New measurements of transverse spin asymmetries at COMPASS

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INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Trieste

on behalf of the COMPASS Collaboration

25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM

September 24 – 29, 2023
Durham Convention Center
Durham, NC, USA

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

fixed target experiment on the M2 beam line at CERN SPS
a facility, built by the COMPASS Collaboration, in the years 1997-2001
with a wide physics program

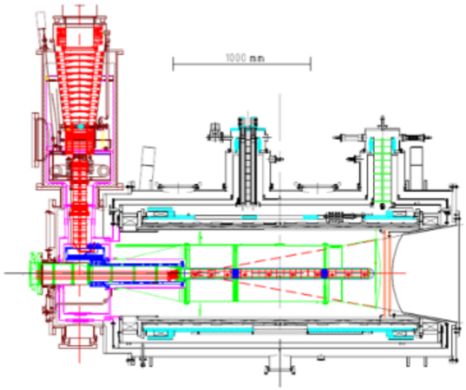
initially approved for 5 years of data taking,
the experiment took data from 2002 to 2022

and the spectrometer
is still there,
being used by the
AMBER Collaboration

the COMPASS spectrometer

designed to

- use high energy muon and hadron beams, and different targets
- have large angular acceptance, as flat as possible
- cover a broad kinematical range



two stages spectrometer

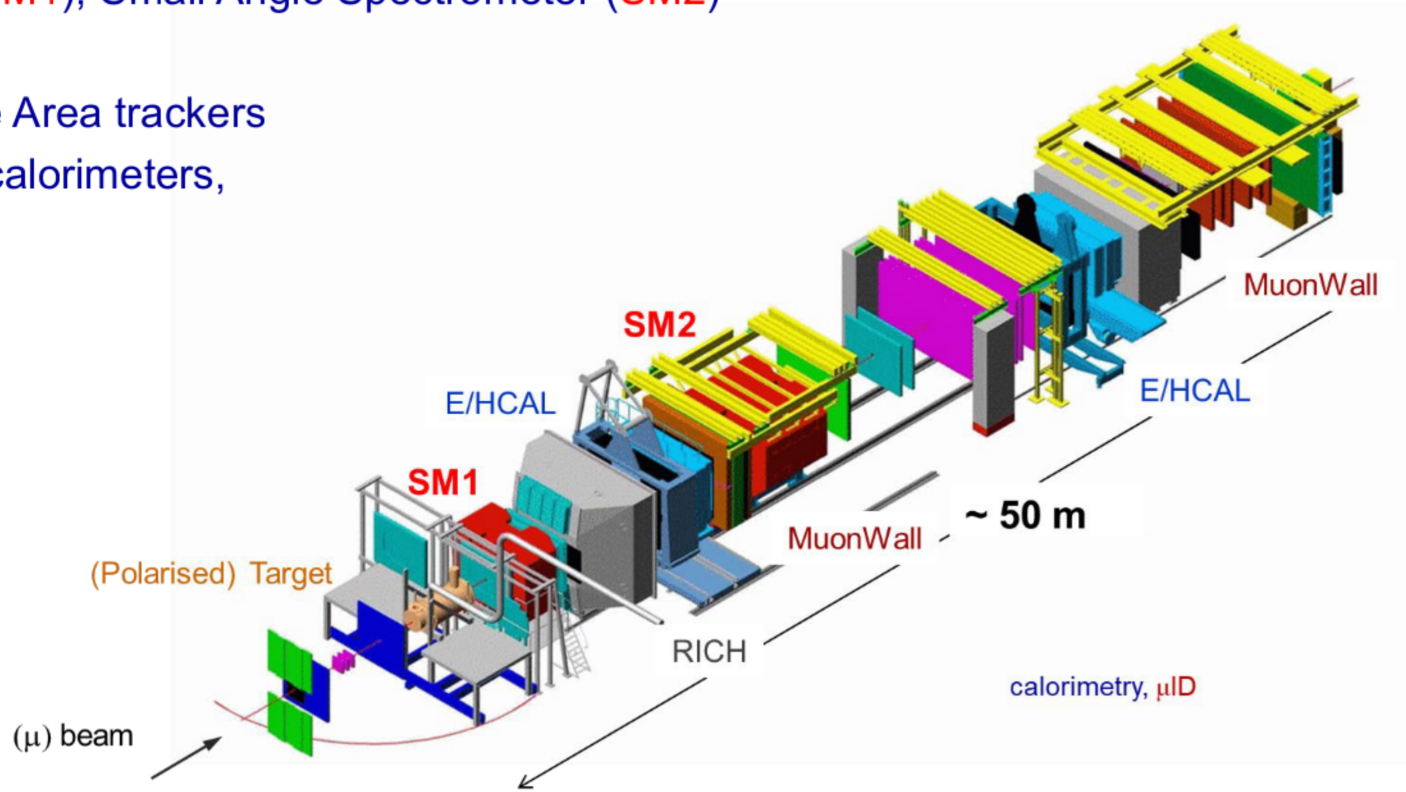
Large Angle Spectrometer (SM1), Small Angle Spectrometer (SM2)

equipped with

Very Small, Small, Large Area trackers

RICH, muon detectors, calorimeters,

trigger hodoscopes



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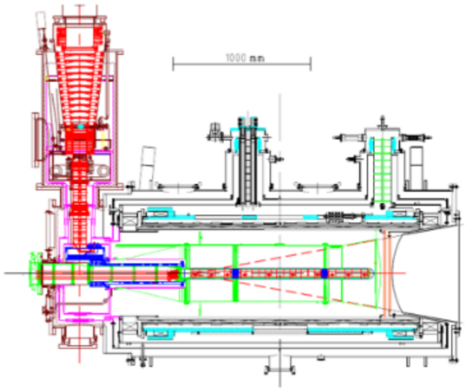

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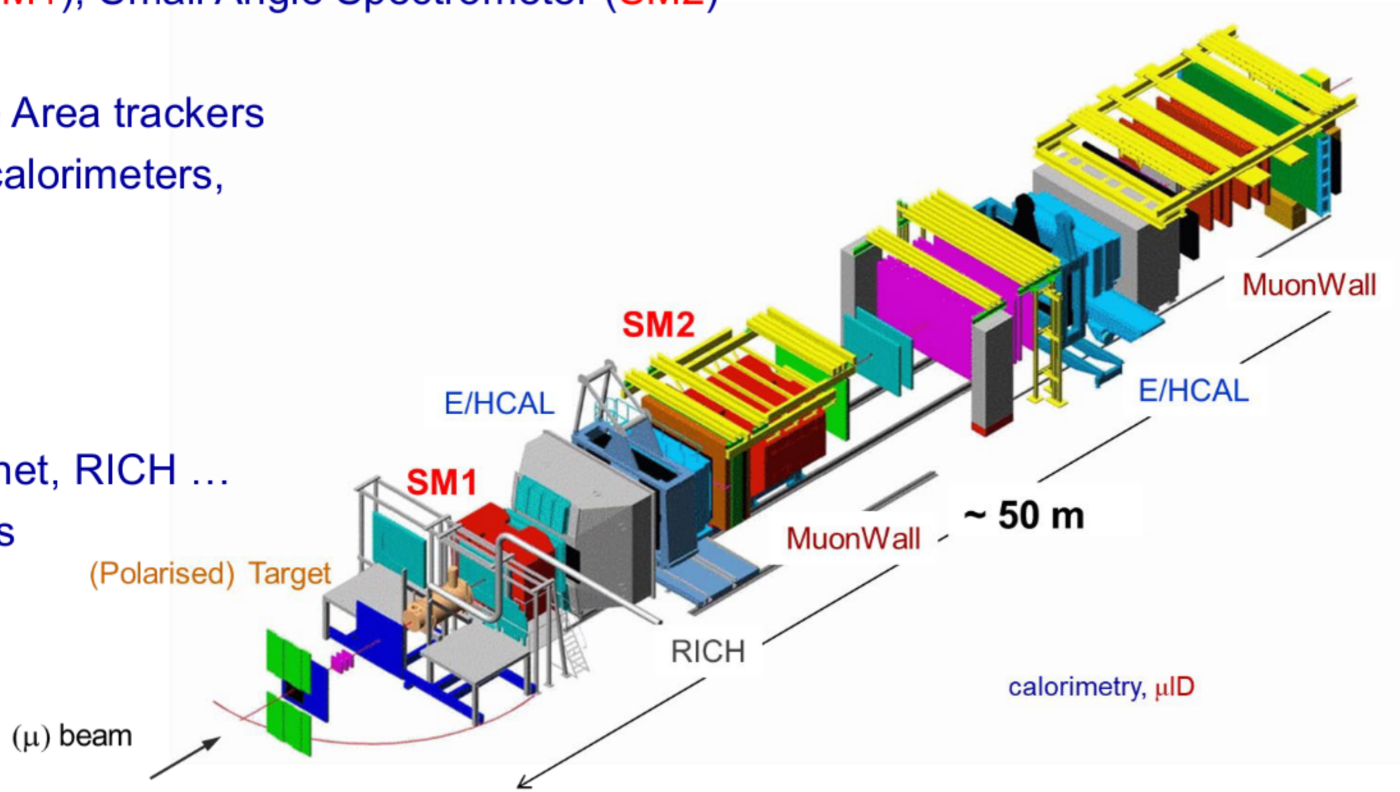

2005 upgrade:

large acceptance PT magnet, RICH …

several upgrades in the years to fulfill the requirements of the different measurements

15 years of data taking

dedicated to **nucleon structure** and **spectroscopy**

	2002-2004	160 GeV/c μ^+ beam L and T polarized d (^{6}LiD) target	ΔG, SIDIS	
	2006	160 GeV/c μ^+ beam L polarized d (^{6}LiD) target	ΔG, SIDIS	spin physics B Parsamyan plenary
	2007	160 GeV/c μ^+ beam L and T polarized p (NH_3) target	SIDIS	
	2008, 2009	hadron beams LH and nuclear targets	Hadron Spectroscopy Primakoff	
Addendum to the COMPASS Proposal	2010	160 GeV/c μ^+ beam T polarized p (NH_3) target	SIDIS	G. Reicherz Polarised targets
	2011	190 GeV/c μ^+ beam L polarized p (NH_3) target	SIDIS	
COMPASS II Proposal	2012	π^- (μ) beam Ni (LH) target	Primakoff (DVCS)	
	2015	190 GeV/c π^- beam T polarized p (NH_3) target	Drell-Yan	
	2016, 2017	160 GeV/c μ^+ and μ^- beam LH target	DVCS / SIDIS	J. Matoušek GPDs/TMDs
	2018	190 GeV/c π^- beam T polarized p (NH_3) target	Drell-Yan	V. Andrieux TMDs A. Vijayakumar, poster
Addendum to the COMPASS II Proposal	2022	160 GeV/c μ^+ beam T polarized d (^{6}LiD) target	SIDIS	

2005, 2013, 2014, 2019, 2020, 2021 - CERN accelerators shut-down: no run or very short runs

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	2011	190 GeV/c μ^+ beam L polarized p (NH_3) target	SIDIS	Collins and Sivers asymmetries
COMPASS II Proposal	2012	π^- (μ) beam Ni (LH) target	Primakoff (DVCS)	
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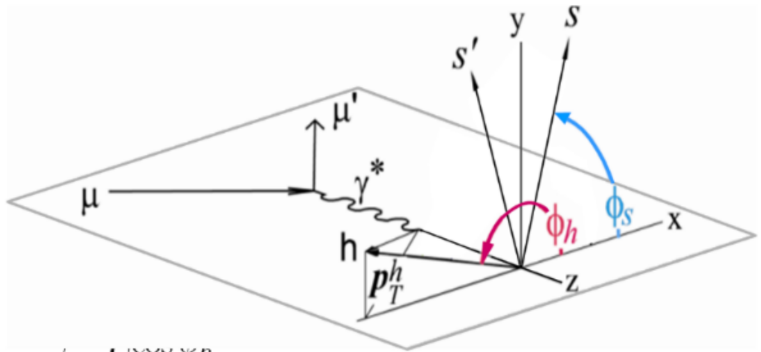
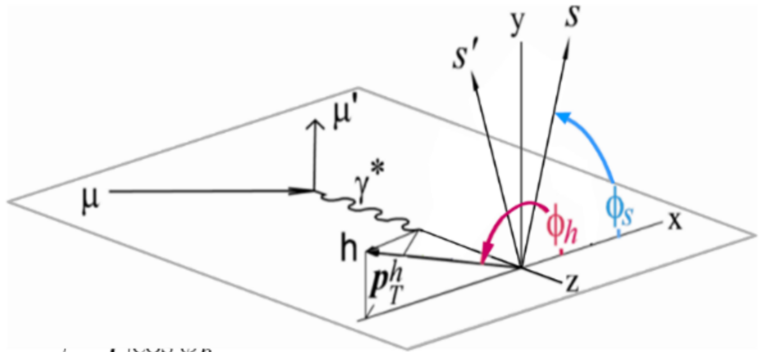
SIDIS cross-section



