SIDIS: most recent results and open issues

XIV International Workshop on Hadron Structure and Spectroscopy

Cortona (Italy), 2 - 5 April 2017

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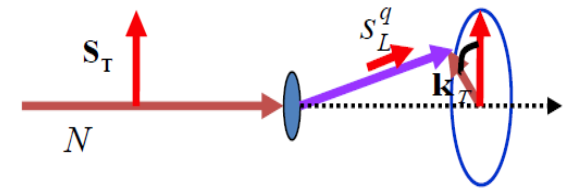
Focusing on a selection
of results mainly on
transverse momentum dependent effects
and transverse spin
in SIDIS
(and some related open issues)

The structure of the nucleon

there are **8 TMD PDF** at leading twist appear in the nucleon description taking into account the
intrinsic transverse momentum of the quark $k_\perp$



$\mathbf{k}_\perp$ – intrinsic transverse momentum of the quark

nucleon polarisation / **quark** polarisation

quark polarisation \ nucleon polarisation	U	L	T	
U	f_1 number density q		$f_{1T}^\perp$ Sivers	$\Delta_0^T q$
L		g_1 helicity Δq	g_{1T}	
T	$h_1^\perp$ Boer Mulders	$h_{1L}^\perp$	h_1 transversity $h_{1T}^\perp$	$\Delta_T q$

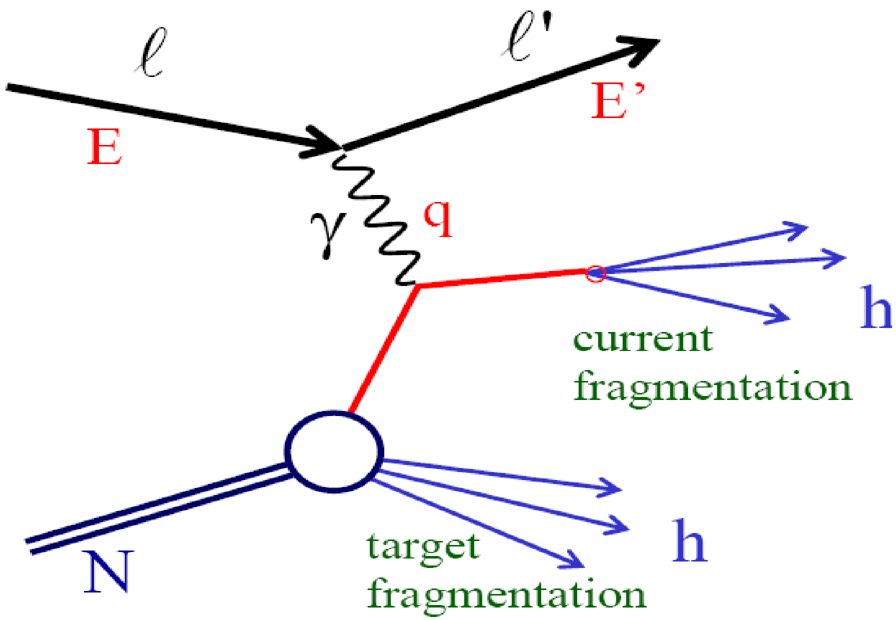
SIDIS: *a key process to* ***investigate*** *the* ***structure of the nucleon***

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

$$q = \ell - \ell' \qquad x = \frac{Q^2}{2P \cdot q} \quad \textit{Bjorken scaling variable} \qquad y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

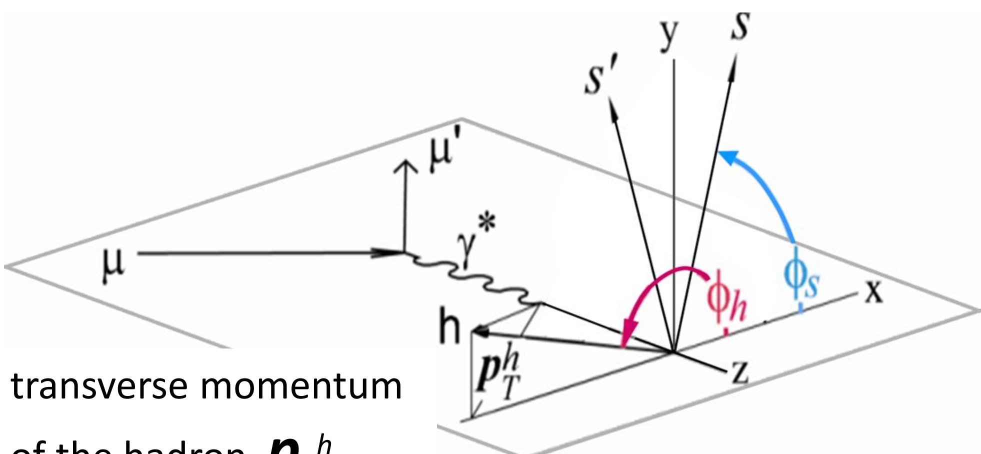
$$Q^2 = -q^2 \qquad W^2 = (P + q)^2$$

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



at least one hadron is detected in the final state

(information on the struck quark)



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

polarised SIDIS azimuthal cross section

"one photon exchange approximation"

Bacchetta et al. JHEP 0702:093,2007

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

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

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

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

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

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

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

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

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

target polarisation

beam polarisation

14 ***independent modulations*** *in* $\boldsymbol{\varphi_h}$ *and* $\boldsymbol{\varphi_S}$

polarised SIDIS azimuthal cross section

"one photon exchange approximation"

Bacchetta et al. JHEP 0702:093,2007

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

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

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

unpolarised part

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

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

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

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

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

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

target polarisation

beam polarisation

transverse spin dependent part

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

Why SIDIS?

all these amplitudes can be **extracted simultaneously** from the same data
all the different **TMD PDFs appear** in the cross section
and the **different effects** can be **disentangled**

Outline

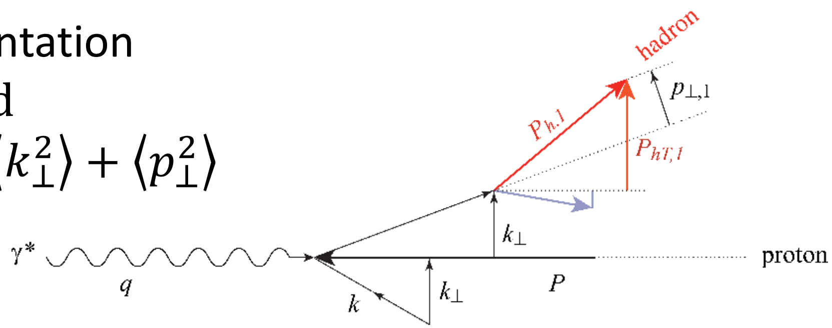
- Unpolarised SIDIS
  - P_T^h dependent multiplicities
  - azimutal asymmetries
- Transversely polarised SIDIS
  - Sivers asymmetries
    - PTh weighted Sivers asymmetries
  - Collins asymmetries
    - two hadrons asymmetries
  - other 6 asymmetries

Unpolarised SIDIS

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

- The cross-section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - Usual assumptions: Gaussian and

$$\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$$

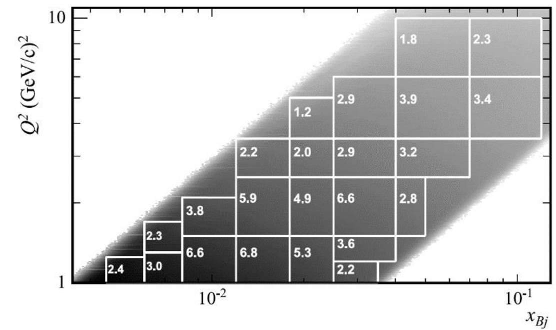


COMPASS and HERMES have

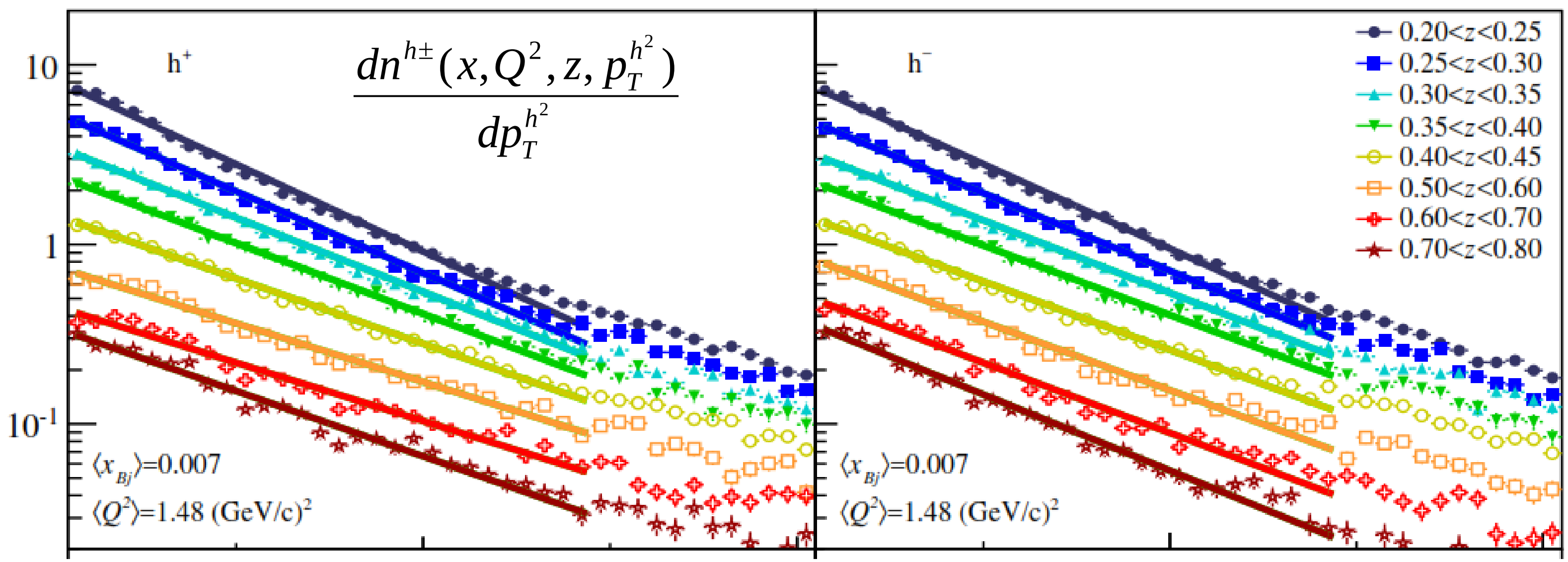
results on deuteron and on protons (Hermes only)

No COMPASS measurements on p since on NH_3 nuclear effects may be important

COMPASS results on deuteron
(2004 data)



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



$(P_T^h)^2$ *(GeV/c)^2* ***$(P_T^h)^2$*** *(GeV/c)^2*

for each bin in **x, Q²** and **z**
fit using

→ extract $A\cdot e^{-P_T^{h^2}/\langle P_T^{h^2}\rangle}$

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

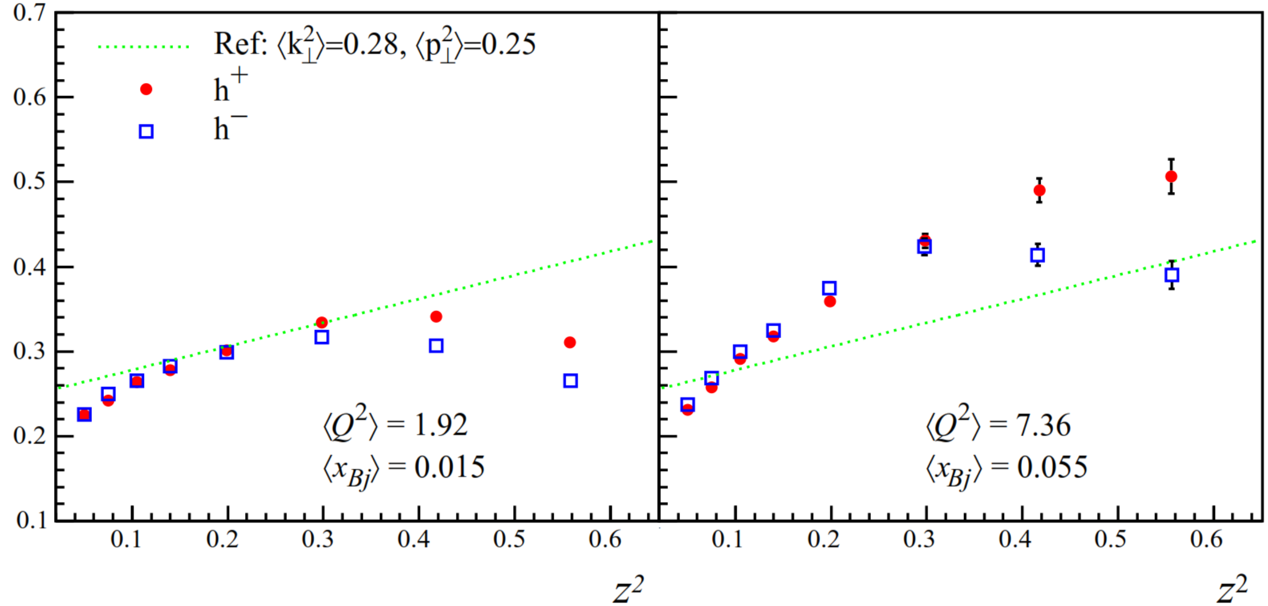
EPJ73 (2013) 2531

COMPASS results on deuteron (2004 data)

z^2 dependence

$$\langle P_T^{h\,2}(z^2)\rangle$$

EPJ73 (2013) 2531



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

linear dependence on z^2 does not reproduce data
effect from fragmentation $P_\perp(z)$ (not so easy to calculate…)

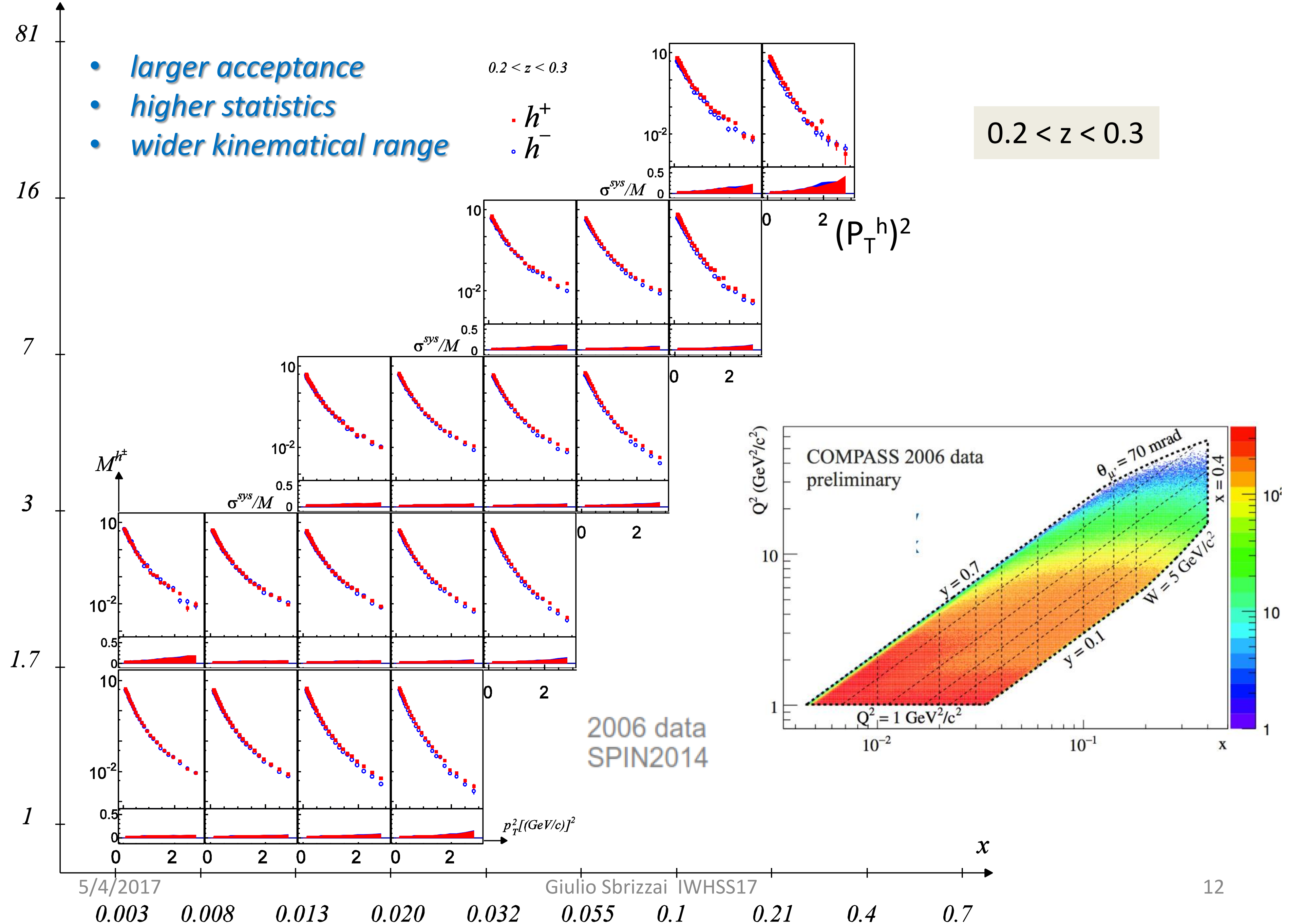
Results given with a 10% uncertainty on the normalization *EPJ75 (2015) 94*

