The Transverse Spin Structure of the Nucleon: overview and perspectives of COMPASS SIDIS measurements

Participation with support from STRONG-2020 project

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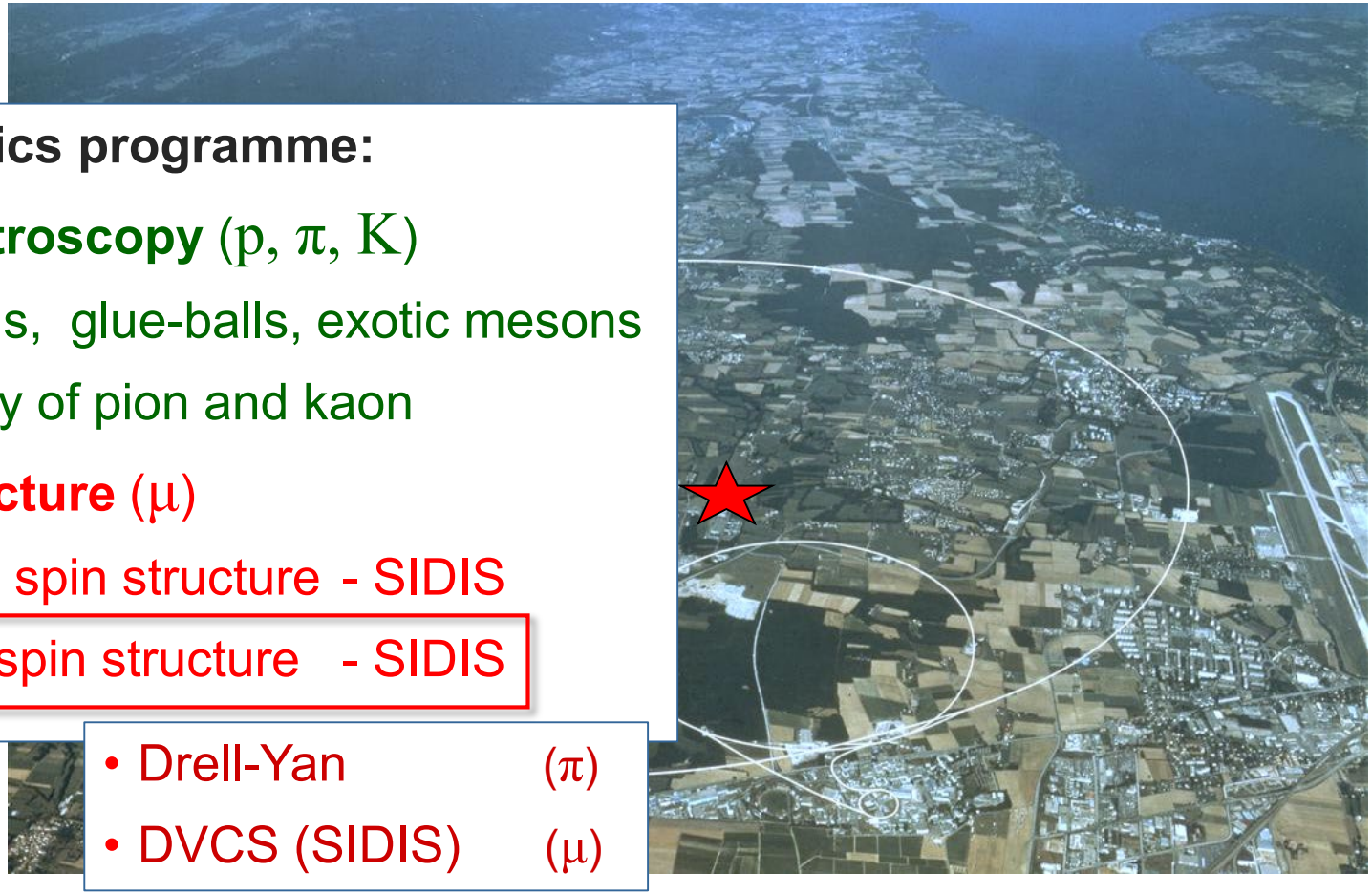
Trieste University and INFN
on behalf of the COMPASS Collaboration

Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment at the CERN SPS



proposed physics programme:

hadron spectroscopy (p, π, K)

- light mesons, glue-balls, exotic mesons
- polarisability of pion and kaon

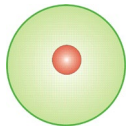
nucleon structure (μ)

- longitudinal spin structure - SIDIS
- transverse spin structure - SIDIS

- Drell-Yan (π)
- DVCS (SIDIS) (μ)

the structure of the nucleon

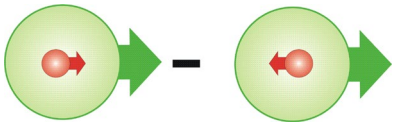
collinear description leading twist



q

number density

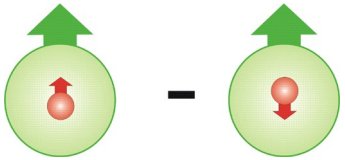
very well known



Δq

helicity distribution

well known



$\Delta_T q$

transversity distribution

nucleon polarisation

quark polarisation	U	L	T
U	f_1		
L		g_1	
T			h_1

- correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark
- a chirally-odd distribution, not observable in DIS
- related to **tensor charge**
- first experimental evidence in 2005

the structure of the nucleon

taking into account the quark intrinsic transverse momentum k_T, at leading order
8 TMD PDFs are needed for a full description of the nucleon structure

correlations between parton transverse momentum, parton spin and nucleon spin

SIDIS gives access to all of them

nucleon polarisation

quark polarisation	U	L	T
U	f_1		$f_{1T}^{\perp}$
L		g_1	g_{1T}
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 $h_{1T}^{\perp}$

h_1

$f_{1T}^{\perp}$ **Sivers PDF**

correlation between the transverse polarization of the nucleon and the transverse momentum of the partons

Semi-Inclusive Deep Inelastic Scattering

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

Semi-Inclusive Deep Inelastic Scattering

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

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

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

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

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

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

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

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

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

8 independent azimuthal modulations

leading twist amplitudes
→ convolutions of the transversity and TMD PDFs and FFs

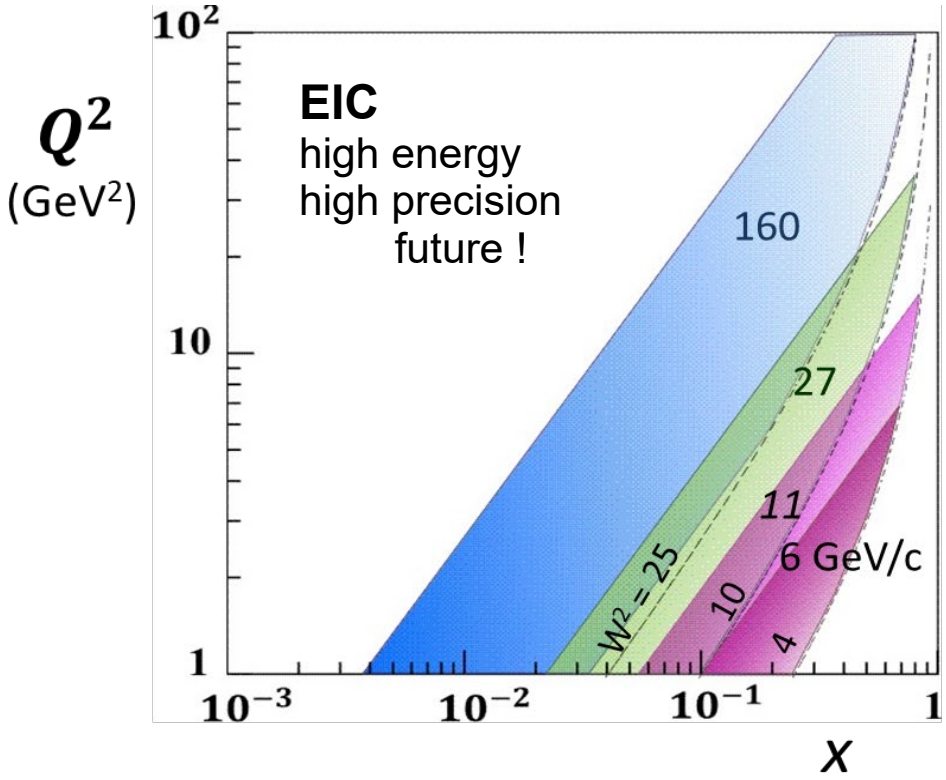
SIDIS

- allows to disentangle the effects related to the different TMD PDFs and to access all of them
- by identifying the final state hadrons and using different targets allows for flavour separation

→ *very powerful tool*

a big experimental effort

SIDIS



COMPASS ongoing

hermes over
results still coming

Jefferson Lab 6 GeV over
11 GeV: to be started
high precision data

Fragmentation Functions Collins, DiHadron, ….

BELLE BABAR BESIII

COMPASS spectrometer – SIDIS with polarized targets

designed to

- use high energy beams
- have large angular acceptance
- cover a broad kinematical range

two stages spectrometer

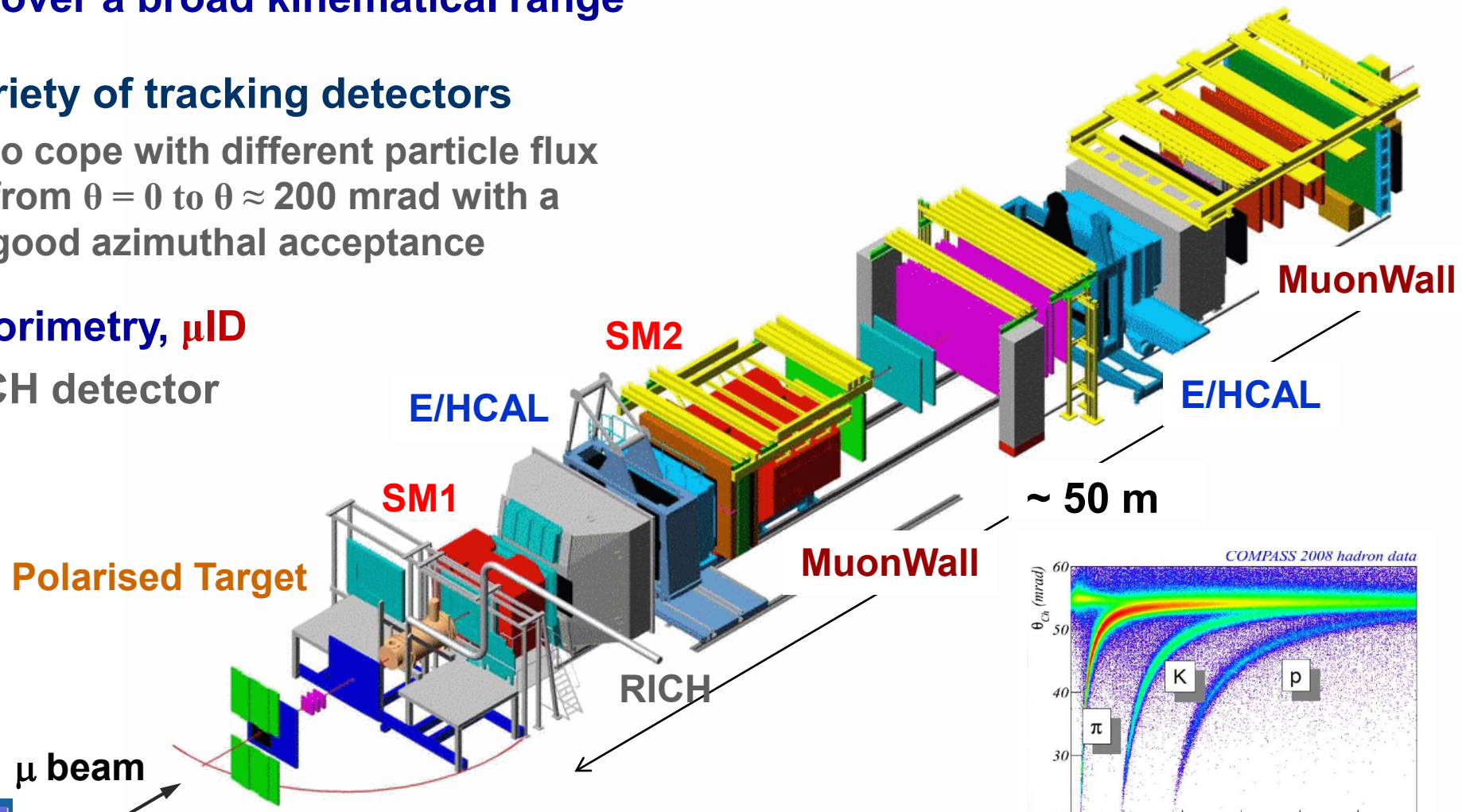
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

