Transversity 2024

Trieste, 3-7 June 2024

New Measurements of

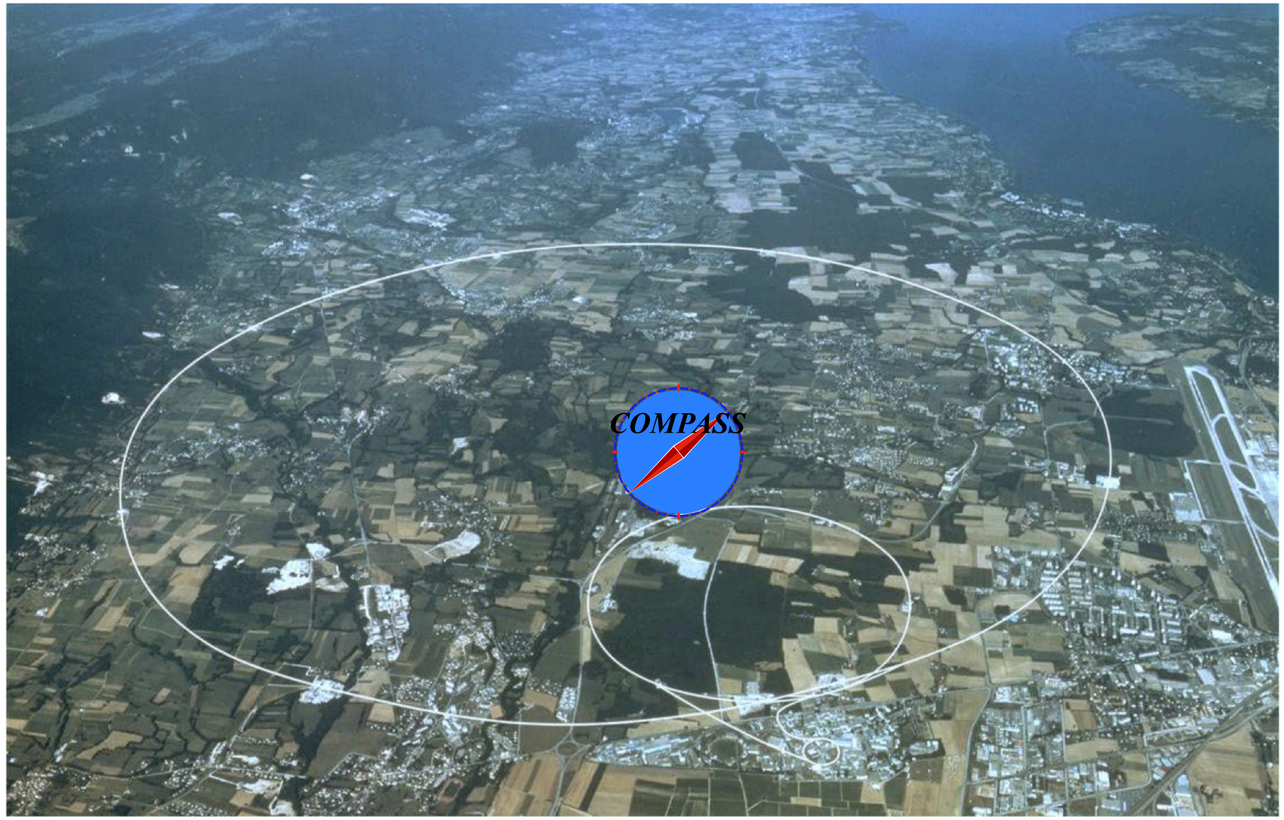
Transverse Spin Asymmetries in SIDIS

At COMPASS

Athira Vijayakumar

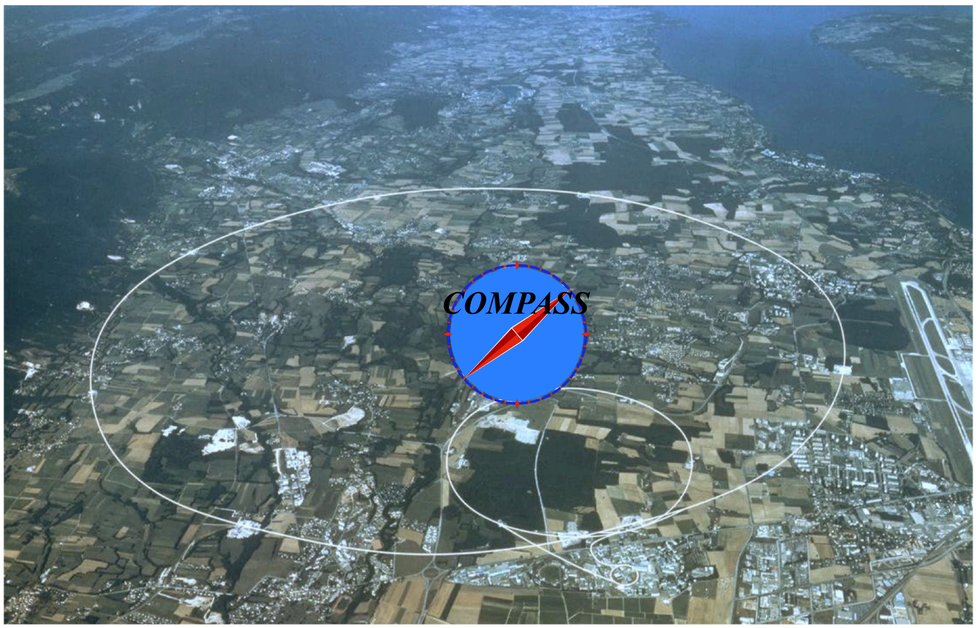
On behalf of the COMPASS collaboration

Common Muon and Proton Apparatus for Structure and Spectroscopy



- Fixed target experiment located at the M2 beam line of CERN SPS
- High energy muon and hadron beams enabling a wide physics program , from spectroscopy to nucleon structure
- First physics data taken in 2002
- Last physics data in 2022
- The COMPASS spectrometer is being used by the AMBER collaboration - **talk by Oleg Denisov**

Common Muon and Proton Apparatus for Structure and Spectroscopy



NUCLEON STRUCTURE WITH COMPASS

High energy muon beam

- longitudinally polarized targets: longitudinal spin structure of the nucleon
- transversely polarized targets: transversity and TMDs - **my talk**
- unpolarized targets: TMDs - **talk by Andrea Bressan**
- GPDs - **talk by Nicole d'Hose**

High energy pion beam

polarized and unpolarized targets: TMDs in DY process - **talk by Catarina Quintans**

COMPASS Spectrometer

Two stages: to accommodate for the high beam intensity and offers large acceptance

Large Angle Spectrometer (SM1),

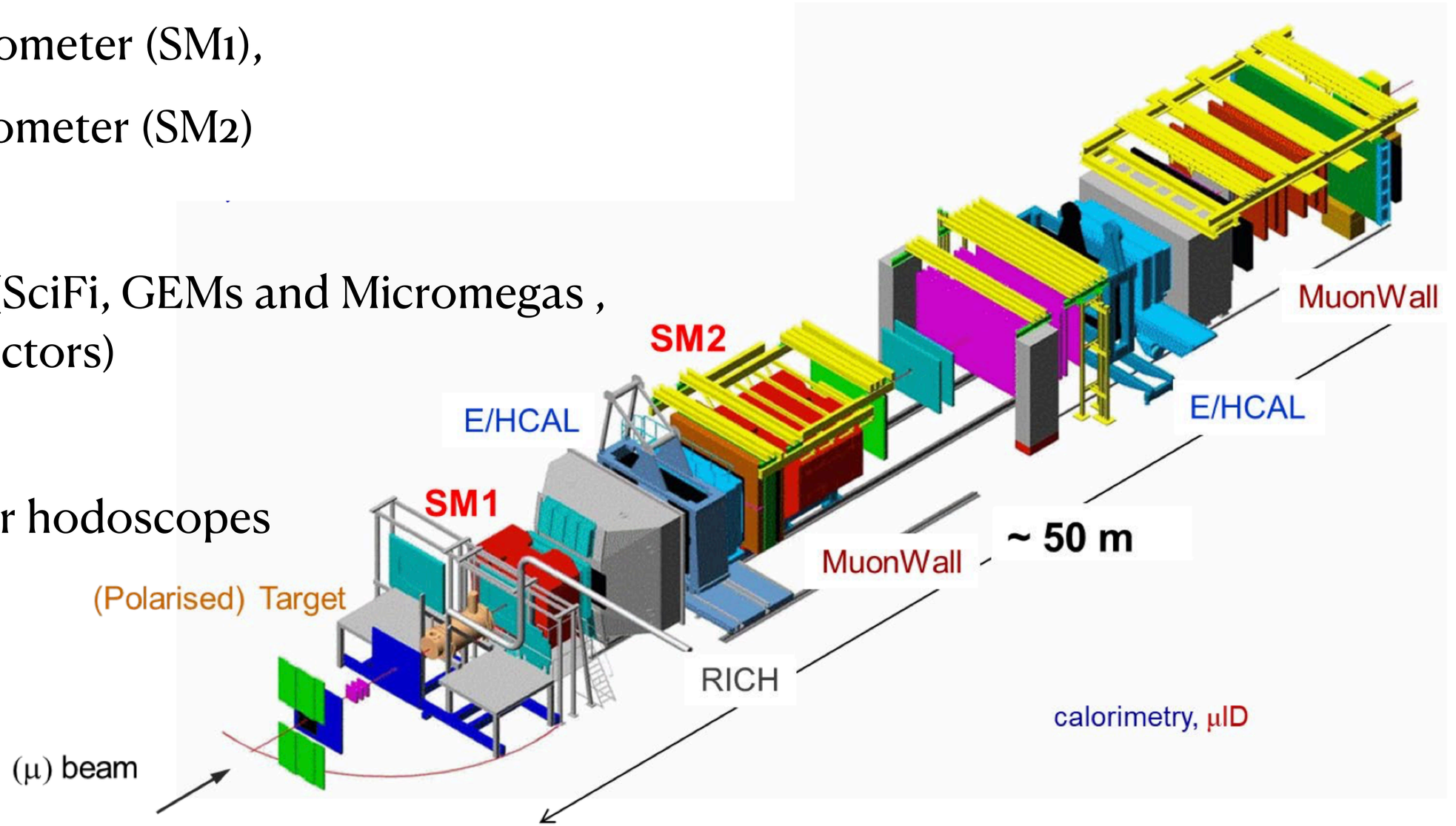
Small Angle Spectrometer (SM2)

equipped with

tracking detectors (SciFi, GEMs and Micromegas , MWPCs, Drift Detectors)

