COMPASS contribution to the study of the three-dimensional structure of the nucleon in SIDIS

Anna Martin
Trieste University and INFN
on behalf of the COMPASS Collaboration

BOLOGNA, ITALY
33rd INTERNATIONAL WORKSHOP ON **DEEP INELASTIC SCATTERING AND RELATED SUBJECTS**

COMPASS

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

fixed target experiment at the CERN SPS

PROPOSAL	**March ’96**
APPROVED	**February ’97**
TAKING DATA	**2002-2022**
ANALYSIS PHASE	**2023-…**

The Physics Programme

SPECTROSCOPY
many results

NUCLEON STRUCTURE
muon beam, L and T polarised ^{6}LiD targets
open charm, SIDIS 2002-2004, 2006, 2022
muon beam, L and T polarised NH_3 targets
SIDIS 2007, 2010, 2011
muon beam, LH target
DVCS - HEVMP, SIDIS 2016, 2017
pion beam, T polarised NH_3 target
Drell-Yan 2015, 2018

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Drell-Yan 2015, 2018

GPDs, today:
Po-Ju Lin
Gursimran Kainth
Kamil Augsten

study of the
transverse spin and transverse momentum structure of the nucleon
in SIDIS with transversely polarised and unpolarised targets

not included: TMD effects in SIDIS off L polarised targets

The Spectrometer – SIDIS with polarised targets

two stages spectrometer

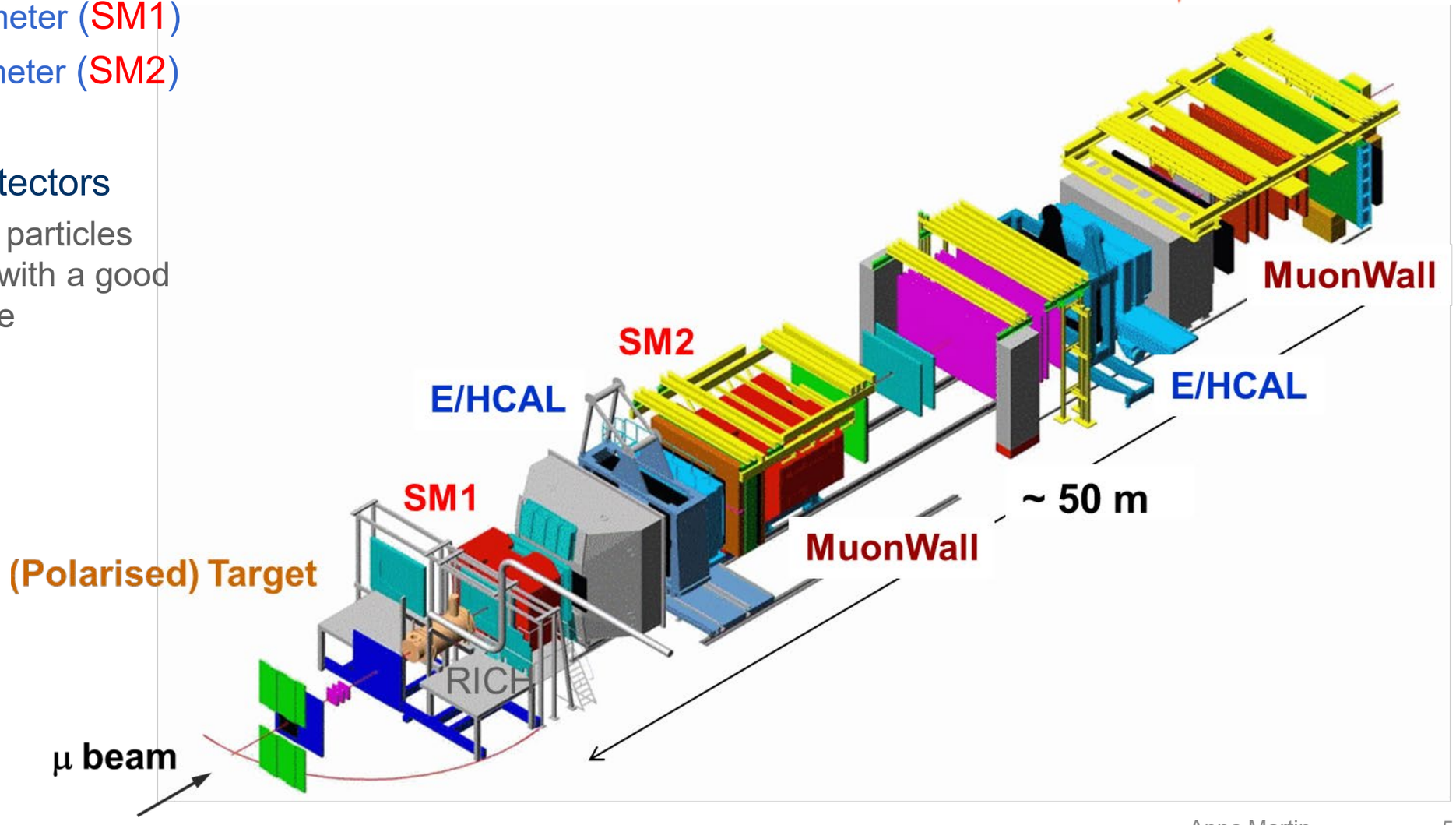
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

variety of tracking detectors

to measure outgoing particles from 0 to ~200 mrad with a good azimuthal acceptance

calorimetry, μID

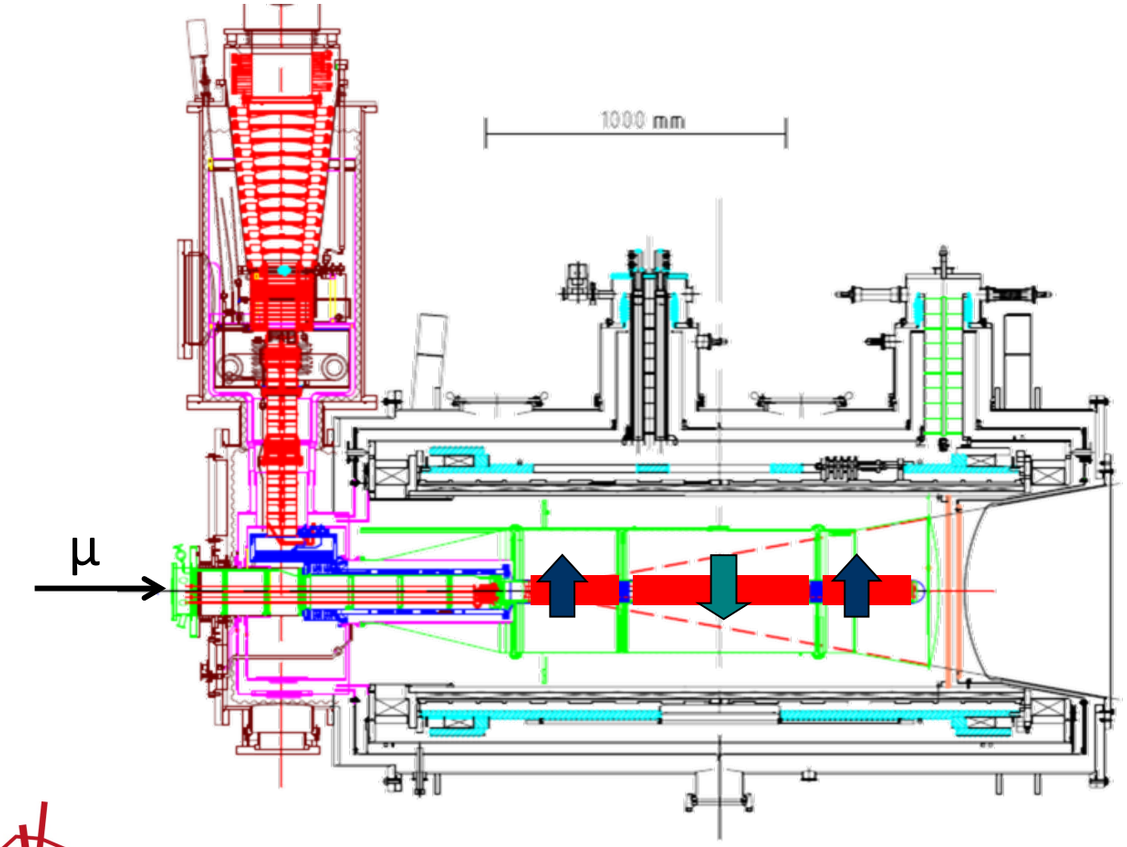
RICH detector



The Polarised Target System – SIDIS >2005

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

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long
opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarisation	40-50%	90%
dilution factor	40%	16%

the structure of the nucleon

today it is well known that

taking into account the parton intrinsic transverse momentum k_T, at leading order

8 TMD PDFs are needed for a full description of the nucleon structure

correlations among parton transverse momentum, parton spin and nucleon spin

nucleon polarisation

quark polarisation	U	L	T
U	f_1		$f_{1T}^{\perp}$ Sivers
L		g_1	g_{1T} Kotzinian- Mulders
T	$h_1^{\perp}$ Boer - Mulders	$h_{1L}^{\perp}$ Transversity	h_1 $h_{1T}^{\perp}$ pretzelosity

all accessible in SIDIS

SIDIS cross section

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

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

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

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

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

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

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

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

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

several modulations In azimuthal angles
their amplitudes are convolutions of TMD PDFs and FFs

the measurement of the azimuthal asymmetries with unpolarised and longitudinally and transversely polarised targets give access to all the TMD PDFs

A. Bacchetta et al JHEP 02 (2007) 093

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

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

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several modulations In azimuthal angles
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$$A_{Siv}\sim\frac{\sum_q e_q^2\,\boldsymbol{f_{1T}^{\perp q}}\otimes D_{1q}}{\sum_q e_q^2\,f_1^q\otimes D_{1q}}$$

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

flavour separation:
identification of final state hadrons,
measurements with p and n (d) targets

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all accessible in SIDIS

when COMPASS was proposed the situation was different

- collinear f_1 and g_1: well known / established
- transversity PDF h_1: completely unknown – measurable?
- Sivers PDF $f_{1T}^{\perp}$: expected to vanish (until 2002)
- all other TMD PDFs: in progress…

the HELP proposal (1993, SIDIS with transversely polarised target at LEP) was rejected by CERN

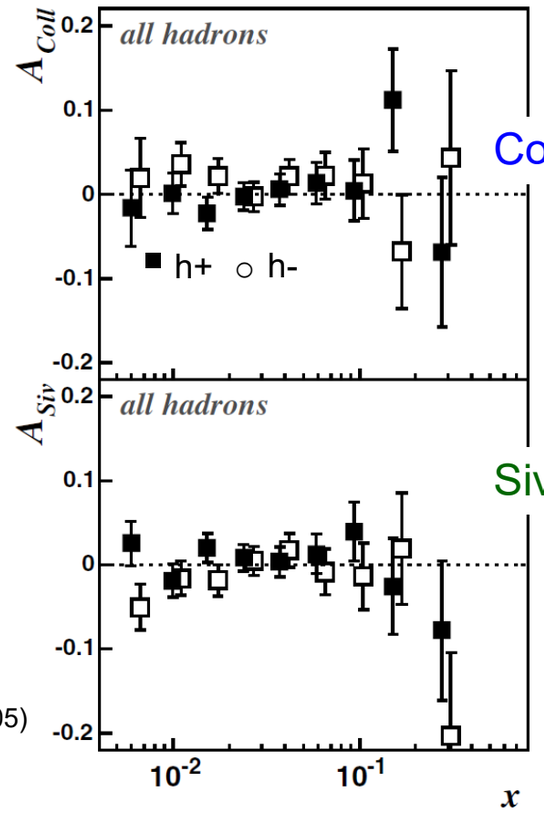
the HERMES experiment at DESY started data taking with a transversely polarised proton target in 2001

the COMPASS Collaboration decided to dedicate 20% of the running time with muon beam to SIDIS measurements with transversely polarised targets

the first deuteron data - 2002-2004

- the first data with a transversely polarised target in COMPASS were collected in 2002, using the deuteron target
- the first results for the Collins asymmetry and for the Sivers asymmetry were published in 2005

