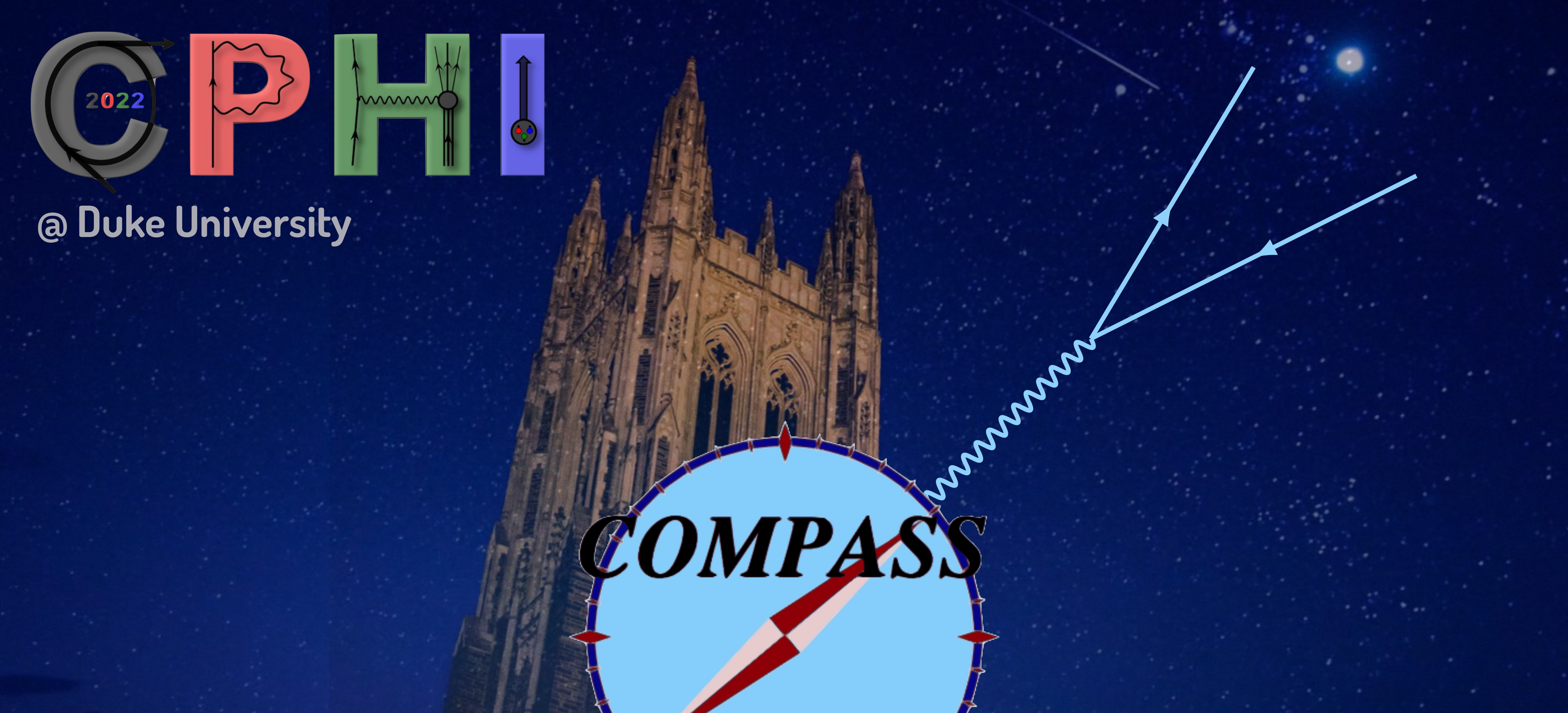


COMPASS DRELL-YAN PROGRAM

Riccardo Longo
on behalf of the COMPASS Collaboration
7th March 2022

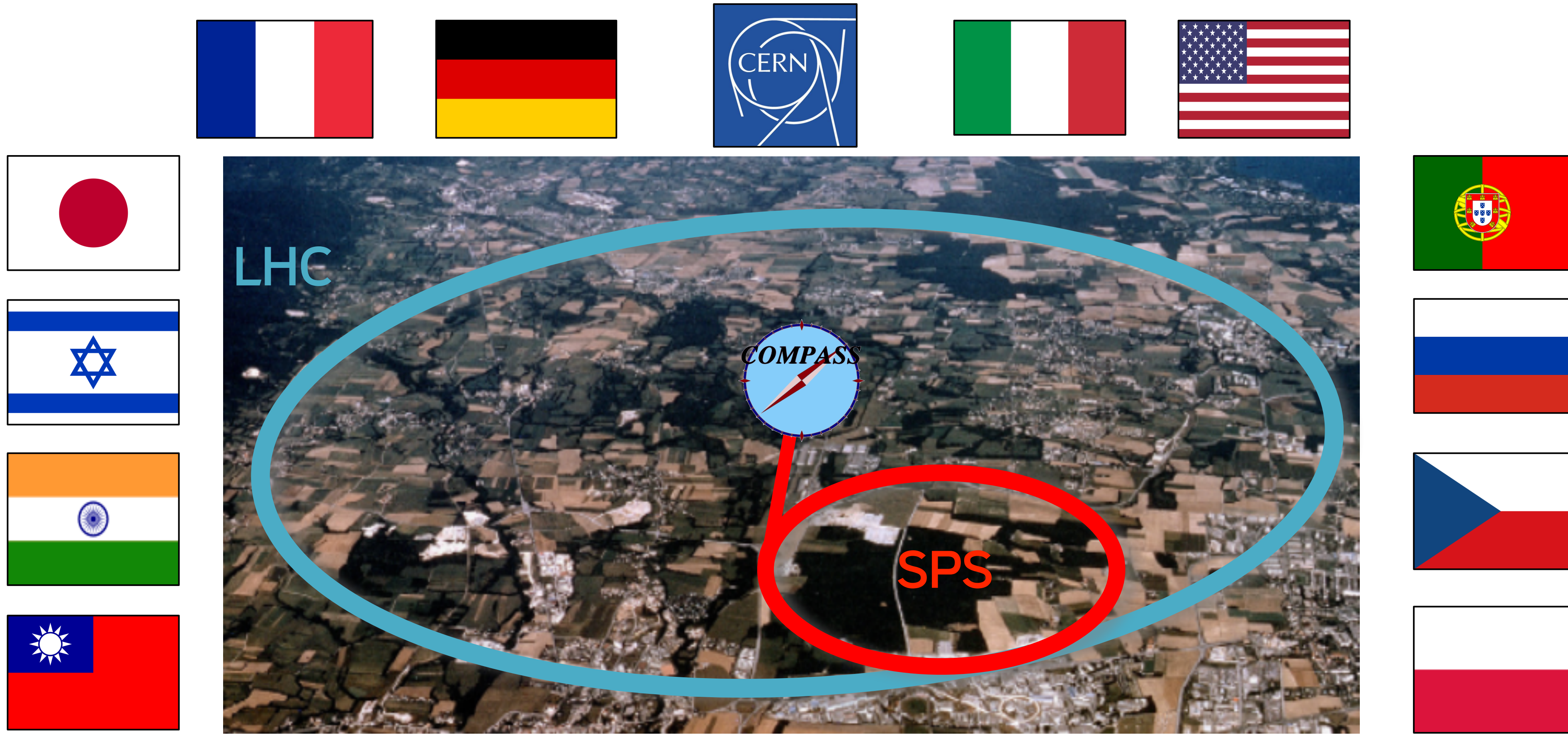
NSF
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

OUTLINE

- Introduction
- COMPASS Experimental apparatus
- COMPASS Drell-Yan measurements
- COMPASS Drell-Yan Transverse Spin Asymmetries results
  [NEW RESULTS - 2015+2018 FULL DATA SET]
- COMPASS alternative ways to investigate Sivers:
  A_N and q_T-weighted Transverse Spin Asymmetries results
- COMPASS Drell-Yan Unpolarized Asymmetries results
- Summary

THE COMPASS COLLABORATION

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



Phase I

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

See talk by A.Martin

Phase II

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

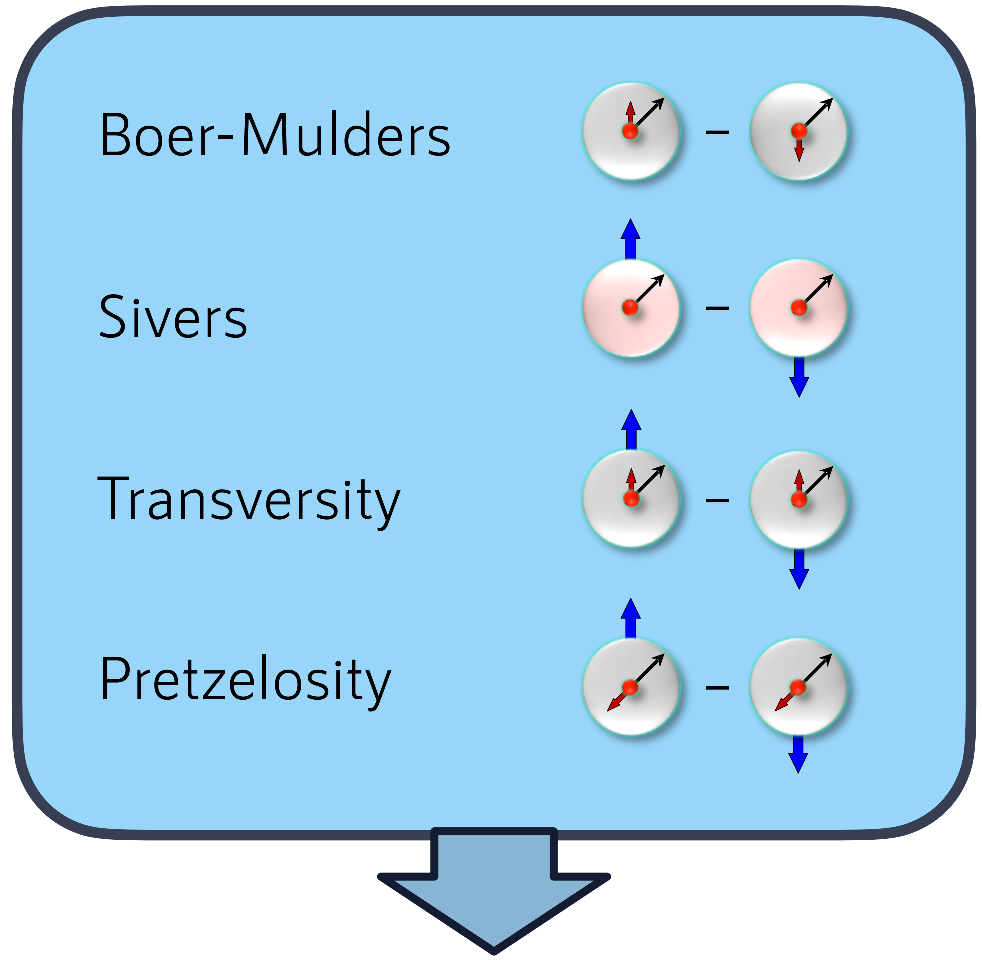
See talks by A.Moretti, C.Riedl,

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

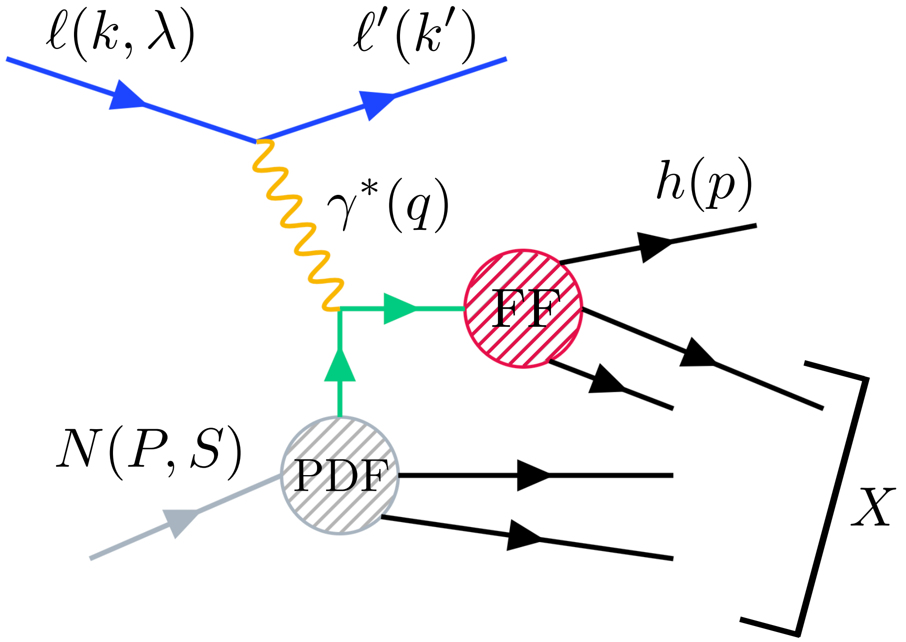
Nucleon | Nucleon spin | quark | quark spin | $\mathbf{k_T}$



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

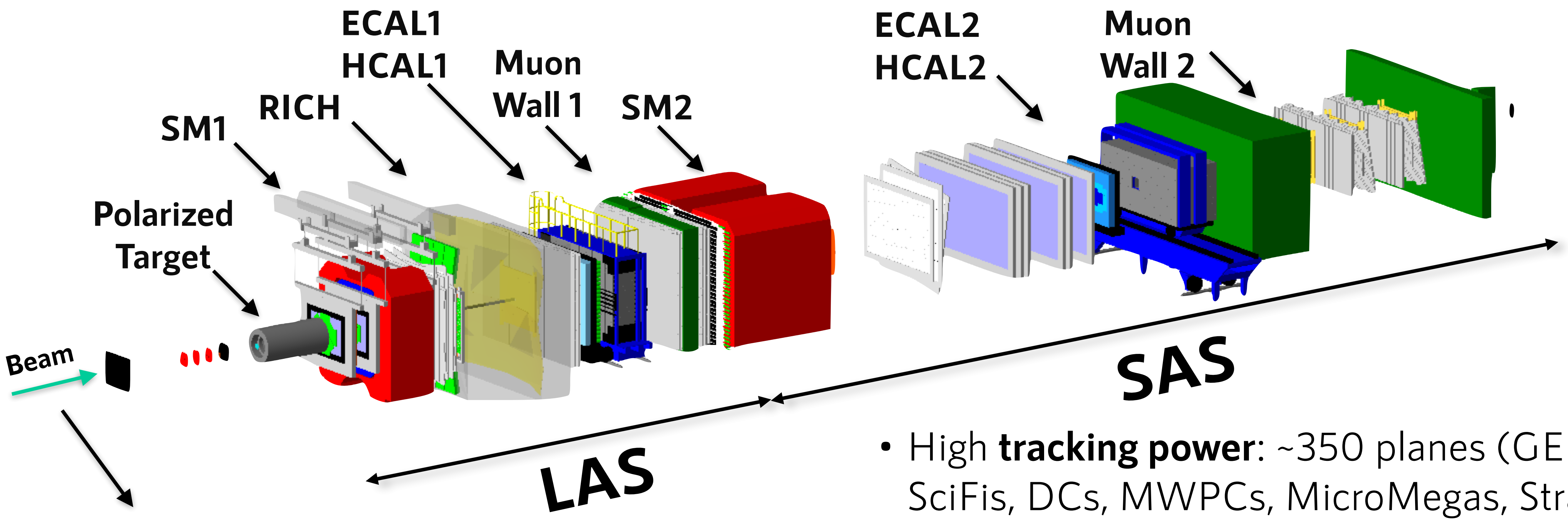
$$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$$

