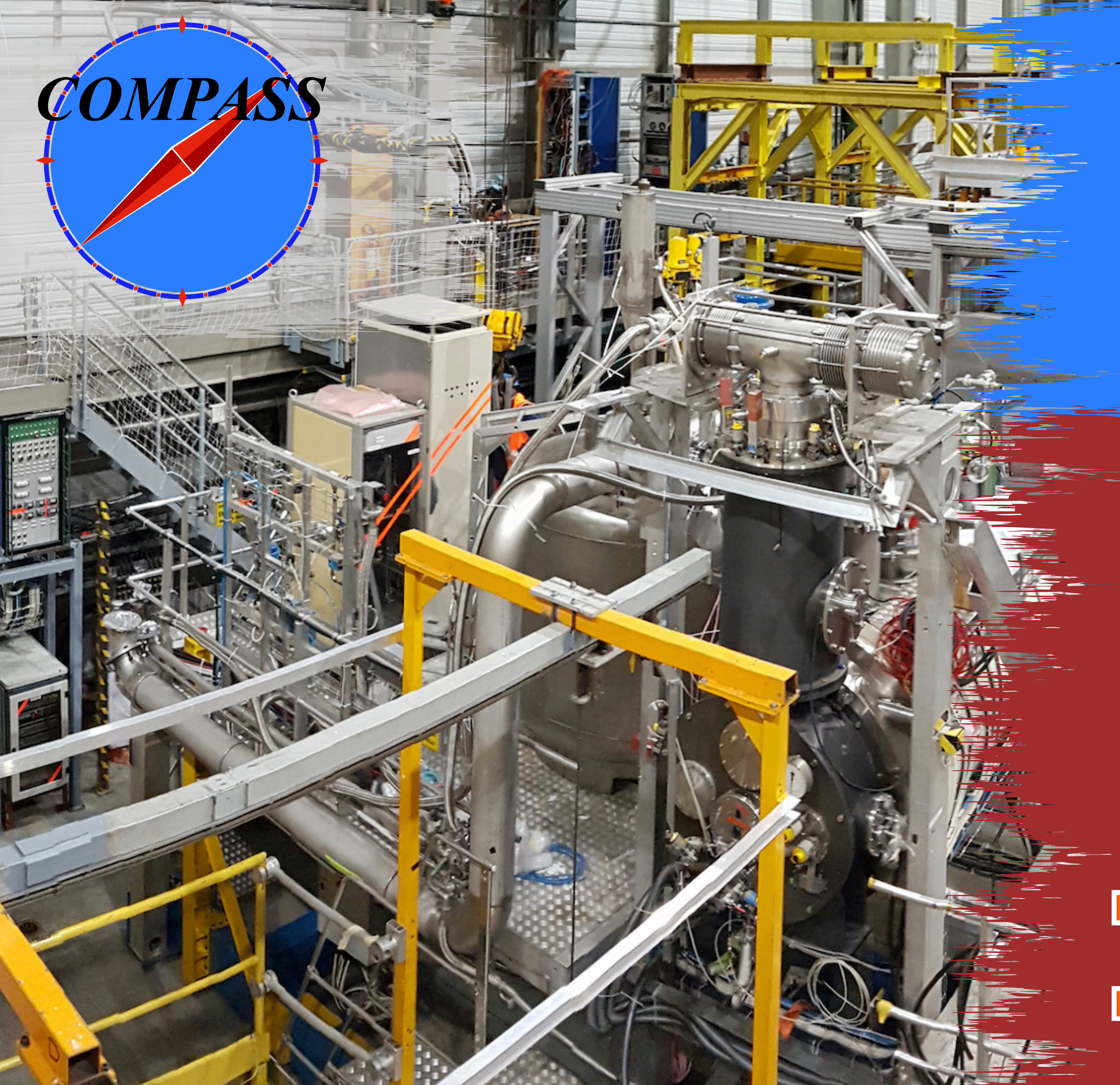


COMPASS

RECENT PROGRESS ON COMPASS TMD PROGRAMME

Riccardo Longo

On behalf of the COMPASS Collaboration

June 18th 2024

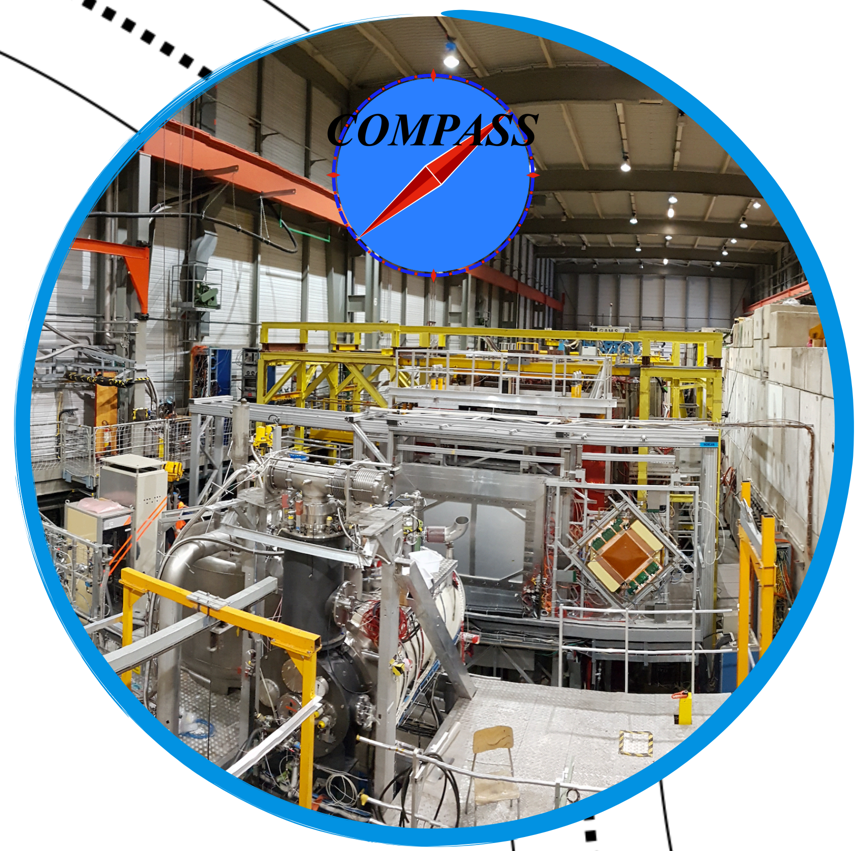
SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier Workshop

Argonne National Laboratory

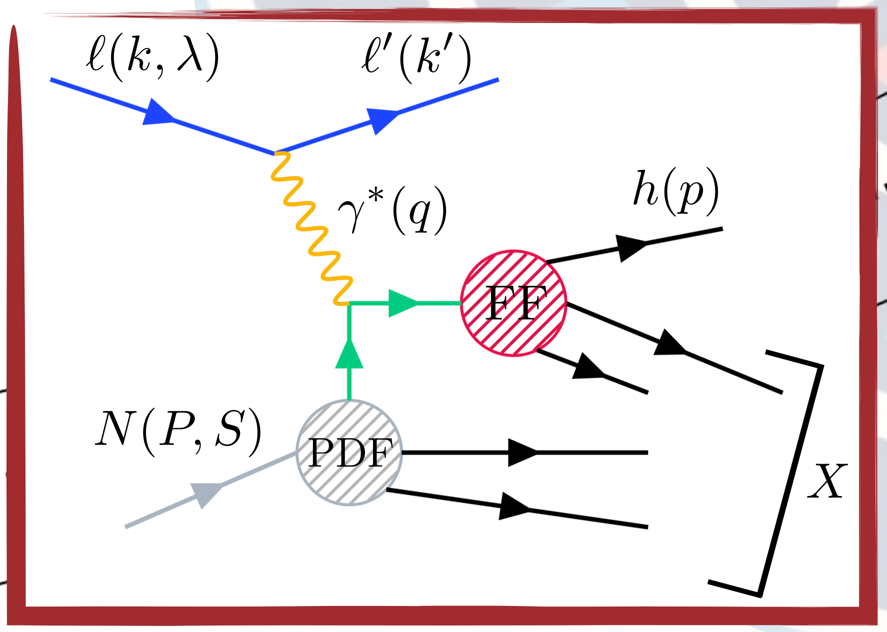
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

NSF

Roadmap of this talk

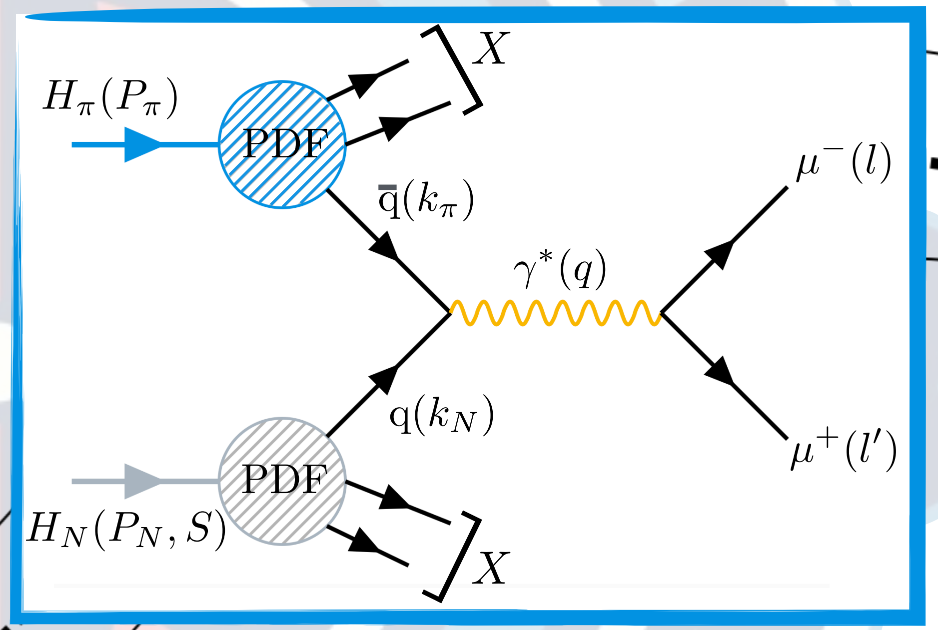


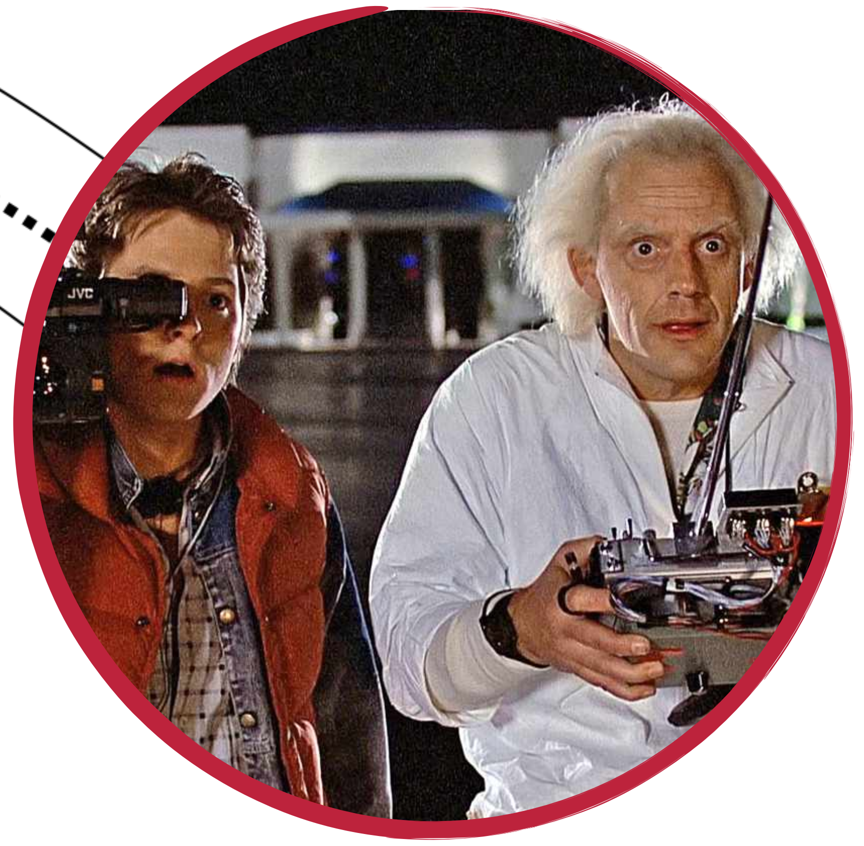
COMPASS & ITS TMD PROGRAM



RECENT COMPASS SIDIS RESULTS

RECENT COMPASS DRELL-YAN RESULTS

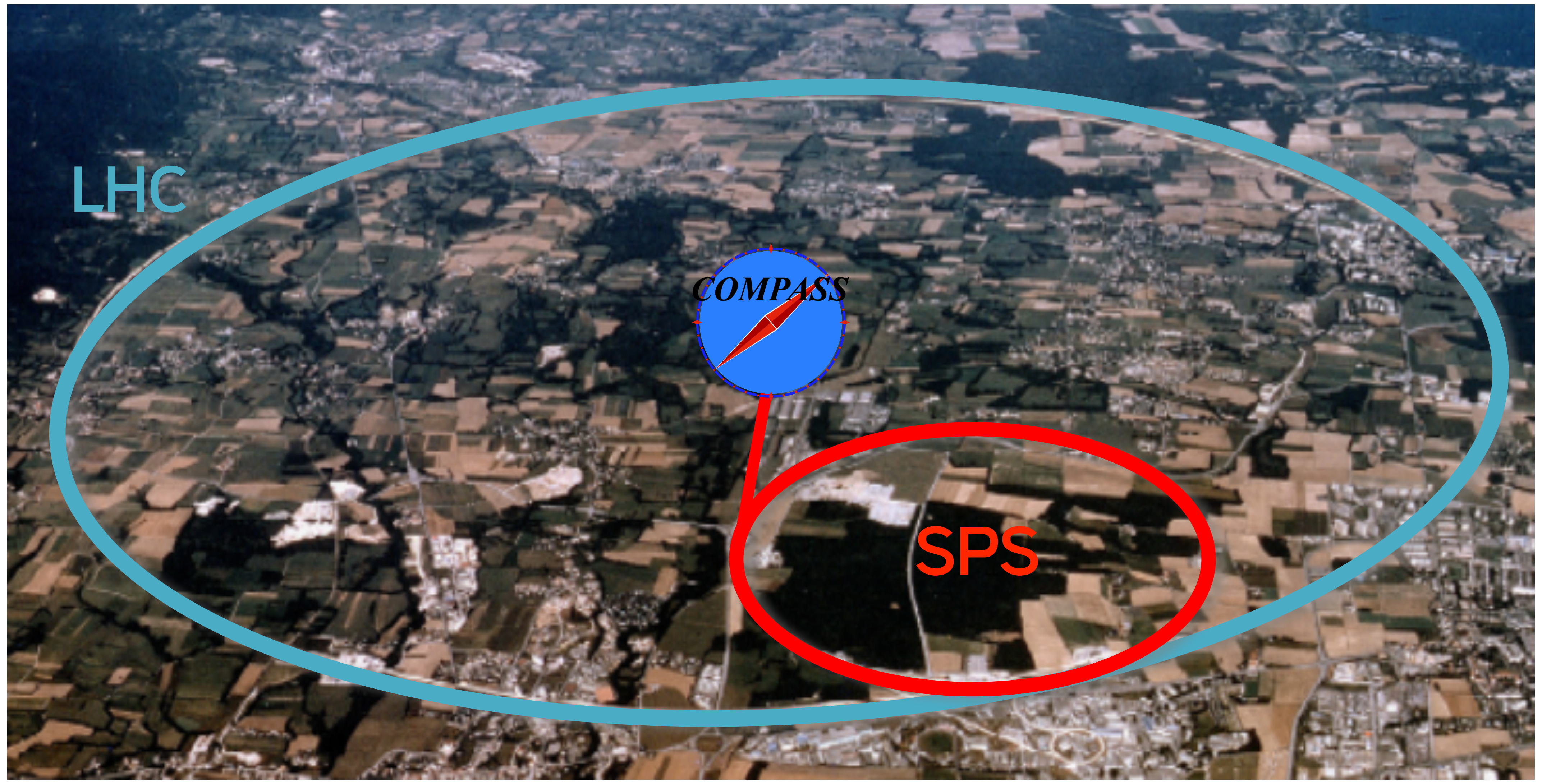




SUMMARY & THE FUTURE

THE COMPASS COLLABORATION

- Fixed target experiment
- CERN SPS North-Area (**M2 beam-line**)
- First data taking in 2002
- 28 institutions from 14 countries
- Broad physics program



COMPASS-I (2002 - 2011)

- Hadron Spectroscopy
- Nucleon spin structure (L/T p/D Targets)

→

COMPASS-II (2012 - 2022)

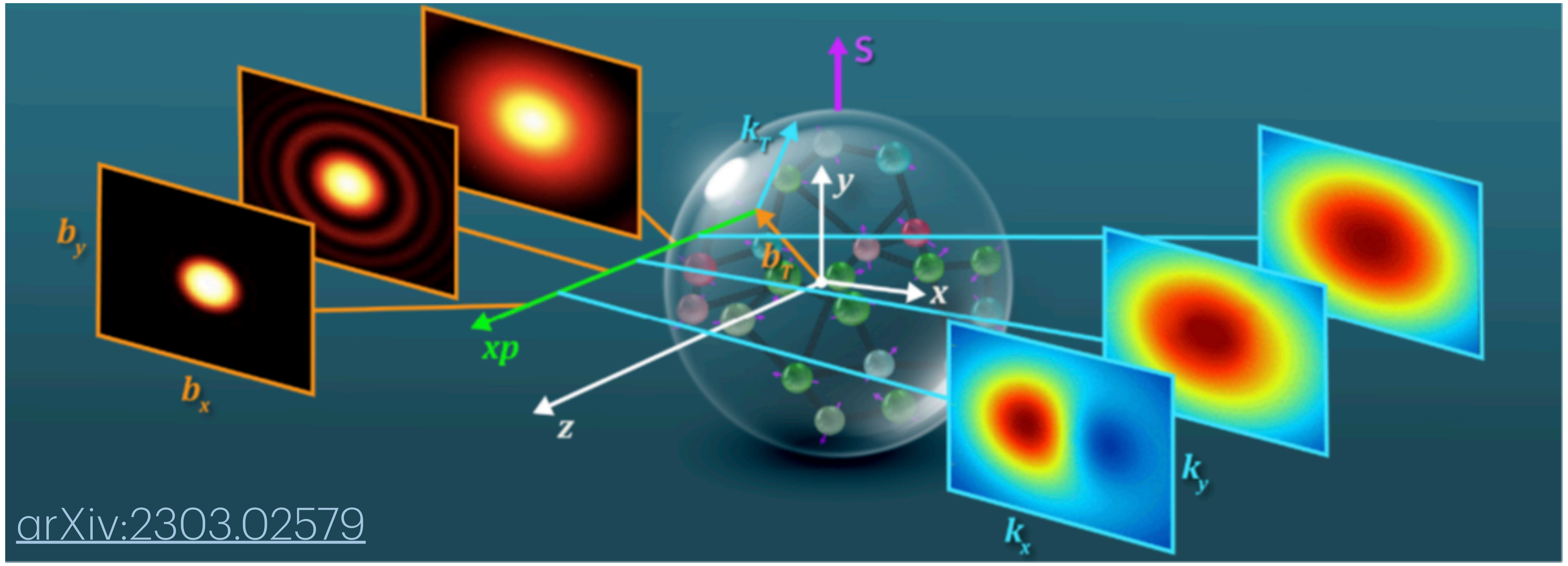
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018)
- DVCS + Unpolarized SIDIS(2016-2017)
- Transversely polarized SIDIS on D target (2022)

→

COMPASS ANALYSIS PHASE (Started in 2023)

HIGHLIGHTS FROM THE TMD PROGRAMME

Generalized Parton Distributions (GPDs)



Transverse Momentum Dependent PDFs (TMDs)

THIS TALK

COMPASS-I (2002 - 2011)

- Hadron Spectroscopy
- Nucleon spin structure (L/T p/D Targets)

→

COMPASS-II (2012 - 2022)

- Primakoff + DVCS pilot run (2012)
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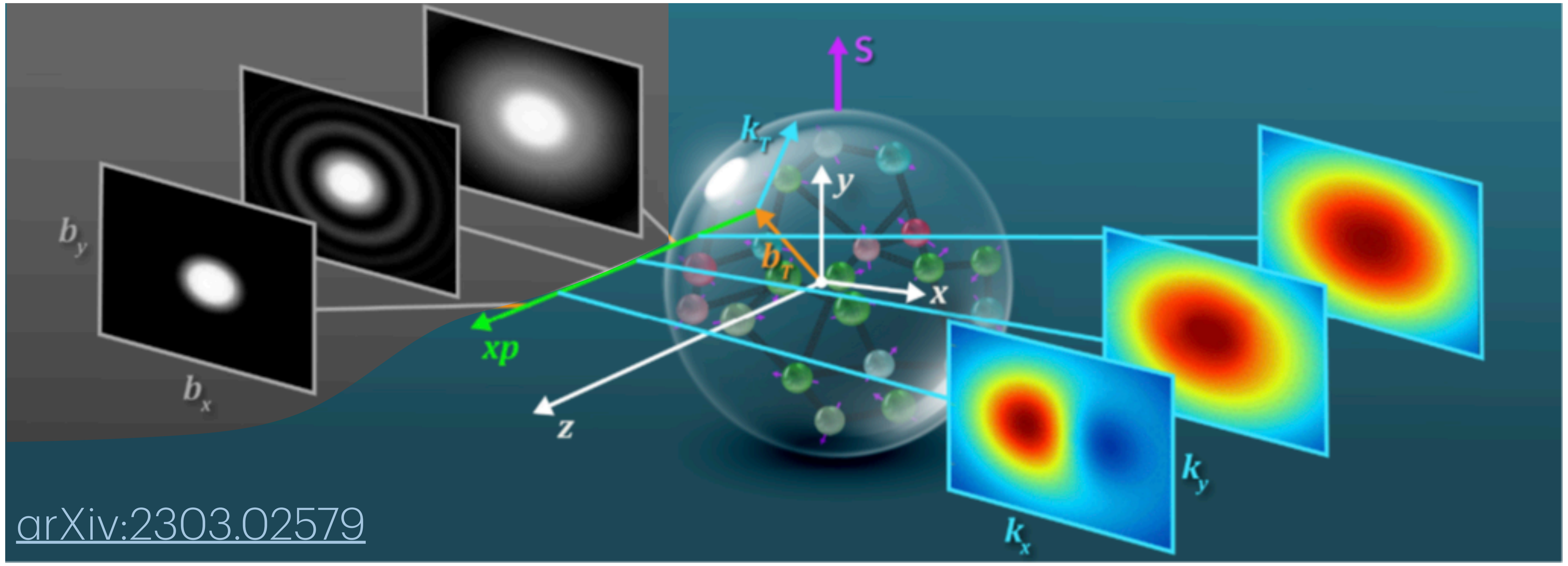
→

COMPASS ANALYSIS PHASE (Started in 2023)

HIGHLIGHTS FROM THE TMD PROGRAMME

Generalized Parton Distributions (GPDs)



Transverse Momentum Dependent PDFs (TMDs)

THIS TALK

COMPASS-I (2002 - 2011)
- Hadron Spectroscopy
- **Nucleon spin structure (L/T p/D Targets)**

→

COMPASS-II (2012 - 2022)
- Primakoff + DVCS pilot run (2012)
- **Drell-Yan (2015, 2018)**
- DVCS + **Unpolarized SIDIS(2016-2017)**
- **Transversely polarized SIDIS on D target (2022)**

→

COMPASS ANALYSIS PHASE (Started in 2023)

TRANSVERSE MOMENTUM DEPENDENT PDFS

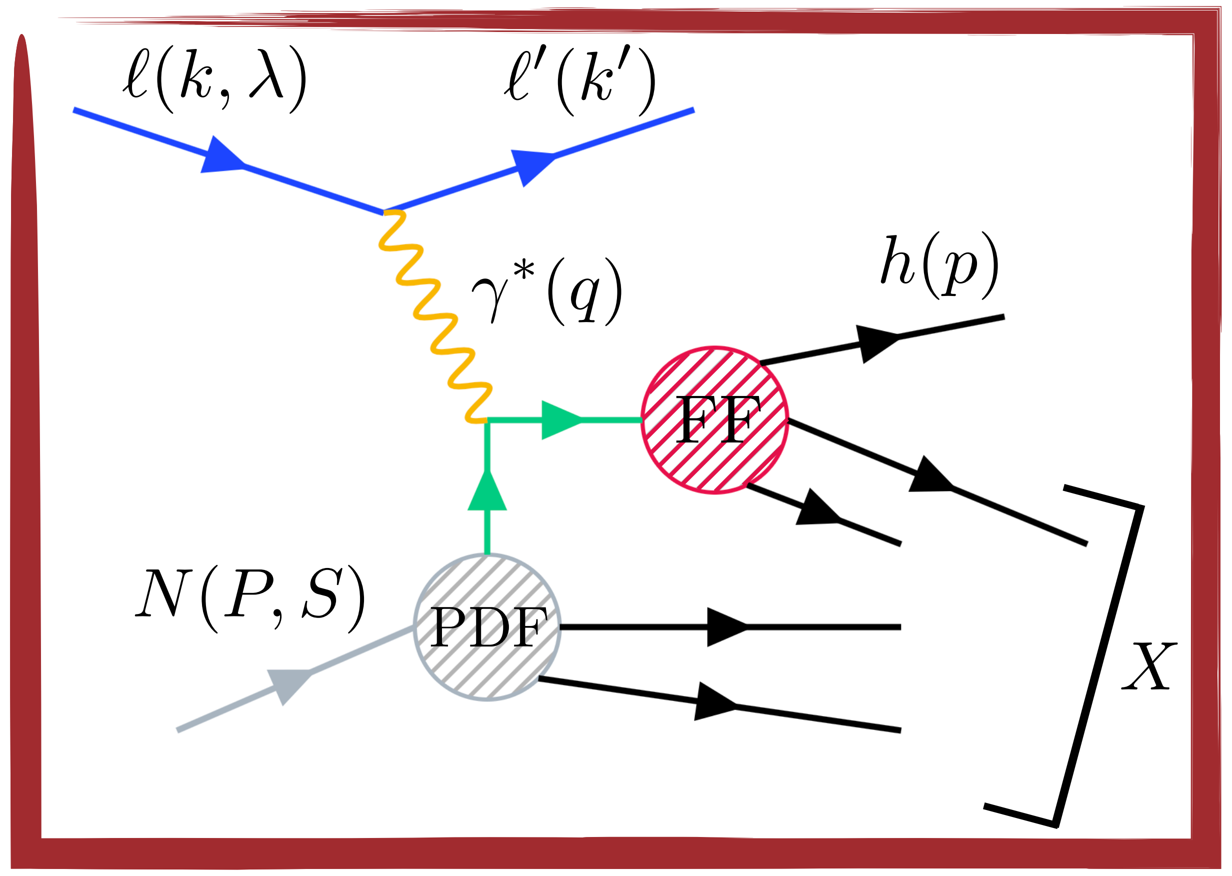
		Nucleon Polarisation		
		U	**L**	**T**
Quark Polarisation	**U**	$f_1^q(x,\mathbf{k_T^2})$ Number Density		$f_{1T}^{q\perp}(x,\mathbf{k_T^2})$ Sivers
	L		$g_1^q(x,\mathbf{k_T^2})$ Helicity	$g_{1T}^q(x,\mathbf{k_T^2})$ Worm-Gear T
	T	$h_1^{q\perp}(x,\mathbf{k_T^2})$ Boer-Mulders	$h_{1L}^{q\perp}(x,\mathbf{k_T^2})$ Worm-Gear L	$h_{1T}^q(x,\mathbf{k_T^2})$ Transversity $h_{1T}^{q\perp}(x,\mathbf{k_T^2})$ Pretzelosity

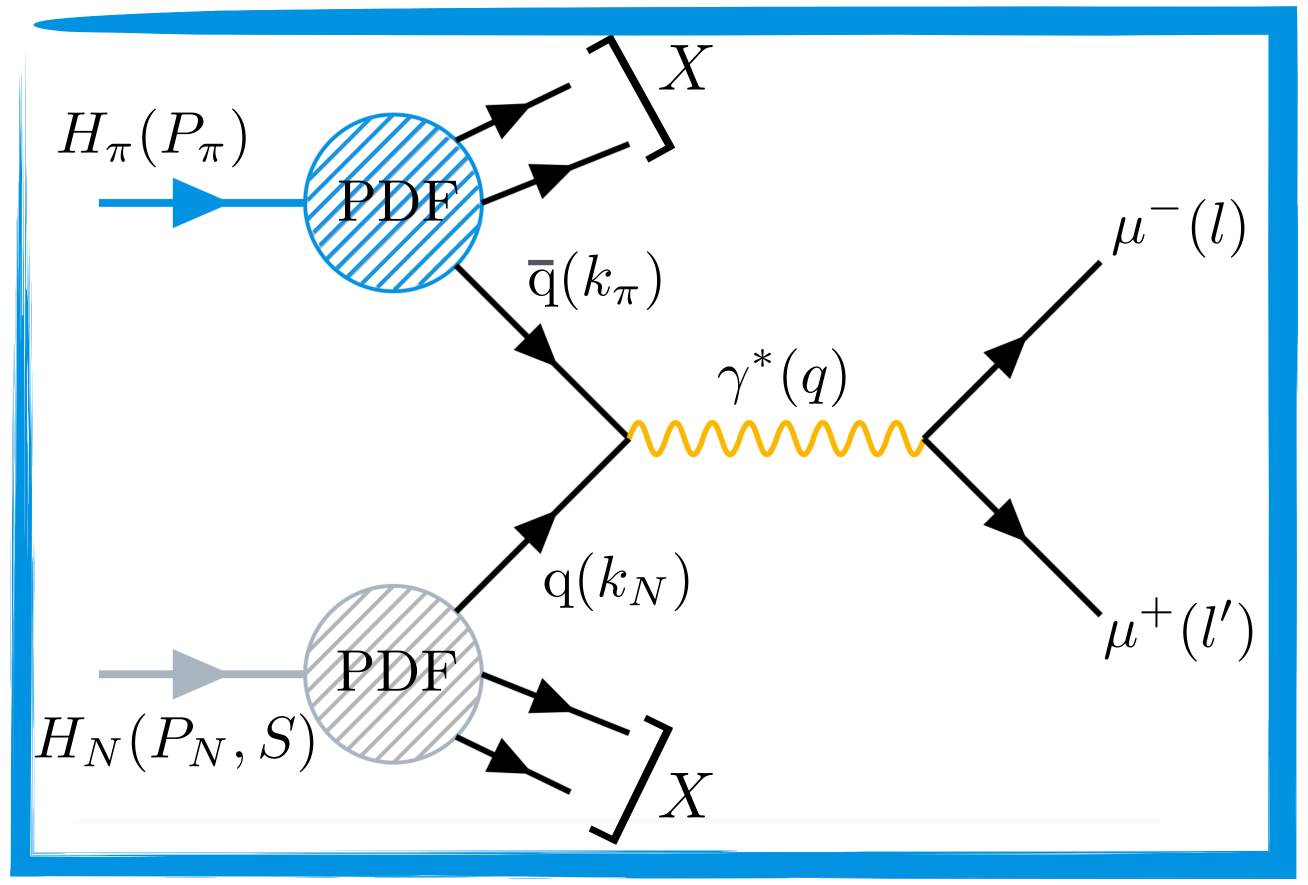
Nucleon · Nucleon spin · quark · quark spin · $\mathbf{k_T}$

In the leading order QCD parton model, nucleon spin-structure can be parametrized in terms of **8 twist-2** quark intrinsic transverse momentum (k_T) dependent **TMD PDFs.**

TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in

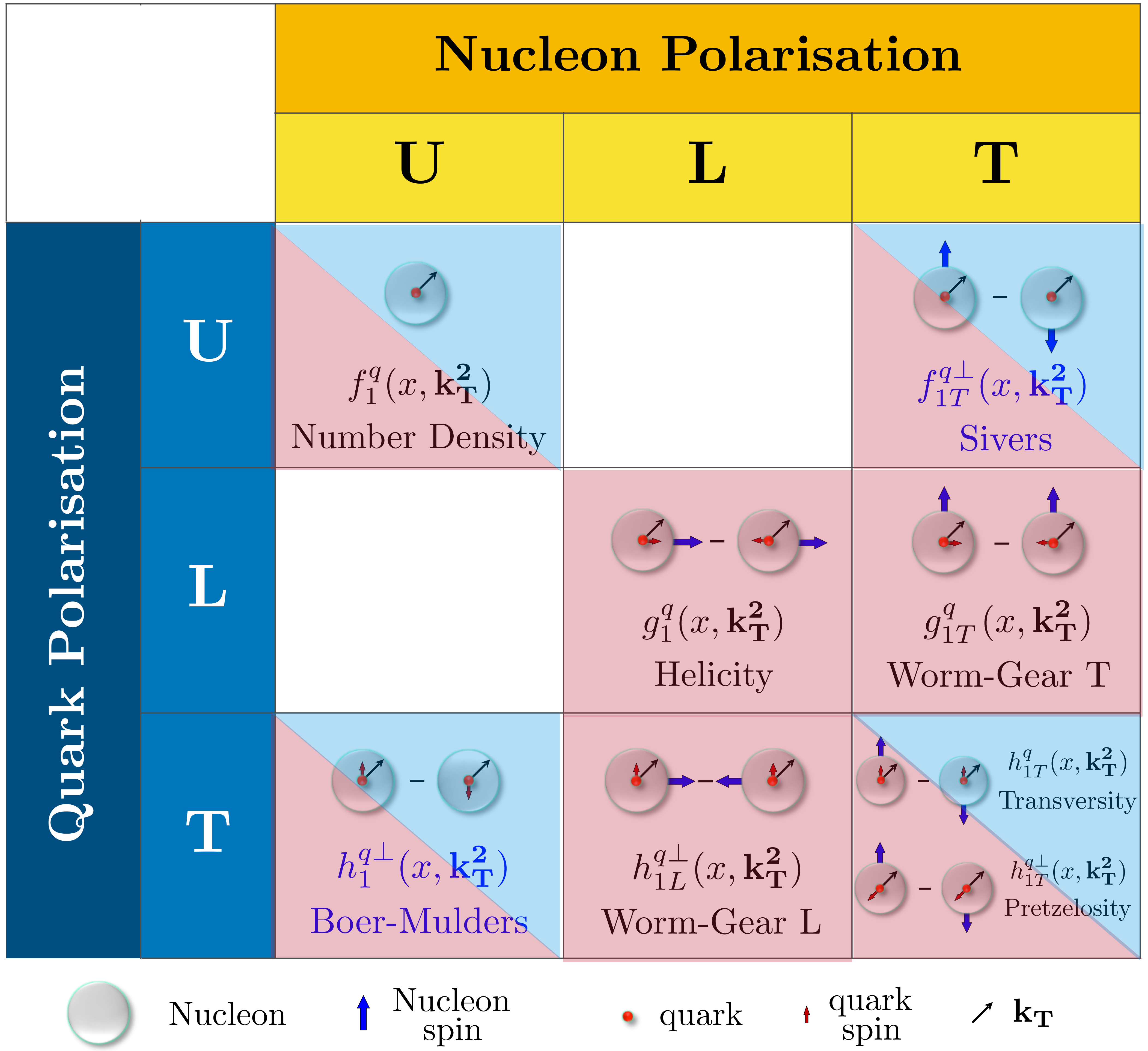
SIDIS and **Drell-Yan**





See talk by M.Radici & J.Qiu (Tuesday Morning)

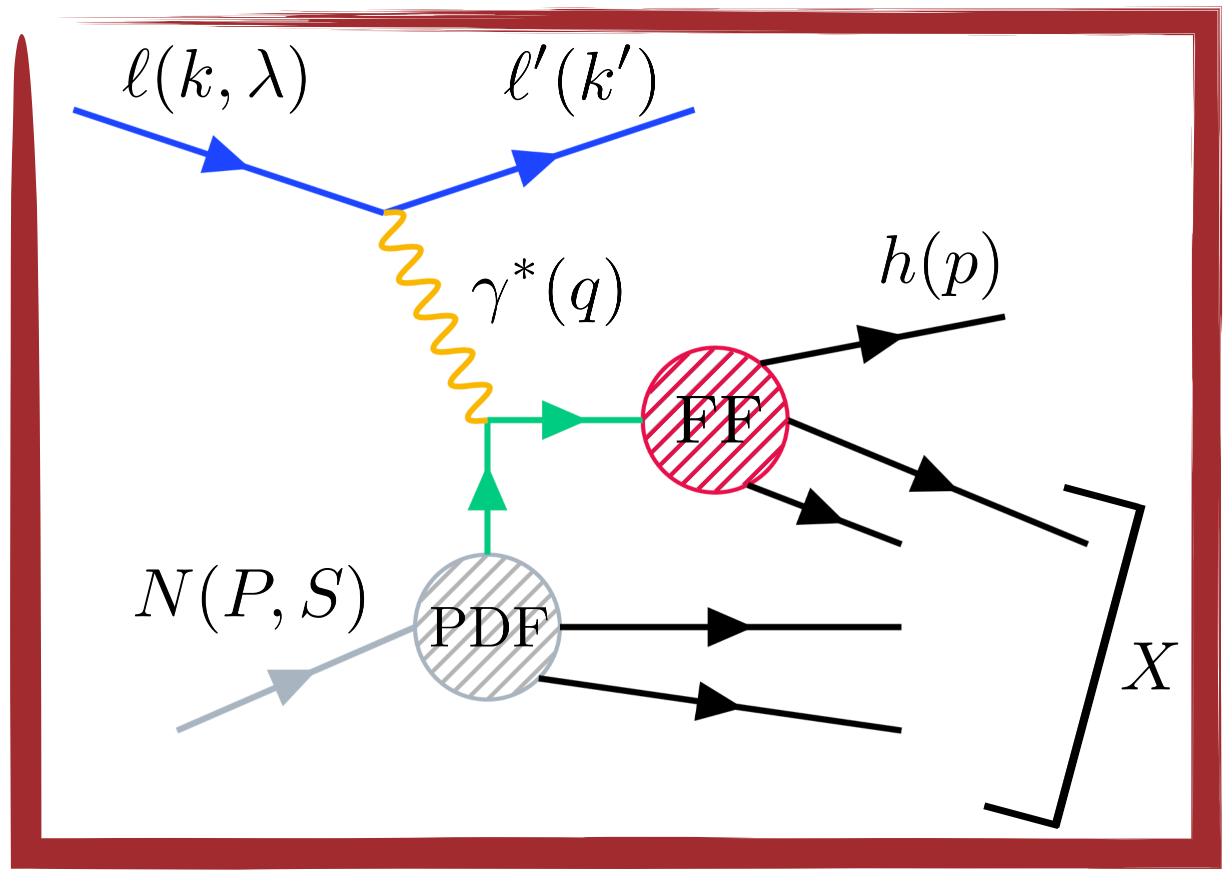
TRANSVERSE MOMENTUM DEPENDENT PDFs @ COMPASS

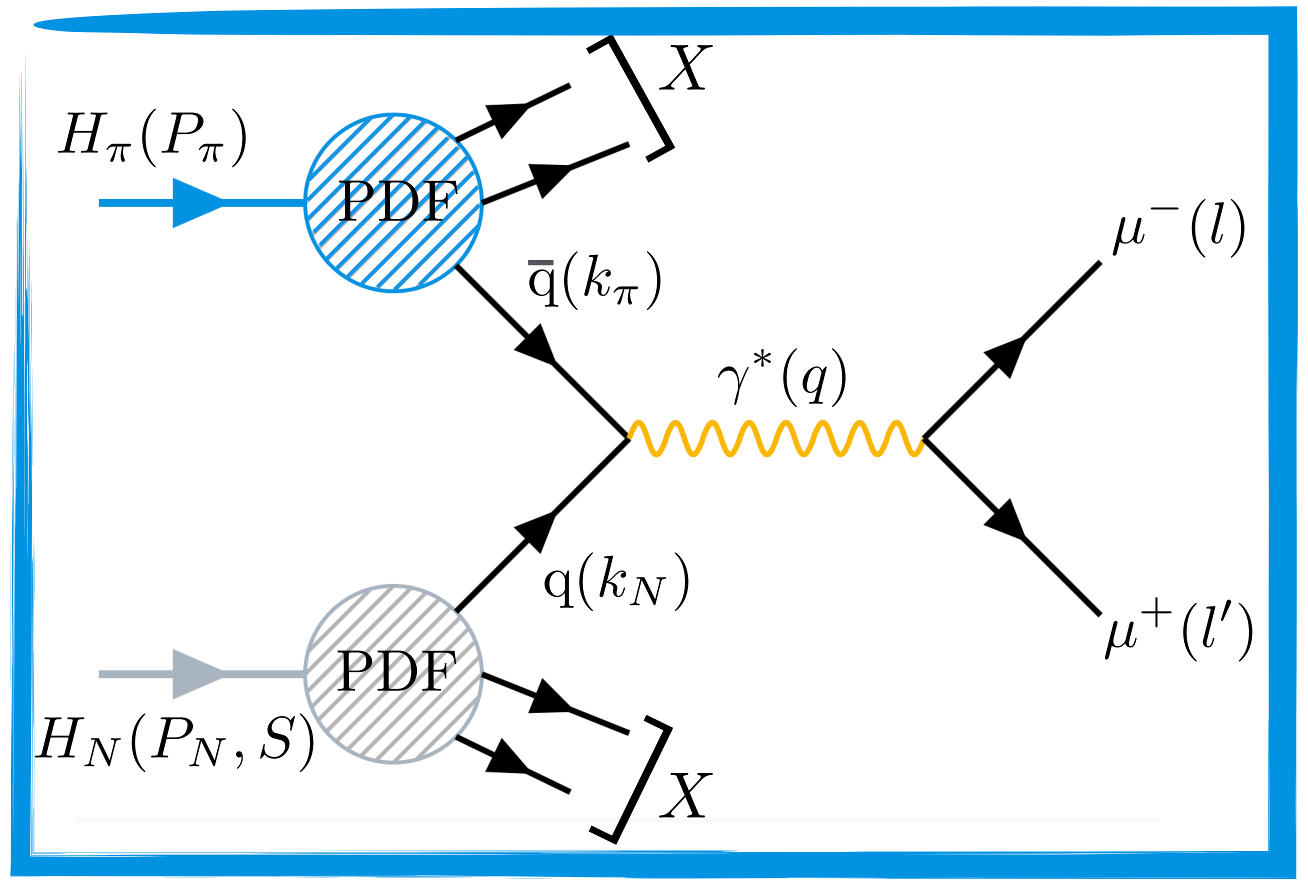


Both processes measured at COMPASS!

Experimental access to all TMD PDFs via different channels

SIDIS and **Drell-Yan**

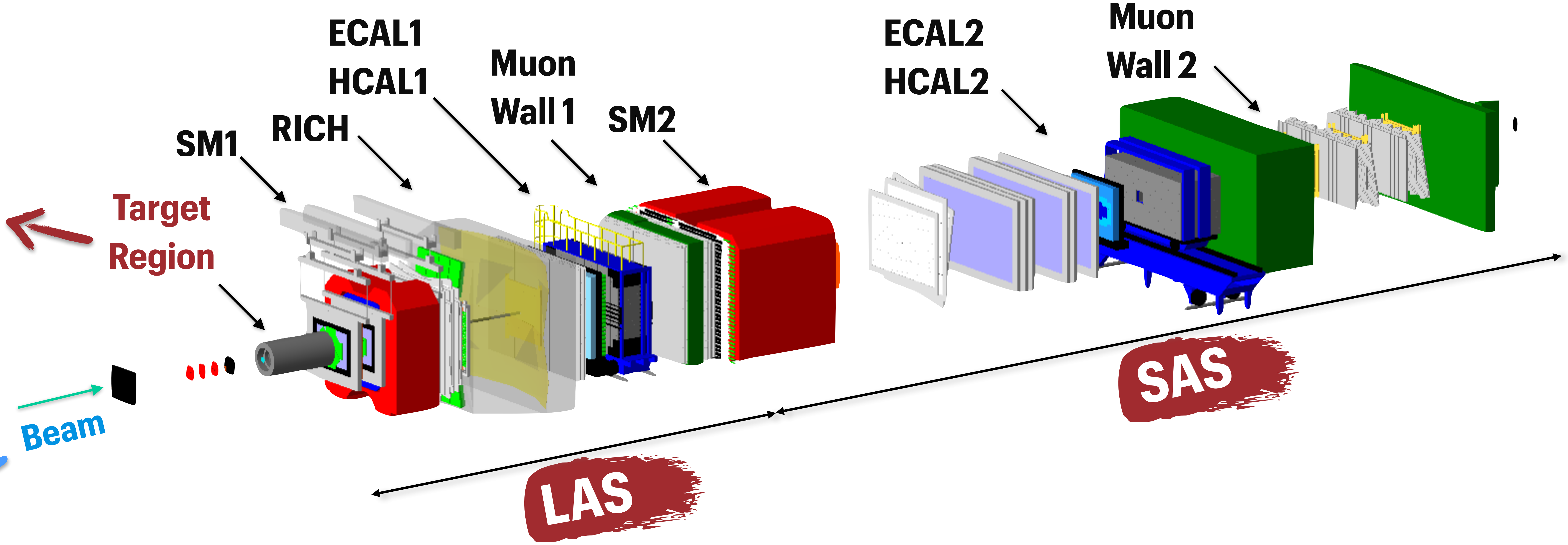




See talk by
M.Radici & J.Qiu
(Tuesday Morning)

COMPASS SETUP

- Different targets available:
  - Polarized Solid state NH_3 or ^6LiD
  - Unpolarized Liquid H_2
  - Unpolarized solid-state nuclear targets (e.g. Ni, W, Pb)



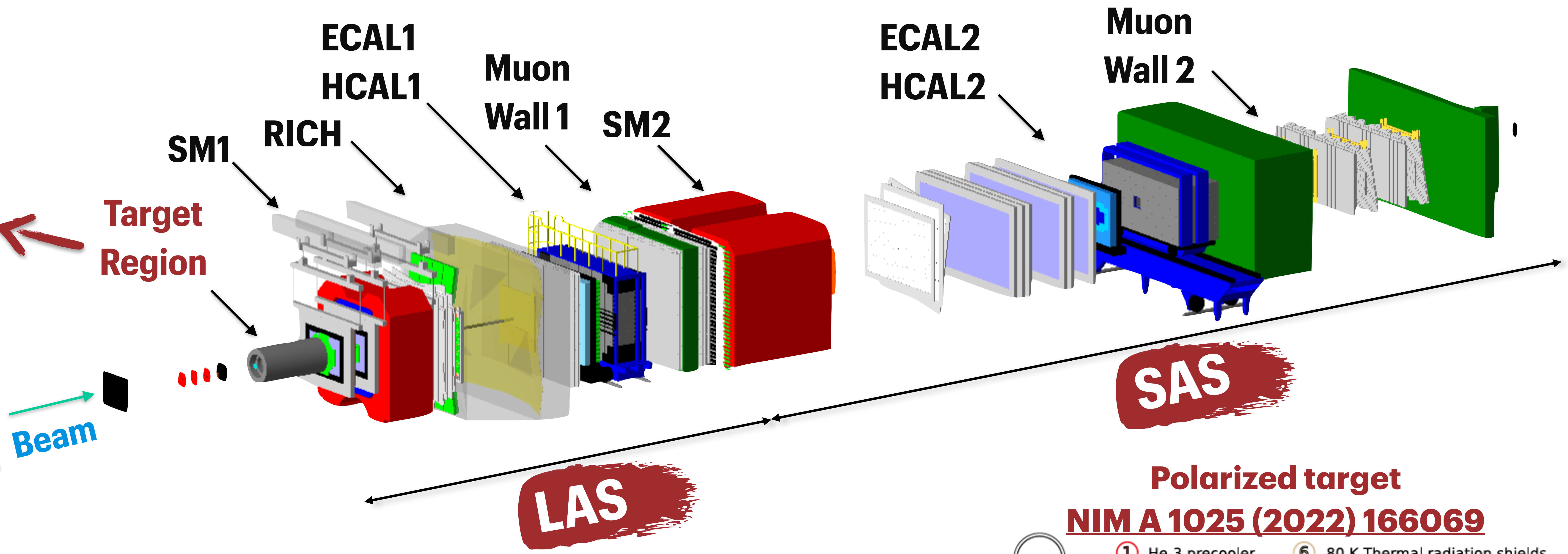
- 400 GeV p primary SPS beam impinging on Be production target
  - 190 GeV secondary hadron beams
    - h^- beam: 97% π^-, 2% K^-, 1% $\bar{p}$
    - h^+ beam: 75% π^+, 24% p, 2% K^+
  - 160 GeV tertiary $\mu^\pm$ beams longitudinally polarized

HIGH VERSATILITY!

