TMD studies with COMPASS

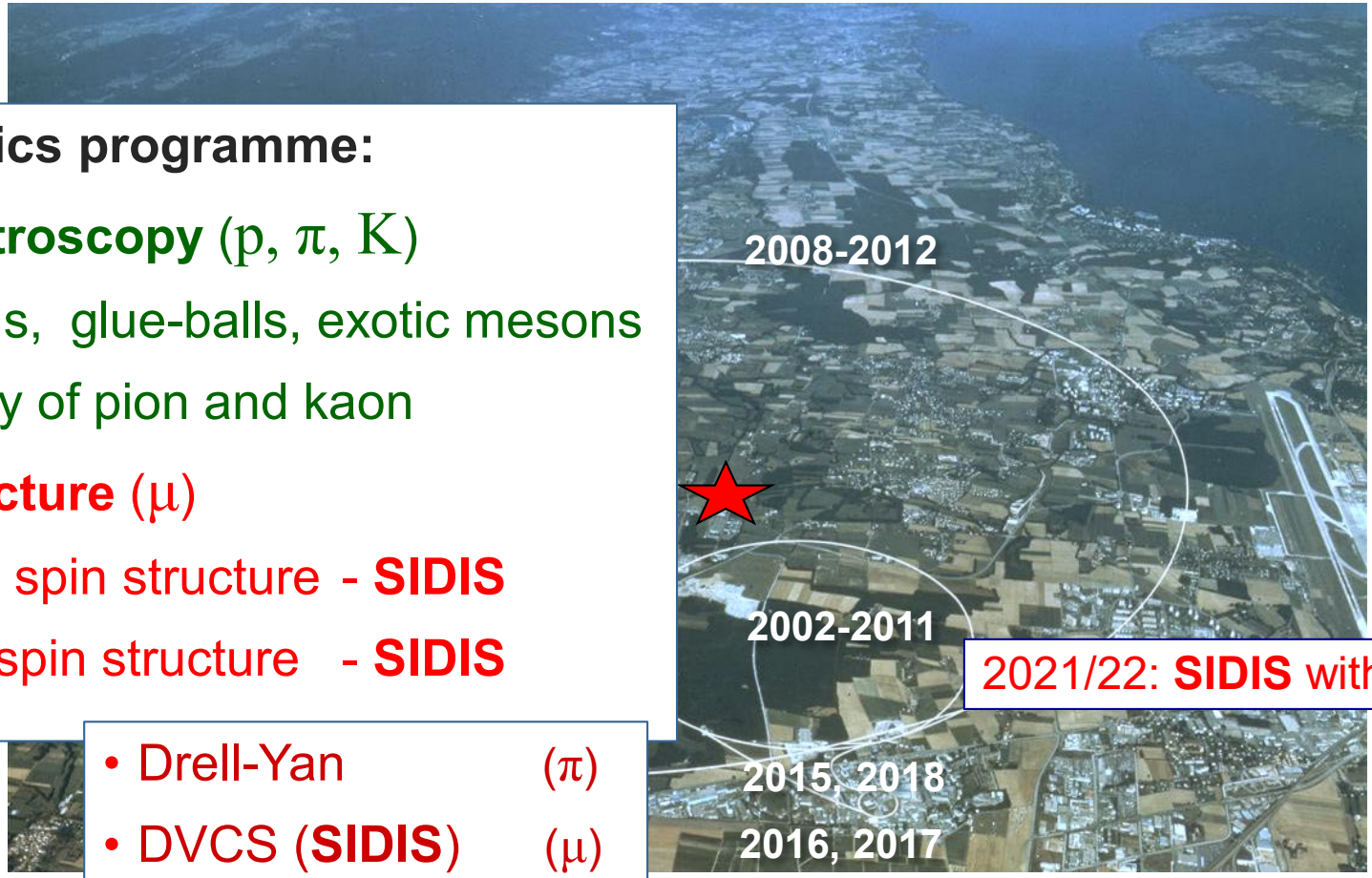
Anna Martin
Trieste University and INFN

TMD Studies: from JLab to EIC, 6-7 May 2021

COMPASS

***CO**mmon*
***M**uon and*
***P**roton*
***A**pparatus for*
***S**tructure and*
***S**pectroscopy*

fix 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**

2021/22: **SIDIS** with d↑

- Drell-Yan (π)
- DVCS (**SIDIS**) (μ)

COMPASS spectrometer – SIDIS with polarized targets

designed to

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

two stages spectrometer

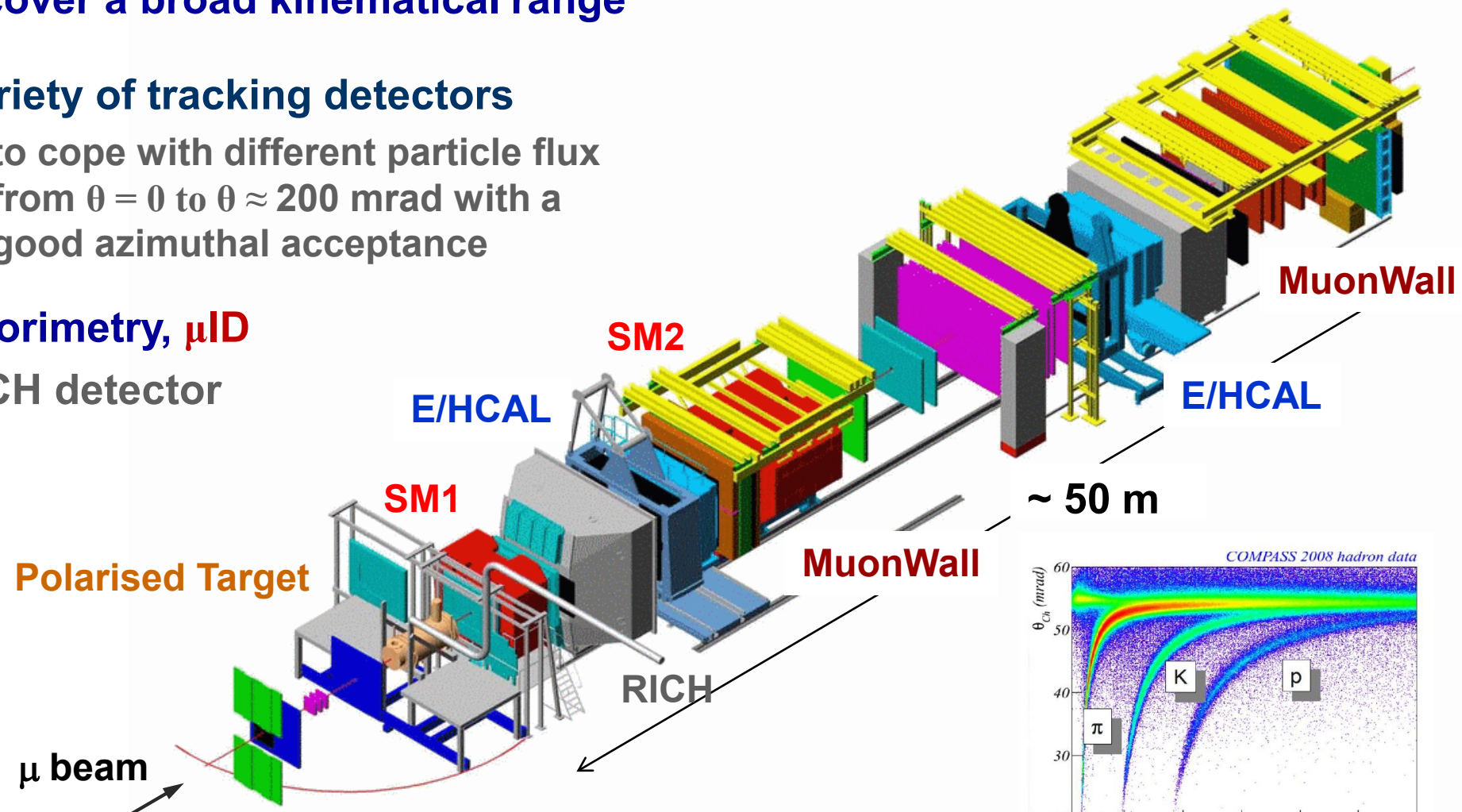
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

variety of tracking detectors

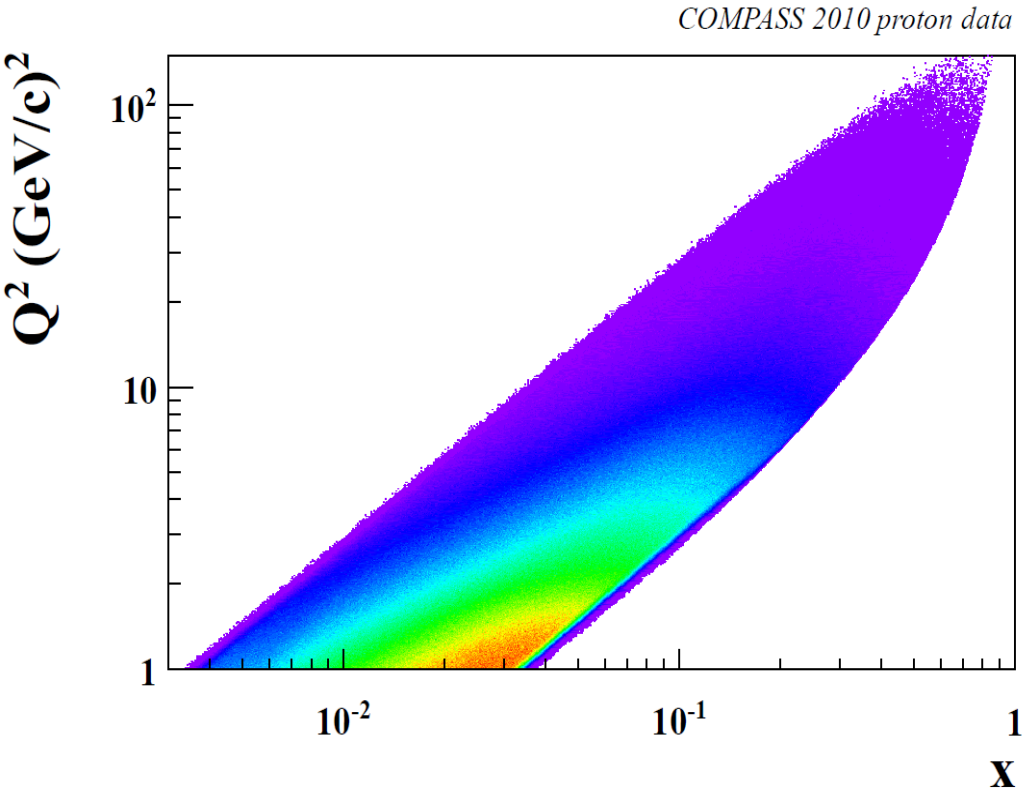
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance

calorimetry, μID

RICH detector



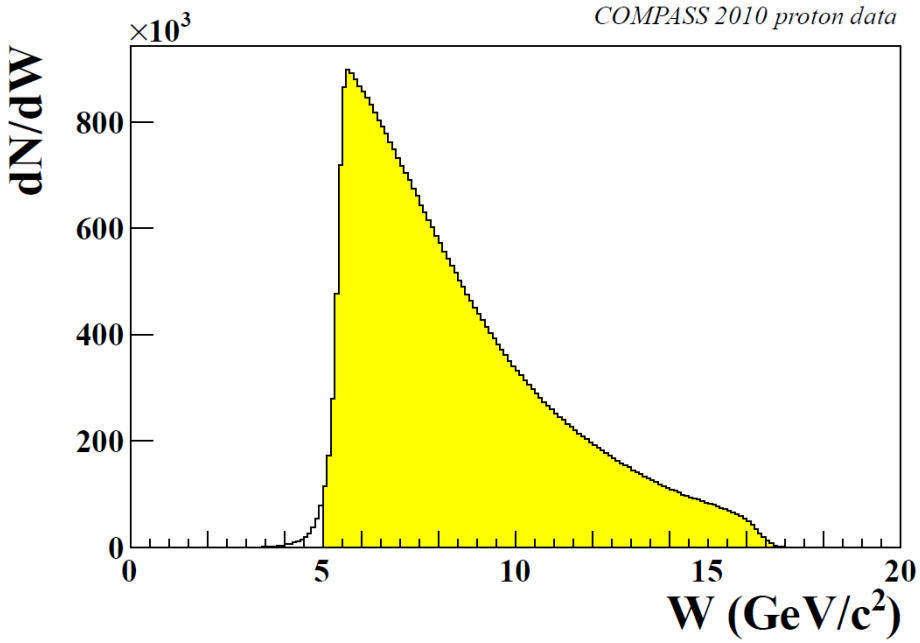
SIDIS kinematic regions



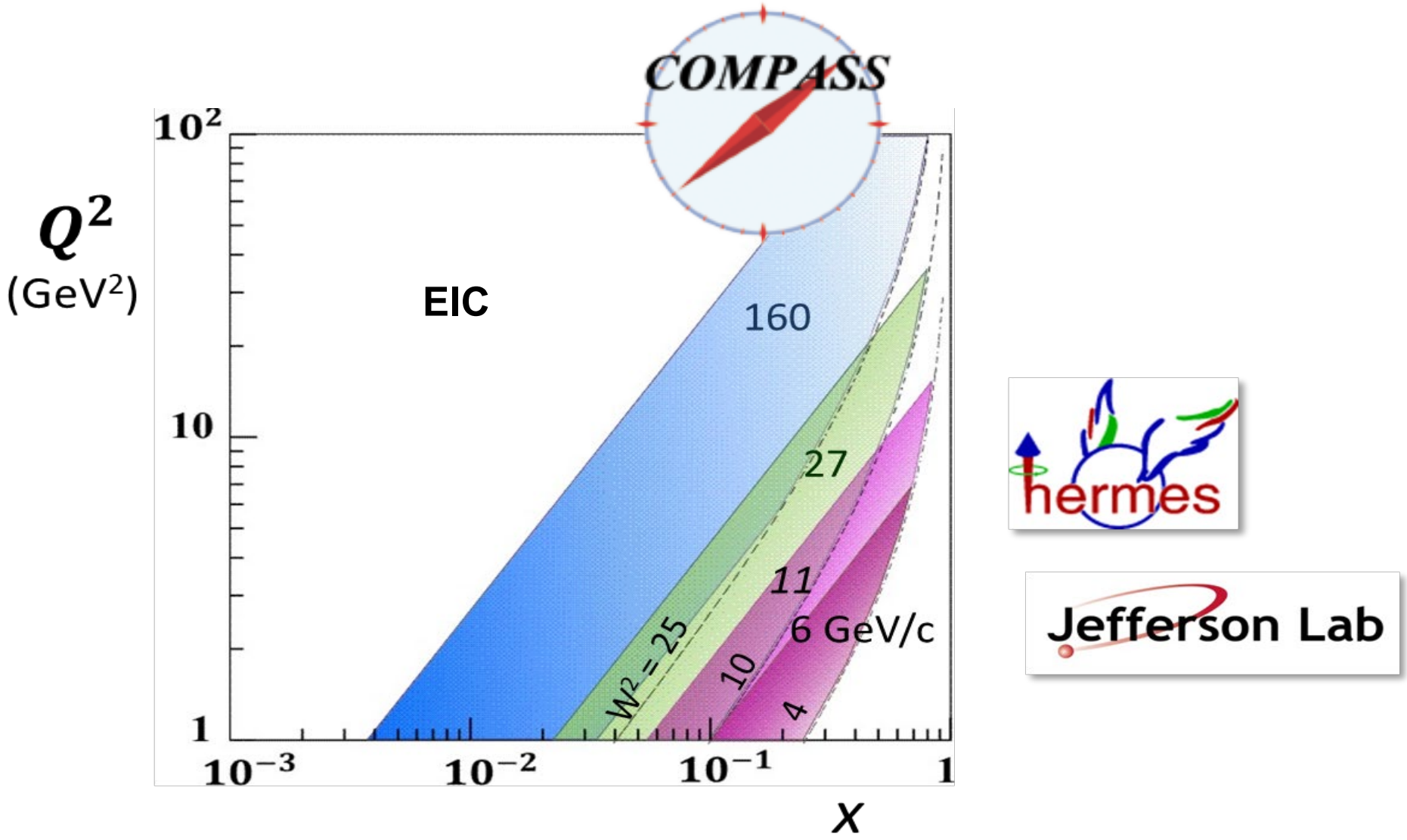
160 GeV μ^+ beam

transversely and longitudinally polarised deuteron (^6LiD) and proton (NH_3) targets

