Update on transverse-spin azimuthal asymmetries in single-hadron SIDIS on transversely polarised deuterons at COMPASS

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on behalf of the COMPASS Collaboration

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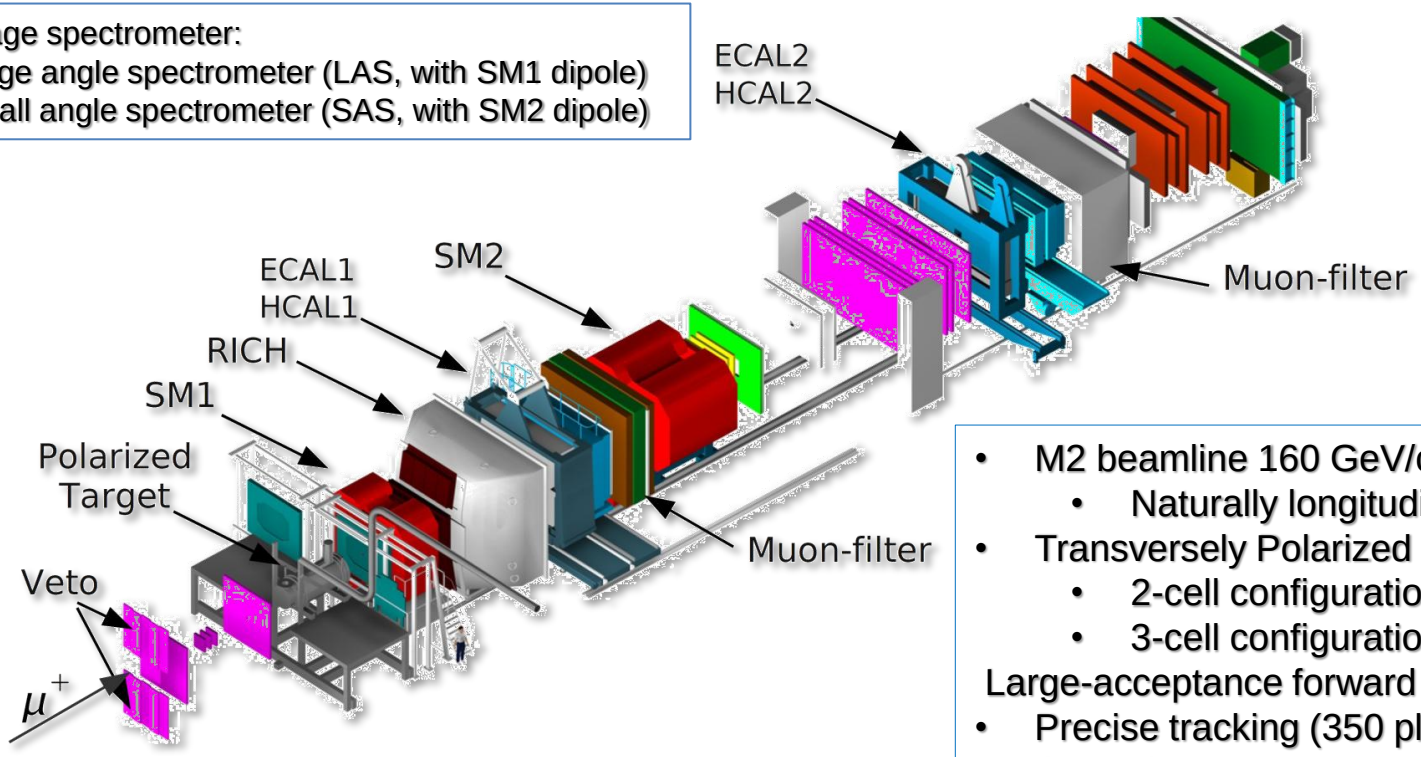
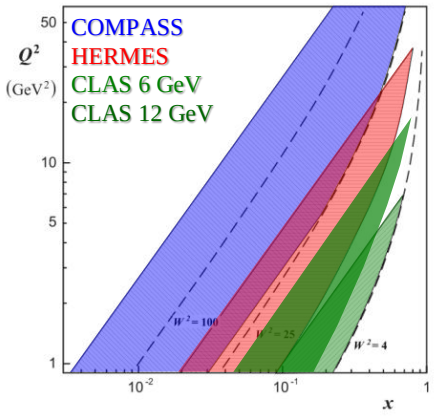
CA24159

COMPASS setup: transversely polarized SIDIS

Two-stage spectrometer:
- Large angle spectrometer (LAS, with SM1 dipole)
- Small angle spectrometer (SAS, with SM2 dipole)





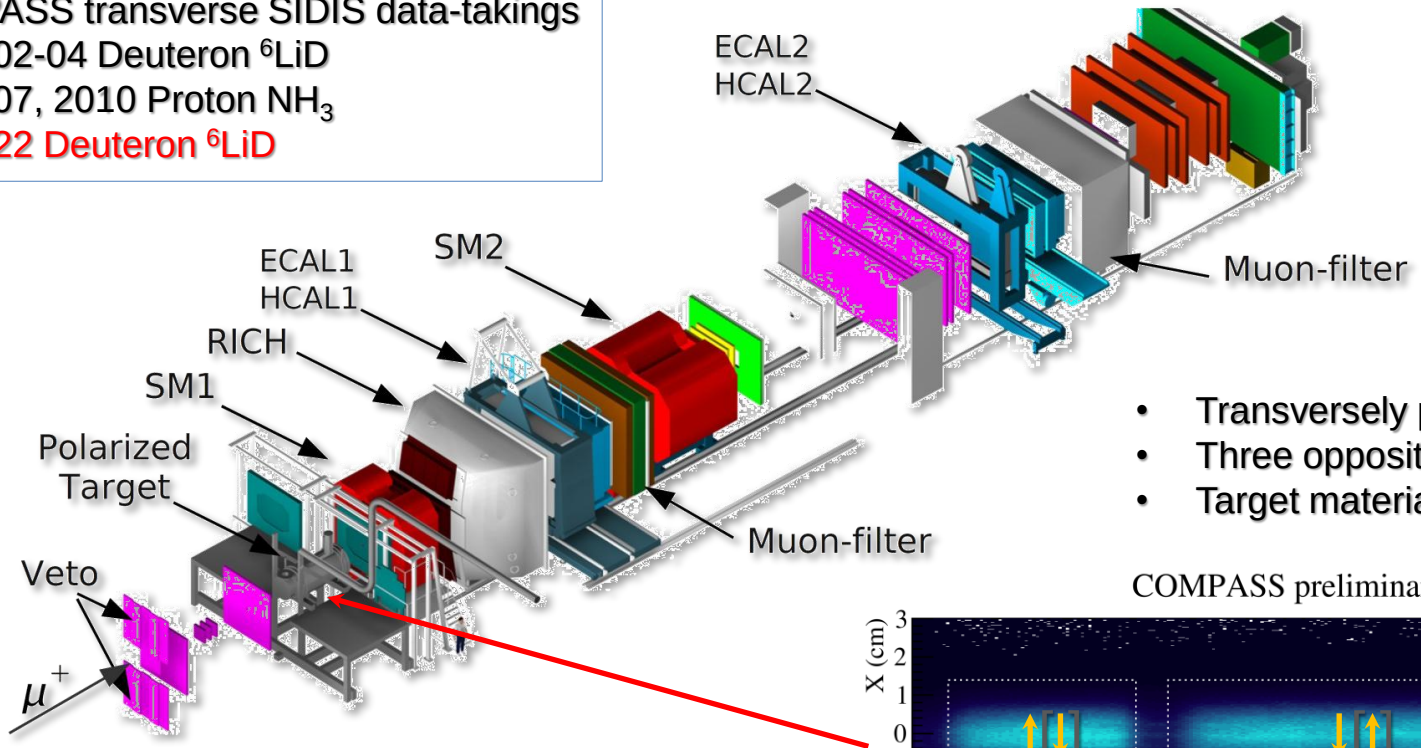
- M2 beamline 160 GeV/c μ+ beam
  - Naturally longitudinally polarized (≈ −80%)
- Transversely Polarized solid-state NH_3 or ^{6}LiD targets
  - 2-cell configuration in 2002-04
  - 3-cell configuration in 2007, 2010 and 2022

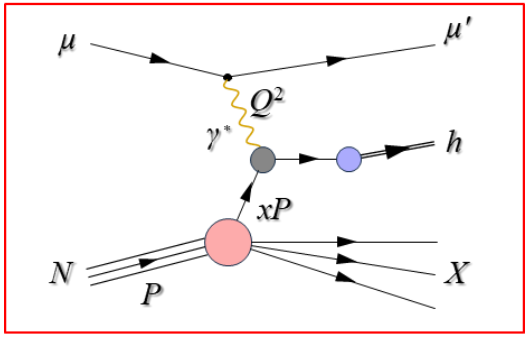
Large-acceptance forward spectrometer

- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC,
  Drift Chambers (DC), Straws, Muon walls
- PID - RICH, calorimeters, MWs

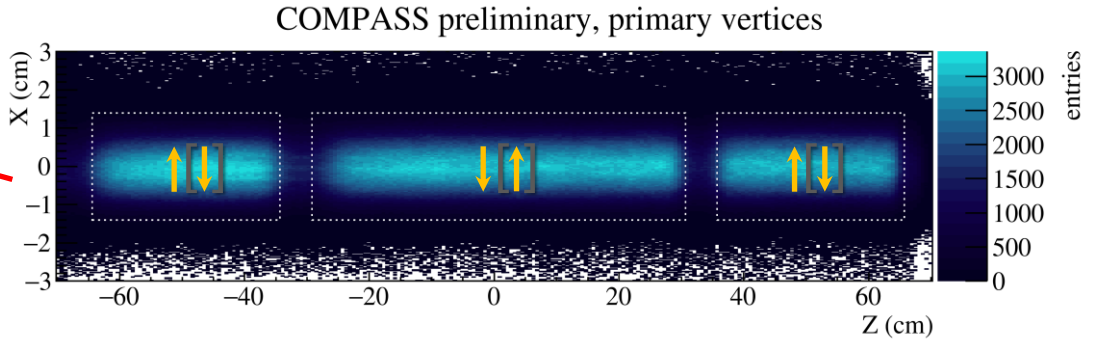
COMPASS setup: transversely polarized SIDIS

COMPASS transverse SIDIS data-takings
- 2002-04 Deuteron ^{6}LiD
- 2007, 2010 Proton NH_3
- 2022 Deuteron ^{6}LiD





- Transversely polarized solid-state target
- Three oppositely polarized cells
- Target material in 2022 - ^{6}LiD ($f \approx 0.38$)



