

NEW MEASUREMENT OF TRANSVERSE SPIN EFFECTS IN HADRON PRODUCTION FROM MUON-DEUTERON SEMI-INCLUSIVE DIS AT COMPASS

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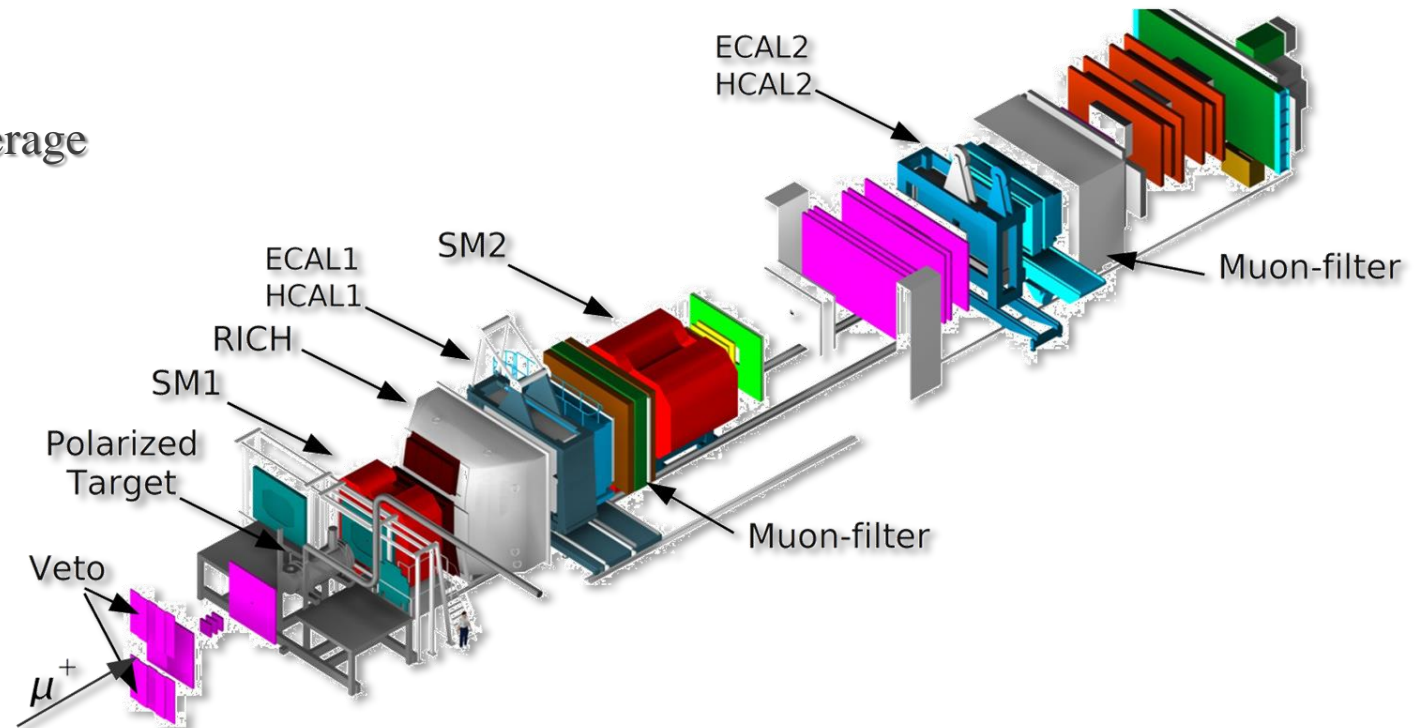
ON BEHALF OF THE COMPASS COLLABORATION

31st International Workshop on Deep Inelastic Scattering (DIS 2024)
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COMPASS EXPERIMENT

- Location: CERN SPS North Area at the M2 beamline.
- Two-stage spectrometer:
 - Large Angle Spectrometer (SM1 magnet)
 - Small Angle Spectrometer (SM2 magnet)
- Large geometrical acceptance, wide kinematic coverage
- Comprise a variety of tracking detectors
 - SciFi-s, Silicons, MicroMegas, GEMs, MWPCs, DCs, Straws
- PID and calorimetry
 - RICH, Muon identification systems (Muon walls)
 - hadron and electromagnetic calorimeters
- Trigger system (hodoscope stations)
- Polarized three-cell target (two-cells in some years)

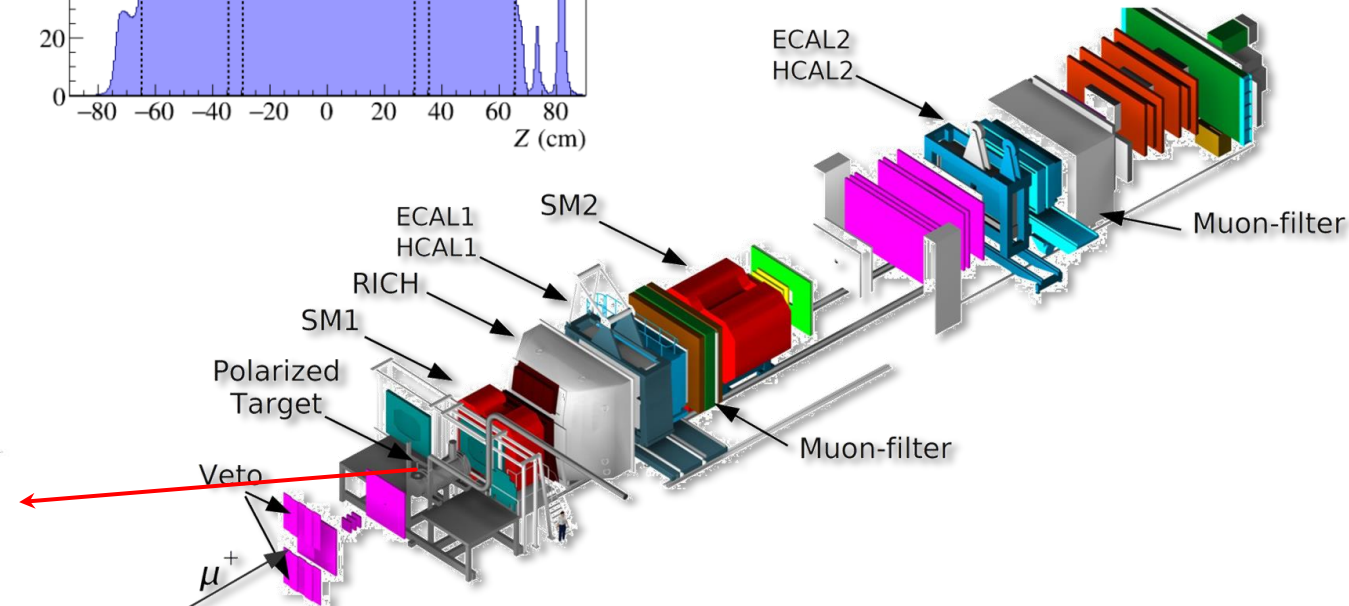
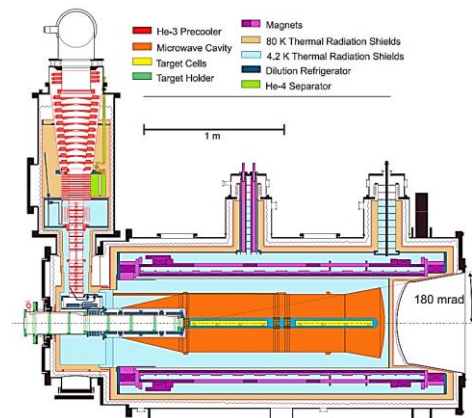
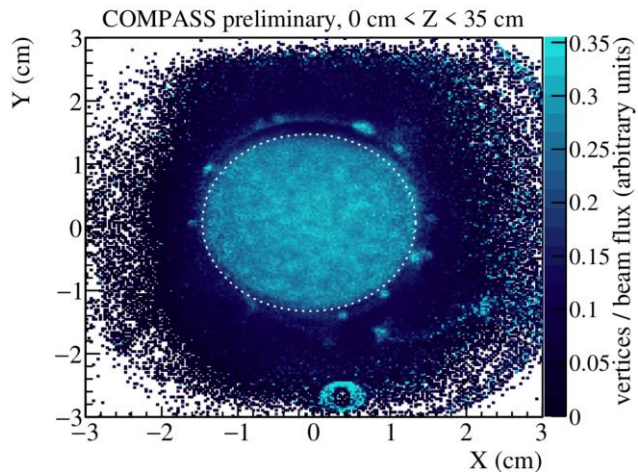
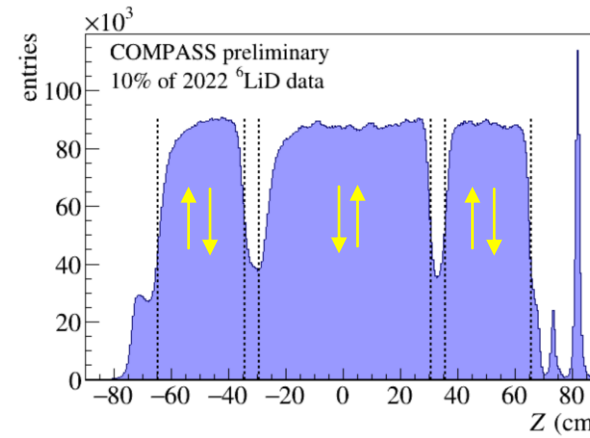
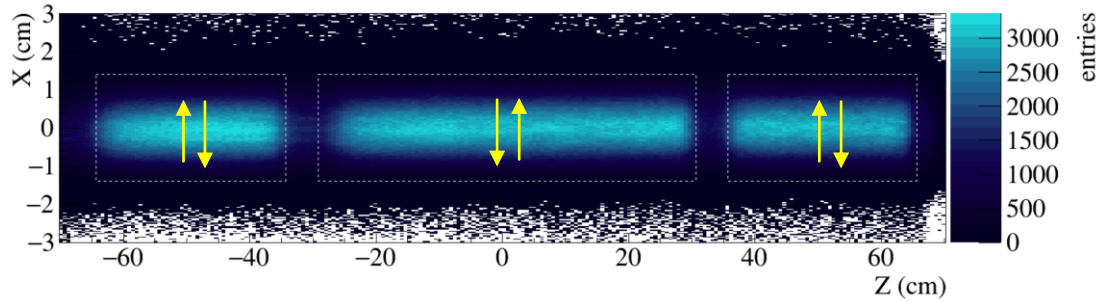


