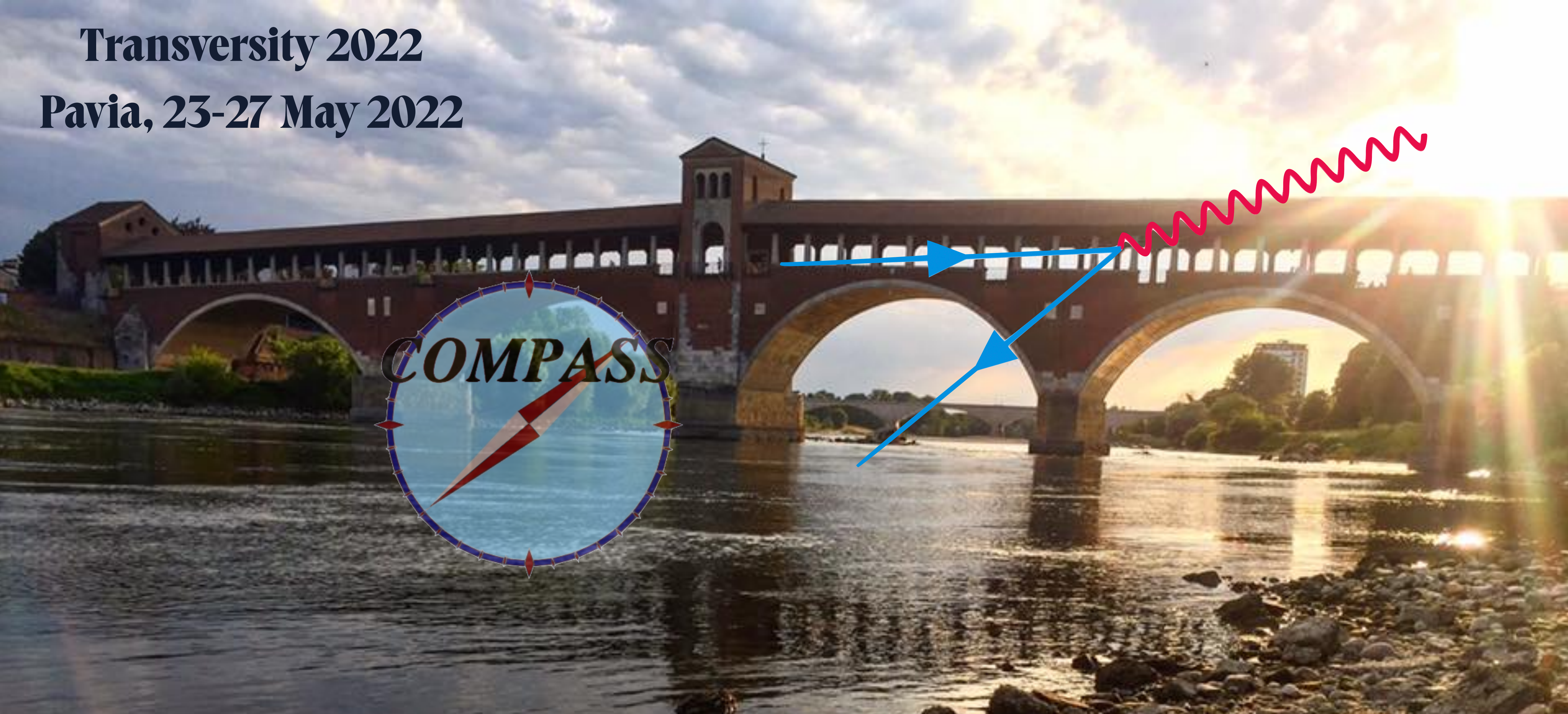
Transversity 2022
Pavia, 23-27 May 2022



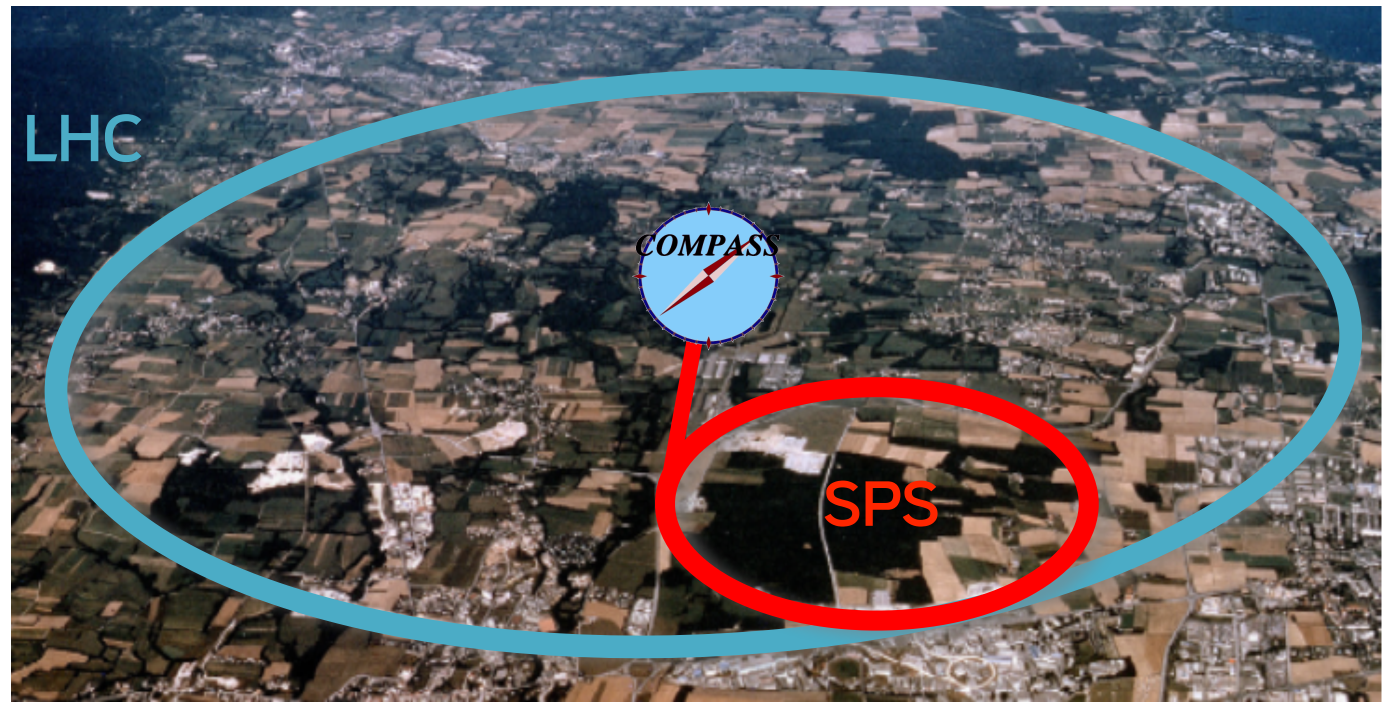
RECENT RESULTS FROM COMPASS DRELL-YAN PROGRAM

Riccardo Longo
on behalf of the COMPASS Collaboration
27th May 2022

NSF
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

THE COMPASS COLLABORATION

- Fixed target experiment
- CERN SPS North-Area (M2 beam-line)
- First data taking in 2002
- 2022 run just started!



Phase I

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

See talk by F.Bradamante

Phase II

- 2012 - 2022
- Primakoff + DVCS pilot run (2012)
- **Drell-Yan (2015, 2018)** → **This talk**
- DVCS + Unpolarized SIDIS(2016-2017)
- SIDIS on Transversely polarized D target (2021-2022)

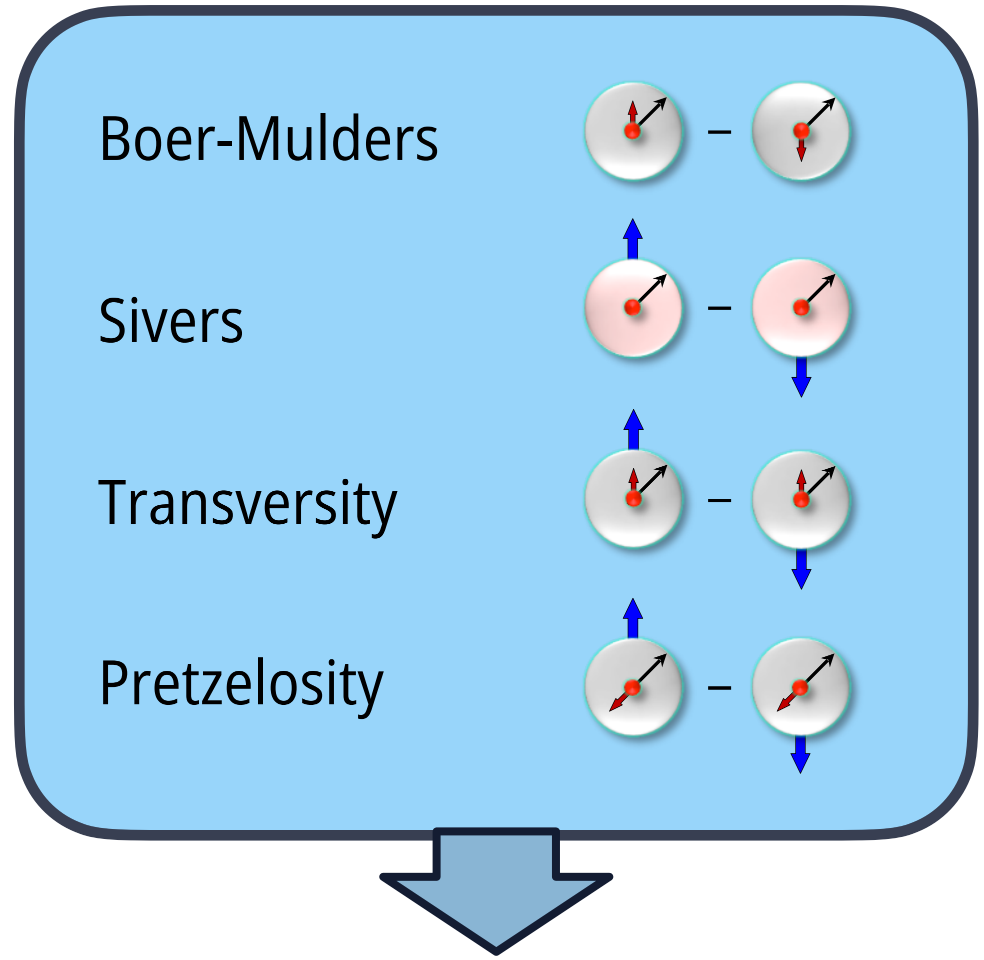
See talks by A.Moretti,J.Matousek, N.D'Hose, F.Bradamante

TRANSVERSE MOMENTUM DEPENDENT PDFs

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.

		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	$g_{1T}^{q\perp}(x, \mathbf{k_T^2})$ 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

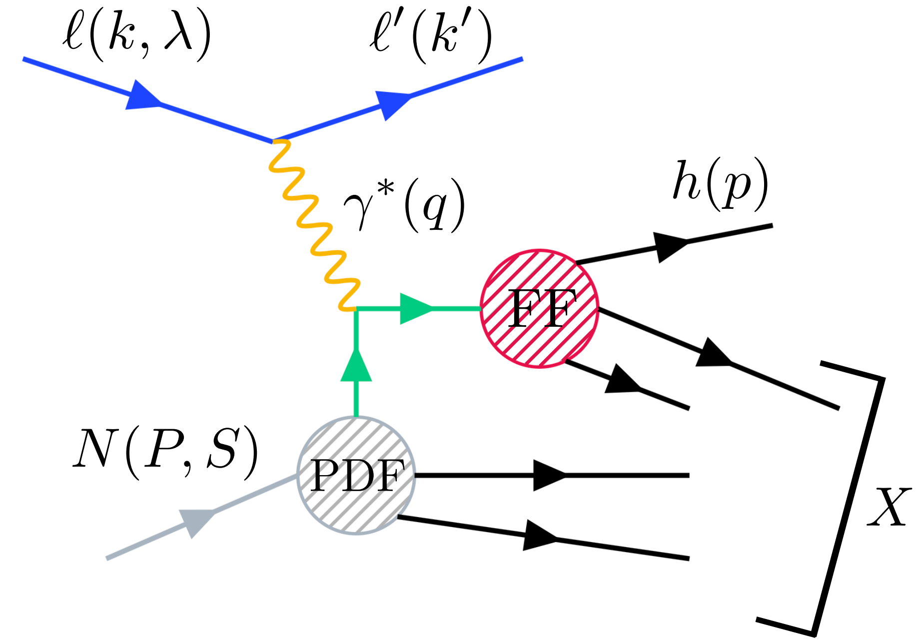
Nucleon · Nucleon spin · quark · quark spin · $\mathbf{k_T}$



TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries both in SIDIS and Drell-Yan

TRANSVERSELY POLARIZED SIDIS CROSS-SECTION

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



SIDIS on transversely polarized nucleons

$$\mu + p^{\uparrow} \rightarrow \mu' + h + X$$

COMPASS 2007, 2010

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

1 Unpolarized Asymmetry

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

3 Single Spin Asymmetries

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

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

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

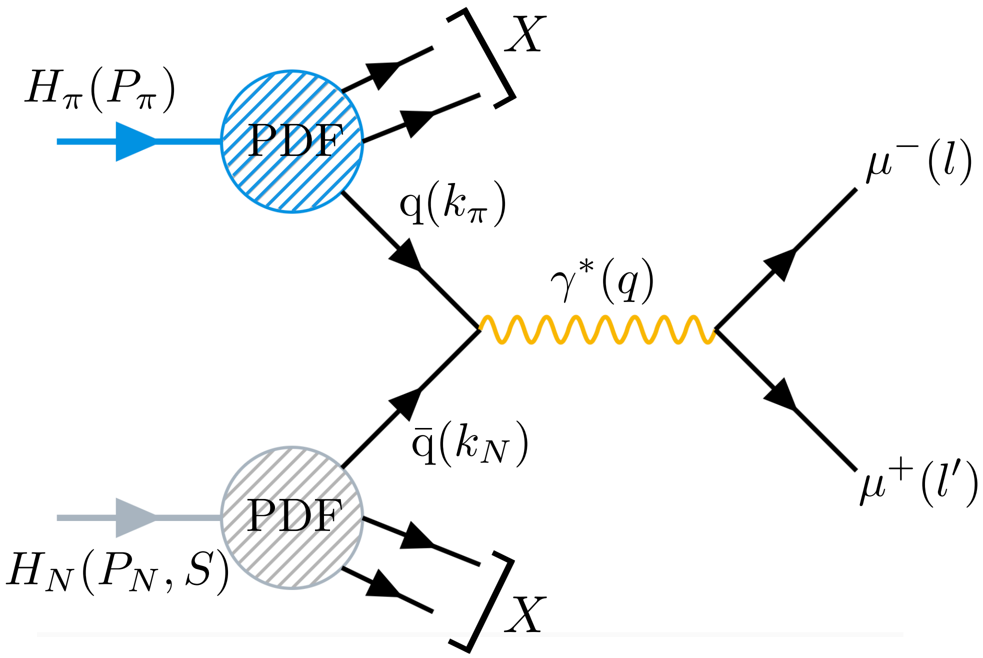
		Nucleon Polarization		
		U	L	T
Quark Polarization	U	$f_1^q(x,\mathbf{k}_T^2)$ Number Density		$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers
	L		$g_1^q(x,\mathbf{k}_T^2)$ Helicity	$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Worm-Gear T
	T	$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$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

See talk by F.Bradamante

SINGLE POLARIZED DRELL-YAN PROCESS

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

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



Pion induced polarized Drell-Yan

$$\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$$

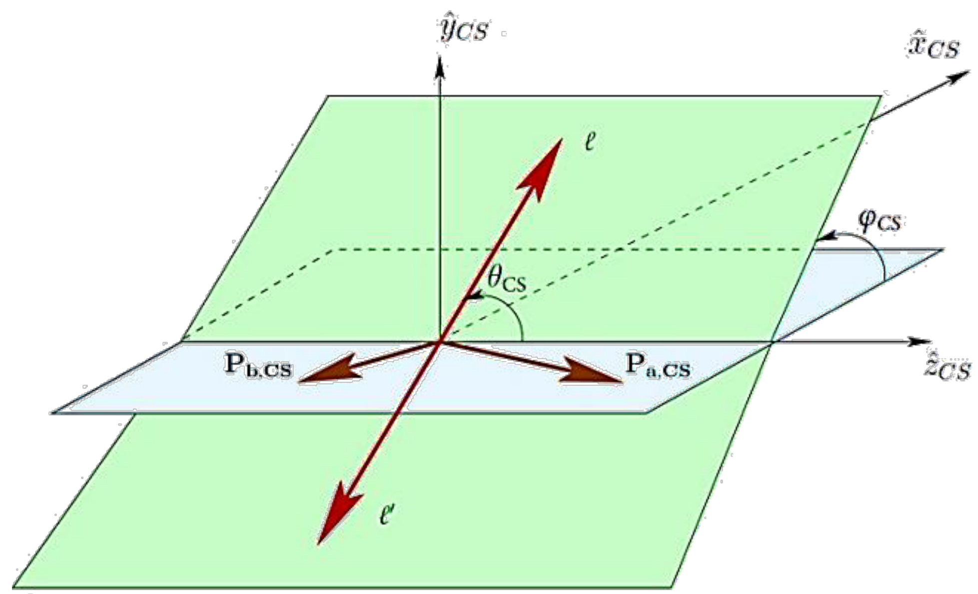
COMPASS 2015, 2018

D-factors

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

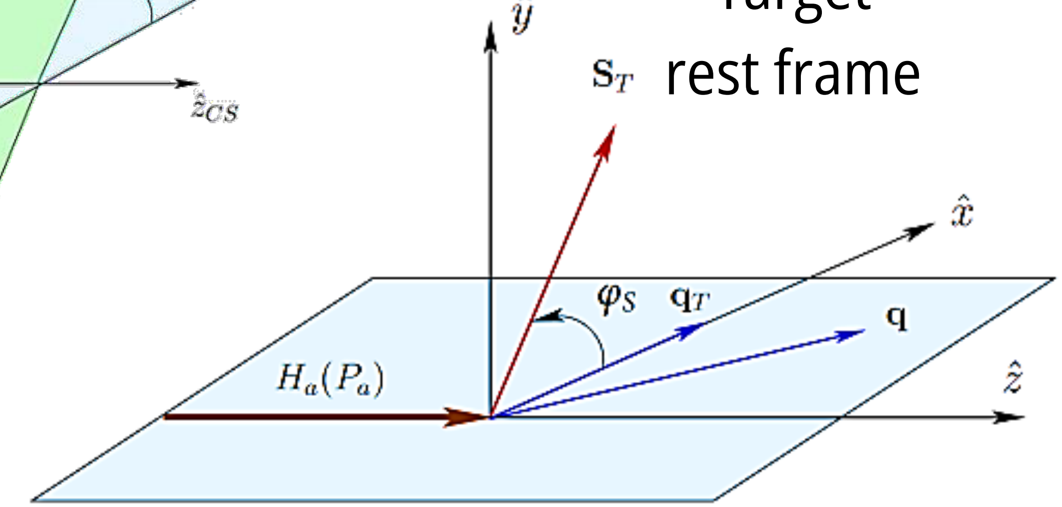
Azimuthal asymmetries

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



Collins-Soper frame

Target rest frame



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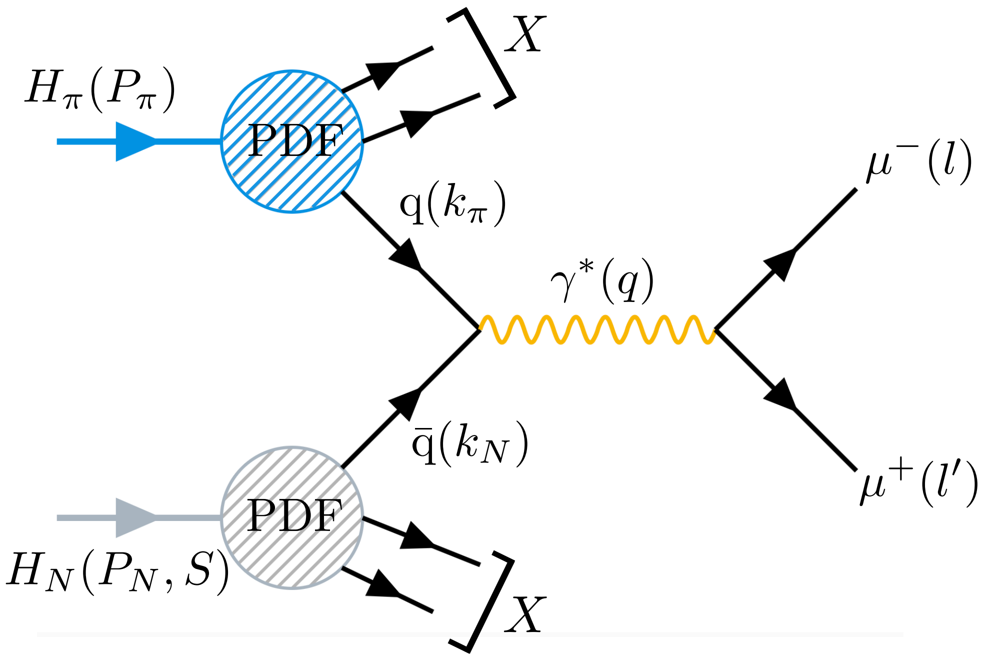

$$A_{DY} \propto PDF_\pi \otimes PDF_p$$

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

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

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

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

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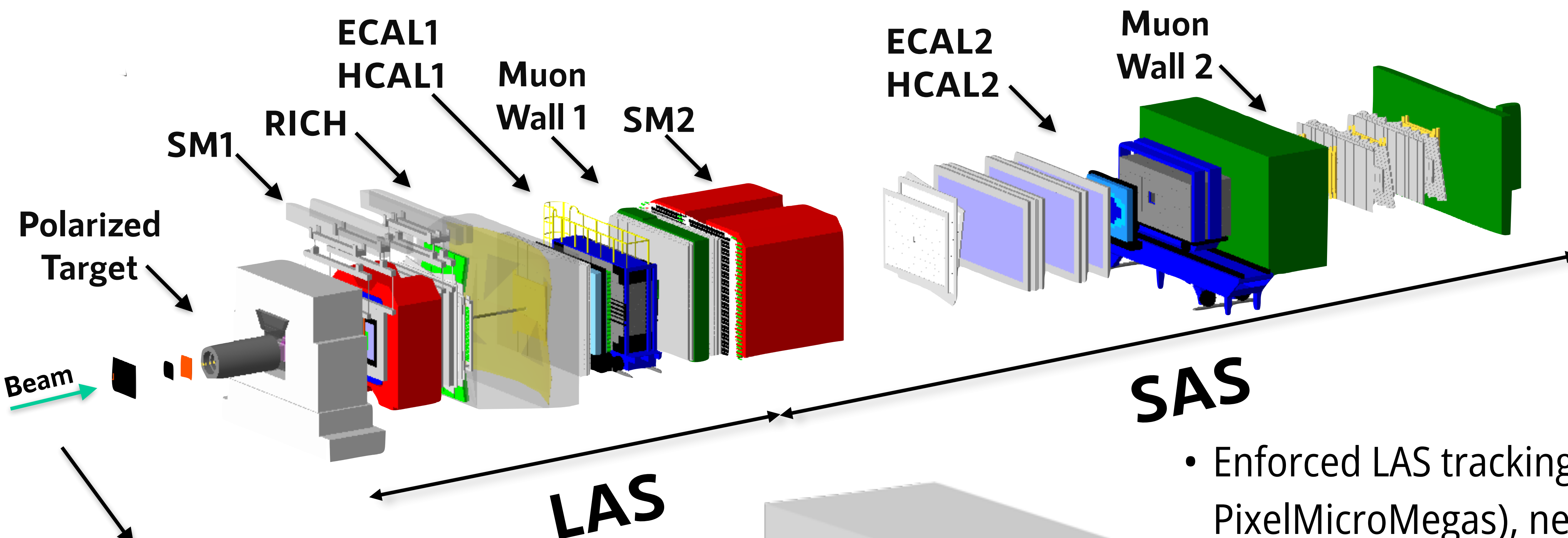
	T	$h_1^{q\perp}(x, \mathbf{k_T^2})$ Boer-Mulders	$h_{1L}^{q\perp}(x, \mathbf{k_T^2})$ Worm-Gear L	$h_{1T}^q(x, \mathbf{k_T^2})$ Transversity; $h_{1T}^{q\perp}(x, \mathbf{k_T^2})$ Pretzelosity

COMPASS SETUP FOR DRELL-YAN

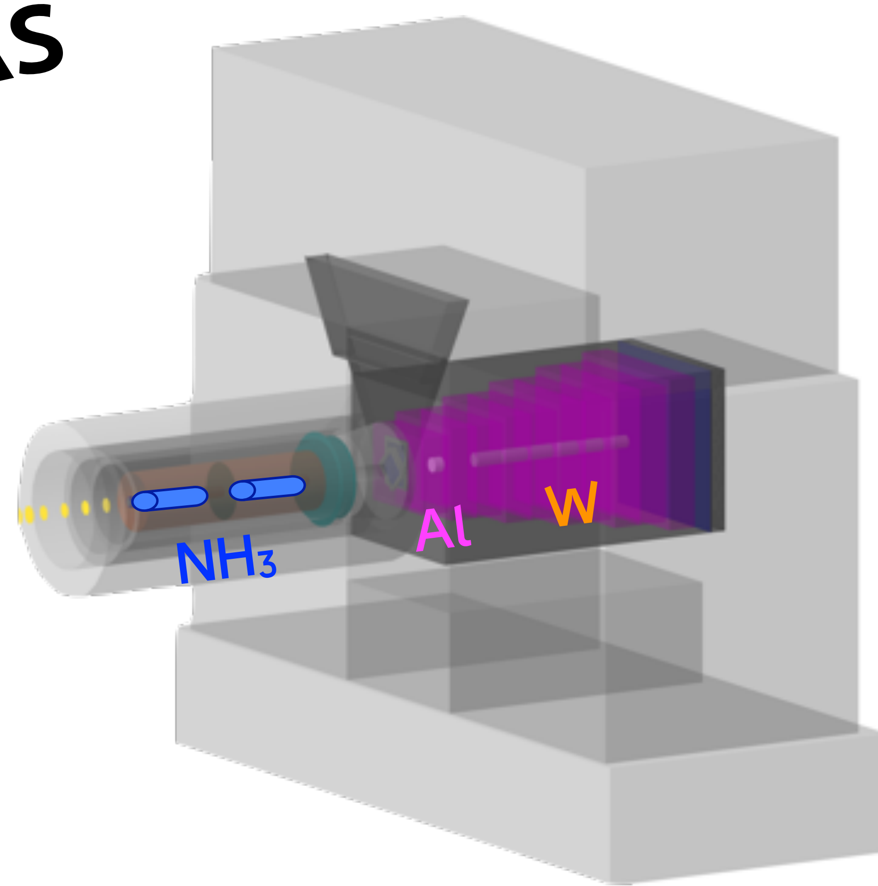


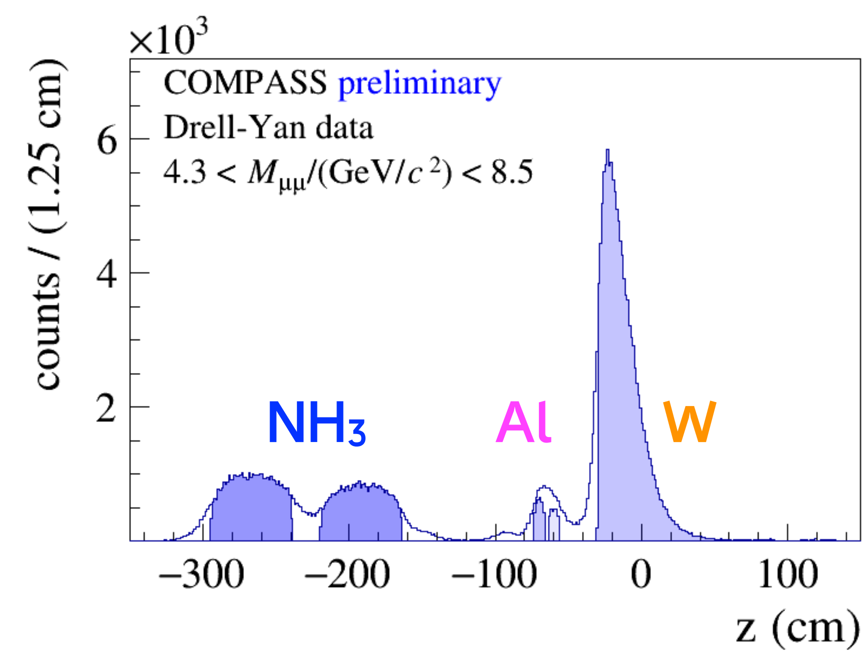
- Enforced LAS tracking (DC05, PixelMicroMegas), new DAQ ...

