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

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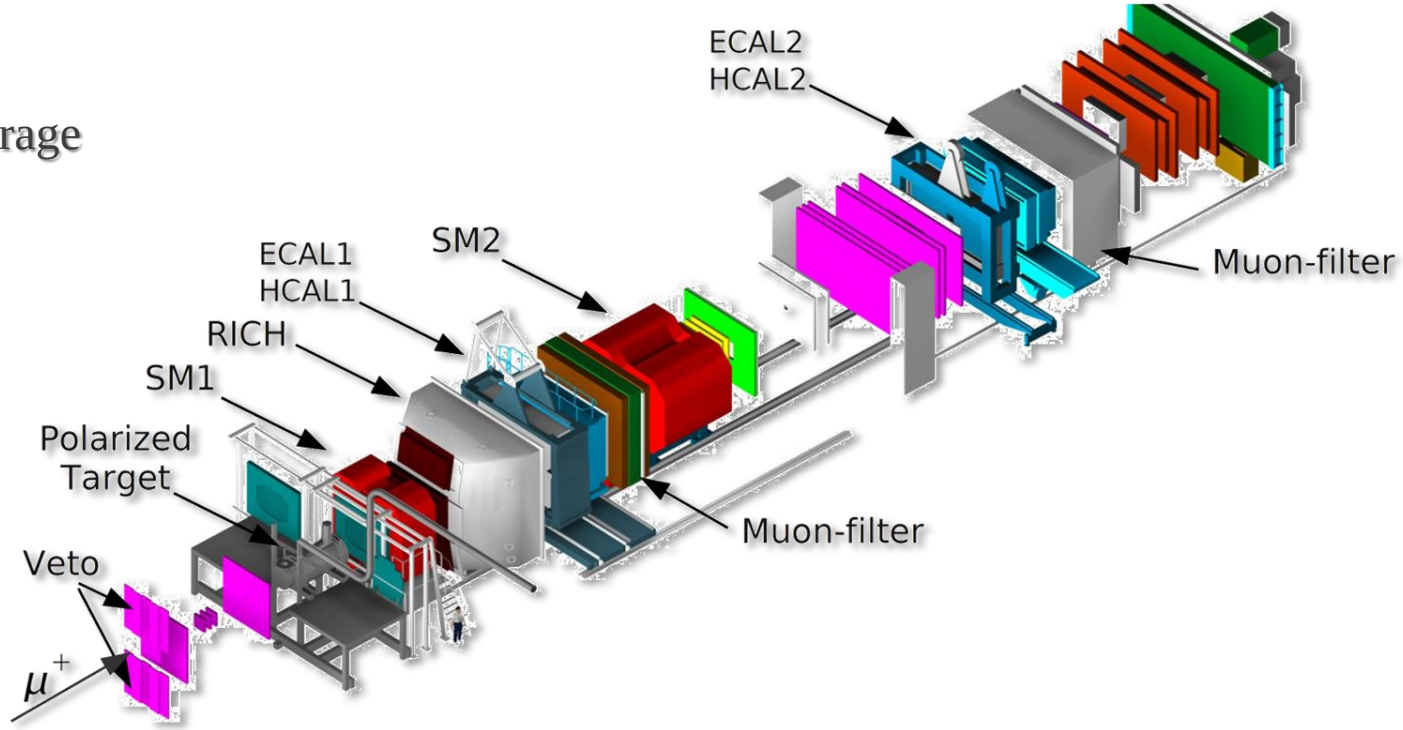
ON BEHALF OF THE COMPASS COLLABORATION

20th *International Workshop on Hadron Structure and Spectroscopy*" and 5th workshop on "*Correlations in Partonic and Hadronic Interactions*" (IWHSS-CPHI-2024)
September 30 – October 4, Ramada Hotel & Suites by Wyndham, Yerevan, Armenia

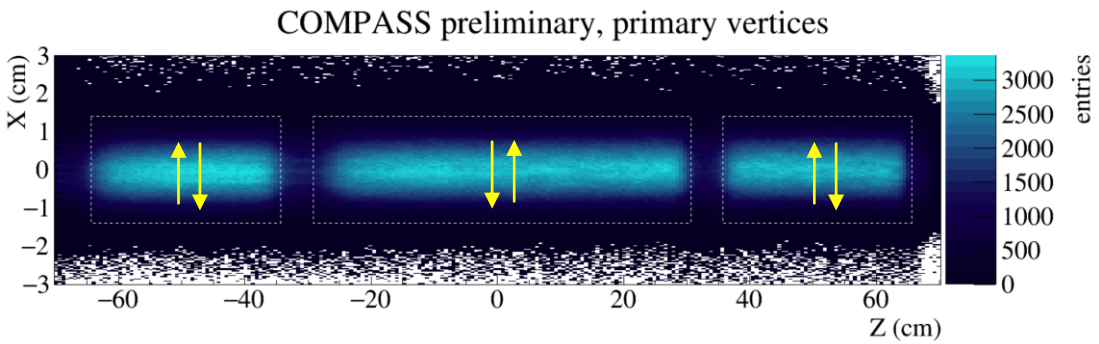
COMPASS EXPERIMENT

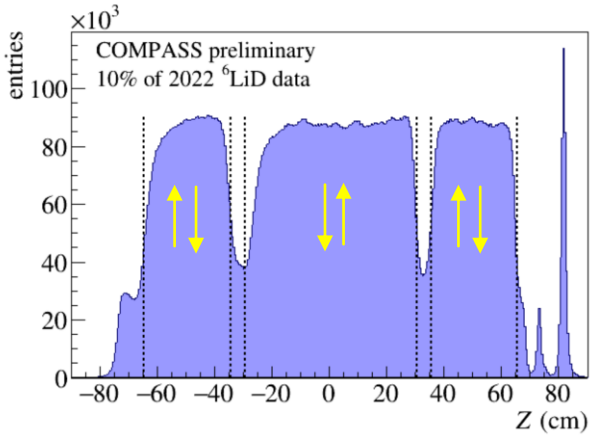
- Location: CERN SPS North Area at the M2 beamline.
- Two-stage spectrometer:
  - Large Angle Spectrometer (SM1 magnet)
  - Small Angle Spectrometer (SM2 magnet)
- Large geometrical acceptance, wide kinematic coverage
- Comprise a variety of tracking detectors
  - SciFi-s, Silicons, MicroMegas, GEMs, 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)