- **Two-stage** forward spectrometer
  - Large Angle Spectrometer (LAS), Θ up to ±180 mrad
  - Small Angle Spectrometer (SAS), Θ up to ±30 mrad
- High **tracking power**: ~350 planes (GEMs, SciFis, DCs, MWPCs, MicroMegas, Straws);
- PID via RICH, Calorimetric measurements, Muon Walls;

COMPASS SETUP: PHASE II - SIDIS

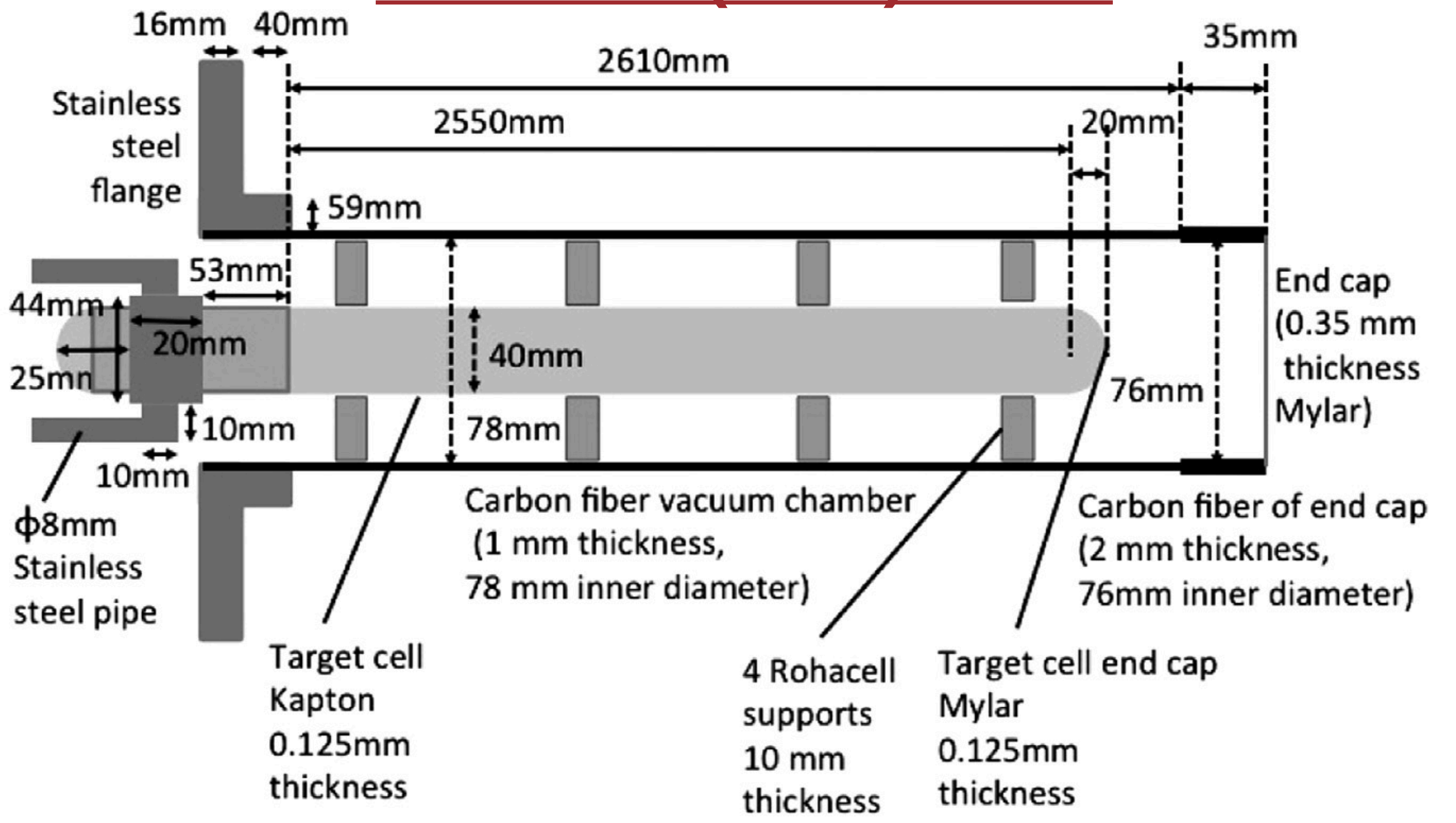
- Different targets available:
  - Polarized Solid state NH_3 or **^{6}LiD (2022)**
  - Unpolarized Liquid **H_2** **(2016)**
  - Unpolarized solid-state nuclear targets (e.g. Ni, W, Pb)



- 400 GeV p primary SPS beam impinging on Be production target
  - 190 GeV secondary hadron beams
    - h^- beam: 97% π^-, 2% K^-, 1% $\bar{p}$
    - h^+ beam: 75% π^+, 24% p, 2% K^+
  - 160 GeV tertiary $\mu^\pm$ beams longitudinally polarized

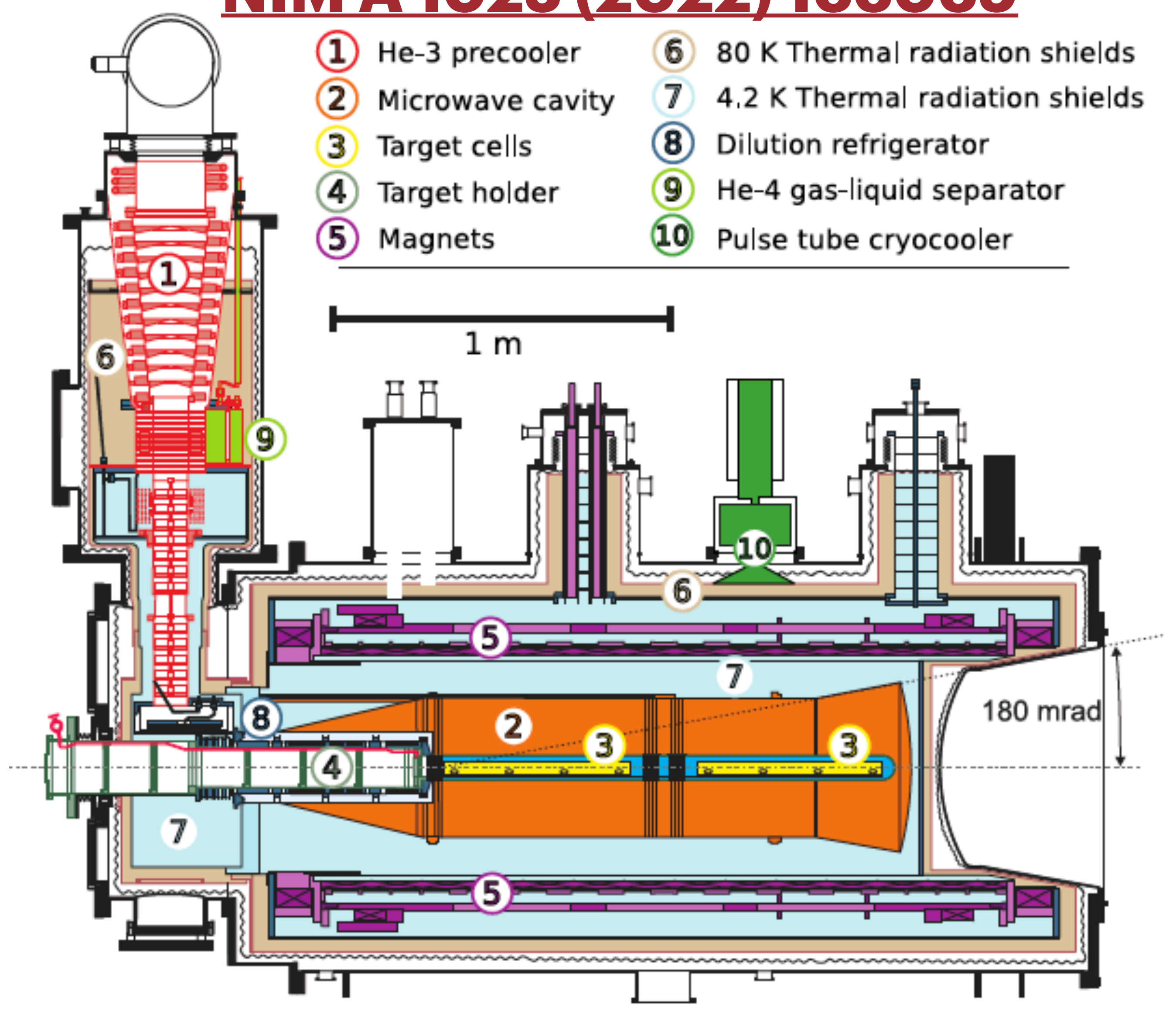
2.5 m long liquid H2 target

NIM A 746 (2014) 20–25



Polarized target

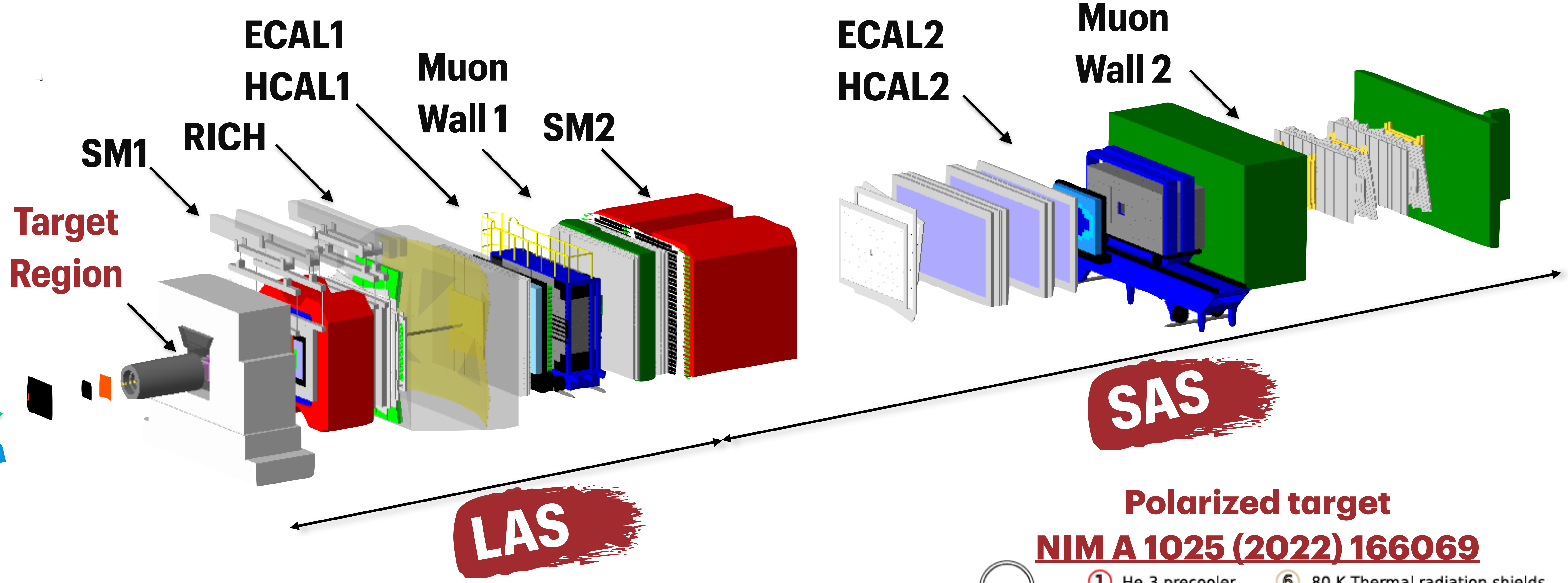
NIM A 1025 (2022) 166069



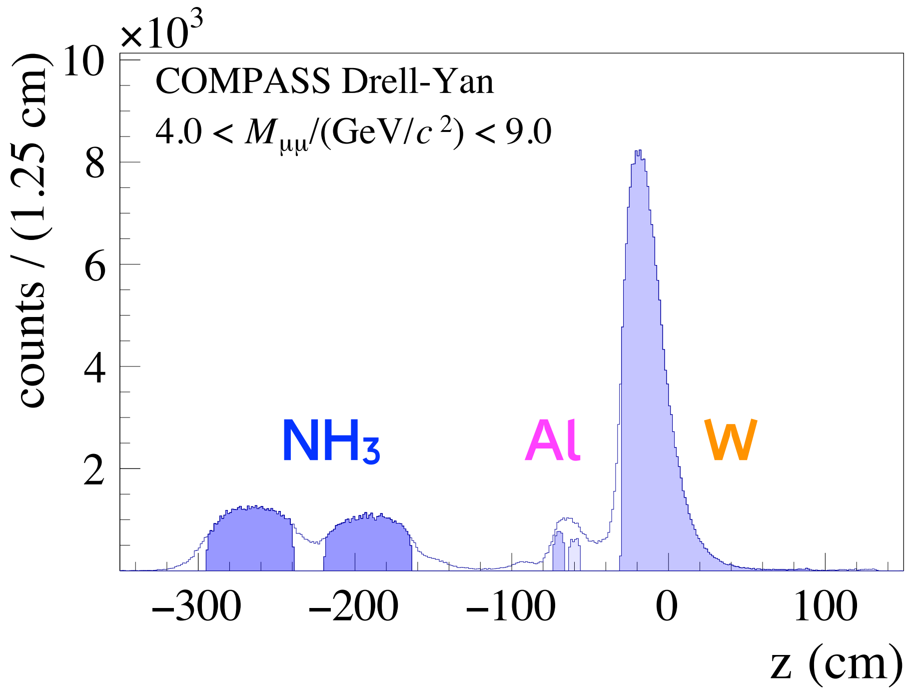
3-cells configuration

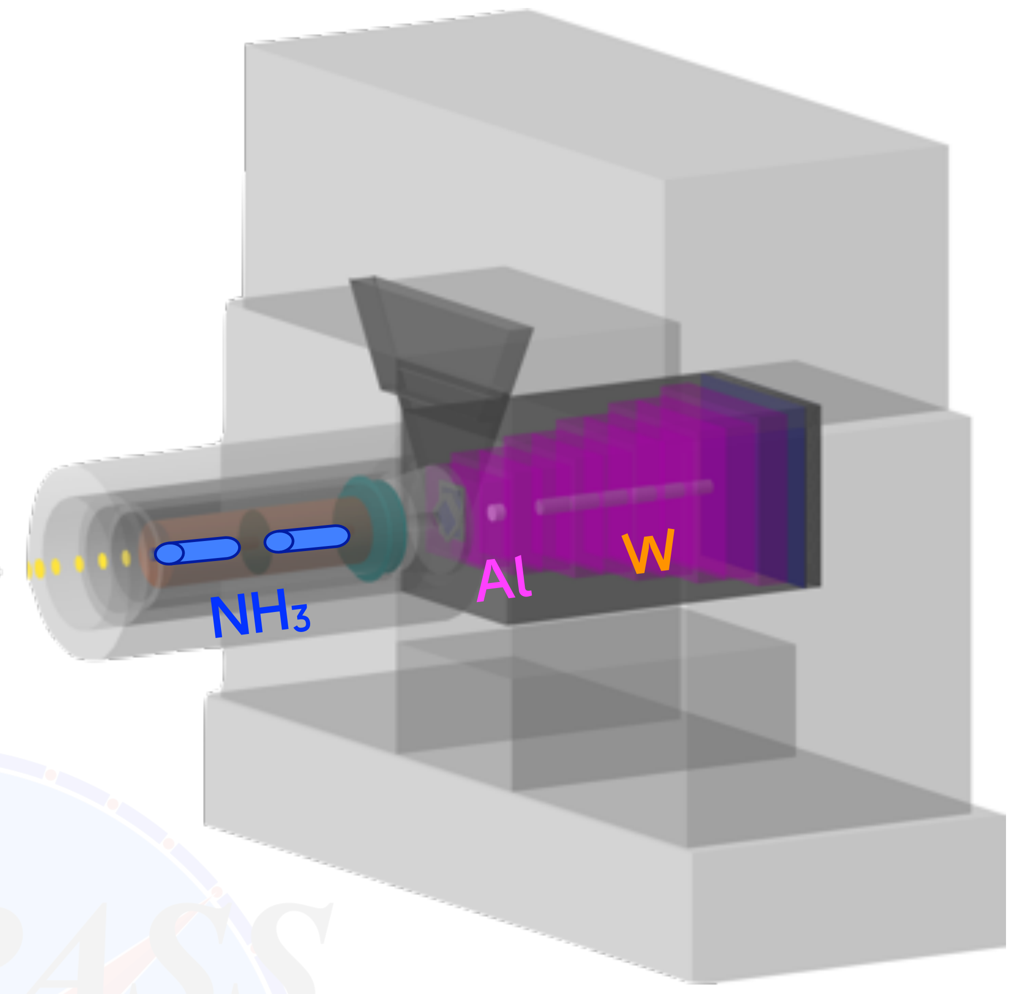
COMPASS SETUP: PHASE II - DRELL-YAN

- Different targets available:
  - Polarized Solid state NH_3 **(2015 + 2018)**
  - Unpolarized Liquid H_2
  - Unpolarized solid-state nuclear targets (e.g. Ni, W, Pb)



- 400 GeV p primary SPS beam impinging on Be production target
  - 190 GeV secondary hadron beams
    - h^- beam: 97% π^-, 2% K^-, 1% $\bar{p}$
    - h^+ beam: 75% π^+, 24% p, 2% K^+
  - 160 GeV tertiary $\mu^\pm$ beams longitudinally polarized

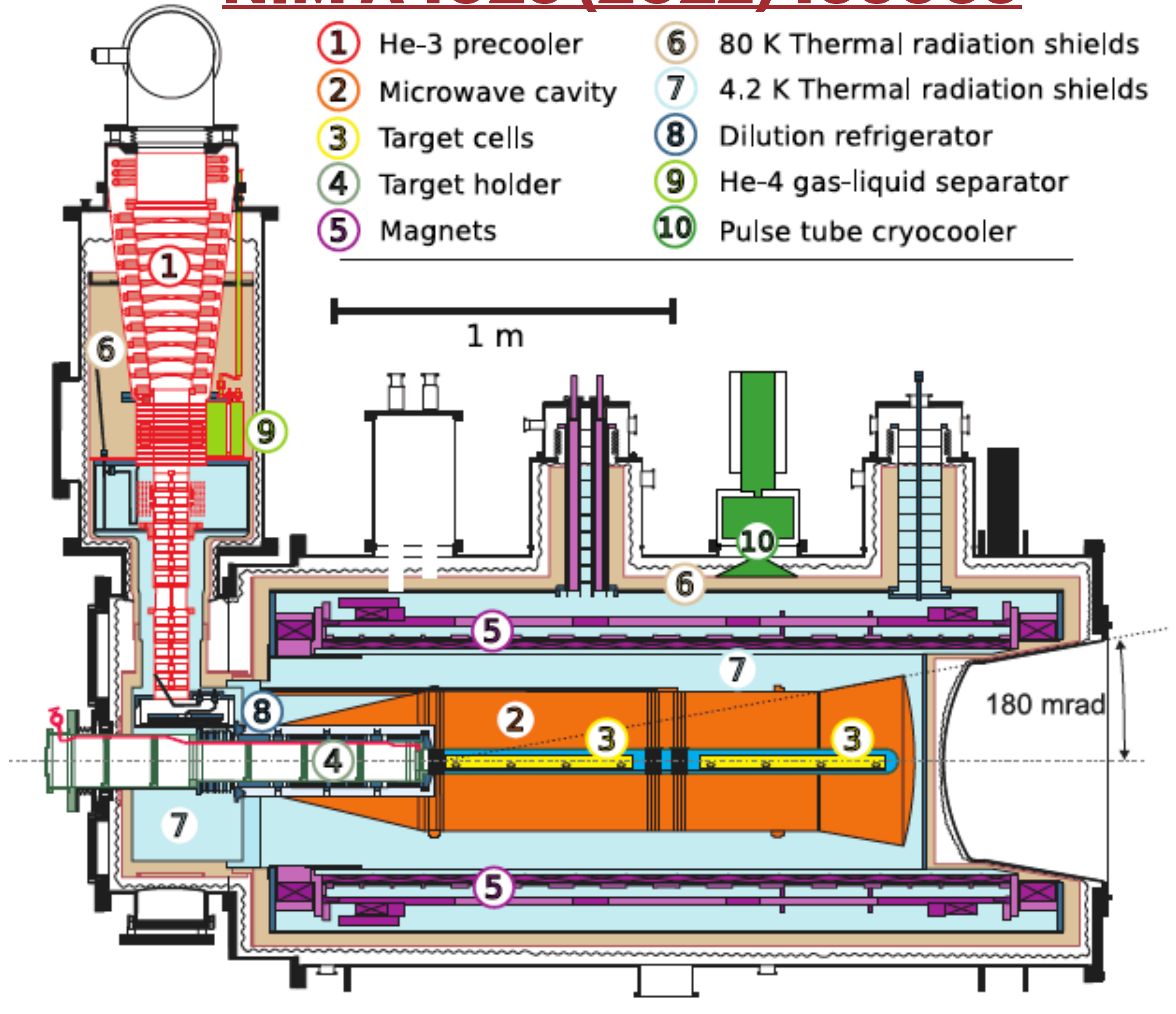




Hadron absorber + Nuclear unpolarized targets (Al, W)

Polarized target

NIM A 1025 (2022) 166069



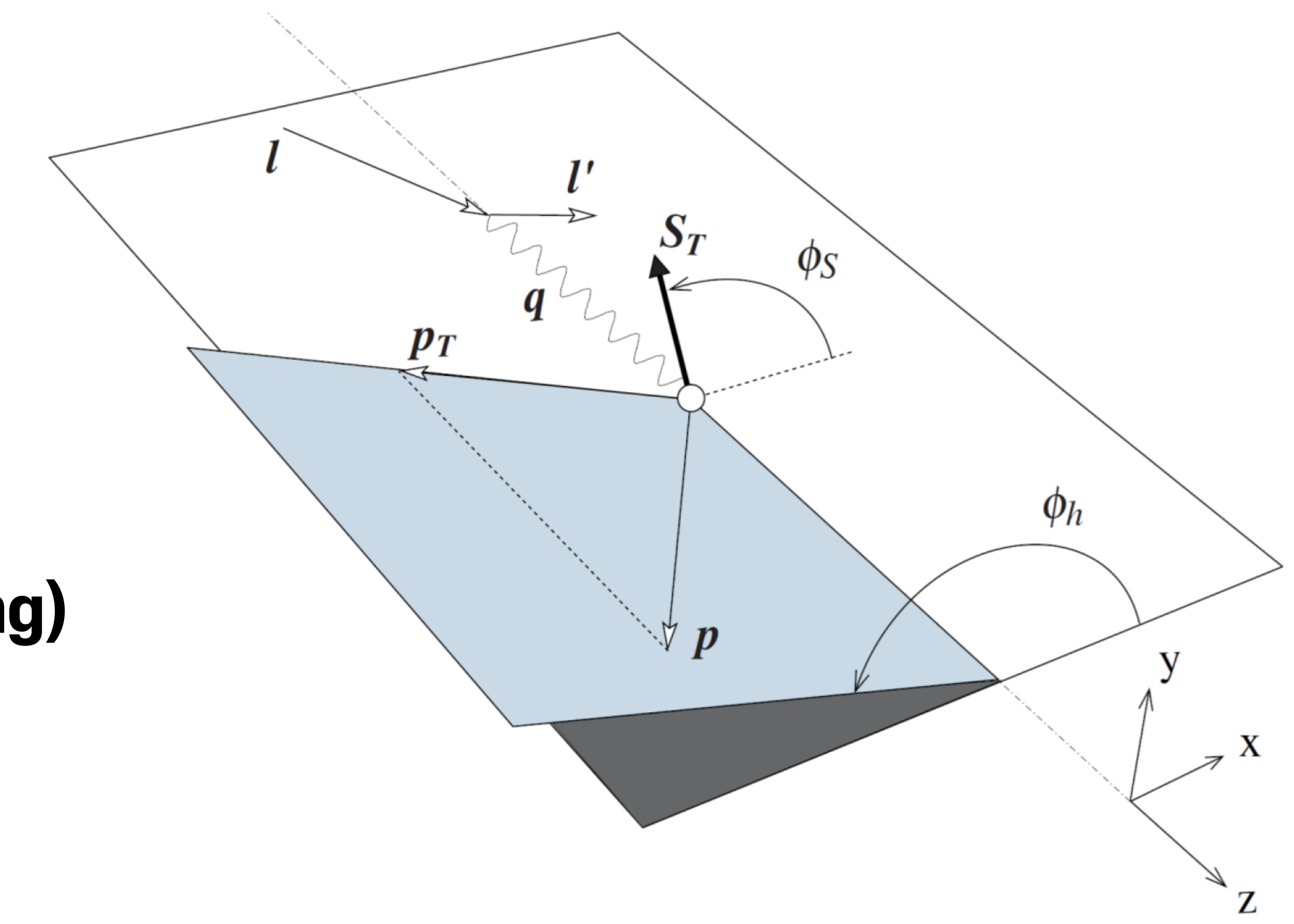
2-cells configuration

SIDIS CROSS-SECTION

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

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

See talk by J.Qiu
(Tuesday Morning)



$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2} \qquad \gamma = \frac{2Mx}{Q}$$

$$A_{X,Y}^{\omega(\phi_h,\phi_S)} = \frac{F_{X,Y}^{\omega(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}} \qquad x = \frac{Q^2}{2P\cdot q}$$

$\lambda \rightarrow$ Beam polarization $\qquad y = 1-\frac{E'}{E}$

Twist-2 **Twist-3**

SIDIS MEASUREMENTS AT COMPASS

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

$$\times\Bigg\{ 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

Unpolarized

Longitudinally polarized

Transversely polarized

Each azimuthal modulation of the SIDIS cross-section gives access to a specific convolution of a TMD PDF of the target proton and a TMD fragmentation function

$$A_{X,Y}^{\omega(\phi_h,\phi_S)} \propto PDF_{\text{Target}} \otimes FF \;\; (+\ldots)$$

All asymmetries measured by COMPASS!

Twist-2 Twist-3

SIDIS MEASUREMENTS AT COMPASS: LEGACY

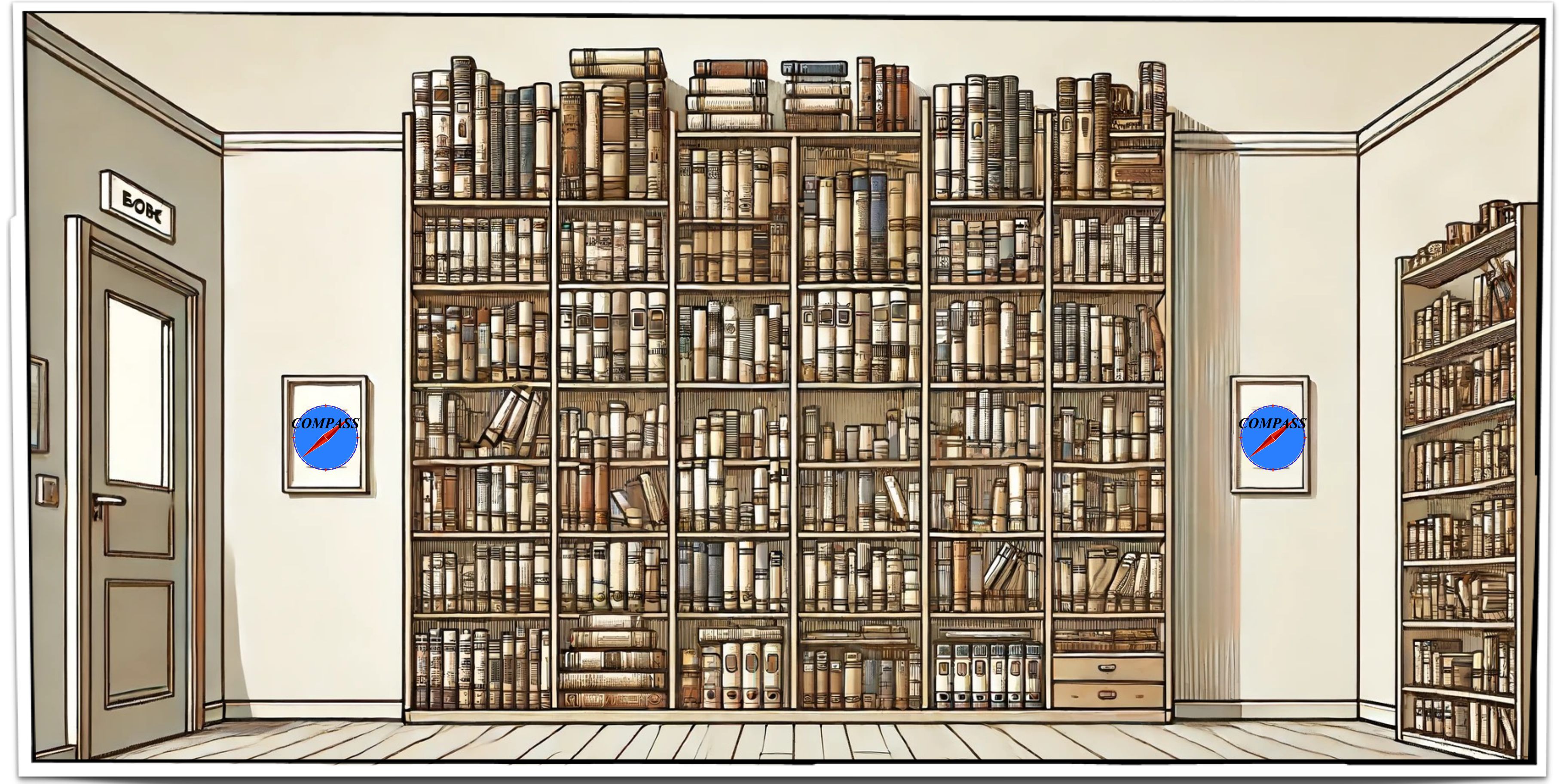
$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

UNPOLARIZED

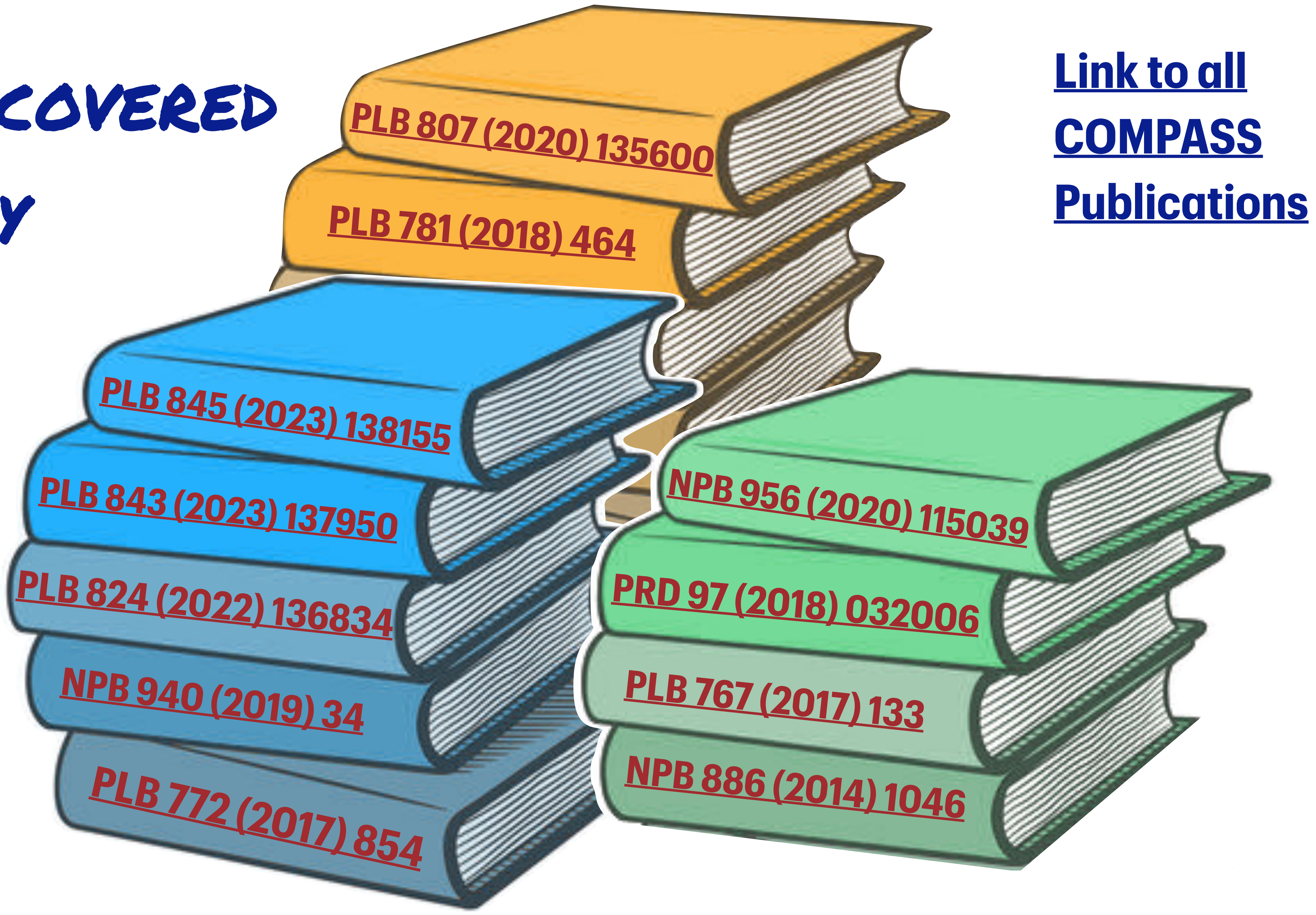
LONGITUDINALLY POLARIZED

TRANSVERSELY POLARIZED

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



NOT COVERED TODAY



[Link to all COMPASS Publications]

Twist-2 **Twist-3**

Next: selection of recent results

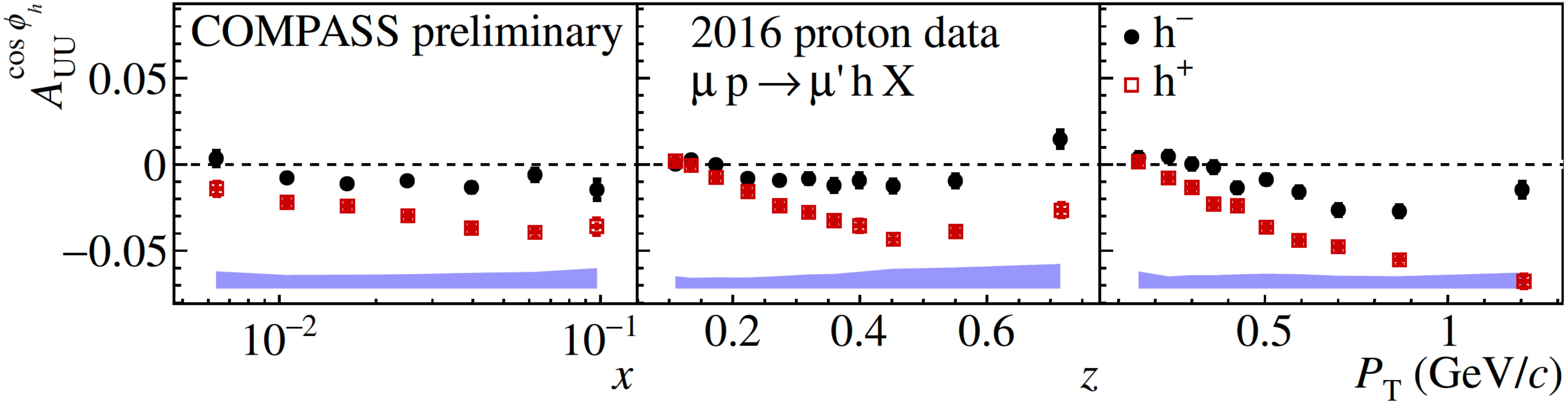
SIDIS UNPOLARIZED MEASUREMENTS: CAHN EFFECT

$$\frac{d\sigma}{dxdydzdP_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

$$A_{UU}^{\cos\phi_h} \leftrightarrow F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M_h}\left[xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{D_q^{\perp h}}{z}\right]-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M}\left[xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{Z}\right]\right\}$$

Cahn effect (1978): non-zero k_T induces an azimuthal modulation

New - presented at DIS 2024



See talk by L.Gamberg
(Tuesday Afternoon)

- Complex structure function - different contributions from twist-2 and twist-3 functions
- Several corrections: (acceptance effects, **diffractively produced vector mesons**, **radiative corrections**, etc...)

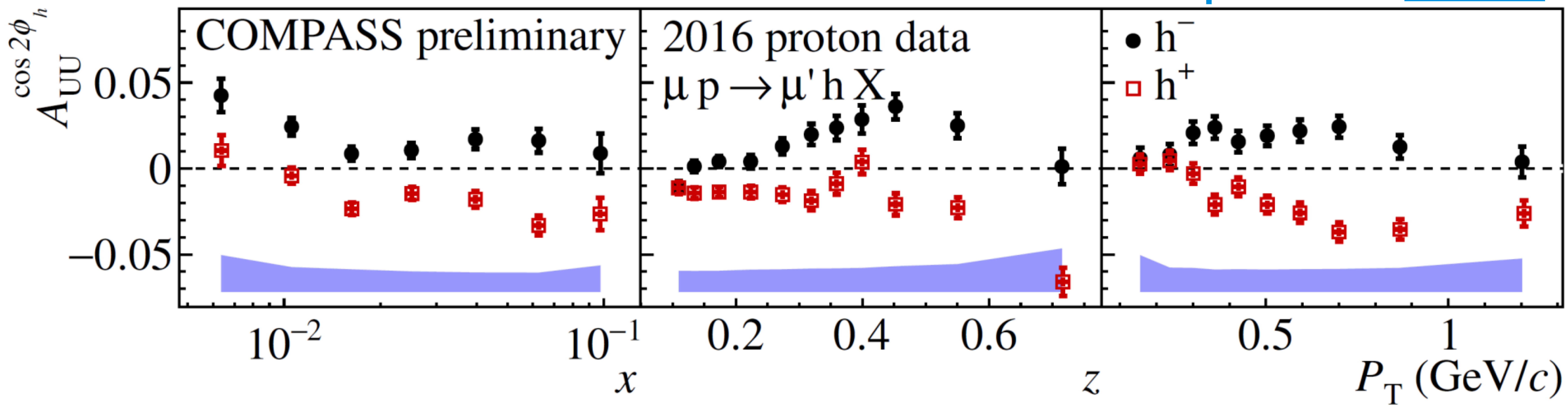
SIDIS UNPOLARIZED MEASUREMENTS: BOER-MULDERS EFFECT

$$\frac{d\sigma}{dxdydzdP_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\dots\right)$$

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q}\otimes H_{1q}^{\perp h} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h + \dots$$

Receives contribution from Boer-Mulders effect and from twist-4 Cahn effect

New - presented at DIS 2024



Same corrections as applied for $A_{UU}^{\cos\phi_h}$

Collins-like behavior (h⁺h⁻ mirror symmetry)?

SIDIS TRANSVERSELY POLARIZED MEASUREMENTS

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

Twist-2

Twist-3

Unpolarized

$$\times\Big\{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h$$
$$+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

Longitudinally polarized

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

Transversely polarized

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

$$+S_T\lambda\left\{\begin{array}{l}\sqrt{1-\varepsilon^2}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{array}\right\}\Big\}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)}\propto f_{1T}^{\perp q}\otimes D_{1q}^h$$
$$A_{UT}^{\sin(\phi_h+\phi_s)}\propto h_1^q\otimes H_{1q}^{\perp h}$$
$$A_{UT}^{\sin(3\phi_h-\phi_s)}\propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$$
$$A_{UT}^{\sin(\phi_s)}\overset{WW}{\propto} Q^{-1}\left(h_1^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h+\dots\right)$$
$$A_{UT}^{\sin(2\phi_h-\phi_s)}\overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h+\dots\right)$$
$$A_{LT}^{\cos(\phi_h-\phi_s)}\propto g_{1T}^q\otimes D_{1q}^h$$
$$A_{LT}^{\cos(\phi_s)}\overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\dots\right)$$
$$A_{LT}^{\cos(2\phi_h-\phi_s)}\overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\dots\right)$$

SIDIS TRANSVERSELY POLARIZED MEASUREMENTS

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

Unpolarized

$$\times\Big\{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h +\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

Longitudinally polarized

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

Transversely polarized

$$+S_T\left\{\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{array}\right\} +S_T\lambda\left\{\begin{array}{l}\sqrt{1-\varepsilon^2}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S\\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{array}\right\}\Big\}$$

Twist-2 **Twist-3**

THIS TALK

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

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

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

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

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

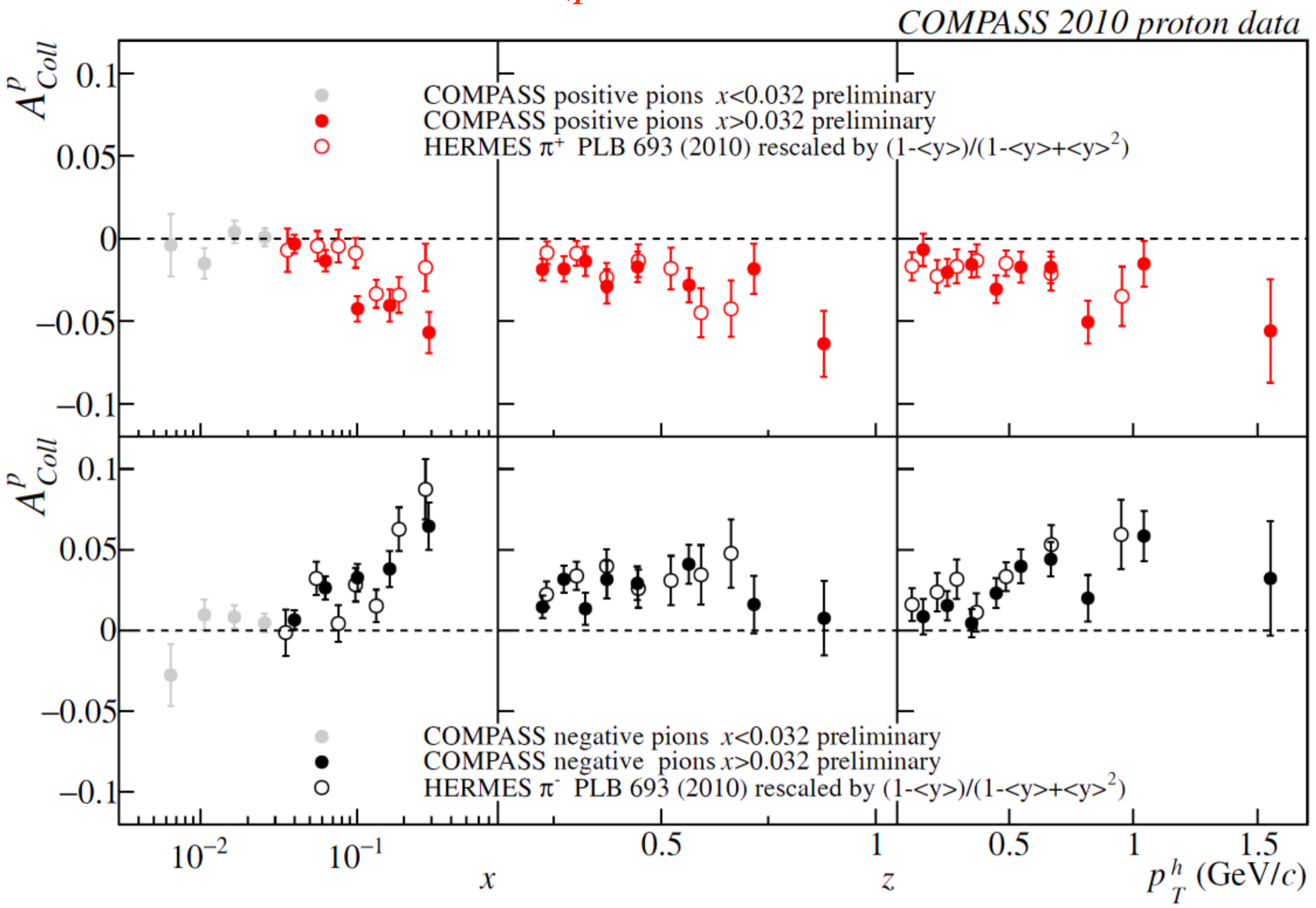
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q\otimes D_{1q}^h$

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

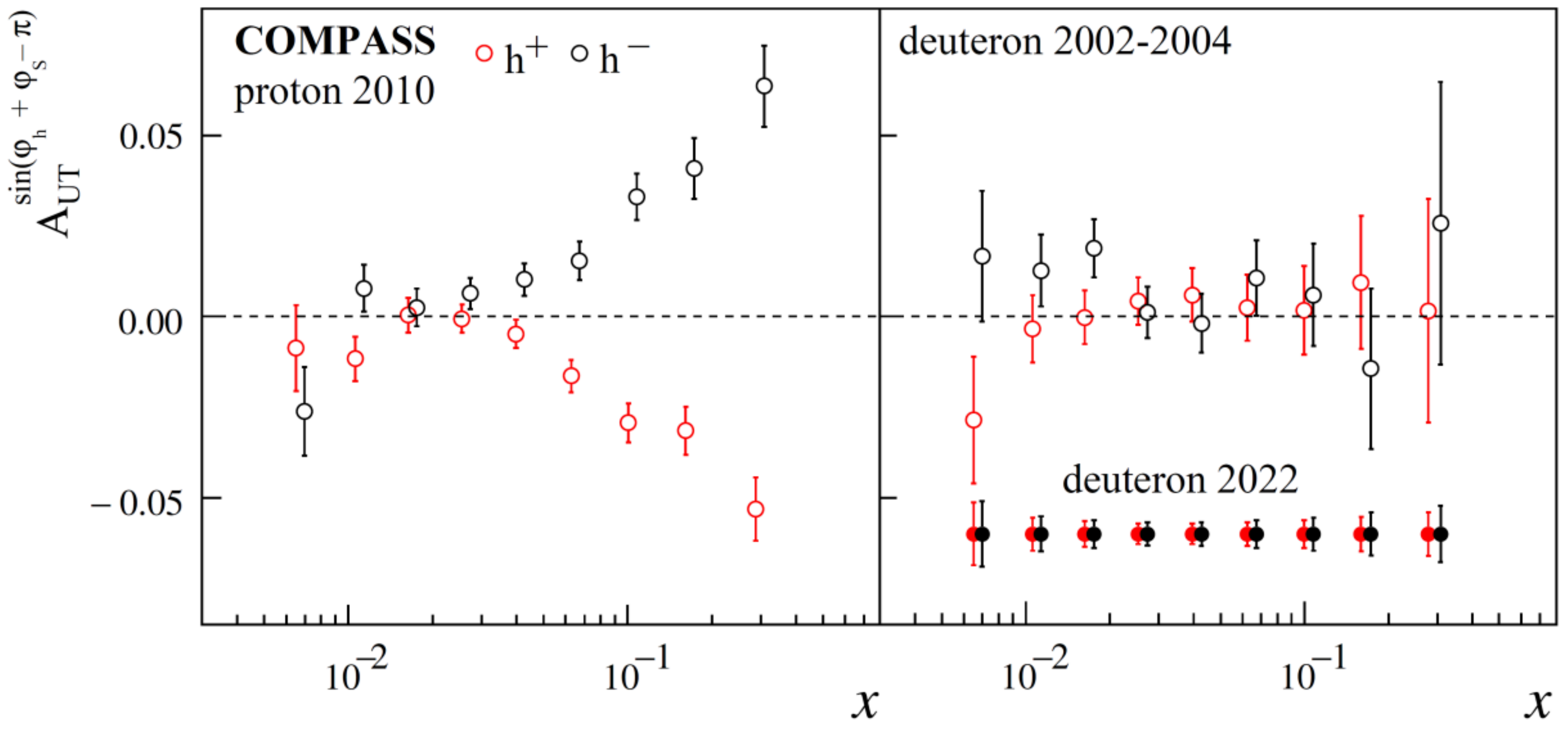
$A_{LT}^{\cos(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\dots\right)$

SIDIS POLARIZED MEASUREMENTS: COLLINS EFFECT

$A_{UT}^{\sin(\phi_h+\phi_S-\pi)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$ → Measured by COMPASS on p/D targets in SIDIS and di-hadron SIDIS



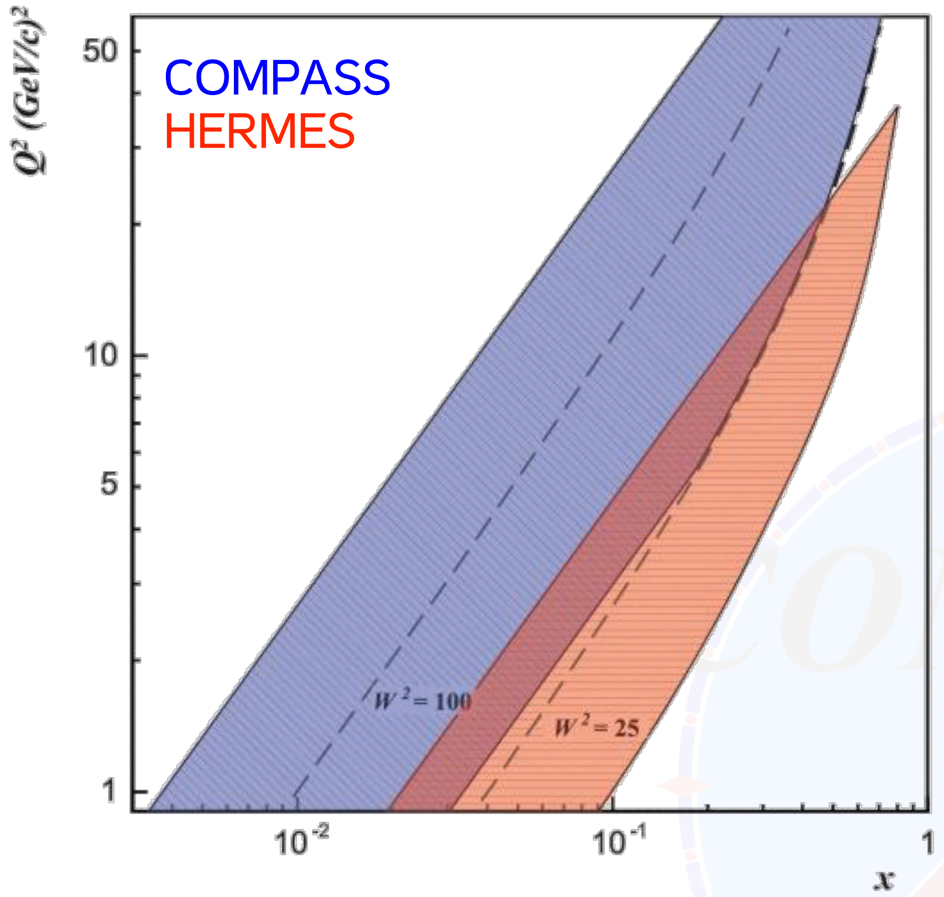
PLB 744 (2015) 250

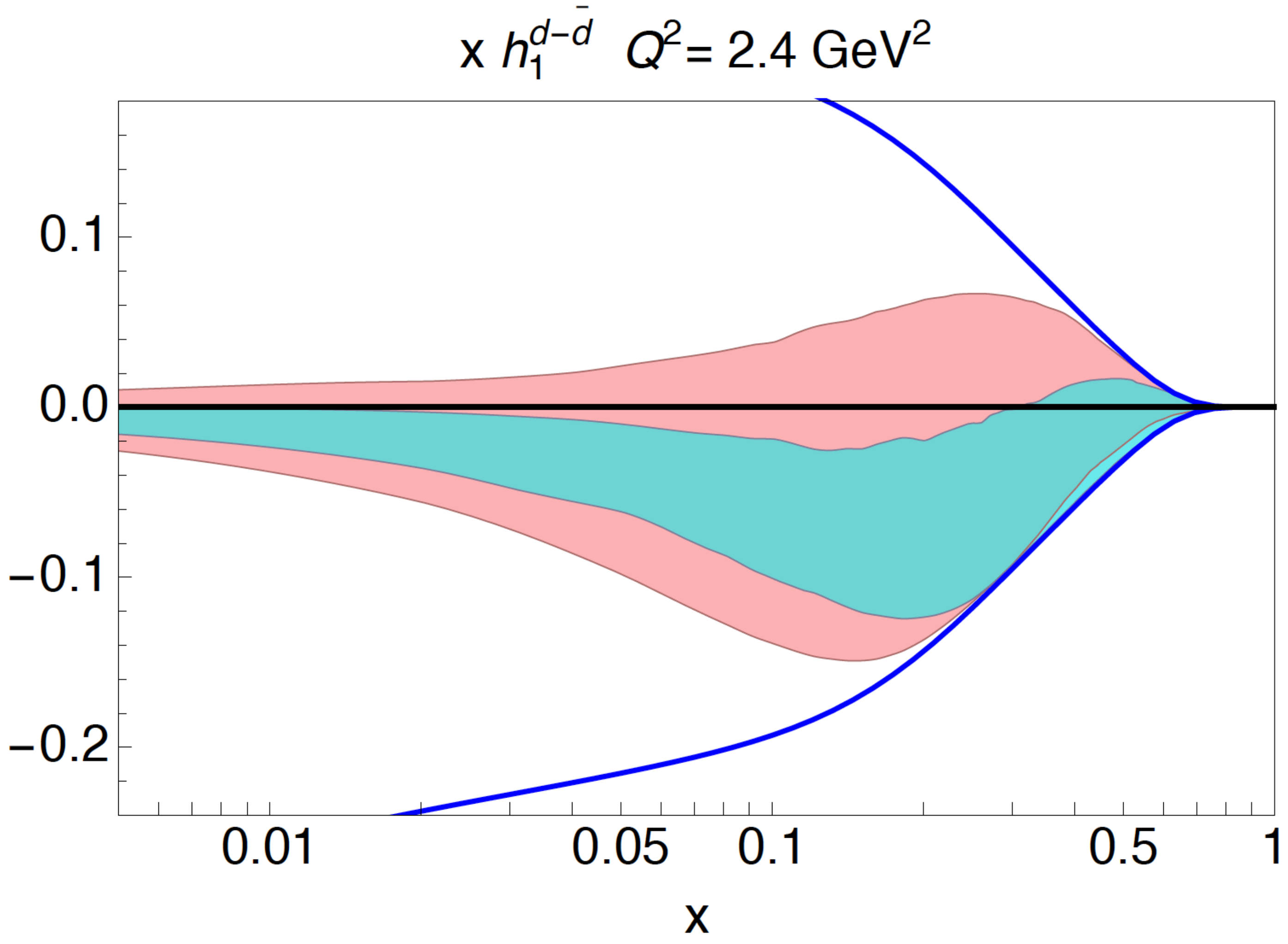


Addendum to COMPASS-II Proposal

Projected uncertainties for $A_{UT}^{\sin(\phi_h+\phi_S-\pi)}$

- Compatible results COMPASS/ HERMES for Collins effect
- No Q^2 evolution effects?