2002 data



Collins, d

Sivers, d

PRL 94, 202002 (2005)

compatible with zero,
with large statistical uncertainties

?

confirmed, with higher precision,
using the 2003-2004 data

fortunately, the zero signals did not imply zero PDFs,
but hinted at a cancellation between the u- and the d-quark contributions in deuteron

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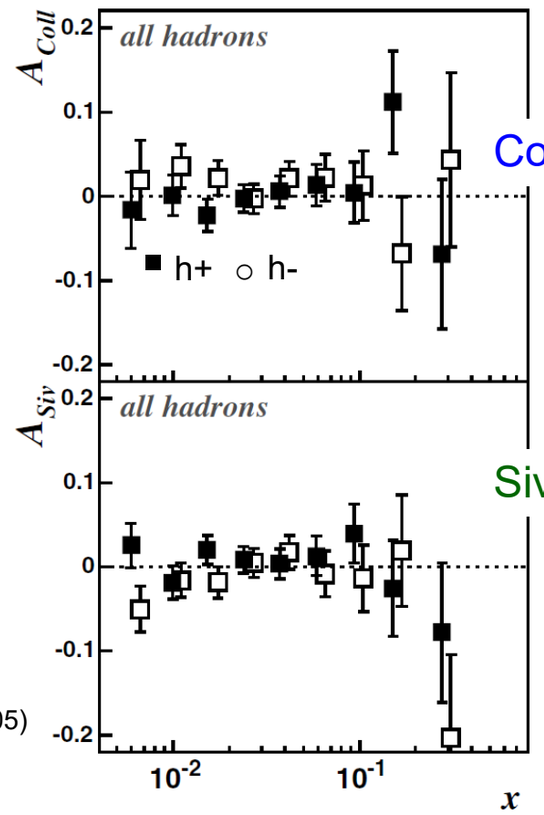
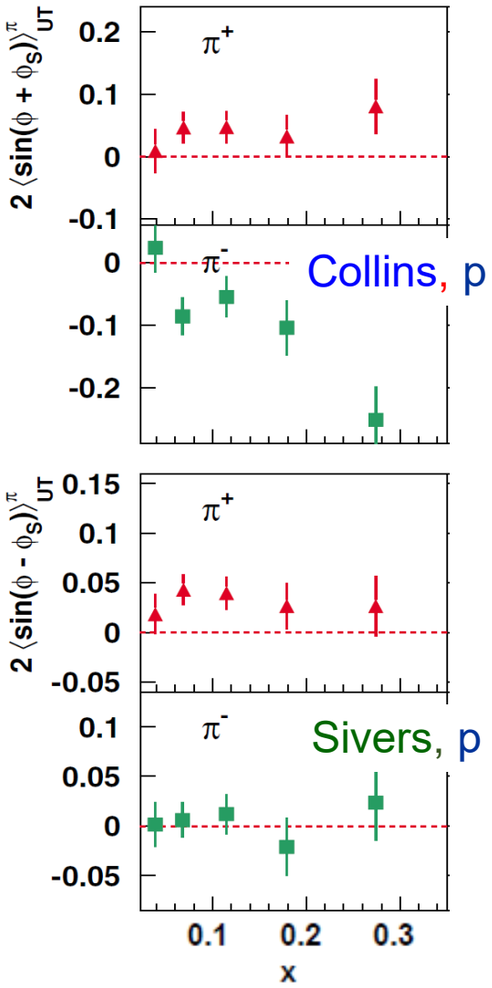


PRL 94, 202002 (2005)

in the mean time, HERMES measurements with a proton target

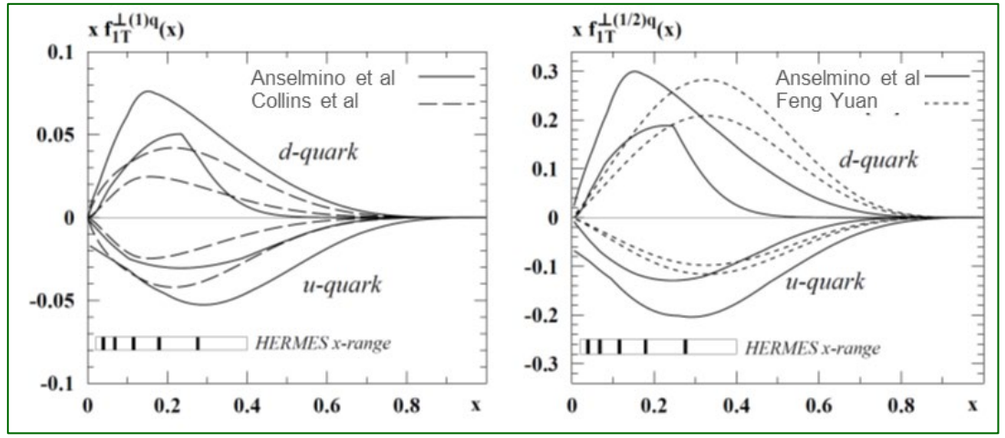
for the first time clear signals: real effects !



PRL. 94 (2005) 012002

first extractions of the new PDFs

- the first extractions of the **Sivers functions** from these p and d measurements came very soon
- the HERMES and COMPASS data could be well described with opposite sign of the u and d-quark functions



proceedings of Transversity 2005

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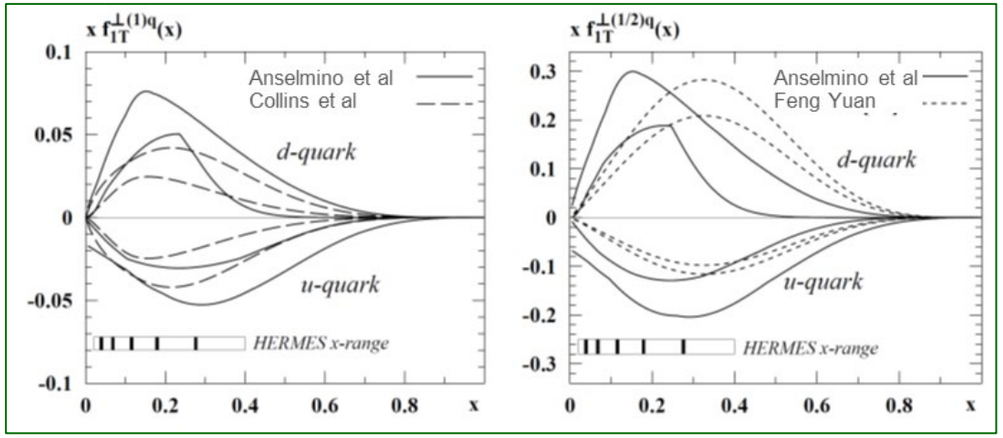
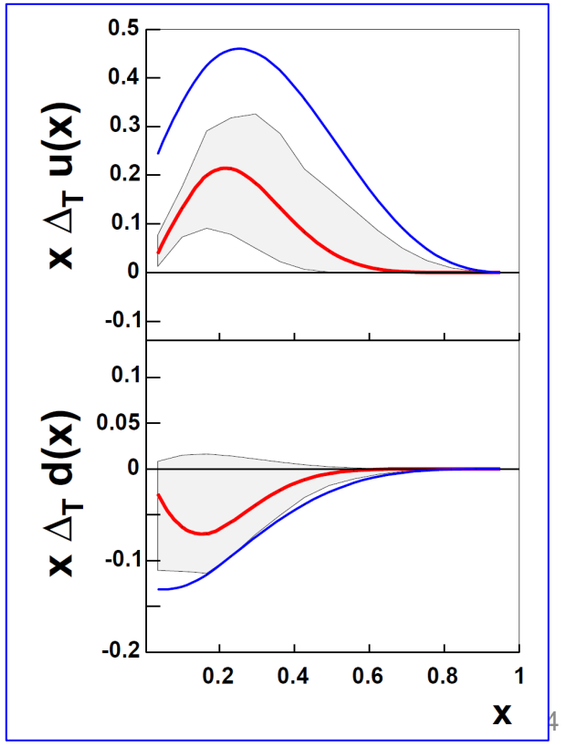


proceedings of Transversity 2005

- first measurements the Collins-like asymmetry in $e^+e^- \rightarrow hadrons$ at BELLE (2006)
  clear independent indication of non-zero Collins FF, the missing piece
- first extractions of the **transversity functions**

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

Anselmino et al PRD 2007



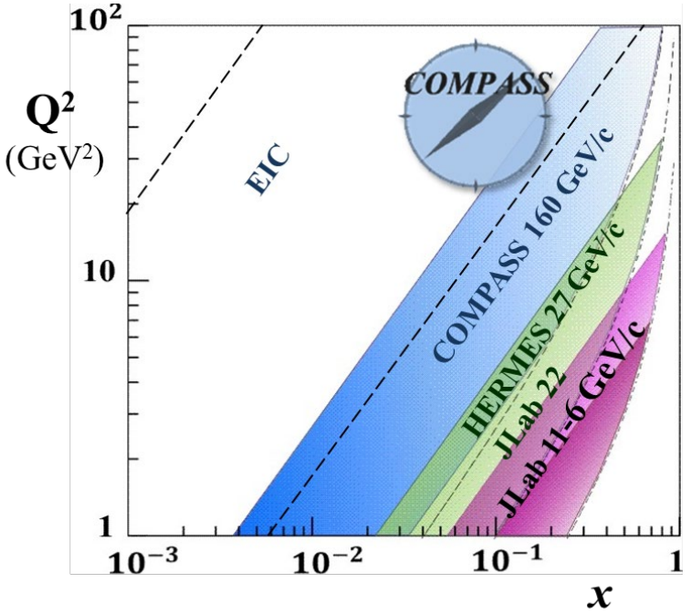
first extractions of the new PDFs

in 2005-2006 milestone measurements
clear signals that the new TMD PDFs and FFs are different from zero

still, more data were needed !

- HERMES had no deuteron data
- COMPASS had no proton data

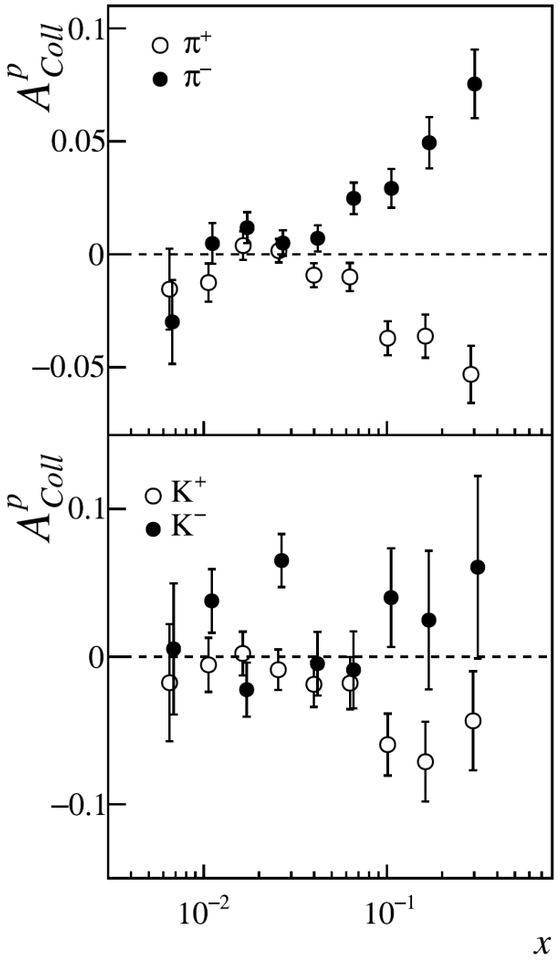
and the different beam energy (160 vs 27.5 GeV) could also have a role



2007: first COMPASS data taking with proton target, half a (SPS) year
limited statistics and precision
2010: a whole year of data taking with proton target

the proton data - 2007, 2010

Collins asymmetries: the signals are there!