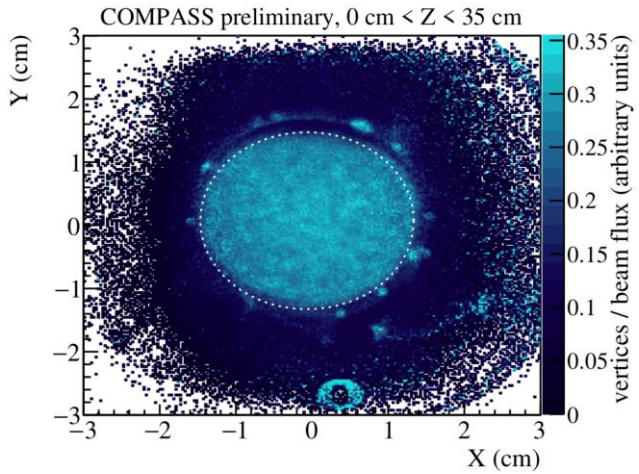


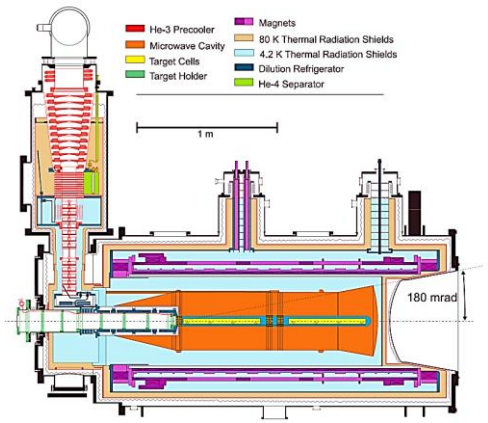
COMPASS EXPERIMENT

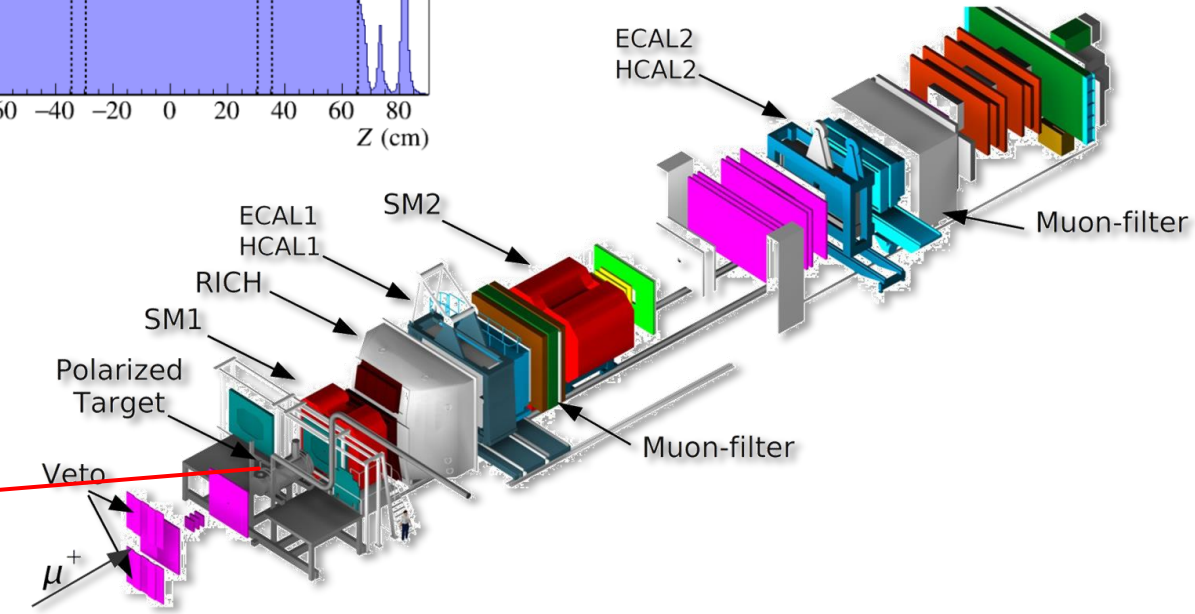
- COMPASS took data from 2002 to 2022.
- 2022 SIDIS data: μ^+ beam with a nominal momentum of 160 GeV/c.
- Beam polarization: ~ 80%
- Target material: ^{6}LiD



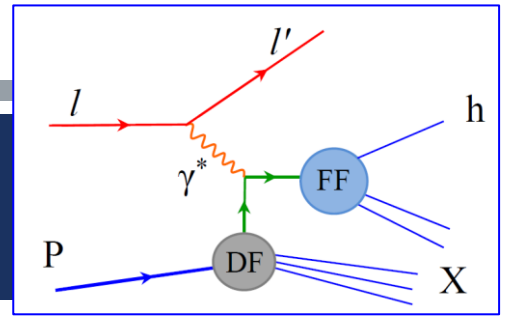








SIDIS X-SECTION AND TMDS



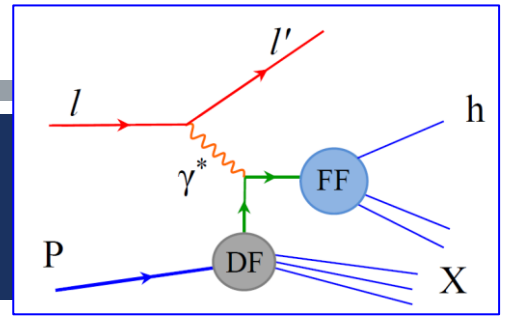
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

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

15 asymmetries
all measured at COMPASS

SIDIS X-SECTION AND TMDS



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

15 asymmetries
all measured at COMPASS

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

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

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

$A_{UT}^{\sin(\phi_S)} \overset{WW}{\propto} Q^{-1}\left(h_1^{q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{UT}^{\sin(2\phi_h-\phi_S)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