Expected impact of new COMPASS deuteron data

M.Radici @Spin 2018

SIDIS POLARIZED MEASUREMENTS: COLLINS EFFECT

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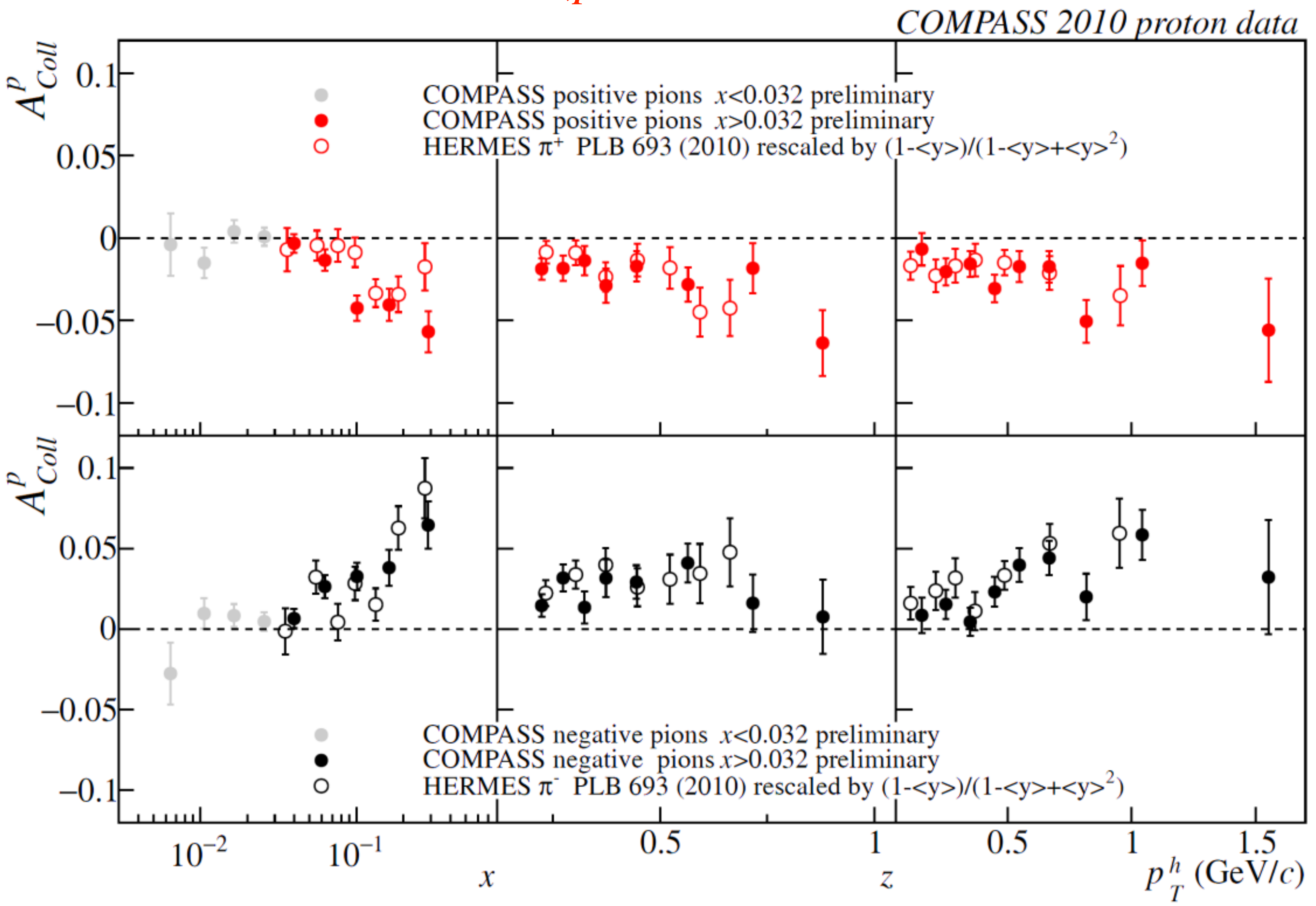
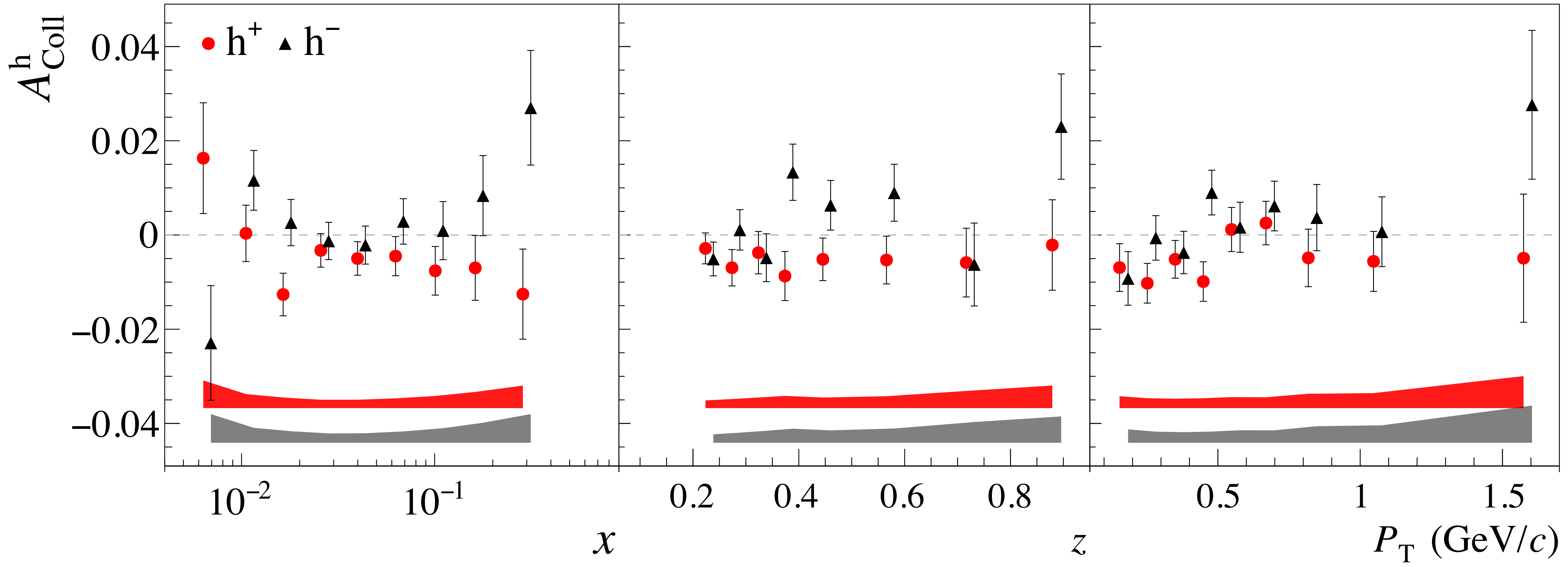


PLB 744 (2015) 250



New 2022 polarized D results!
[hep-ex/2401.00309](hep-ex/2401.00309) - accepted by PRL

- Compatible results COMPASS/ HERMES for Collins effect
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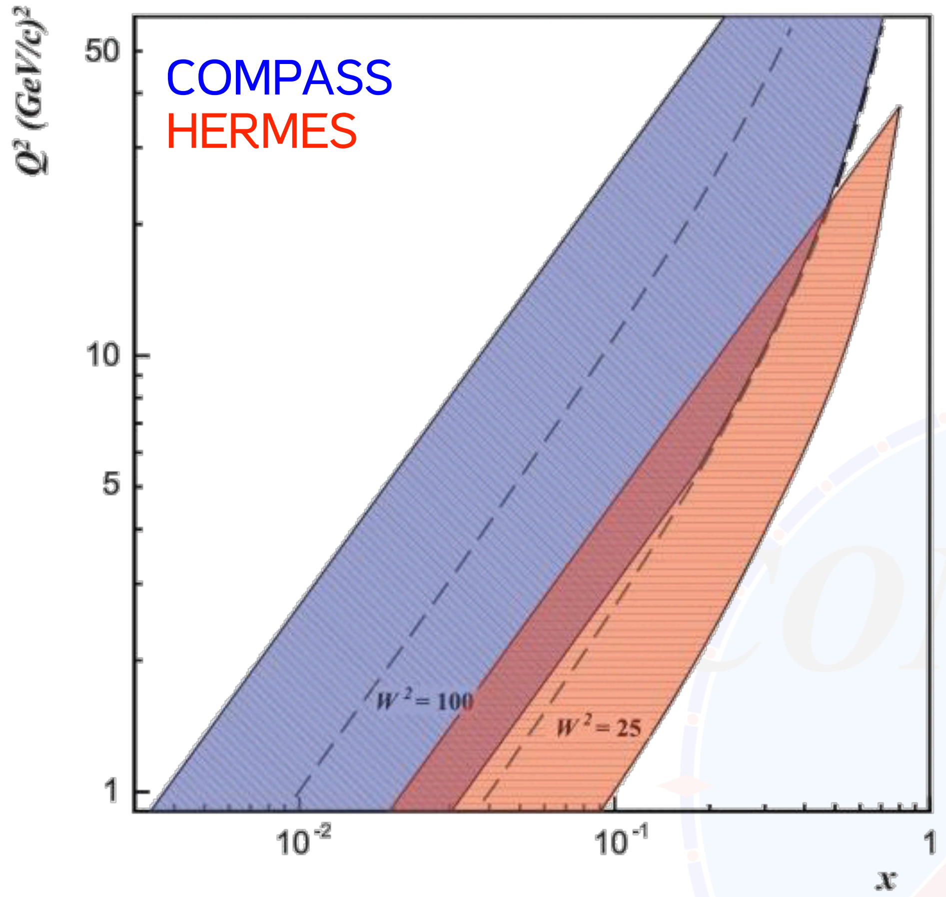

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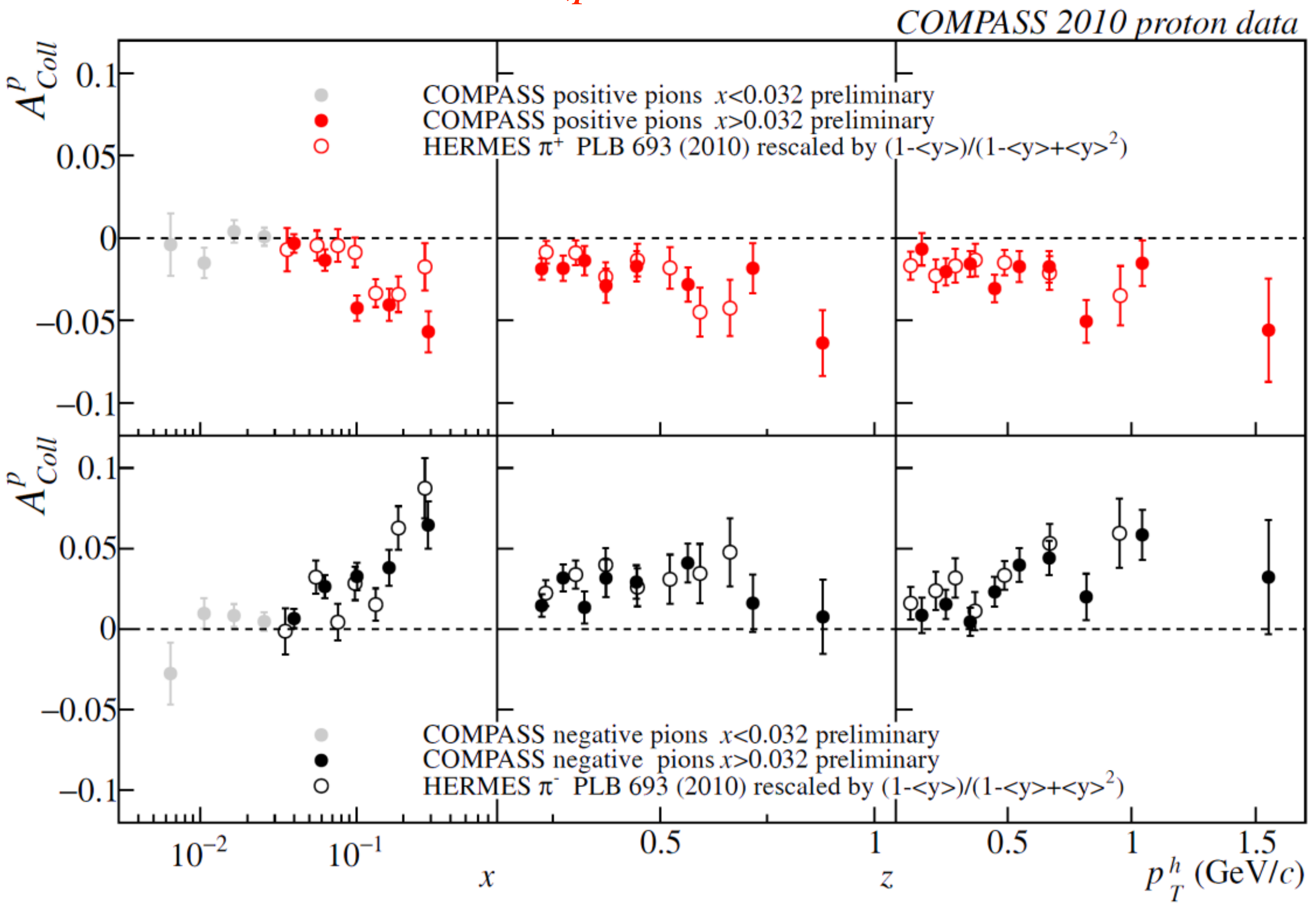
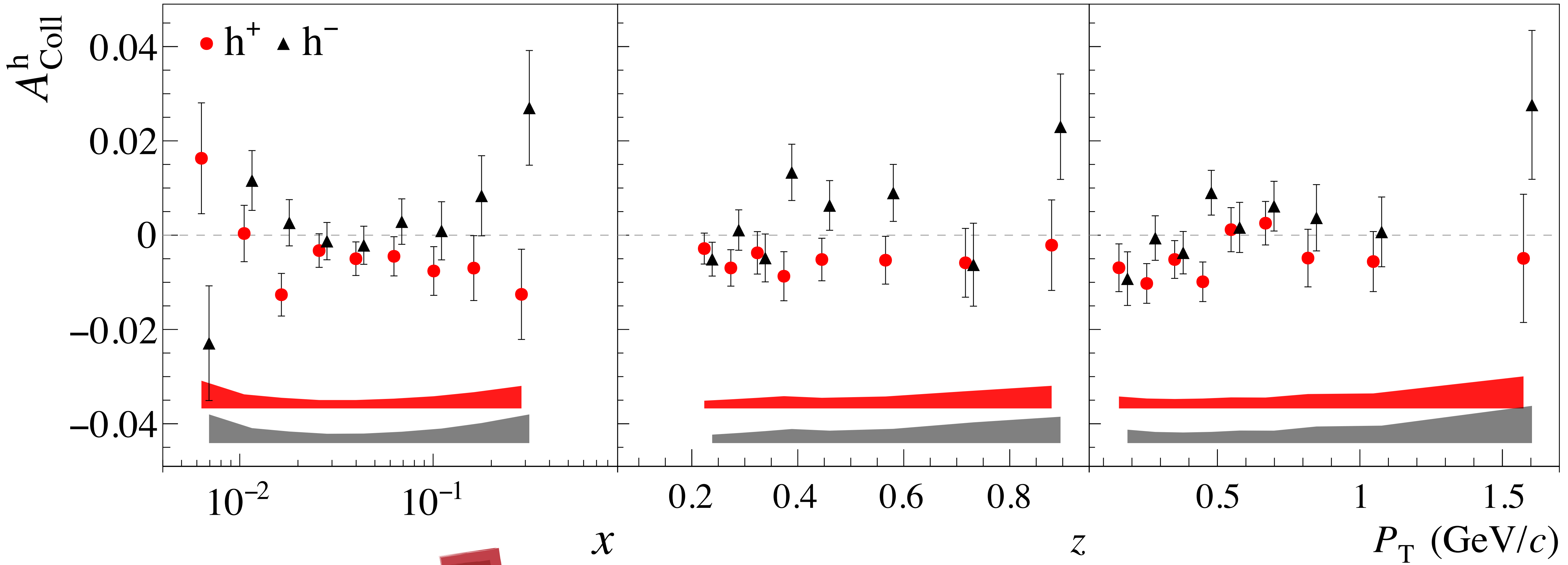


PLB 744 (2015) 250



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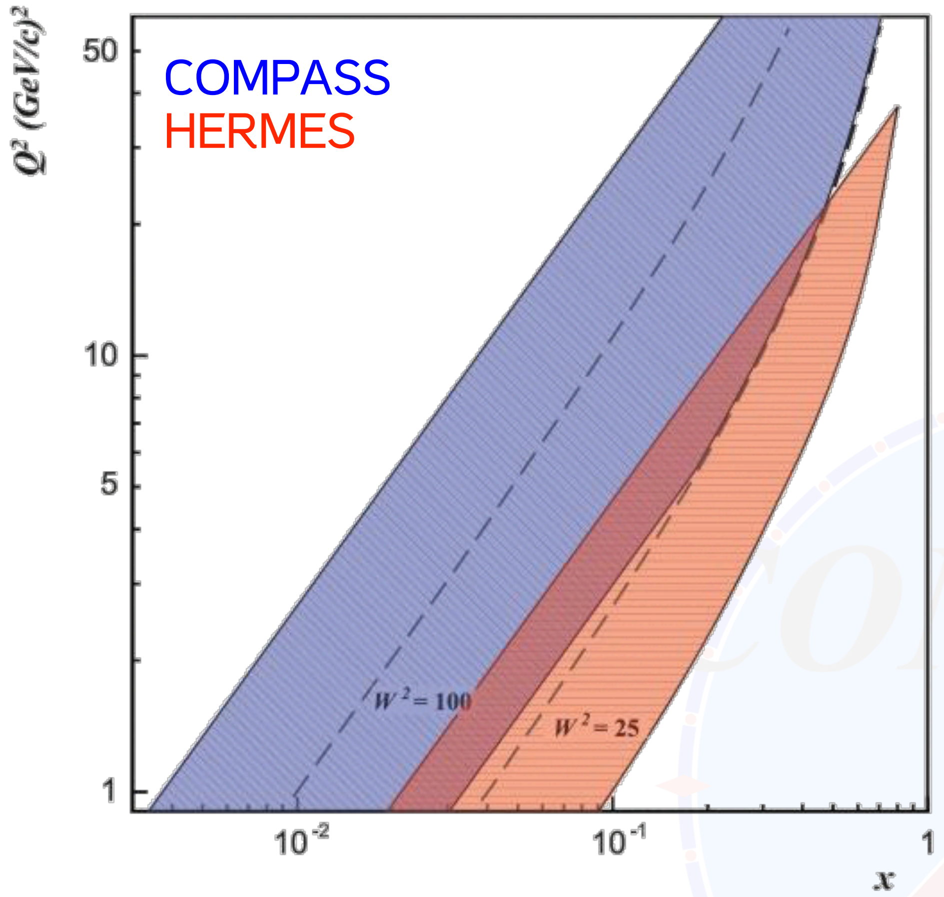

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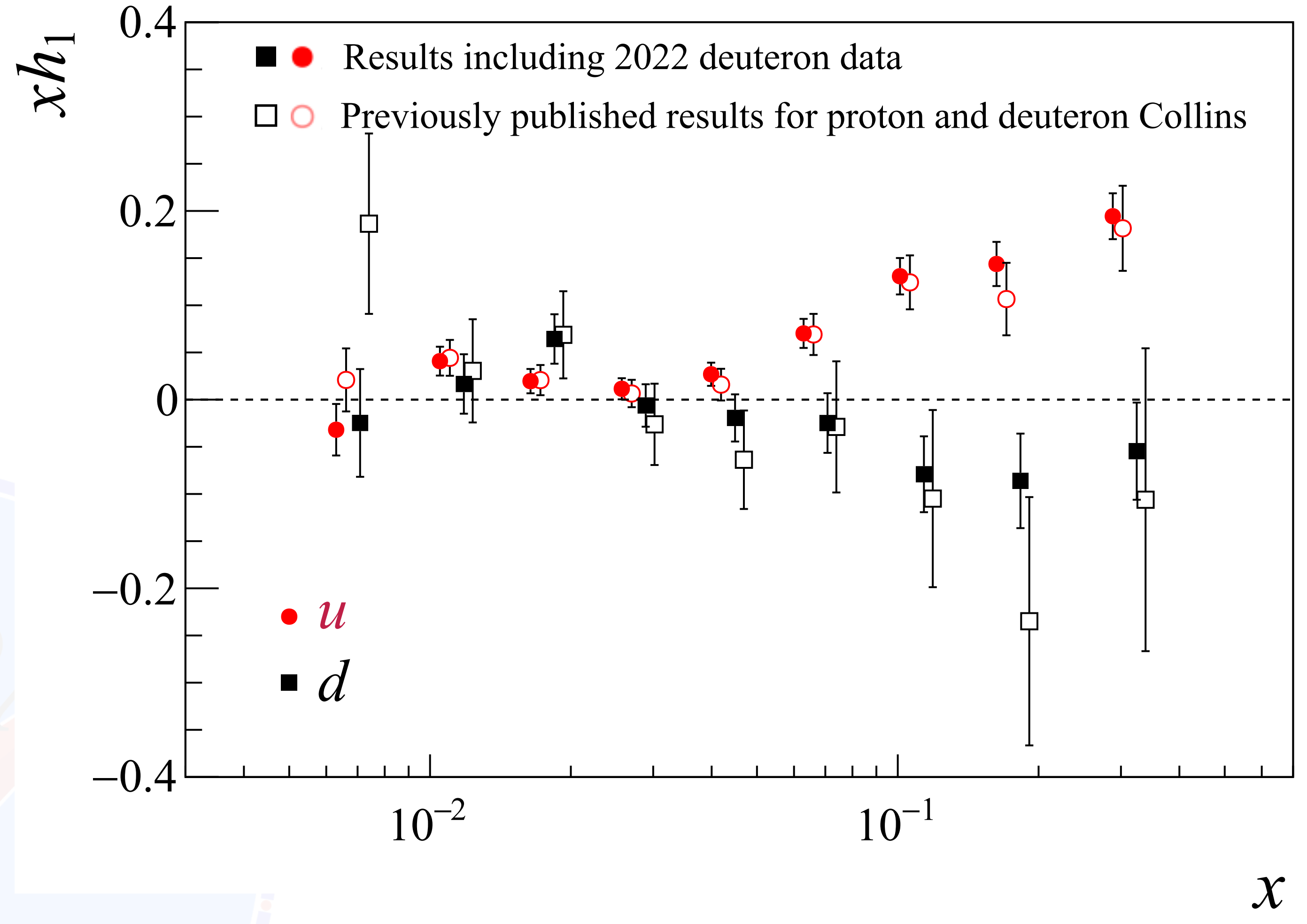
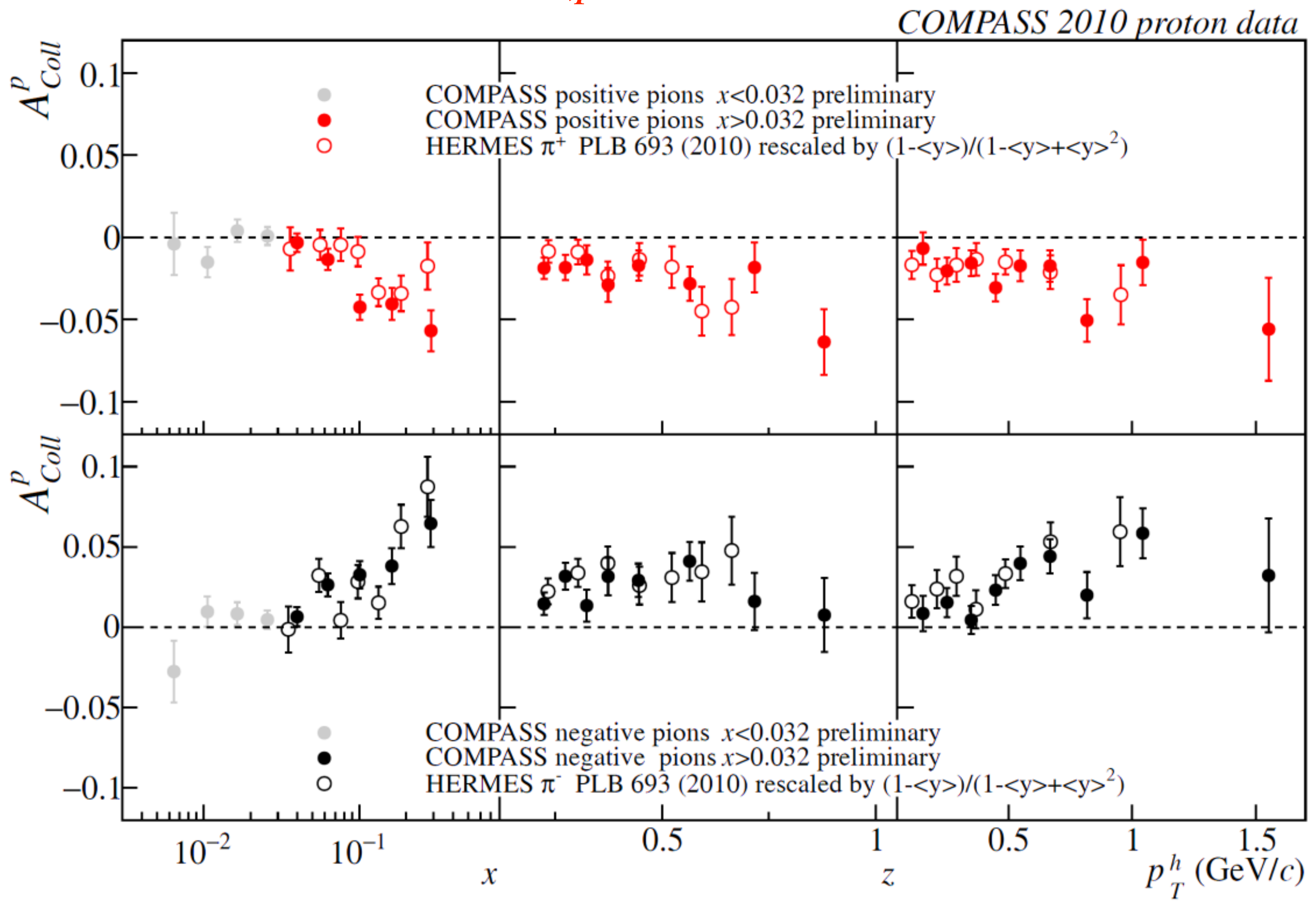


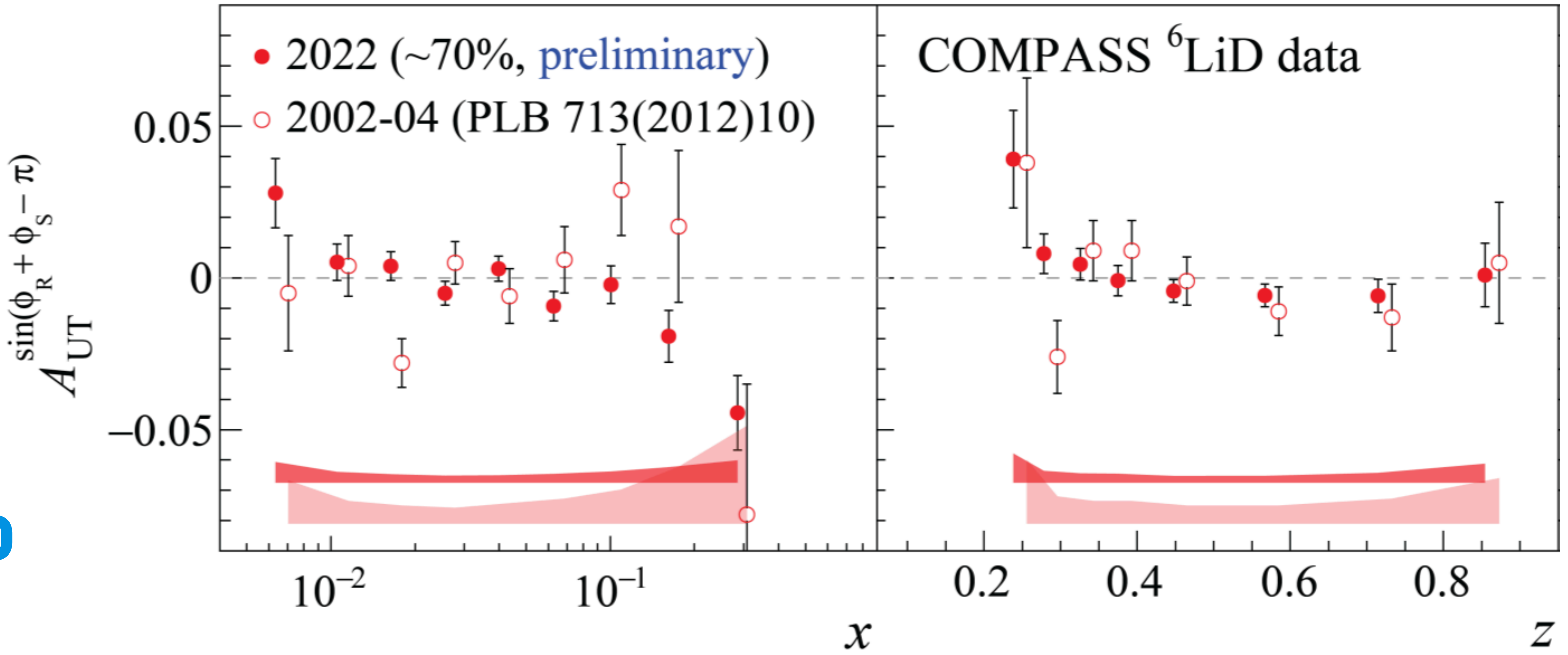
Point by point extraction framework
PRD 91, 014034 (2015)
PRD 95, 094024 (2017)

SIDIS POLARIZED MEASUREMENTS: COLLINS EFFECT

$A_{UT}^{\sin(\phi_h+\phi_S-\pi)} \propto h_{1,p}^q \otimes H_{1q}^{\perp h}$ → Measured by COMPASS on p/D targets in SIDIS and **di-hadron** SIDIS



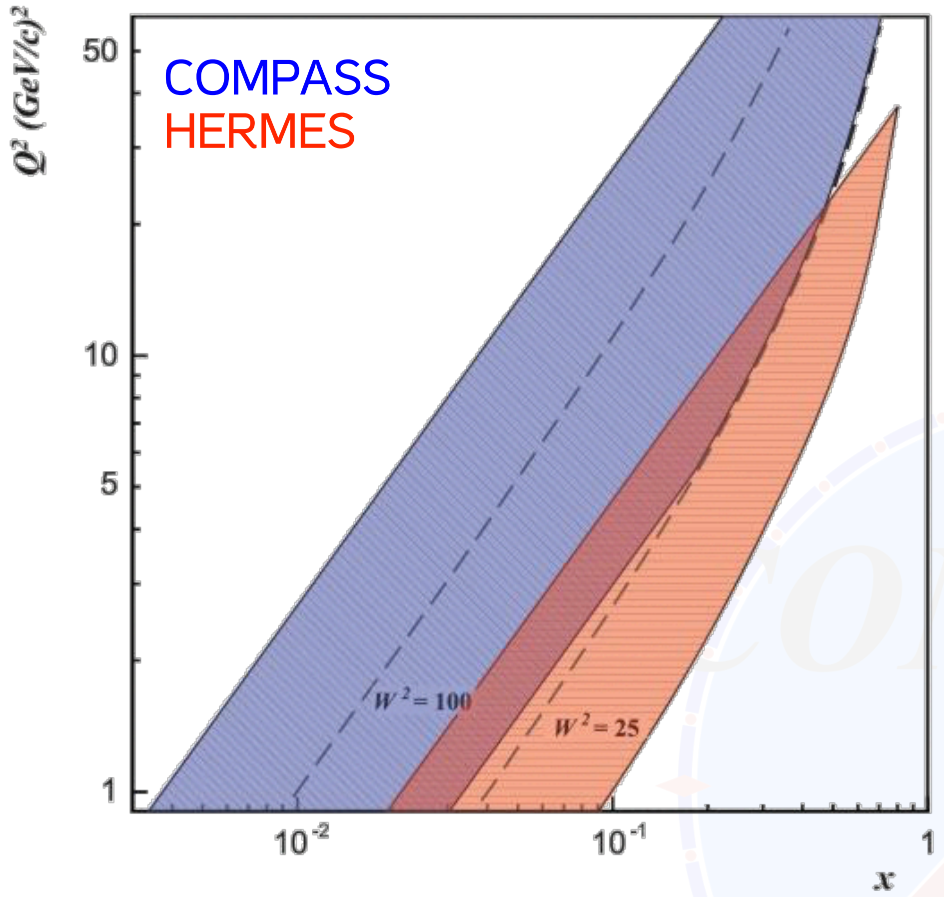
PLB 744 (2015) 250

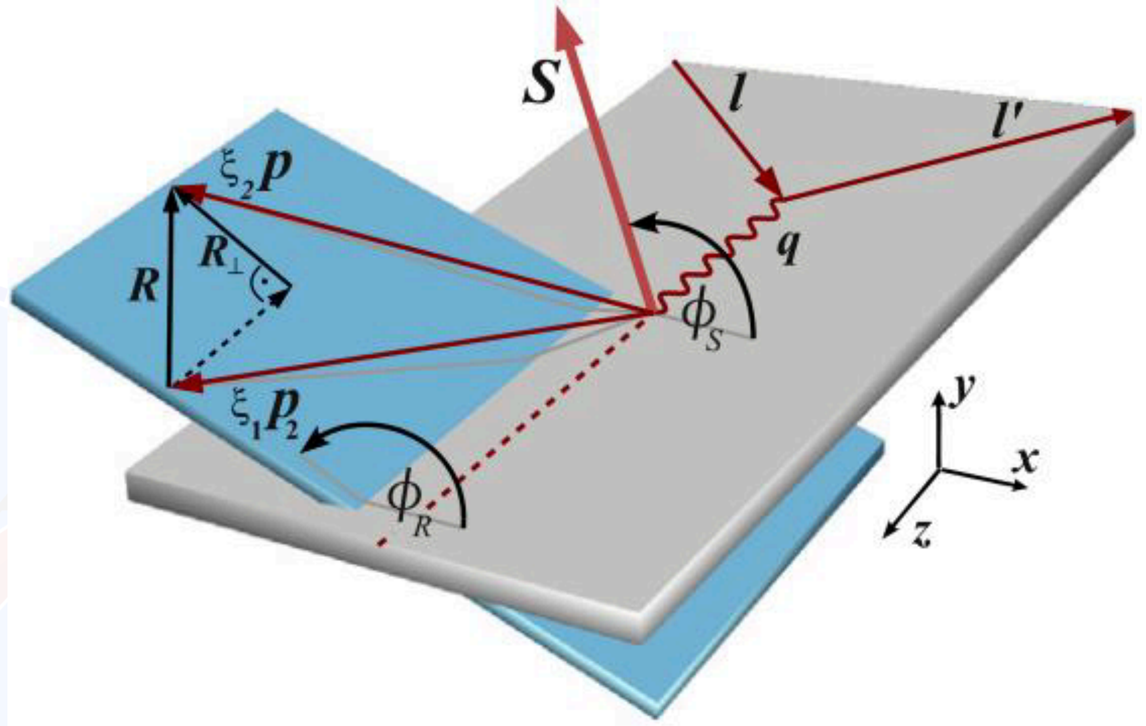


New 2022 polarized D results!

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

Access to collinear Transversity PDF; Non-zero trend at large-x



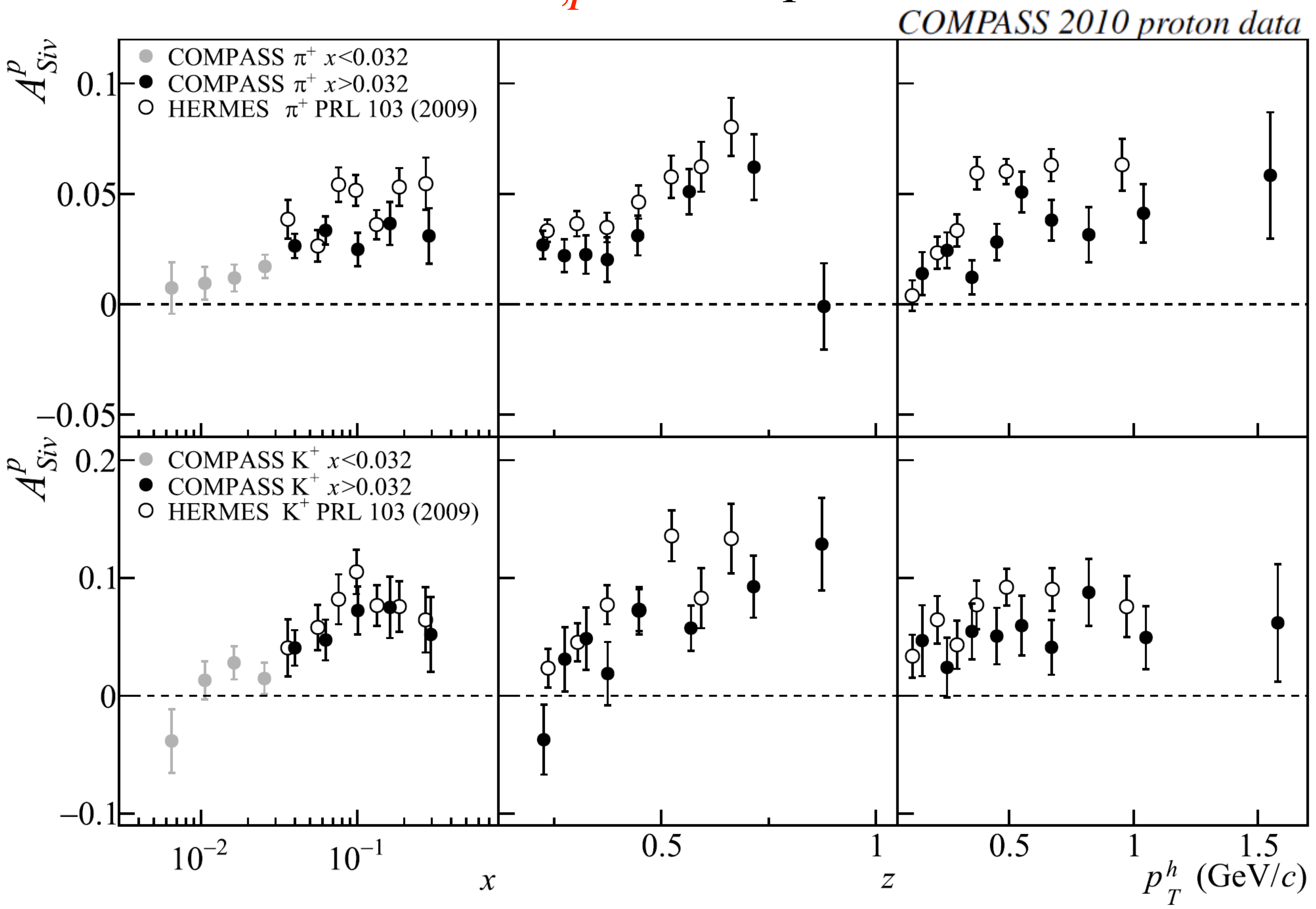


- Compatible results COMPASS/ HERMES for Collins effect
- No Q² evolution effects?

Precision now comparable with proton results

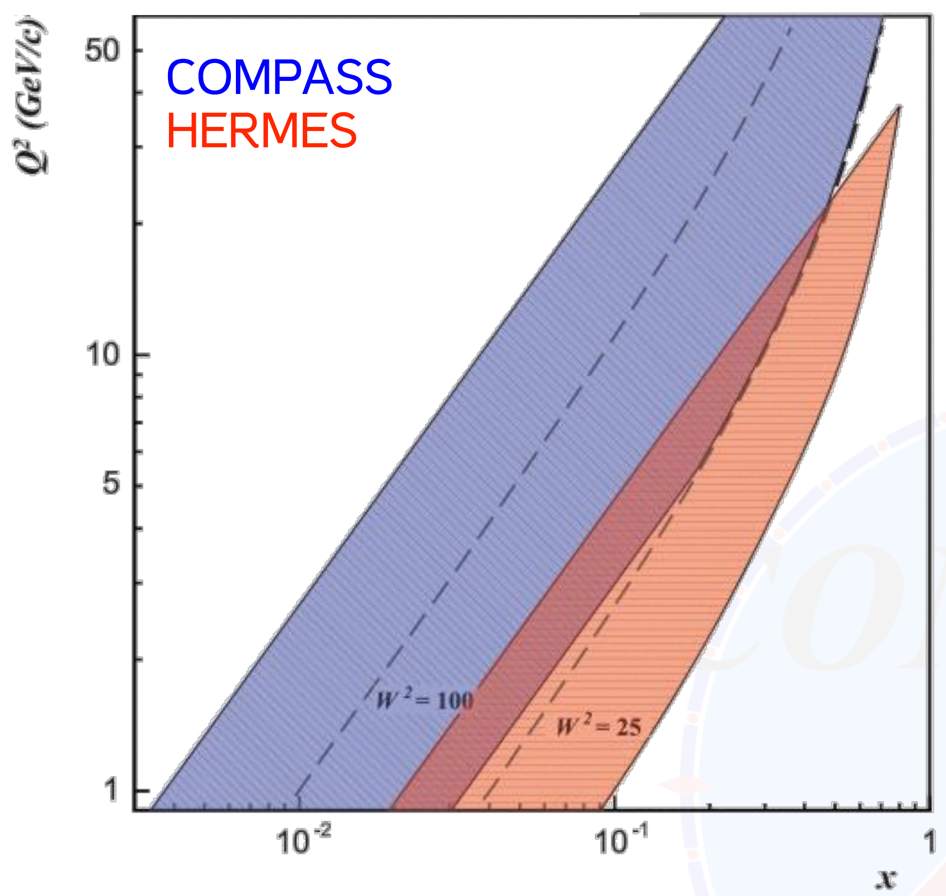
SIDIS POLARIZED MEASUREMENTS: SIVERS EFFECT

$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$ → Measured by COMPASS on p/D targets in SIDIS



PLB 744 (2015) 250

- Discrepancy COMPASS/HERMES for Sivers effect
- Q^2 evolution effects?



