Measurements of transverse spin asymmetries at COMPASS

Anna Martin

Trieste University and INFN

on behalf of the COMPASS Collaboration



Common Muon and Proton Apparatus for Structure and Spectroscopy

fixed target experiment at the CERN SPS

approved in 1997, data taking from 2002 to 2022

Franco Bradamante talk



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wide physics program

SPECTROSCOPY

NUCLEON STRUCTURE

high energy μ beam

- L and T polarised ^{6}LiD and NH_3 targets
  open charm, SIDIS
- LH target
  DVCS - HEVMP, SIDIS

high energy π^- beam

- T polarised NH_3 target
  Drell-Yan

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Kamil Augsten talk

this talk

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the COMPASS Spectrometer – SIDIS with polarised targets

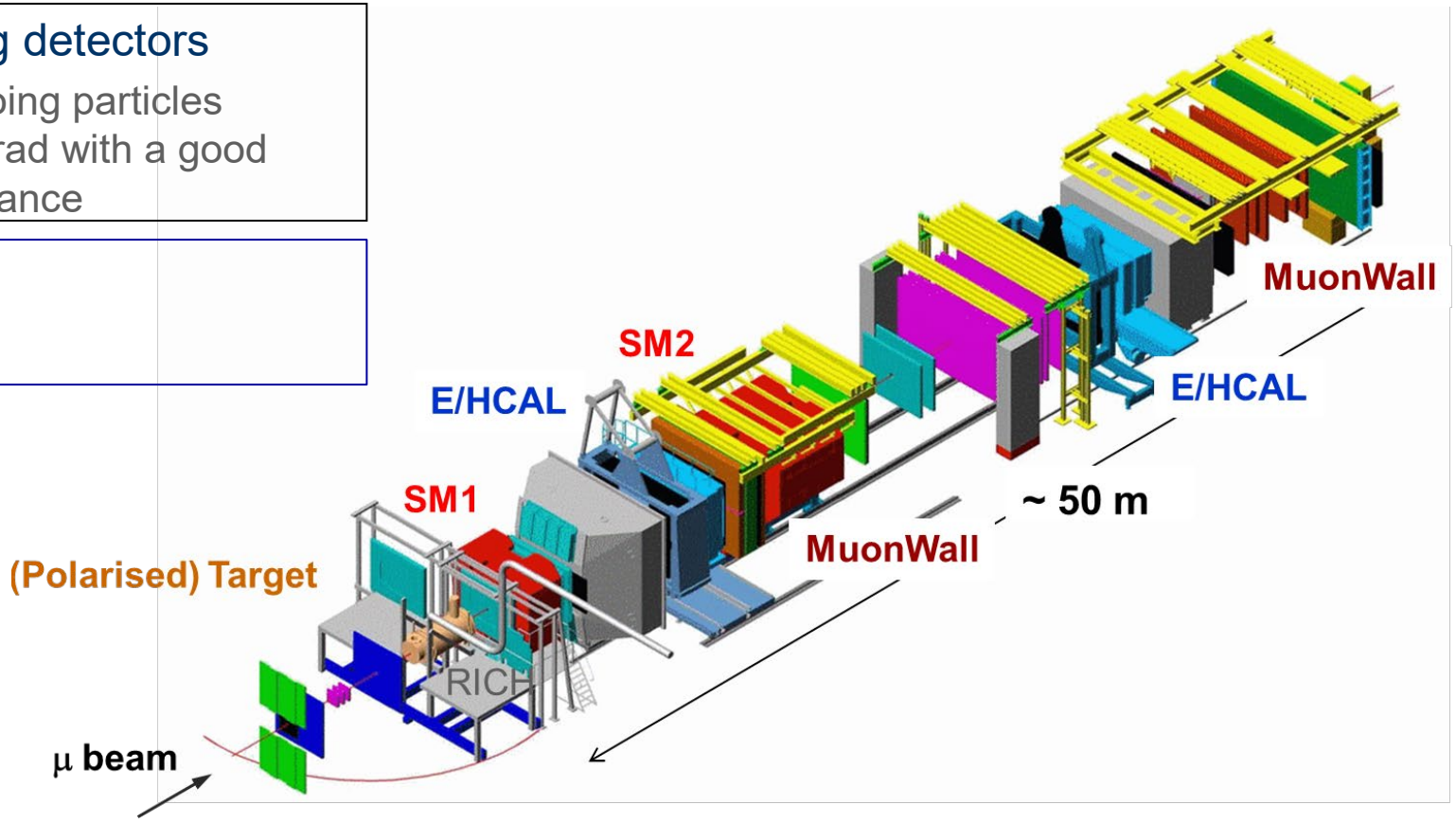
two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

variety of tracking detectors

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

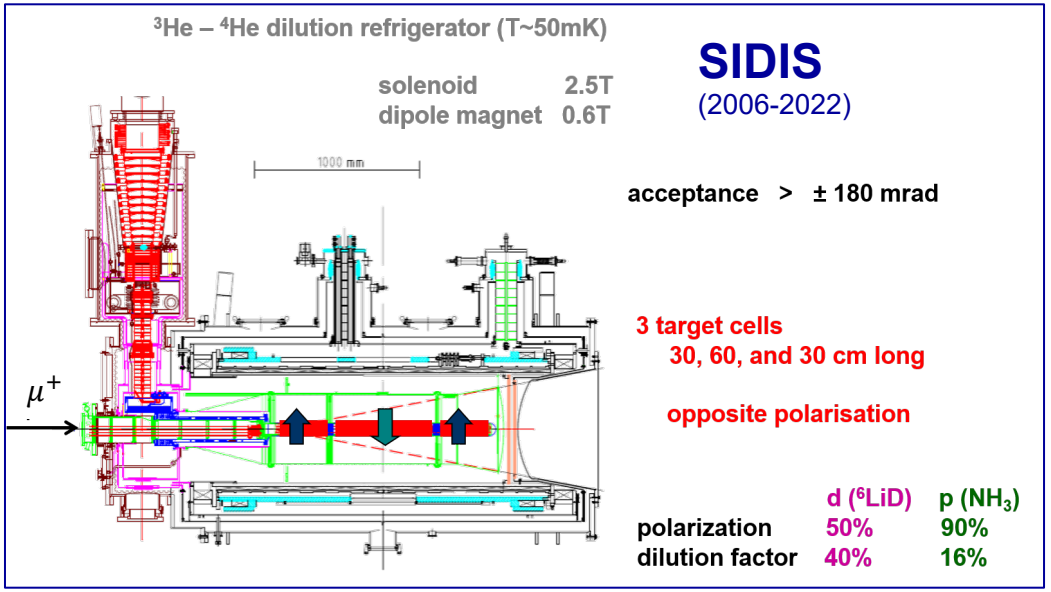
calorimetry, μID

RICH detector



the COMPASS Spectrometer – polarised targets

the target region



SIDIS
(2006-2022)

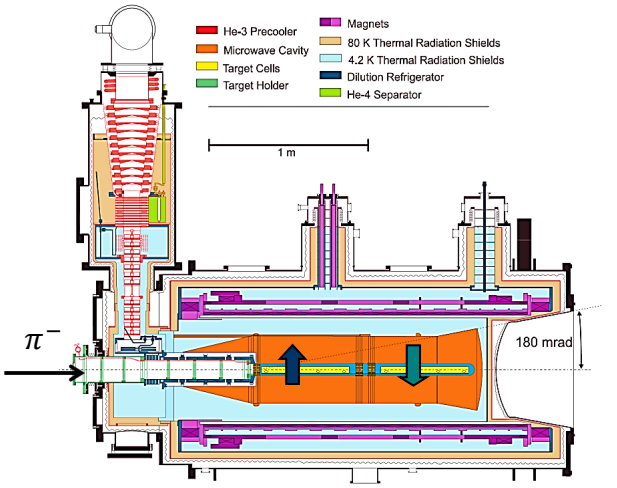
acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

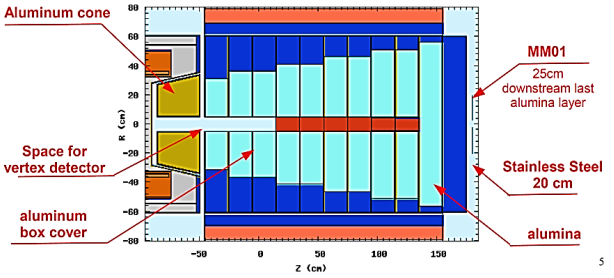
opposite polarisation

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

Drell-Yan
(2015,2018)



p (NH_3)

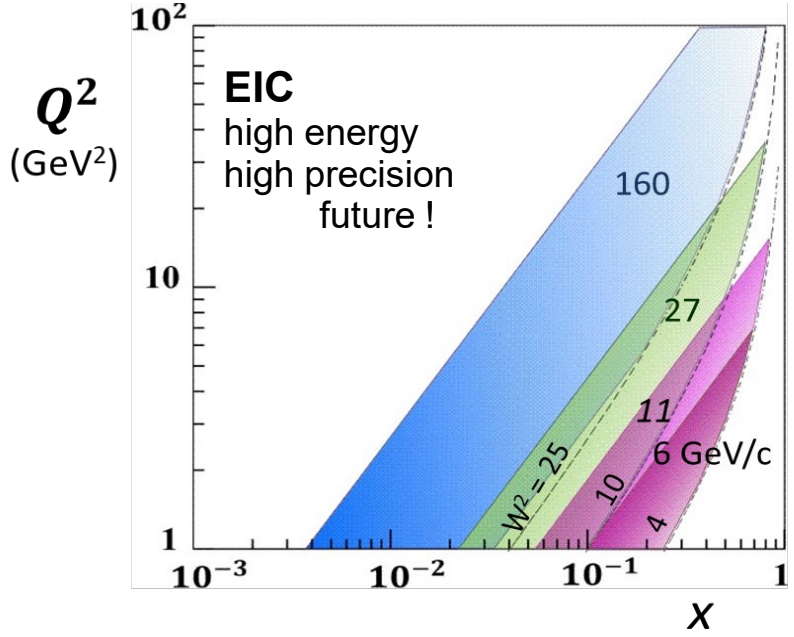


the structure of the nucleon

the structure of the nucleon – transverse spin

a big experimental effort

SIDIS



COMPASS

hermes

Jefferson Lab

Drell-Yan processes

transversely polarized nucleons

COMPASS

SpinQuest, RHIC experiments

hard p↑p scattering

RHIC experiments
STAR, sPHENIX

Fragmentation Functions

Collins, DiHadron, ….

BELLE BABAR BESIII

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 Transverse Momentum Dependent PDFs are needed

for a full description of the nucleon structure

the TMD PDFs encode the correlations among

parton transverse momentum,

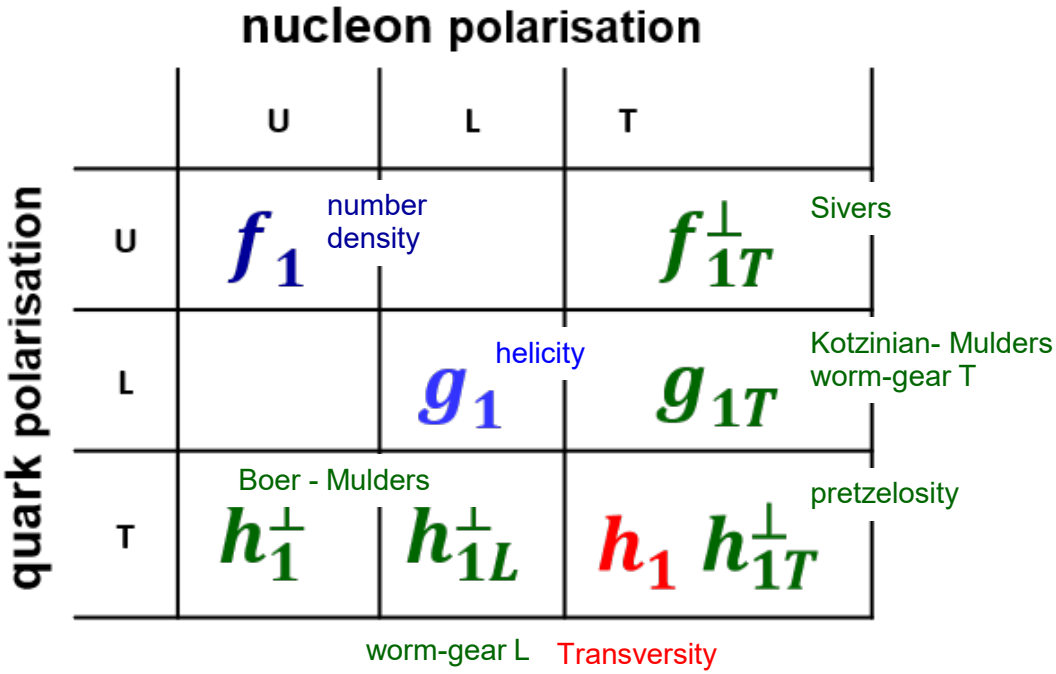
parton spin and

nucleon spin

only f_1, g_1 and h_1 survive after integration over transverse momenta

only f_1 and g_1 can be accessed in inclusive DIS

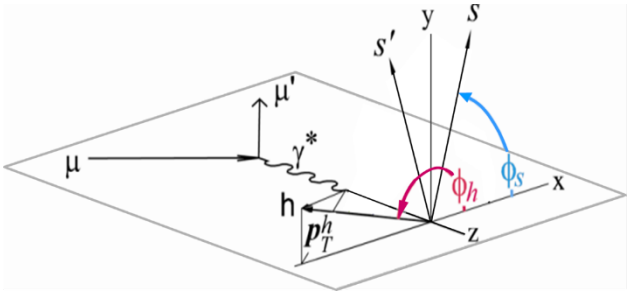
all accessible in SIDIS
when measuring the azimuthal angles of the final state hadrons



SIDIS cross section

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\ (h_1^\perp H_1^\perp) + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\ (h_{1L}^\perp H_1^\perp)\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}\ (f_{1T}^\perp D_1)+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}\ (h_{1T}^\perp H_1^\perp)+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\ (h_{1T}^\perp H_1^\perp) \\
&\quad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\ (g_{1T}D_1)+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\quad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

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



A. Bacchetta et al JHEP 02 (2007) 093

SIDIS cross section

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&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\quad \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} \\
&\qquad + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \quad (h_1^\perp H_1^\perp) \\
&\qquad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\qquad + 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 (h_{1L}^\perp H_1^\perp) \\
&\qquad + 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] \\
&\qquad + |\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) \quad (f_{1T}^\perp D_1) \\
&\qquad\quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \quad (h_{1T}^\perp H_1^\perp) \\
&\qquad\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \quad (h_{1T}^\perp H_1^\perp) \\
&\qquad\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\qquad + |\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \quad (g_{1T} D_1) \\
&\qquad\quad + \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)}\Bigg]\Bigg\},
\end{aligned}
$$