new results with much better precision from 2006 deuteron data in publication

COMPASS Preliminary

- larger acceptance
- higher statistics
- wider kinematical range

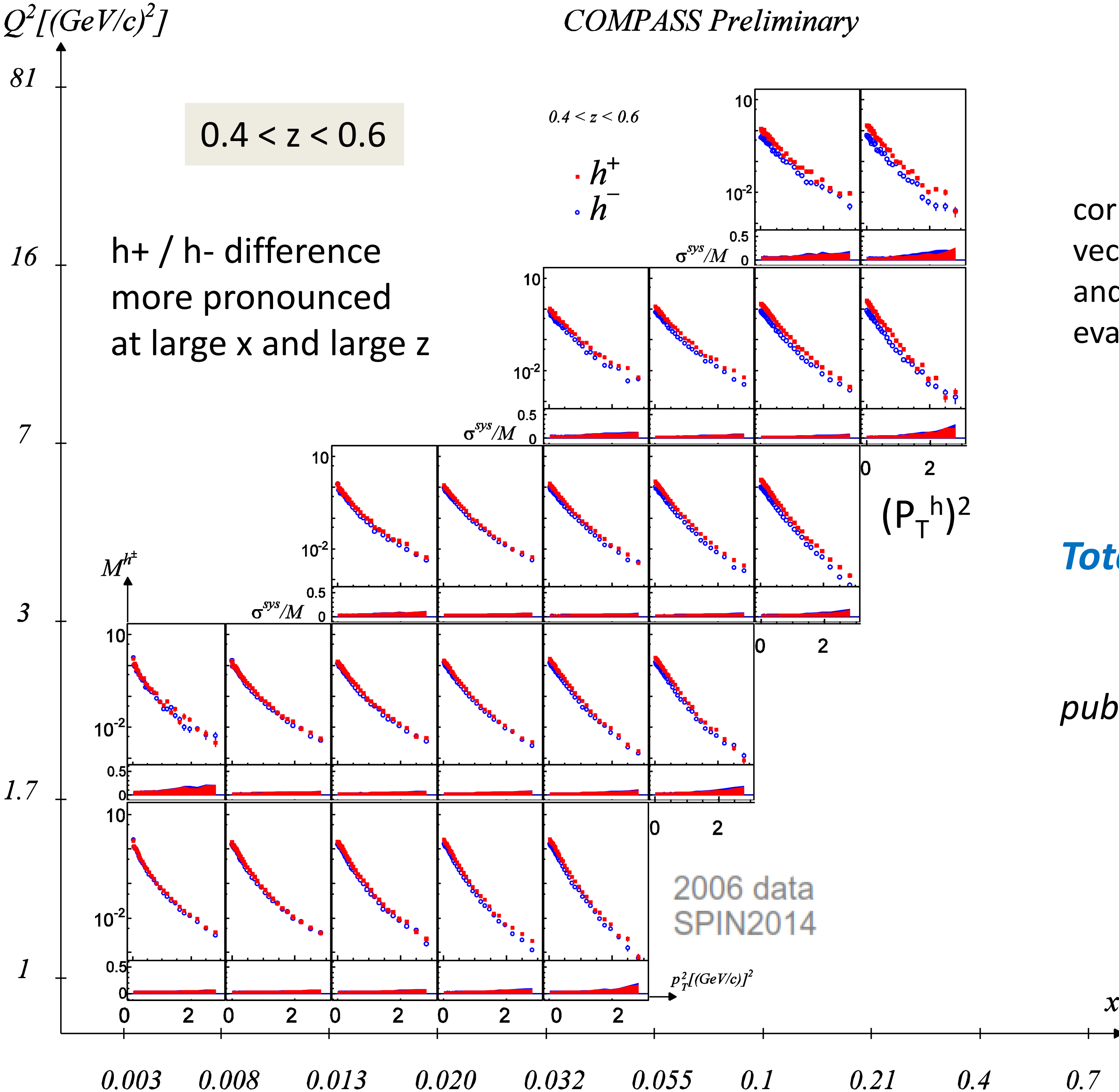
0.2 < z < 0.3



2006 data
SPIN2014

0.4 < z < 0.6

h+ / h- difference more pronounced at large x and large z



correction for vector meson production and radiative corrections evaluated

Total: 4918 points

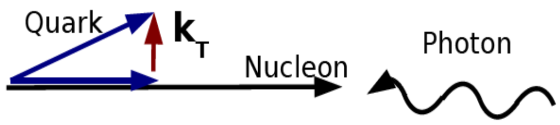
publication on the way

Unpolarised SIDIS

- The azimuthal modulations in the unpolarized cross-sections mainly comes from:

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

$$A^{UU}_{\cos\phi_h} = \frac{F^{UU}_{\cos\phi_h}}{F^{UU}}$$



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

pQCD negligible for P^h_T < 1 GeV/c

$$A^{UU}_{\cos 2\phi_h} = \frac{F^{UU}_{\cos 2\phi_h}}{F^{UU}}$$

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

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

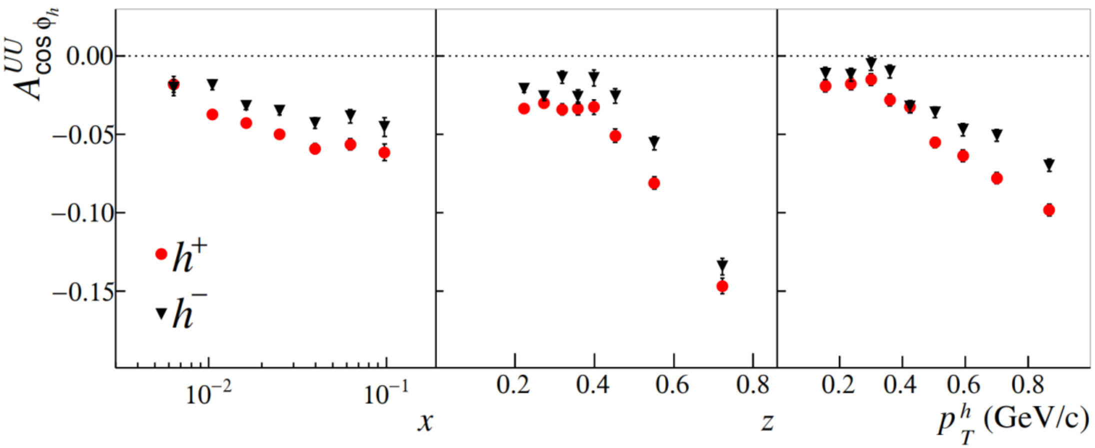
pQCD negligible for P^h_T < 1 GeV/c

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

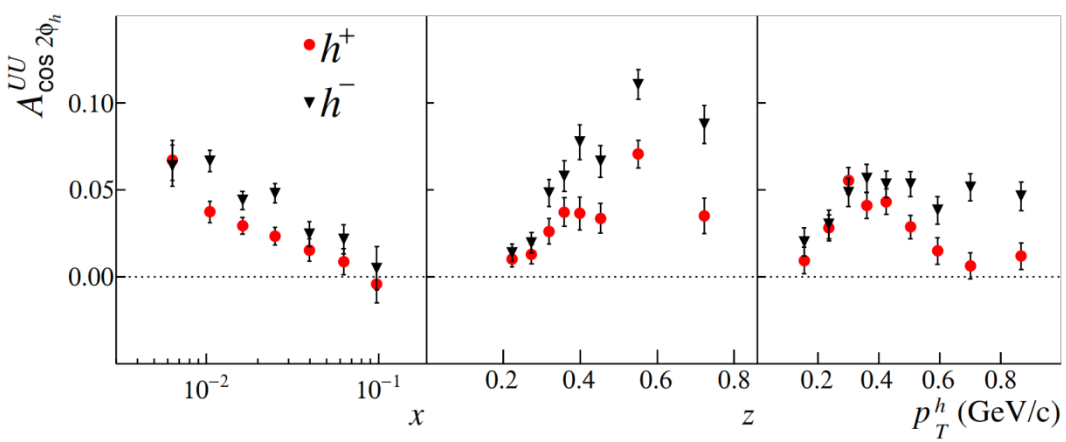
other higher twist effects can contribute…

strong kinematic dependencies not understood….

NPB 886 (2014) 1046



$$= \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM}$$



$$= \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

also CLAS (PRD 80) for π^+
and HERMES (PRD 87)

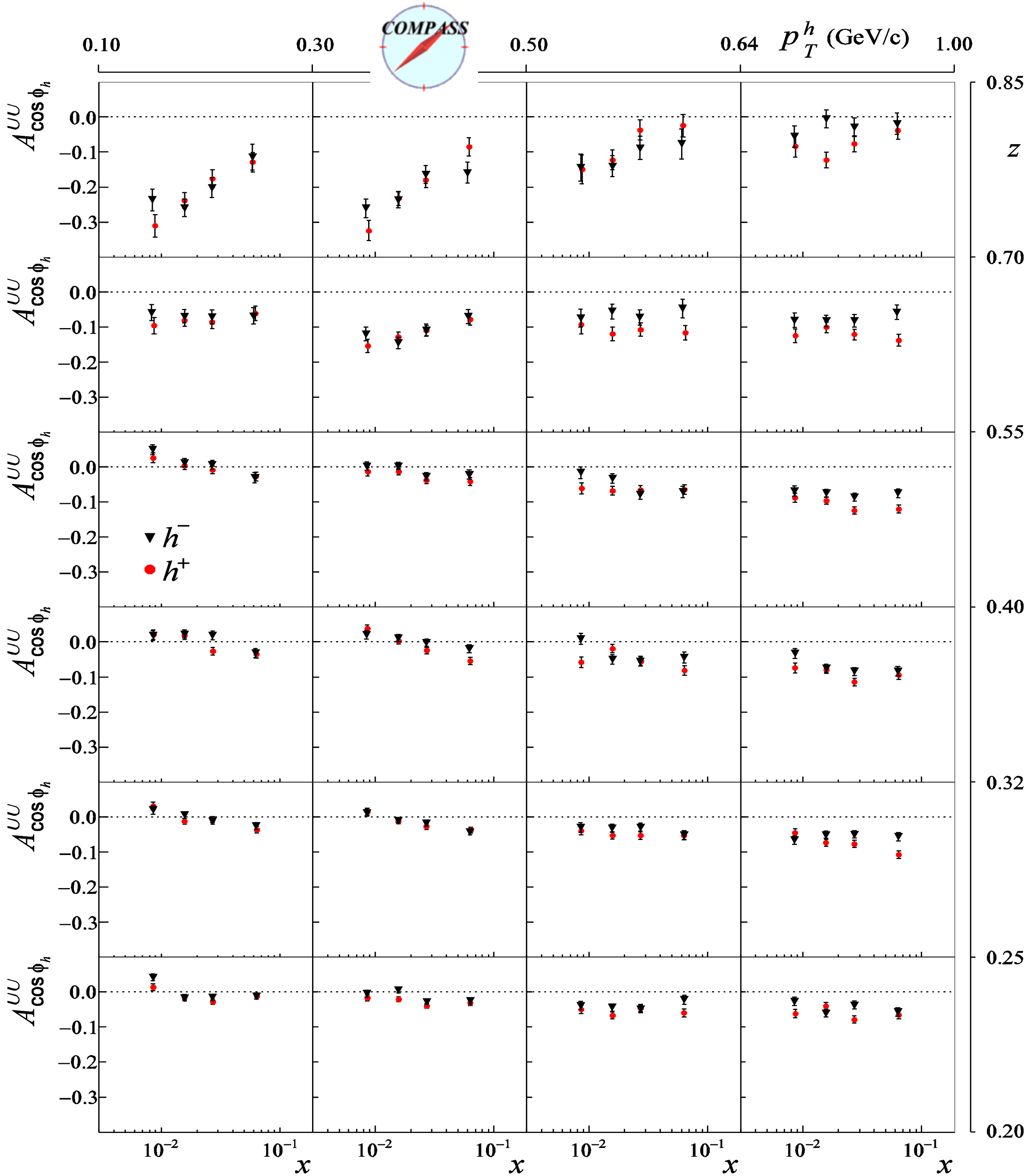
dependencies on z and on P_T^h investigated using multiD analysis !

Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data

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

convoluted with the Collins FF

multiD performed both on **cosϕ** and **cos2ϕ**



Using the info from the P_T^h dependent multiplicities *of COMPASS and HERMES data*
study the azimuthal asymmetries

↓

disentangle $k_\perp$ and $p_\perp$ contribution to P_T^h

P_T^h dependencies
in different bins of z and x

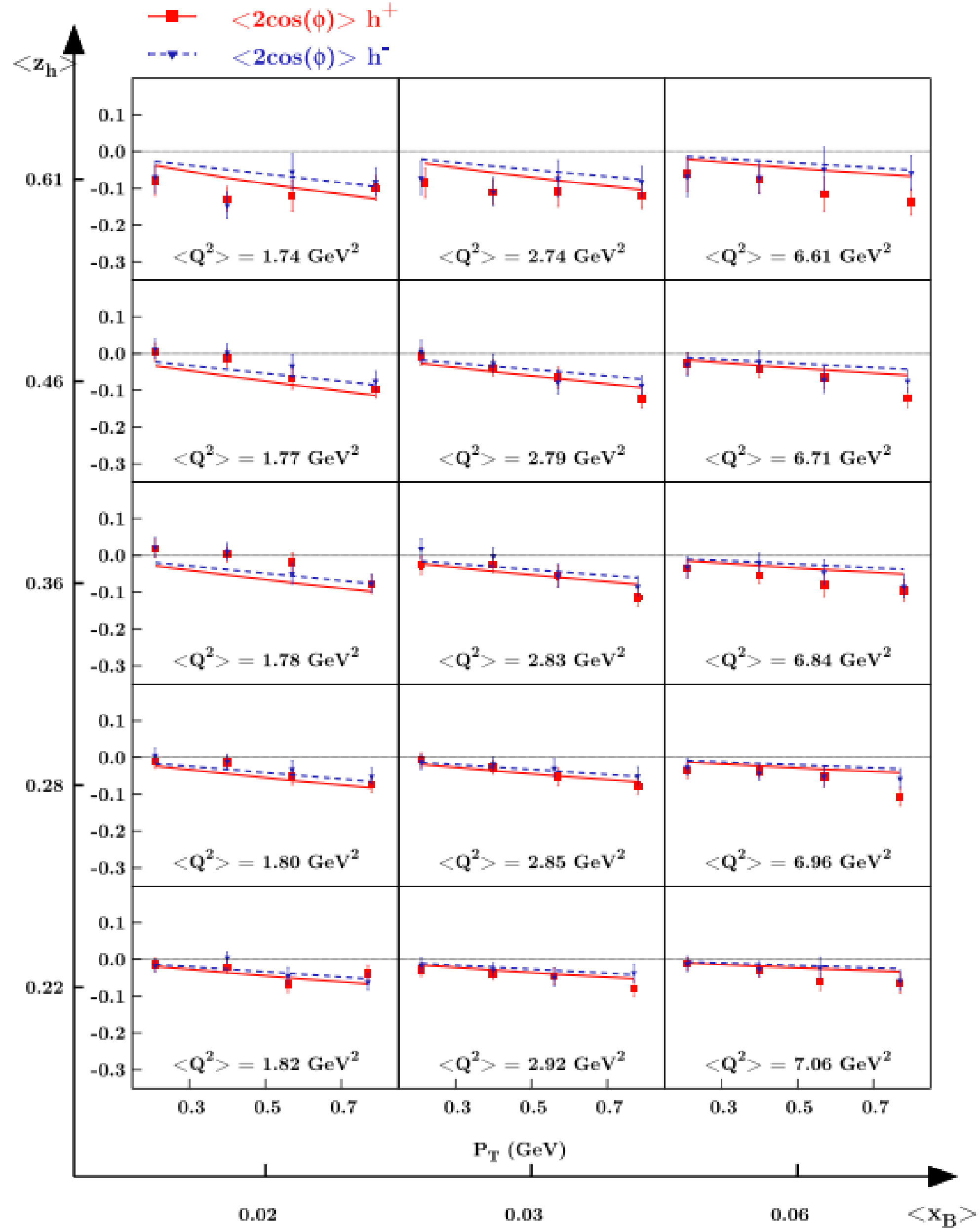
cosϕ asymmetries

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

↓

small contribution
from $k_\perp$

neglecting possible
dynamic twist-3 contributions



PRD91 (2015) *Barone et al*

Using the info from the P_T^h dependent multiplicities *of COMPASS and HERMES data*
study the azimuthal asymmetries

↓

disentangle $k_\perp$ and $p_\perp$ contribution to P_T^h

P_T^h dependencies
in different bins of z and x

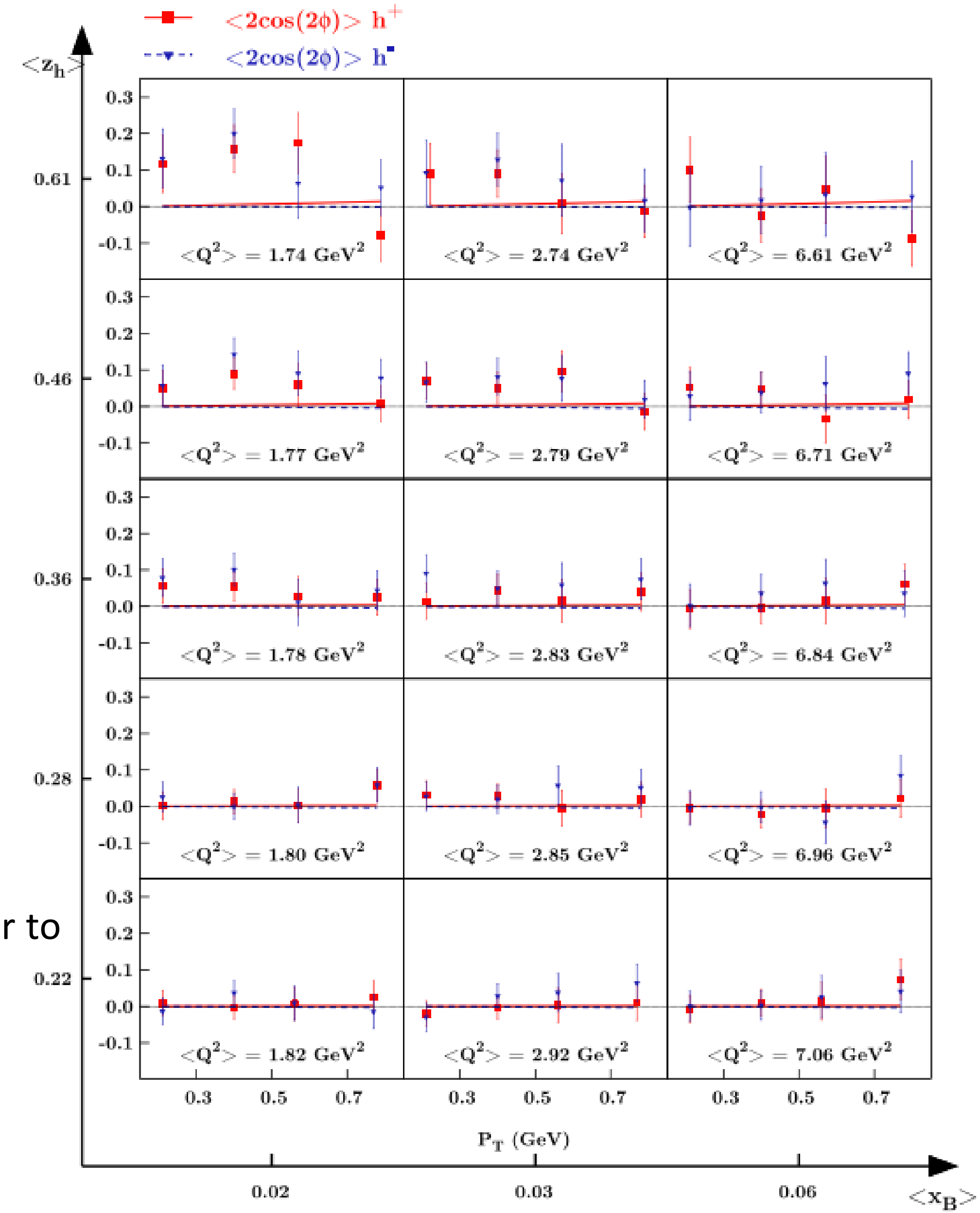
cos2ϕ asymmetries

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

↓

fit results give very small asymmetries

discrepancies with data at low Q^2 and large z



It is crucial to have data with different Q2 in order to
disentangle leading twist from higher twist
(for example BM in cos2ϕ)