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

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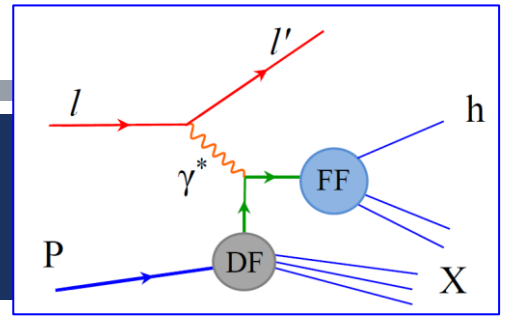
SIDIS X-SECTION AND TMDS



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$$\times\Big\{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h + S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+ S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

$$+ S_T\lambda\Big[\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

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

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

8 TMD PDF at twist-2 level

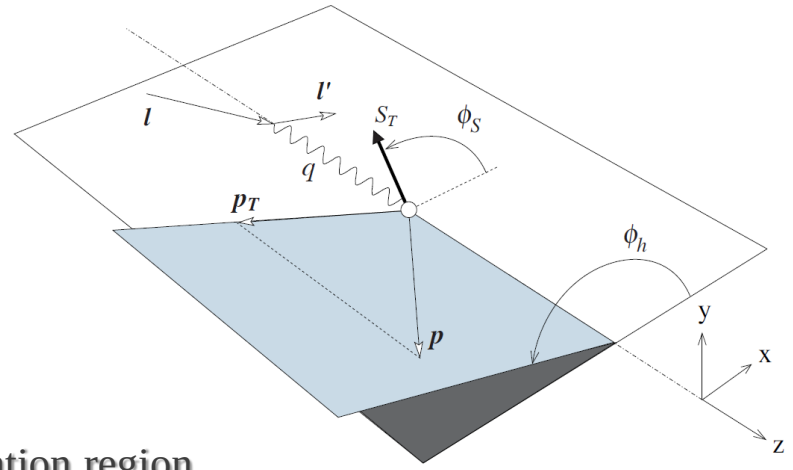
Nucleon \ Quark	U	L	T
U	number density		Boer-Mulders
L		Helicity	(worm-gear L)
T	Sivers	Kotzinian-Mulders (worm-gear T)	Transversity, Pretzelosity

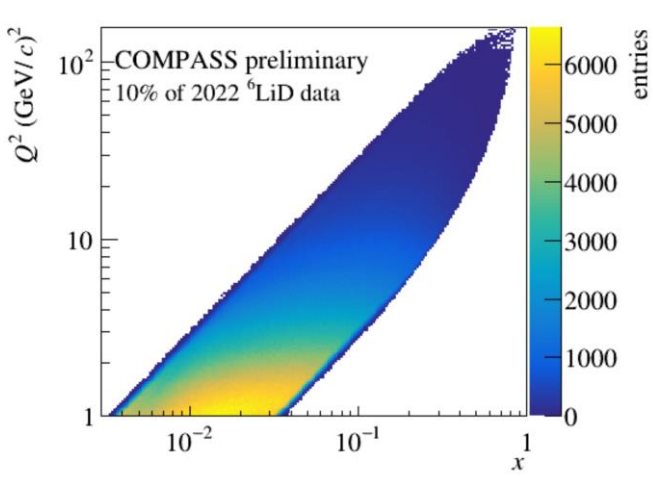
spin of the nucleon ↑ spin of the quark ↑ k_T →

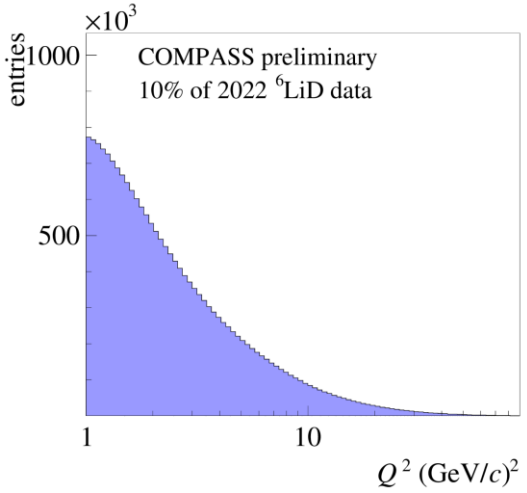
Different correlations between the spins of the nucleon and quarks and intrinsic transverse momentum of quarks

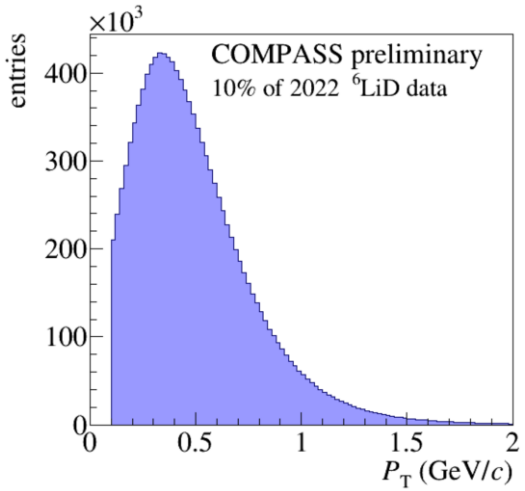
SIDIS MEASUREMENT

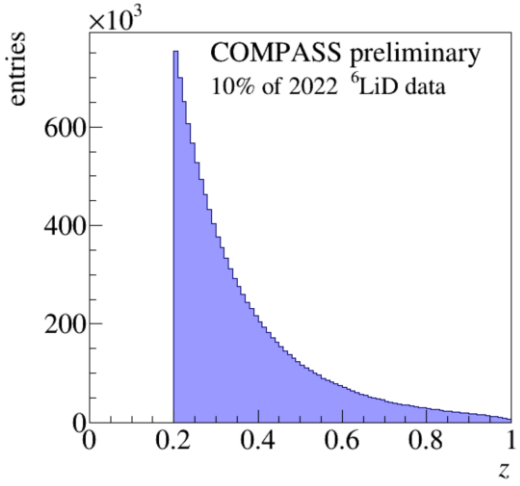
- Azimuthal angles ϕ_h (hadron) and ϕ_S (nucleon spin)
  - Collins angle: $\Phi_{Collins} = \phi_h + \phi_s - \pi$
  - Sivers angle: $\Phi_{Sivers} = \phi_h - \phi_s$
- DIS cuts:
  - $Q^2 > 1\ (\mathrm{GeV}/c^2)^2$
  - $0.1 < y < 0.9$
  - $0.003 < x < 0.7$
  - $W > 5\ \mathrm{GeV}/c$
- Hadron cuts:
  - $z > 0.2$
    current fragmentation region
  - $P_T > 0.1\ \mathrm{GeV}/c$
    sufficient angular resolution