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

SIDIS cross-section



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$$

$$
+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}
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+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]
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+\,|\boldsymbol{S}_\perp|\Big[\boxed{\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)}
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$$

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

in the parton model

Sivers asymmetry

$$
A_{Siv}=\frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}}\simeq\frac{\sum_q e_q^2\,f_{1T}^{\perp q}\otimes D_{1q}}{\sum_q e_q^2\,f_1^q\otimes D_{1q}}
$$

Collins asymmetry

$$
A_{Coll}=\frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU}}\simeq\frac{\sum_q e_q^2\,h_1^q\otimes H_{1q}^\perp}{\sum_q e_q^2\,f_1^q\otimes D_{1q}}
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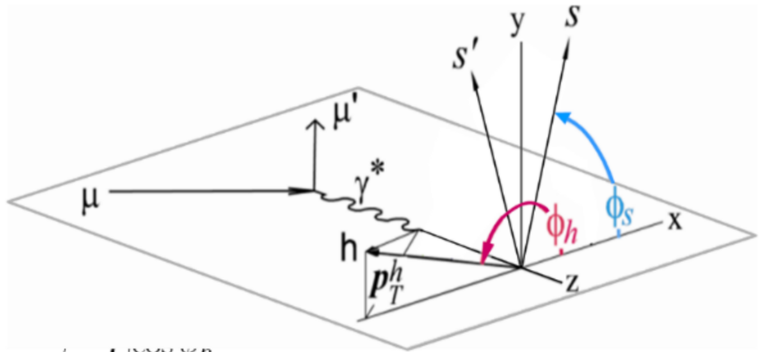
SIDIS cross-section



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Collins asymmetry

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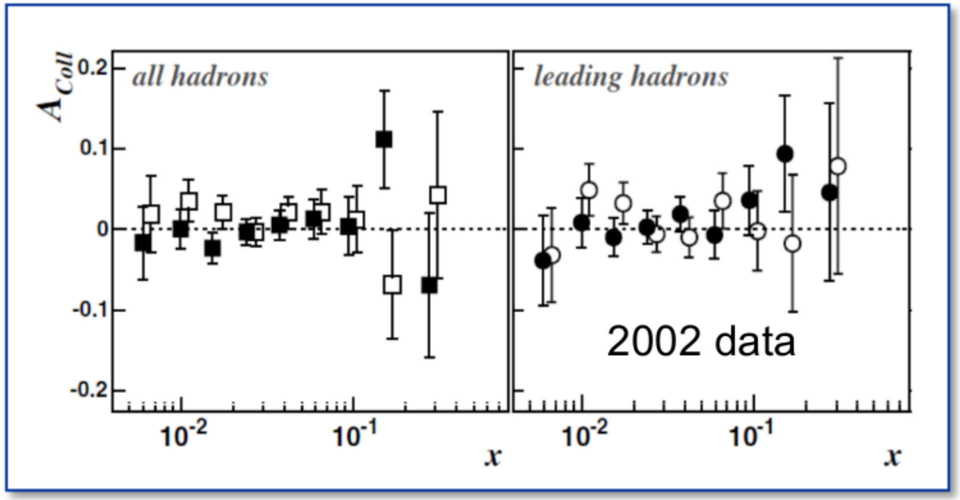
flavour separation:
proton and neutron (or deuteron) data are both essential

transverse spin asymmetries from 2002-2004 data

deuteron target

first results published in 2005

PRL 94, 202002 (2005)



compatible with zero

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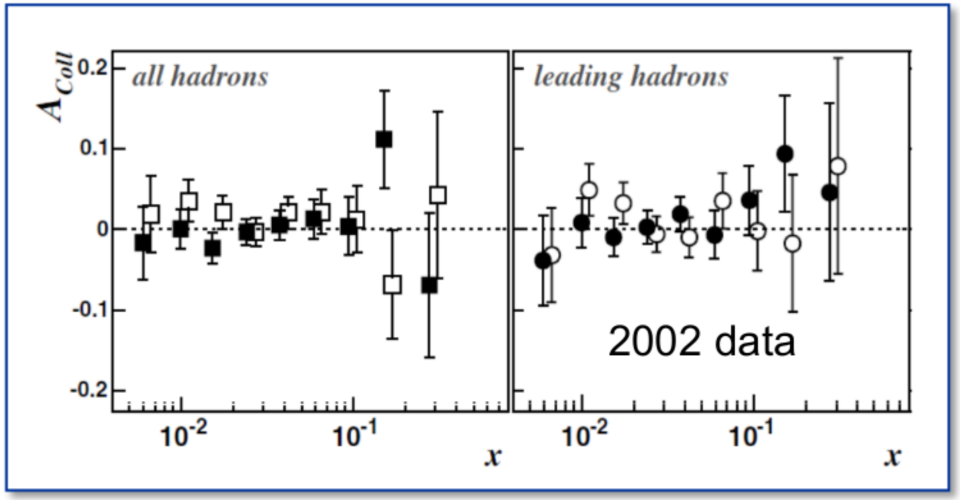
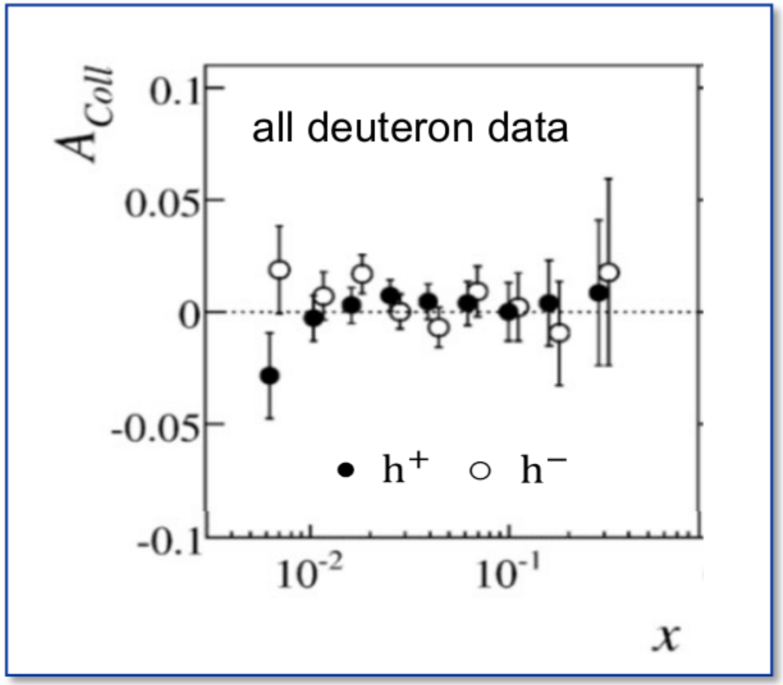


NPB765 (2007) 31



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HERMES, **proton** target

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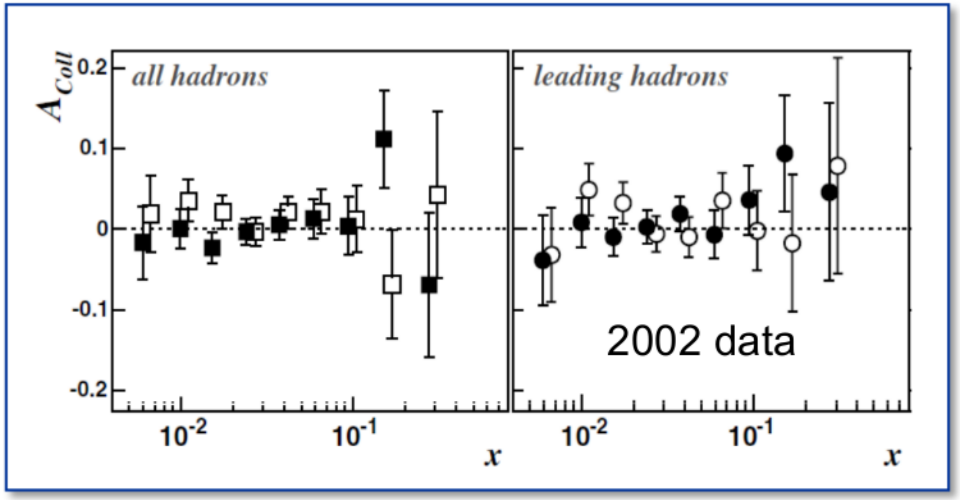
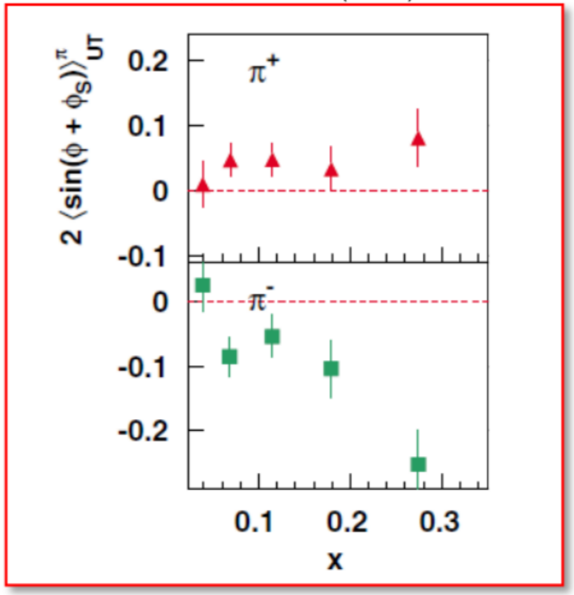


PRL 94, 012002 (2005)



compatible with zero
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clear signal

similar situation for the Sivers asymmetry

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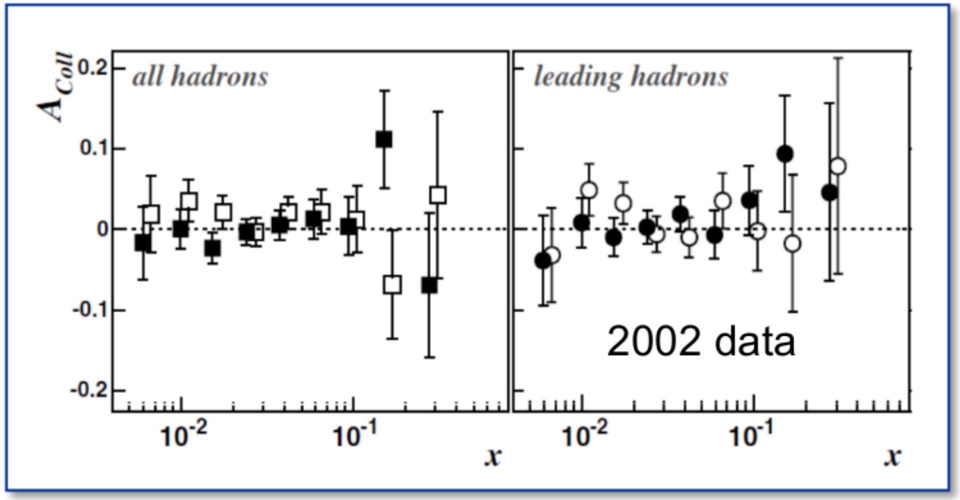