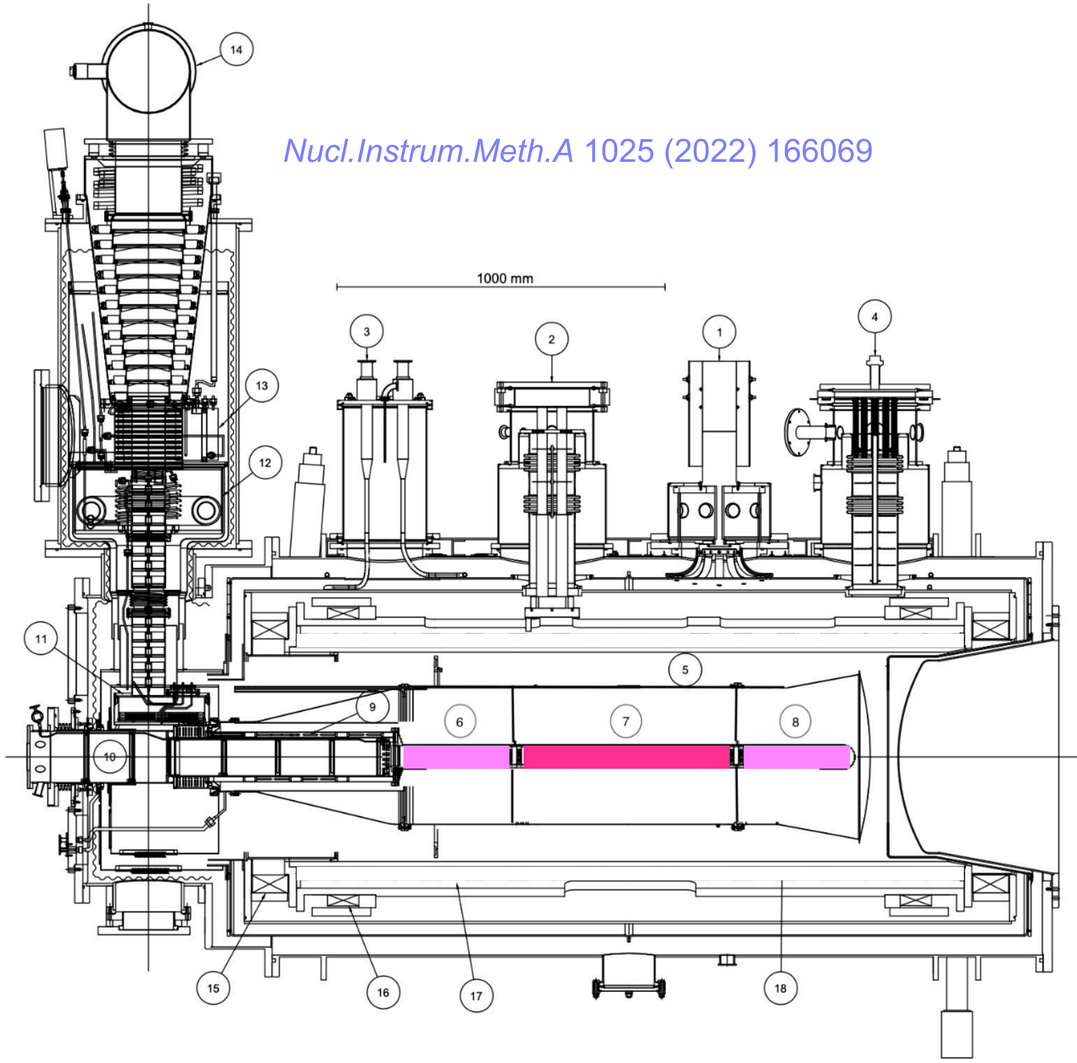
RICH, muon walls,

calorimeters, trigger hodoscopes



COMPASS Polarized Target

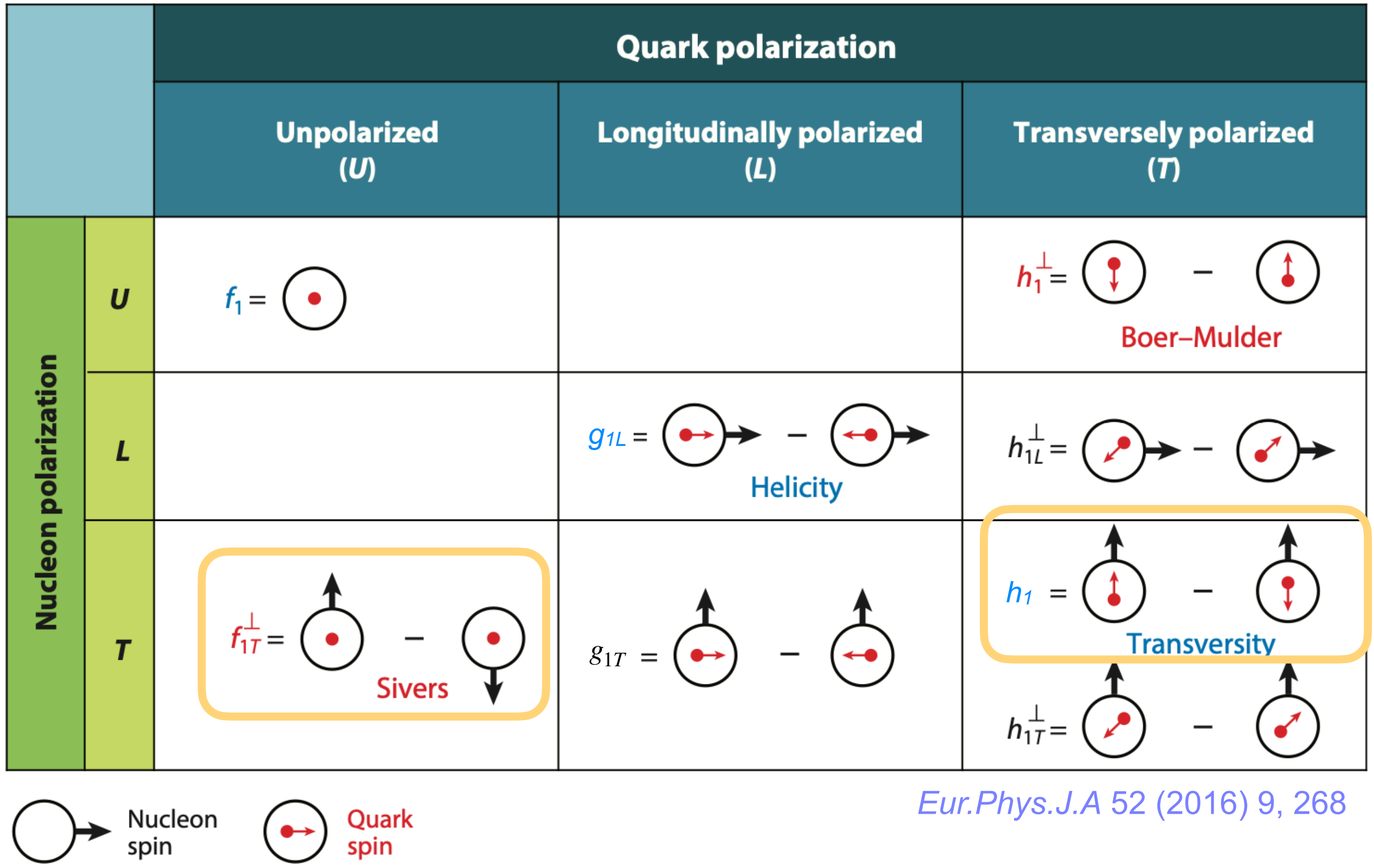
- Large aperture superconducting magnet offer large angular acceptance - 180 mrad since 2006 (70 mrad in 2002 - 2004)
- Three oppositely polarized target cells (30 + **60** + 30 cm)
- DNP method for polarization
- Deuteron (^{6}LiD) in 2022 achieved ~40% polarization with dilution factor f ~ 0.4
- Proton (NH_3) achieved ~80-90% polarization with dilution factor f ~ 0.15



Nucl.Instrum.Meth.A 1025 (2022) 166069

Transverse Structure of the Nucleon

The nucleon's quark structure at leading twist with intrinsic quark transverse momentum described using **eight TMD PDFs.**

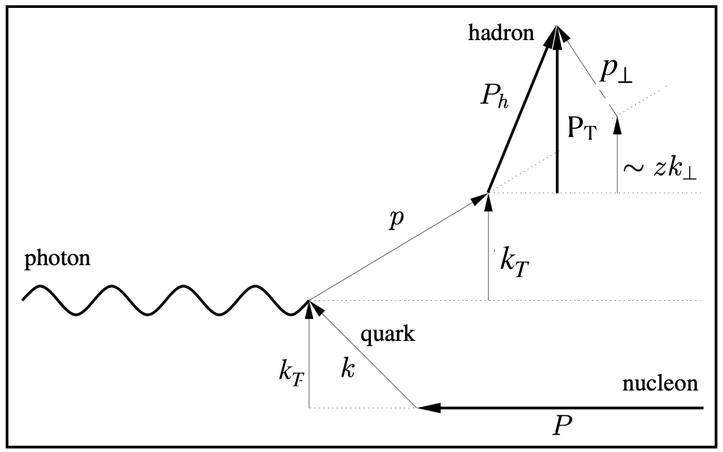


Eur.Phys.J.A 52 (2016) 9, 268

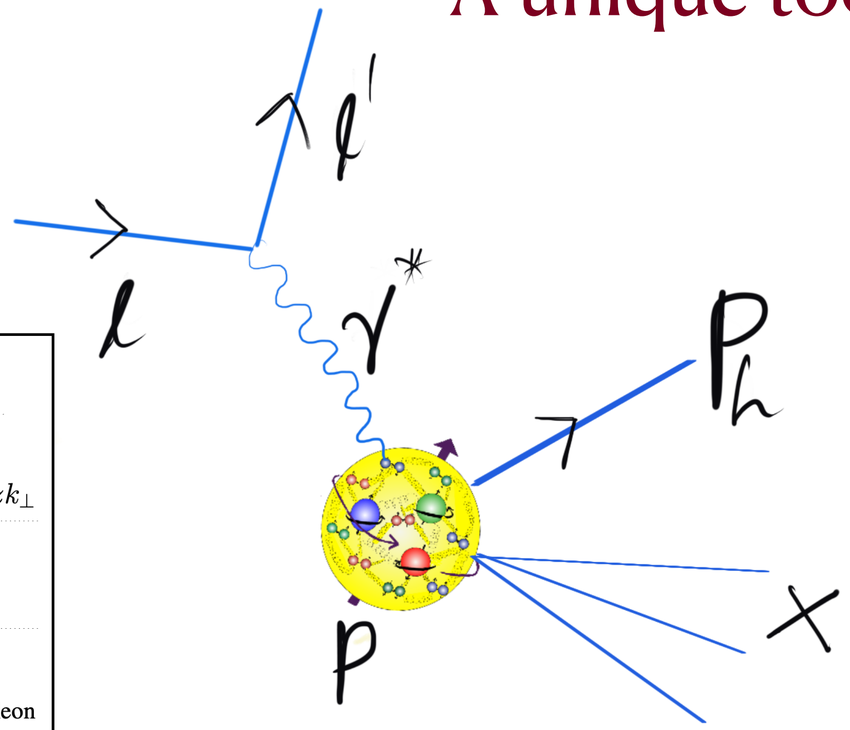
Accessing TMD PDFs

Semi-Inclusive Deep Inelastic Scattering (SIDIS)

A unique tool!



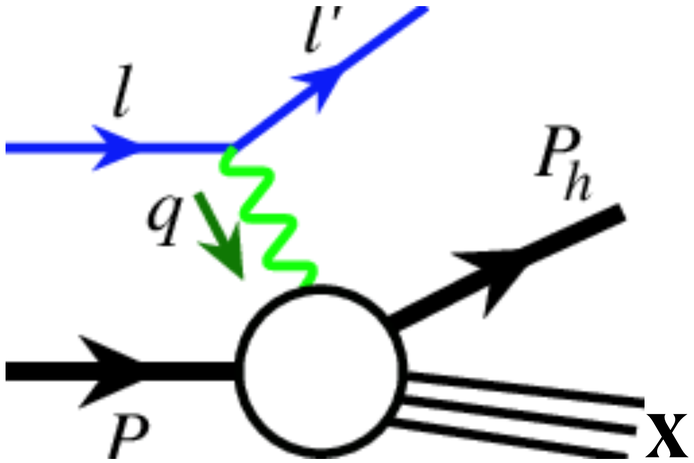
Bacchetta et. al., arXiv:2405.13833 [hep-ph] (2024)



COMPASS Experiment!

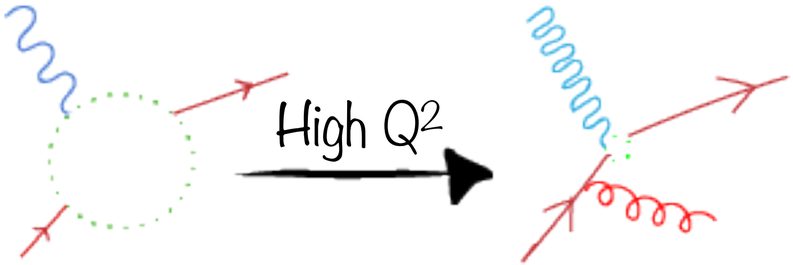
$$\sigma^{lp\to l'hX} \sim f_q(x, Q^2, k_T) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z, Q^2, p_\perp)$$

Semi Inclusive Deep Inelastic Scattering



CoM Energy: $s = (l + P)^2 \simeq 4 E E_p$

Photon virtuality: $Q^2 = -q^2$



Inelasticity: $y = 1 - \frac{E'}{E}$

Invariant mass of the hadronic final state: $W^2 = (P + q)^2$

Bjorken *x*: $x = \frac{Q^2}{2P \cdot q}$

virtual photon's energy fraction carried by hadron: $z = \frac{P \cdot P_h}{P \cdot q}$

Single hadron SIDIS cross-section

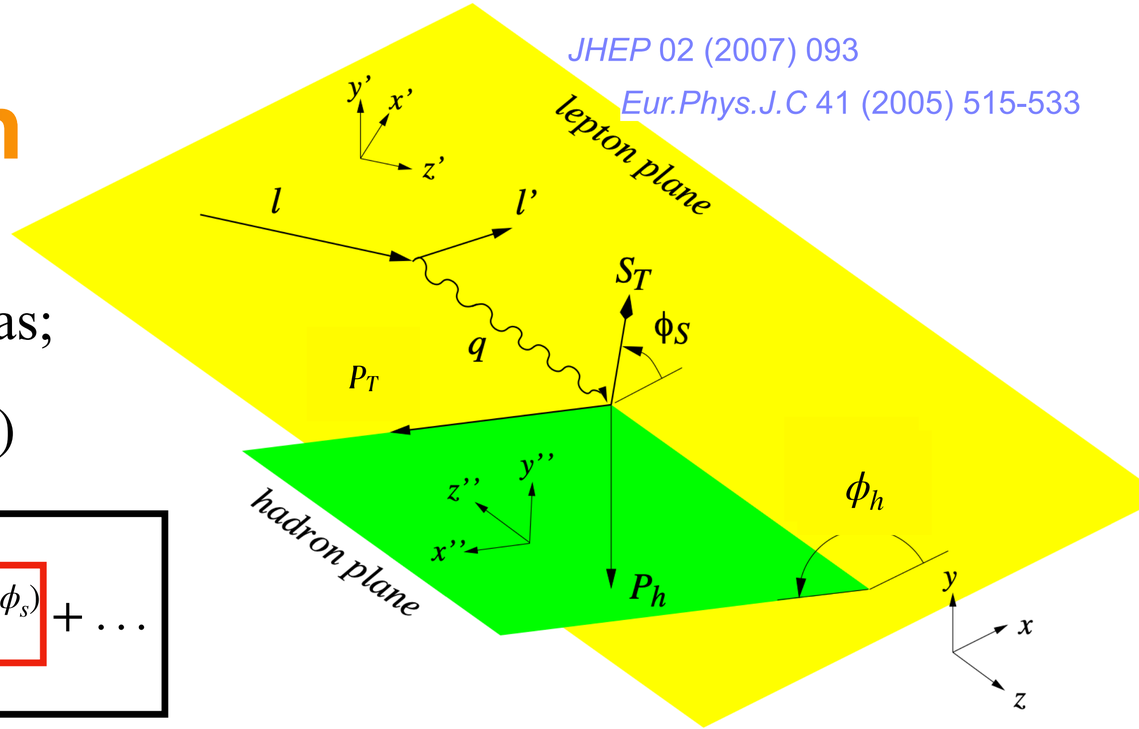
The total differential cross-section of SIDIS can be expressed as;

$$d\sigma = d\sigma_{UU} + \lambda_l d\sigma_{LU} + S_L(d\sigma_{UL} + \lambda_l d\sigma_{LL}) + S_T(d\sigma_{UT} + \lambda_l d\sigma_{LT})$$