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

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

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

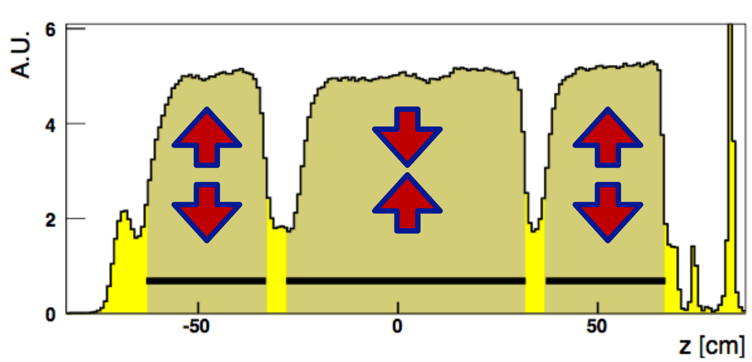
COMPASS SETUP (PHASE I)



μ^+ beam

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

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



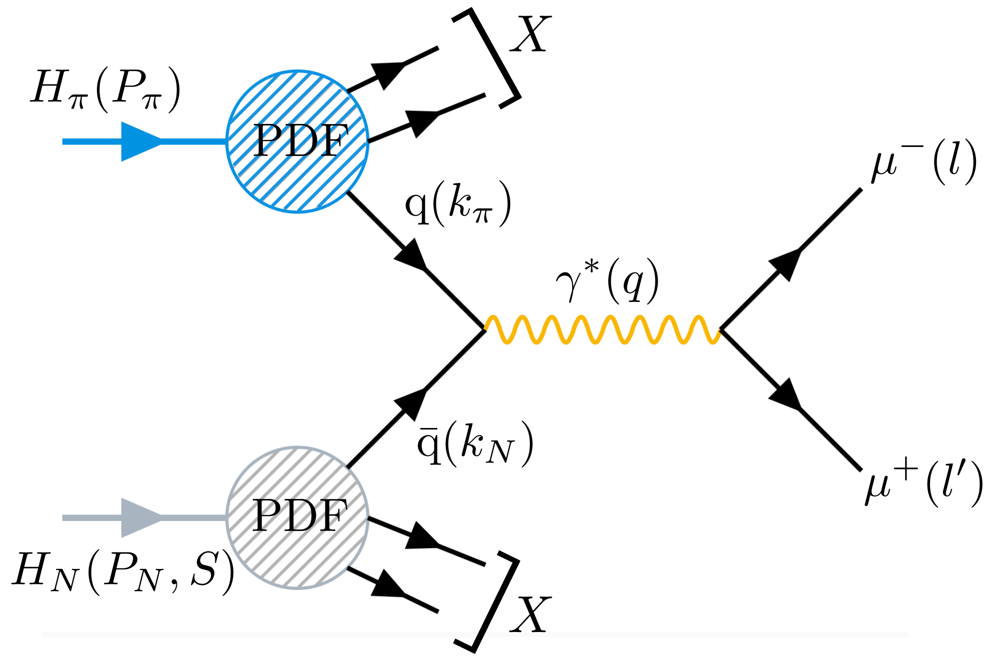
Solid state transversely polarized target (2007, 2010)

- 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

SINGLE POLARIZED DRELL-YAN PROCESS

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

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



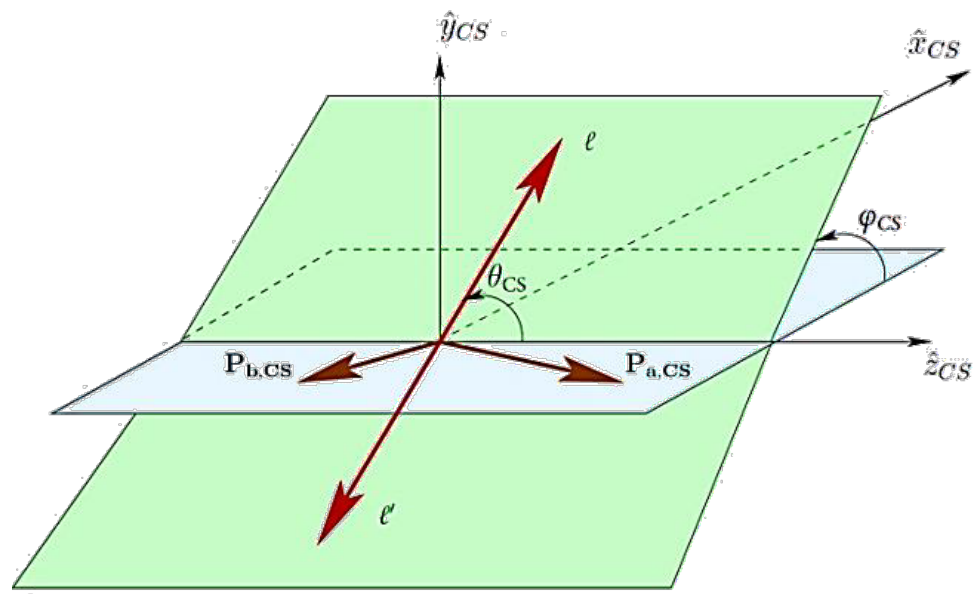
Pion induced polarized Drell-Yan $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$ **COMPASS 2015, 2018**

D-factors

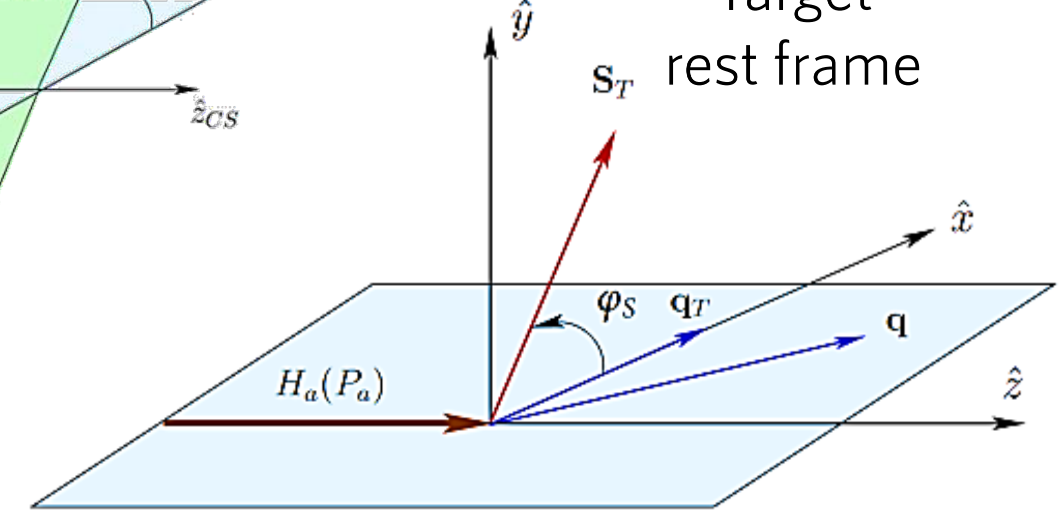
$$D_{f(\theta)} = \frac{f(\theta)}{1 + \cos^2(\theta)}$$

Azimuthal asymmetries

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



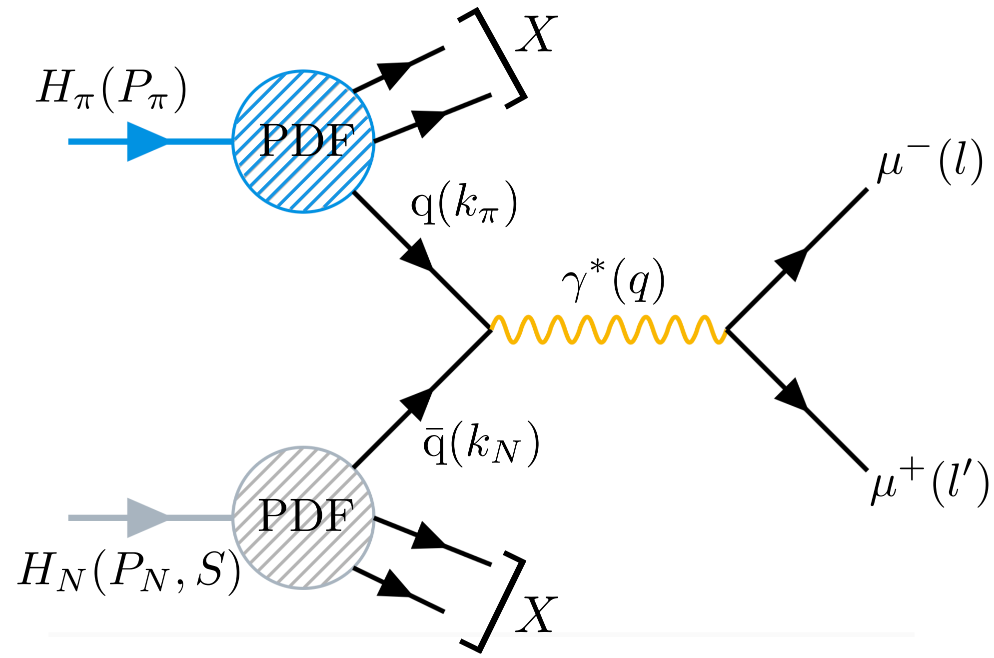
Collins-Soper frame



Target rest frame

SINGLE POLARIZED DRELL-YAN PROCESS

Leading order QCD parton model expression of the Single 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

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

		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
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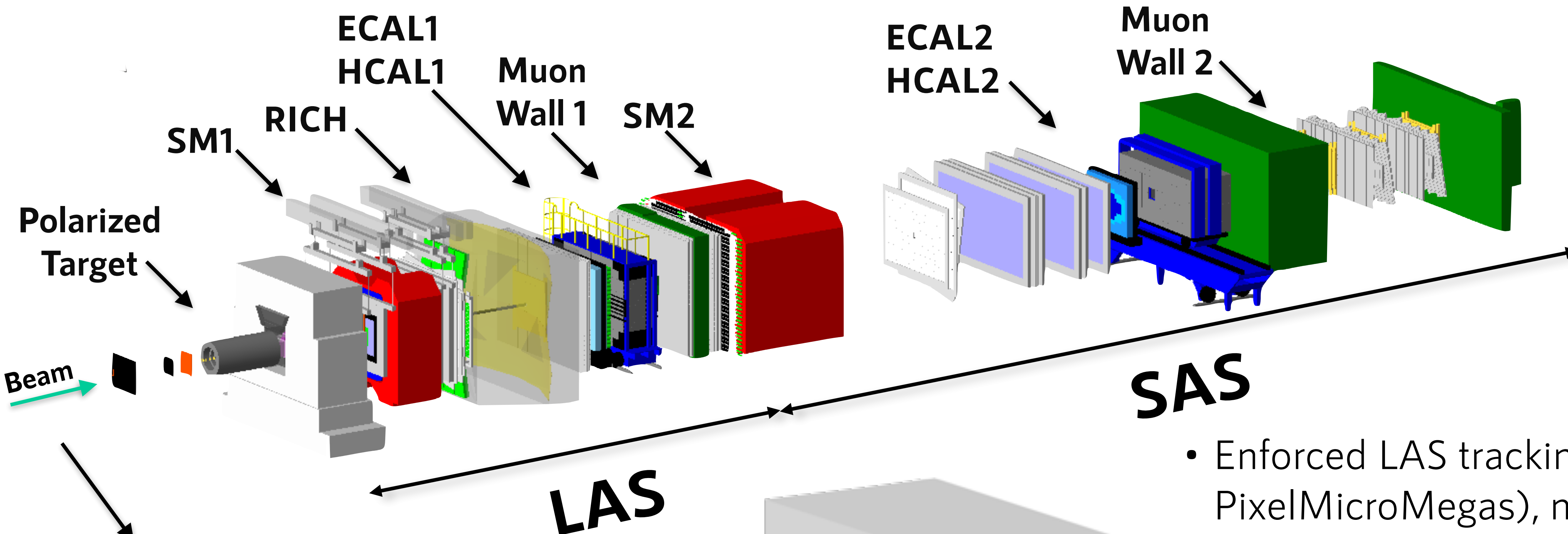
COMPASS SETUP (DY)



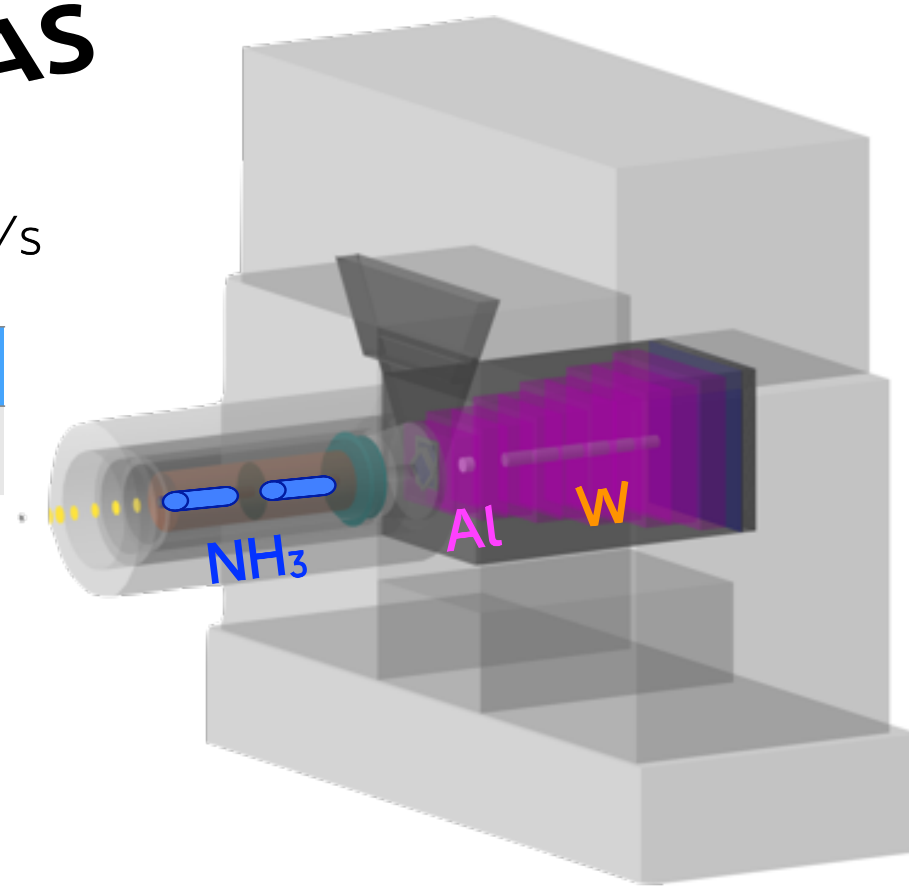
- Enforced LAS tracking (DC05, PixelMicroMegas), new DAQ …