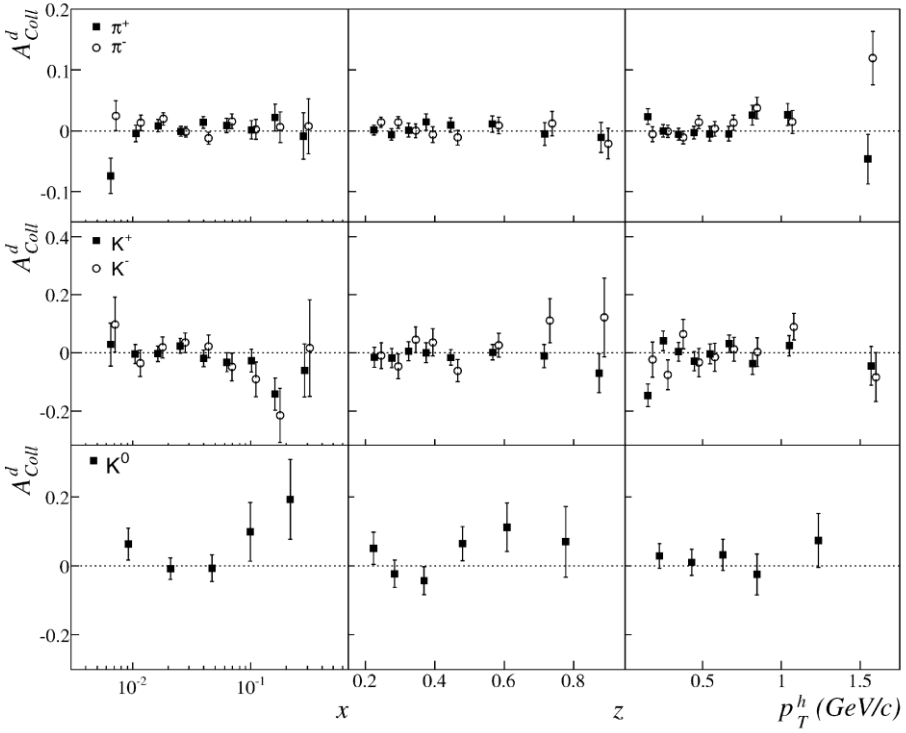




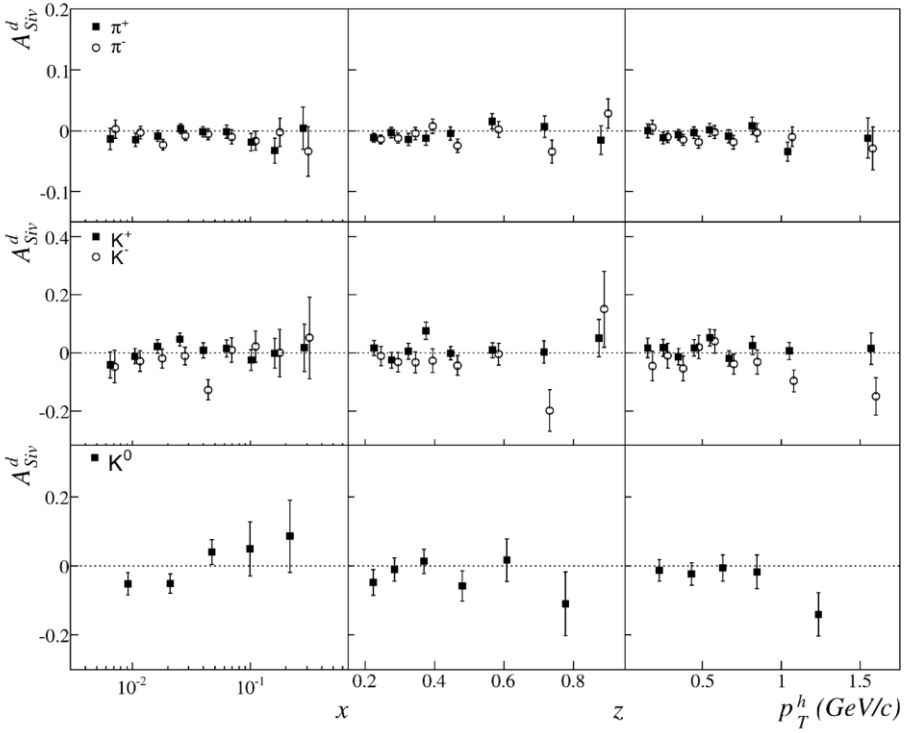
COLLINS AND SIVERS EFFECTS (DEUTERON 2002-2004)

- 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.