$Q^2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W.5\ GeV/c^2$



SIDIS kinematic regions



some results on

Transverse Spin Asymmetries

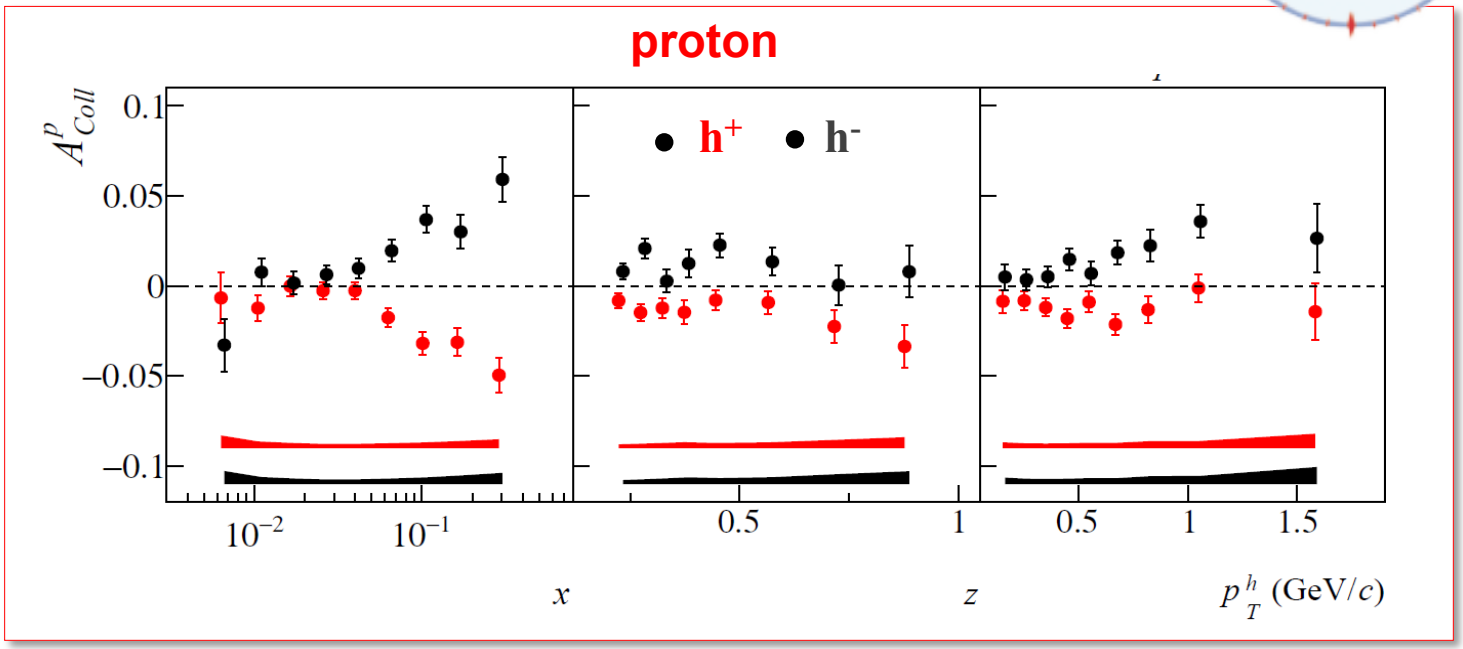
Longitudinal Spin Asymmetries

Unpolarised SIDIS

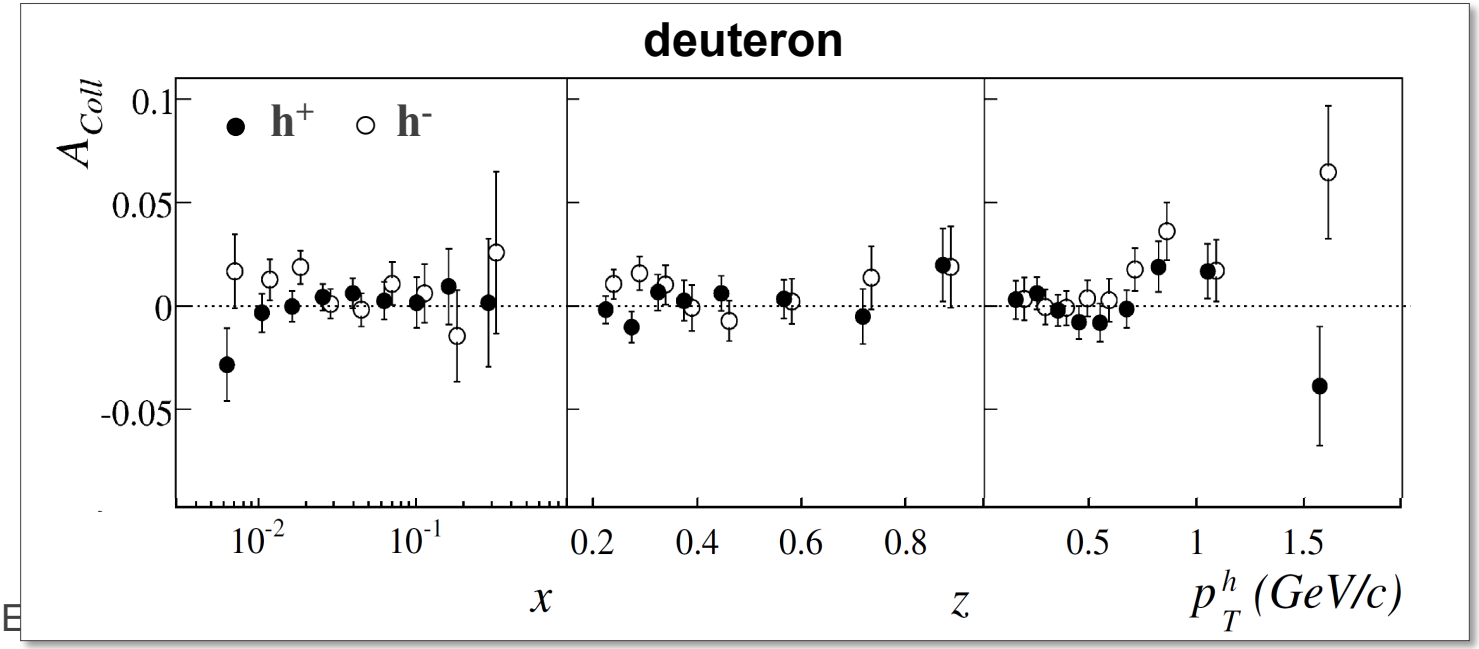
Collins asymmetry

$$A_{Coll}^{h} = \frac{\sum_{q,\bar{q}} e_q^2 x \boldsymbol{h_1^q} \otimes H_{1q}^{\perp h}}{\sum_{q,\bar{q}} e_q^2 x f_1^q \otimes D_{1q}^{h}}$$

Phys. Lett. B 717 (2012) 376



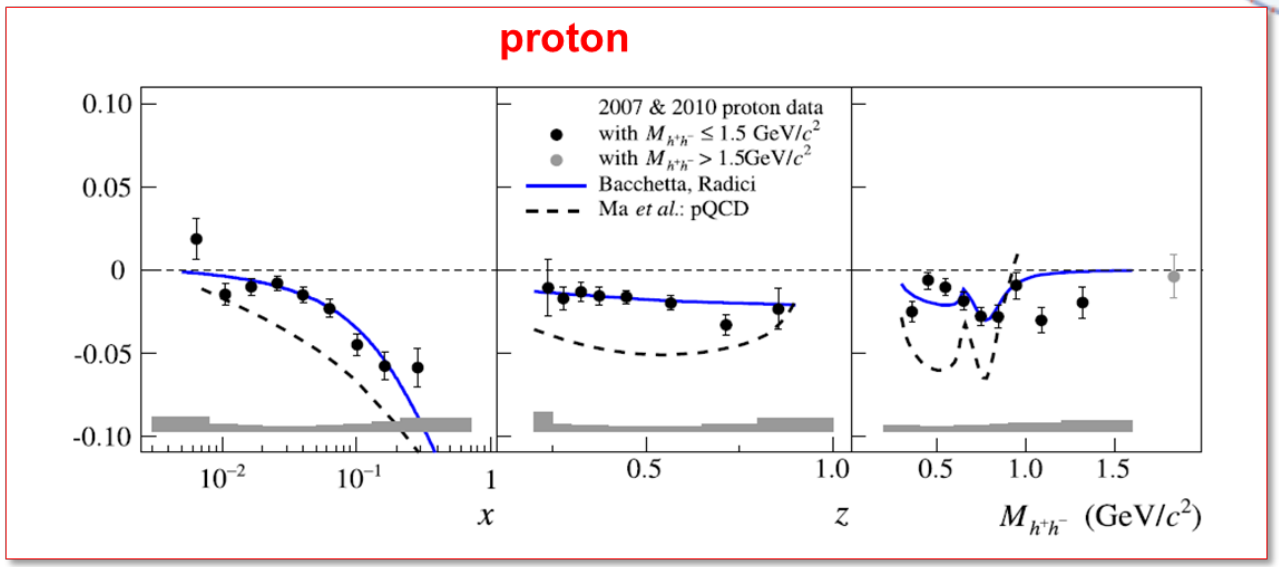
Nucl. Phys. B765 (2007) 31



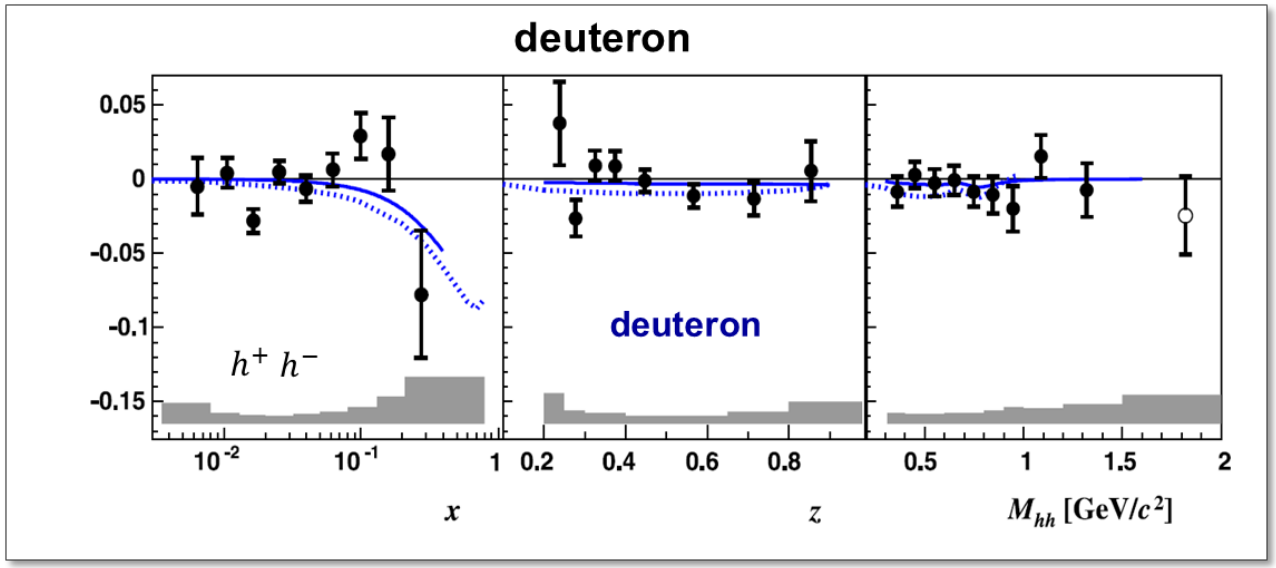
di-hadron asymmetry

$$A^{hh} = \frac{\sum_{q,\bar{q}} e_q^2 x \boldsymbol{h_1^q} H_{1q}^{\sphericalangle}}{\sum_{q,\bar{q}} e_q^2 x f_1^q D_{1q}^{hh}}$$