PLB 744 (2015) 250
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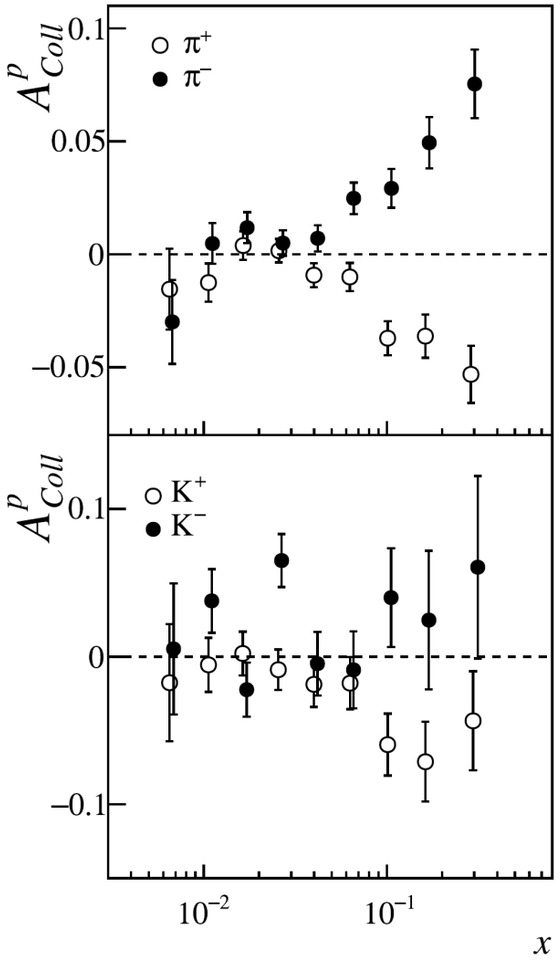

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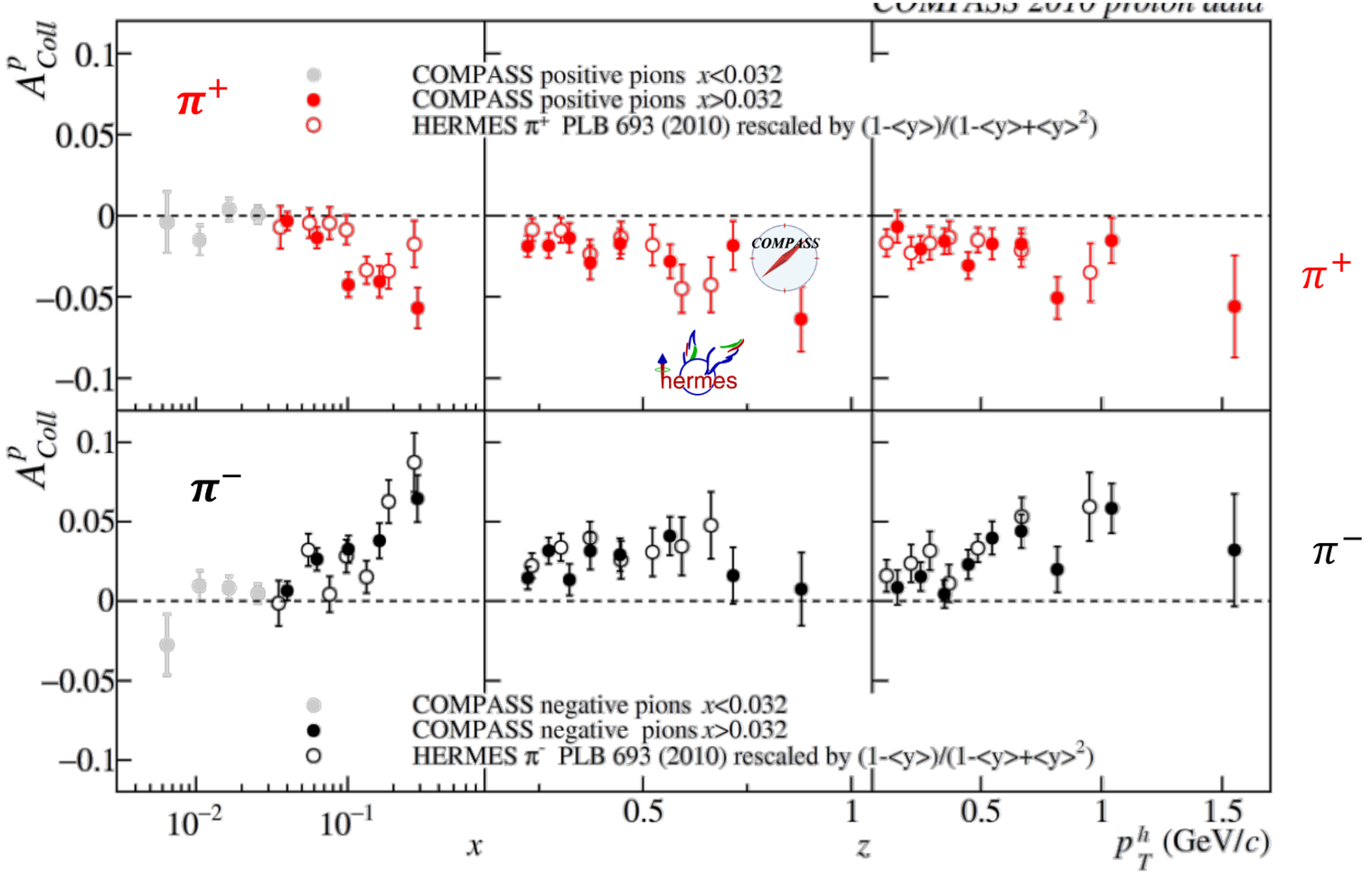
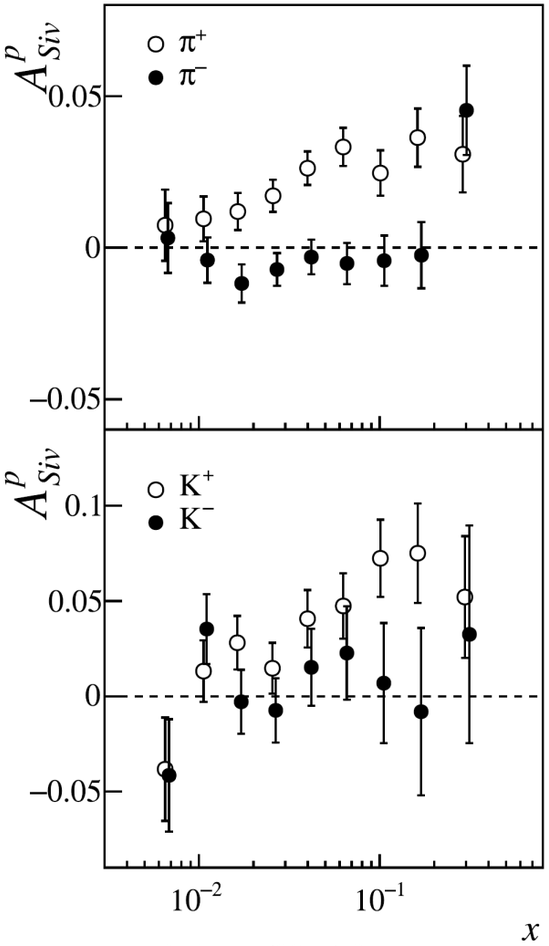
comparison with HERMES



very good agreement !

the proton data - 2007, 2010

Sivers asymmetries: the signals are there!



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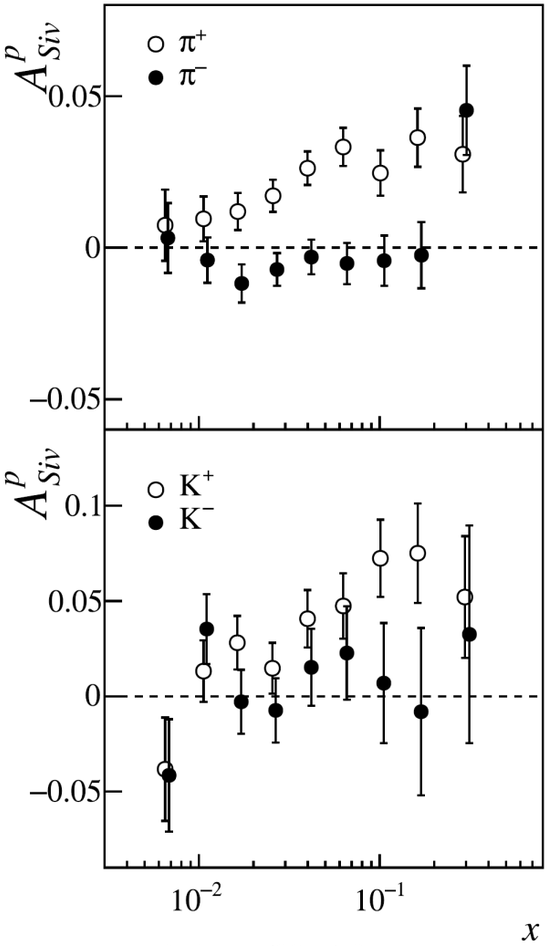

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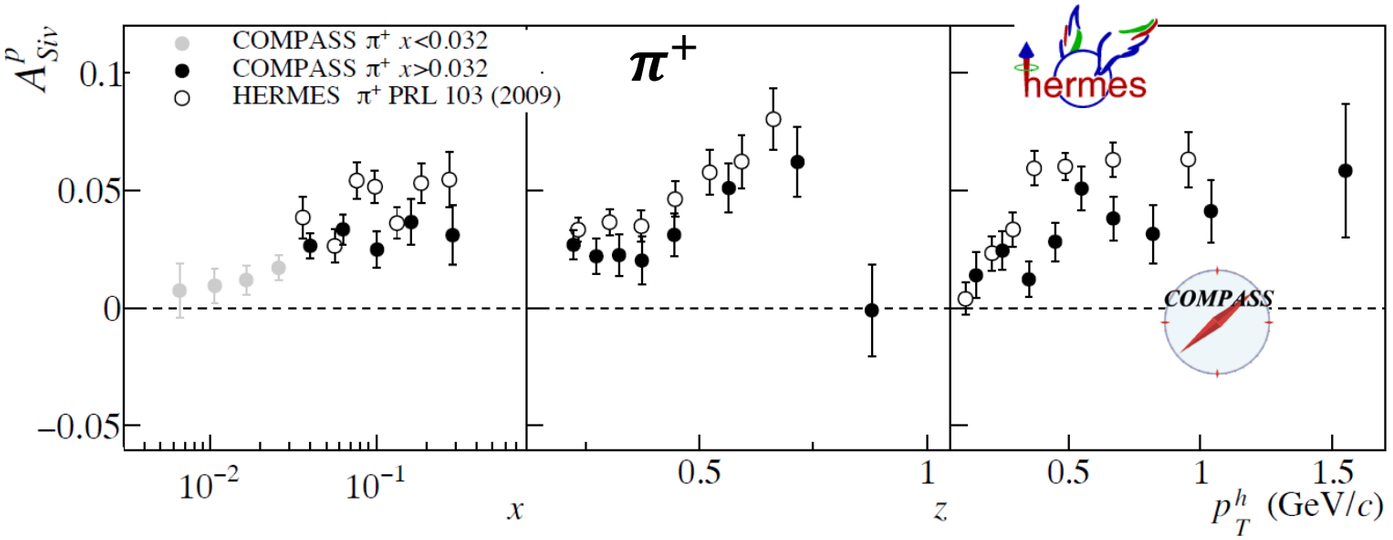

smaller values at COMPASS:
TMD evolution …

the proton data - 2007, 2010

Sivers asymmetries: the signals are there!