SIDIS, azimuthal modulations and the 8 TSAs

All measured by COMPASS

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

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

$$+ S_T\left[\begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ &+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ &+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ &+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{aligned}\right]$$

$$+ S_T\lambda\left[\begin{aligned} &\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ &+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ &+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{aligned}\right]\Bigg\}$$

Twist-2

Twist-3

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

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

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

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

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

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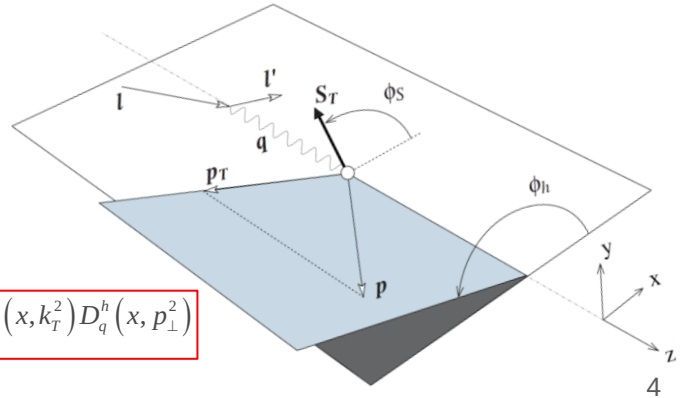
$$\otimes \equiv \left[wf\,D\right] = x\sum_q e_q^2\int d^2\boldsymbol{k}_T d^2\boldsymbol{p}_\perp \delta^{(2)}\left(z\boldsymbol{k}_T+\boldsymbol{p}_\perp-\boldsymbol{P}_h\right)w\left(\boldsymbol{k}_T,\boldsymbol{p}_\perp\right)f^q\left(x,k_T^2\right)D_q^h\left(x,p_\perp^2\right)$$

quark

nucleon	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ chiral-odd Boer-Mulders T-odd
L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ chiral-odd worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x,\boldsymbol{k}_T^2)$ chiral-odd transversity; $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity



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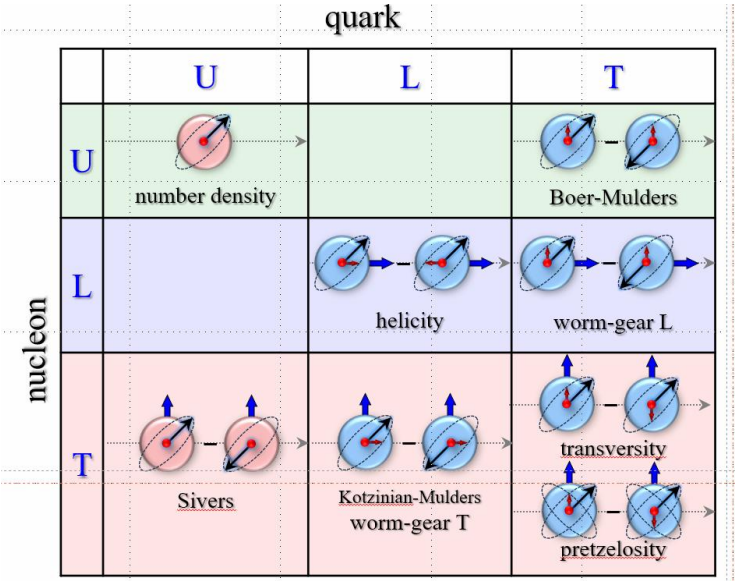

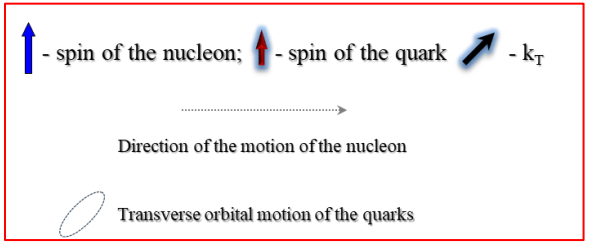

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Event selection and kinematic coverage

SIDIS event selection

- $Q^2 > 1$ GeV$^2/c^2$
- $W > 5$ GeV$/c^2$
- $0.1 < y < 0.9$
- $0.003 < x < 0.7$

Hadron selection

- $z > 0.2$
- $p_T > 0.1$ GeV$/c$
- h^+ / h^-

Full 2022 ^{6}LiD dataset ≈ 114 M hadrons

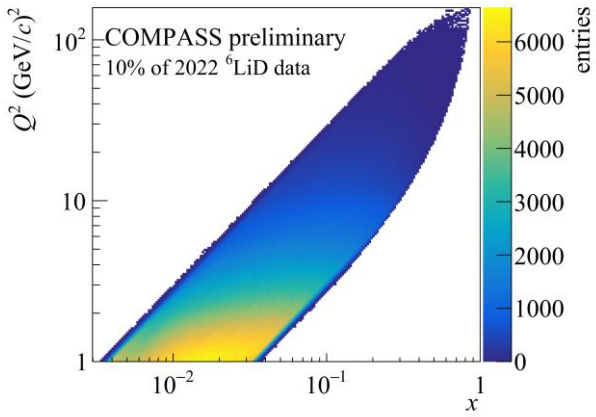
Mean kinematics (2022)

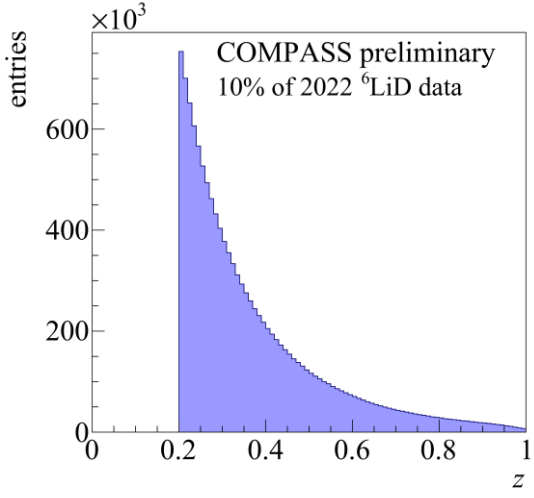
$\langle x \rangle \approx 0.06$

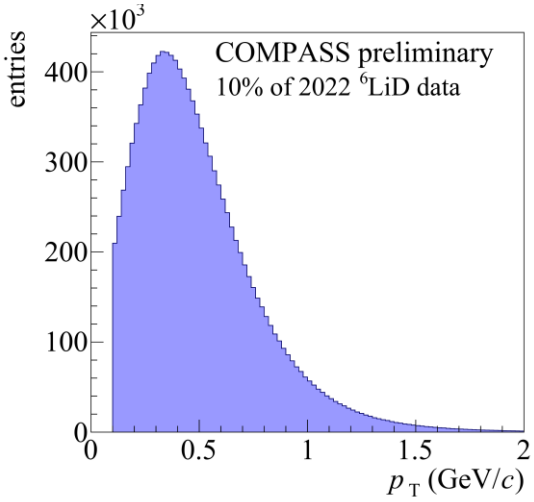
$\langle z \rangle \approx 0.35$

$\langle Q^2 \rangle \approx 3.0$ GeV$^2/c^2$

$\langle p_T \rangle \approx 0.47$ GeV$/c$







TSA extraction and what is new?

Method

- 2D (φ_h, φ_S) EUML fit
- All 8 modulations extracted simultaneously
  - together with the full covariance matrix
- 1D bins in x, z, p_T
- $h^+$and h^- samples treated separately
- Results for Collins and Sivers are in agreement with previously published results
  PRL 133 (2024) 101903 (70% of 2022 statistics)

What is new with respect to PRL 133 (2024) 101903

- Full 2022 ^{6}LiD dataset (≈114 M hadrons)
- Six “Beyond Collins and Sivers” TSAs shown for the first time
- Estimation of systematic uncertainties for the other six TSAs
- Refined detector alignment and calibrations
- Re-evaluated target polarisation
- Updated dilution factor

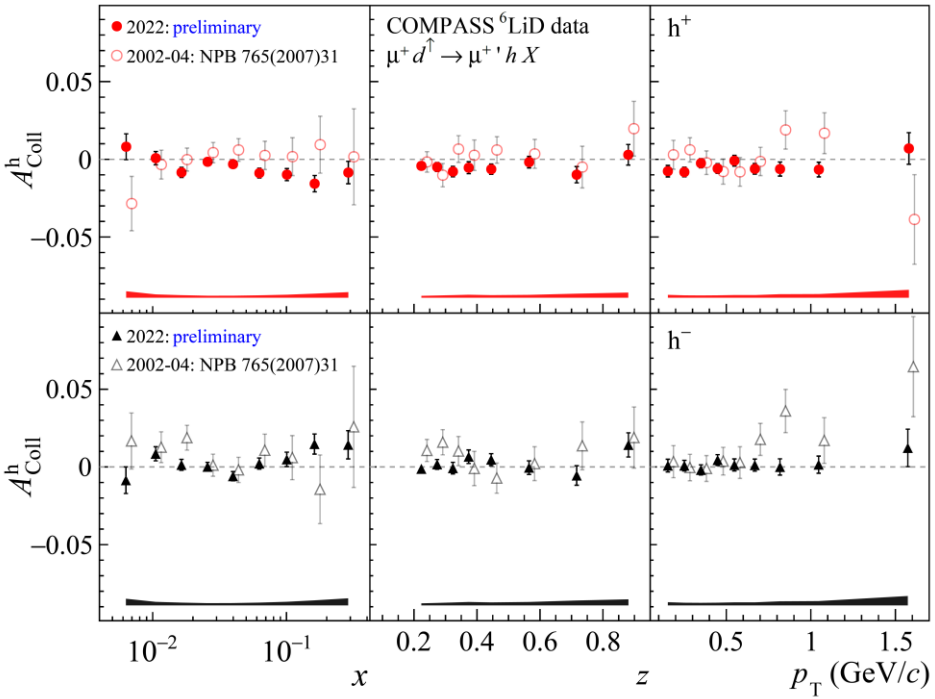
$$\mathcal{L} = \prod_{c=1}^{n_{\text{cell}}} \left\{ \left(e^{-I_c^+} \prod_{n=1}^{N_c^+} P^+(\phi_{h,n}, \phi_{S,n}; a_c^+, \boldsymbol{A}) \right)^{\frac{\bar{N}}{N_c^+}} \left(e^{-I_c^-} \prod_{m=1}^{N_c^-} P^-(\phi_{h,m}, \phi_{S,m}; a_c^-, \boldsymbol{A}) \right)^{\frac{\bar{N}}{N_c^-}} \right\}$$