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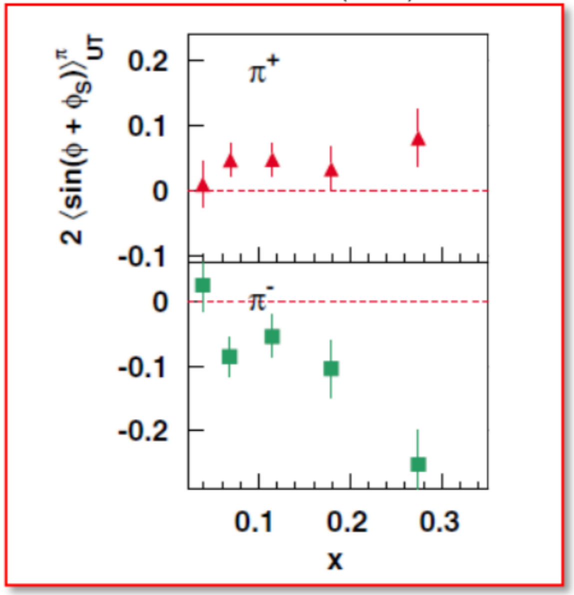

compatible with zero
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similar situation for the Sivers asymmetry

the COMPASS results were interpreted ad
cancellation between u- and d-quark contributions

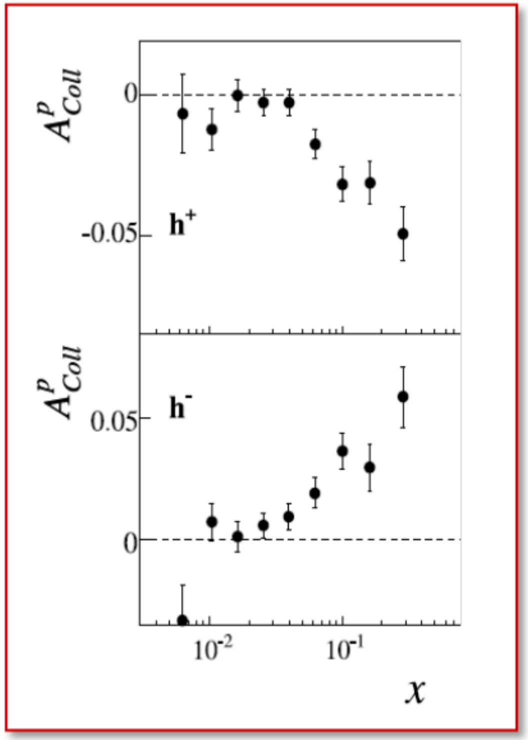
the different beam energy (160 vs 27.5 GeV/c) could also have a role

transverse spin asymmetries from 2007 and 2010 data

proton target
first results published in 2010 and 2012

Collins

2010 data PLB 717 (2012) 376



very clear signal in the valence region
opposite sign for h^+ and h^-, mirror symmetry vs x

in very good agreement with the HERMES results

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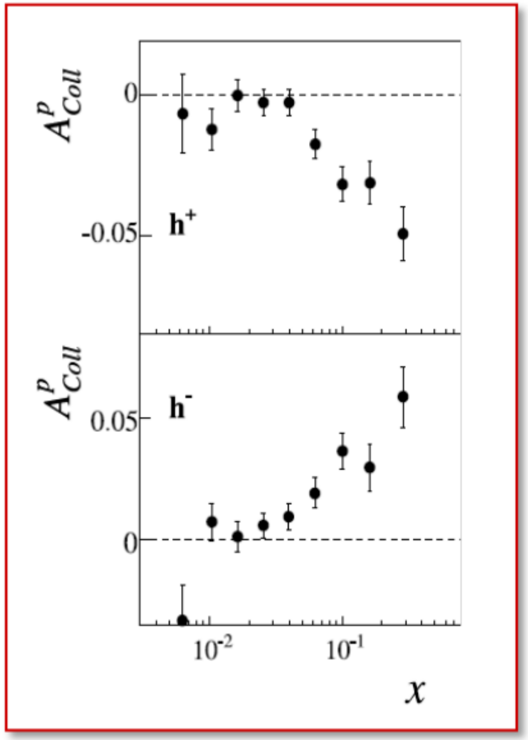
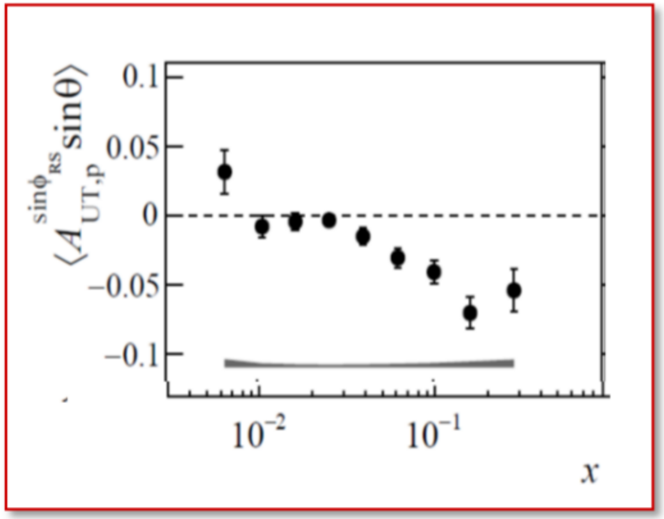
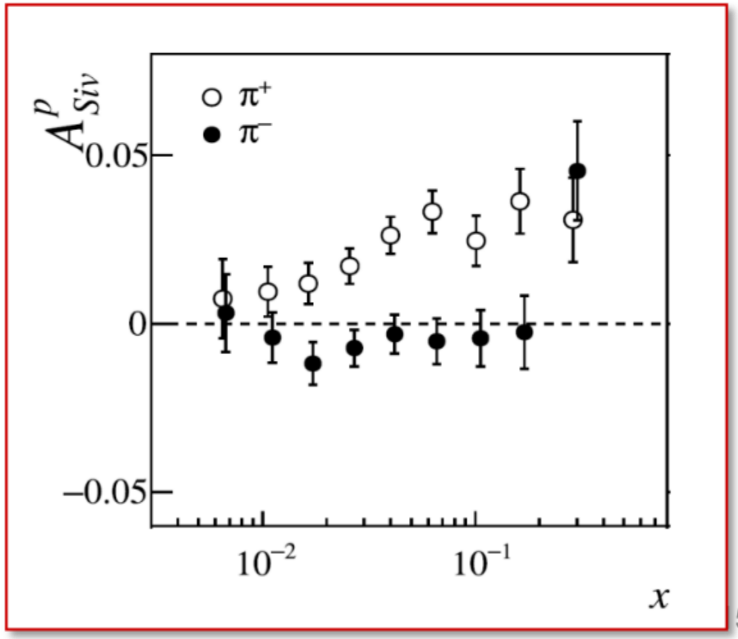




di-hadron

Sivers



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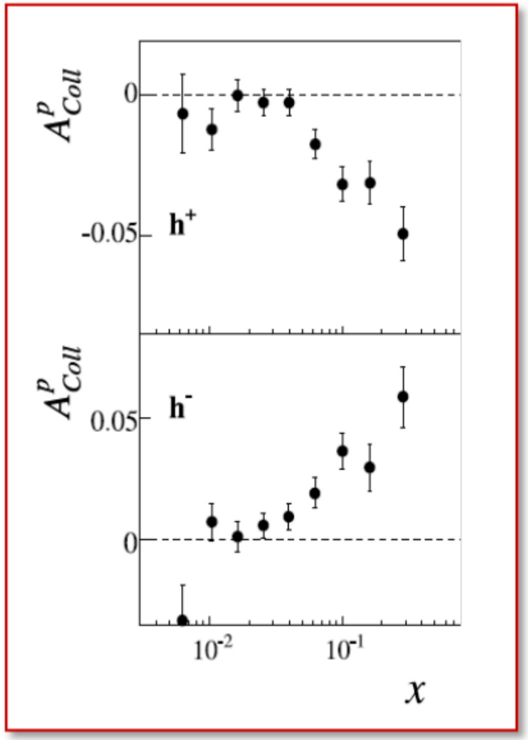

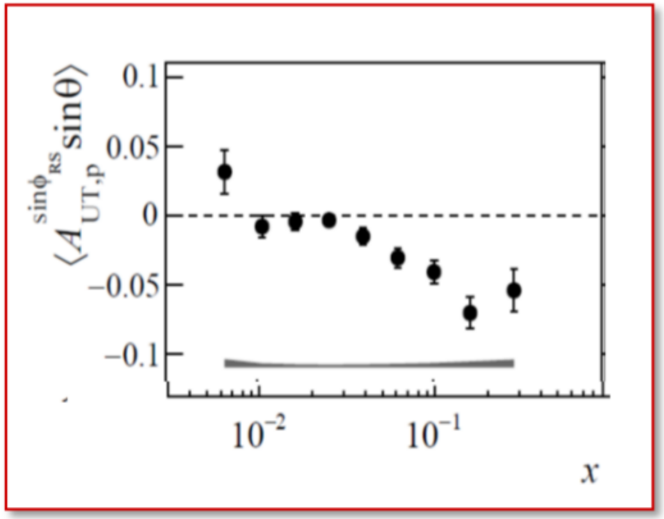

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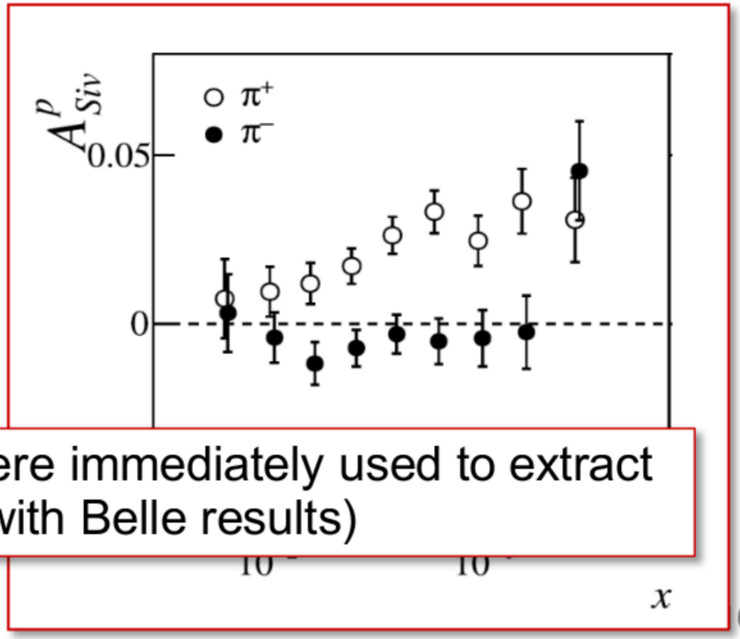
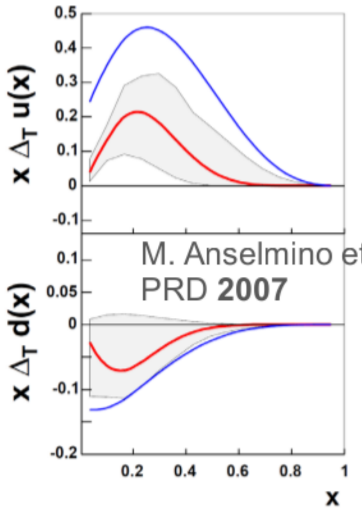
Sivers