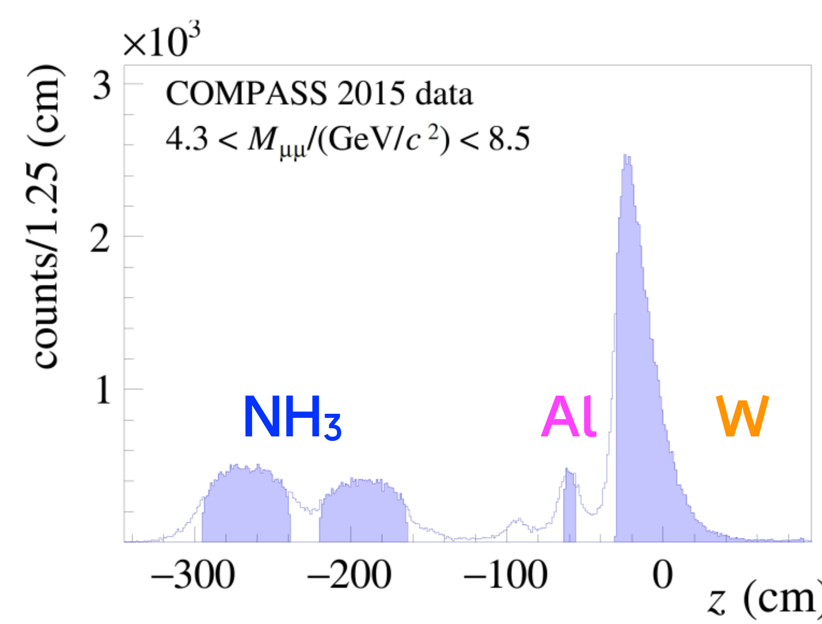
π^- beam

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

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

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

Pion induced polarized Drell-Yan

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

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

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

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)

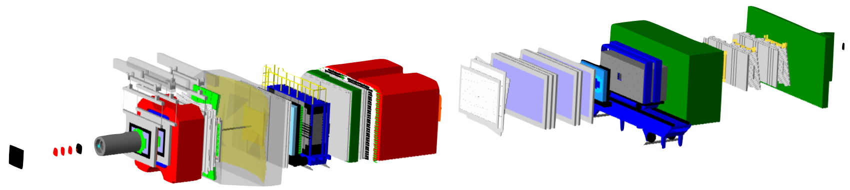
Boer Mulders and **Sivers** TMD PDFs "conditionally" universal (**sign change** between SIDIS and DY)

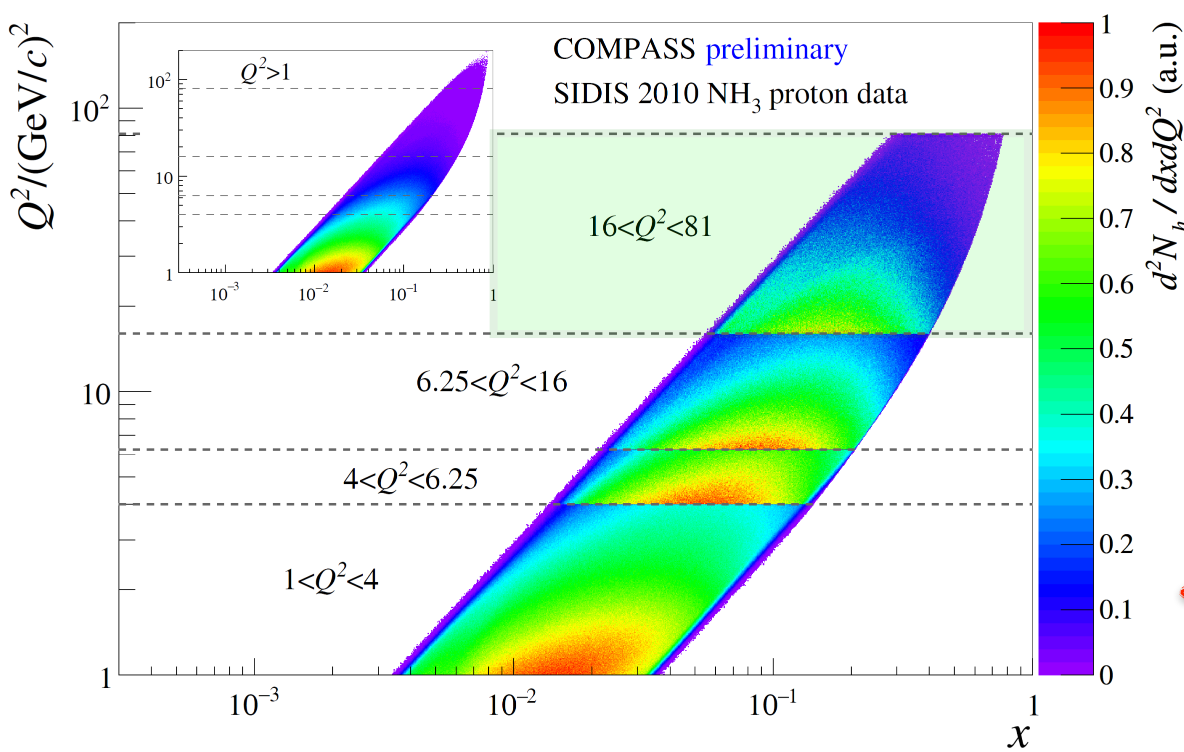
$$h_{1,p}^q|_{SIDIS} = h_{1,p}^q|_{DY}$$
$$h_{1T,p}^{\perp q}|_{SIDIS} = h_{1T,p}^{\perp q}|_{DY}$$
$$f_{1T,p}^{\perp q}|_{SIDIS} = -f_{1T,p}^{\perp q}|_{DY}$$
$$h_{1,p}^{\perp q}|_{SIDIS} = -h_{1,p}^{\perp q}|_{DY}$$

COMPASS SIDIS-DY BRIDGE

SIDIS on transversely polarized nucleons

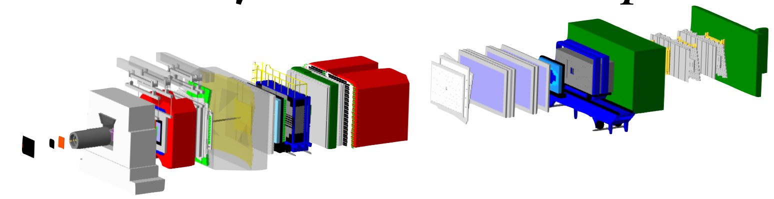
COMPASS 2007, 2010 $\mu + p^{\uparrow} \rightarrow \mu' + h + X$

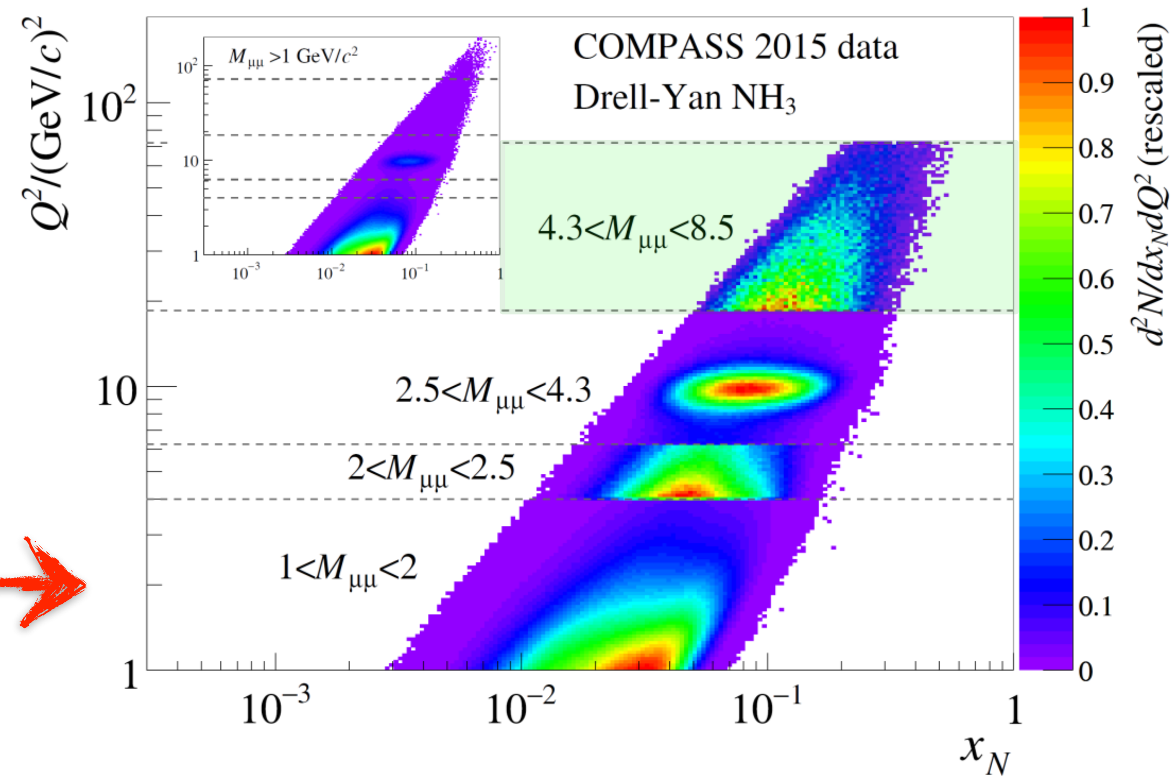




Pion induced polarized Drell-Yan

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





Comparable x:Q^2 kinematic coverage

minimization of possible Q^2 evolution effects

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

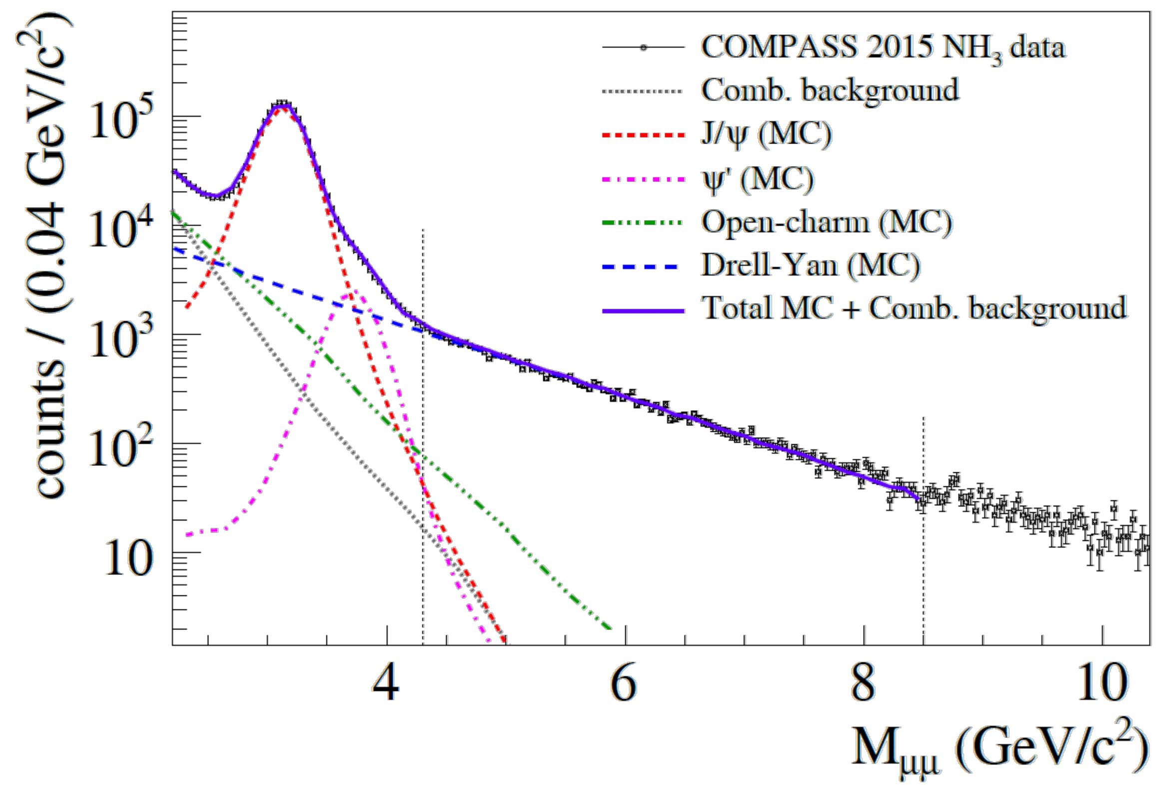
DRELL-YAN MEASUREMENTS AT COMPASS

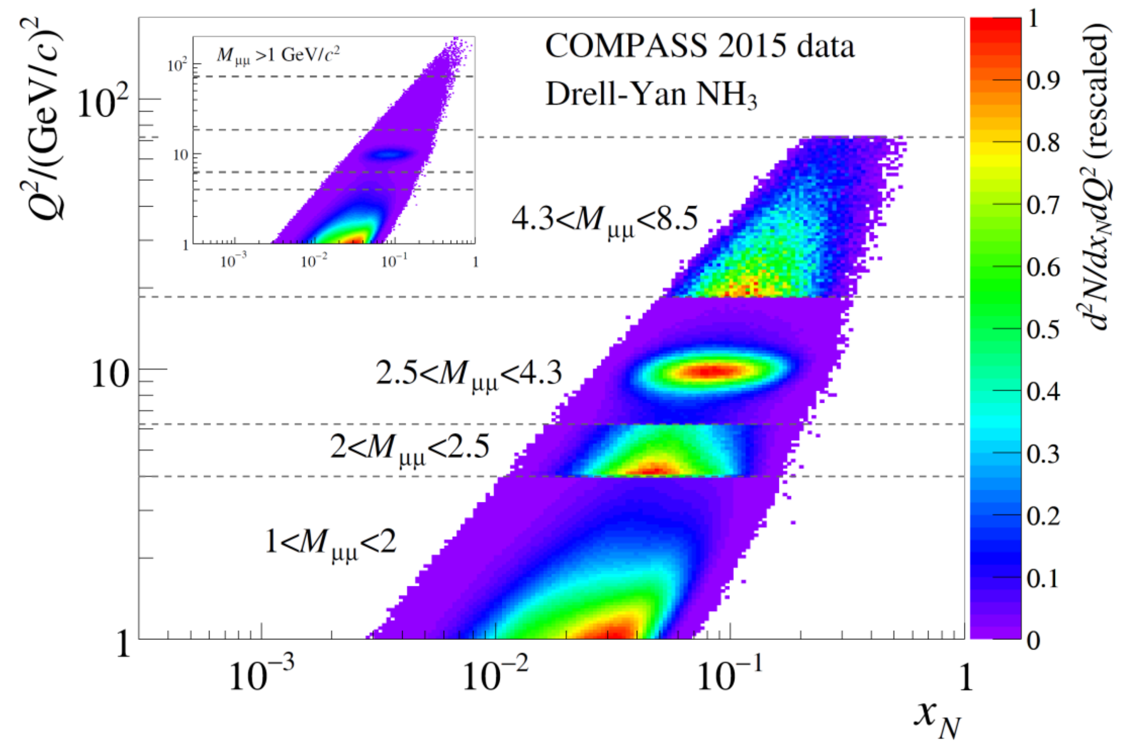
I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
- Large background contamination