Collins



Sivers

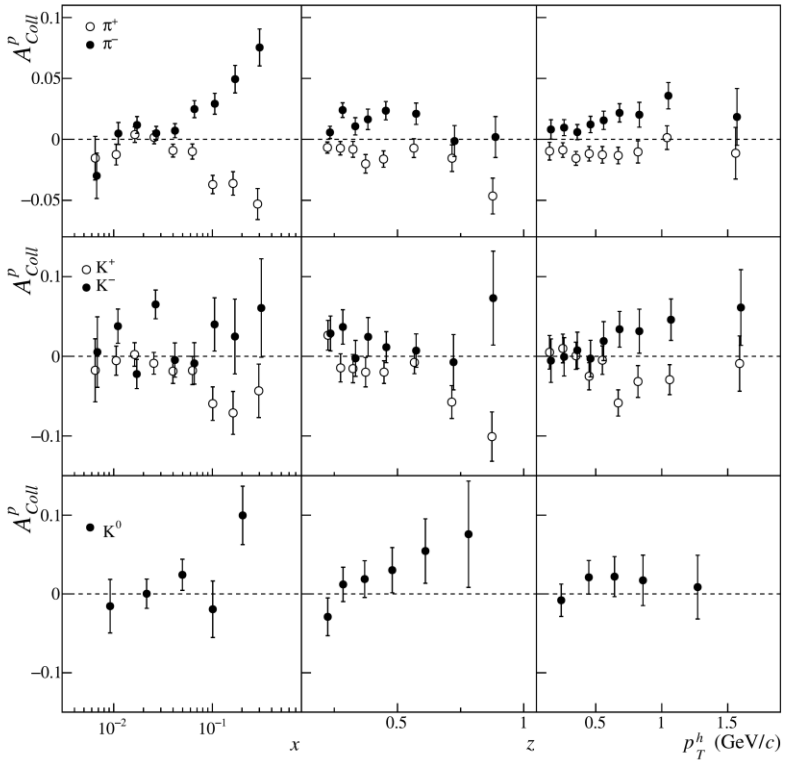


COMPASS PLB 673 (2009) 127

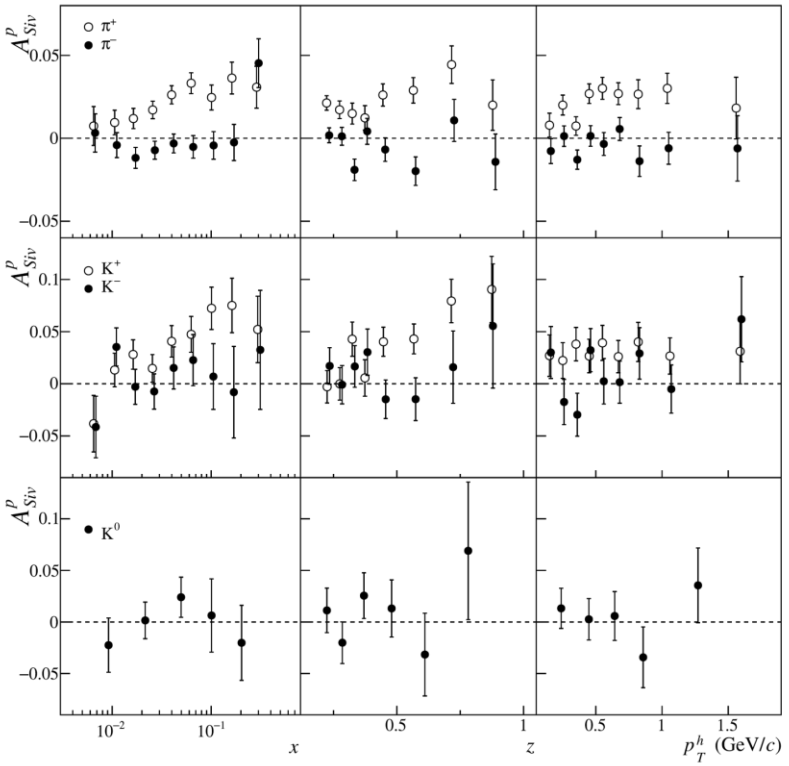
COLLINS AND SIVERS EFFECTS (PROTON-2010)

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

Collins



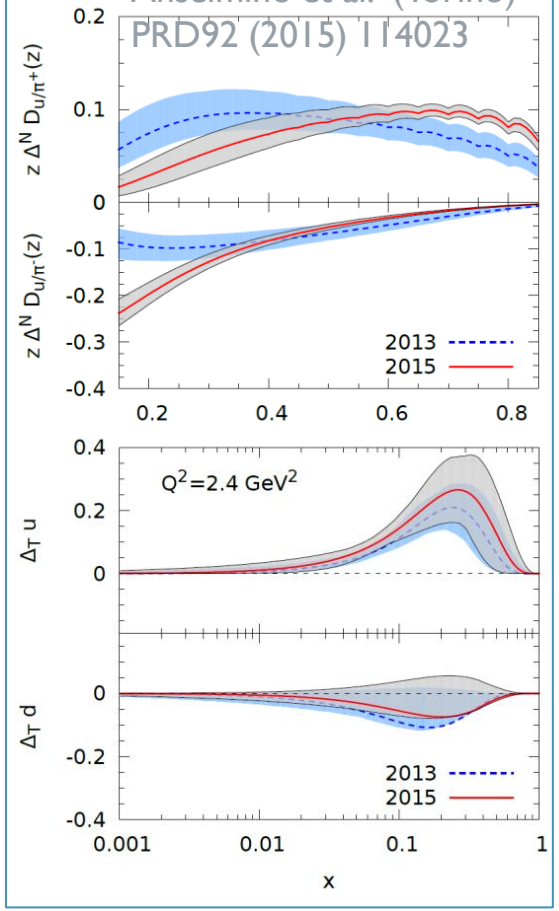
Sivers



COMPASS PLB 744(2015)250

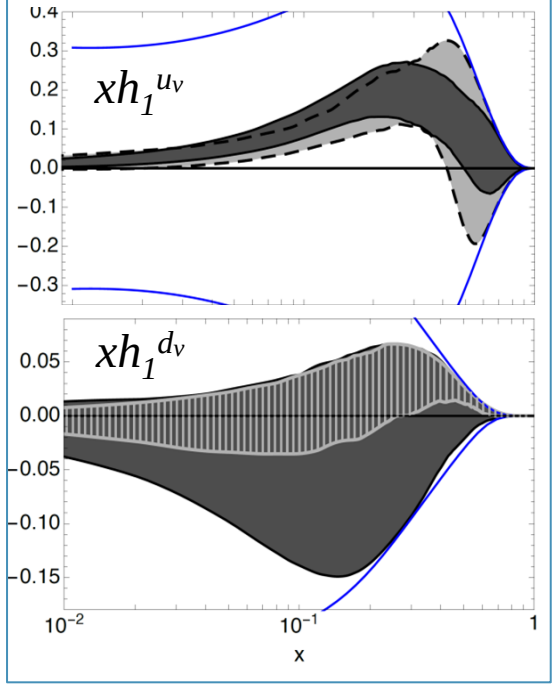
TRANSVERSITY PDF FROM GLOBAL PHENOMENOLOGICAL FITS