- The Sivers functions of the u- and d- quarks are clearly different from zero and have opposite sign

- Proposal to test its “pseudo universality” J. C. Collins, PLB536 (2002) 43. measuring the Sivers asymmetry in pion-induced Drell-Yan muon pair production at COMPASS → data taking in 2017-2018 PRL 119 (2017) 112002 PRL 133 (2024) 071902

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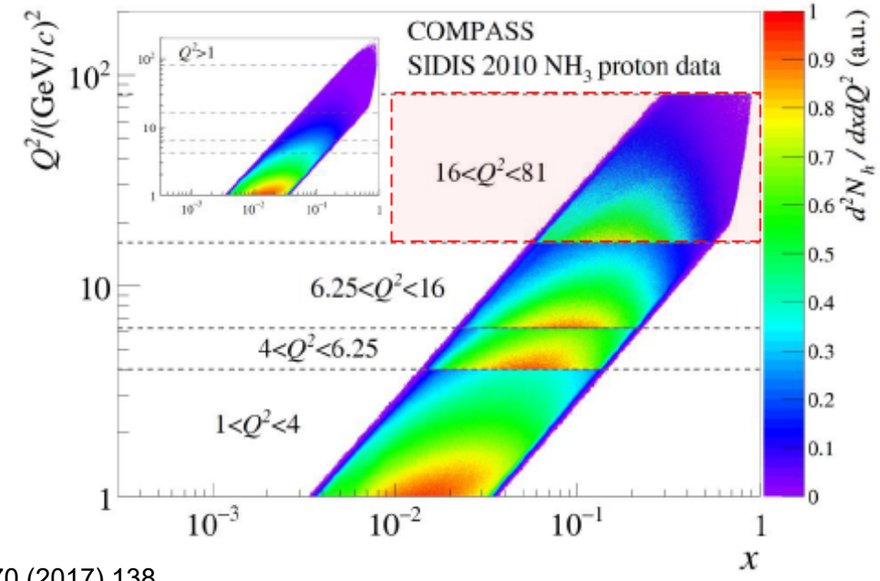
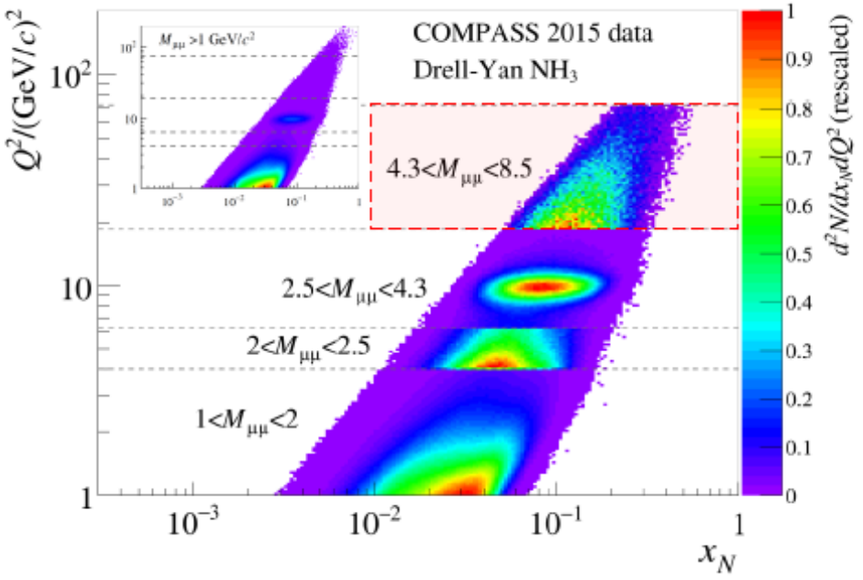
to make easier the comparison with DY, avoiding Q^2 evolution problems,
we have measured the SIDIS Sivers asymmetry in Q^2 bins

SIDIS



PBL 770 (2017) 138



DY

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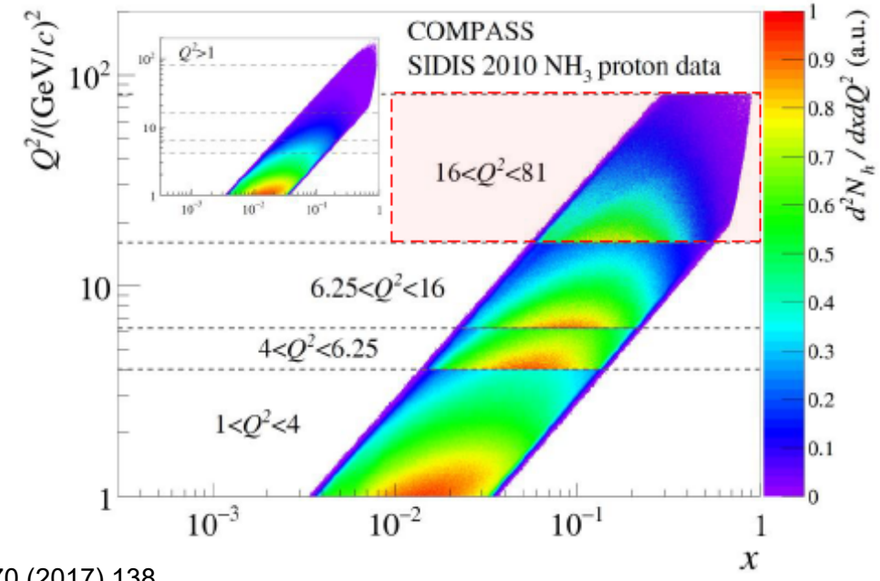

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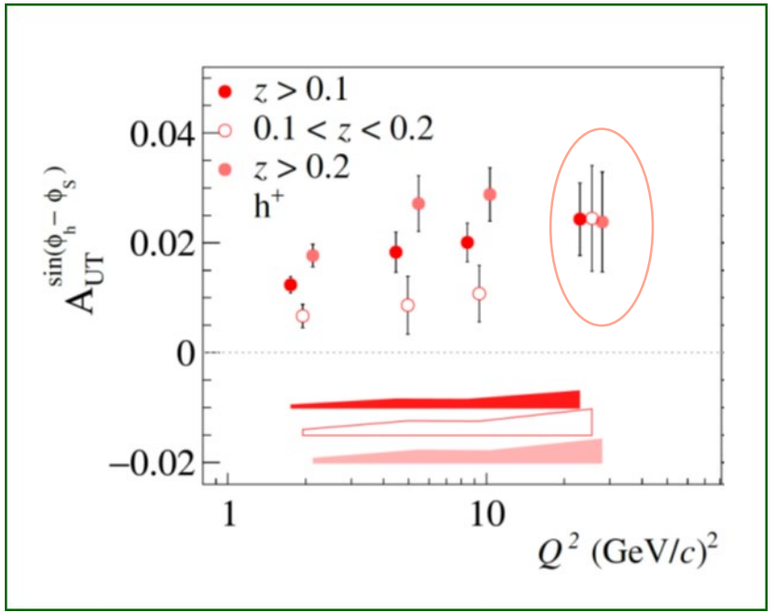

the proton data - 2007, 2010

several measurements have been performed

- Collins and Sivers asymmetries $h^{\pm}$ $\pi^{\pm}, K^{\pm}, K^{0}$ — PLB 692 (2010) 240, PLB 717 (2012) 376 , PLB 717 (2012) 383; PLB 744 (2015) 250
- Sivers asymmetry in Q2 bins $h^{\pm}$ — PLB 770 (2017) 138
- di-hadron TSAs $h^{+}h^{-}$ $\pi^{+}\pi^{-}, \pi^{\pm}K^{\mp}, K^{+}K^{-}$ — PLB 713 (2012) 10, PLB 736 (2014) 124, PLB 753 (2016) 406; PLB 845 (2023) 138155

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

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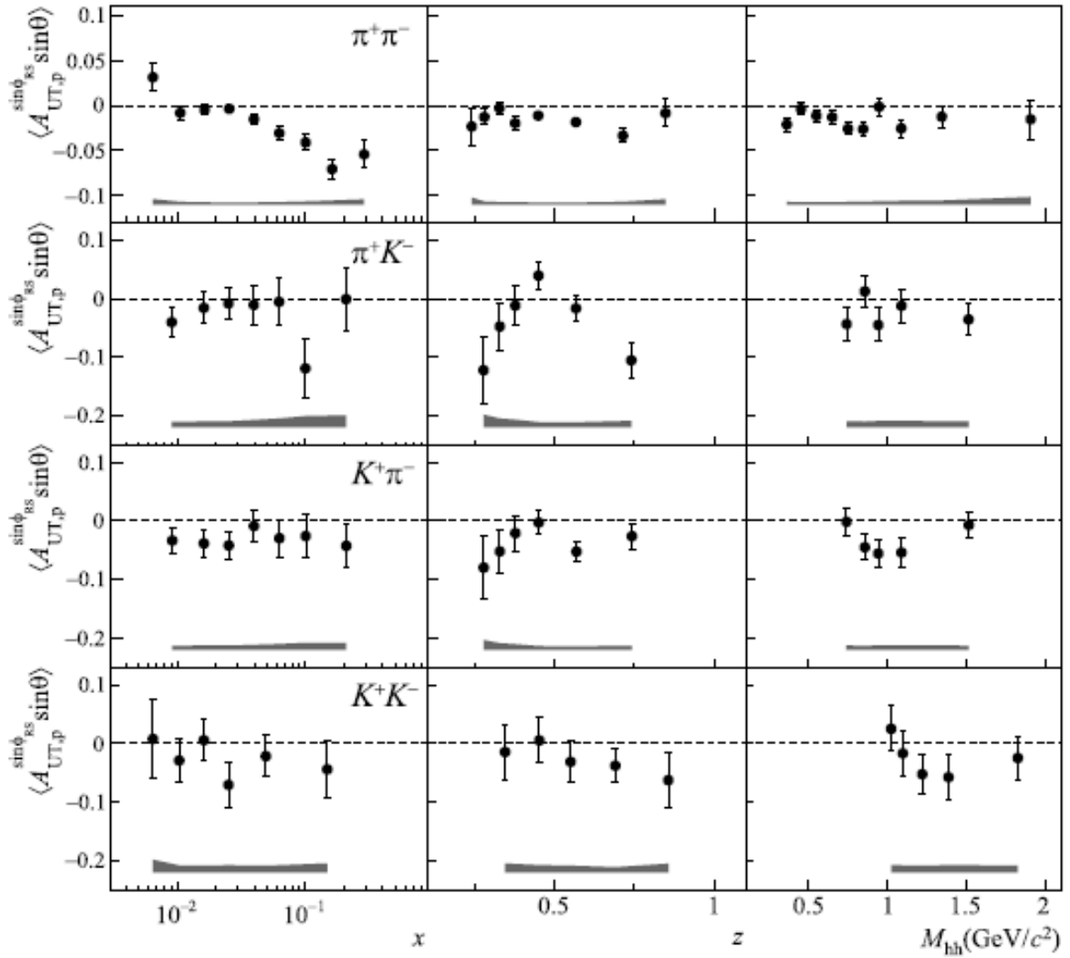