variety of tracking detectors

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

calorimetry, μID

RICH detector



results on
Transverse Spin Asymmetries

15 years after the first publication

- **a review of well know results**
- **a few less known results**
- **expected results**

the deuteron data

the first SIDIS data with a transversely polarized target in COMPASS

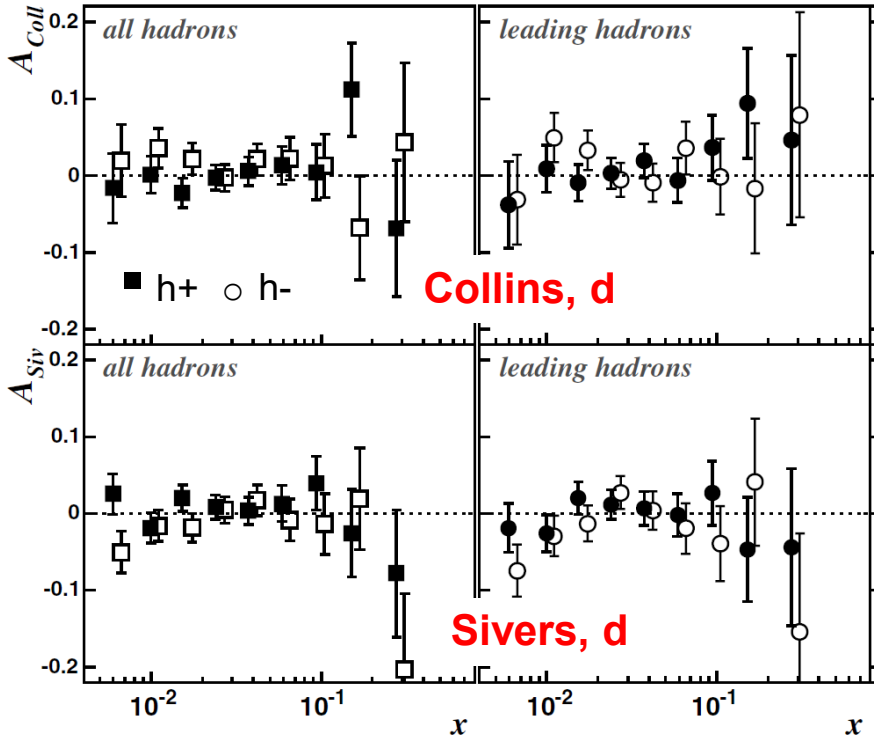
2002: 0.5 effective weeks of data taking

in 2004 first results for the **Collins asymmetry** $A_{Coll} \sim \frac{\sum_q e_q^2 \, h_1^q \otimes H_{1q}^\perp}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$

and for the **Sivers asymmetries** $A_{Siv} \sim \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$

first publication in 2005

PRL 94, 202002 (2005)

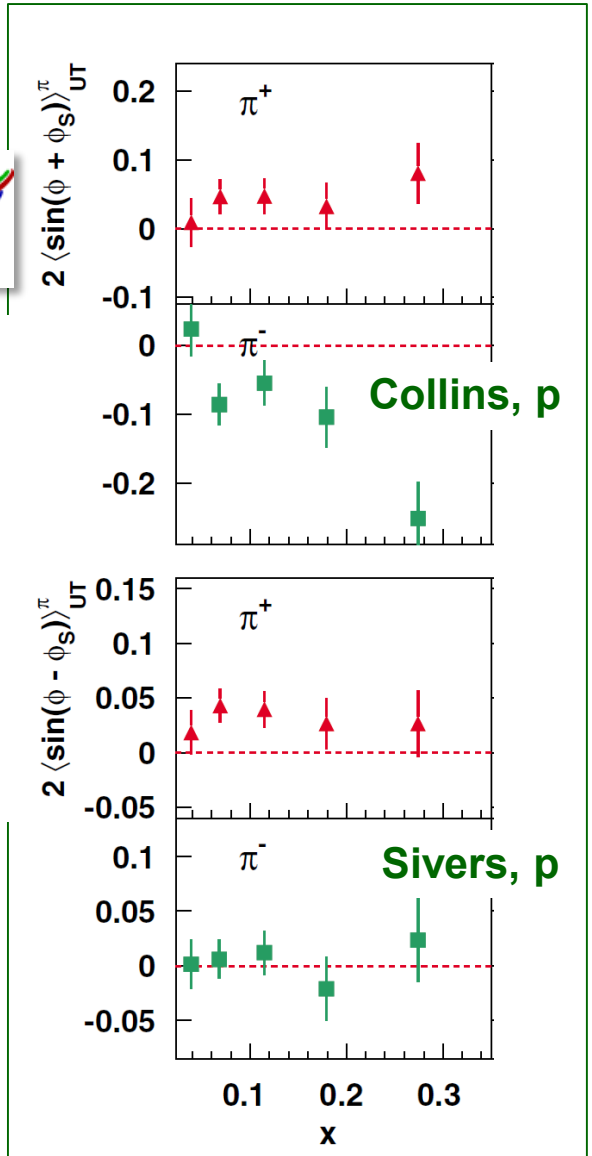


large statistical uncertainties compatible with zero

in the mean time, HERMES measurements with a proton target

for the first time clear signals: real effects !

u d quark cancellation?

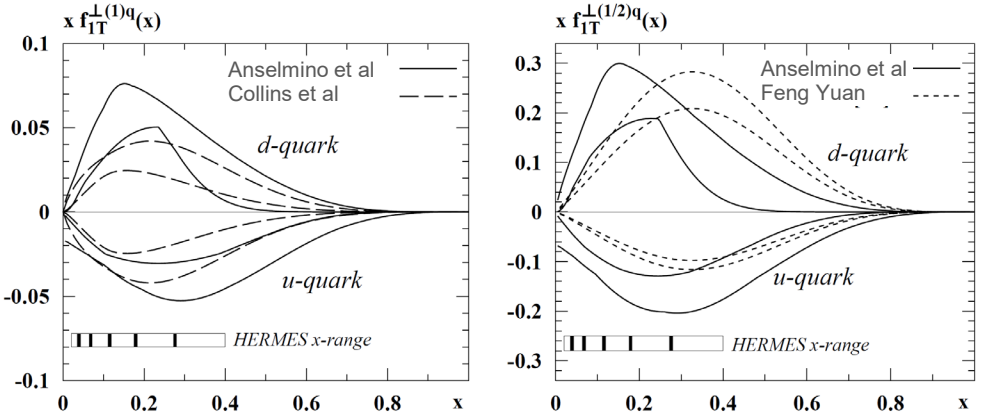


first extractions of the new PDFs

the first extractions of the Sivers functions from the p and d Sivers asymmetries came very soon

- the HERMES and COMPASS data could be well described

confirmation that the COMPASS results could be due to u d quark cancellation



Transversity 2005 proceedings

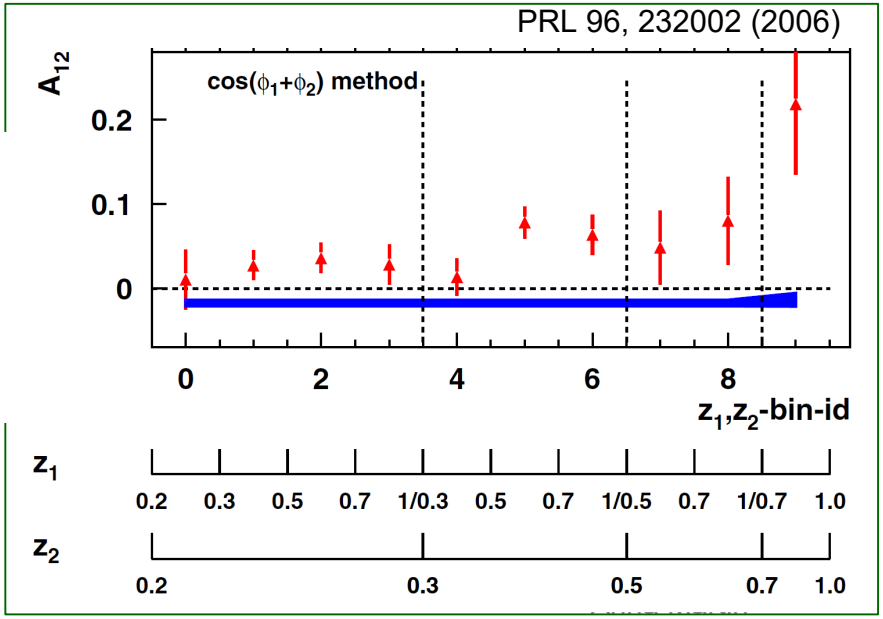
the extraction of the transversity distributions took some more time

- the Collins FF was the missing piece
- it was qualitatively described by the Artru $^3P_0$ model

$$A_{Coll} \sim \frac{\sum_q e_q^2 \, h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}}$$

first measurements the Collins-like asymmetry in $e^+e^- \rightarrow hadrons$ at BELLE

clear independent indication of non-zero Collins FFs



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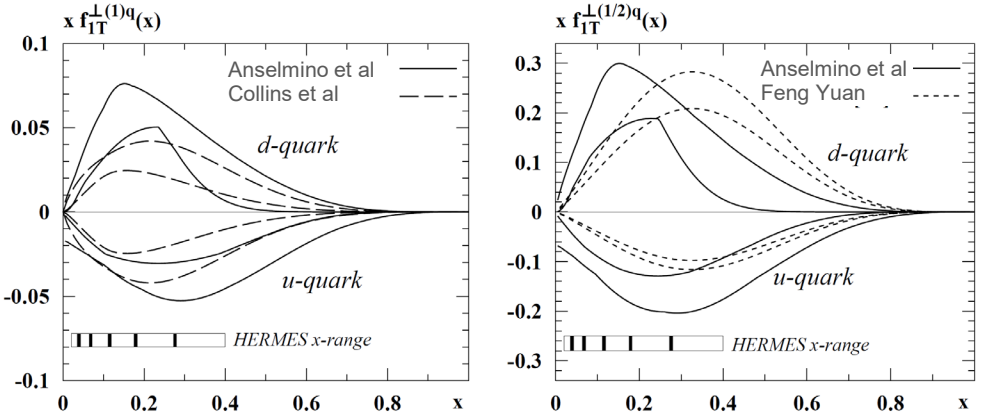

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- first measurements at BELLE