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

8 independent azimuthal modulations

A. Bacchetta et al JHEP 02 (2007) 093



SIDIS cross section

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

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

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\ (h_1^\perp H_1^\perp) + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\ (h_{1L}^\perp H_1^\perp)\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\left[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}\ (f_{1T}^\perp D_1)+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}\ (h_{1T}^\perp H_1^\perp)+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\ (h_{1T}^\perp H_1^\perp)$$

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

$$+\,|\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\ (g_{1T}D_1)+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}\right.$$

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

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

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

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

the identification of the final state hadrons and the use of different targets allow for flavour separation

A. Bacchetta et al JHEP 02 (2007) 093

COMPASS measurements of SIDIS TSAs

proton target

data taking: 2007 half year, 2010 one year
a high statistics sample that allows for several new measurements

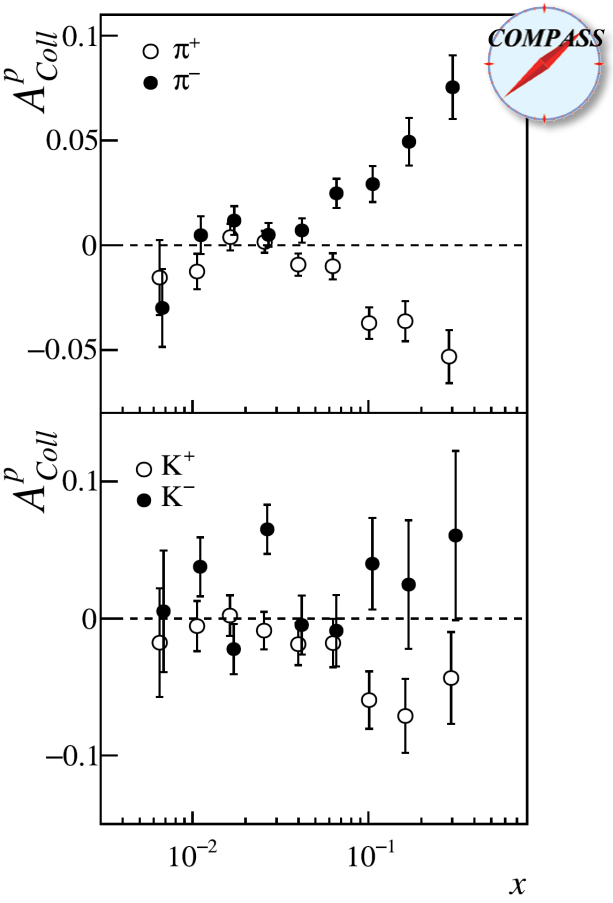
proton target - Collins asymmetry

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

measured for $h^{\pm}, \pi^{\pm}, K^{\pm}, K^0$ as functions of x, z, P_T

clear signals !

all proton data



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

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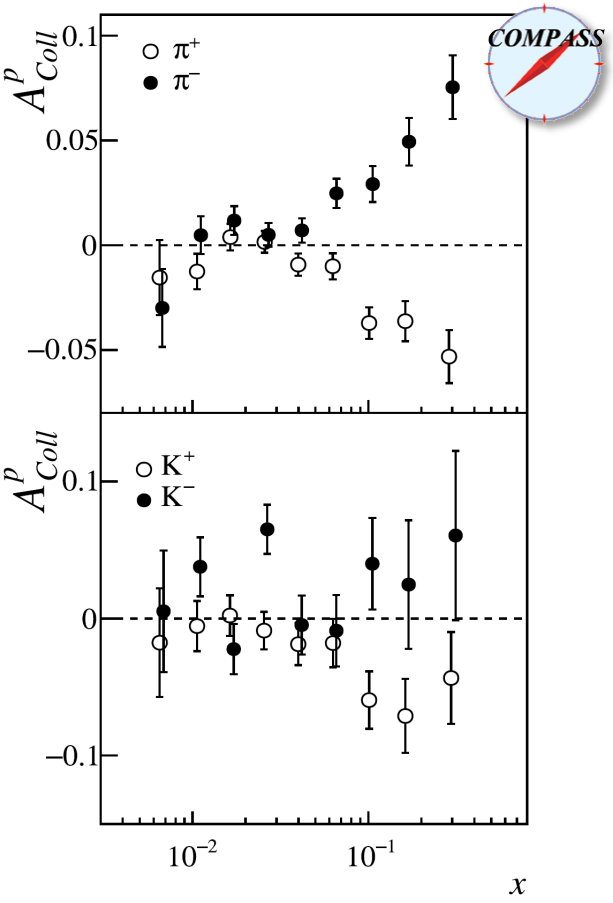
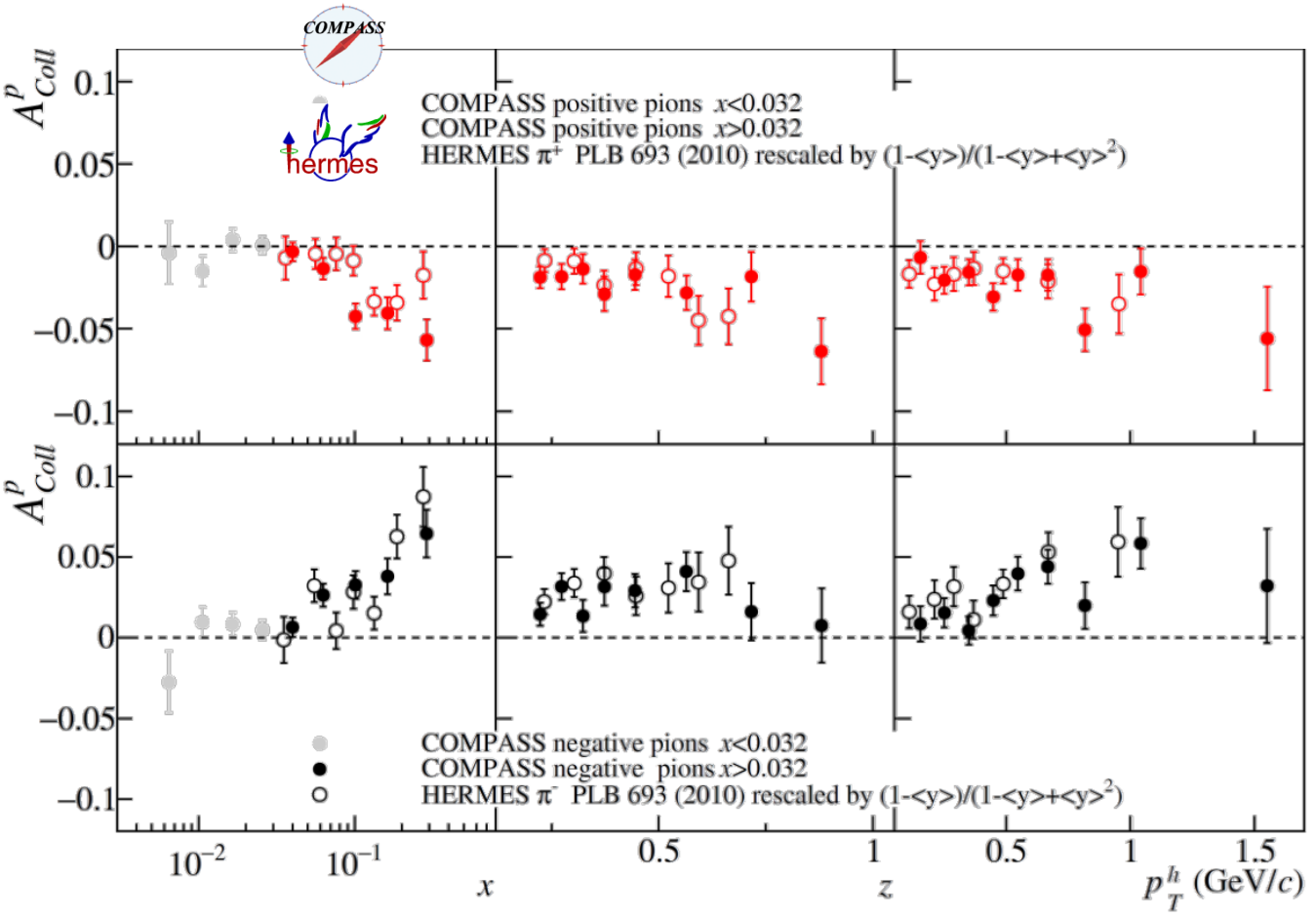




PLB 744 (2015) 250
PLB 717 (2012) 376

very good agreement

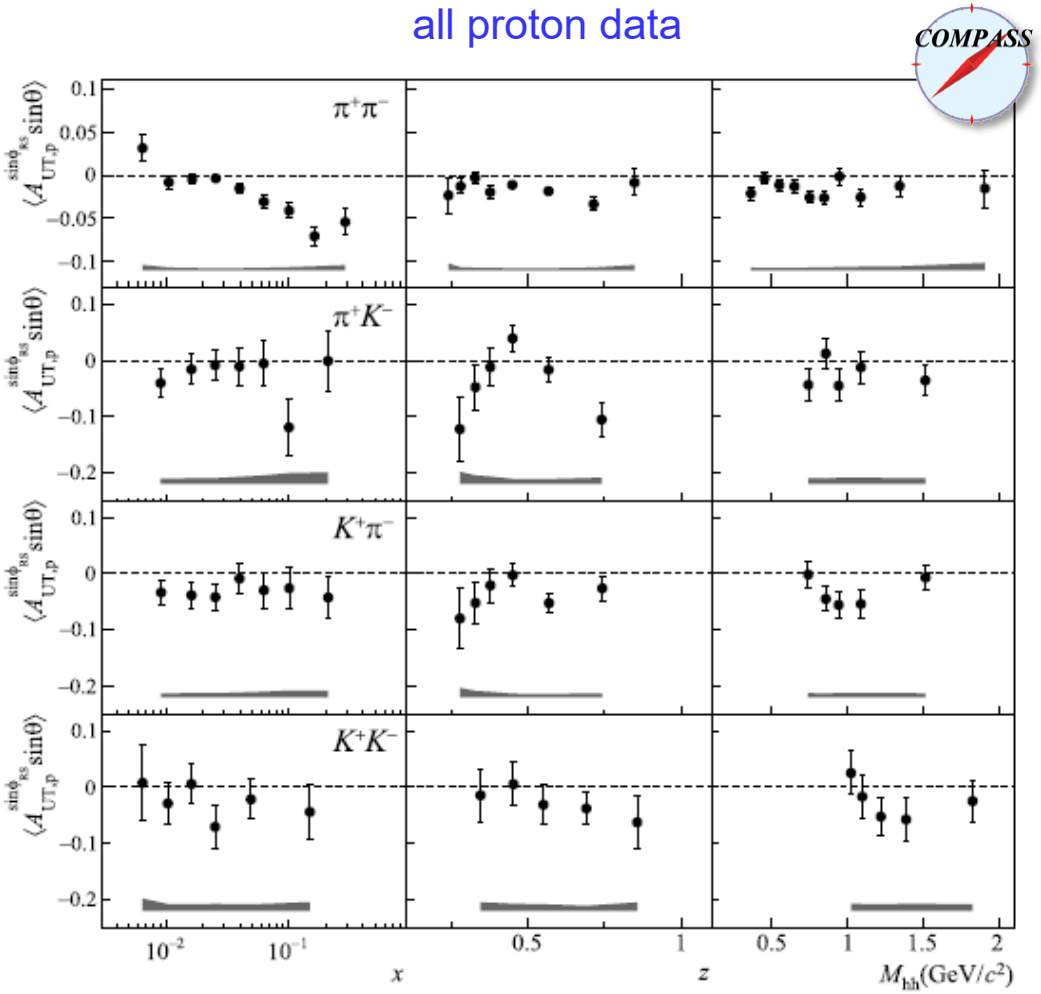
proton target – dihadron asymmetry

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

it is the amplitude of the $sin(\phi_R - \phi_S + \pi)$ in hadron pair production in SIDIS off transversely polarized targets

measured for $h^+h^-, \pi^+\pi^-, \pi^\pm K^\mp, K^+K^-$ as functions of x, Z, M_{2h}