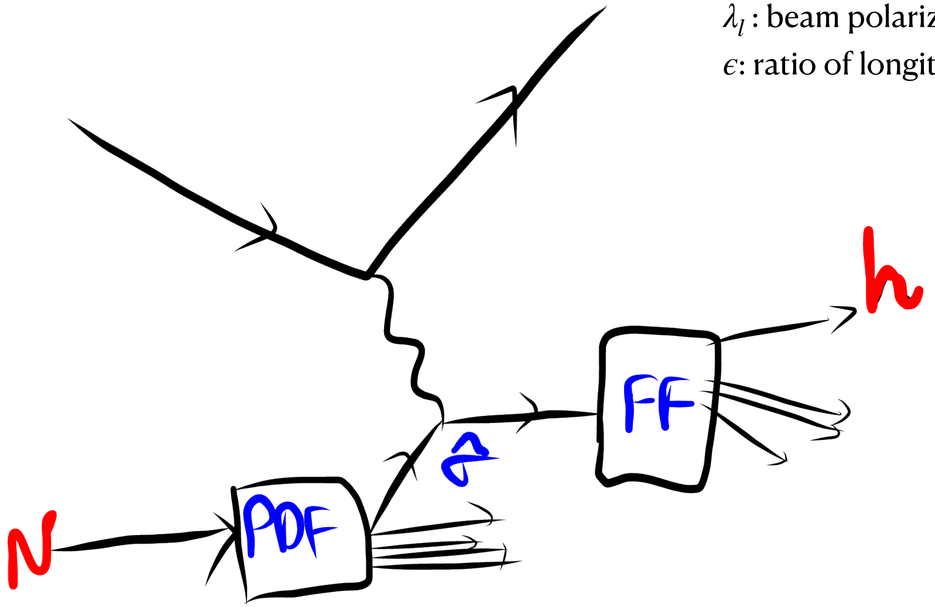
$$d\sigma_{UT} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)} \cdot \{\sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h-\phi_s)} + \epsilon \sin(\phi_h + \phi_s) F_{UT}^{\sin(\phi_h+\phi_s)} + \dots$$

λ_l : beam polarization

ϵ: ratio of longitudinal to transverse photon flux



JHEP 02 (2007) 093
Eur.Phys.J.C 41 (2005) 515-533



$f_{1T}^{\perp} \otimes D_1$ Sivers PDF ⊗ unpol. FF

$h_1 \otimes H_1^{\perp}$ transversity PDF ⊗ Collins FF

Connecting to experiment

JHEP 02 (2007) 093

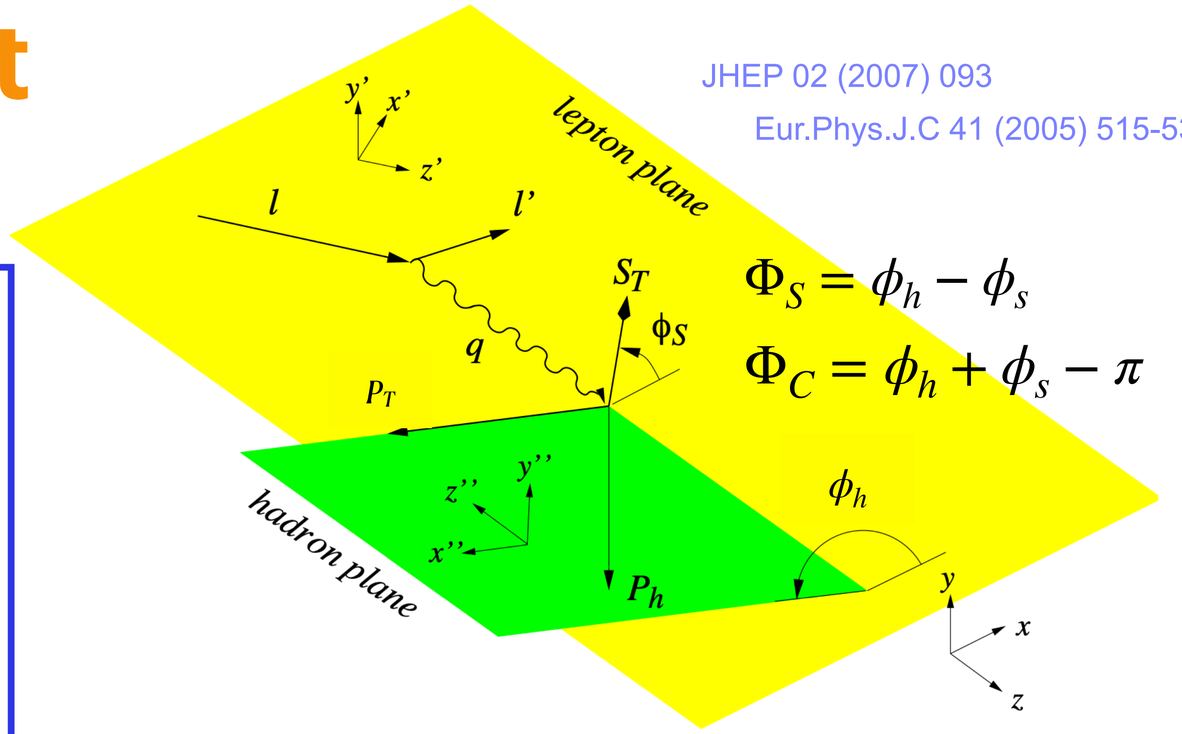
Eur.Phys.J.C 41 (2005) 515-533

At leading order:

$$A_{Siv} = \frac{F_{UT}^{\sin(\Phi_S)}}{F_{UU}} = \frac{\Sigma_q e_q^2 \,.\, f_{1T,q}^{\perp}(x) \otimes D_{1,q}(z)}{\Sigma_q e_q^2 \,.\, f_{1,q}(x) \otimes D_{1,q}(z)}$$

$$A_{Coll} = \frac{F_{UT}^{\sin(\Phi_C)}}{F_{UU}} = \frac{\Sigma_q e_q^2 \,.\, h_{1,q}(x) \otimes H_{1,q}^{\perp}(z)}{\Sigma_q e_q^2 \,.\, f_{1,q}(x) \otimes D_{1,q}(z)}$$

Ref. ***JHEP* 02 (2007) 093** for details on convolution (⊗) including kinematic pre-factors



Experimentally, for a given target configuration, we obtain the yield as a function of the angles :

f : target dilution factor

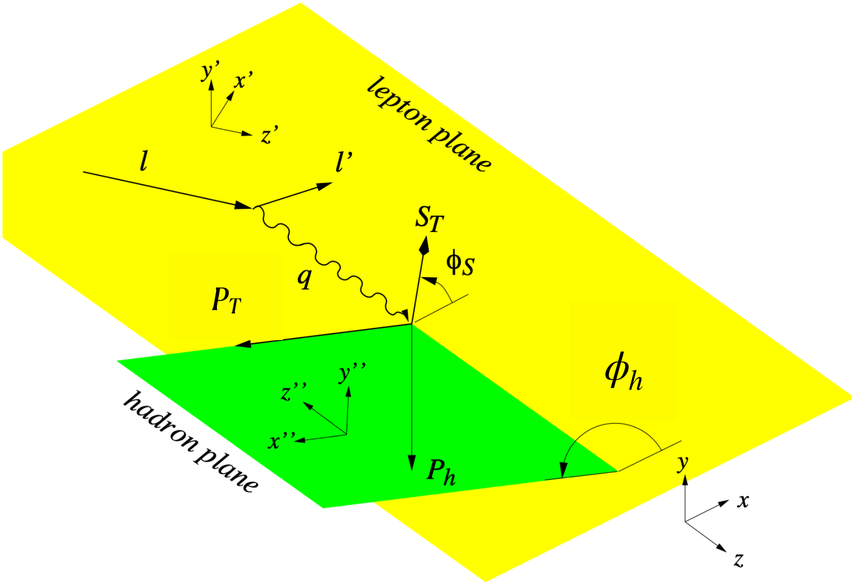
P_t : target polarization

$D_{NN}(y) = \frac{2(1-y)}{1+(1-y)^2}$: transverse spin transfer coefficient

$$N(\Phi_S) \propto 1 + A_{Siv} \,.\, P_t \,.\, f \sin\Phi_S$$

$$N(\Phi_C) \propto 1 + A_{Col} \,.\, P_t \,.\, f \,.\, D_{NN} \sin\Phi_C$$

SIDIS Event Selection



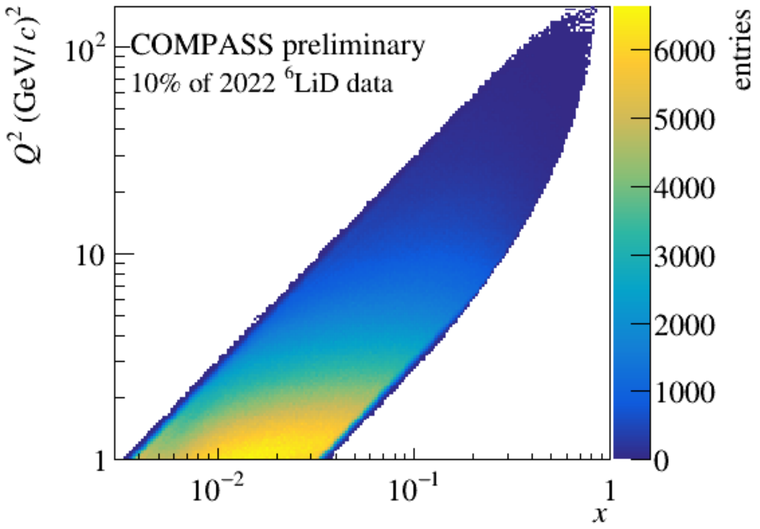
$Q^2 > 1$ (GeV/c)²

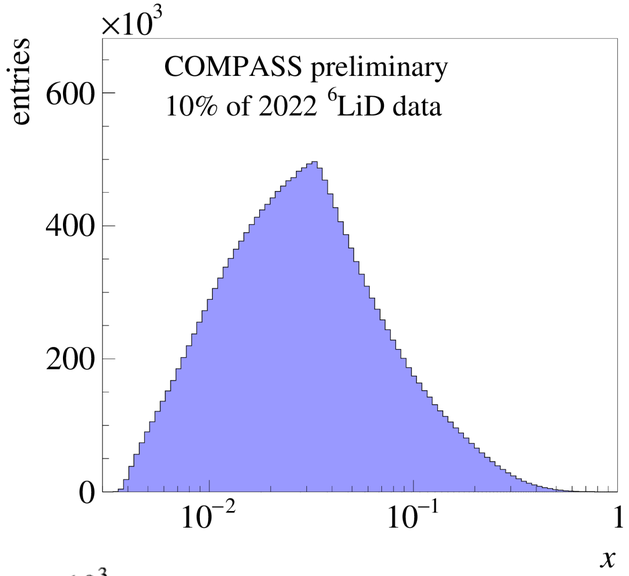
$W^2 > 25$ (GeV/c²)²

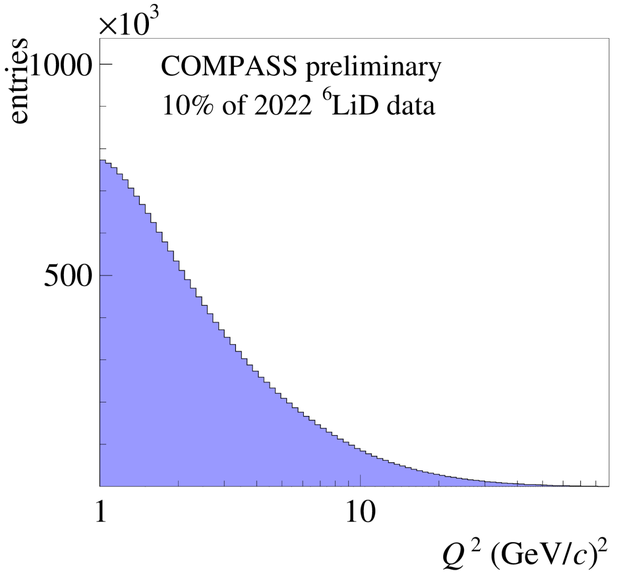
$0.1 < y < 0.9$

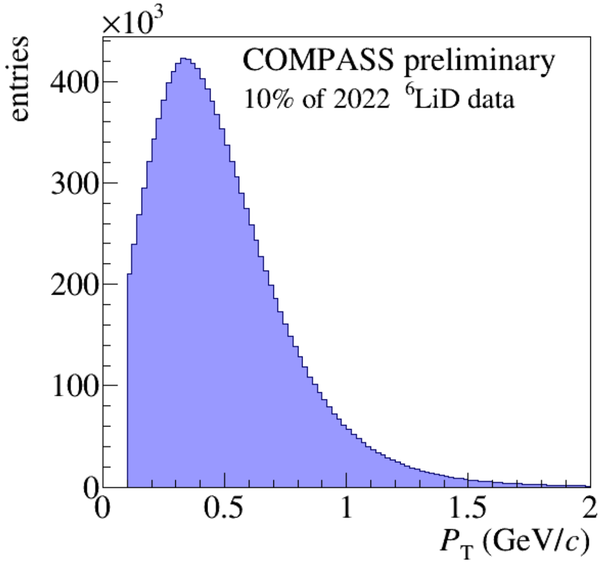
$z > 0.2$

$P_T > 0.1$ (GeV/c)