Anselmino et al. (Torino)
PRD92 (2015) 114023

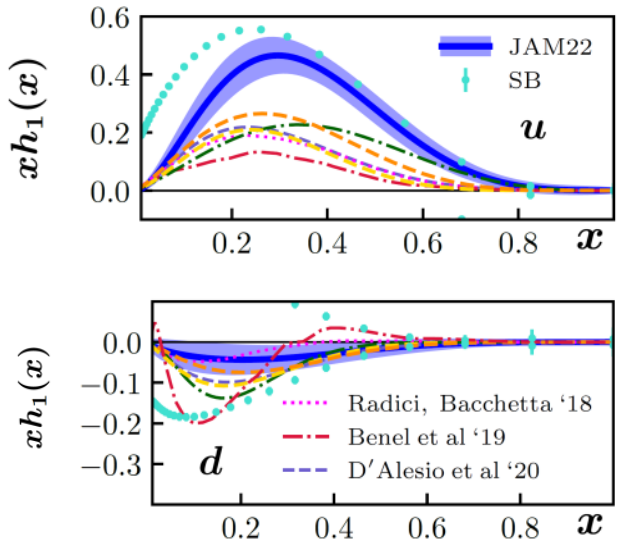


- Large uncertainties for the d-quark transversity
  - More deuteron (or neutron) data needed to better constrain the PDF(s)

M. Radici and A. Bacchetta (Pavia)
PRL 120 (2018) no.19, 192001



JAM Collaboration, US
PRD 106 (2022) 3, 034014



- A number of global phenomenological fits by different groups

COLLINS AND SIVERS ASYMMETRIES

Phys. Rev. Lett. **133**, 101903

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

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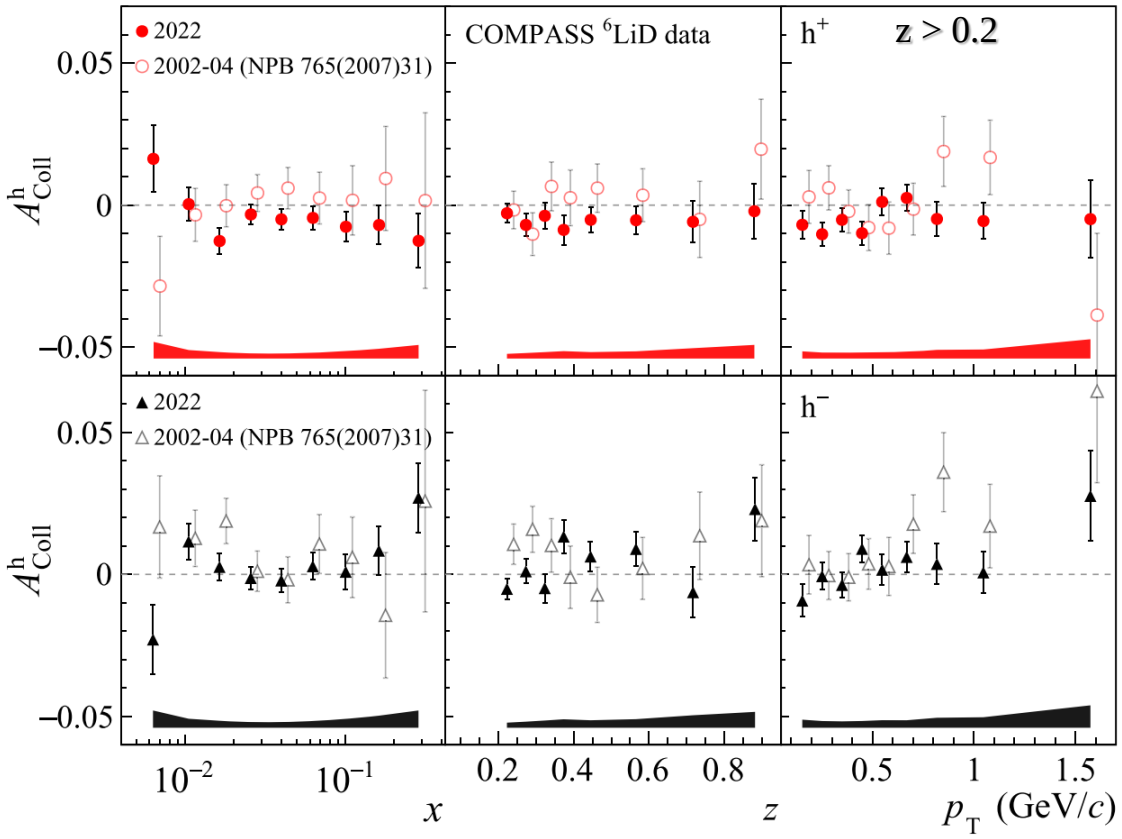
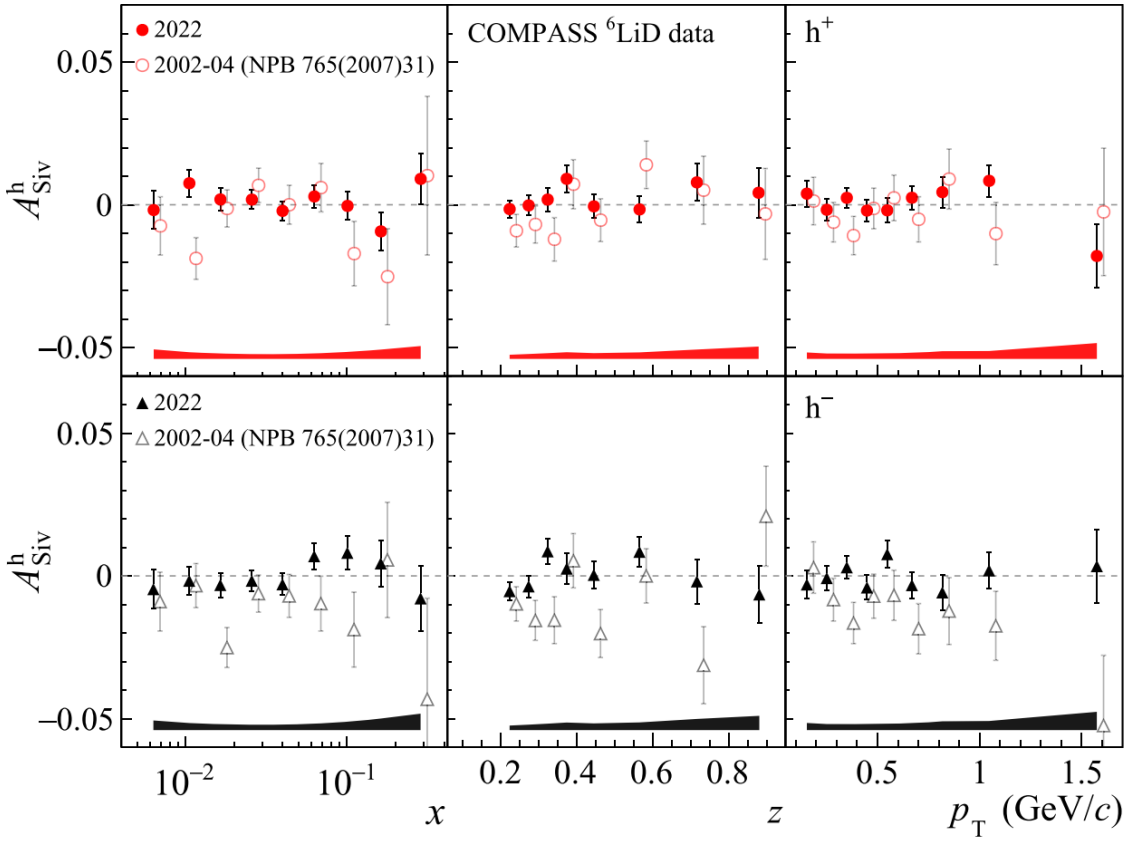