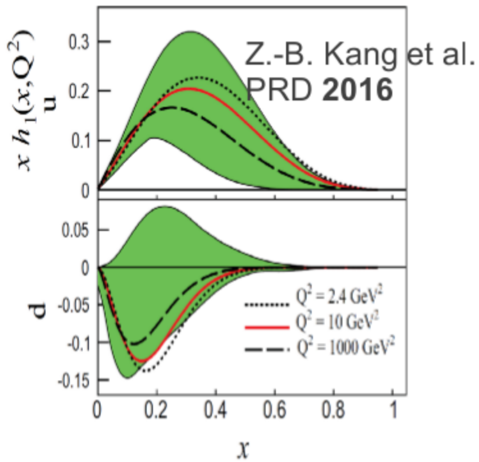


very clear signal in the valence region

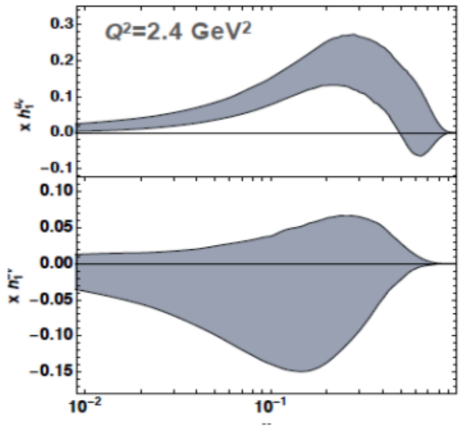
the HERMES p and the COMPASS p and d data were immediately used to extract the Sivers function and transversity (with Belle results)

accessing transversity



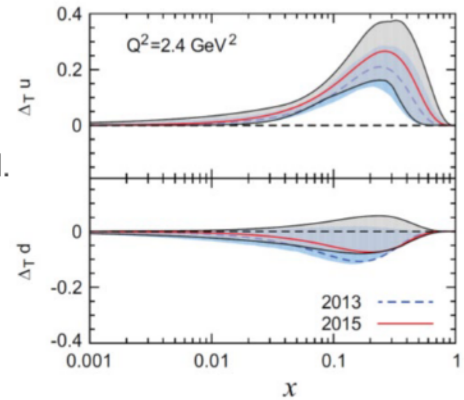


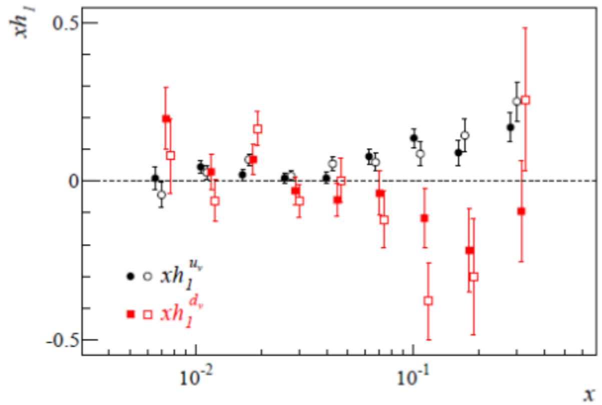
M. Radici A.Bacchetta
PRL **2018**



SIDIS and
e^+e^- data
only

M. Anselmino et al.
PRD 2015

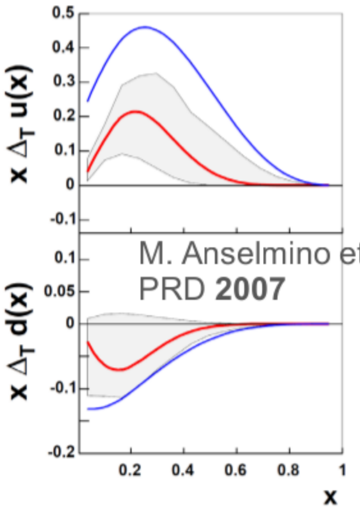


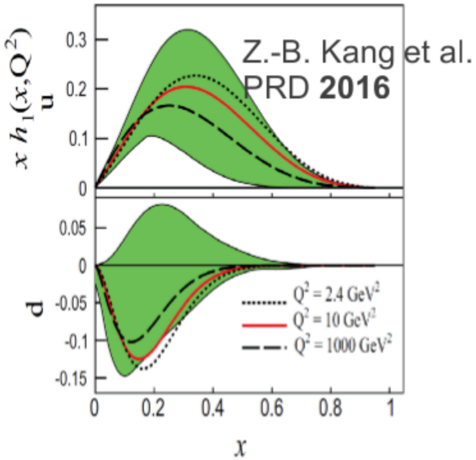


A.M., V. B. F.B
PRD 2015

- u-quark transversity is different from zero
- indication that u- and d-quark transversity PDFs have opposite sign

accessing transversity





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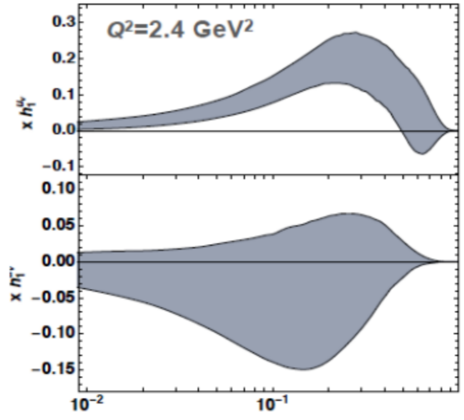

SIDIS and
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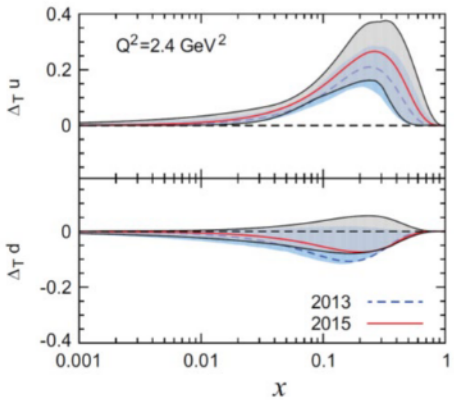
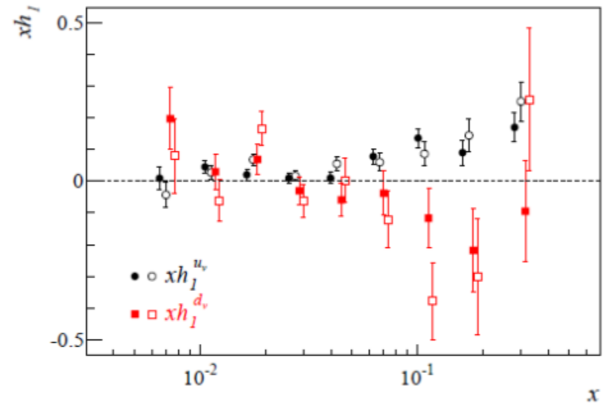




A.M., V. B. F.B
PRD 2015

- u-quark transversity is different from zero
- indication that u- and d-quark transversity PDFs have opposite sign
- d-quark transversity much worse determined than u-quark transversity because of the scarcity of deuteron (neutron) data:
  all the HERMES data and most of the COMPASS data were collected with p target

→ ***2022 COMPASS run***

the 2022 run

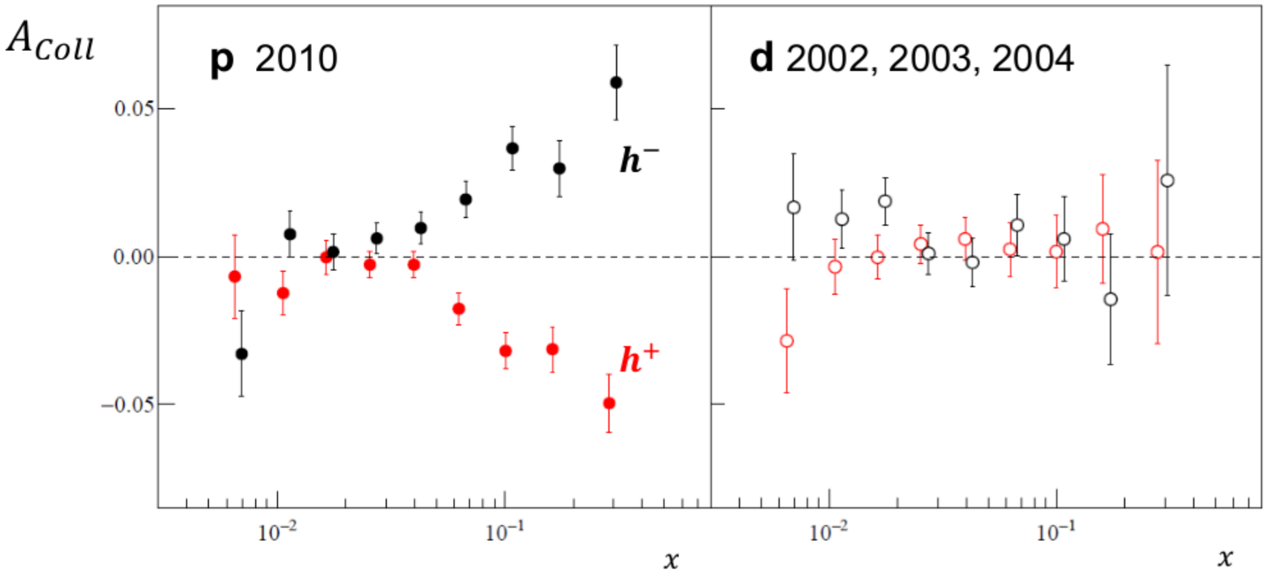
request to CERN (2017):

one year of data taking dedicated to SIDIS off transversely polarized deuteron (^{6}LiD) in the same conditions of the 2010 proton run

CERN-SPSC-2017-034
SPSC-P-340-ADD-1

aim:

balance the proton and deuteron statistics to improve, in particular, the knowledge of the d-quark transversity and of the tensor charge, in a unique $x - Q^2$ range, complementary to that of the future JLab experiments



the 2022 run

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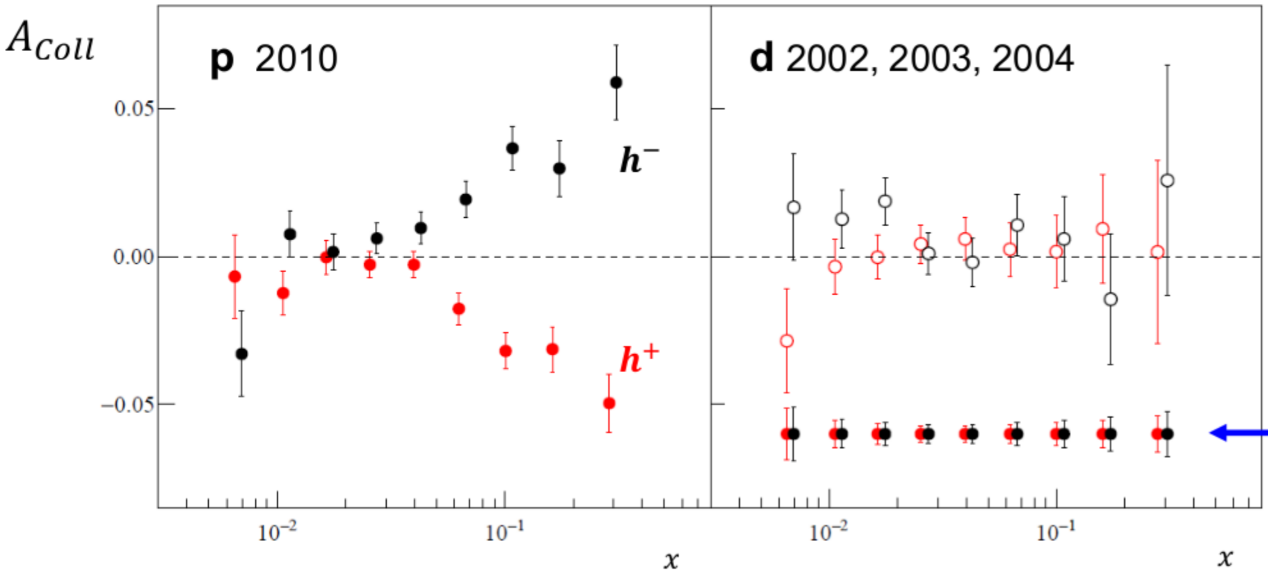
in a unique $x - Q^2$ range, complementary to that of the future JLab experiments

expected statistical uncertainties $\boldsymbol{\sigma^d_{2022} \simeq 0.6 \cdot \sigma^p_{2010}}$ **for all the TSAs**