all proton data



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

PLB 713 (2012) 10, PLB 736 (2014) 124 , PLB 753 (2016) 406
PLB 845 (2023) 138155

proton target – dihadron asymmetry

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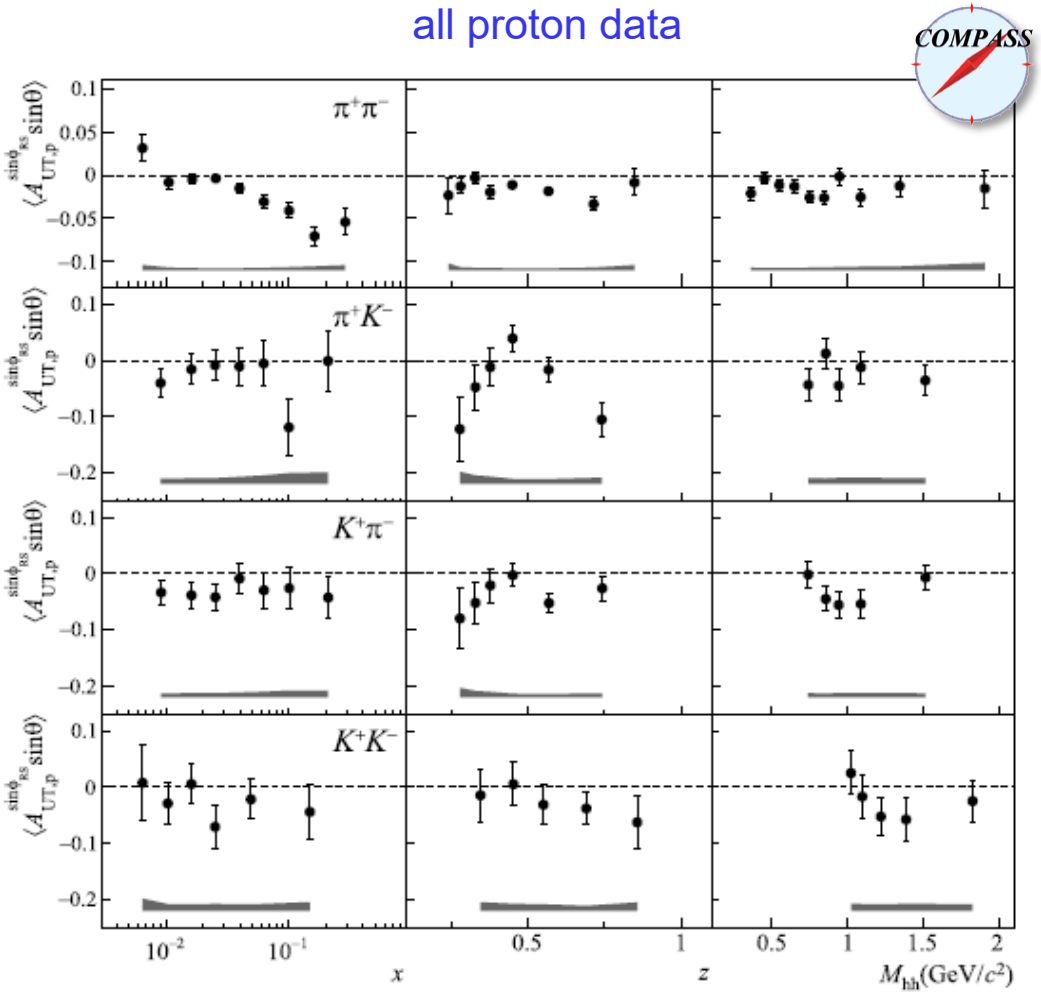
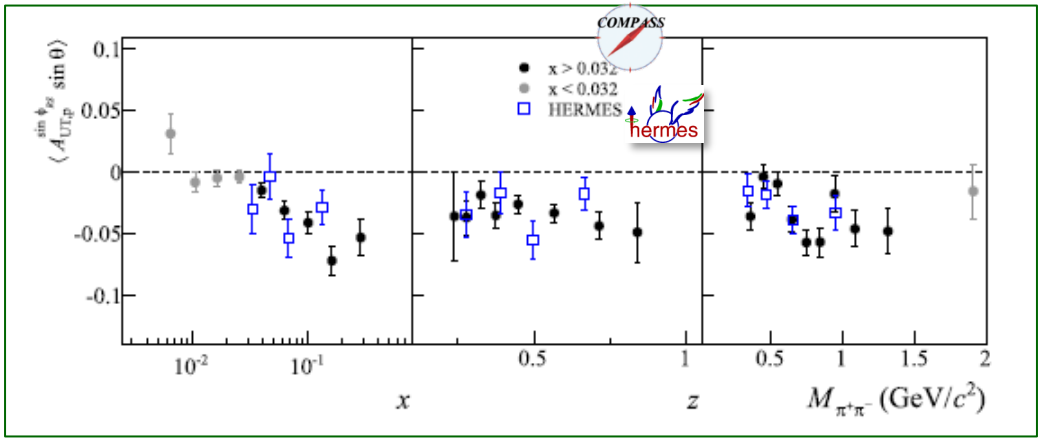


$\pi^+\pi^-$ asymmetry:
clear signal in the valence region,
similar to the h^+h^- asymmetry

in agreement with the HERMES results



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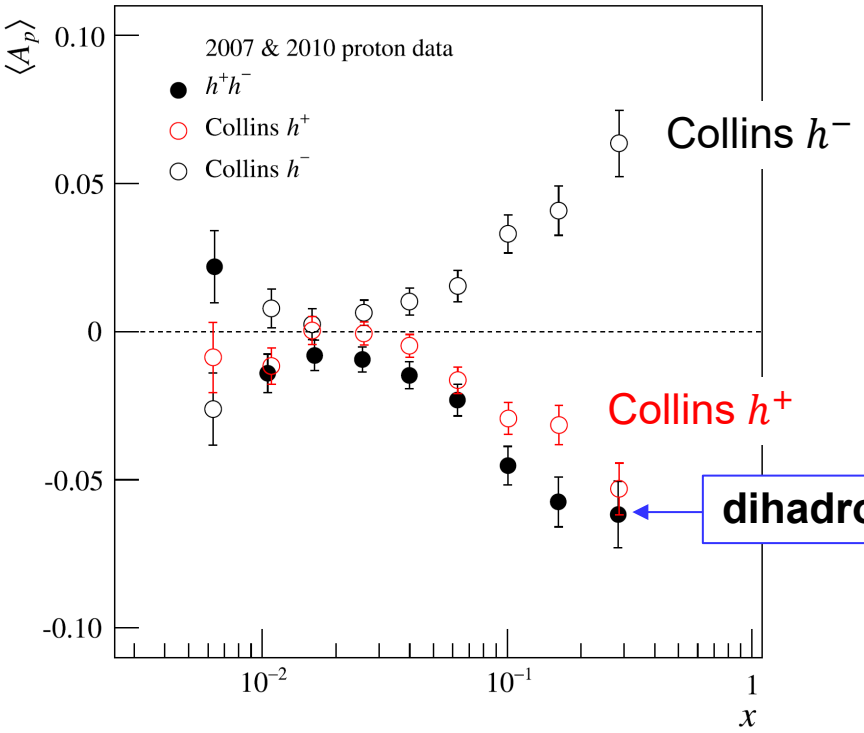
measured for $h^+h^-, \pi^+\pi^-, \pi^\pm K^\mp, K^+K^-$ as functions of x, Z, M_{2h}

comparison with the Collins asymmetry



Collins h^-

Collins h^+

dihadron h^+h^- asymmetry

PLB 736 (2014) 124

study of the interplay between Collins and dihadron asymmetries – not independent

PLB 753 (2016) 406

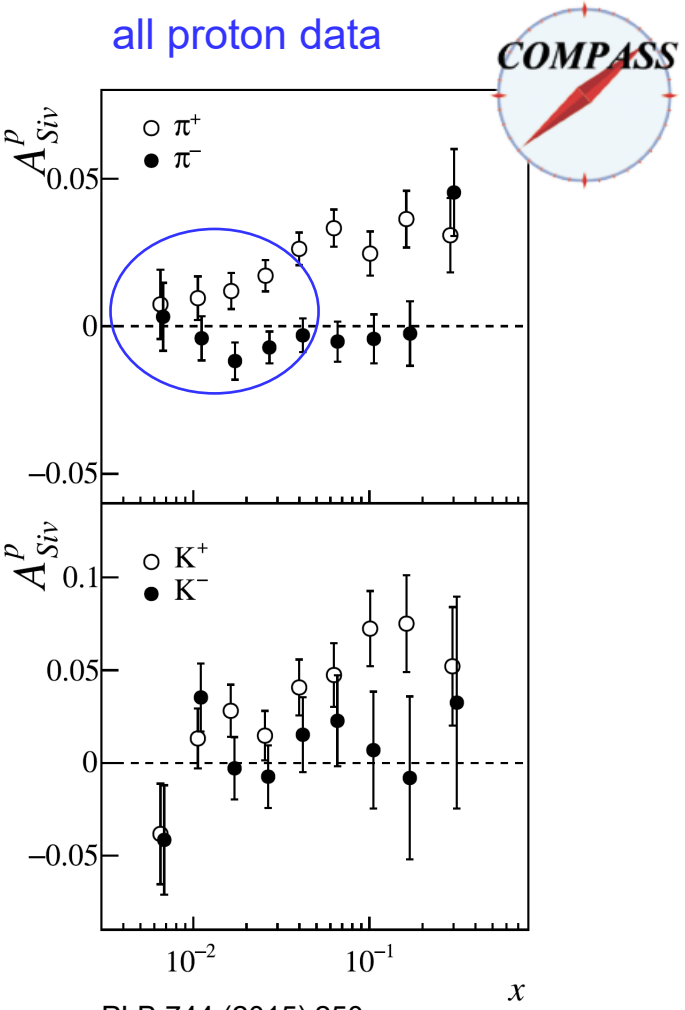
similar studies for Sivers asymmetry

proton target - Sivers asymmetry

measured for $h^{\pm}, \pi^{\pm}, K^{\pm}, K^{0}$ as functions of x, z, P_T

clear signals for positive hadrons !

all proton data



PLB 744 (2015) 250
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proton target - Sivers asymmetry

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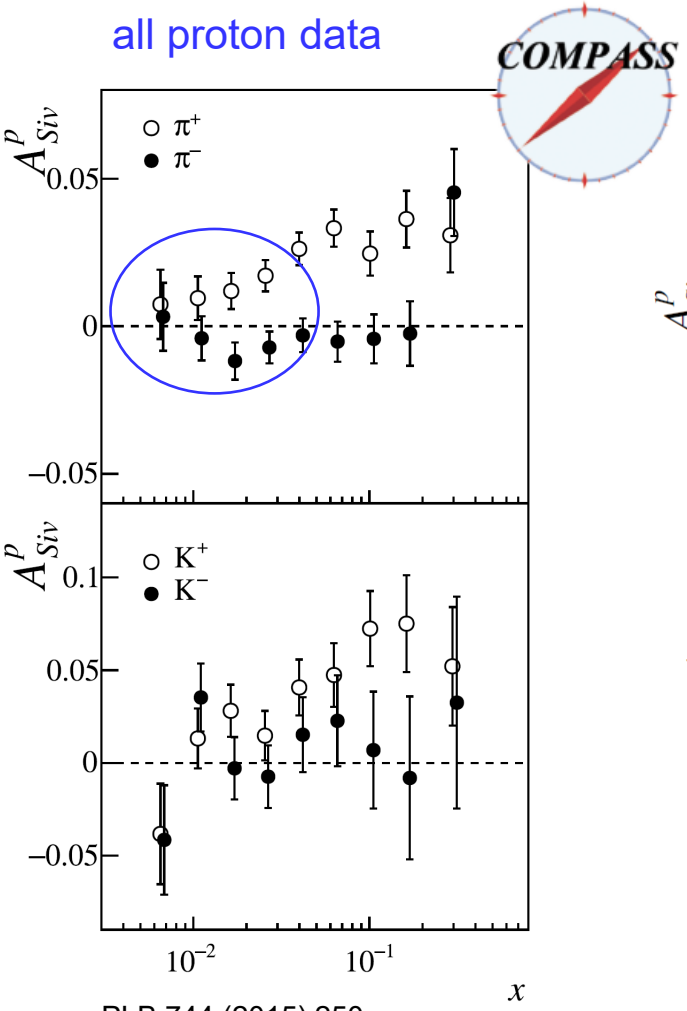

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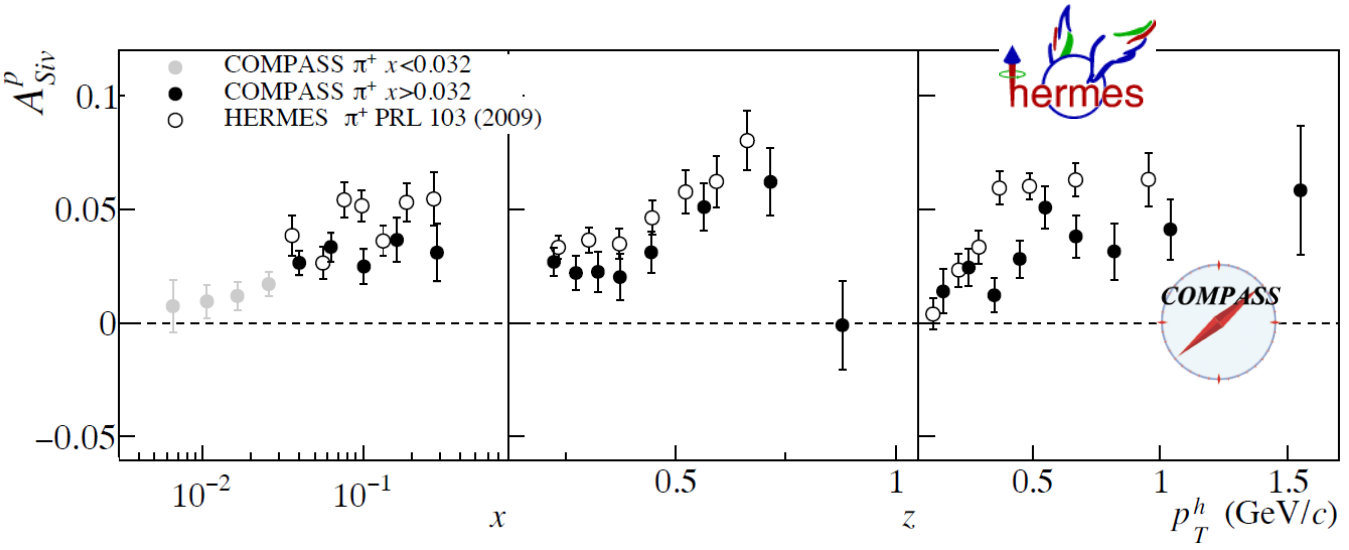
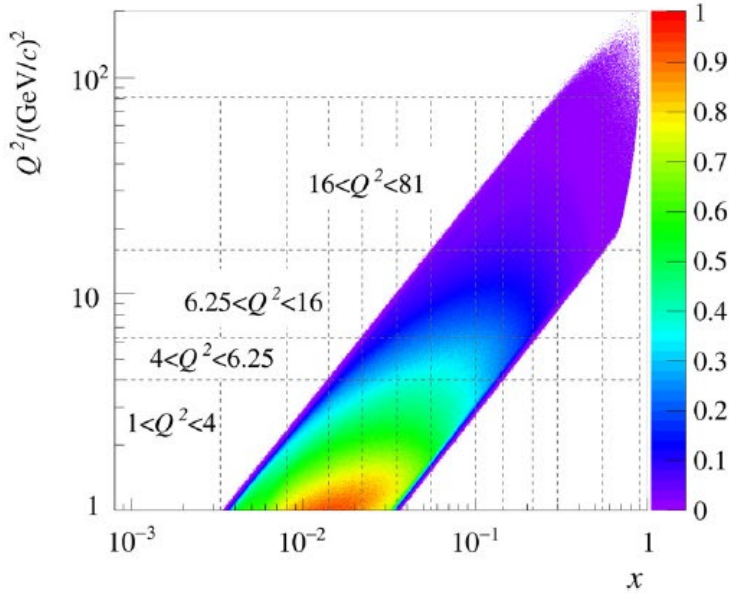