$\pi^+\pi^-$ asymmetry:
clear signal in the valence region,
similar to the h^+h^- asymmetry

the proton data - 2007, 2010

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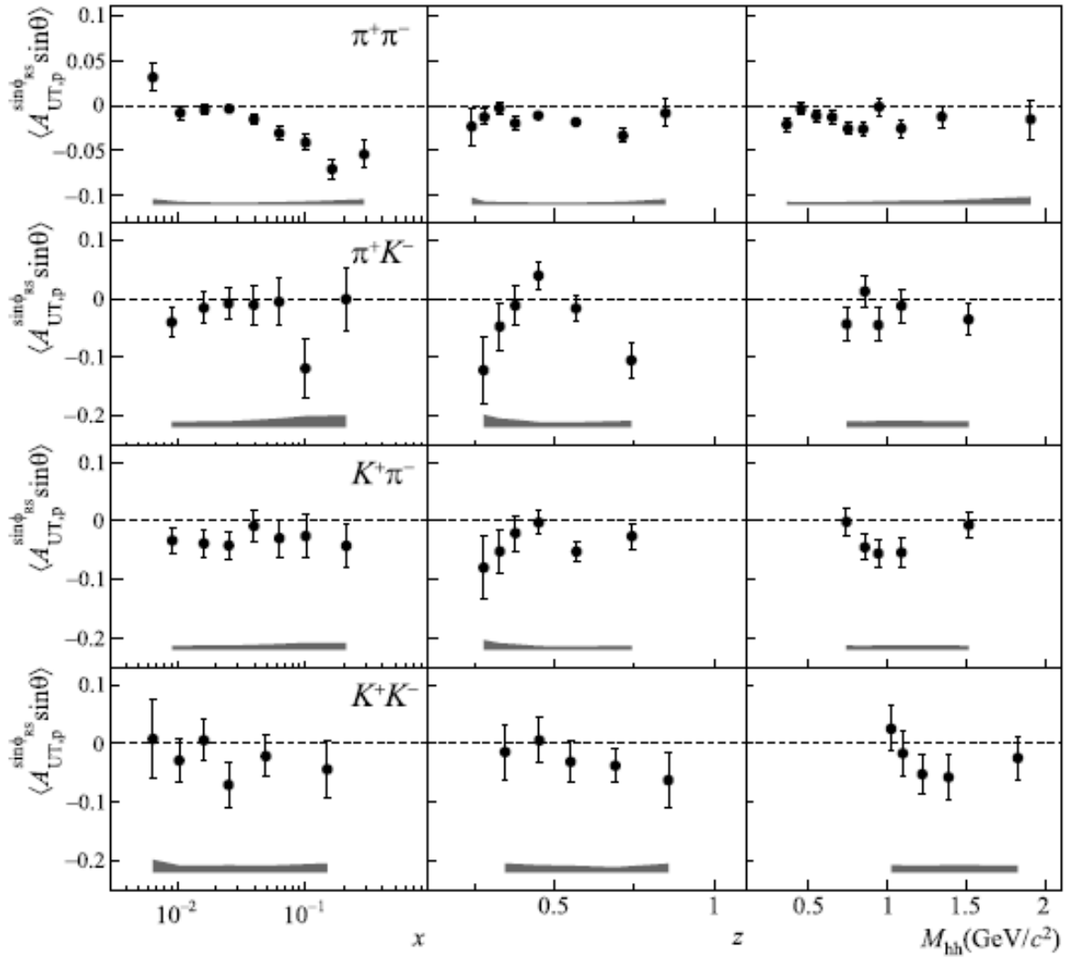

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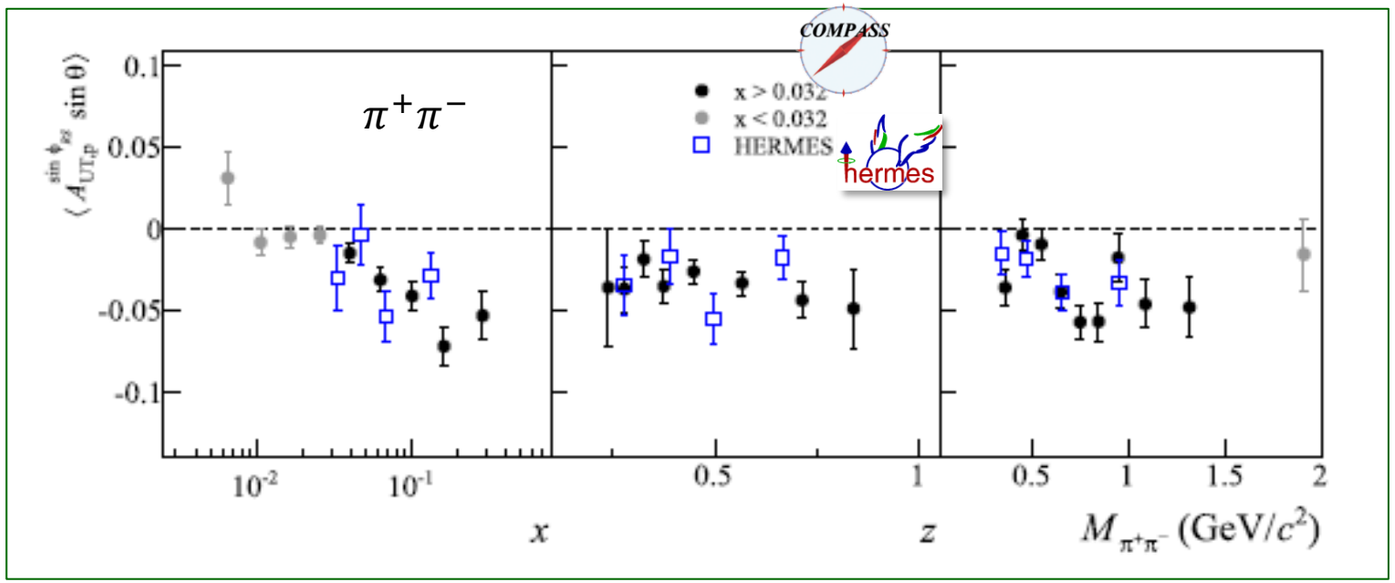
in agreement with the HERMES results



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  $\pi^{+}\pi^{-}, \pi^{\pm}K^{\mp}, K^{+}K^{-}$ PLB 845 (2023) 138155

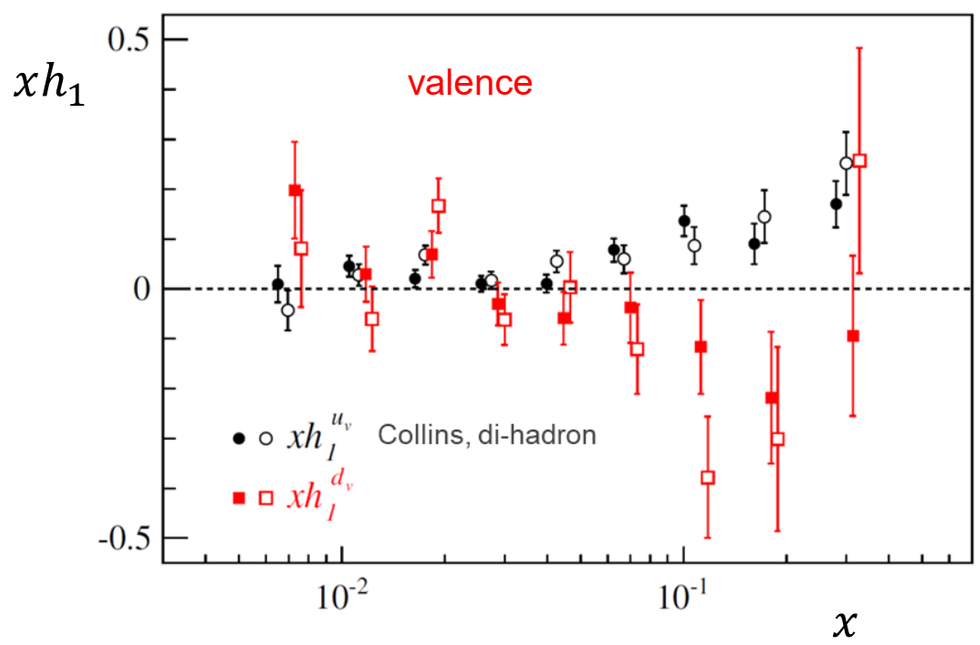
- 1h TSAs beyond Collins and Sivers $h^{\pm}$ PLB 770 (2017) 138
- MultiD Collins and Sivers asymmetries $h^{\pm}$
- P_T-weighted Sivers asymmetries $h^{\pm}$ NPB 940 (2019) 34
- inclusive ρ^0 Collins and Sivers PLB 843 (2023) 137950
- TSAs for high P_T pairs from PGF events – gluon Sivers PLB 772 (2017) 854
- transversity induced $\Lambda/\bar{\Lambda}$ polarisation PLB 824 (2022) 136834
- J/Ψ Sivers asymmetry
- …

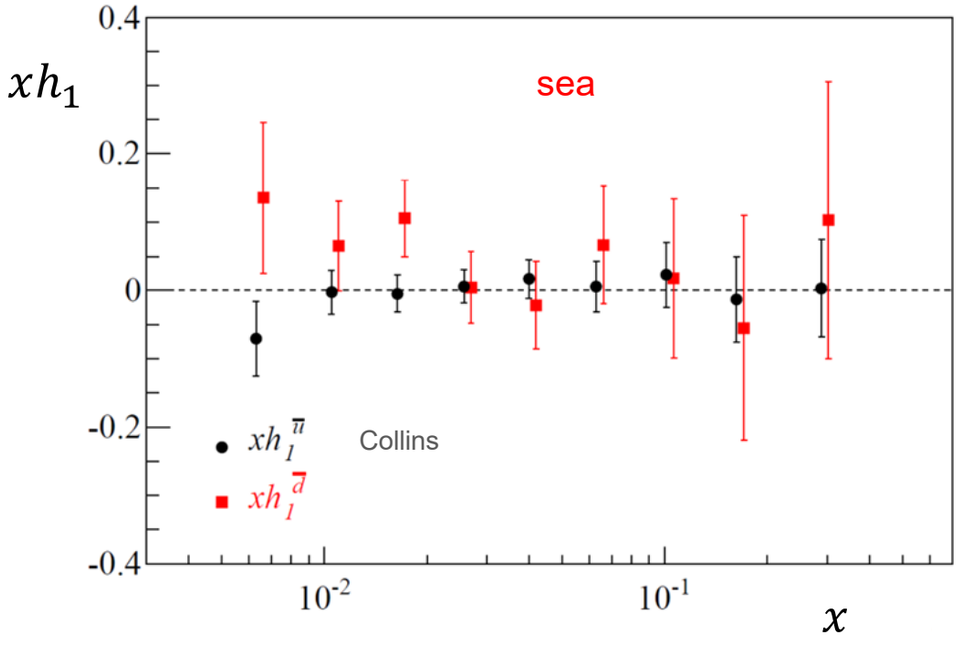
new extractions of the transversity and Sivers functions

as soon as the new SIDIS measurements became available, they were used, together with the e^+e^- and, more recently, pp data, in **global analyses** to extract the transversity and the Sivers functions

also, the COMPASS proton and deuteron measurements, performed at the same energy and in the same x bins allowed for a simple, leading order **point-by-point extraction** of the transversity and Sivers function

