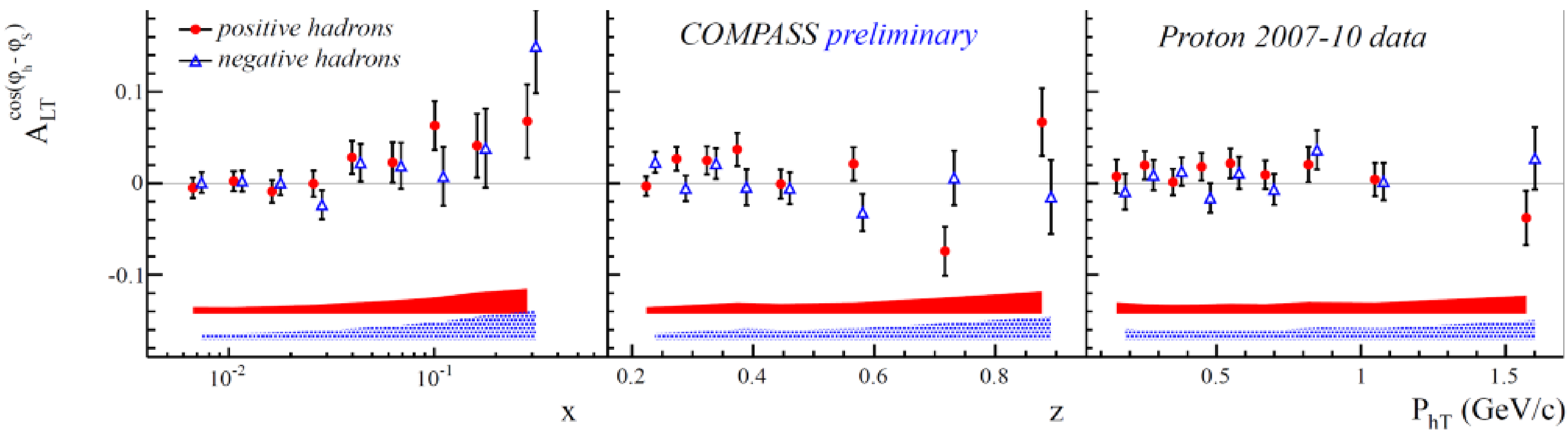
higher twist effects

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$, **pretzelosity** $h_{1T}^{\perp q}$:

sensitive to the D-wave component
non spherical shape of the nucleon



$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$, **worm-gear** g_{1T}^{q} :



Azimuthal hadrons distribution on transversely polarised target

there are also other 6 modulations related to different TMDs
they all have been measured at COMPASS

$$+|\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big)$$
$$+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$
$$+ |\boldsymbol{S}_\perp|\lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

both on deuteron and on proton
in general the **asymmetries are small and compatible with zero**

The Sivers asymmetry

$$A_{Siv} \approx \frac{\sum_q e_q^2 \cdot \boxed{f_{1T}^{\perp q}(k_\perp^2, x})\otimes D_{1q}^h(p_\perp^2, z)}{\sum_q e_q^2 \cdot f_1^{\,q}(k_\perp^2, x)\otimes D_{1q}^h(p_\perp^2, z)}$$

convolution on the intrinsic
transverse momentum of the quark

sivers PDF
(time odd)

→ correlation between the nucleon transverse polarisation and the quark transverse momenutm $k_\perp$

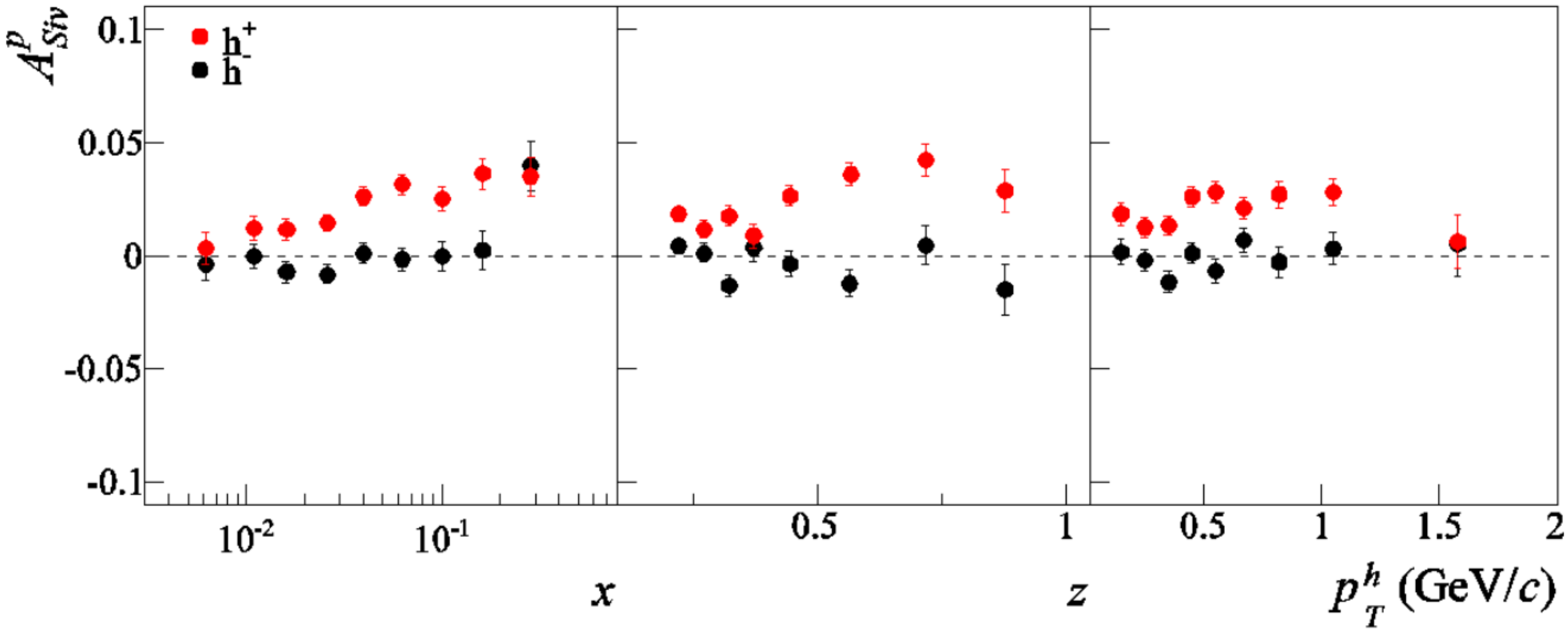
fundamental prediction pQCD (like B-M TMD)
sign change between Sivers TMD measured in SIDIS and in Drell-Yan
(future measurements from COMPASS)

related with quark orbital angular momentum

The Sivers asymmetry *charged hadrons*

combined **2007** - PLB 692 (2010) 240 - and **2010** - PLB 717 (2012) 383 - **measurements on proton**

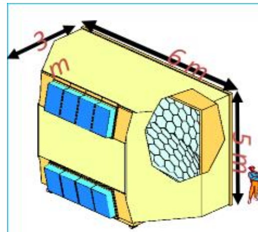
very good agreement between two independent data set



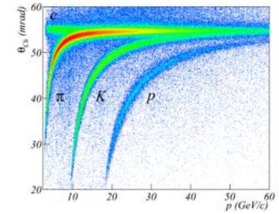
h+ : clear signal down to low x, in the previously unmeasured region

results on deuteron (2002-2004 data) compatible with zero

The Sivers asymmetry
pions and kaons



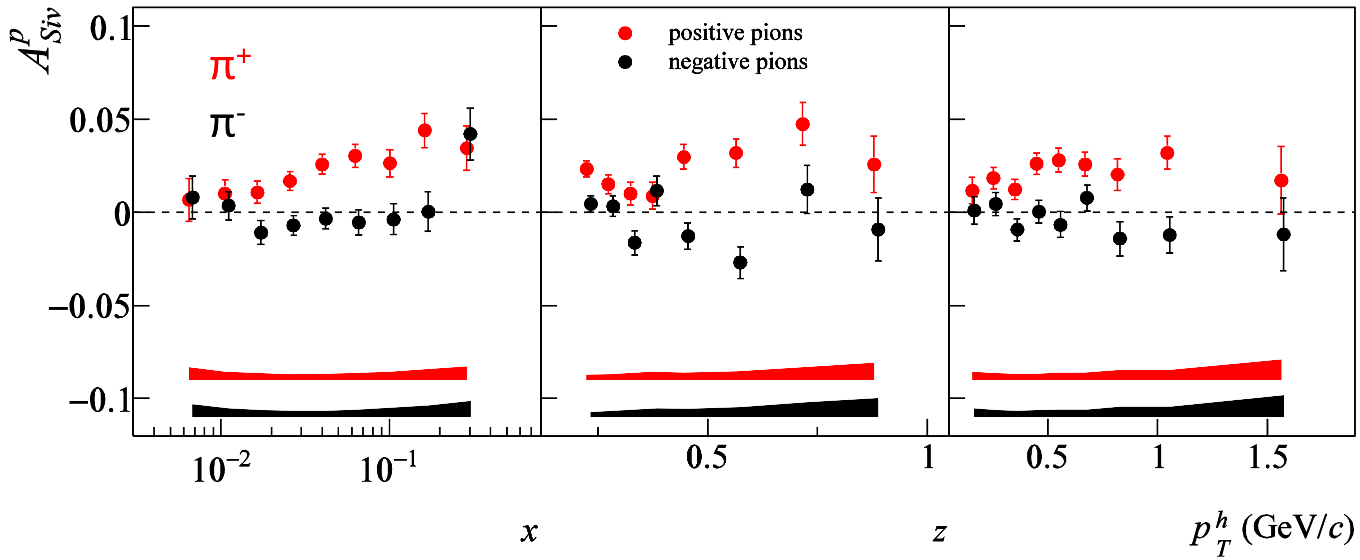
Hadron identification:
$\pi^{\pm}$ $K^{\pm}$
based on RICH-1 response
(likelihood algorithm)