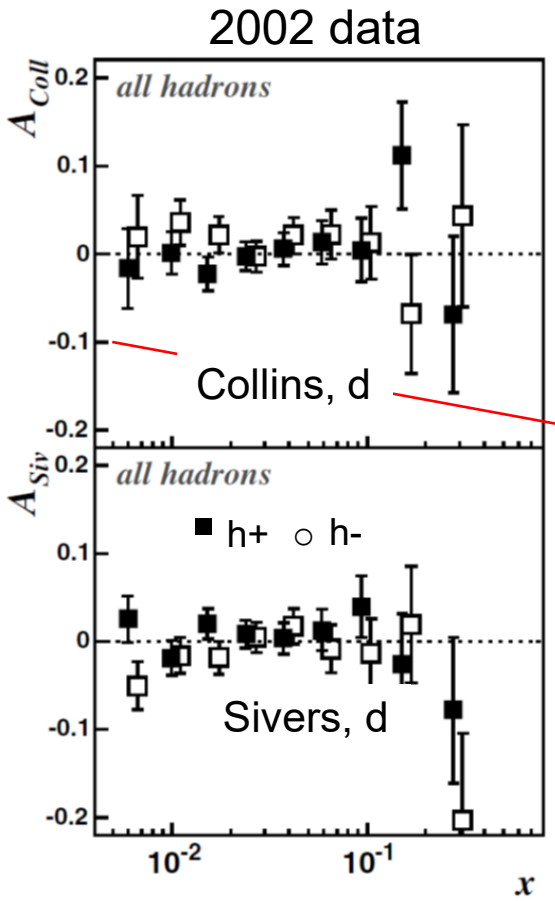
again indication that the COMPASS result on the Collins asymmetry could be due to u d cancellation

to summarize:

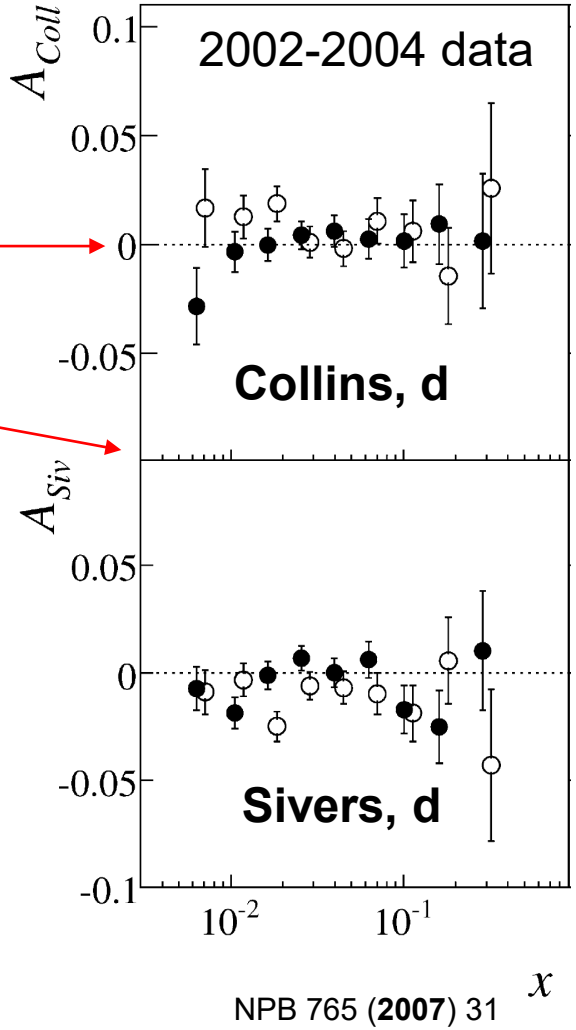
- clear signals of the new transverse spin effects seen at HERMES and Belle
- a consistent picture of transverse spin effects was coming out, which could explain the both the HERMES proton and the COMPASS deuteron data

the deuteron data

2002: ~0.5 effective weeks of data taking
2003: 2 weeks of data taking
2004: 2 weeks of data taking



PRL 94, 202002 (**2005**)



NPB 765 (**2007**) 31

final results for deuteron

a much more precise measurements of zero

still, large statistical uncertainties

today, these are the only existing deuteron data

JLab6: He3, statistically limited

the deuteron data

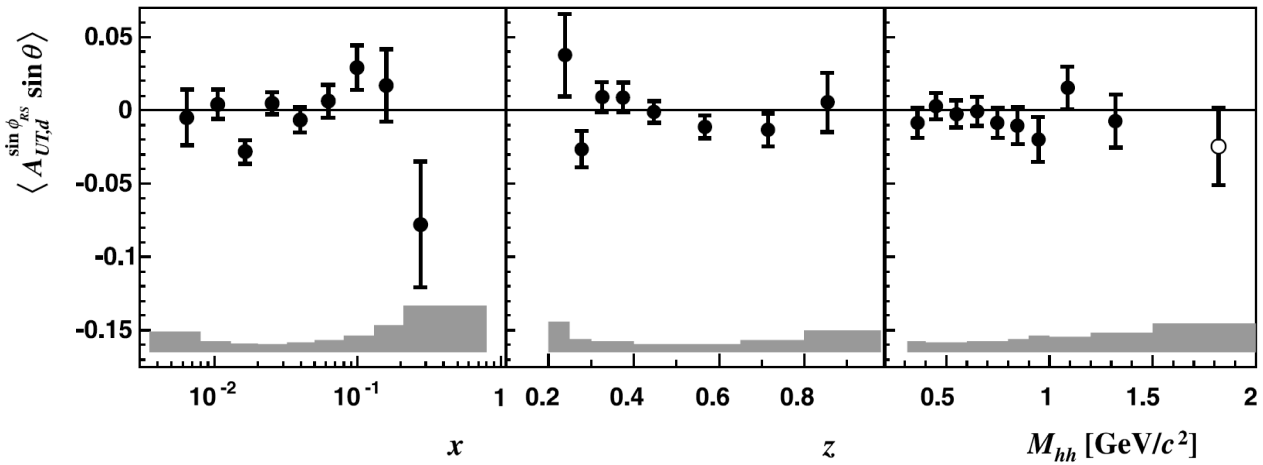
looking for a signal

di-hadron asymmetries:
a different approach to transversity

$$A_{hh} \sim \frac{\sum_q e_q^2 \, h_1^q \cdot H_{1q}^{\sphericalangle}}{\sum_q e_q^2 \, f_1^q \cdot D_{1q}^{hh}}$$

Belle

2002-2004 deuteron data
$all\ h^+h^-\ pairs$



PLB713 (2012) 10

many tests measurements:

- z ordering, leading + or - with subleading like or unlike sign
- particle identification
- ….

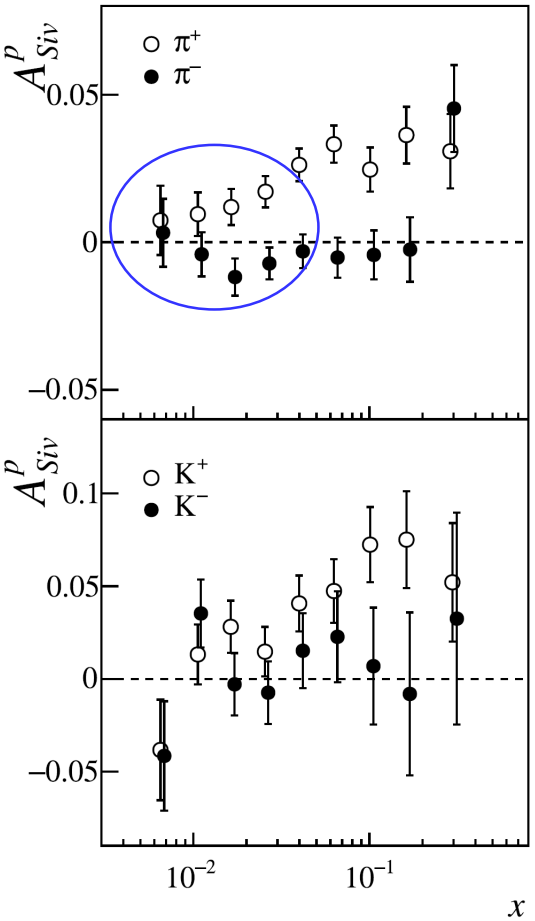
a lot of expectation for the COMPASS proton results
(higher energy)

the proton data

2007 half year, **2010** one year of data taking - the signals are there!

Sivers asymmetry

all proton data



PLB 744 (2015) 250
PLB 717 (2012) 383

the proton data

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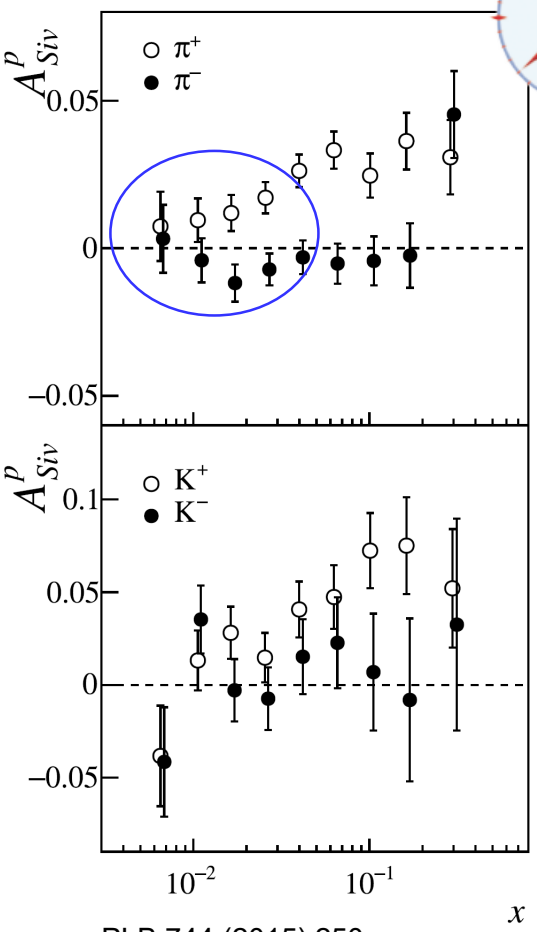
Sivers asymmetry
all proton data



PLB 744 (2015) 250
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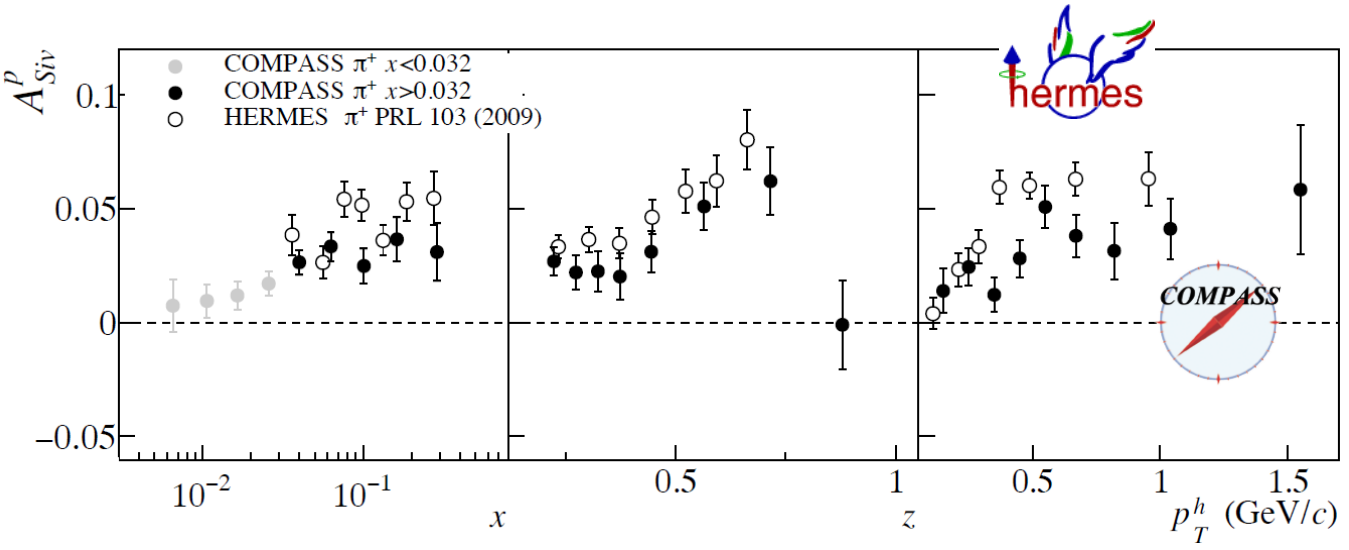