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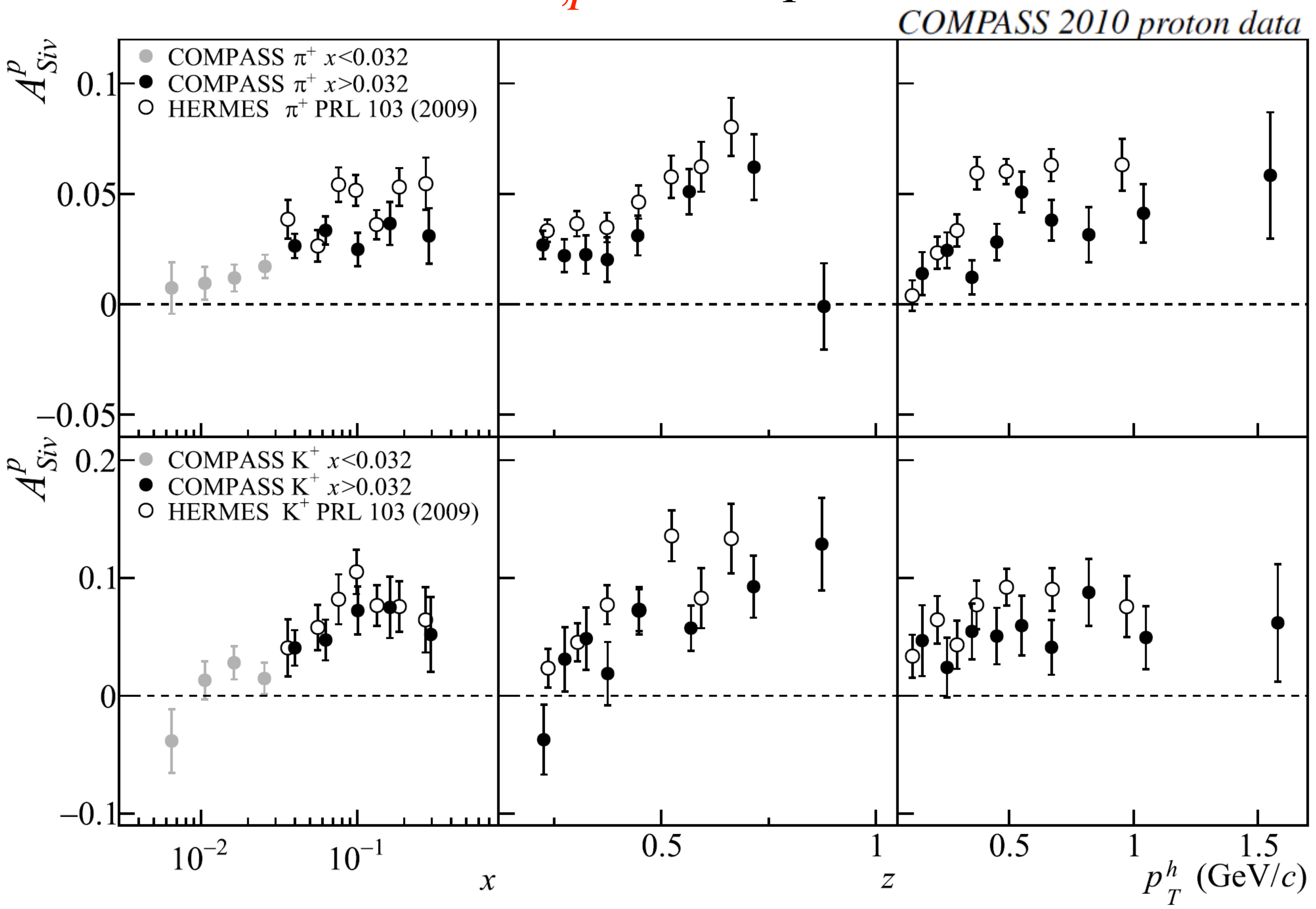
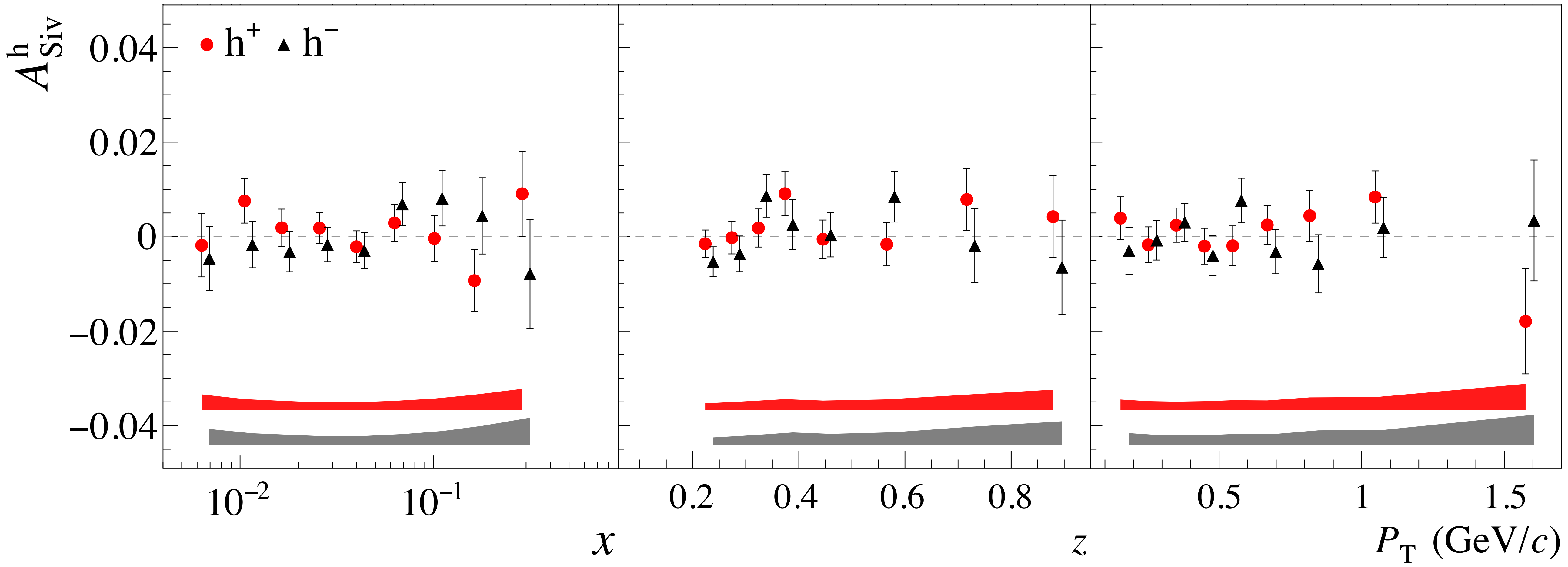


PLB 744 (2015) 250



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hep-ex/2401.00309 - accepted by PRL

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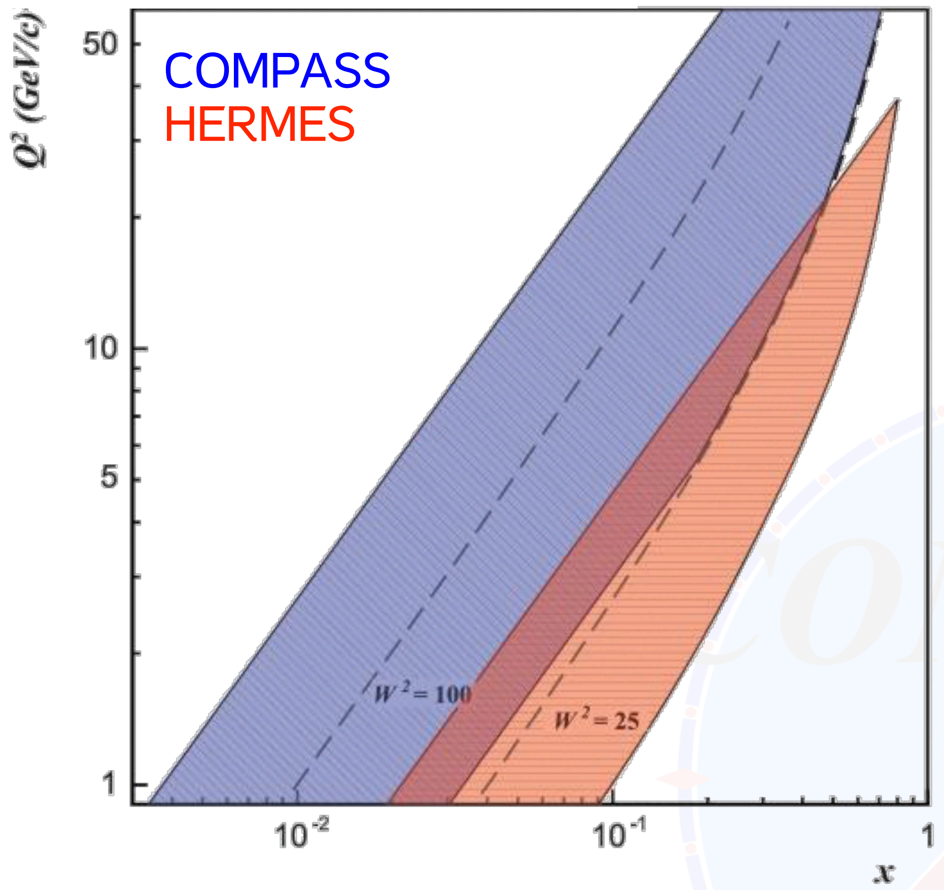

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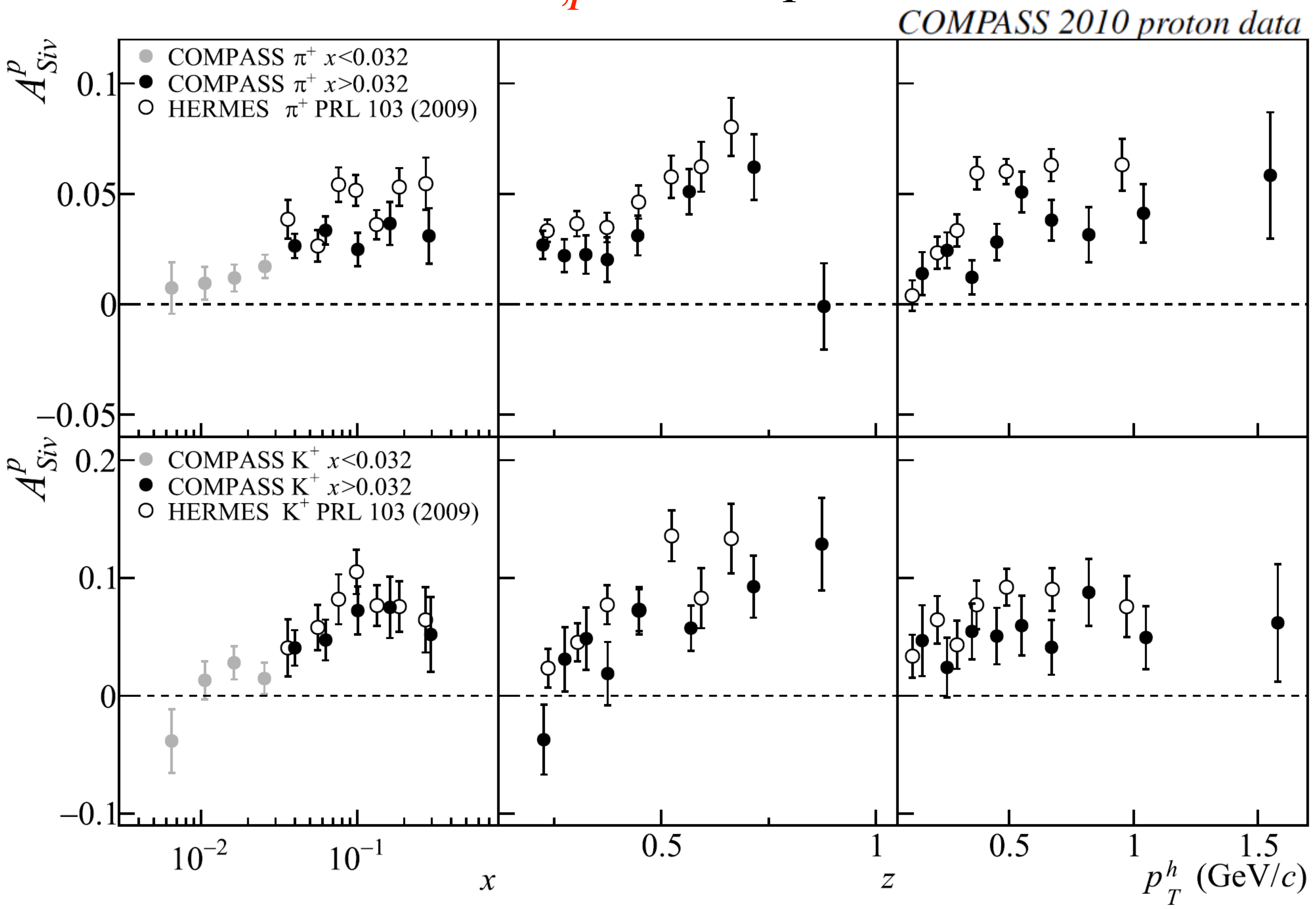
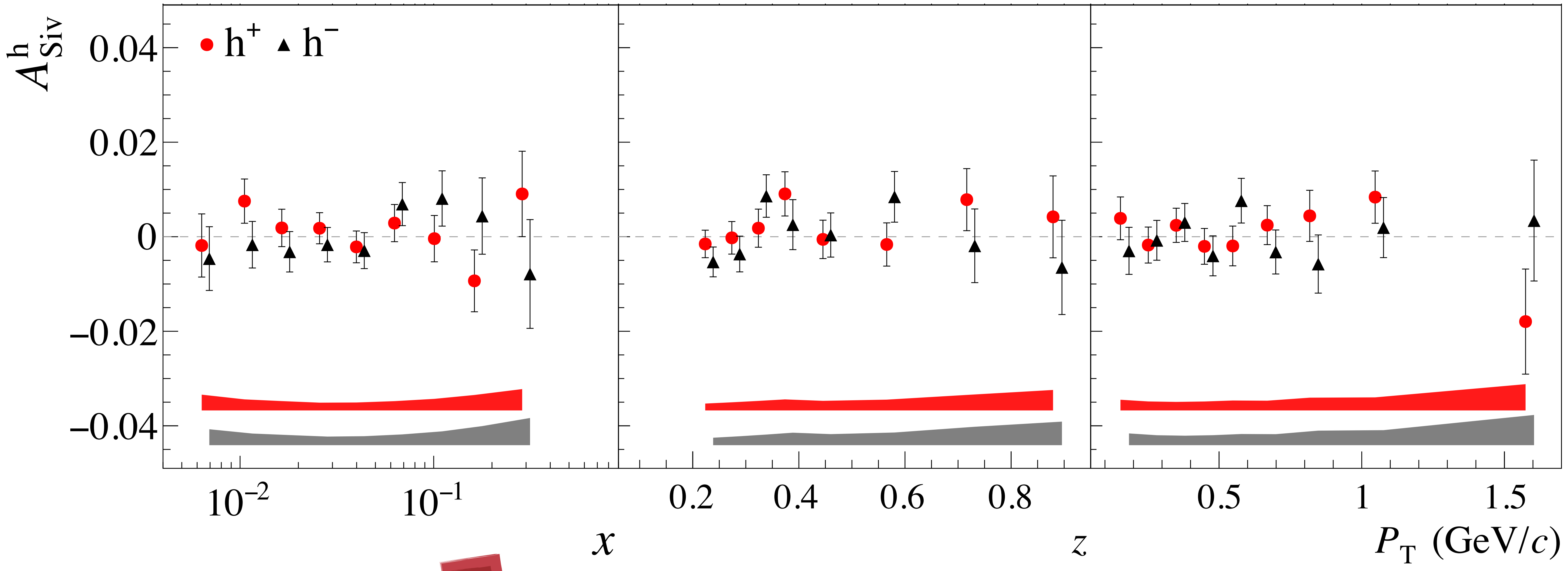
Measured by COMPASS on p/D targets in SIDIS



PLB 744 (2015) 250



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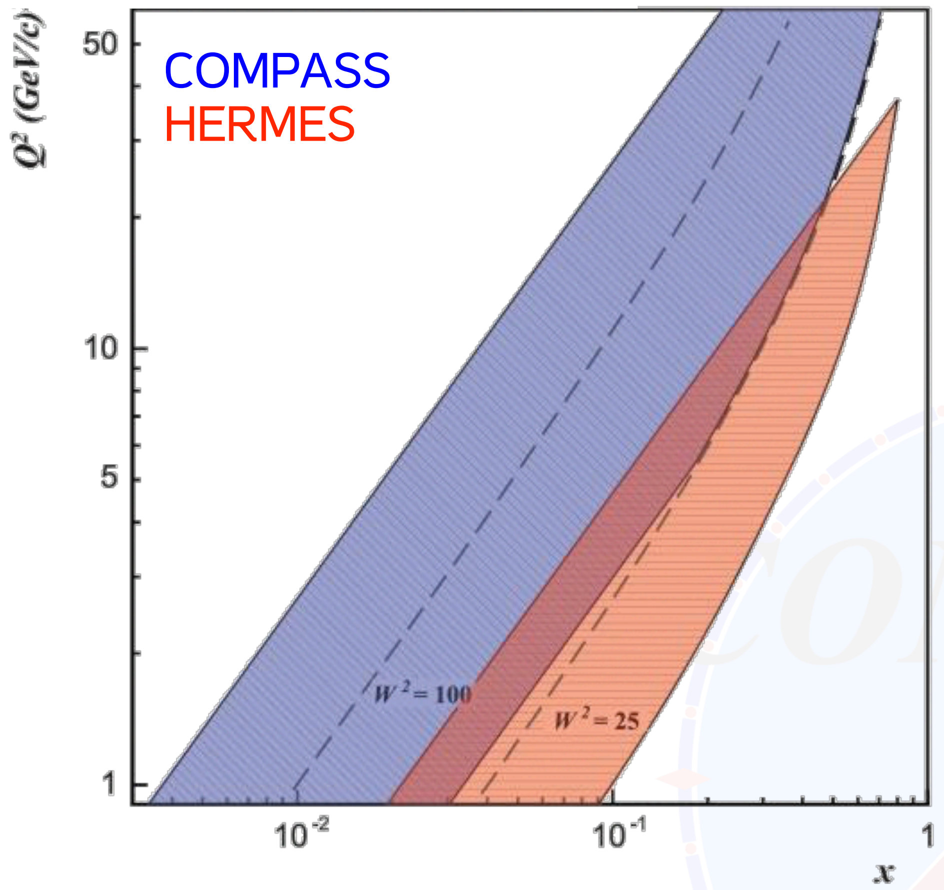

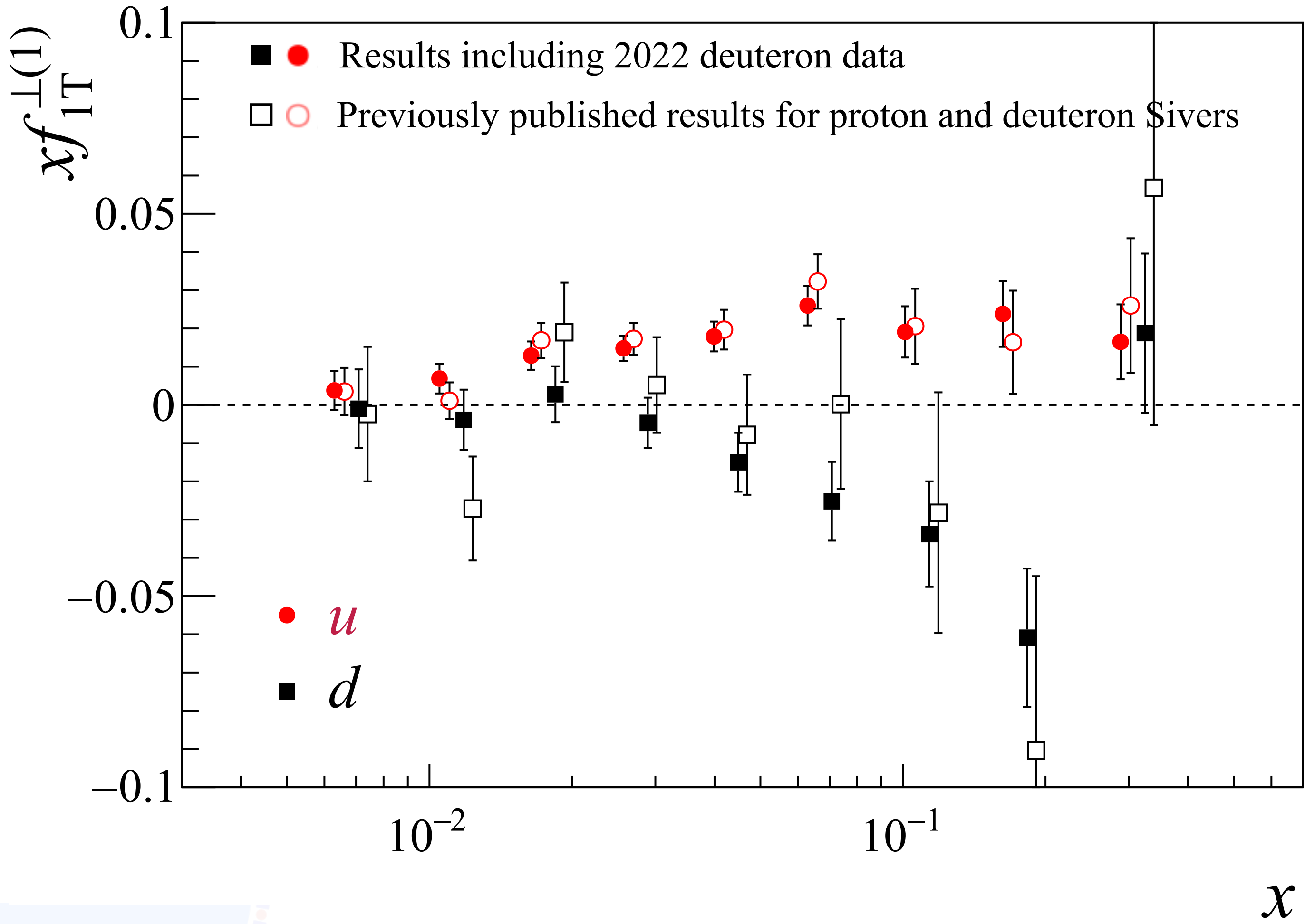

Point by point extraction framework

PRD 91, 014034 (2015)
PRD 95, 094024 (2017)

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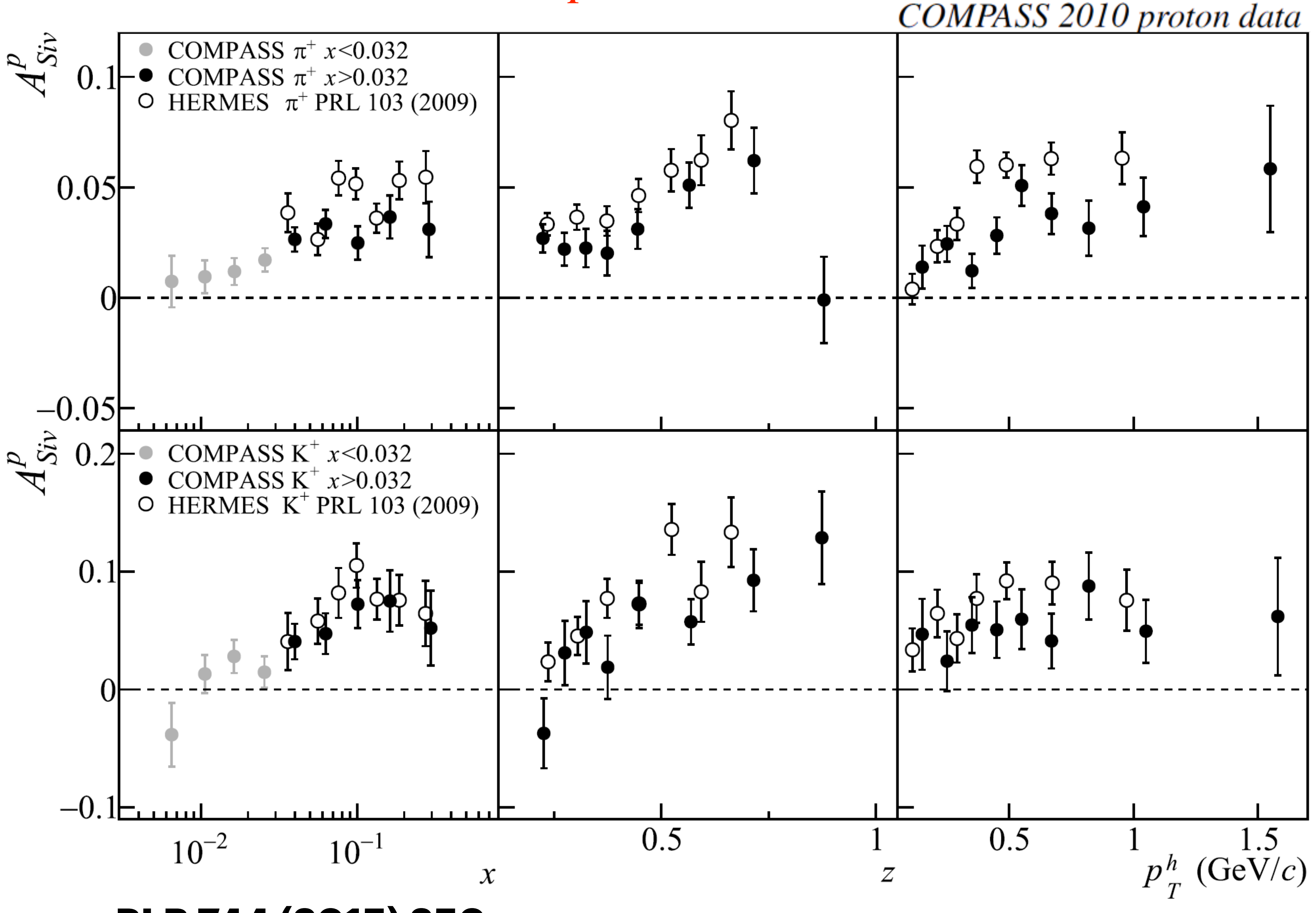
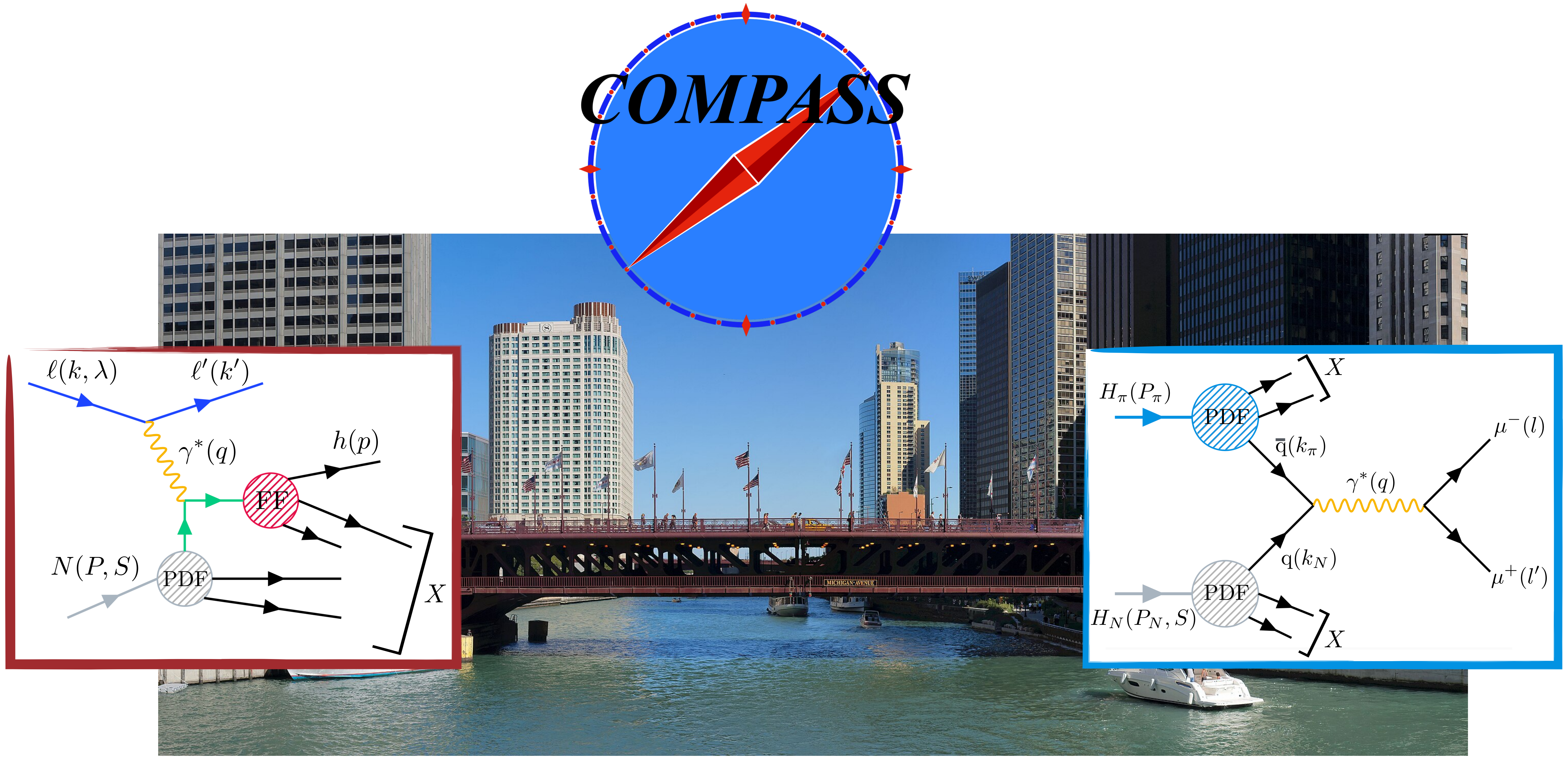


PLB 744 (2015) 250

- Discrepancy COMPASS/HERMES for Sivers effect
- Q^2 evolution effects?
- **Test of sign change prediction?**



COMPASS

SIDIS – DRELL-YAN

BRIDGE

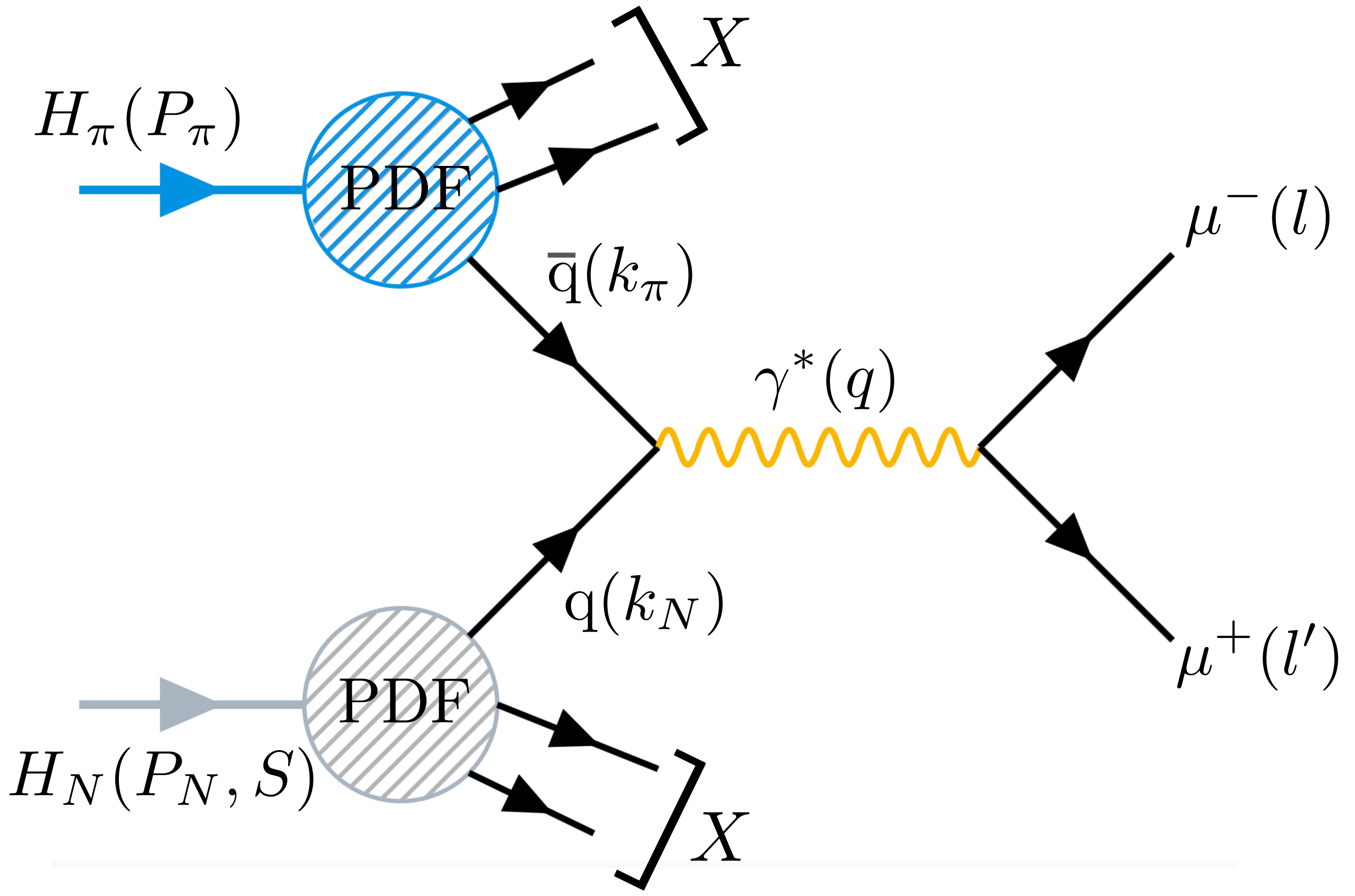
SINGLE POLARIZED DRELL-YAN AT COMPASS

Leading order QCD parton model expression of the Transversely Polarized DY cross-section

$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]} \cos(2\varphi_{CS}) A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \end{array} \right\}$$

Pion on transversely polarized nucleon Drell-Yan process @ COMPASS

$\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$ **2015, 2018**



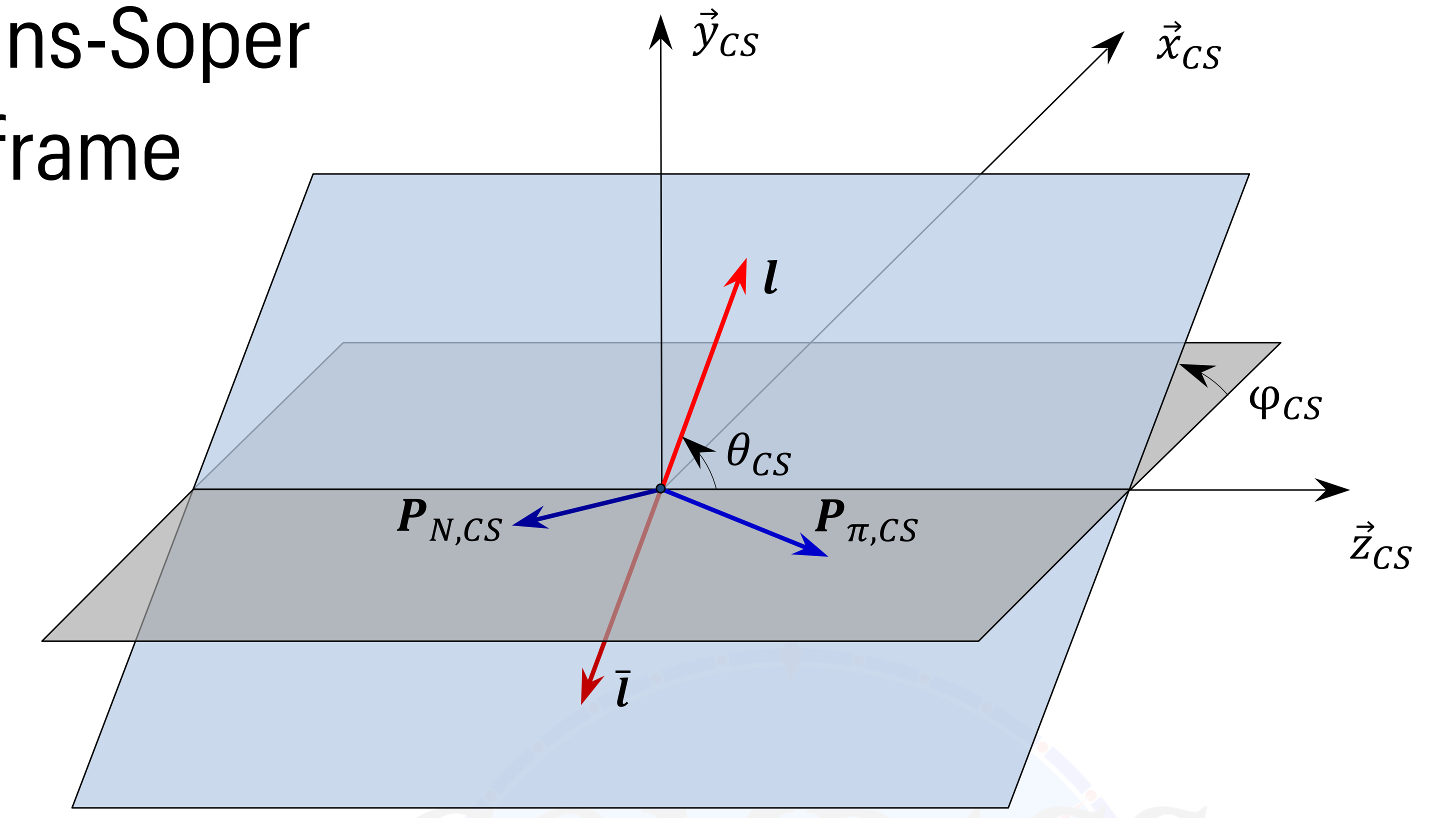
D-factors

$$D_{f(\theta)} = \frac{f(\theta)}{1+\cos^2(\theta)}$$

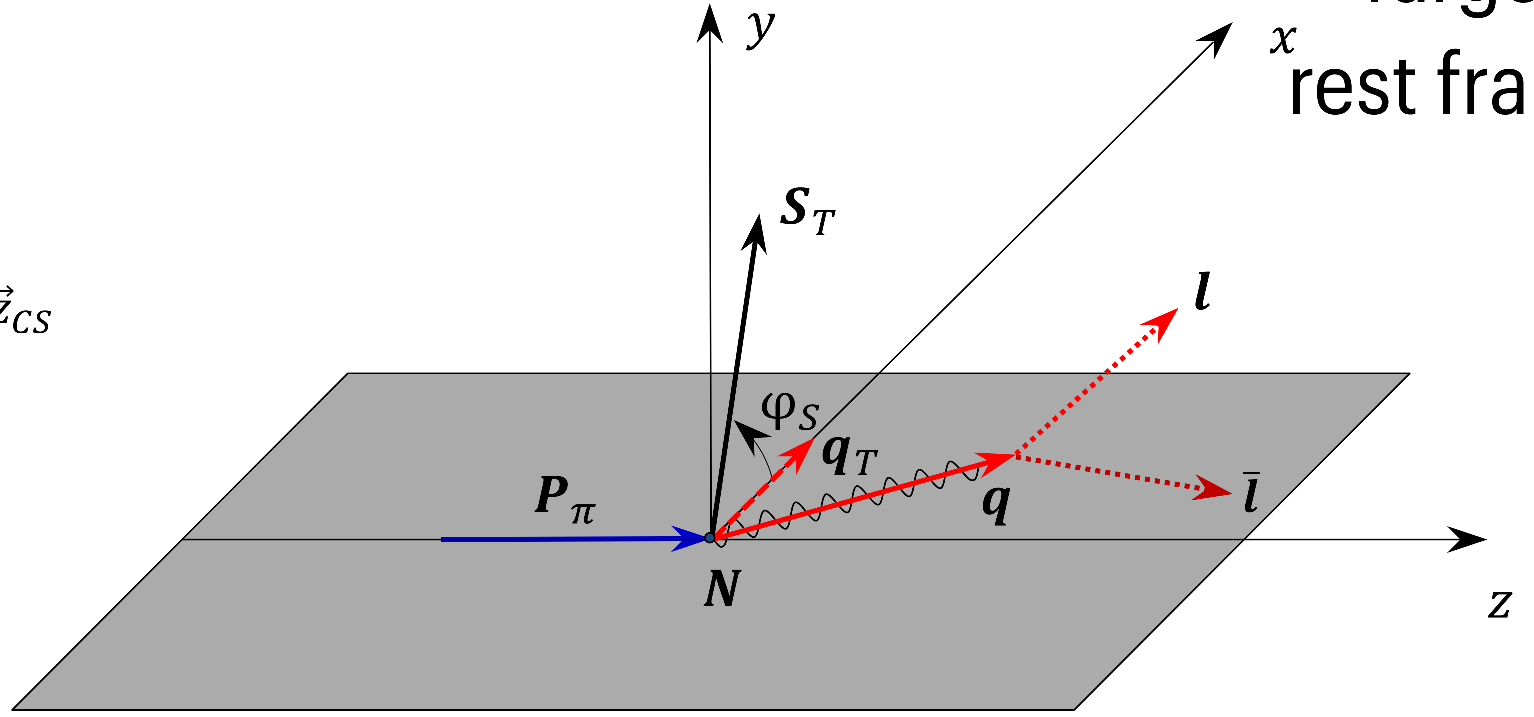
Azimuthal asymmetries

$$A_{U,T}^{w(\varphi_{CS},\varphi_S)} = \frac{F_{U,T}^{w(\varphi_{CS},\varphi_S)}}{F_U^1 + F_U^2}$$

Collins-Soper frame



Target rest frame



SINGLE POLARIZED DRELL-YAN AT COMPASS

Leading order QCD parton model expression of the Transversely Polarized DY cross-section

$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]} \cos(2\varphi_{CS}) A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \end{array} \right\}$$

$$A_{DY} \propto PDF_\pi \otimes PDF_p$$

1 Unpolarized Asymmetry

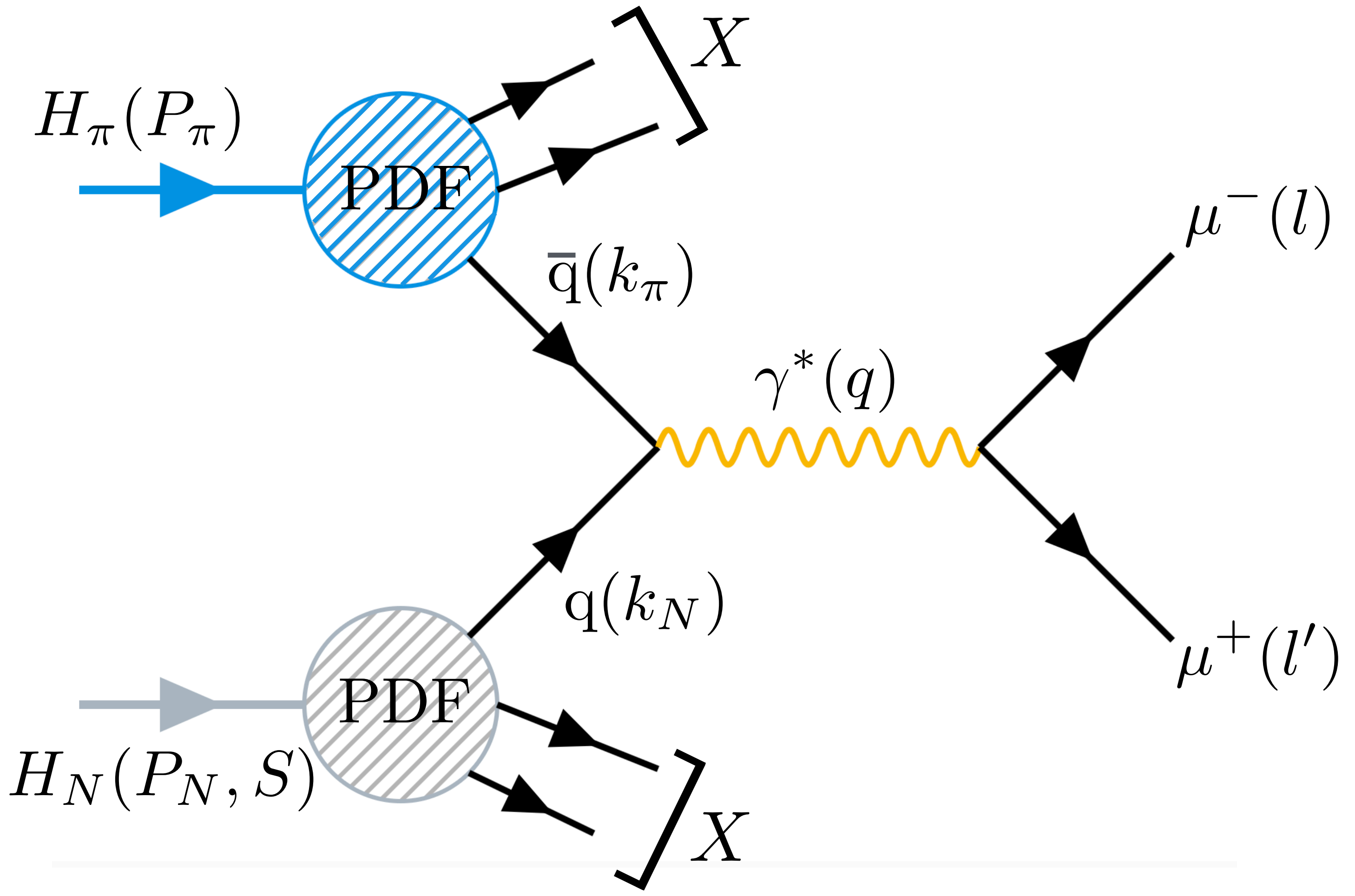
$$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$$

3 Single Spin Asymmetries

$$\left\{ \begin{array}{l} A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q} \\ A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q} \\ A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q} \end{array} \right.$$

Pion on transversely polarized nucleon
Drell-Yan process @ COMPASS

$\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$ **2015, 2018**



Quark Polarisation	Nucleon Polarisation: U	L	T
U	$f_1^q(x,\mathbf{k}_T^2)$ Number Density		$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers
L		$g_1^q(x,\mathbf{k}_T^2)$ Helicity	$g_{1T}^q(x,\mathbf{k}_T^2)$ Worm-Gear T
T	$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ Worm-Gear L	$h_{1T}^q(x,\mathbf{k}_T^2)$ Transversity; $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Pretzelosity

Nucleon · Nucleon spin · quark · quark spin · $\mathbf{k}_T$

Single polarized SIDIS cross section, Twist-2 only

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} \propto \left\{ \begin{array}{l} 1 + \cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ + S_T \left[\begin{array}{l} \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h-\phi_s)} \\ + \sin(\phi_h + \phi_S)\varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \\ + \sin(3\phi_h - \phi_S)\varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \end{array} \right] \end{array} \right\}$$

$$A_{SIDIS} \propto PDF_p \otimes FF$$

1 Unpolarized Asymmetry

$$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$$

3 Single Spin Asymmetries

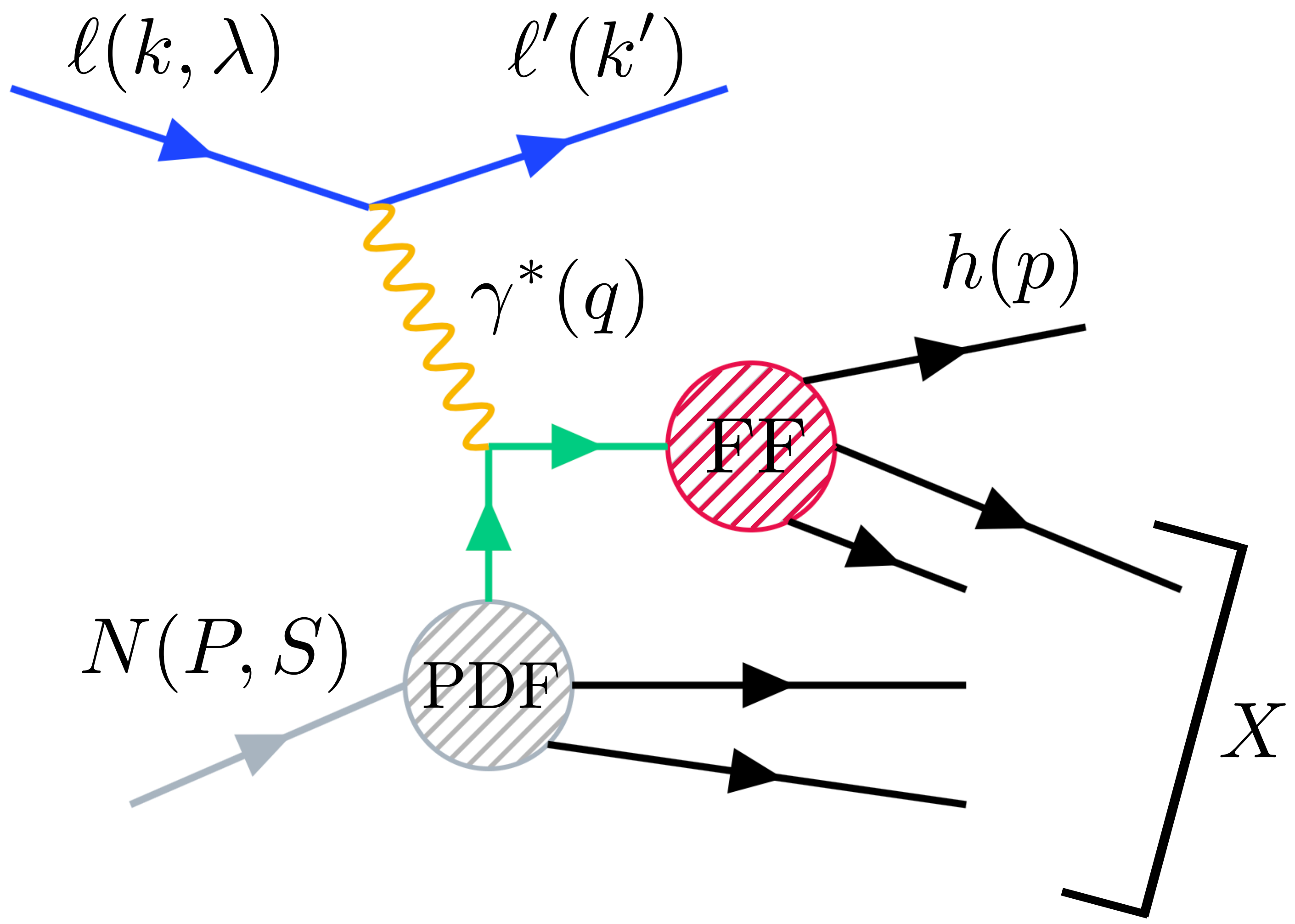
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$$

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

SIDIS on transversely polarized p @ COMPASS

$\mu + p^{\uparrow} \rightarrow \mu' + h + X$ **2007, 2010**



		Nucleon Polarisation		
		U	L	T
Quark Polarisation	U	$f_1^q(x,\mathbf{k}_T^2)$ Number Density		$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers
	L		$g_1^q(x,\mathbf{k}_T^2)$ Helicity	$g_{1T}^q(x,\mathbf{k}_T^2)$ Worm-Gear T
	T	$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ Worm-Gear L	$h_{1T}^q(x,\mathbf{k}_T^2)$ Transversity; $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Pretzelosity

Nucleon · Nucleon spin · quark · quark spin · $\mathbf{k}_T$

COMPASS EXPERIMENTAL ACCESS TO TMDs

SIDIS on transversely polarized nucleons

COMPASS 2007, 2010 - $\mu + p^{\uparrow} \rightarrow \mu' + h + X$

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\varphi_h d\psi} \propto \left\{ \begin{array}{l} 1 + \cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ + S_T \left[\begin{array}{l} \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_s)} \\ + \sin(\phi_h + \phi_S)\varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \\ + \sin(3\phi_h - \phi_S)\varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \end{array} \right] \end{array} \right\}$$

$$A_{SIDIS} \propto PDF_p \otimes FF$$

$$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$$

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

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

$$A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$$

Pion on transversely polarized nucleon DY process

COMPASS 2015, 2018 -$\pi^- + p^{\uparrow} \rightarrow \mu^+\mu^- + X$

$$\frac{d\sigma^{LO}}{d\Omega d^4 q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS}) A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS} + \varphi_S) A_T^{\sin(2\varphi_{CS} + \varphi_S)} \\ \sin(2\varphi_{CS} - \varphi_S) A_T^{\sin(2\varphi_{CS} - \varphi_S)} \end{array} \right) \end{array} \right] \end{array} \right\}$$

$$A_{DY} \propto PDF_{\pi} \otimes PDF_p$$

$$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

Boer-Mulders ↔ (links $A_{UU}^{\cos(2\phi_h)}$ and $A_U^{\cos(2\varphi_{CS})}$)

Sivers ↔ (links $A_{UT}^{\sin(\phi_h - \phi_S)}$ and $A_T^{\sin\varphi_S}$)

Pretzelosity ↔ (links $A_{UT}^{\sin(3\phi_h - \phi_S)}$ and $A_T^{\sin(2\varphi_{CS} + \varphi_S)}$)

Transversity ↔ (links $A_{UT}^{\sin(\phi_h + \phi_S)}$ and $A_T^{\sin(2\varphi_{CS} - \varphi_S)}$)

Universality in TMD-QCD parton model approach

Transversity and **Pretzelosity** TMD PDFs "genuinely" universal
(**no sign change** between SIDIS and DY)

Boer Mulders and **Sivers** TMD PDFs "conditionally" universal
(**sign change** between SIDIS and DY)

$$h_{1,p}^{q}|_{SIDIS} = h_{1,p}^{q}|_{DY}$$

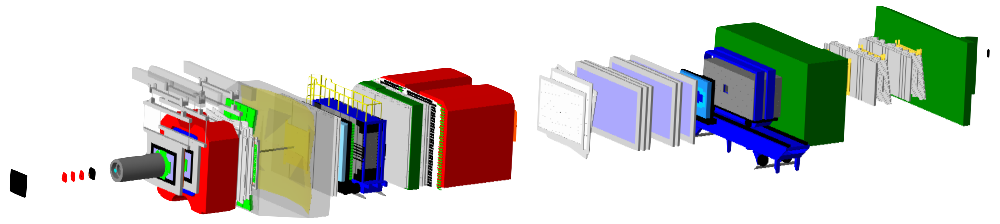
$$h_{1T,p}^{\perp q}|_{SIDIS} = h_{1T,p}^{\perp q}|_{DY}$$