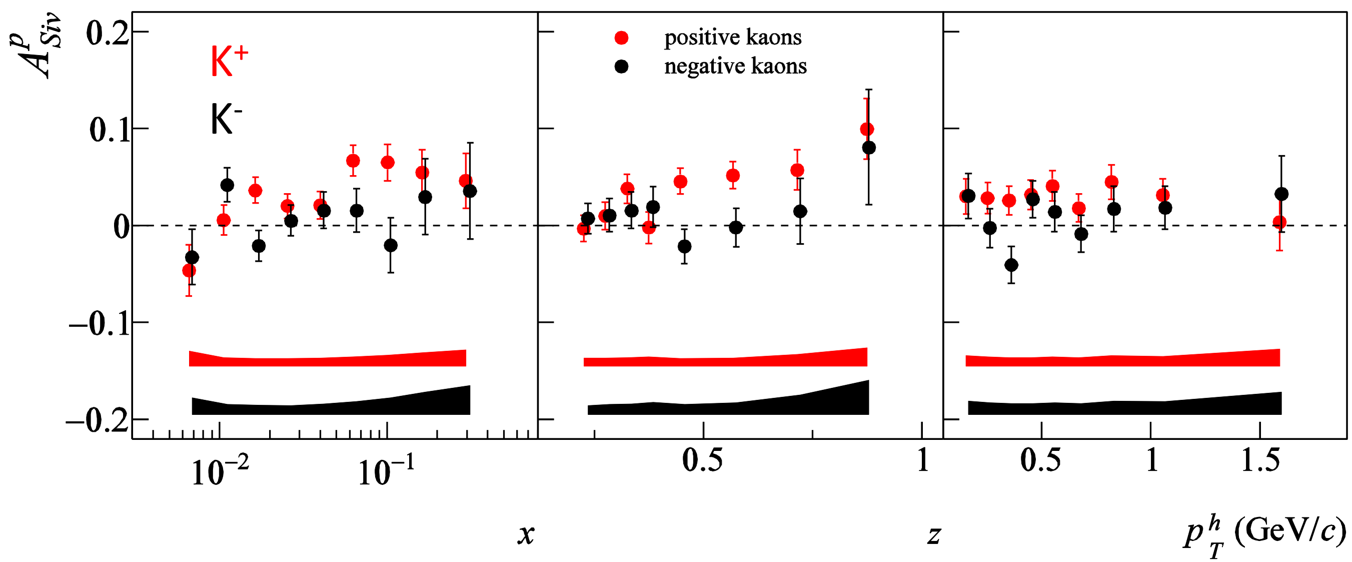
Cherenkov thresholds
π ~ 3 GeV/c
K ~ 9 GeV/c
p ~ 18 GeV/c