Phys. Lett. B 736 (2014) 124



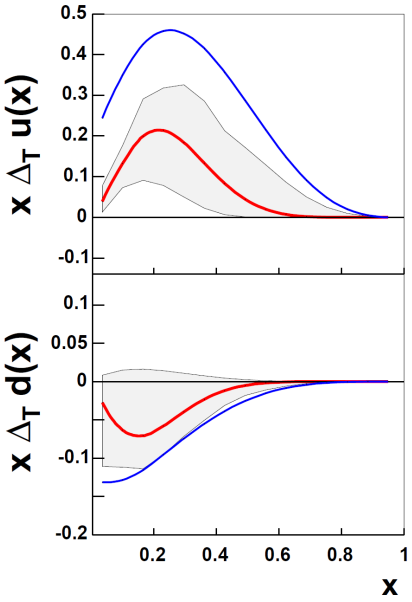
Phys. Lett. B 713 (2012) 10



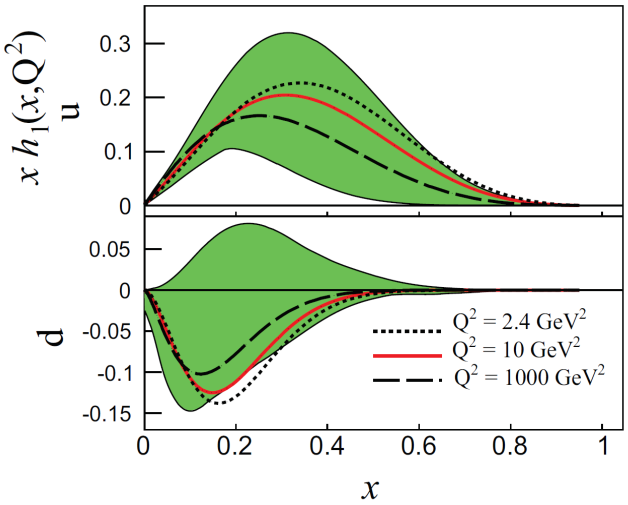
extractions of transversity

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

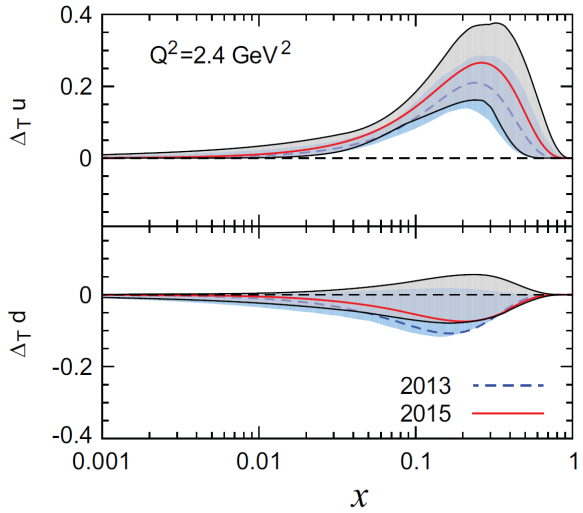
Anselmino et al PRD **2007**



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

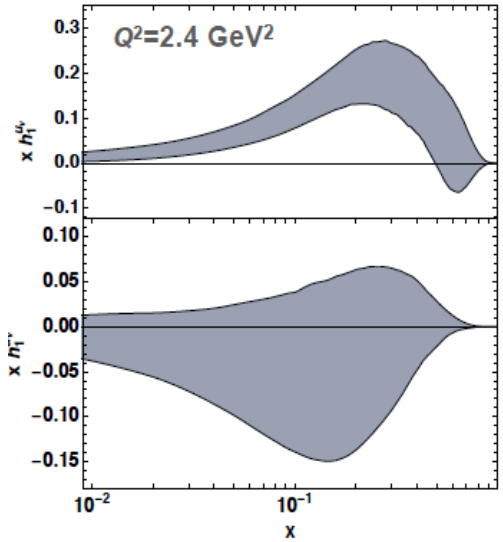


M. Anselmino et al.PRD **2015**



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

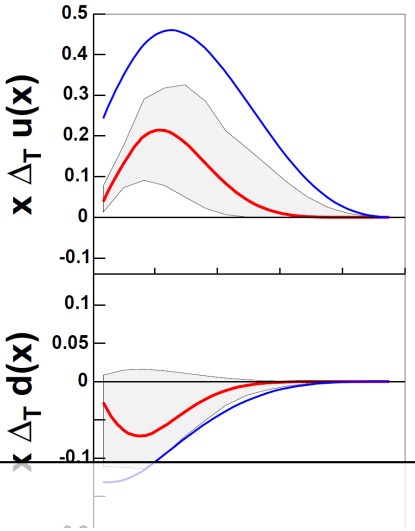
Radici Bacchetta PRL **2018**



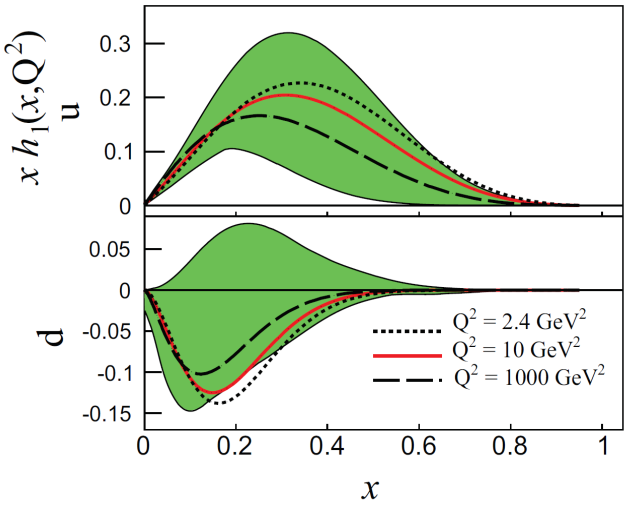
extractions of transversity

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

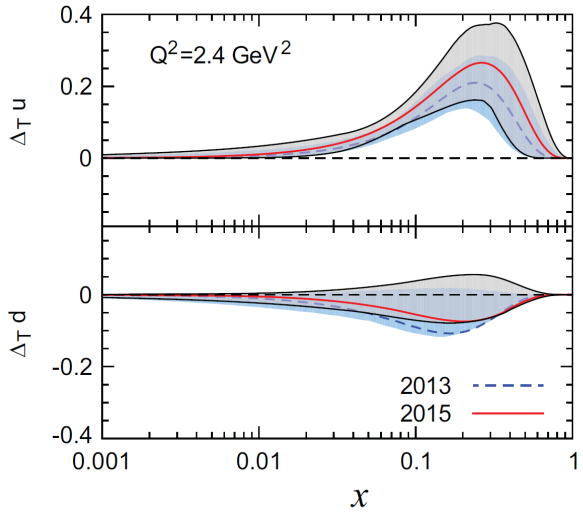
Anselmino et al PRD **2007**



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

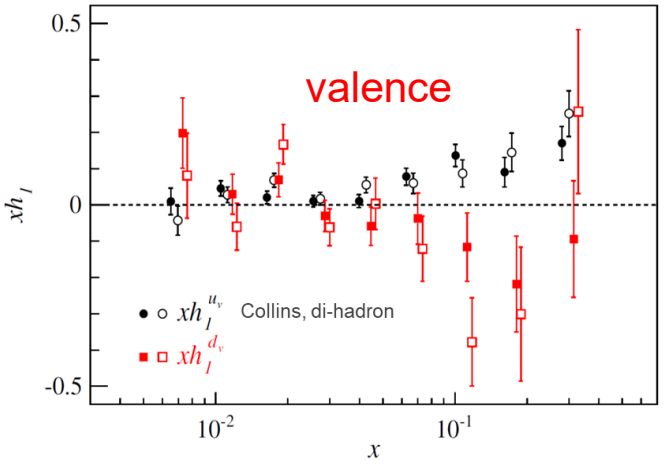


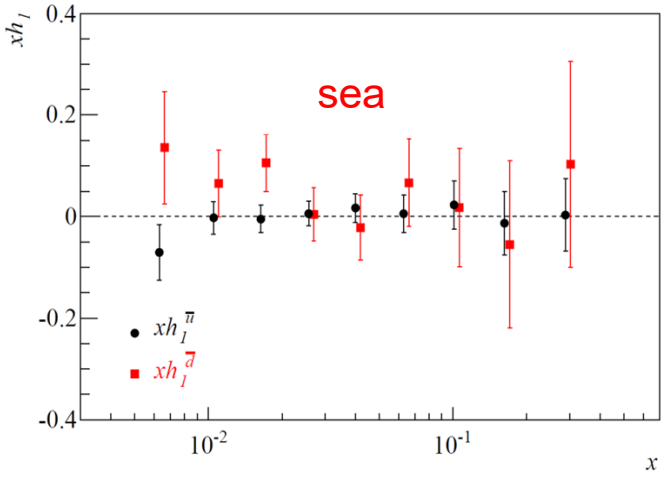
M. Anselmino et al.PRD **2015**



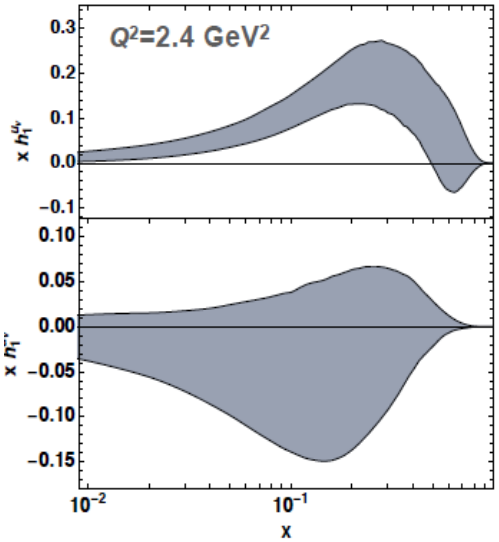
global fits of
di-hadron asymmetries
SIDIS, e^+e^-, pp data

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





Radici Bacchetta PRL **2018**

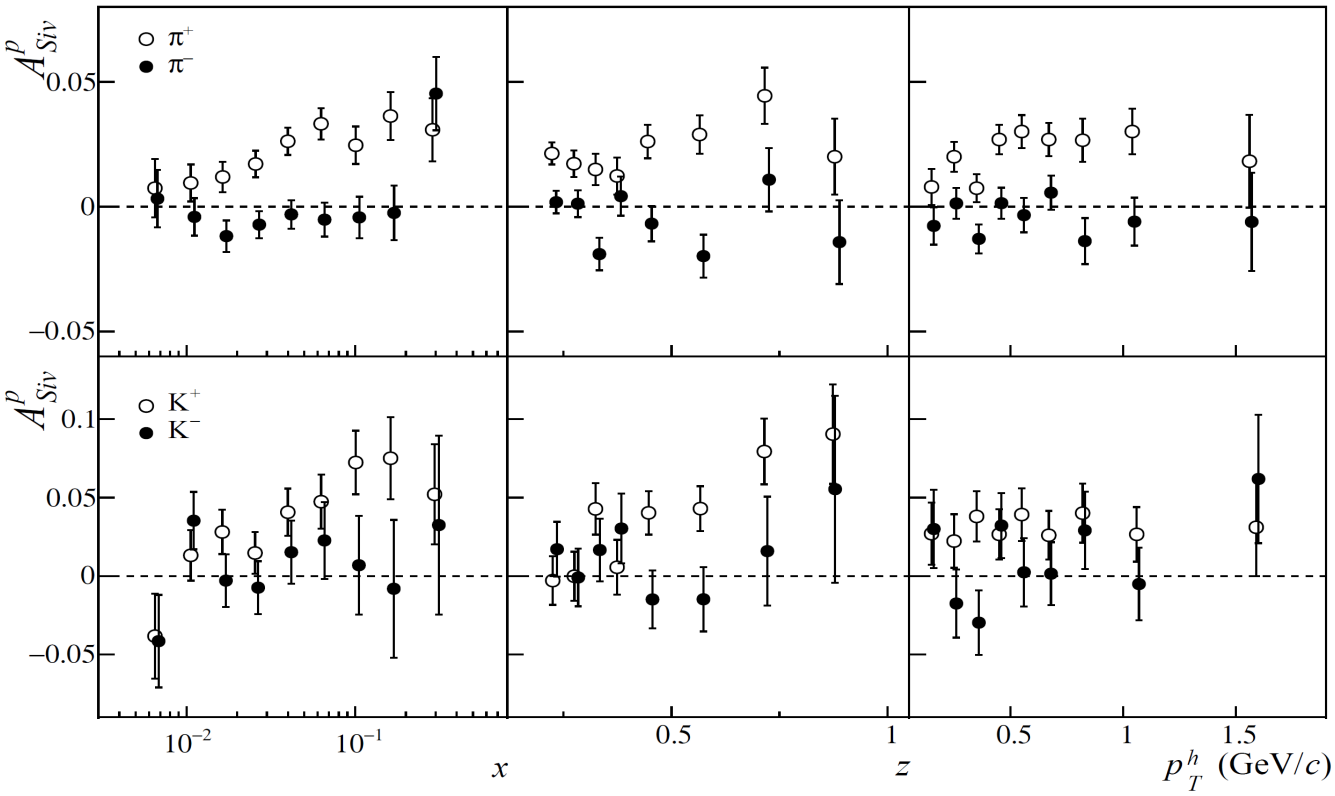


point by point extraction using COMPASS p and d data, and e^+e^- data

Sivers asymmetry

$$A_{Siv}^{h} = \frac{\sum_{q,\bar{q}} e_q^2 x \boldsymbol{f_{1T}^{\perp q}} \otimes D_{1q}^{h}}{\sum_{q,\bar{q}} e_q^2 x f_1^q \otimes D_{1q}^{h}}$$