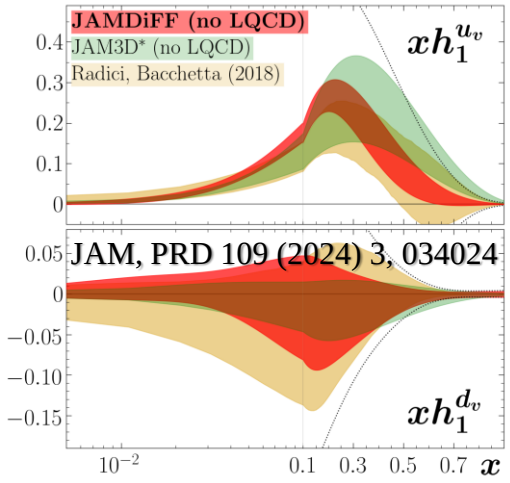
COMPASS: PLB 713 (2012) 10

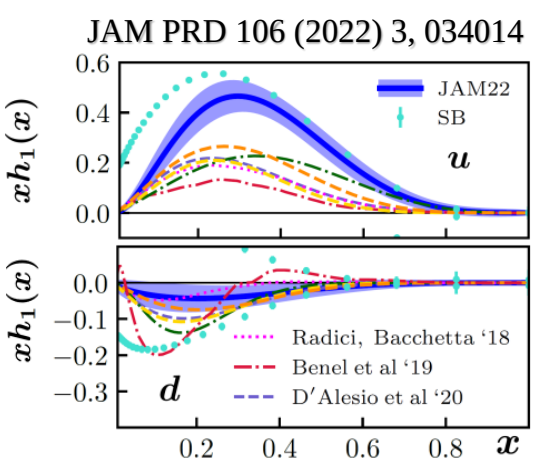
$$P^{\pm}(\phi_h, \phi_S; a_c^{\pm}, \boldsymbol{A}) = a_c^{\pm}(\phi_h, \phi_S)\, \sigma^{\pm}(\phi_h, \phi_S; \boldsymbol{A}), \quad \sigma^{\pm}(\phi_h, \phi_S; \boldsymbol{A}) = 1 \pm \sum_{i=1}^{8} \langle P_T \rangle f\, D_i(y)\, A_{BT}^{w_i(\phi_h,\phi_S)}\, w_i(\phi_h, \phi_S). \quad I_c^{\pm} = \int d\phi_h\, d\phi_S\, P^{\pm}(\phi_h, \phi_S; a_c^{\pm}, \boldsymbol{A})$$

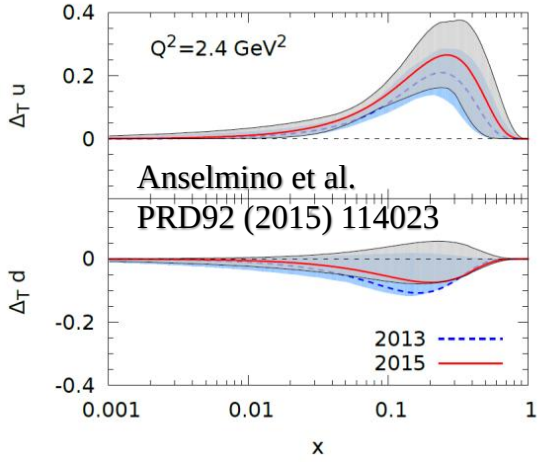
Collins asymmetries: 2022 ^{6}LiD vs 2002–04 ^{6}LiD

Collins TSA - $F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$





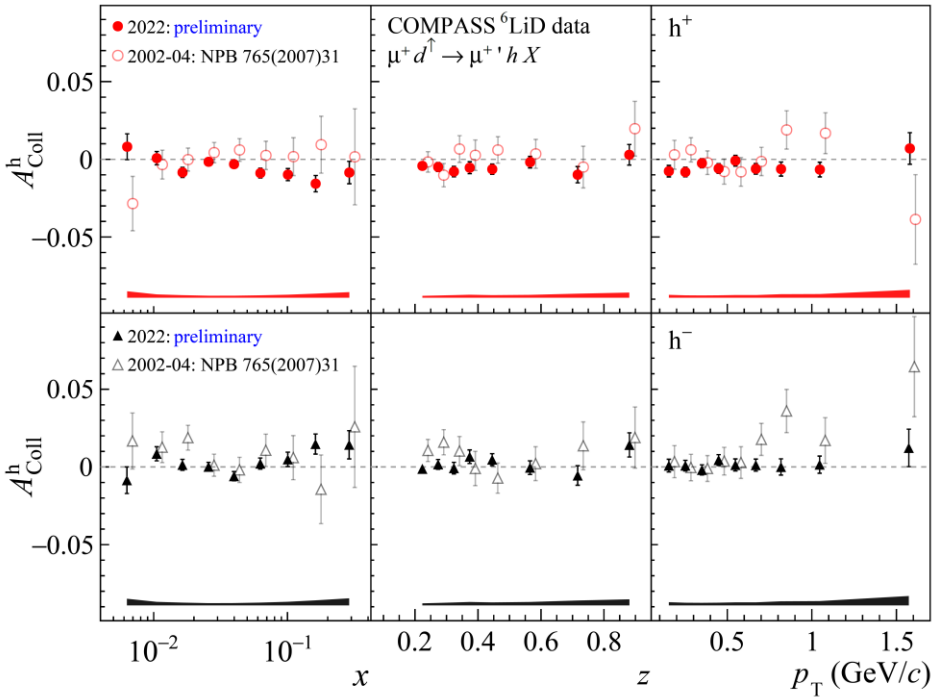




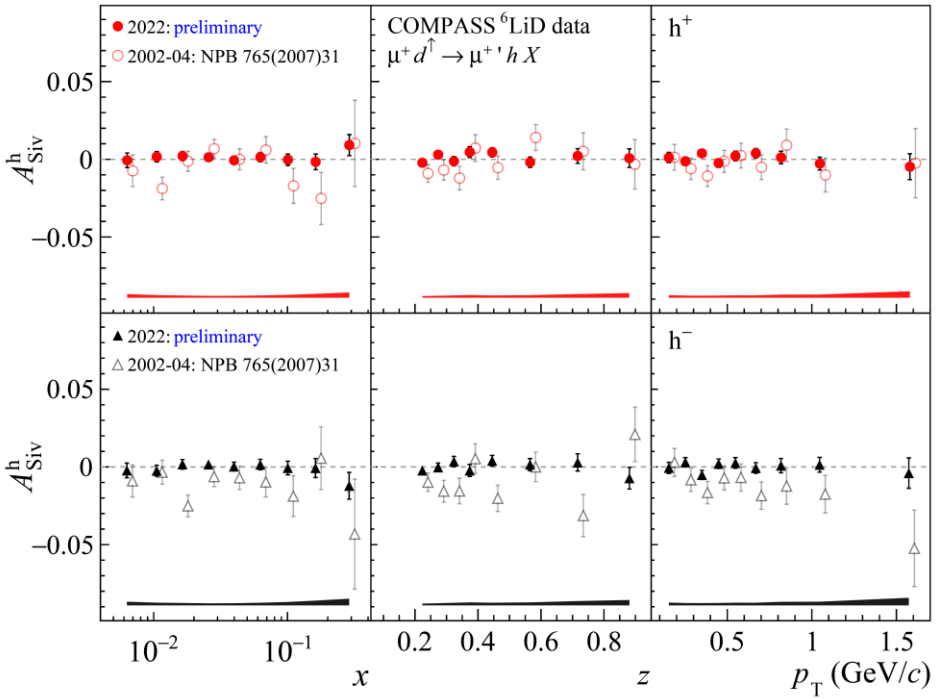
- COMPASS 2022 run – highly successful data-taking!
- COMPASS 2022 deuteron data is crucial to constrain *d*-quark TMD PDFs
- Much higher precision compared to 2002-04 data. Non-zero trend at large *x*.

Collins and Sivers asymmetries: 2022 ^{6}LiD vs 2002–04 ^{6}LiD

Collins TSA - $F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$



Sivers TSA - $F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$



- COMPASS 2022 deuteron data is crucial to constrain *d*-quark TMD PDFs
- Much higher precision compared to 2002-04 data. Non-zero trend at large *x*.
- Huge improvement also for Sivers effect. The asymmetry is very small and compatible with zero within ~ 0.5 - 1%