PRD 91 (2015) 1, 014034 PRD 95 (2017) 9, 094024





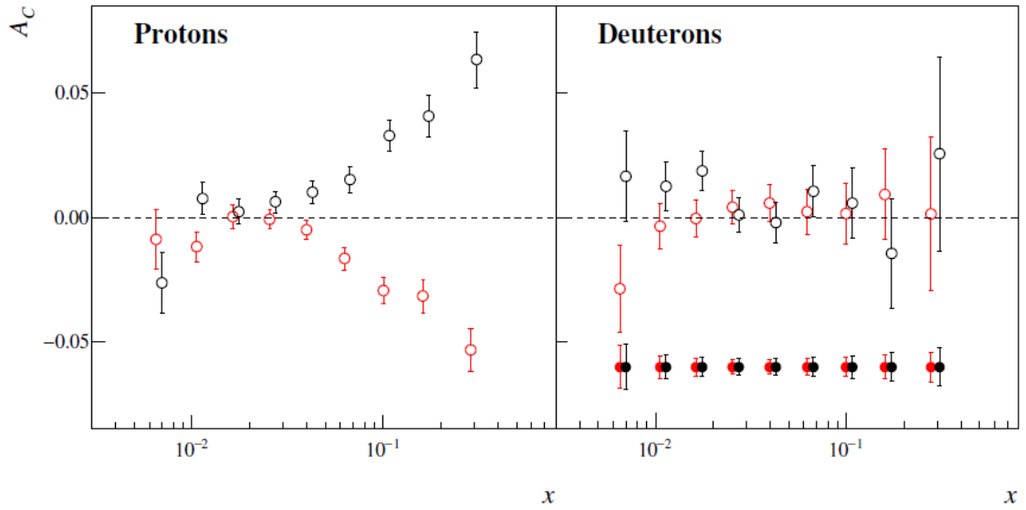
→ the low statistics of the COMPASS deuteron data prevent a precise extraction of the d-quark PDFs from SIDIS data: more data are needed

the new deuteron data - 2022

aim of the 2022 run: **balance the proton and deuteron statistics**
to improve, in particular, the knowledge of the d-quark transversity and of the tensor charge,

in one year of data taking, expected statistical uncertainties:

$$\sigma^{d}_{2022} \simeq 0.6 \cdot \sigma^{p}_{2010}$$ for all the TSAs

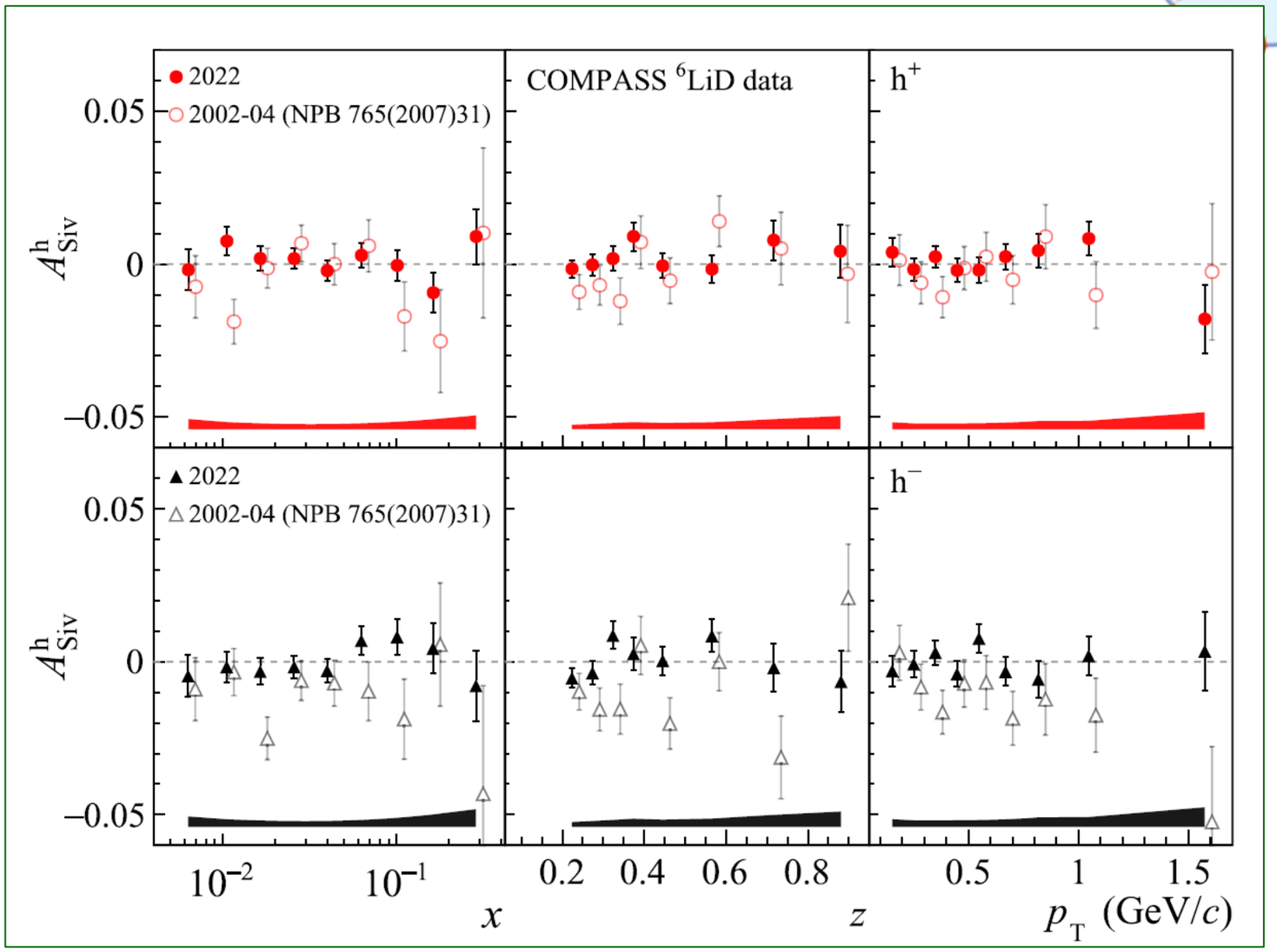


a very successful run: **the goal was achieved**

the new deuteron data - 2022

Sivers asymmetry

h^+, h^-, 70% of statistics

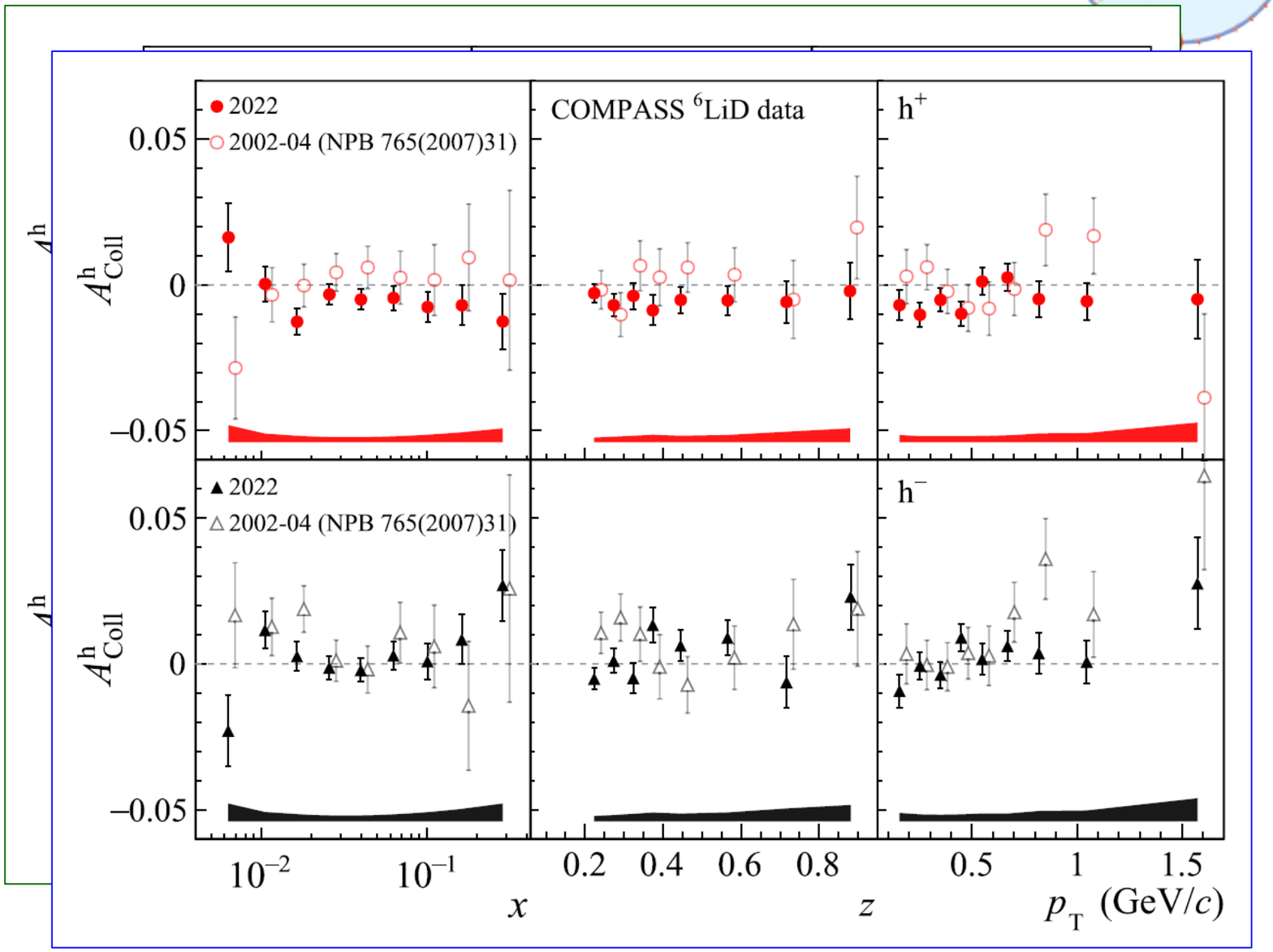


PRL 133 (2024) 101903

the new deuteron data - 2022

Sivers asymmetry
h^+, h^-, 70% of statistics

Collins asymmetry



PRL 133 (2024) 101903

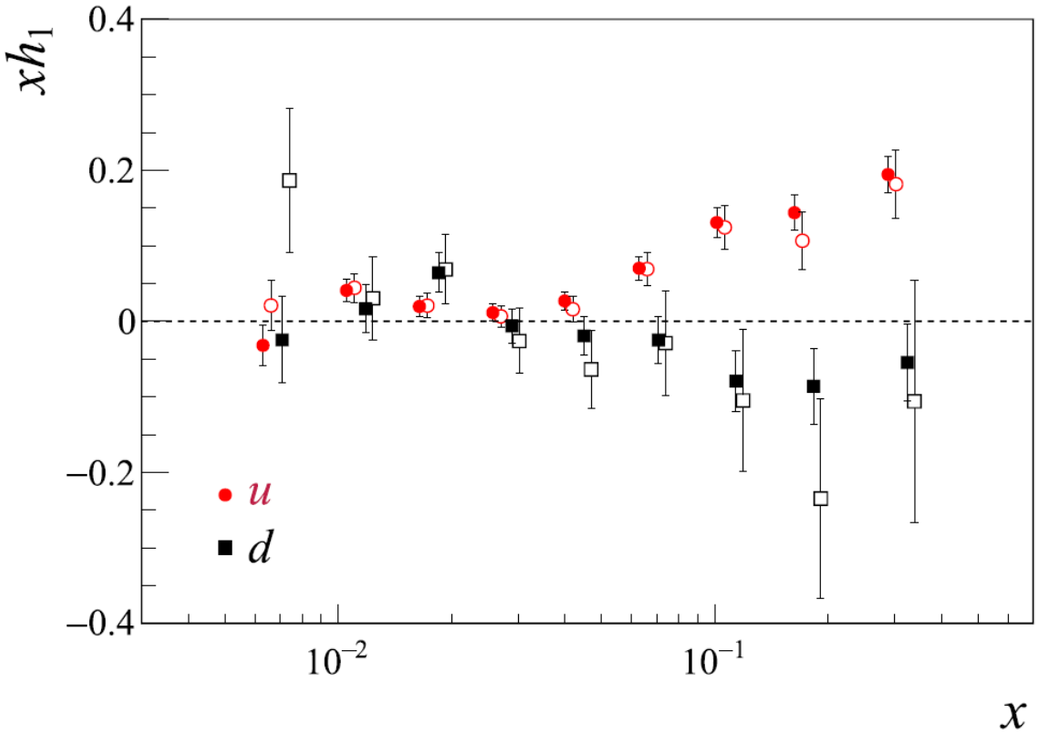
the new deuteron data - 2022

Sivers asymmetry
h^+, h^-, 70% of statistics

Collins asymmetry

these data, together with the COMPASS proton data, allowed for a new point by point extraction of the **Sivers** and **Transversity PDFs**