proton



Phys. Lett. B 744 (2015) 250

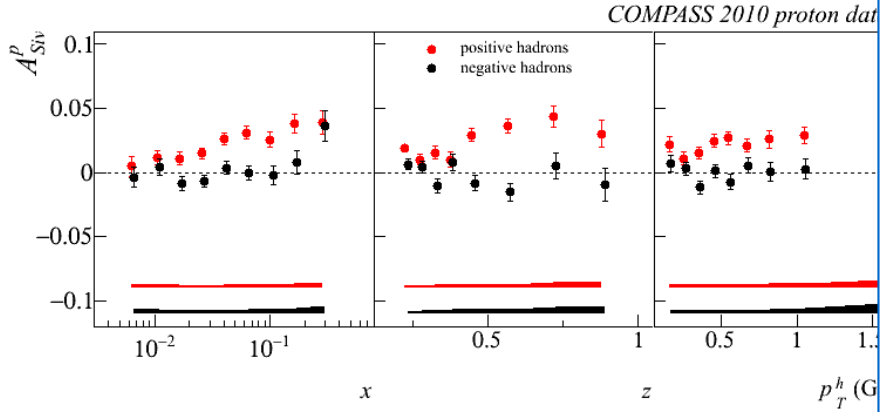
deuteron:
Phys. Lett. B 673 (2009) 127

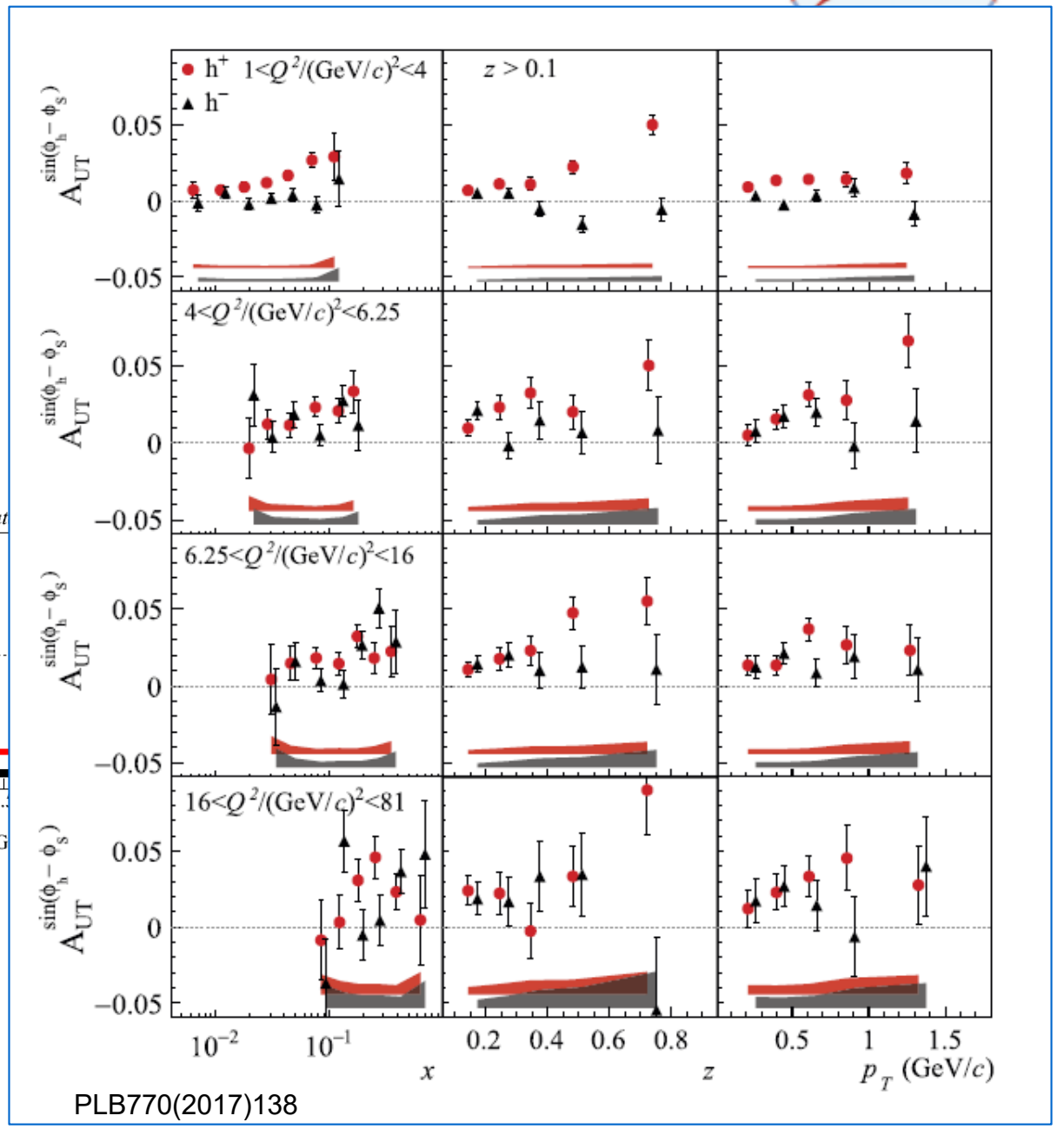
the proton data

multidimensional measurements of TSAs

(x, Q^2, z, P_T) *bins*

Sivers asymmetry





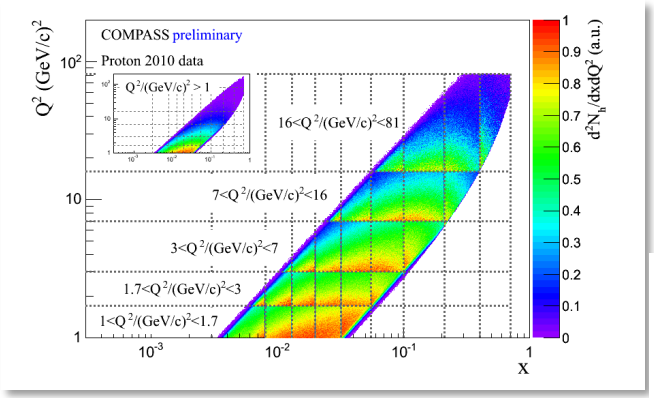
PLB770(2017)138

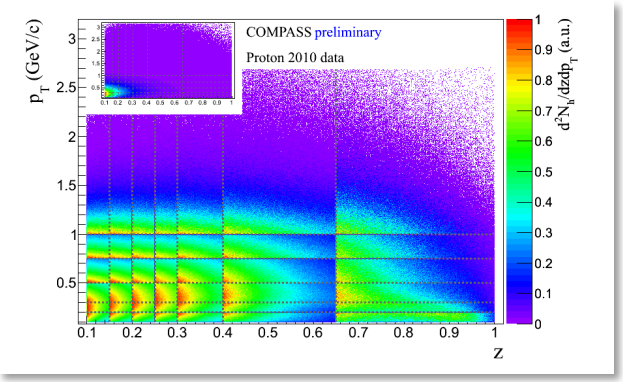
the proton data

multidimensional measurements of TSAs

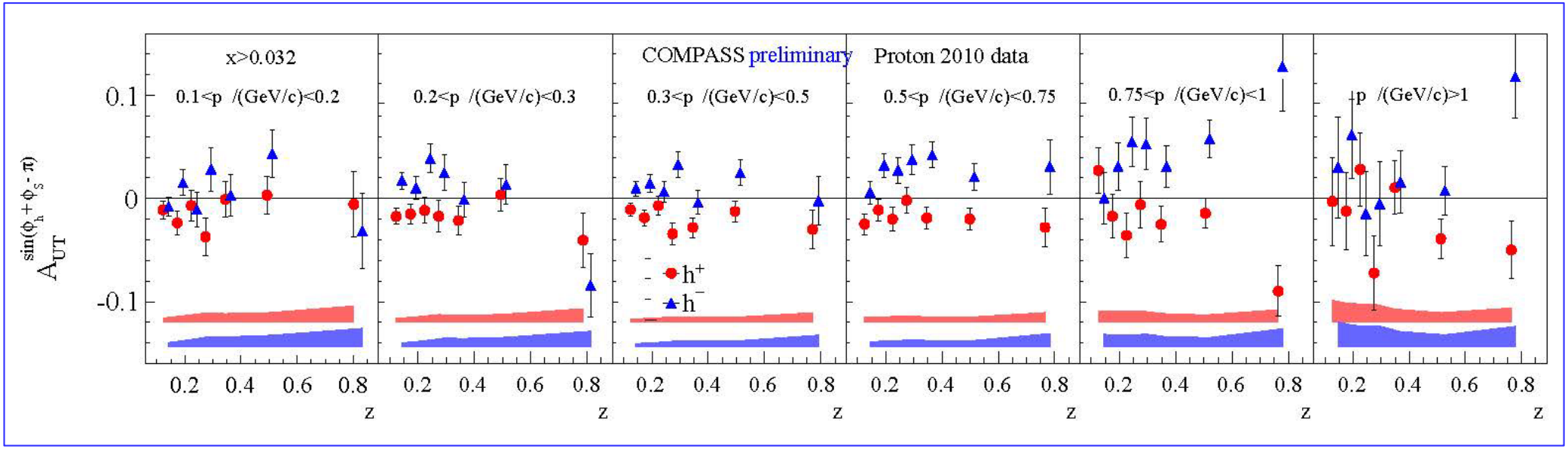
(x, Q^2, z, P_T) *bins*

Collins asymmetry





an example



the P_T weighted Sivers asymmetries

we have measured
the weighted Sivers asymmetries on transversely polarised protons vs x and z
using as weights both $w = P_T/zM$ and $w' = P_T/M$

NPB 940 (2019) 34

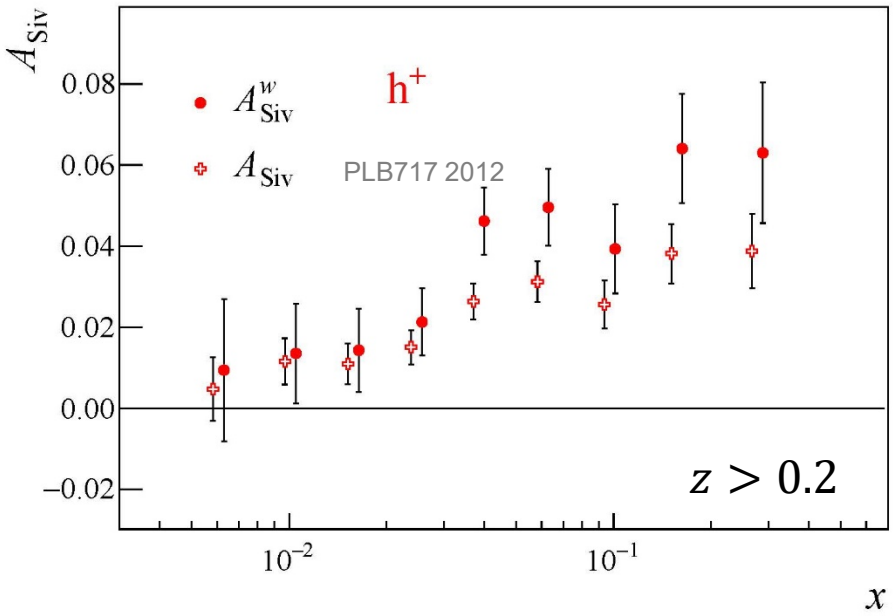
allow to avoid assumptions on the transverse momentum dependence of PDFs and FFs
to solve the convolution

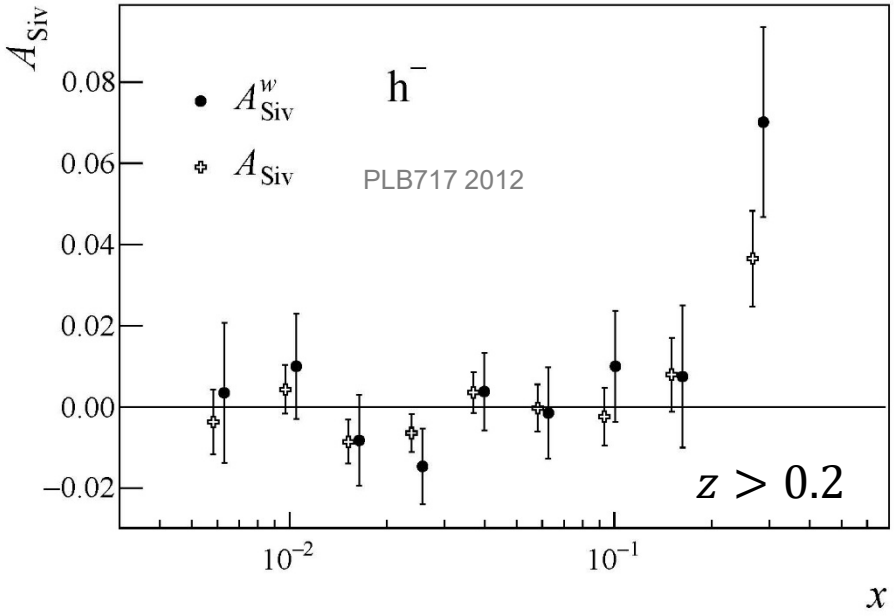
$$w = P_T/zM \qquad A_{Siv}^{w}(x,z) = 2\frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x)\, D_1^q(z)}{\sum_q e_q^2\, x f_1^q(x)\, D_1^q(z)}$$

$$w' = P_T/M \qquad A_{Siv}^{w'}(x,z) = 2\frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x)\, zD_1^q(z)}{\sum_q e_q^2\, x f_1^q(x)\, D_1^q(z)}$$

the P_T weighted Sivers asymmetries

$$A_{Siv}^{w}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\tilde{D}_1^q}{\sum_q e_q^2 x f_1^q(x)\tilde{D}_1^q} \qquad \tilde{D}_1^q = \int_{z_{min}}^{z_{max}} dz D_1^q(z)$$





more results in the paper

- all the results confirm the naïve expectations
- no indication that we are nor in the current fragmentation region or that factorisation does not work in our kinematic range

also,
from the weighted asymmetries, we have extracted the first transverse moment of the Sivers function, inagreement with previous extractions

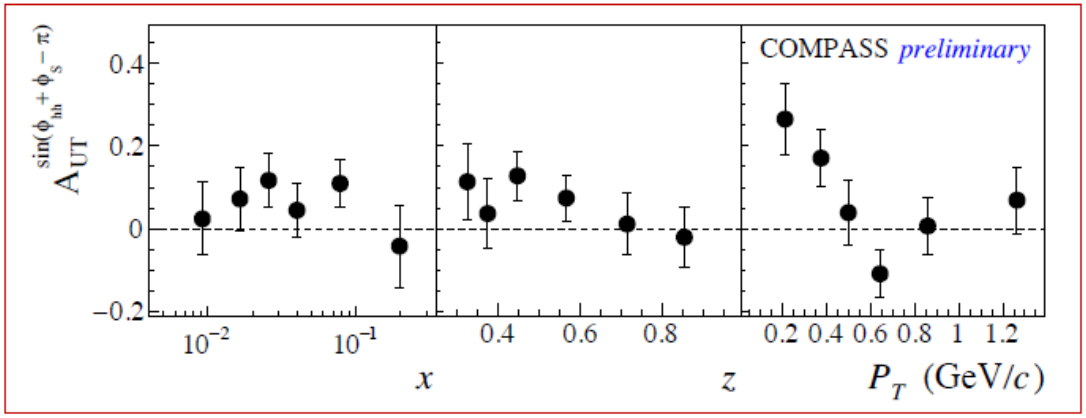
other TSAs

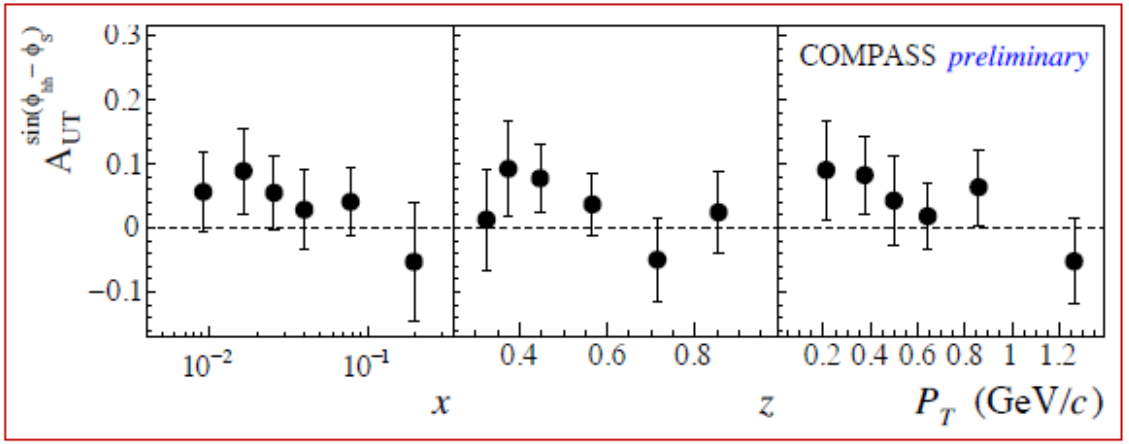
several other measurements have been performed

- other SIDIS TSAs
- transversity induced $\Lambda/\overline{\Lambda}$ polarization
- TSAs for high P_T pairs from PGF events PLB 772 (2017) 854
- J/Ψ Sivers asymmetry

new: Collins and Sivers asymmetries of inclusively produced ρ^0

(*A. Kerbizi talk at DIS2021*)





target longitudinal spin asymmetries

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

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

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

measured with unprecedented precision

$A_{UL}^{\sin\phi_h}$

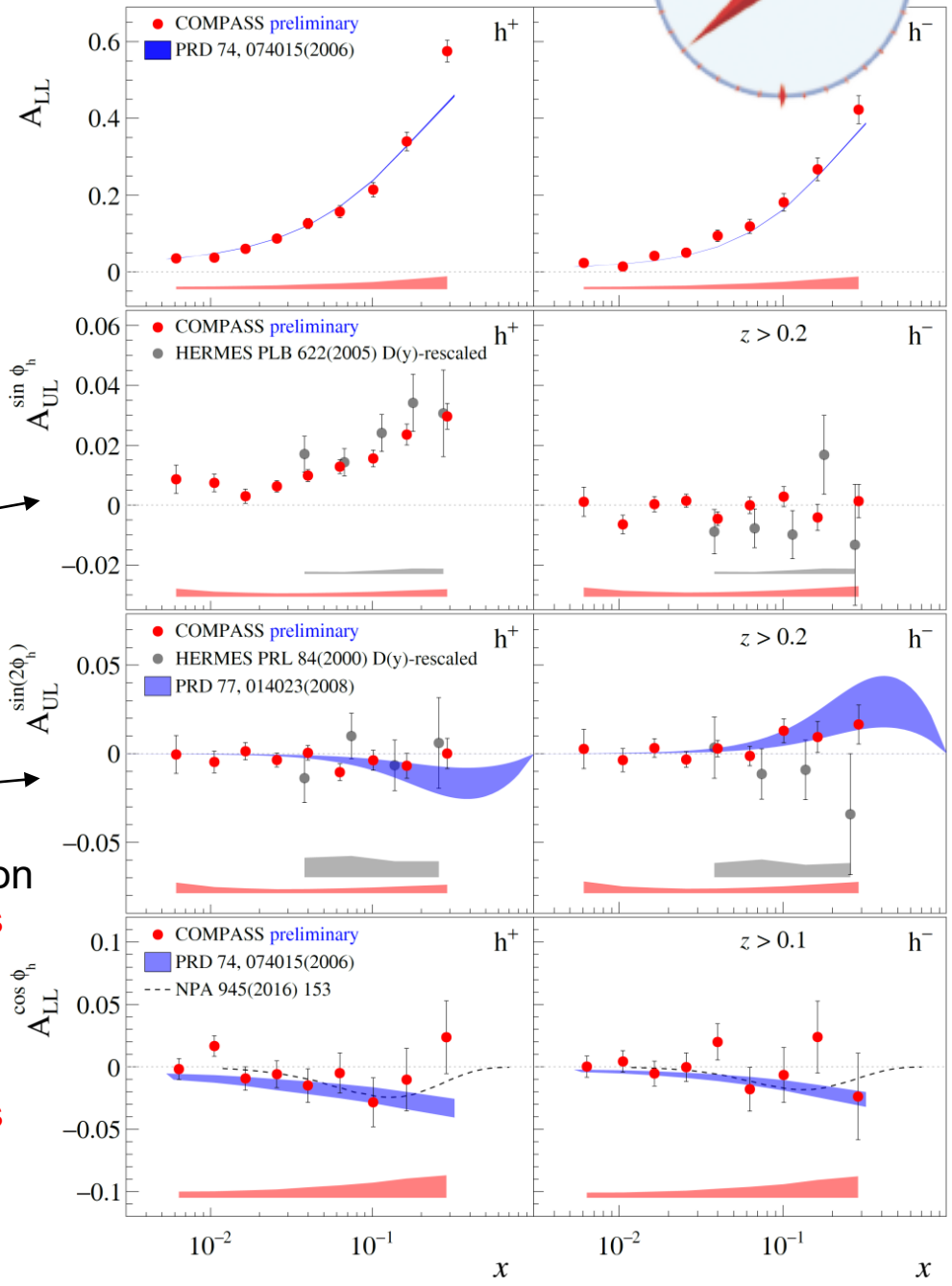
- Q-suppression, different “twist” contributions
- **significant h⁺ asymmetry**