Collins and Sivers asymmetries: 2022 ^{6}LiD vs 2010 NH_3

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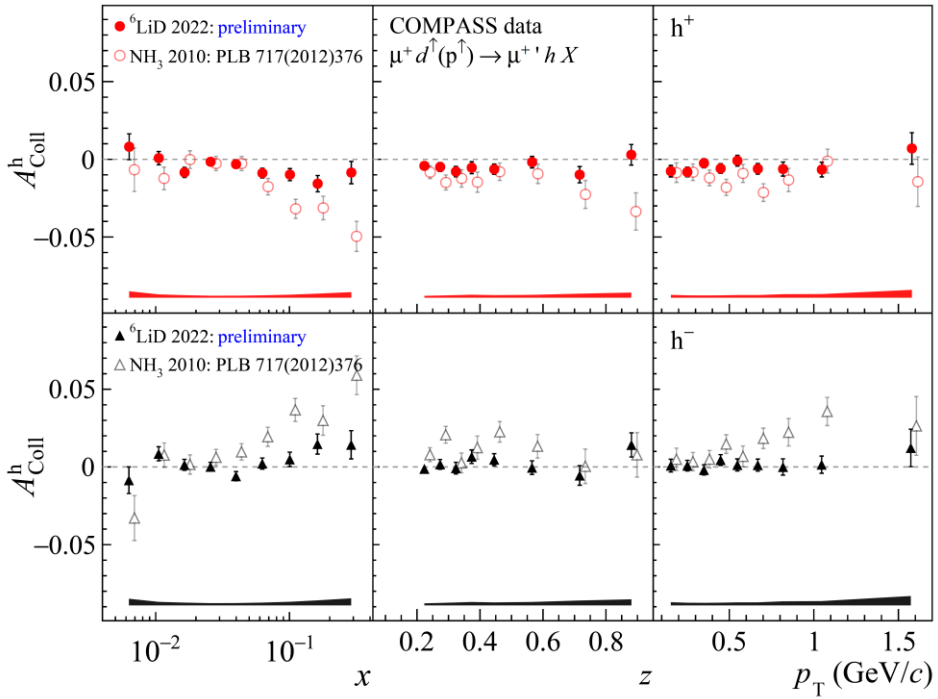
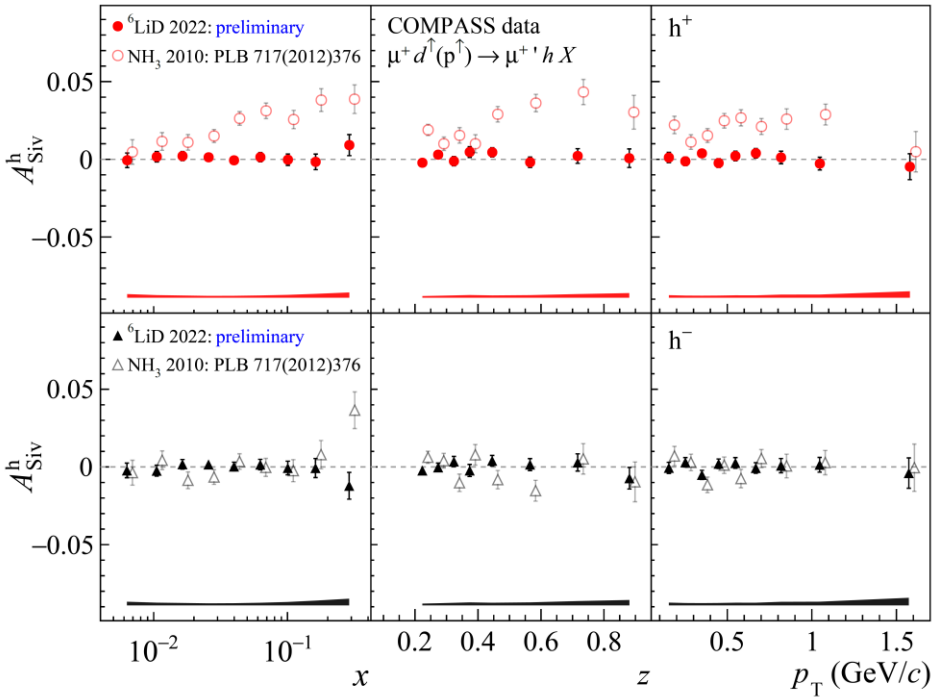
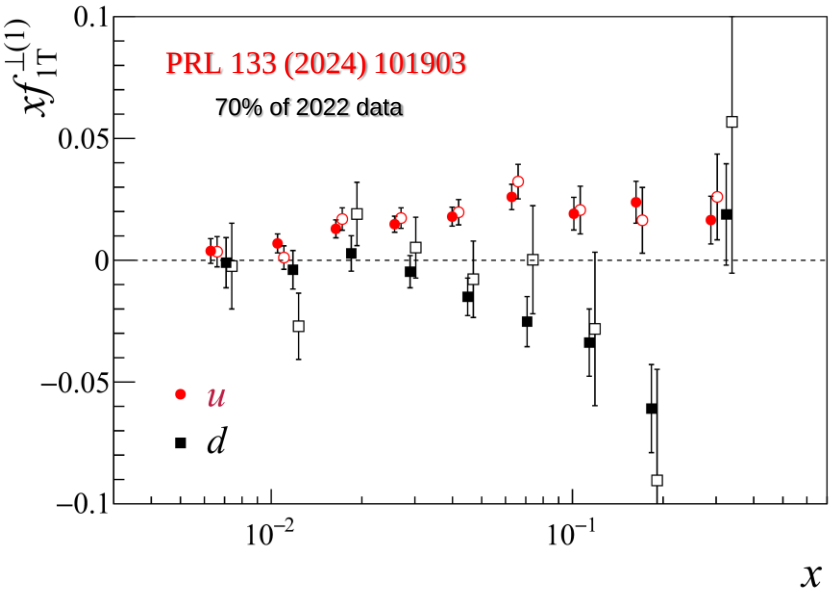




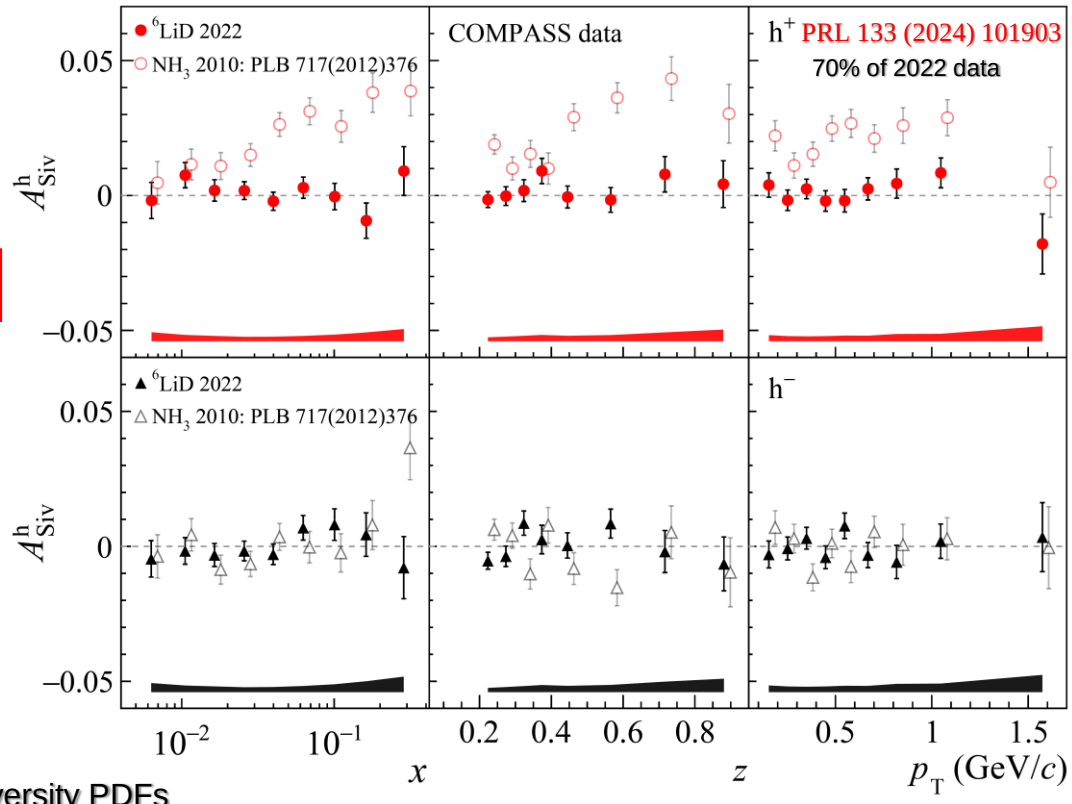
- Precision comparable with proton 2010 results
- Small signal for a significant non-zero Collins effect at large *x* (mirror symmetry behavior, characteristic for Collins FF)
- Sivers TSA is strikingly small compared to the proton case (strong u-d cancellation in deuteron?).

Sivers TSA: 2022 ^{6}LiD vs 2010 NH_3, accessing the Sivers PDF



Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

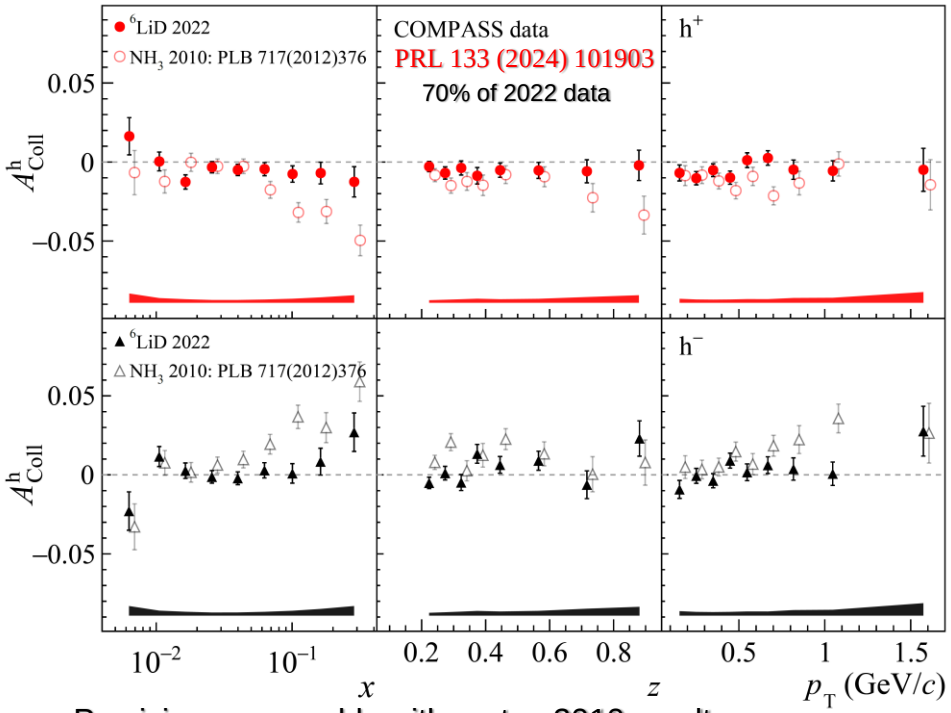
$$\text{Sivers TSA - } F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

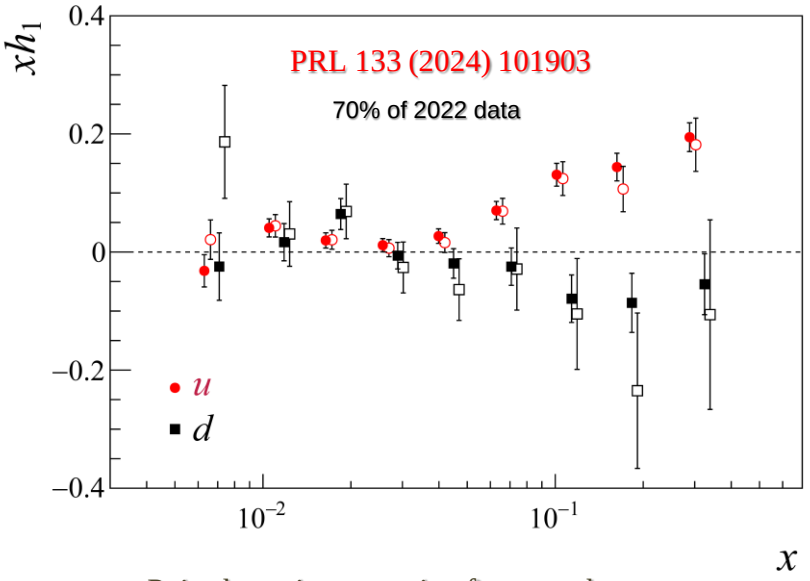


- Precision comparable with proton 2010 results
- Point-by-point extraction of Sivers and Transversity PDF
  - Strong reduction of uncertainties for both Sivers and Transversity PDFs

Collins TSA: 2022 ^{6}LiD vs 2010 NH_3 and the Transversity PDF

$$\text{Collins TSA - } F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$





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Collins and dihadron TSA: accessing transversity PDF