impact on the Collins asymmetry



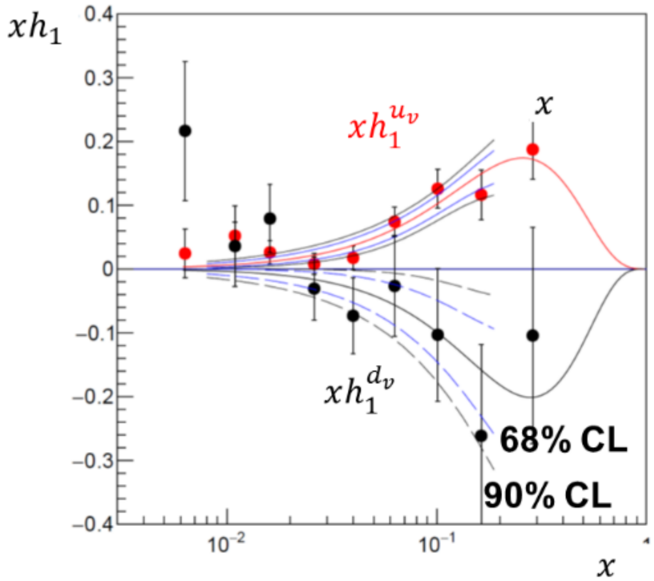
expected 2022 uncertainties

the 2022 run

expected impact on **transversity**

quantified using the point-by-point extraction from SIDIS and e^+e^- data and replicas   A.M., V. B. F.B PRD 2015

present: all p and d data



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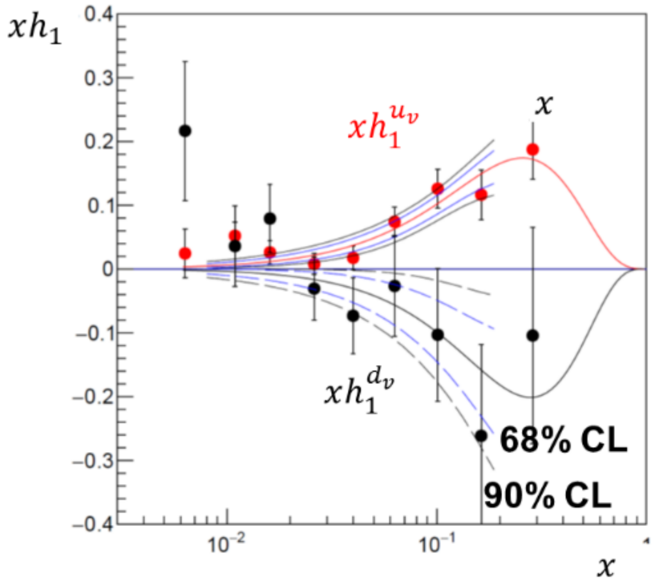
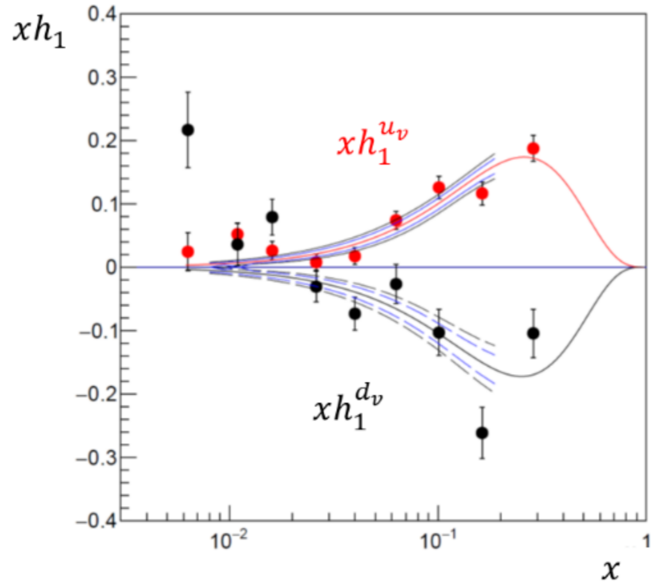


projected: all p and 2022 d data



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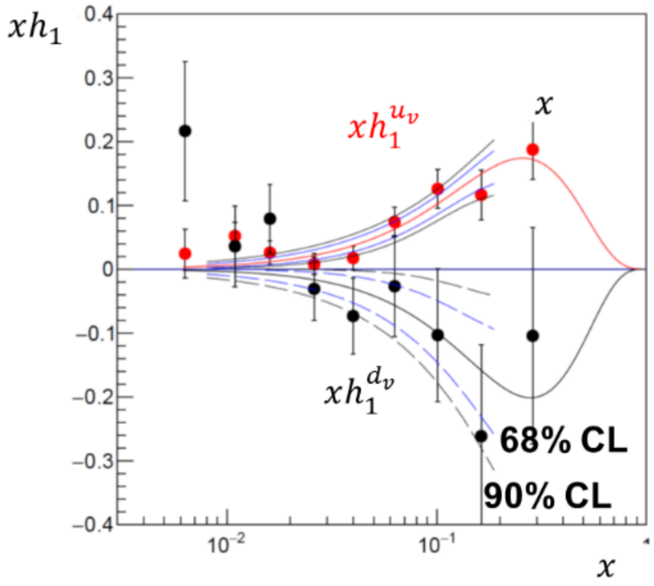

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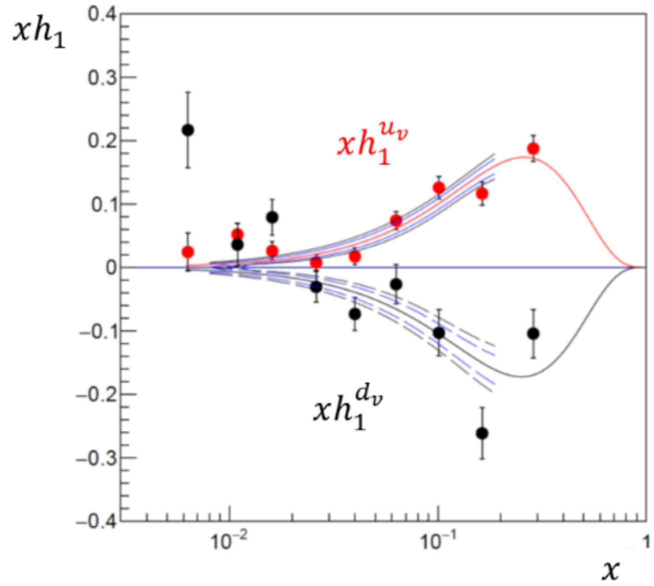

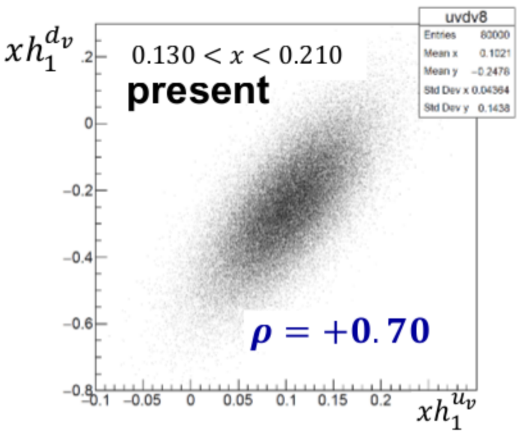

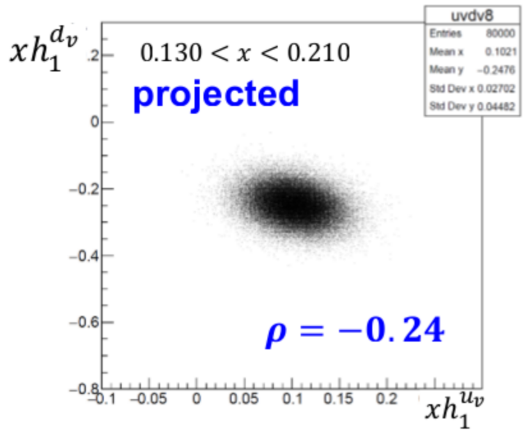

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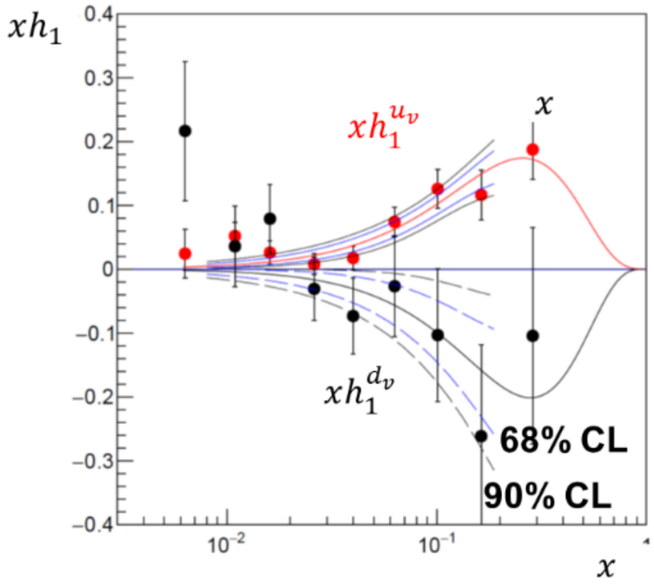

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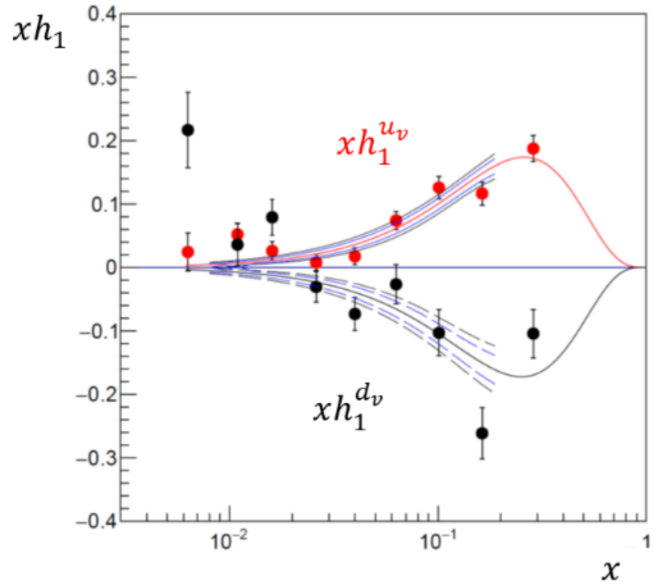


and on the **tensor charge**

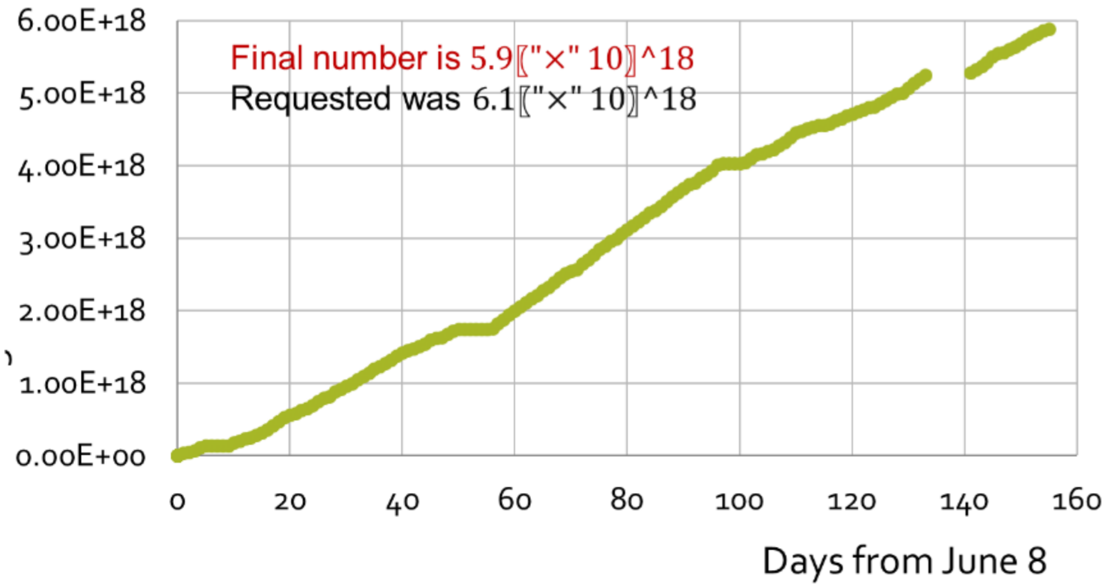
$\Omega_x: 0.008 \div 0.210$

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

the 2022 run

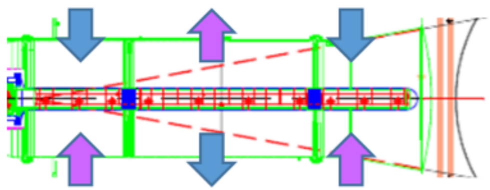
we took data from June 8 to November 9, 2022, with some short break

integrated number of protons delivered on the muon production target



in total 10 data taking periods,

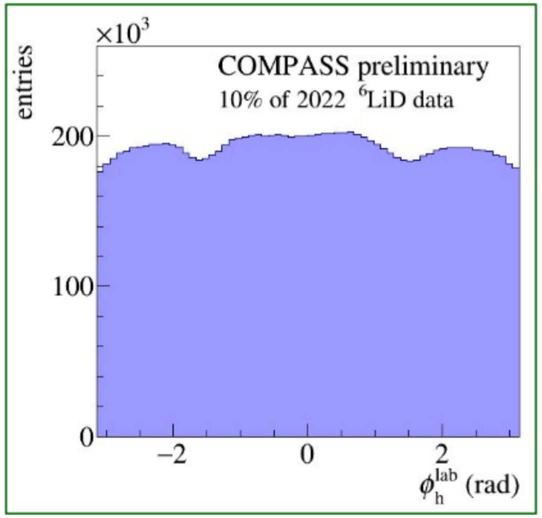
each divided in 2 sub periods
with opposite polarization in the target cells
to minimize possible systematic effects