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





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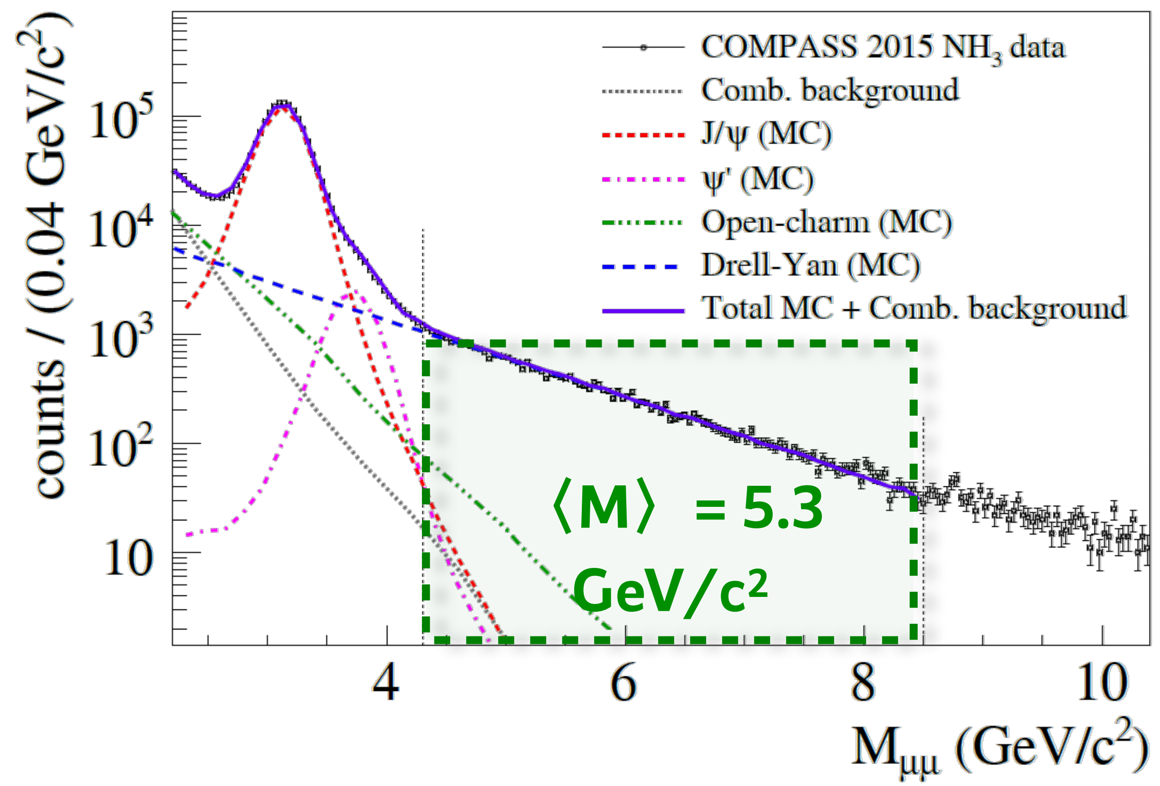

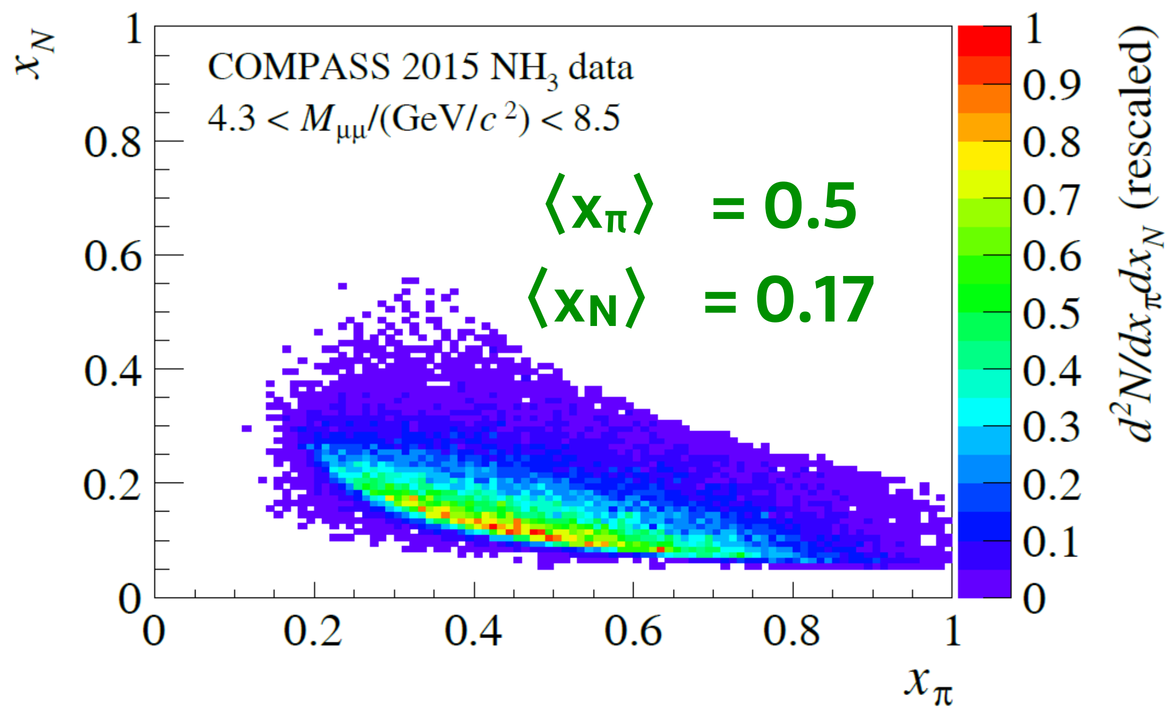

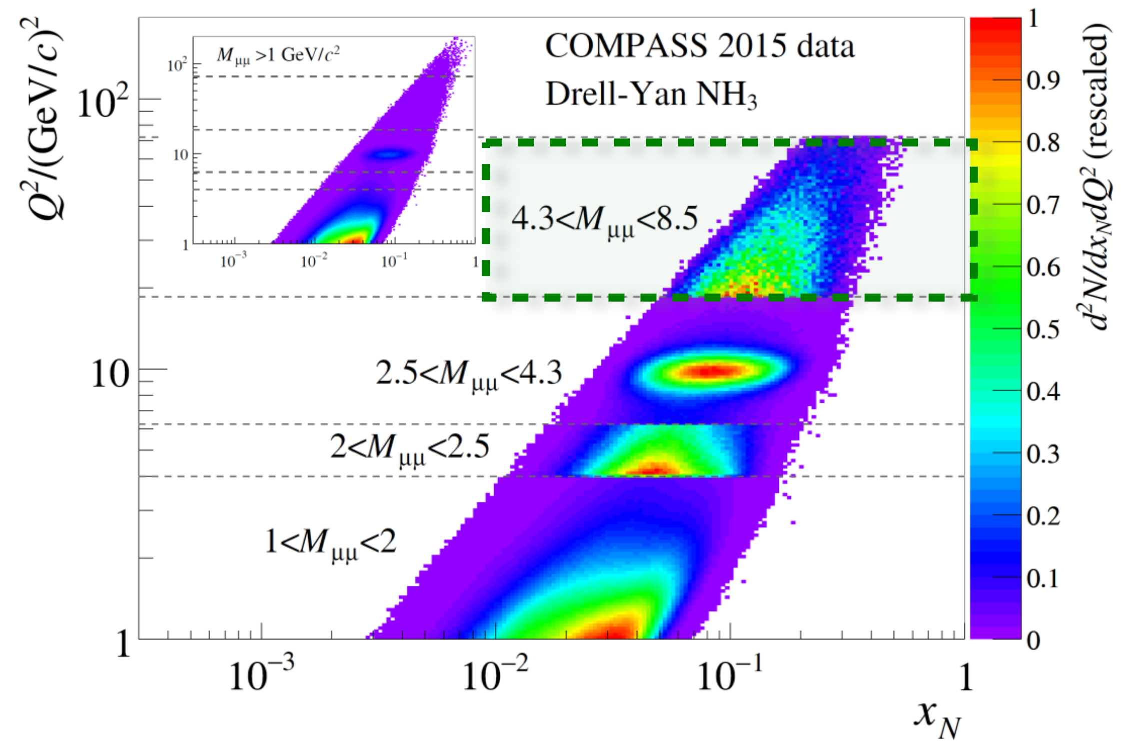

HM events are in the valence quark region

DRELL-YAN MEASUREMENTS AT 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”**
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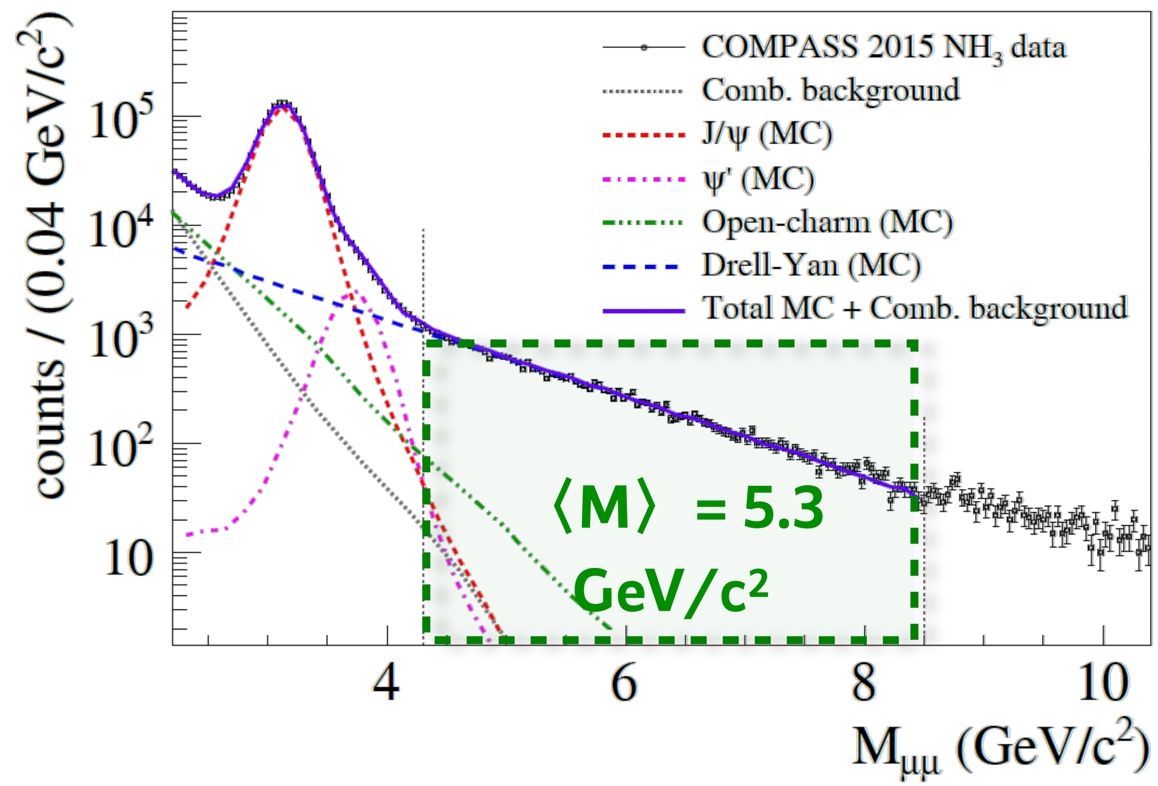
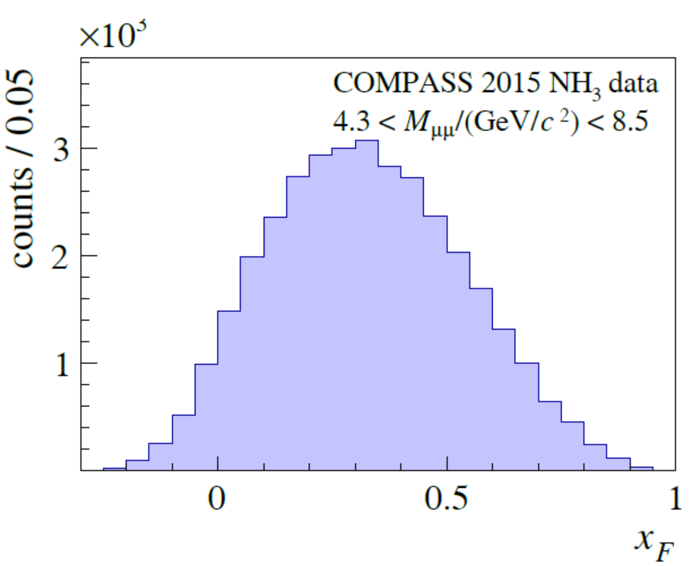
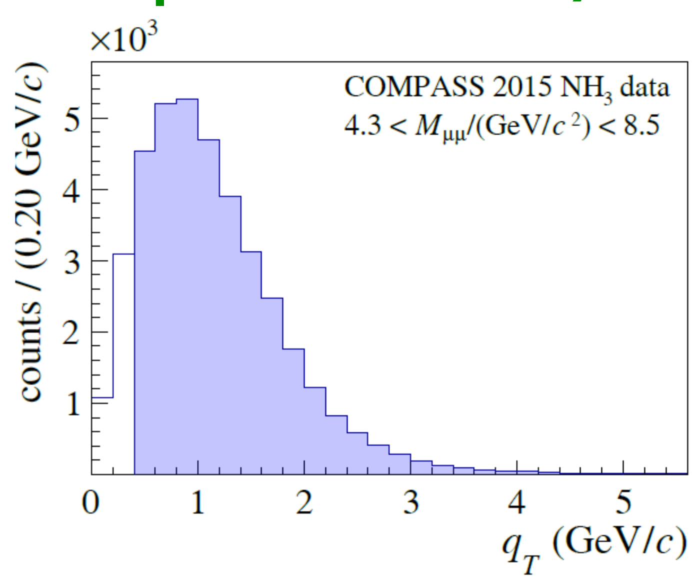