 PRD91 (2015) *Barone et al*

more to come from COMPASS:

- unpolarised LH2 (proton) in parallel to the DVCS measurement (2016-2017)
- work started and the analysis is ongoing on the 2016 data

Polarised SIDIS

The Sivers asymmetry

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

convolution on the intrinsic
transverse momentum of the quark

sivers PDF
(time odd - final state interations)

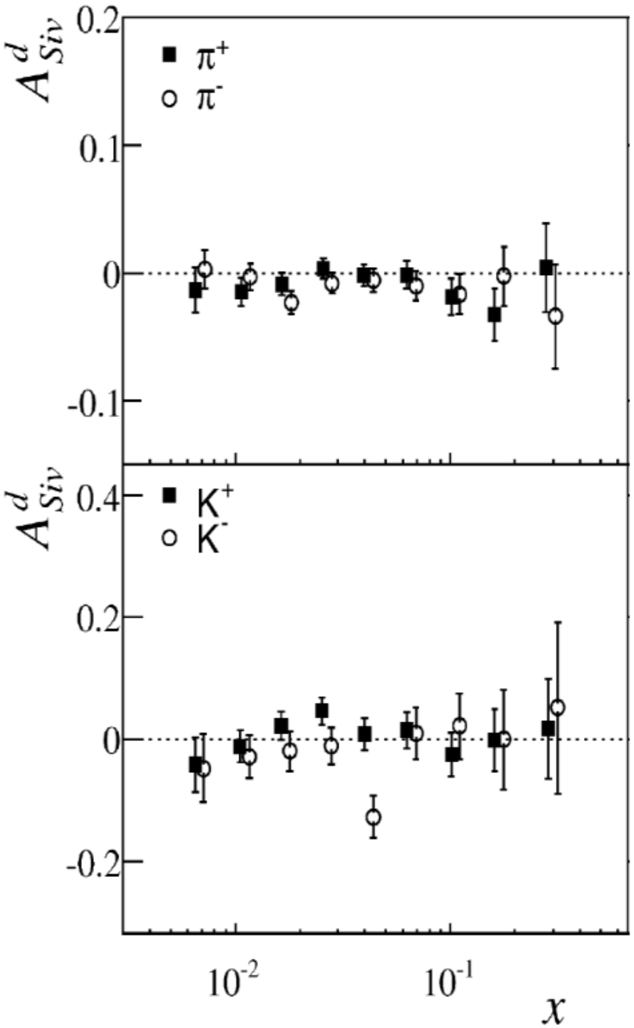
"purely" TMD effect

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

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

The Sivers asymmetry

- *results on polarised deuteron*



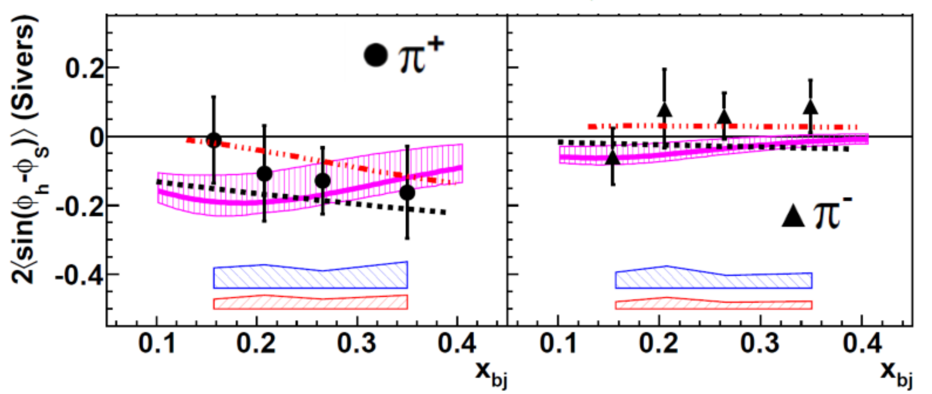
final results on **deuteron**

2002-2004 data
NPB765 2007, PLB673 2009

compatible with zero

and **neutron**

Hall A PRL107, 2011

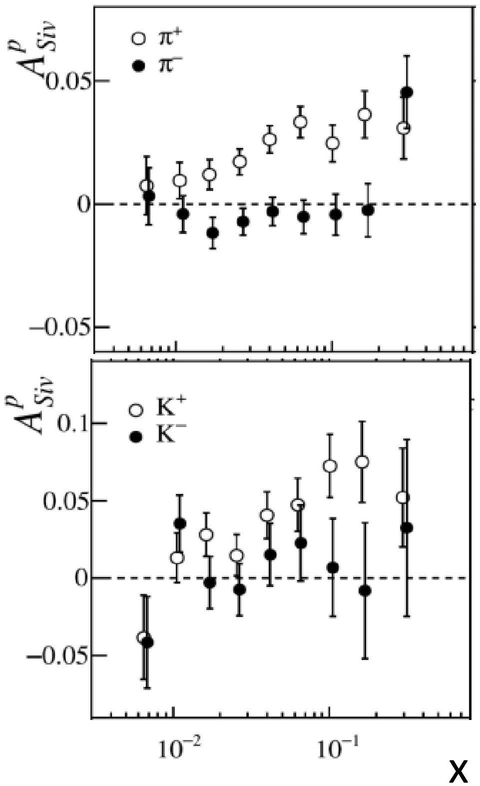


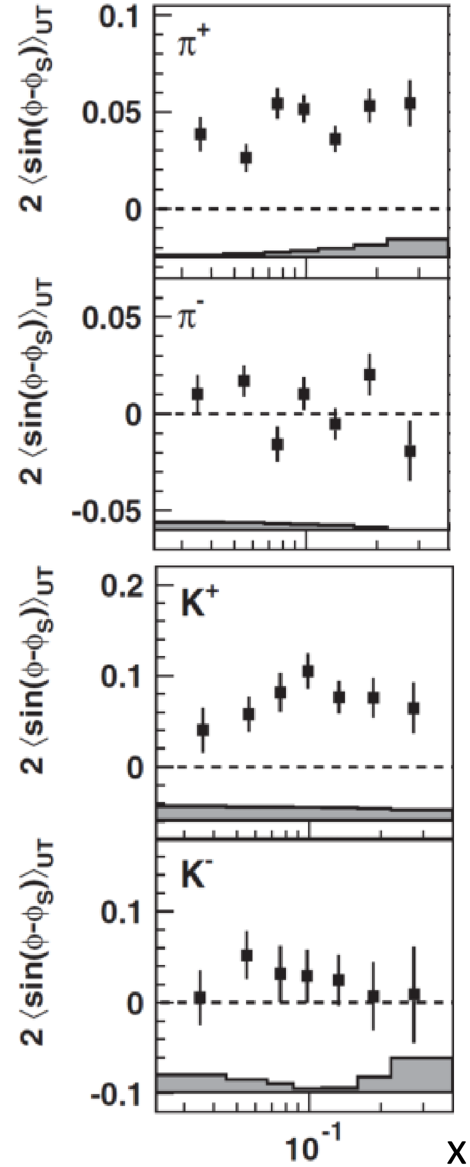
The Sivers asymmetry

data on **polarised proton**

COMPASS

PLB744 2015





hermes

PRL103 2009

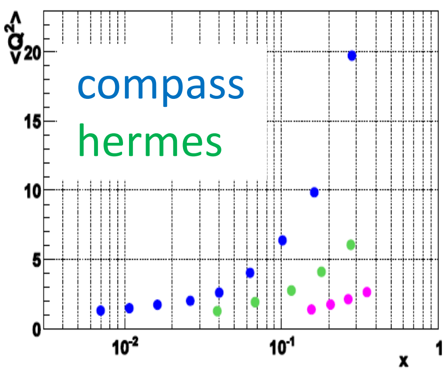
clear signal for positive hadrons

K asymmetry larger than π

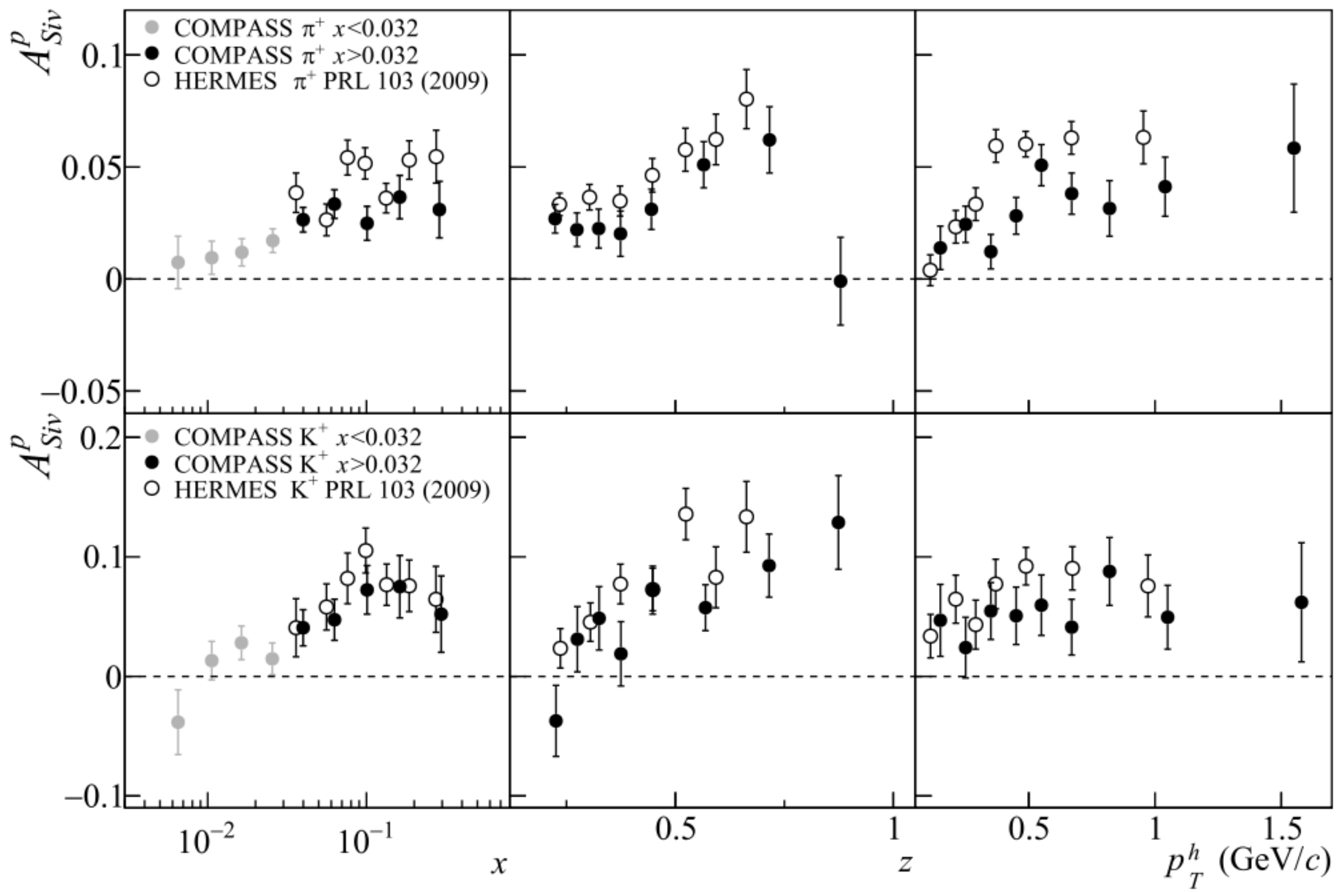
The Sivers asymmetry

x>0.032 vs

we can have the same range in x but
Q^2 is different



step toward TMD evolution



more info from multi dimensional analysis

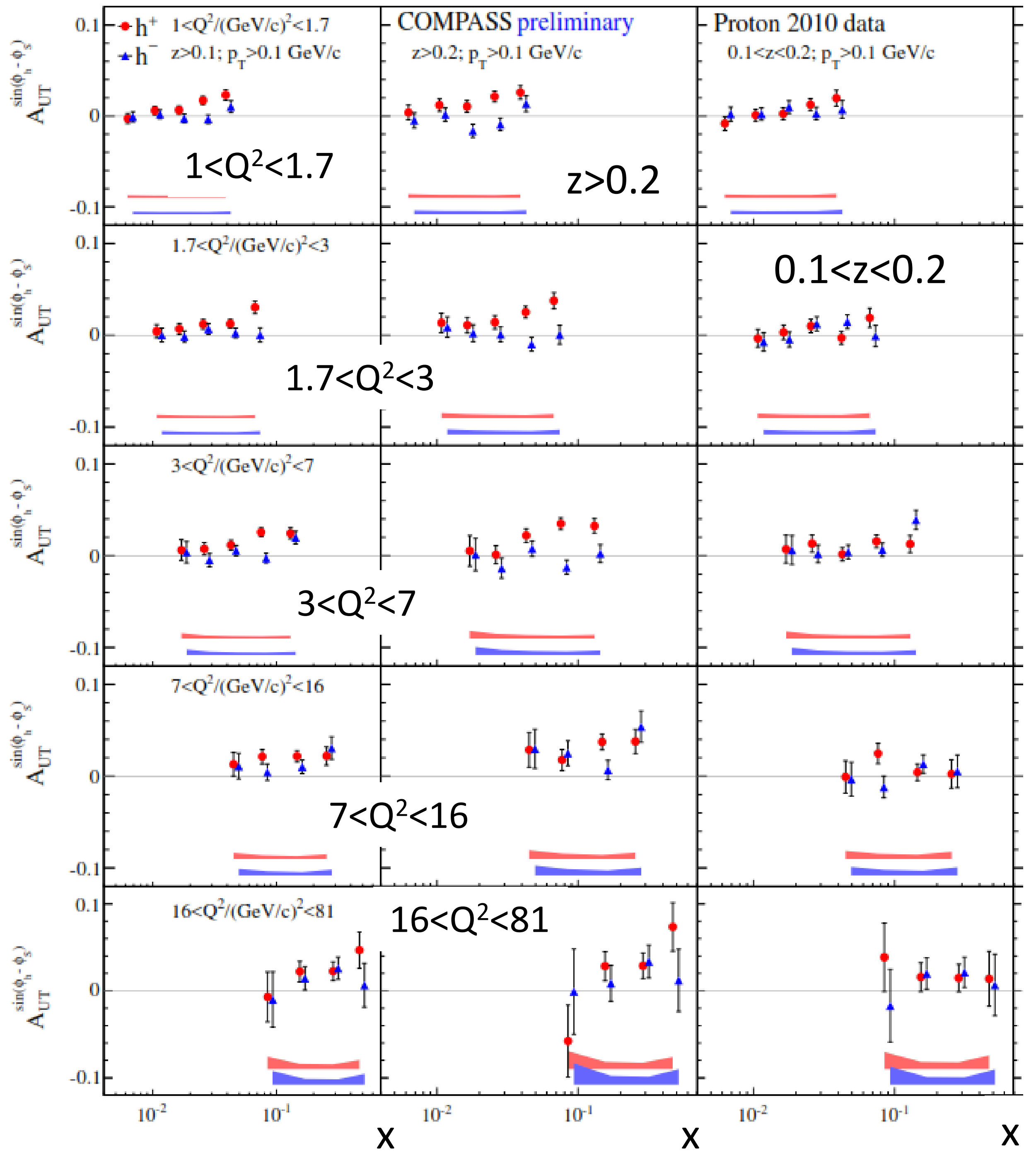
The Sivers asymmetry

multi dimensional analysis

COMPASS

no visible Q^2 dependence

(negative hadrons: asymmetries tend to become different from zero at high Q^2)



New measurement: P_T^h - weighted Sivers Asymmetry

P_T^h /zM weighted Sivers Asymmetry

A. Kotzinian and P. J. Mulders, PLB 406 (1997) 373
D. Boer and P. J. Mulders, PRD 57 (1998) 5780
J. C. Collins et al. PRD 73 (2006) 014021

$$f_{1T}^{\perp(1)}(x) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2)$$

convolution over TM → product of first moment Sivers and FF

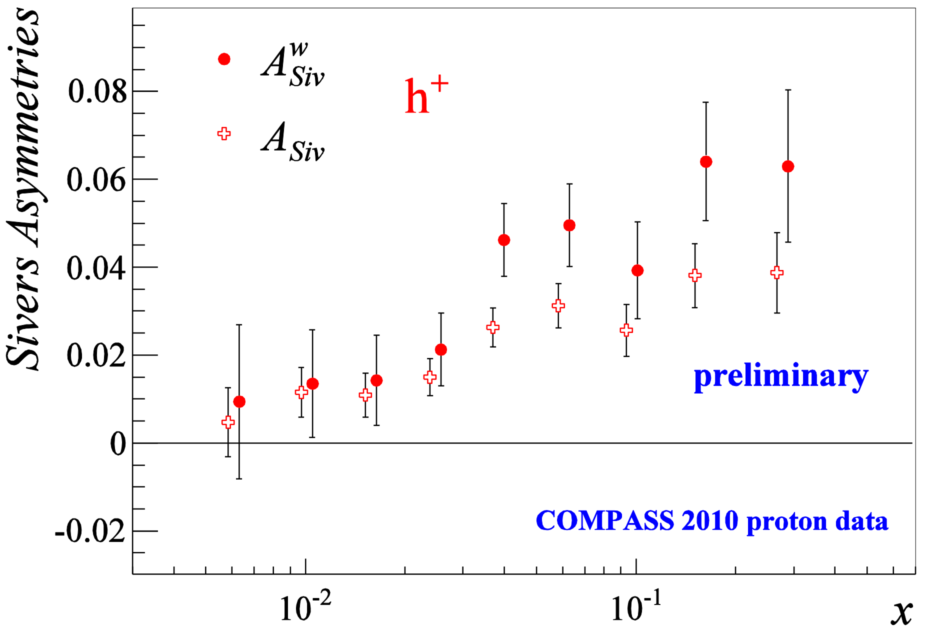
$$A_{Siv}^{w}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)\,q}(x) \int_{\Omega_z} dz\, D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) \int_{\Omega_z} dz\, D_1^q(z)}$$

in a ***model independent way*** (no assumption on the shape of PDFs and FFs)