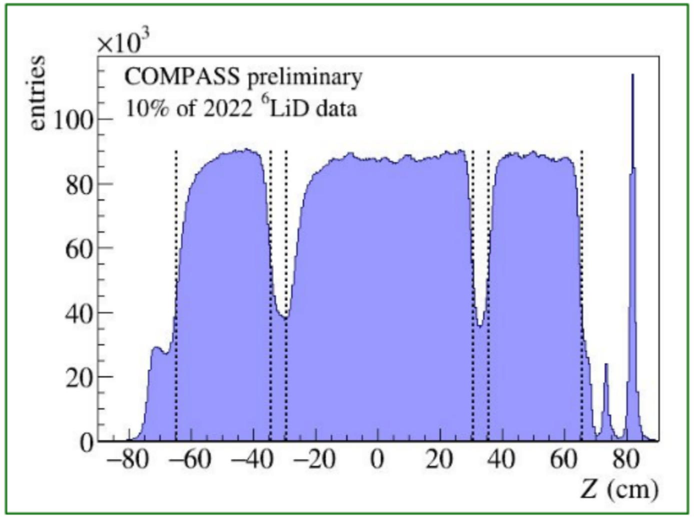


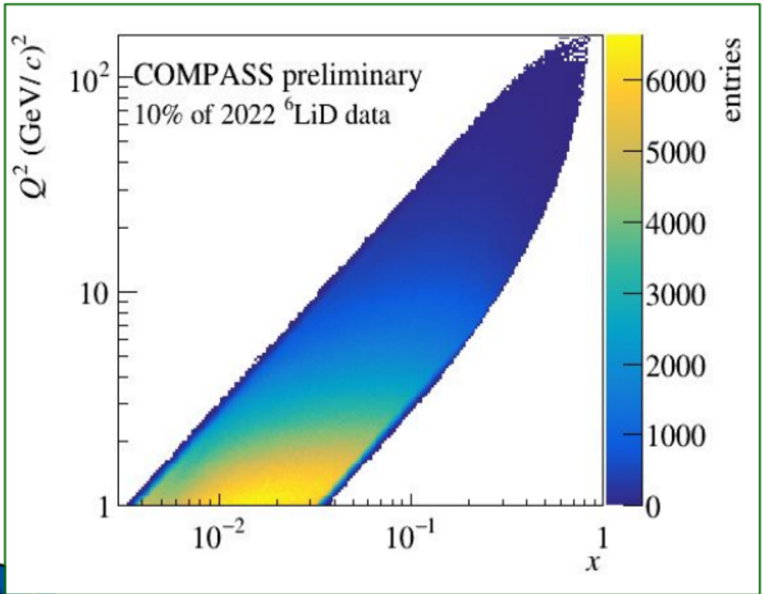
data analysis started during data taking, and is going on as expected

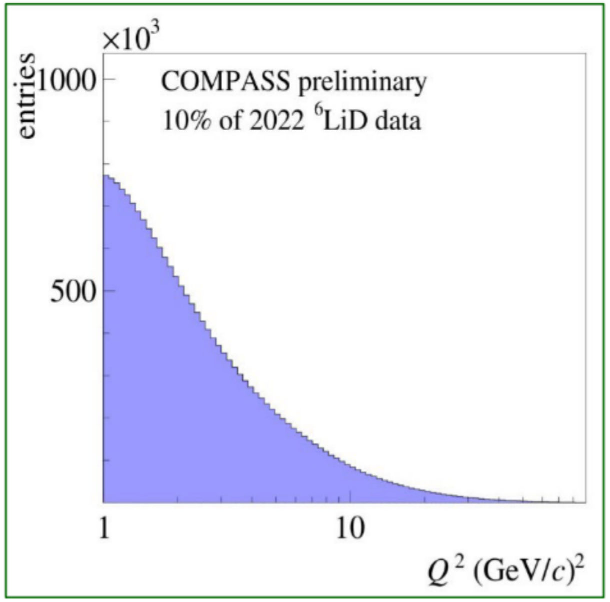
the 2022 run

some distribution









the 2022 run

the processing of all the collected data has been completed
the data quality tests have been performed

in June 2023 (IWHSS2023) we could give
solid estimate of the final statistical uncertainties
which are in agreement with the expectations of the proposal

a very successful run,
these data will allow us to performed on d target all the measurements done on p target, and more
… in the future

d & p	Collins and Sivers asymmetries (1D)	several papers
d & p	di-hadron asymmetries (1D)	several papers
d & p	other TSAs (1D)	conf
p	multiD measurements of TSAs (x, Q^2, z, P_T) $bins$	conf
p	interplay 1h -2h asymmetries	PLB 753 (2016) 406
p	Sivers (et al) asymmetry in Q^2 bins	PLB 770 (2017) 138
p	P_T - weighted Sivers asymmetries	NPB 940 (2019) 34
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today, the very new results for the
Collins and Sivers asymmetries
for charged hadrons from ~50% of the data collected in 2022