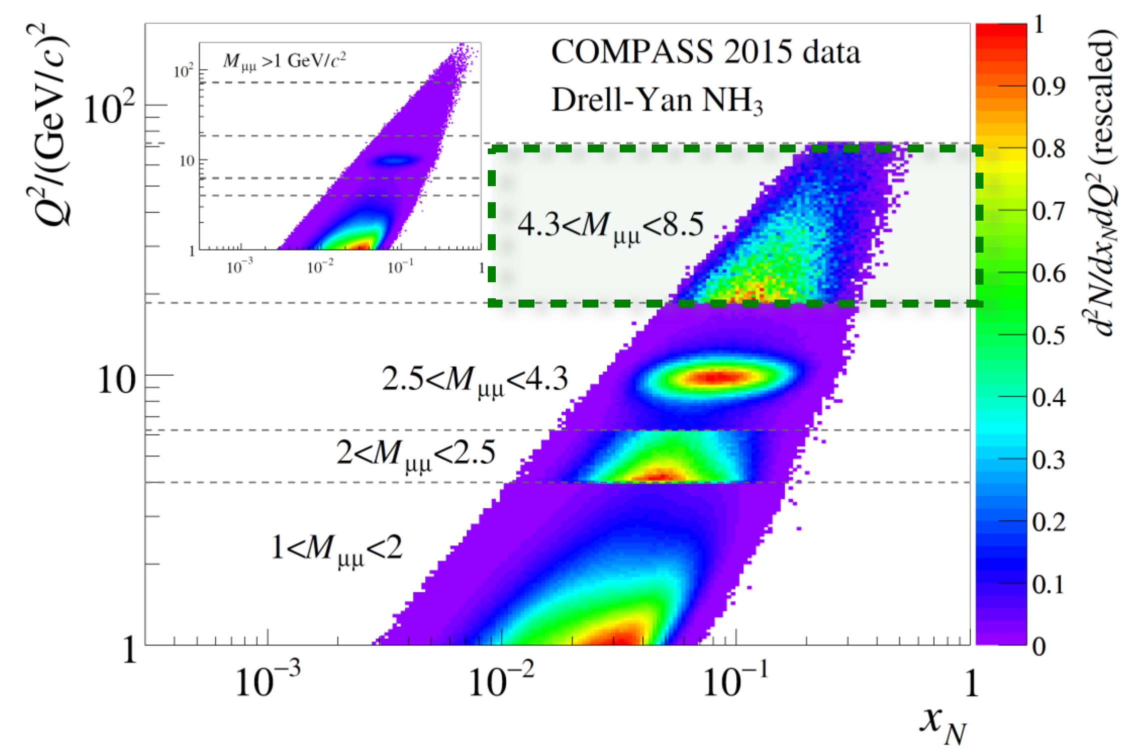
$q_T > 0.4$ GeV/c

$\langle x_F \rangle = 0.33$

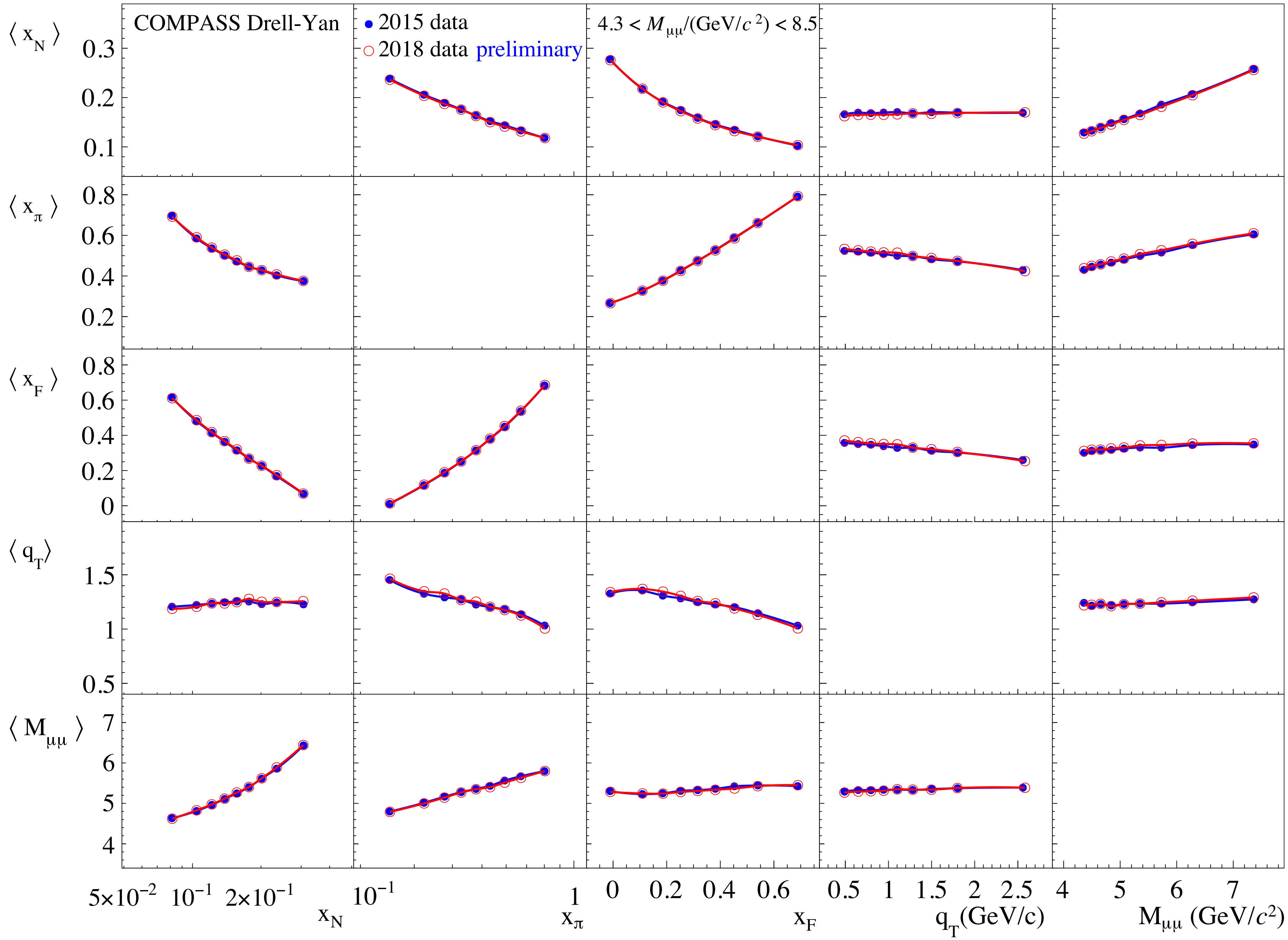
$\langle q_T \rangle = 1.17$ GeV/c







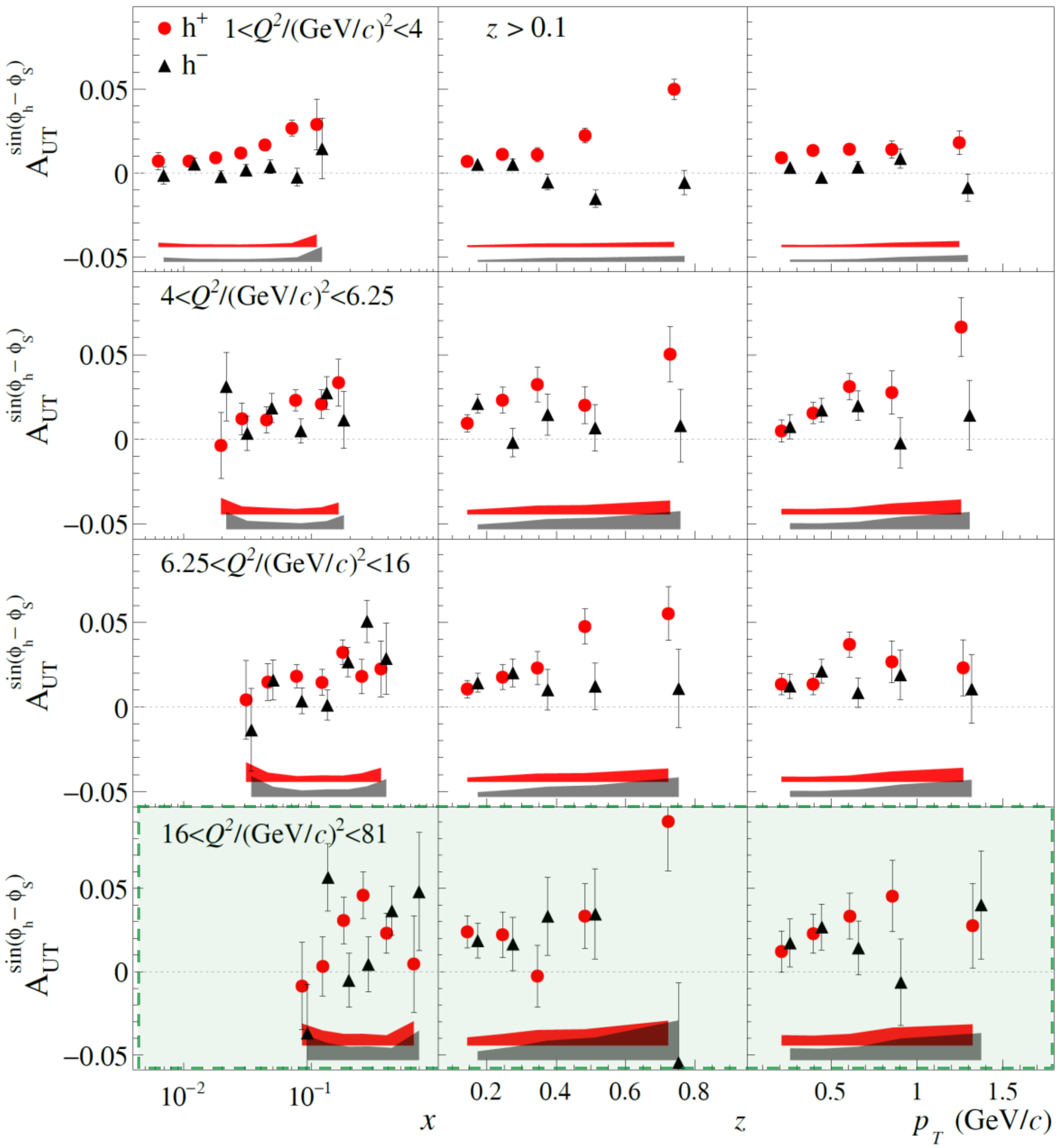
2015-2018 PHASE SPACE COVERAGE



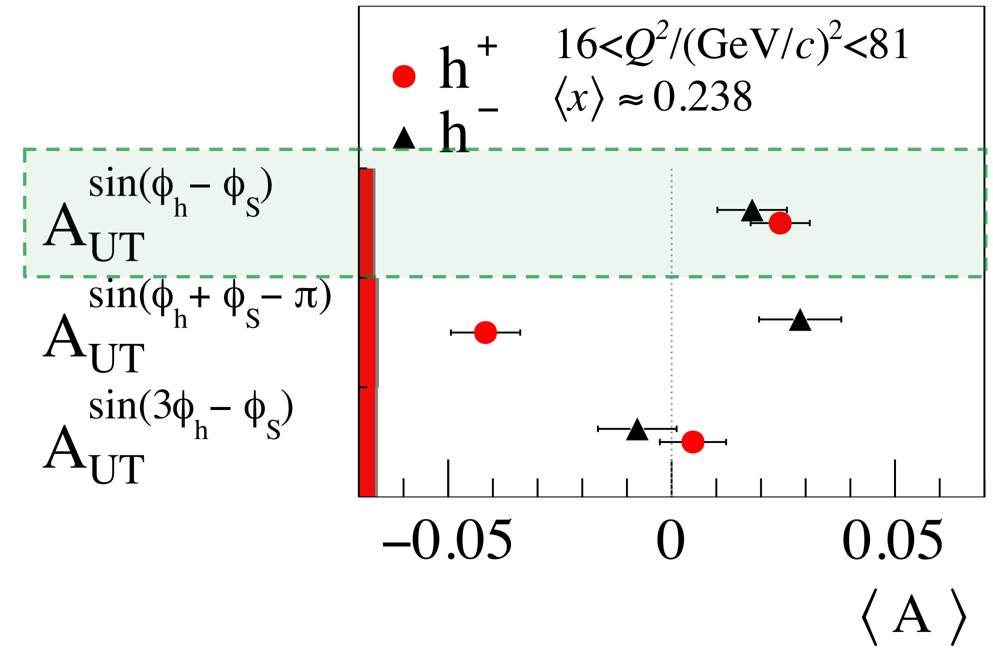
B. Parsamyan, **PoS DIS 2019 (2019) 195**

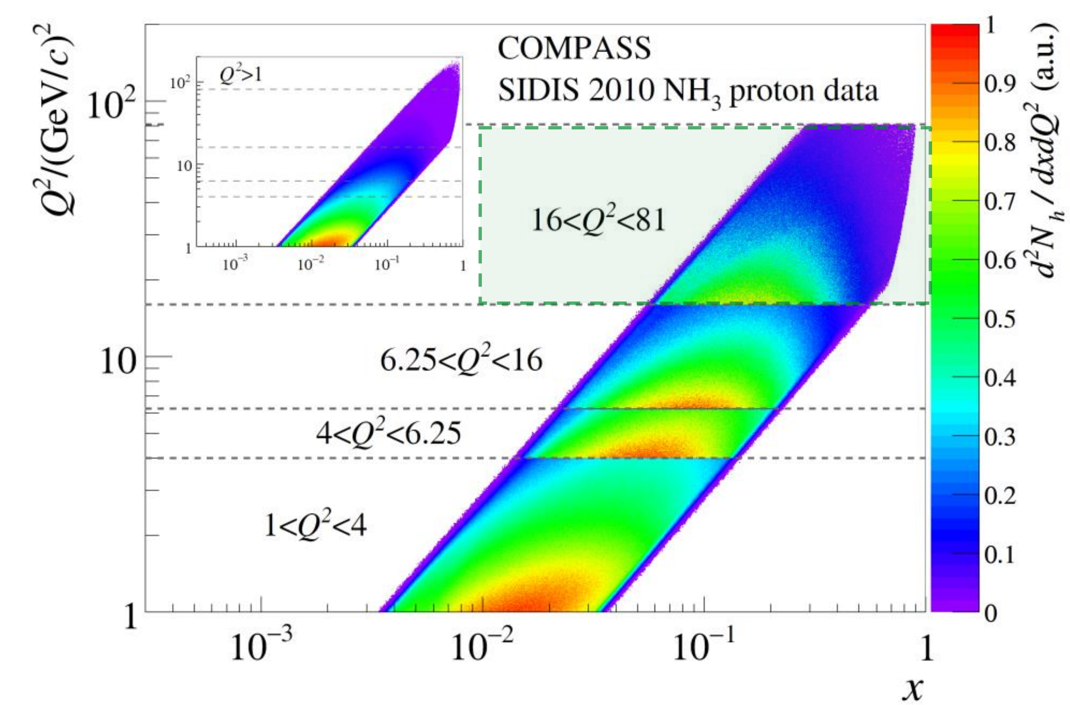
Same kinematic coverage of 2015 and 2018 data!

COMPASS: SIDIS IN DY RANGES



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





- Dedicated 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+;**

DY HM TSA RESULTS: SIVERS

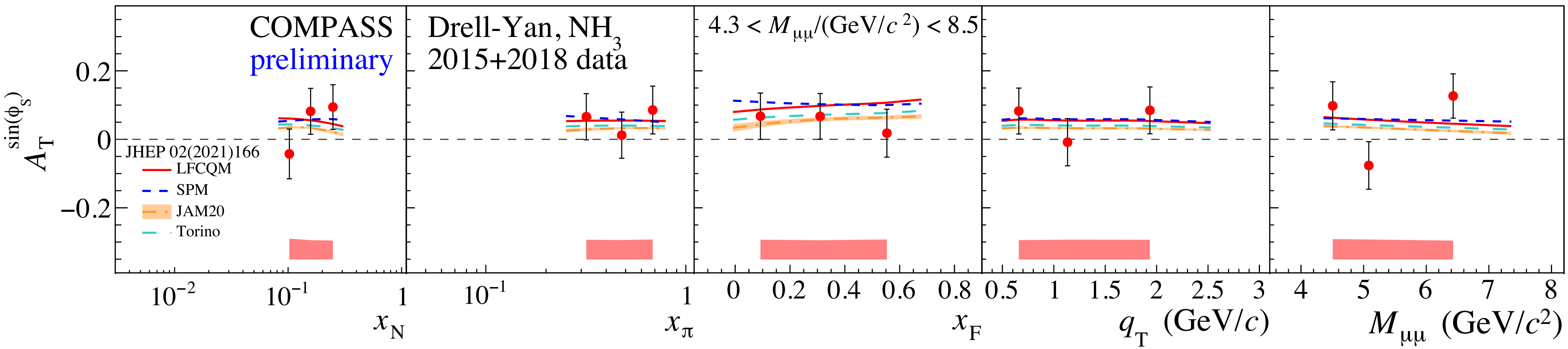
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$

DY - HM range

NEW RESULTS! FIRST SHOWN TODAY!