COMPASS EXPERIMENT

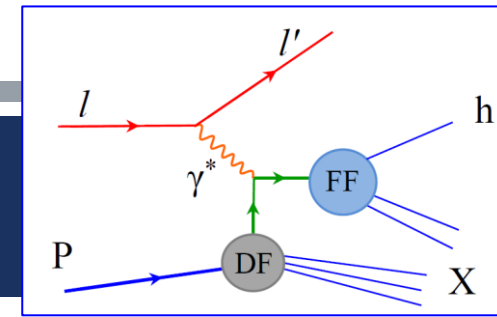
- COMPASS took data from 2002 to 2022.
- 2022 SIDIS data: μ^+ beam with a nominal momentum of 160 GeV/c.

- Beam polarization: $\sim 80\%$
- Target material: ${}^6\text{LiD}$

COMPASS preliminary, primary vertices



SIDIS X-SECTION AND TMDS

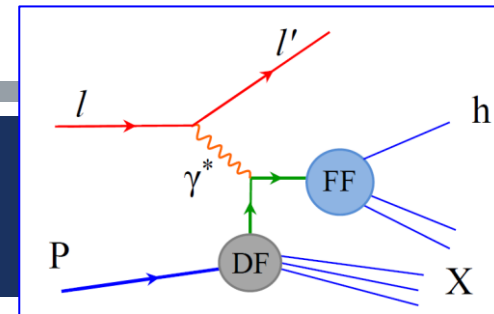


$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

15 asymmetries
all measured at COMPASS

$$\times \left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_s)} \sin(\phi_h-\phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h+\phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h-\phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h-\phi_s) \end{array} \right] \\ + S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_s)} \cos(\phi_h-\phi_s) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h-\phi_s) \end{array} \right] \end{array} \right.$$

SIDIS X-SECTION AND TMDS



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

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$$\left\{ \begin{aligned} &1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ &+ \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ &+ S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ &+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ &\times \left\{ \begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_s)} \sin(\phi_h-\phi_s) \\ &+ \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h+\phi_s) \\ &+ S_T \left[\varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h-\phi_s) \right. \\ &+ \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ &+ \left. \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h-\phi_s) \right] \\ &+ S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_s)} \cos(\phi_h-\phi_s) \right. \\ &+ \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ &+ \left. \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h-\phi_s) \right] \end{aligned} \right\} \end{aligned} \right.$$

Twist-2

Twist-3

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

Sivers

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

Collins

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin\phi_s} \propto Q^{-1} (h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots)$$

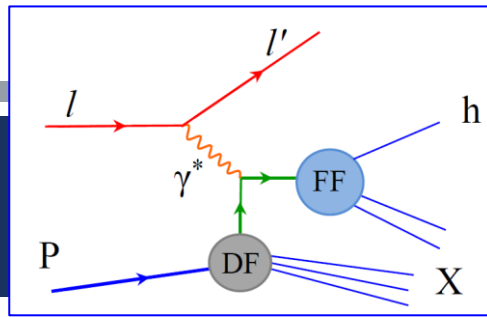
$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1} (h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots)$$

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{LT}^{\cos\phi_s} \propto Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots)$$

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots)$$

SIDIS X-SECTION AND TMDs



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

15 asymmetries
all measured at COMPASS

$$\begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ & + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ & \times \left\{ \begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_s)} \sin(\phi_h-\phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h+\phi_s) \\ & + S_T \left[\varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h-\phi_s) \right. \\ & \quad + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ & \quad \left. + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h-\phi_s) \right] \\ & \text{---} \\ & \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_s)} \cos(\phi_h-\phi_s) \\ & + S_T \lambda \left[\sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \right. \\ & \quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h-\phi_s) \right] \end{aligned} \right\} \end{aligned}$$

Twist-2

Twist-3

$$\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \quad \text{Sivers} \\ & A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \text{Collins} \\ & A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} \\ & A_{UT}^{\sin\phi_s} \propto Q^{-1} (h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots) \\ & A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1} (h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots) \\ & A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h \\ & A_{LT}^{\cos\phi_s} \propto Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots) \\ & A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots) \end{aligned}$$

8 TMD PDF at twist-2 level

Quark \ Nucleon	U	L	T
U	number density		Boer-Mulders
L		Helicity	(worm-gear L)
T	Sivers	Kotzinian-Mulders (worm-gear T)	Transversity Pretzelocity

↑ spin of the nucleon ↑ spin of the quark ↗ k_T

Different correlations between the spins of the nucleon and quarks and intrinsic transverse momentum of quarks

SIDIS MEASUREMENT

- Azimuthal angles ϕ_h (hadron) and ϕ_S (nucleon spin)