π^- beam

- P_{π^-} : 190 GeV/c, intensity $10^8\ \pi^-$/s

Target	# of cells	Polarization
NH_3	2	T, ~73 %





- Polarized DY Data takings:
  - 2015 run ~4 months;
  - 2018 run ~6 months;
- The polarization was **reversed** after each week;

DY AND SIDIS CROSS-SECTIONS @ LO

SIDIS on transversely polarized nucleons

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

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

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

Pion induced polarized Drell-Yan

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

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

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

SIDIS		DY
$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	← **Boer-Mulders** →	$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$	← **Sivers** →	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$	← **Pretzelosity** →	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$	← **Transversity** →	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

Universality in the 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)

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

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

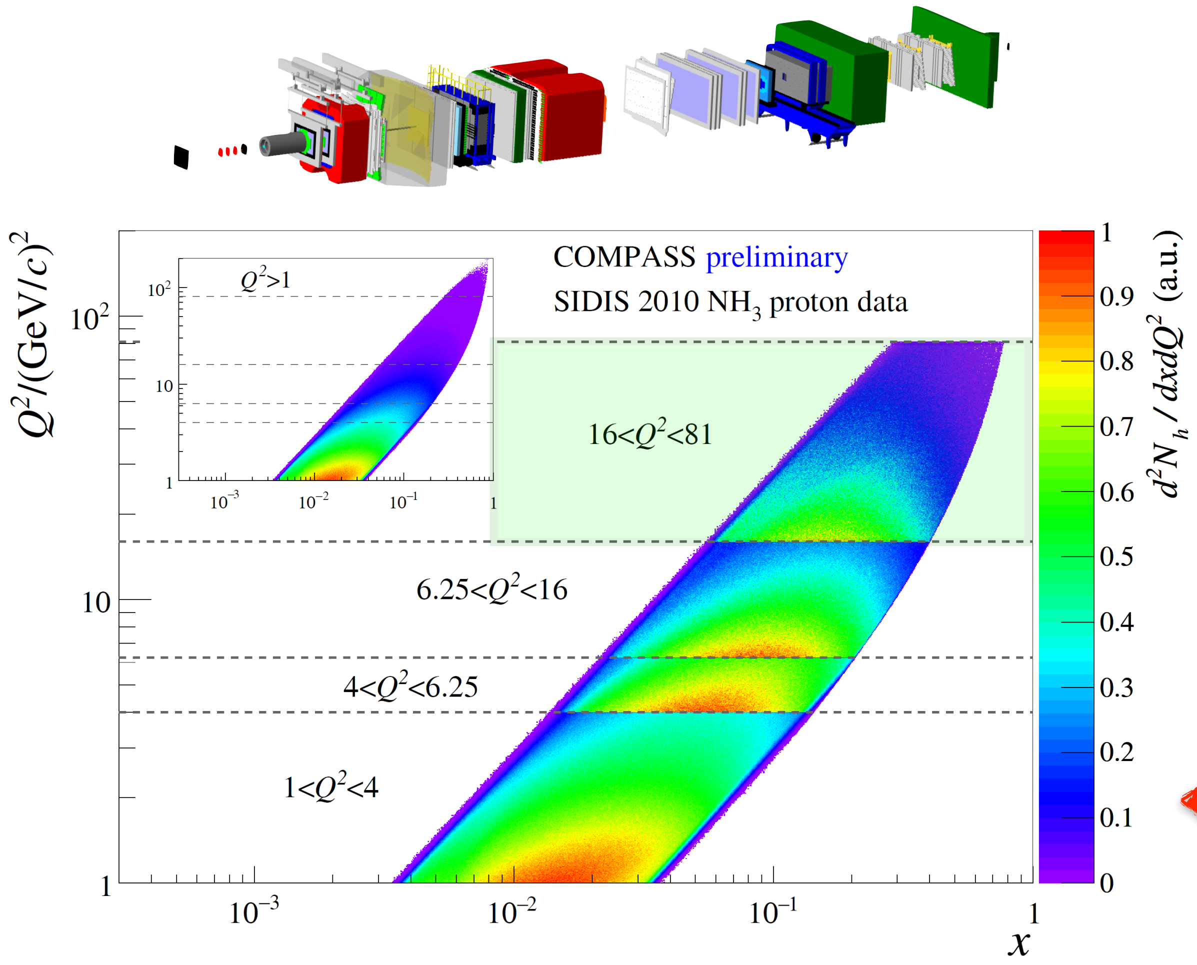
$$f_{1T,p}^{\perp q}|_{SIDIS} = -f_{1T,p}^{\perp q}|_{DY}$$

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

COMPASS SIDIS-DY BRIDGE

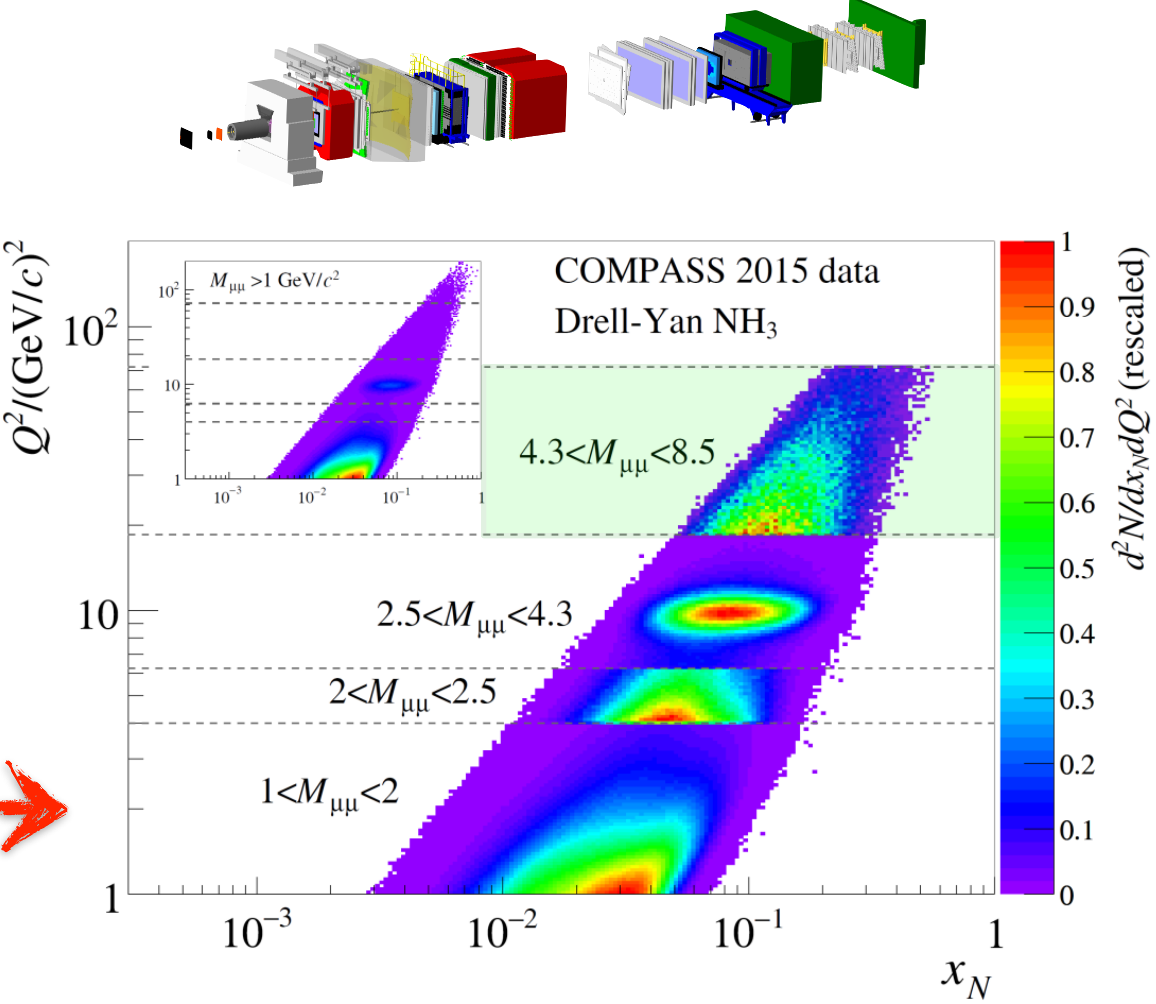
SIDIS on transversely polarized nucleons

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



Pion induced polarized Drell-Yan

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

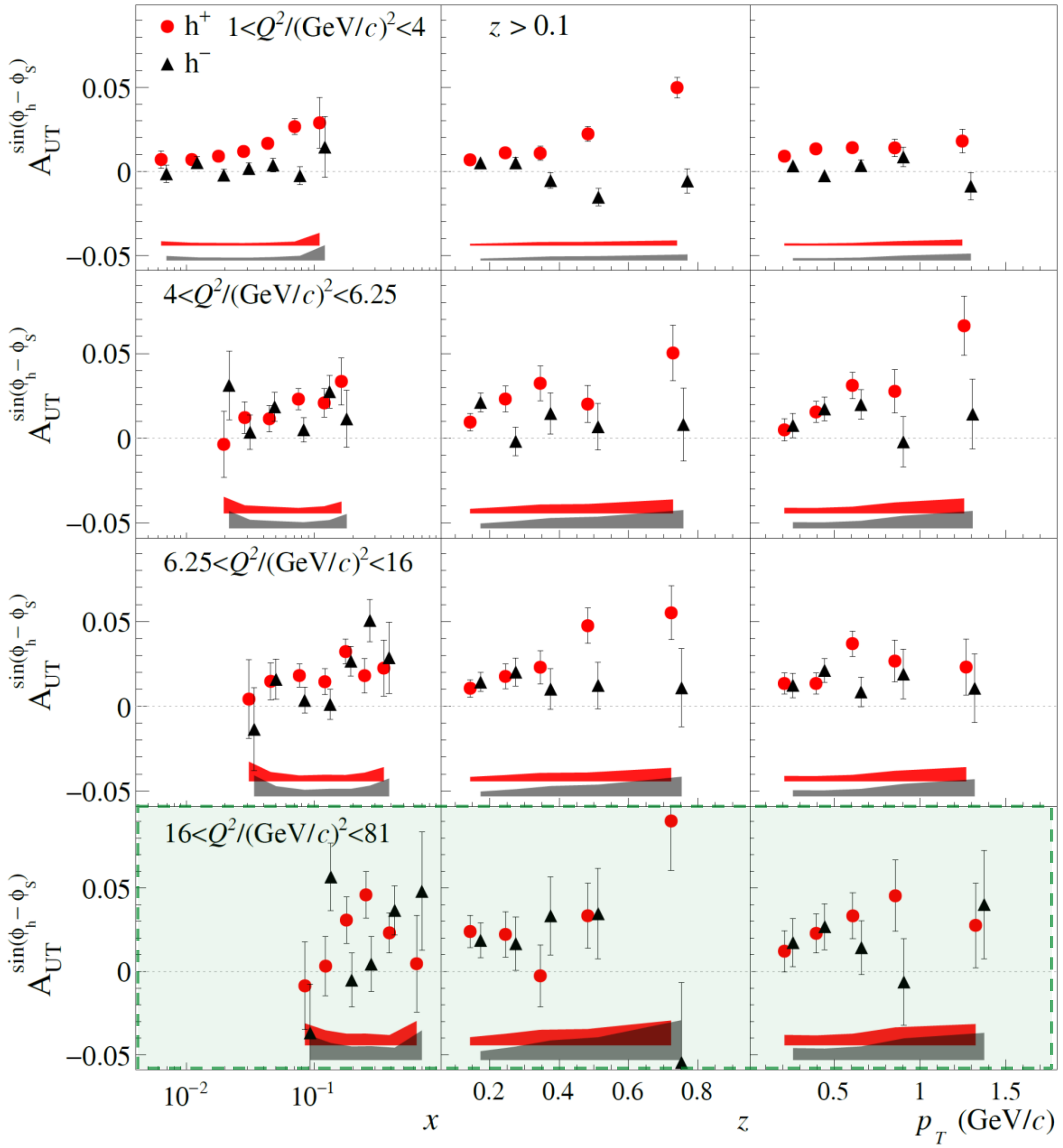


Comparable x:Q² kinematic coverage

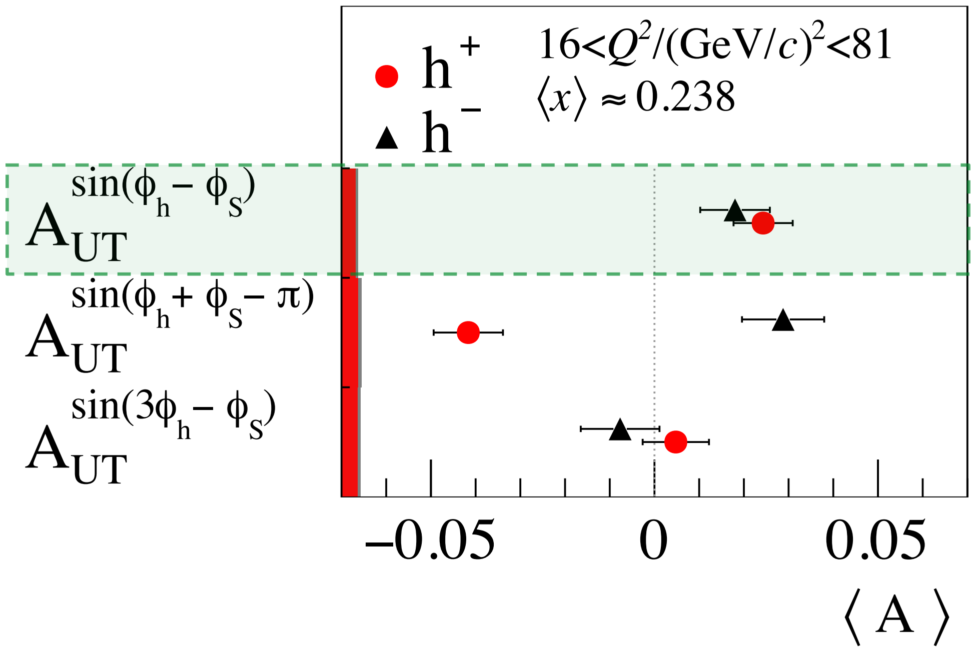
minimization of possible Q² evolution effects

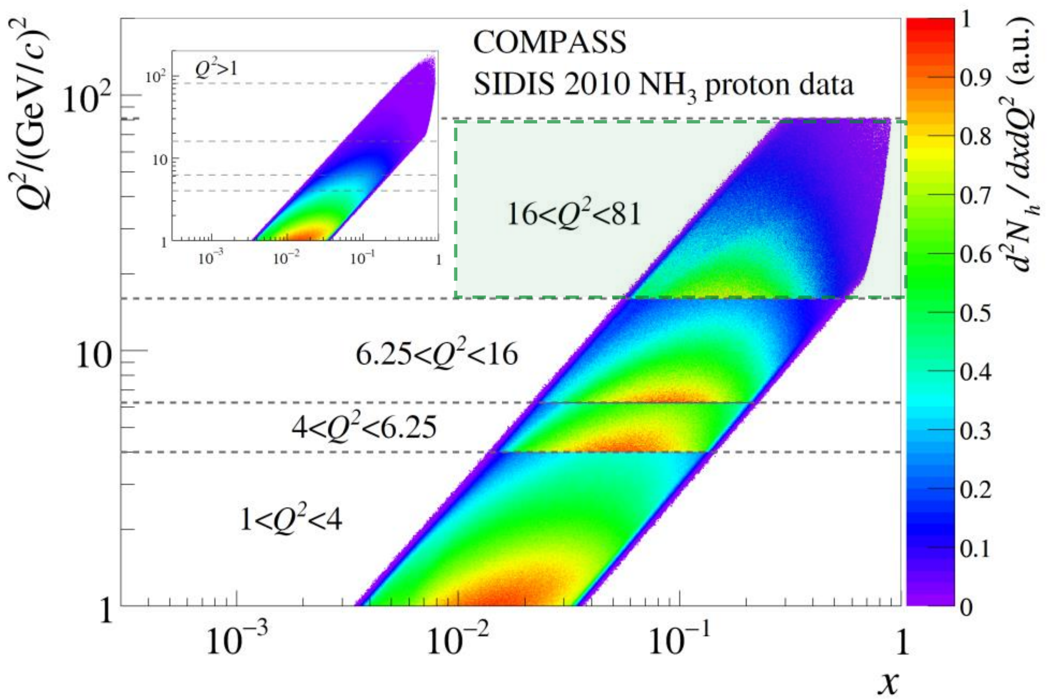
Unique experimental environment to test the TMD universality and the sign change of Sivers and Boer-Mulders!

COMPASS: SIDIS IN DY RANGES



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





- Dedicated 2D-analysis performed by COMPASS dividing Proton 2010 data into the 4 DY Q^2 ranges
- SIDIS TSAs extracted for each Q^2 range
- **Sivers in HM range shows a non-zero signal for h+**

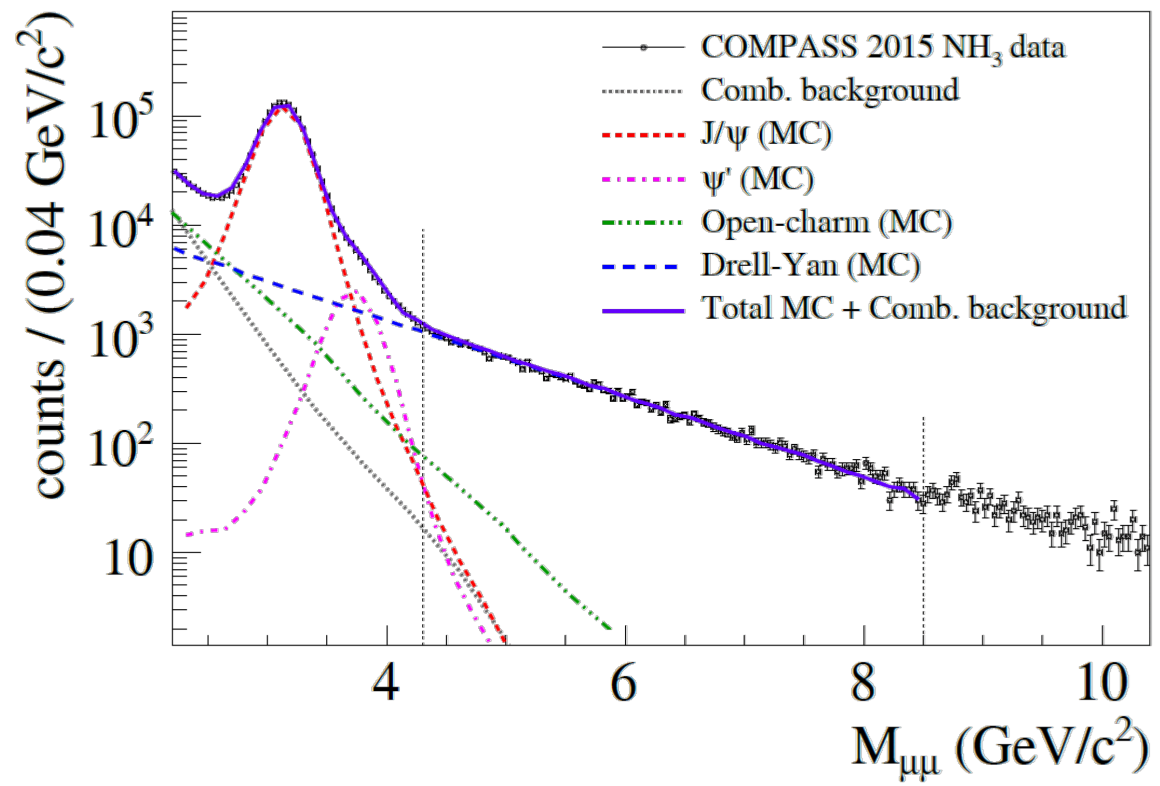
DRELL-YAN MEASUREMENTS @ COMPASS

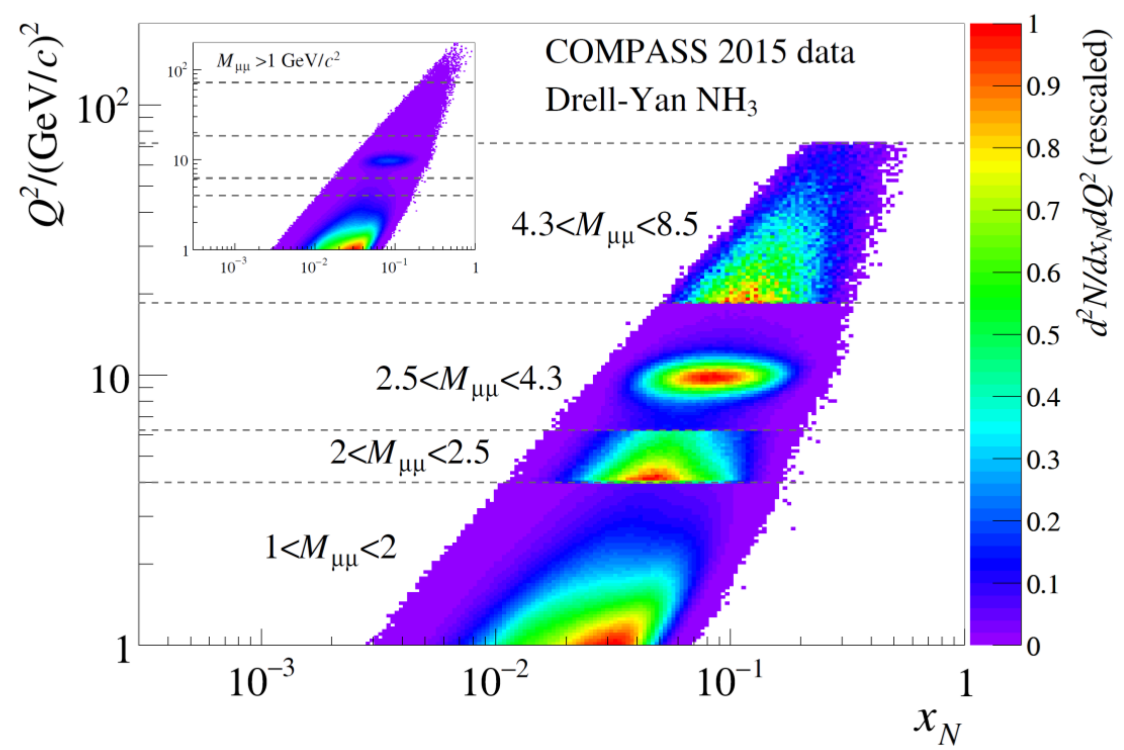
I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
- Large background contamination.

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

III. $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$, "Charmonia mass"
- Strong J/ψ signal → Studies of J/ψ physics.
- Good signal/background.

IV. $4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$, "High mass"
- Beyond J/ψ and ψ' peak, background < 4%.
- Valence quark region → u-quark dominance.
- Low DY cross-section





J/Ψ MEASUREMENTS @ COMPASS

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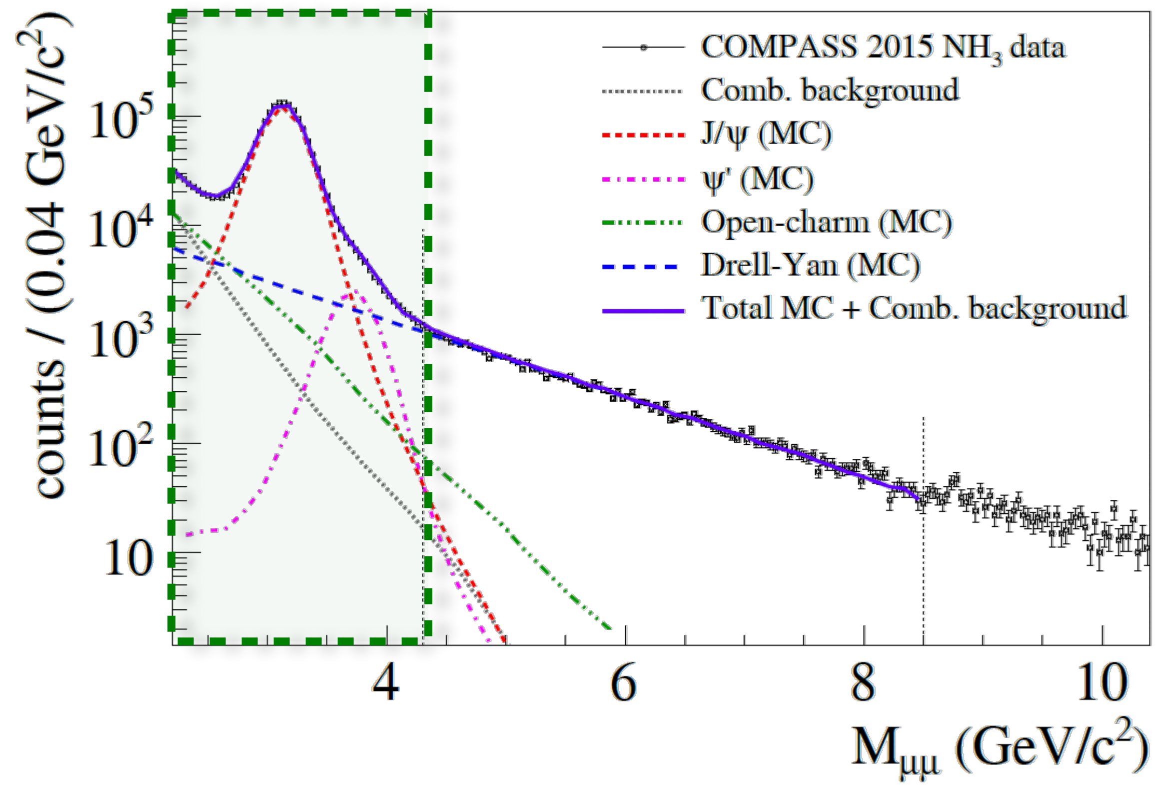
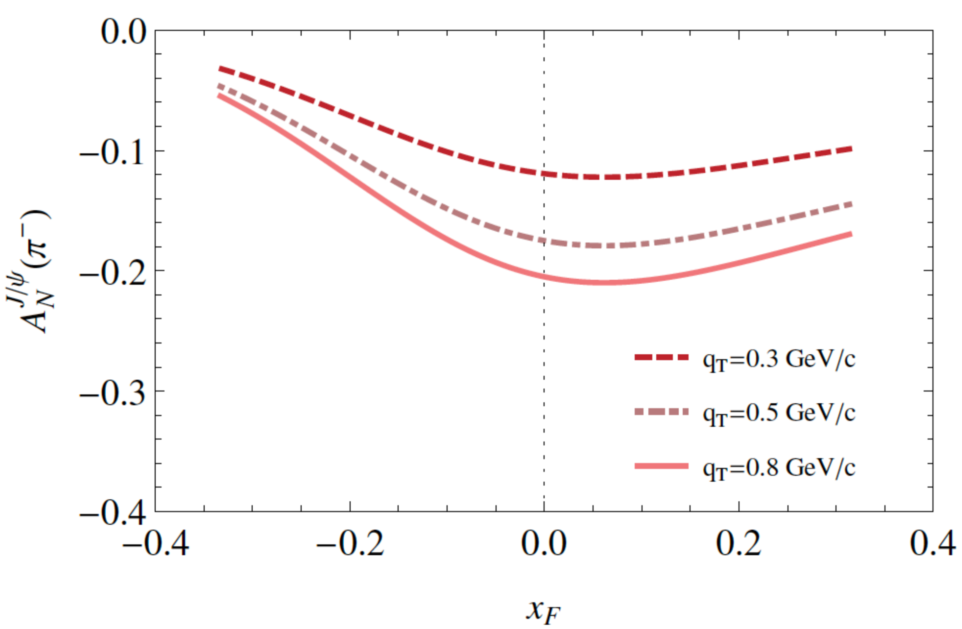
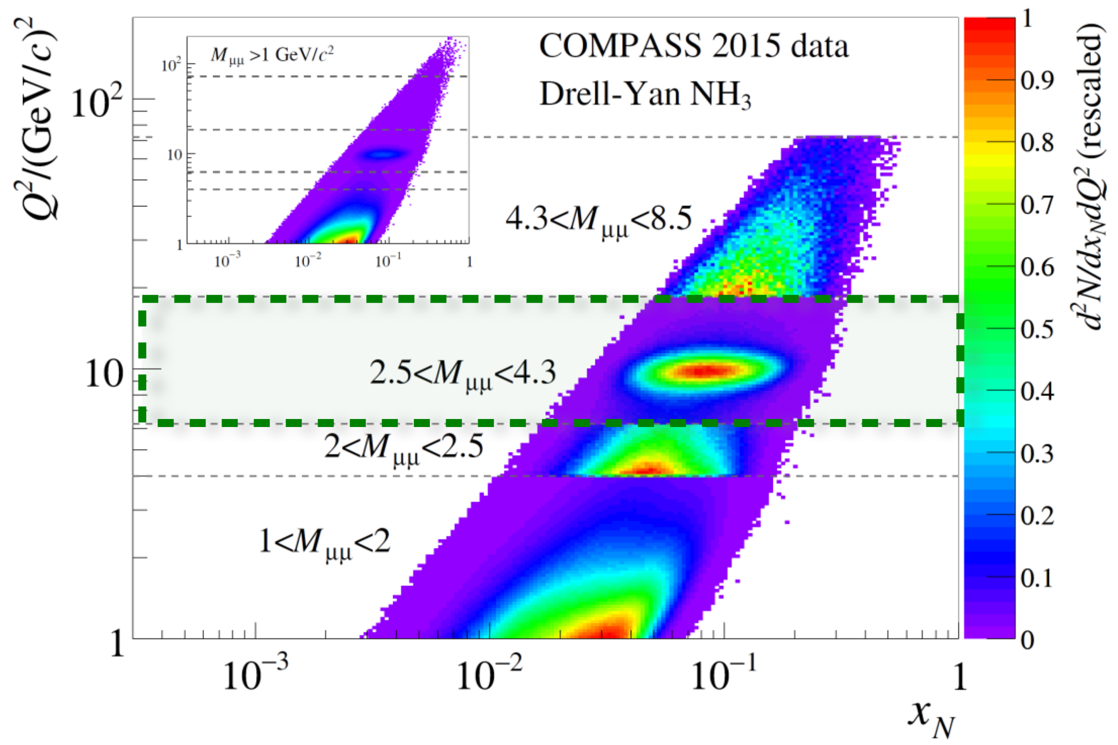




Ongoing analysis!