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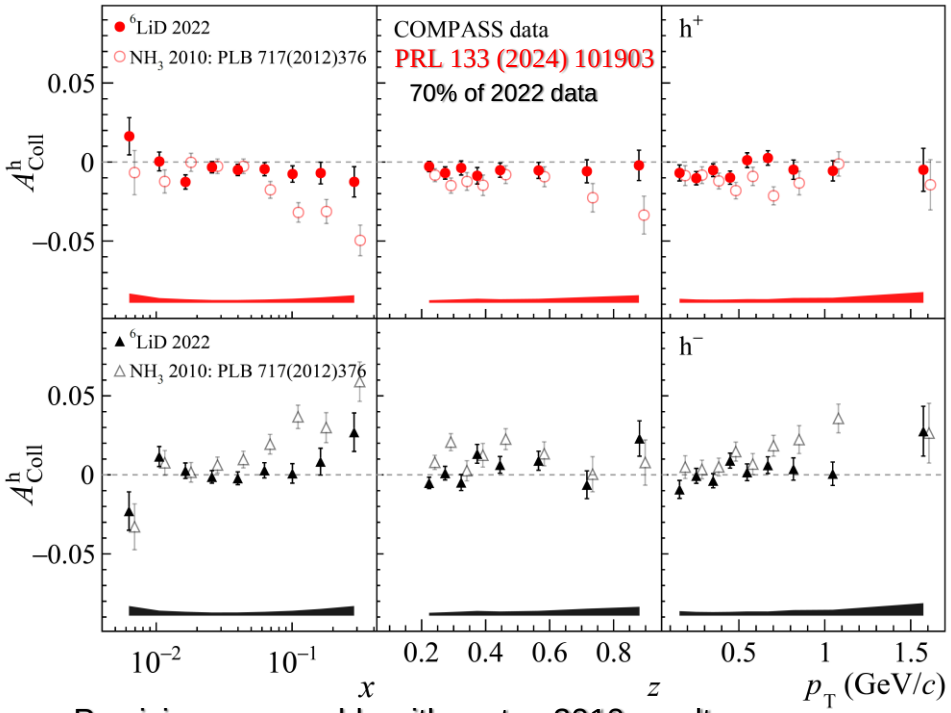
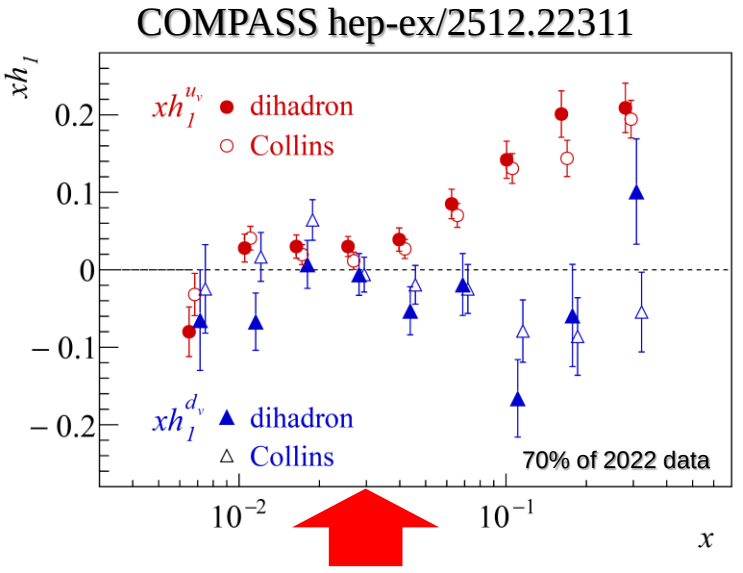
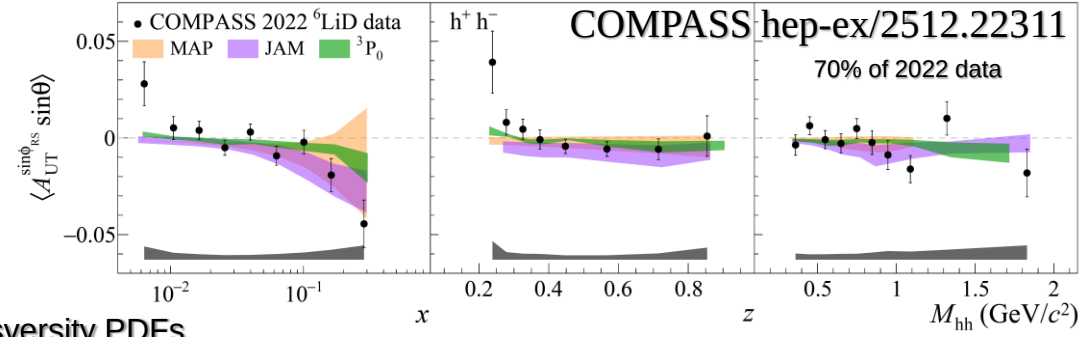
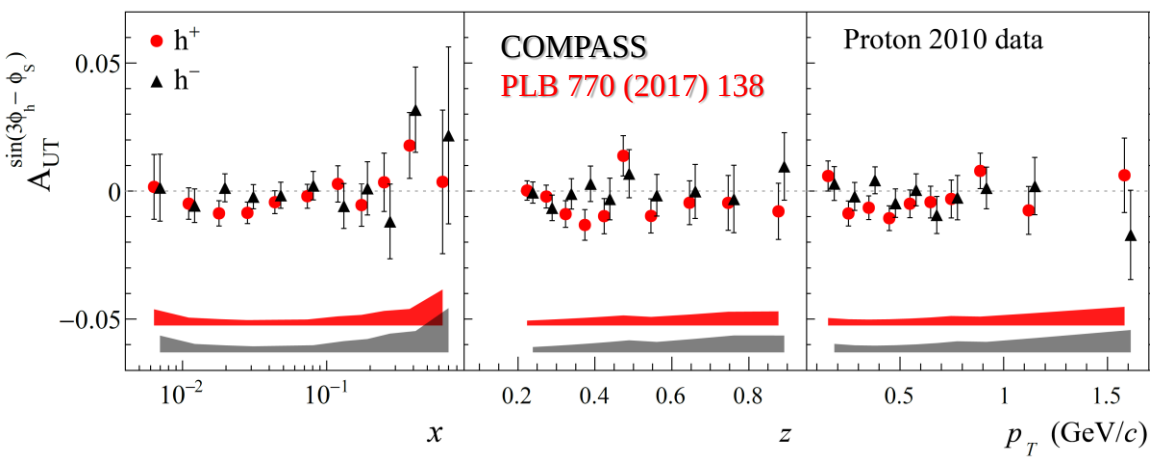






- Precision comparable with proton 2010 results
- Point-by-point extraction of Sivers and Transversity PDF
  - Strong reduction of uncertainties for both Sivers and Transversity PDFs

Pretzelosity TSA: proton measurements



$$F_{UT}^{\sin(3\phi_h-\phi_S)} = C\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)+\boldsymbol{k}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)}{2M^2M_h}h_{1T}^{\perp q}H_{1q}^{\perp h}\right]$$

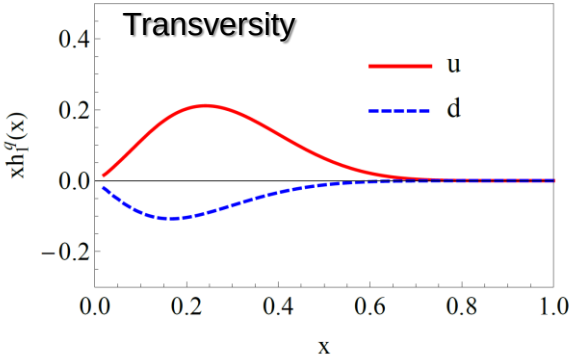
General comments

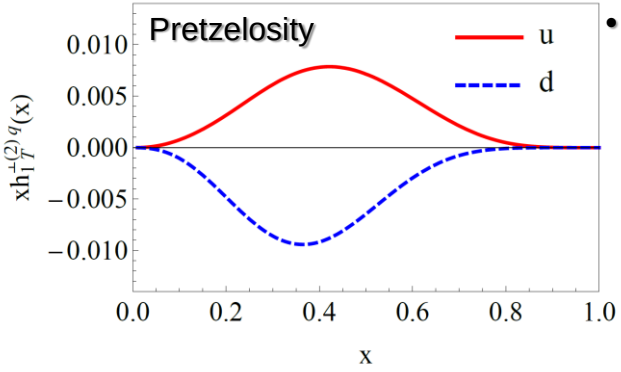
- Only “twist-2” ingredients
- p_T^2-suppressed compared to Sivers and Collins
- The PDF is expected to be small
- Small, compatible with zero asymmetry

COMPASS/HERMES results with proton target

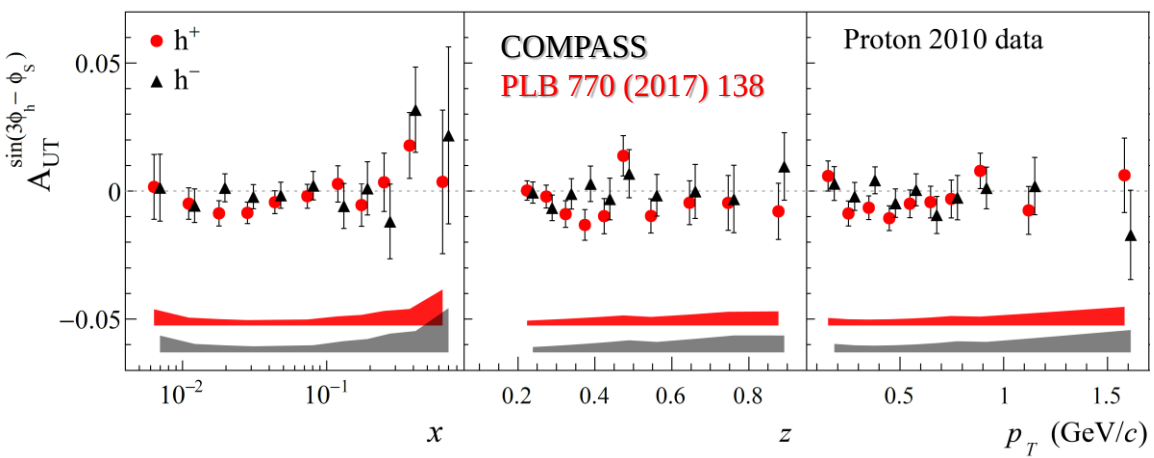
- Proton asymmetry is small (below 1-2 %)
- TSA is compatible with zero for both h^+ and h^-
- The measurements are compatible with models