COMPASS SIDIS Legacy

160 GeV muon beam on:

T polarized **deuteron** target : **2002 - 2004**

T polarized **proton** target : **2007, 2010**

★ T polarized **deuteron** target : **2022** **NEW!**

PRL 94 (2005) 202002

PLB 673 (2009) 127–135

NP B765 (2007) 31–70

PLB 692 (2010) 240–246

PLB 717 (2012) 383

PLB 717 (2012) 376

PLB 713 (2012) 10

PLB 736 (2014) 124

PLB 744 (2015) 250

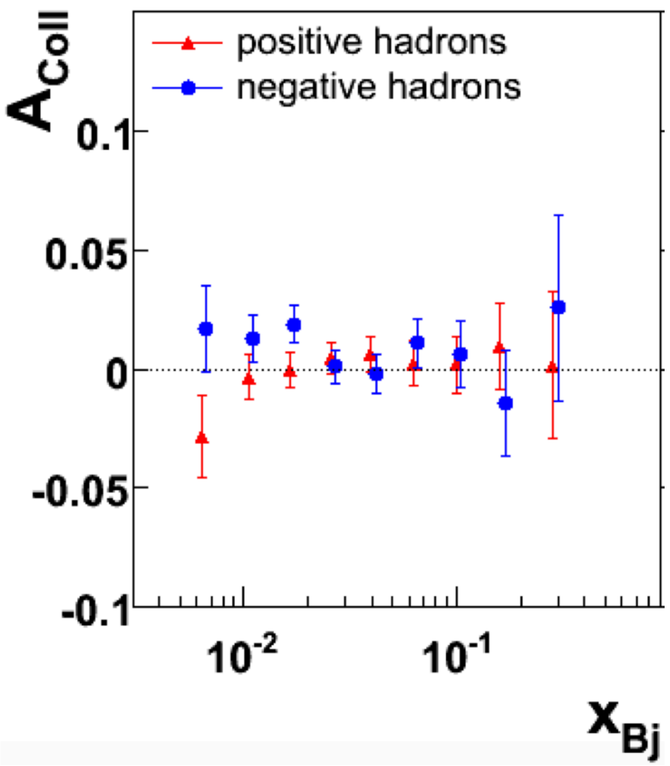
PLB 753 (2016) 406

PLB 845 (2023) 138155

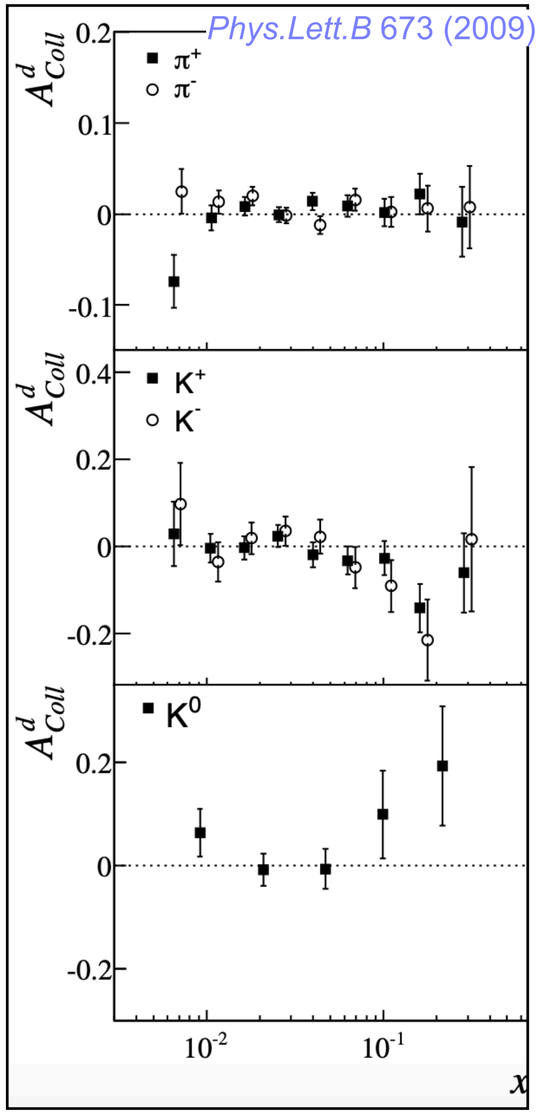
COMPASS SIDIS Legacy

Collins asymmetries from deuteron target (2002 - 2004 data):

Nucl.Phys.B 765 (2007) 31-70



Phys.Lett.B 673 (2009) 127-135



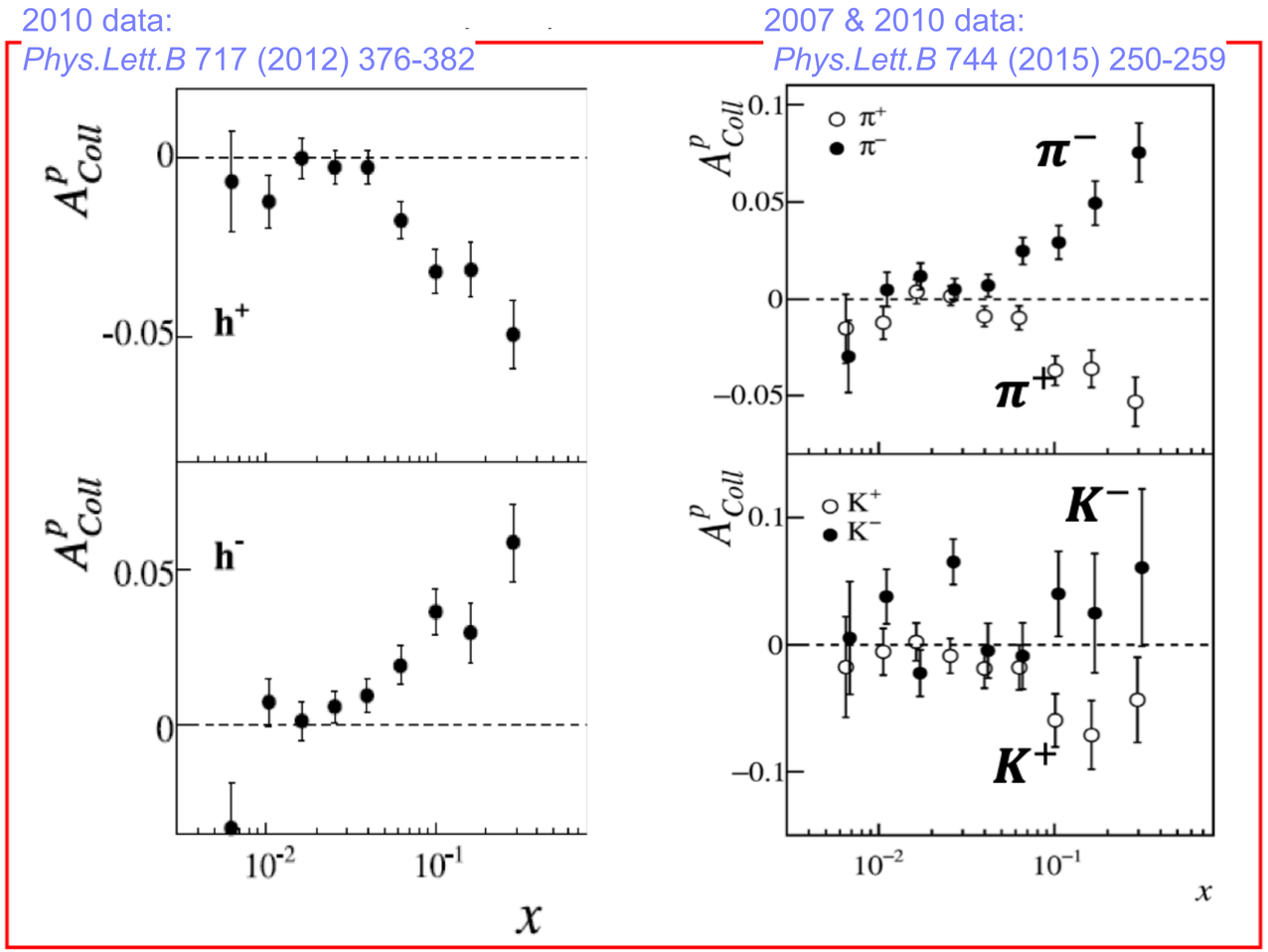
- Asymmetries compatible with zero
- Hinting at cancellation of u and d quark transversity contributions
- The only existing deuteron results until 2022
- But with large statistical uncertainties at large x

COMPASS SIDIS Legacy

Collins asymmetries from proton target (2007, 2010):

2010 data:
Phys.Lett.B 717 (2012) 376-382

2007 & 2010 data:
Phys.Lett.B 744 (2015) 250-259

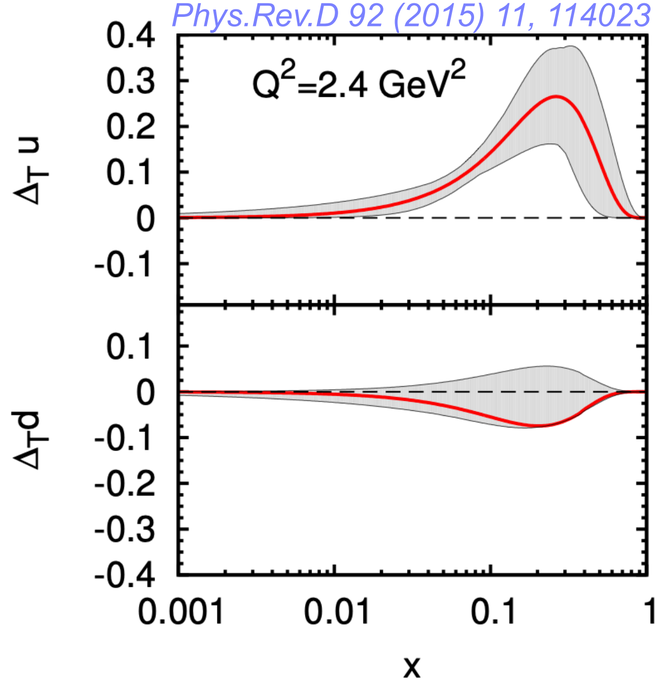


- Distinct signal in the valence region
- Similar magnitude but opposite sign for h+ and h-
- Agrees with 2005 HERMES results despite different beam energies

Towards accessing Transversity PDF

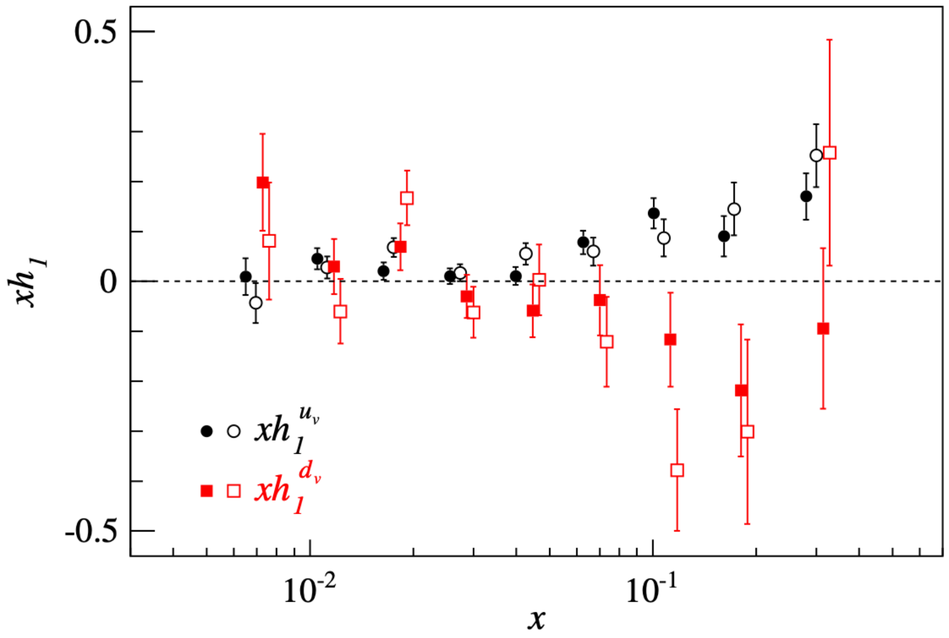
From SIDIS and $e^+ e^-$ annihilation data:

Anselmino et al.
Phys.Rev.D 92 (2015) 11, 114023



A. Martin, F. Bradamante, V. Barone
Phys.Rev.D 91 (2015) 1, 014034

refer talk by Franco Bradamante



Suggests opposite signs for *u* and *d* quark transversity PDFs

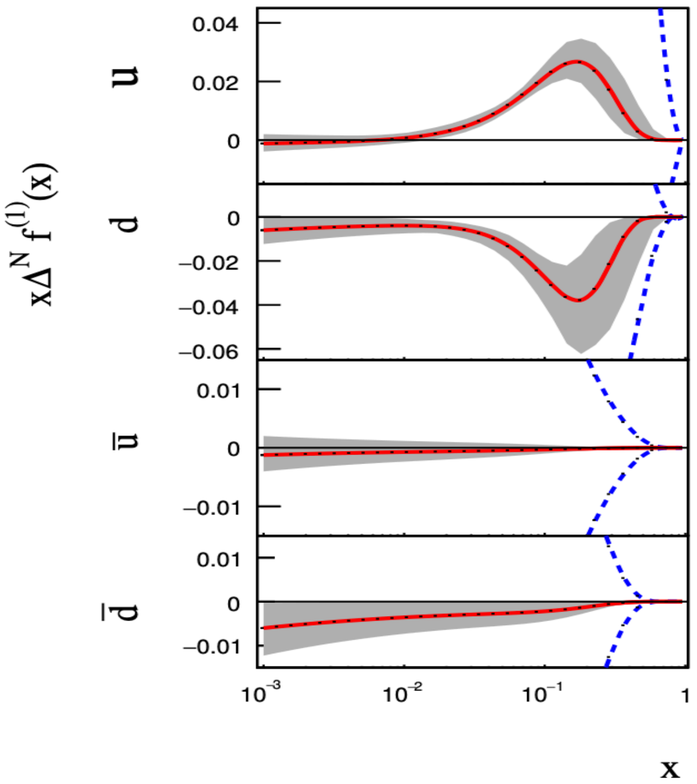
d quark transversity PDF determination limited by statistics of neutron/deuteron data

Motivation for COMPASS deuteron run 2022!

Towards accessing Sivers PDF

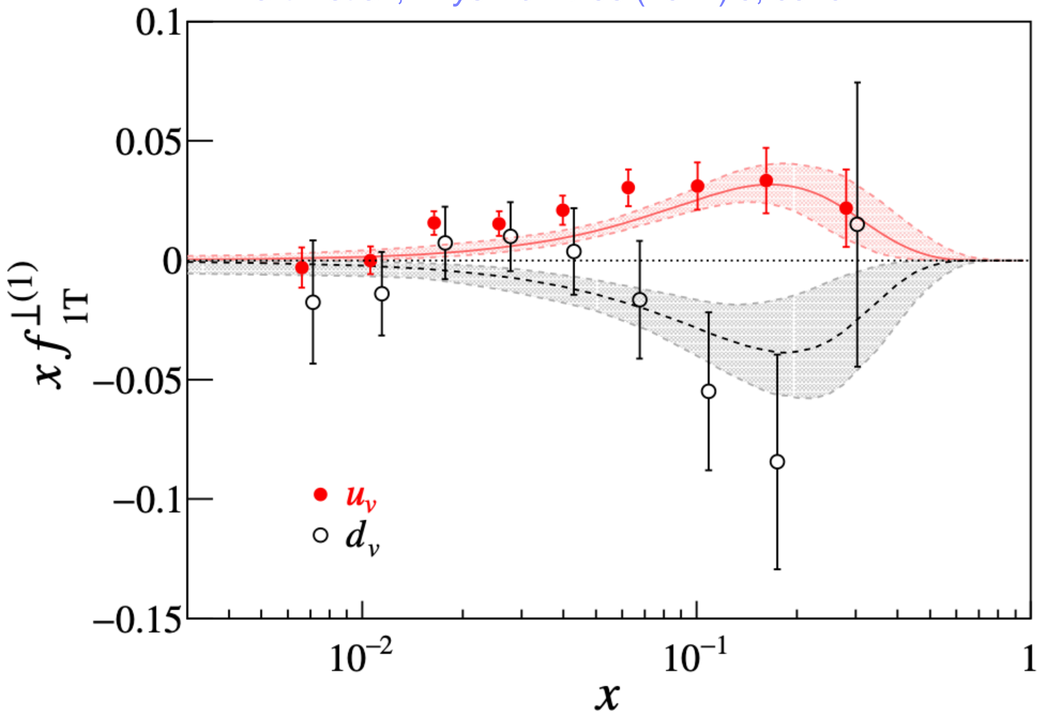
from HERMES, COMPASS and JLab

Anselmino et al., *JHEP* 04 (2017) 46



from SIDIS on proton and deuteron targets at COMPASS

A.Martin et al., *Phys.Rev.D* 95 (2017) 9, 094024



Suggests opposite signs for *u* and *d* quark Sivers PDFs

d quark Sivers PDF determination limited by statistics of neutron/deuteron data

Motivation for COMPASS deuteron run 2022!

Addendum to COMPASS II

COMPASS Deuteron Run 2022!

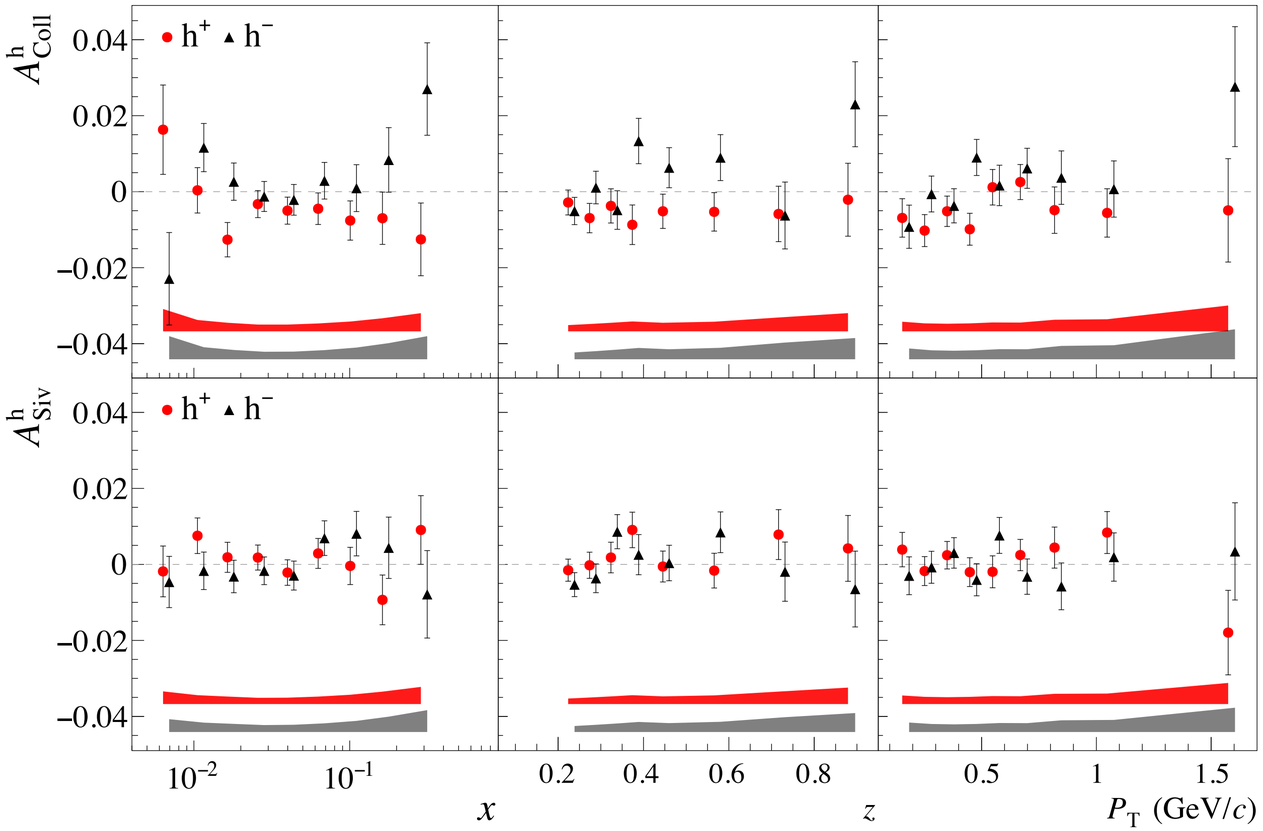
- To complete the COMPASS physics program on transverse spin effects in SIDIS
- Muon on deuteron (^{6}LiD) SIDIS - with similar conditions as 2010 proton run
- Aim to improve the statistical uncertainties in *d* quark distributions
- Improvement in statistical uncertainties expected with one year of data taking :

$$\sigma^{d}_{2022} \approx 0.6\sigma^{p}_{2010}$$

First results from 2022 data: **Sivers and Collins TSAs, dihadron TSAs**

Uncertainties on the asymmetries are in line with the expectation

Sivers and Collins Asymmetries from 2022 data



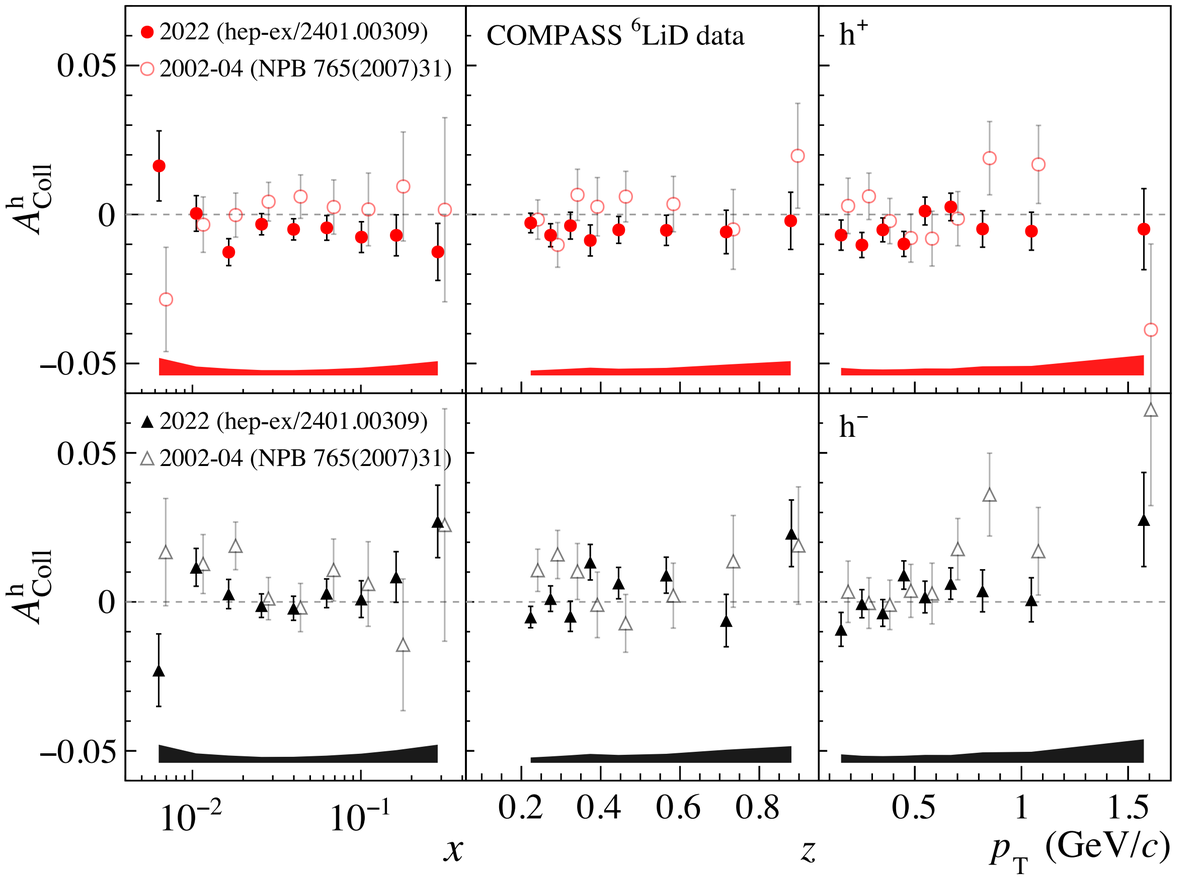
NEW. arXiv:2401.00309
To appear in PRL

- Largely improved precision by a factor of 3
- Sivers asymmetries are compatible with zero
- Collins asymmetries show opposite trend for positive and negative hadrons at large x - similar to the proton results