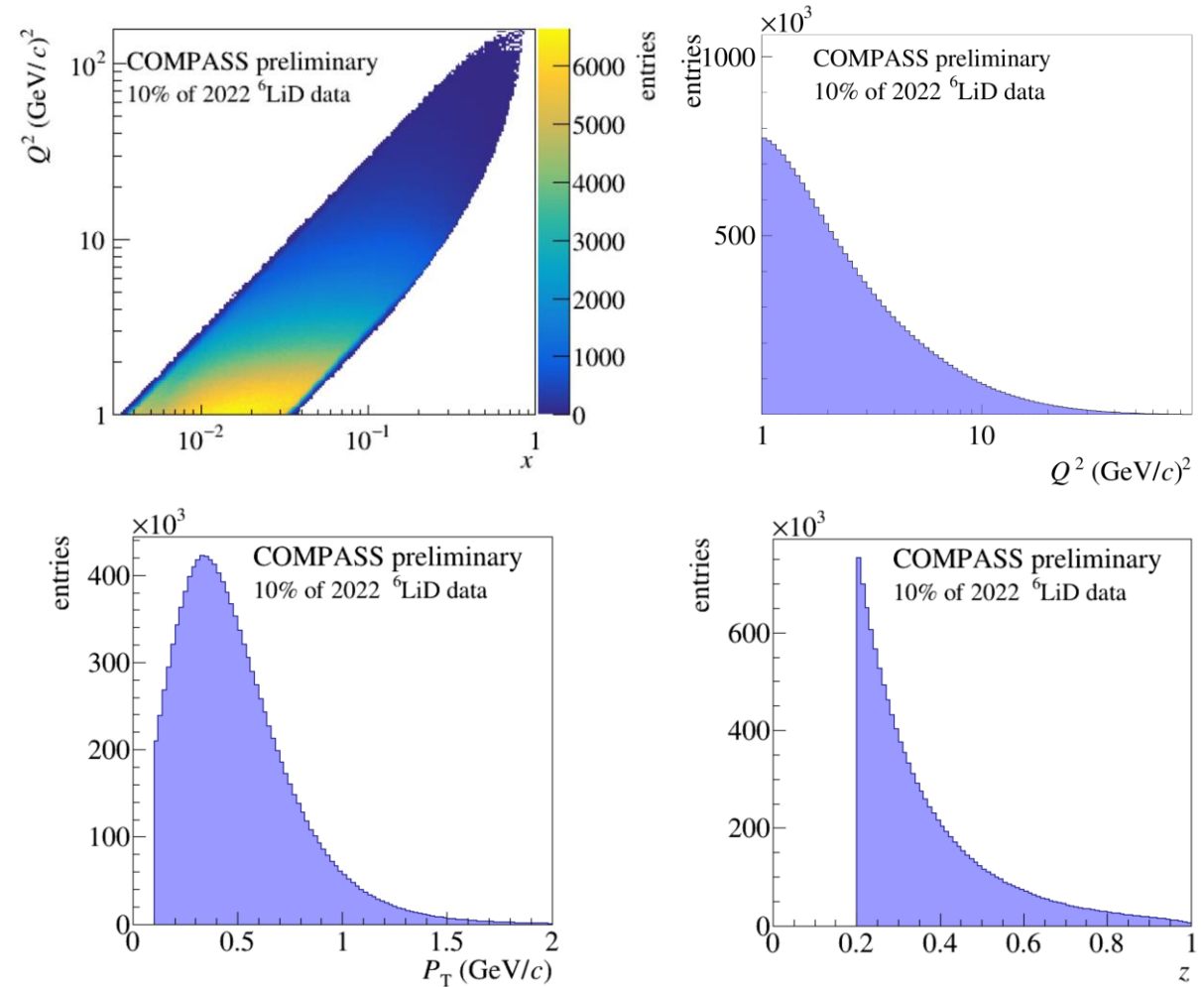
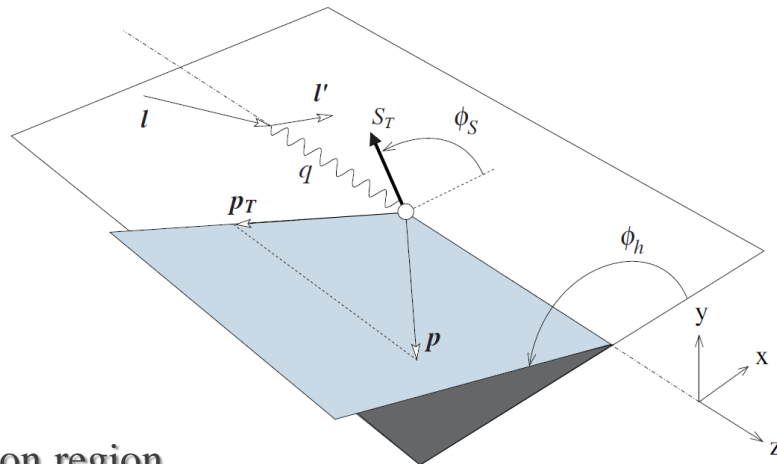
- Collins angle: $\Phi_{\text{Collins}} = \phi_h + \phi_S - \pi$
- Sivers angle: $\Phi_{\text{Sivers}} = \phi_h - \phi_S$

- DIS cuts:

- $Q^2 > 1 \text{ (GeV/c}^2\text{)}^2$
- $0.1 < y < 0.9$
- $0.003 < x < 0.7$
- $W > 5 \text{ GeV/c}$

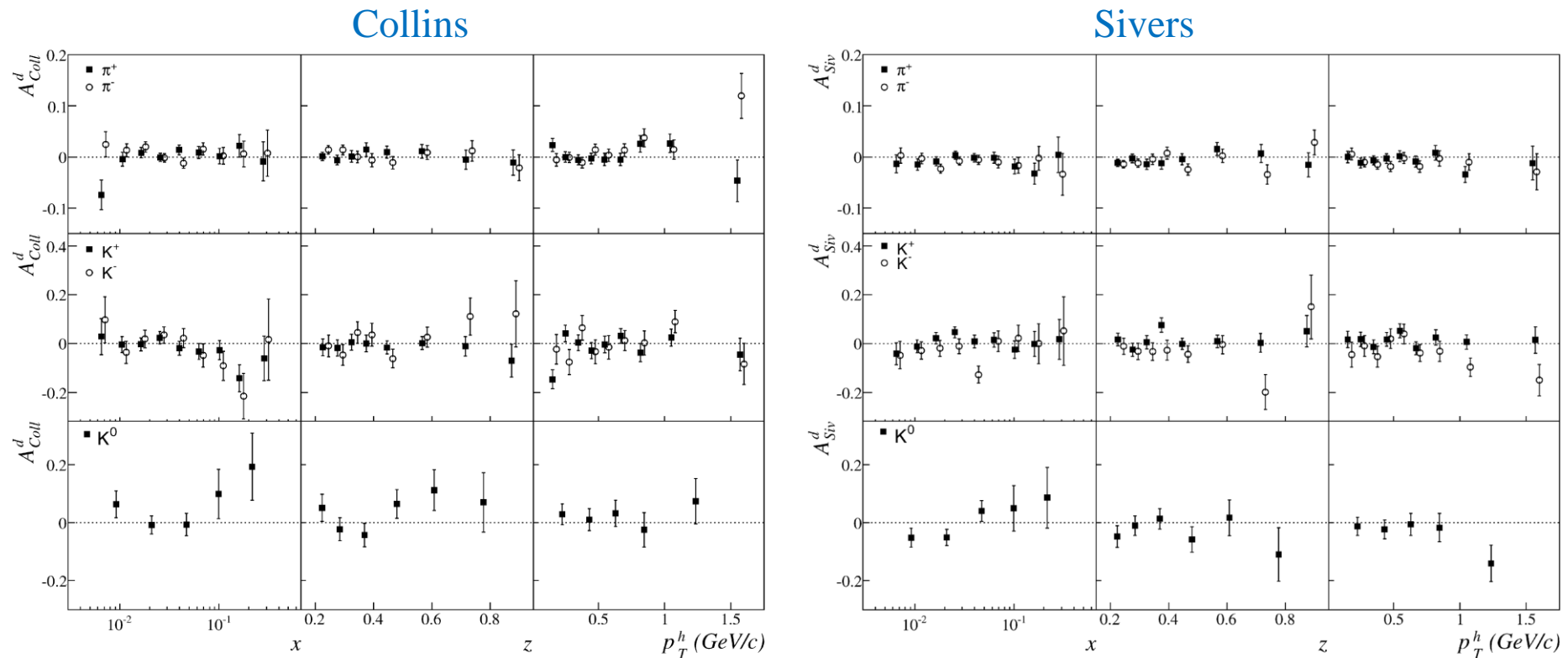
- Hadron cuts:

- $z > 0.2$ ($z > 0.1$)
current fragmentation region
- $P_T > 0.1 \text{ GeV/c}$
sufficient angular resolution



COLLINS AND SIVERS EFFECTS (DEUTERON 2002-2004)

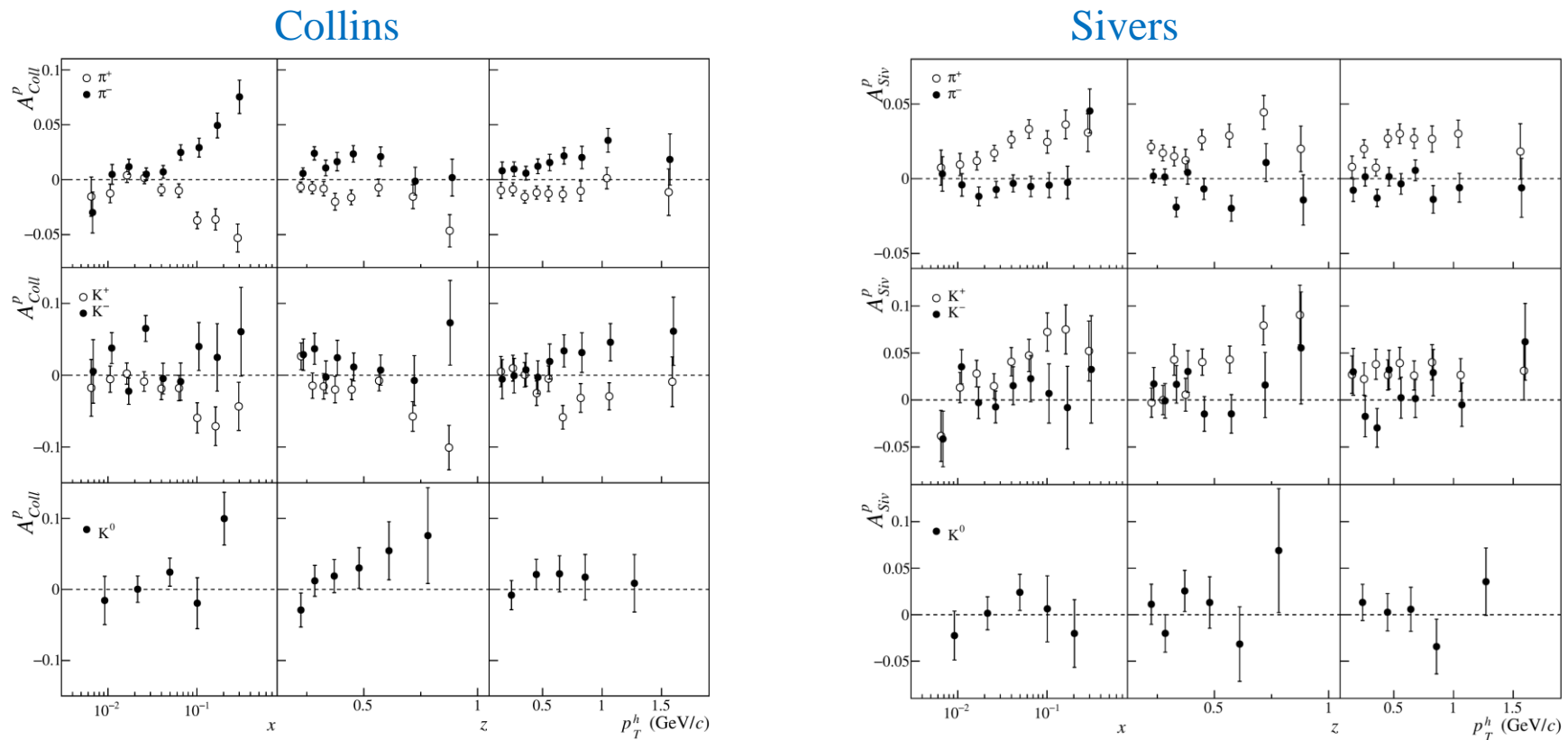
- 1st COMPASS deuteron measurements 2002-2004 (the only existing transverse deuteron target data up to 2022)
- Collins and Sivers asymmetries compatible with zero within uncertainties.



COMPASS PLB 673 (2009) 127

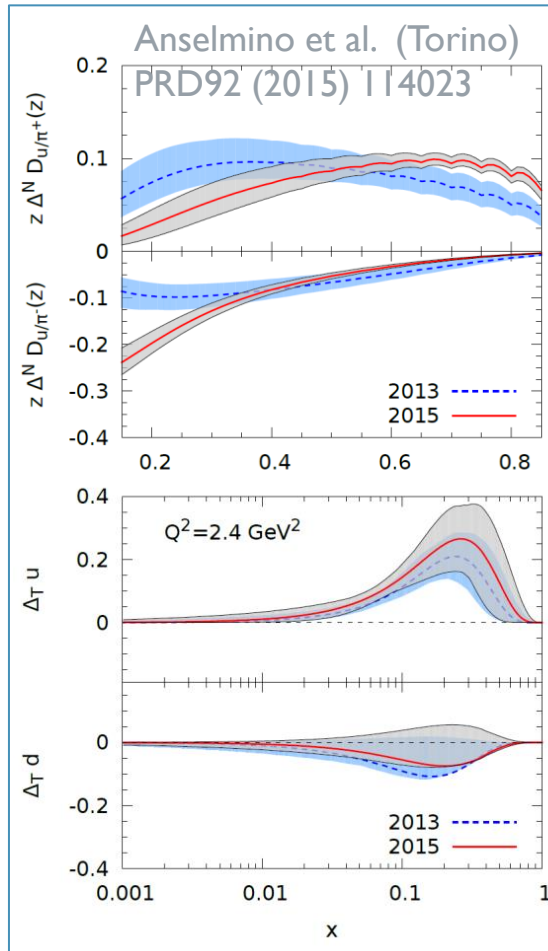
COLLINS AND SIVERS EFFECTS (PROTON-2010)

- COMPASS proton measurements – clear non-zero signal for both asymmetries (similar to HERMES measurements)