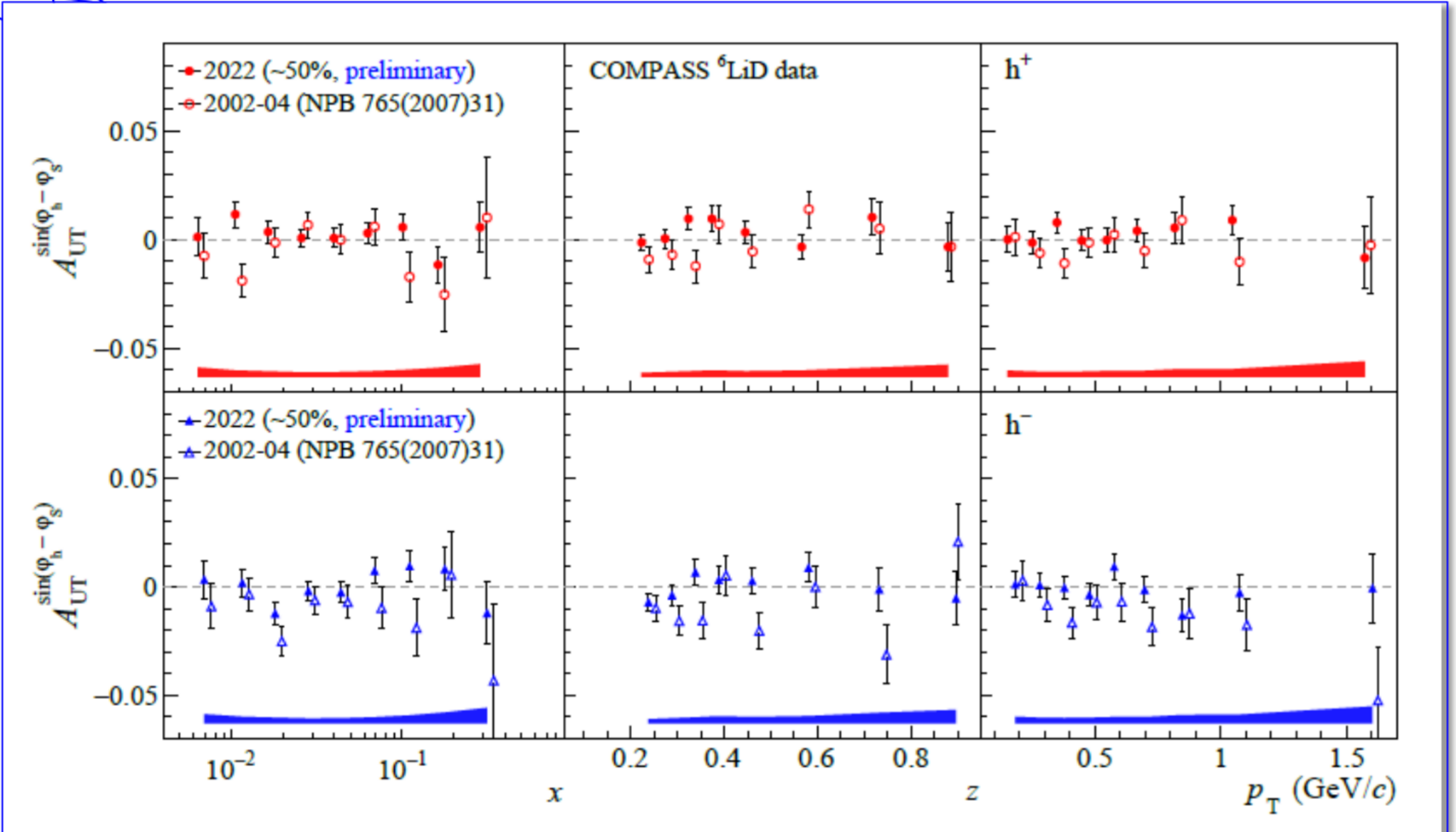
results - Sivers asymmetry

~50% of the data collected in 2022
SIDIS of 160 GeV μ^+ off **deuteron**

NEW

$Q^2 > 1\ (\mathrm{GeV}/c)^2$
$W^2 > 25\ (\mathrm{GeV}/c^2)^2$
$0.1 < y < 0.9$

$z > 0.2$
$p_T > 0.1\ \mathrm{GeV}/c$



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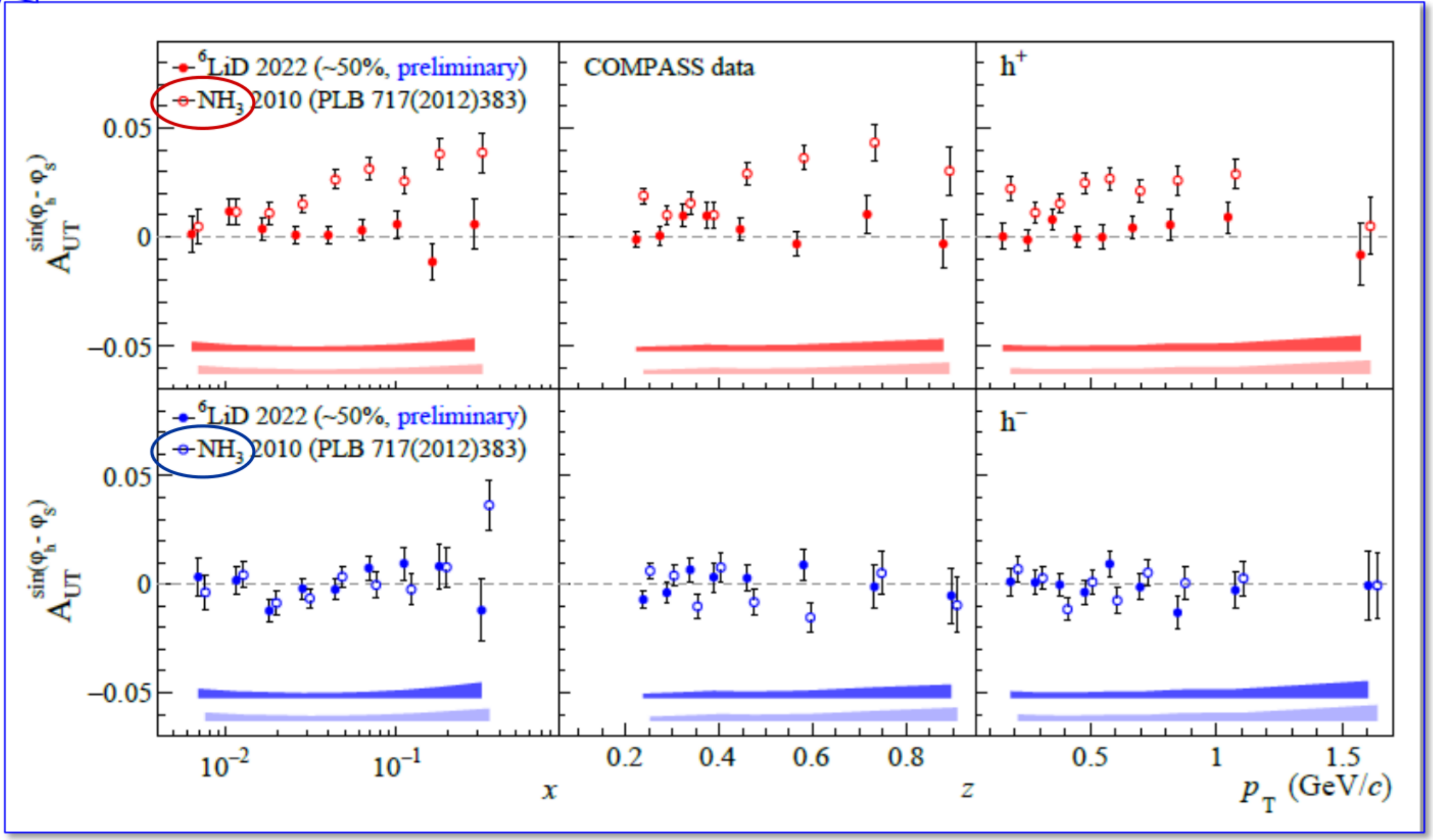

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$Q^2 > 1\ (\mathrm{GeV}/c)^2$
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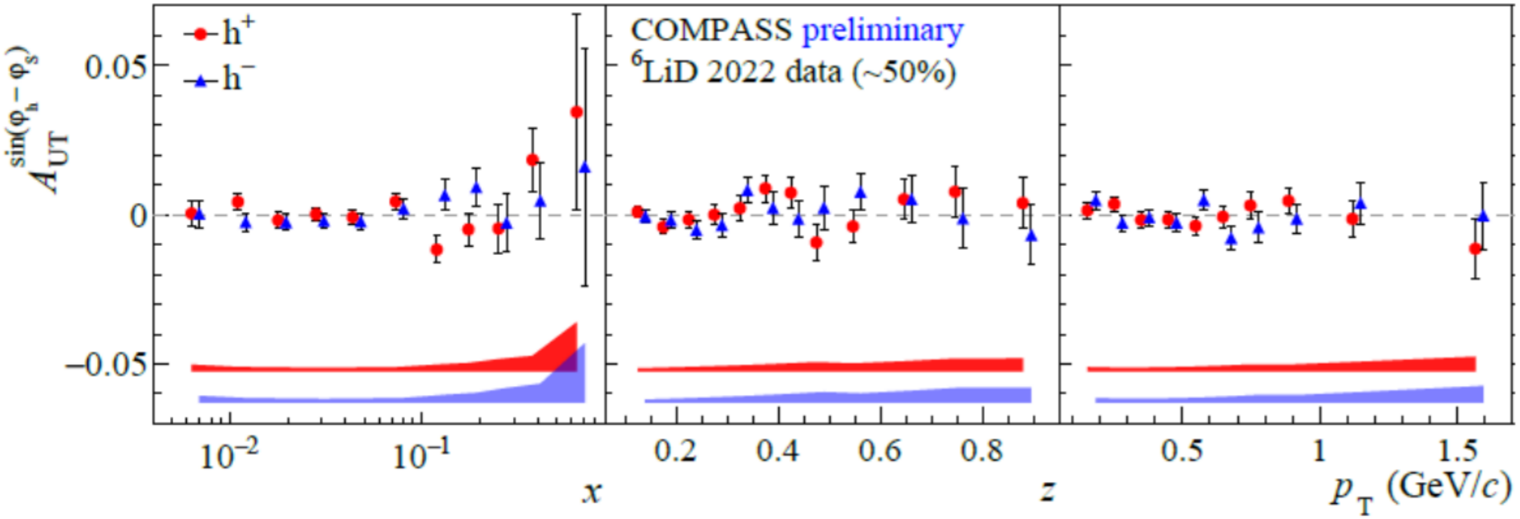

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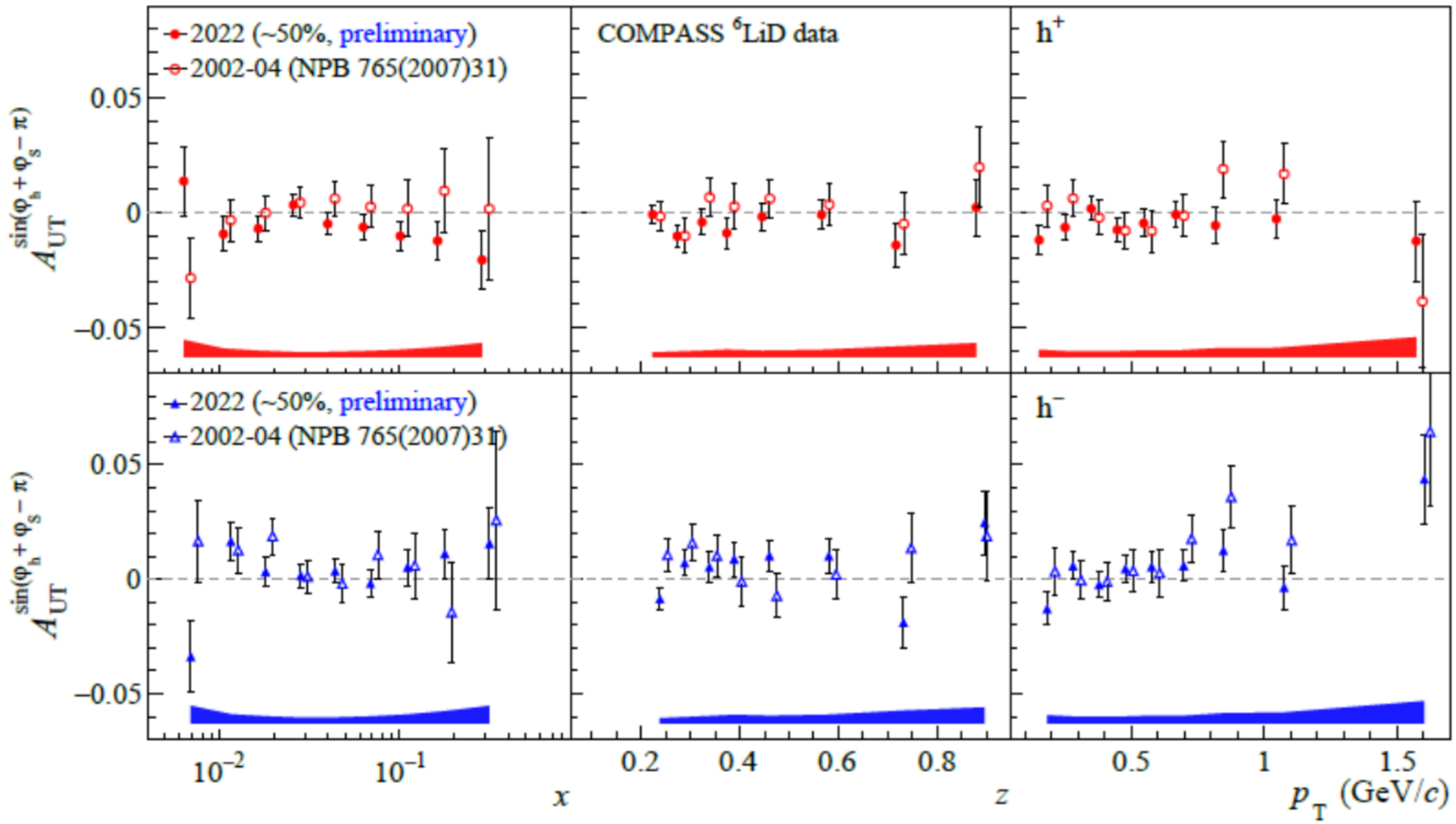

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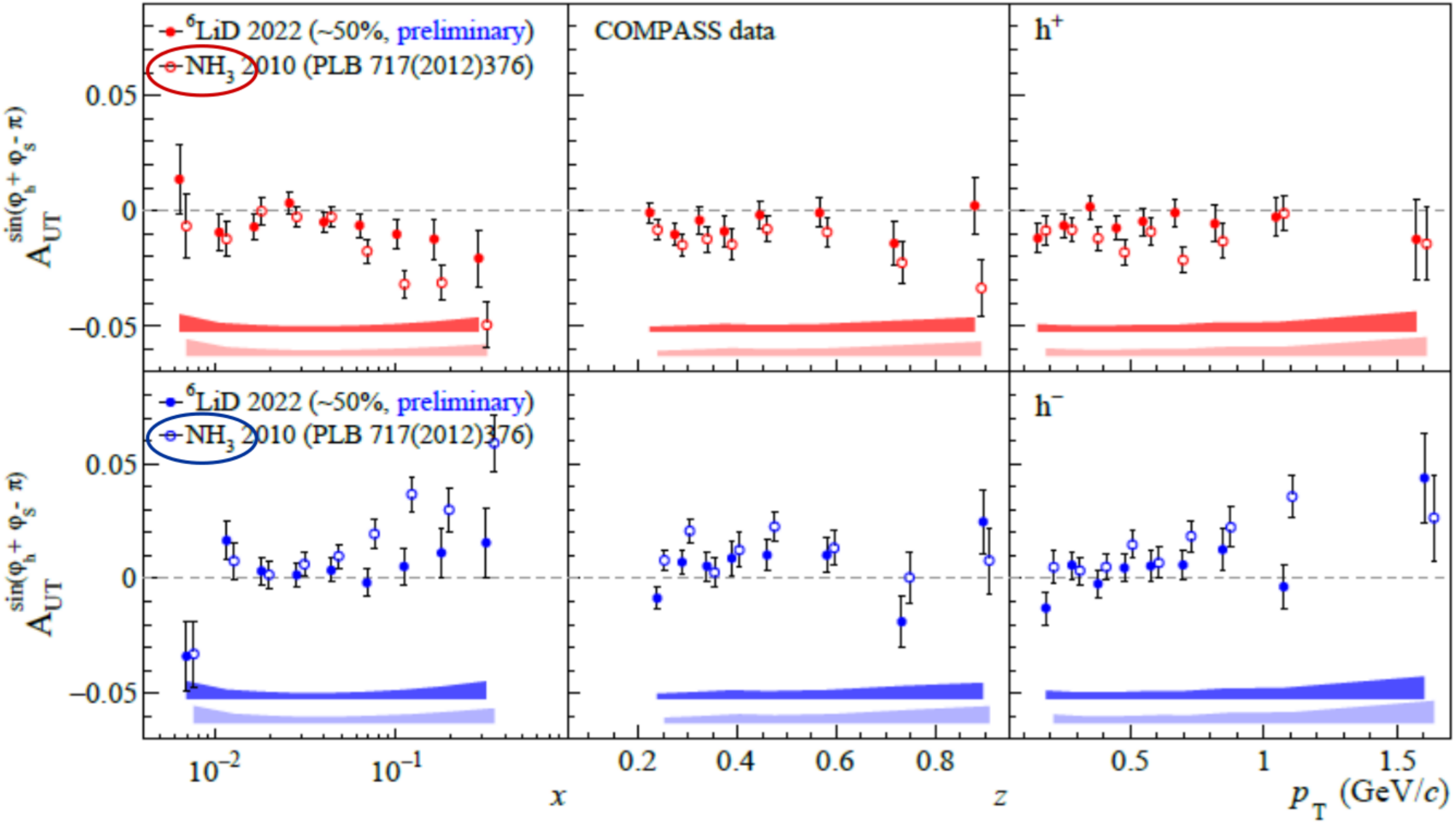