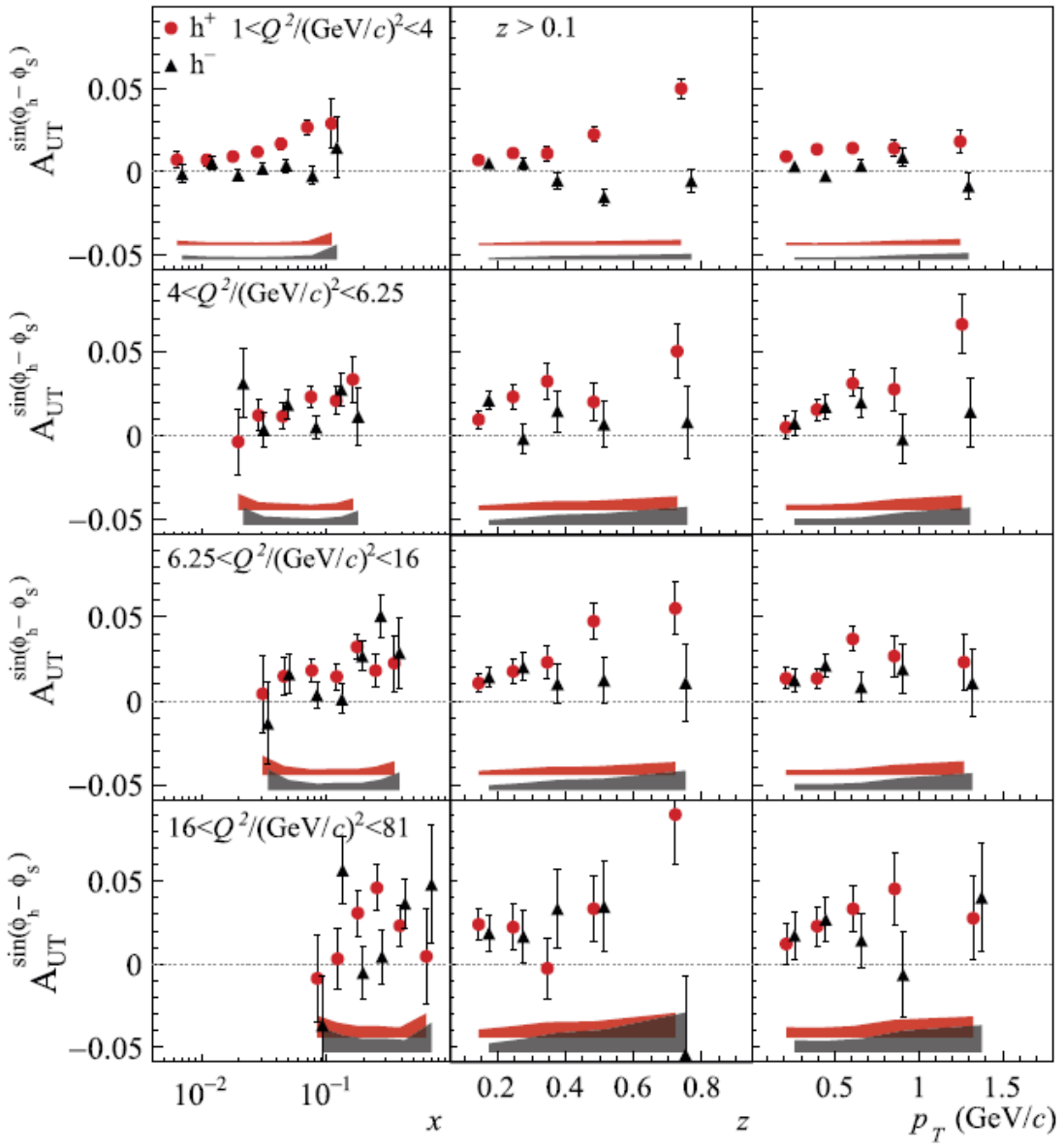
smaller values at COMPASS:
TMD evolution …

proton target - Sivers asymmetry

measured for $h^{\pm}$ as function of x, z, P_T in bins of Q^2

PBL 770 (2017) 138





no indication of Q^2 dependence different from zero in all Q^2 bins

relevant for
- measurement of TSAs in Drell-Yan
- TMD evolution

proton target - P_T weighted Sivers asymmetry

measured for $h^{\pm}$ as function of x, z

$$A_{Siv} \sim \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}}{\sum_q e_q^2 \, f_1^q \otimes D_{1q}}$$

the convolution over transverse momenta can not be solved analytically without assumptions on the PDFs and FFs dependence on he transverse momenta

usually, "Gaussian ansatz"

$$A_{\mathrm{Siv,G}}(x,z) = \frac{a_{\mathrm{G}} \sum_q e_q^2 x f_{1T}^{\perp\,(1)\,q}(x) z D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)} \qquad a_{\mathrm{G}} \simeq \frac{\pi M}{2\langle P_T \rangle}.$$

if the hadrons are weighted with $w = P_T / zM$ the integral can be evaluated

and

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

for this work, the discussions with A. Efremov and P. Schweitzer as well the paper

Physics Letters B 612 (2005) 233–244

Sivers effect in semi-inclusive DIS and in the Drell–Yan process

A.V. Efremov [a], K. Goeke [b], S. Menzel [b], A. Metz [b], P. Schweitzer [b]

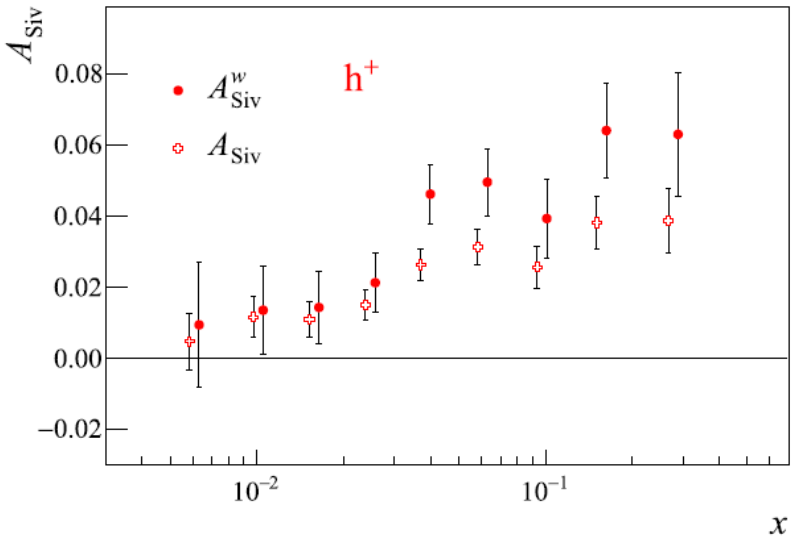
have been very useful!

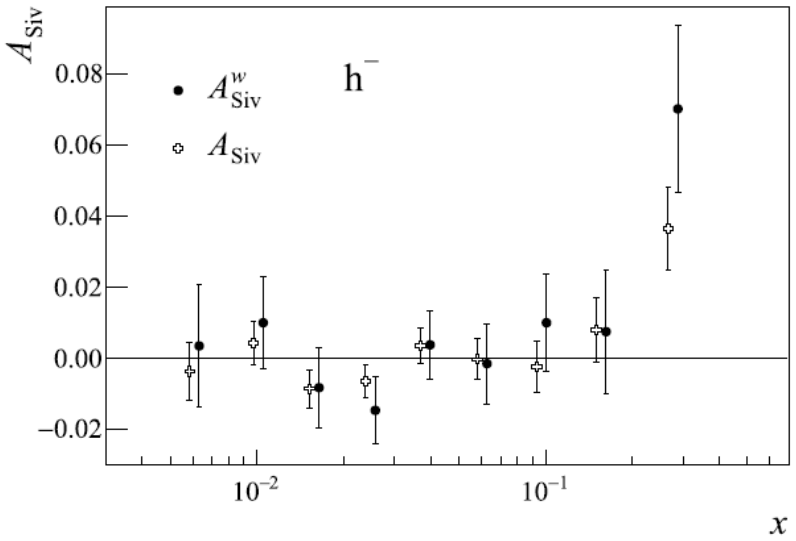
proton target - P_T weighted Sivers asymmetry

measured for $h^{\pm}$ as function of x, z

$$A^{w}_{\mathrm{Siv}}(x,z) = 2\,\frac{\sum_q e_q^2 x f_{1T}^{\perp\,(1)\,q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)} \qquad w = P_T/zM$$

NPB940(2019)34





all results in line with expectations in the TMD framework

Sivers function extracted point-by-point with assumptions, due to missing deuteron data

proton target – other SIDIS TSAs

measured for $h^{\pm}$ as function of x, z

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

subleading twist
similar to HERMES results

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

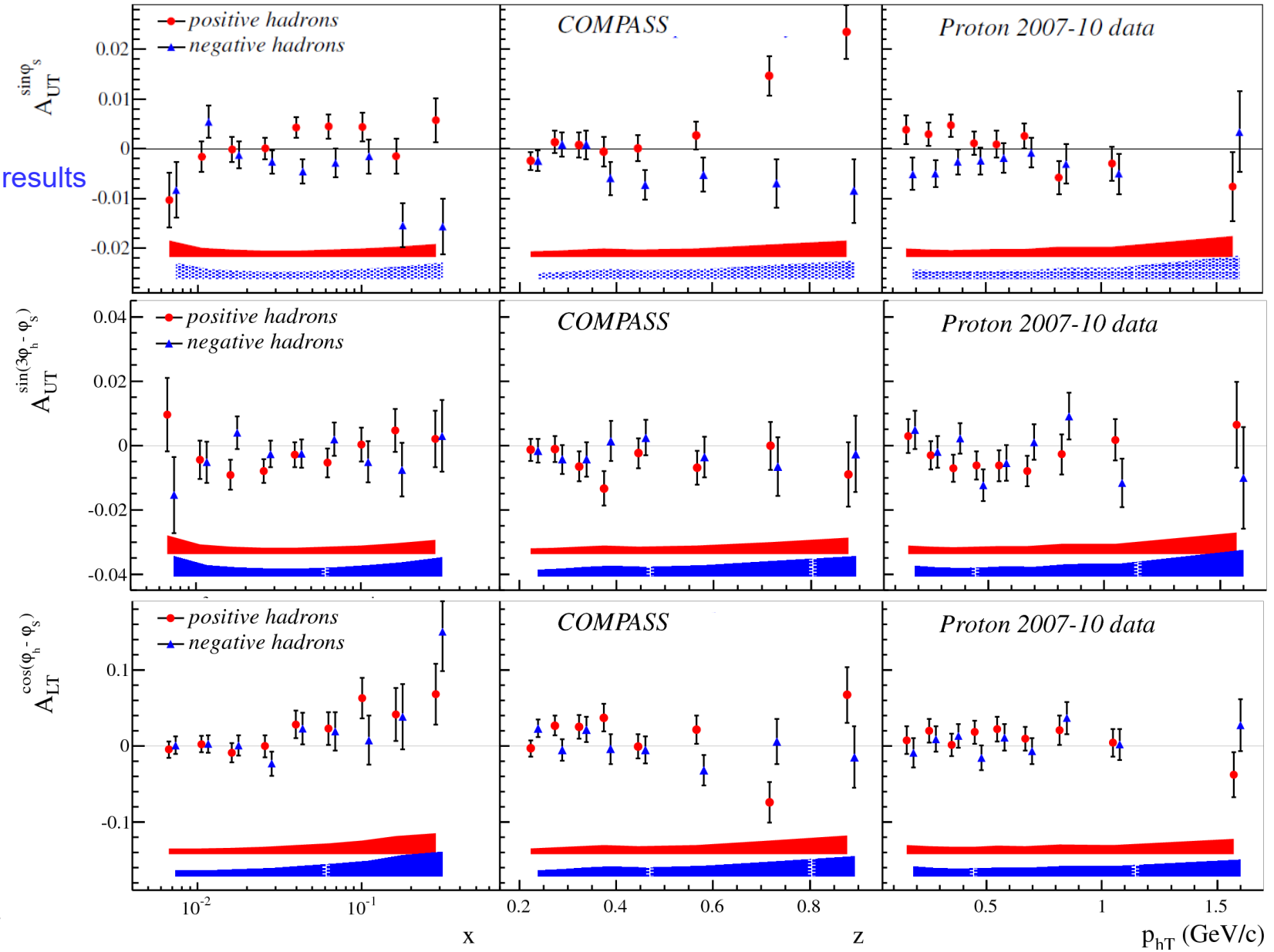
$h_{1T}^{\perp} \otimes H_1^{\perp}$

pretzelosity

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

$g_{1T} \otimes D_1$

worm-gear T
Kotzinian- Mulders



proton target – summary

TSA measurements

- 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
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- Sivers asymmetry in Q^2 bins $h^{\pm}$ — PLB 770 (2017) 138
- P_T-weighted Sivers asymmetries $h^{\pm}$ — NPB 940 (2019) 34
- 1h TSAs beyond Collins and Sivers $h^{\pm}$ — PLB 770 (2017) 138

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proton target – summary

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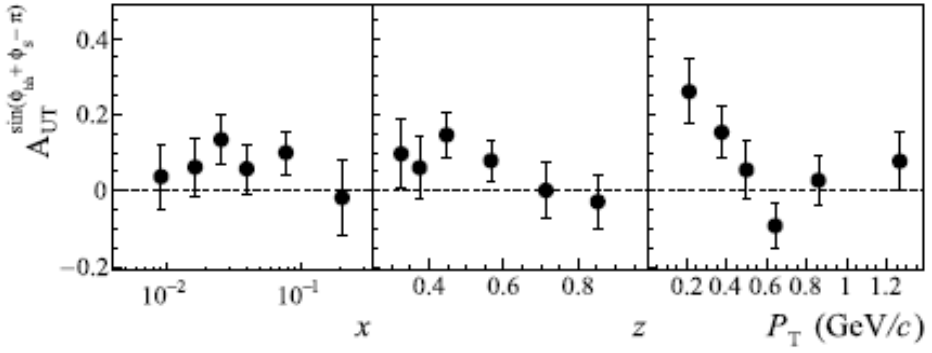
- multiD Collins and Sivers asymmetries $h^{\pm}$
- inclusive ρ^0 Collins and Sivers asymmetries — PLB 843 (2023) 137950



Collins asymmetry in the ρ^0 region

proton target – summary

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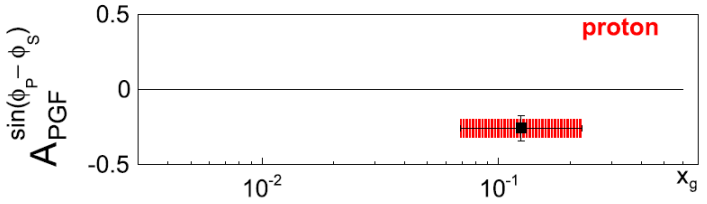
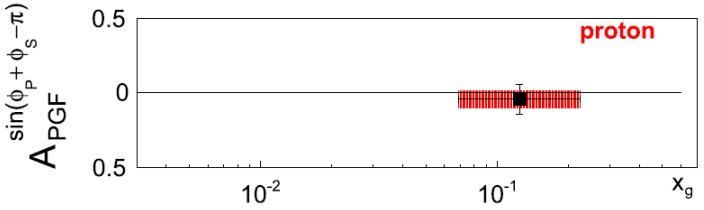
- TSAs for high P_T pairs– gluon Sivers — PLB 772 (2017) 854