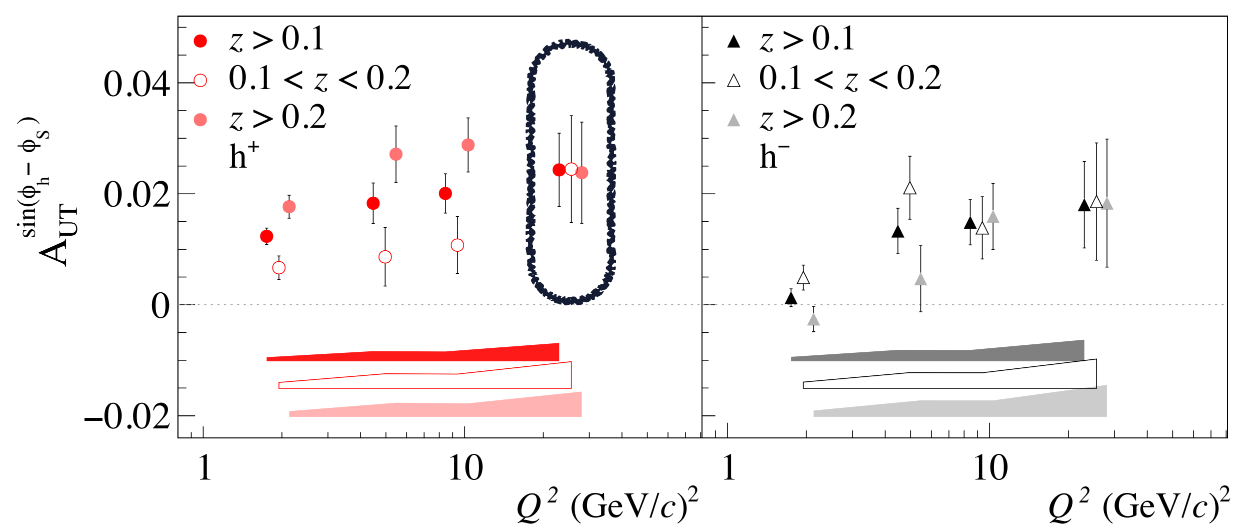
● COMPASS, **2015 + 2018 Full Data Sample**

Curves from JHEP 02, 166 (2021)



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

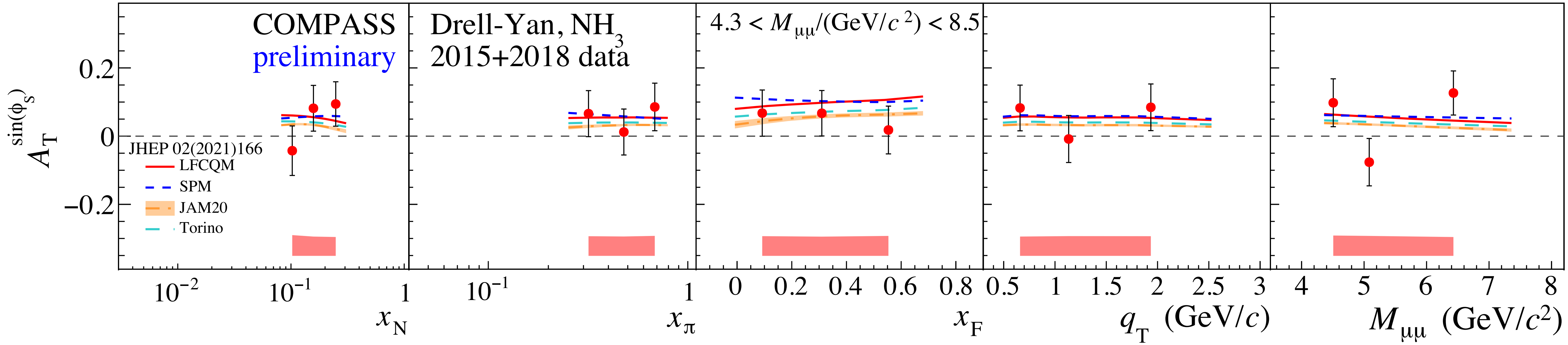
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$

DY - HM range

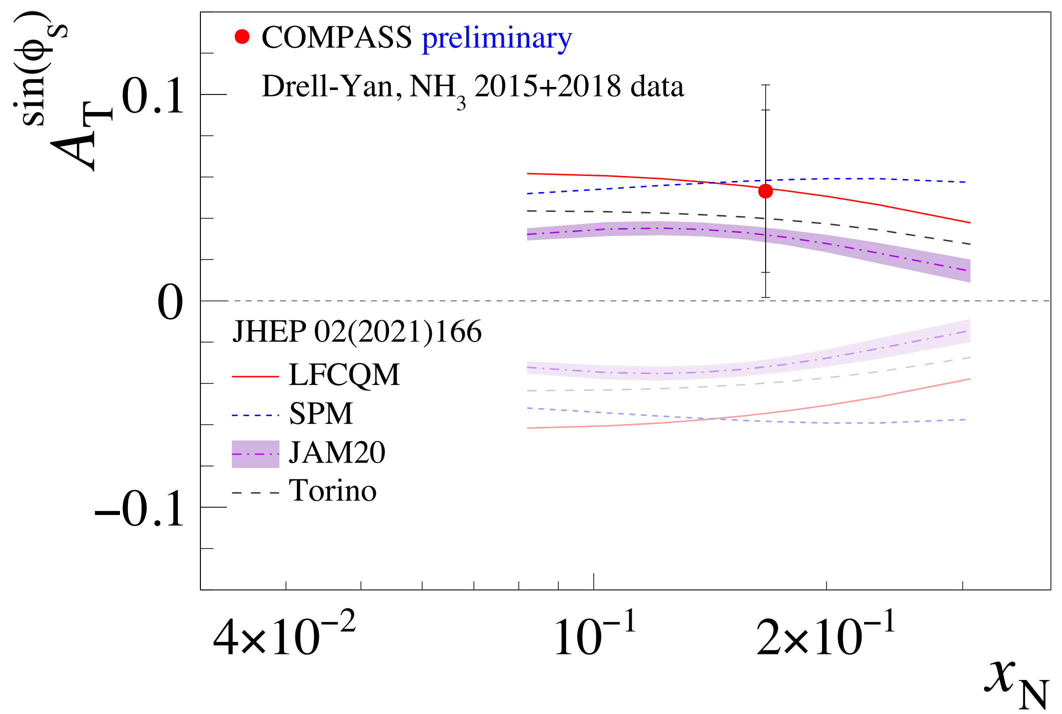
NEW RESULTS! FIRST SHOWN TODAY!

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

Curves from JHEP 02, 166 (2021)



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



sign change

no sign change

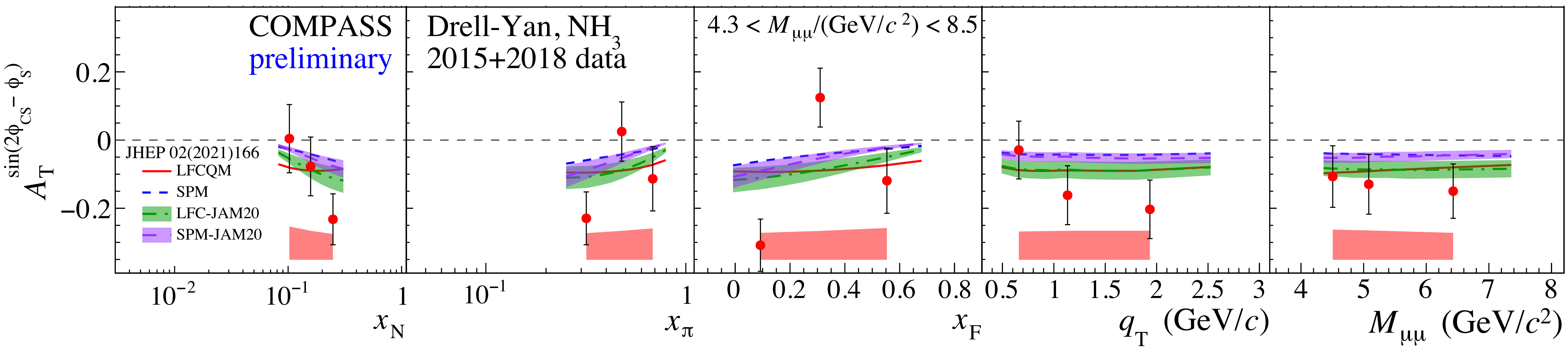
DY HM TSA RESULTS: TRANSVERSITY

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

NEW RESULTS! FIRST SHOWN TODAY!

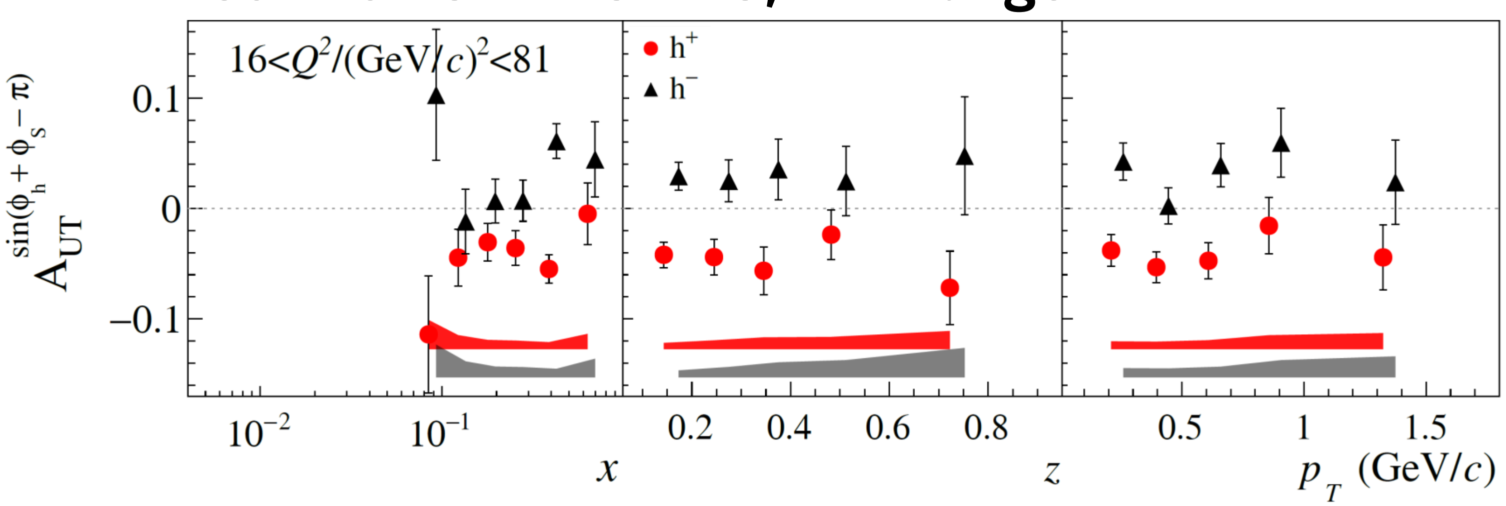
- COMPASS, **2015 + 2018 Full Data Sample**

Curves from JHEP 02, 166 (2021)



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

Collins TSA in SIDIS, HM range



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

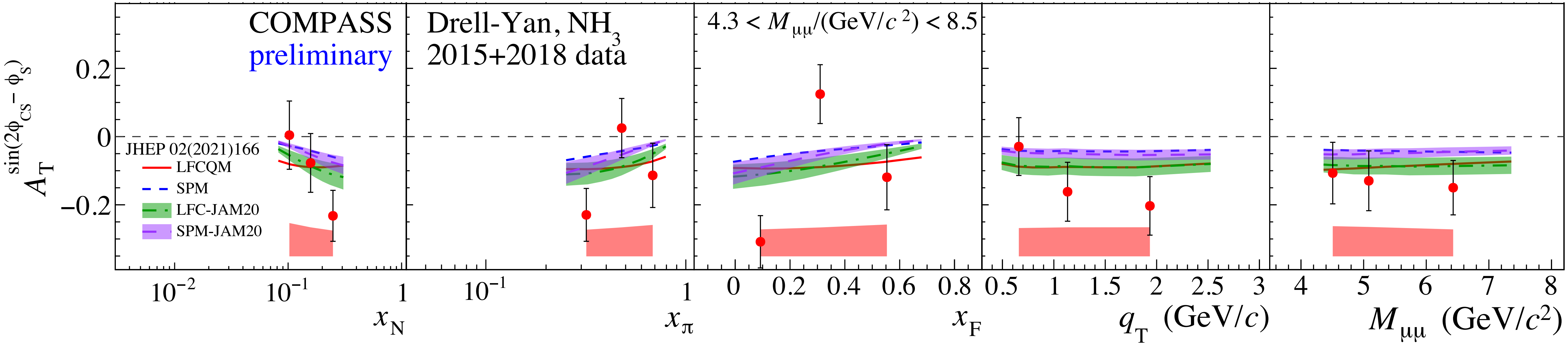
DY HM TSA RESULTS: TRANSVERSITY

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

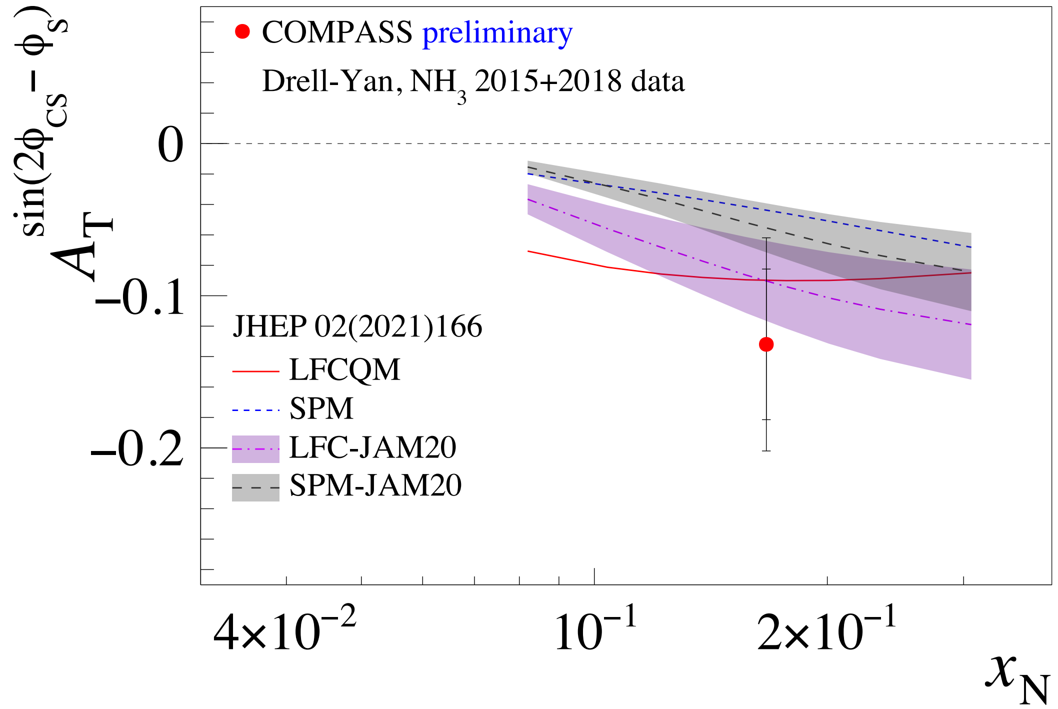
NEW RESULTS! FIRST SHOWN TODAY!