smaller values at COMPASS:
TMD evolution …

the proton data

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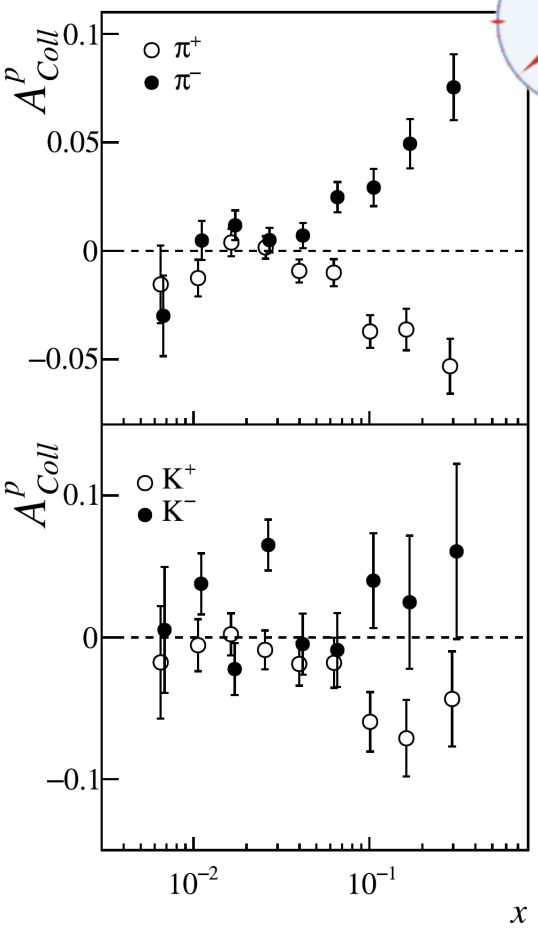
Collins asymmetry
all proton data



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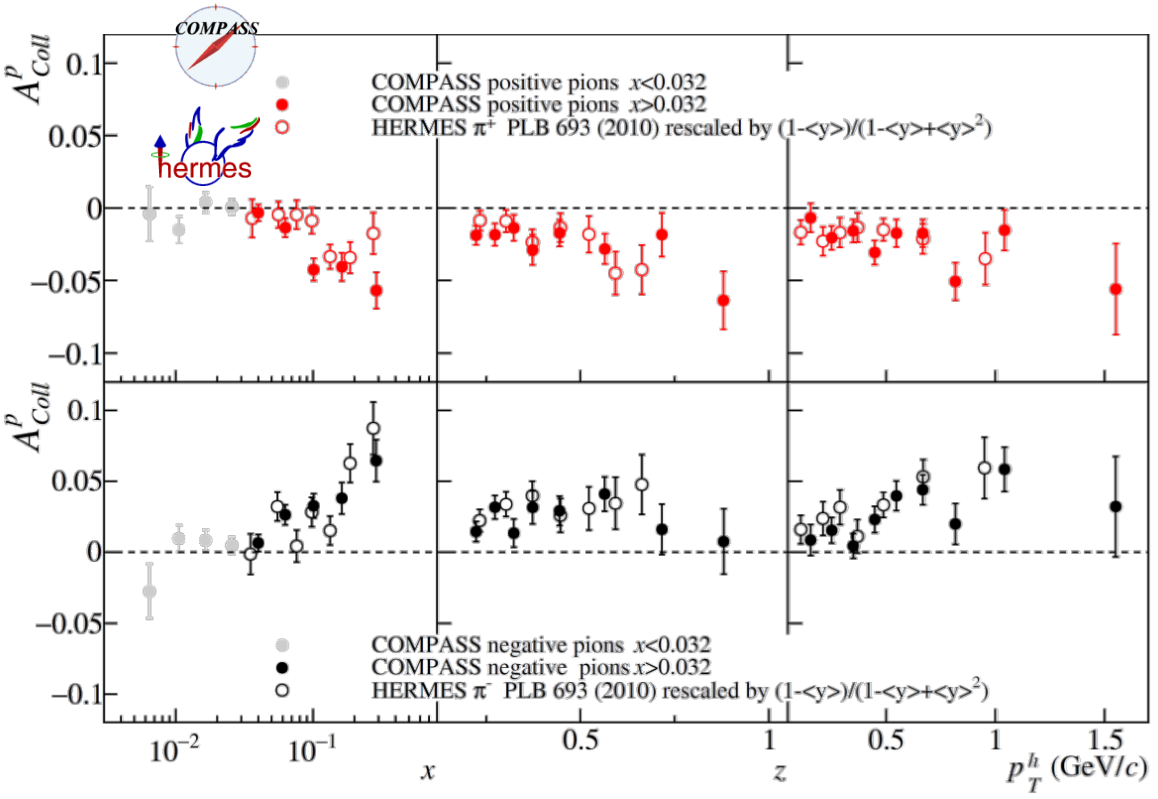
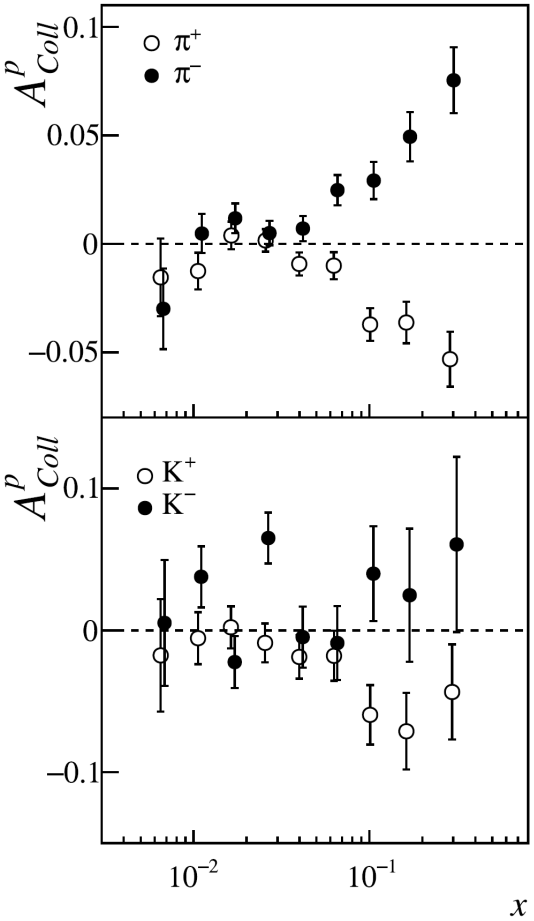


very good agreement !

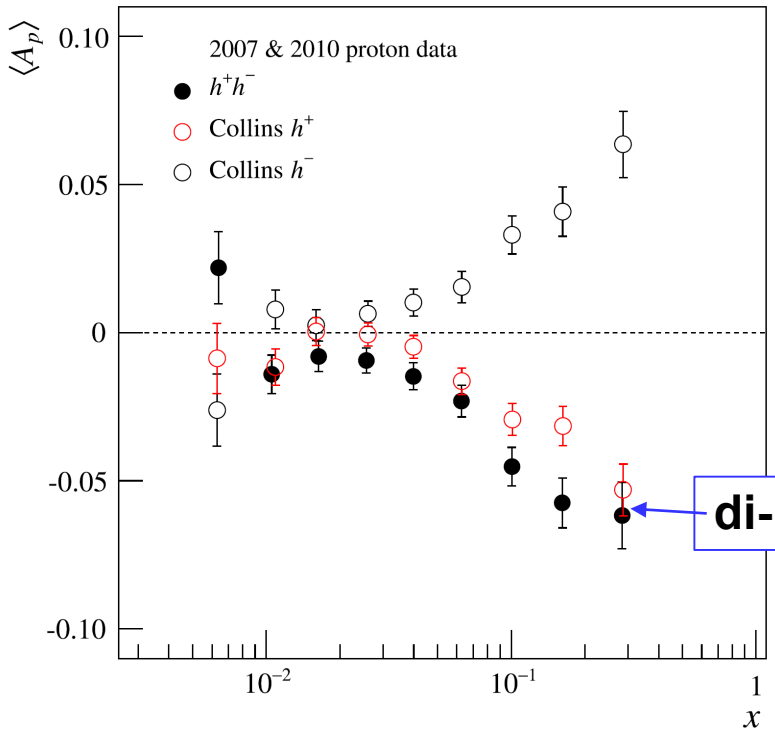
the proton data

2007 half year, **2010** one year of data taking - the signals are there!

Collins asymmetry
all proton data



PLB 744 (2015) 250
PLB 717 (2012) 376



di-hadron asymmetry

PLB 736 (2014) 124

study of the interplay between Collins and di-hadron asymmetries
– not independent