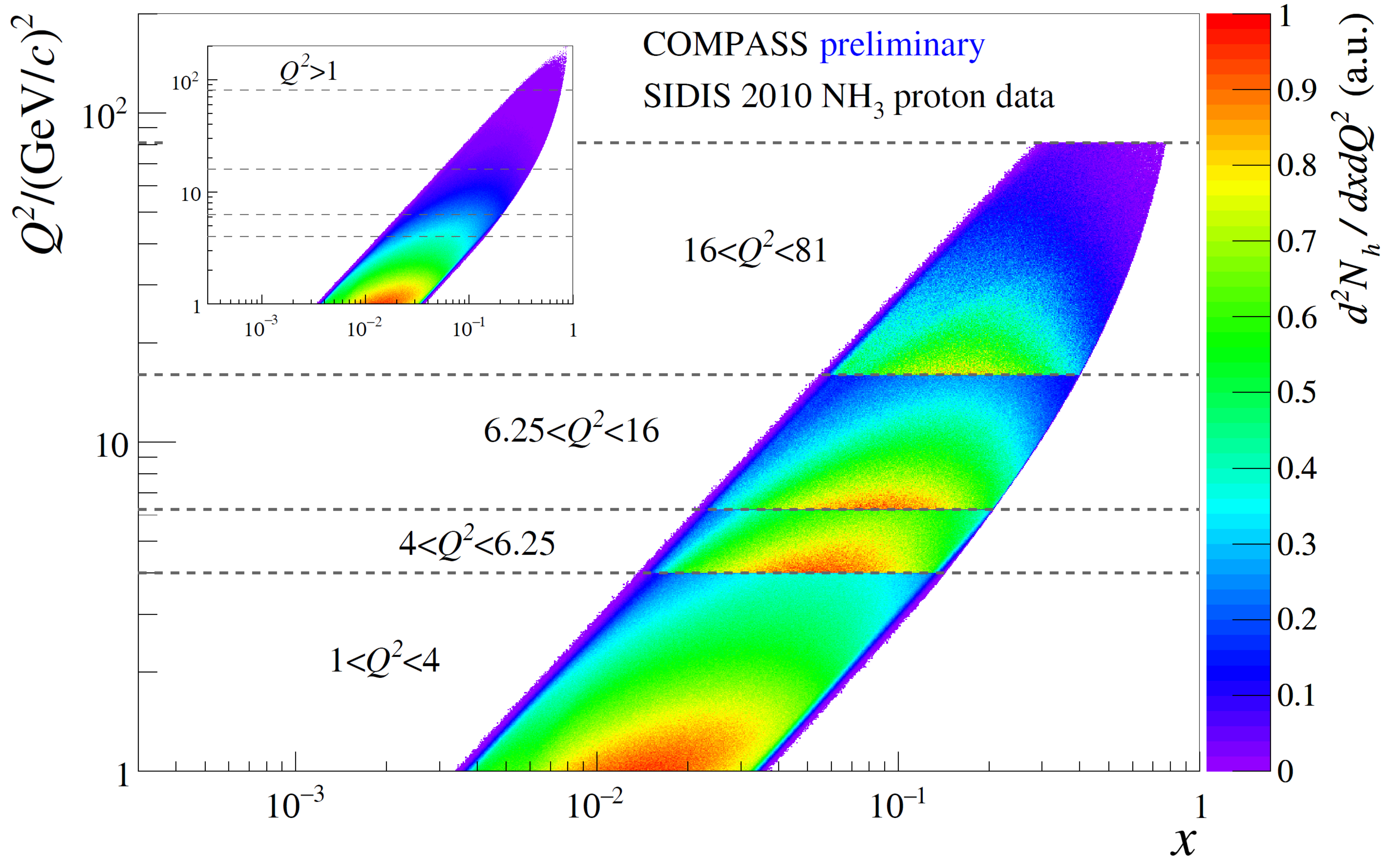
$$f_{1T,p}^{\perp q}|_{SIDIS} = -f_{1T,p}^{\perp q}|_{DY}$$

$$h_{1,p}^{\perp q}|_{SIDIS} = -h_{1,p}^{\perp q}|_{DY}$$

SIDIS on transversely polarized nucleons

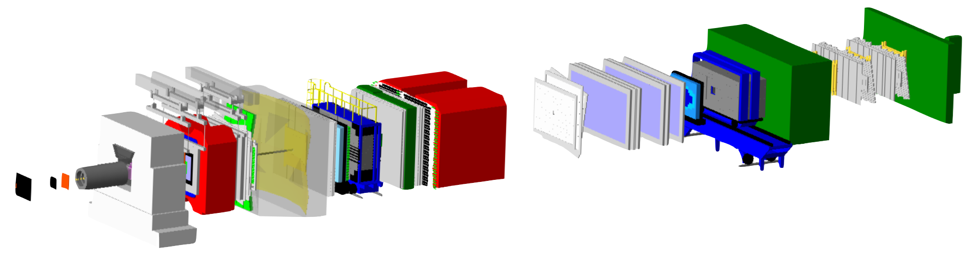
COMPASS 2007, 2010 - $\mu + p^{\uparrow} \rightarrow \mu' + h + X$

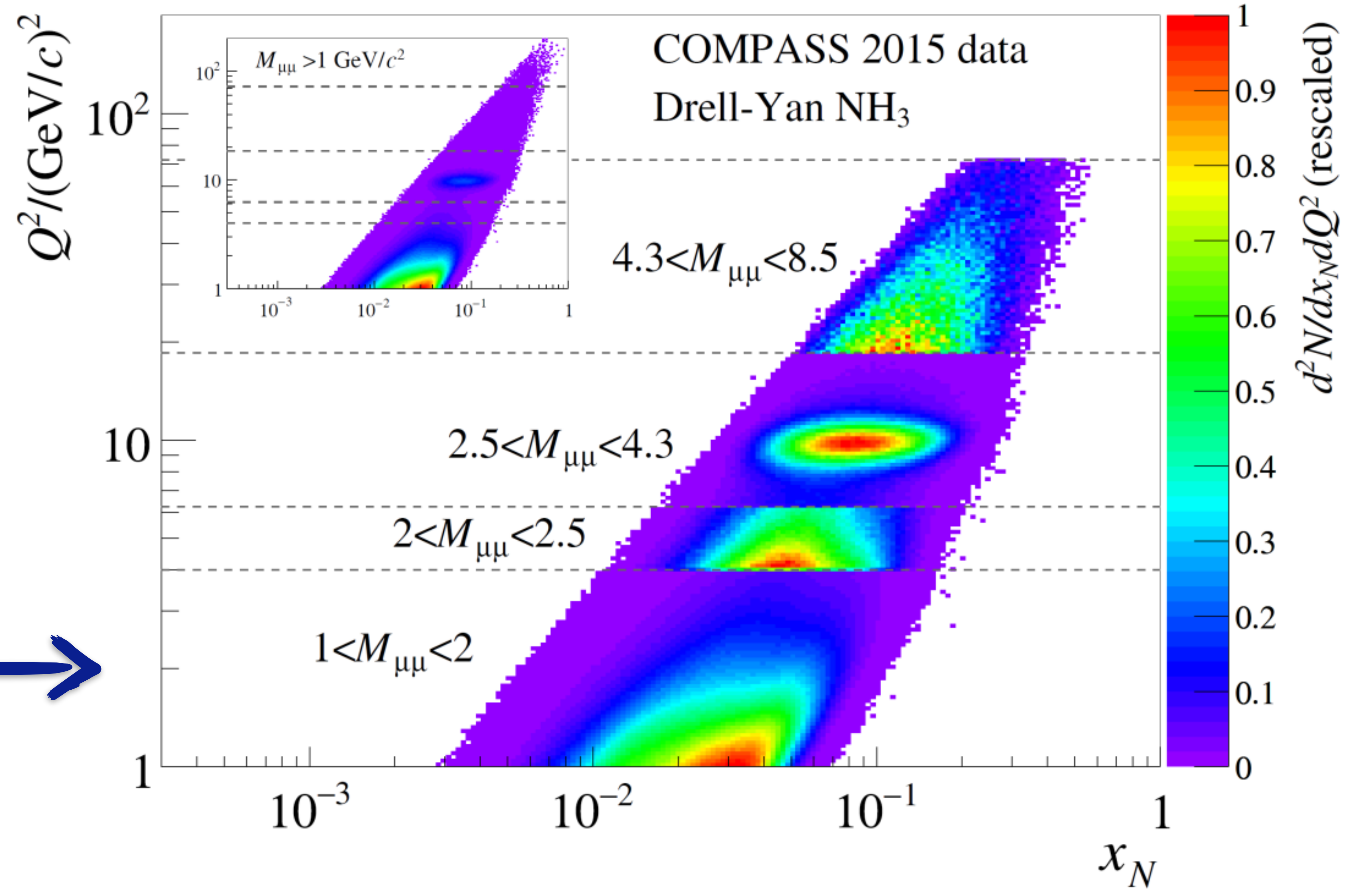




Pion on transversely polarized nucleon DY process

COMPASS 2015, 2018 -$\pi^{-} + p^{\uparrow} \rightarrow \mu^{+}\mu^{-} + X$





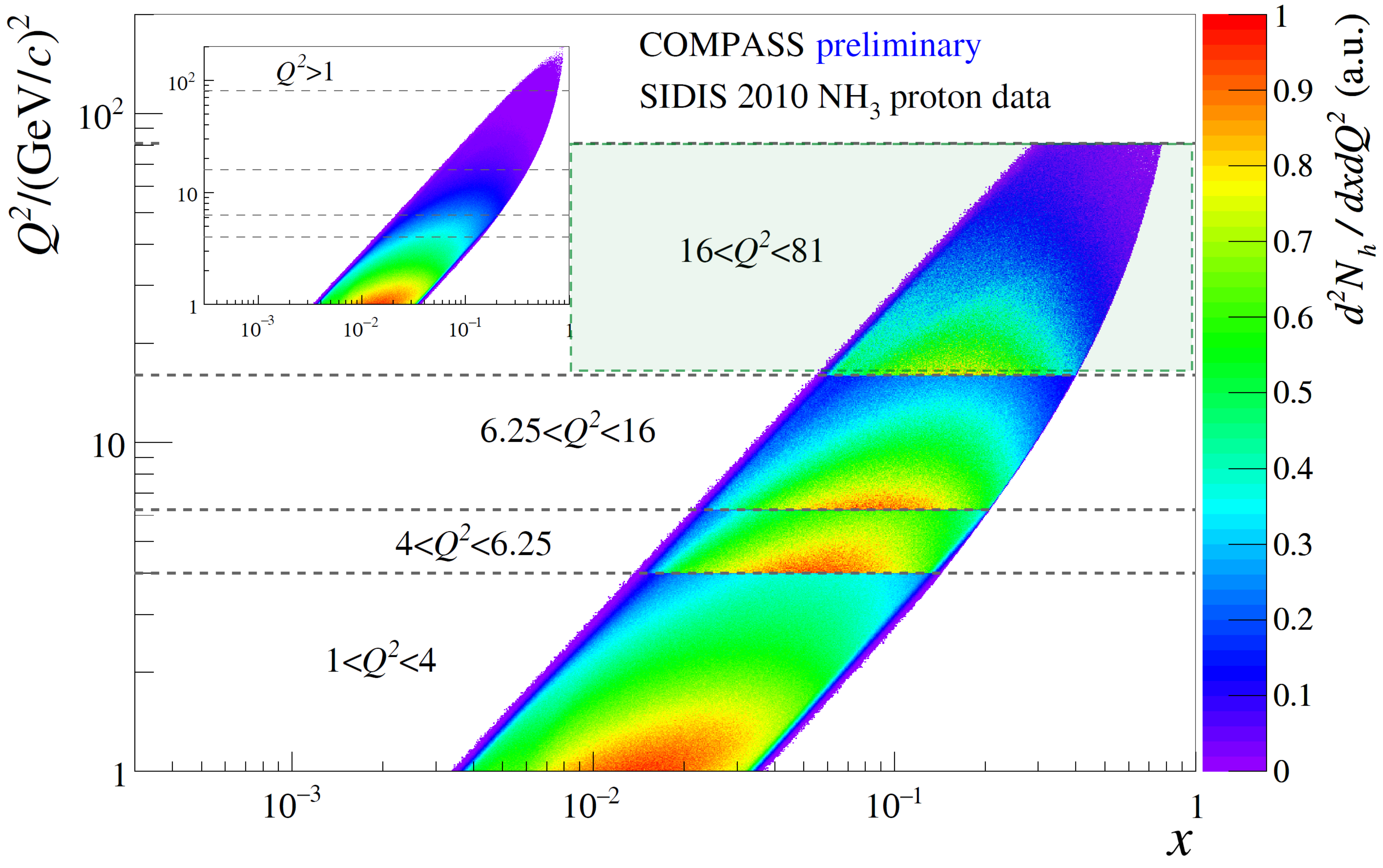
Essentially the same experimental setup +

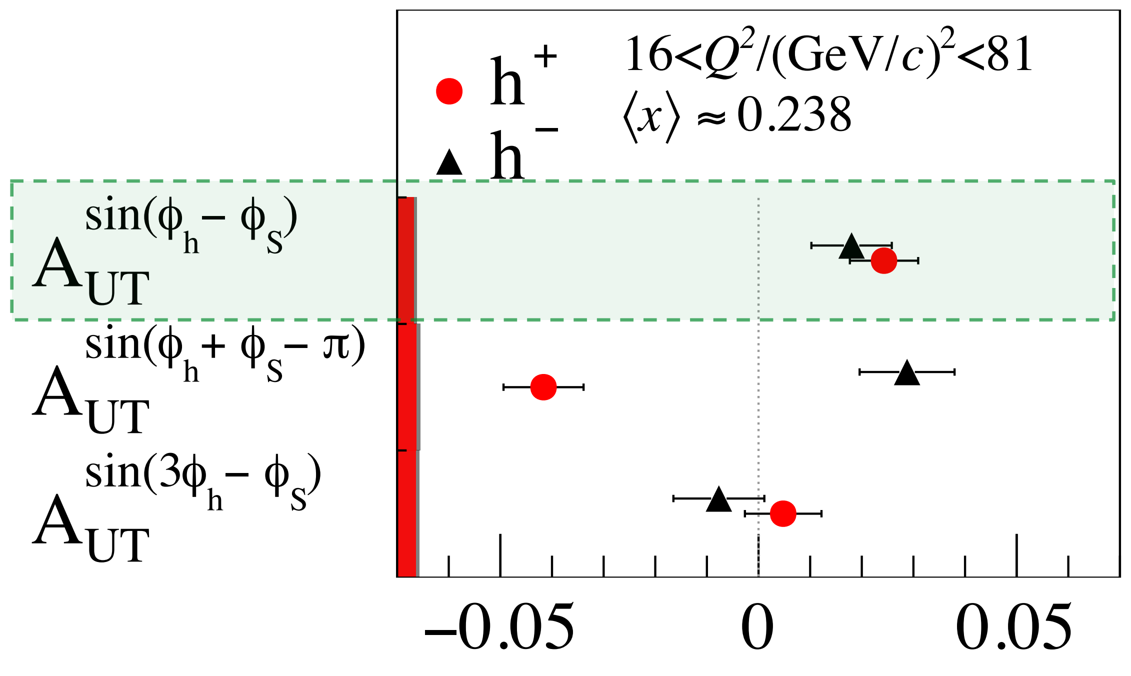
Comparable x:Q² kinematic coverage =

Unique experimental environment to test TMD Universality

SIDIS IN DRELL-YAN MASS RANGES

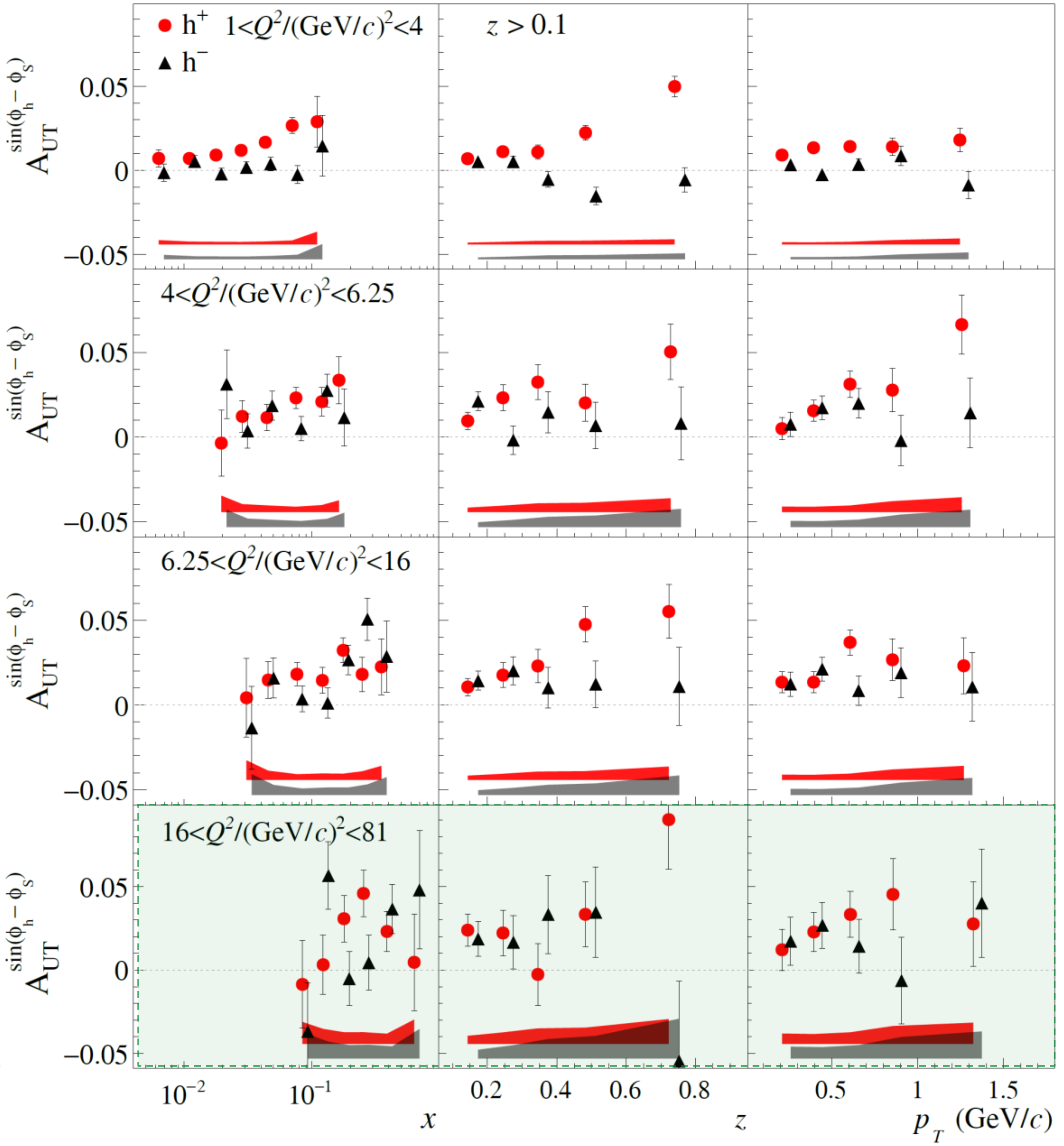
- Dedicated 2D-analysis performed by COMPASS dividing Proton 2010 data into the 4 DY Q^2 ranges
- SIDIS TSAs extracted for each DY Q^2 range





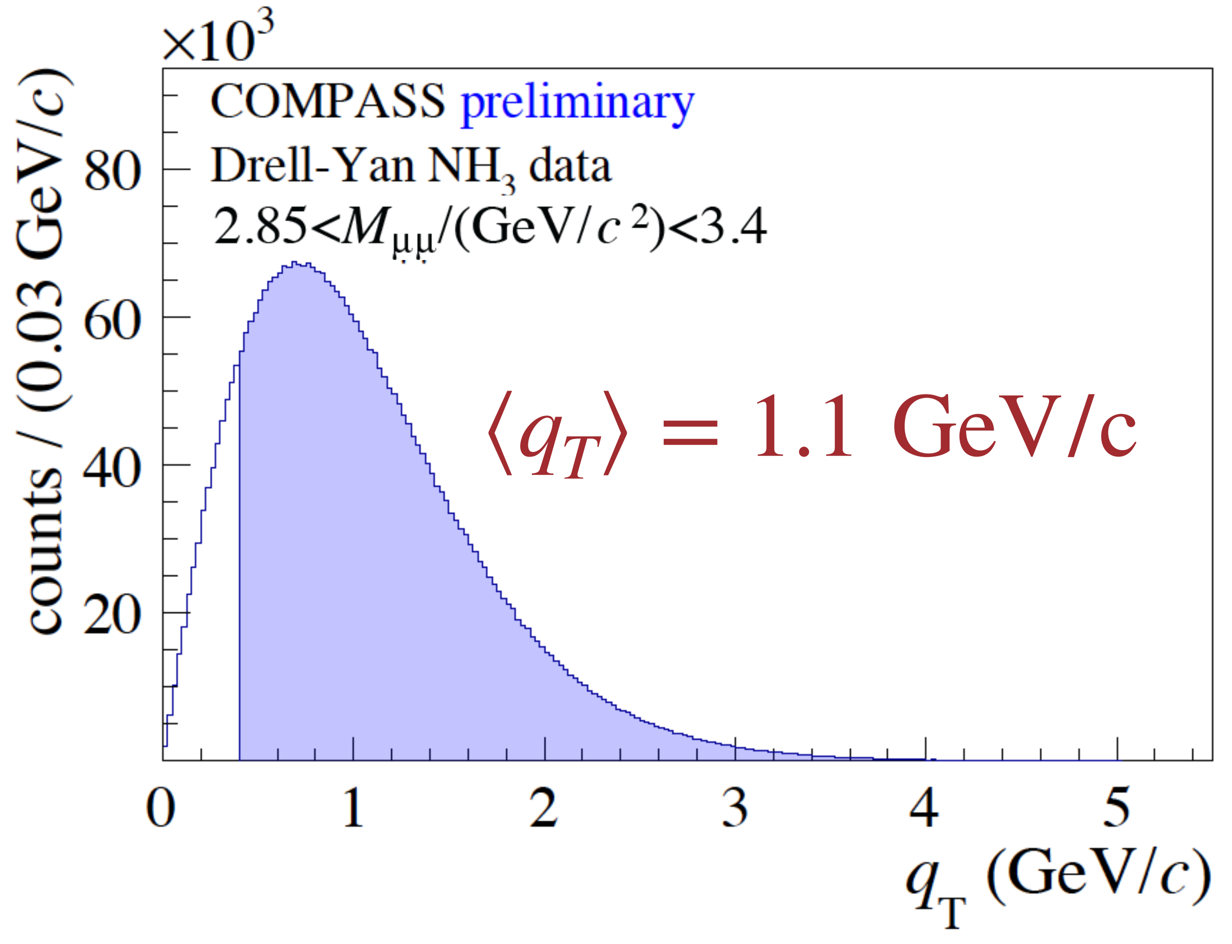
COMPASS, **PLB 770 (2017) 138**

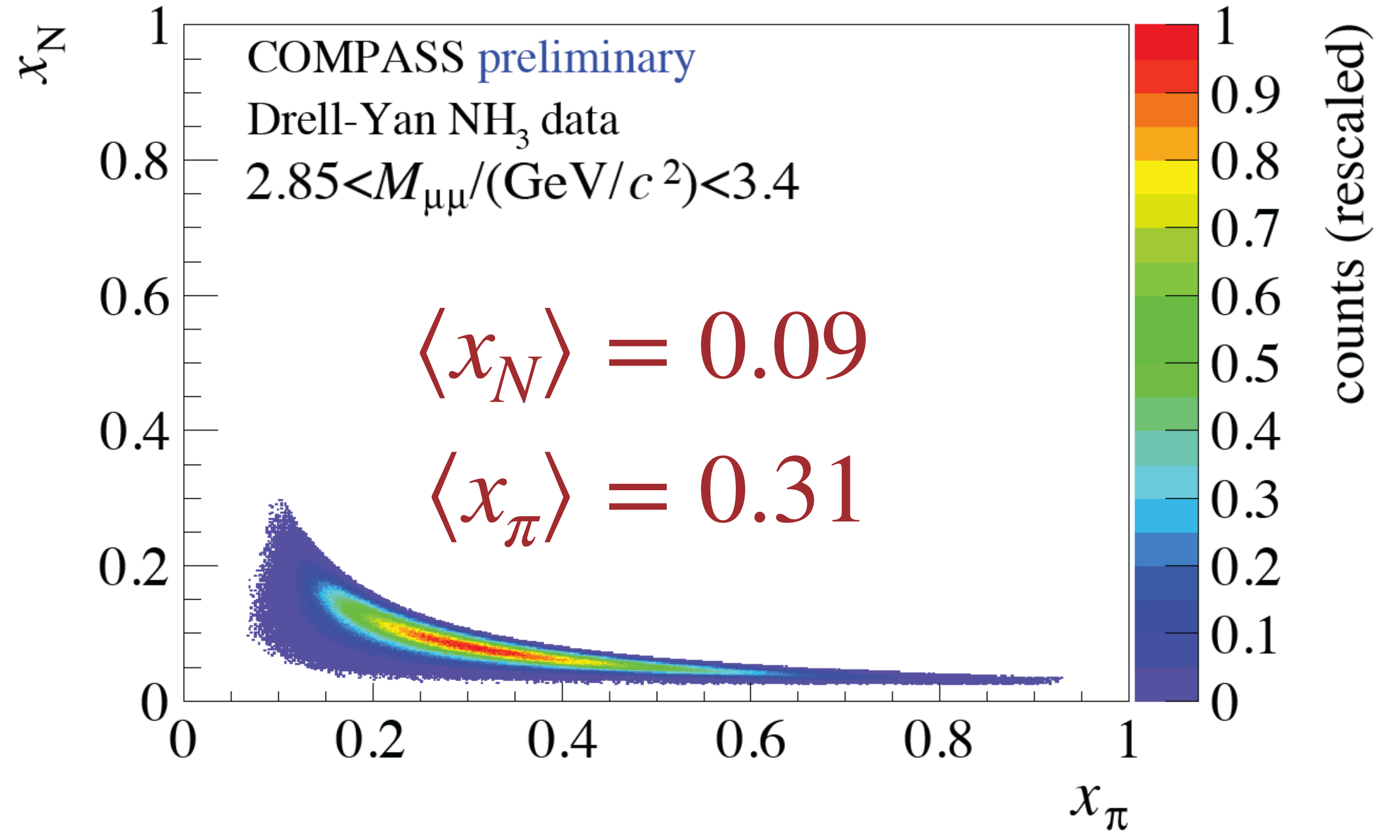
Sivers in HM range shows a non-zero signal for h+

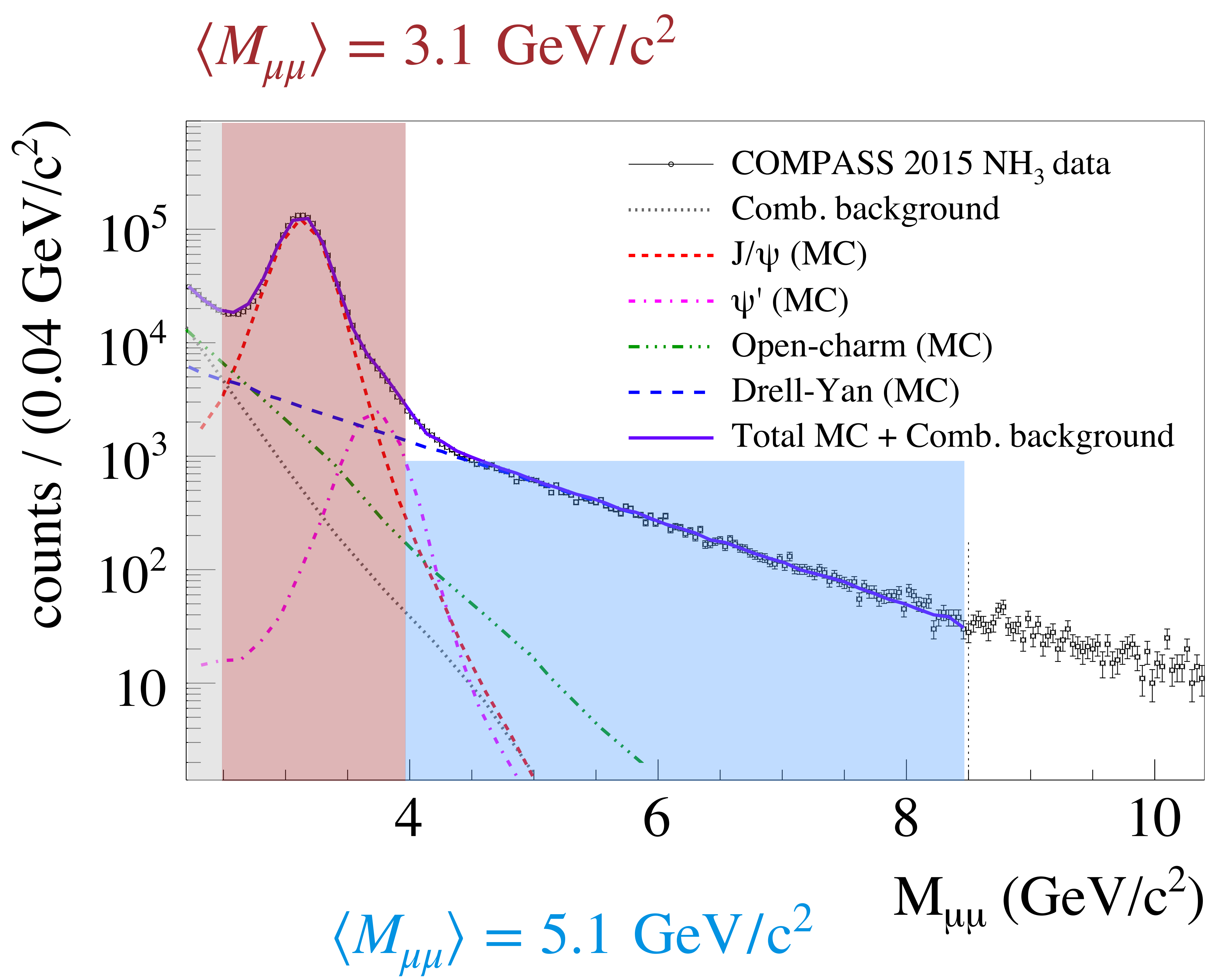


DRELL-YAN & J/PSI KINEMATICS @ COMPASS

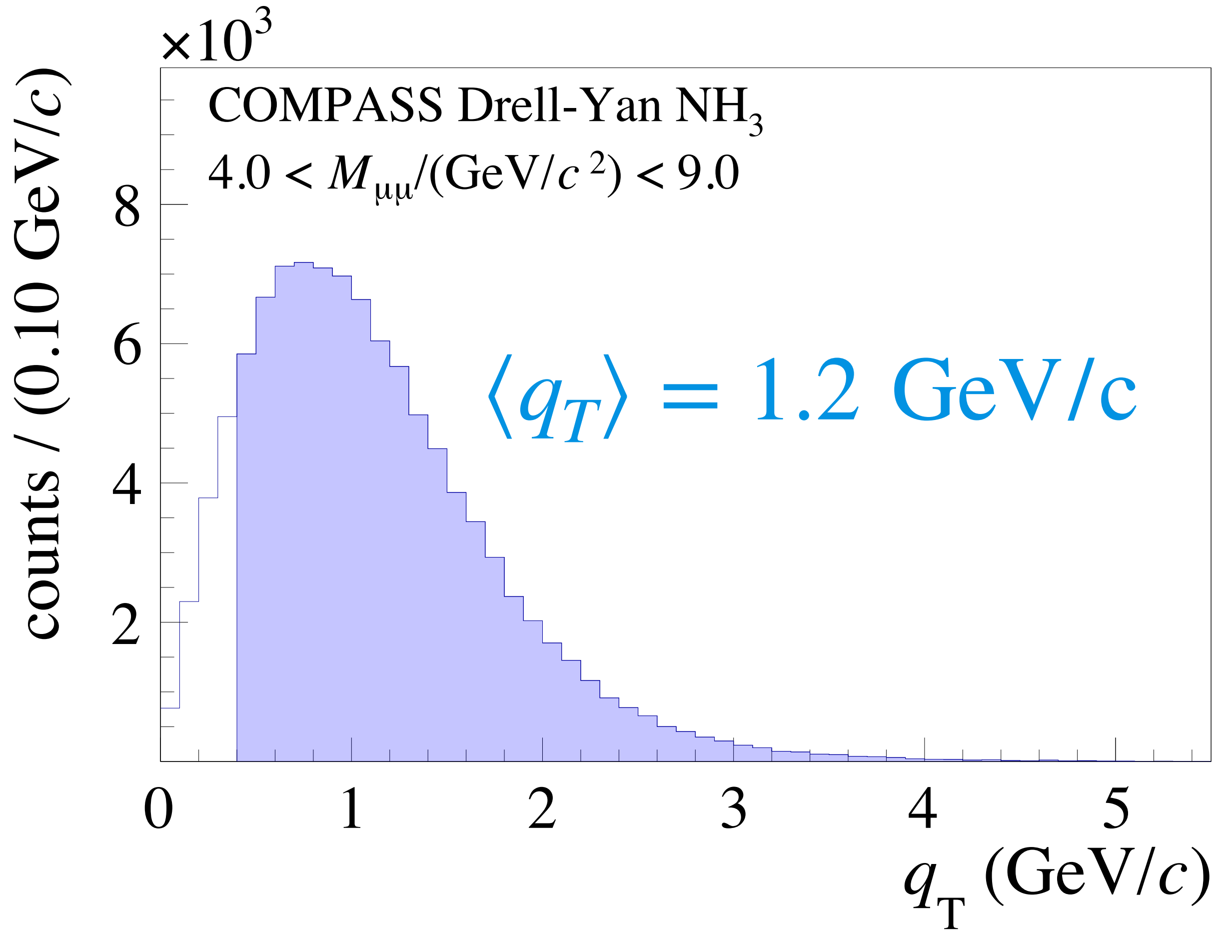
I. $2.85 < M_{\mu\mu}/(GeV/c^2) < 3.4$, "Charmonia mass"

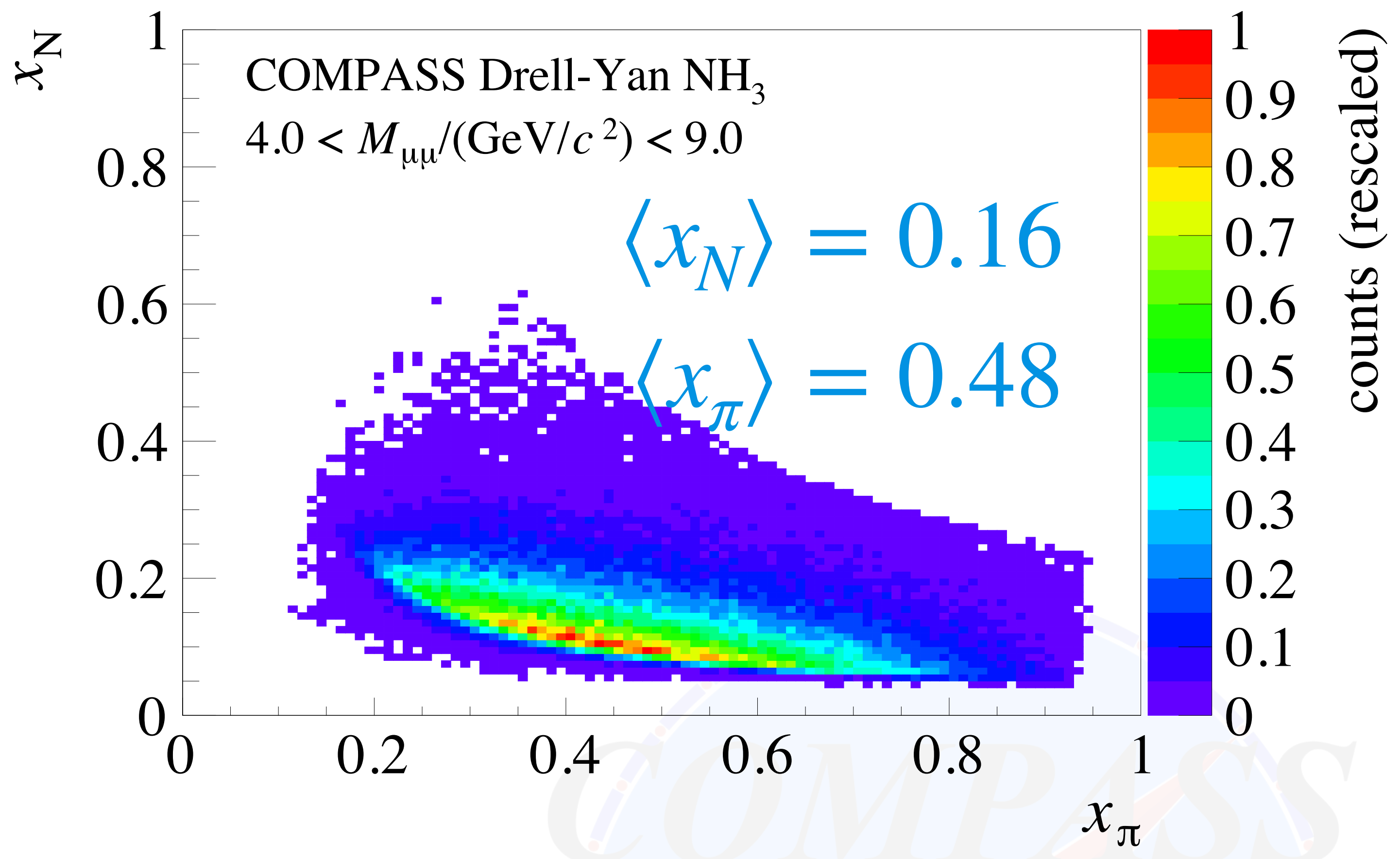




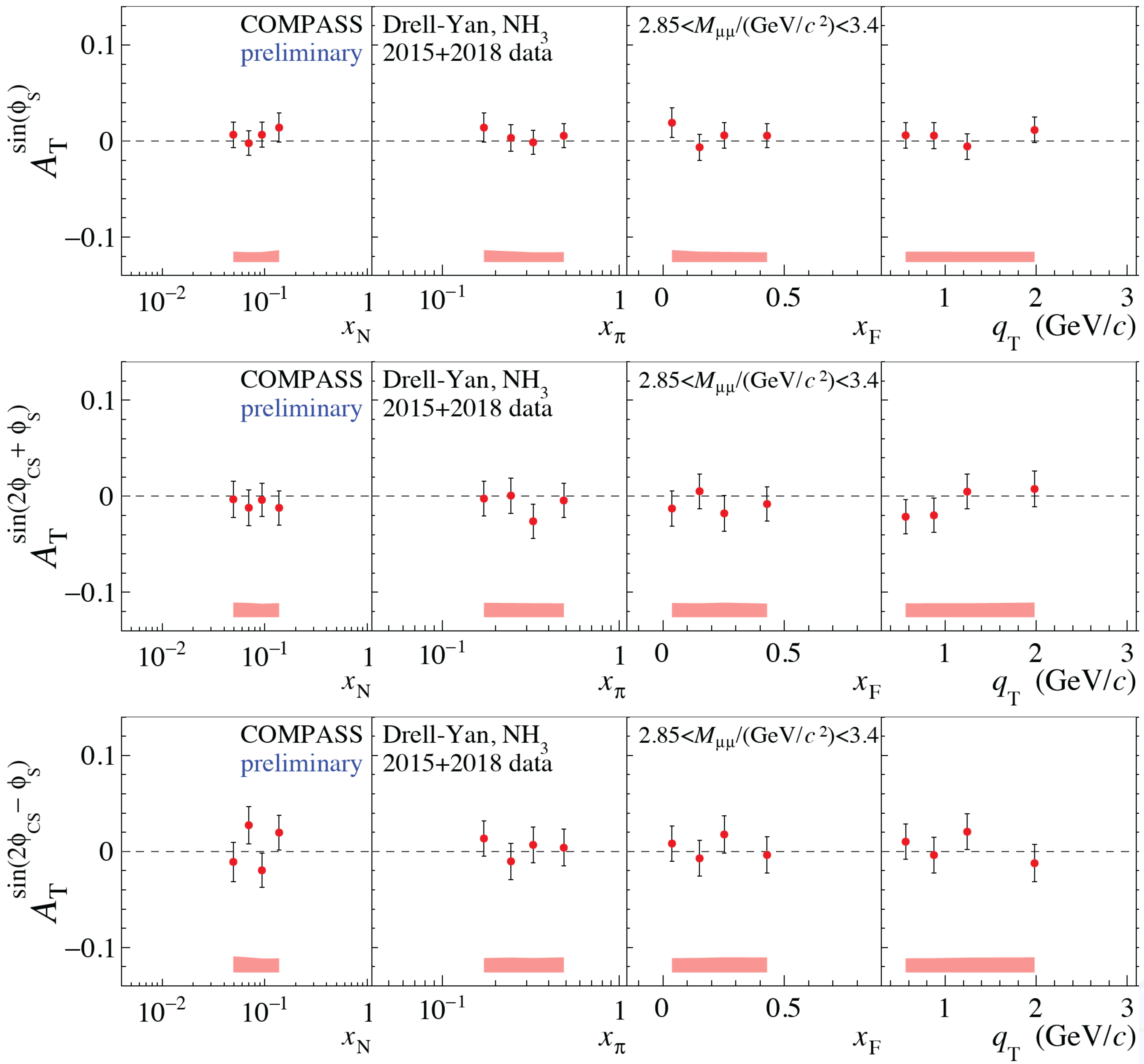


II. $4.0 < M_{\mu\mu}/(GeV/c^2) < 9.0$, "High mass"





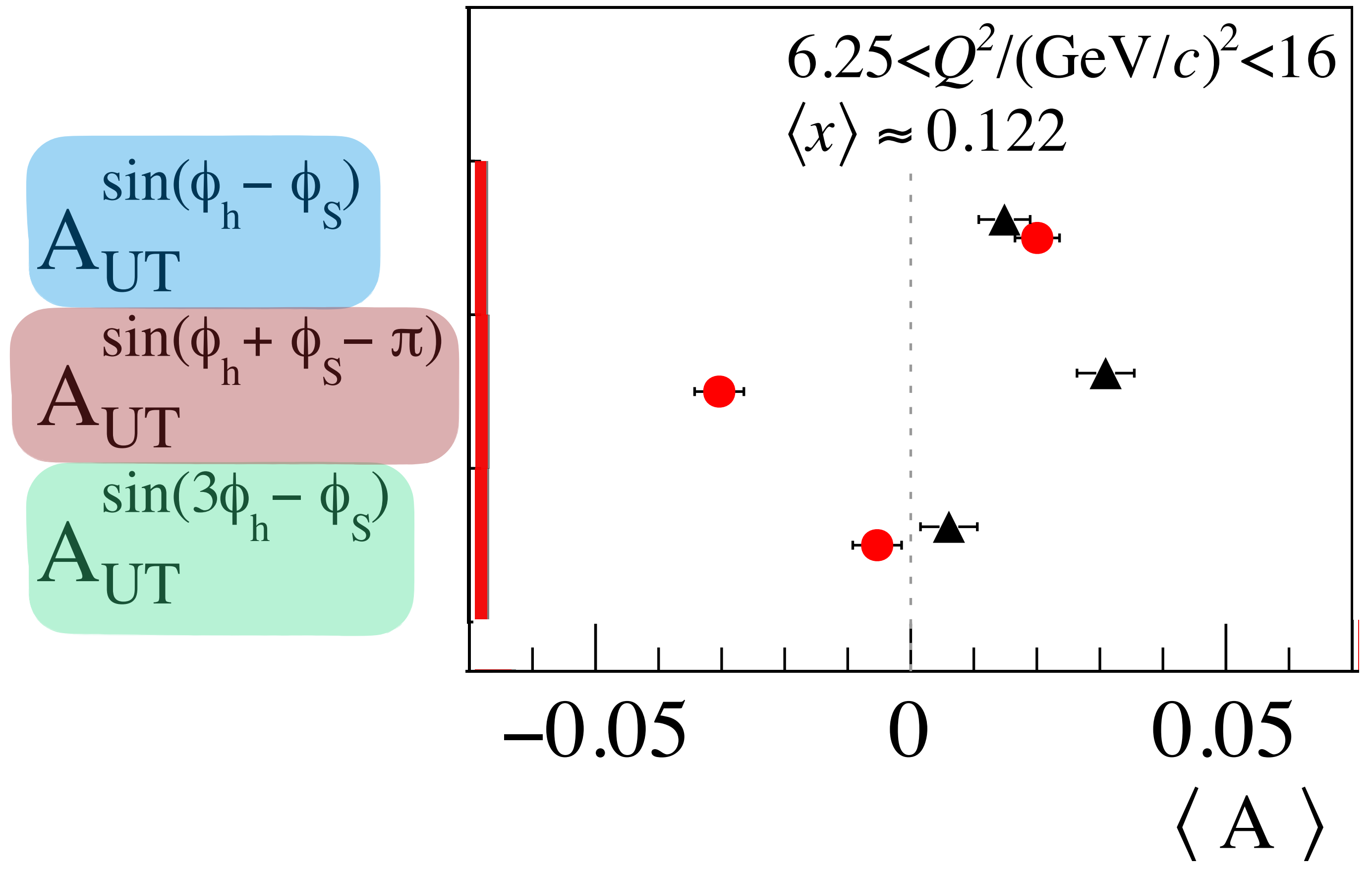
J/Ψ RESULTS



Sivers

Pretzelosity

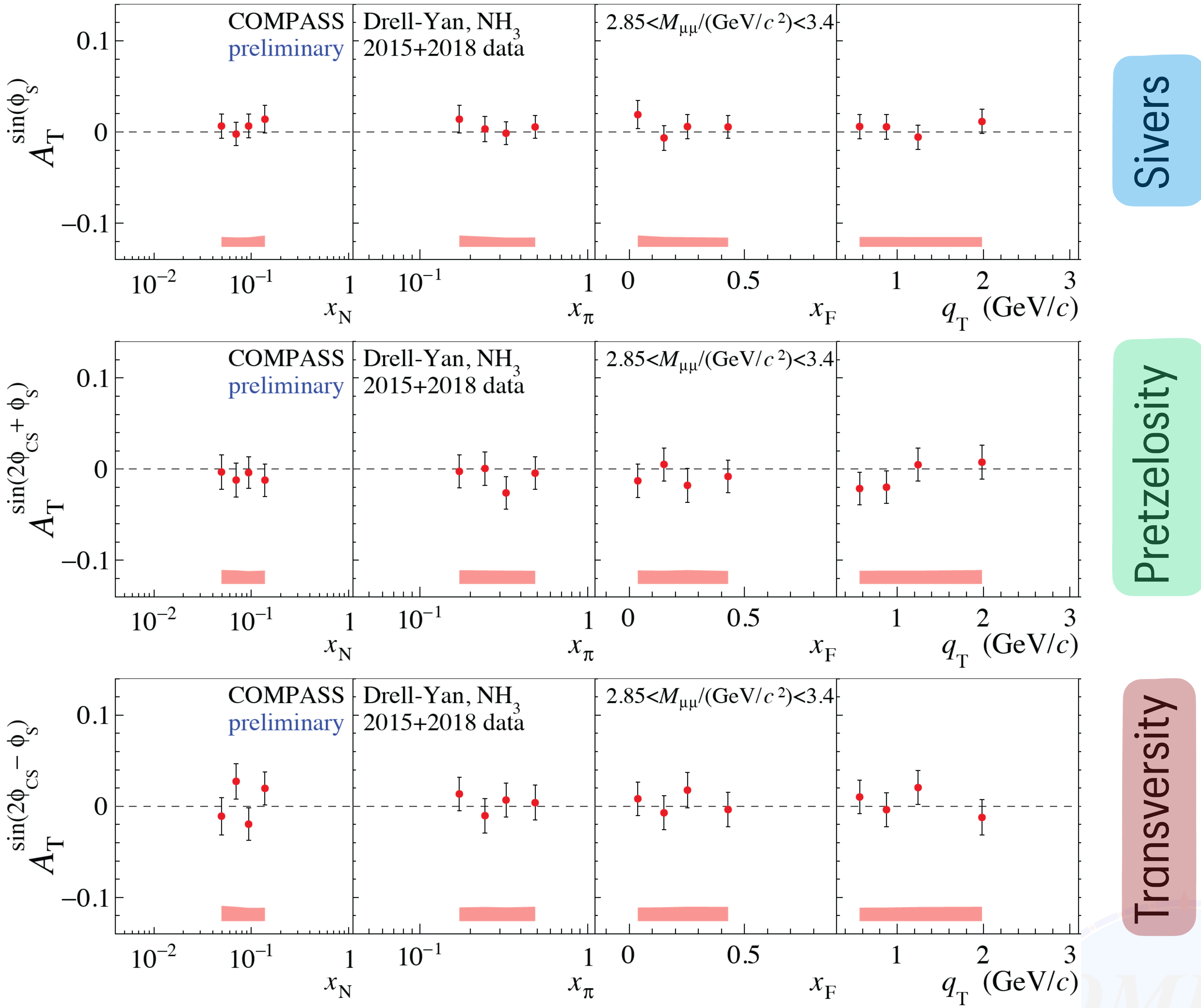
Transversity



COMPASS, SIDIS in DY

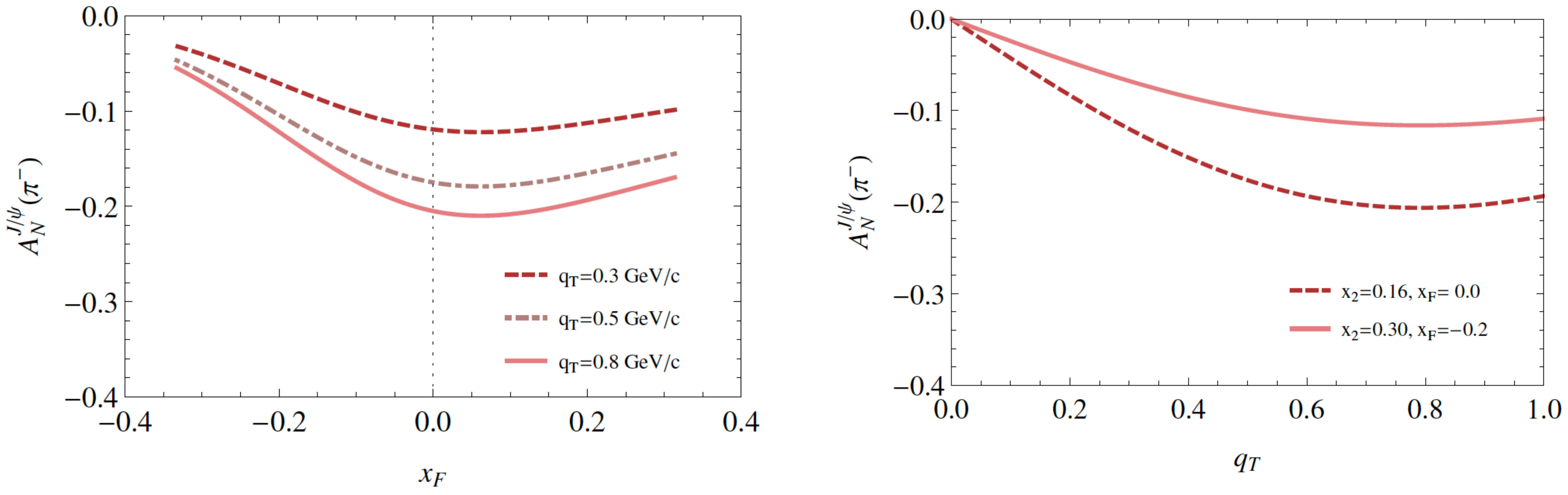
PLB 770 (2017) 138

All DY TSAs in the J/ψ mass range are small and **compatible with zero**



Anselmino et al., **PLB 770 (2017) 302**

Assuming $q\bar{q}$ dominant channel + neglecting gg fusion & feed down J/ψ



All DY TSAs in the J/ψ mass range are small and **compatible with zero**

Interpretation of the results not straightforward (TMD framework, J/ψ production mechanism, …)