$A_{UL}^{\sin 2\phi_h}$ $\quad h_{1L}^{\perp} \otimes H_1^{\perp}$

- 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



unpolarised SIDIS

- published results on
  - hadron multiplicities from 2004 and 2006 deuteron data
  - azimuthal asymmetries from 2004 deuteron data

- new:
  - hadron multiplicities and azimuthal asymmetries from 2016 proton data

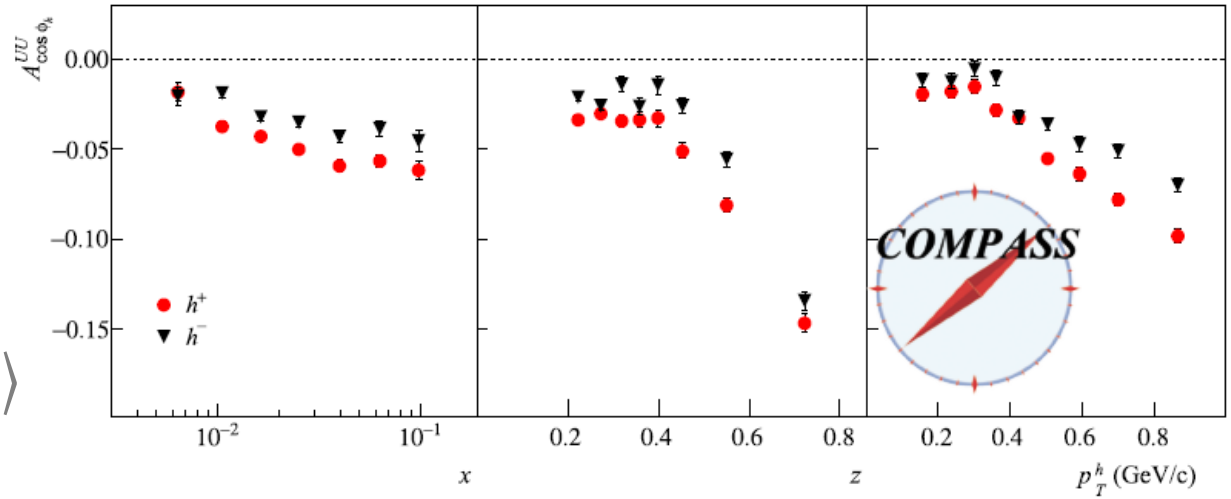
unpolarised SIDIS

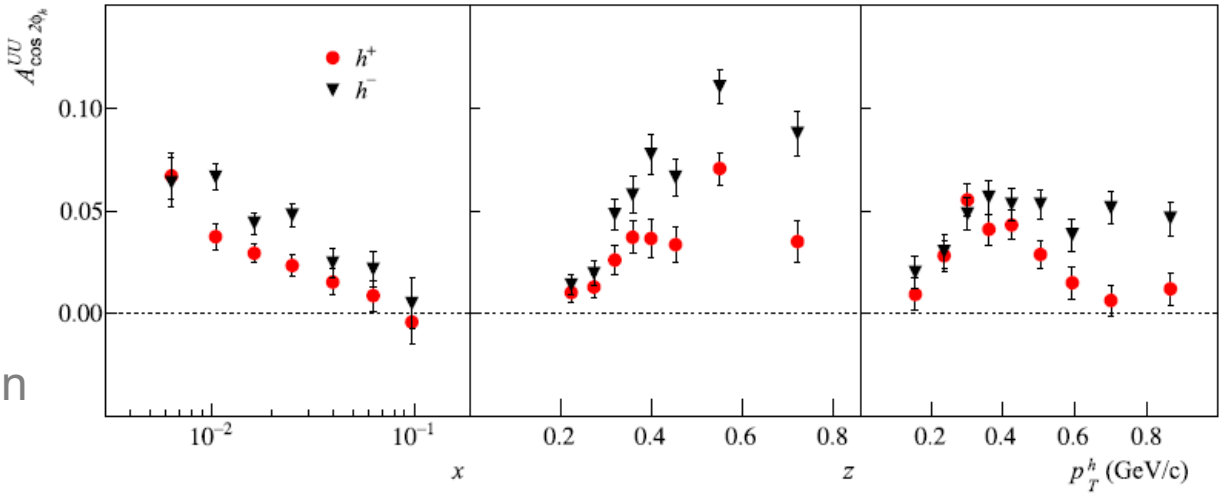
azimuthal asymmetries
from 2004 deuteron data

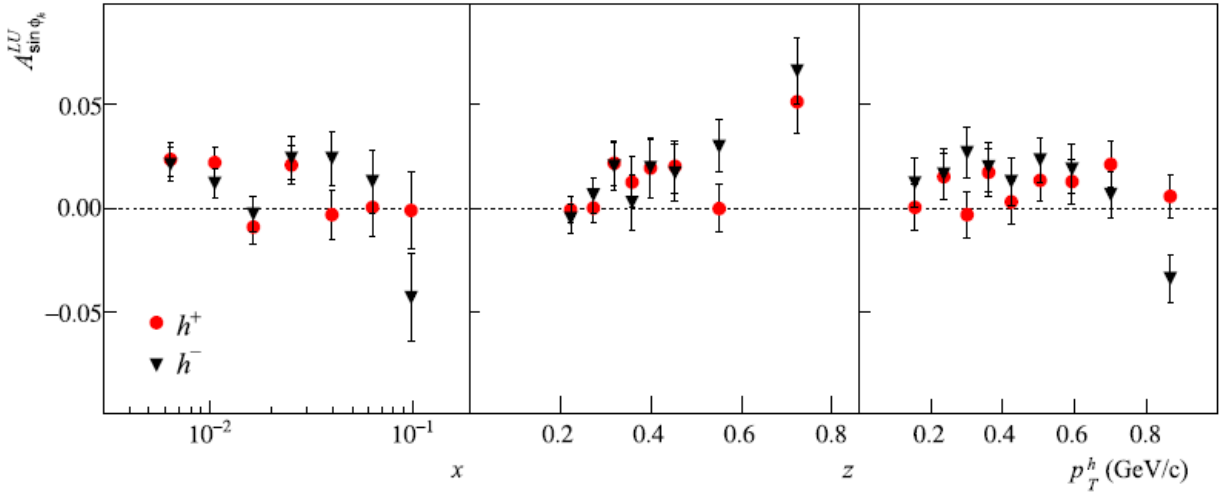
1D and
3D (x, z, P_T) results

NPB 886 (2014) 1046

$\langle k_T^2 \rangle$







strong kinematic dependence
no easy interpretation…

BM function

unpolarised SIDIS

azimuthal asymmetries
from 2004 deuteron data

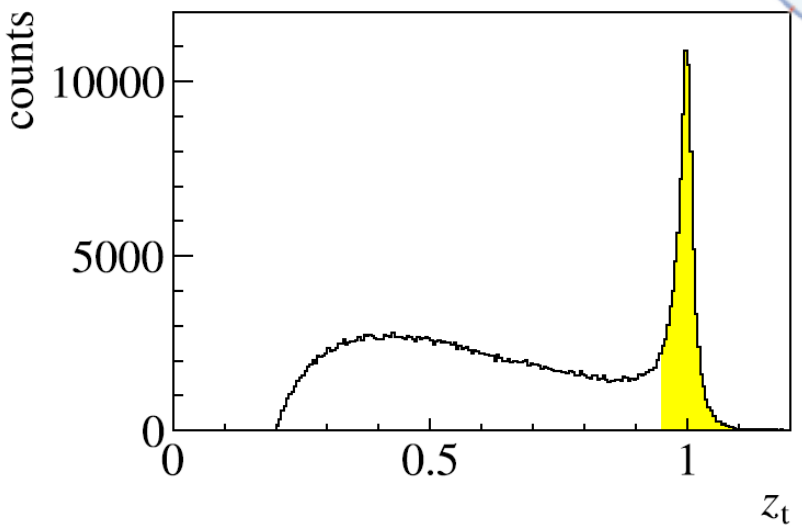
1D and
3D (x, z, P_T) results

NPB 886 (2014) 1046

Contribution of exclusive diffractive processes

NPB 956 (2020) 115039

largest contribution
at high z, low P_T



$\mu N \rightarrow \mu'(h^+h^-)r$

unpolarised SIDIS

azimuthal asymmetries
from 2004 deuteron data

1D and
3D (x, z, P_T) results

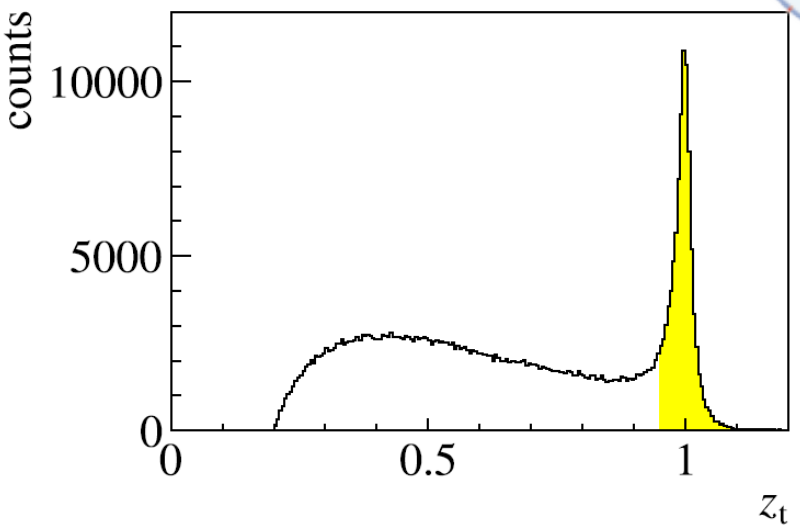
NPB 886 (2014) 1046

Contribution of exclusive diffractive processes

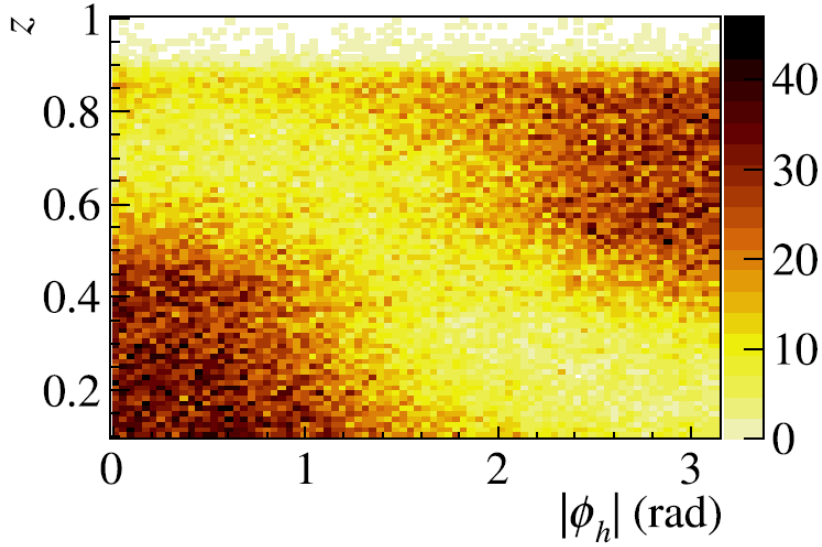
NPB 956 (2020) 115039

largest contribution
at high z, low P_T

strong $\cos\phi_h$ modulation
changing sign



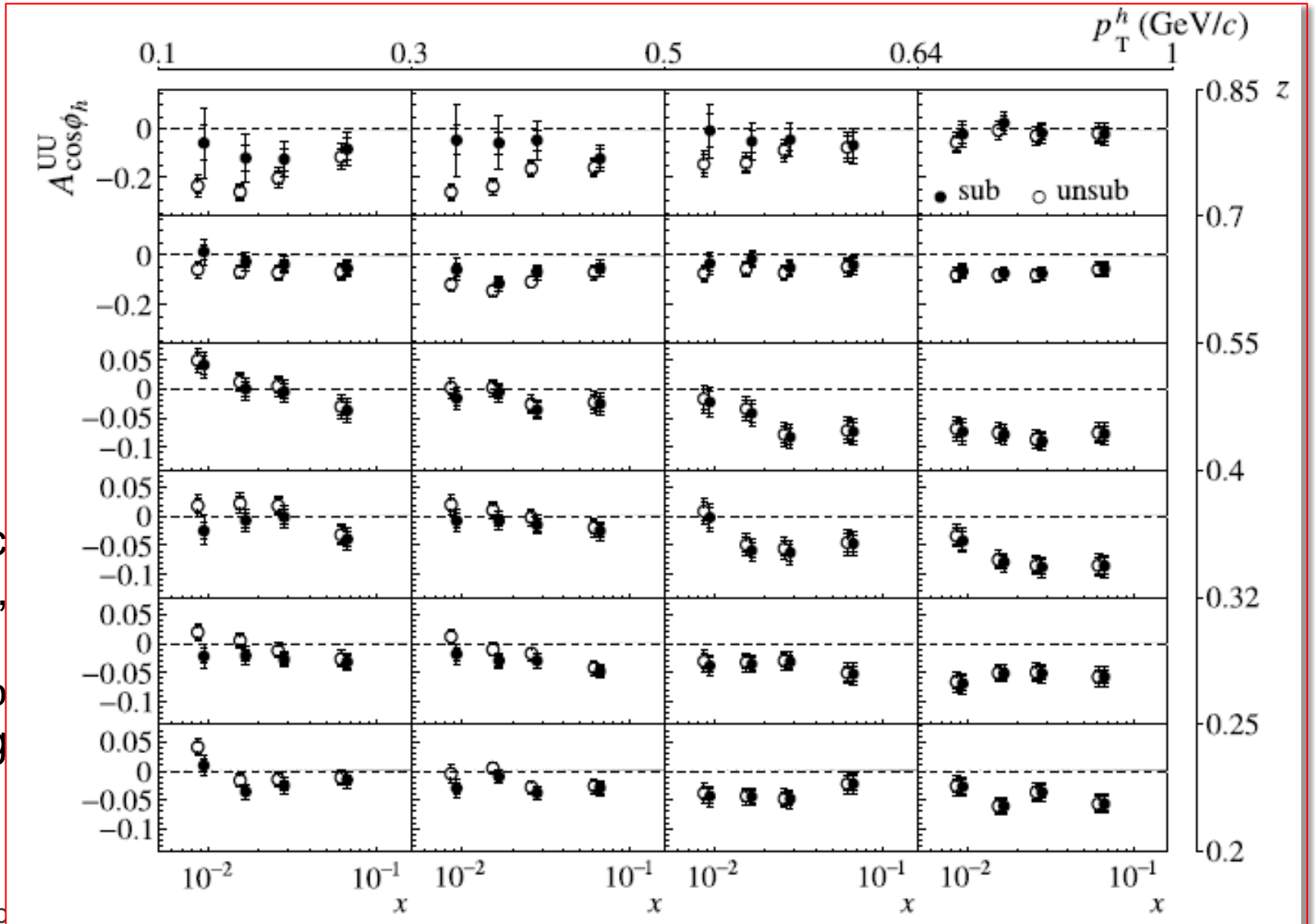
$\mu N \to \mu'(h^+h^-)r$



unpolarised SIDIS

azimuthal asymmetries
from 2004 deuteron data

NPB 956 (2020) 115039



highest c
at high z,

strong co
changing

unpolarised SIDIS

P_T multiplicities from 2006 deuteron data

EPJC 73 (2013) 2531

PRD 97, 032006 (2018)