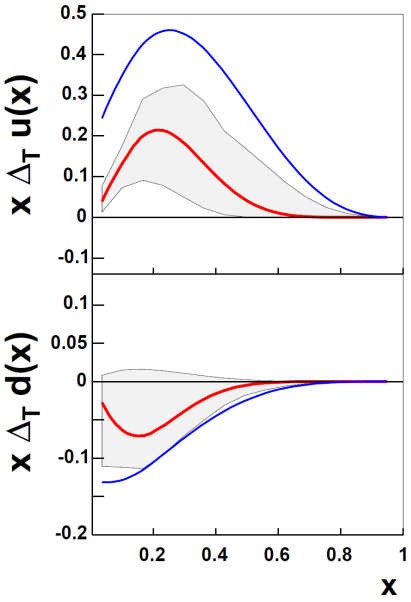
PLB 753 (2016) 406

similar studies for Sivers asymmetry

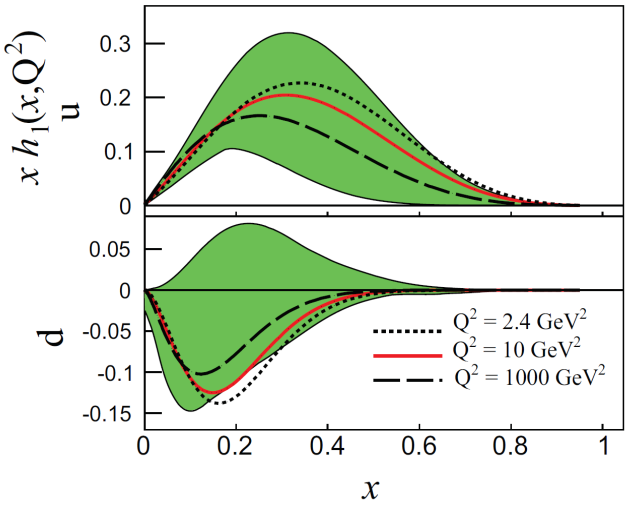
extractions of transversity

global fits of
Collins asymmetries
SIDIS, e^+e^- data

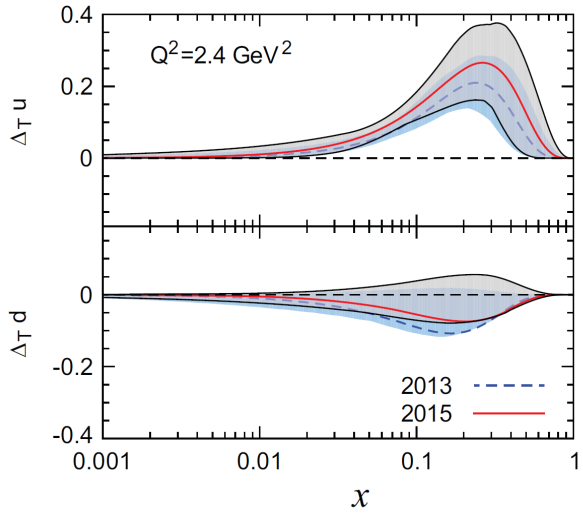
Anselmino et al PRD **2007**



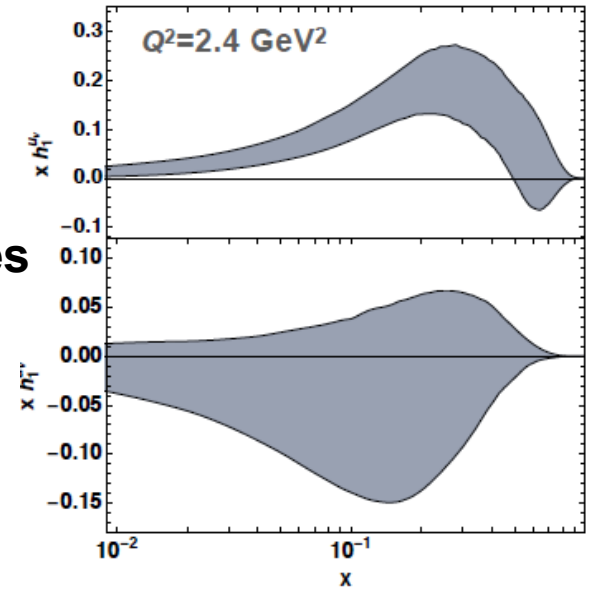
Z.-B. Kang et al. PRD **2016**



M. Anselmino et al.PRD **2015**



Radici Bacchetta PRL **2018**



global fits of
di-hadron asymmetries
SIDIS, e^+e^-, pp data

extractions of transversity

global fits of
Collins asymmetries
SIDIS, e^+e^- data

Z.-B. Kang et al. PRD **2016**

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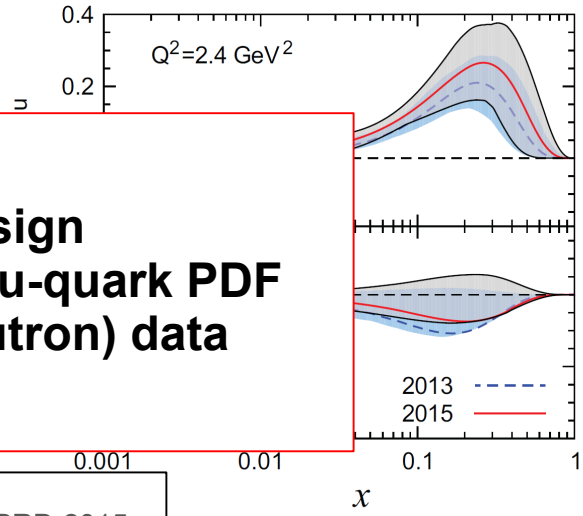
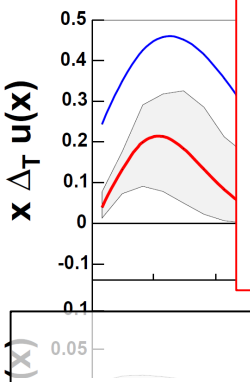
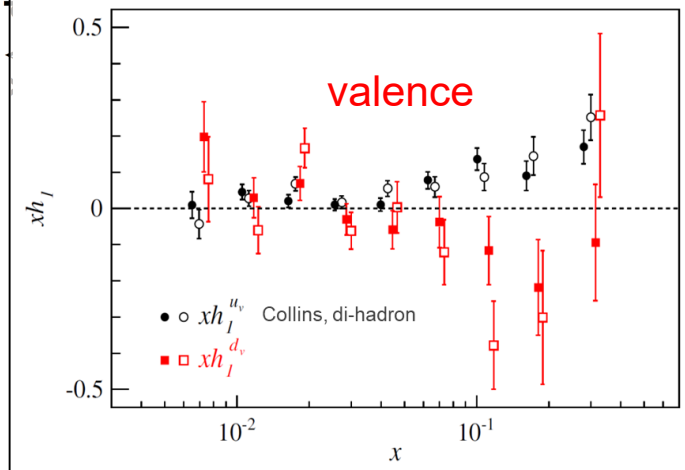


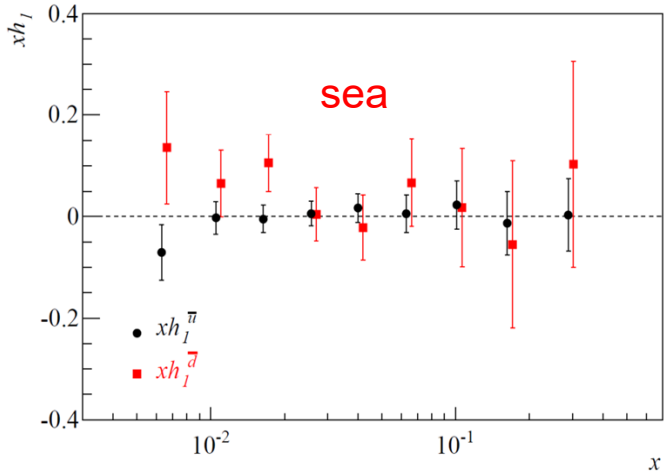
Anselmino et al



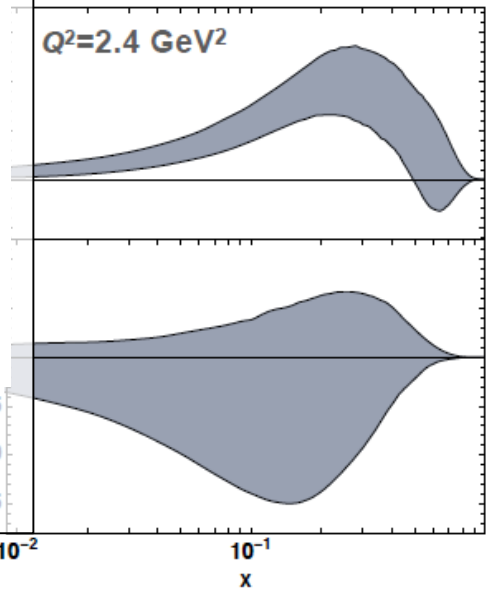
work still ongoing …
u- and d-quark transversity have opposite sign
d-quark PDF much worse determined than u-quark PDF
because of the scarcity of deuteron (neutron) data
→ 2021 COMPASS run

A.M., F. Bradamante, V. Barone PRD 2015





Radici Bacchetta PRL **2018**



point by point extraction
using COMPASS p and d asymmetries, and e^+e^- data, no Soffer bound
advantage: no Monte Carlo nor parametrisation is needed

the proton data

several other measurements have been performed

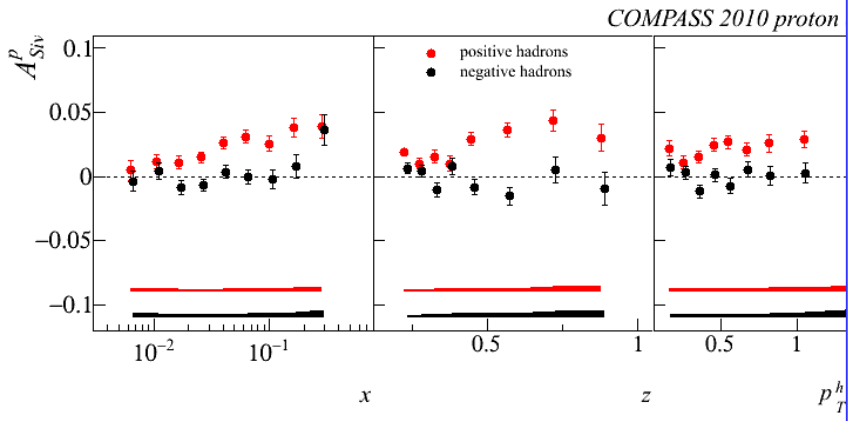
- Sivers asymmetry in Q^2 bins
  in particular for the COMPASS Drell-Yan measurement PBL 770 (2017) 138
- P_T - weighted Sivers asymmetries
  no convolution, important tests, extraction of the Sivers function NPB 940 (2019) 34

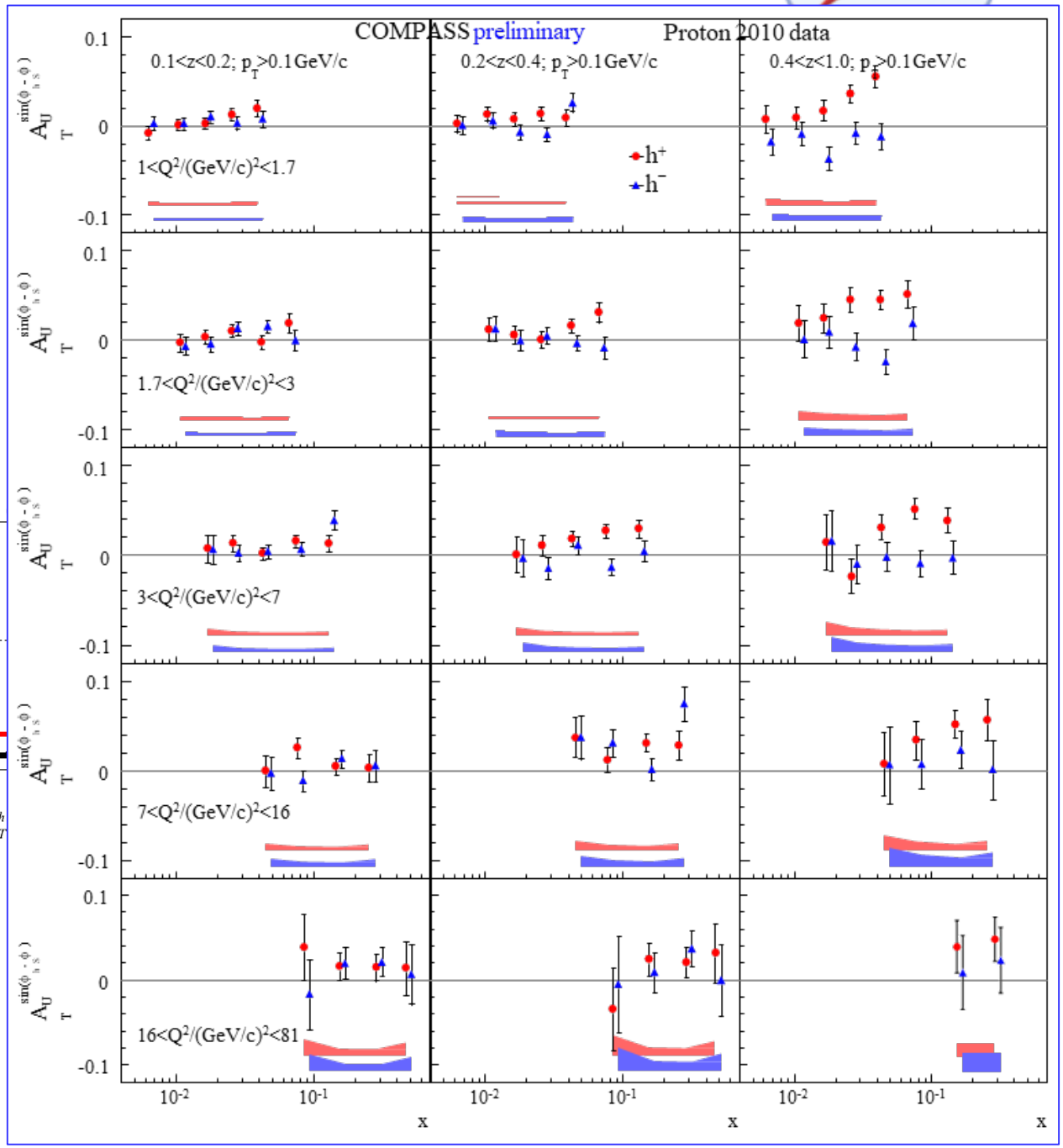
- other TSAs
- multidimensional measurement of TSAs