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

Curves from JHEP 02, 166 (2021)



COMPASS HM DY result for Transversity asymmetry found to be below zero about 1.5 σ (stat.+syst.)



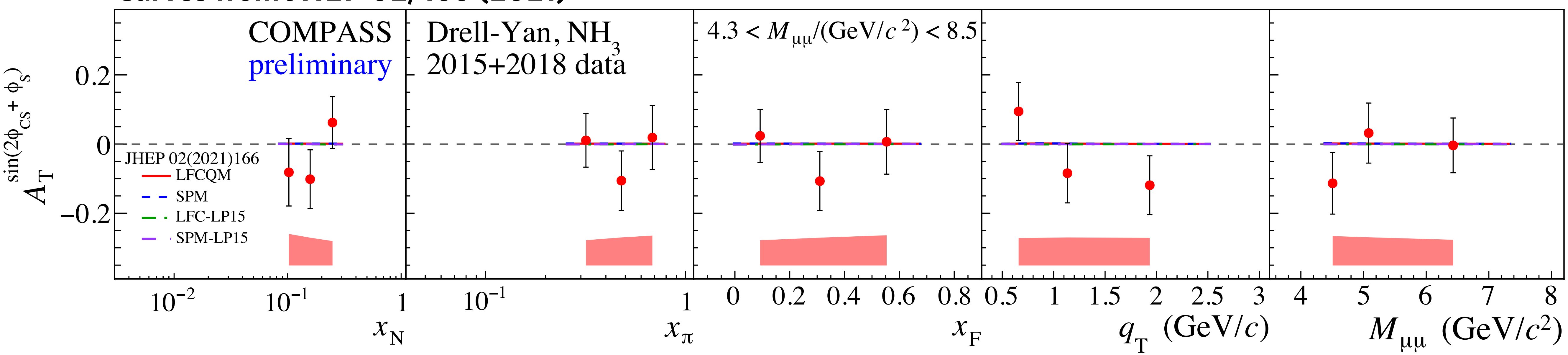
DY HM TSA RESULTS: PRETZELOSITY

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

NEW RESULTS! FIRST SHOWN TODAY!

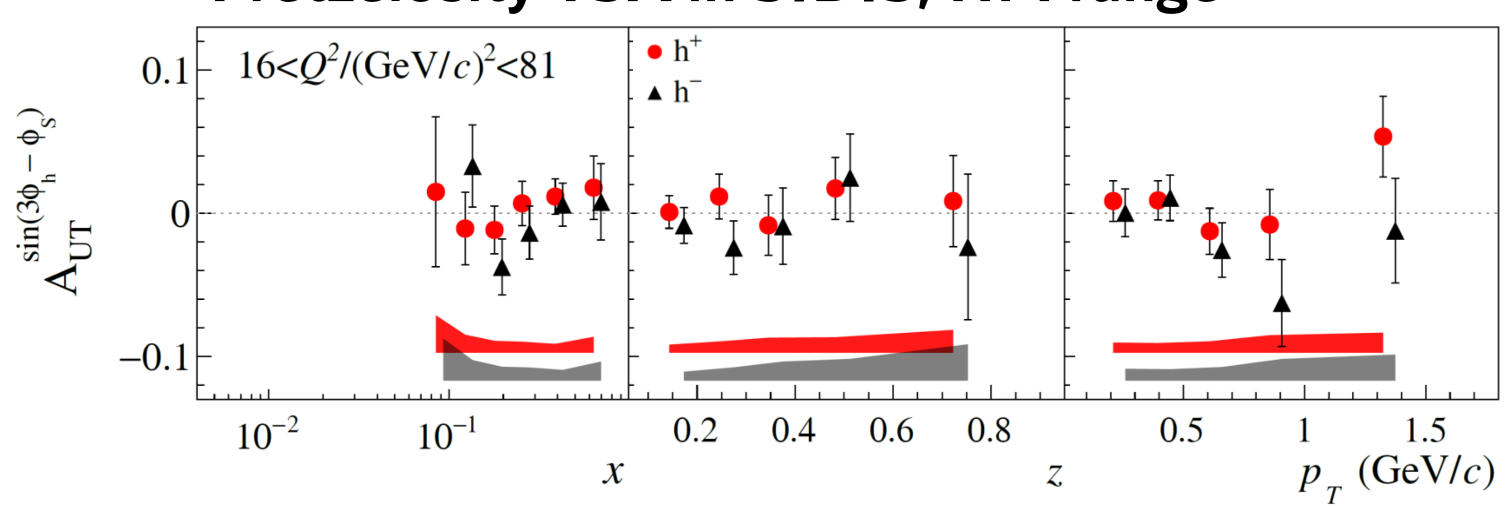
● COMPASS, **2015 + 2018 Full Data Sample**

Curves from JHEP 02, 166 (2021)



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

Pretzelosity TSA in SIDIS, HM range



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

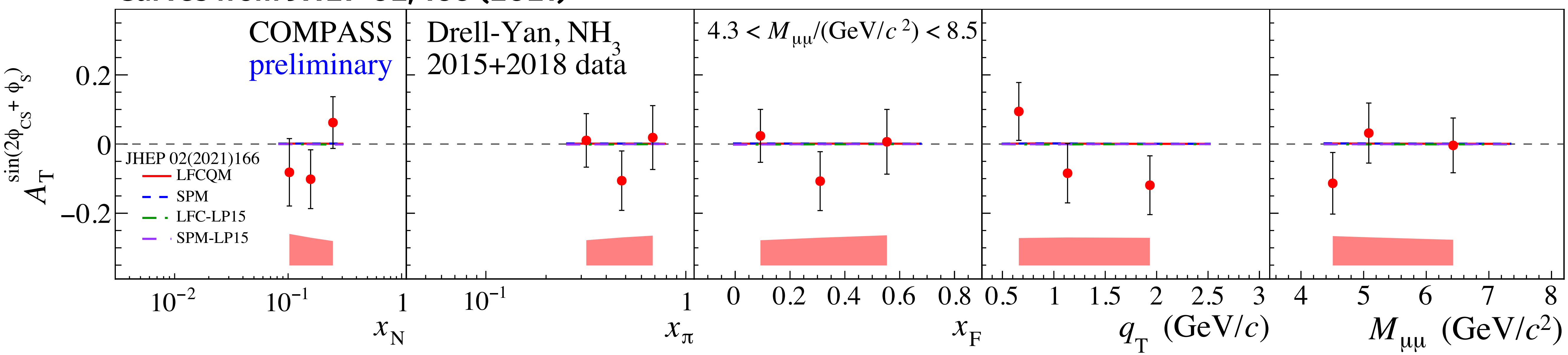
DY HM TSA RESULTS: PRETZELOSITY

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

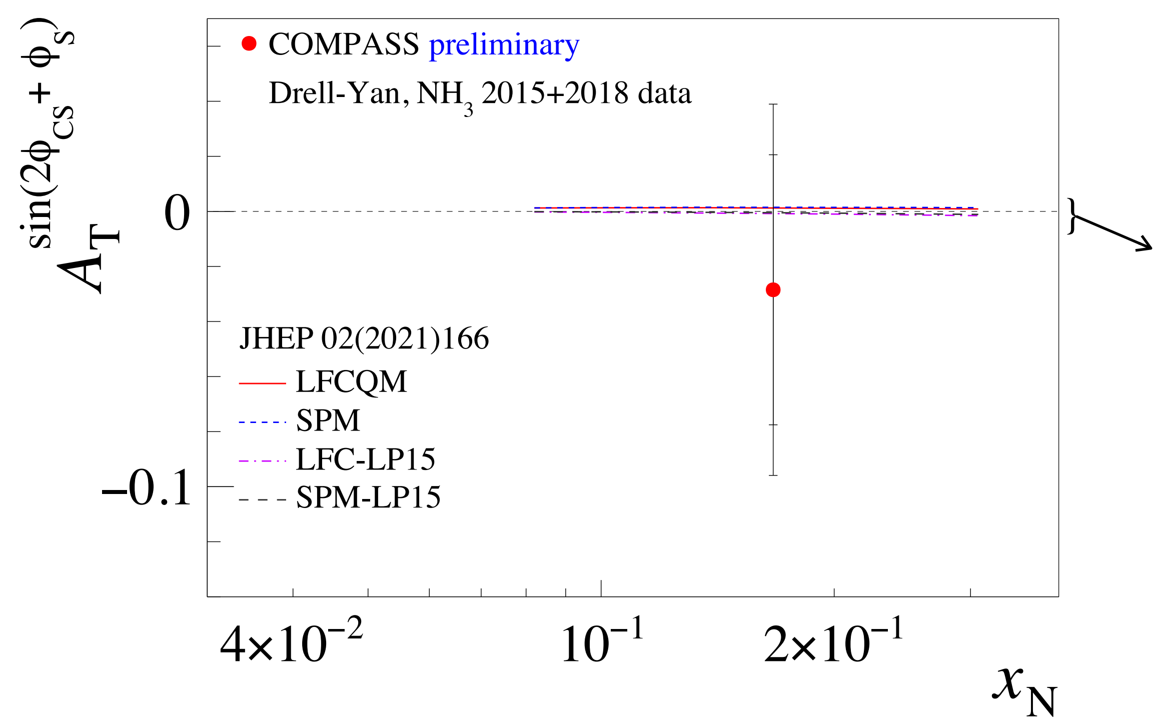
NEW RESULTS! FIRST SHOWN TODAY!

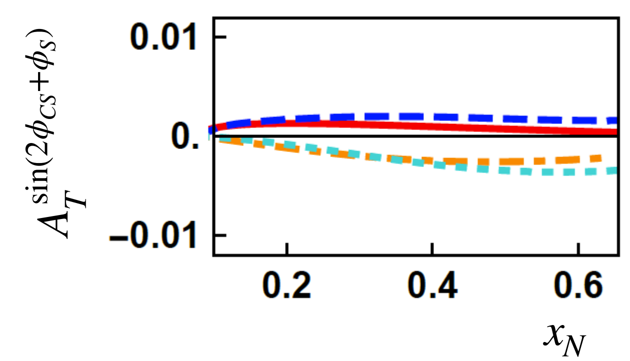
● COMPASS, **2015 + 2018 Full Data Sample**

Curves from JHEP 02, 166 (2021)



COMPASS HM DY result for Pretzelosity asymmetry found to be compatible with zero

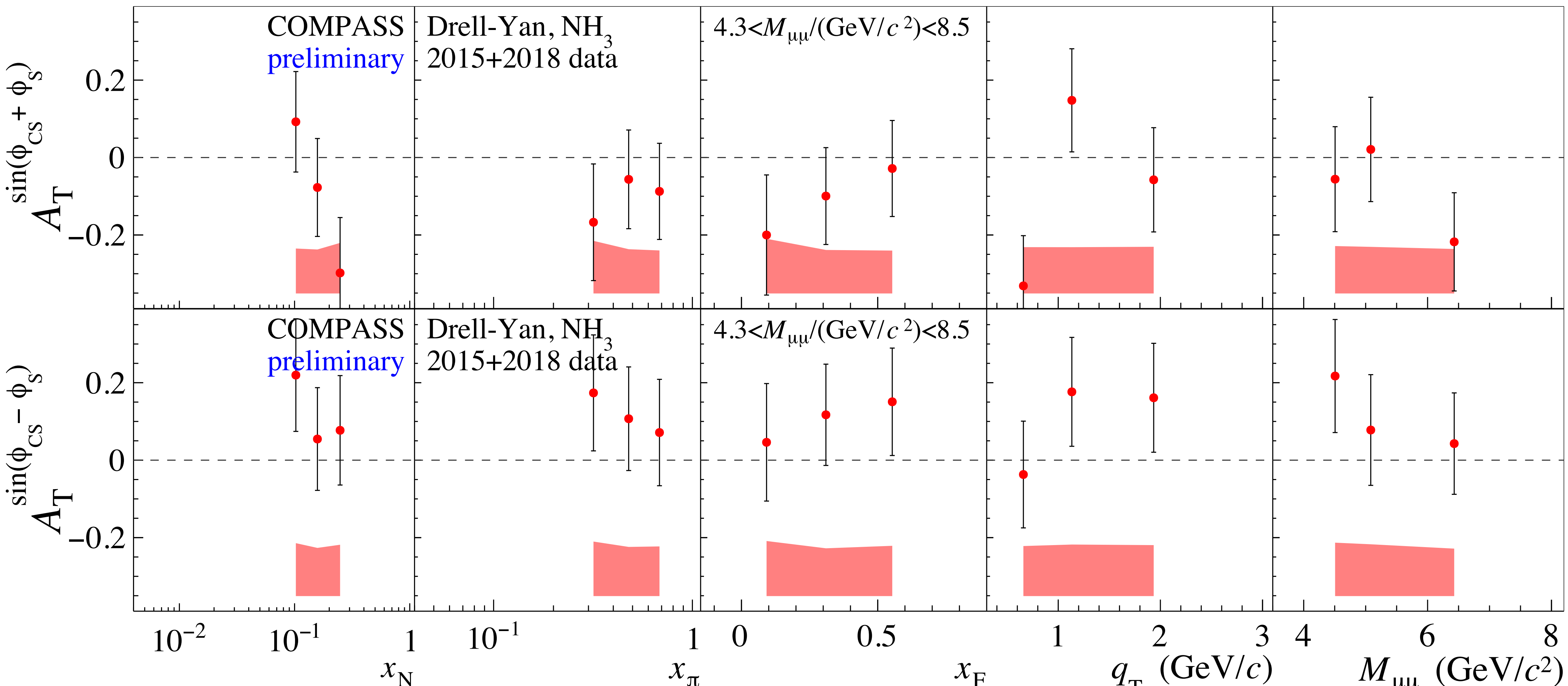




TSAs : HIGHER TWIST

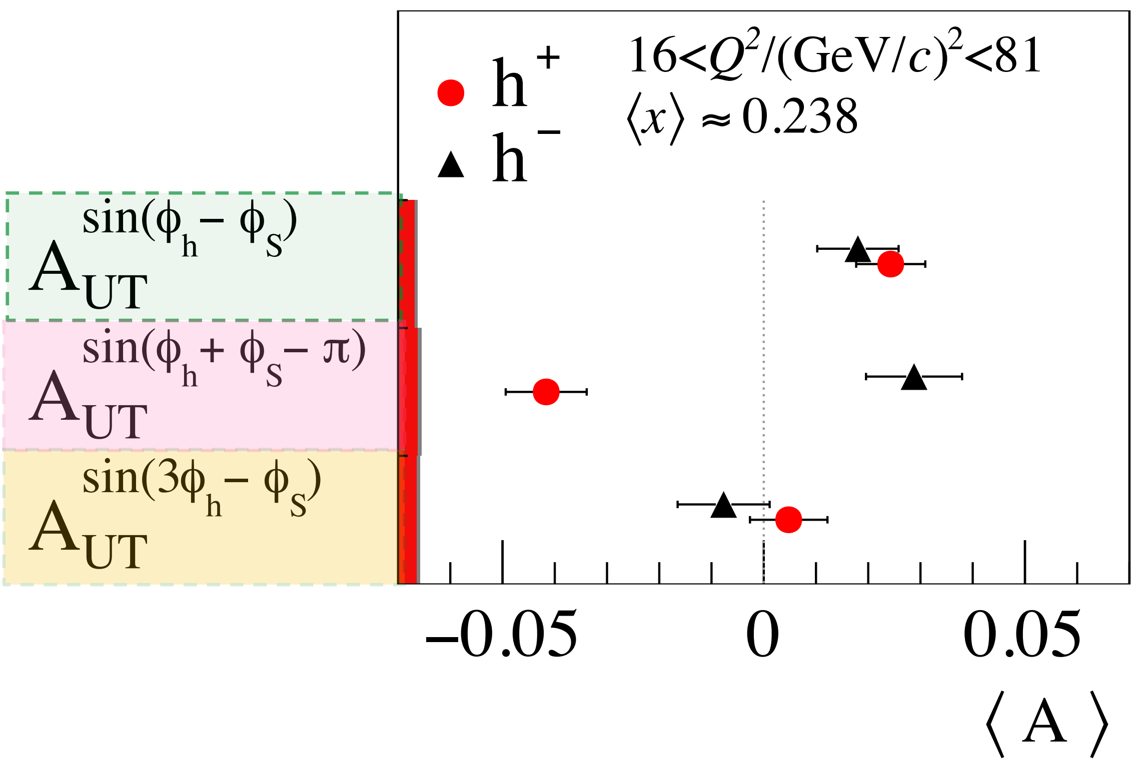
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \\ + S_T \left[\begin{array}{l}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