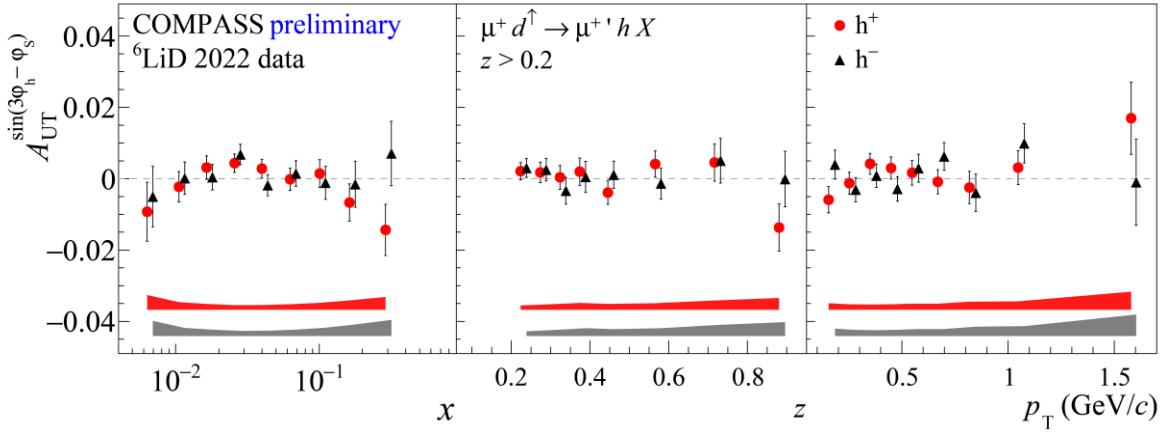
Bastami et al. JHEP 06 (2019) 007





Pretzelosity TSA: proton measurements and 2022 results





$$F_{UT}^{\sin(3\phi_h-\phi_S)} = C\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)+\boldsymbol{k}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)}{2M^2M_h} h_{1T}^{\perp q} H_{1q}^{\perp h}\right]$$

General comments

- Only “twist-2” ingredients
- p_T^2-suppressed compared to Sivers and Collins
- The PDF is expected to be small
- Small, compatible with zero asymmetry

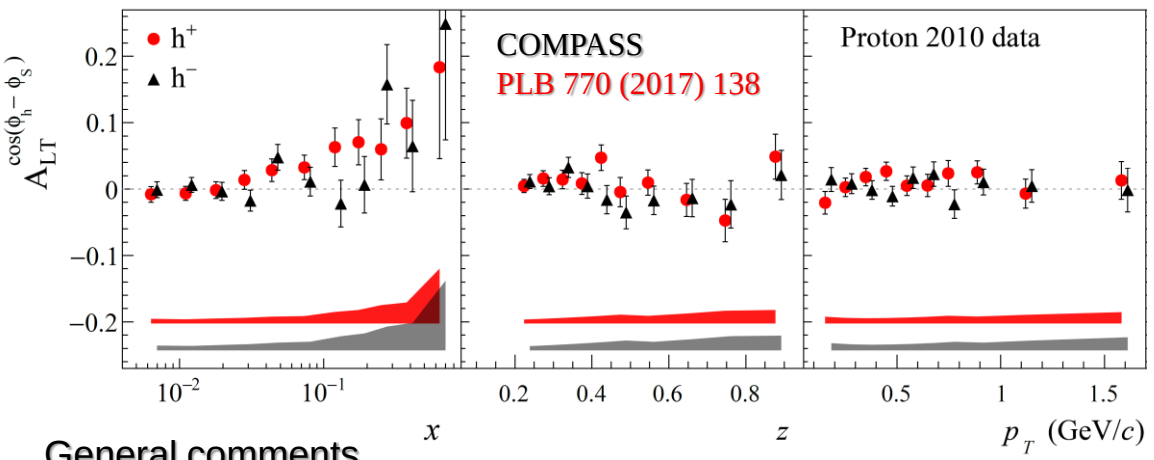
COMPASS/HERMES results with proton target

- Proton asymmetry is small (below 1-2 %)
- TSA is compatible with zero for both h^+ and h^-
- The measurements are compatible with models

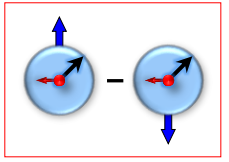
New COMPASS 2022 deuteron data

- The asymmetry is small and compatible with zero
- Comparable precision with proton results
- In agreement with model expectations

Kotzinian-Mulders asymmetry: proton measurements

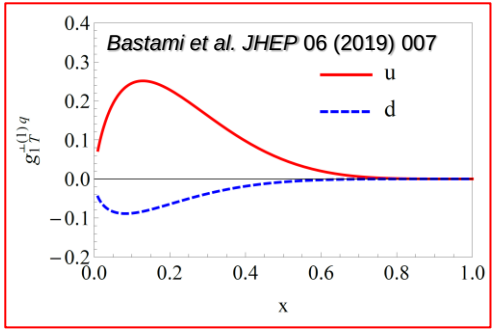


$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^{q} D_{1q}^{h}\right]$$



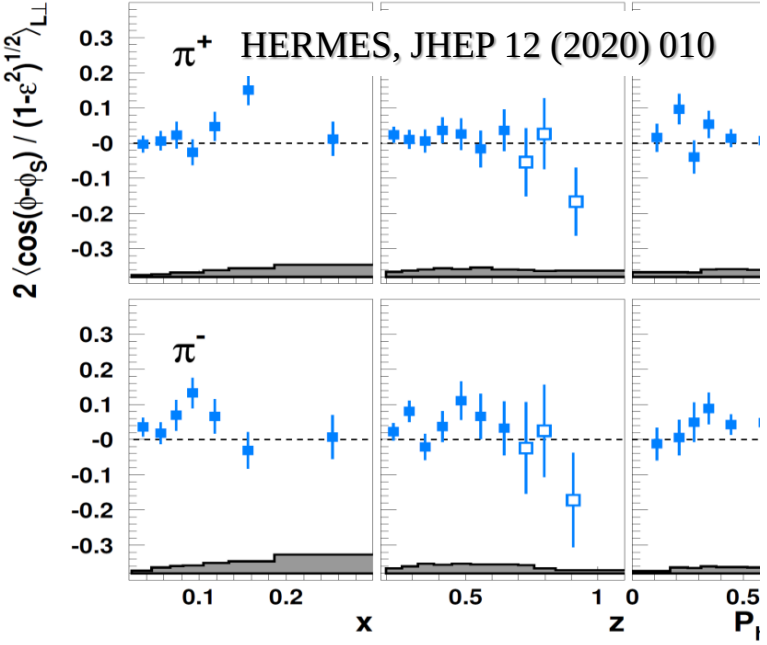
General comments

- Only “twist-2” ingredients
- The SF is similar to Sivers
- The PDF is expected to be non-zero

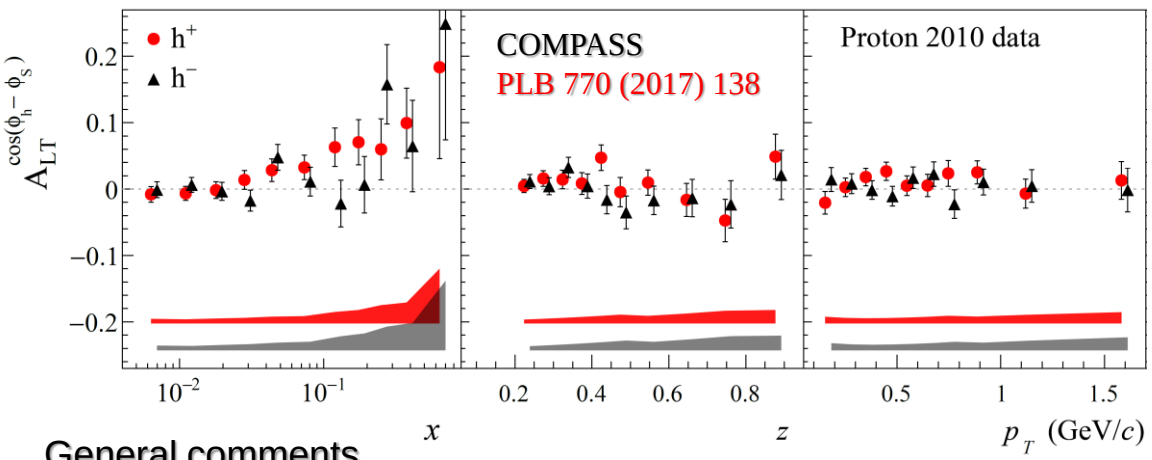


COMPASS/HERMES results with proton target

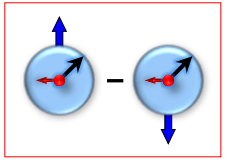
- Proton asymmetry is rather large (5-10 %)
- Hint for a positive signal for both h^+ and h^-
- In agreement with model predictions; first global fits



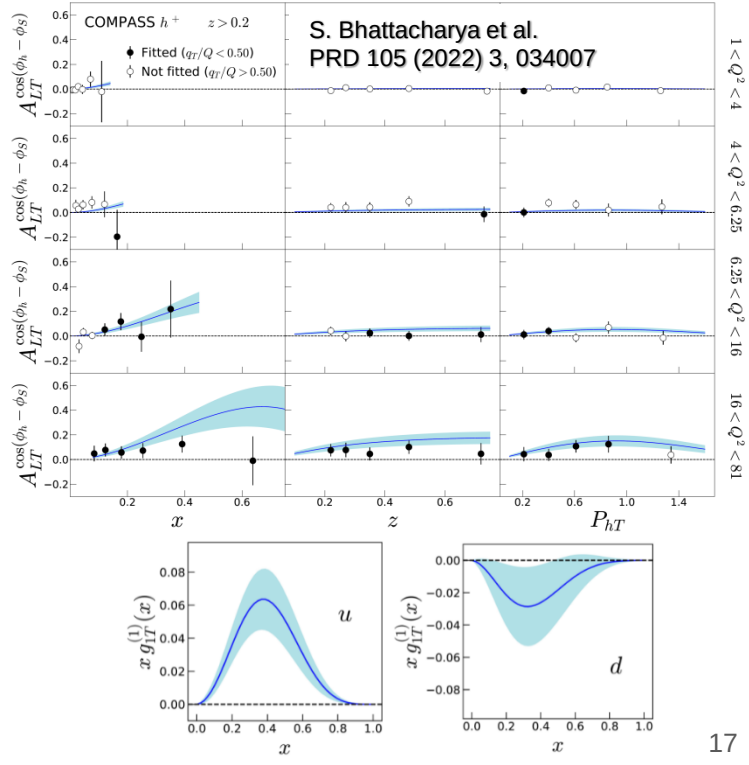
Kotzinian-Mulders asymmetry: proton measurements