Sivers-like



Collins-like



proton target – summary

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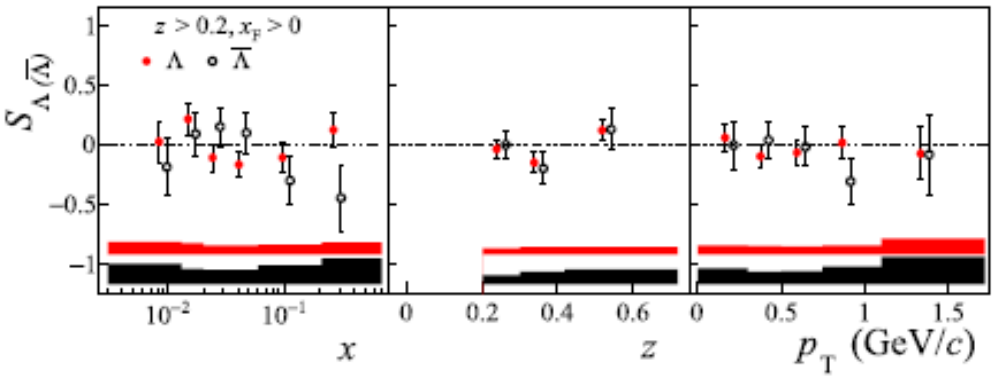
- transversity induced $\Lambda/\bar{\Lambda}$ polarisation — PLB 824 (2022) 136834



Spin transfer

proton target – summary

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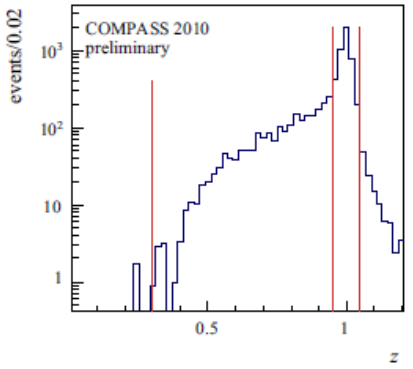

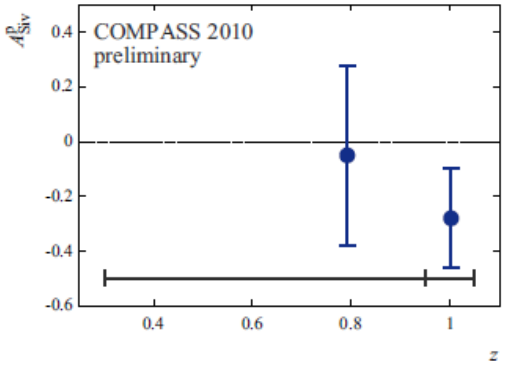

proton target – summary



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- J/Ψ Sivers asymmetry
- …

what about deuteron data?
needed for PDF extractions and to
improve some measurements

COMPASS measurements of SIDIS TSAs

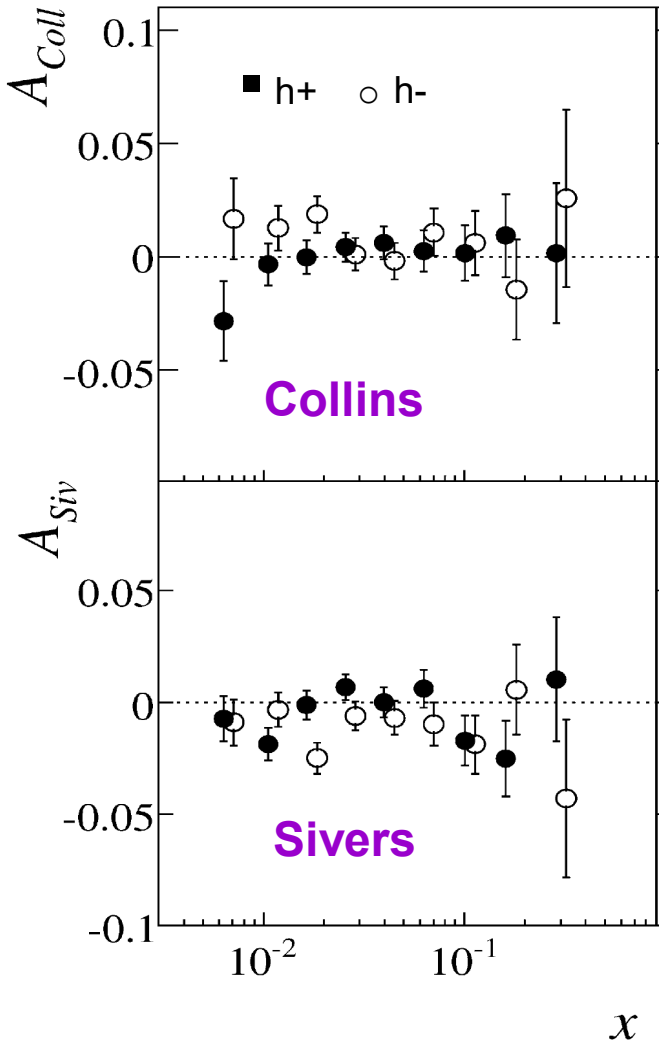
deuteron target

data taking: 2002-2004, low statistics
2022 one full year

deuteron target - Collins and Sivers asymmetries

2002-2004 data: the only existing deuteron data before 2022

JLab6: He3, statistically limited



compatible with zero
important measurements!

COMPASS

deuteron target - Collins and Sivers asymmetries

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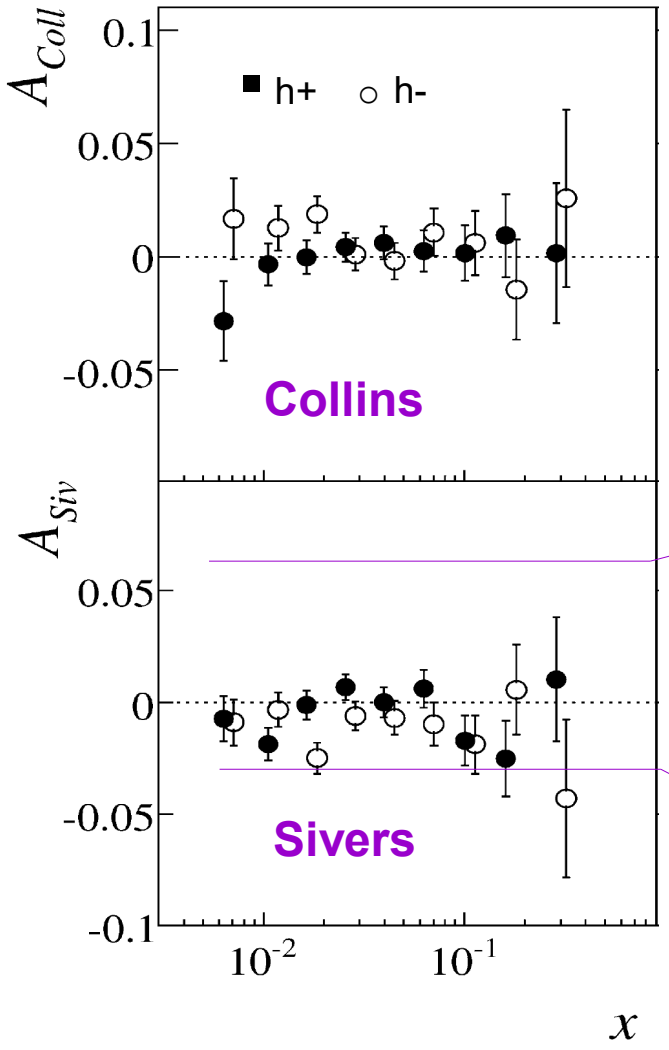
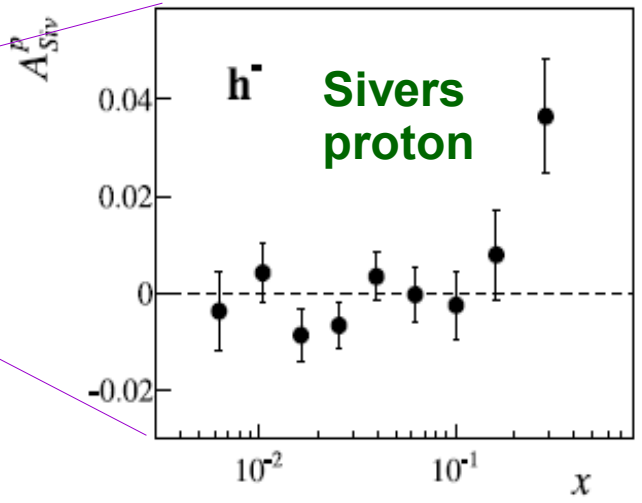


compatible with zero
important measurements!

large statistical uncertainties

much larger than in the proton case



and there are also the p HERMES results…!

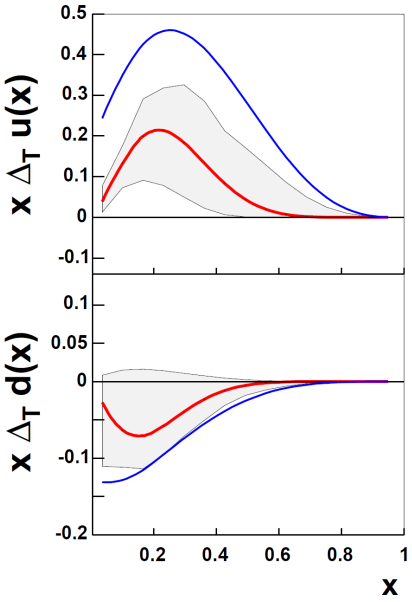
same situation for the dihadron asymmetries

extractions of transversity

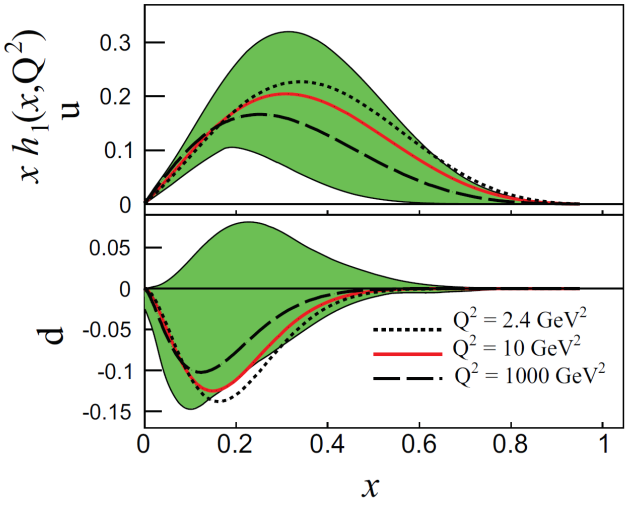
using the 2002-2004 d data

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

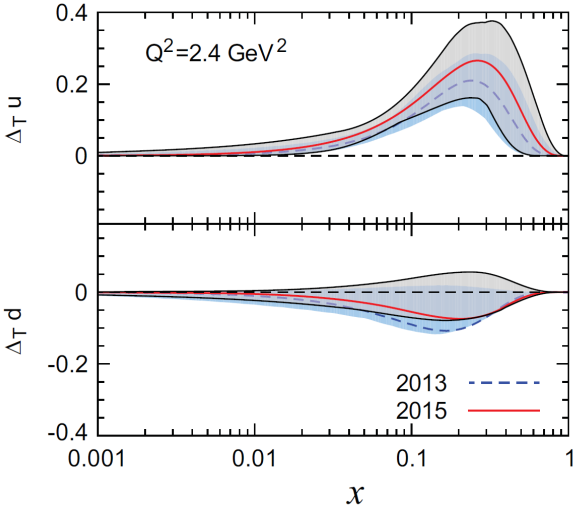
Anselmino et al PRD 2007



Z.-B. Kang et al. PRD 2016

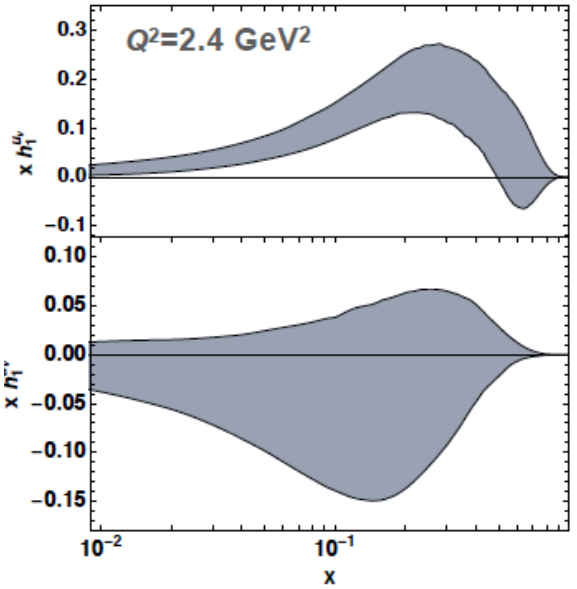


M. Anselmino et al.PRD 2015



phenomenological fits of
dihadron asymmetries
SIDIS, e^+e^-, pp data

Radici Bacchetta PRL 2018



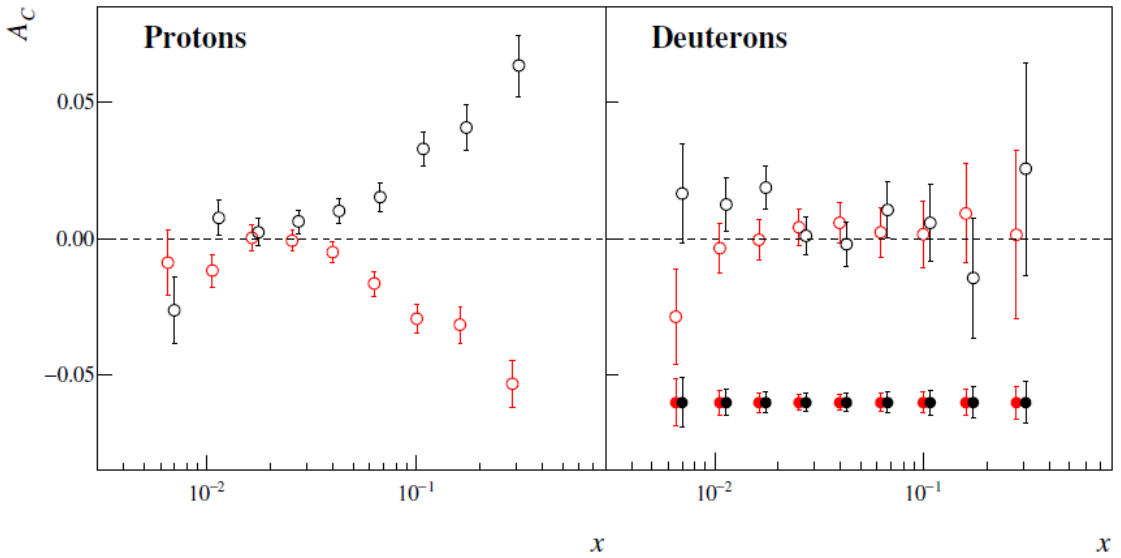
conclusion
u- and d-quark transversity have opposite sign
d-quark PDF much worse determined than u-quark PDF
because of the scarcity of deuteron (neutron) data
much more will be learned using the 2022 d data