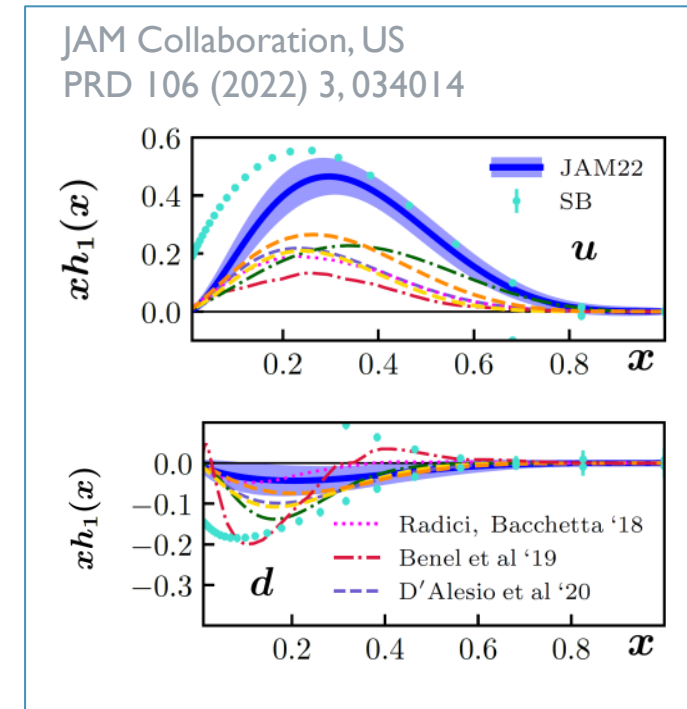
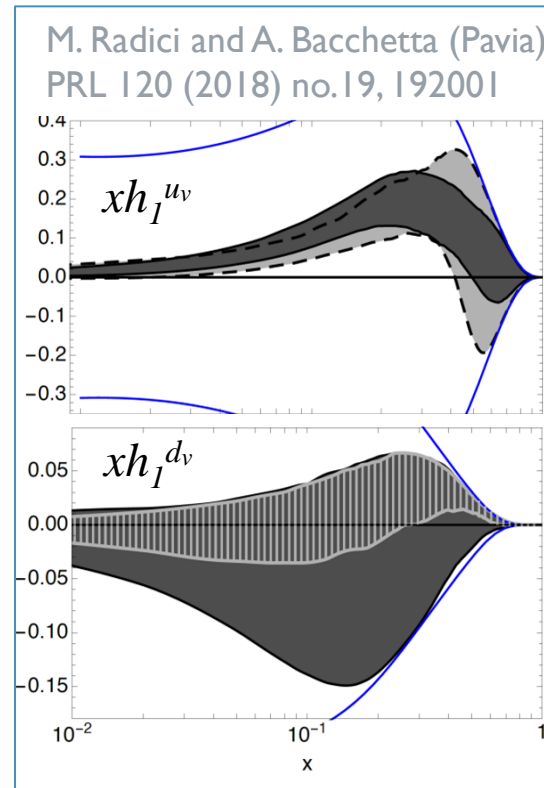


COMPASS PLB 744(2015)250

TRANSVERSITY PDF FROM GLOBAL PHENOMENOLOGICAL FITS



- Large uncertainties for the d-quark transversity
 - More deuteron (or neutron) data needed to better constrain the PDF(s)

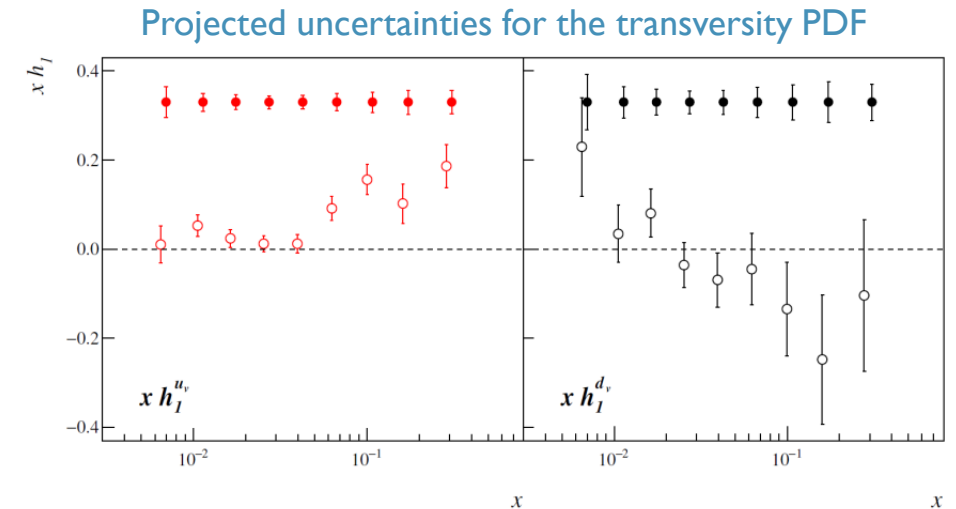
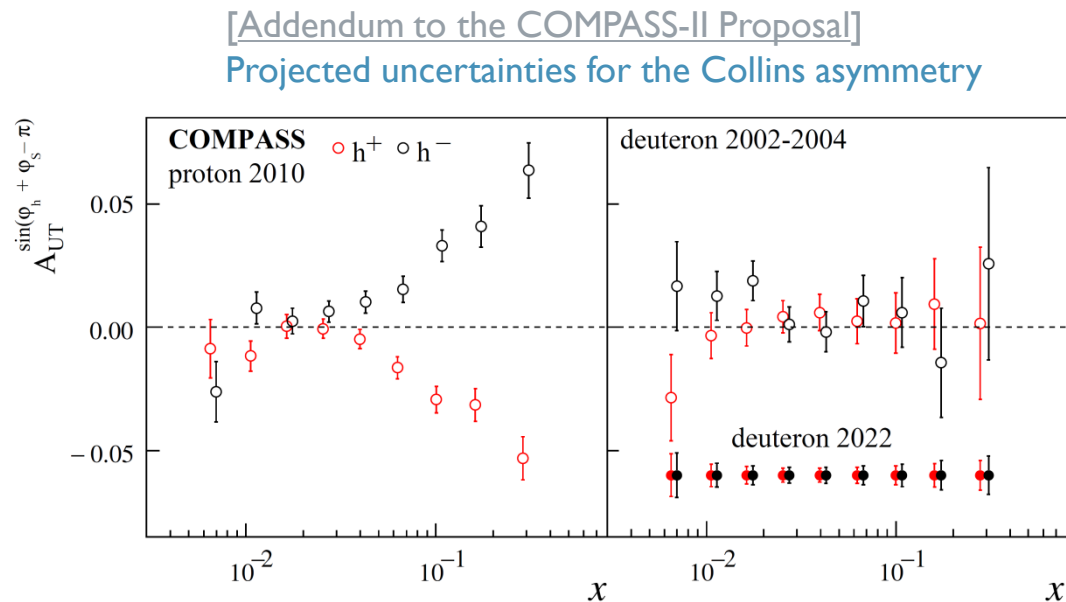


- A number of global phenomenological fits by different groups

ADDENDUM TO THE COMPASS-II PROPOSAL

COMPASS-II (2022)