$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^{q} D_{1q}^{h}\right]$$

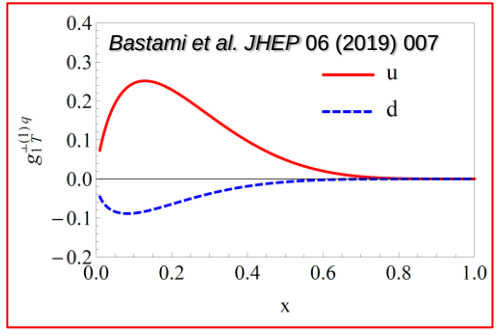


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



General comments

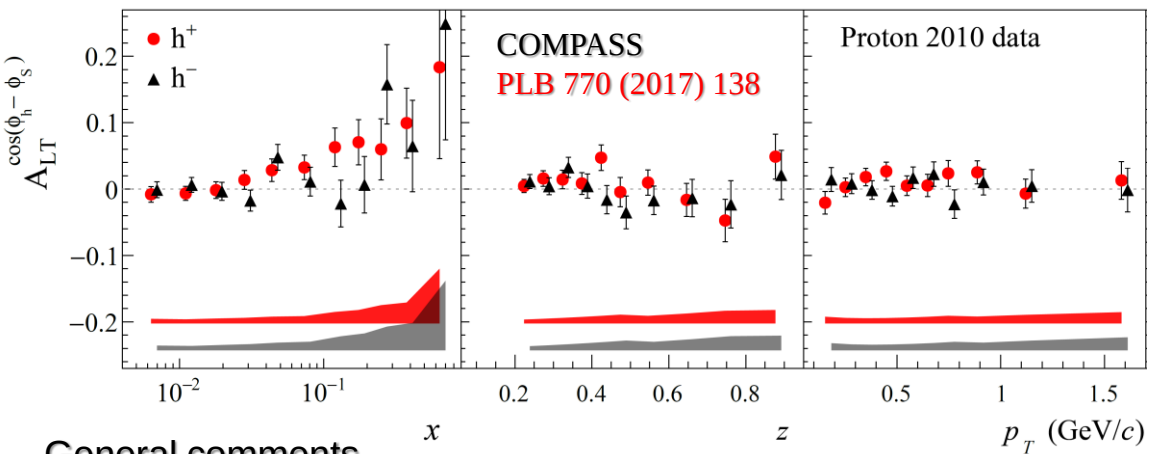
- Only “twist-2” ingredients
- The SF is similar to Sivers
- The PDF is expected to be non-zero



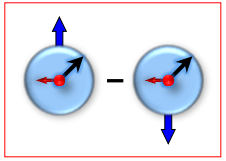
COMPASS/HERMES results with proton target

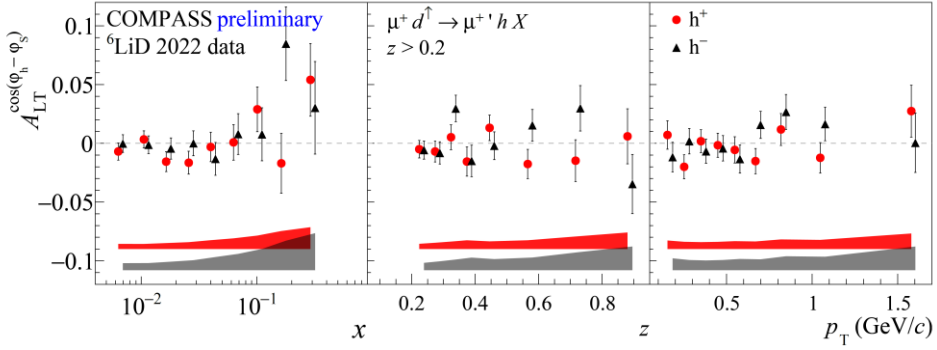
- Proton asymmetry is rather large (5-10 %)
- Hint for a positive signal for both h^+ and h^-
- In agreement with model predictions; first global fits

K-M TSA: proton measurements and 2022 results



$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^{q} D_{1q}^{h}\right]$$



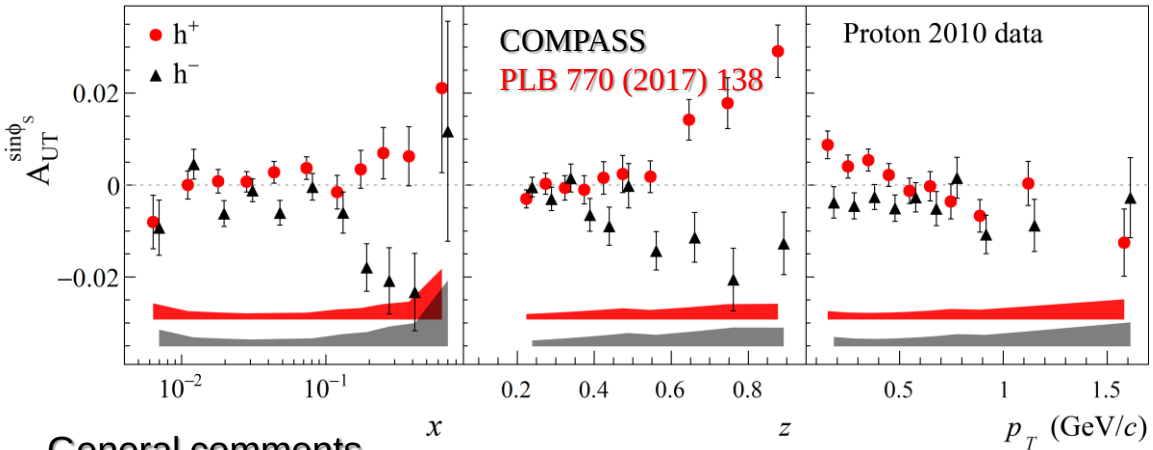


General comments
- Only “twist-2” ingredients
- The SF is similar to Sivers
- The PDF is expected to be non-zero

COMPASS/HERMES results with proton target
- Proton asymmetry is rather large (5-10 %)
- Hint for a positive signal for both h^+ and h^-
- In agreement with model predictions; first global fits

New COMPASS 2022 deuteron data
- The asymmetry is compatible with zero within the uncertainties
- Some hints for a non-zero signal at large *x*
- Potential signal is compatible with model expectations

$A_{UT}^{\sin(\varphi_s)}$ TSA: proton measurements



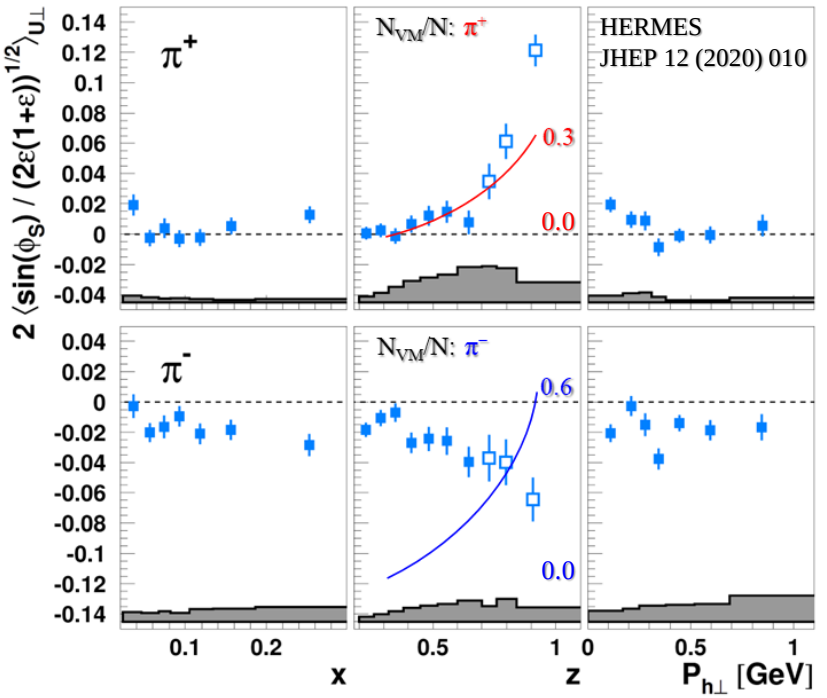
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

General comments

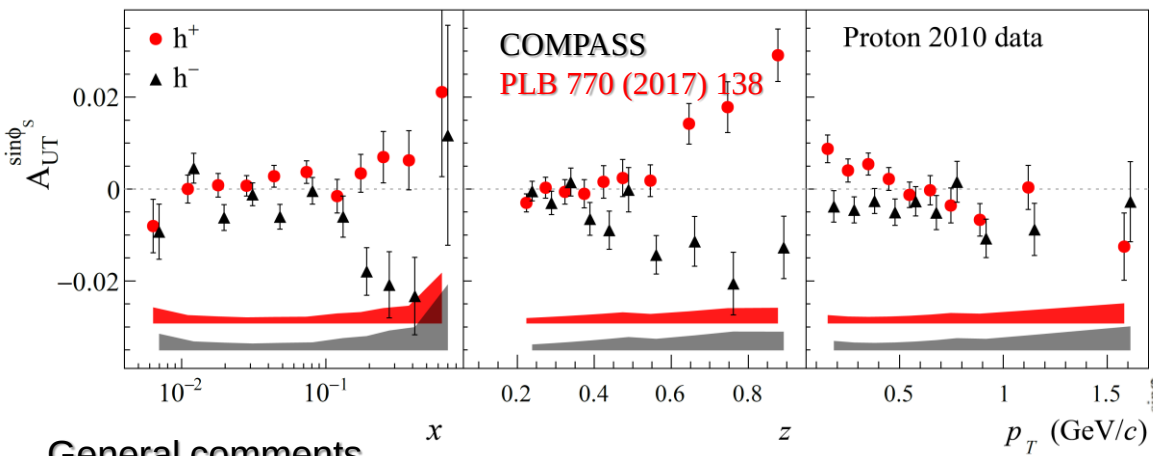
- Complex SF, various “twist-2” and “twist-3” ingredients, Q^{-1} and other suppressions
- Expected to be zero in WW approximation

COMPASS/HERMES results with proton target

- Small TSA; signal at large z for both h^+ and h^-
  - Can large-z signal be induced by DVMs?