~ h+, h-

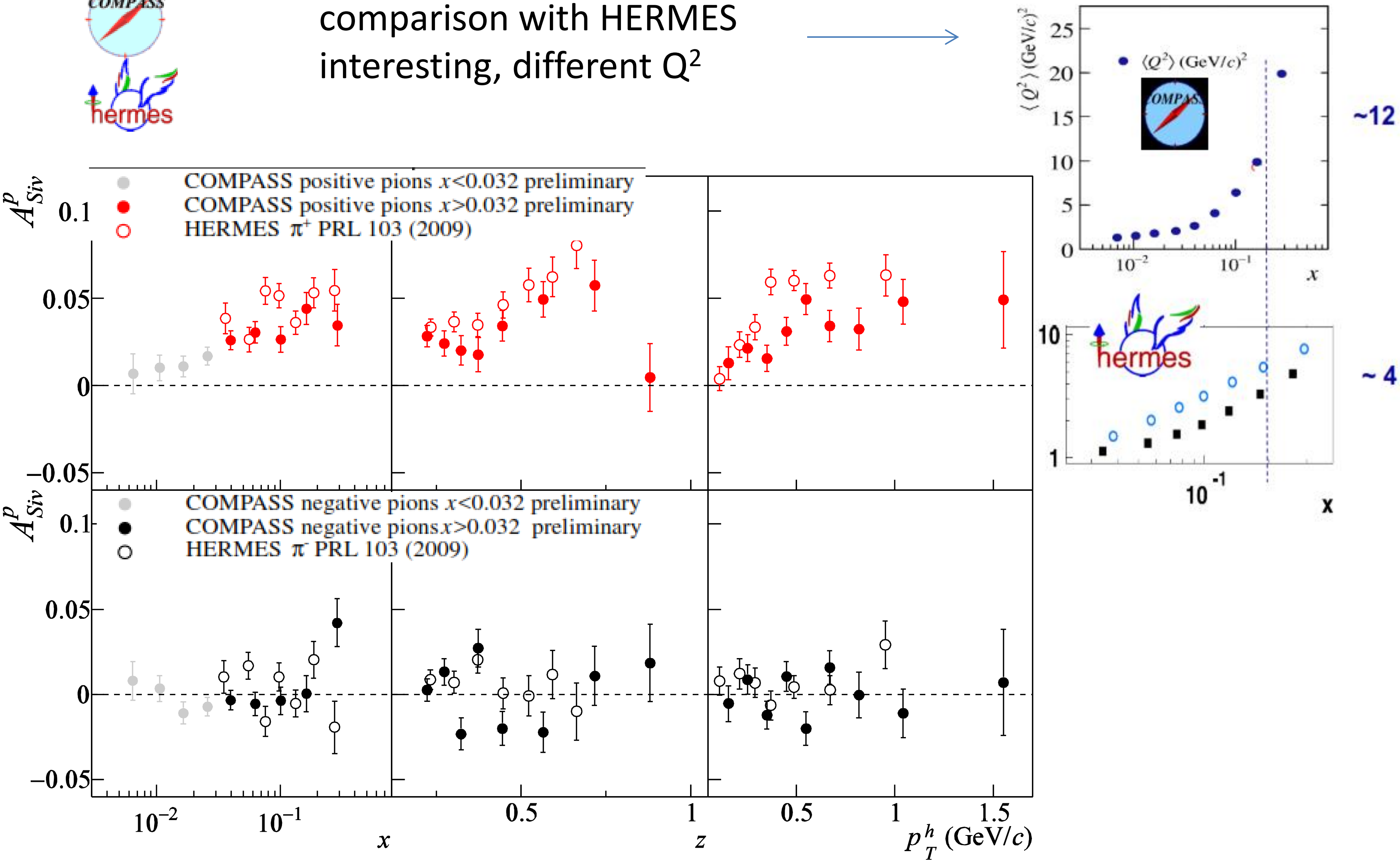
~85% of hadrons are pions



larger than for π^+

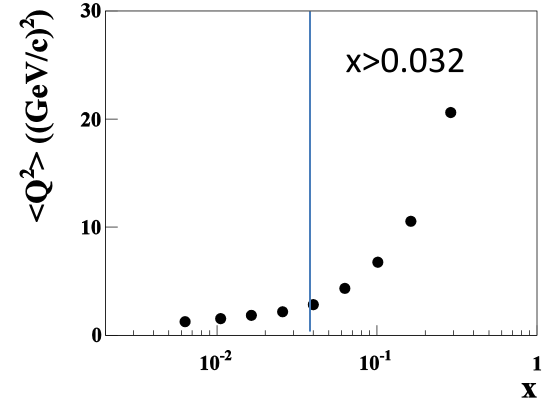


comparison with HERMES
interesting, different Q^2

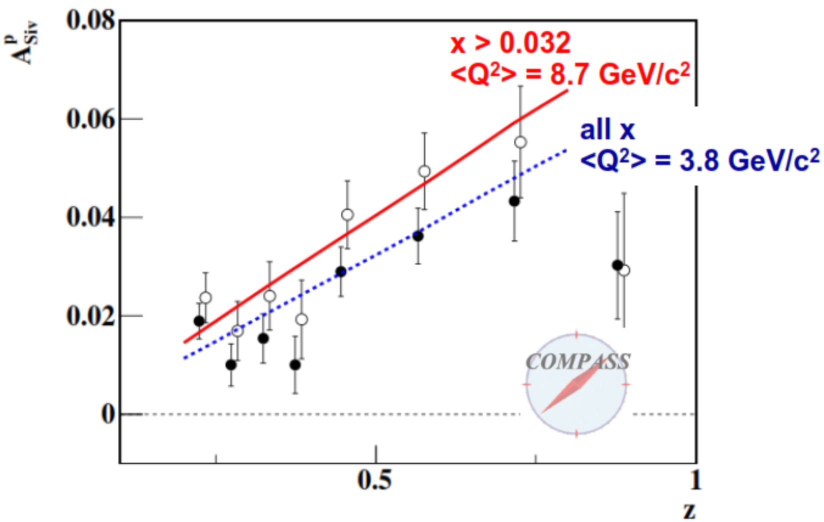


→ Q^2 TMD evolution ?

Sivers asymmetries measured for **all x** and for **x>0.032**
(different Q^2 values)

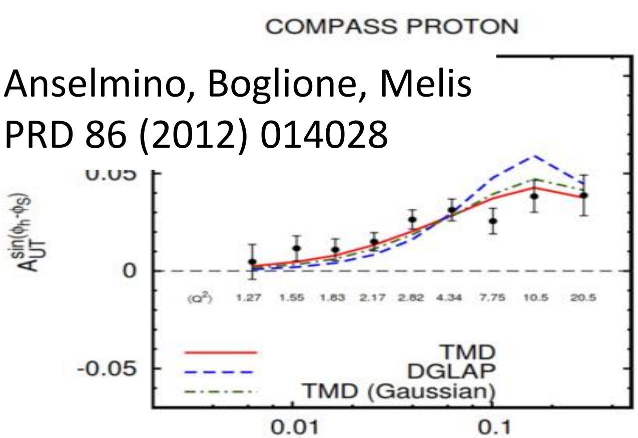


compared with the calculations based on the **TMD evolution**

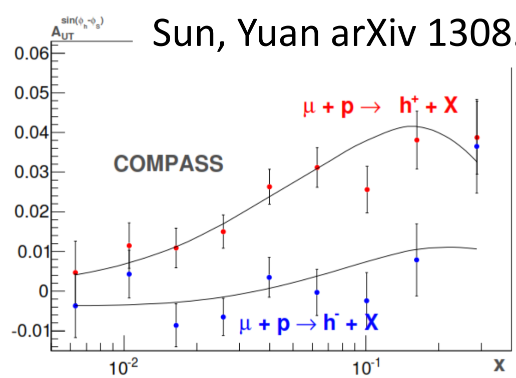


solid lines:
calculations from
Aybat, Prokudin, Rogers
PRL 108 (2012) 242003

Anselmino, Boglione, Melis
PRD 86 (2012) 014028



Sun, Yuan arXiv 1308.5003



a lot of theoretical work ongoing …

The Collins asymmetry

transversity PDF
(chiral odd
cannot be measured in DIS)

→ gives the difference between the number of quarks which have parallel and antiparallel transverse polarisation

collinear PDF: it survives after integration on the transverse momenta

$$A_{Coll} \approx \frac{\sum_q e_q^2 \cdot h_1^q(k_\perp^2, x) \otimes H_{1q}^{\perp h}(p_\perp^2, z)}{\sum_q e_q^2 \cdot f_1^q(k_\perp^2, x) \otimes D_{1q}^h(p_\perp^2, z)}$$

convolution on the intrinsic
transverse momentum of the quark

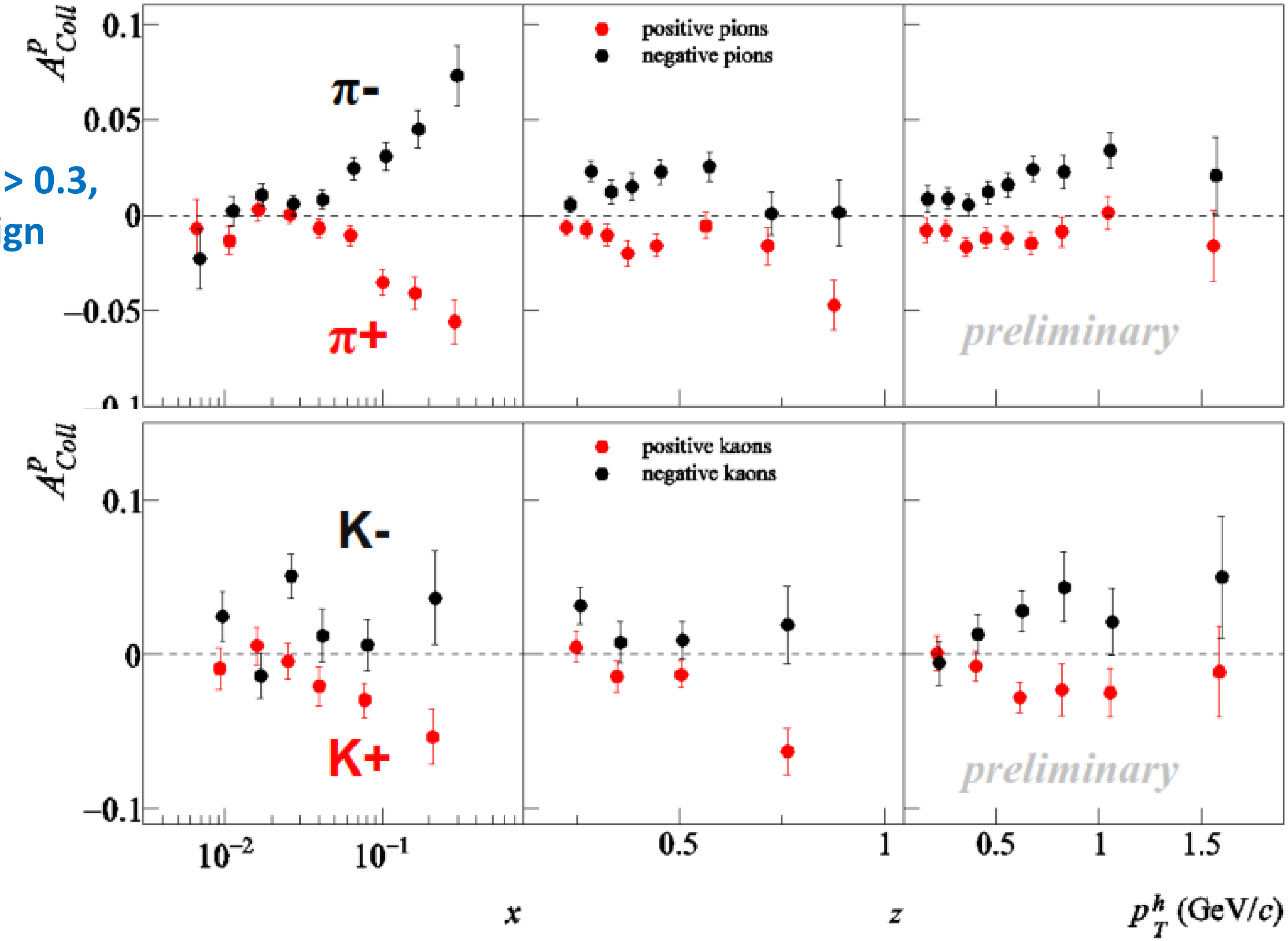
Collins FF *(chiral odd)*
describes the hadronisation of a transversely polarised quark