the proton data

multidimensional measurements of TSAs
(x, Q^2, z, P_T) *bins*

Sivers asymmetry

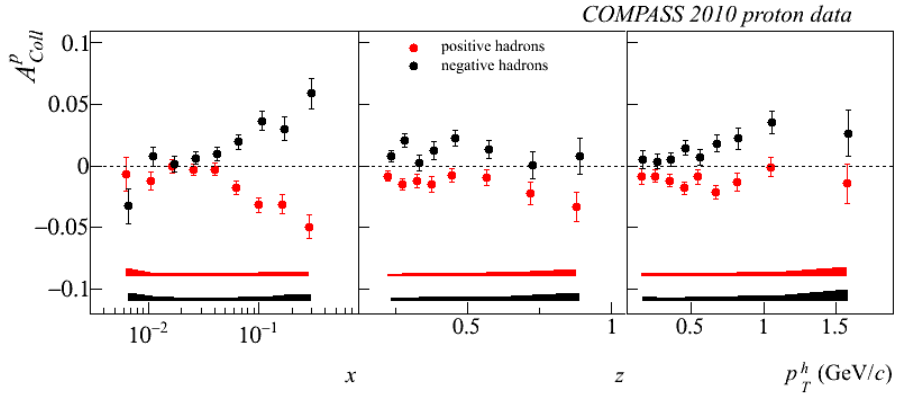


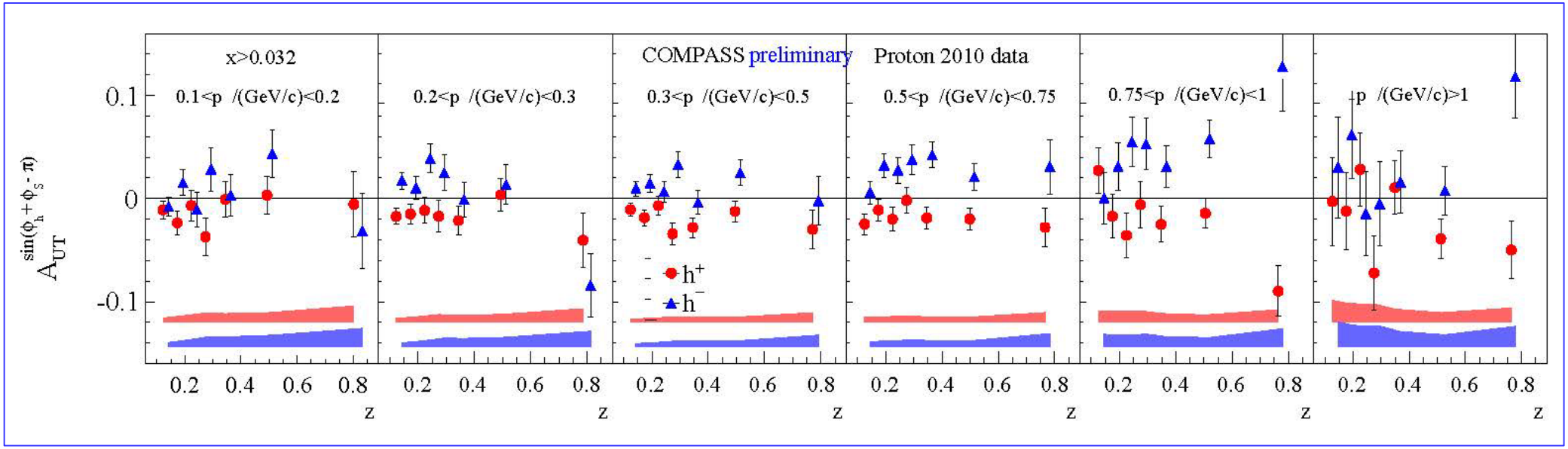


the proton data

multidimensional
measurements of TSAs
(x, Q^2, z, P_T) *bins*

Collins asymmetry





the proton data

multidimensional measurements of TSAs (x, Q^2, z, P_T) *bins*

other TSA

$A_{UT}^{\sin\phi_s}$

subleading twist
similar to HERMES results

$A_{UT}^{\sin(3\phi_h-\phi_s)}$

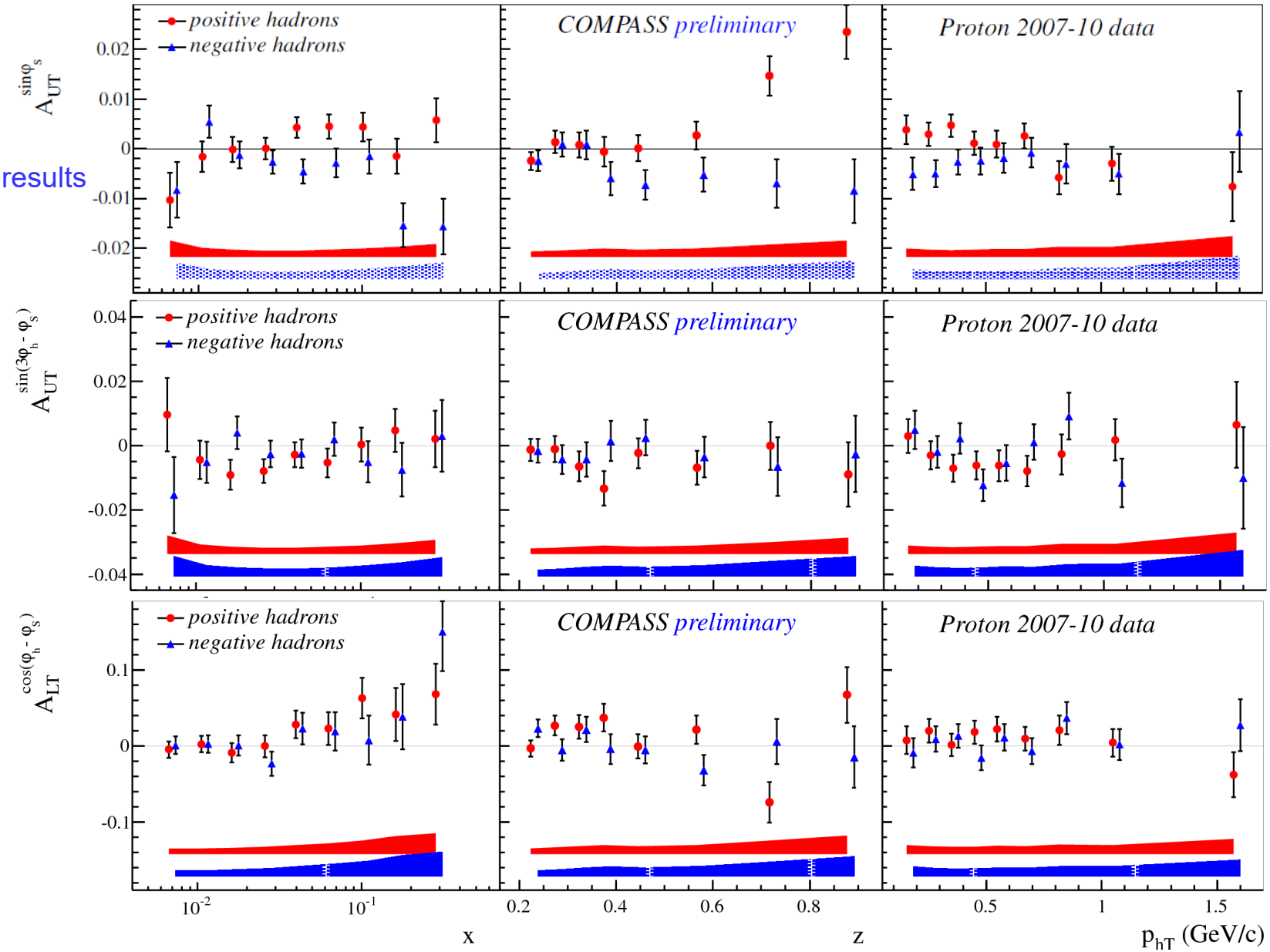
$h_{1T}^{\perp} \otimes H_1^{\perp}$

pretzelosity

$A_{UT}^{\cos(\phi_h-\phi_s)}$

$g_{1T} \otimes D_1$

worm-gear T
Kotzinian- Mulders



target longitudinal spin asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \ldots \right.$$

$$+ S_L \begin{bmatrix} \sqrt{2\varepsilon(1+\varepsilon)}\, A_{UL}^{\sin\phi_h} \sin\phi_h \\ +\varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \end{bmatrix}$$

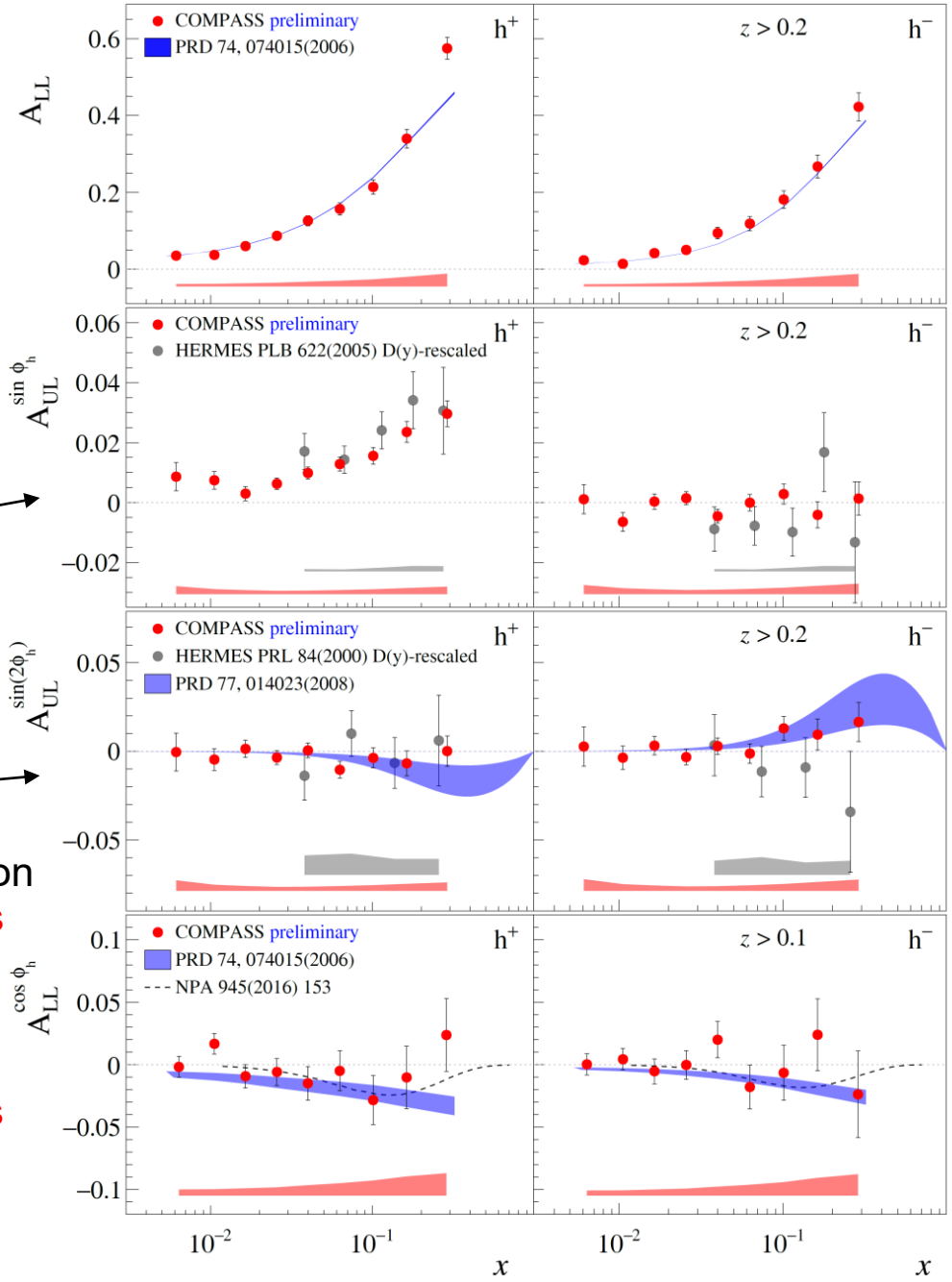
$$\left. + S_L \lambda \begin{bmatrix} \sqrt{1-\varepsilon^2}\, A_{LL} \\ +\sqrt{2\varepsilon(1-\varepsilon)}\, A_{LL}^{\cos\phi_h} \cos\phi_h \end{bmatrix} \right\}$$

measured with unprecedented precision

$A_{UL}^{\sin\phi_h}$
- Q-suppression, different "twist" contributions
- **significant h^+ asymmetry**