$A_{UT}^{\sin(\varphi_S)}$ TSA: proton measurements



$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

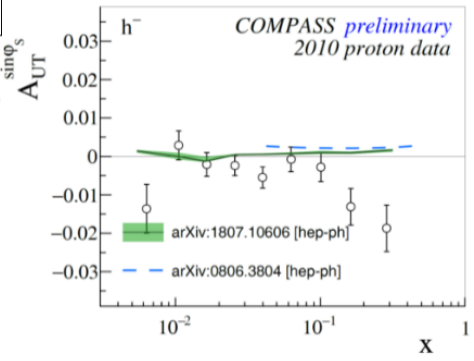
General comments

- Complex SF, various “twist-2” and “twist-3” ingredients, Q^{-1} and other suppressions
- Expected to be zero in WW approximation

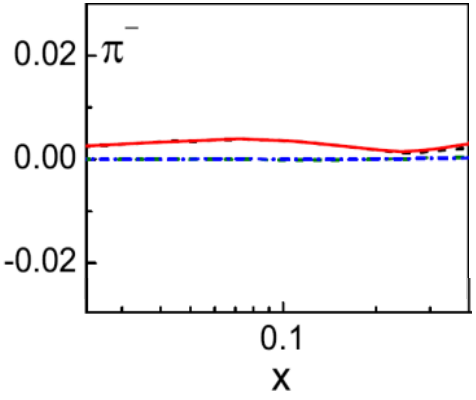
COMPASS/HERMES results with proton target

- Small TSA; signal at large z for both h^+ and h^-
  - Can large-z signal be induced by DVMs?
- Not explained by models…

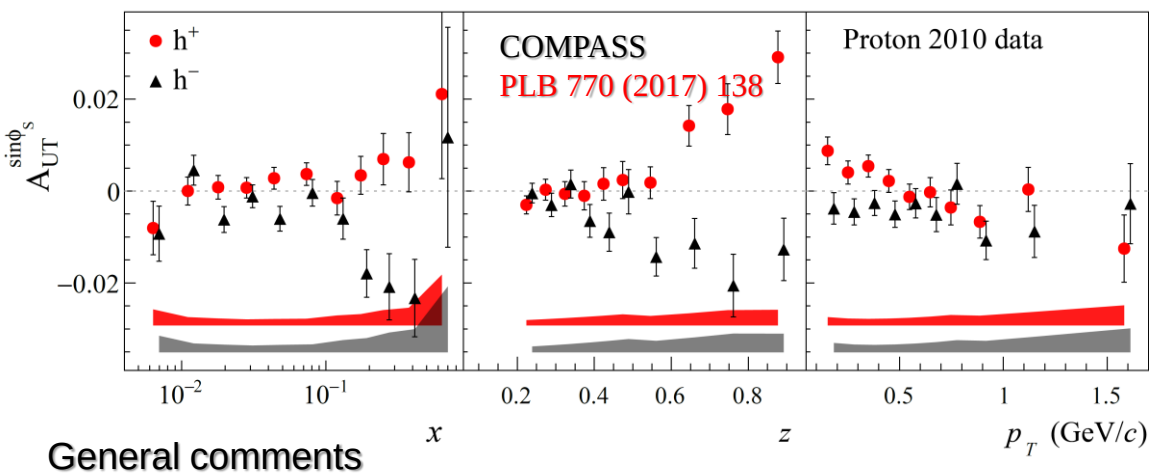
S. Bastami et al.
JHEP 1906 (2019) 007



W. Mao et al.
PRD 90 (2014) 014048



$A_{UT}^{\sin(\varphi_S)}$ TSA: proton measurements and 2022 results



$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

New COMPASS 2022 deuteron data

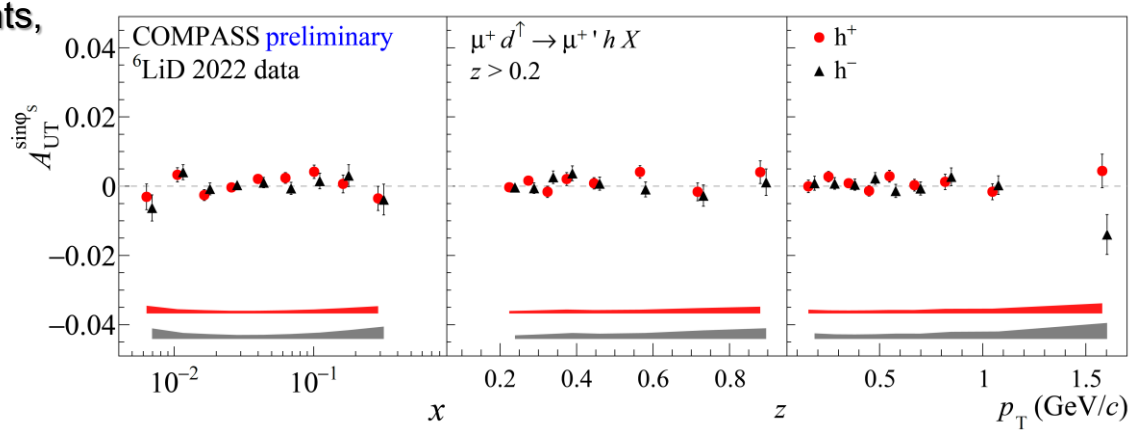
- The asymmetry is compatible with zero within the uncertainties
- The measured amplitudes are below 1%

General comments

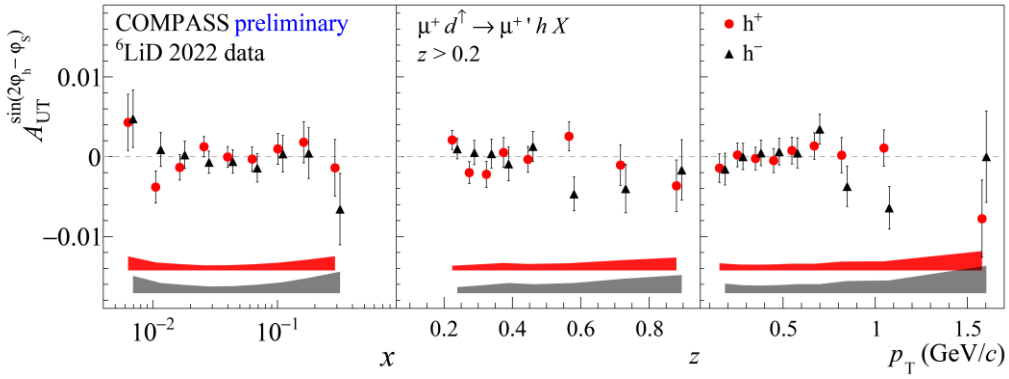
- Complex SF, various “twist-2” and “twist-3” ingredients, Q^{-1} and other suppressions
- Expected to be zero in WW approximation

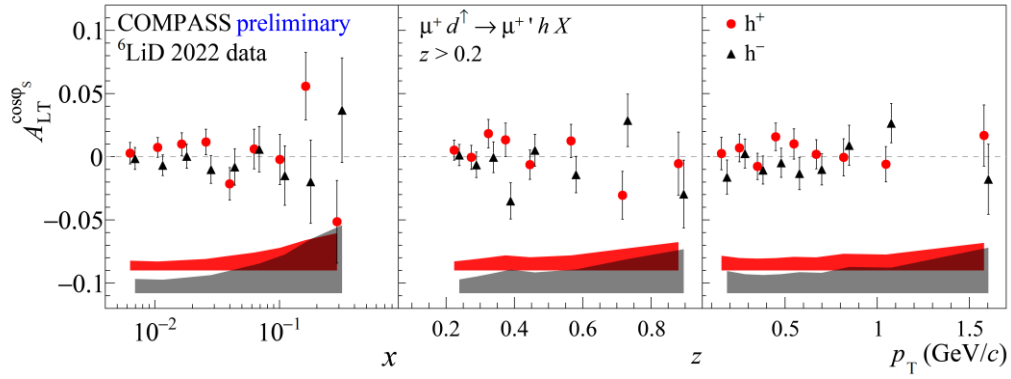
COMPASS/HERMES results with proton target

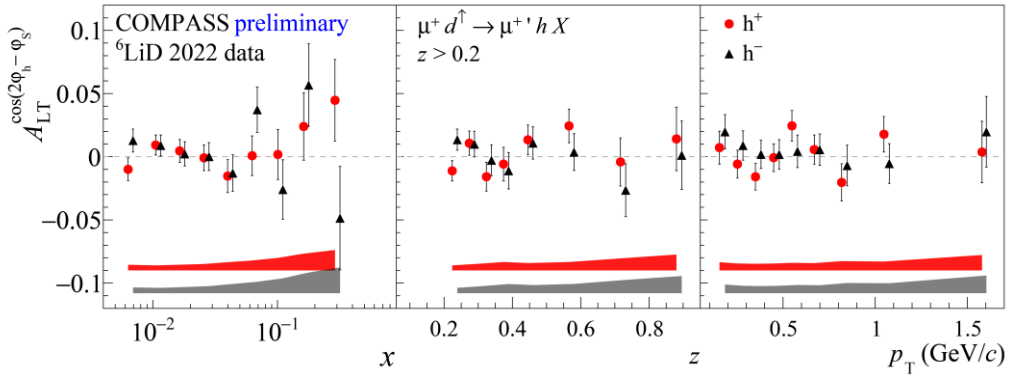
- Small TSA; signal at large z for both h^+ and h^-
  - Can large-z signal be induced by DVMs?
- Not explained by models…



Other higher-twist (twist-3) asymmetries







New COMPASS 2022 deuteron data

- Complex SF, various “twist-2” and “twist-3” ingredients, Q^{-1} and other “kinematic” suppressions
- The measured amplitudes are small
- The asymmetries are compatible with zero within the uncertainties
- Similar picture was observed for proton data

Summary

- **COMPASS 2022 provided a high-statistics deuteron SIDIS sample:**
  - full transversely polarised ^{6}LiD data set, about **114 M charged hadrons**.
- **Eight transverse-spin asymmetries extracted simultaneously**
  - with a 2D (ϕ_h,ϕ_S) EUML fit, including the full covariance matrix.
- **Strong improvement with respect to 2002-04 deuteron data:**
  - statistical precision comparable to the 2010 proton measurement.
- **Updated Collins and Sivers TSAs in agreement with recently published results** PRL 133 (2024) 101903 (70% of 2022 data)
- **Collins asymmetry:** small on deuteron, but with hints of a non-zero trend at large *x*;
  - important input for constraining **d-quark transversity**.
- **Sivers asymmetry:** remains very small, compatible with zero at the sub-percent level;
  - consistent with strong **u-d cancellation** in the deuteron.
- **Pretzelosity asymmetry:** compatible with zero, as expected from the small PDF and kinematic suppression
- **Other beyond-Collins/Sivers TSAs:** measured for the first time with the full 2022 deuteron statistics;
  - amplitudes are generally small and compatible with zero within uncertainties.

Next steps:
RICH-identified π/K asymmetries, weighted asymmetries, and multi-dimensional studies.

Thank you!