COMPASS data from 2010 polarised proton have been analysed
same sample as the one used for the published standard Sivers asymmetries

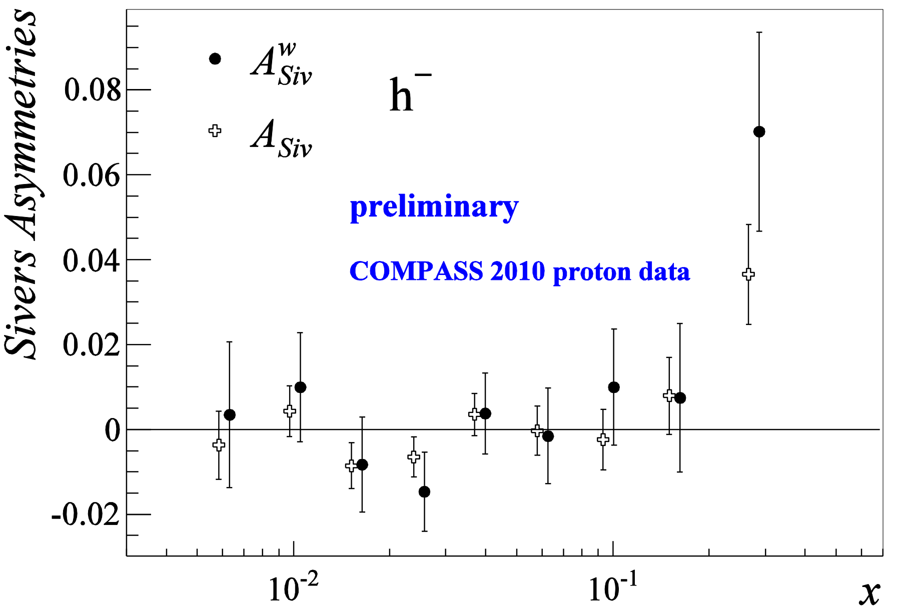
only spin dependent part of the cross section must be weighted

Final results ● compared with the standard Sivers Asymmetries ✚ (PLB 717 (2012) 383)



positive hadrons

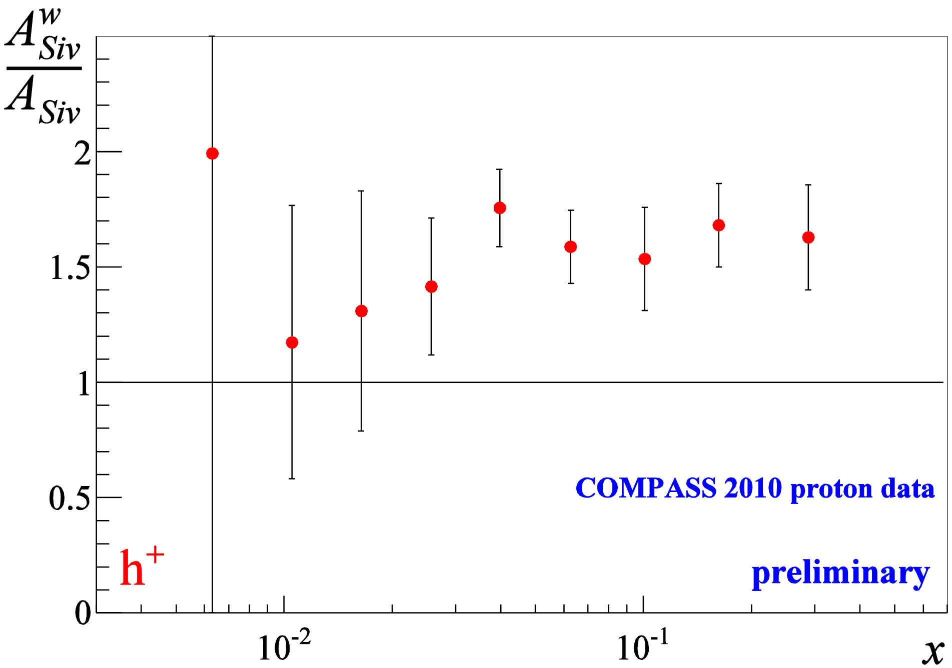
negative hadrons



$$A^w_{Siv}(x) \simeq 2\frac{x f_{1T}^{\perp(1)\,u}(x)}{x f_1^u(x)}$$

assuming u dominance
and for π+

Ratio between weighted and standard Sivers asymmetries



$$A^w_{Siv}(x) \simeq 2\frac{x f_{1T}^{\perp(1)u}(x)}{x f_1^u(x)}$$

~ constant in x

using ***Gaussian*** *model for the dependence on the intrinsic transverse momenta of the quarks*

the **standard Sivers asymmetries** can be expressed as (u dominance)

$$A_G(x) \approx \frac{\pi M}{2}\frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}\frac{\int z/P^h_{T,S}D_1^q(z)dz}{\int D_1^q(z)dz} \qquad (P^h_{T,S})^2 = z^2k^2_{\perp,S} + p^2_\perp$$

Sivers intrinsic quark transverse momentum

COMPASS results on the Sivers weighted asymmetries : paper is in preparation

more work done for the paper:

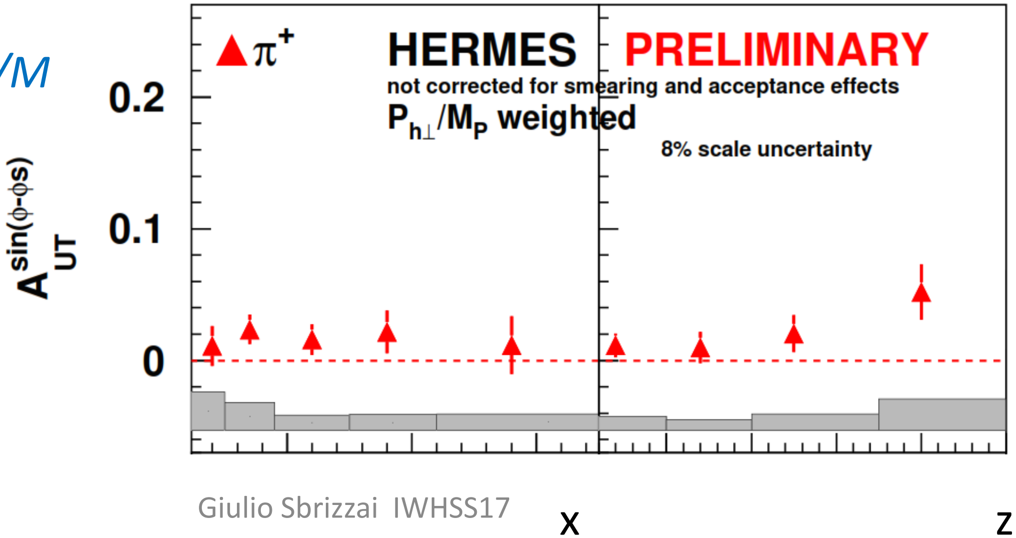
- weighted asymmetries for 0.1<z<0.2
- weighted asymmetries as function of z
- using PTh/M instead of PTh/zM

→ **next to come: Bessel weighted Sivers**

Also HERMES previously extracted Sivers (and Collins) weighted asymmetries

HERMES preliminary results
pion Sivers with weight=P_T^h/M

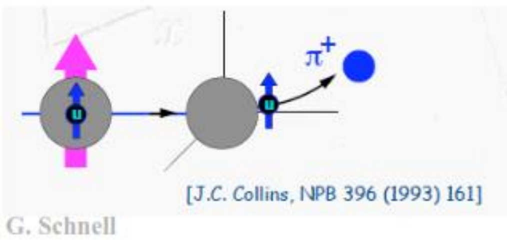
I.M. Gregor , Acta Phys.Polon. B36 (2005) 209



The Collins asymmetry

$$A_{UT}^{\sin(\phi_h+\phi_S-\pi),h} = \frac{\sum_q e_q^2\, h_1^q(k_\perp) \otimes H_1^{\perp q\to h}(p_\perp)}{\sum_q e_q^2\, f_1^q \otimes D_1^{q\to h}}$$

convolution of **transversity** with **Collins FF**



correlation between
transverse spin of the fragmenting quark
and
transverse momentum of hadrons