The Collins asymmetry *charged **pions** and **kaons***

combined **2007** - SPIN 2010 - and **2010** - SPIN 2012 -

measurements on transversely polarised proton

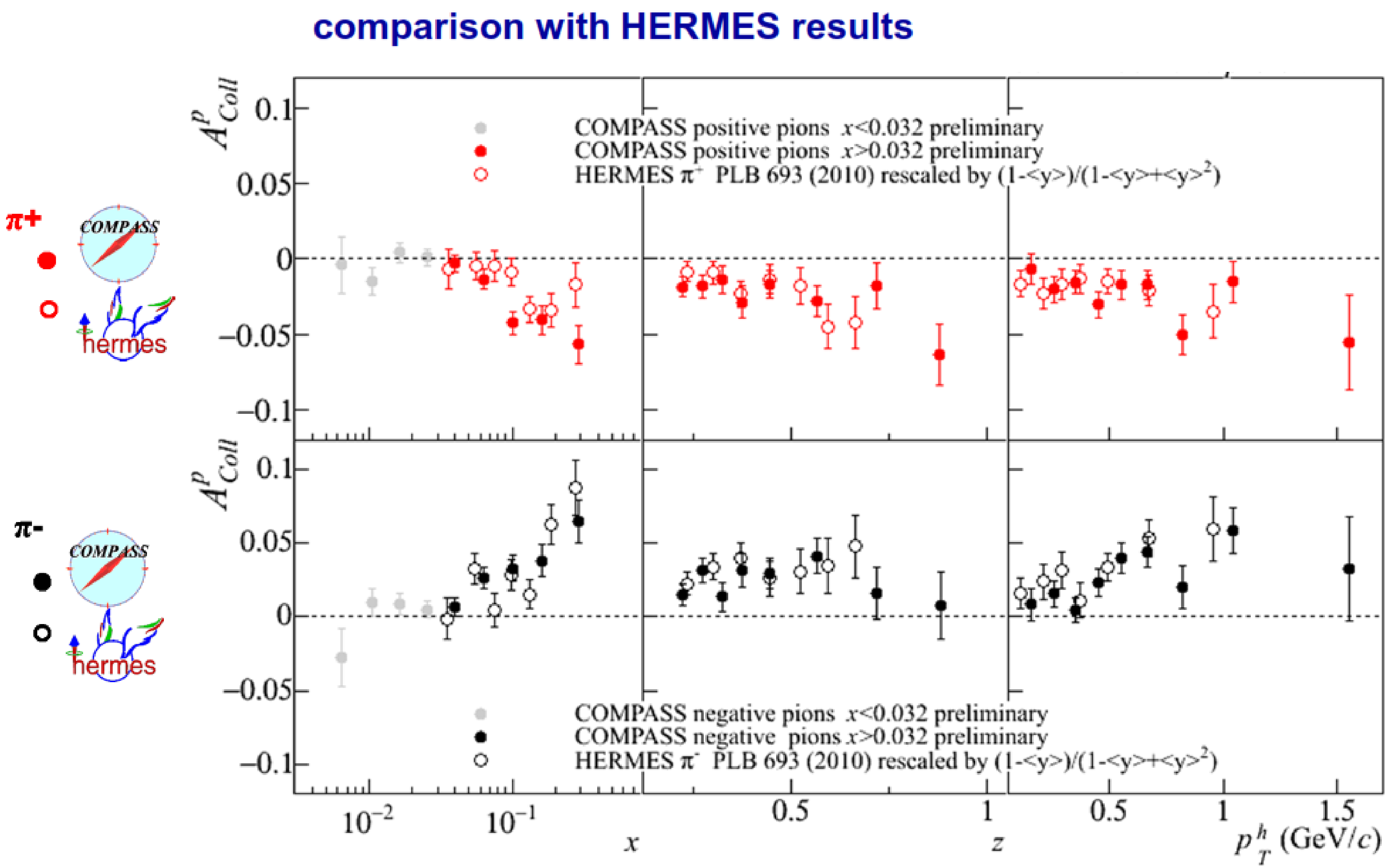
clear signal at x > 0.3, with opposite sign for h+ and h-



compatible with π+, π-

results on deuteron (2002-2004 data) compatible with zero

The Collins asymmetry



same strength: **no strong dependence on Q^2**

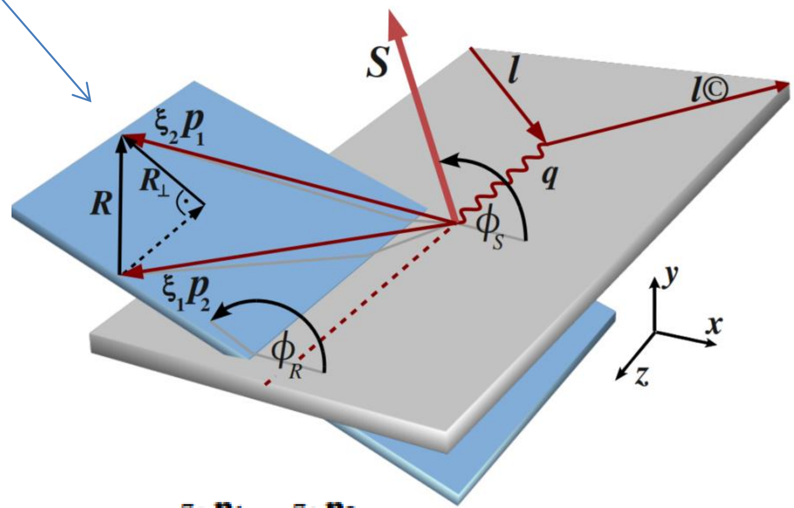
HERMES p + COMPASS p&d + BELLE → extraction of transversity for u and d quarks

The transversity PDF can be measured coupled with the 2-hadron interference fragmentation function

it gives rise to another azimuthal asymmetry in the 2h cross section, on an angle ϕ_{RS} defined as $\phi_R + \phi_S - \pi$

$$A^{p}_{h^+h^-} \approx \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1q}^{\angle}(z, M_{hh}^2)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1q}^{h}(z, M_{hh}^2)}$$

simple product



$$A_{Coll} \approx \frac{\sum_q e_q^2 \cdot h_1^q(k_\perp^2, x) \otimes H_{1q}^{\perp h}(p_\perp^2, z)}{\sum_q e_q^2 \cdot f_1^q(k_\perp^2, x) \otimes D_{1q}^{h}(p_\perp^2, z)}$$

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

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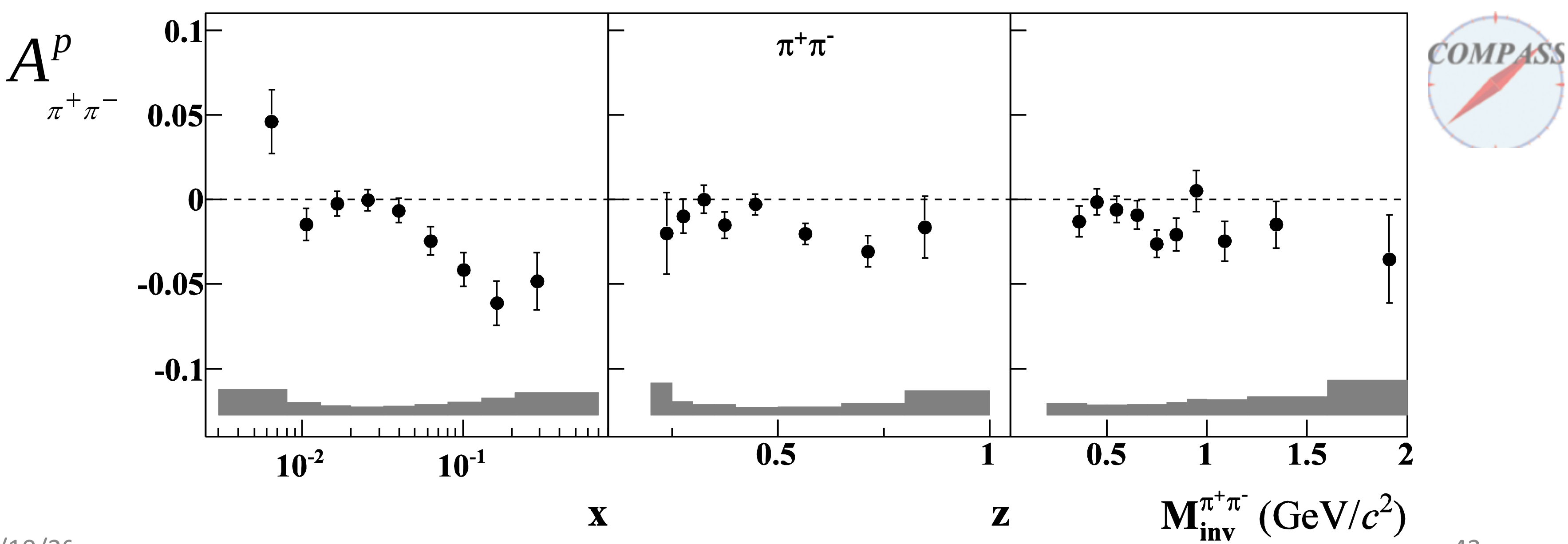


Conclusions

The exploration of the **3-dimensional structure of the nucleon**
is one of the major issues in high energy hadron physics.
embedded in the *Transverse Momentum Dependent Distributions Functions* (TMD PDFs)
→ SIDIS polarised azimuthal cross section is a very useful tool to measure them

COMPASS has given an important contribution with the measurement at high energy of all the structure functions which are expected to appear in the SIDIS cross section