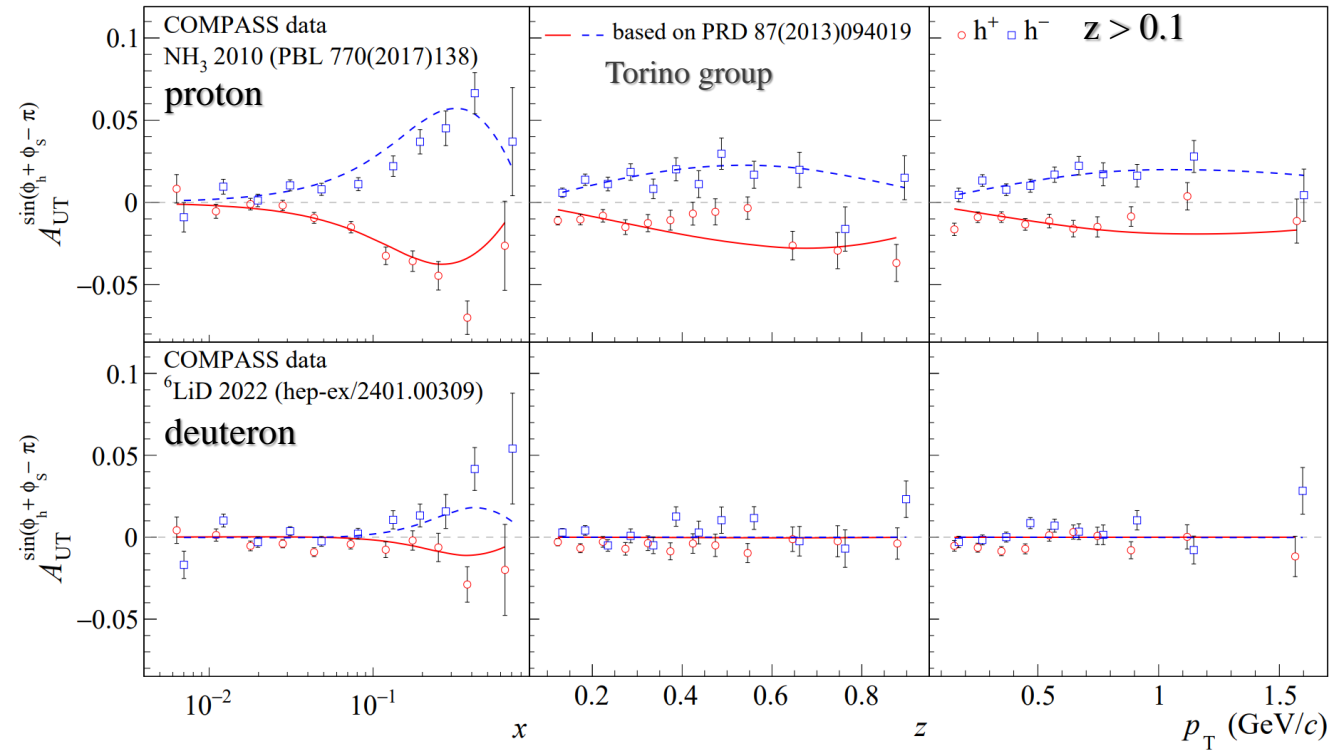
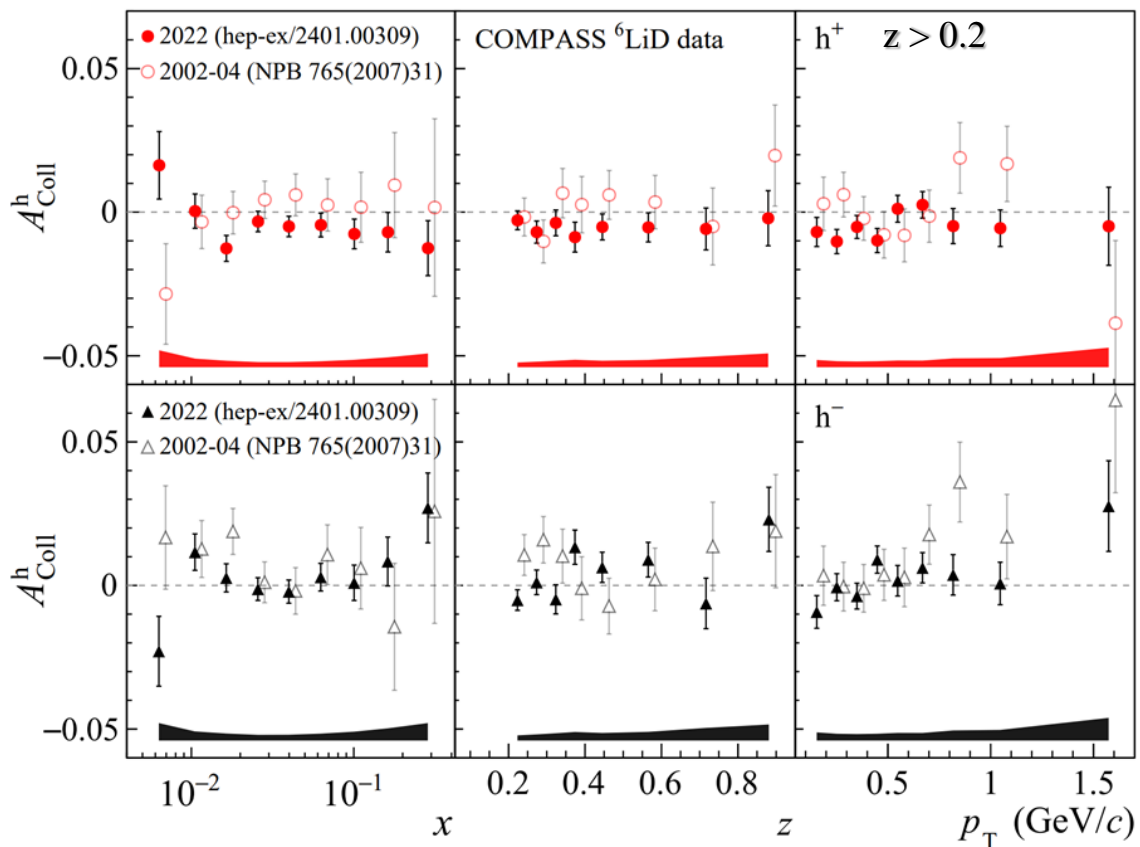
- 2nd series of COMPASS transverse deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark



- Significant improvement expected also for the u-quark transversity PDF
- Important input for Sivers and other TMDs

COLLINS ASYMMETRY

$$A_{UT}^h \sin(\phi_h + \phi_s) \propto h_1^q \otimes H_{1q}^{\perp h}$$



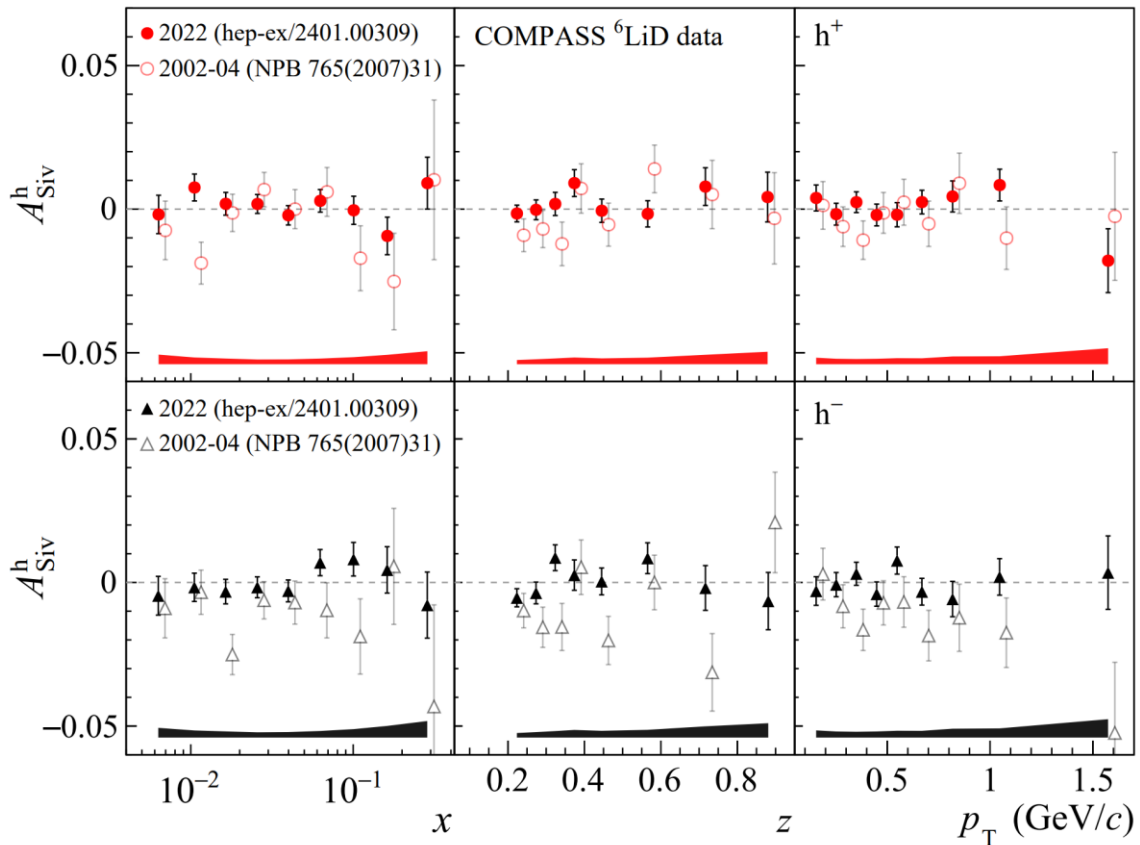
New and very precise deuteron data!