deuteron target – the 2022 run

one year of SIDIS data taking with the transversity polarized target

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



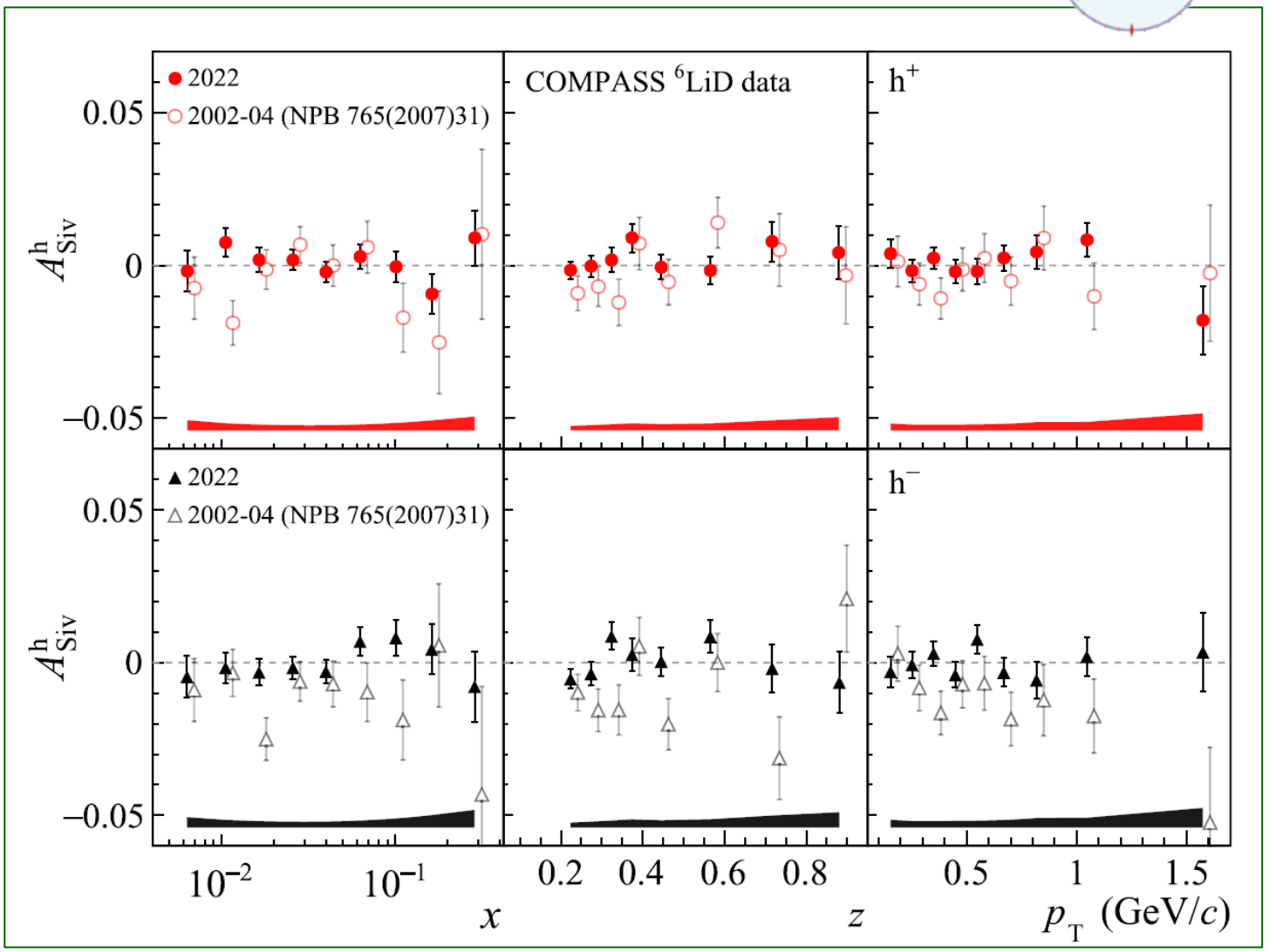
expected statistical uncertainties:
$\sigma^{d}_{2022} \simeq 0.6 \cdot \sigma^{p}_{2010}$
for all the TSAs

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

deuteron target - Sivers asymmetry

2022 data

comparison with results from 2002-2004 data

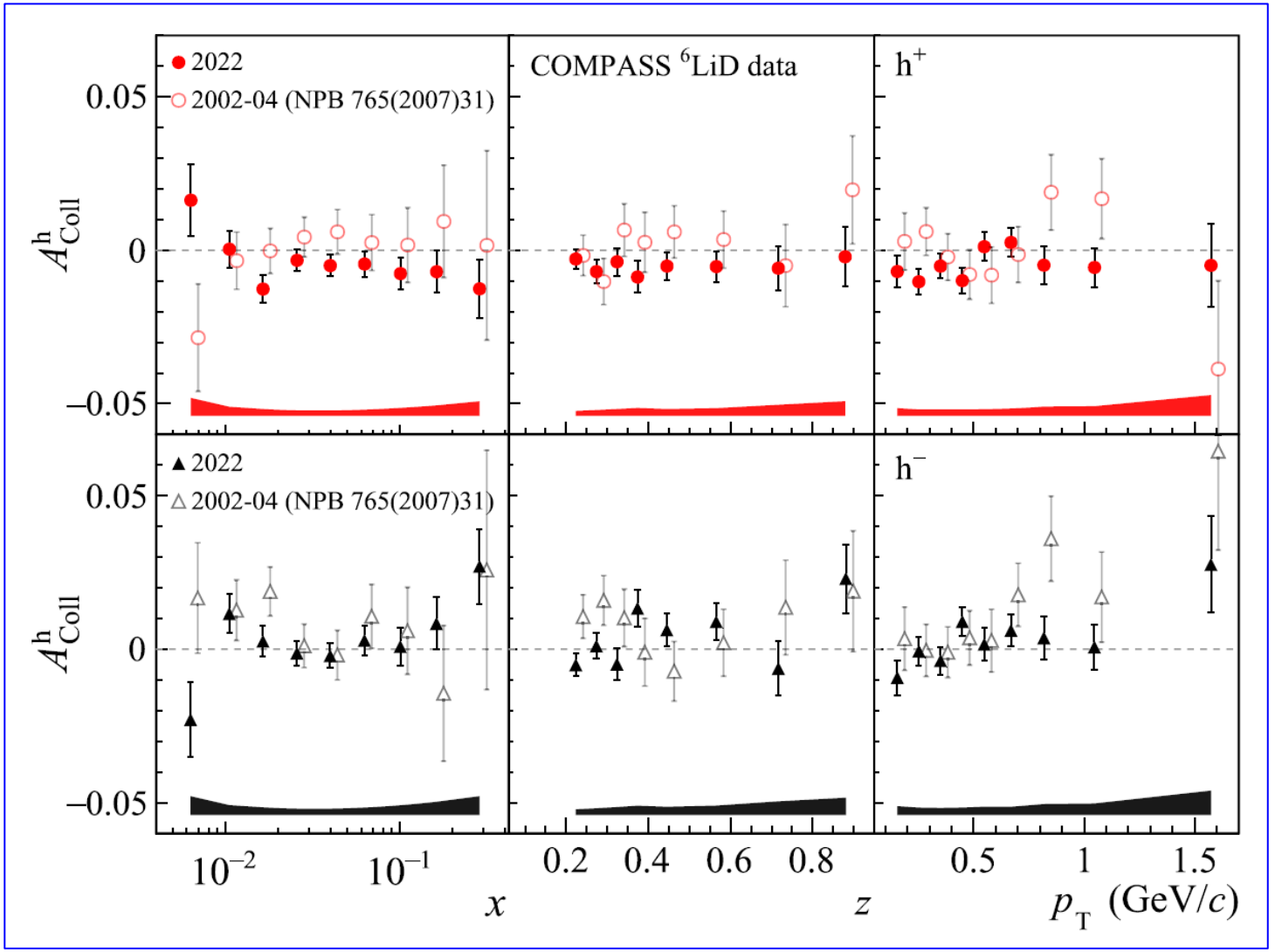


PRL 133 (2024) 101903

deuteron target - Collins asymmetry

2022 data

comparison with results from 2002-2004 data



PRL 133 (2024) 101903

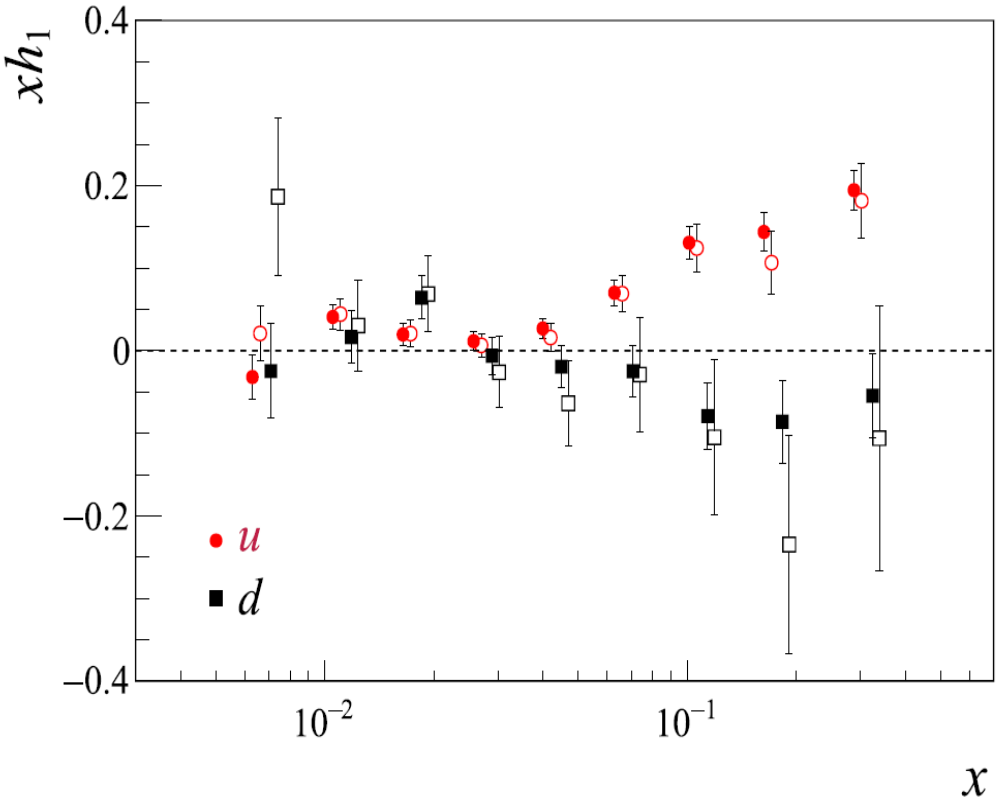
deuteron target - Collins asymmetry

2022 data

impact on transversity
point by point extraction
from COMPASS data

open points:
without 2022 results
closed points:
with 2022 results

- smaller statistical errors
- impressive improvement for $h_1^{d_v}$

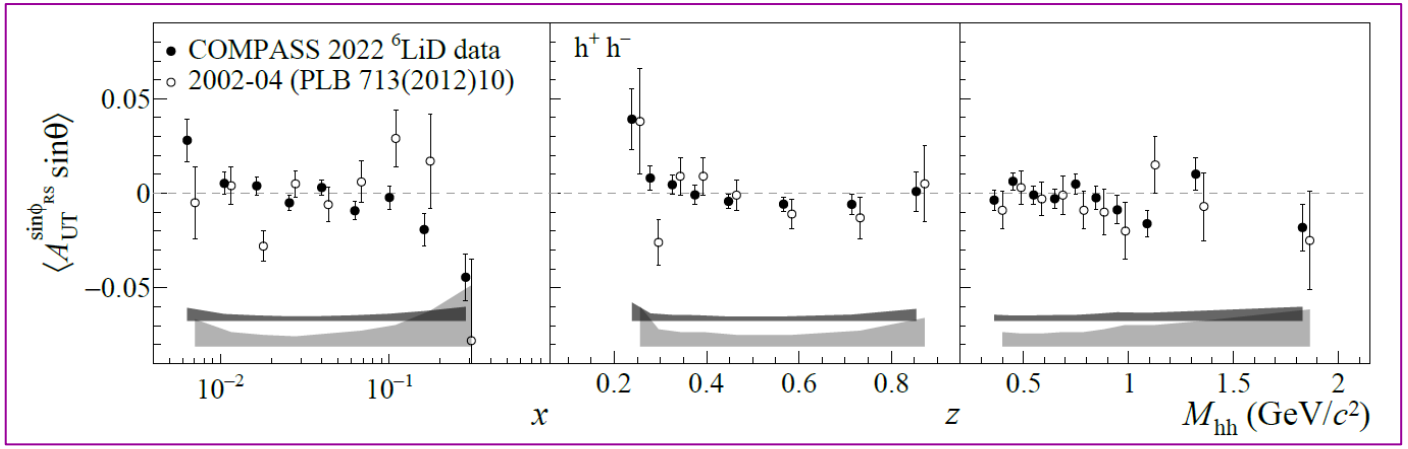


$h_1^{d_v}$ still negative, smaller absolute values

PRL 133 (2024) 101903

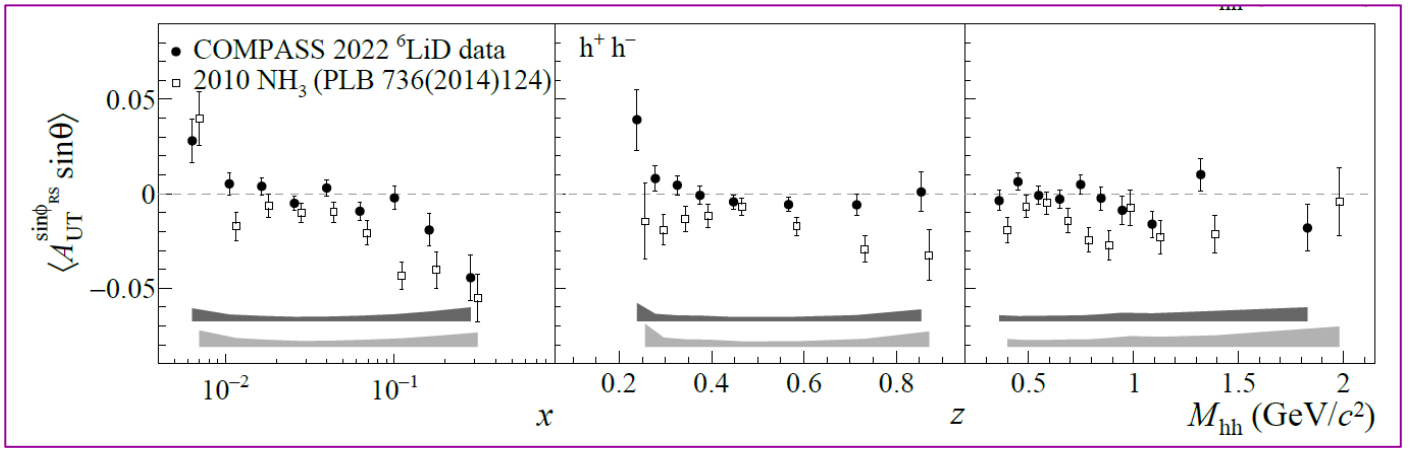
deuteron target - dihadron asymmetry

2022 data



comparison with results from 2002-2004 data

comparison with the proton results



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

dueteron target – summary

- the first measurements of TSA asymmetries on deuteron were performed using the 2002-2004 data
  - compatible with zero
  - large statistical errors
- the high statistics 2022 data allows to perform all the measurements done with the proton data, with similar uncertainties