- ***both transversity and Sivers PDFs are clearly different from zero***
- the results give an ***important input to TMD Q^2 evolution***
- ***interesting kinematic dependences*** have been found in ***unpolarised SIDIS***

outlook

more results are coming

- ***hadron multiplicities*** in SIDIS off ***unpolarised*** target from ***2006 deuteron*** data
- ***azimuthal asymmetries*** in SIDIS off ***unpolarised*** target from ***2006 deuteron*** data
- ***multi dimensional analysis*** for the azimuthal asymmetries in SIDIS off ***transversely polarised*** target from the ***2010 proton data***

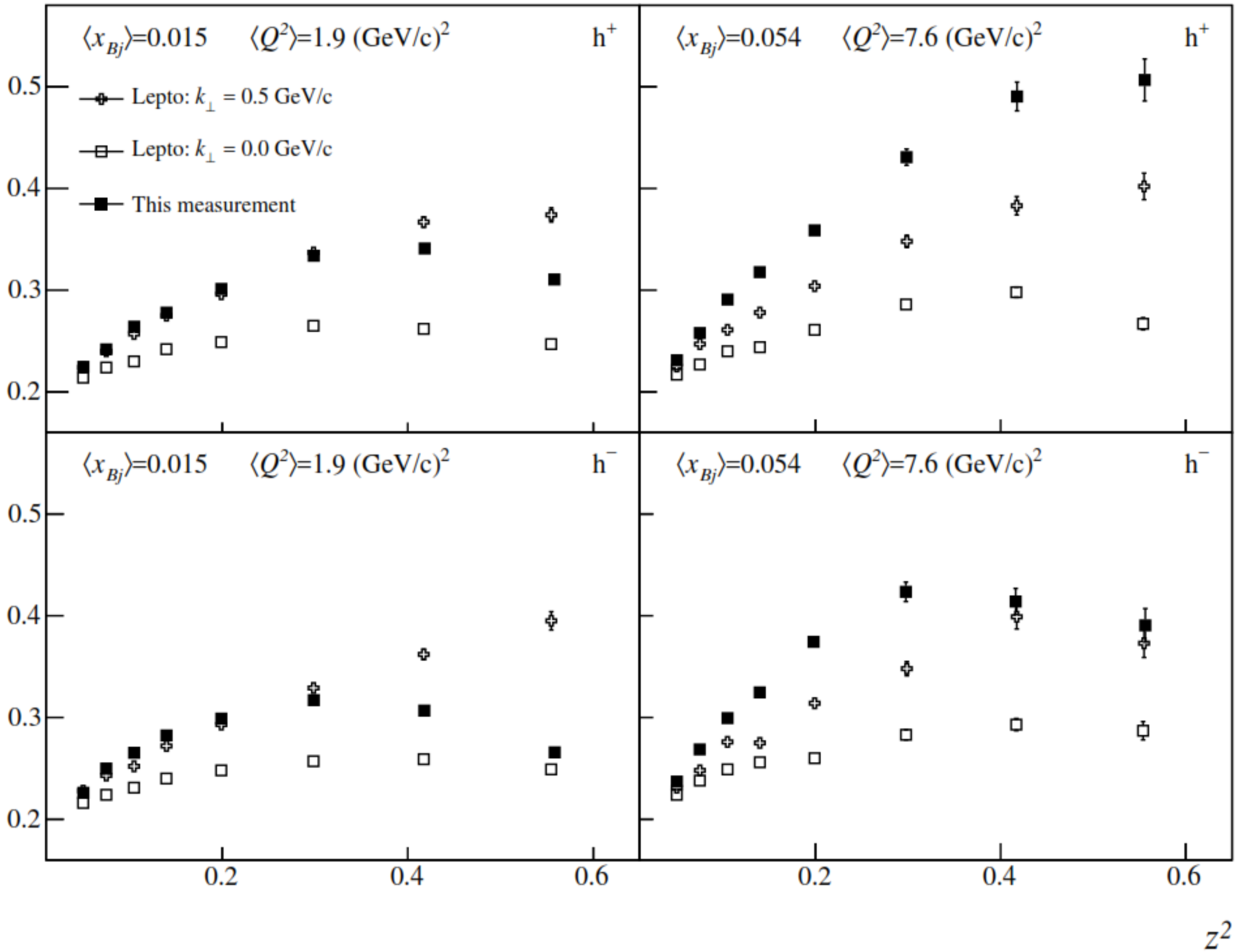
also (COMPASS-II, 2014-2017)

- ***complementary information on TMDs*** will come from (polarised) Drell-Yan
  → Sivers, Boer-Mulders

- ***precise measurements from SIDIS*** on a long liquid H_2 target will be performed in parallel to the DVCS measurement
  → Cahn effect, Boer-Mulders

backup

$\langle P_T^{h\,2} \rangle$

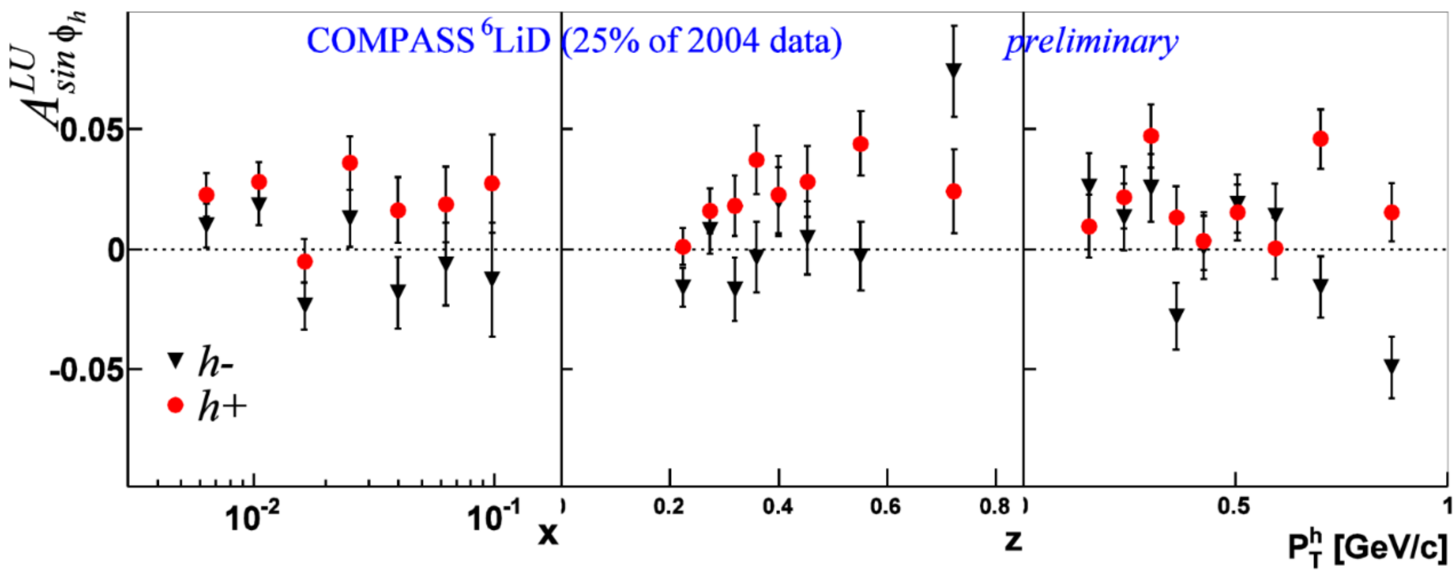


the more relevant features (like the z dependence for h+ and for h-) are not reproduced by the Monte Carlo