Original parametrization (for pions) extended to the low z range

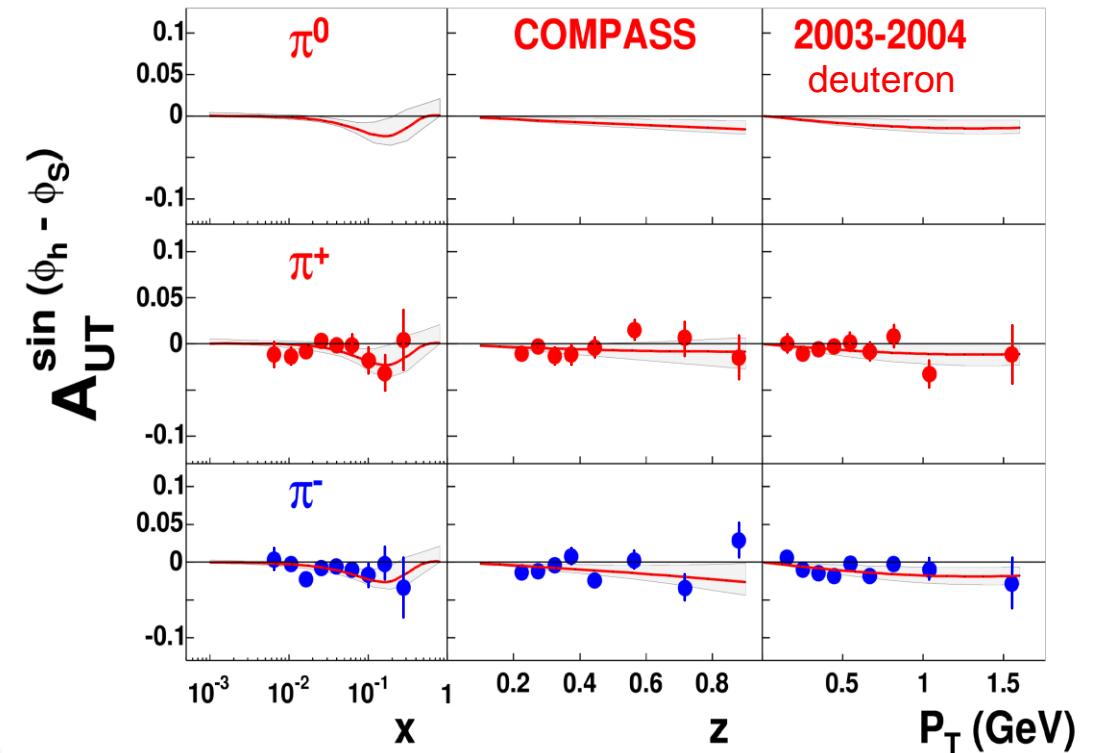
Qualitative agreement, effect at large x

SIVERS ASYMMETRY

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$



S. Melis et al. (Torino) 2010

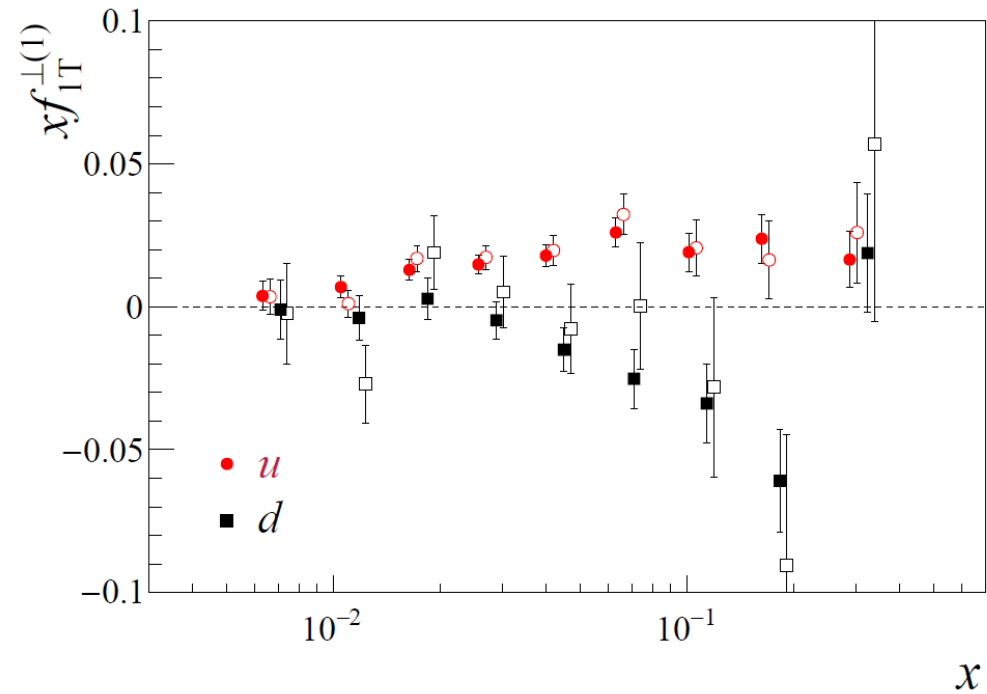
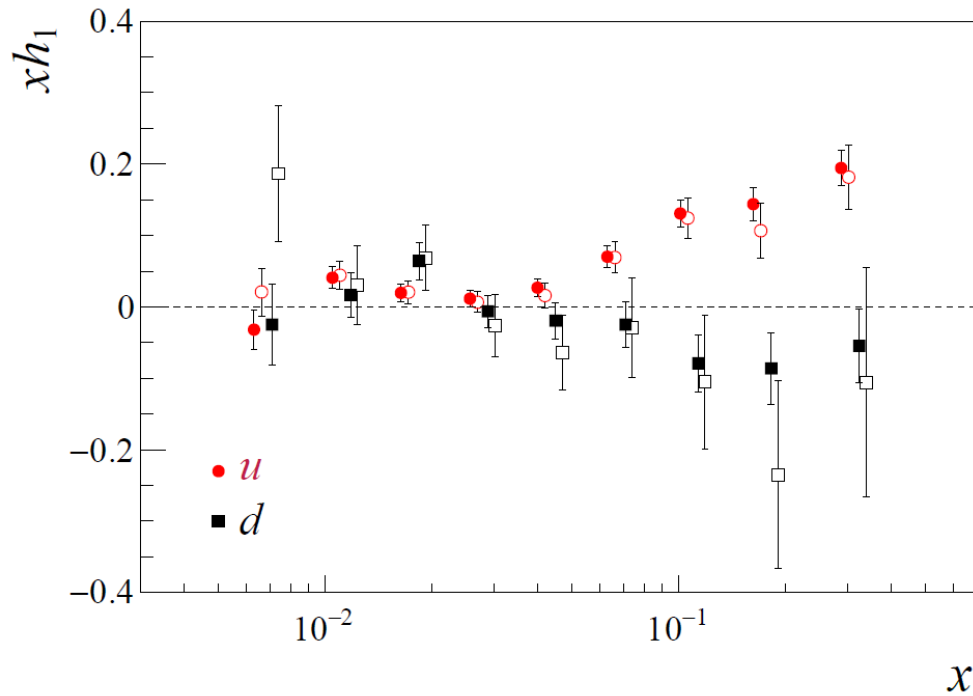


Highly improved precision, important input for the models
 The asymmetry is expected to be small

TRANSVERSITY AND SIVERS FUNCTIONS

$$A_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$



Overall precision improves by up to a factor of three!