2022 data

already published

- Collins and Sivers asymmetries $h^{\pm}$ PRL 133 (2024) 101903
- di-hadron TSA $h^{+}h^{-}$ accepted PRL

ongoing (coming soon - some preliminary results already produced)

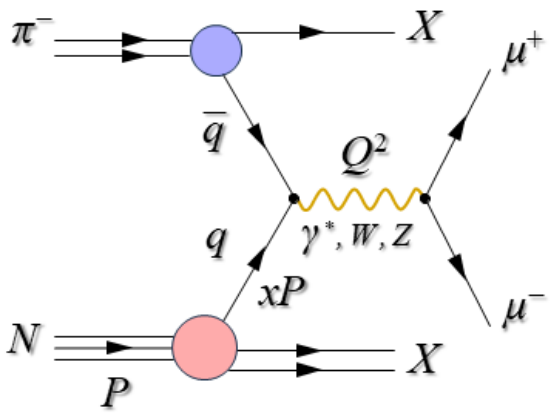
- 1h TSAs beyond Collins and Sivers $h^{\pm}$
- single and dihadron TSAs with PID
- P_T-weighted Sivers asymmetries $h^{\pm}$

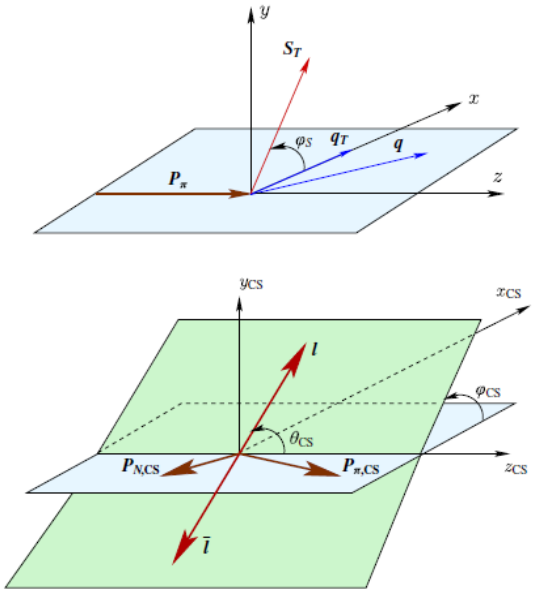
and more will follow
including unpolarized SIDIS measurements

COMPASS measurements of TSAs in pion induced Drell-Yan process



Drell-Yan process





transversely polarized nucleon target

differential cross section

$$\frac{d\sigma}{dq^4 d\Omega} \propto (F_U^1 + F_U^2)(1 + A_U^1 \cos^2\theta_{CS})$$

$$\times \{1 + S_T [D_1 A_T^{\sin\varphi_S} \sin\varphi_S$$

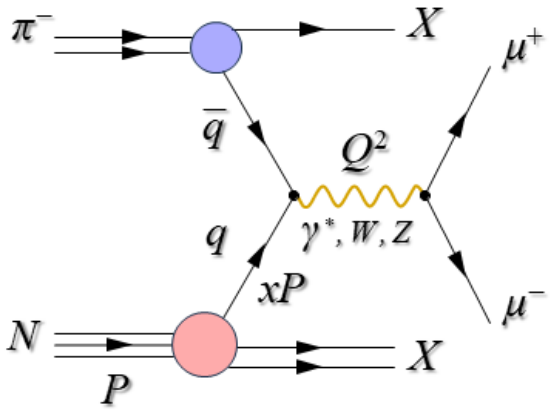
$$+ D_2 (A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS} + \varphi_S)$$

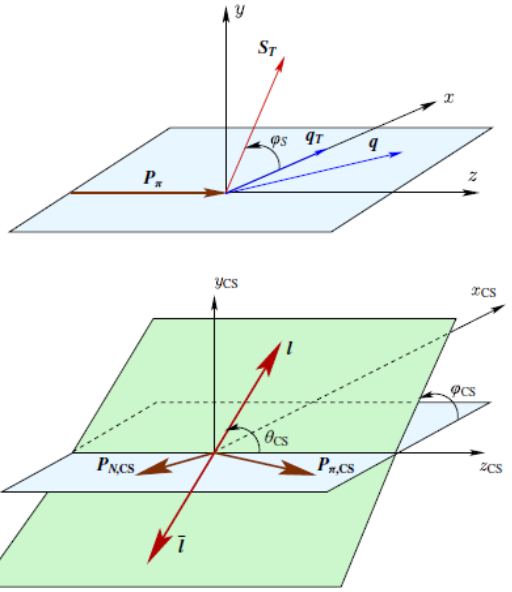
$$+ A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S))$$

$$+ D_3 (A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS} + \varphi_S)$$

$$+ A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS} - \varphi_S))] \}$$

Drell-Yan process





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$$+ A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS} - \varphi_S))]\}$$

$D_i = D_i(\varphi_{CS}, \lambda)$

like SIDIS …

conv TMD PDFs and FFs → conv between TMD PDFs

$f_{1\pi}^q \otimes f_{1T\,p}^{\perp q}$ Sivers

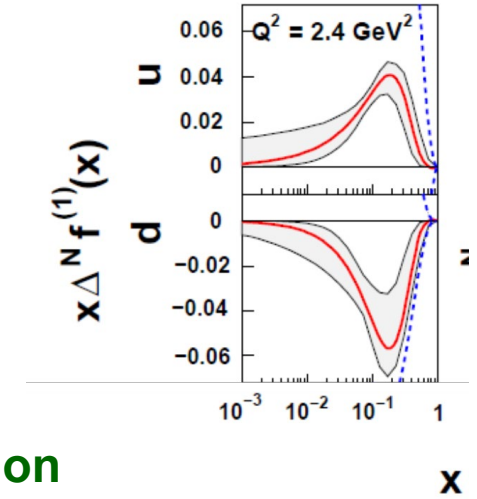
$h_{1\pi}^{\perp q} \otimes h_{1T\,p}^{\perp q}$ Pretzelosity

$h_{1\pi}^{\perp q} \otimes h_{1\,p}^q$ Transversity

Boer-Mulders

Drell-Yan process at COMPASS

once clearly established
that $f_{1T}^{\perp u}$ **and** $f_{1T}^{\perp d}$ **are clearly different from zero**
from SIDIS measurements at high energy too



M. Anselmino et al
EPJA 39, 89 (2009)

the COMPASS Collaboration proposed to measure the
TSAs in pion-induced Drell-Yan muon pair production
to test the "pseudouniversality" of the Sivers function
the strong QCD prediction of **change of sign** of the
T-odd TMD PDFs in Drell-Yan with respect to SIDIS

CERN-SPSC-2010-014 SPSC-P-340 May 17, 2010 COMPASS II proposal: DY and DVCS

- **transversely polarized proton** $(\mathrm{NH_3})$ **target**
- 190 GeV π^- **beam**

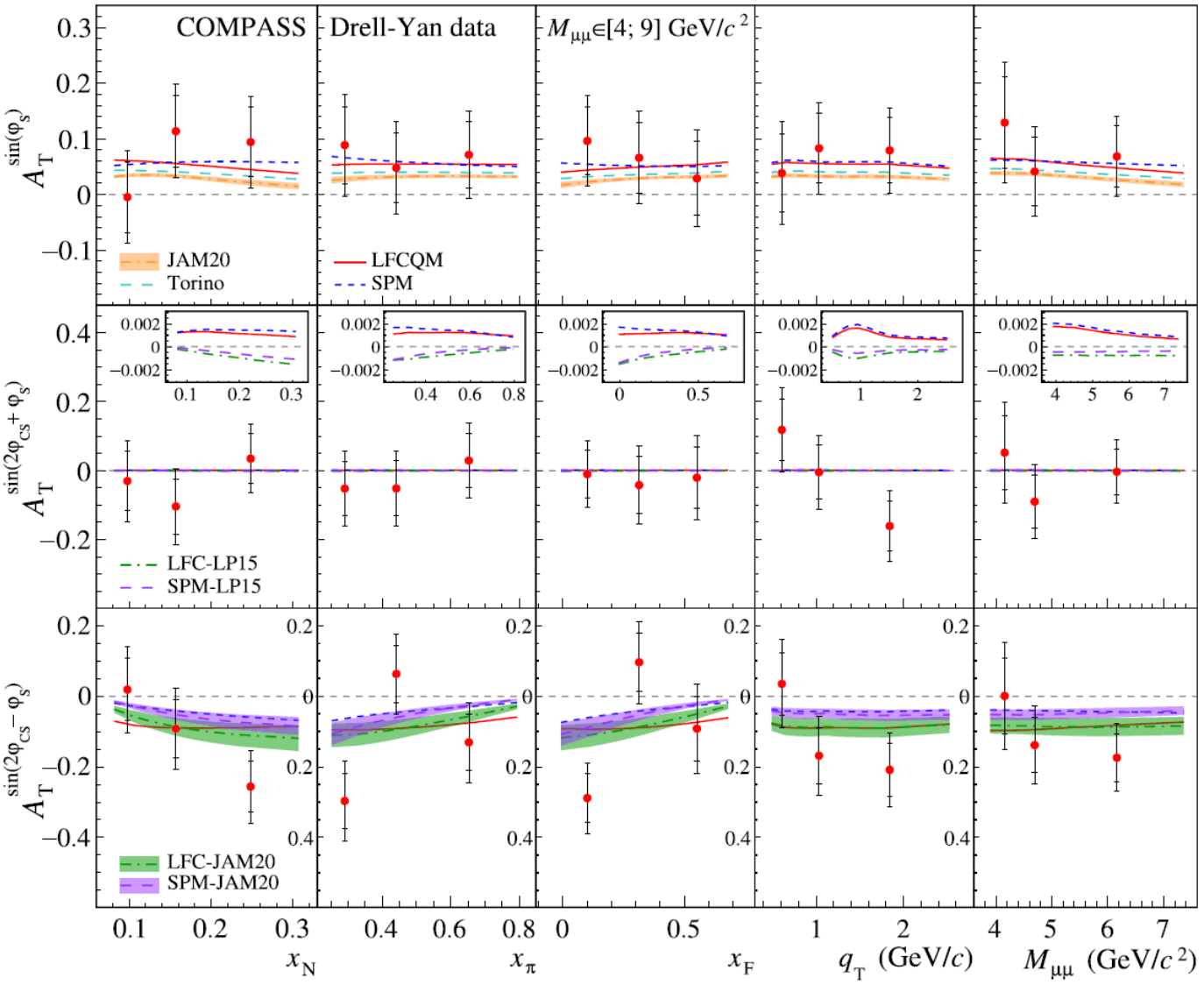
$$A_T^{sin\varphi_S} \propto \sum_q f_{1\pi}^q \otimes f_{1T\,p}^{\perp q} \sim f_{1\pi}^u \otimes f_{1T\,p}^{\perp u}$$

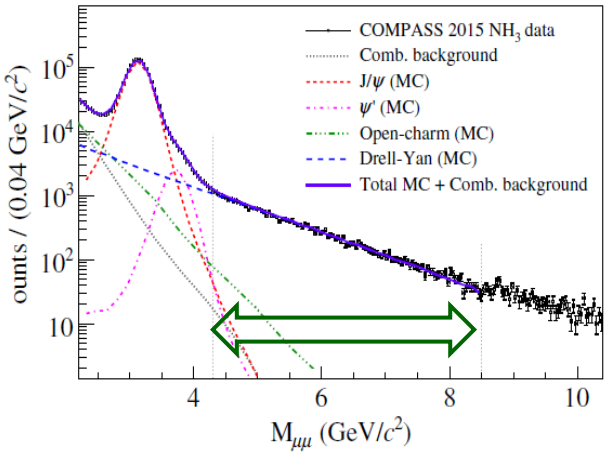
Drell-Yan process at COMPASS

data collected in 2015 and 2018

TSAs final results

PRL133, 071902 (2024)





$$f_{1\,\pi}^{q} \otimes f_{1T\,p}^{\perp q}$$

$$h_{1\,\pi}^{\perp q} \otimes h_{1T\,p}^{\perp q}$$

$$h_{1\,\pi}^{\perp q} \otimes h_{1\,p}^{q}$$

Drell-Yan process at COMPASS

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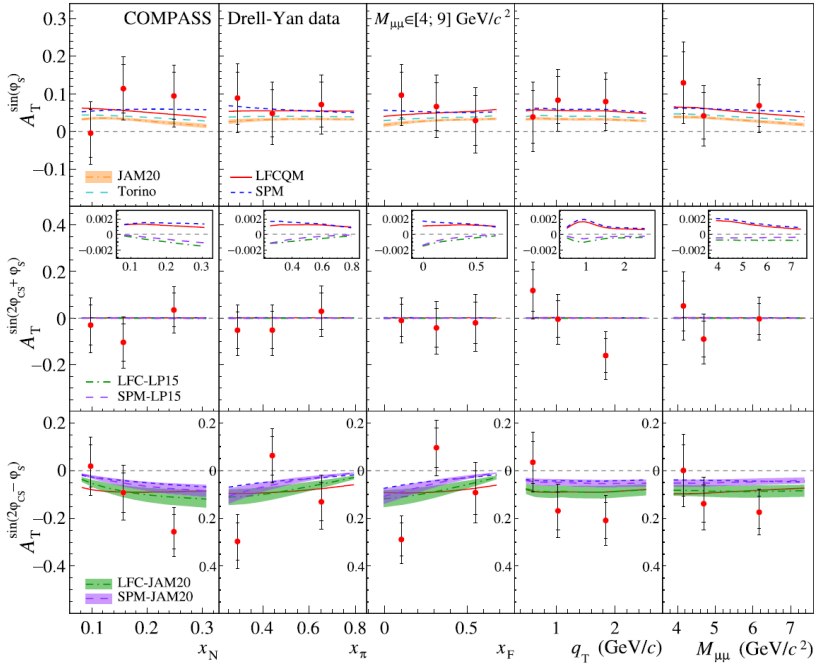
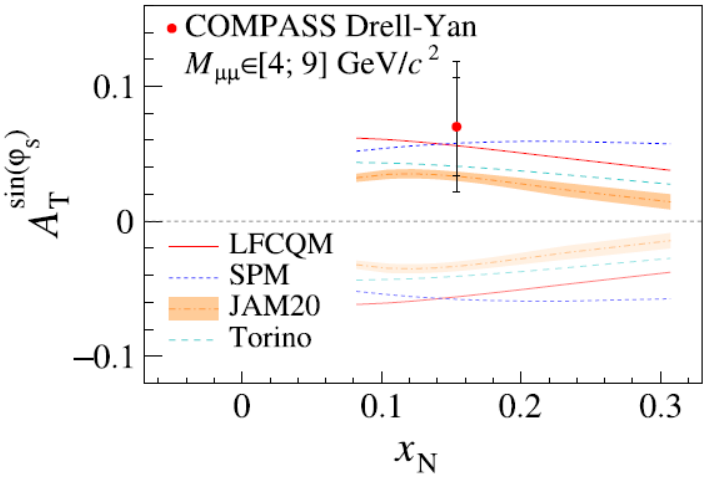
TSAs final results