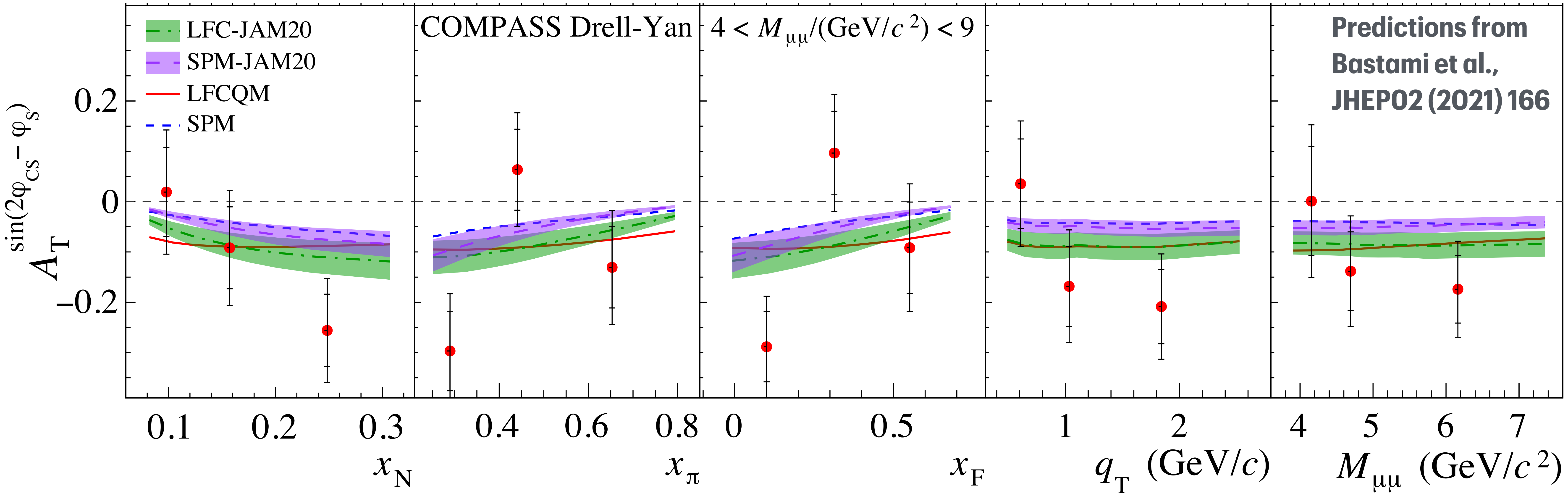
Hint that J/ψ production might go via gg fusion in COMPASS kinematic regime

See also talk by J.C.Peng
Monday Afternoon Session

DRELL-YAN TSAs : TRANSVERSITY

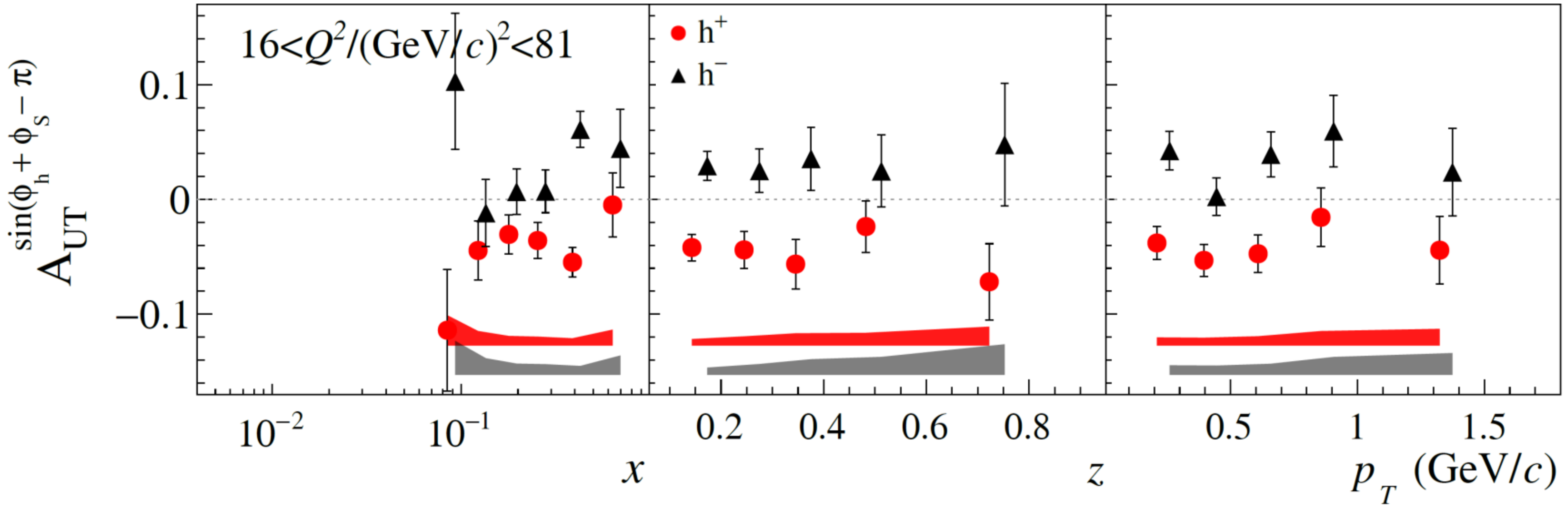
COMPASS DY 2015+2018
Final results
arXiv:2312.17379,
accepted by PRL

DY - HM range $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$



$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$

COMPASS Collins TSA in SIDIS, HM range



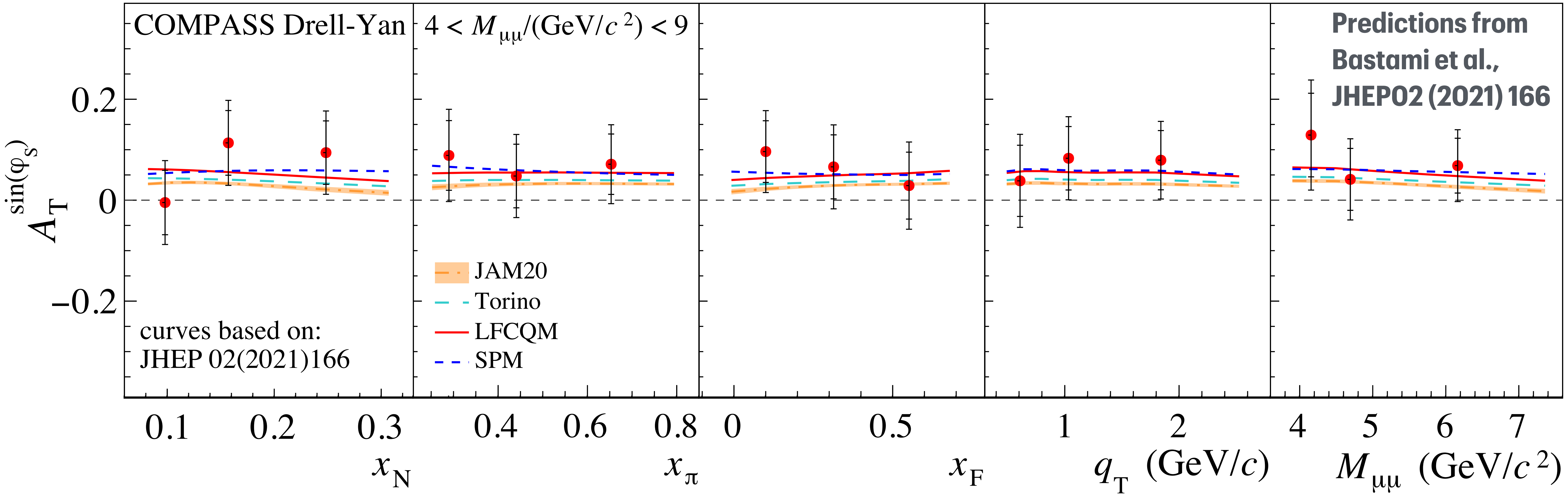
PLB 770 (2017) 138

DRELL-YAN TSAs : SIVERS

DY - HM range

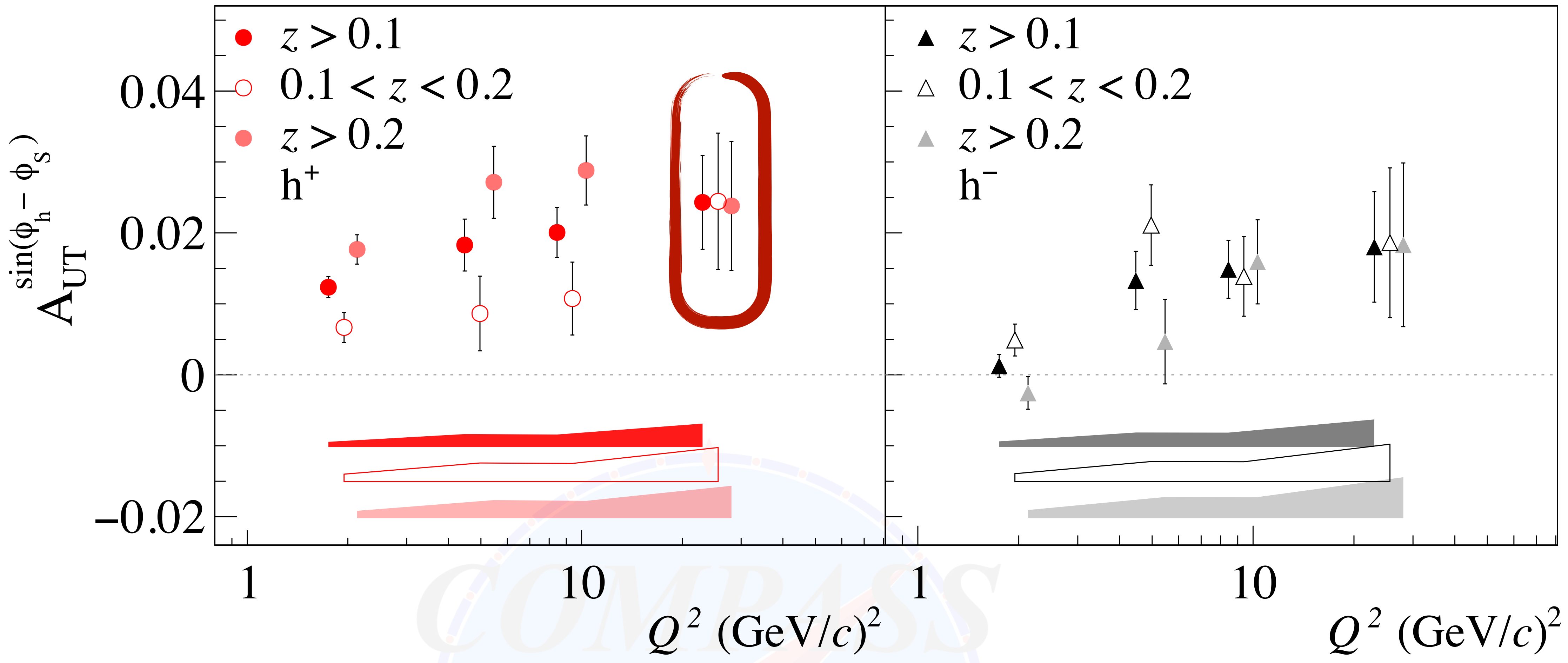
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

COMPASS DY 2015+2018
Final results
arXiv:2312.17379,
accepted by PRL



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

COMPASS Sivers
TSA in SIDIS, HM
range



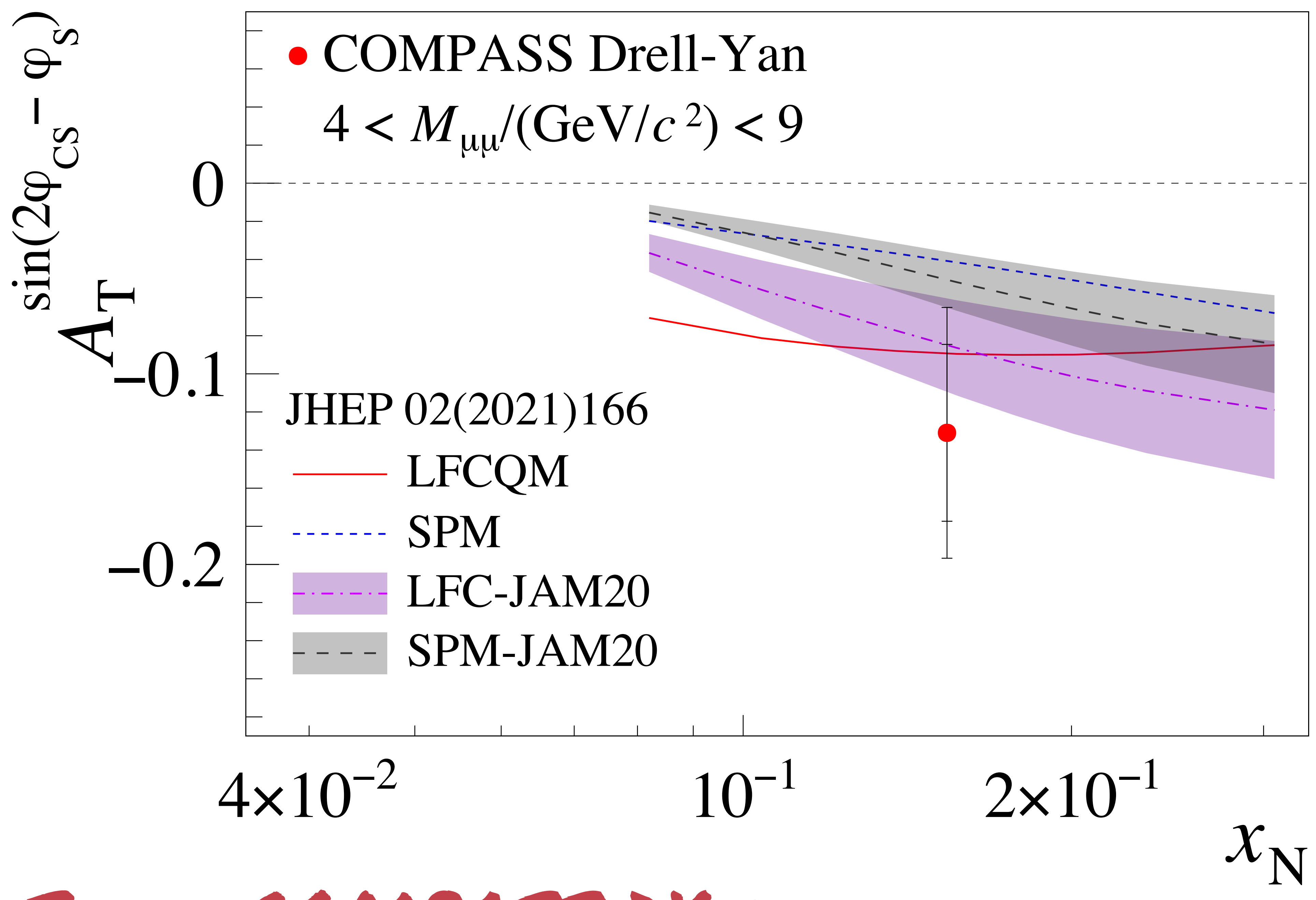
PLB 770 (2017) 138

COMPASS UNIQUE TEST OF TMD UNIVERSALITY

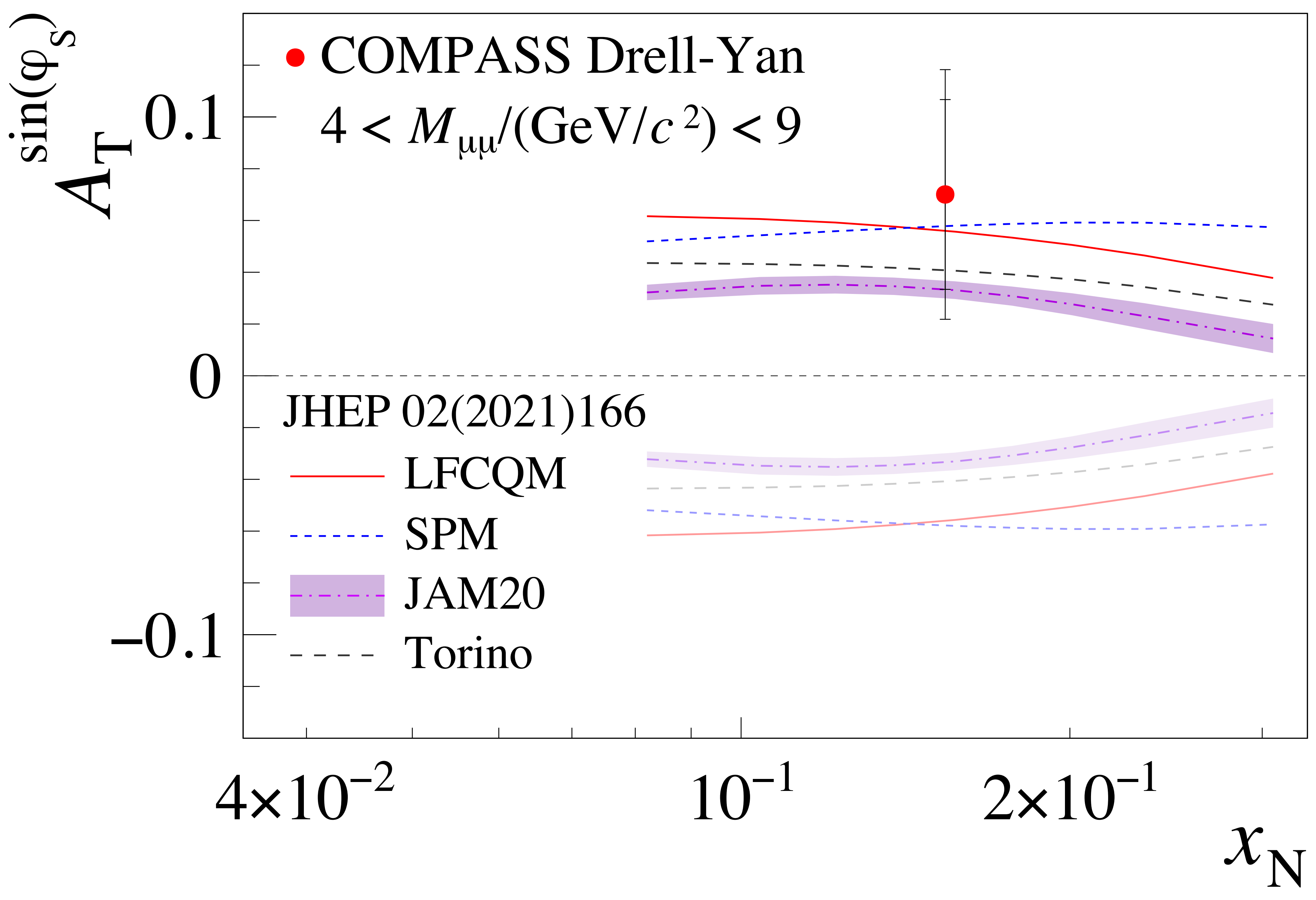
COMPASS DY 2015+2018 Final results

arXiv:2312.17379, accepted by PRL

Transversity



Sivers



Sign change

No sign change

Final COMPASS DY results:

- general agreement with universality in TMD-QCD parton model approach
- favors the sign-change of Sivers TMD PDF in DY
- What about Boer-Mulders?

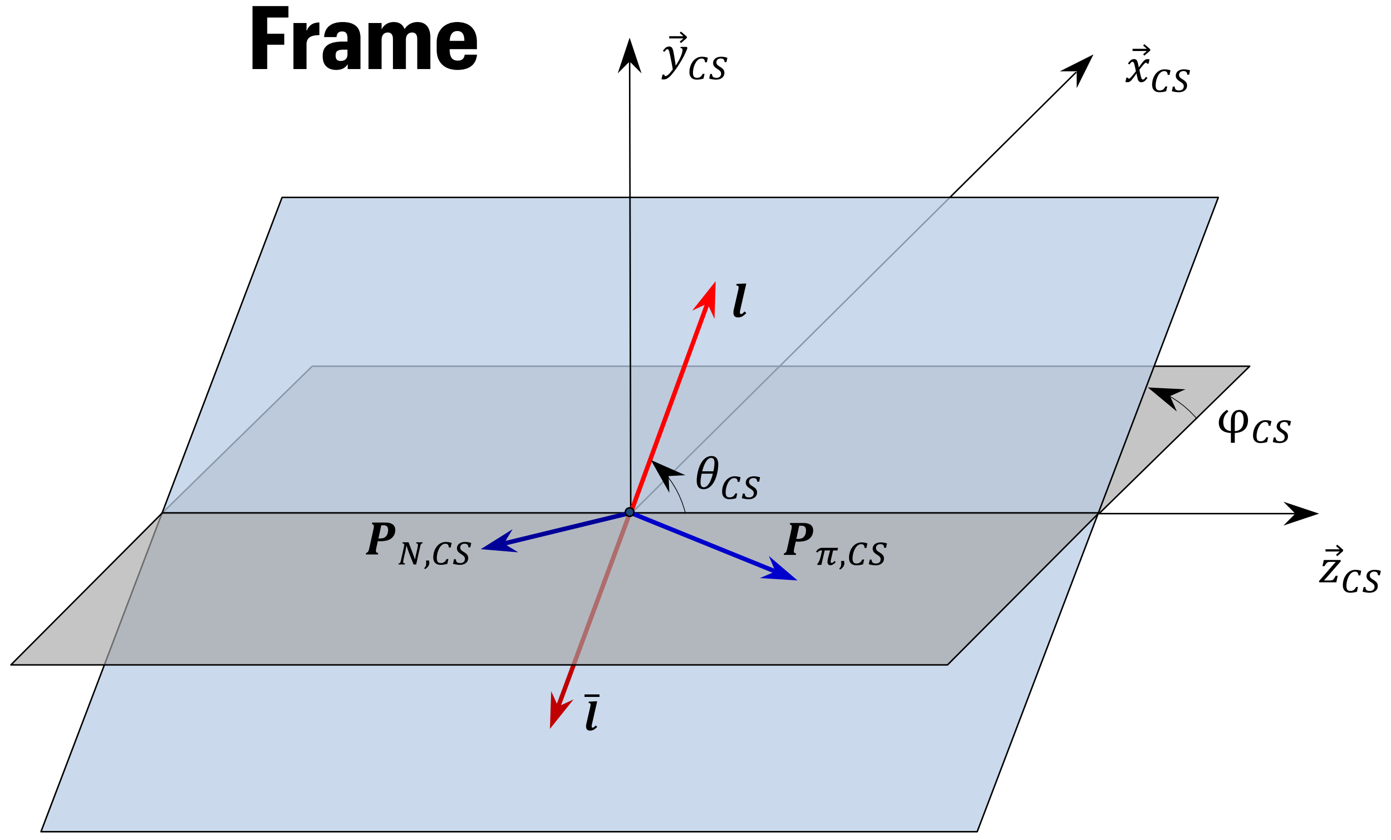
DRELL-YAN UNPOLARIZED CROSS-SECTION

- General expression for the unpolarized part of the DY cross-section:

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin 2\theta_{CS}\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

3 Unpolarized Asymmetries (UAs) $\lambda = A_U^1 \quad , \quad \mu = A_U^{\cos\varphi_{CS}} \quad , \quad \nu = 2A_U^{\cos 2\varphi_{CS}}$

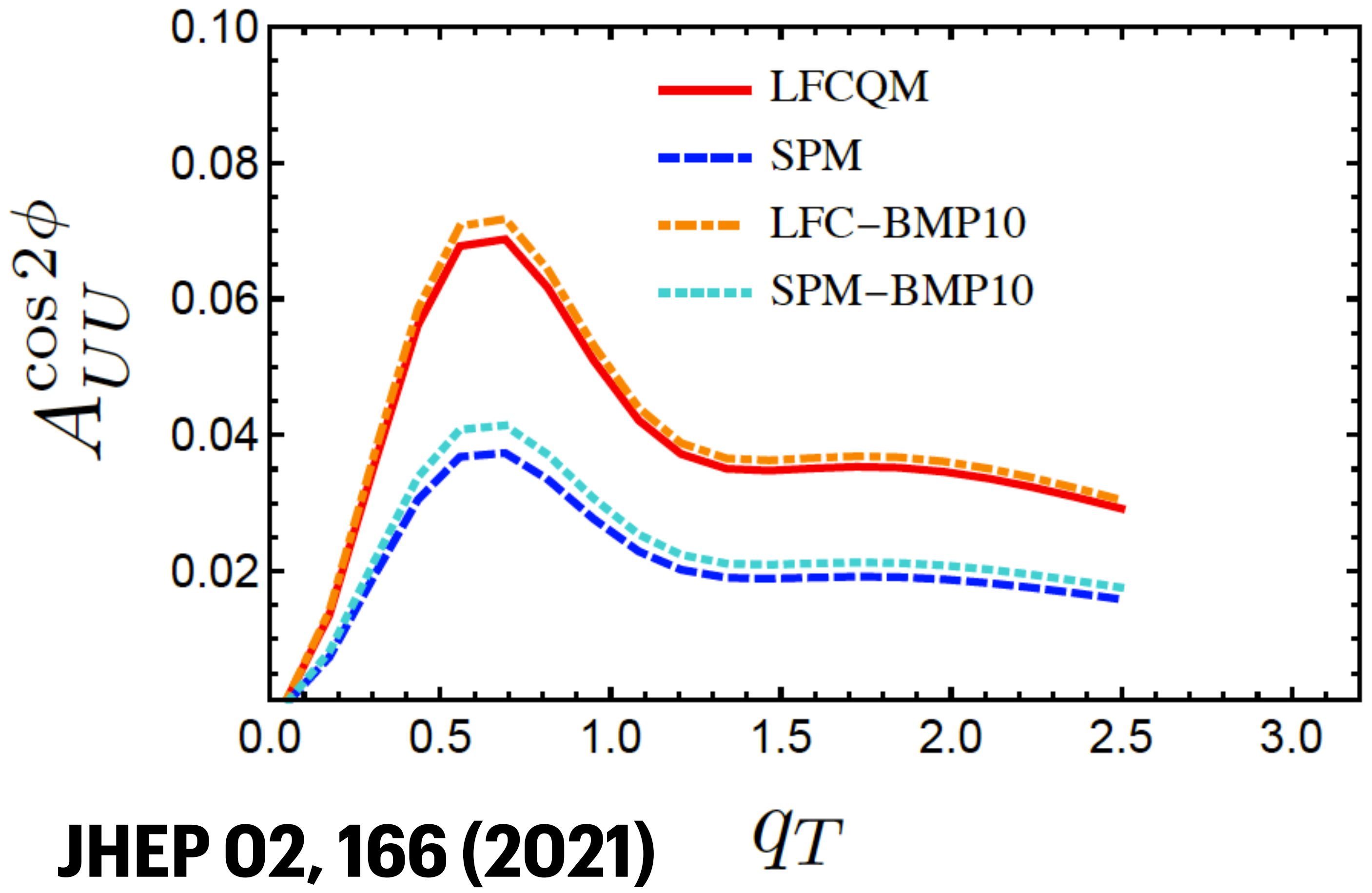
Collins-Soper Frame



- At LO of Drell-Yan process, the virtual photon is produced purely by the electromagnetic $q+\bar{q}$ annihilation: $\lambda=1,\ \mu=\nu=0$
- Lam-Tung relation [**PRD 18(1978) 2447**]: $1-\lambda=2\nu$

ν **interpretation in terms of TMDs**

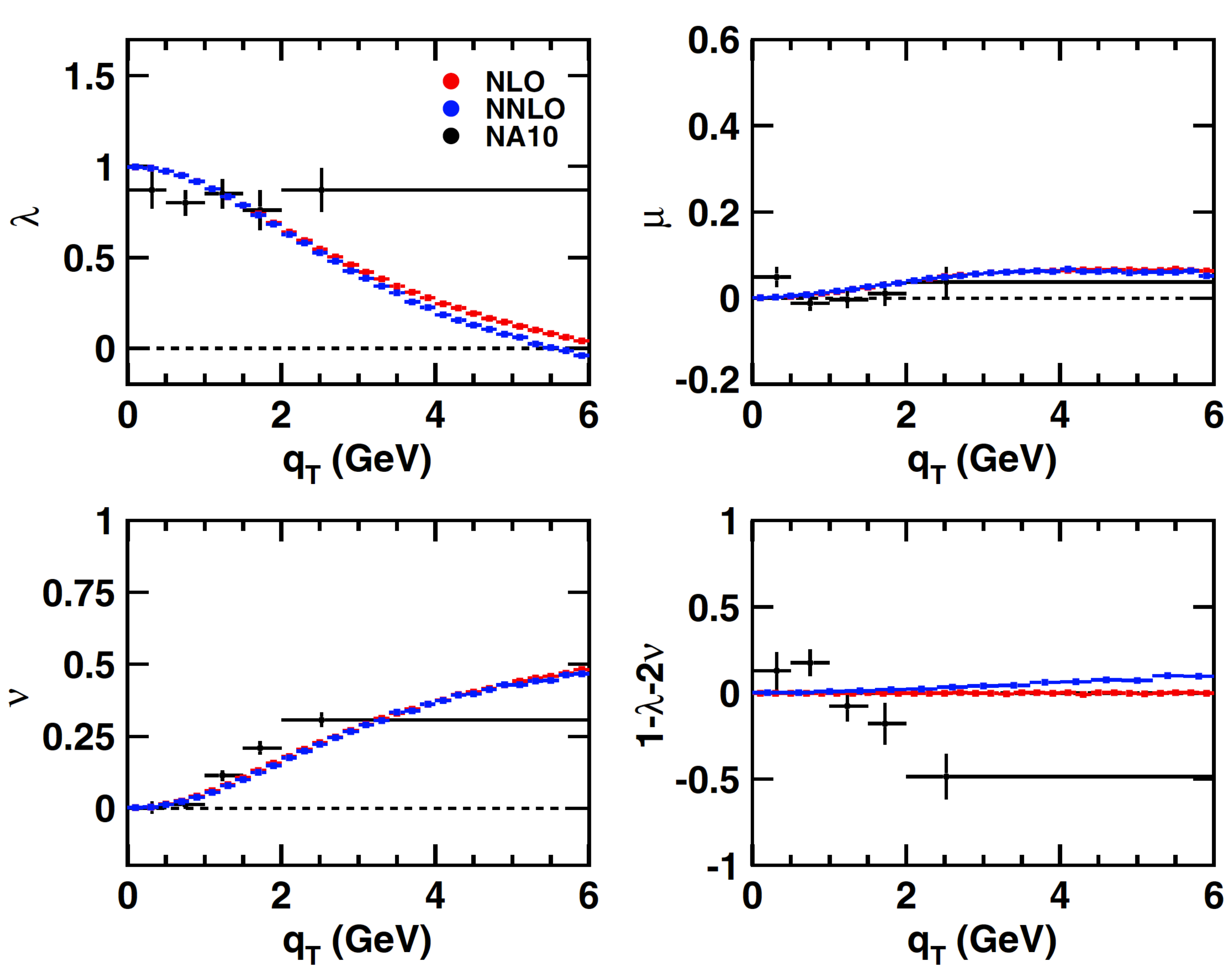
$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto h_1^{\perp q}(p) \otimes h_1^{\perp\bar{q}}(\pi^-)$$



JHEP 02, 166 (2021)

$A_{UU}^{\cos 2\phi}$ prediction for COMPASS kinematics

NA10 π^-+W at 194 GeV

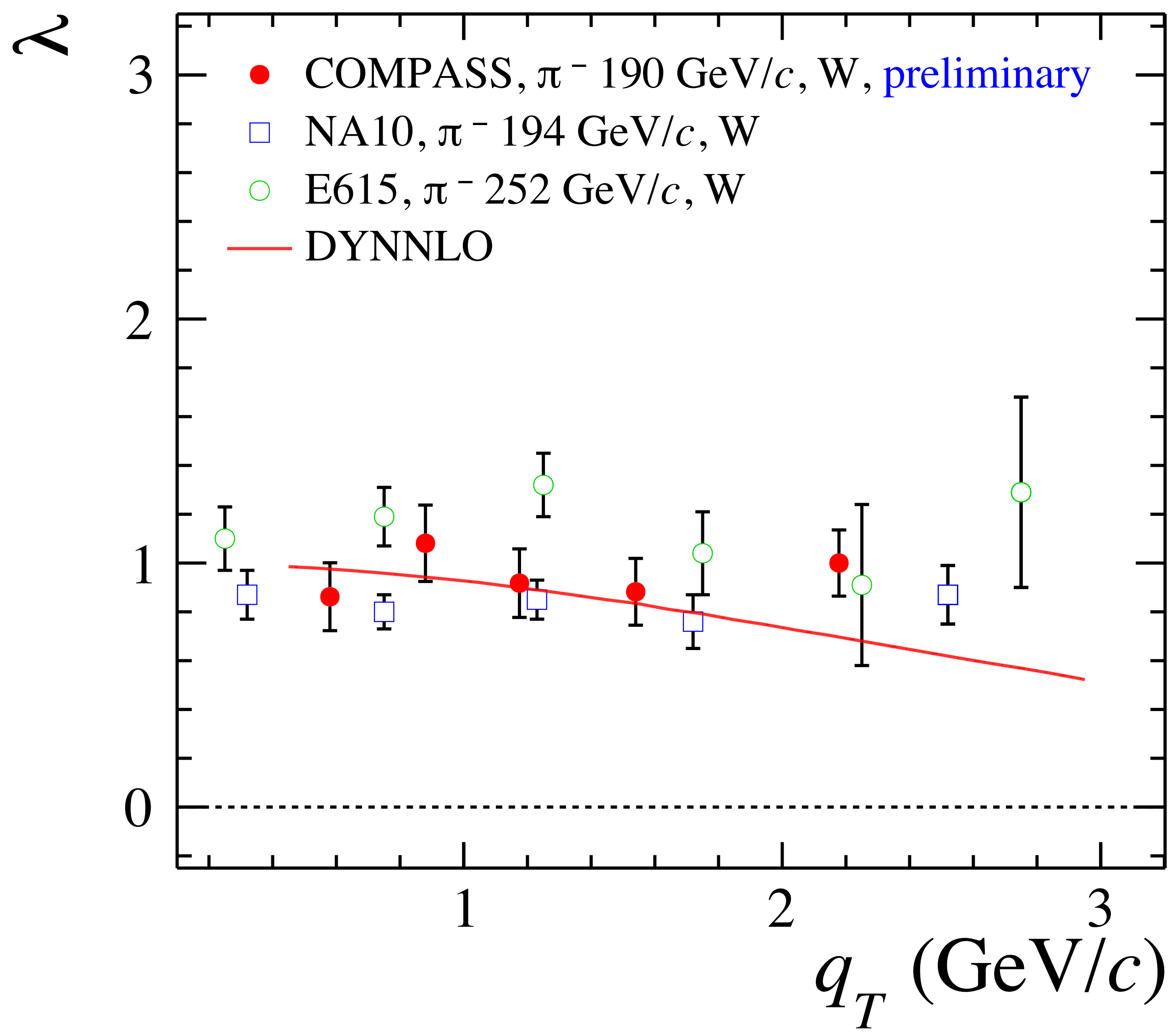


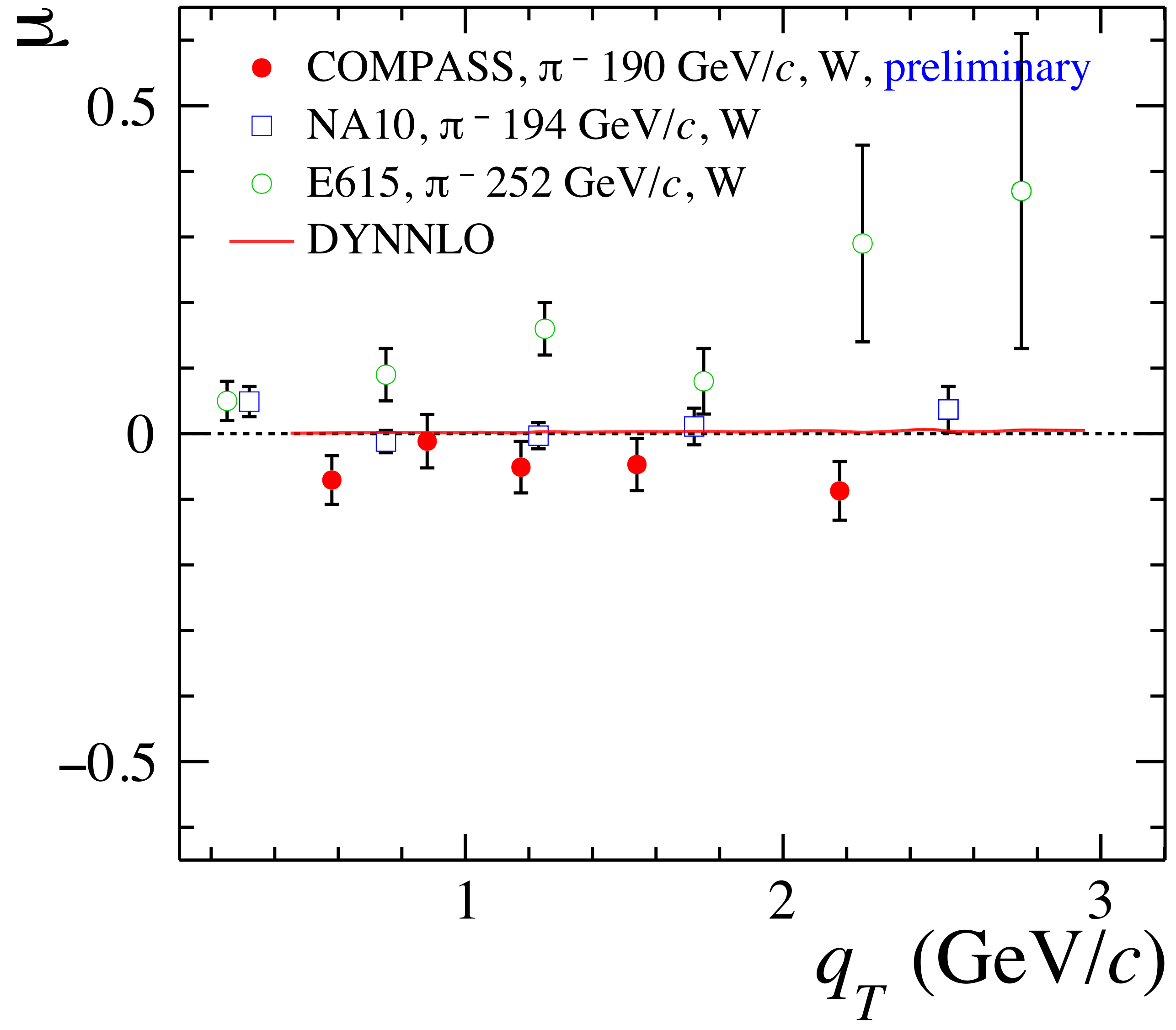
Also room for contributions from NLO and NNLO effects

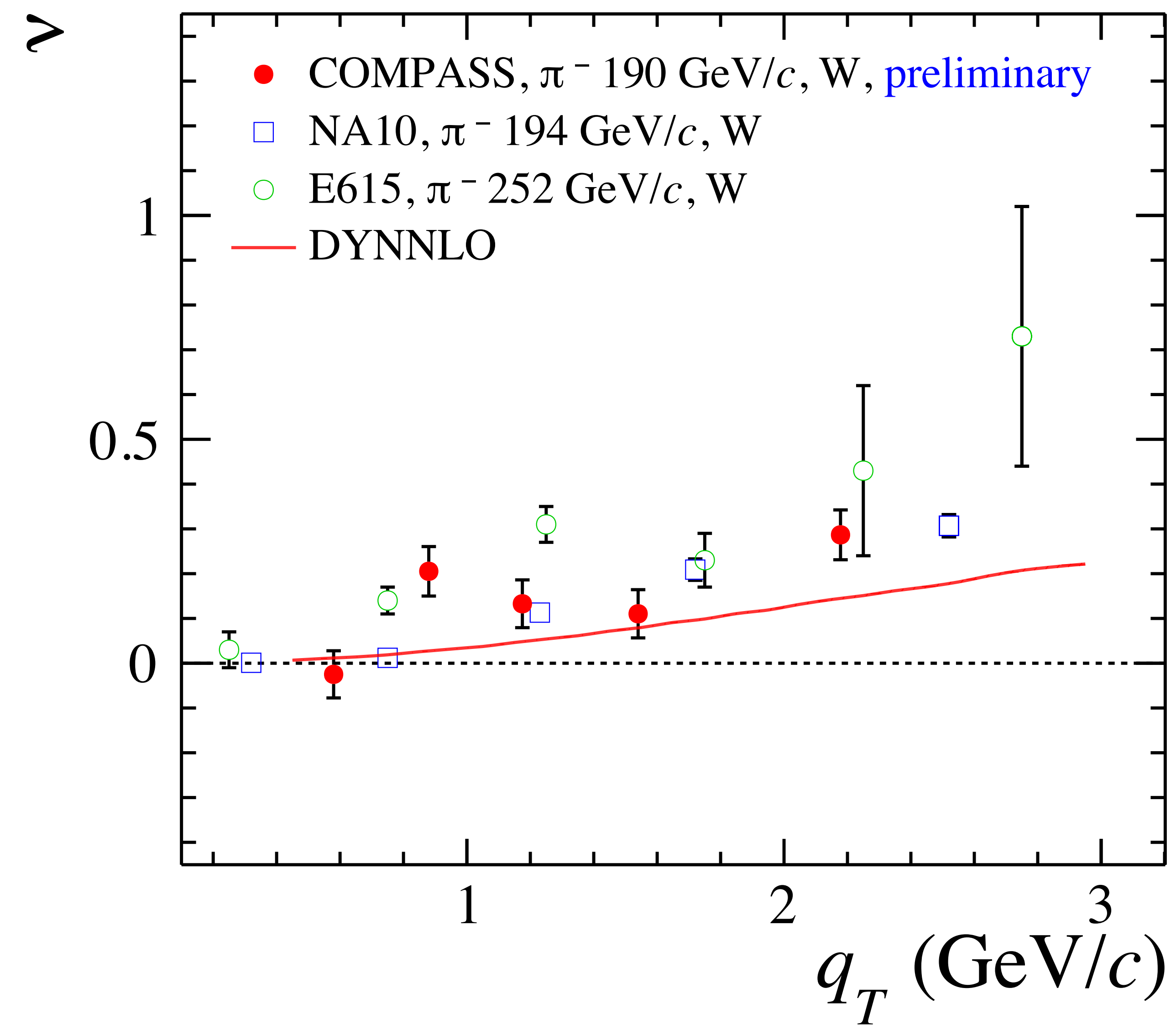
PRD 99, 014032 (2019)

DRELL-YAN UNPOLARIZED CROSS-SECTION

Y.Lien, **SciPost Phys. Proc. 2021**



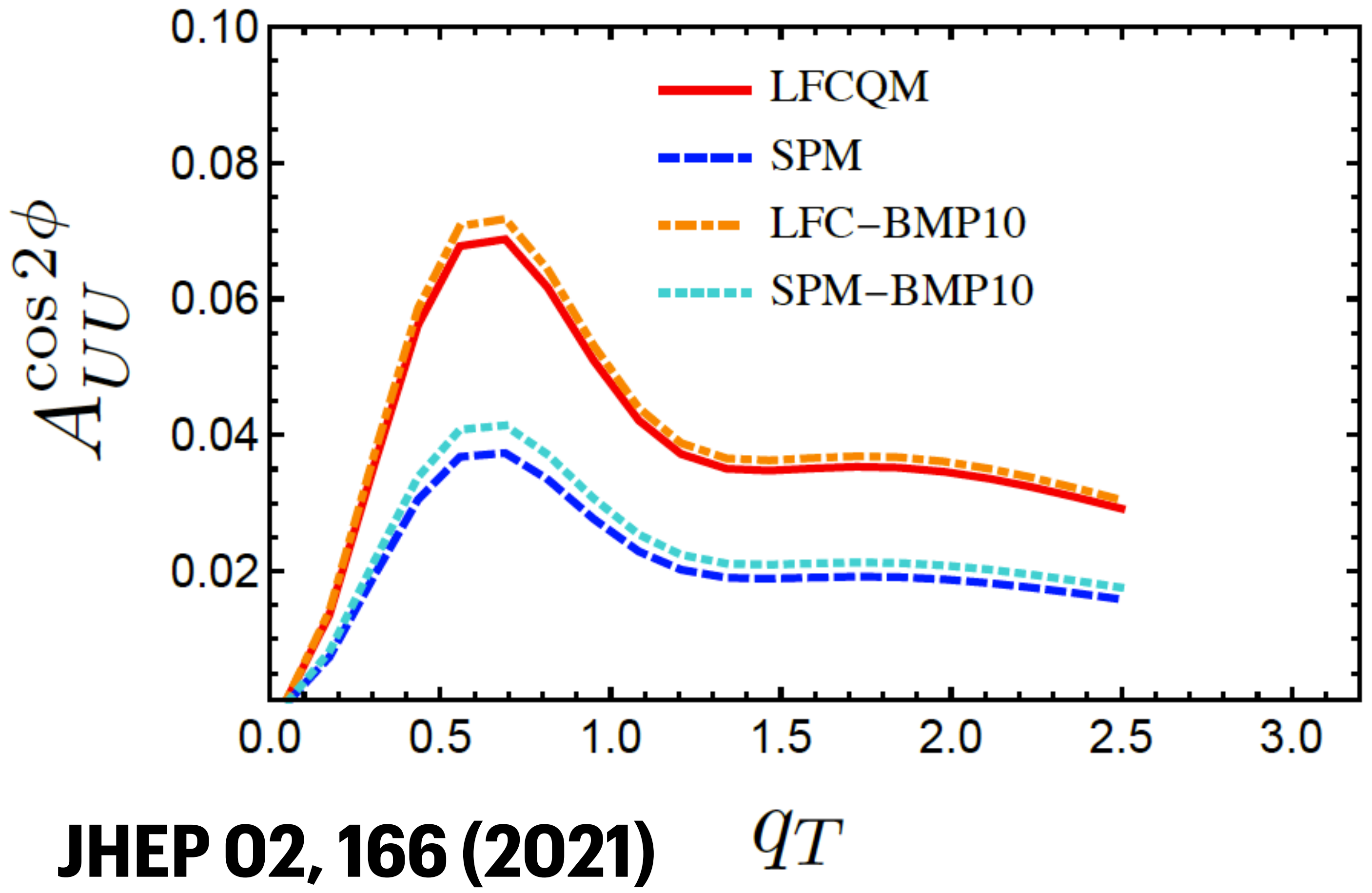




COMPASS DY data confirms $A_{UU}^{\cos 2\varphi} > 0$

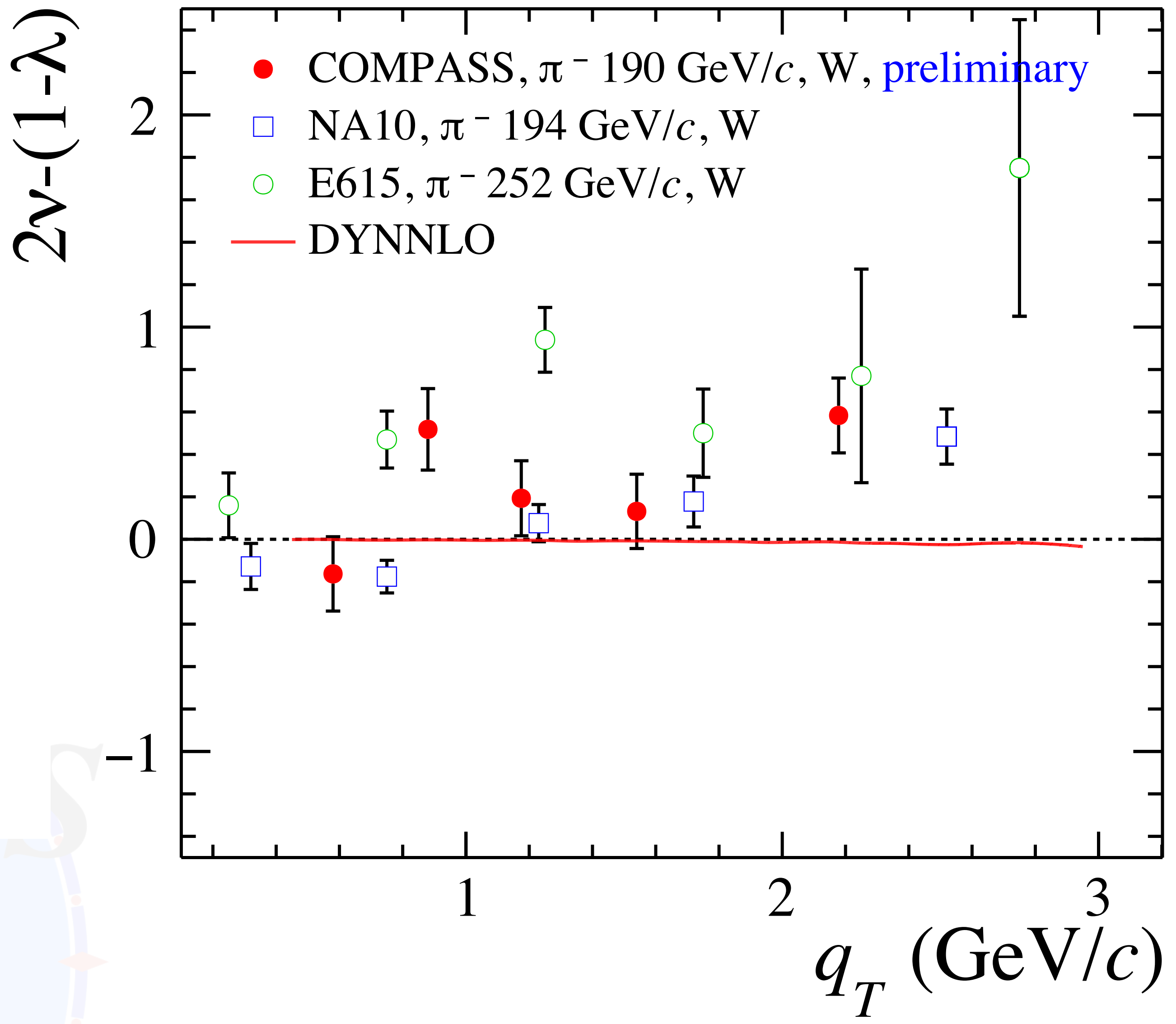
ν interpretation in terms of TMDs

$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto h_1^{\perp q}(p) \otimes h_1^{\perp \bar{q}}(\pi^-)$$



JHEP 02, 166 (2021)