Anselmino et al., Phys.Lett. B770 (2017) 302-306



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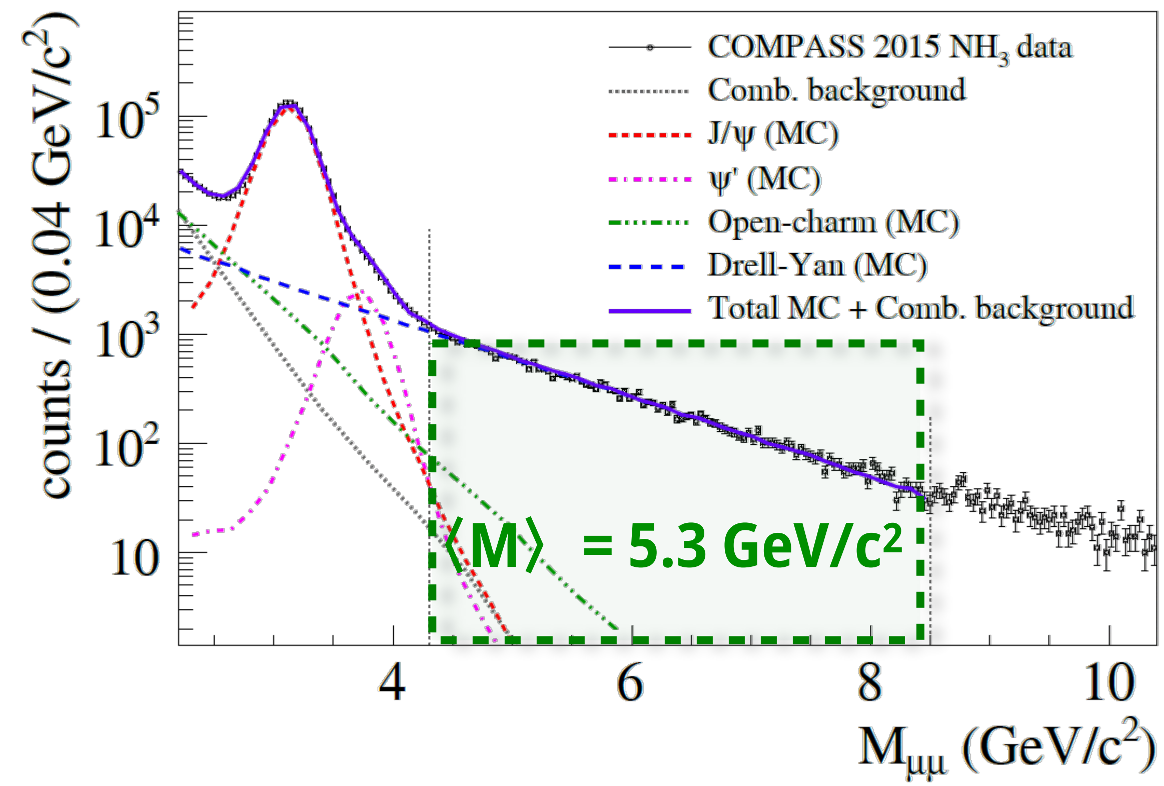
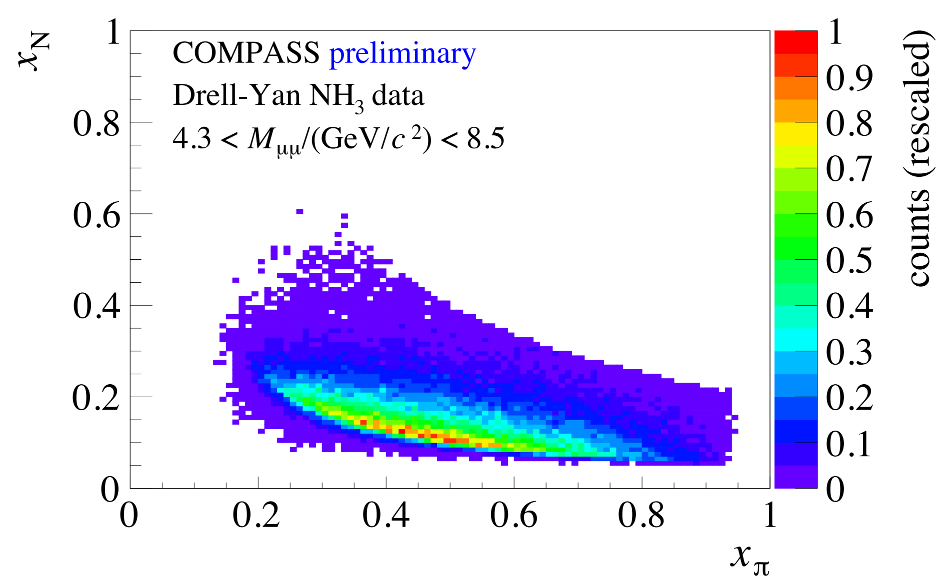
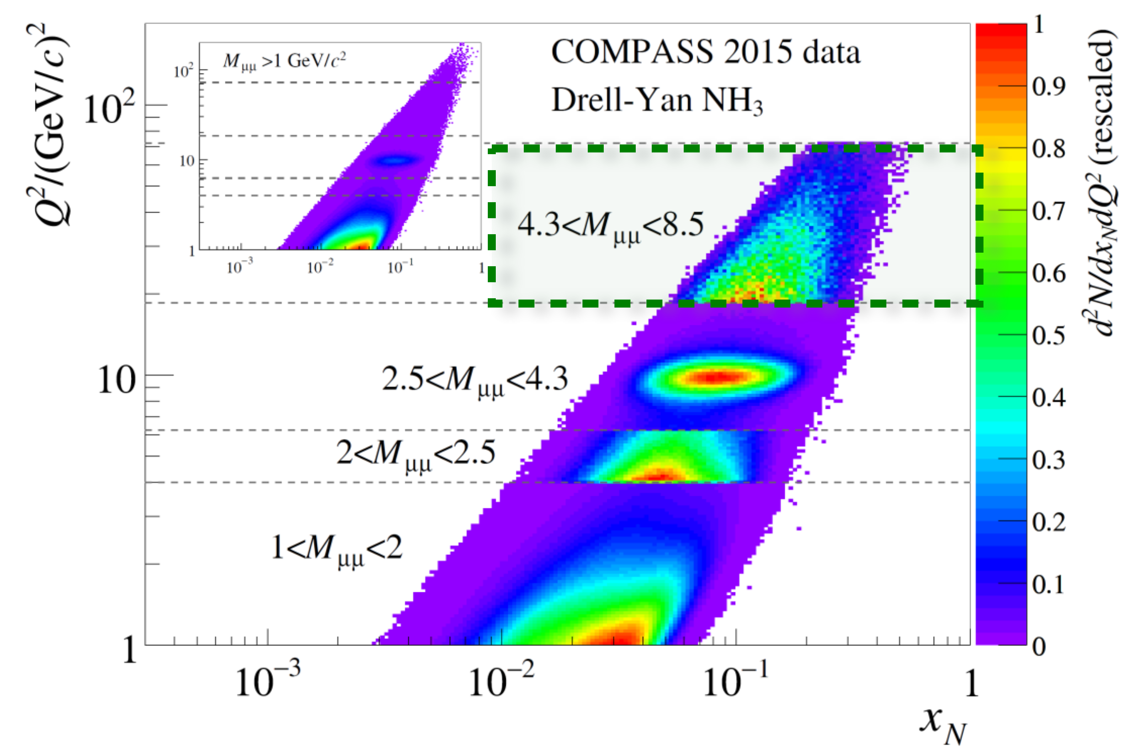


$\langle x_\pi \rangle = 0.5$

$\langle x_N \rangle = 0.17$





HM events are in the valence quark region

DRELL-YAN MEASUREMENTS @ COMPASS

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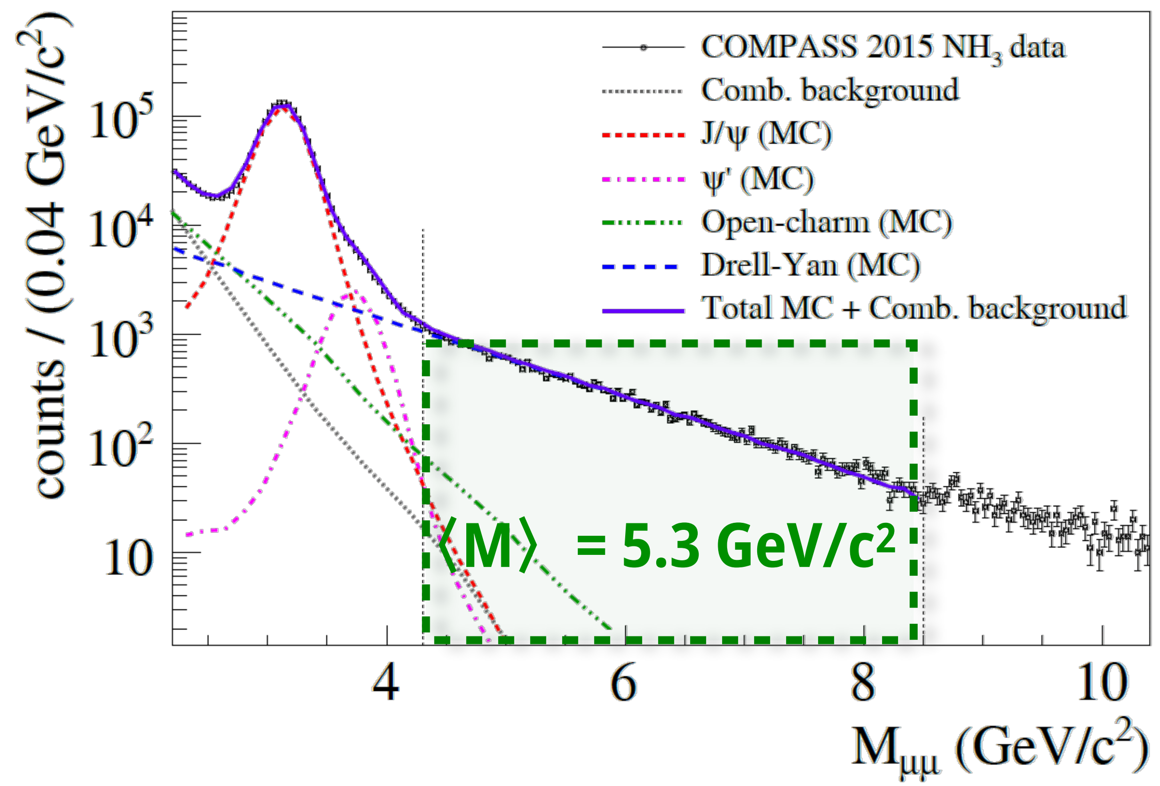
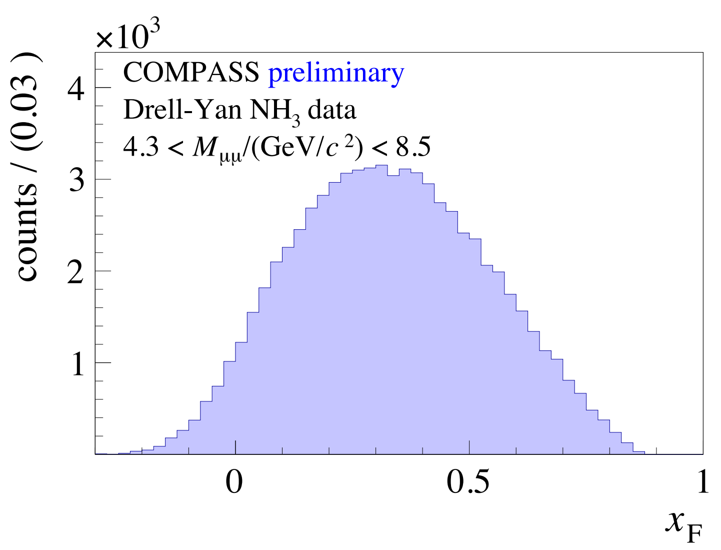
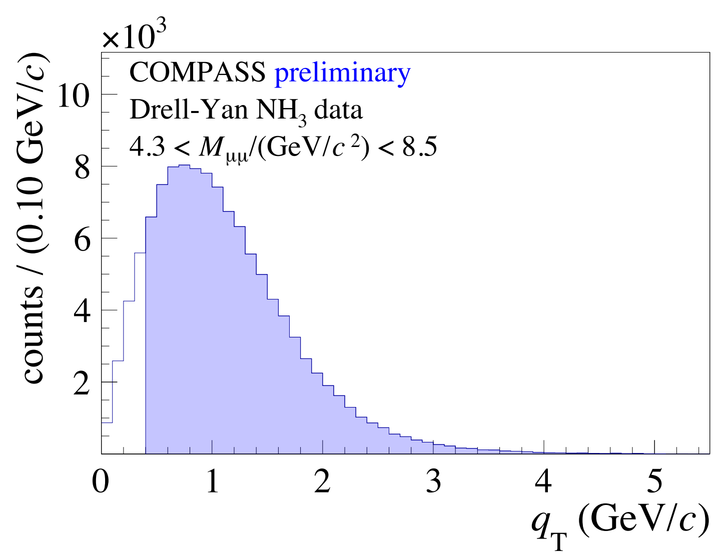
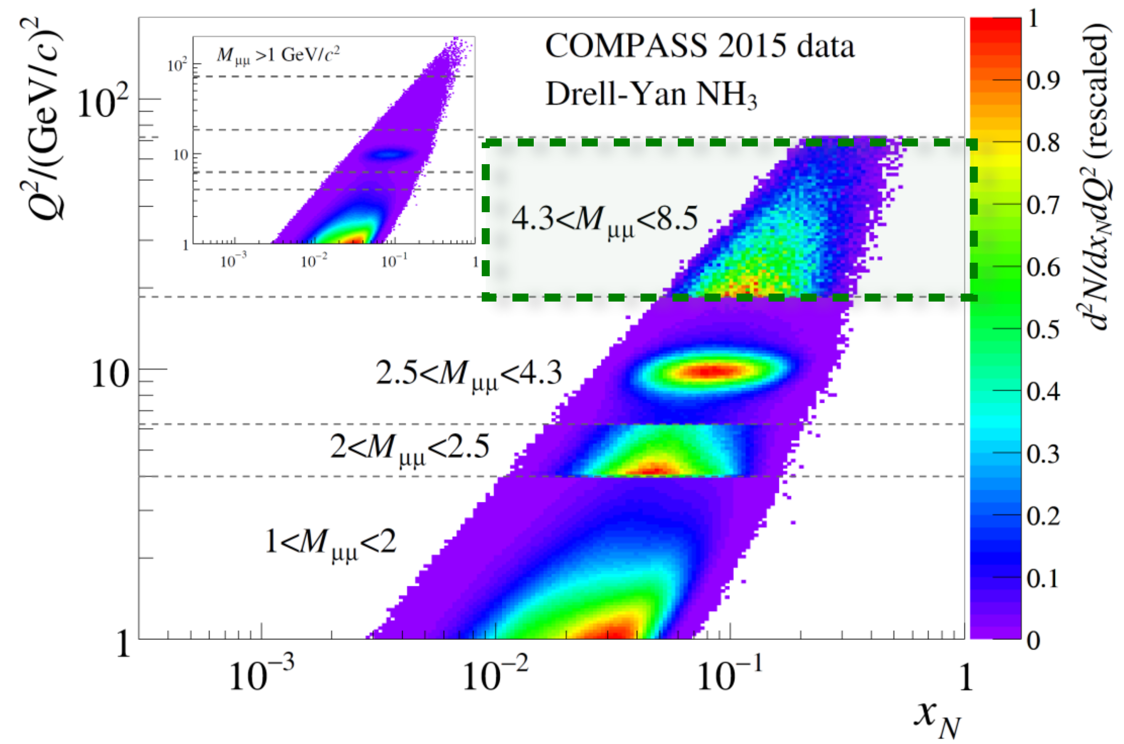


$q_T > 0.4$ GeV/c

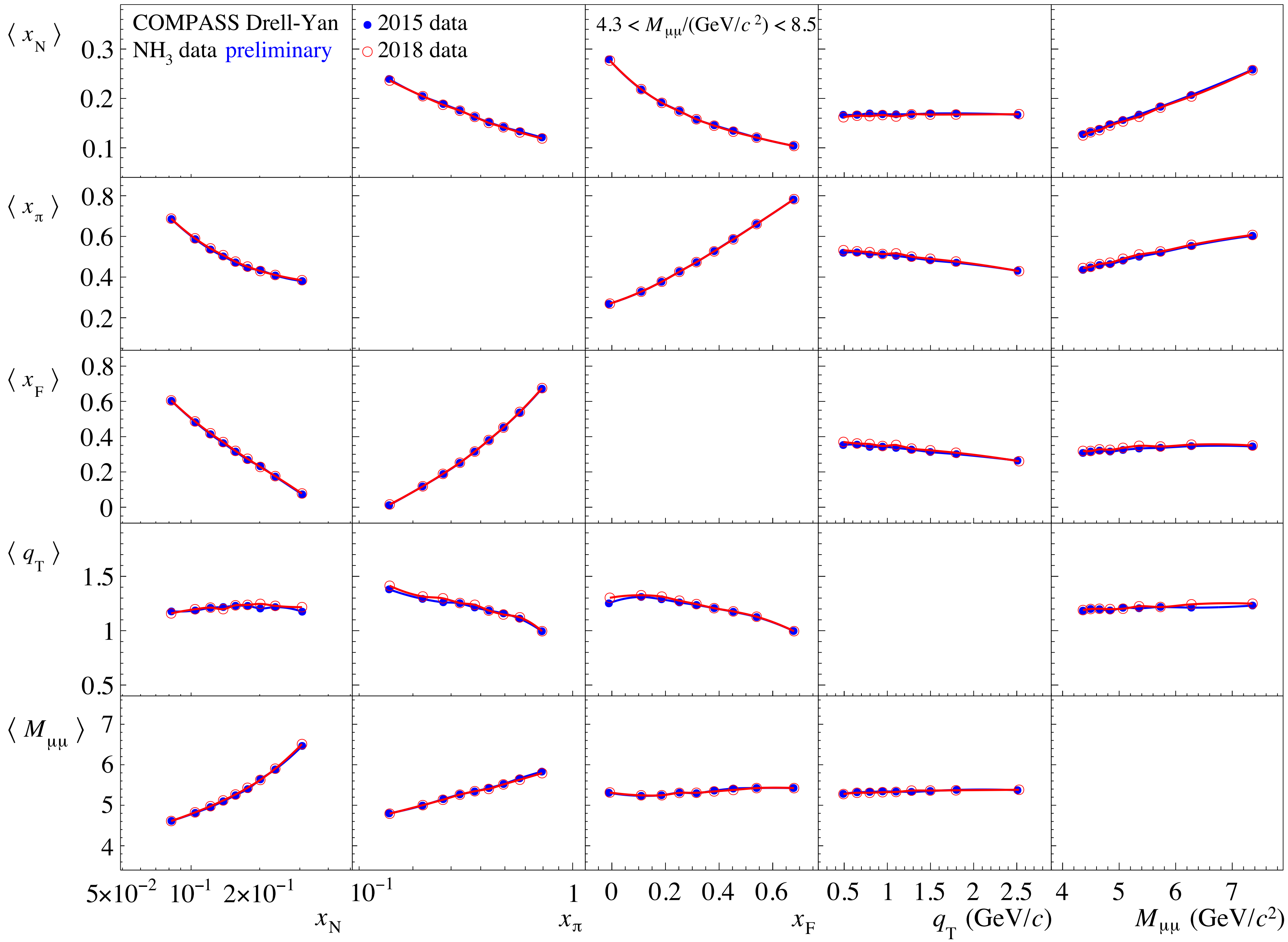
$\langle x_F \rangle = 0.33$ $\langle q_T \rangle = 1.17$ GeV/c







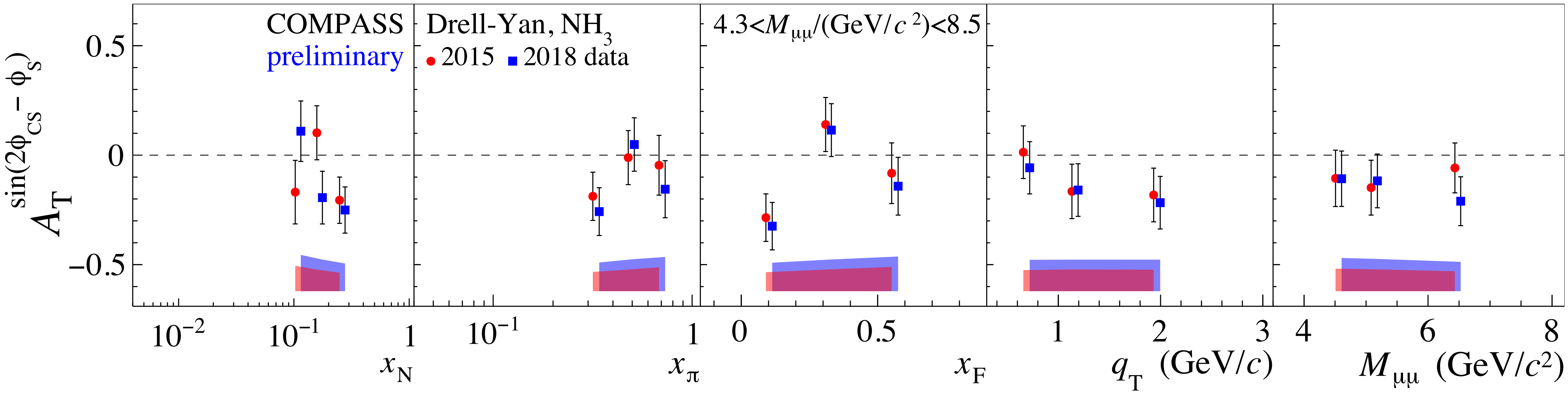
2015-2018 PHASE SPACE COVERAGE



Same kinematic coverage of 2015 and 2018 data!

DY HM TSA RESULTS: TRANSVERSITY

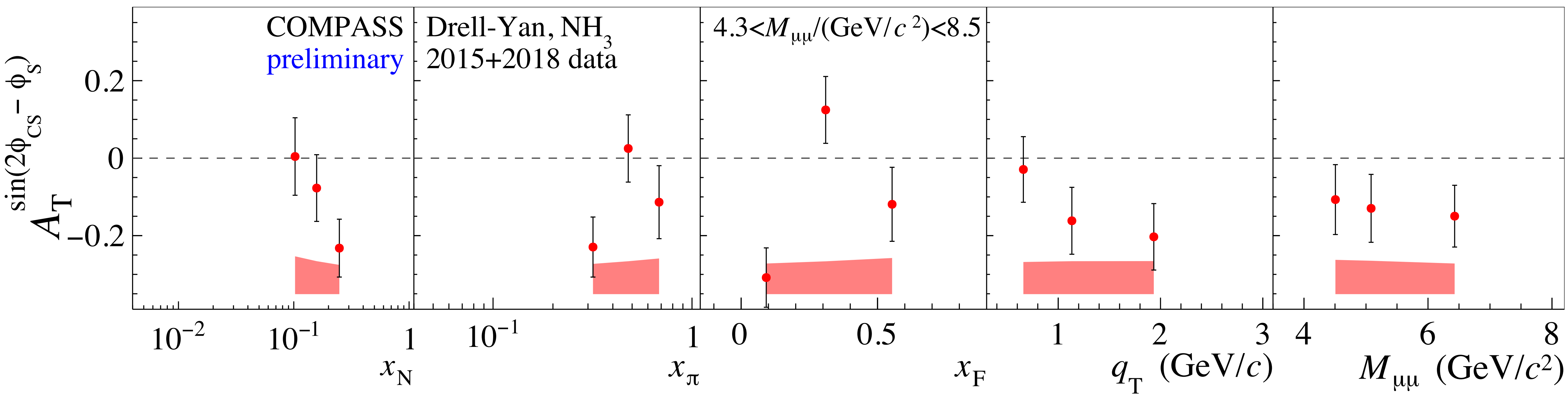
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ **DY - HM range**



- Full re-processing and combined analysis of 2015 and 2018 data samples
- Agreement between results obtained from 2015 and 2018 data separately
  - 2018 sample characterized by somewhat larger systematic errors
- In the following, combined 2015 + 2018 results are presented! **NEW**

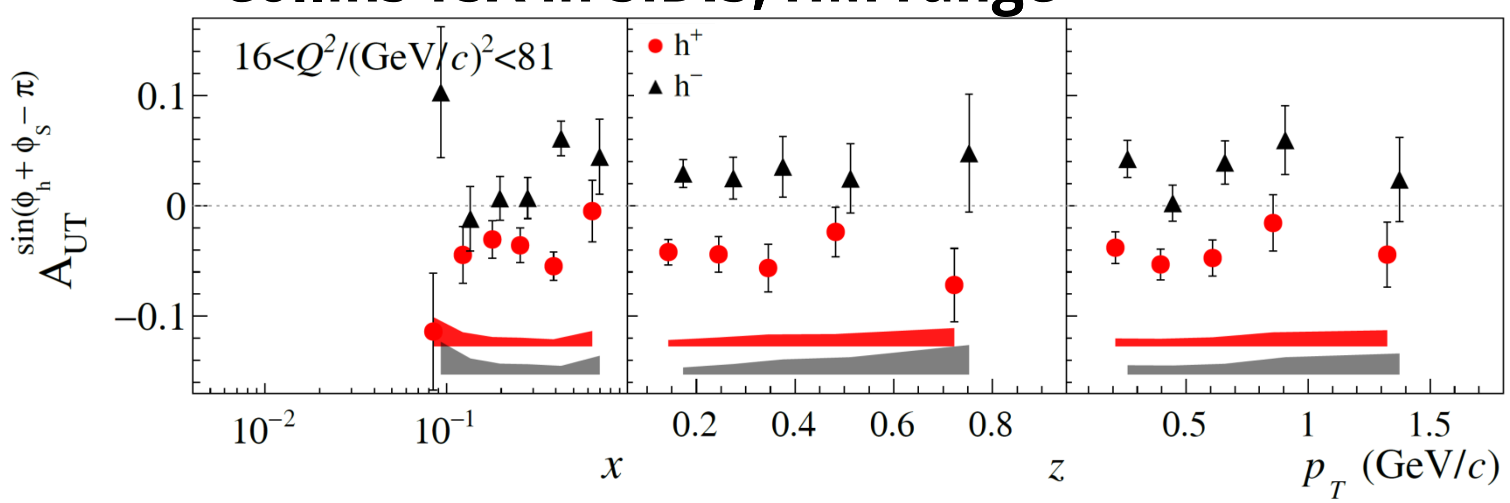
DY HM TSA RESULTS: TRANSVERSITY

$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ **DY - HM range** ● COMPASS, **2015 + 2018 Full Data Sample** **NEW!**