corrected for exclusive diffractive processes

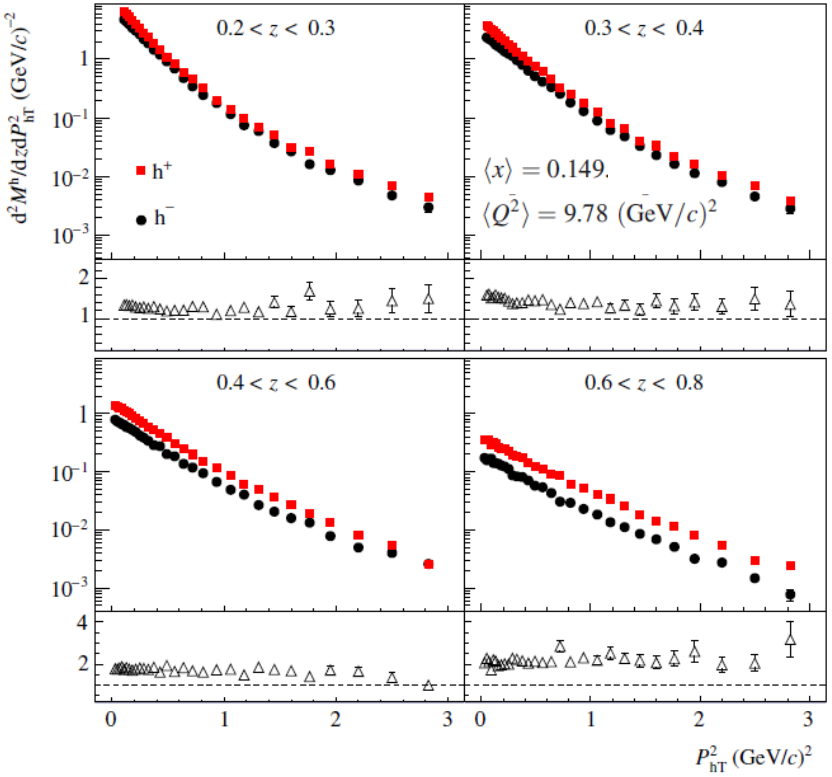
$$\frac{\mathrm{d}^2 M^{\mathrm{h}}(z, P_{\mathrm{hT}}^2)}{\mathrm{d}z \mathrm{d}P_{\mathrm{hT}}^2} = \frac{1}{\mathrm{d}^2 N^{\mathrm{DIS}}} \frac{\mathrm{d}^4 N^{\mathrm{h}}(z, P_{\mathrm{hT}}^2)}{\mathrm{d}z \mathrm{d}P_{\mathrm{hT}}^2} \left(1 - \frac{\eta^{\mathrm{h}}}{\eta^{\mathrm{DIS}}}\right) \times \frac{1}{a^{\mathrm{h}}(z, P_{\mathrm{hT}}^2)} \frac{C^{\mathrm{h}}(z, P_{\mathrm{hT}}^2)}{C^{\mathrm{DIS}}}.$$

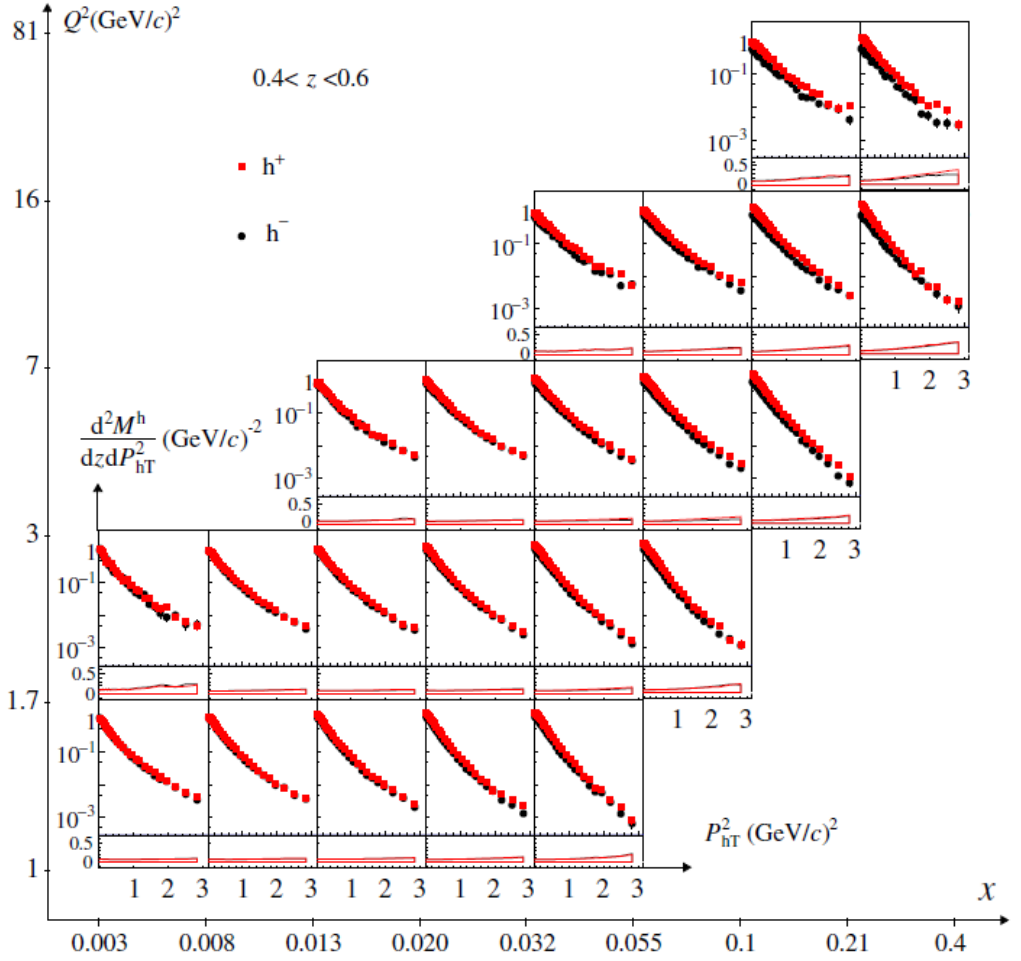
$P_{hT}^2 (GeV/c)^2$	M^{h^+}	C^{h^+}	C^{DIS}
0.0899 (bin: 0.08 - 0.1)	6.2719 ±0.3126 stat ±0.6593 sys	0.9520	0.9980
0.1101 (bin: 0.1 - 0.12)	6.2175 ±0.3135 stat ±0.6510 sys	0.9760	0.9980
0.1298 (bin: 0.12 - 0.14)	5.0537 ±0.2711 stat ±0.5406 sys	0.9715	0.9980

https://www.hepdata.net/record/ins1624692

unpolarised SIDIS

P_T multiplicities
from 2006 deuteron data





PRD 97, 032006 (2018)

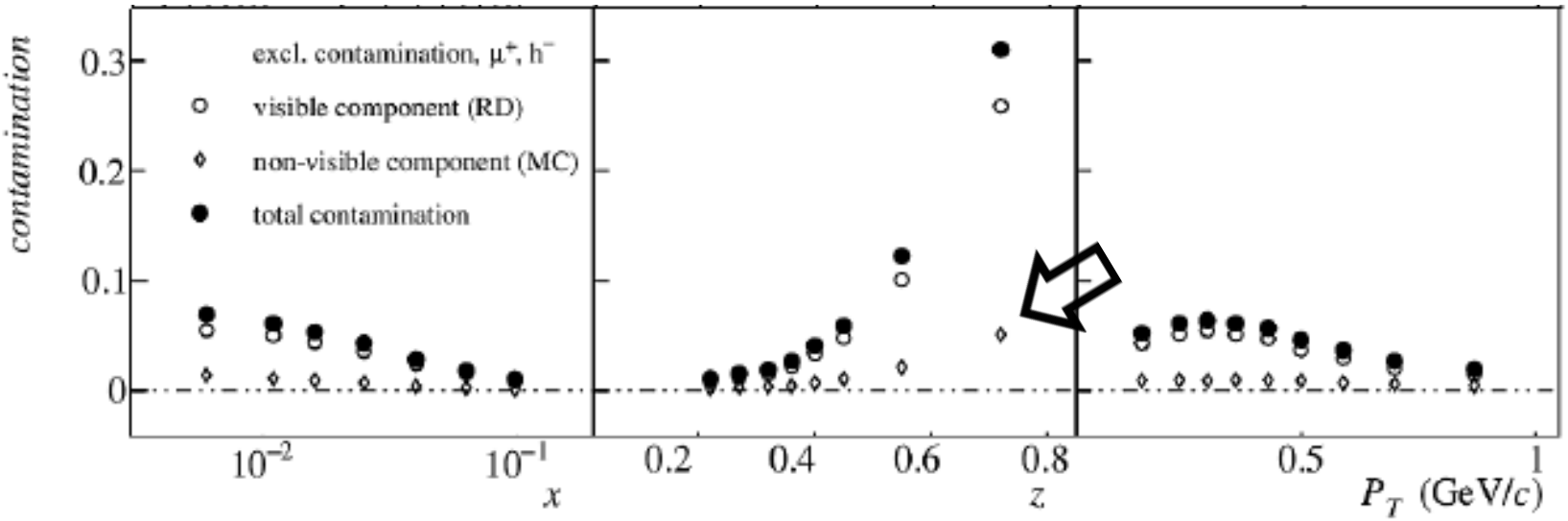
unpolarised SIDIS off proton

from 2016 data
limited kinematic coverage (apparatus optimized for DVCS)

a complete set of P_T **distributions** and **azimuthal asymmetries**
for more results → A. Moretti presentation at DIS2021

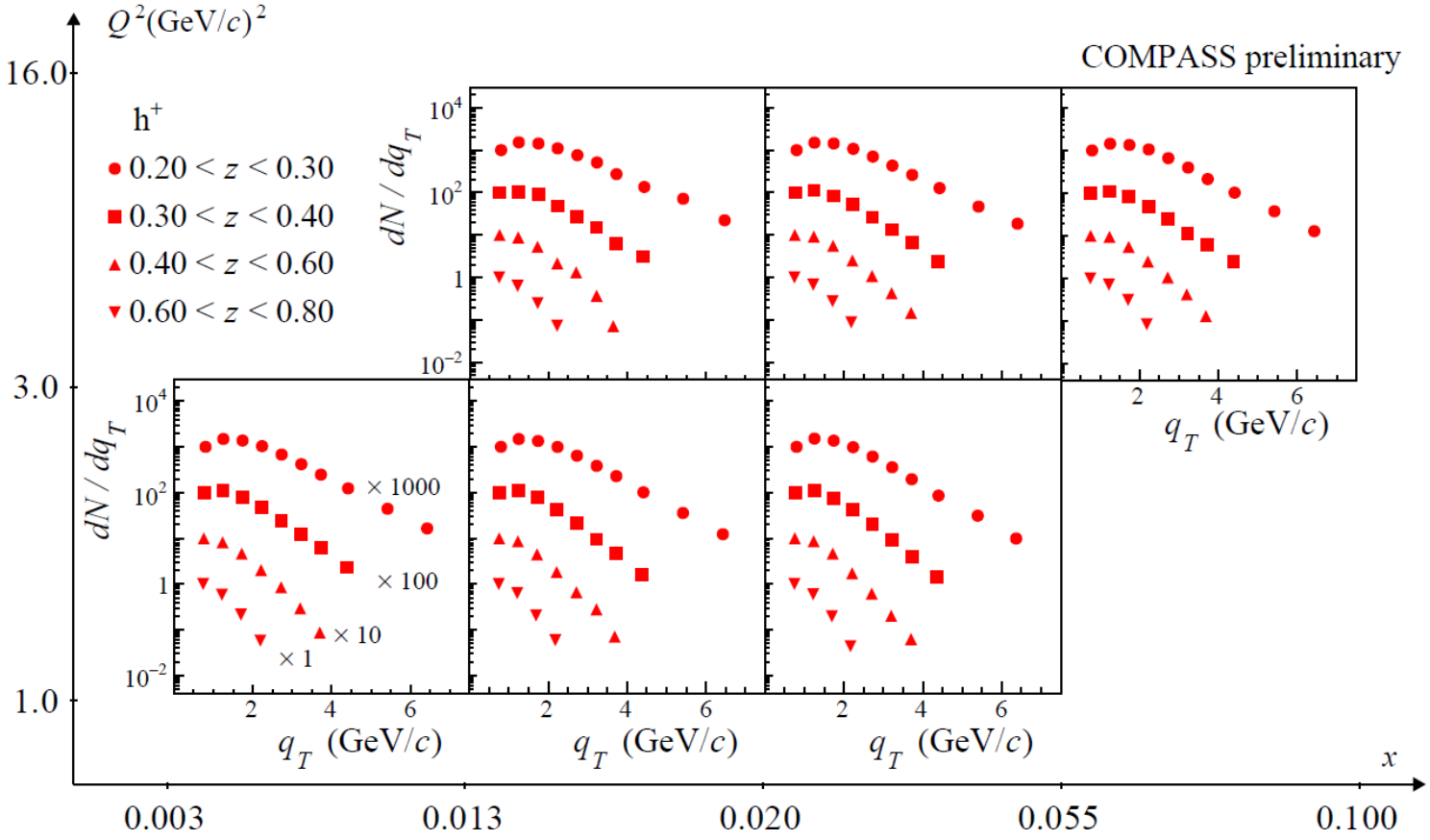
corrected for exclusive diffractive processes

new method: remove reconstructed exclusive events
use MC only for the **remaining hadrons**



unpolarised SIDIS off proton

q_T distributions

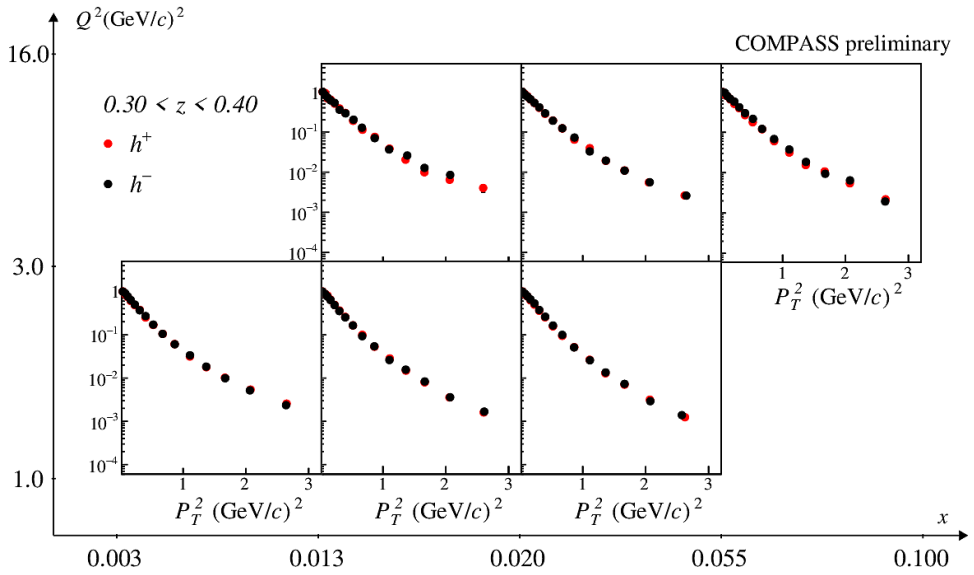


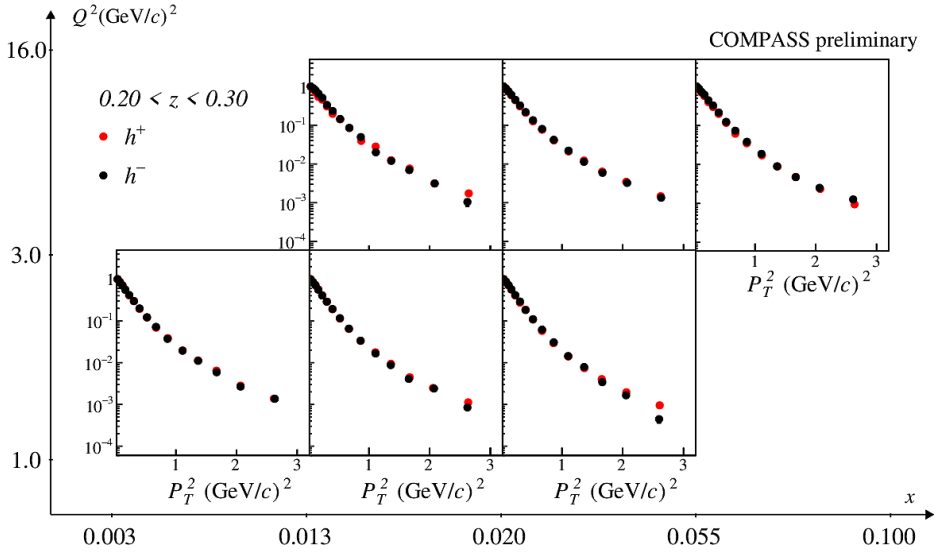
how many points would be used after the "q_T/Q" cut?