PRL133, 071902 (2024)



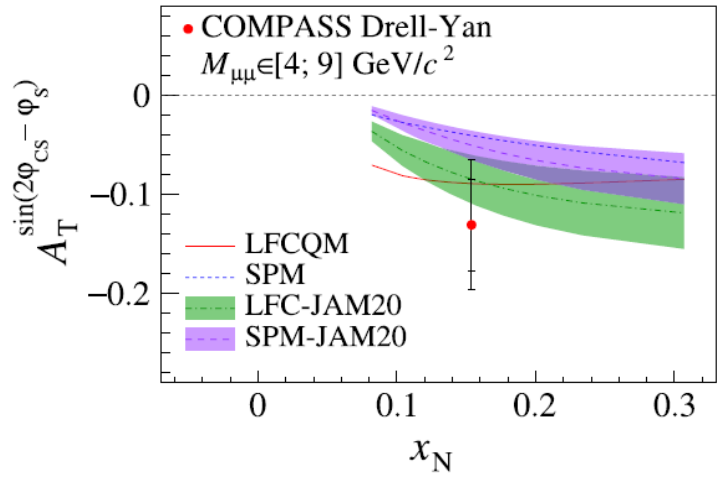


$f_{1\,\pi}^{q} \otimes f_{1T\,p}^{\perp q}$

the Sivers asymmetry tends to be positive

~ 1.5 s.d. from zero

~ 2.5 s.d. from the no-sign-change hypothesis



$h_{1\,\pi}^{\perp q} \otimes h_{1\,p}^{q}$

the Transversity asymmetry is negative

~2 s.d. from zero → $h_{1\,\pi}^{\perp u} > 0$



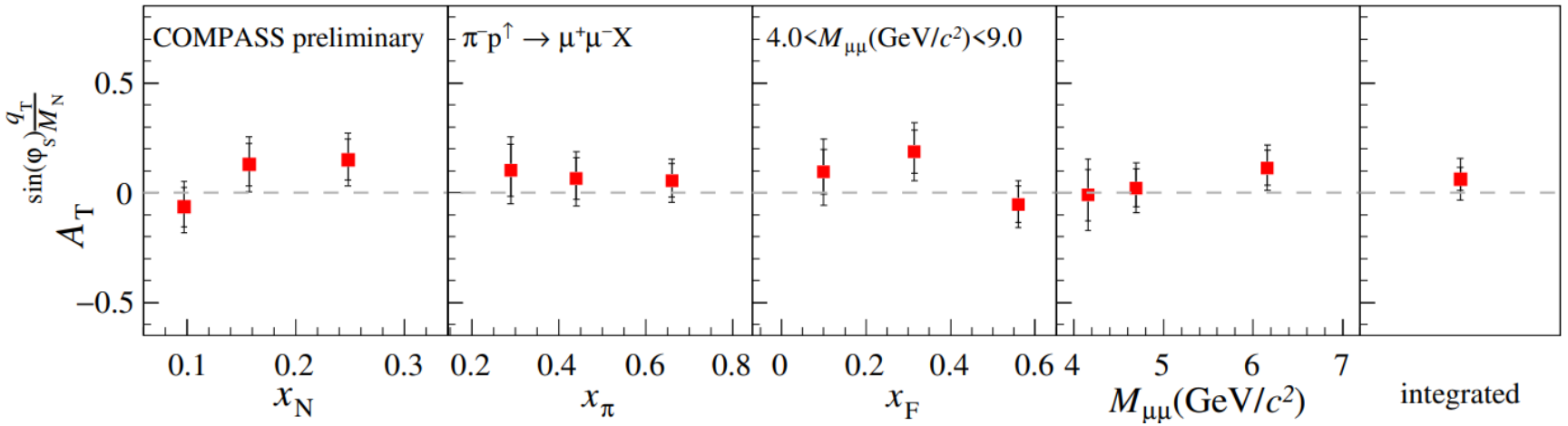
Drell-Yan process at COMPASS

data collected in 2015 and 2018

other measurements

- **q_T-weighted TSAs**

$$f_{1\,\pi}^{q} \otimes f_{1T\,p}^{\perp q} \rightarrow f_{1\,\pi}^{q} \cdot f_{1T\,p}^{\perp q}$$

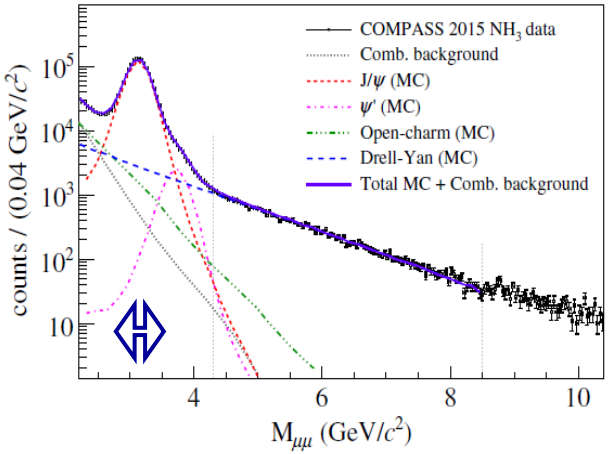


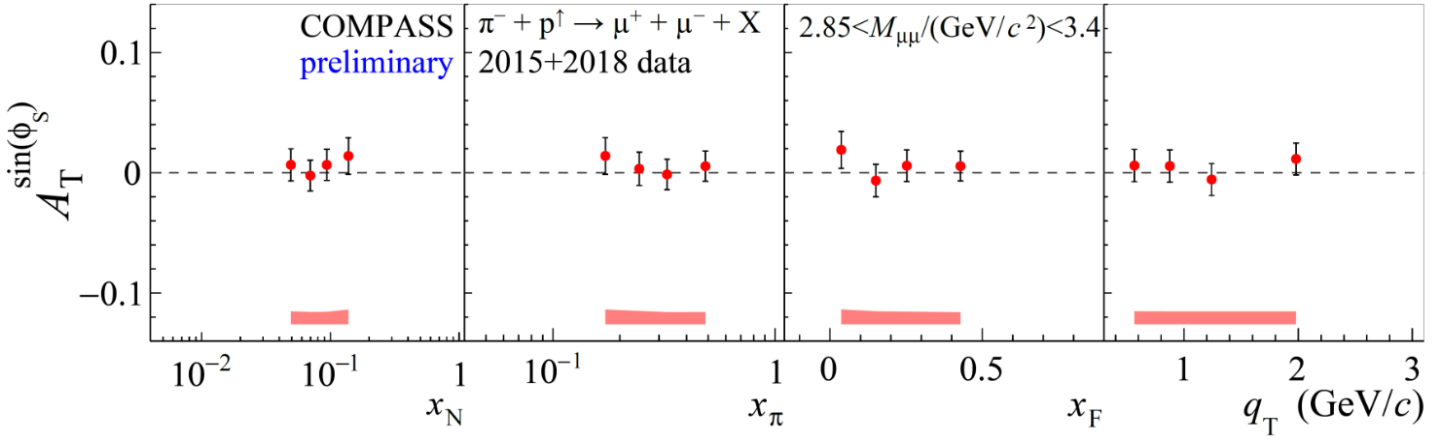
Drell-Yan process at COMPASS

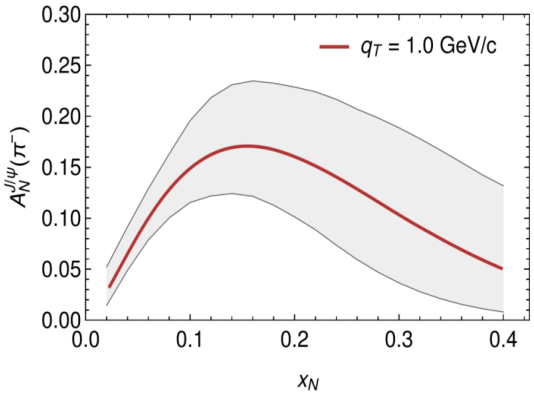
data collected in 2015 and 2018

other measurements

- q_T-weighted TSAs
- **J/Ψ TSAs**







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PLB 770 (2017) 302

Drell-Yan process at COMPASS

data collected in 2015 and 2018

other measurements

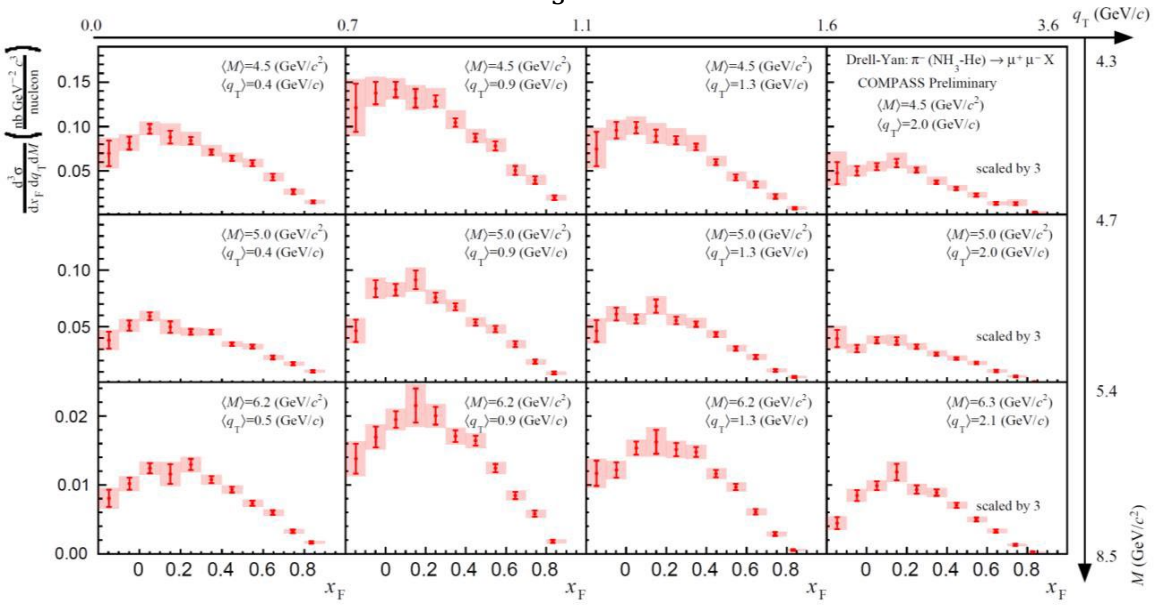
- q_T-weighted TSAs
- J/Ψ TSAs
- **unpolarized cross-sections**

$NH_3 - He$, Al, W targets

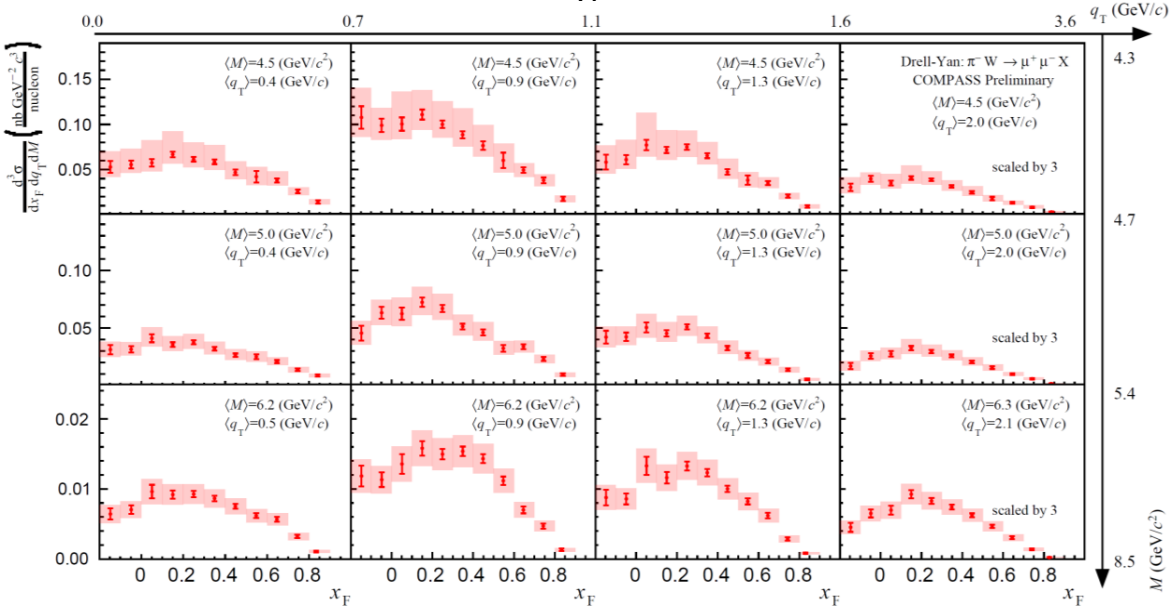
1D/2D/3D results: x_F q_T M

unique data to access
collinear and TMD distributions

$NH_3 - He$



W



Drell-Yan process at COMPASS

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other measurements

- **q_T-weighted TSAs**
- **J/Ψ TSAs**
- **unpolarized cross-sections**

papers in preparation

- **…**

Conclusion

- over many years of measurements, COMPASS has given a remarkable contribution to the study of the transverse spin and transverse momentum structure of the nucleon
- many important results have been produced measuring SIDIS and Drell-Yan with high energy beams and transversely polarised nucleons
- the data collected will stay unique for several years;
  the analysis work continues to produce new and interesting results!