$A_{UU}^{\cos 2\phi}$ prediction for COMPASS kinematics

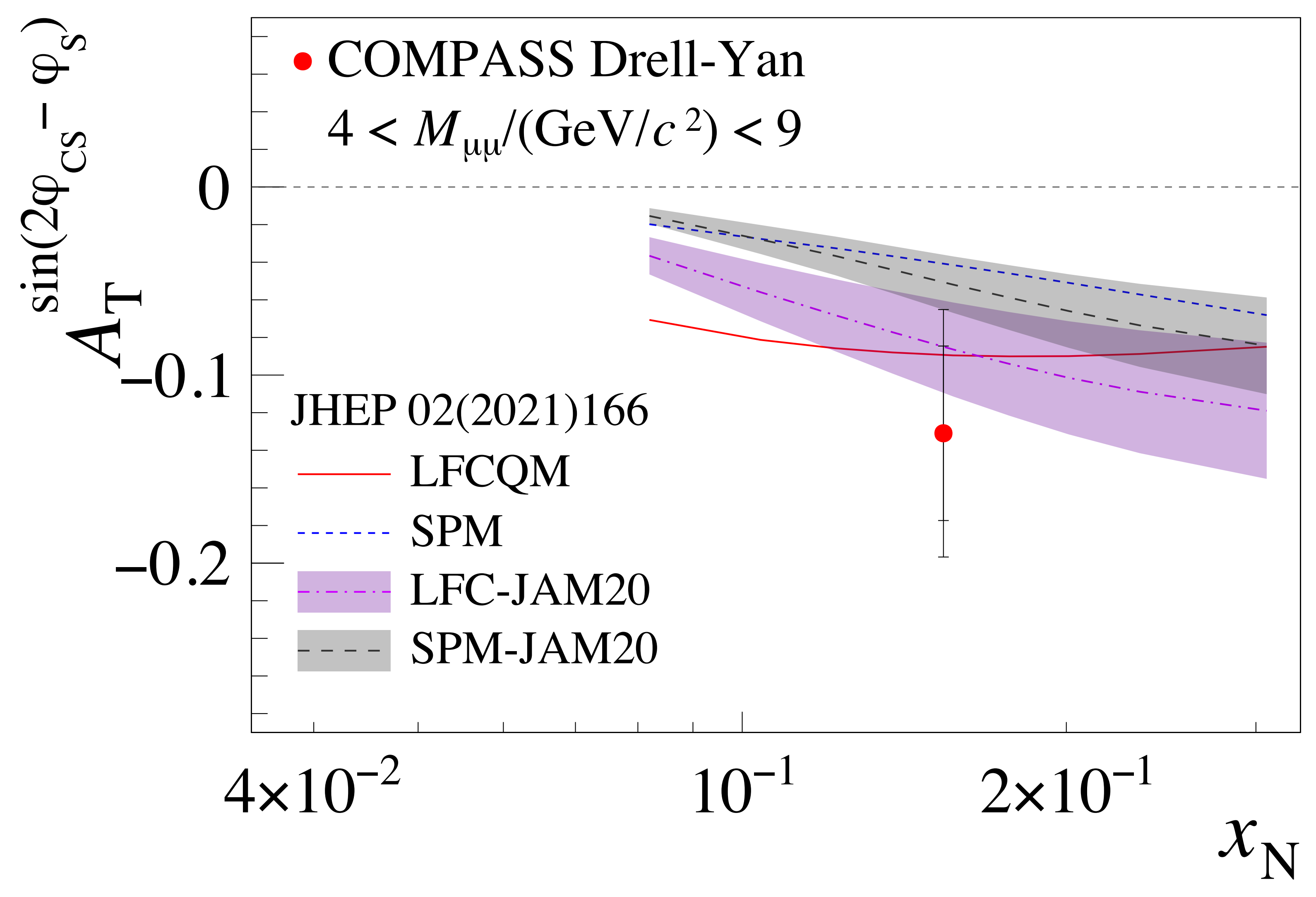


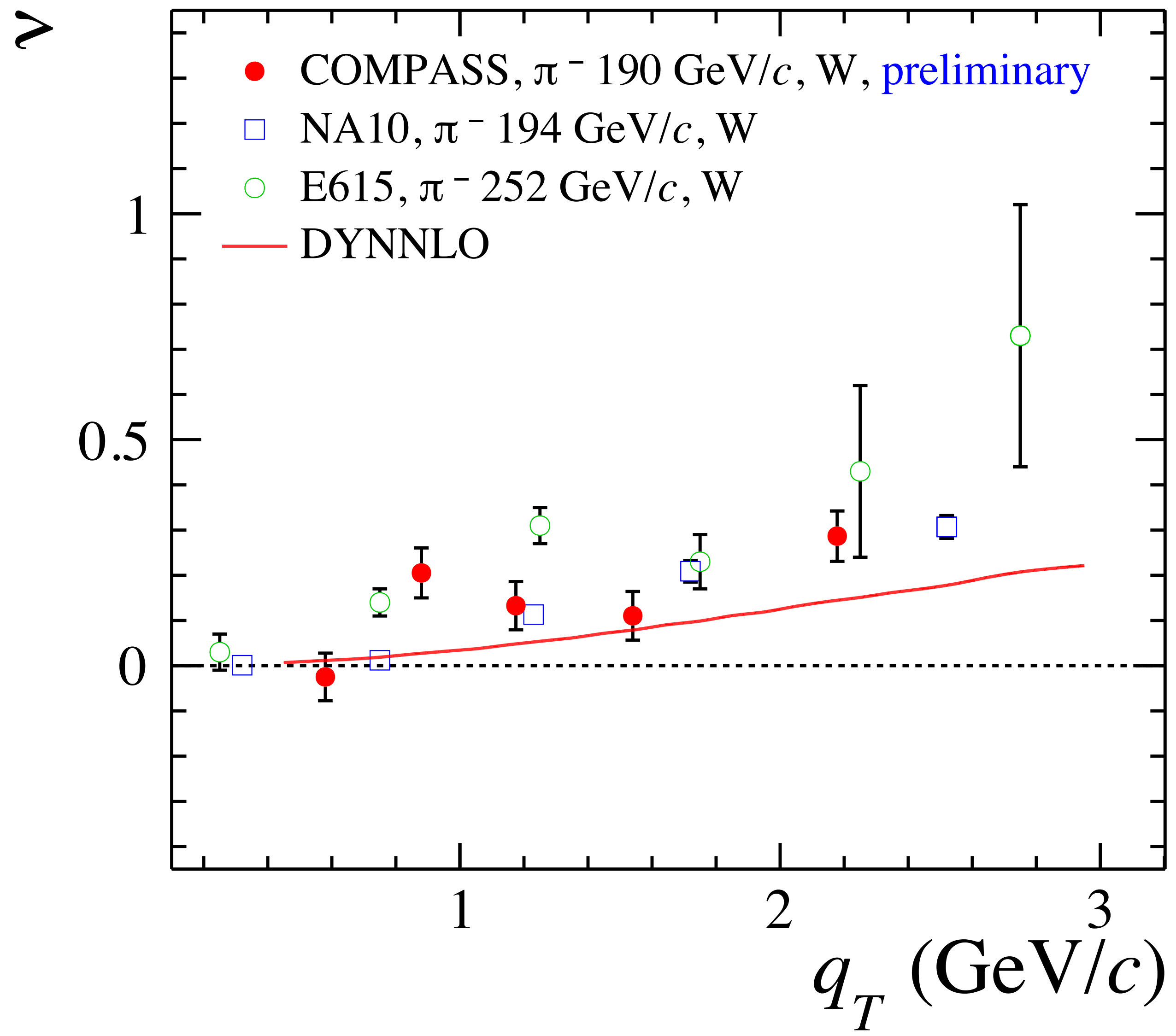
COMPASS DY data confirms Lam-Tung violation as observed by other fixed target experiments

BONUS TRACK: BOER-MULDERS SIGN CHANGE TEST

DY Input

COMPASS DY 2015+2018 Final results
arXiv:2312.17379, accepted by PRL





$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h^{\perp\bar{u}}_{1,\pi^-} \otimes h^{u}_{1,p}\right\} < 0 \implies h^{\perp\bar{u}}_{1,\pi^-} > 0$$

$$A_T^{\cos 2\varphi_{CS}} \propto \left\{h^{\perp\bar{u}}_{1,\pi^-} \otimes h^{\perp u}_{1,p}\right\} > 0 \implies h^{\perp,u}_{1,p} > 0$$

SIDIS Input

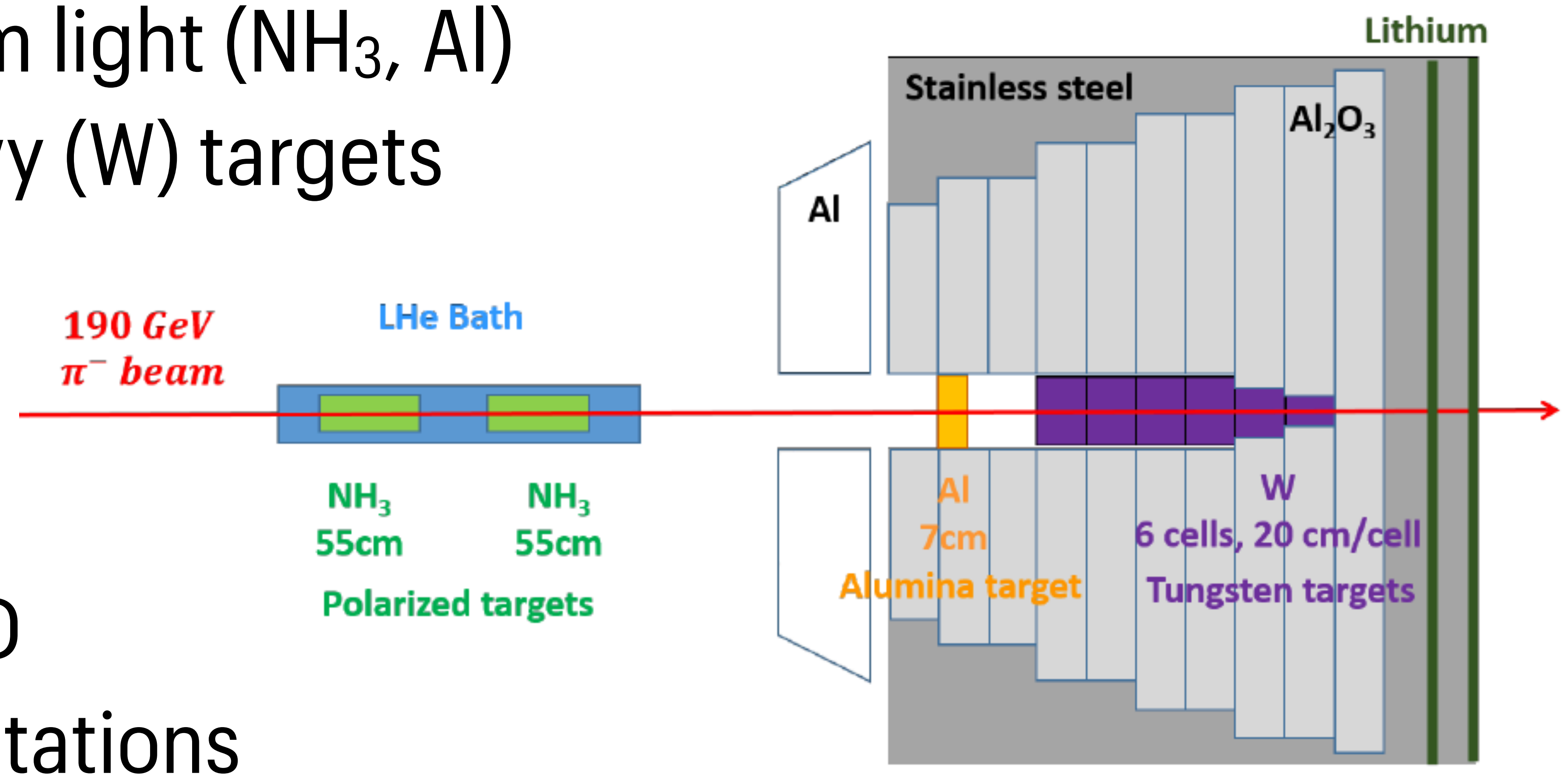
$$h^{\perp,u}_{1,p} < 0$$

From fits to COMPASS SIDIS data
See Barone et al, PRD (2010) 114025

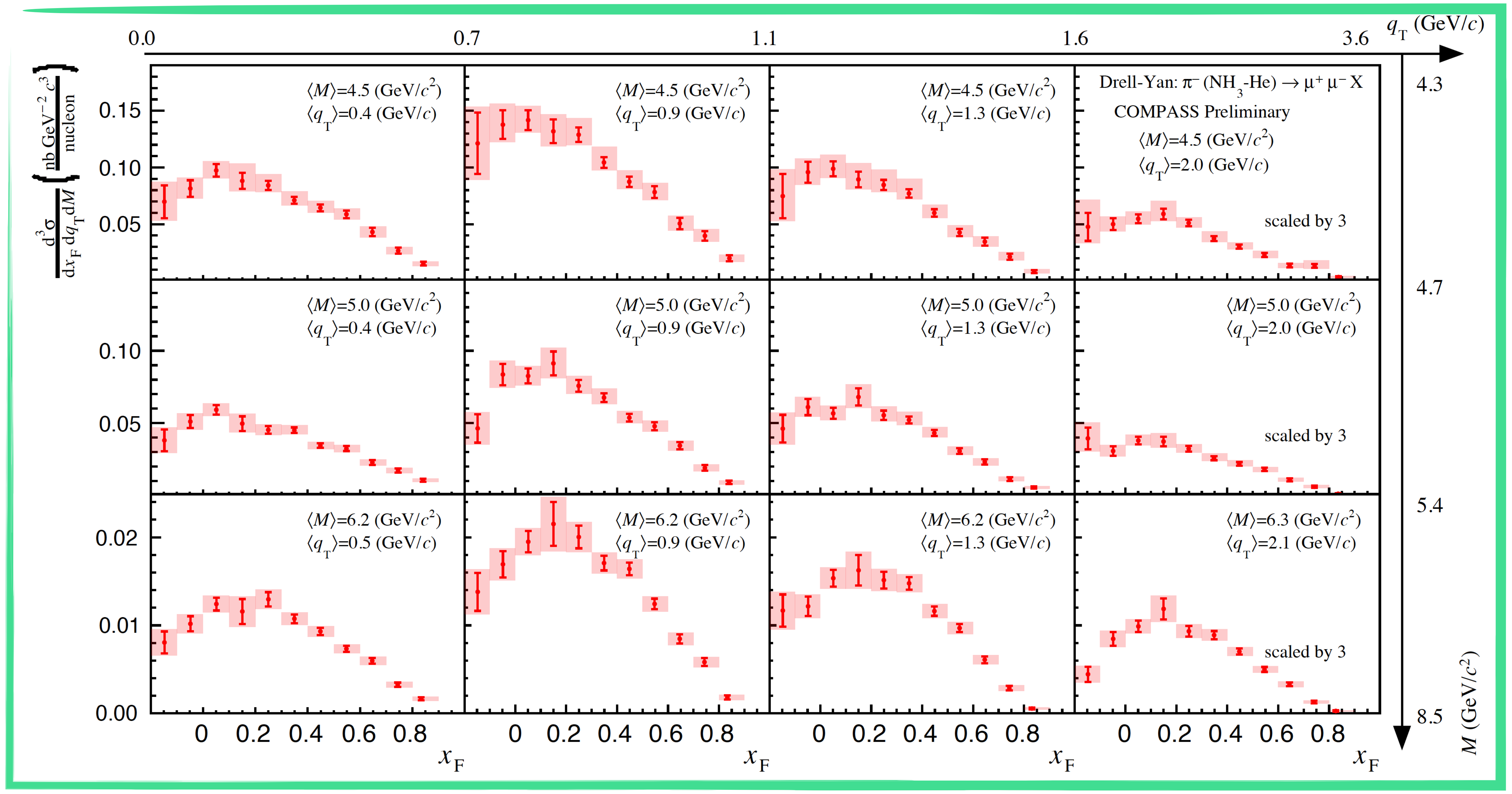
COMPASS data also favors the proton Boer-Mulders TMD PDF sign-change

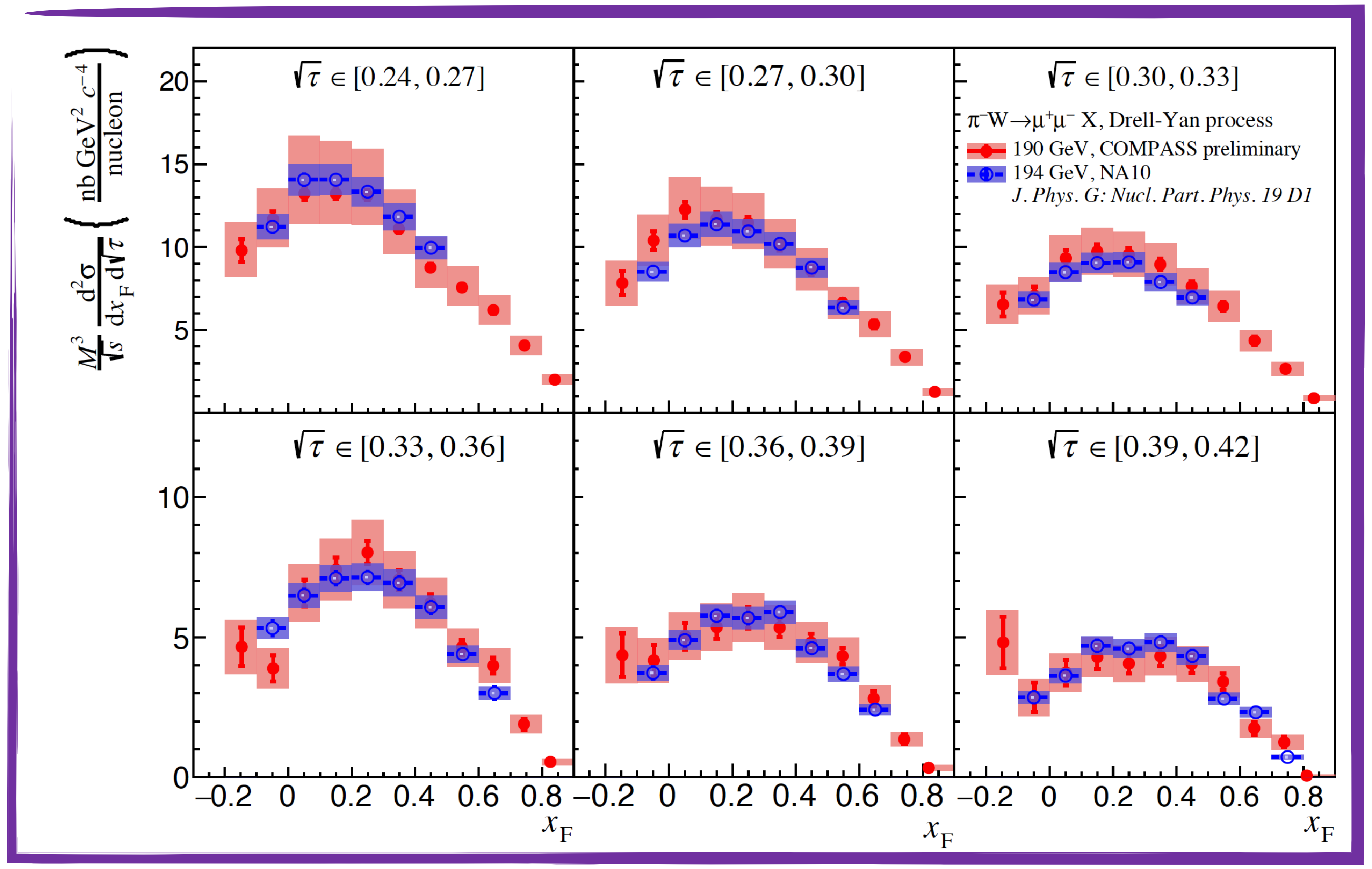
ACCESSING π PDF AND p NPDF VIA DY CROSS-SECTION

Data from light (NH_3, Al) and heavy (W) targets



1D/2D/3D representations

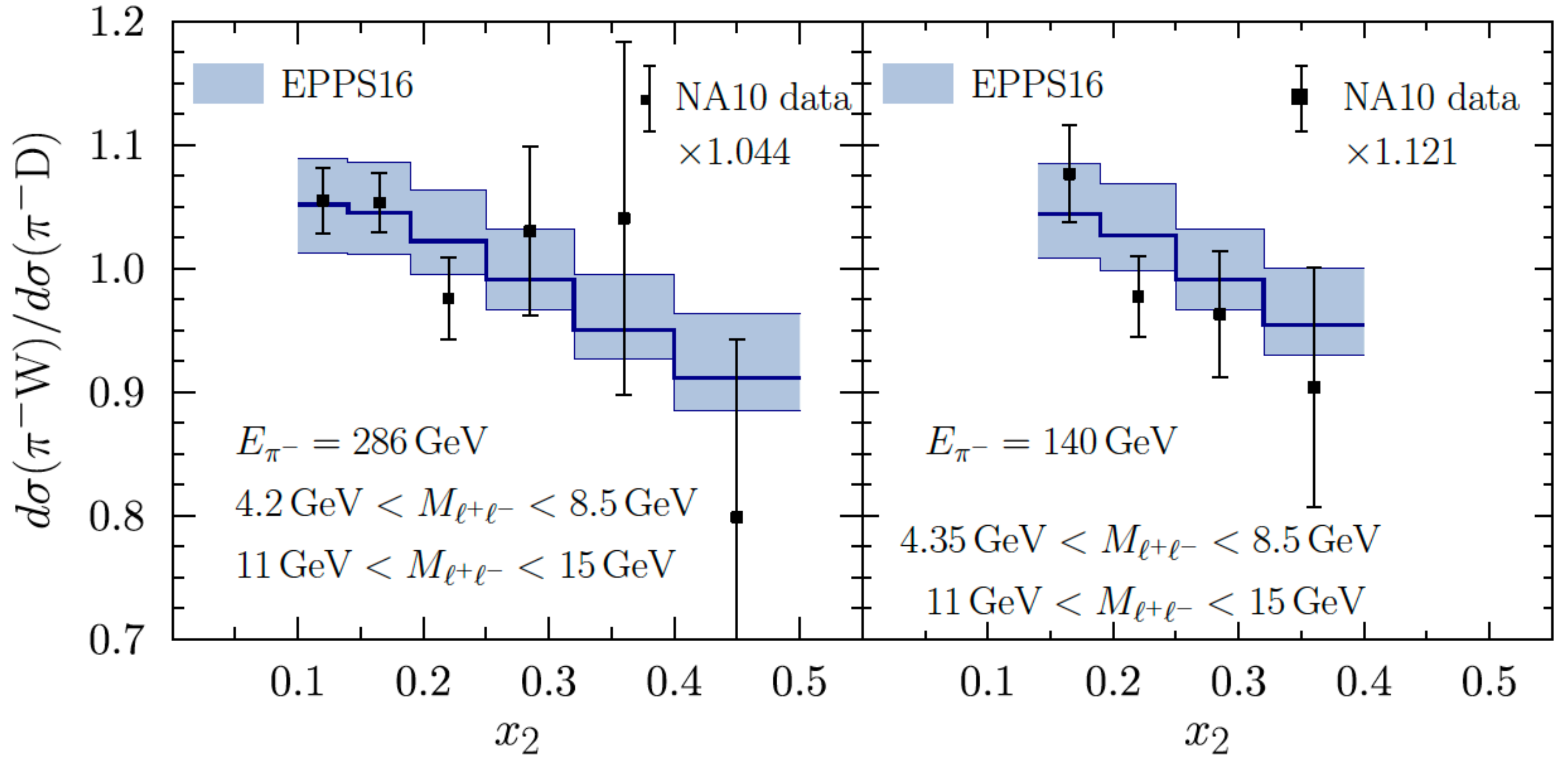




New - presented at SPIN 2023

FIRST NEW RESULT IN THE LAST 30 YEARS!

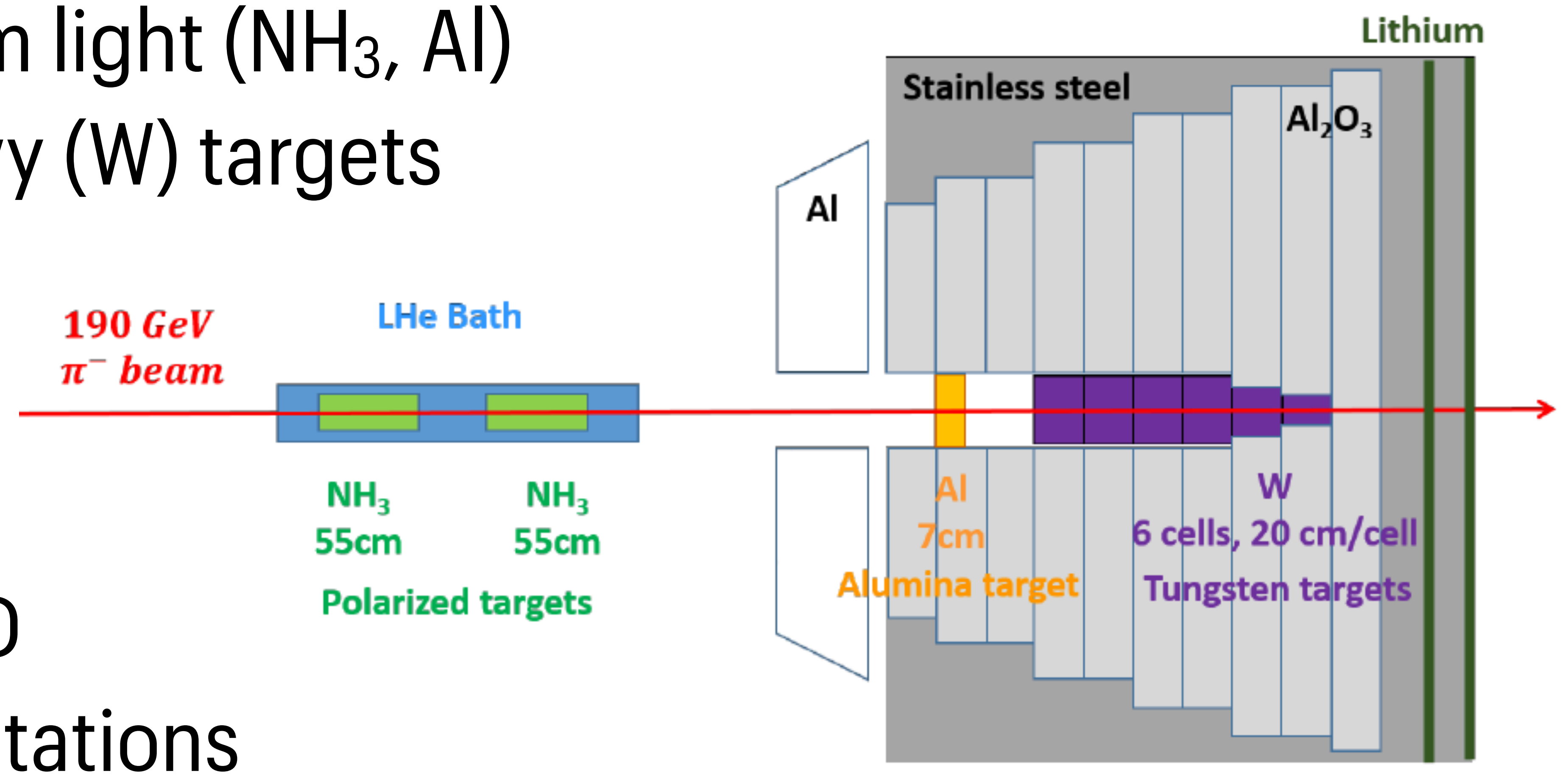
Unique data to inform π collinear PDF & p nPDFs



Eur. Phys. J. C (2017) 77:163

ACCESSING π TMD PDF VIA DY CROSS-SECTION

Data from light (NH_3, Al) and heavy (W) targets



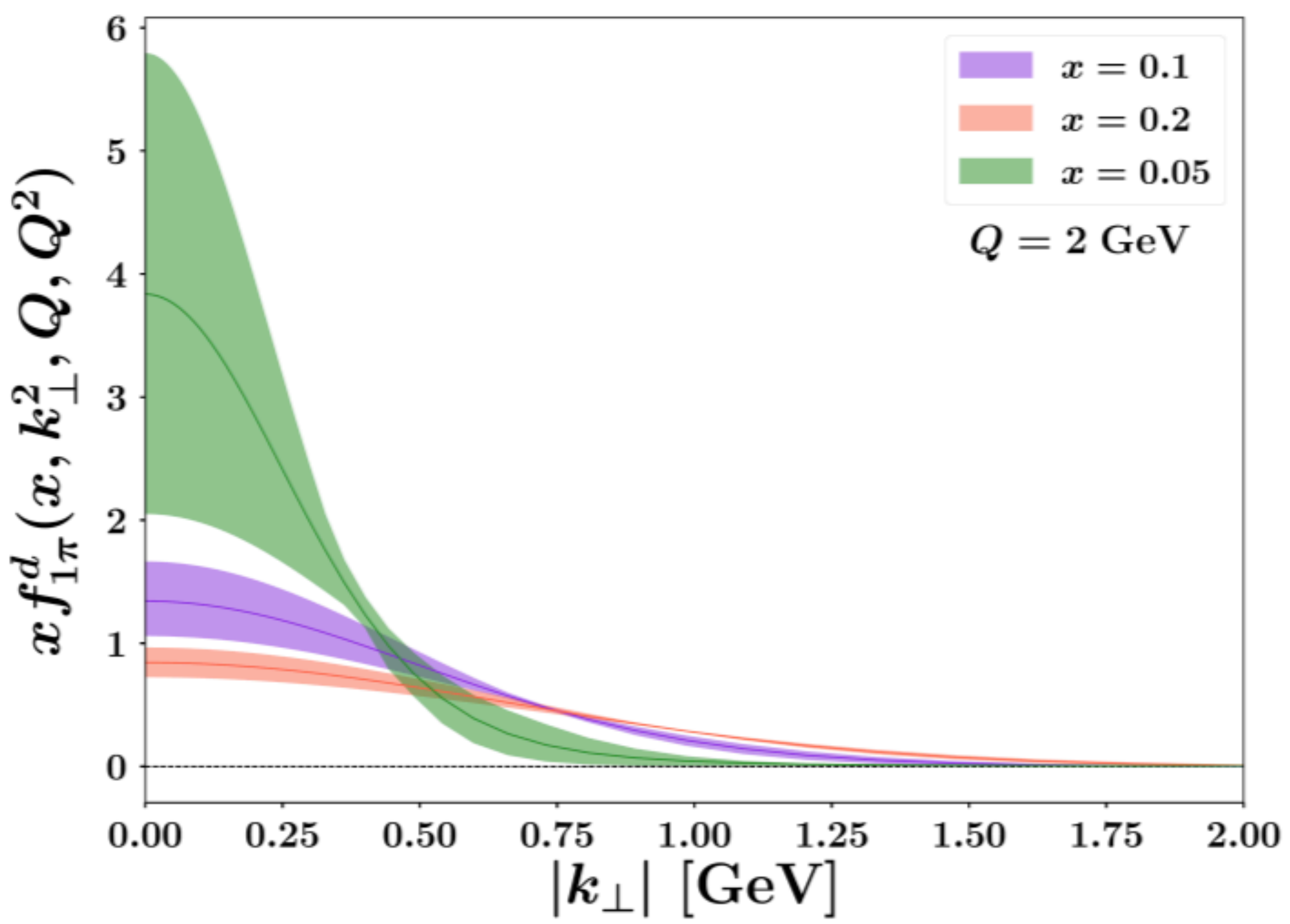
1D/2D/3D representations

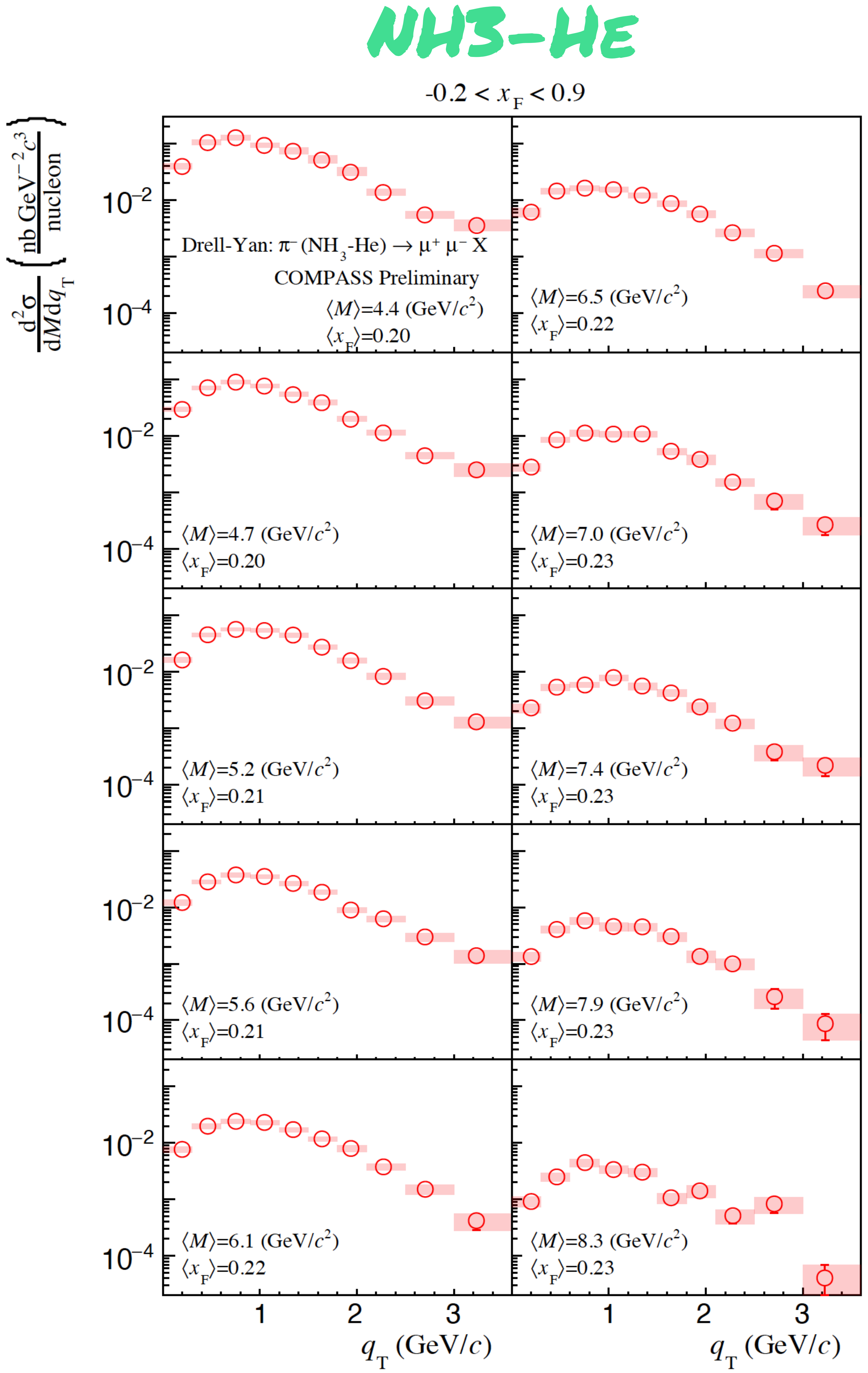
Data to be included in future global fits (MAP, JAM, etc.) to also inform the π TMD PDF!

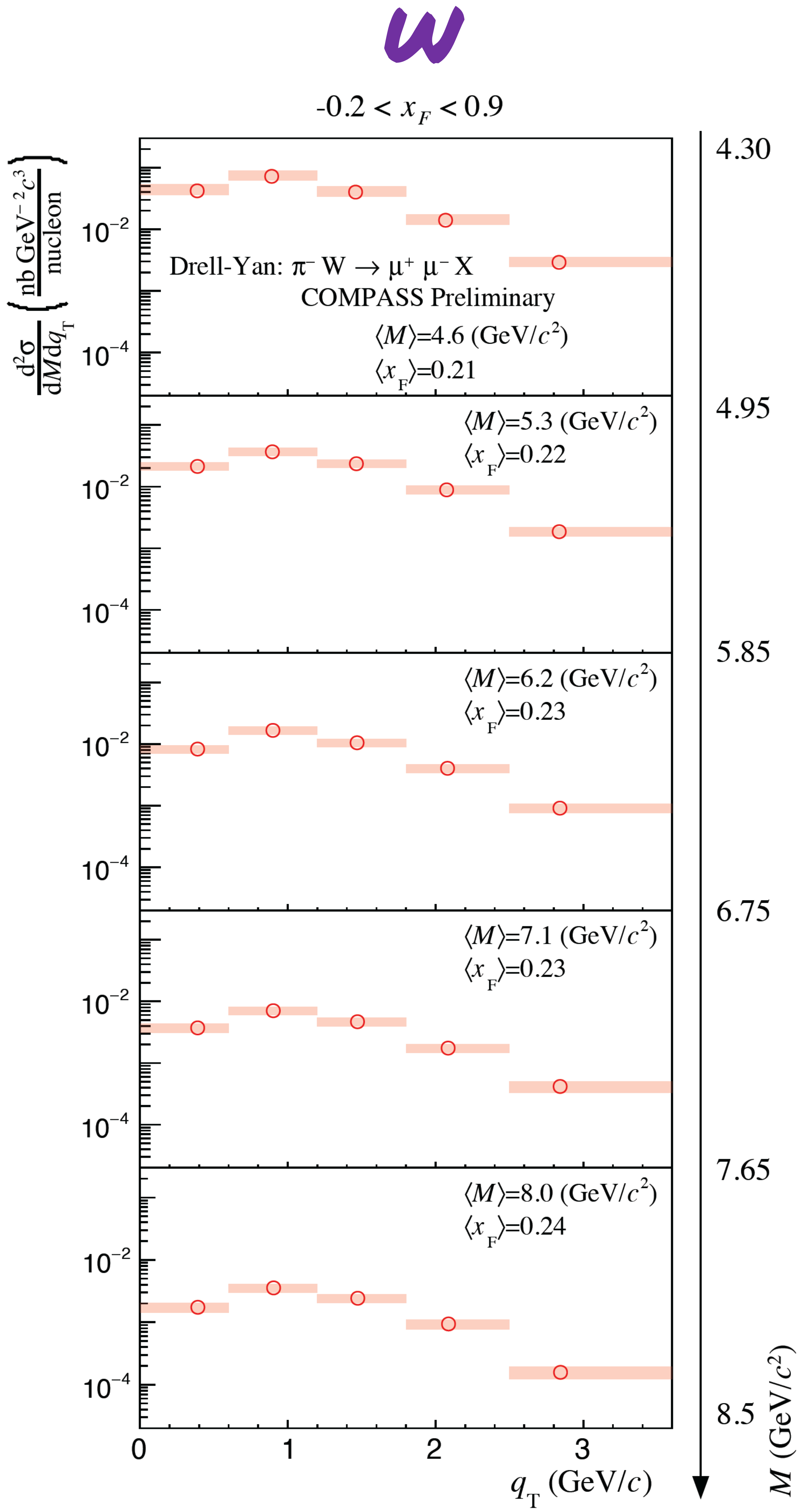
MAP collaboration
PRD 107, 014014

See talk by J.C.Peng
Monday Afternoon Session

See talk by M.Radici
(Tuesday Morning)







New - presented at DIS 2024

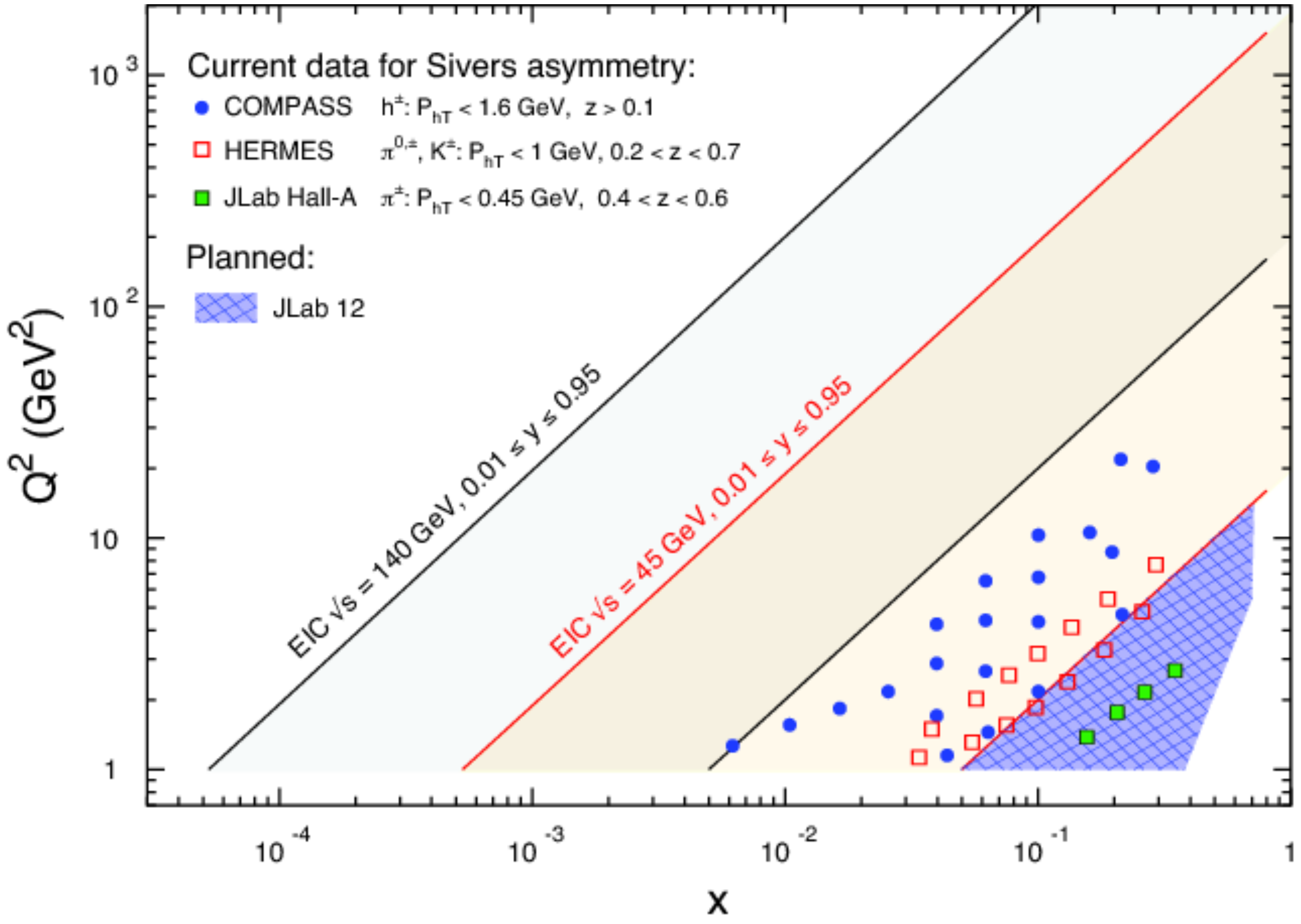
SUMMARY

- COMPASS recently completed his physics programme - with **20 years** of data-taking
- **Several successful measurements that helped to unravel the nucleon spin structure**
  - Wide and unique phase space coverage in x and Q^2
  - Polarized and unpolarized **(SI)DIS on p and D targets**
    - All asymmetries of the SIDIS cross- section measured
    - New, high-statistics D data from 2022 - several ongoing measurements
  - First ever **π^--induced polarized Drell-Yan**
    - All asymmetries of the Drell-Yan cross-section measured in both HM and J/Psi range
    - New preliminary results on cross-section & unpolarized asymmetries
  - **Unique experimental environment to test the universality of TMD PDFs**
  - **Analysis Phase started in 2023**
    - Petabytes of unique data still being analyzed - several opportunities for new studies waiting for the next generation of experiments …

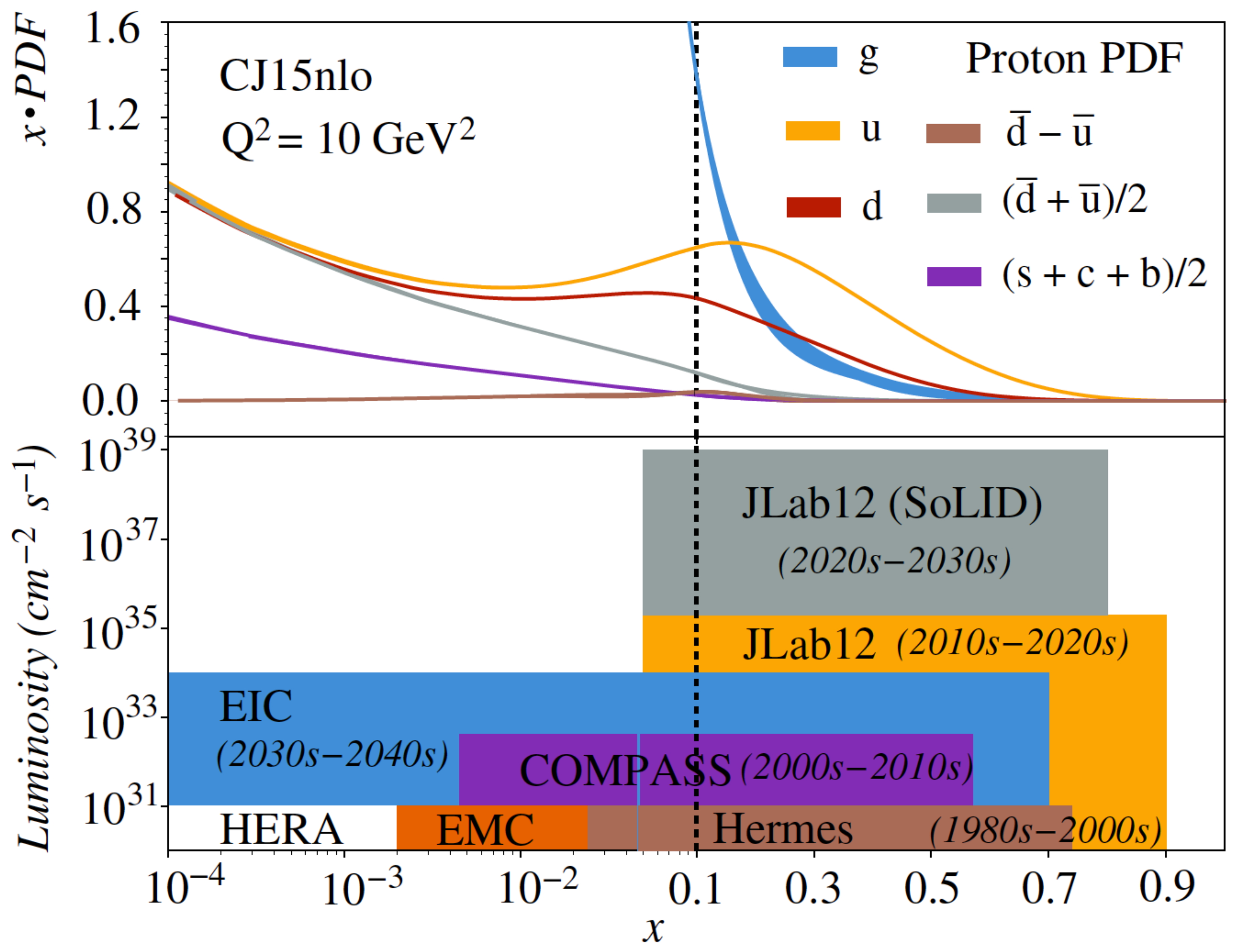
THE HD ERA: EIC+SOLID

COMPASS pioneer multi-dimensional SIDIS analyses to explore the TMD nucleon structure

Nucl. Phys. A 1026 (2022) 122447



SoLID White Paper (2022)



New 'HD' era w/ high-luminosity data samples:

EIC: detailed mapping of the TMD nucleon structure at intermediate/low-*x*

SoLID and JLab12 @ JLab: precision measurement of nucleon's TMDs in the valence region

COMPLEMENTARY HD CAMERAS FOR UNPRECEDENTED NUCLEON IMAGING!

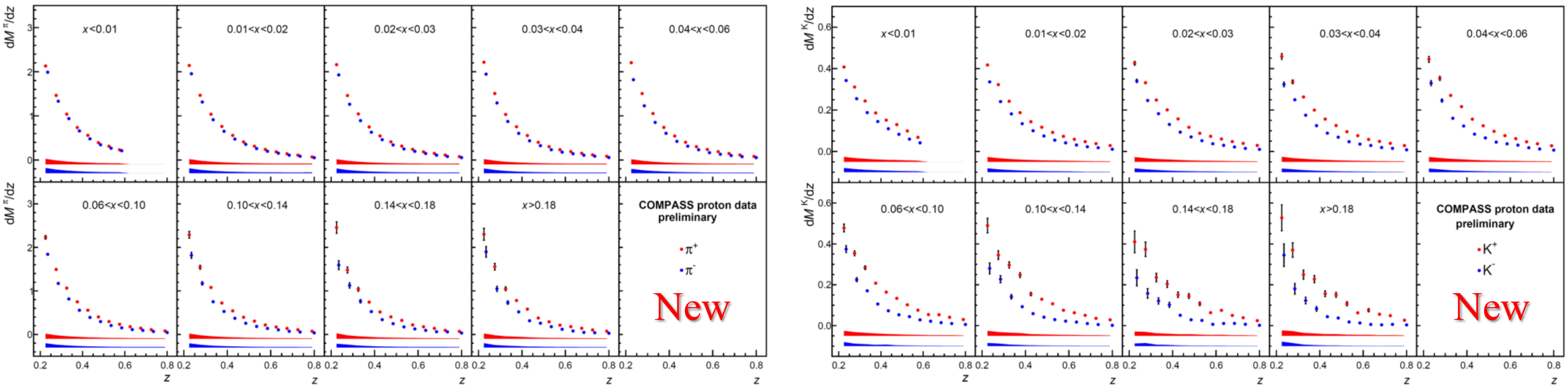
See talks by A.Vossen (Tuesday Afternoon)
And Z. Zhao (Wednesday Morning)

Thank you for your attention!