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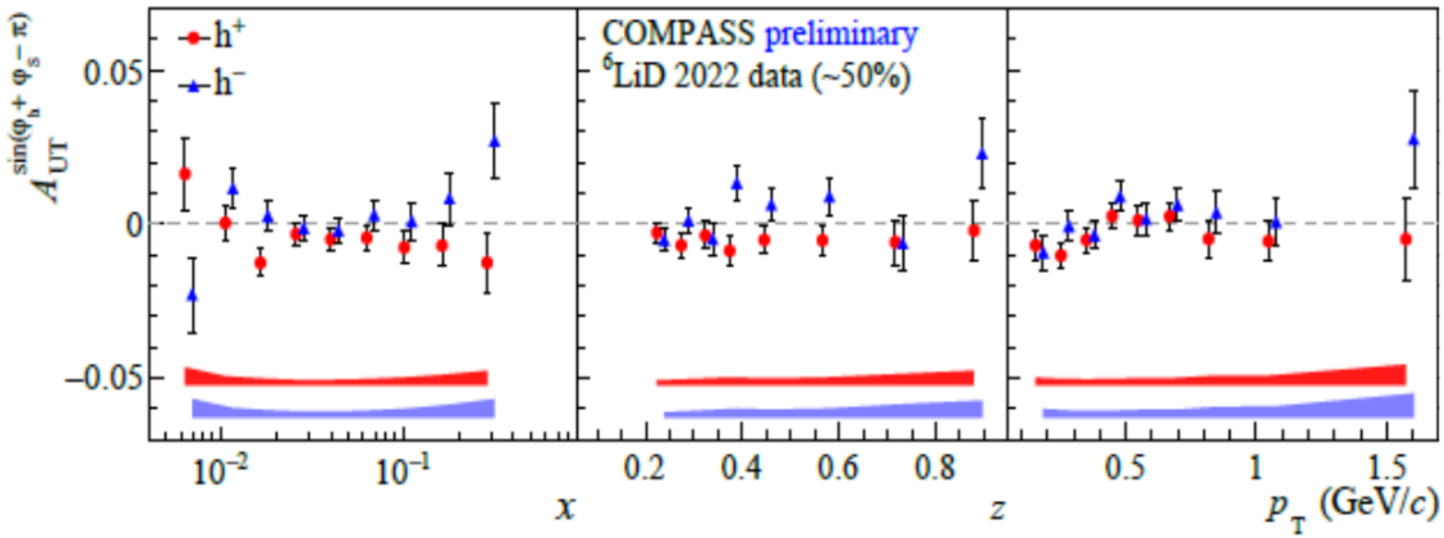

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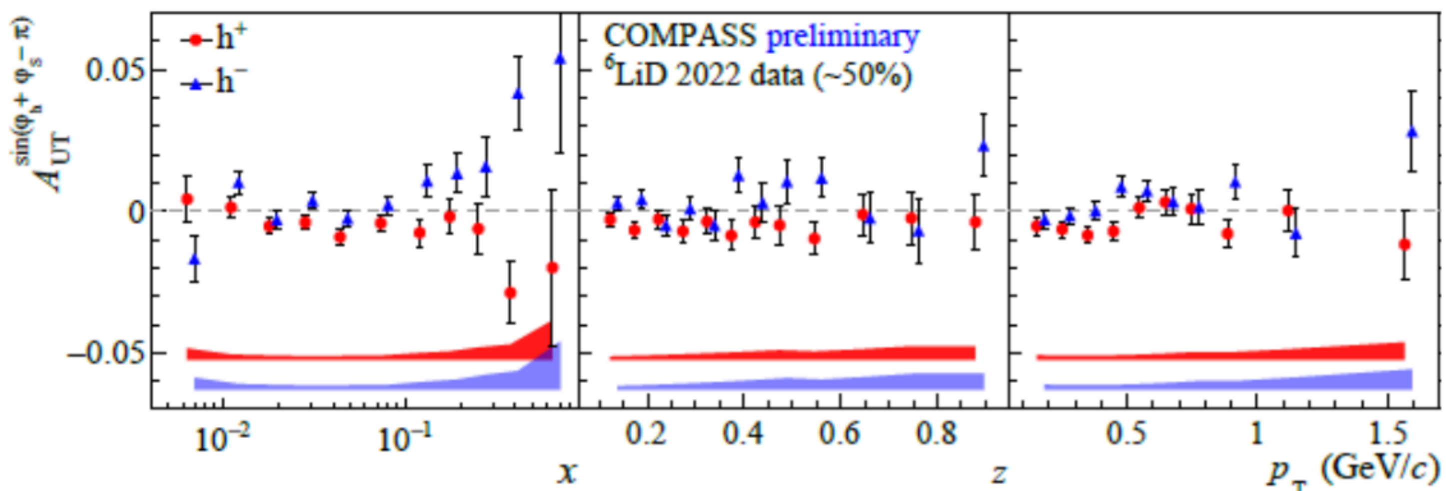

summary

in the last 20 years
COMPASS has performed many relevant SIDIS measurements with transversely polarized targets

the 2022 run with the transversely polarized deuteron target has been successful, and a lot of new results will come

they will stay unique for several years

first results shown here for the first time:

Collins and Sivers asymmetries for charged hadrons

- much higher precision than the previous COMPASS data
- an important step forward to constrain the extraction of the transversity function, the tensor charge, and of the Sivers function

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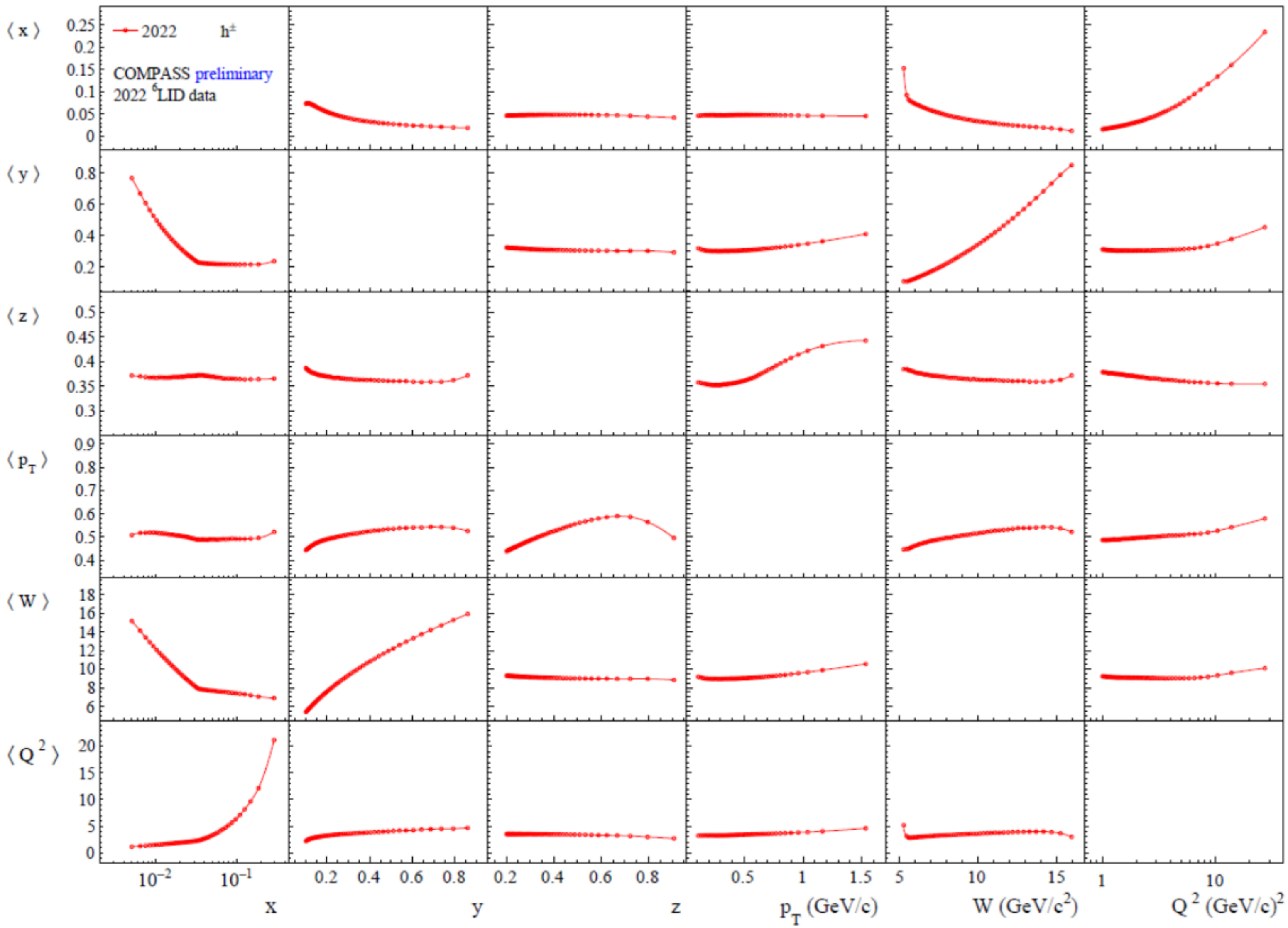
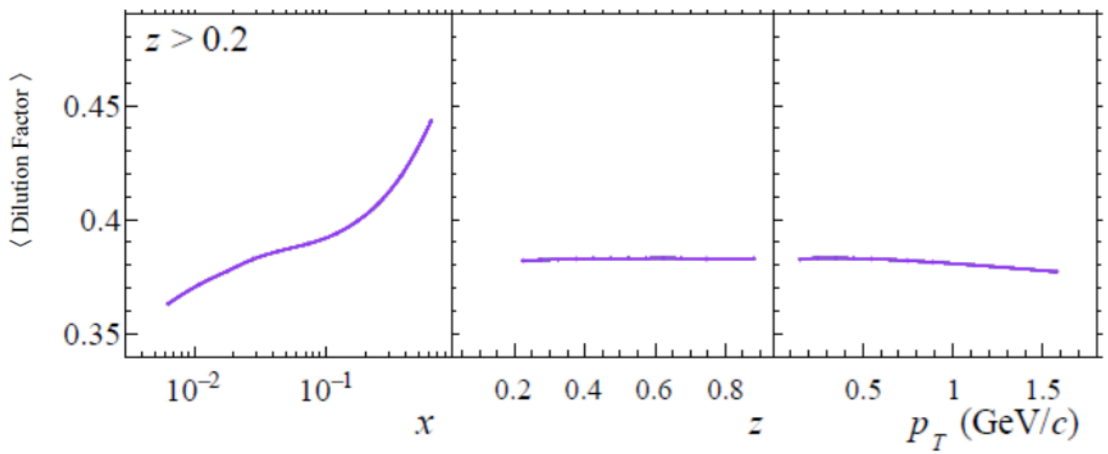
thank you !


2022
h±
COMPASS preliminary
2022 6LiD data
⟨x⟩
⟨y⟩
⟨z⟩
⟨pT⟩
⟨W⟩
⟨Q2⟩
x
y
z
pT (GeV/c)
W (GeV/c2)
Q2 (GeV/c)2



z > 0.2
⟨ Dilution Factor ⟩
0.45
0.4
0.35
10^−2
10^−1
x
0.2
0.4
0.6
0.8
z
0.5
1
1.5
p_T (GeV/c)