Collins TSA in SIDIS, HM range

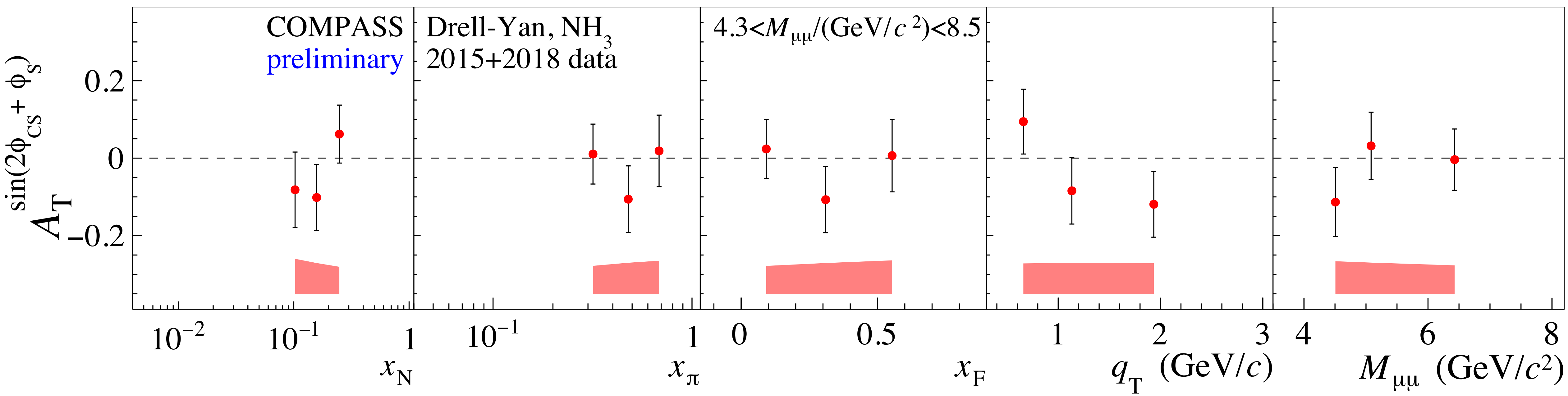
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$



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

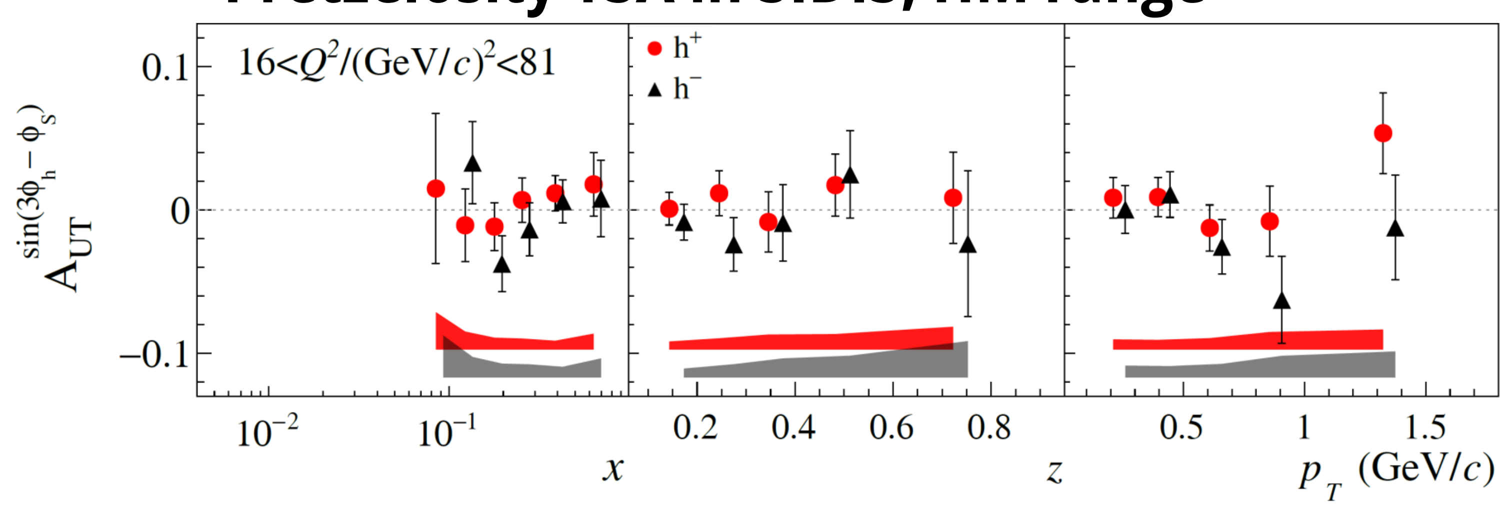
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$ **DY - HM range**

● COMPASS, **2015 + 2018 Full Data Sample** **NEW!**



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

Pretzelosity TSA in SIDIS, HM range



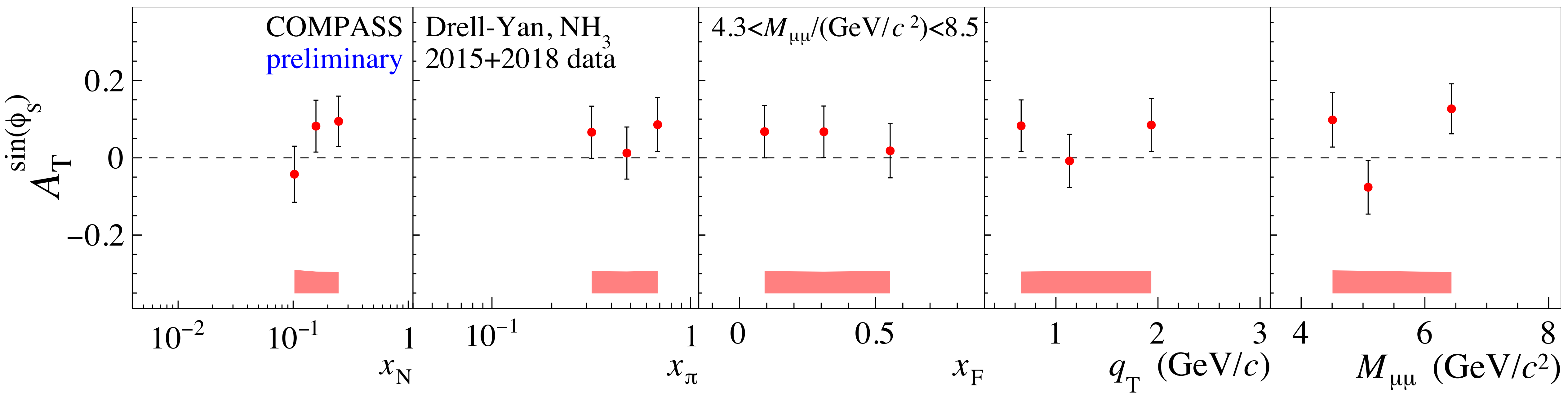
COMPASS, **PLB 770 (2017) 138**

DY HM TSA RESULTS: SIVERS

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

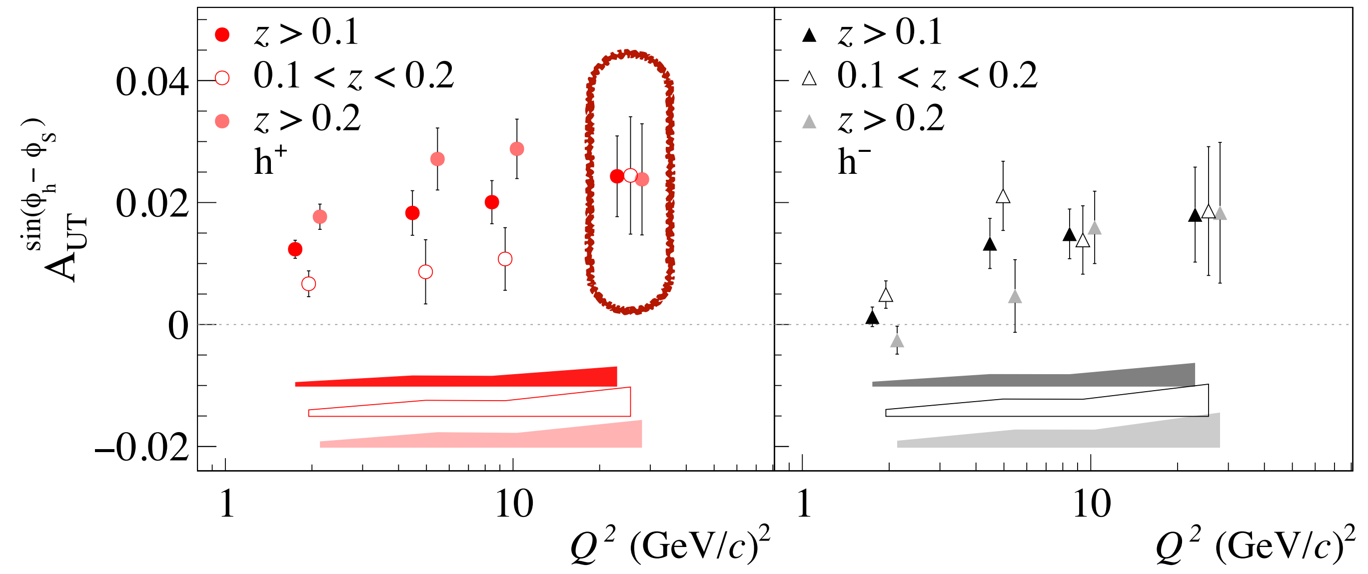
DY - HM range

● COMPASS, **2015 + 2018 Full Data Sample** **NEW!**



Sivers TSA in SIDIS, HM range

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



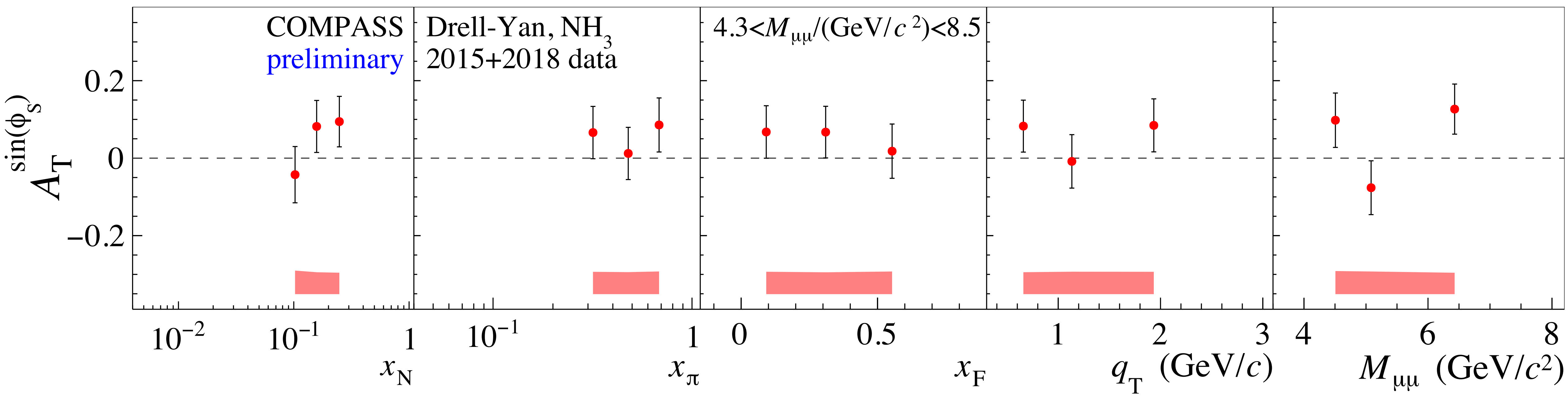
COMPASS, **PLB 770 (2017) 138**

DY HM TSA RESULTS: SIVERS

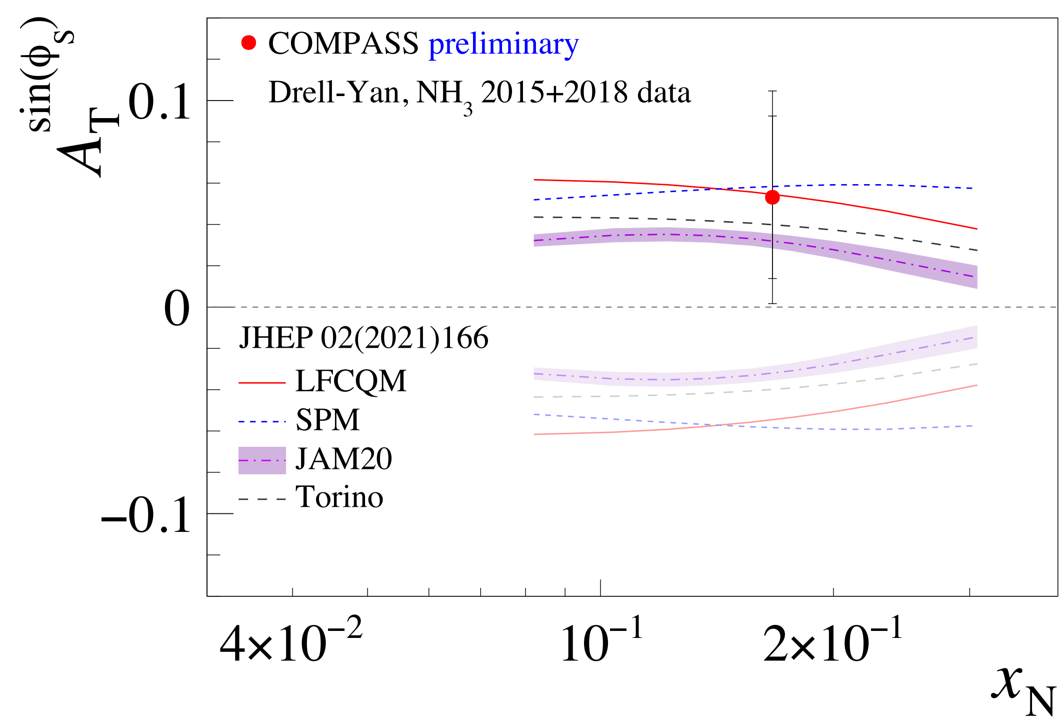
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$

DY - HM range

● COMPASS, **2015 + 2018 Full Data Sample** **NEW!**



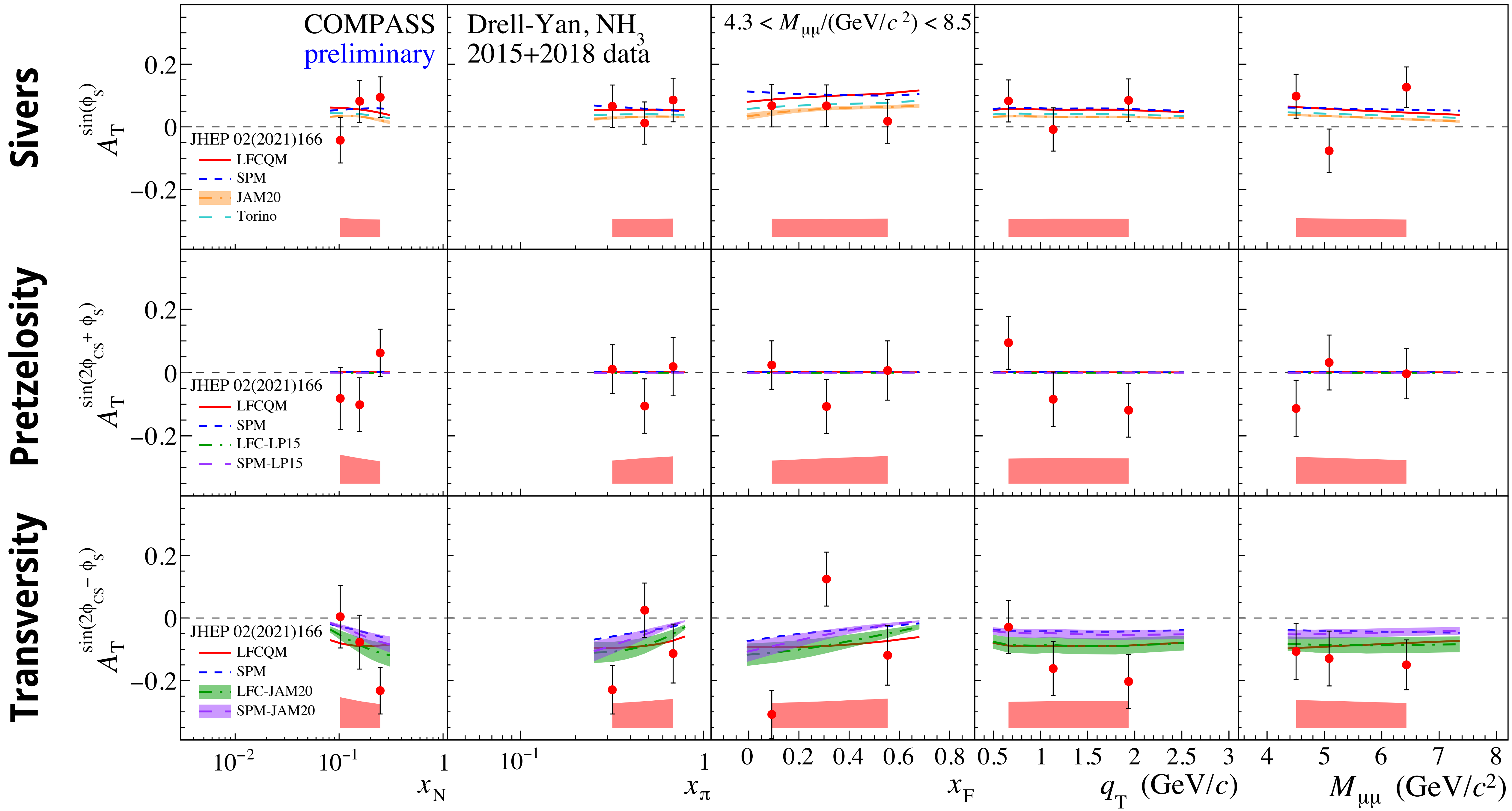
COMPASS HM DY result for Sivers asymmetry is consistent with the predicted change of sign for the Sivers function



sign change

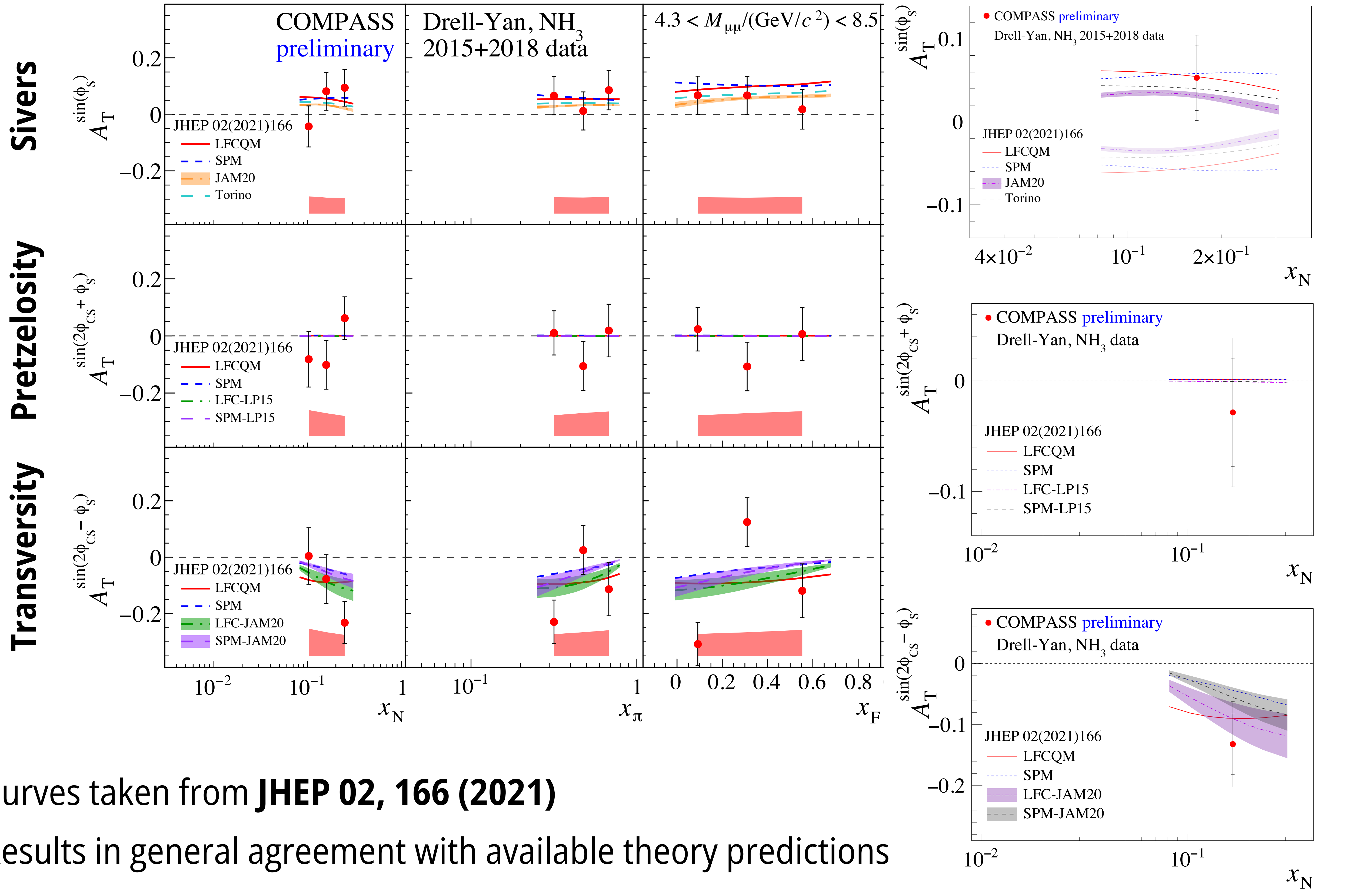
no sign change

DY HM TSA RESULTS VS PREDICTIONS



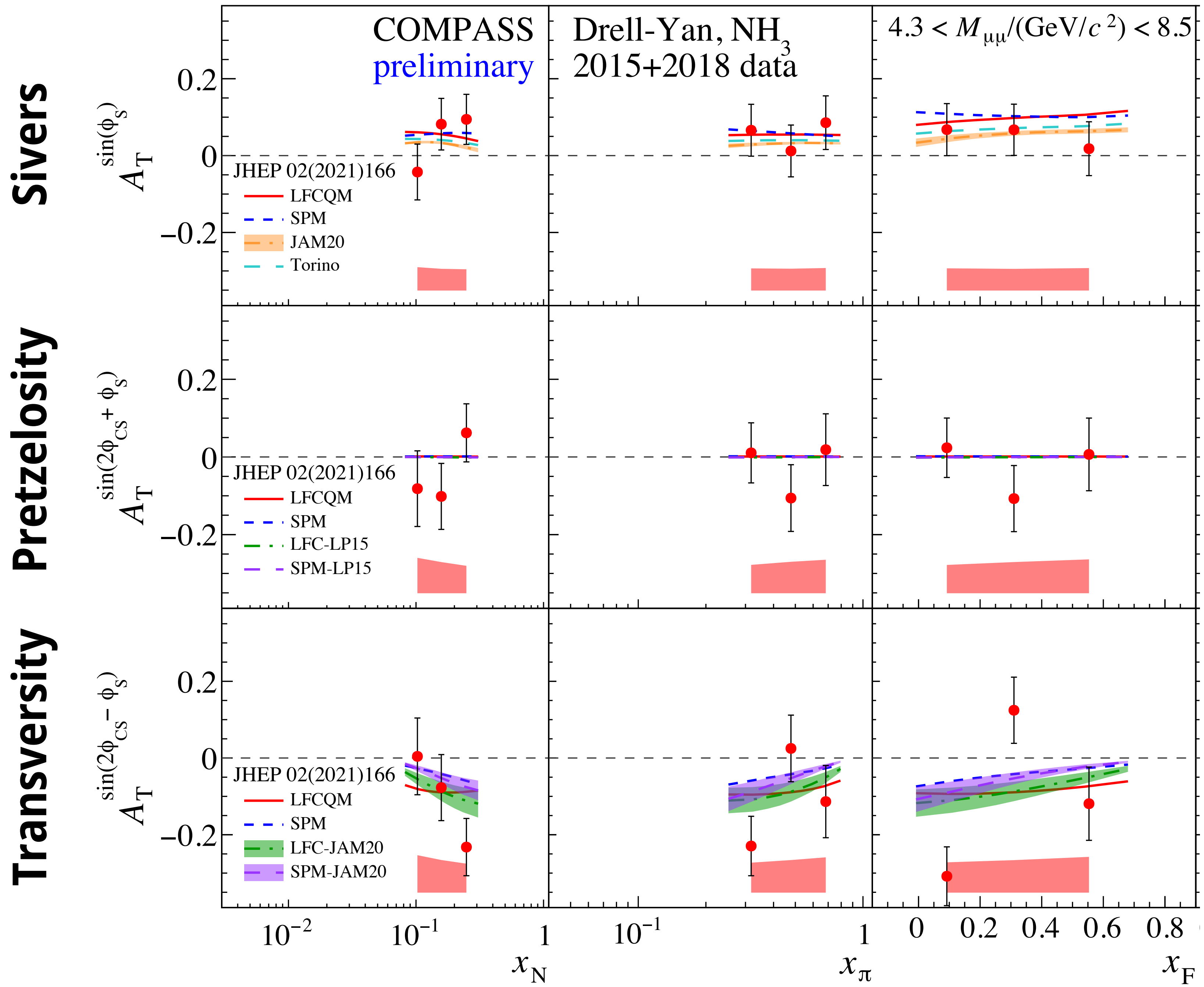
- Curves taken from **JHEP 02, 166 (2021)**

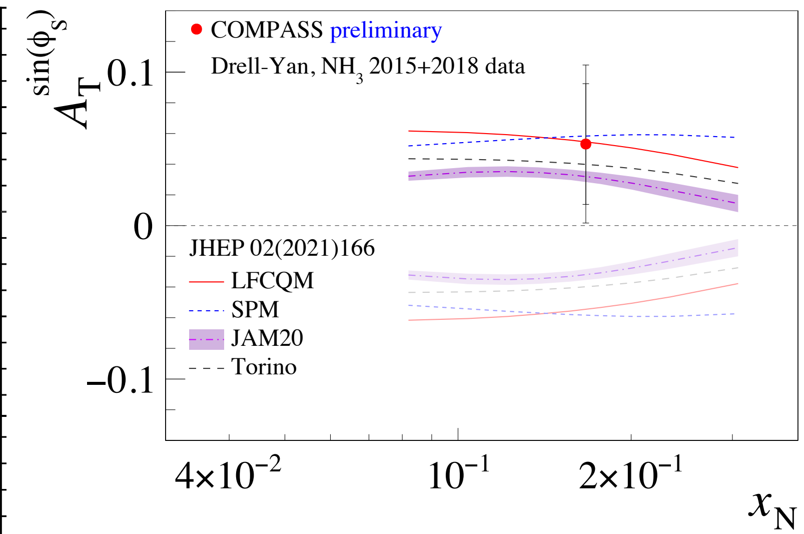
DY HM TSA RESULTS VS PREDICTIONS

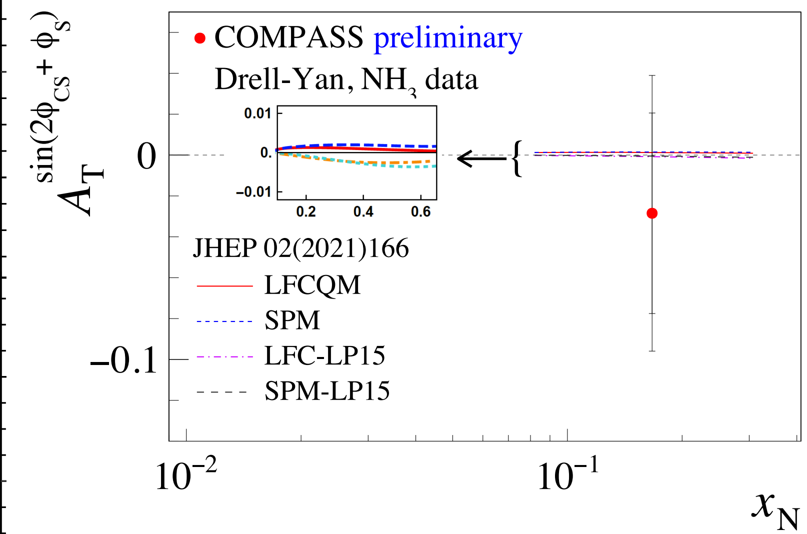


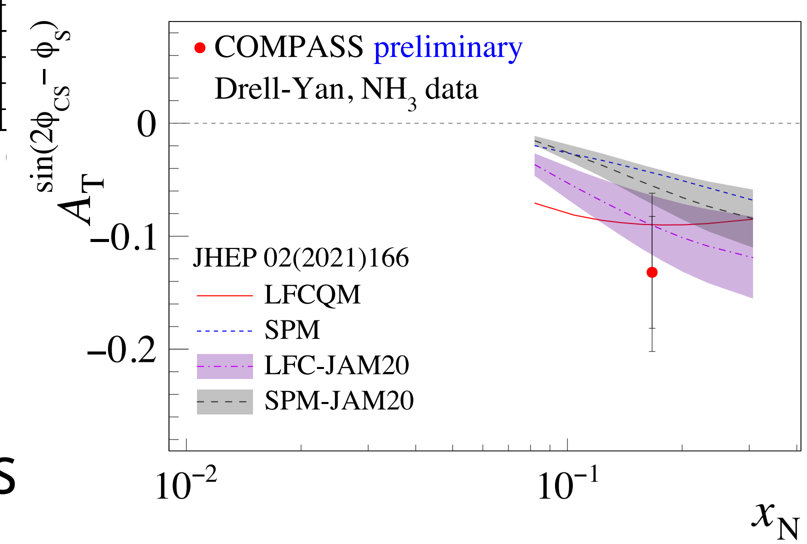
- Curves taken from **JHEP 02, 166 (2021)**
- Results in general agreement with available theory predictions