more work is needed to extract $\langle k_\perp^2 \rangle$

Results extracted binning alternatively in x, z and P_T^h

shown at SPIN2010



$$A^{LU}_{\sin\phi_h}$$ higher twist effect

sys ≈ 2 · stat

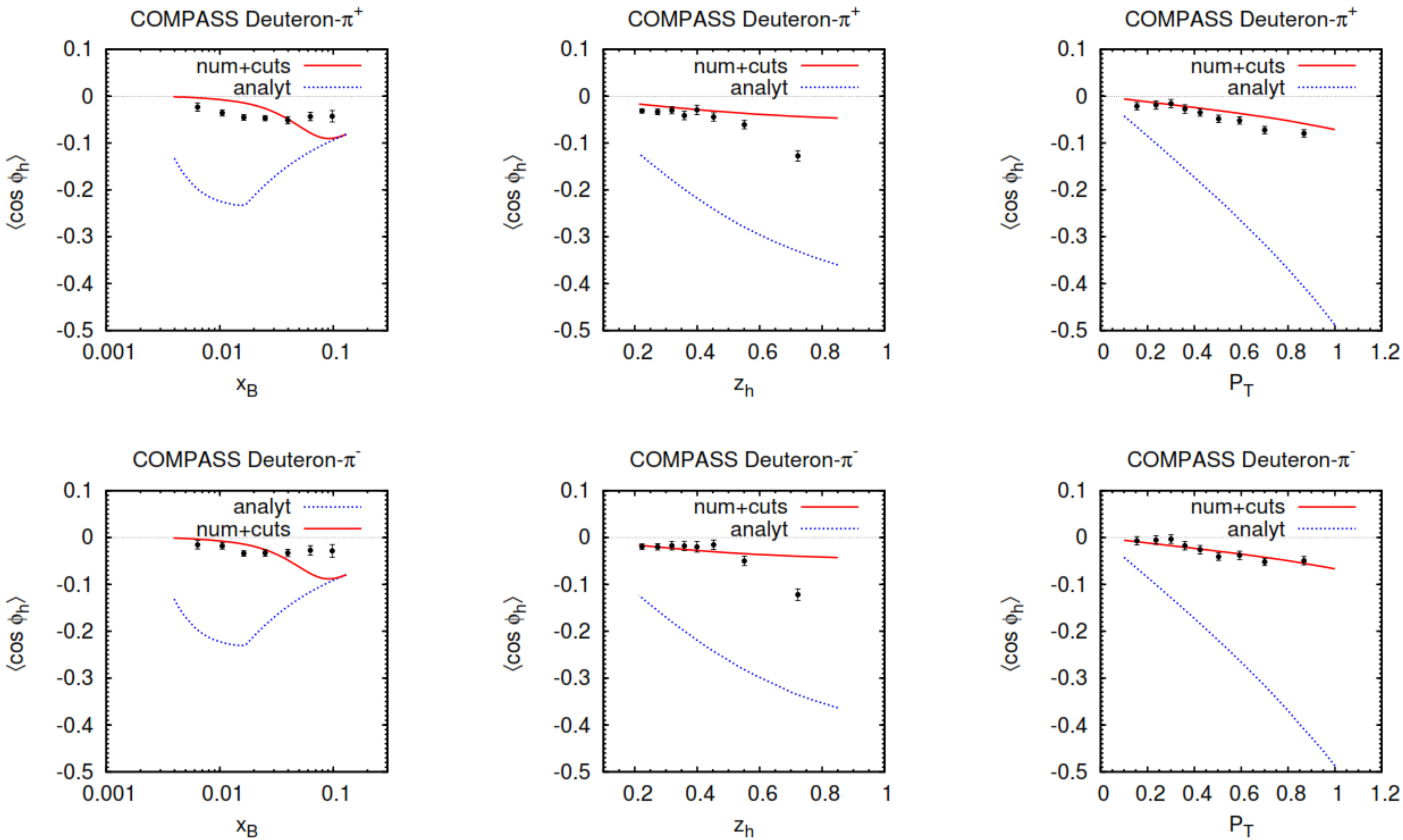
slightly positive signal for h+

h- compatible with zero

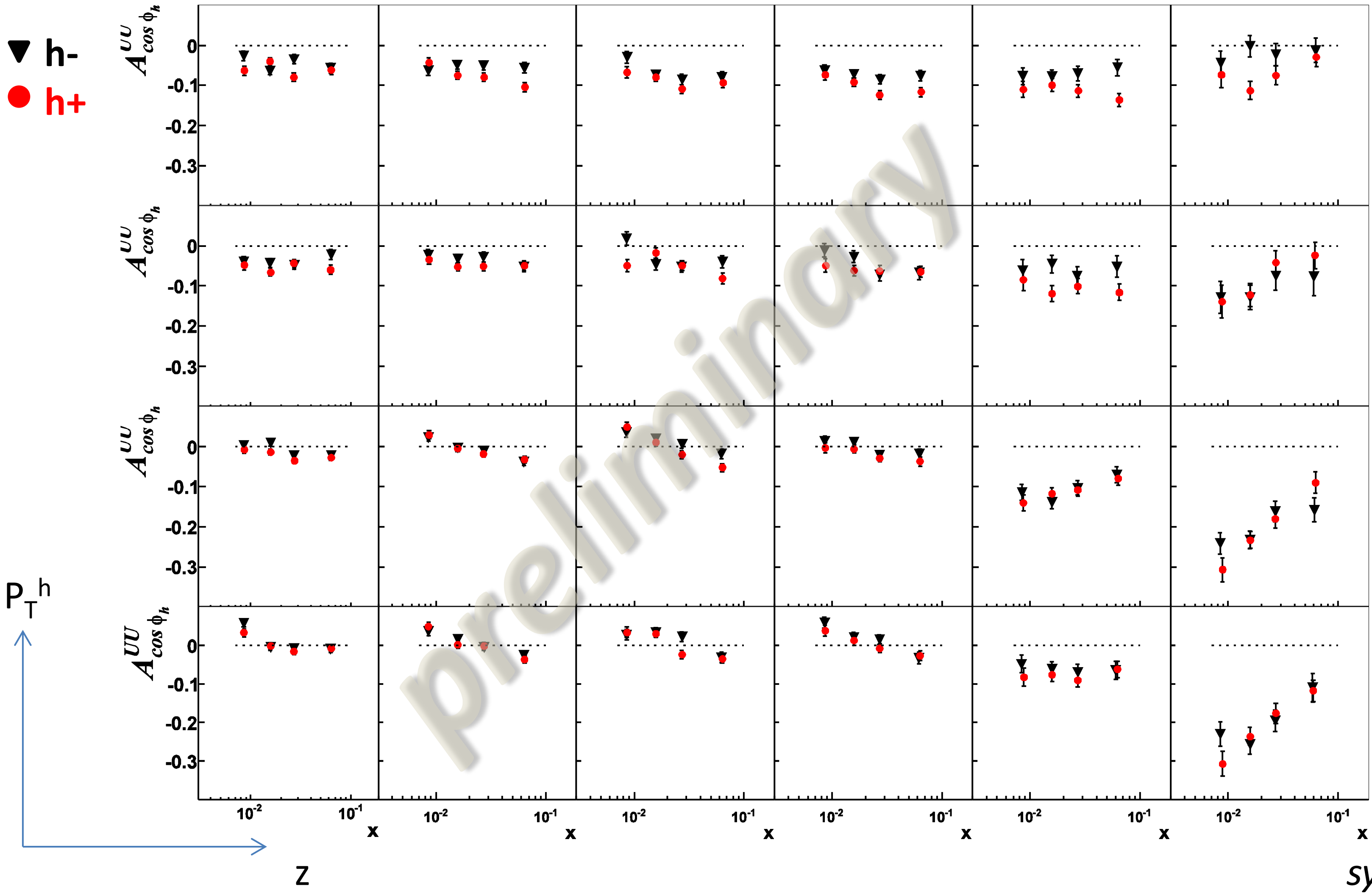
important input to phenomenological predictions

kinematical cuts had to be introduced for the quark intrinsic transverse momentum

$$f_{q/p}(x, k_\perp) = f_{q/p}(x)\,\frac{1}{1 - e^{-(k_\perp^{\max})^2/\langle k_\perp^2\rangle}}\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$



COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

largest difference between positive and negative hadrons at large P_T^h
x trend changes going from small to large z values