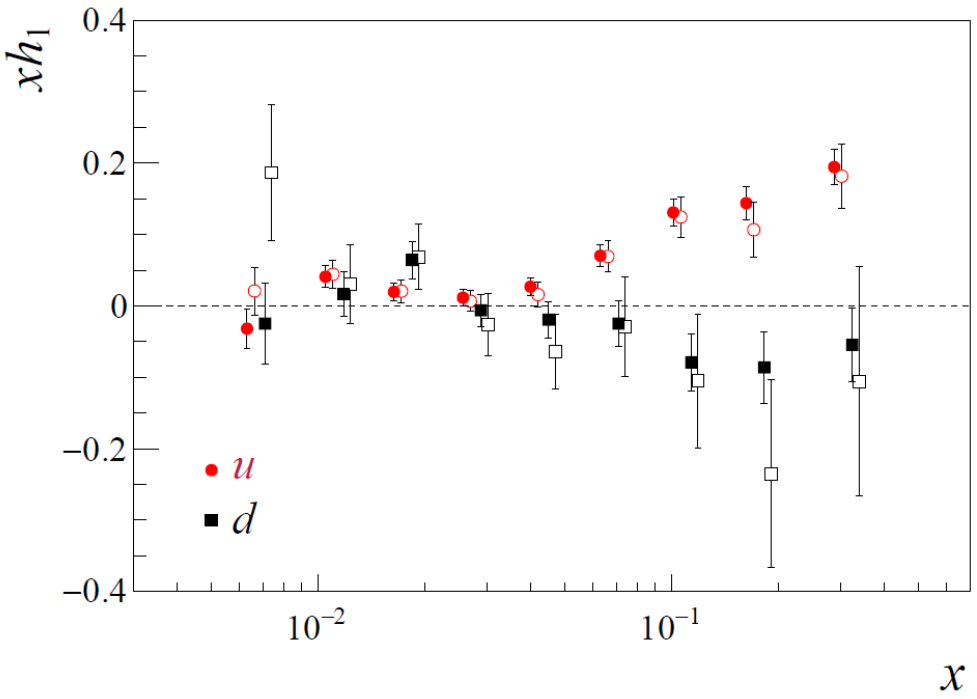


New and very precise deuteron data!

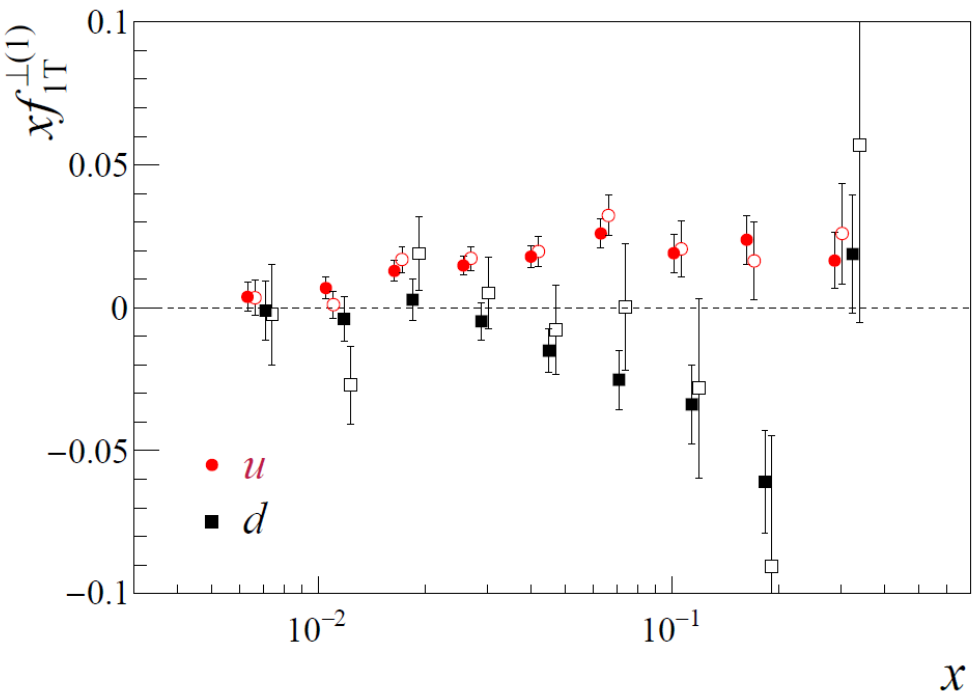
Highly improved precision, the asymmetry is expected to be small