DY HM TSA RESULTS VS PREDICTIONS







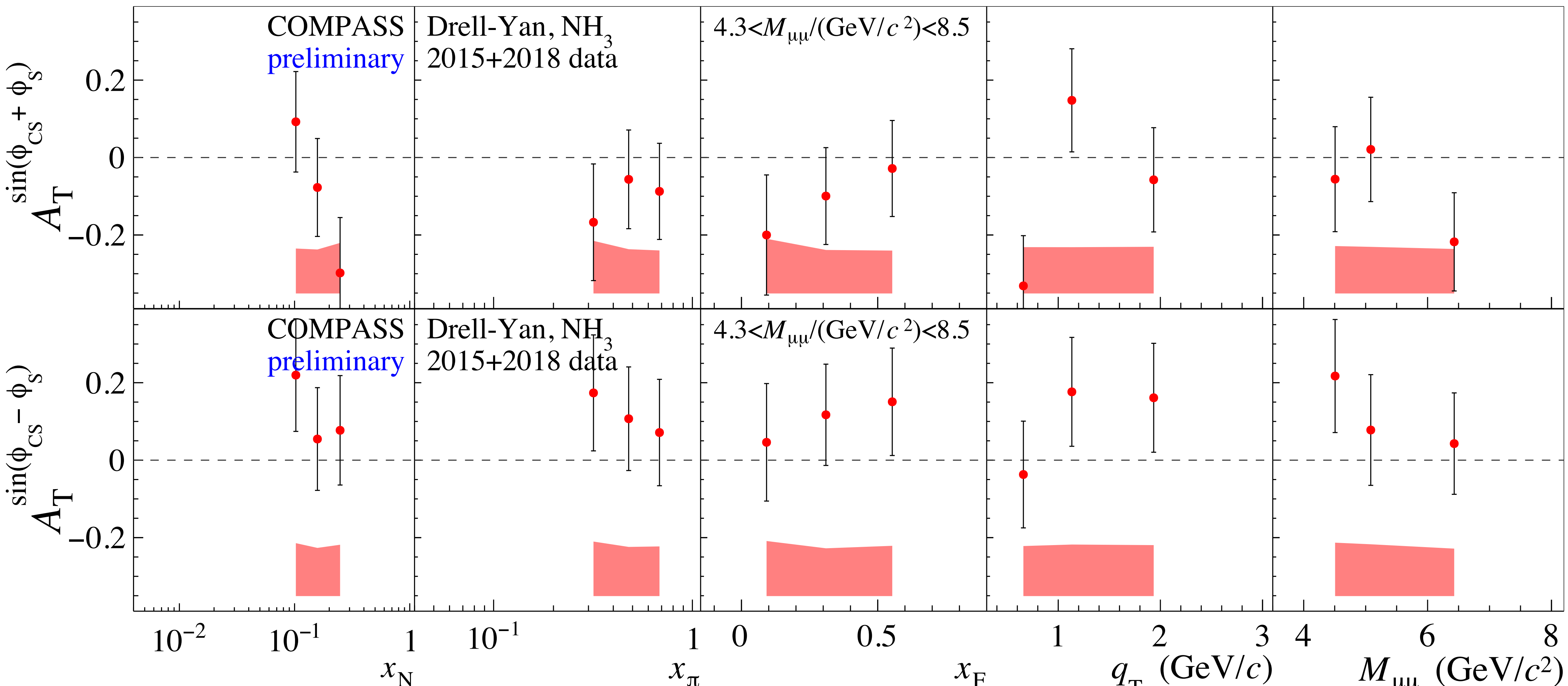


- Curves taken from **JHEP 02, 166 (2021)**
- Results in general agreement with available theory predictions

TSAs : HIGHER TWIST

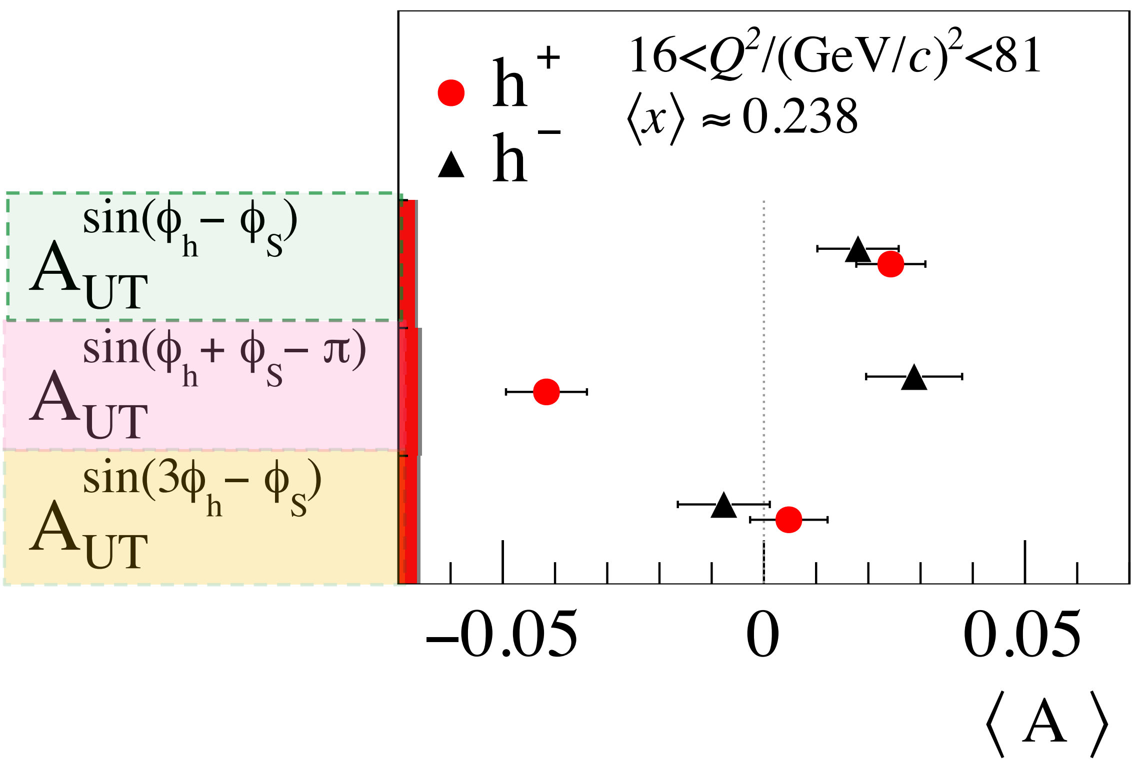
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \\ + S_T \left[\begin{array}{l}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

- **Two higher twist asymmetries**
- Extracted simultaneously together with the other three TSAs;

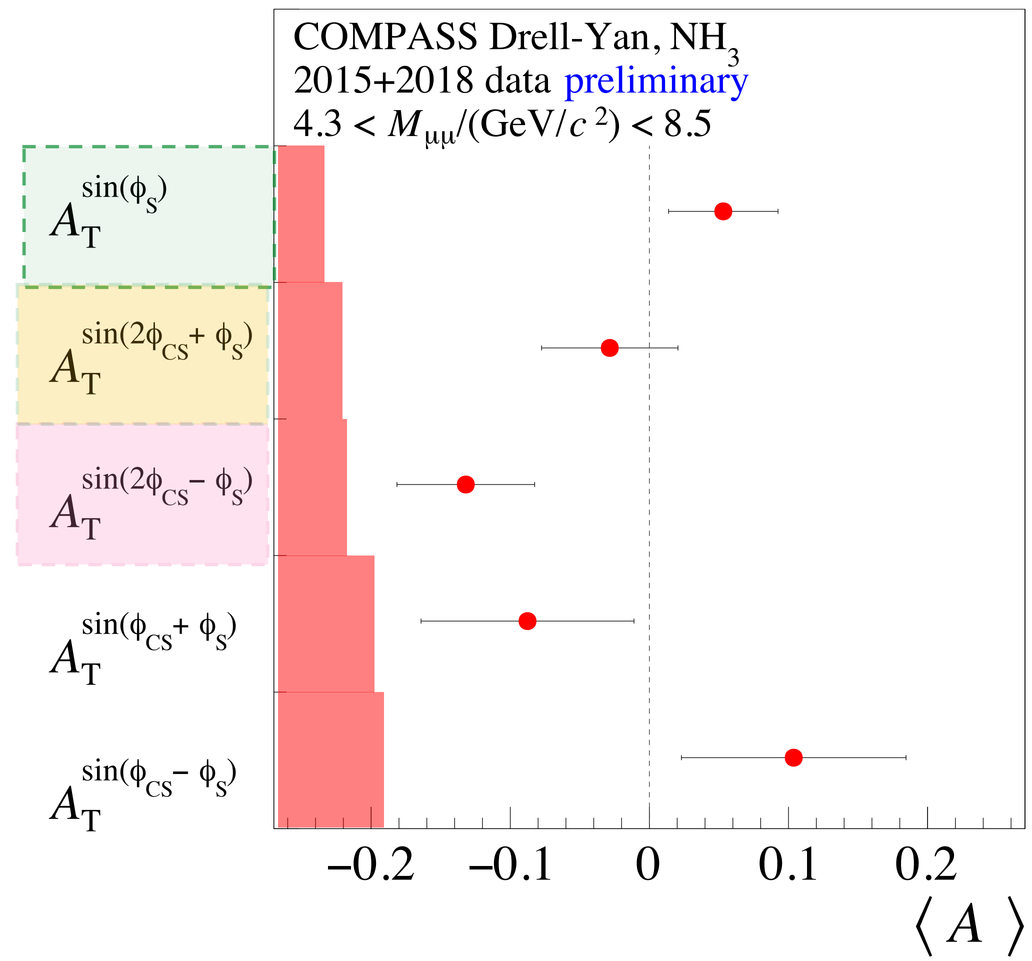


DY HM TSA RESULTS: 2015+2018 SUMMARY

COMPASS SIDIS Data,
PLB 770 (2017) 138



NEW RESULTS!



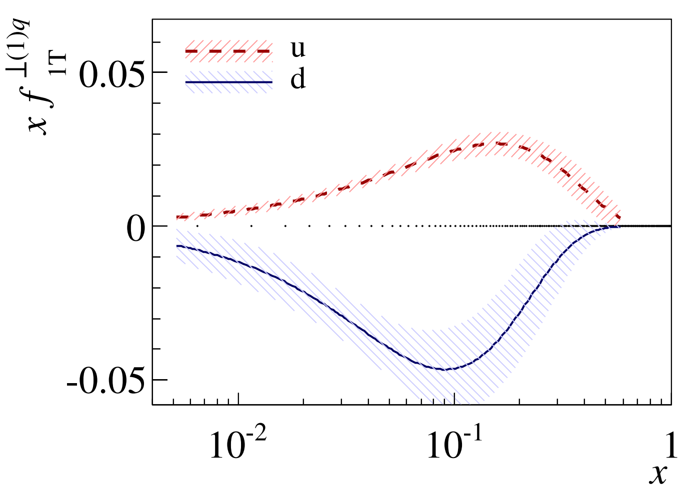
- **Full 2015+2018 combined Drell-Yan TSA data analysis is now completed!**
  - Sivers found to be positive, ~1 σ away from zero. Results favour the sign-change of Sivers TMD-PDF
  - Transversity found to be negative, ~1 .5 σ away from zero
  - Pretzelosity found to be compatible with zero
- COMPASS SIDIS and Drell-Yan TSAs measurements represent a unique experimental input to study the universality of TMD PDFs

TESTING SIVERS SIGN CHANGE W/ WEIGHTED TSA

- General formalism firstly developed for SIDIS **[A. Kotzinian & P. Mulders, PLB 406 (1997) 373];**
- It allows to avoid assumptions on k_T (e.g. gaussian);
- Already measured in SIDIS by COMPASS, **NPB 940 (2019) 34**;
- Complementary way to test the Sivers sign-change!

	SIDIS	DY
TSA	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
wTSA	$A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}} \propto f_{1T}^{\perp q(1)} \times D_{1q}^{h}$	$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q(1)}$

See talk by F.Bradamante



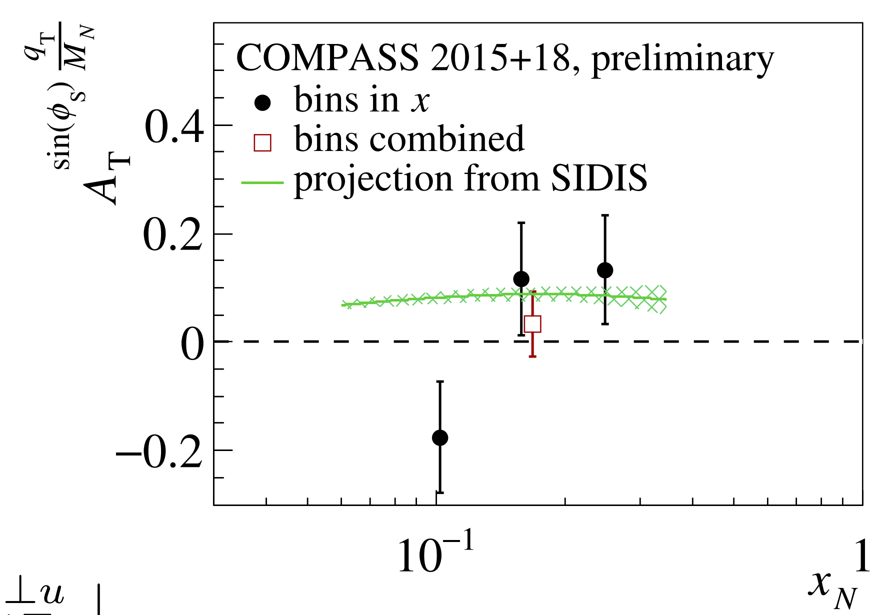
1st k_T^2 -moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$

Assuming:

- *u* quark dominance
- No Q^2 evolution for Sivers
- Sivers sign-change

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

R.Longo, **PoS (DIS2019) 186**



Results to be updated with the analysis of the full 2018 sample (same as standard TSAs)

DY UNPOLARIZED CROSS-SECTION

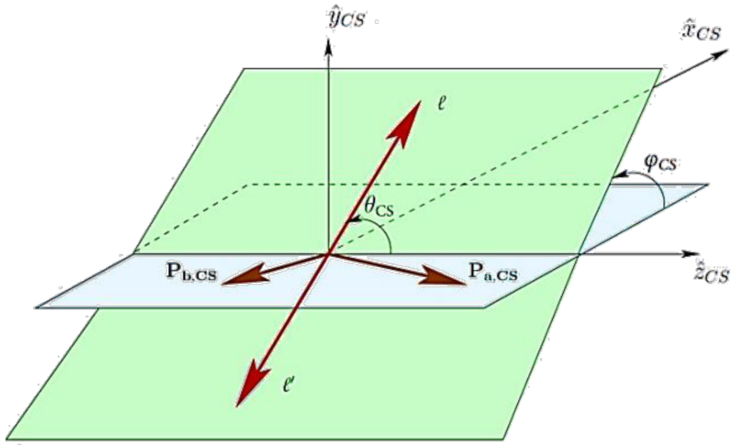
- General expression for the unpolarized part of the DY cross-section:

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

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



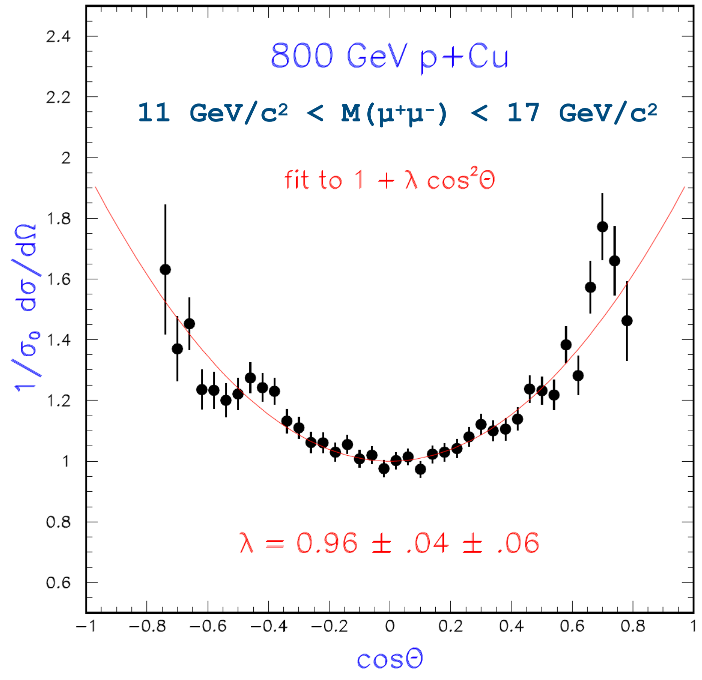
- Values of λ, μ and ν depends on the reference frame definition.
- At LO of Drell-Yan process, the virtual photon is produced purely by the electromagnetic $q+\bar{q}$ annihilation.

$$\lambda = 1, \mu = \nu = 0$$

- Lam-Tung relation [**PRD 18(1978) 2447**]:

$$1-\lambda = 2\nu$$

- Reflects the spin 1/2 nature of the quarks;
- Analogous of Callan-Gross relation in DIS;



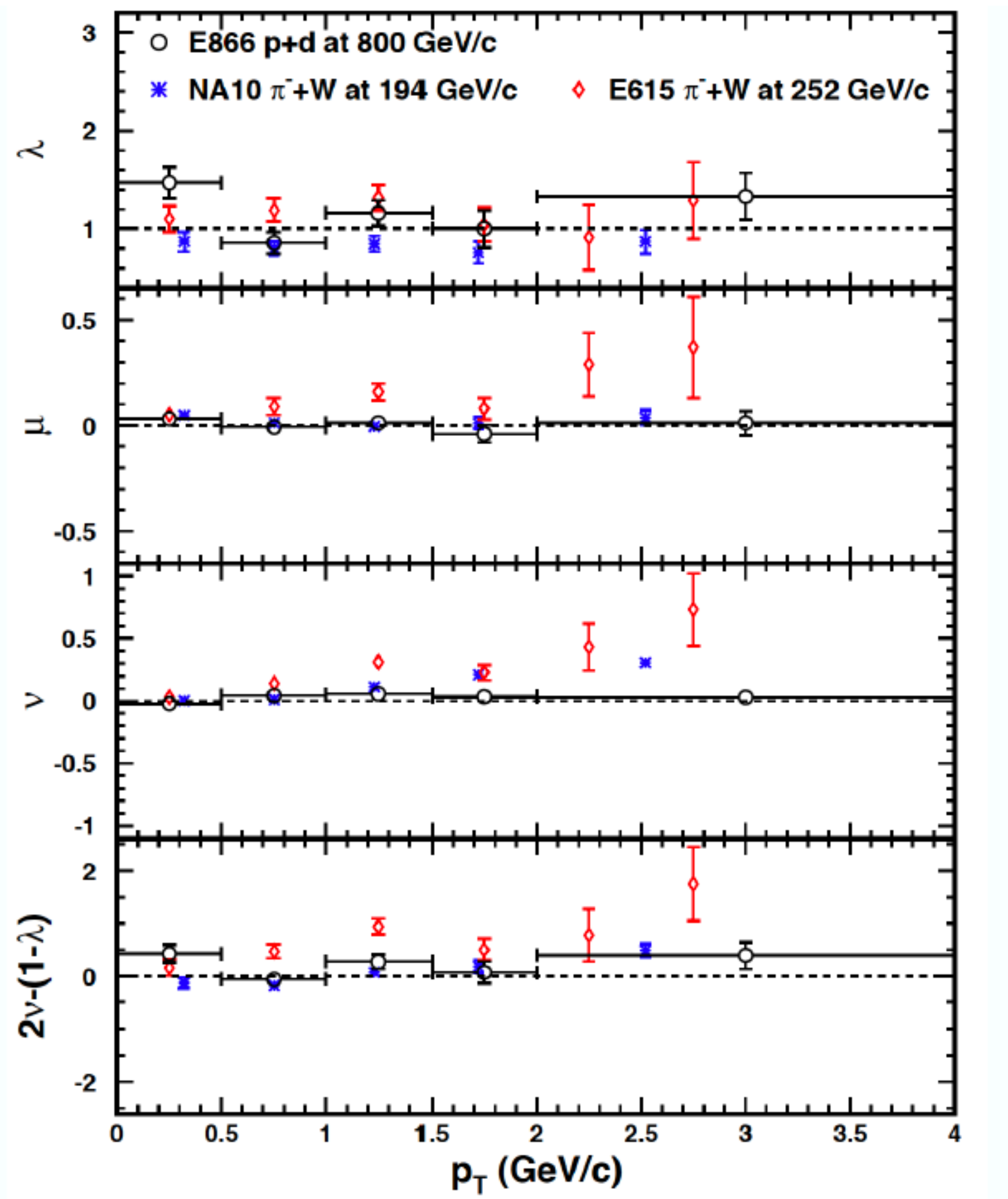
FNAL E772 Data (Ann. Rev. Nucl. Part. Sci. 49 (1999) 217-253)

UAs: NON-PERTURBATIVE EFFECT?

E615, π⁻ (252 GeV) + W, PRD 39, 92 (1989)

E866/NuSea, p (800 GeV) + d, Phys. Rev. Lett. 99, 082301

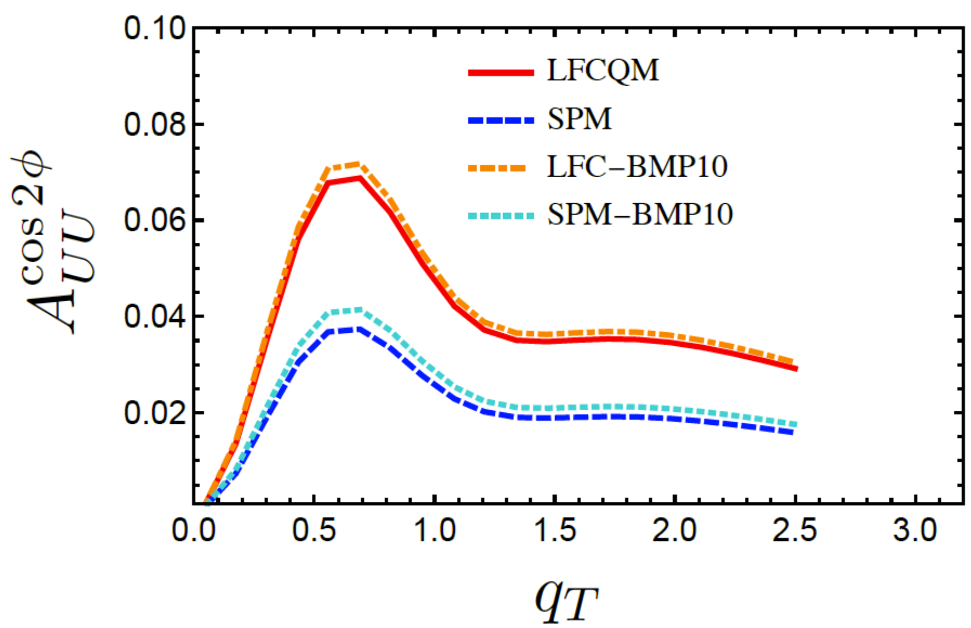
NA10, π⁻ (194 GeV) + W, Z.Phys.C 31, 513 (1986)



$h_1^{\perp q}$ = 

- Sizable ν asymmetry strongly dependent on q_T measured by different experiments in π^- induced DY.
- Can be explained in terms of non-perturbative Boer-Mulders effect;

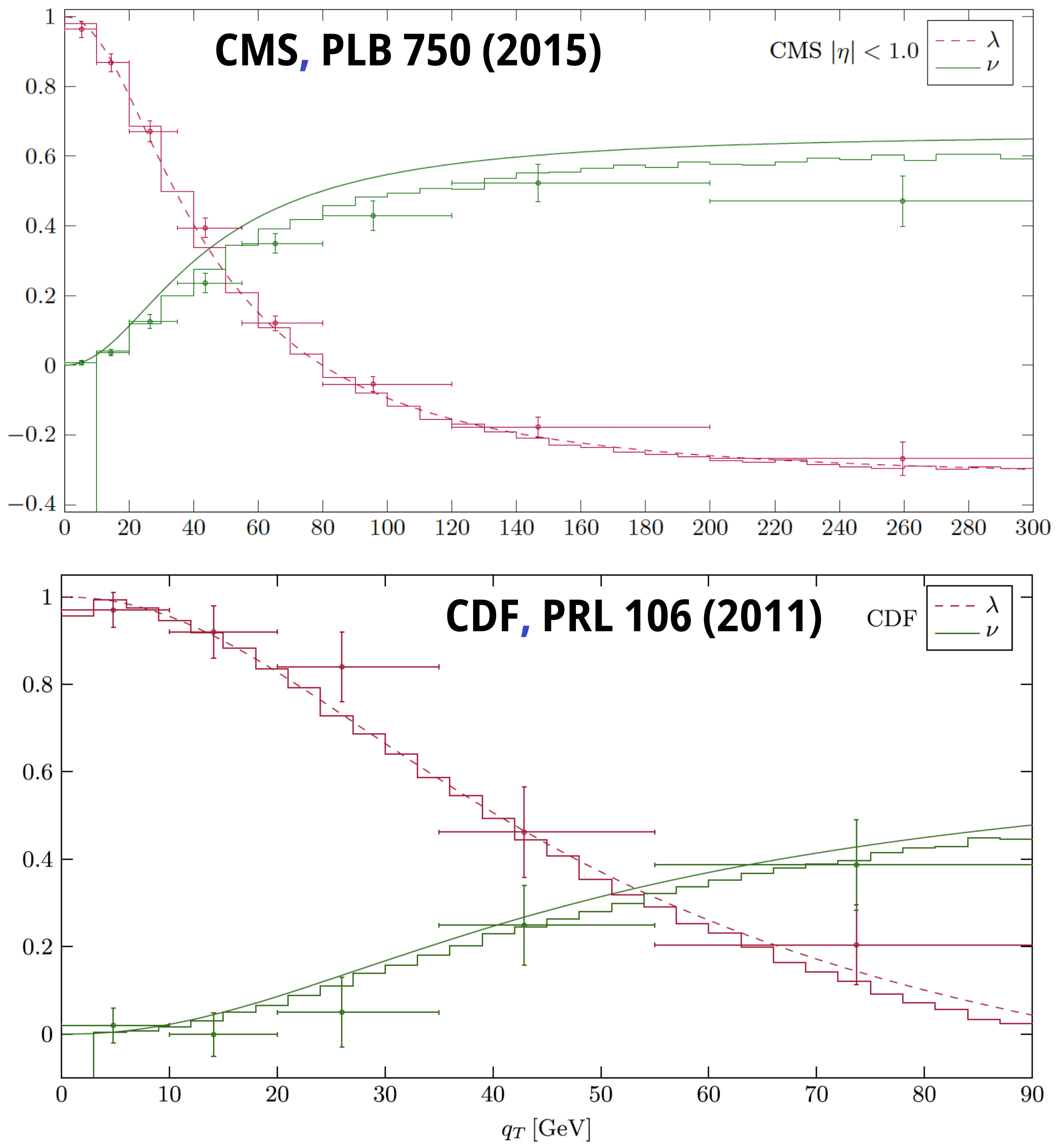
$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto h_1^{\perp q}(p) \otimes h_1^{\perp \bar{q}}(\pi^-)$$



JHEP 02, 166 (2021)
$A_{UU}^{\cos 2\phi}$ prediction for COMPASS kinematics

- **Lam-Tung** relation found to be **violated** in π^- induced DY !