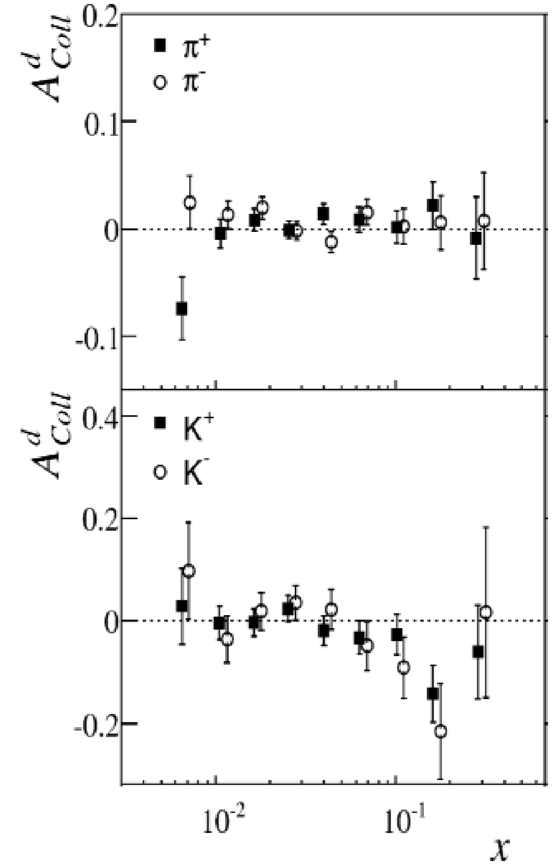
2004:
non-zero values on proton

compatible with zero on deuteron

global fits
first extraction of
transversity and Collins FF

using also e+e- data from Belle

The Collins asymmetry



final results on **deuteron**

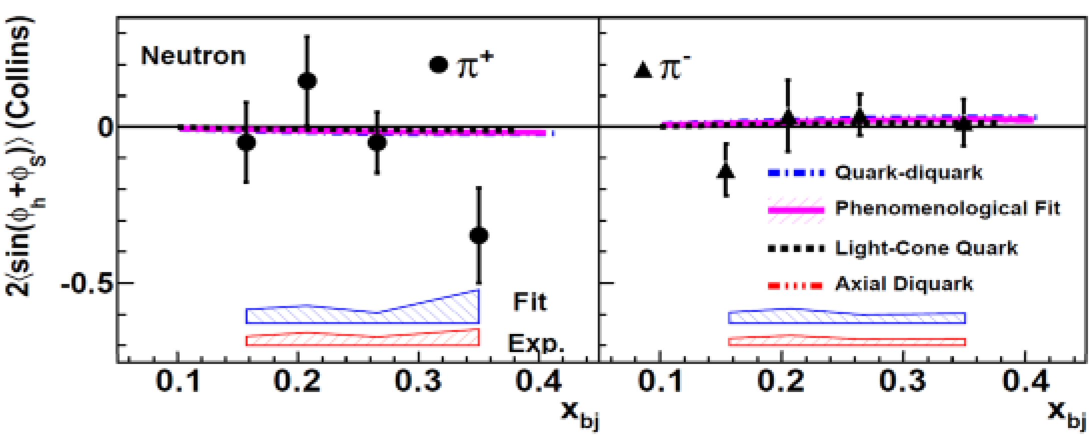
COMPASS

2002-2004 data
NPB765 2007, PLB673 2009

and **neutron**

Jefferson Lab

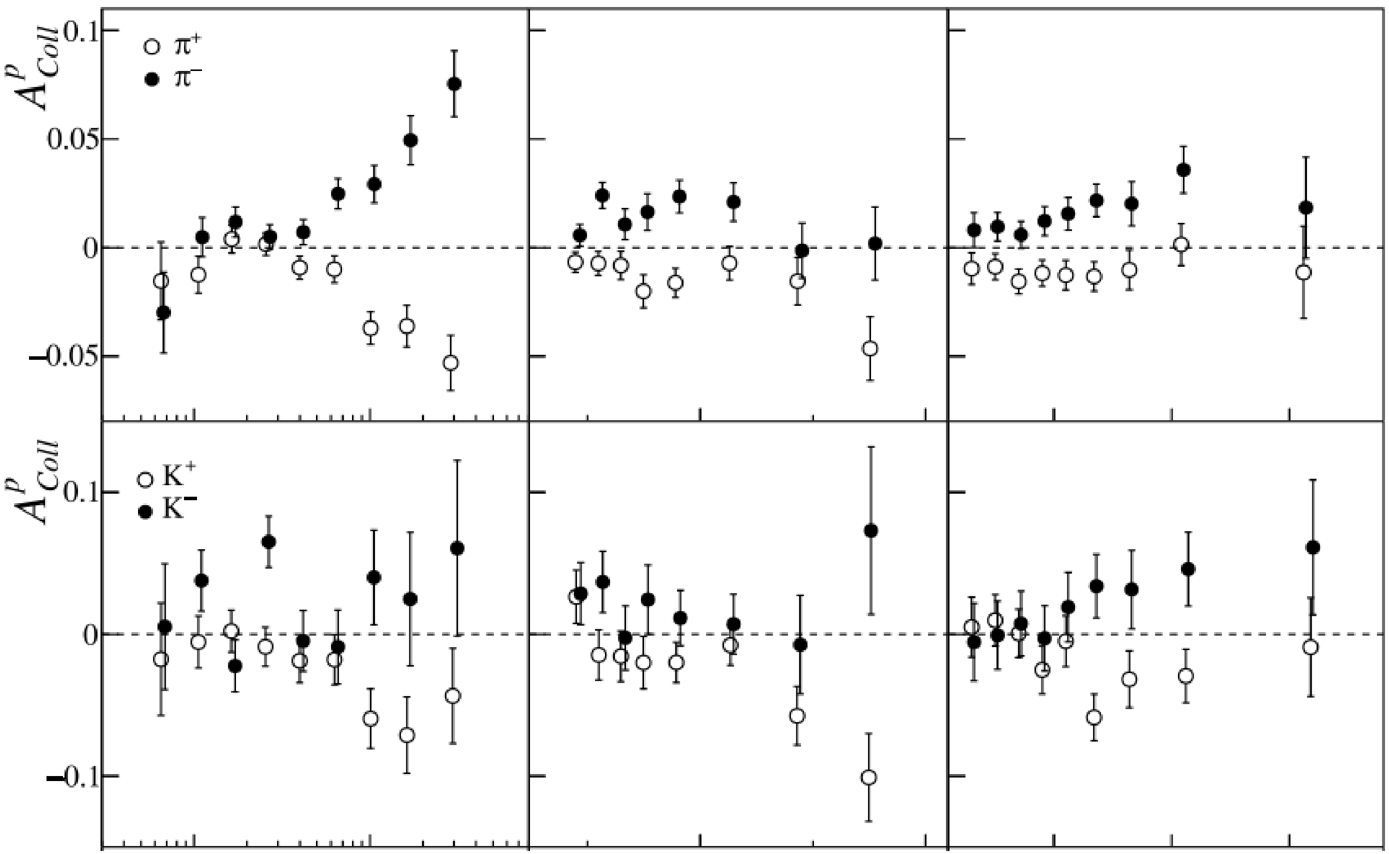
Hall A PRL107, 2011



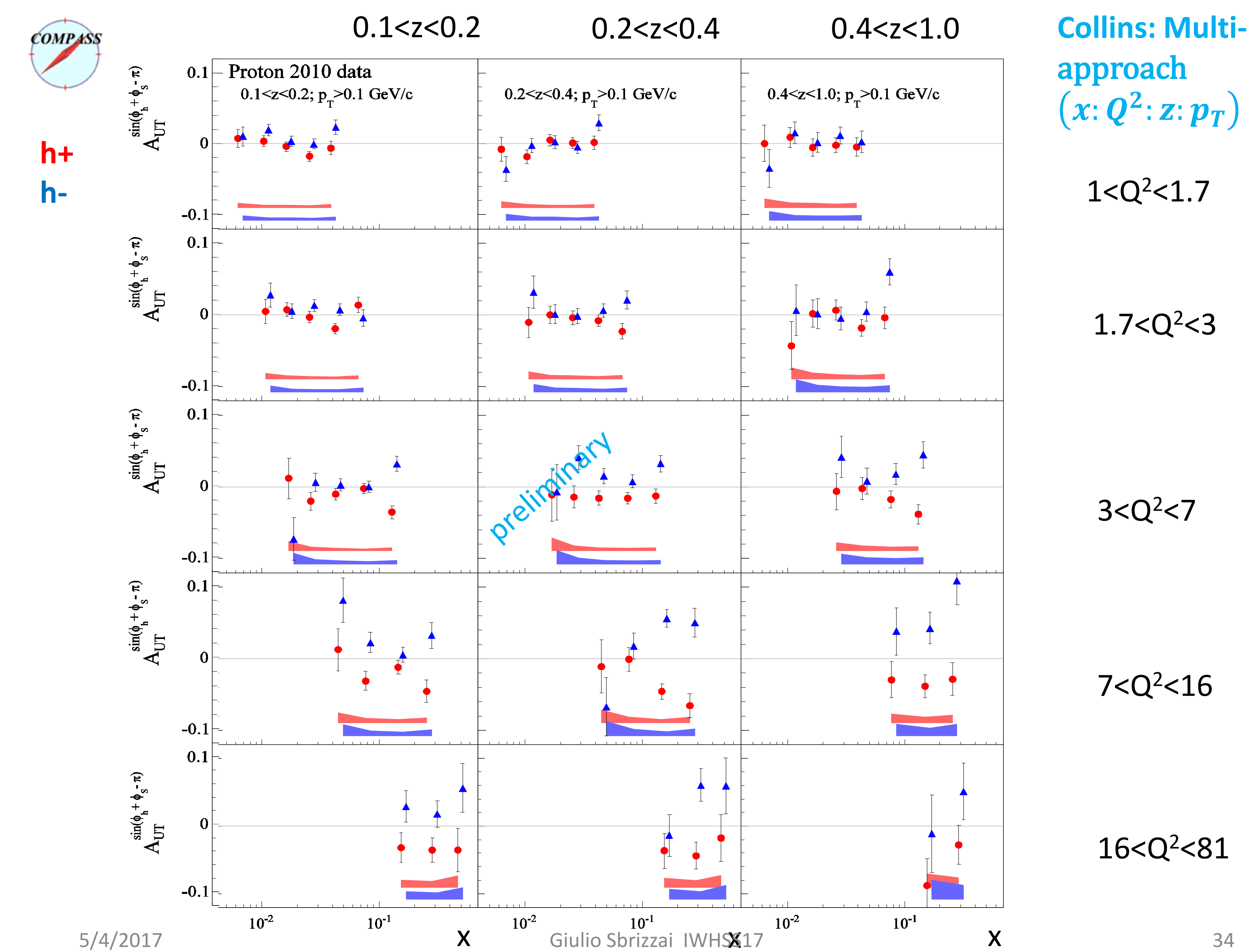
The Collins asymmetry

1d **measurements on transversely polarised proton**

PLB744 2015



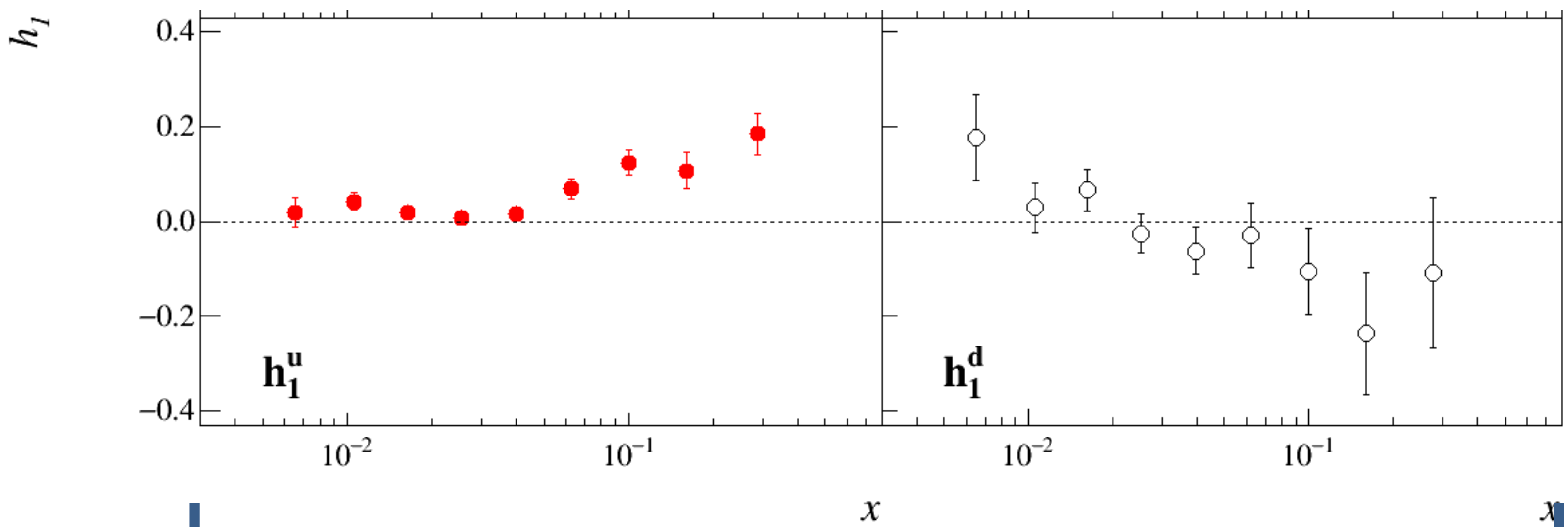
Collins: Multi-D approach
$(x: Q^2: z: p_T)$



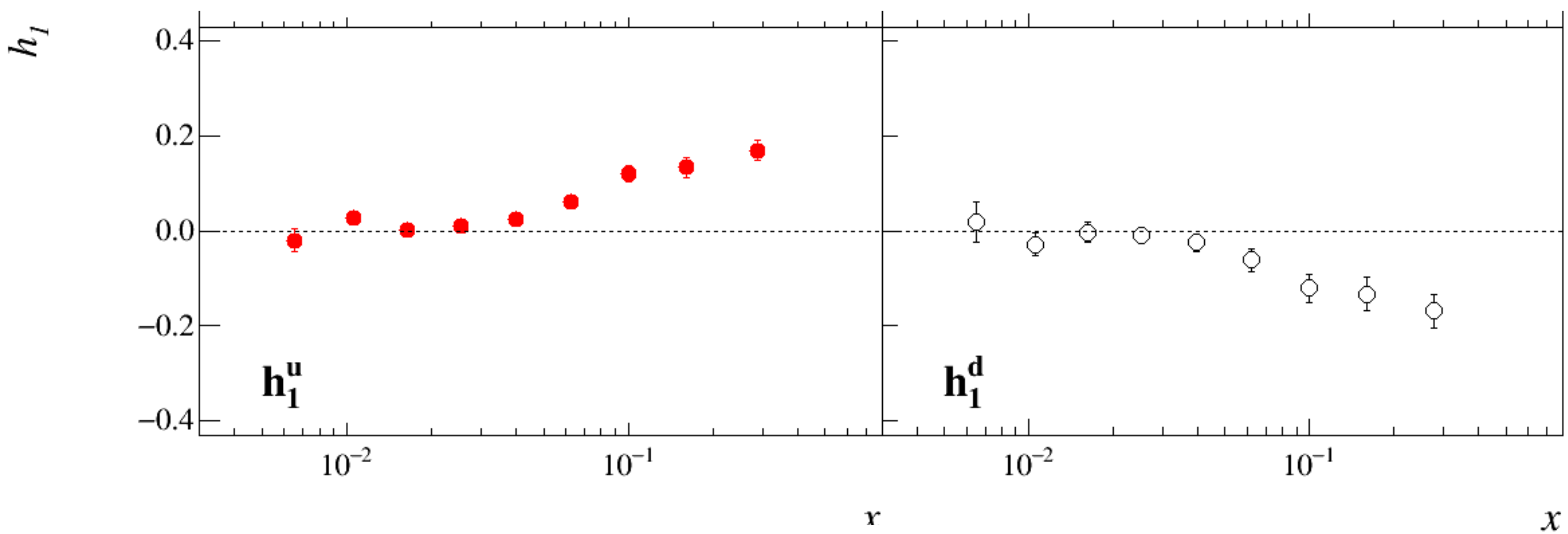
still data on polarised deuteron suffer from statistic
(wrt data on polarised proton)

affect the error on the extraction of Transversity and Sivers functions for the d quark
(but also other analyses…)

one example: Transversity

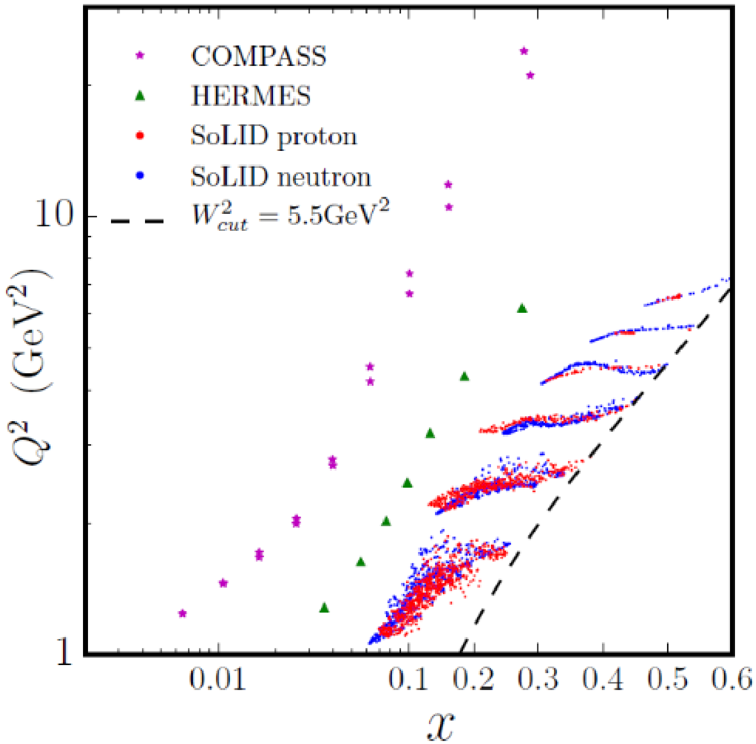


one more year of data taking on polarised deuteron at COMPASS



Projection from A Bressan, COMPASS beyond 2020 Workshop, CERN, March 2016

an enormous amount of data will come from JLab12 experiments
but in a **different x range!**



Z. Ye et al. JLAB-THY-16-2328

COMPASS:

no competition on precision!

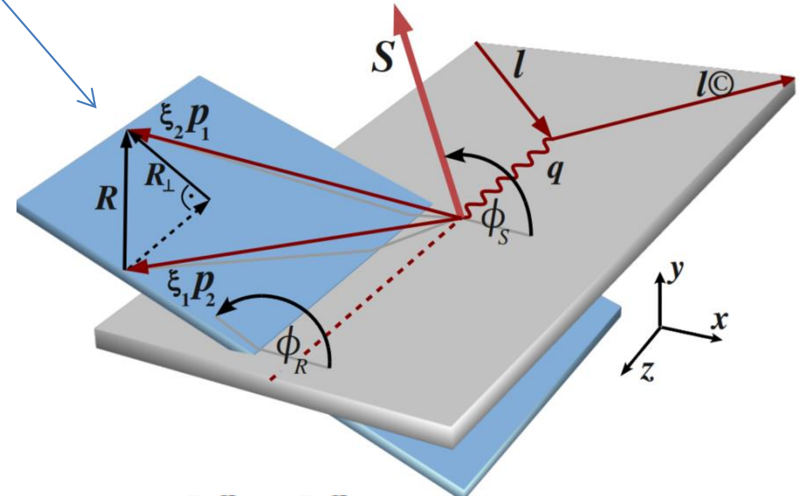
smaller x, factor > 5 in Q^2, …

the kinematical region is relevant and new d data coming soon are needed

The dihadron asymmetry

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

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



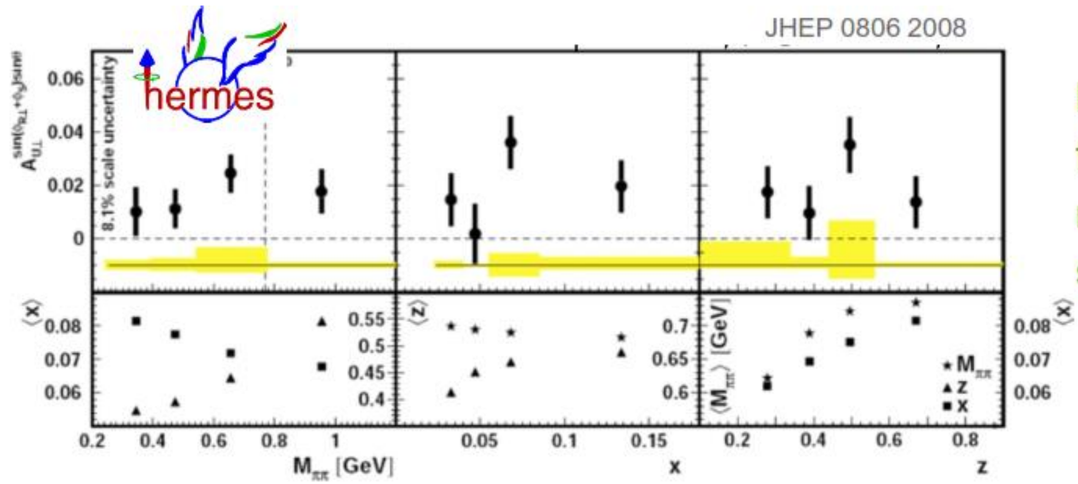
$$R = \frac{z_2 p_1 - z_1 p_2}{z_1 + z_2}$$

product of **transversity** with **dihadron FF**

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

The dihadron asymmetry

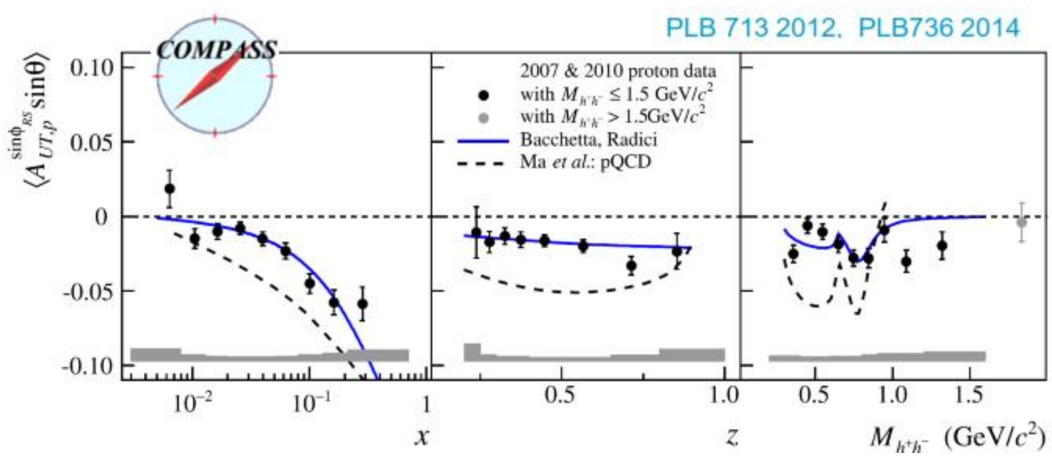
JHEP 0806 2008



HERMES proton

first evidence for non-zero dihadron FF, same sign of Collins asymmetry for π^+

PLB 713 2012, PLB736 2014



COMPASS

deuteron:

compatible with zero

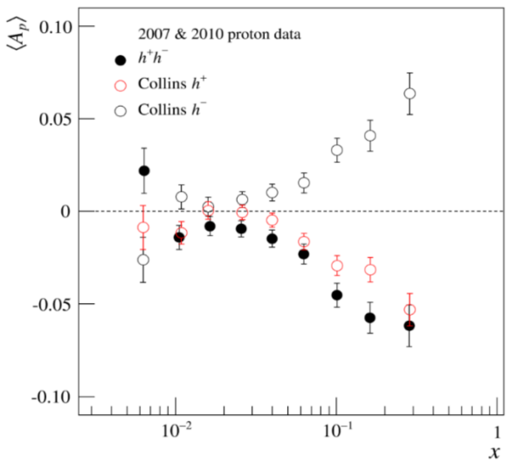
proton:

same sign and shape

slightly higher than Collins asymmetry for h^+

Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

- Collins asymmetry for h+ and for h- :
  "mirror symmetry"
- dihadron asymmetry vs Collins asymmetry:
  only somewhat larger



analysis of the single hadron and di-hadron asymmetries performed ***on a common data sample*** *(2010 transversely polarised proton)*

↓

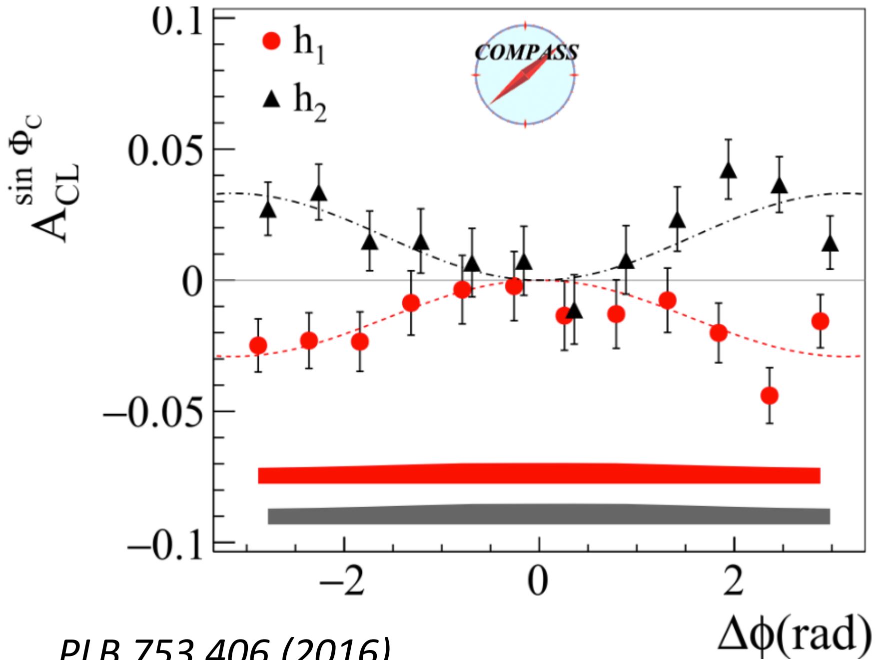
derive the formalism to describe the two asymmetries together

the general expression for the $lN \rightarrow l'h^+h^-X$ cross section

$$\frac{d\sigma^{h^+h^-}}{d\phi_{h^+}d\Delta\phi\, d\phi_S} = \sigma_U^{h^+h^-} + S_T \cdot \left[\left(\sigma_{1C}^{h^+h^-} + \sigma_{2C}^{h^+h^-}\cos\Delta\phi\right)\sin(\phi_{h^+} + \phi_S - \pi) + \ldots\right]$$

$$\Delta\phi = \phi_{h^+} - \phi_{h^-}$$

A.Kotzininan PRD91 (2015) 054001



PLB 753 406 (2016)