TRANSVERSITY AND SIVERS FUNCTIONS

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



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

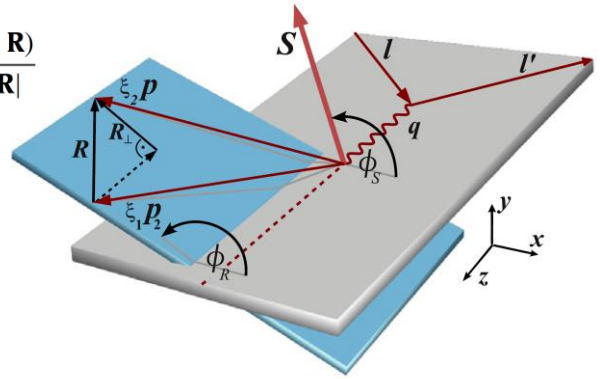


Overall precision improves by up to a factor of three!

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)

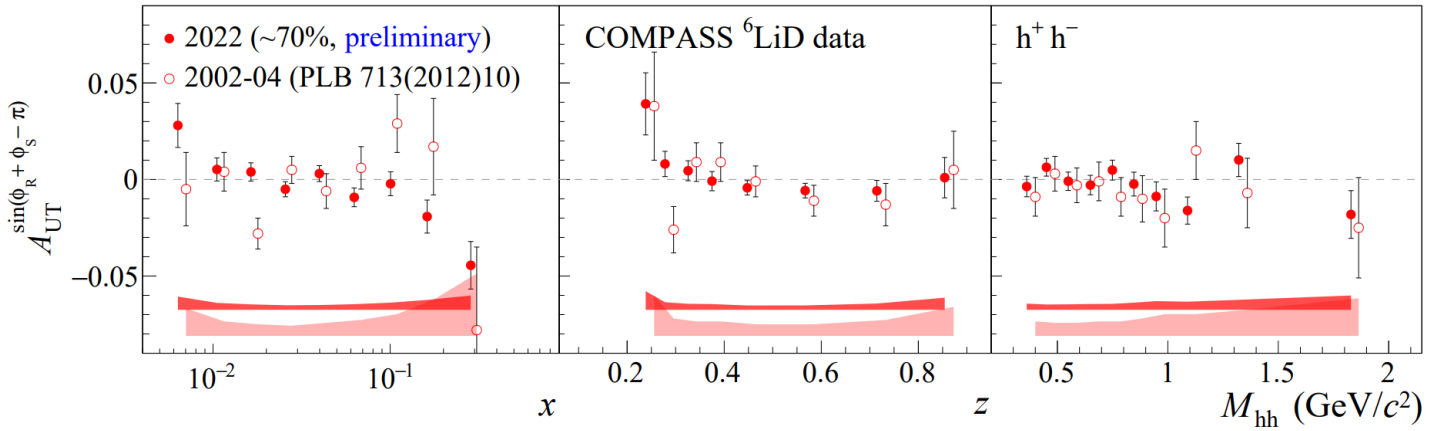
DIHADRON COLLINS ASYMMETRIES

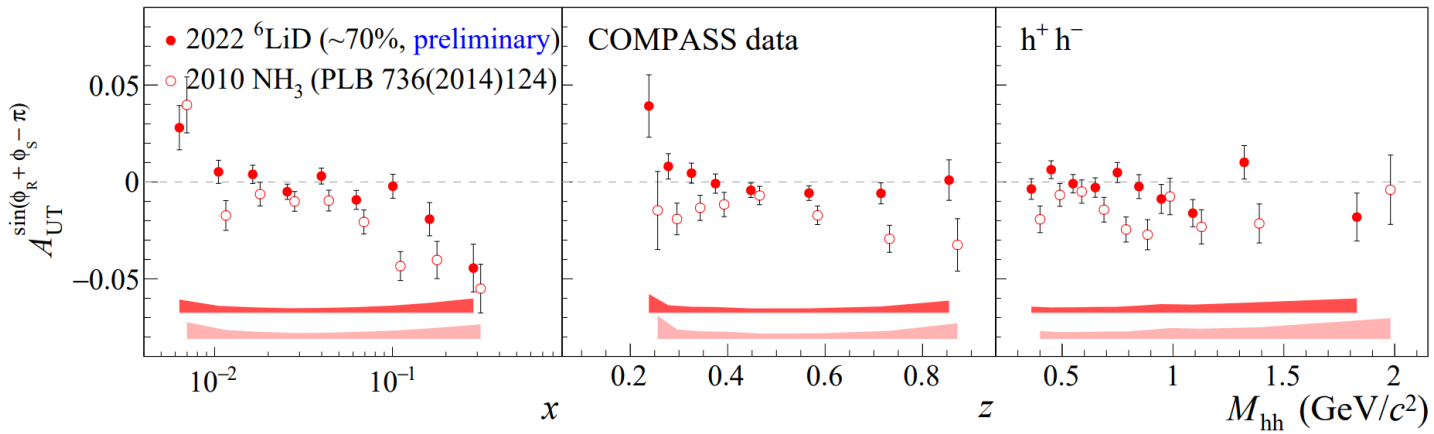
$$\phi_R = \frac{(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}}{|(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}|}\arccos\frac{(\mathbf{q}\times\mathbf{l})\cdot(\mathbf{q}\times\mathbf{R})}{|\mathbf{q}\times\mathbf{l}|\,|\mathbf{q}\times\mathbf{R}|}$$



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

$$\frac{d^7\sigma}{d\cos\theta\, dM_{hh}\, d\phi_R\, dz\, dx\, dy\, d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\left((1-y+\frac{y^2}{2})\sum_q e_q^2\, f_1^q(x)\, D_{1,q}(z, M_{hh}^2, \cos\theta) + S_\perp(1-y)\sum_q e_q^2 \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{hh}}\sin\theta\, \sin\phi_{RS}\, h_1^q(x)\, H_{1,q}^{\sphericalangle}(z, M_{hh}^2, \cos\theta)\right)$$





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 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!

THANK YOU