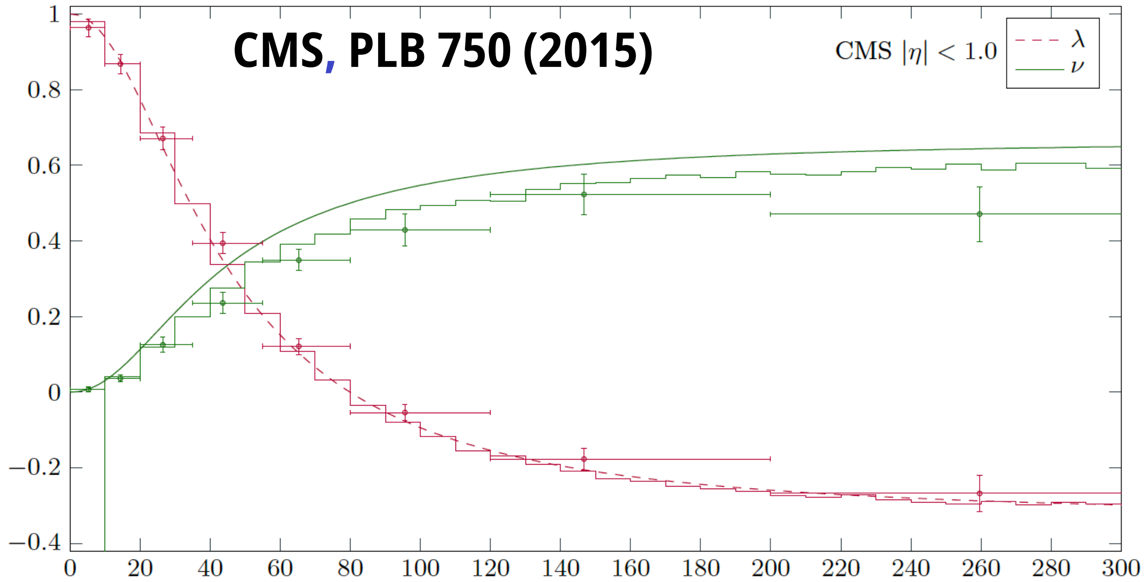
UAs: NLO & NNLO EFFECTS?

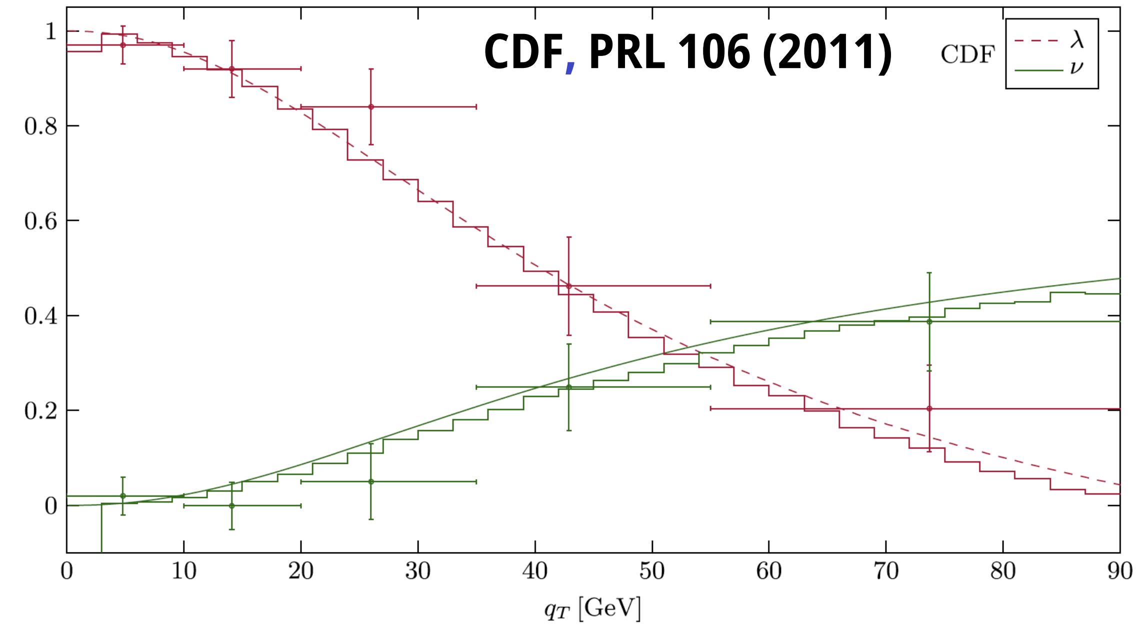


M.Lambertsen and W.Vogelsang PRD 93 (2016)

- Sizable ν asymmetry strongly dependent on q_T also measured by different experiments at colliders (CMS, CDF)
- Room for explanation in terms of NLO and NNLO effects
- Still room for non-perturbative Boer-Mulders effect?
- At lower energies - and much lower $\langle q_T \rangle$ - the picture is far to be clear - more data are needed!

UAs: NLO & NNLO EFFECTS?





M.Lambertsen and W.Vogelsang
PRD 93 (2016)

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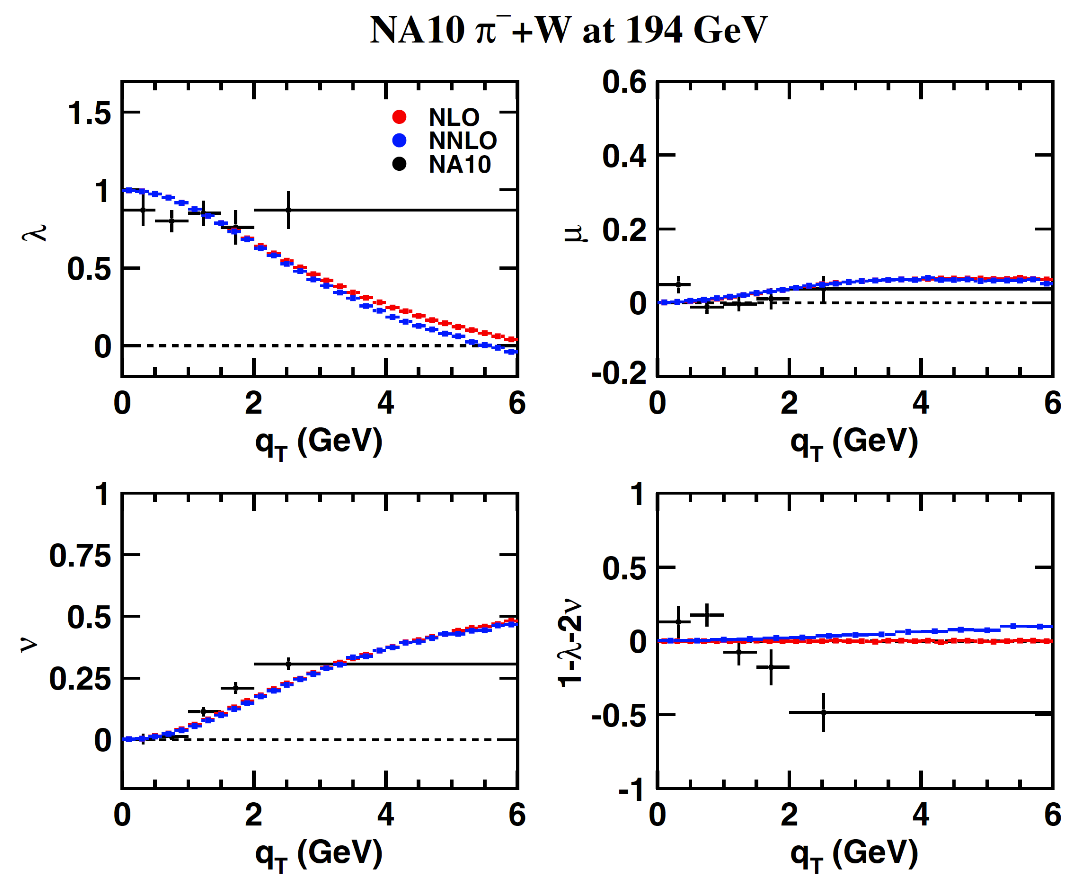
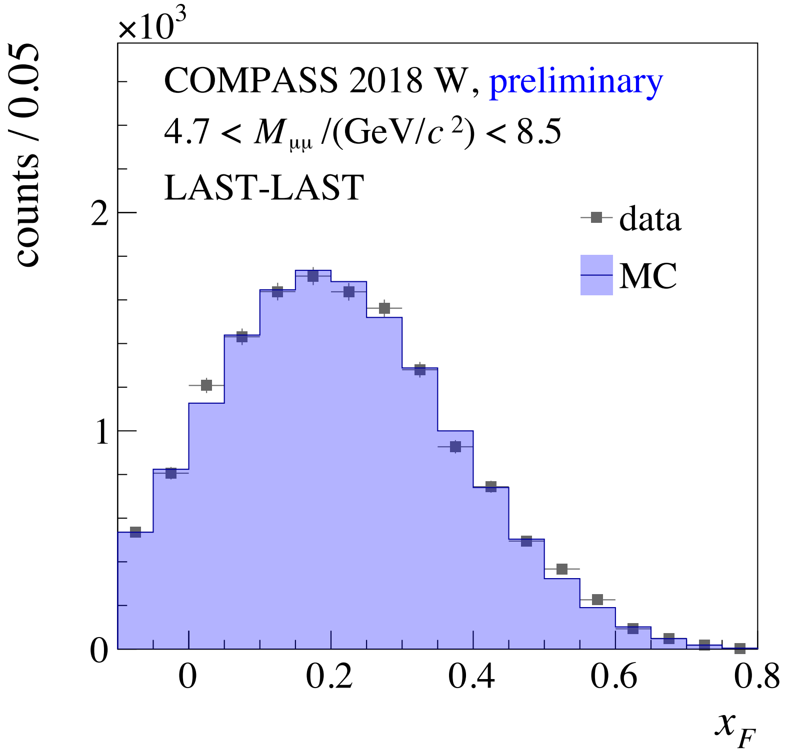
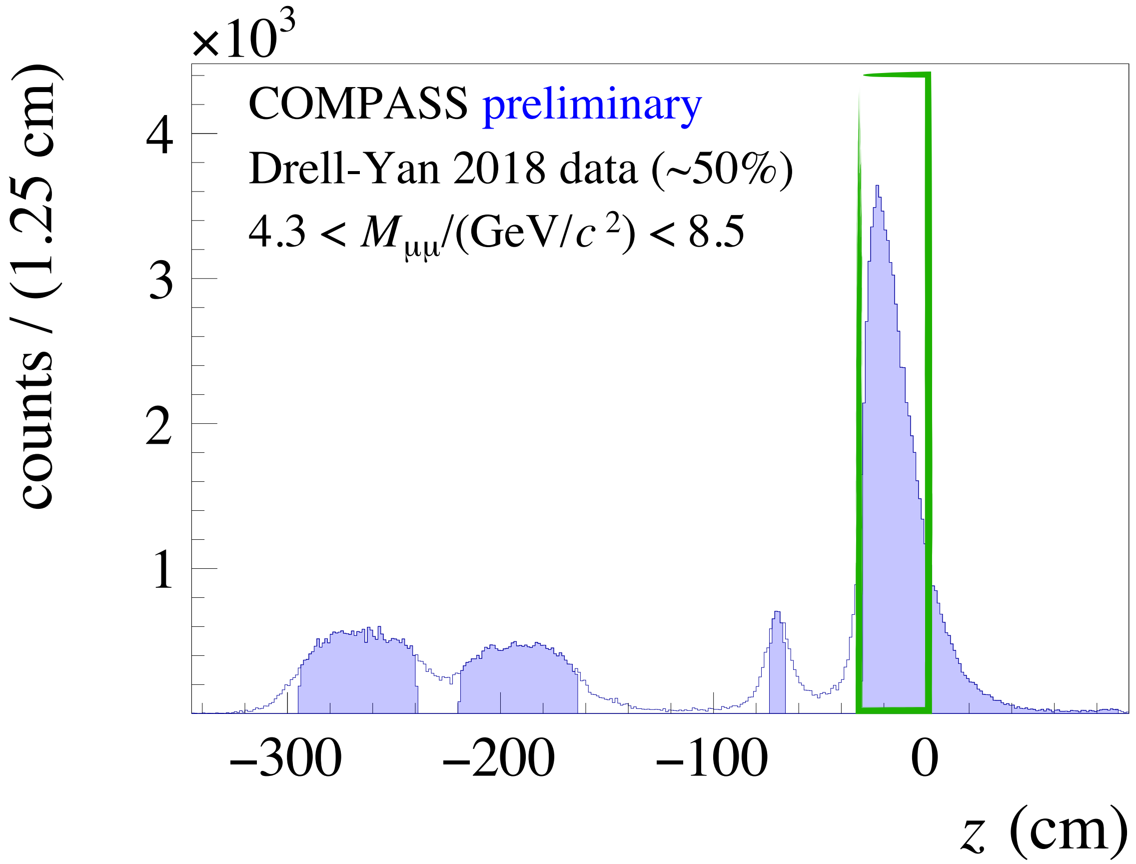
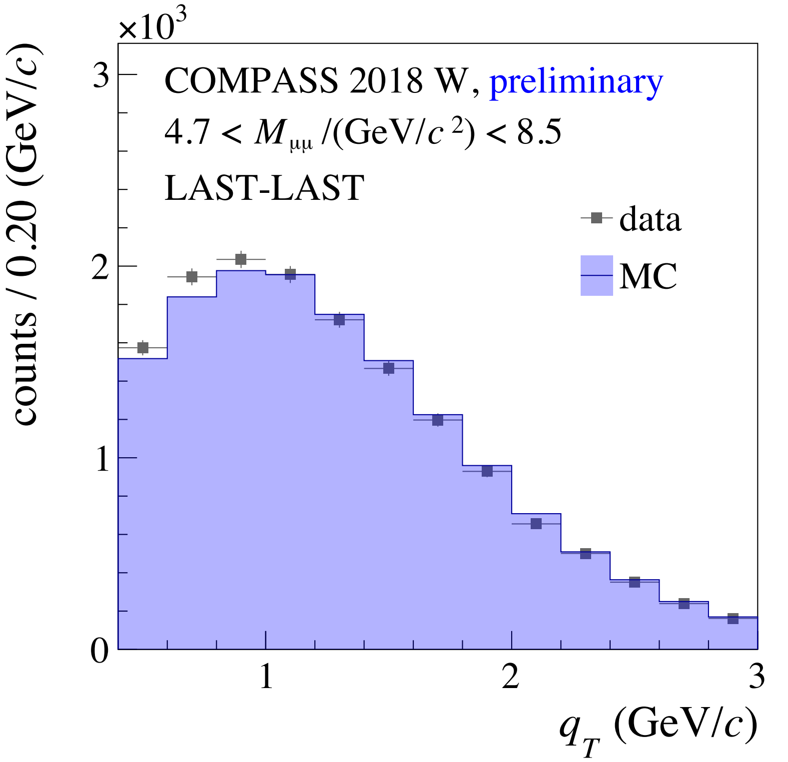


W.Chang, R. McClellan, J.C.Peng, O.Teryaev
PRD 99, 014032 (2019)

UAs: COMPASS INPUT



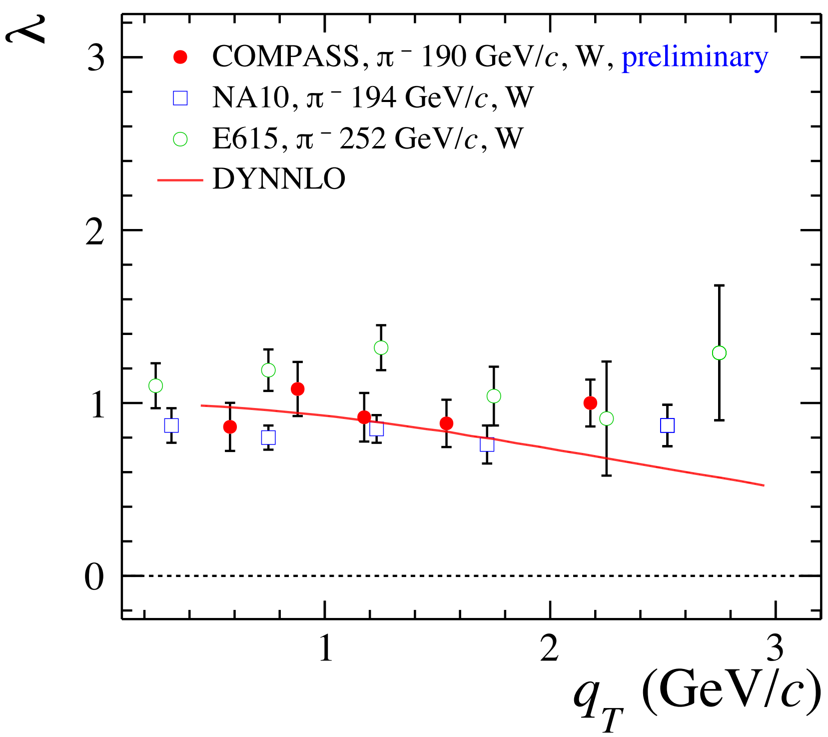


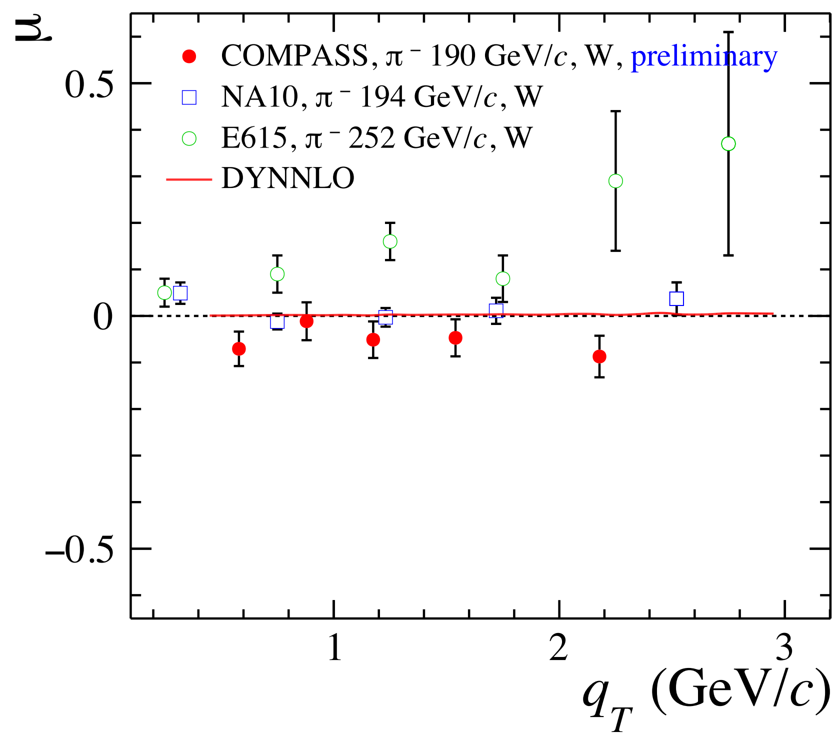


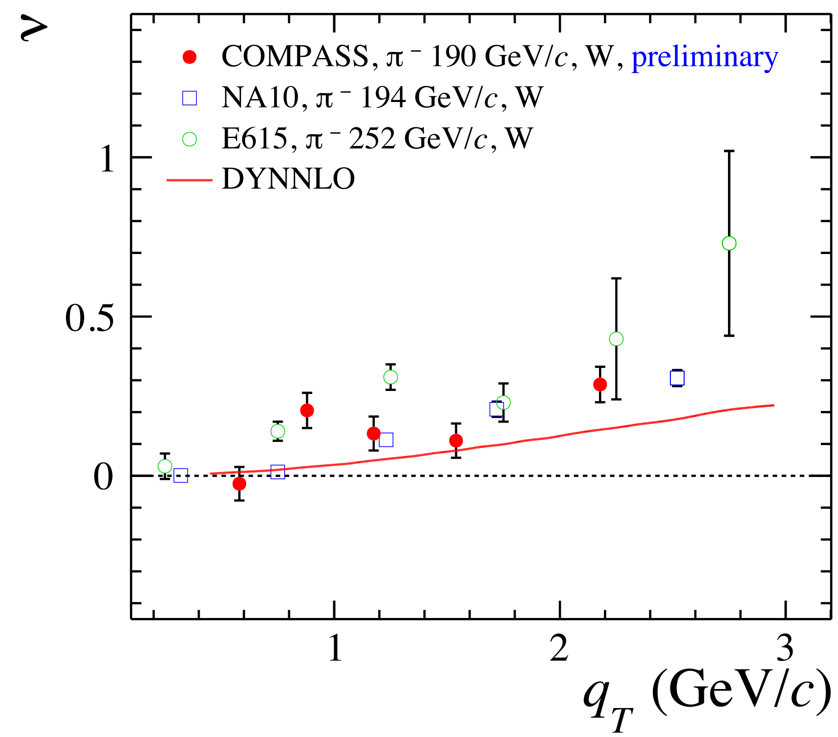
- **π^- (190 GeV) + NH_3:** analysis ongoing
- **π^- (190 GeV) + W: preliminary results**
  - 70% of 2018 data
  - "reduced" HM range due lower mass resolution for events in W, $4.7 < M_{\mu\mu}/(GeV/c^2) < 8.5$
  - First 20 cm of W to minimize effects of reinteraction of secondaries
- Angular distribution of unpolarized Drell-Yan event corrected for acceptance making use of Monte Carlo (MC)

$\pi^- + W$: UNPOLARIZED ASYMMETRIES

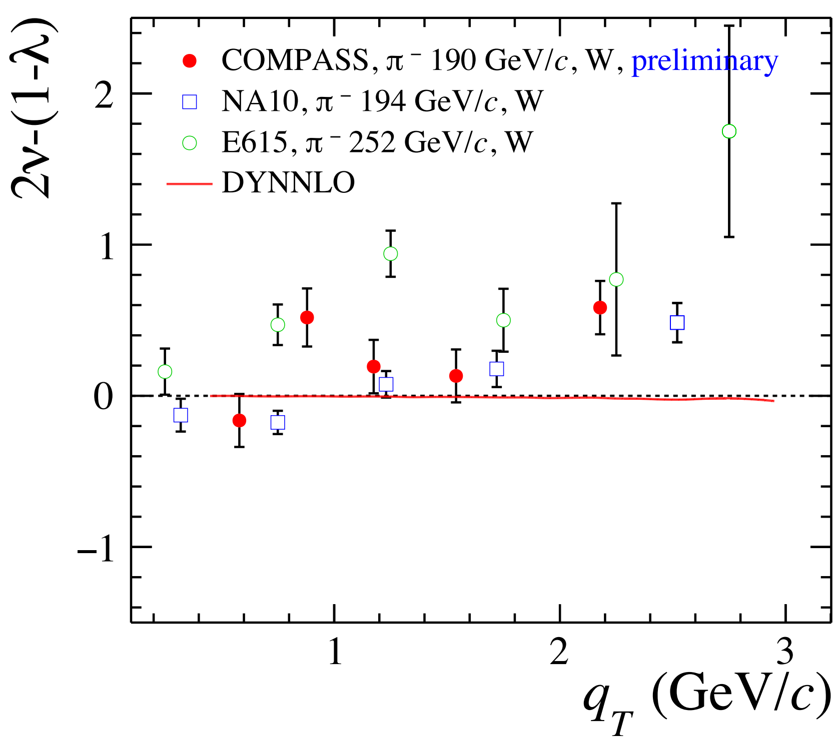
Y.Lien, **SciPost Phys. Proc. 2021**





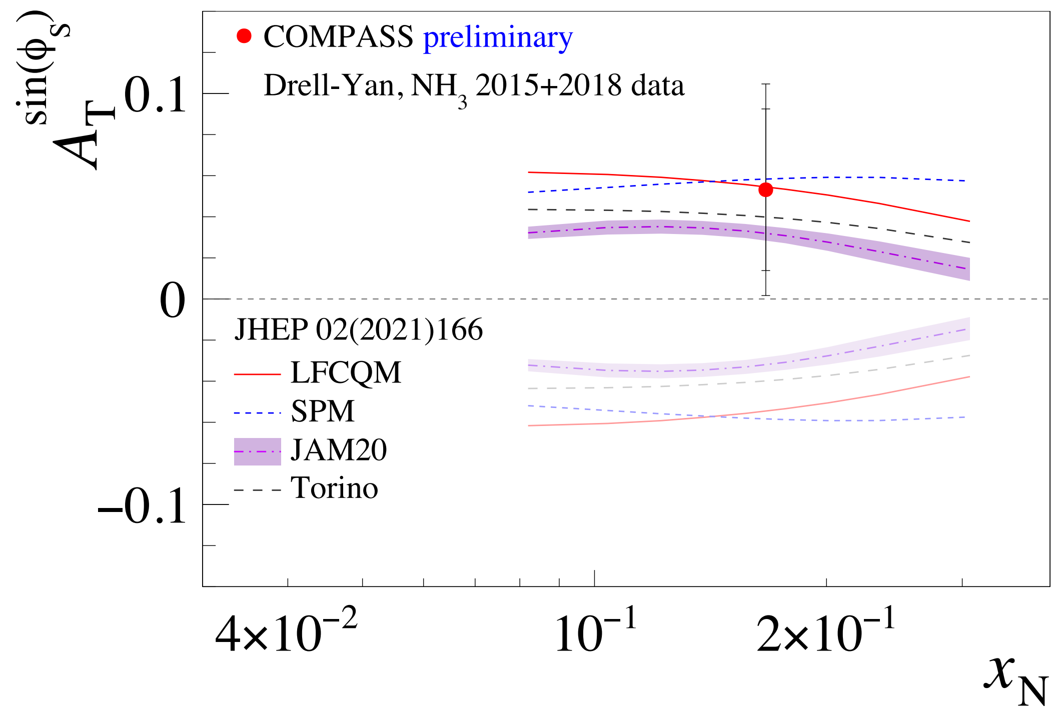


- DYNNLO pQCD calculation not enough to well describe the ν-dependence measured by COMPASS
  - Room for a non-zero TMD Boer-Mulders effect
  - DY input to study sign-change of the Boer-Mulders function
- λ, μ, ν preliminary results from COMPASS indicate a possible violation of Lam-Tung relation
  - Consistent with results obtained by previous pion-induced DY experiments



SUMMARY

- COMPASS successfully collected polarized Drell-Yan data in 2015 and 2018
- **Full 2015+2018 combined Drell-Yan TSA data analysis is now completed! NEW RESULTS!**
  - Sivers found to be positive, ~1 σ away from zero
  - Transversity found to be negative, ~1.5 σ away from zero
  - Pretzelosity found to be small and compatible with zero



- **COMPASS data favors the sign-change of Sivers TMD PDF**
- **COMPASS** SIDIS and Drell-Yan TSAs **measurements** represent a **unique experimental input** to study the universality of TMD PDFs

- COMPASS is investigating the TMD PDFs also using weighted asymmetries in SIDIS and Drell-Yan, as well as extracting TSA and the A_N in the J/ψ region
- COMPASS is also extracting the unpolarized asymmetries of the Drell-Yan cross-section. First results from the analysis of 2018 W data are already available, and more to come in the future!

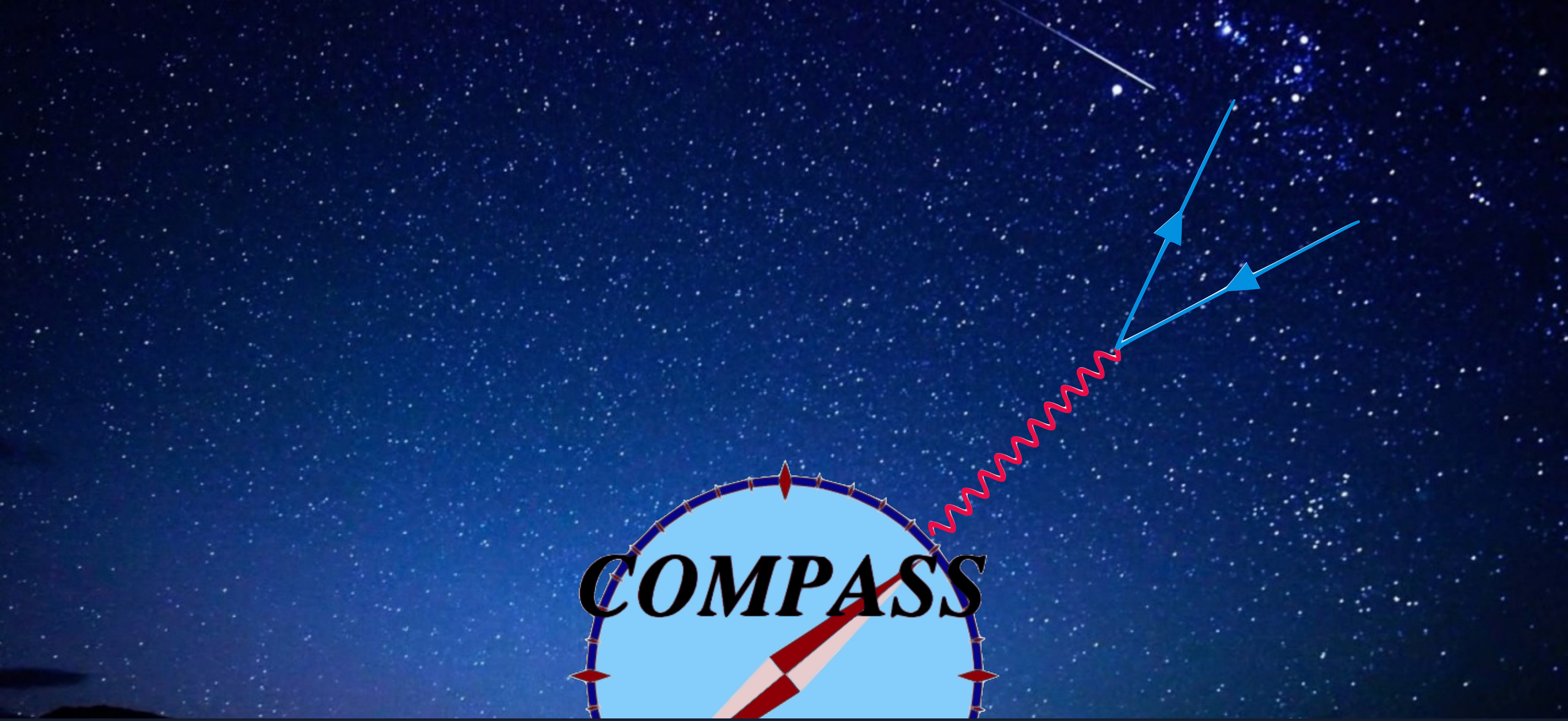
THANKS FOR YOUR ATTENTION!