$A_{UL}^{\sin 2\phi_h}$ $\quad h_{1L}^{\perp} \otimes H_1^{\perp}$
- only "twist-2" ingredients, additional p_T-suppression
- **compatible with zero**, in agreement with models

$A_{LL}^{\cos\phi_h}$
- Q-suppression, different "twist" contributions
- **compatible with zero**, in agreement with models



B. Parsamyan, COMPASS Coll arXiv:1801.01488

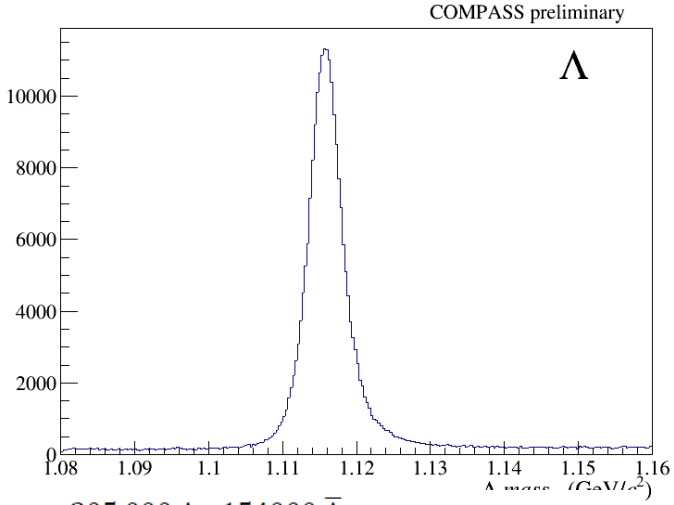
the proton data

several other measurements have been performed

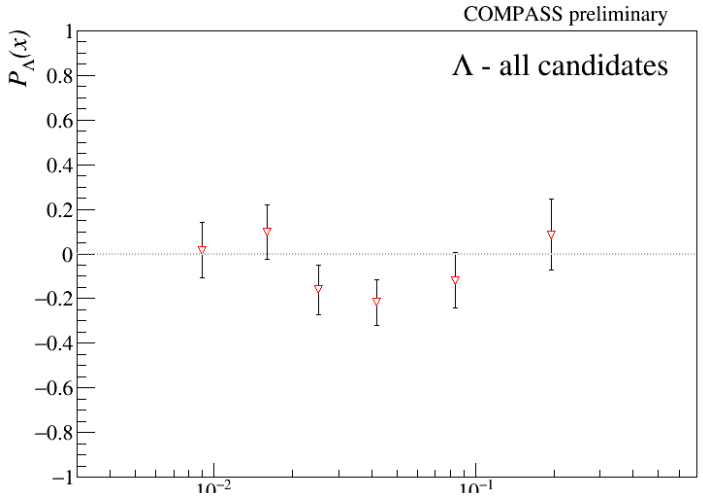
- Sivers asymmetry in Q^2 bins
  in particular for the COMPASS Drell-Yan measurement PBL 770 (2017) 138
- P_T - weighted Sivers asymmetries
  no convolution, important tests, extraction of the Sivers function NPB 940 (2019) 34

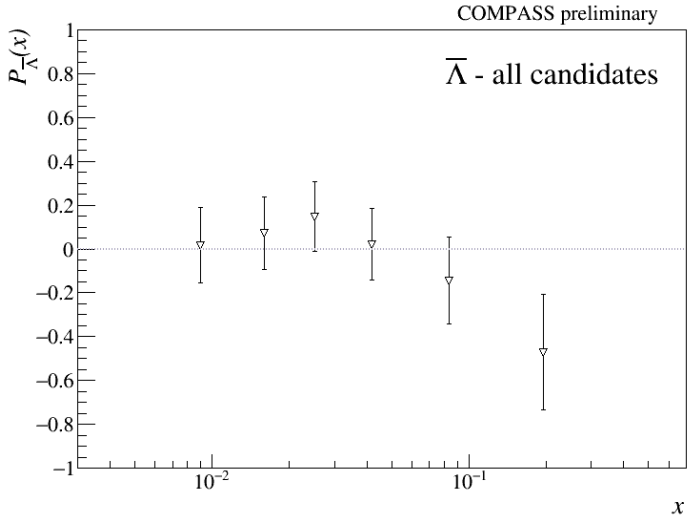
- other TSAs
- multidimensional measurement of TSAs
  - some LSAs
- transversity induced $\Lambda/\bar{\Lambda}$ polarization

$$P_\Lambda(x,z) = \frac{\sum e_q^2 h_1^{q(\bar{q})} H_1^{\Lambda,q(\bar{q})}(z)}{\sum e_q^2 f_1^{q(\bar{q})} D_1^{\Lambda,q(\bar{q})}(z)}$$



~ 305 000 Λs, 154000 $\bar{\Lambda}$s.





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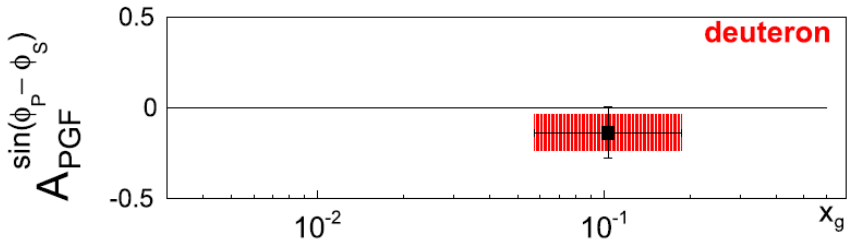
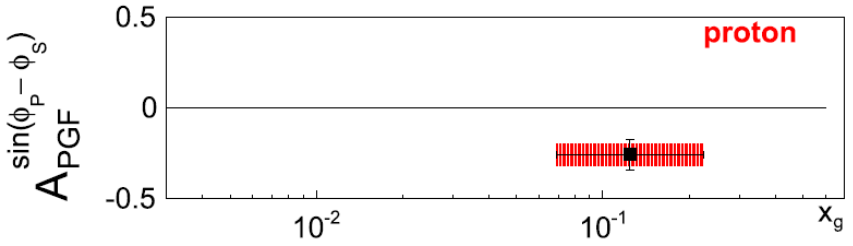
- TSAs for high P_T pairs from PGF events PLB 772 (2017) 854

Sivers-like





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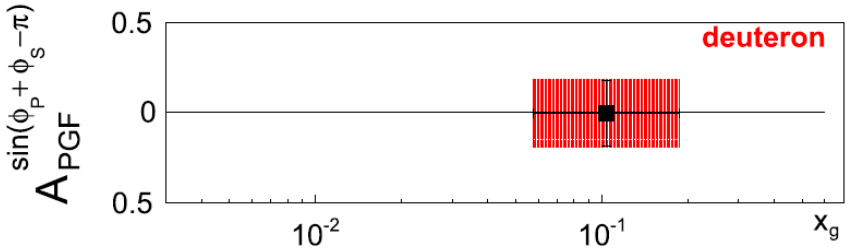

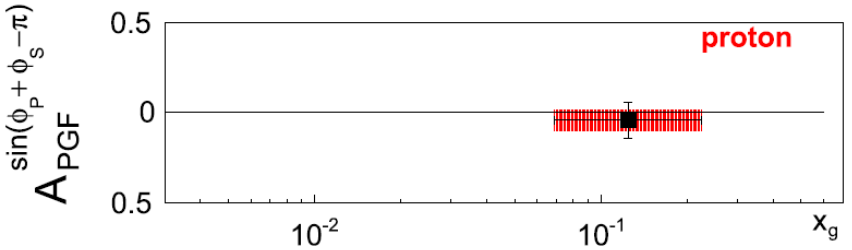

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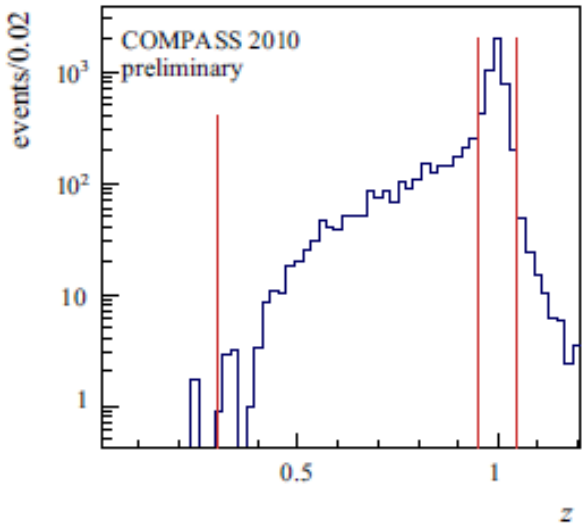

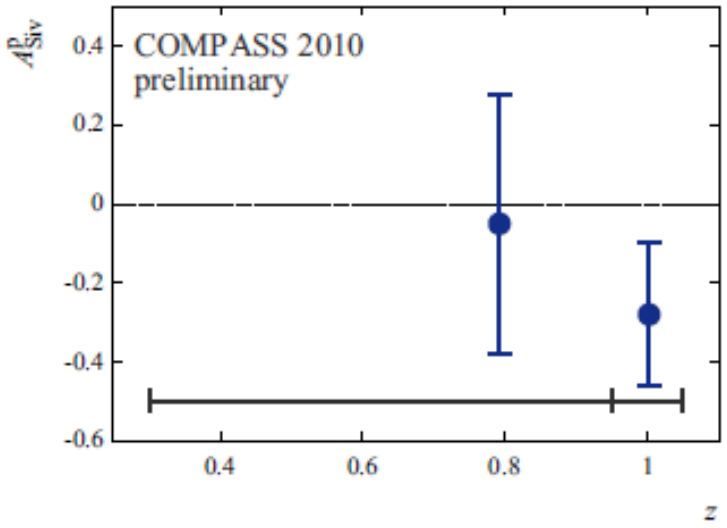

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and there are ideas for new measurements

- measurement of the g_2 structure function
- other weighted asymmetries
- other di-hadron asymmetries ….