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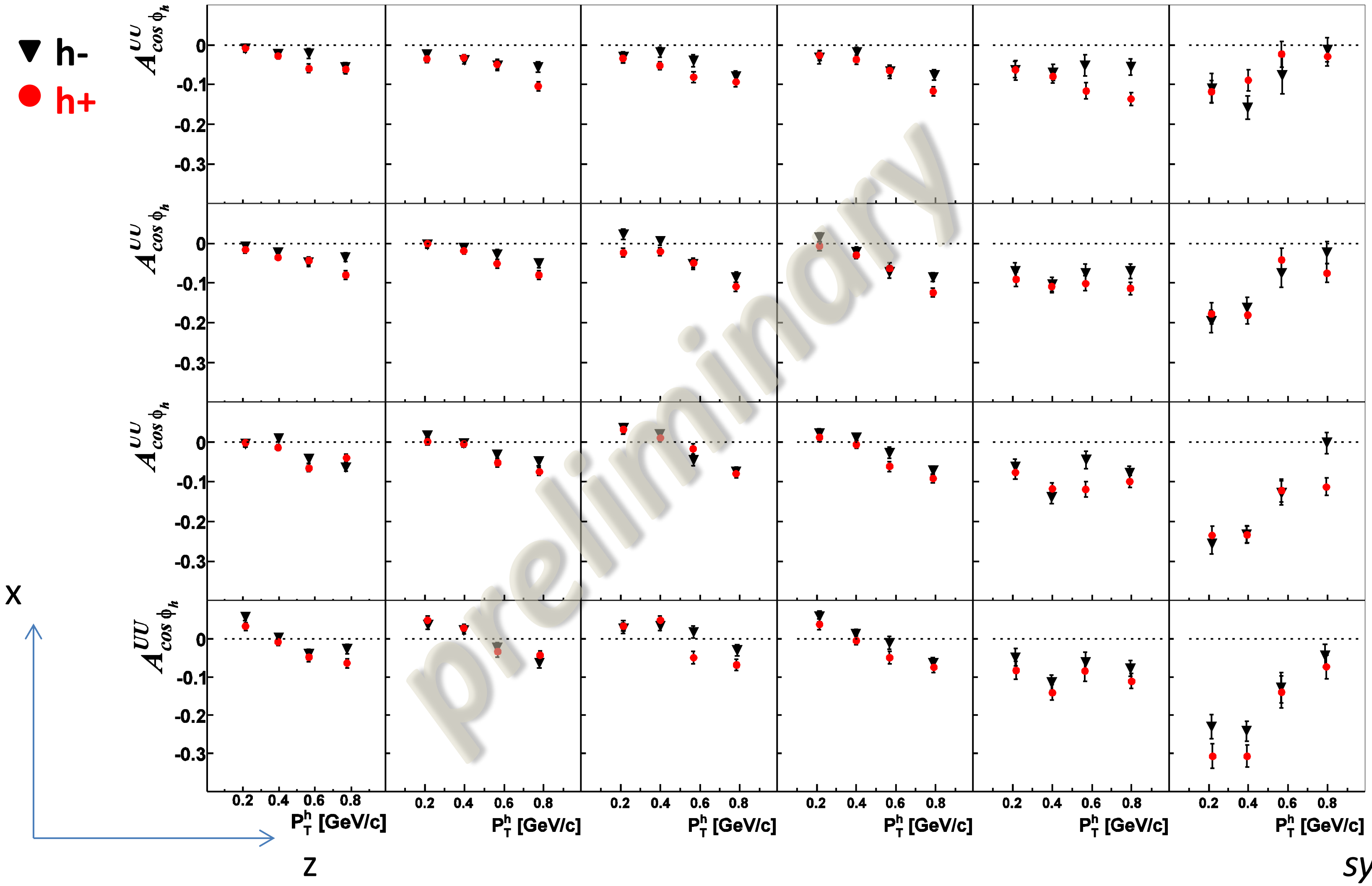

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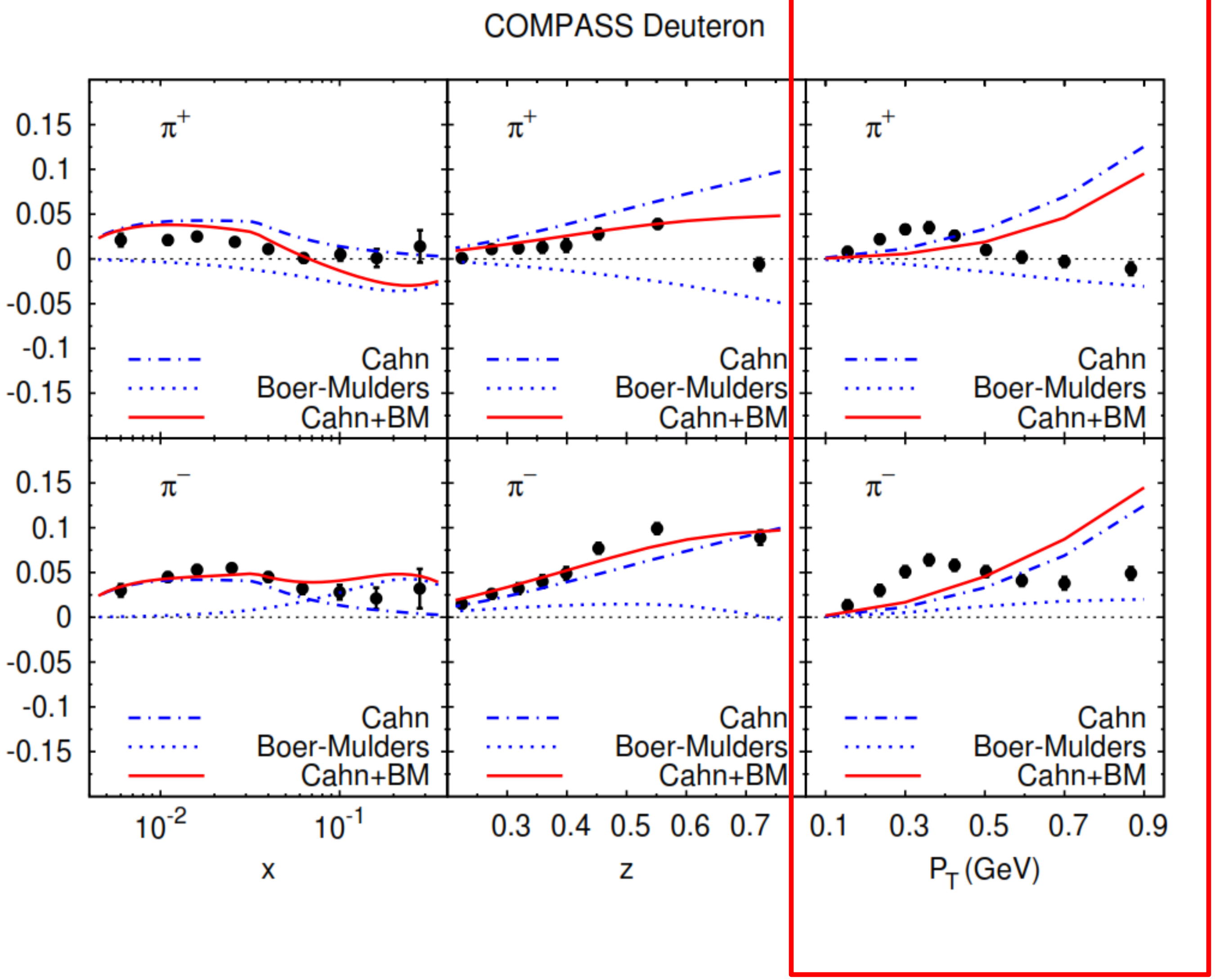
P_T^h trend changes going from small to large z values and it is roughly the same for all x intervals

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



P_T^h dependence difficult to reproduce (PRD81, Barone,Melis,Prokudin)

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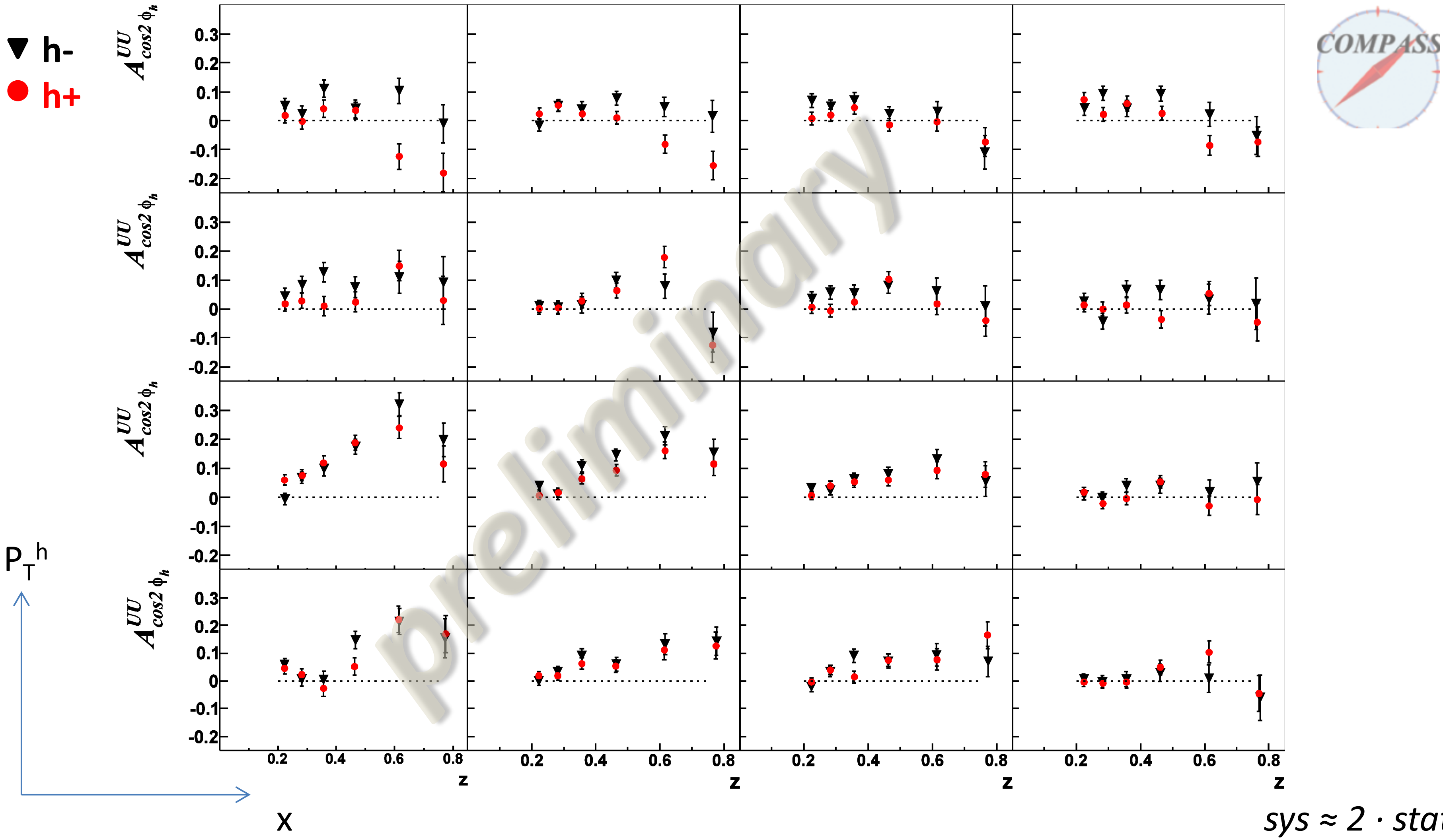