International Workshop on Hadron Structure and Spectroscopy - 2022

29–31 Aug 2022
CERN

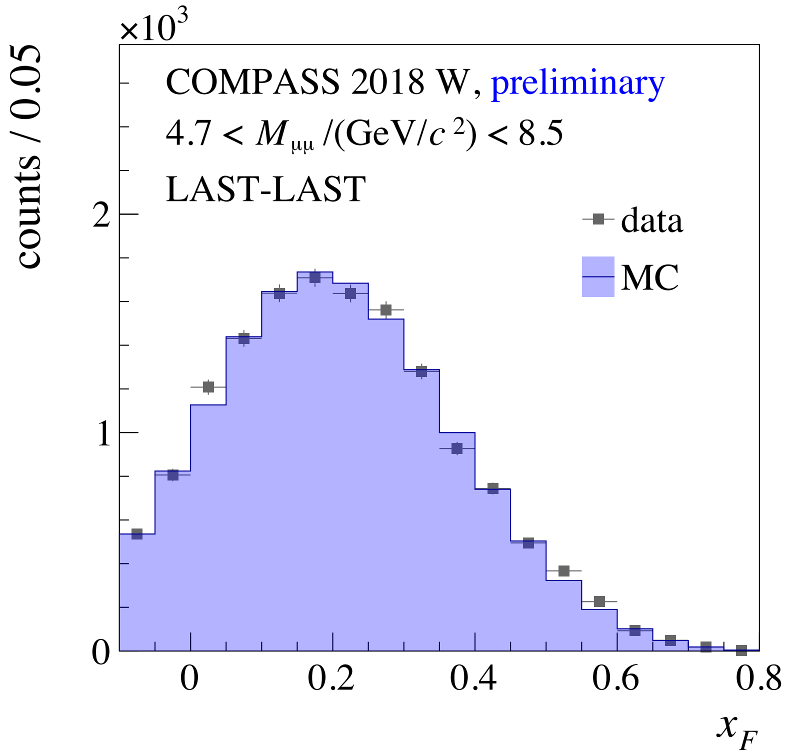
COMPASS ANNIVERSARY!

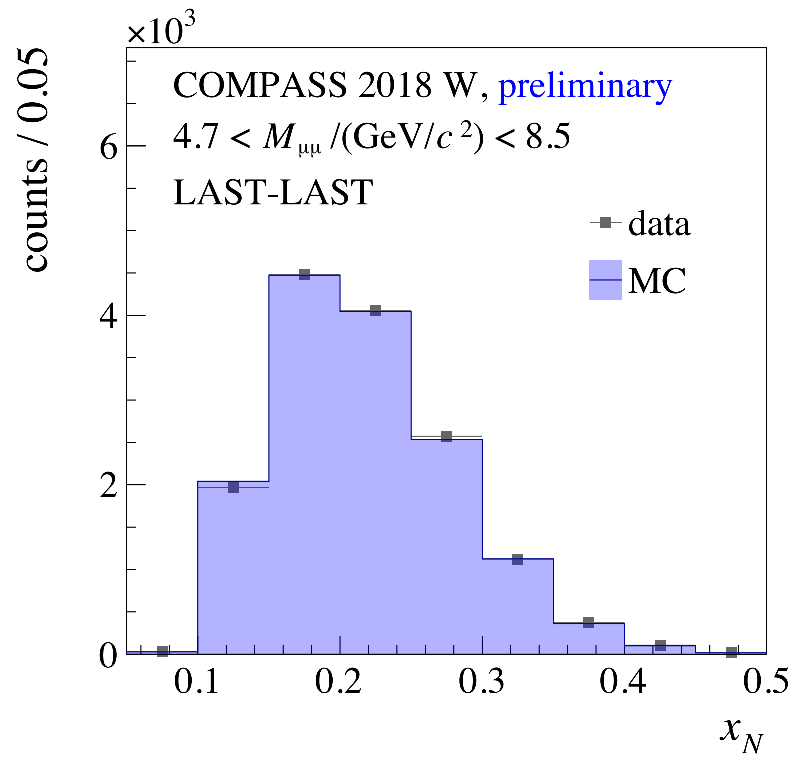
25 YEARS SINCE APPROVAL, 20 SINCE FIRST RUN

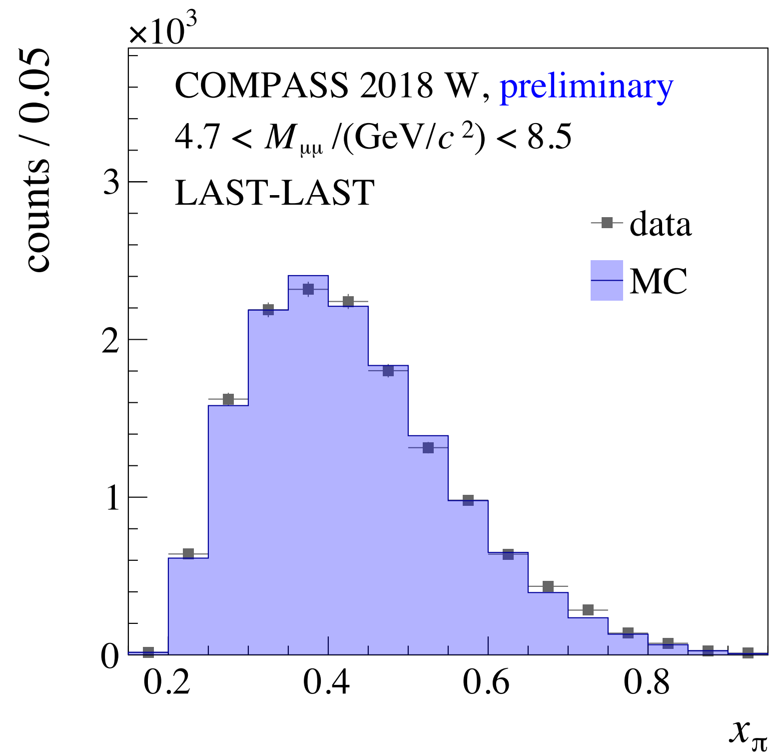


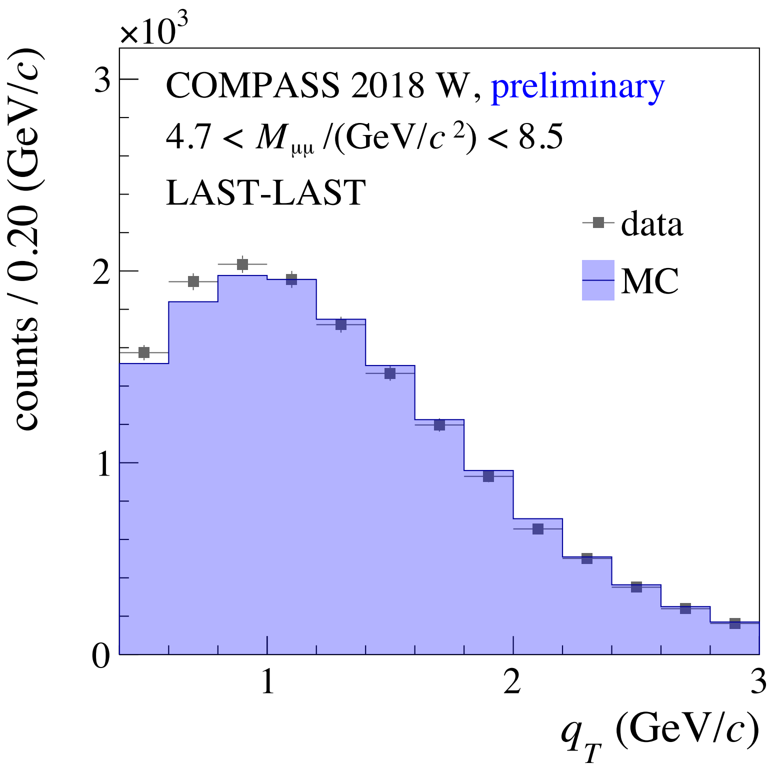
BACKUP SLIDES

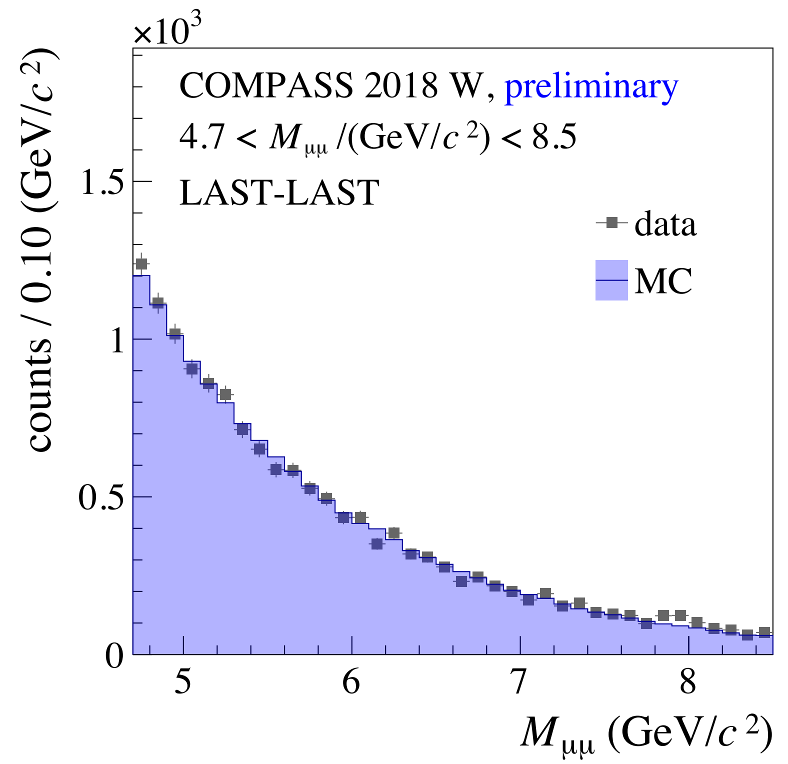
MONTECARLO FOR ACCEPTANCE CORRECTION











- Angular distribution of unpolarized Drell-Yan event corrected for acceptance making use of Monte Carlo (MC)
- Good MC/data agreement achieved for all the MC distributions related to the W target

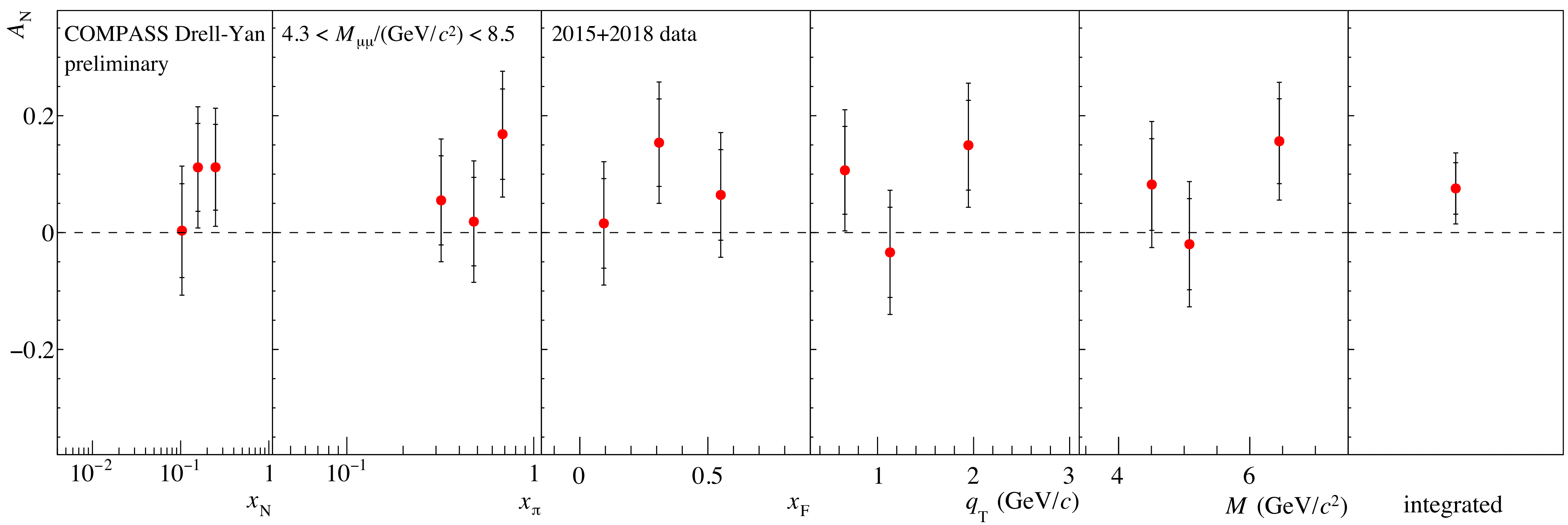
DY HM BONUS TRACK: A_N

- Alternative way to investigate the Sivers effect
- Acceptance cancellation implemented and understood in different way compared to TSAs extraction
- Receives contributions from all the amplitudes $\sin(n\phi_S)$
- Also studied in J/ψ region where it can provide information on the resonance production mechanism

$$A_{\ell r} = \frac{1}{|S_T|} \frac{N_\ell - N_r}{N_\ell + N_r}$$

$$\frac{d\sigma}{d^4q\, d\phi_S} \propto \hat{\sigma}_U \left(1 + |S_T| A_N \sin(\phi_S)\right)$$

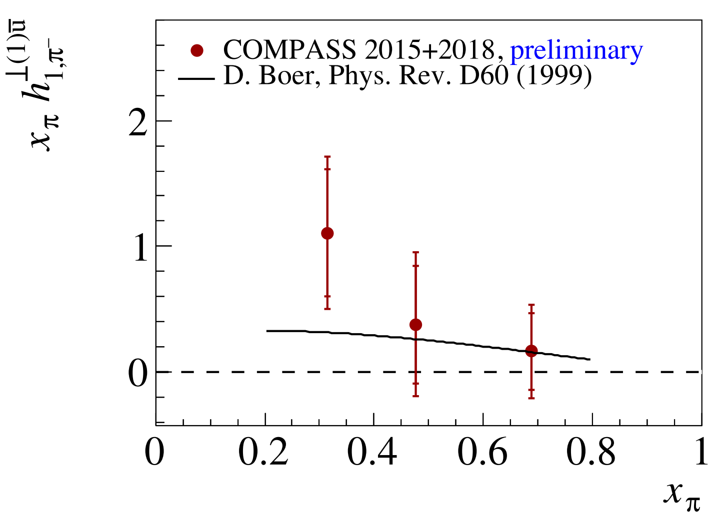
$$\rightarrow A_{\ell r} = \frac{1}{|S_T|} \frac{\int_0^\pi \frac{d\sigma}{d^4q\, d\phi_S}\, d\phi_S - \int_{-\pi}^0 \frac{d\sigma}{d^4q\, d\phi_S}\, d\phi_S}{\int_0^\pi \frac{d\sigma}{d^4q\, d\phi_S}\, d\phi_S + \int_{-\pi}^0 \frac{d\sigma}{d^4q\, d\phi_S}\, d\phi_S} = \frac{2A_N}{\pi}$$

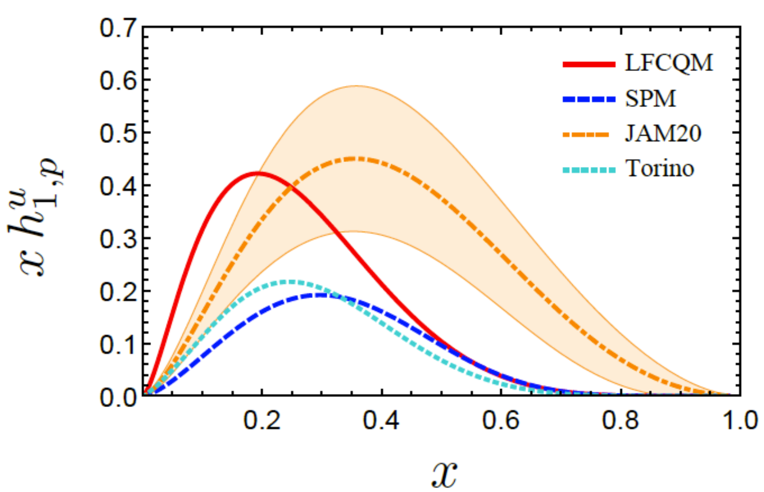


NEW RESULTS!

TESTING BM SIGN-CHANGE

- Thanks to a simultaneous measurement of $A_{UU}^{\cos 2\phi}$ and $A_{UT}^{\sin(2\phi-\phi_S)}$, COMPASS DY TSAs results can also be used to test sign change of the proton Boer-Mulders function - as discussed in **JHEP 02, 166 (2021)**
  - Transversity sign is positive, as well as the first k_T moment of the pion Boer-Mulders
  - Neglecting sea quark effects, the asymmetry is dominated by $A_{UU}^{\cos 2\phi} \propto h_{1,\pi^-}^{\perp(1)\bar{u}}(x_\pi) h_{1,p}^{\perp(1)u}(x_p)$
  - With the indication of the positive sign for the pion Boer-Mulders function from the COMPASS data on $A_{UT}^{\sin(2\phi-\phi_S)}$ and from the q_T weighted analysis, one can conclude a **positive sign also for the proton u quark Boer-Mulders** function in DY, which is opposite to the sign of Boer-Mulders extracted in SIDIS analyses and hence in **agreement with the sign change prediction**





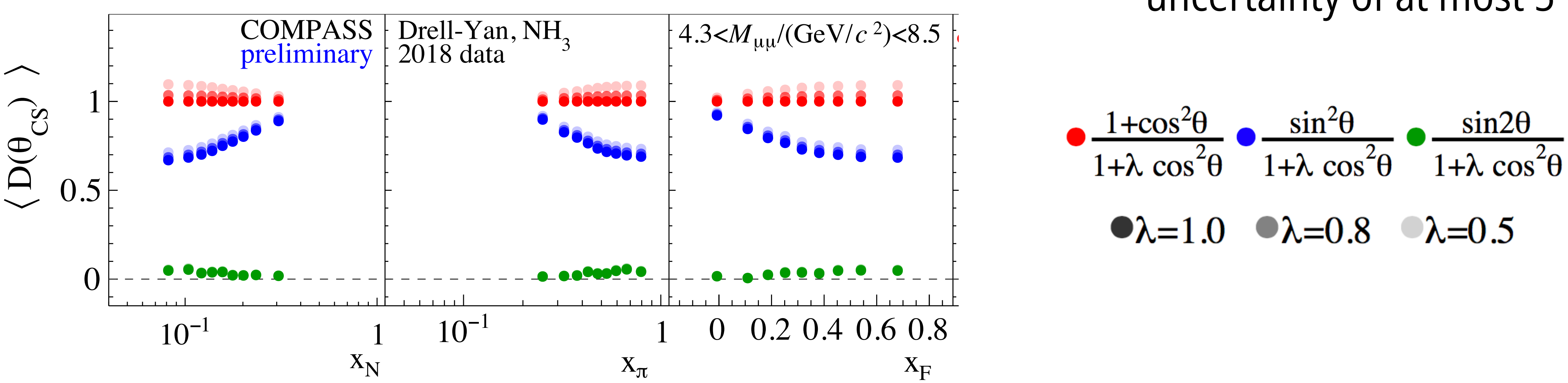
$$A_{UT}^{\sin(2\phi-\phi_S)} \propto - h_{1,\pi^-}^{\perp(1)\bar{u}}(x_\pi) h_{1,p}^{u}(x_p)$$

DRELL-YAN TSAs EXTRACTION

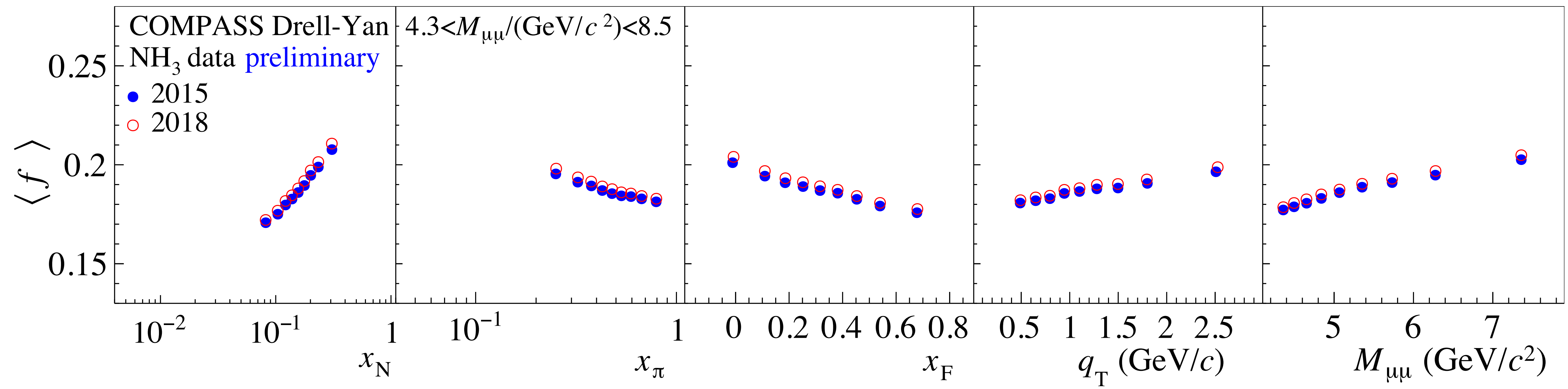
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right)$$
$$\times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}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

$$D_{[f(\theta_{CS})]} = \frac{f(\theta_{CS})}{1 + A_U^1 \cos^2\theta_{CS}}$$

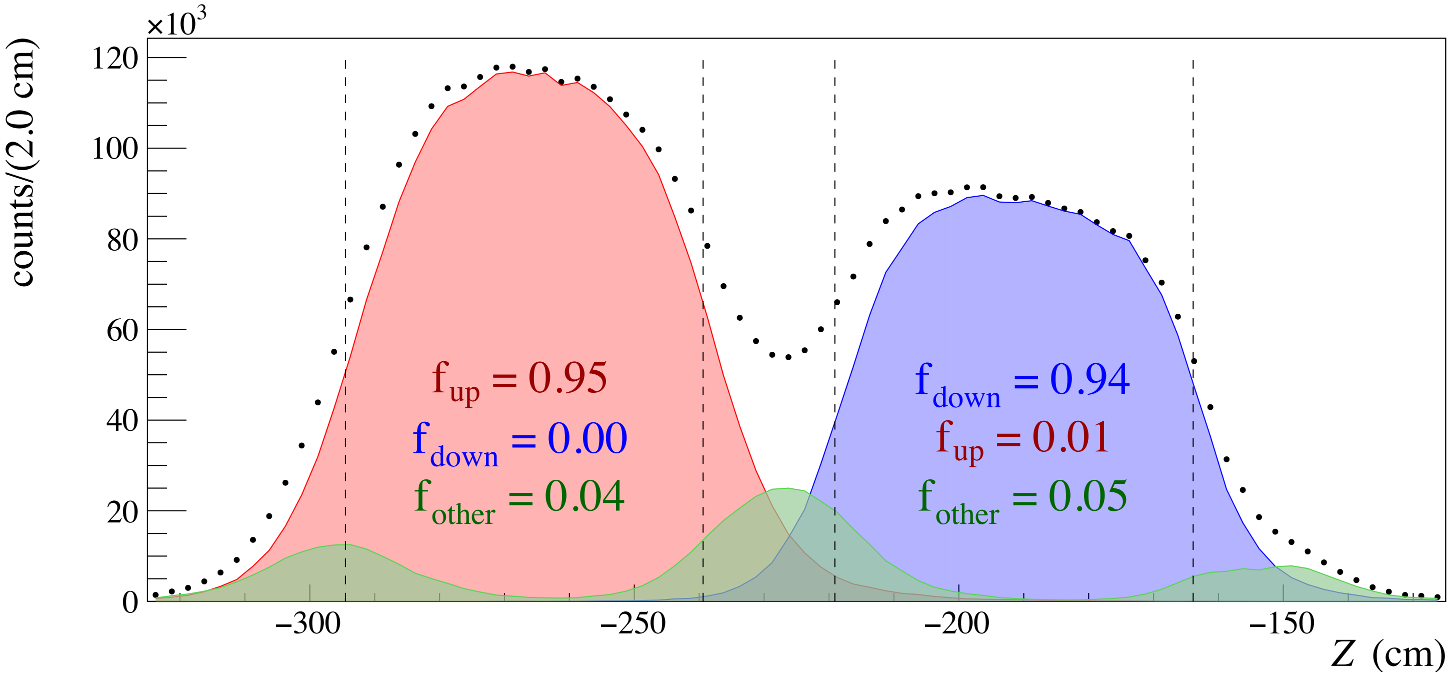
- All five DY TSAs are extracted simultaneously using an extended Unbinned Maximum Likelihood estimator;
- Depolarization factors are evaluated under assumption $A_U^1 = 1$;
- Possible scenarios with $A_U^1 \neq 1$ were evaluated , leading to a normalization uncertainty of at most 5 %;



DILUTION FACTOR



$$f = \frac{n_H \sigma^{DY}_{\pi-H}}{n_H \sigma^{DY}_{\pi-H} + \Sigma_A n_A \sigma^{DY}_{\pi-A}}$$

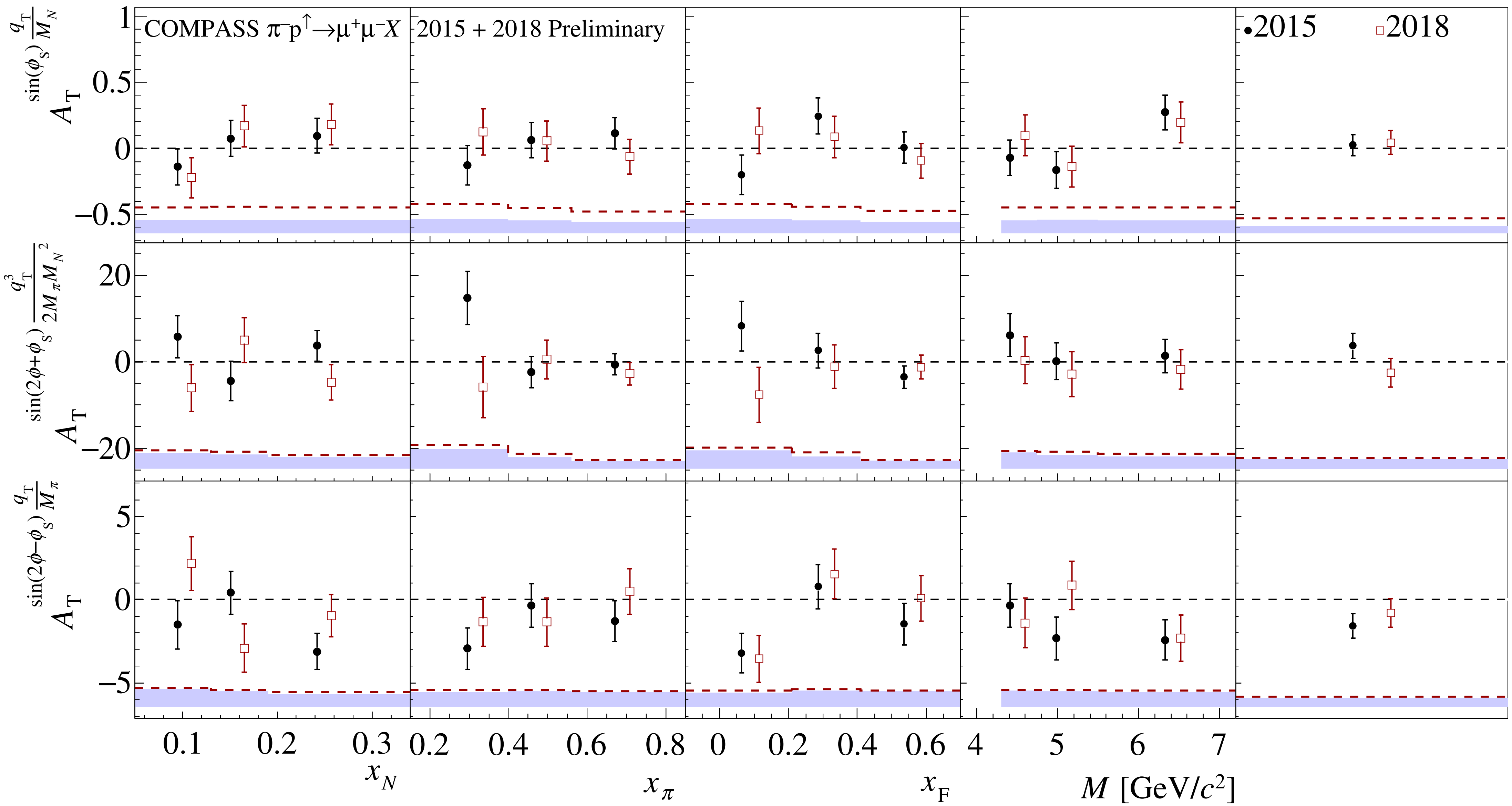


- The dilution factor accounts for the fraction of polarizable material inside the target volume.
- It is corrected to account for the migration of events from one cell to the other (obtained with MC simulation);

TESTING SIVERS SIGN CHANGE W/ WEIGHTED TSA

- General formalism firstly developed for SIDIS **[A. Kotzinian & P. Mulders, PLB 406 (1997) 373];**
- It allows to avoid assumptions on k_T (e.g. gaussian);
- Already measured in SIDIS by COMPASS, **NPB 940 (2019) 34**;
- Complementary way to test the Sivers sign-change!