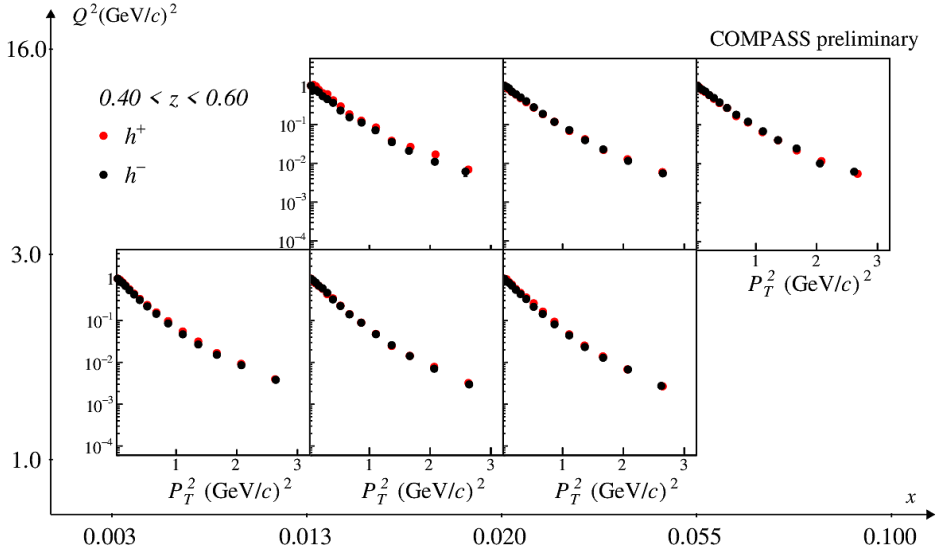
still, we hope that theory will use most of the data …

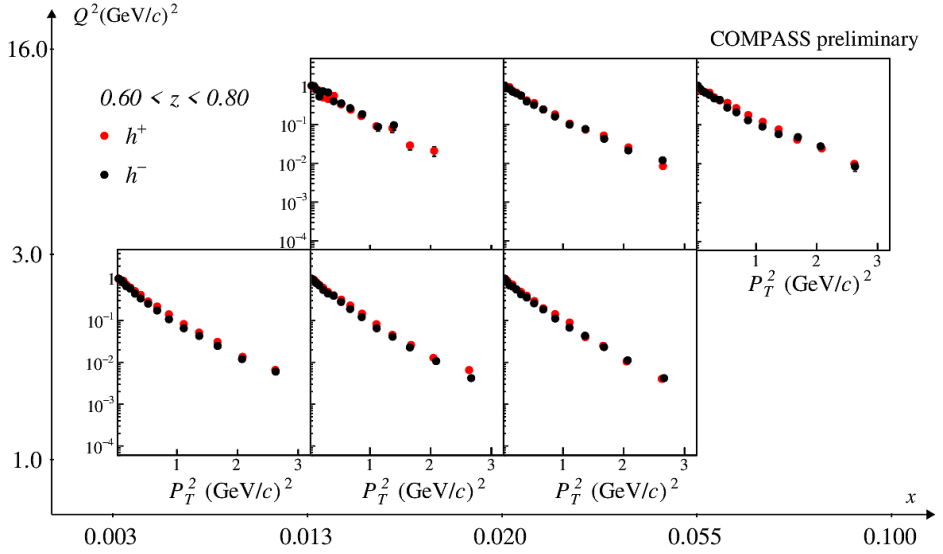
unpolarised SIDIS off proton

P_T distributions





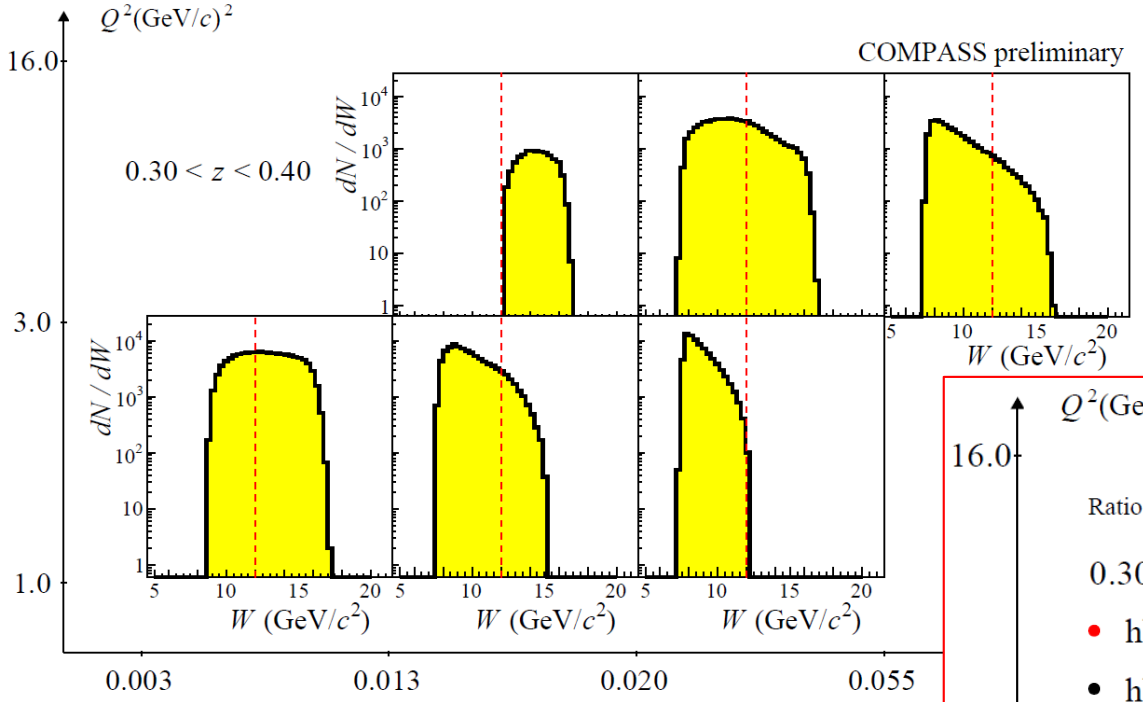


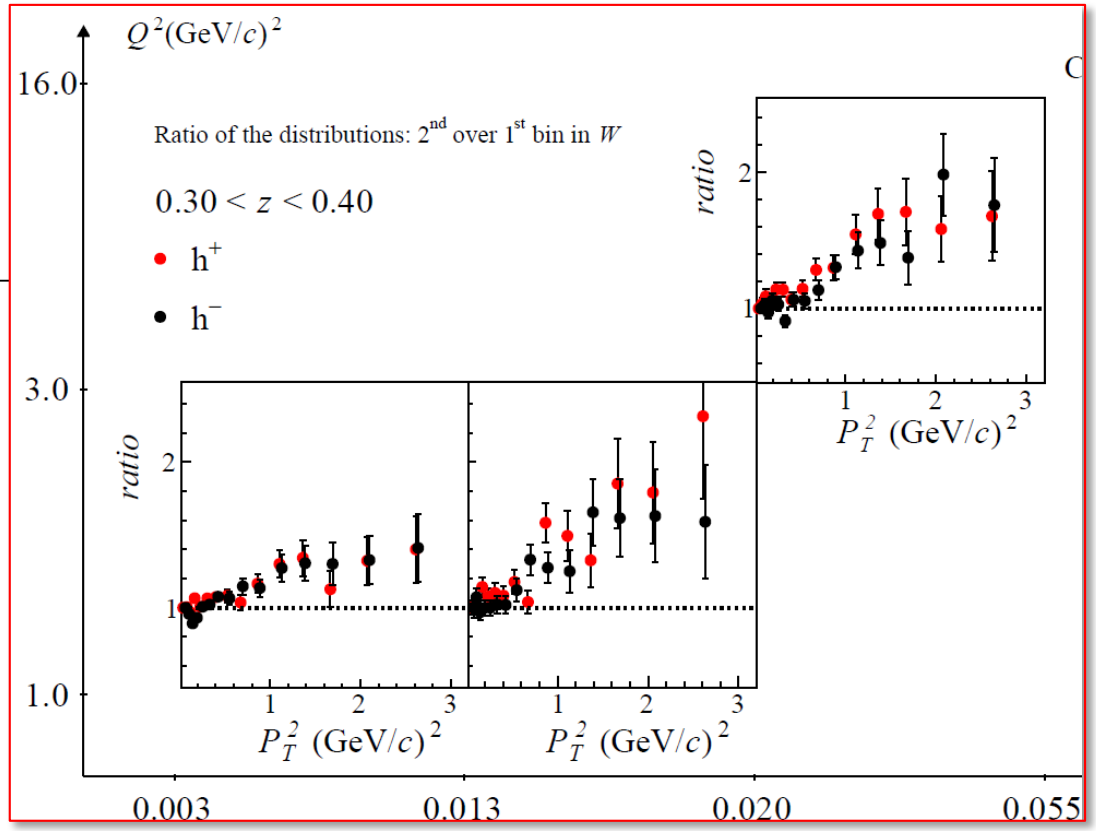


in agreement with d data

unpolarised SIDIS off proton

P_T distributions W dependence





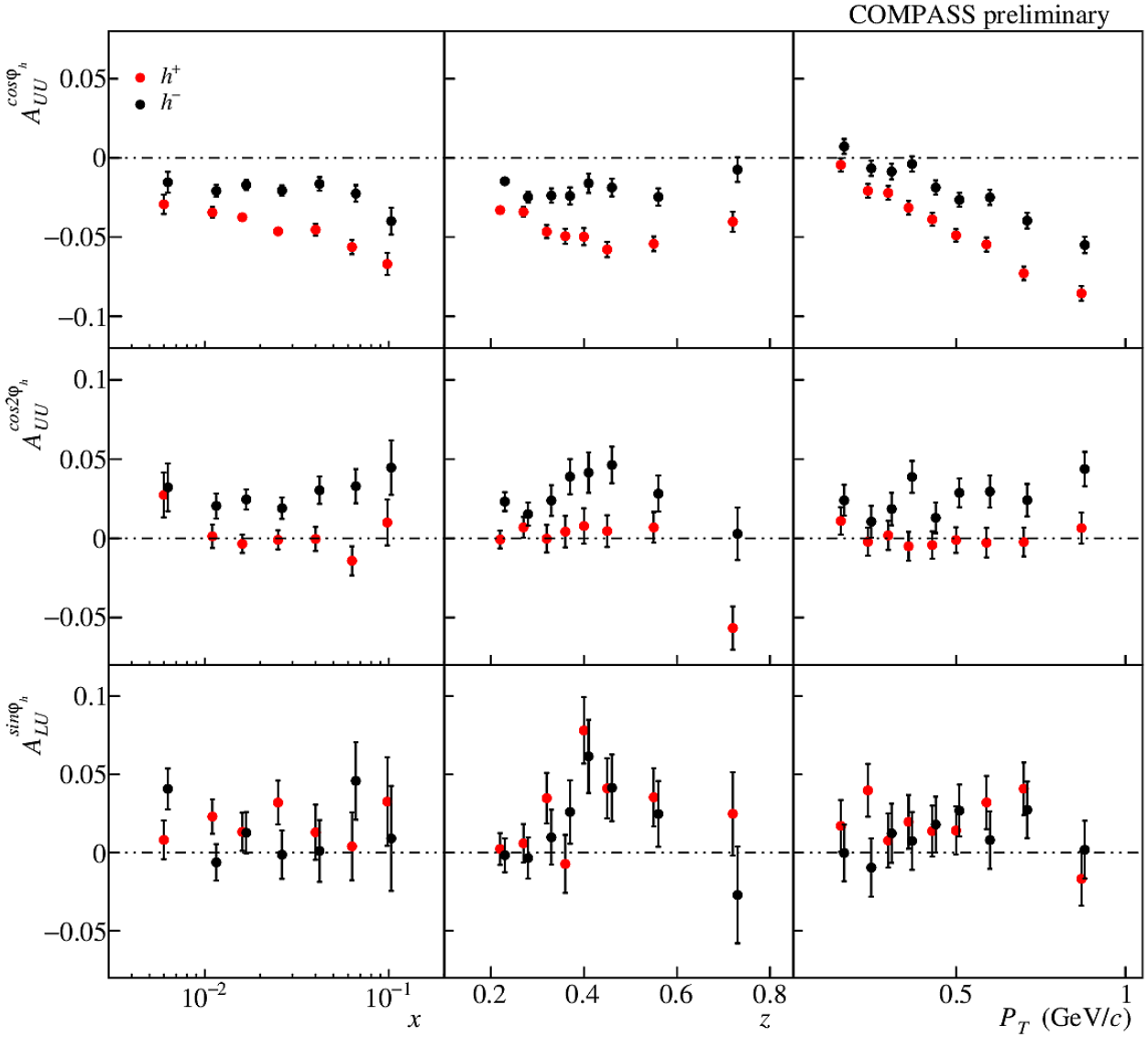
unpolarised SIDIS off proton

azimuthal asymmetries

strong kinematic dependence

large differences between positive and negative hadrons

as observed previously



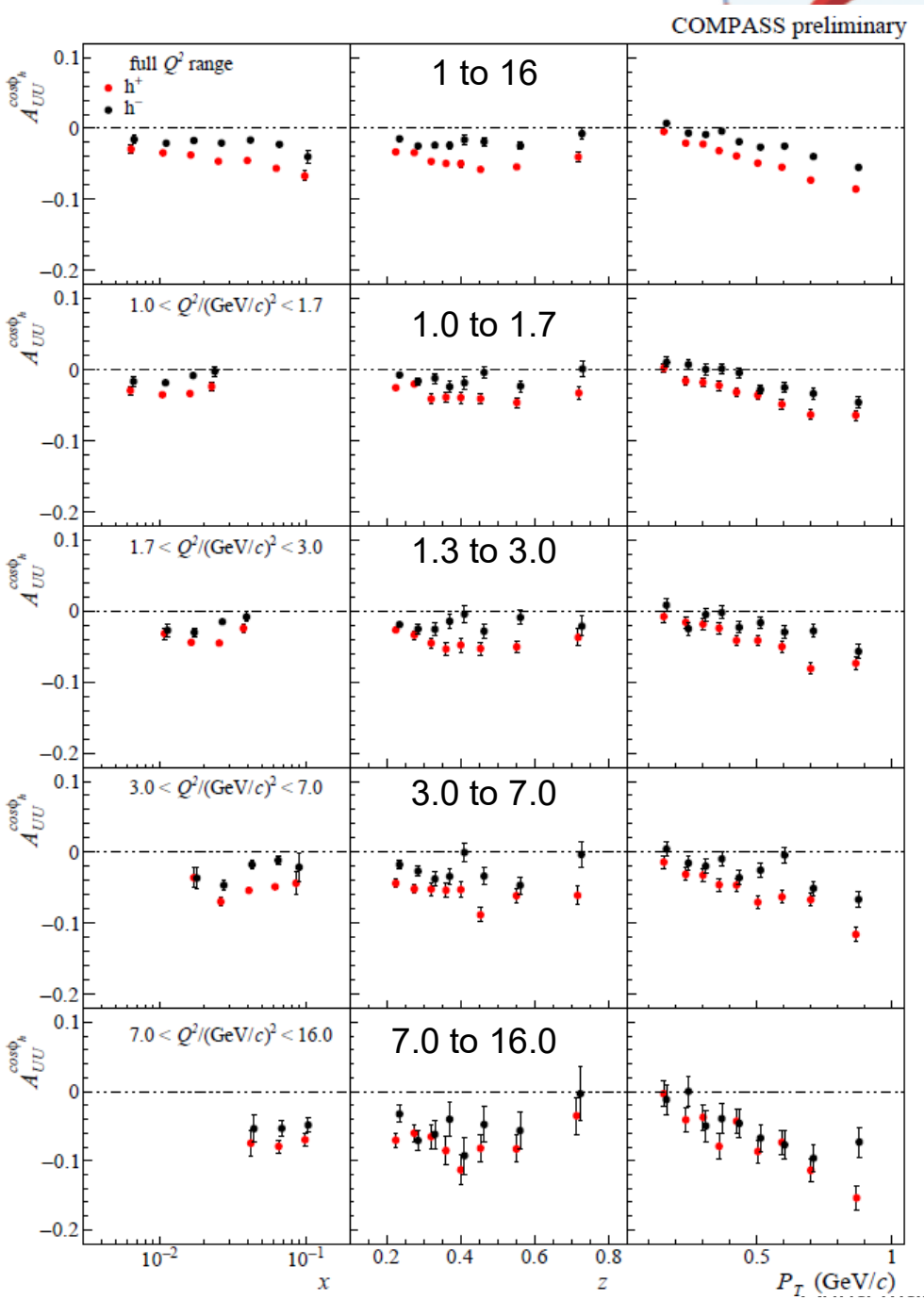
unpolarised SIDIS off proton

azimuthal asymmetries

interesting Q^2 dependence

same for W dependence

→ *A. Moretti presentation at DIS2021*



the 2021/22 run – transversely polarised deuteron

150 days of data taking with 160 GeV muons to measure
SIDIS off transversely polarised d