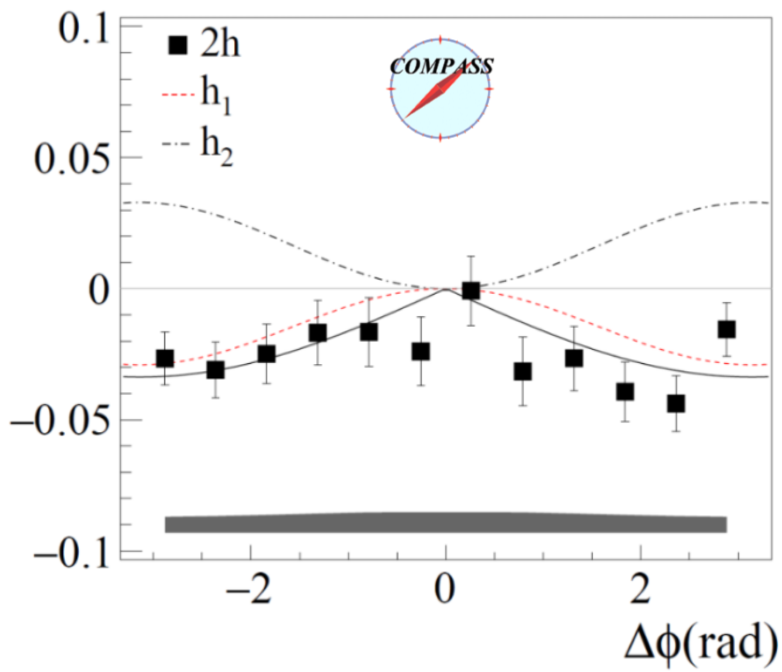
measured Collins asymmetries

$$A_{2CL}^{\sin(\phi_{h^-}+\phi_S-\pi)} = -\frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

$$A_{1CL}^{\sin(\phi_{h^+}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot (1-\cos\Delta\phi)$$

data described assuming mirror asymmetry !

$$\sigma_{1C}^{h^+h^-} = -\sigma_{2C}^{h^+h^-}$$



$$A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h^+h^-}}{\sigma_U^{h^+h^-}} \cdot \sqrt{2\cdot(1-\cos\Delta\phi)}$$

the same quantity which appear in the single hadron asymmetry

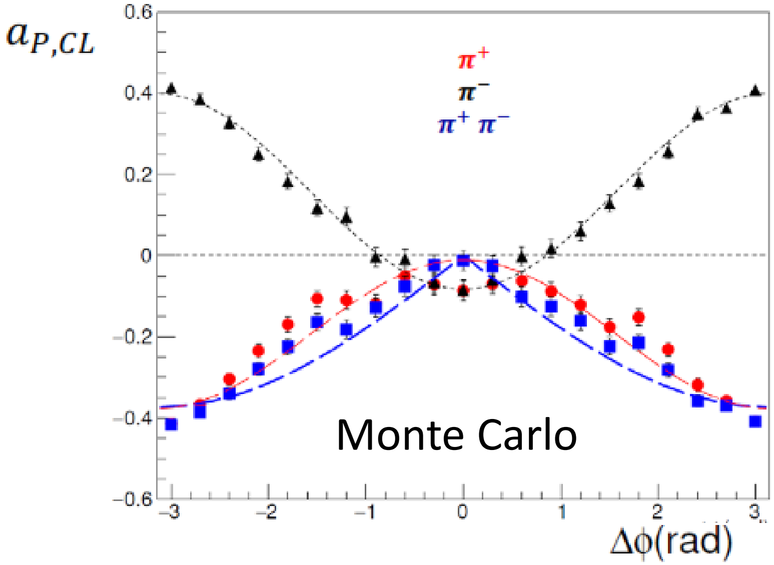
Interesting studies comparing with the Di-hadron Transverse Spin Asymmetries

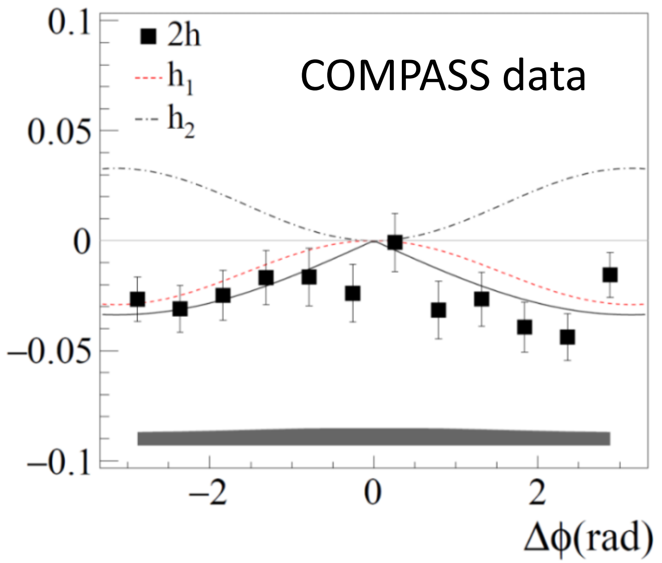
new: preliminary results from a Monte Carlo code for transversely polarized quark jet based on the string fragmentation and including, for the first time, the $^3P_0$ mechanism

→ X.Artru

1h and 2h a_p obtained as COMPASS asymmetries from the same sample of generated events

A. Kerbizi talk at SPIN2016





very encouraging results

Other transverse spin dependent asymmetries

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

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

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

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

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

sivers
collins

pretzelosity

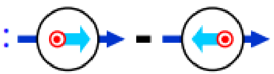
worm-gear

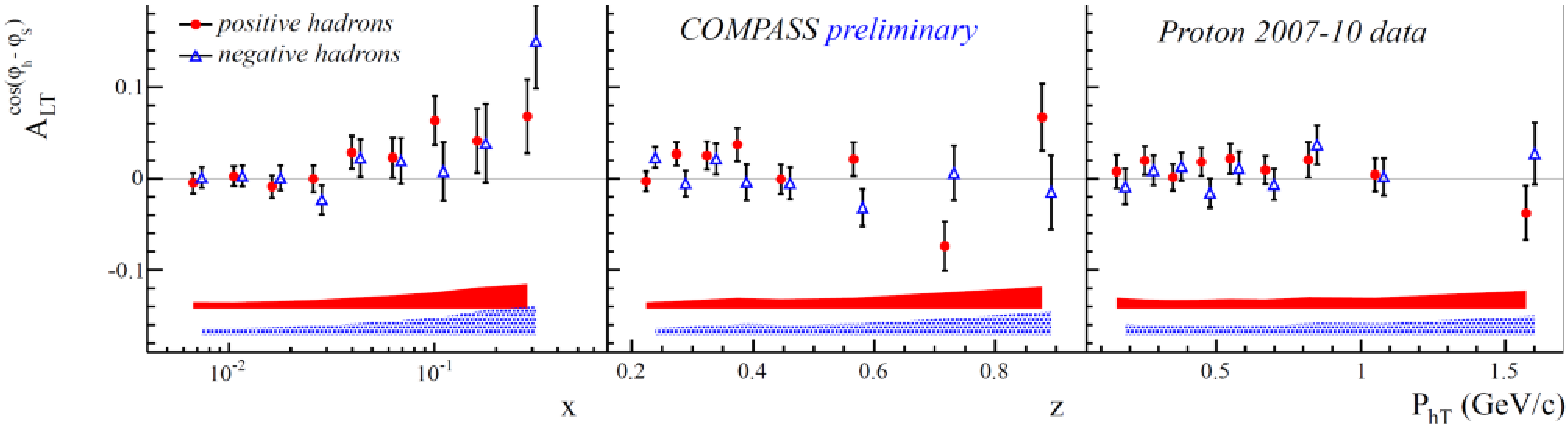
higher twist effects

all of them (and more …) have been measured on p / d / n by COMPASS, HERMES, JLab

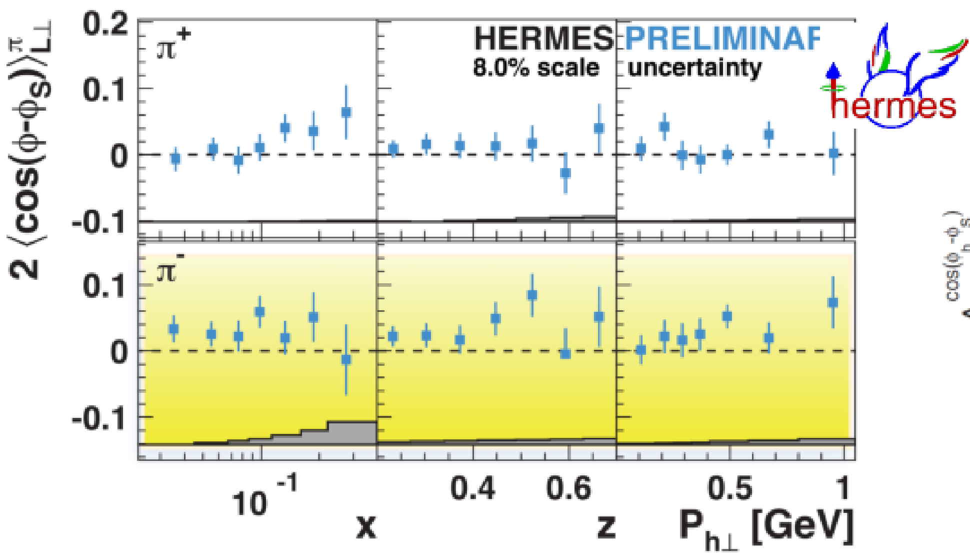
preliminary results for multidimensional analysis also produced at COMPASS and HERMES (SPIN2014)

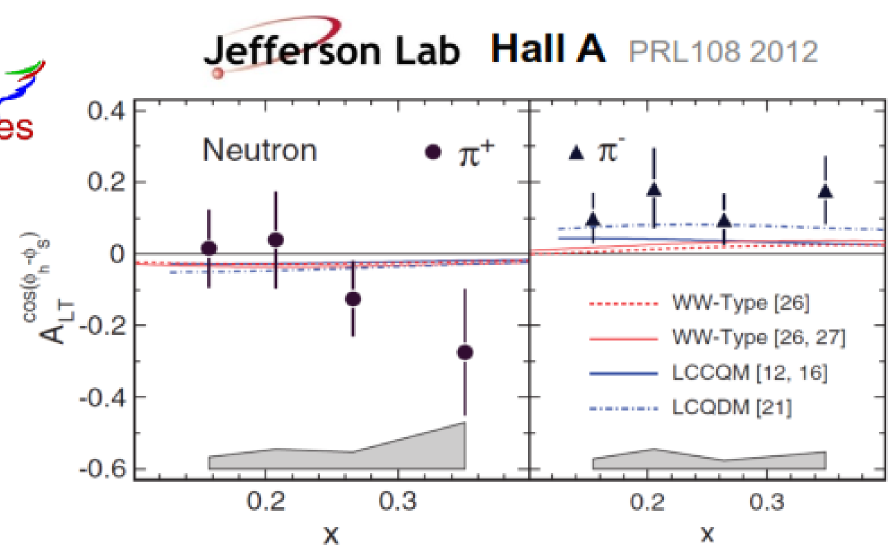
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, **worm-gear** g_{1T}^q :





same trend



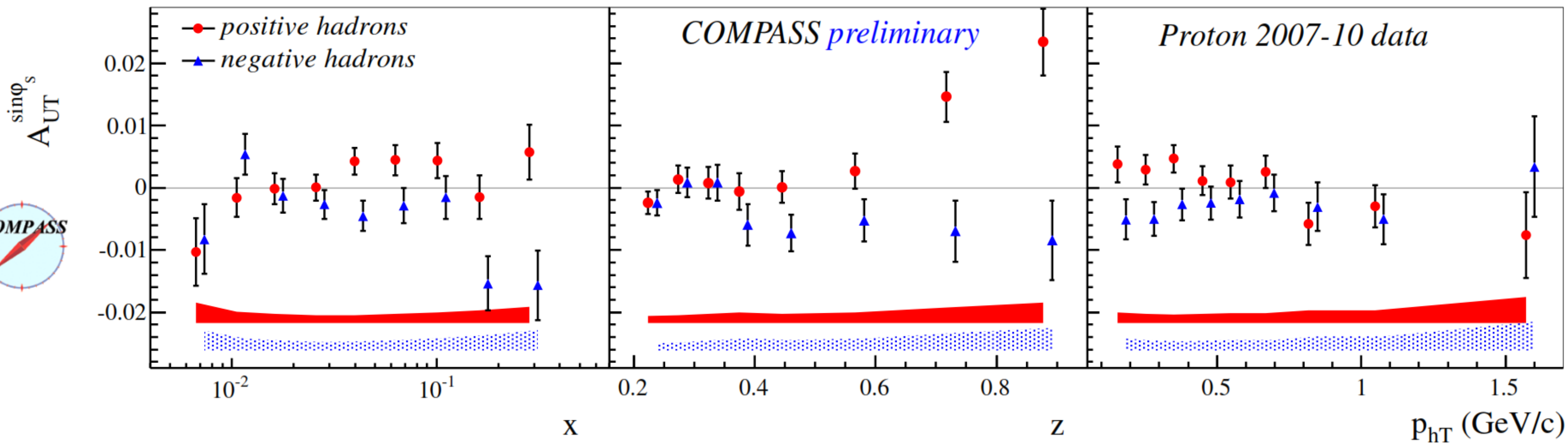


$$A_{UT}^{\sin(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \ldots\right)$$

twist 3 related to Collins and Sivers

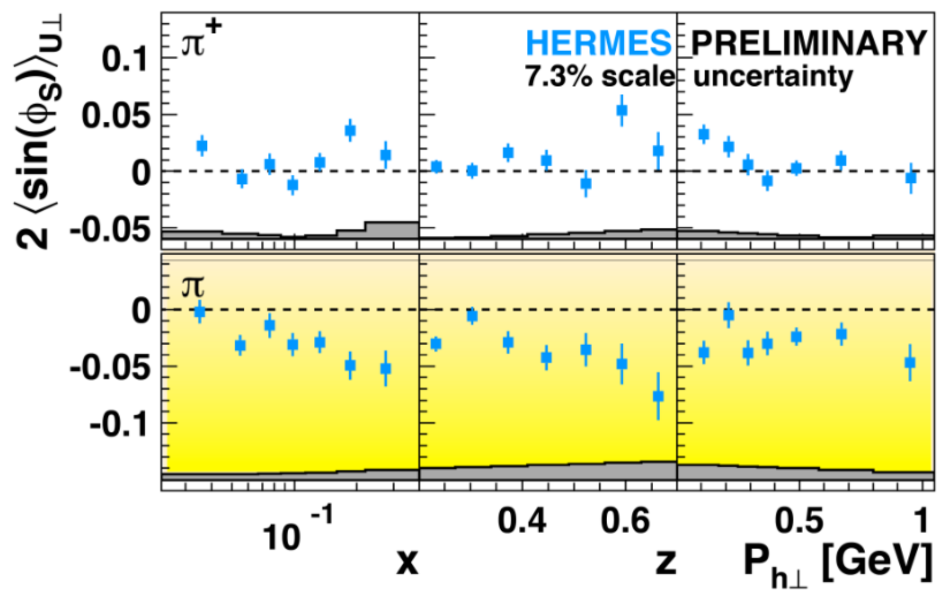
in WW approximation

compatible with zero on deuteron, but on proton signal different from zero



considerably larger at HERMES

as expected



Other results:

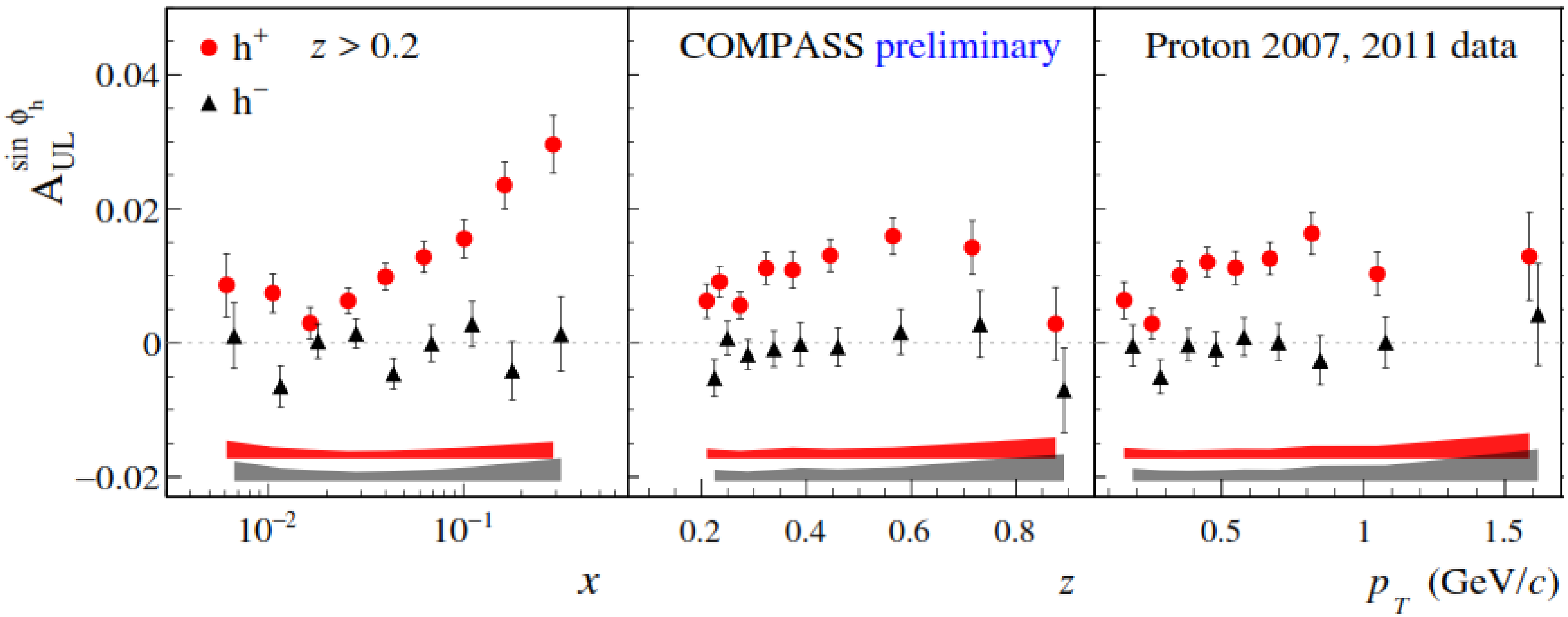
on longitudinal spin azimuthal asymmetries:

Other results:
on longitudinal spin azimuthal asymmetries:

on deteron *EPJC70 (2010)*

results compatible with zero within statistical accuracy

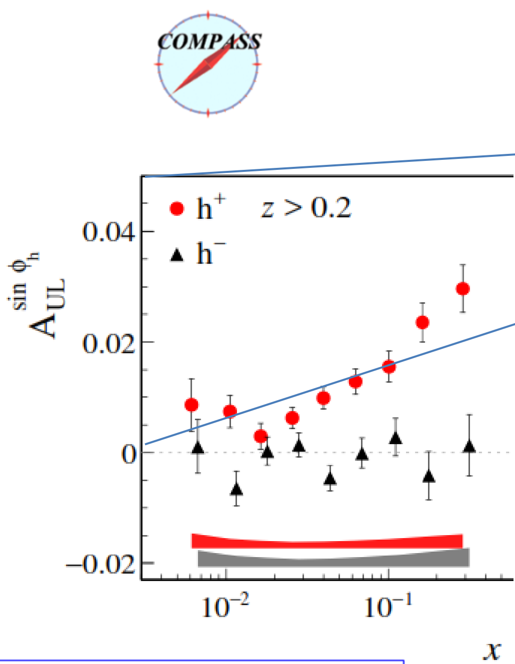
and on proton *(first shown at SPIN2016 B.Parsamyan)*

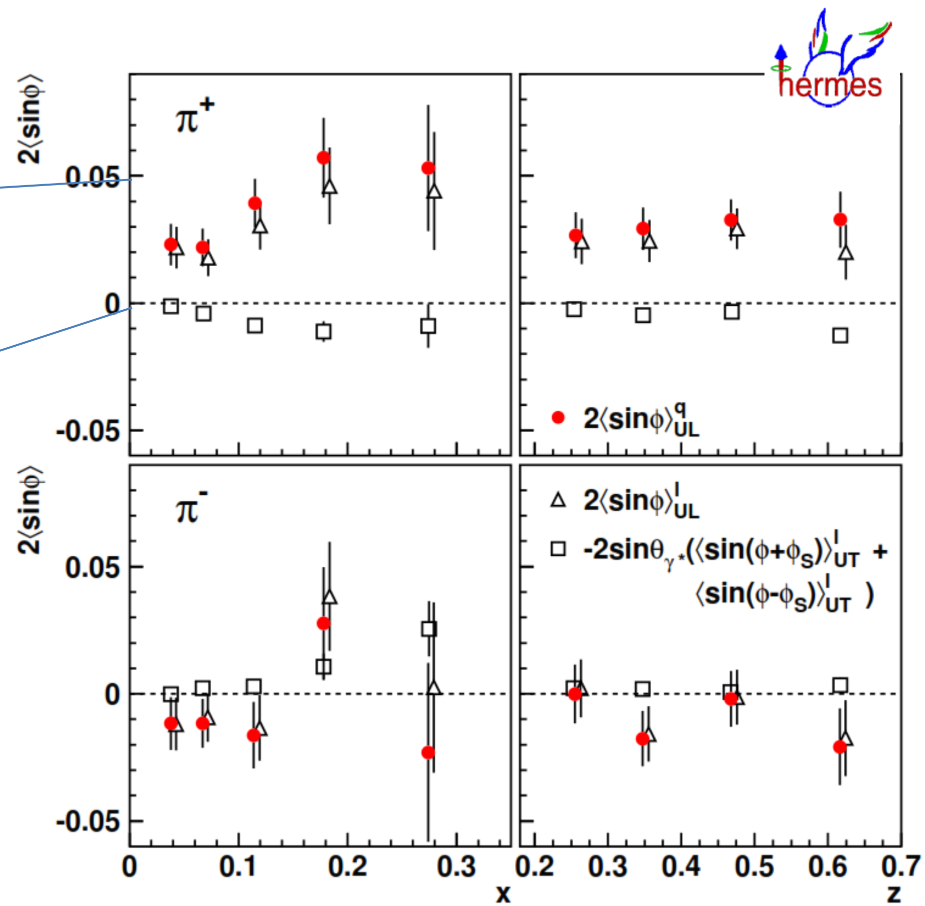


longitudinal spin azimuthal asymmetries on proton

higher twists contributions

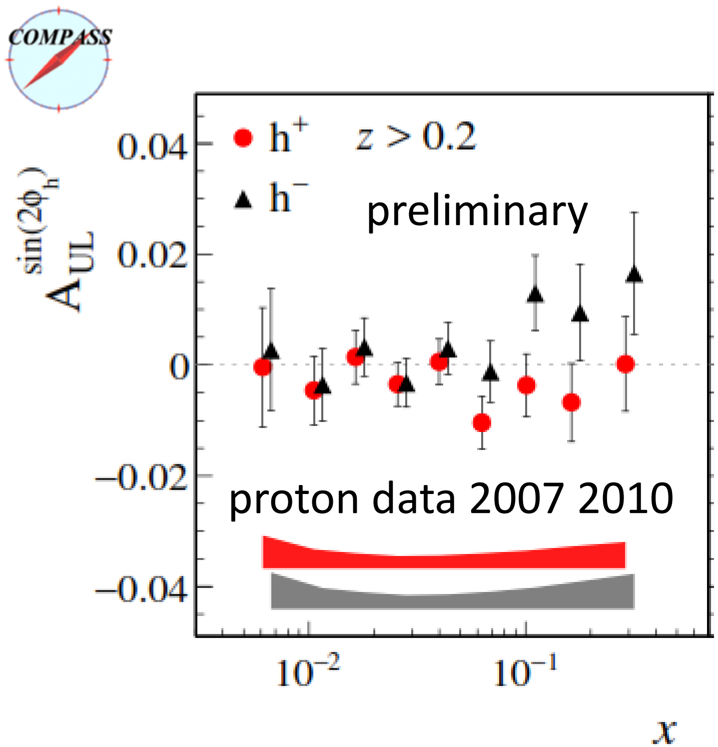
smaller signal than in hermes *PLB 622 (2015)*

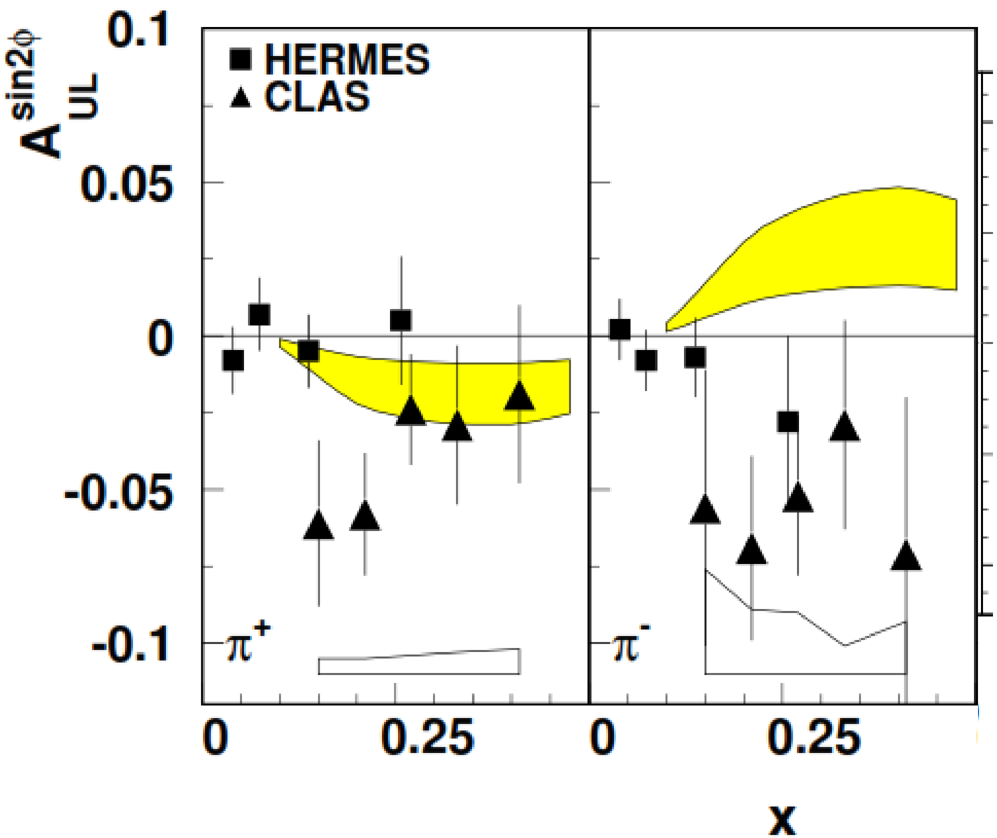




$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}\right)\right\}$$

longitudinal spin azimuthal asymmetries on proton





Conclusions

- many SIDIS results, not all easy to explain
  some interesting analysis still going on

- new data on unpolarised SIDIS coming from COMPASS LH2 in parallel to DVCS (2016 -2017)

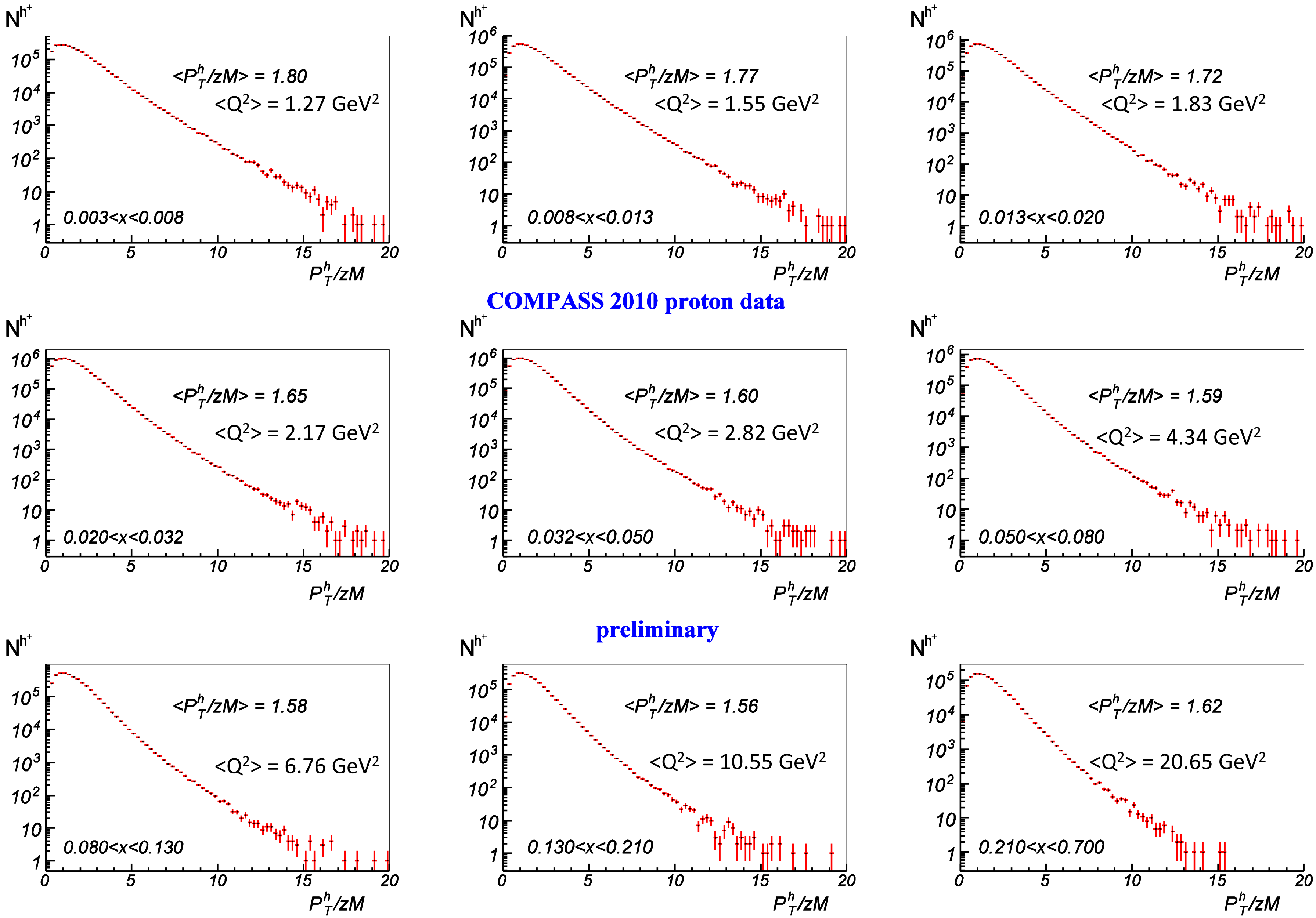
- more data on deuteron are really needed soon….
  one more year on transversely polarised deuteron COMPASS beyond 2020

- new data from JLab12 and EIC…

SPARES

The P_T^h/zM distributions for each bin of x

positive hadrons
not acceptance corrected

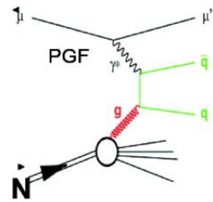


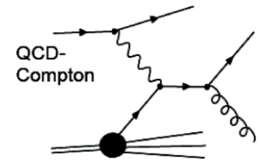
Gluon Sivers

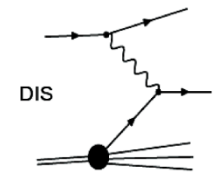
from high-P_T^h two hadrons pairs

submitted to PLB

three different contributions:



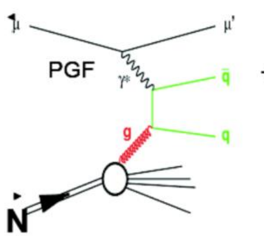




hight P_T^h hadrons pairs
enhance contribution from PGF

Neural Network Monte Carlo to tag different processes on COMPASS data

photon-gluon fusion
(PGF)

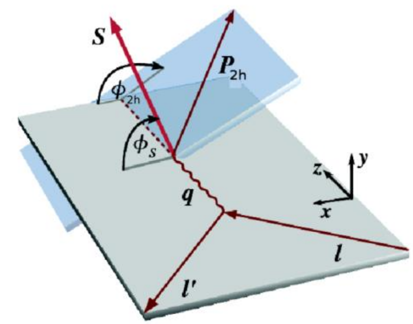


$$\vec{P}_{2h} = \vec{p}_1 + \vec{p}_2$$

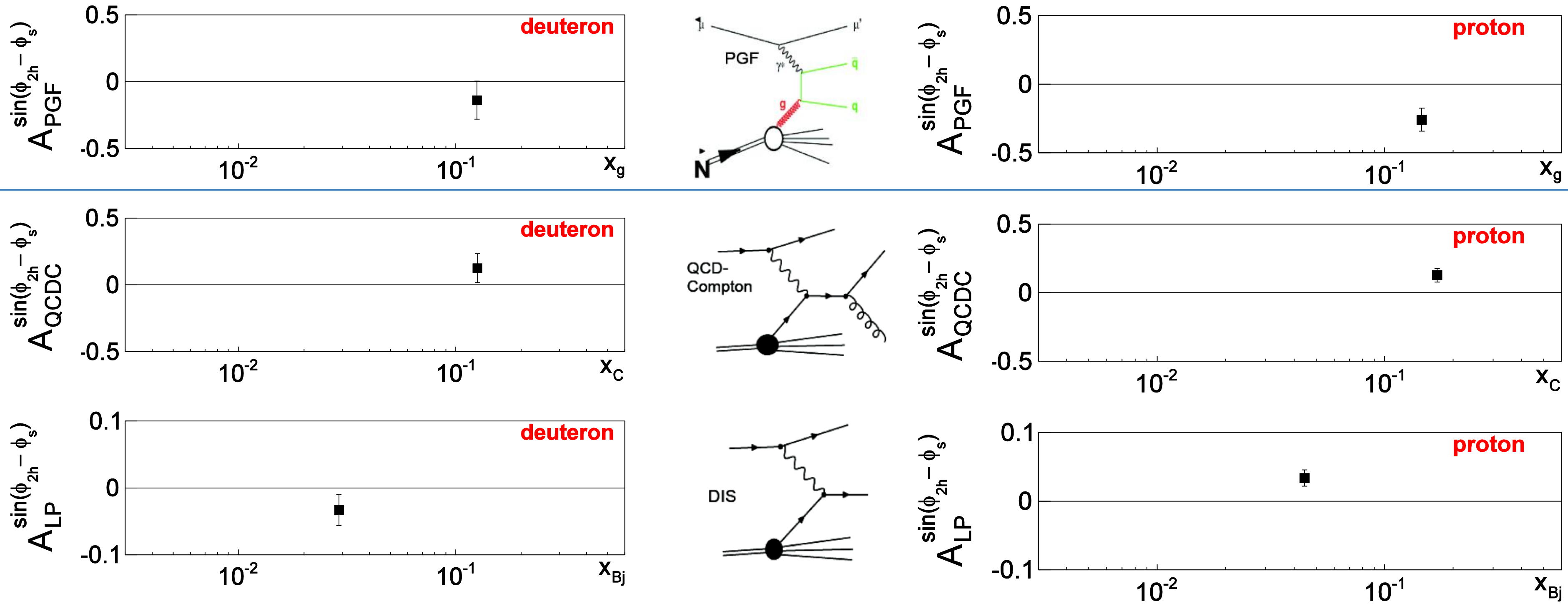
$$\phi = \phi_{2h} - \phi_S$$

ϕ_{2h} correlated to ϕ_{gluon}

$\ell + N \rightarrow \ell' + 2h + X$



Gluon Sivers from high-P_T^h two hadrons pairs

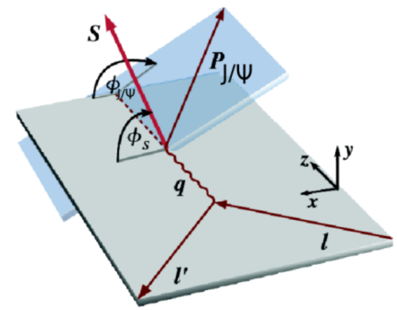


Limited precision on deuteron. More data needed.