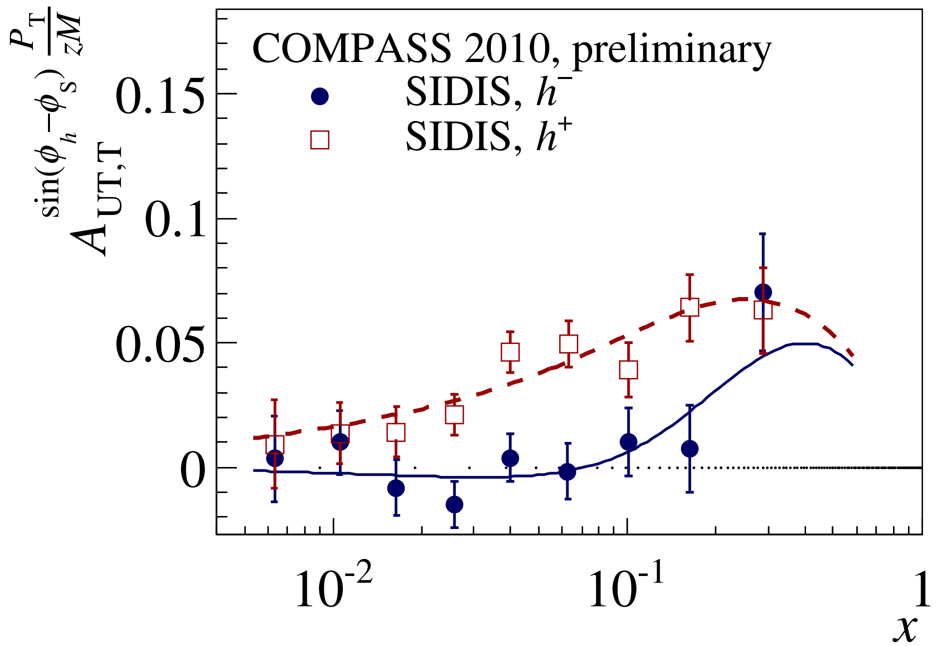
R.Longo, **PoS (DIS2019) 186**



Results to be updated with the analysis of the full 2018 sample (same as standard TSAs)

TESTING SIVERS SIGN CHANGE W/ WEIGHTED TSA

COMPASS, **NPB 940 (2019) 34**

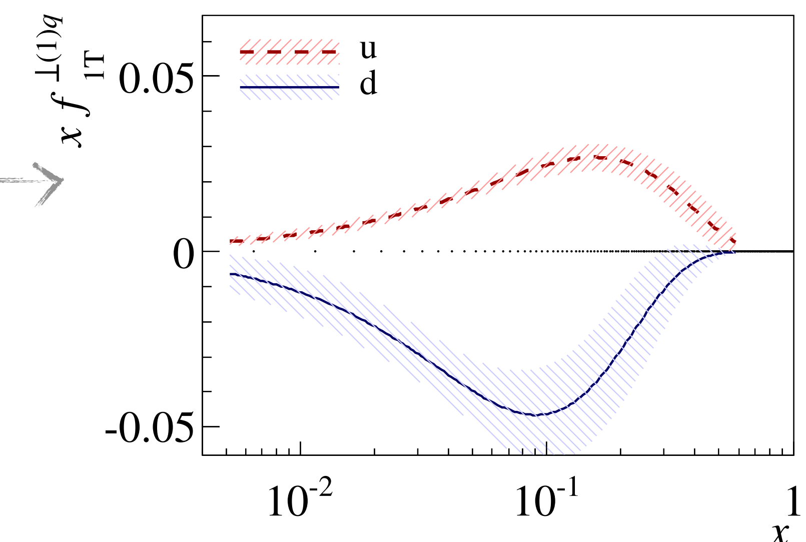


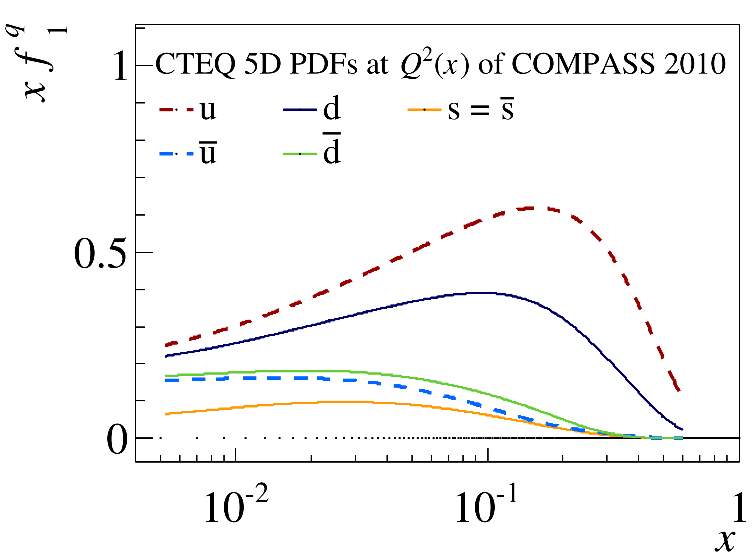
- COMPASS has also measured the p_T weighted TSAs in SIDIS;
- Alternative way to compare TMD PDFs from SIDIS and DY;

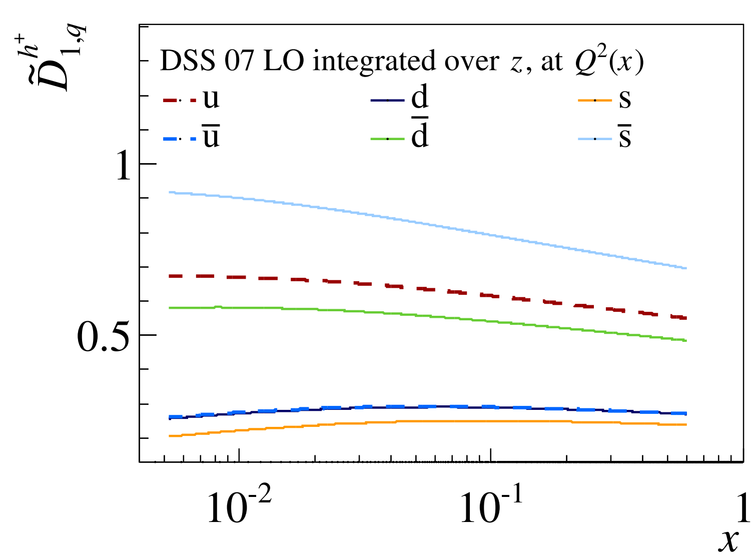
  - Sivers TSA in SIDIS $\quad A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$
  - Sivers wTSA in SIDIS $\quad A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}} \propto f_{1T}^{\perp q(1)} \times D_{1q}^h$

$$A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}}(x,z) = 2\frac{\sum_q e_q^2 f_{1T}^{\perp q(1)}(x) D_1^q(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

$$x f_{1T}^{\perp(1)q}(x) = a_q x^{b_q}(1-x)^{c_q}$$

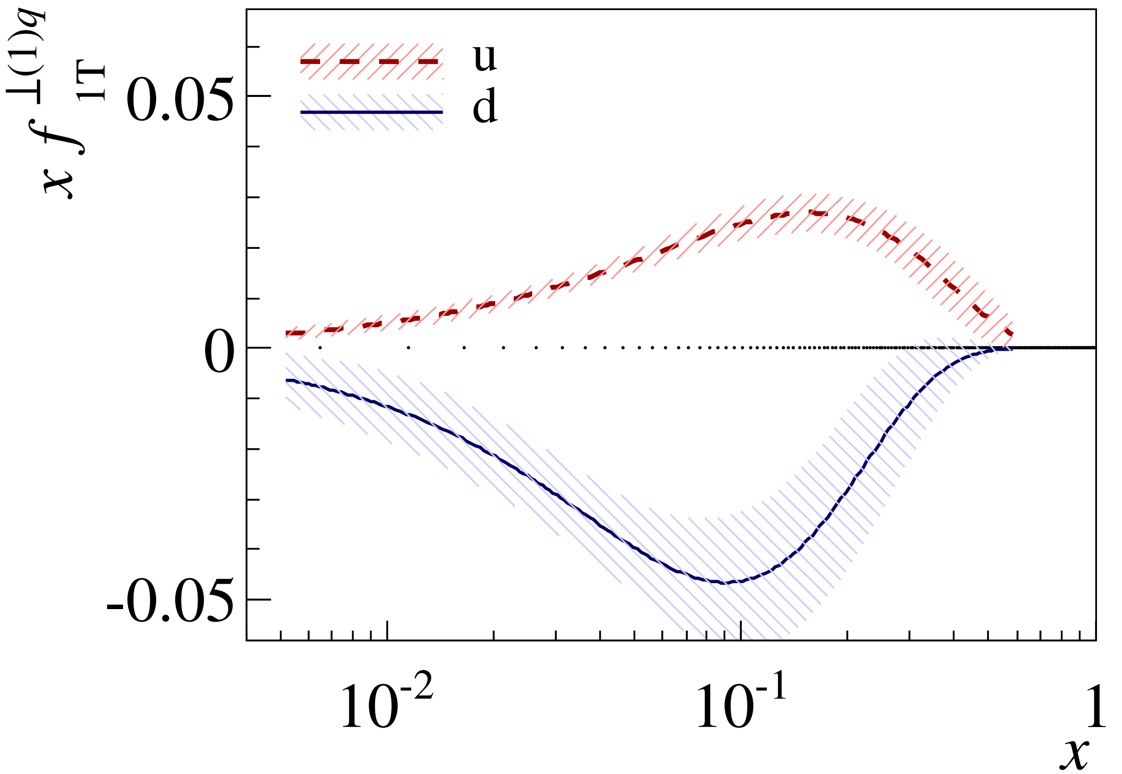






1st k_T^2 -moment of the Sivers function at $Q^2 = Q^2_{SIDIS}(x)$

WEIGHTED ASYMMETRIES: FROM SIDIS TO DY



1st k_T^2 -moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$

Assuming:

- *u* quark dominance

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \sim \frac{f_{1T,p}^{\perp u(1)}}{f_{1,p}^u}$$

- No Q^2 evolution for Sivers
- Sivers sign-change

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

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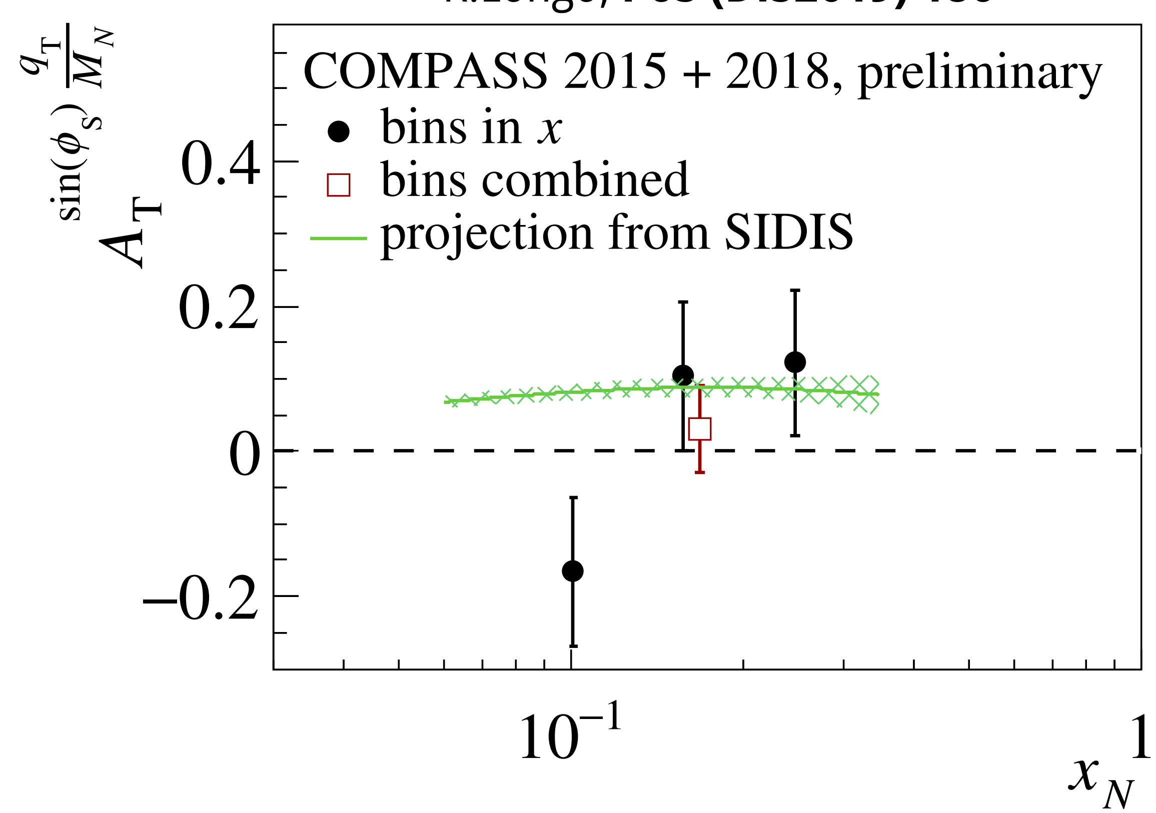
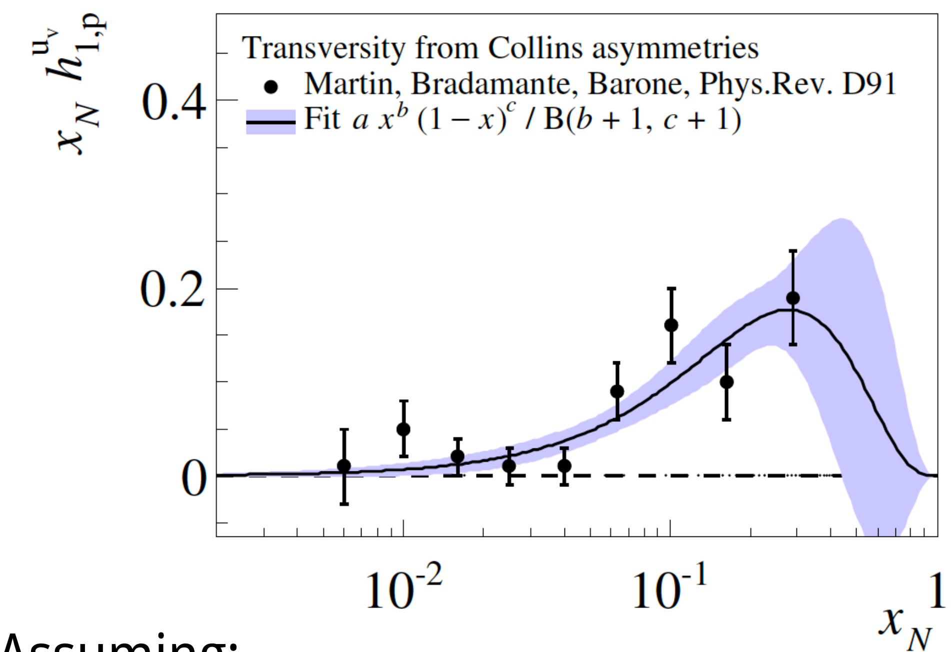
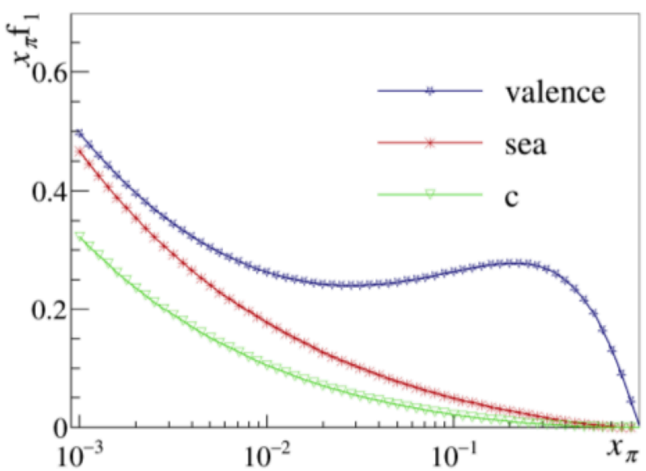


- Preliminary 2015 results, full data sample;
- Preliminary 2018 results, 50% of the sample;
- Analysis will be repeated with the full 2018 sample (same as standard TSAs)

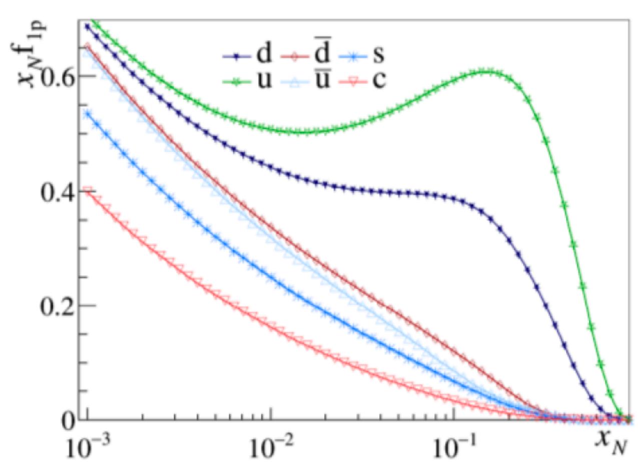
WEIGHTED ASYMMETRIES: FROM SIDIS TO DY

$$A_T^{\sin(2\varphi-\varphi_S)\frac{q_T}{M_\pi}}(x_\pi, x_N) \approx -2\frac{h_{1,\pi}^{\perp\,(1)\,\bar{u}}(x_\pi)\, h_{1,p}^{u}(x_N)}{f_1^{\bar{u}}(x_\pi)\, f_{1,p}^{u}(x_N)}$$





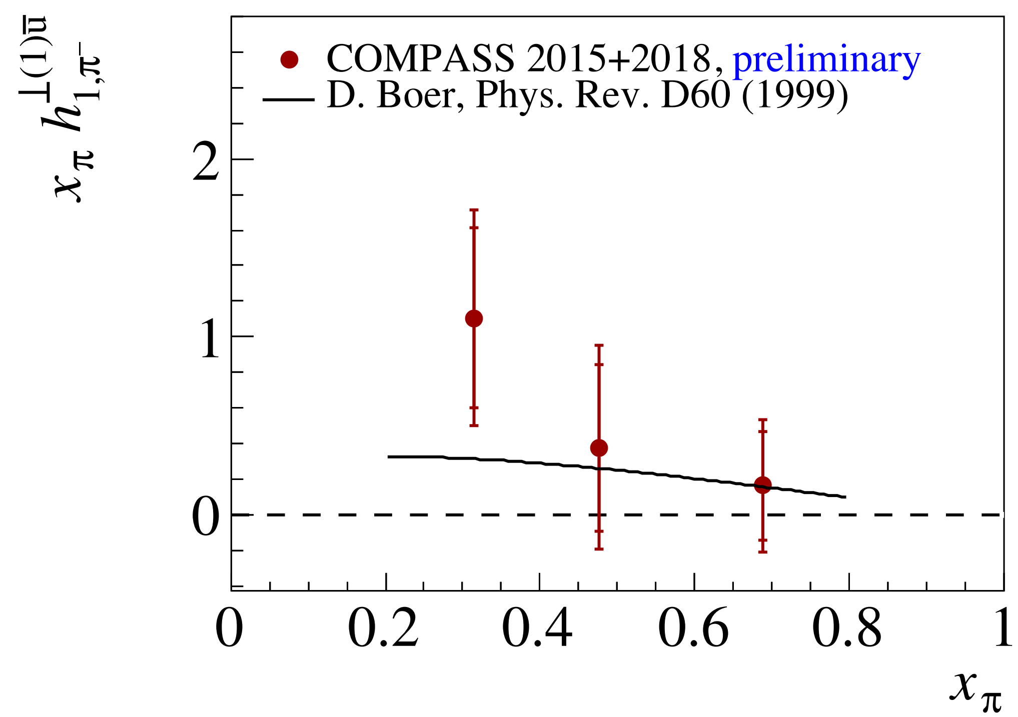
GRV-PI pion PDF
at Q^2 = 25 (GeV/c^2)^2



CTEQ proton PDF
at Q^2 = 25 (GeV/c^2)^2

Assuming:

- *u* quark dominance
- no Q^2 evolution



- Different pion PDFs tested (GRV-Pi, JAM);
- Transversity from different asymmetries (Collins, Dihadron);

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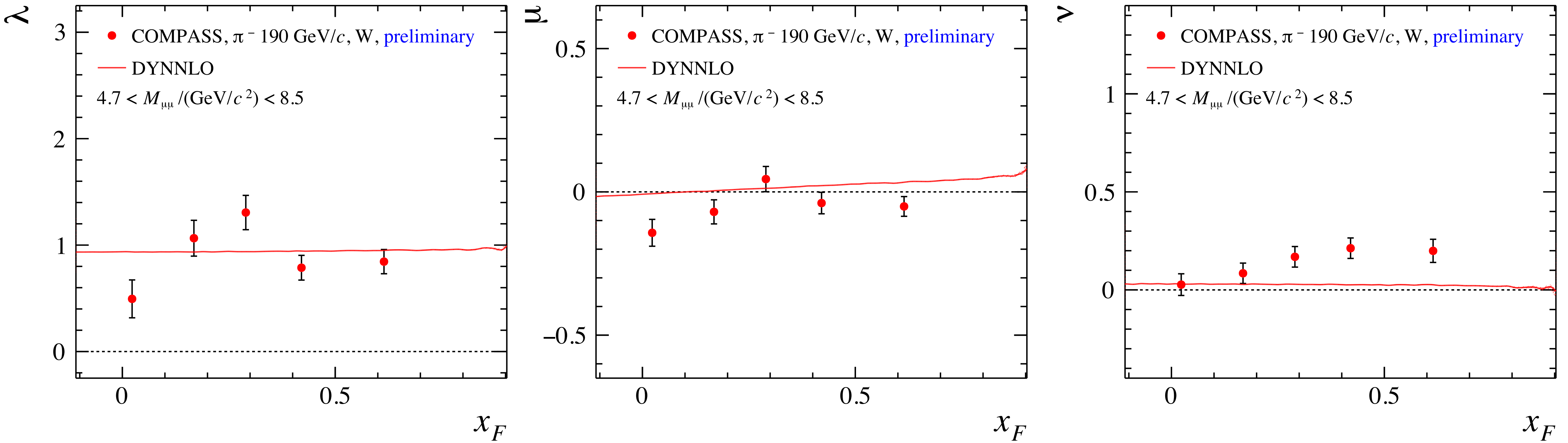
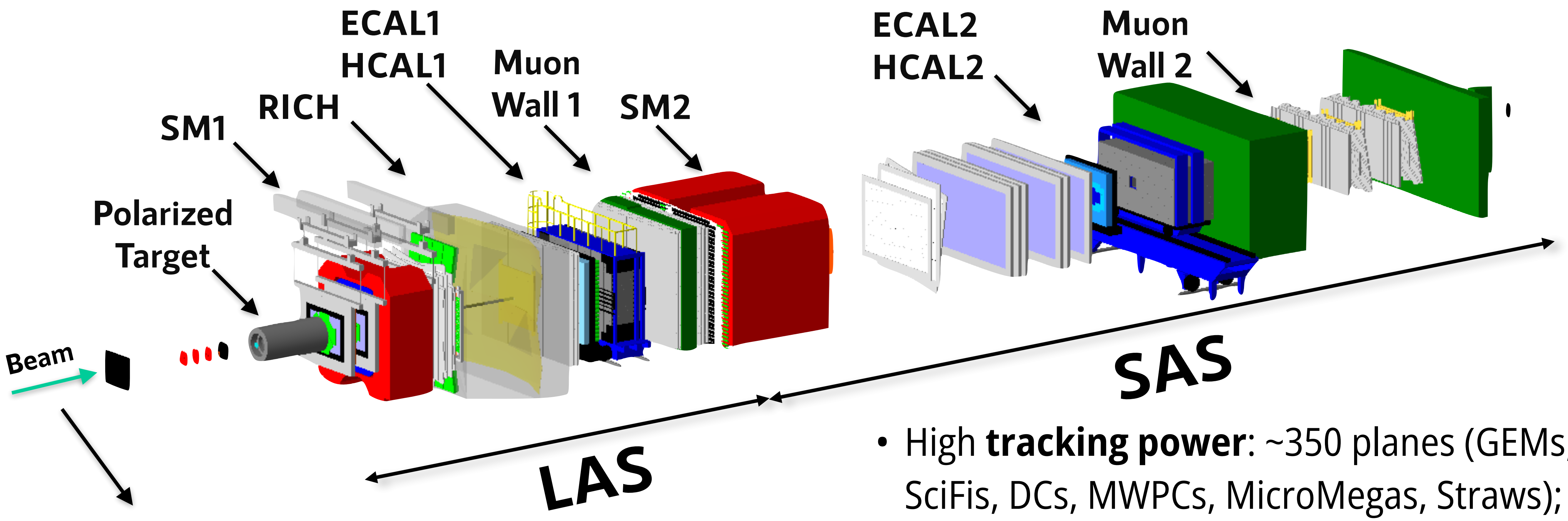
UAs VS X_F


λ
COMPASS, π⁻ 190 GeV/c, W, preliminary
DYNNLO
4.7 < $M_{\mu\mu}$ /(GeV/c^2) < 8.5
x_F
μ
COMPASS, π⁻ 190 GeV/c, W, preliminary
DYNNLO
4.7 < $M_{\mu\mu}$ /(GeV/c^2) < 8.5
x_F
ν
COMPASS, π⁻ 190 GeV/c, W, preliminary
DYNNLO
4.7 < $M_{\mu\mu}$ /(GeV/c^2) < 8.5
x_F

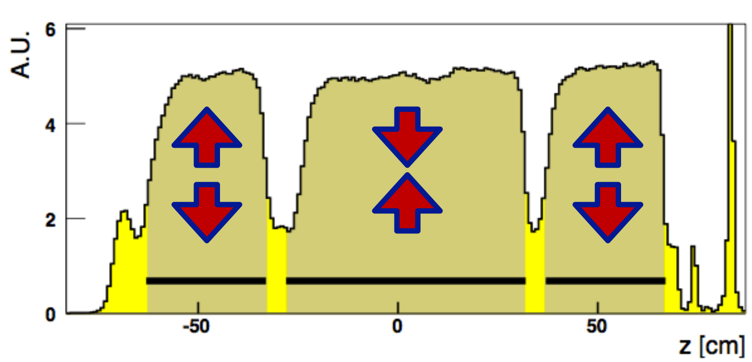
COMPASS SETUP (PHASE I)



μ^+ beam

- $P_{\mu+}$: 160 GeV/c, intensity 2 · 10^8 μ^+/4.8 s

Target	# of cells	Polarization
NH_3	3	T, ~80-90 %



Solid state transversely polarized target (2007, 2010)

- High **tracking power**: ~350 planes (GEMs, SciFis, DCs, MWPCs, MicroMegas, Straws);
- PID via RICH and Calorimetric measurements;
- **Two-stage** spectrometer
  - Large Angle Spectrometer (LAS)
    - SM1 magnet (1 T · m), Θ up to ±180 mrad
  - Small Angle Spectrometer (SAS)
    - SM2 magnet (4.4 T · m), Θ up to ±30 mrad
- Data were collected simultaneously for the two target spin orientation
- For transverse program, the polarization was **reversed** after each 4-5 days