Comparison with COMPASS previous deuteron results

Collins asymmetries

NEW. arXiv:2401.00309
To appear in PRL

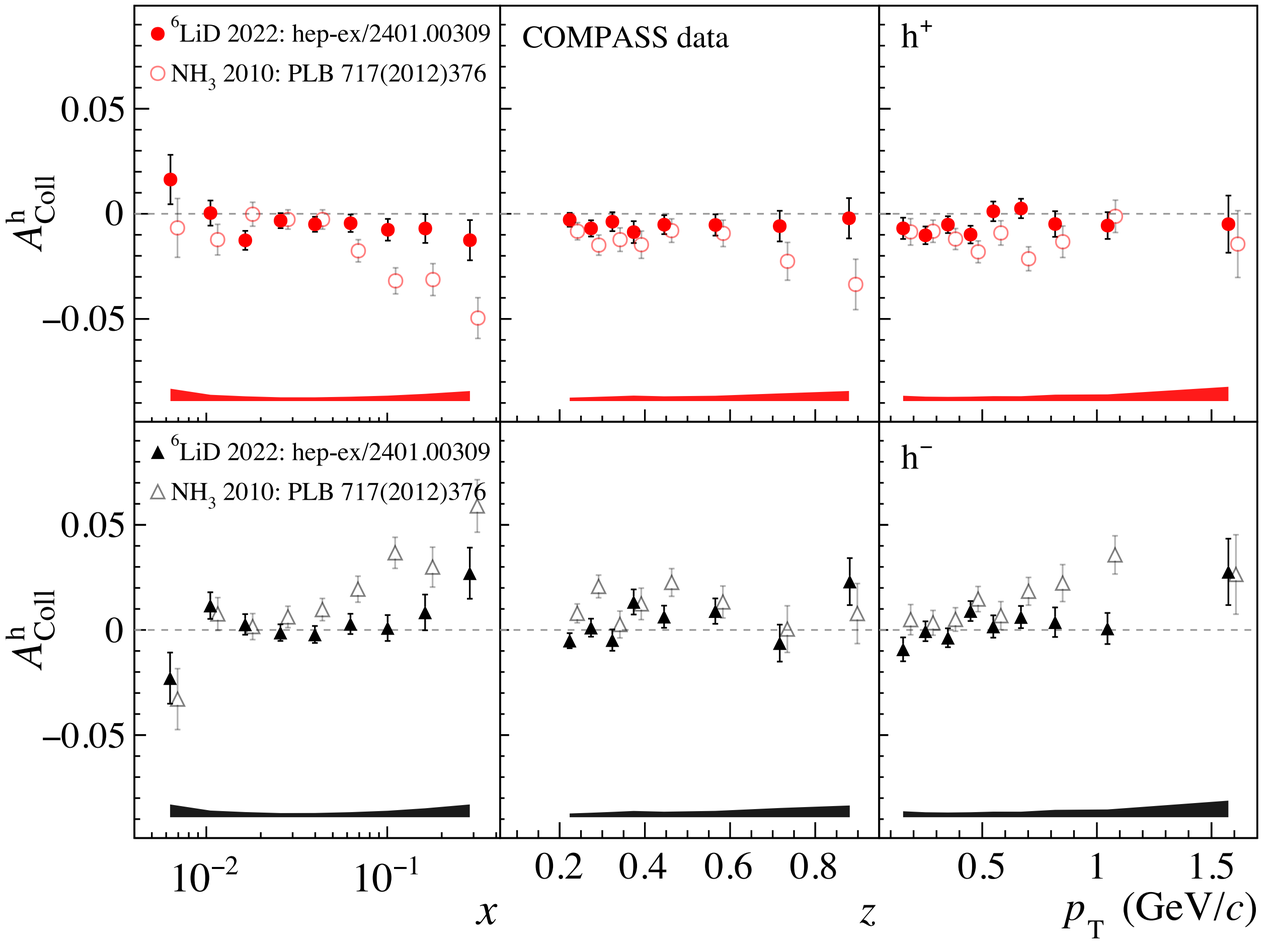


- Improved precision in the new data
- Statistical uncertainties reduced by a factor of 3
- Hints for signal at large x , similar to results from proton

Comparison with COMPASS proton results

NEW. arXiv:2401.00309
To appear in PRL

Collins asymmetries

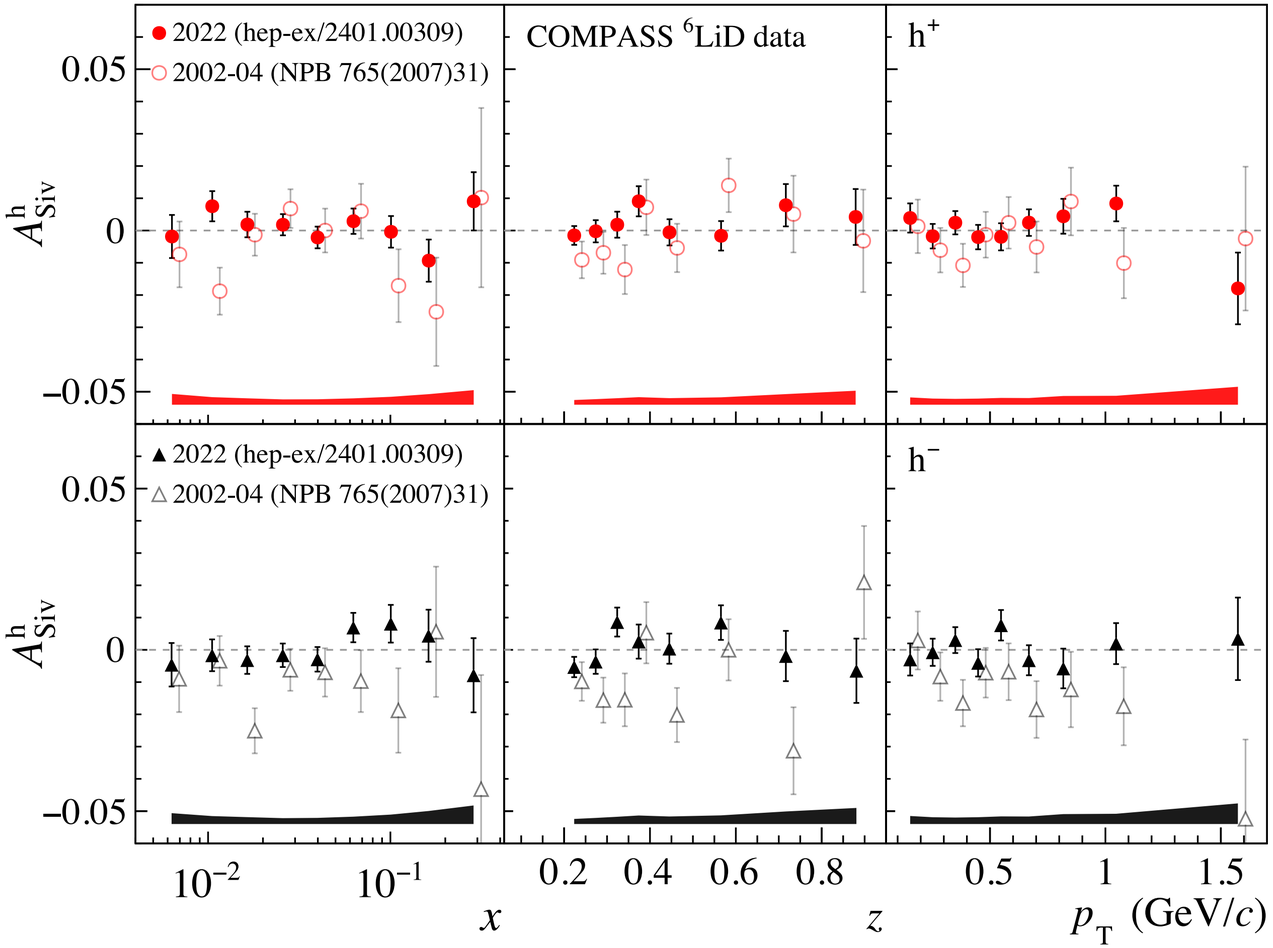


- Small deuteron asymmetries due to cancellation of *u* and *d* quark contributions
- Deuteron asymmetries follow similar trend as the proton at large x
- Comparable statistical uncertainties

Comparison with COMPASS previous deuteron results

NEW. arXiv:2401.00309
To appear in PRL

Sivers asymmetries

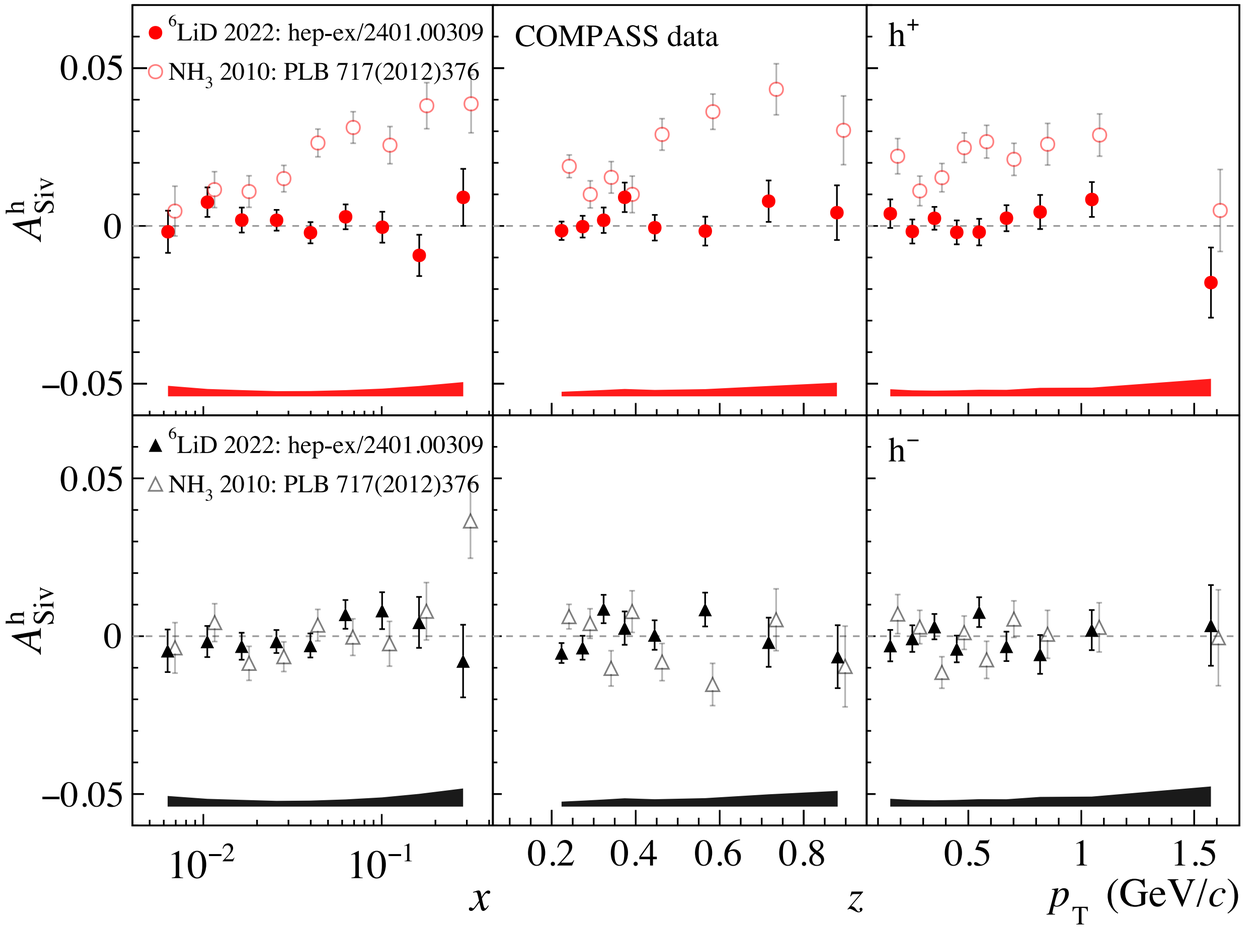


- Improved precision in the new data
- Statistical uncertainties reduced by a factor of 3
- Compatible with zero