all this will be repeated with the new deuteron data,
which will be collected as soon as the LS3 will be over, in 2021

the 2021 run – transversely polarised deuteron

one year of run with 160 GeV muons to measure SIDIS off transversely polarised d

the missing measurement to complete the COMPASS exploratory programme

collecting the same statistics as in 2010,

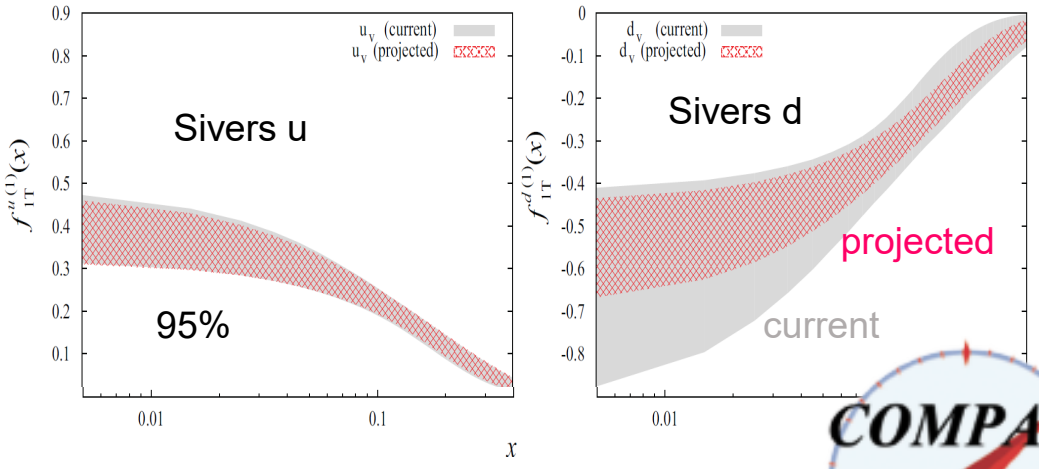
the deuteron asymmetries will have a statistical uncertainty

$$\sigma_d \cong 0.6\,\sigma_p^{2010}$$

in a kinematic range that only COMPASS can cover, as long as EIC will not start, complementary to JLab12

important impact on the knowledge of TMD PDFs

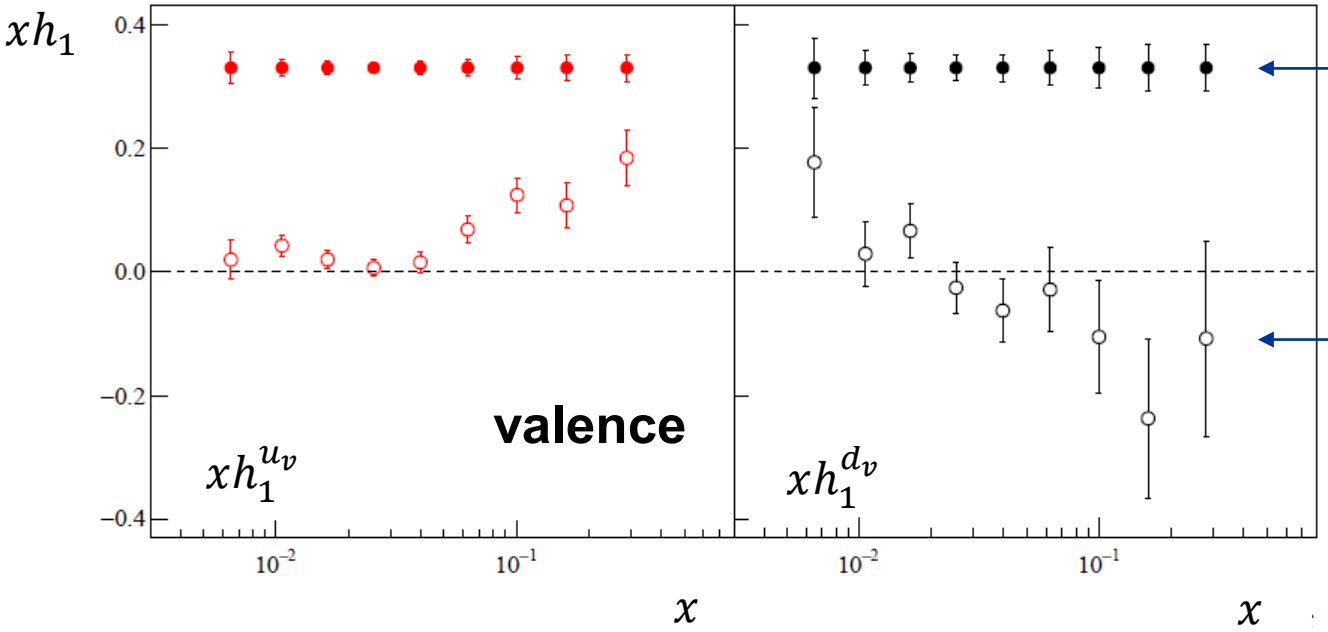
Sivers functions from global fits
M. E. Boglione and J. O. Gonzalez



and in particular
transversity and tensor charge $g_T = \delta_u - \delta_d$

$$\delta_q = \int_0^1 dx h_1^{q_v}(x)$$

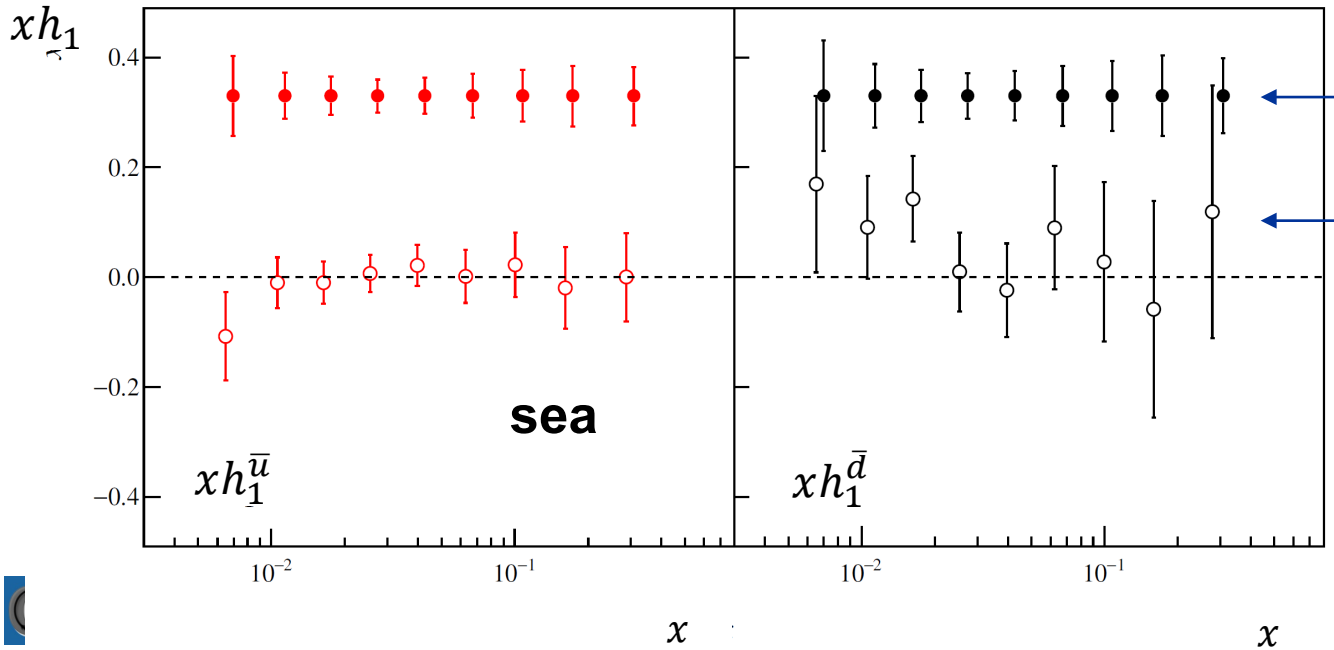
the 2021 run: impact on the transversity functions



projected
gain 1.2 to 2.0 for u
1.8 to 4.0 for d

present

PRD 91(2015) 014034
from COMPASS p, d
and e+e- data



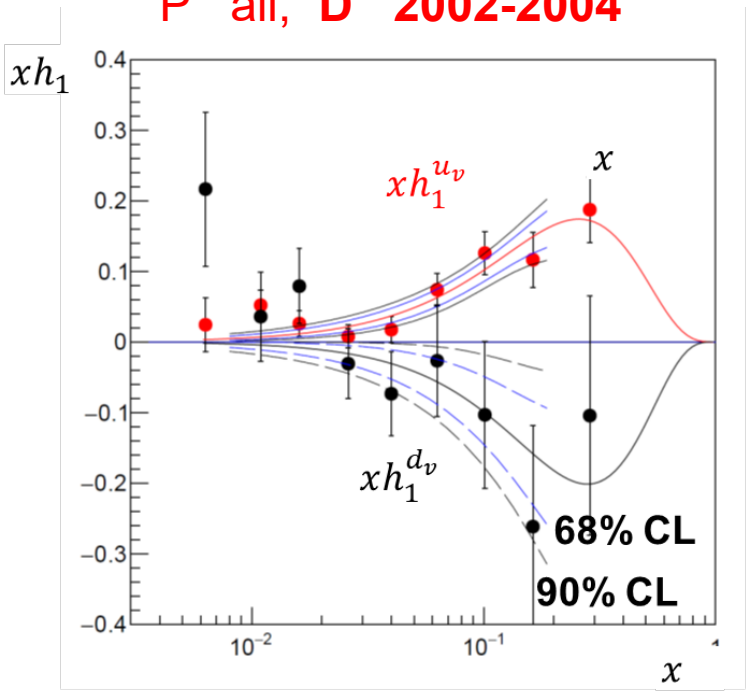
projected

present

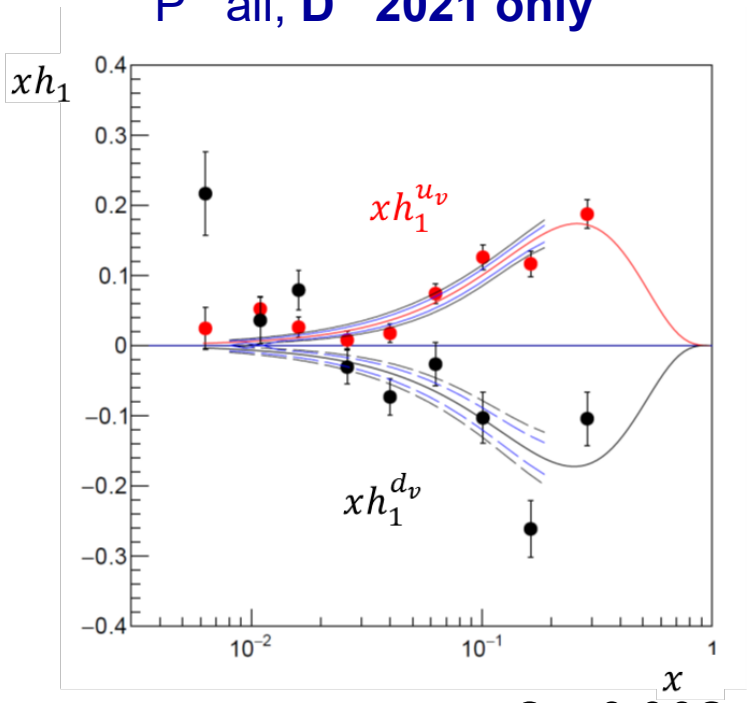
the 2021 run: impact on the tensor charge

for the proposal, we have evaluated the tensor charge in the measured x range

present
P all, **D 2002-2004**



projected
P all, **D 2021 only**



$\Omega_x: 0.008 \div 0.210$

	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d}(x)$	$g_T = \delta_u - \delta_d$
present	$0.201 \pm \mathbf{0.032}$	$-0.189 \pm \mathbf{0.108}$	$0.390 \pm \mathbf{0.087}$
projected	$0.201 \pm \mathbf{0.019}$	$-0.189 \pm \mathbf{0.040}$	$0.390 \pm \mathbf{0.044}$

summary

COMPASS has given a relevant contribution to the study of the transverse structure of the nucleons with the Transverse Spin Asymmetries in SIDIS

new results from the existing COMPASS proton data will come soon

the 2021 deuteron run COMPASS will allow to complete the exploratory study of the transverse spin structure of the nucleon

the new data will allow to fully use the existing proton data and will be unique in the relatively short future

thank you !