The results for the LP compatible with single hadron measurements

Gluon Sivers from J/ψ

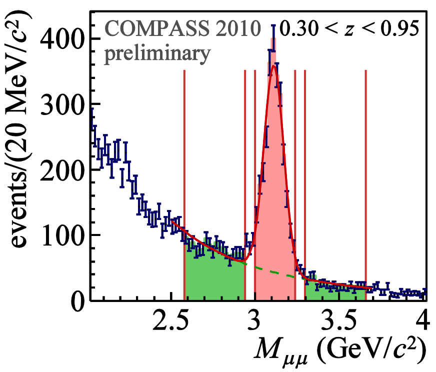
$$\mu^+ + N \to \mu^+ + J/\Psi + X \to 2\mu^+ + \mu^- + X$$

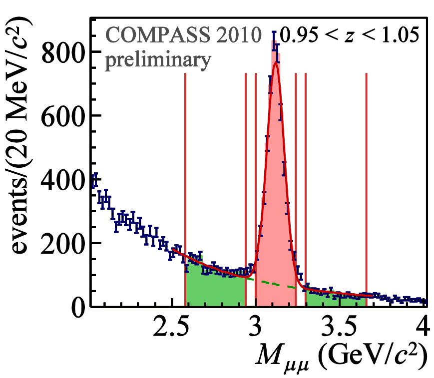


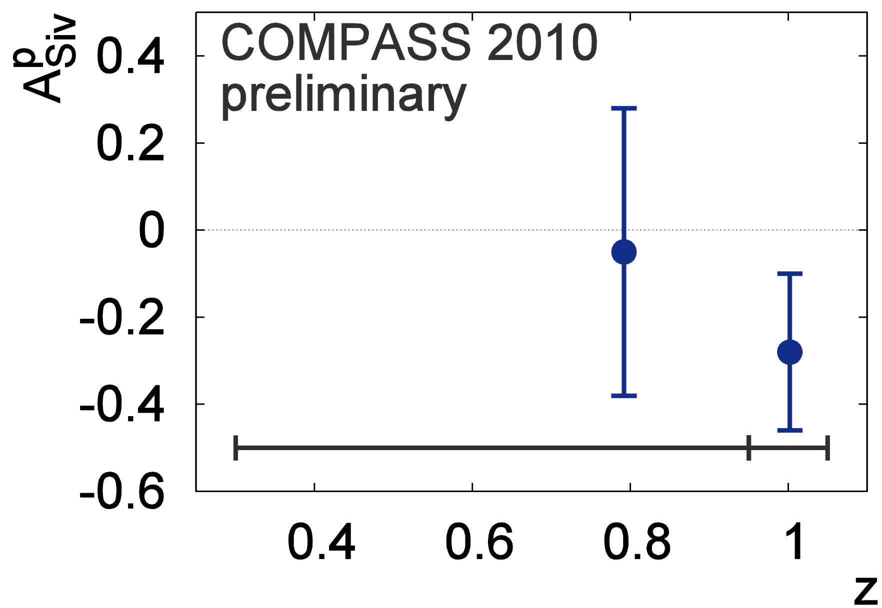
$$\mathbf{P}_{J/\Psi} = \mathbf{p}_{\mu^+} + \mathbf{p}_{\mu^-}$$
$$\phi_{\mu^+\mu^-} = \phi_{J/\Psi} = \phi_g$$

from 2010 transversely polarised proton data
in two z bins 0.30<z<0.95 and 0.95<z<1.05

$$\phi = \phi_{\mu^+\mu^-} - \phi_S$$





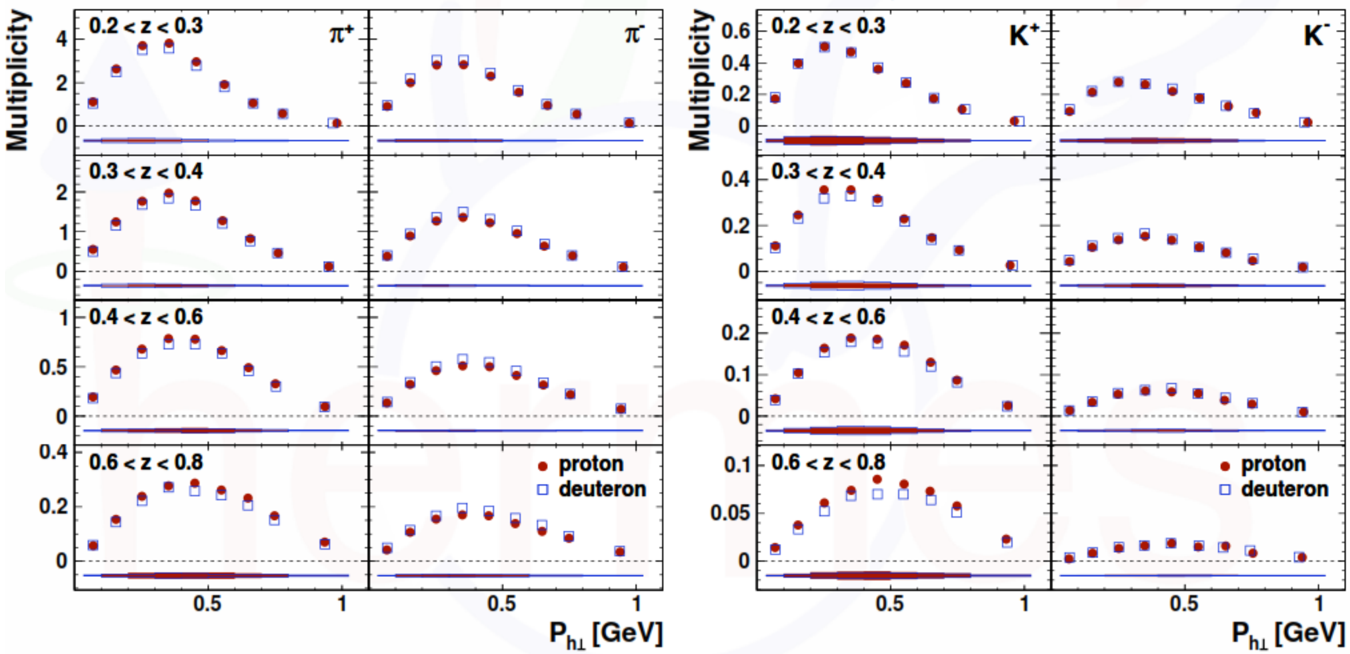


HERMES

Transverse momentum dependence

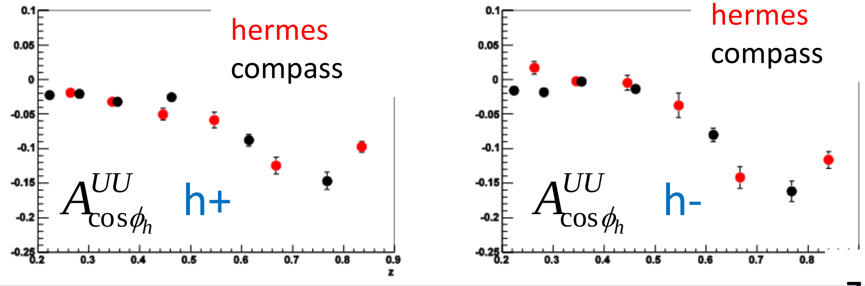
- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

[Airapetian et al., PRD 87 (2013) 074029]

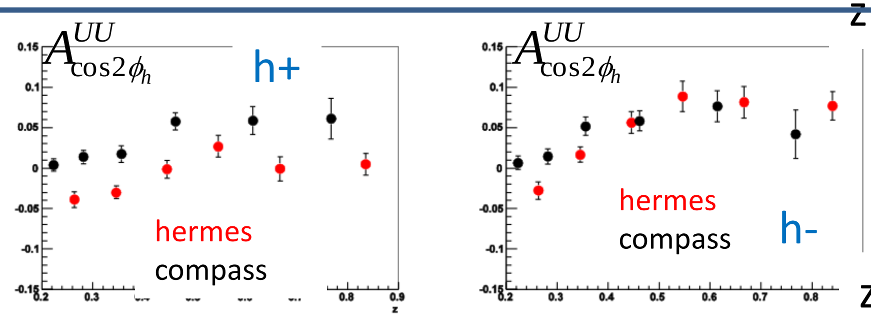


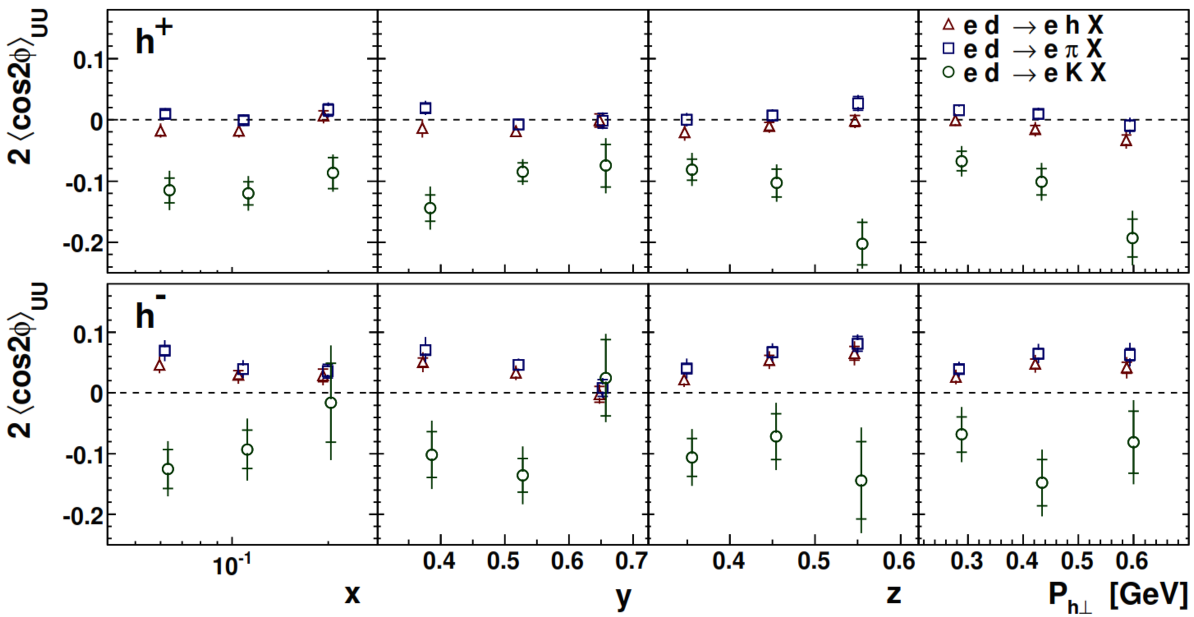
G. Schnell 19 SPIN2016

comparison HERMES COMPASS
in a similar kinematic region



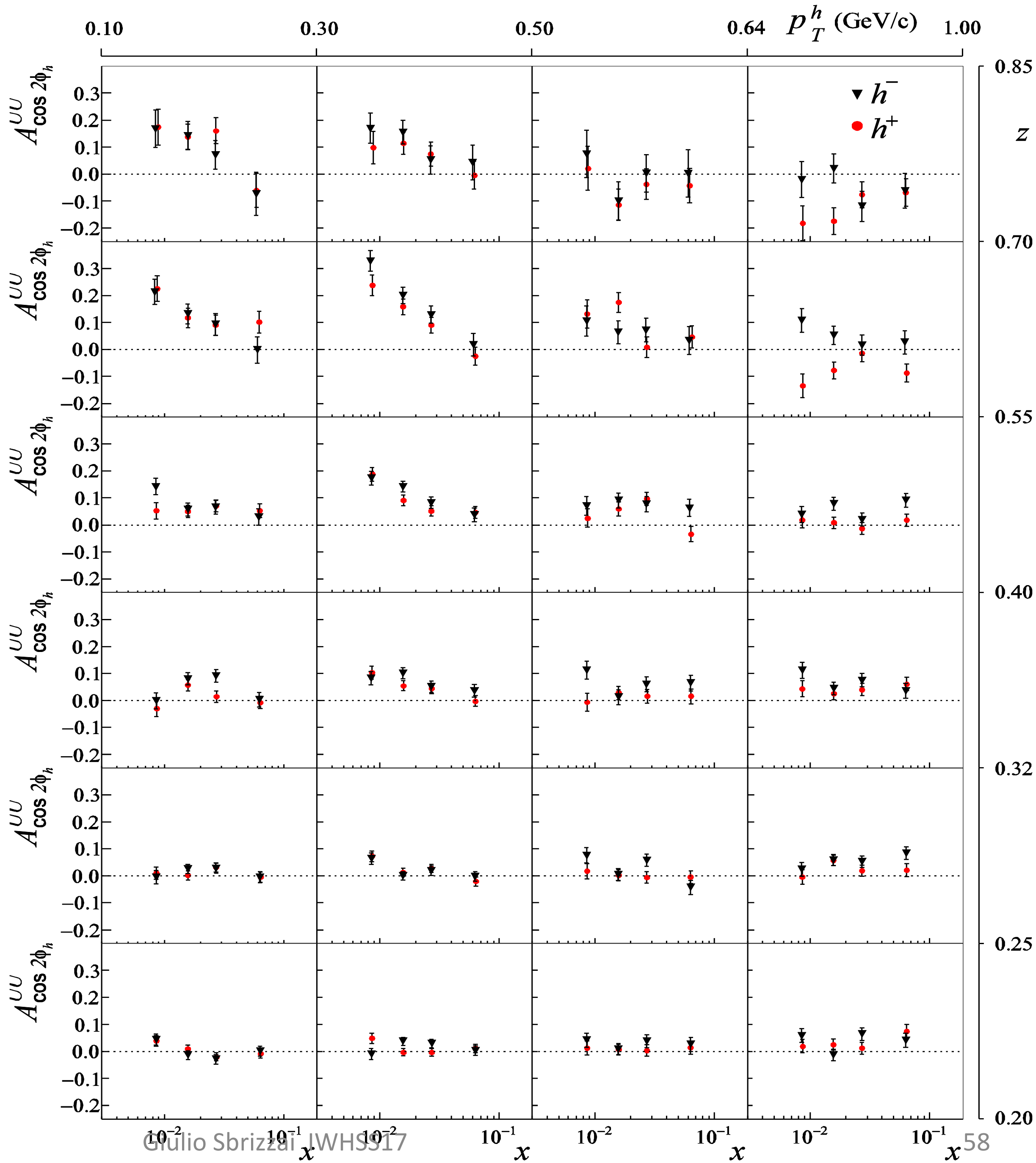
difference for
pos hadrons not
well understood yet





maybe different mixture of Kaons and Pions in the two experiments…?

Unpolarised Azimuthal Asymmetries measured from 2004 deuteron data



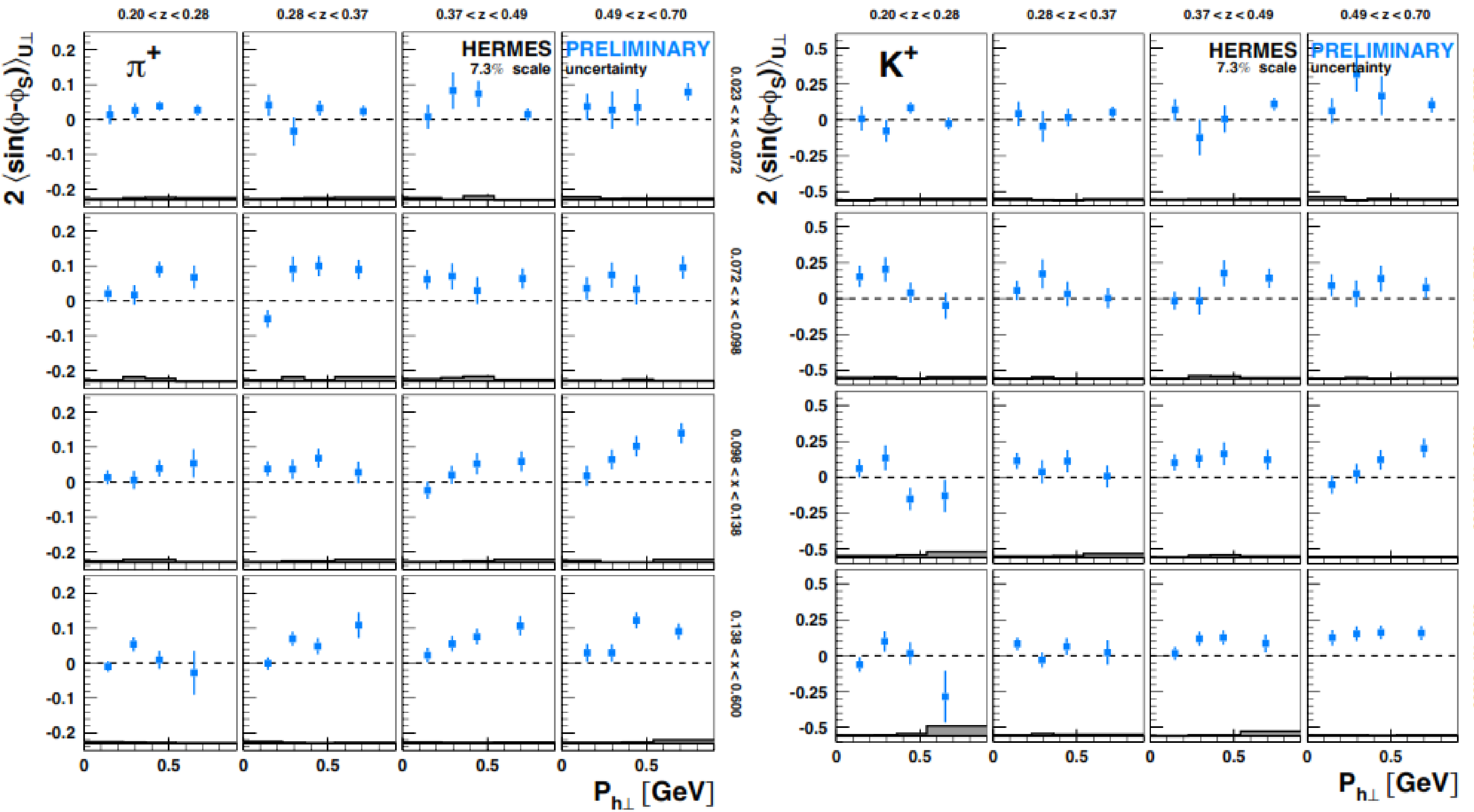
$$A^{UU}_{\cos 2\phi_h} \approx \frac{1}{Q^2} Cahn + BM$$

convoluted with the Collins FF

multiD performed both on **cosϕ** and **cos2ϕ**

on identified hadrons

Gunar Schnell SPIN 2016



preliminary results produced for all TSA, useful also to compare with 1d results