sys ≈ 2 · stat

strongest effect at low x and low P_T^h

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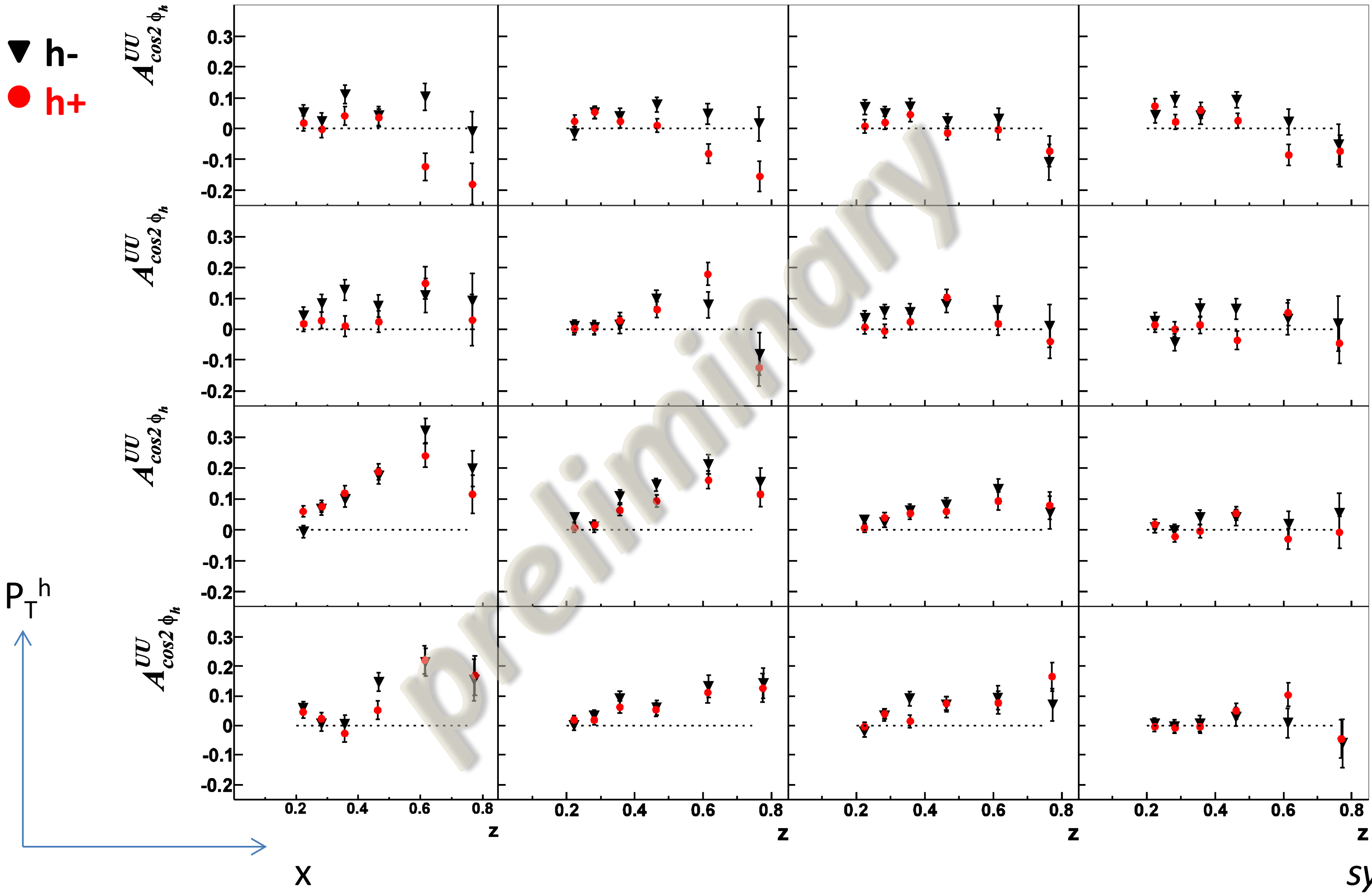

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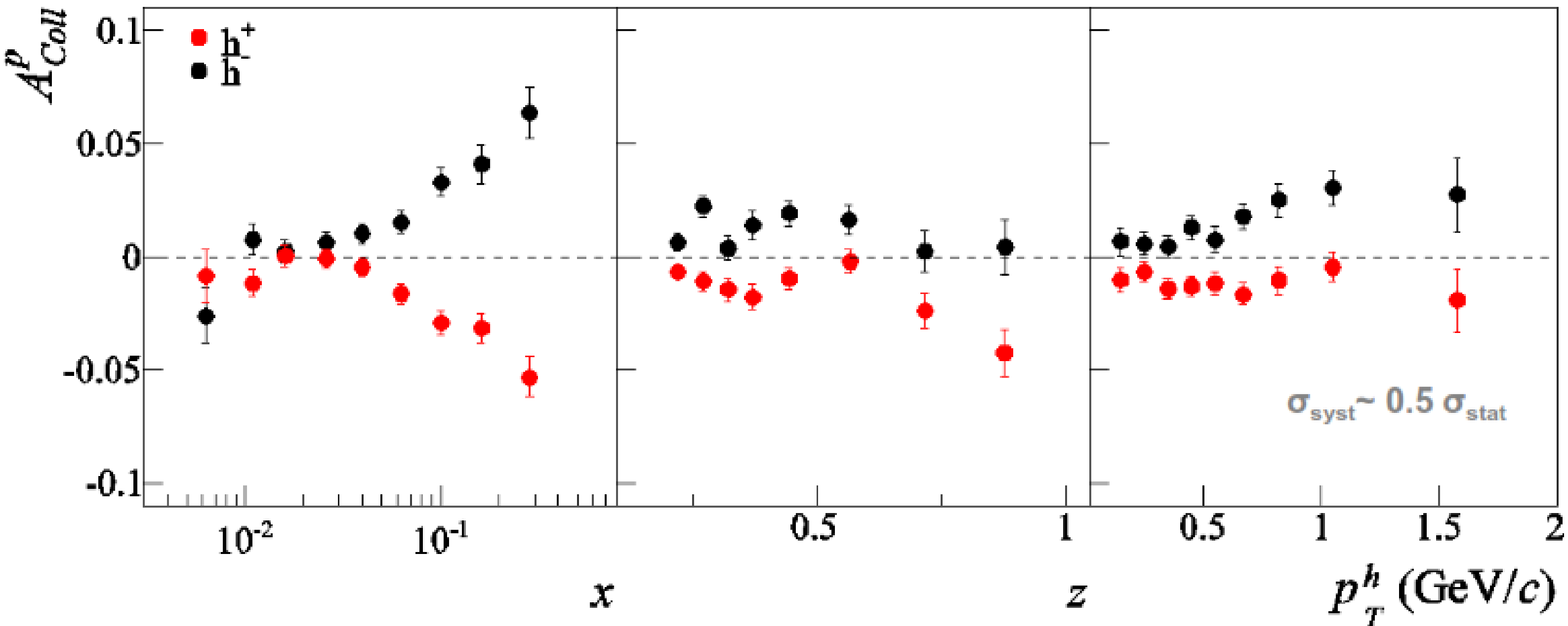
very good agreement between two independent data set



- **precise measurements**
- **clear signal at x > 0.3, with opposite sign for h+ and h-**
  in agreement with the HERMES results

results on deuteron (2002-2004 data) compatible with zero
HERMES p + COMPASS p&d + BELLE → extraction of transversity for u and d quarks