the missing measurement to complete the COMPASS exploratory programme

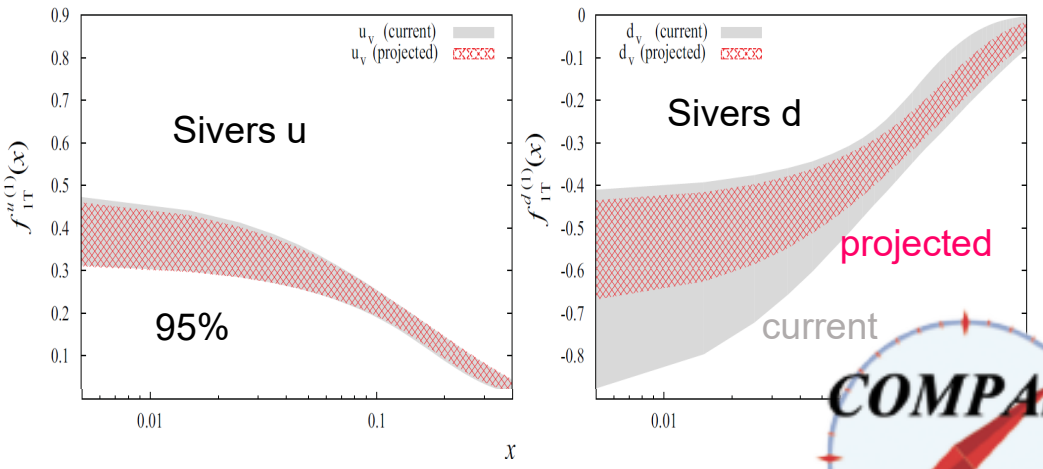
collecting the same statistics as in 2010, the deuteron asymmetries will have a statistical uncertainty

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

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

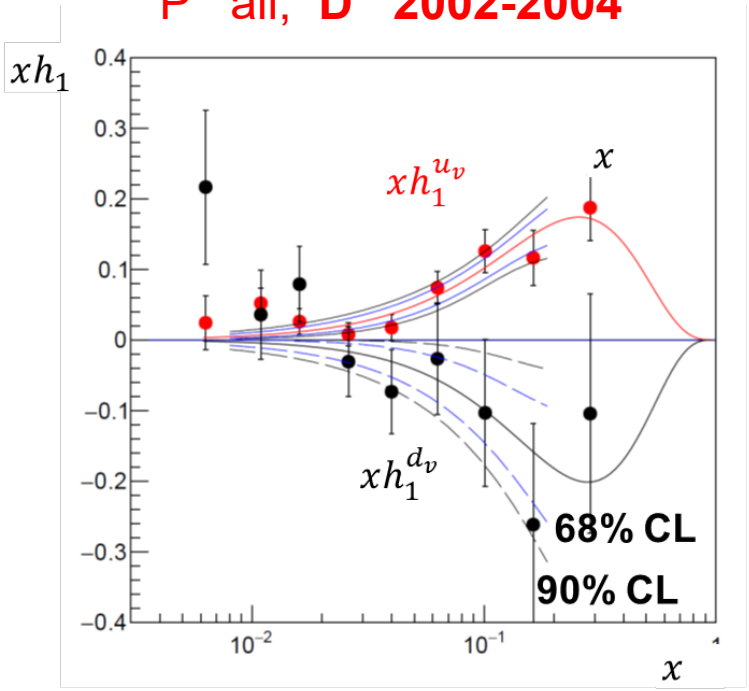


and in particular
transversity and tensor charge

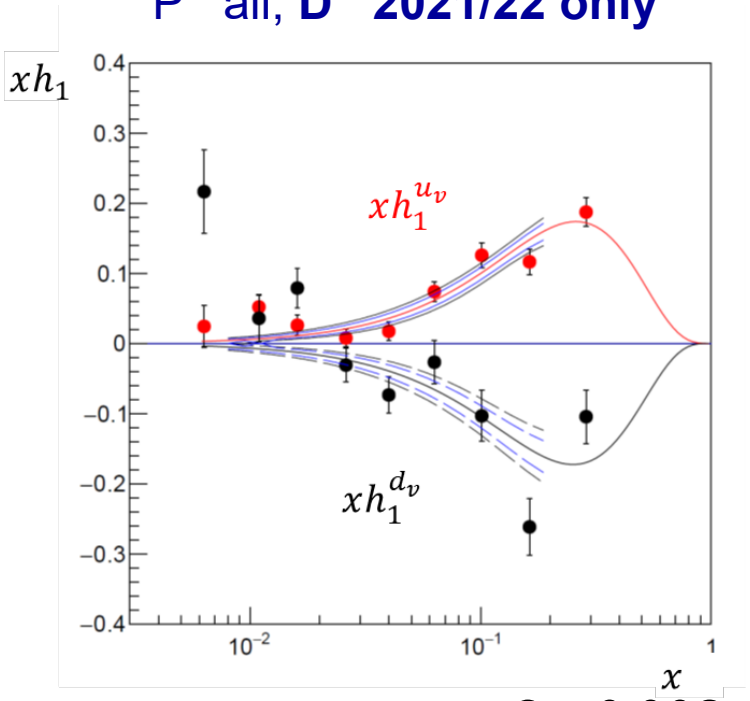
the 2021/22 run: impact on the tensor charge

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

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



projected
P all, **D 2021/22 only**



Ω_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	$0.201 \pm \mathbf{0.019}$	$-0.189 \pm \mathbf{0.040}$	$0.390 \pm \mathbf{0.044}$

conclusions

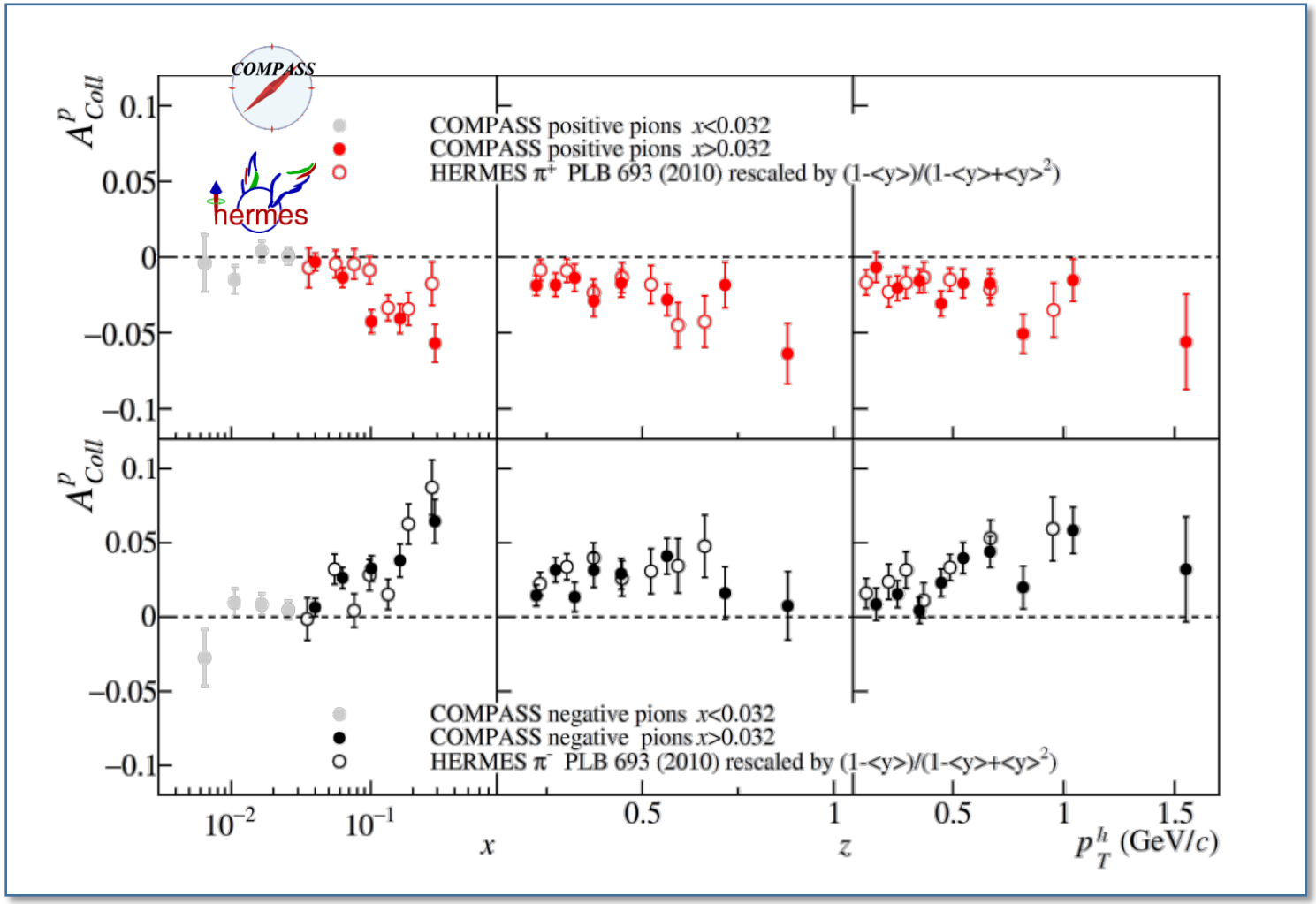
- COMPASS has given a relevant contribution to the study of the transverse spin and transverse momentum structure of the nucleon

- new results have been produced for SIDIS off unpolarised protons, and more will come

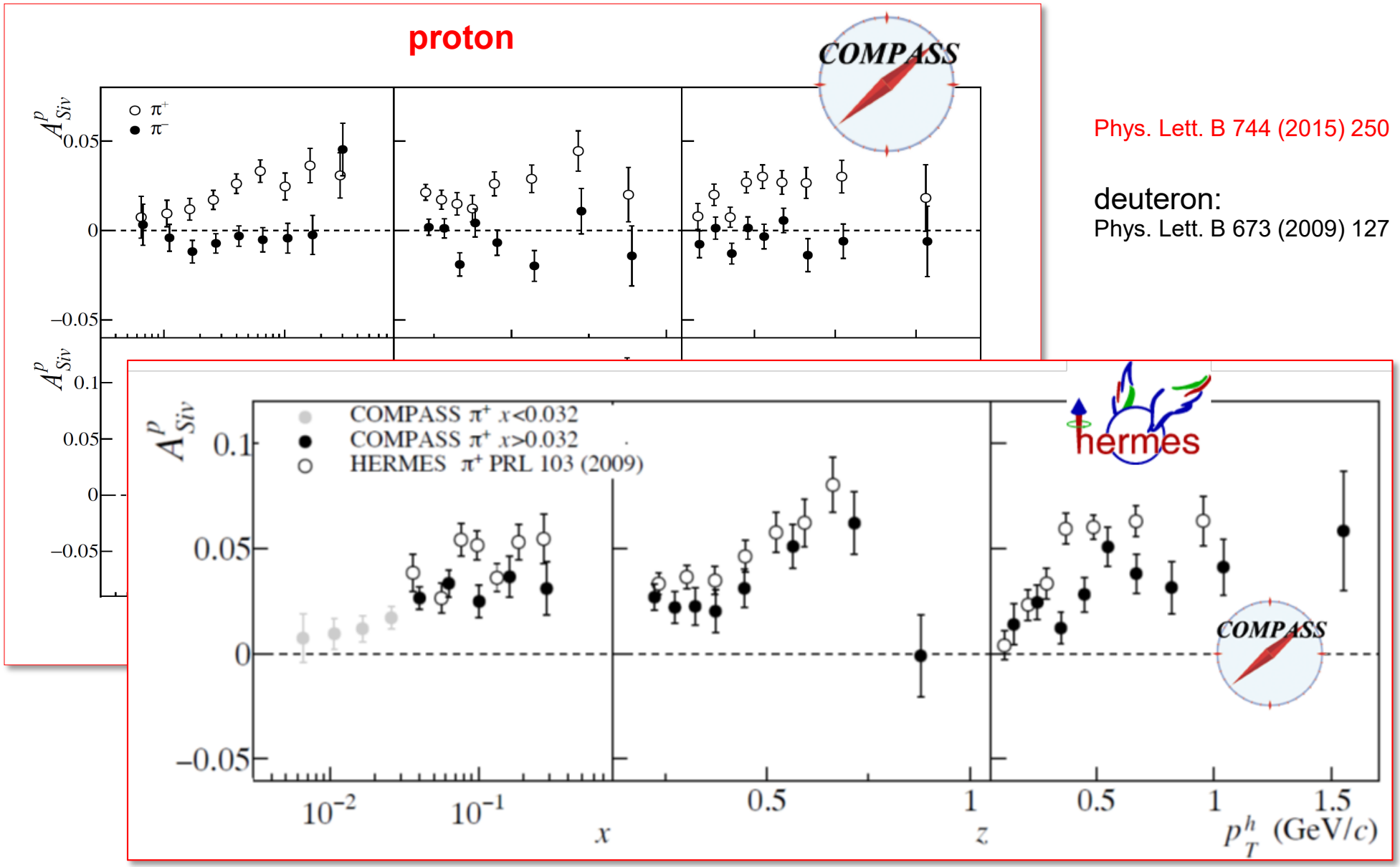
- the 2021/22 run with transversely polarized deuterons will allow to get more insight on transverity, tensor charge, and all TSA,
  but also on TMD effect in unpolarised SIDIS

the kinematical region covered by COMPASS is unique
and we have to take advantage of it, in going from JLab to EIC

Collins asymmetry



Sivers asymmetry



Phys. Lett. B 744 (2015) 250

deuteron:
Phys. Lett. B 673 (2009) 127

unpolarised SIDIS off proton

azimuthal asymmetries

W dependence

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