Comparison with COMPASS proton results

Sivers asymmetries

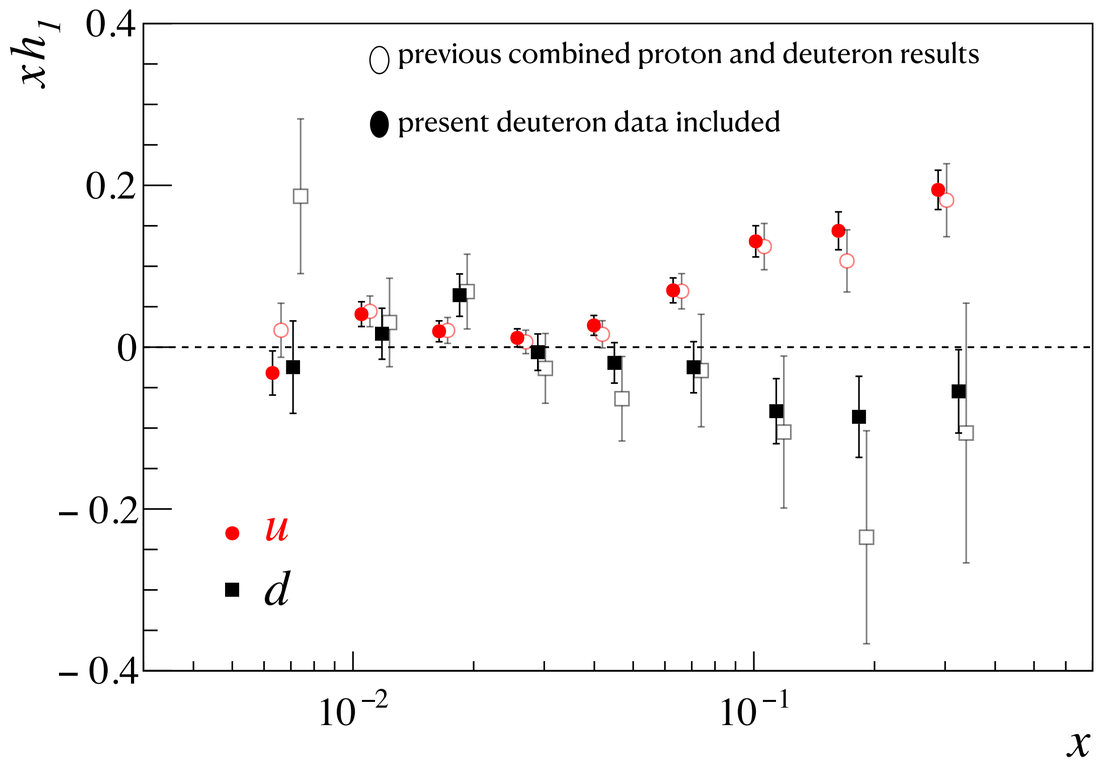
NEW. arXiv:2401.00309
To appear in PRL



- Deuteron results for are compatible with ~zero as expected.
- Comparable statistical uncertainties between deuteron and proton results
- Cancellation of *u* and *d* quark distributions

Extraction of Transversity PDFs

NEW. arXiv:2401.00309
To appear in PRL



Point to point extraction of h_1 was performed
A. Martin et al, Phys. Rev. D 91, 014034 (2015)
Using COMPASS SIDIS (p and d) and Belle e^+e^- data

- Opposite signs for *u* and *d* quarks
- Improved statistical uncertainties including new data.
- Almost a factor of 4 improvement in large x
- Smaller error bars for both *u* and *d* quarks distributions

Extraction of Nucleon Tensor Charge

NEW. arXiv:2401.00309
To appear in PRL

data	$\delta u = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{d_v}(x)$	$g_T = \delta u - \delta d$
previous Nucl. Phys. B 765, 31 (2007), Phys.Lett.B**717**,376(2012) Phys.Lett.B**717**,383(2012),	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
previous and present	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

✓ For the *u* quark, new and old values are consistent;

- 30% reduction in statistical uncertainty

✓ For the *d* quark, the new values are a factor of about 2.5 smaller;

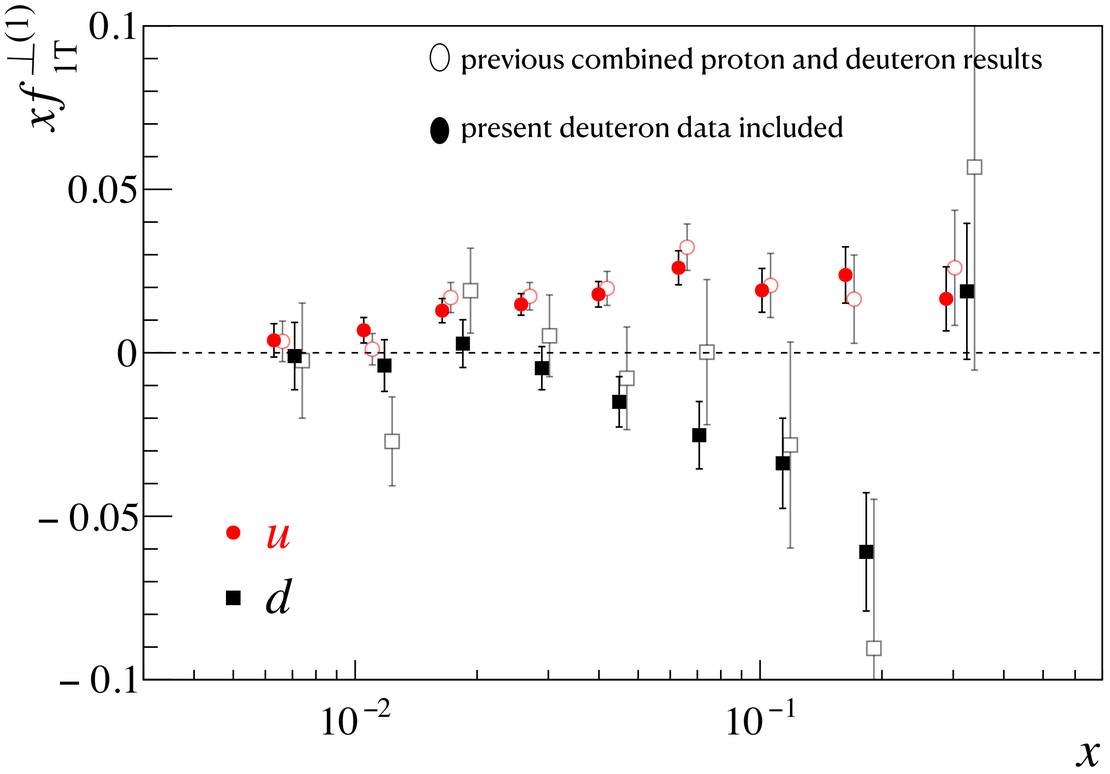
- a factor of two reduction in stat. uncertainty

✓ The truncated nucleon tensor charge g_T is now about 20% smaller;

- a factor of two reduction in stat. uncertainty

Extraction of Sivers PDFs

NEW. arXiv:2401.00309
To appear in PRL

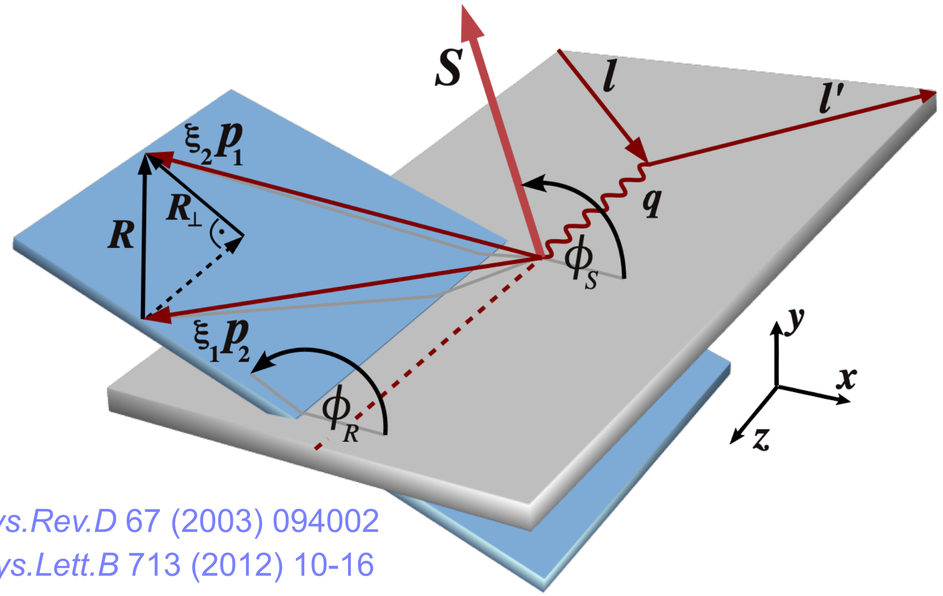


A. Martin et al, Phys. Rev. D 91, 014034

Similar procedure implemented for extraction of the Sivers function $f_{1T}^{\perp(1)}$

- Opposite signs for *u* and *d* quarks distributions
- For the *d* quark, the statistical uncertainties are reduced by about a factor of two
- The different *x* dependence for *u* and *d* quarks is now quite clear.

Dihadron Asymmetries and IFF



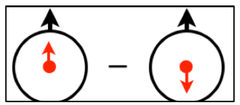
Phys.Rev.D 67 (2003) 094002
Phys.Lett.B 713 (2012) 10-16

$$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$$

Cross-section of semi-inclusive dihadron leptoproduction on a transversely polarized target :

$$\frac{d^7\sigma_{UU}}{d\cos\theta\, dM^2_{h^+h^-}\, d\phi_R\, dz\, dx\, dy\, d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\left(1-y+\frac{y^2}{2}\right) \times \sum_q e_q^2 f_1^q(x)\, D_{1,q}\left(z, M^2_{h^+h^-}, \cos\theta\right),$$

$$\frac{d^7\sigma_{UT}}{d\cos\theta\, dM^2_{h^+h^-}\, d\phi_R\, dz\, dx\, dy\, d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y} S_\perp (1-y) \times \sum_q e_q^2 \frac{|\boldsymbol{p}_1 - \boldsymbol{p}_2|}{2M_{h^+h^-}} \sin\theta \sin\phi_{RS}\, h_1^q(x)\, H_{1,q}^{\sphericalangle}\left(z, M^2_{h^+h^-}, \cos\theta\right).$$



transversity PDF x Interference FF

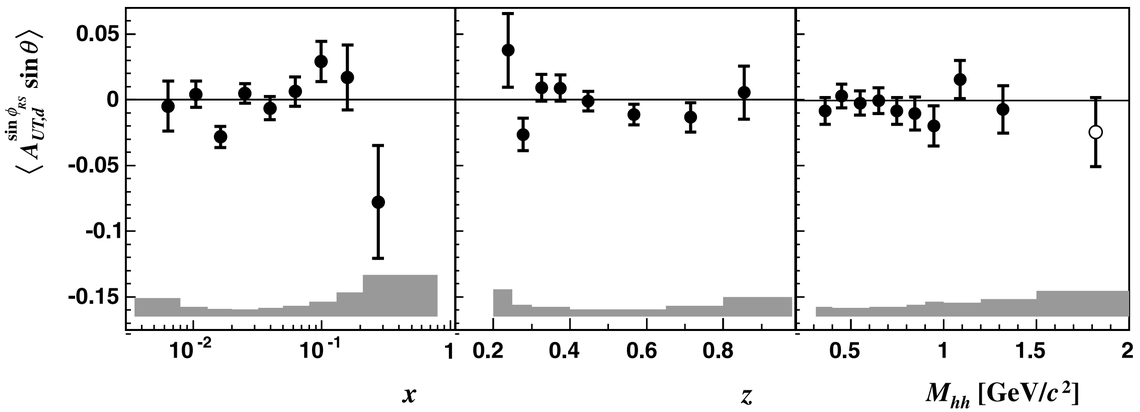
$$A_{UT}^{\sin\phi_{RS}} = \frac{|\boldsymbol{p}_1 - \boldsymbol{p}_2|}{2M_{h^+h^-}} \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^{\sphericalangle}(z, M^2_{h^+h^-}, \cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z, M^2_{h^+h^-}, \cos\theta)}$$

COMPASS SIDIS Legacy

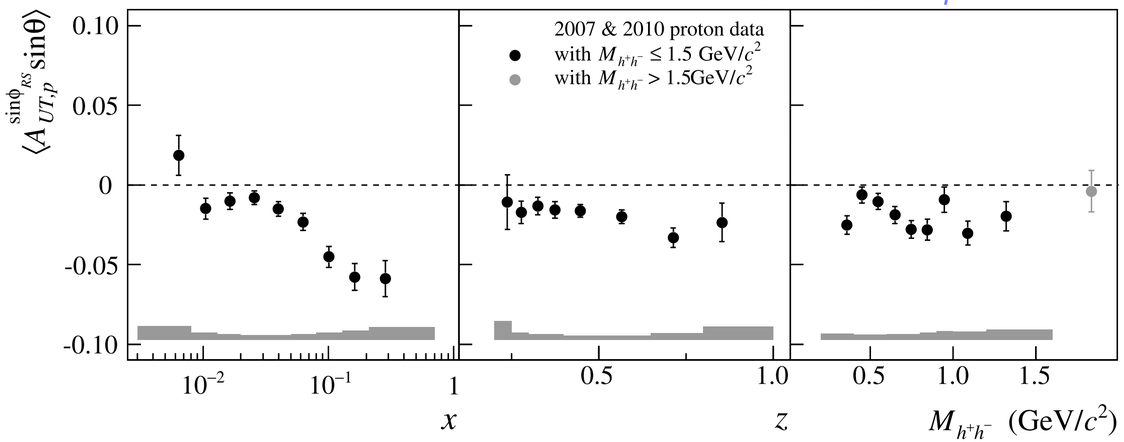
Dihadron asymmetries from proton and deuteron targets :