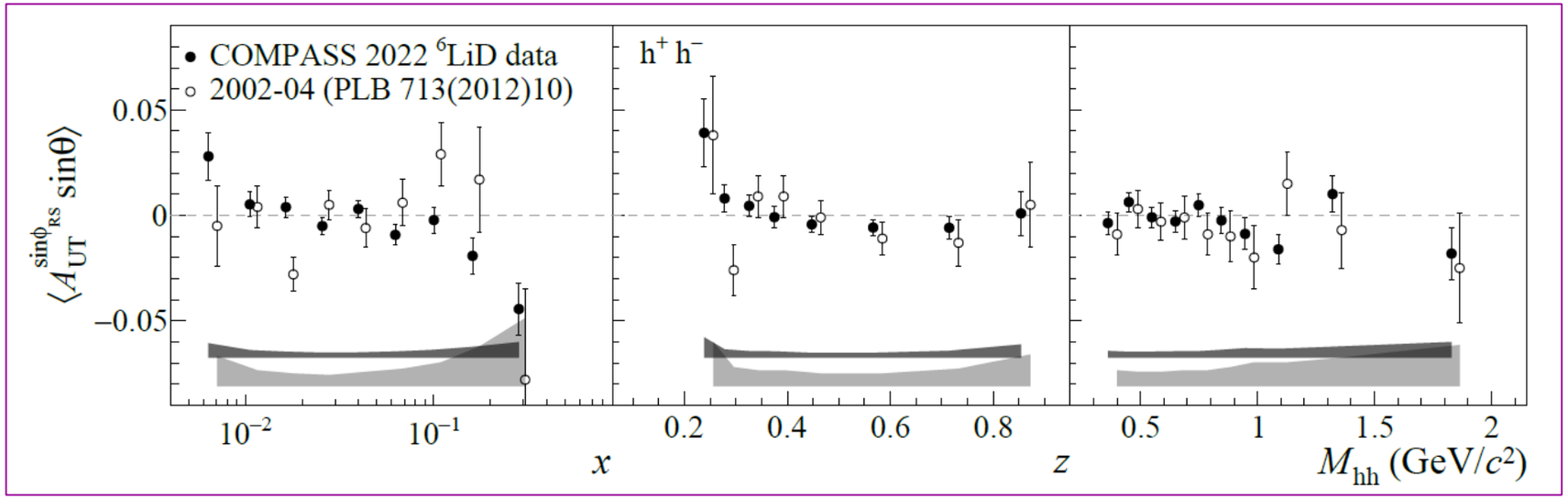
largely increased precision for the u and d quark transversity



PRL 133 (2024) 101903

the new deuteron data - 2022

new result:
dihadron transverse-spin asymmetries

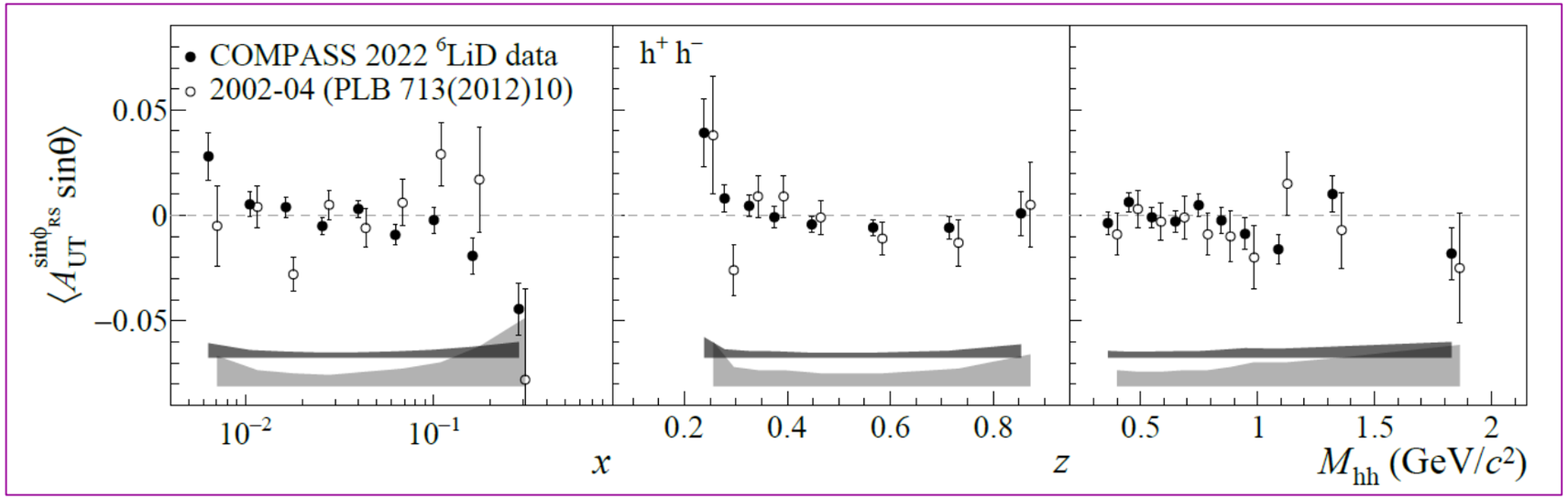


d 2022, d 2002-2004

CERN-EP/2025-298
hep-ex/2512.22311, PRL

the new deuteron data - 2022

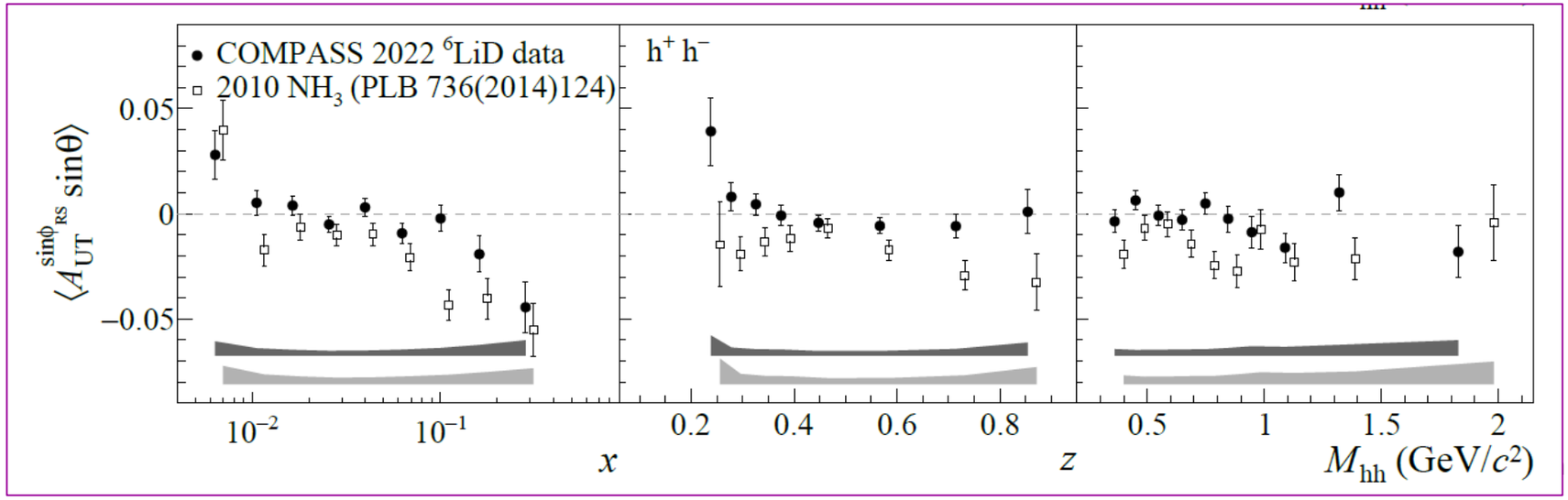
new result:
dihadron transverse-spin asymmetries



d 2022, d 2002-2004

CERN-EP/2025-298
hep-ex/2512.22311, PRL

d 2022, p 2010



the proton data - 2007, 2010

several measurements have been performed

- Collins and Sivers asymmetries $h^{\pm}$ — PLB 692 (2010) 240, PLB 717 (2012) 376 , PLB 717 (2012) 383
  $\pi^{\pm}, K^{\pm}, K^{0}$ — PLB 744 (2015) 250
- Sivers asymmetry in Q^2 bins $h^{\pm}$ — PLB 770 (2017) 138
- di-hadron TSAs $h^{+}h^{-}$ — PLB 713 (2012) 10, PLB 736 (2014) 124, PLB 753 (2016) 406
  $\pi^{+}\pi^{-}, \pi^{\pm}K^{\mp}, K^{+}K^{-}$ — PLB 845 (2023) 138155

- 1h TSAs beyond Collins and Sivers $h^{\pm}$ — PLB 770 (2017) 138
- MultiD Collins and Sivers asymmetries $h^{\pm}$
- P_T-weighted Sivers asymmetries $h^{\pm}$ — NPB 940 (2019) 34
- inclusive ρ^0 Collins and Sivers — PLB 843 (2023) 137950
- TSAs for high P_T pairs from PGF events – gluon Sivers — PLB 772 (2017) 854
- transversity induced $\Lambda / \overline{\Lambda}$ polarisation — PLB 824 (2022) 136834
- J/Ψ Sivers asymmetry
- …

most of these measurements will be repeated with the new deuteron data

the new deuteron data - 2022

- Collins and Sivers asymmetries $h^{\pm}$ PRL 133 (2024) 101903
  $\pi^{\pm}, K^{\pm}, K^{0}$ ongoing, **new** $\boldsymbol{K^{0}}$ → Siranush Asatryan, today
- Sivers asymmetry in Q^2 bins $h^{\pm}$
- di-hadron TSAs $h^{+}h^{-}$ hep-ex/2512.22311, PRL
  $\pi^{+}\pi^{-}, \pi^{\pm}K^{\mp}, K^{+}K^{-}$ ongoing

- 1h TSAs beyond Collins and Sivers $h^{\pm}$ **new** → Artur Hoghmrtsyan, May 7
- MultiD Collins and Sivers asymmetries $h^{\pm}$
- P_T-weighted Sivers asymmetries $h^{\pm}$ ongoing
- inclusive ρ^0 Collins and Sivers
- TSAs for high P_T pairs from PGF events – gluon Sivers
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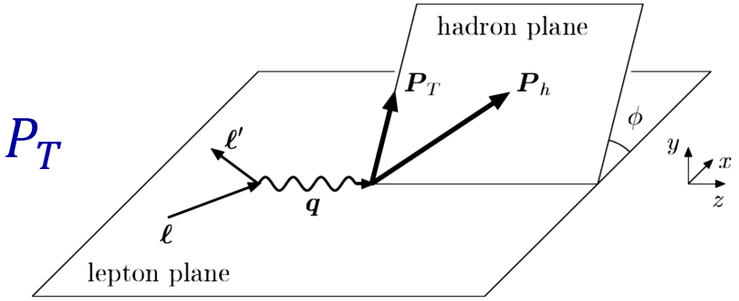
- …

plus measurements of unpolarised SIDIS

unpolarised SIDIS

unpolarised SIDIS

the most studied observables in the TMD framework are:



- the **hadron multiplicities** as functions of the hadron transverse momentum P_T
  the P_T dependence originates from:
  - the transverse momentum k_T of the struck quark wrt the nucleon direction
  - the transverse momentum $p_\perp$ of the hadron wrt the fragmenting quark direction

  at leading order: $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle$

- the **azimuthal asymmetries**, e.g. the amplitudes of the azimuthal angle modulations in the cross section mainly due to
  - the Cahn contribution, related to the k_T of the quarks
  - Boer-Mulders TMD PDFs $h_1^\perp$convoluted with the Collins FF $H_1^\perp$

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

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

unpolarised SIDIS

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the first measurements in COMPASS were performed using the 2004 and 2006 deuteron data

unpolarised SIDIS

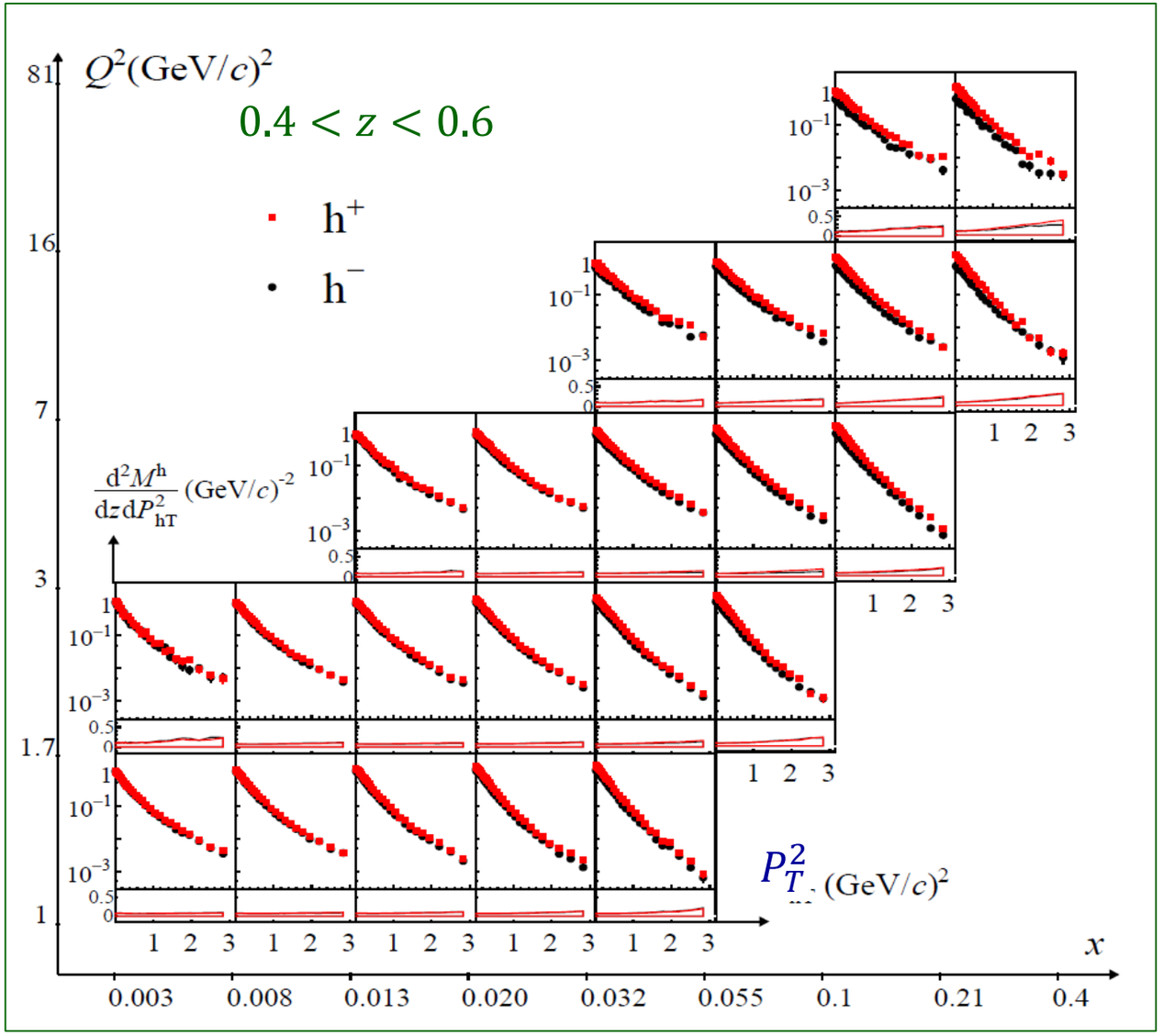
- the **hadron multiplicities** as functions of the hadron transverse momentum P_T

2006 data

deuteron target
160 $\mathbf{GeV/c^2}$ μ^+ beam

$1 < Q^2 < 16\ \mathrm{GeV}^2$ 5 bins
$0.003 < x < 0.4$ 8 bins
$0.2 < z < 0.8$ 4 bins

$P_T^2 < 3\ (\mathrm{GeV/c})^2$



PRD 97 (2018) 032006

2004 data: EPJC 73 (2013) 2531

unpolarised SIDIS

- the **azimuthal asymmetries**

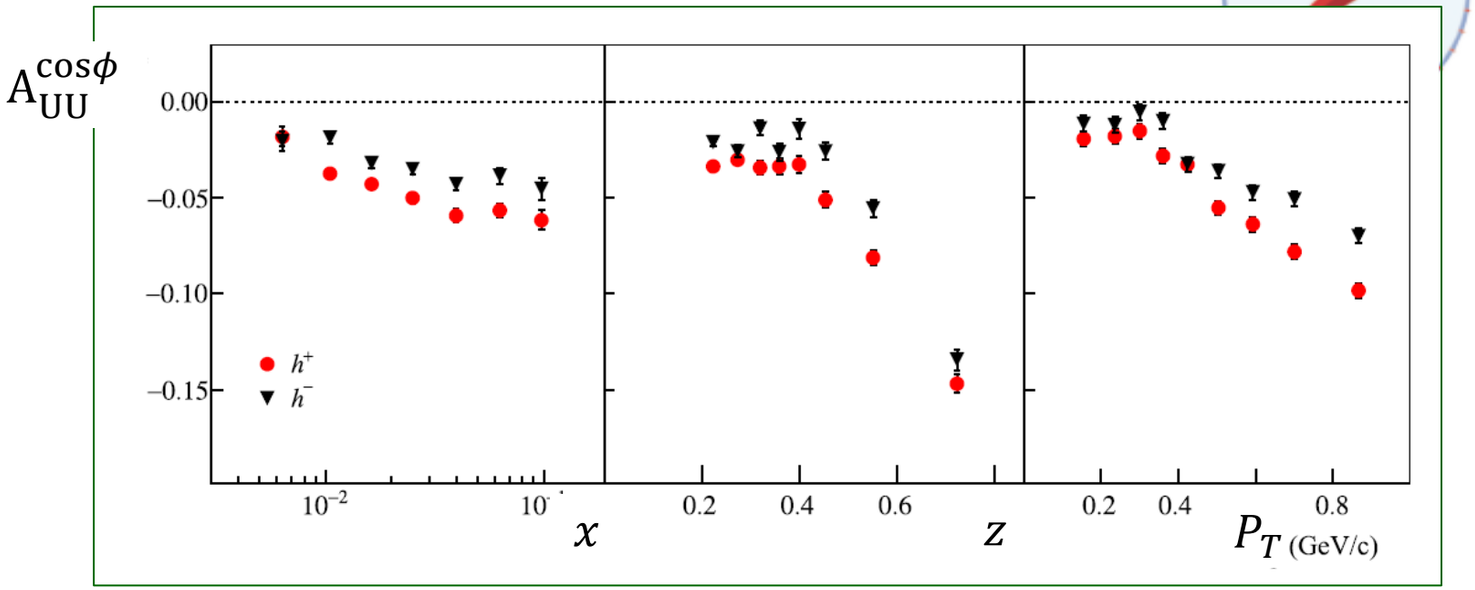
2004 data

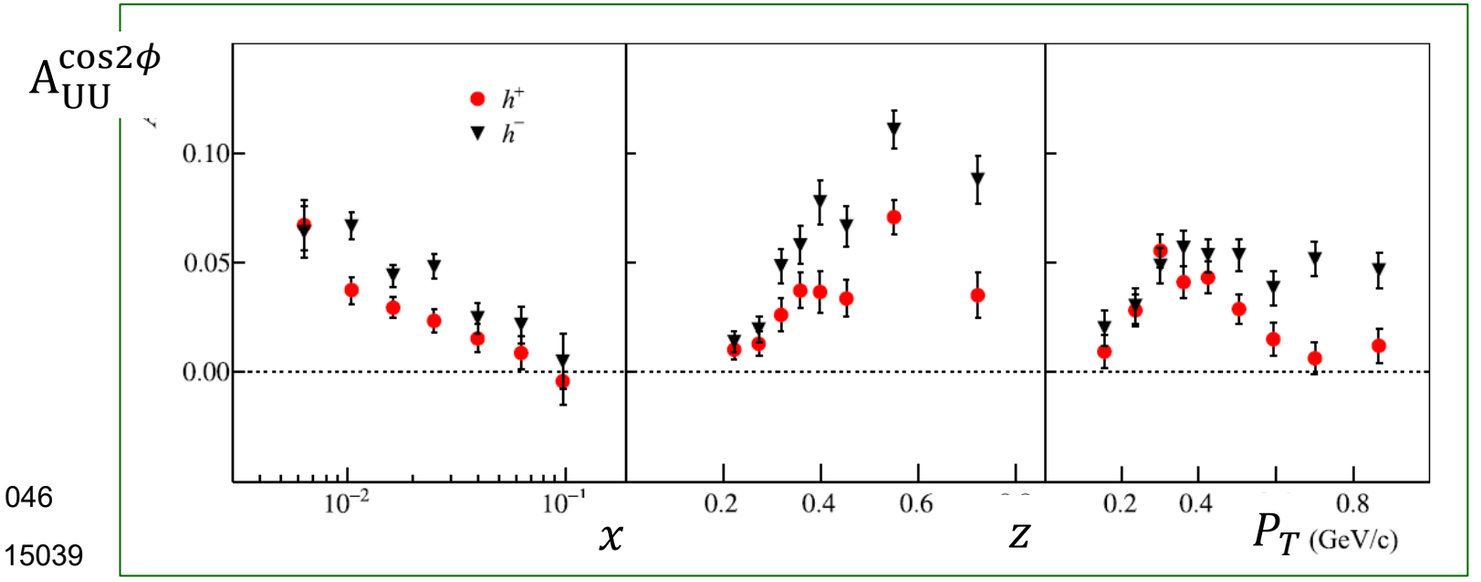
deuteron target
160 GeV/c² μ^+ beam

$0.003 < x < 0.13$
$0.2 < z < 0.85$
$0.1 < P_T < 1.0$ GeV/c
no diffractive vector meson subtraction
no correction for radiative effects
also, bins of x, z, P_T

- strong kinematic dependence
- different for h^+ and h^-

$h_1^\perp$ still essentially unknown





NPB 886 (2014) 1046

NPB 956 (2020) 115039

unpolarised SIDIS

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NEW MEASUREMENTS using the 2016 data collected using a PROTON target → Vendula Benešová, today

ongoing analyses: hadron pair multiplicities, …

colinear multiplicities on p and d → Marcin Stolarski, May 6, WG1

summary

- over many years COMPASS has studied the transverse spin and transverse momentum structure of the nucleon measuring SIDIS off polarised and unpolarised targets
- many important results have been produced
- the work is going on, and new results are being and will be produced using the unique data sets we collected with the 160 GeV/c μ beam and the unpolarised and transversely polarised proton and deuteron targets