Thanks to B.Parsamyan for useful discussions and suggestions

BACKUP

SIDIS PROTON COLLINEAR MULTIPLICITIES



- Collinear multiplicities for identified hadrons on p target recently released (see also **talk by M.Stolarski at DIS2024**)
- Expected to be published soon
- Next in line: TMD multiplicities

SIDIS UNPOLARIZED MEASUREMENTS: CAHN EFFECT

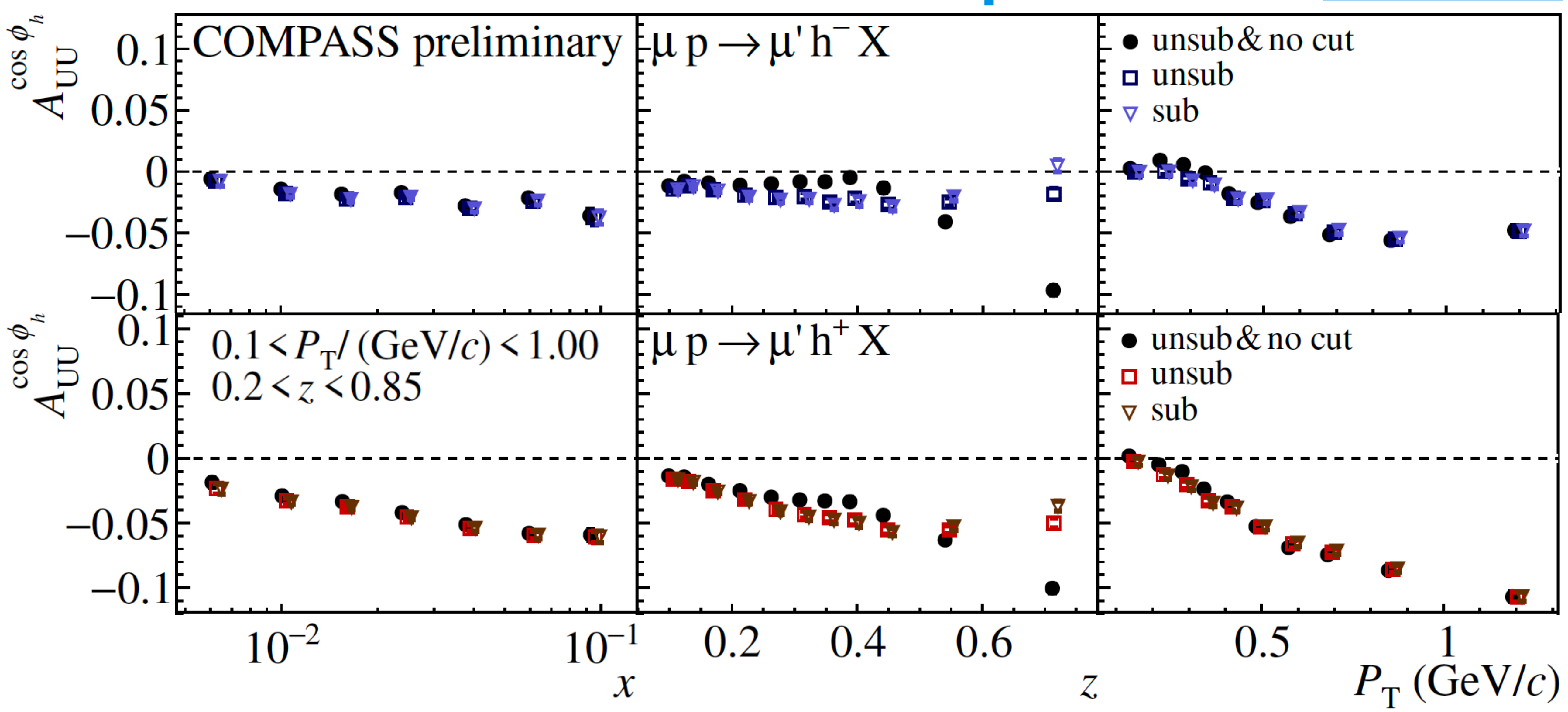
$$\frac{d\sigma}{dxdydzdP_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

$$A_{UU}^{\cos\phi_h} \leftrightarrow F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M_h}\left[xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{D_q^{\perp h}}{z}\right]-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M}\left[xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{Z}\right]\right\}$$

Cahn effect (1978): non-zero k_T induces an azimuthal modulation

- Complex structure function - different contributions from twist-2 and twist-3 functions
- Several, non-trivial, corrections: (acceptance effects, **diffractively produced vector mesons (VM)**, radiative corrections (RC), etc…

New - presented at DIS 2024



Impact of VM corrections, 2016 data

SIDIS UNPOLARIZED MEASUREMENTS: CAHN EFFECT

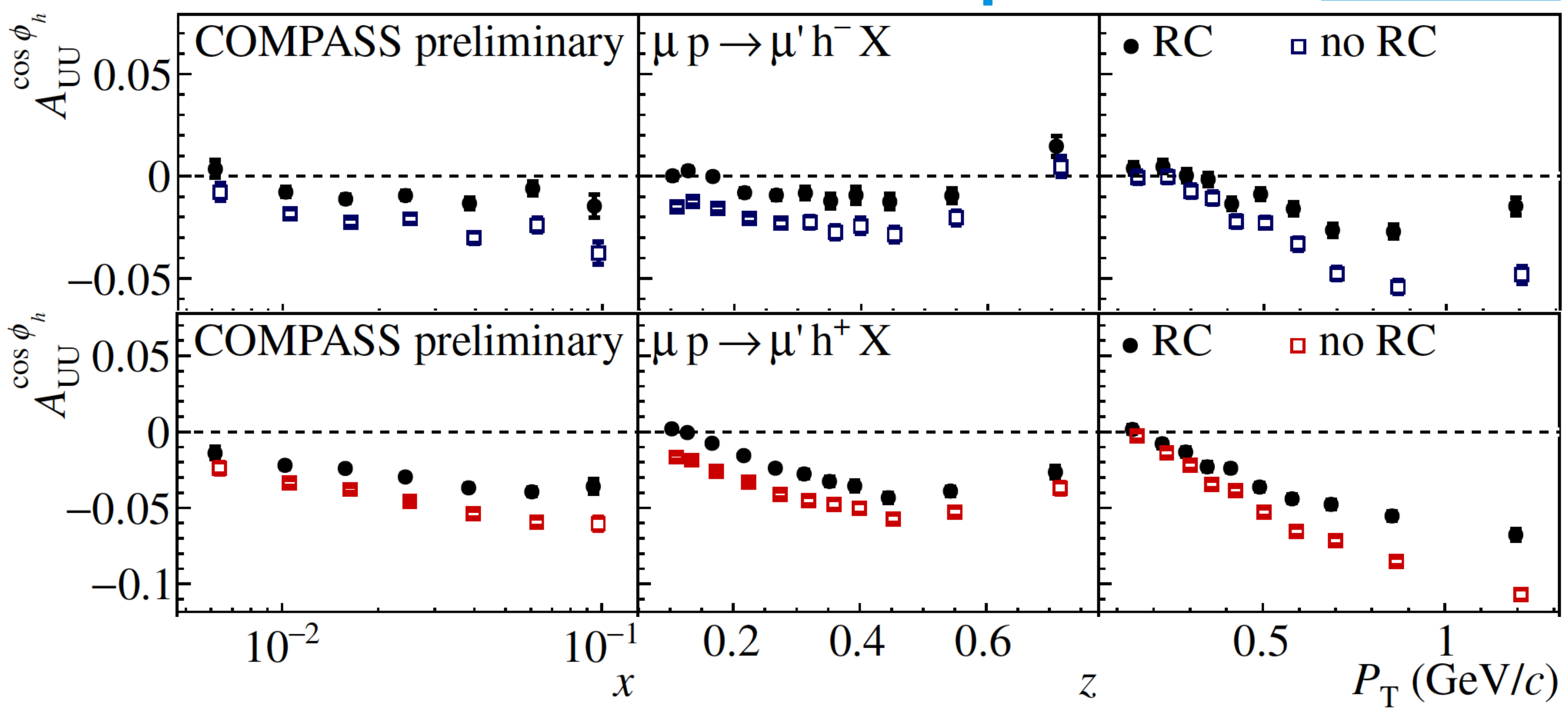
$$\frac{d\sigma}{dxdydzdP_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L}) \times (1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \dots)$$

$$A_{UU}^{\cos\phi_h} \leftrightarrow F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M_h}\left[xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{D_q^{\perp h}}{z}\right]-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M}\left[xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{Z}\right]\right\}$$

Cahn effect (1978): non-zero k_T induces an azimuthal modulation

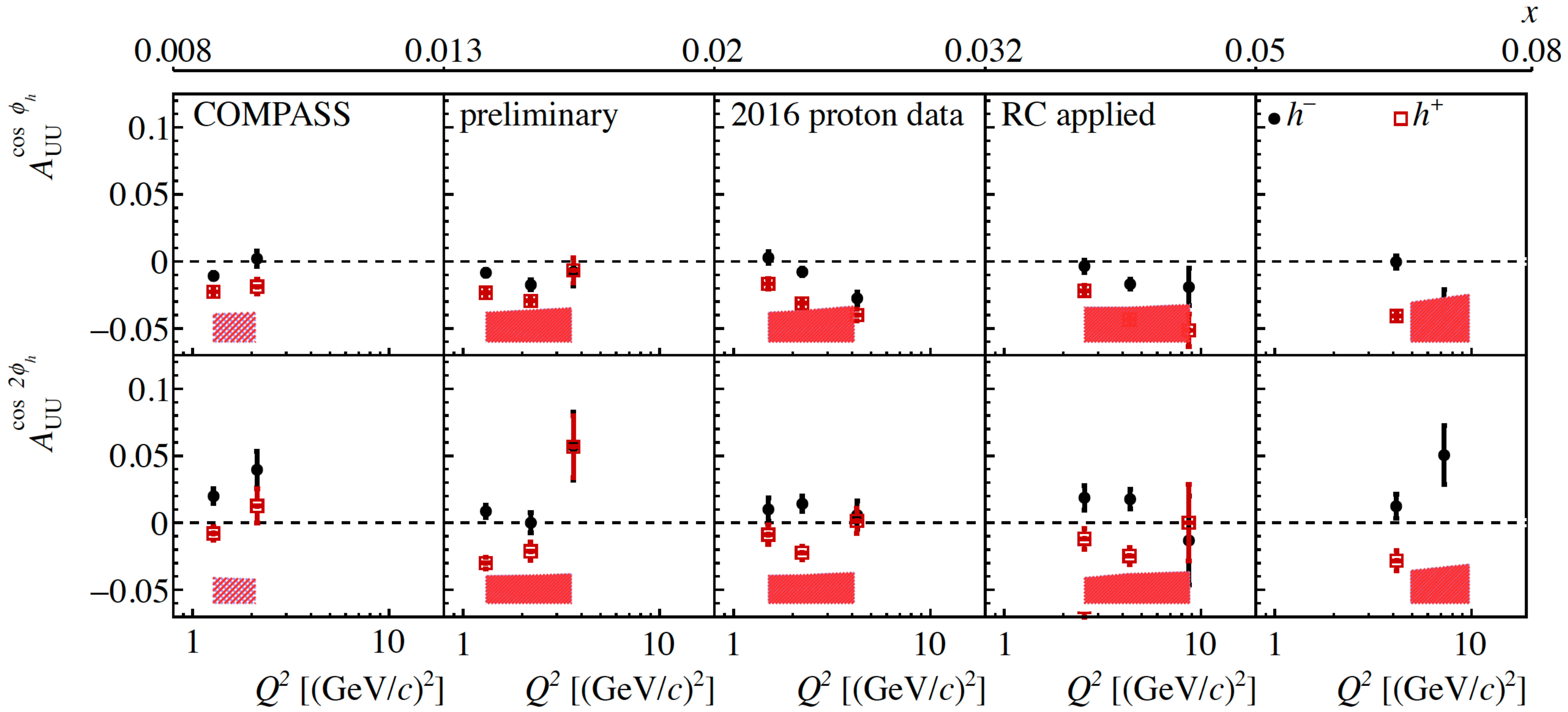
- Complex structure function - different contributions from twist-2 and twist-3 functions
- Several, non-trivial, corrections: (acceptance effects, diffractively produced vector mesons (VM), **radiative corrections (RC)**, etc…

New - presented at DIS 2024



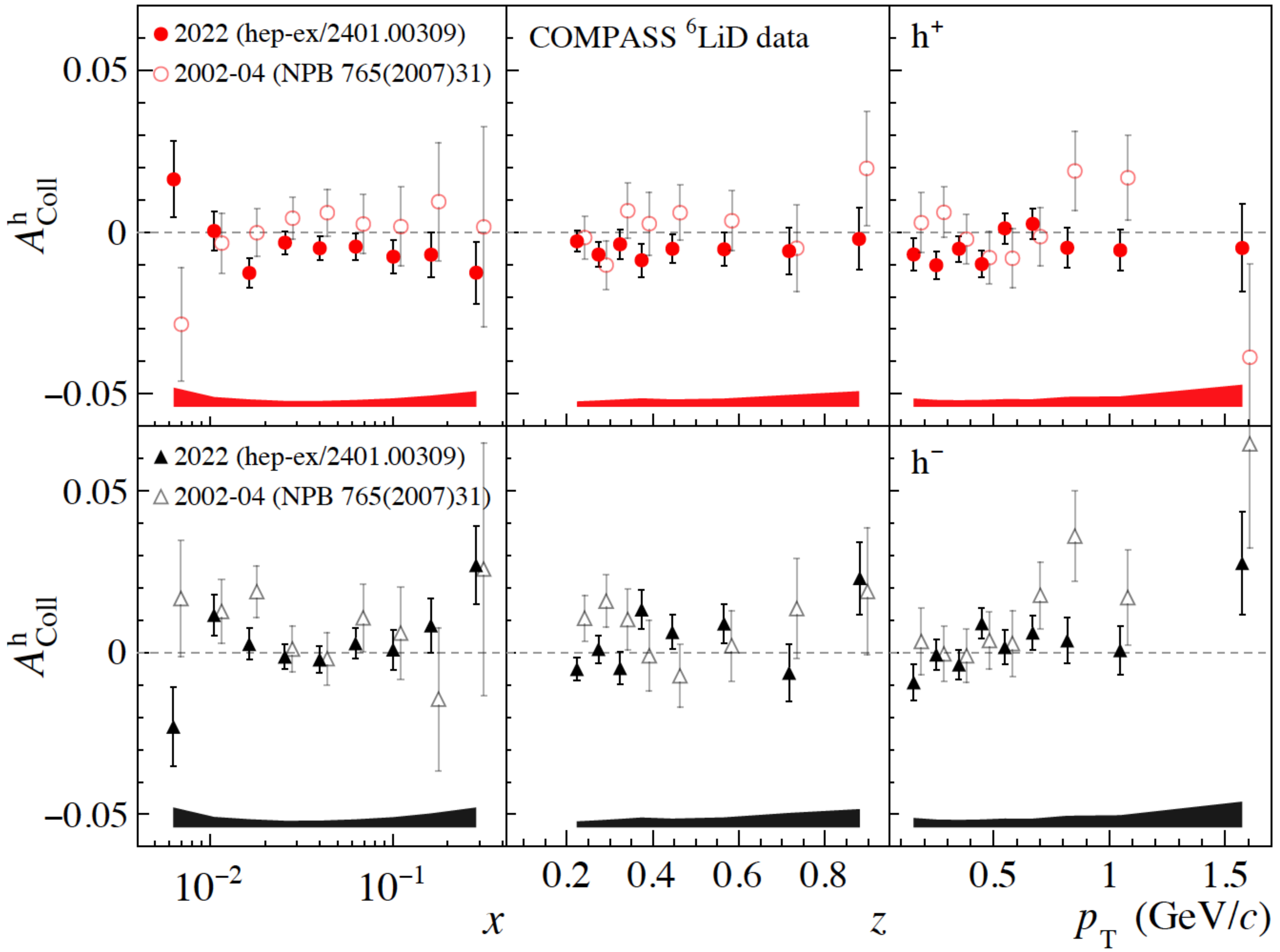
Impact of RC, 2016 data

CAHN AND COS $2\phi_h$: Q^2 DEPENDENCE

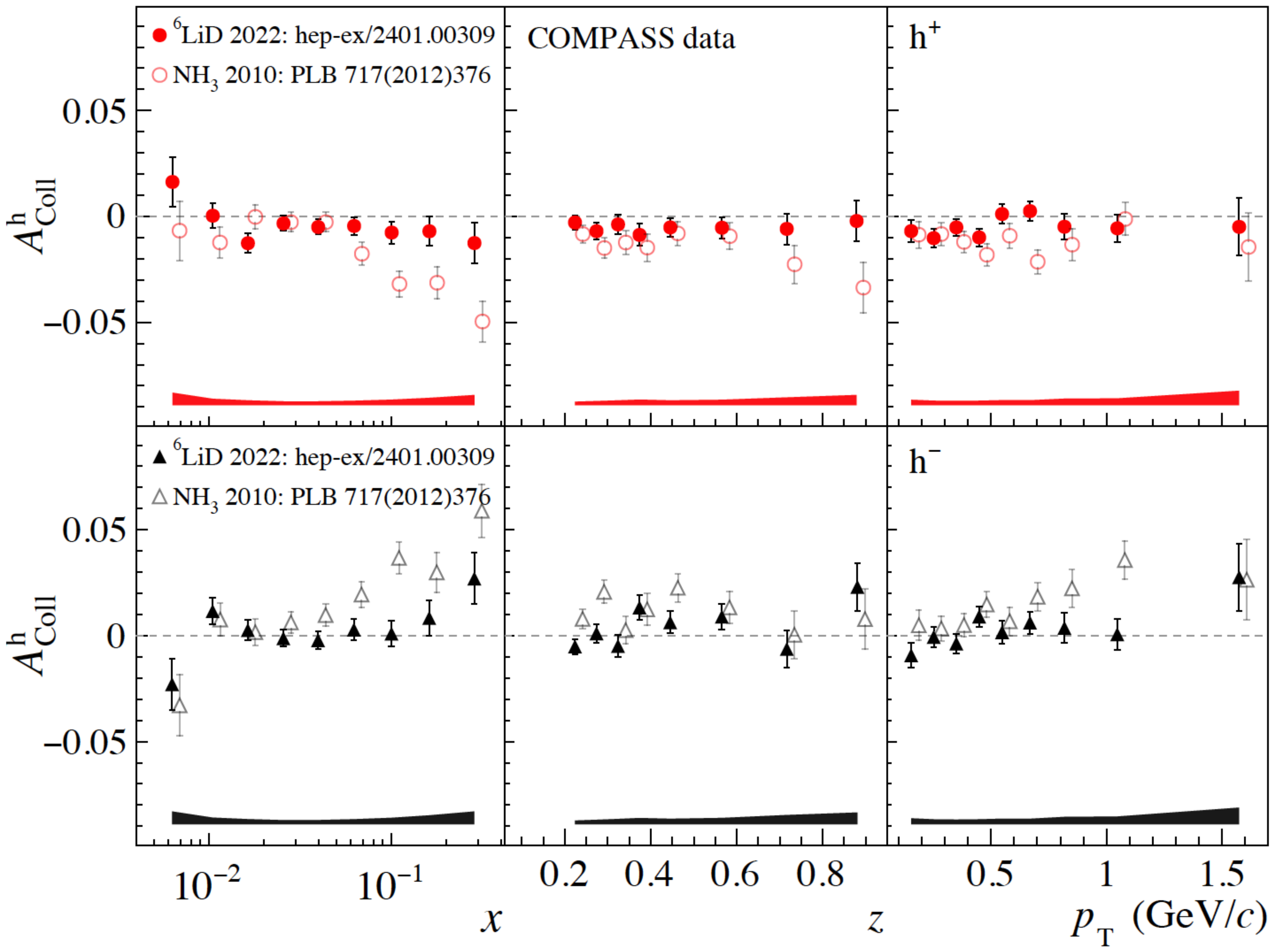


2022 DATA VS PREVIOUSLY PUBLISHED RESULTS

Vs Deuteron 2002-2004



Vs proton 2010



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 [25, 28, 29]	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
previous [25, 28, 29] and present	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

LONGITUDINALLY POLARIZED SIDES

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ 1 + \ldots$$

$$+ S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right]$$

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

$$F_{LL}^{1} = \mathcal{C}\left\{ g_{1L}^{q} D_{1q}^{h} \right\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{ -\frac{\hat{h}\cdot p_T}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{h}\cdot k_T}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left\{ -\frac{2(\hat{h}\cdot p_T)(\hat{h}\cdot k_T) - p_T\cdot k_T}{M M_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{ -\frac{\hat{h}\cdot p_T}{M_h}\left(x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \frac{\hat{h}\cdot k_T}{M}\left(x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$

COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- Significant h$^+$ asymmetry, clear z-dependence
- h$^-$ compatible with zero

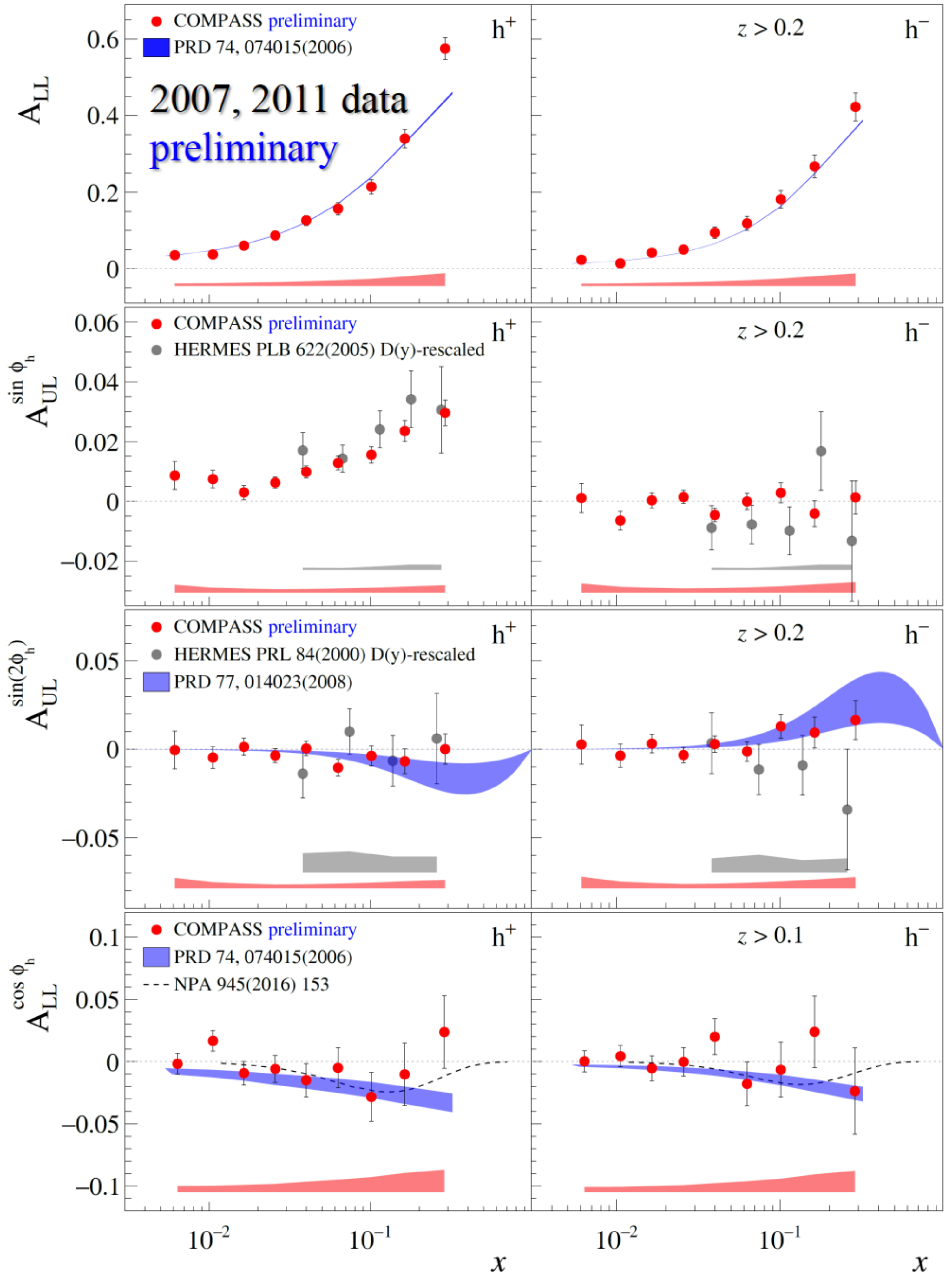
$A_{UL}^{\sin 2\phi_h}$

- Only "twist-2" ingredients
- Additional p_T-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

$A_{LL}^{\cos\phi_h}$

- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



16 May 2024 B. Parsamyan 31

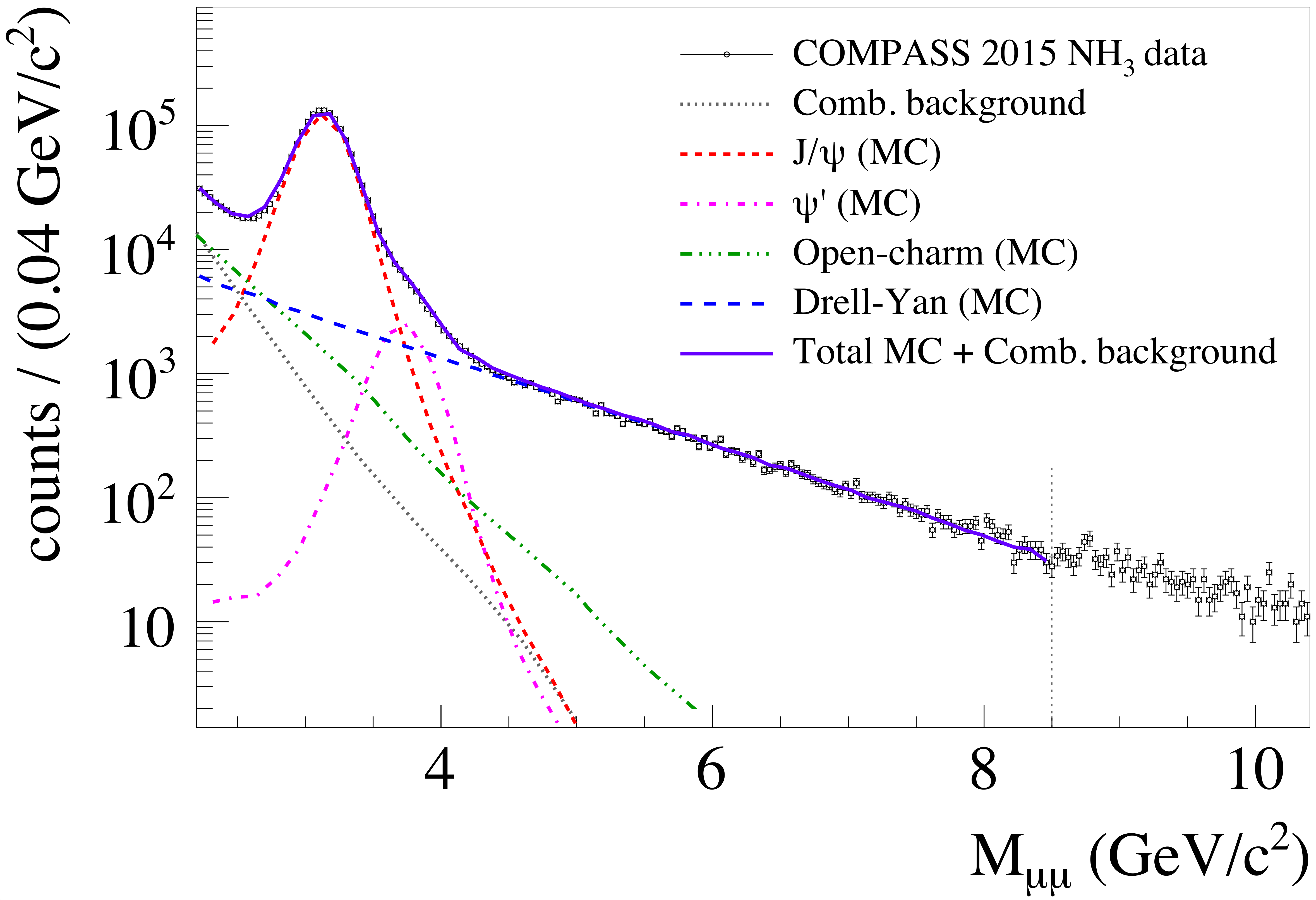
DRELL-YAN MASS RANGES @ COMPASS

I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
- Large background contamination

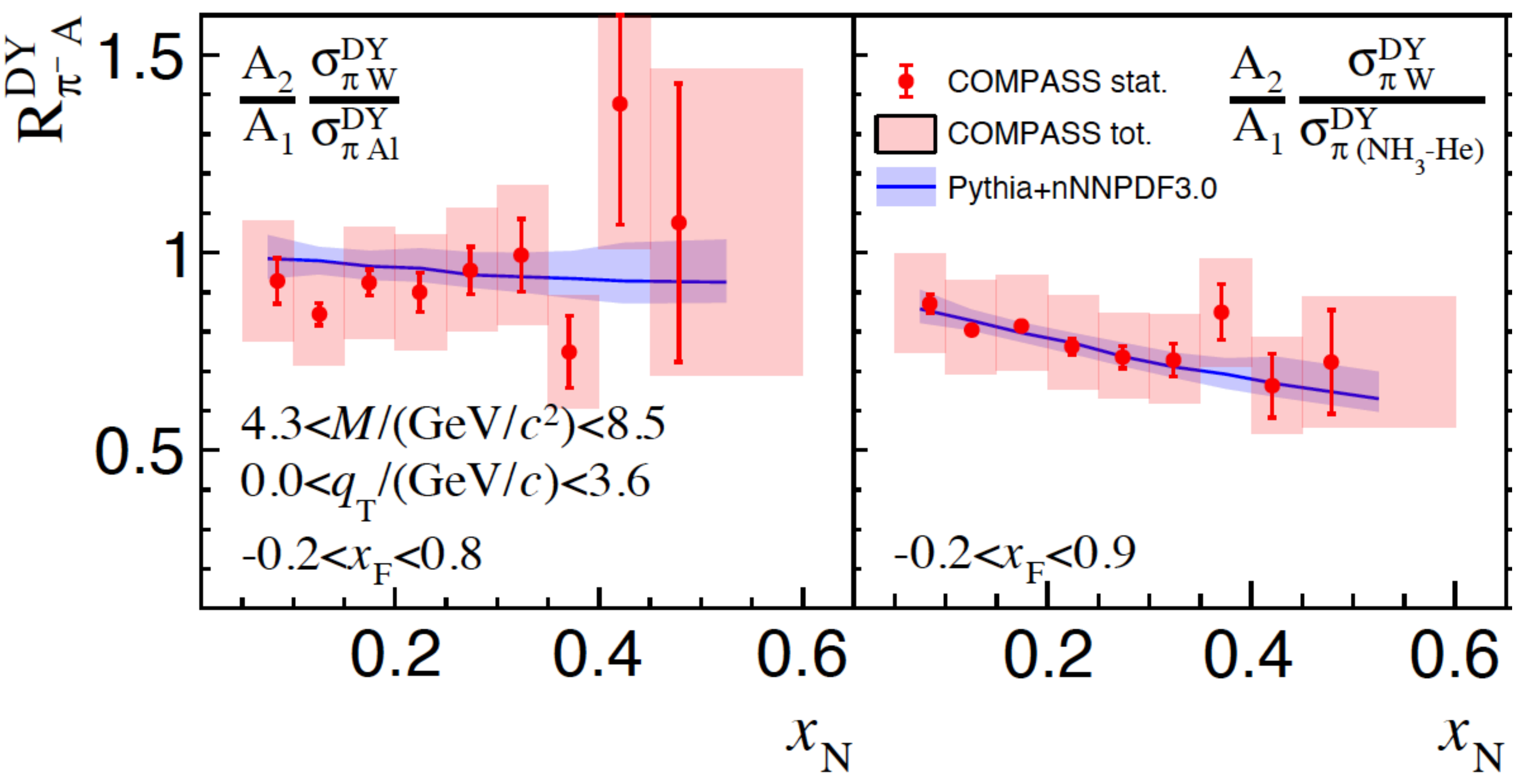
II. $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$, "Intermediate mass"
- High DY cross-section.
- Low DY-signal/background ratio.

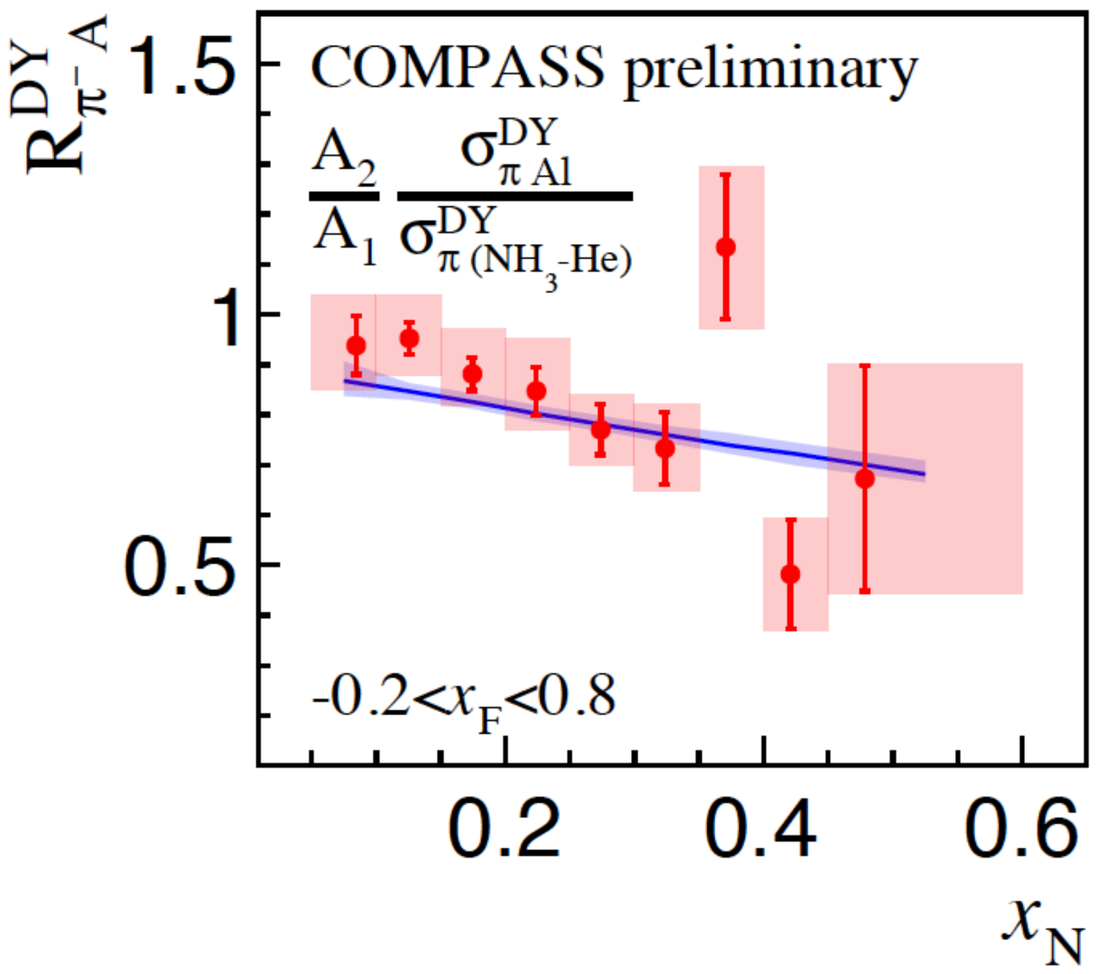
III. $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.0$, "Charmonia mass"
- Strong J/ψ signal ➔ Studies of J/ψ physics.
- Good signal/background.

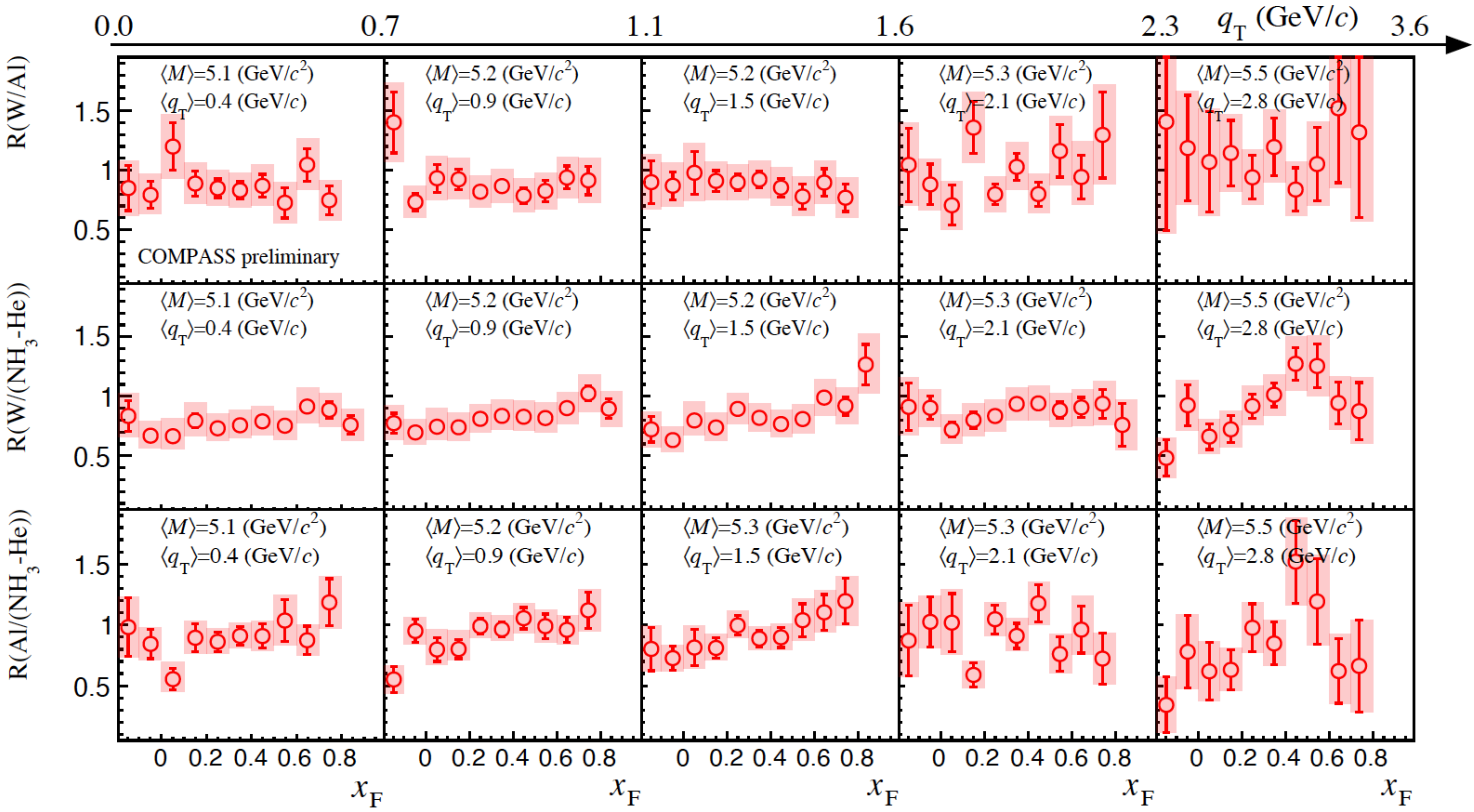
IV. $4.0 < M_{\mu\mu}/(GeV/c^2) < 8.5$, "High mass"
- Beyond J/ψ and ψ′ peak, background < 4%.
- Valence quark region ➔ u-quark dominance.
- Low DY cross-section



DRELL-YAN X-SECTION RATIOS







DY Statistics:

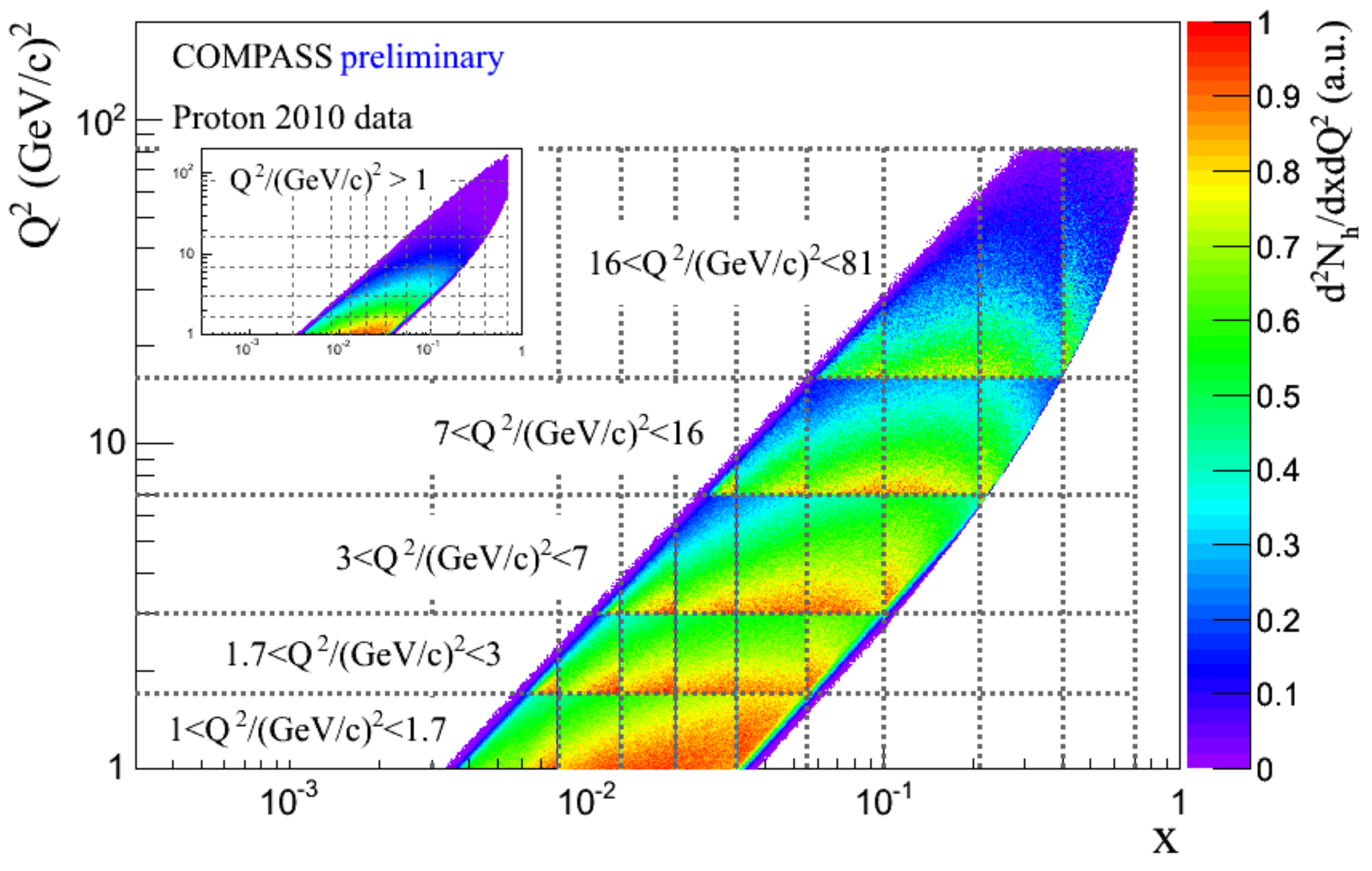
NH3 → 36000

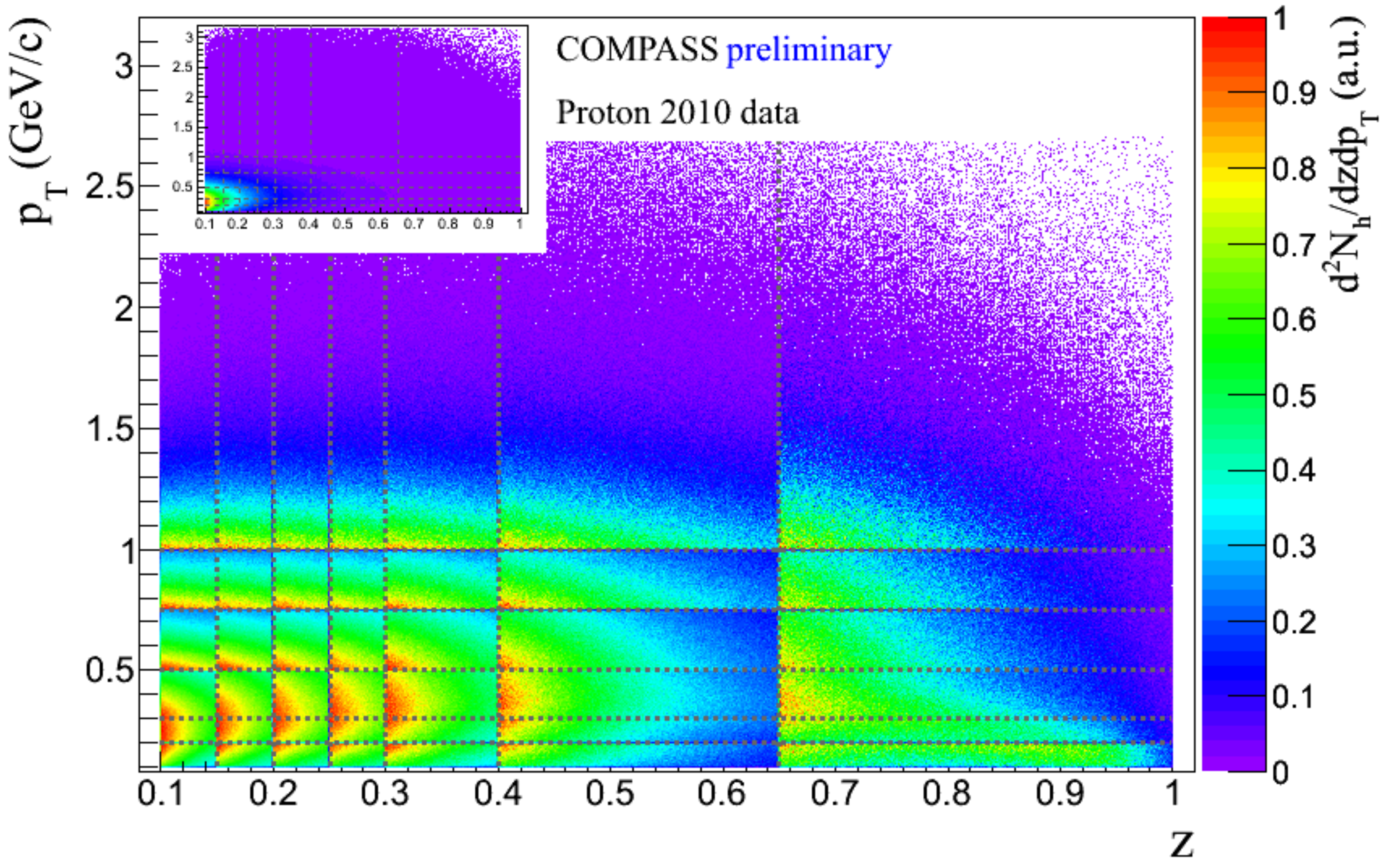
Al → 6000

W → 43000

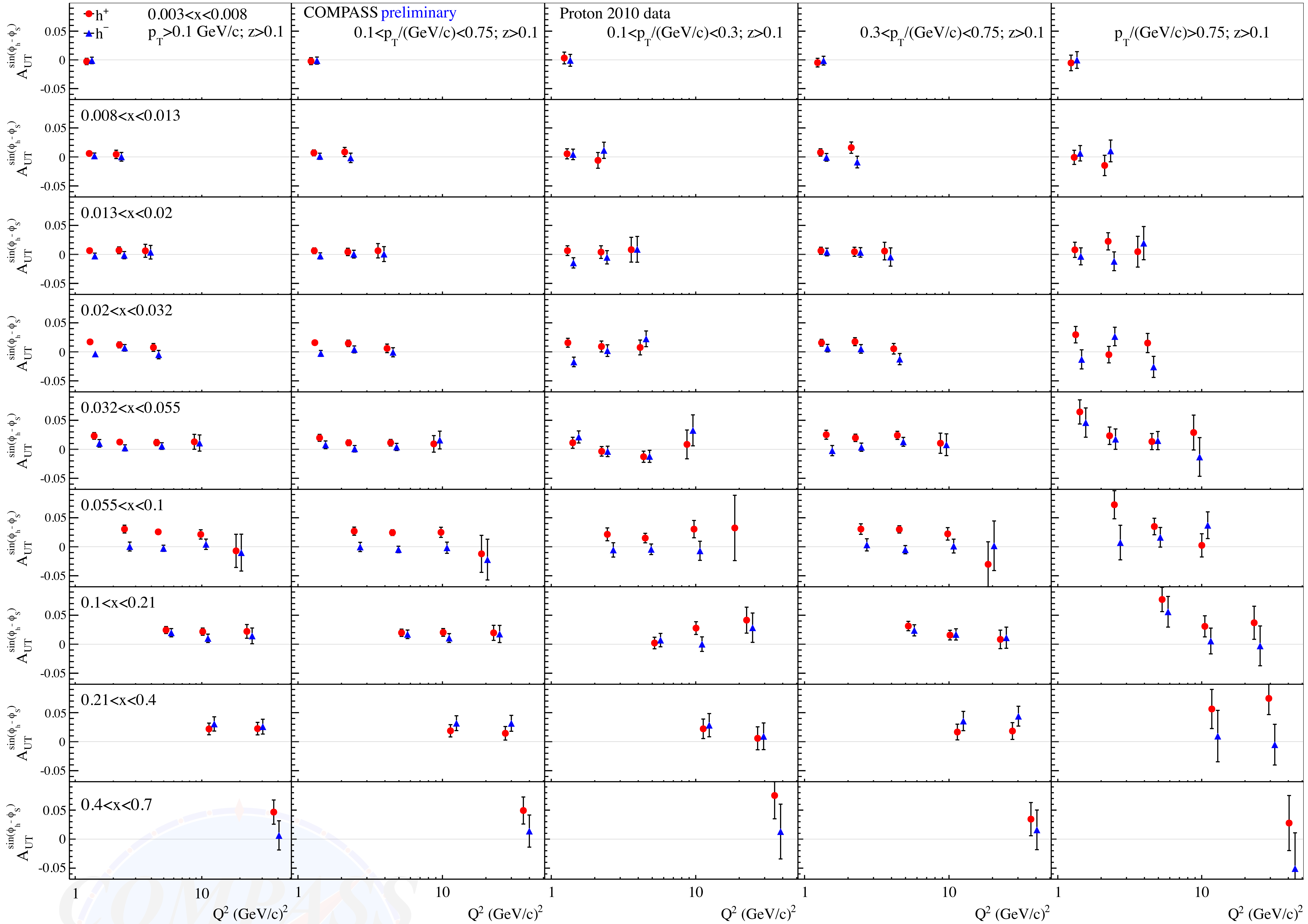
BEYOND UNIVERSALITY: PRECISION W/ MULTI-D SIDIS ANALYSIS

Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660029





COMPASS **3D** SIDIS analysis - **Sivers** example - **x:Q^2:p_T**



3D binning **x:Q^2:p_T or x:Q^2:z or x:z:p_T**