Phys.Lett.B 713 (2012) 10-16

2002-2004 deuteron data



2007 & 2010 proton data



For deuteron target:

- No significant asymmetries observed

For proton target:

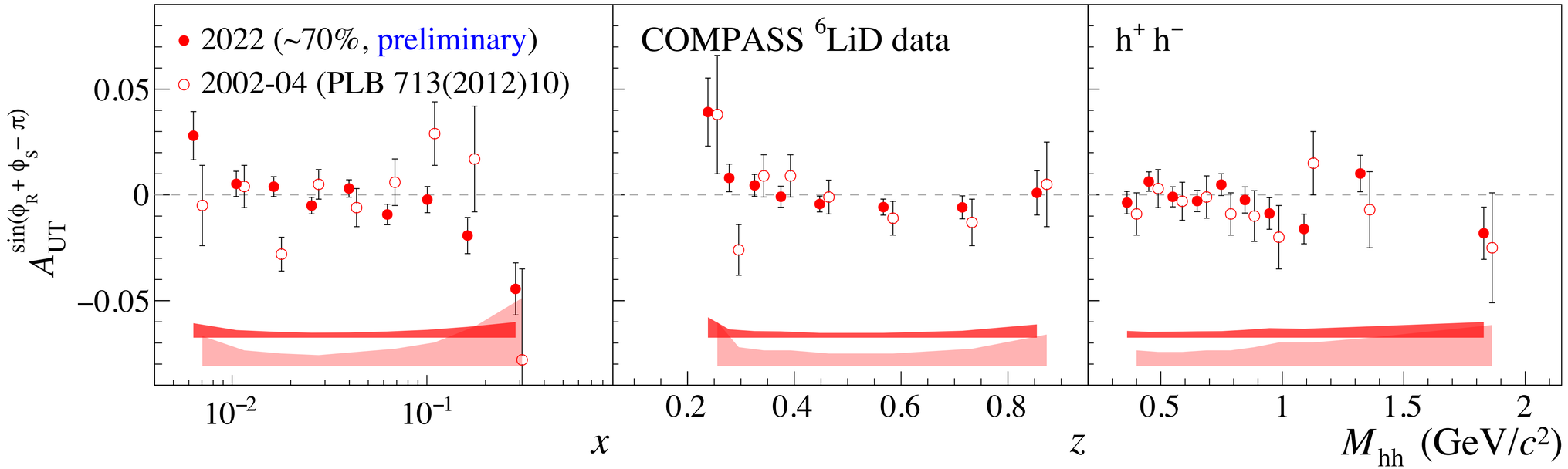
- Signal in valence region indicate non-vanishing transversity PDF and interference FF
- Asymmetry is very close to and somewhat larger than the Collins asymmetry for positive hadrons

  ✦ same mechanism behind 1h and 2h transverse spin dependent FFs

Dihadron Asymmetries from 2022 data

NEW

Comparison with previous **deuteron** results

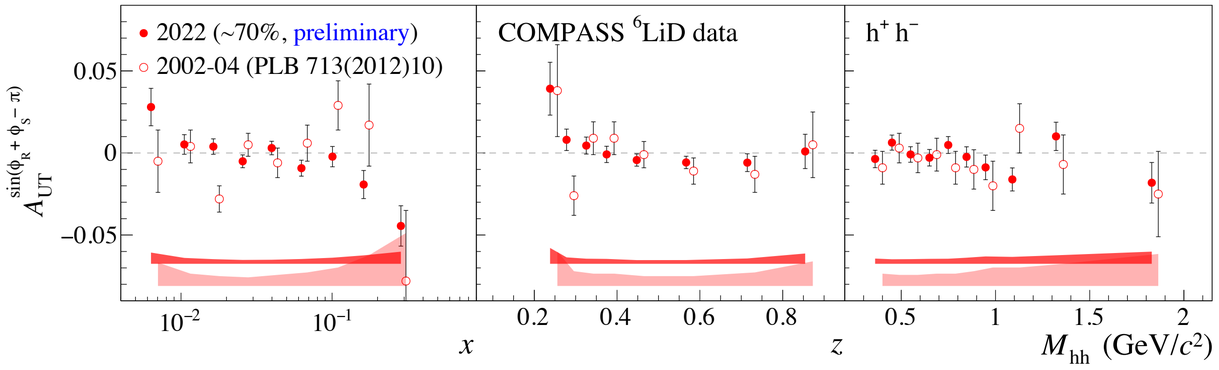


- Improved statistical uncertainties with the new data, **up to a factor of 4 at large x**
- Suggests signal in large x region

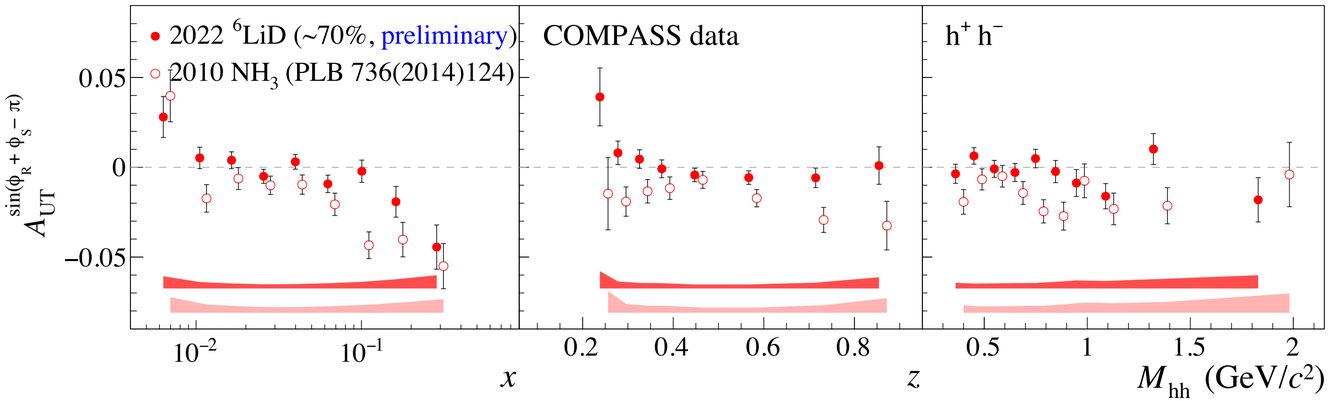
Comparison with previous COMPASS results

NEW

Comparison with previous **deuteron** results



Comparison with previous **proton** results



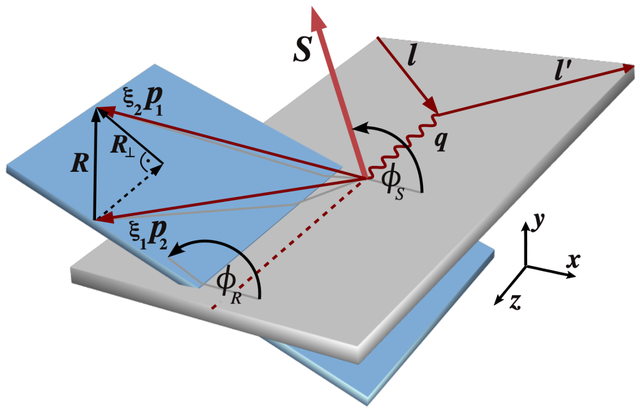
- Improved statistical uncertainties with the new data
- Similar trend in large x region between proton and deuteron

Summary

- New high-statistics COMPASS results for the TSAs with deuteron target.
- Improved statistical uncertainties are as expected
- The 2022 deuteron data will stay unique for several years at least until the JLab and EIC results are available
- COMPASS has made yet another important contribution to the study of the nucleon structure.
- Many new analyses to come in the near future

BACKUP

Interplay between Collins and Dihadron asymmetries



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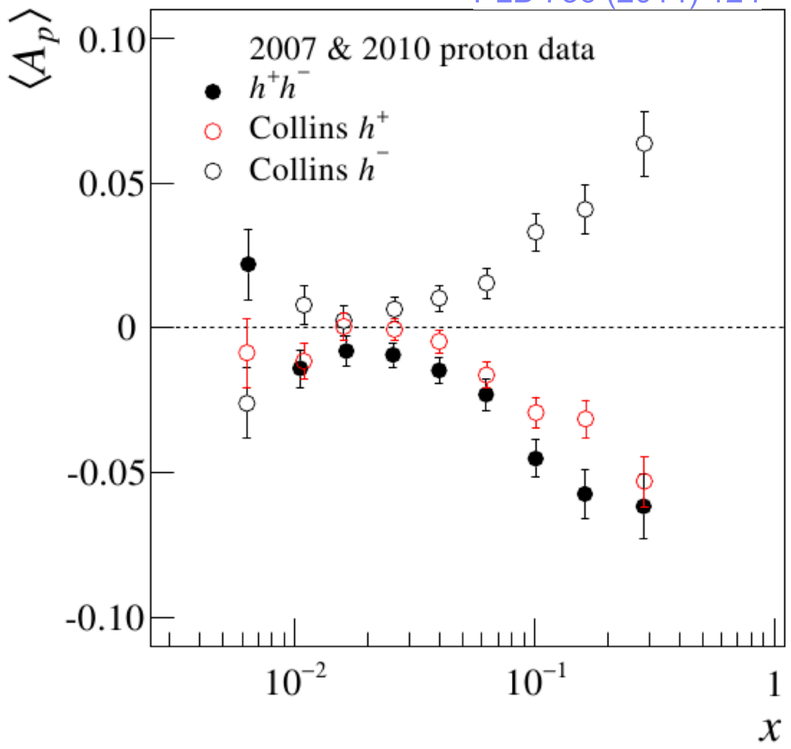
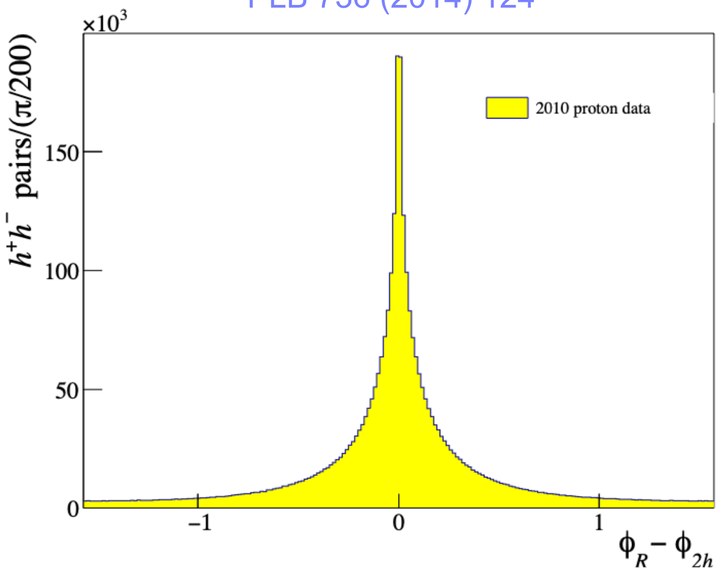
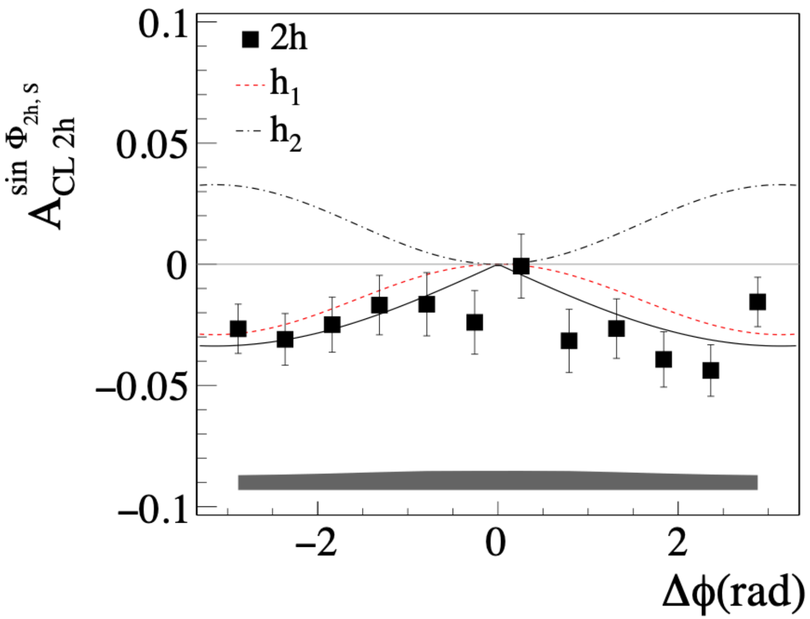


PLB 736 (2014) 124



PLB 753 (2016) 406



Hints for a common physical origin for the Collins mechanism and the polarized dihadron FF