Point-by-point extraction framework

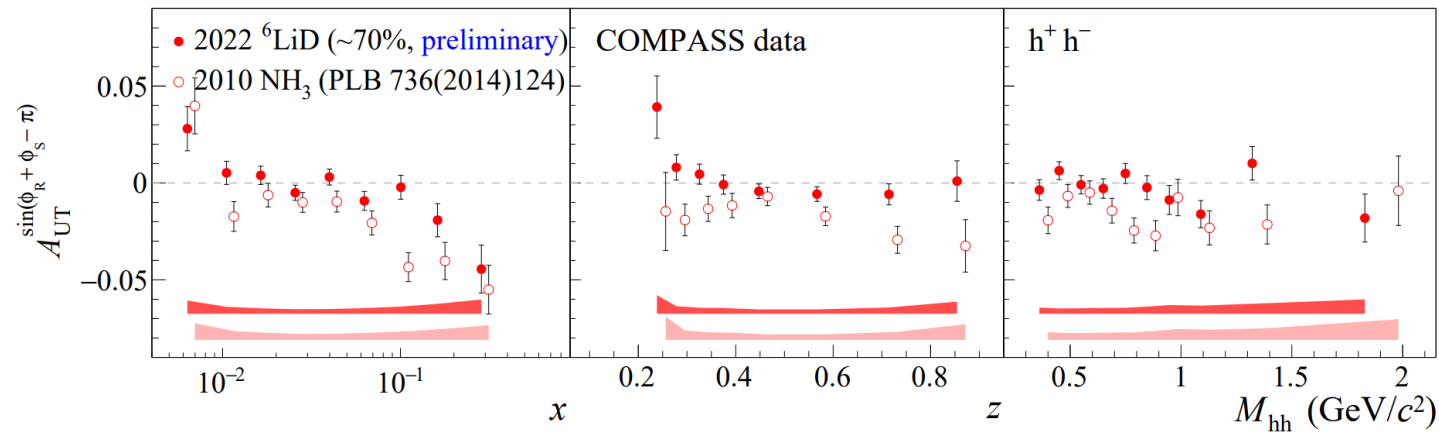
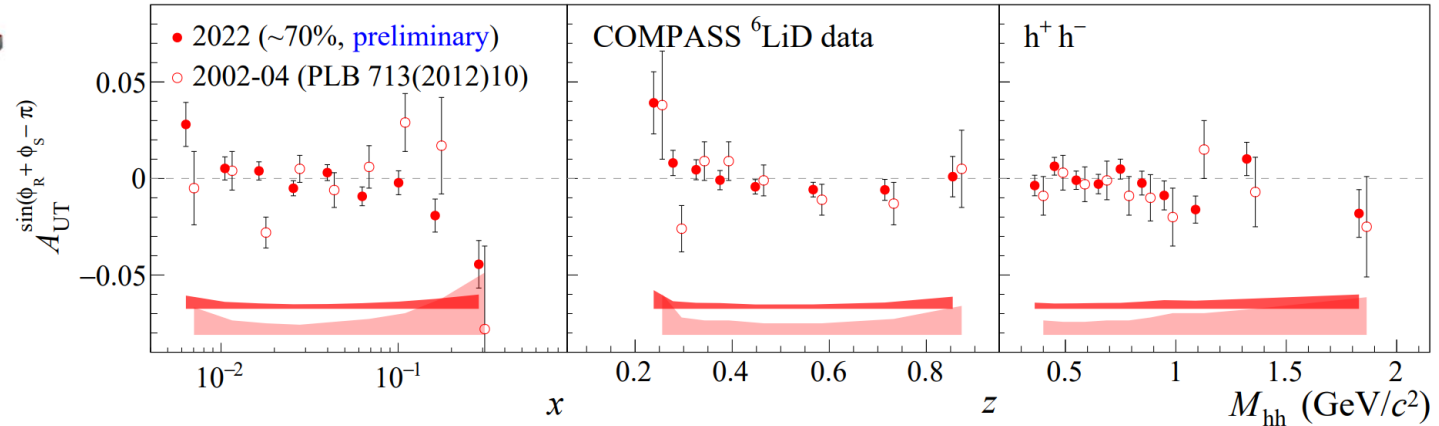
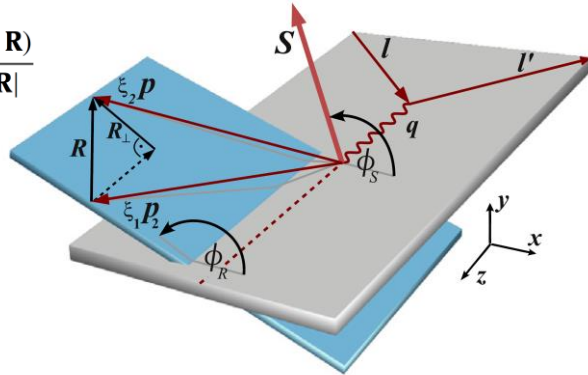
V. Barone, F. Bradamante and A. Martin, Phys. Rev. D **91**, 014034 (2015)

V. Barone, F. Bradamante and A. Martin, Phys. Rev. D **95**, 094024 (2017)

DIHADRON COLLINS ASYMMETRIES

NEW!

$$\phi_R = \frac{(\mathbf{q} \times \mathbf{l}) \cdot \mathbf{R}}{|(\mathbf{q} \times \mathbf{l}) \cdot \mathbf{R}|} \arccos \frac{(\mathbf{q} \times \mathbf{l}) \cdot (\mathbf{q} \times \mathbf{R})}{|\mathbf{q} \times \mathbf{l}| |\mathbf{q} \times \mathbf{R}|}$$



$$A_{UT}^{\sin \phi_{RS}} = \frac{|\mathbf{p}_1 - \mathbf{p}_2| \sum_q e_q^2 h_1^q(x) H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos \theta)}{2M_{hh} \sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos \theta)}$$

$$\frac{d^7 \sigma}{d \cos \theta d M_{hh} d \phi_R d z d x d y d \phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y} \left((1-y + \frac{y^2}{2}) \sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos \theta) + \right.$$

$$\left. S_{\perp}(1-y) \sum_q e_q^2 \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{hh}} \sin \theta \sin \phi_{RS} h_1^q(x) H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos \theta) \right)$$

Alternative way to access transversity PDF (collinear approach)

Highly improved precision, signal at large x

CONCLUSIONS

- **New high-statistics COMPASS results for the Collins and Sivers asymmetries of charged (di-)hadrons with deuteron target**
 - Measured from part (~70%) of the SIDIS data collected in 2022
 - The asymmetries are evaluated as a function of x , z or P_T
- Consistent with the previously published deuteron results
- The overall precision is improved by up to a factor of three.
- Point-to-point extraction of the transversity and Sivers functions for u and d valence quarks.
 - Clearly demonstrates the improvement at the level of the PDFs
- These new COMPASS deuteron results are expected to have strong impact on the knowledge of the transverse-spin structure of the nucleon.
- COMPASS analyses performed on the proton data are currently being repeated for the deuteron.
 - **More deuteron results from COMPASS to come, stay tuned!**

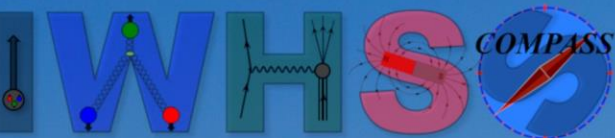


Joint "20th International Workshop on Hadron Structure and Spectroscopy"
and 5th workshop on "Correlations in Partonic and Hadronic Interactions"

Yerevan, Armenia

30 September – 4 October, 2024

<https://indico.cern.ch/e/IWHSS-CPHI-2024>



THANK YOU