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

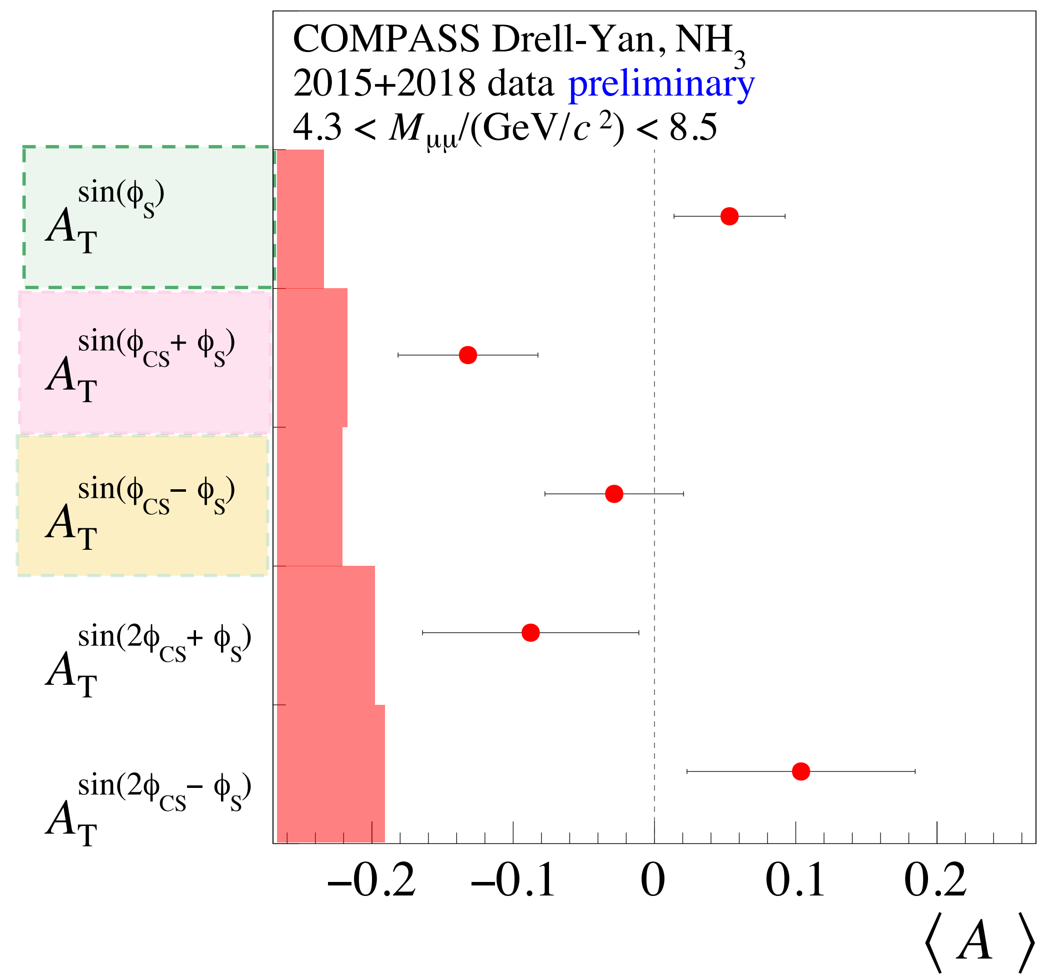


DY HM TSA RESULTS: 2015+2018 SUMMARY

COMPASS SIDIS Data,
PLB 770 (2017) 138



NEW RESULTS! FIRST SHOWN TODAY!



- **Full 2015+2018 combined Drell-Yan TSA data analysis is now completed!**
  - 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 compatible with zero
- COMPASS SIDIS and Drell-Yan TSAs measurements represent a unique experimental input to study the universality of TMD PDFs

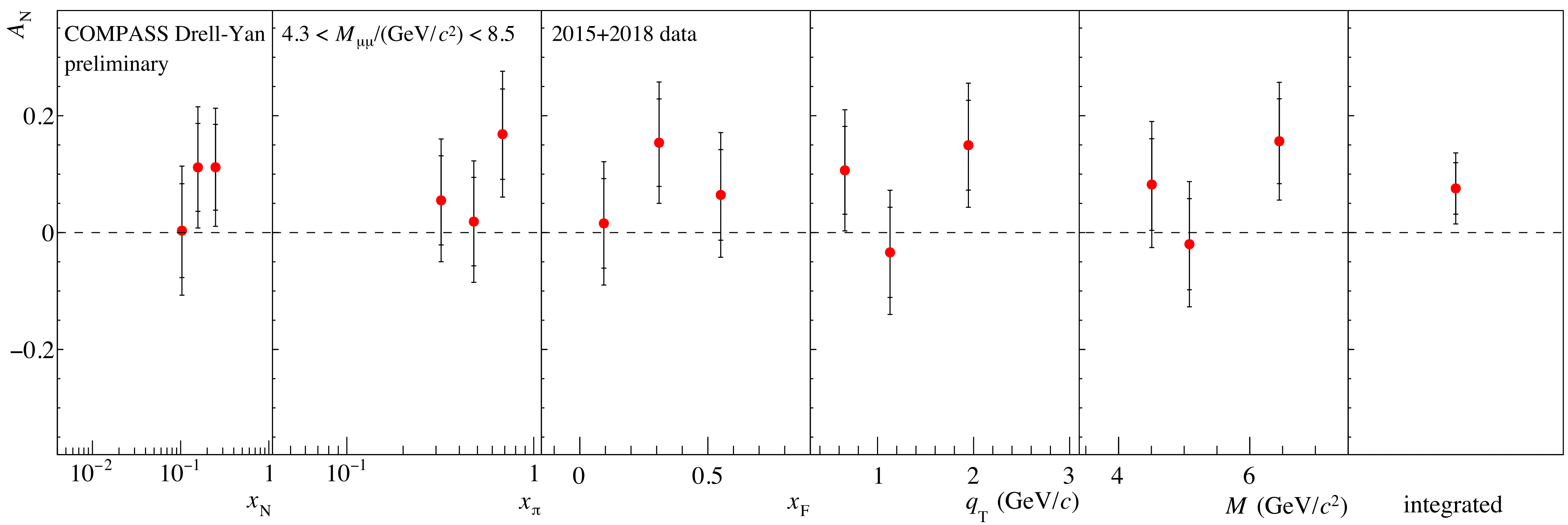
DY HM BONUS TRACK: A_N

- 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

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

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

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



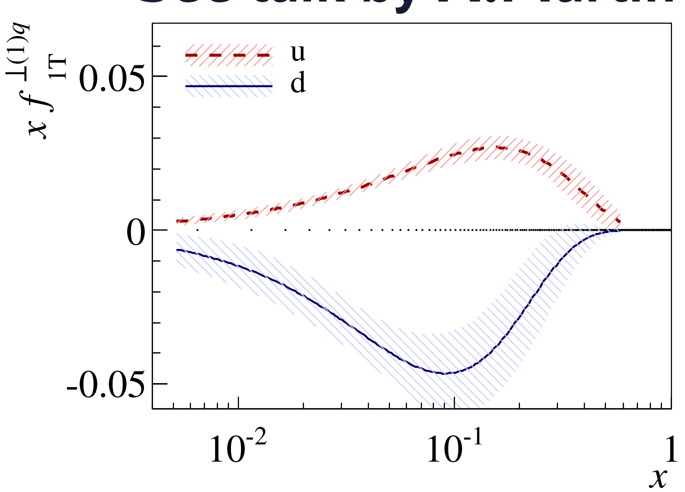
NEW RESULTS! FIRST SHOWN TODAY!

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	Drell-Yan
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 A.Martin



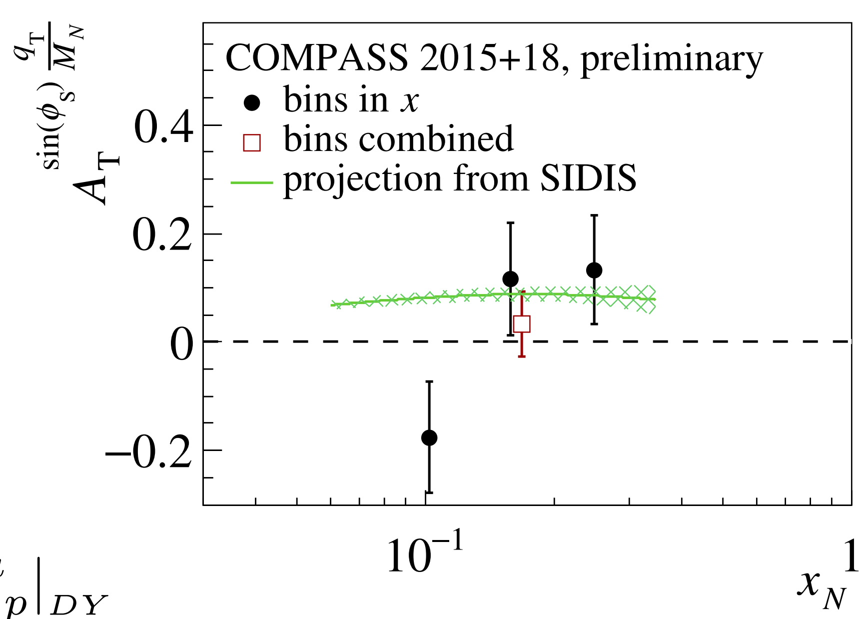
1st k_T^2 -moment of the Sivers function from SIDIS data at $Q^2 = Q^2_{SIDIS}(x)$

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

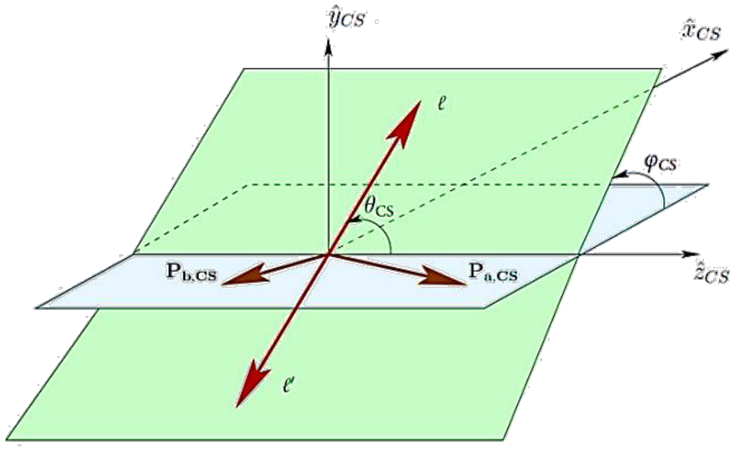
- General expression for the unpolarized part of the DY cross-section:

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

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



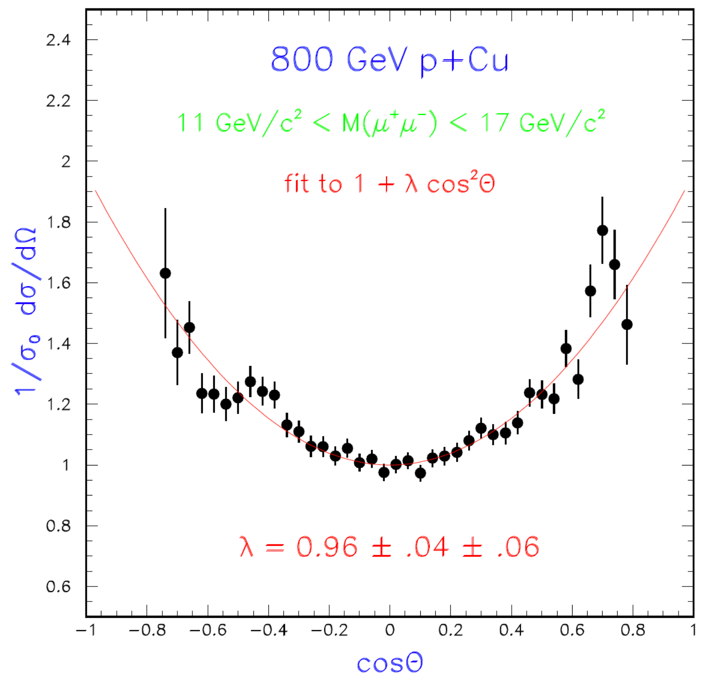
- Values of λ, μ and ν depends on the reference frame definition.
- At LO of Drell-Yan process, the virtual photon is produced purely by the electromagnetic $q+\bar{q}$ annihilation.

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

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

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

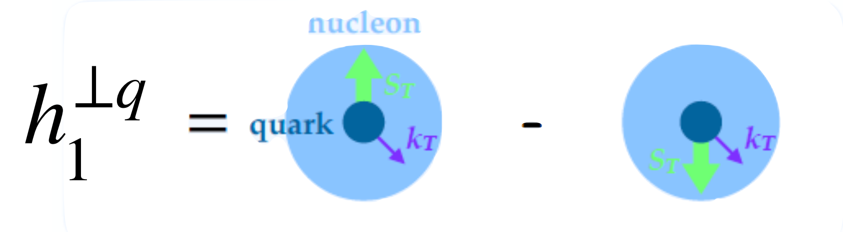
- Reflects the spin 1/2 nature of the quarks;
- Analogous of Callan-Gross relation in DIS;

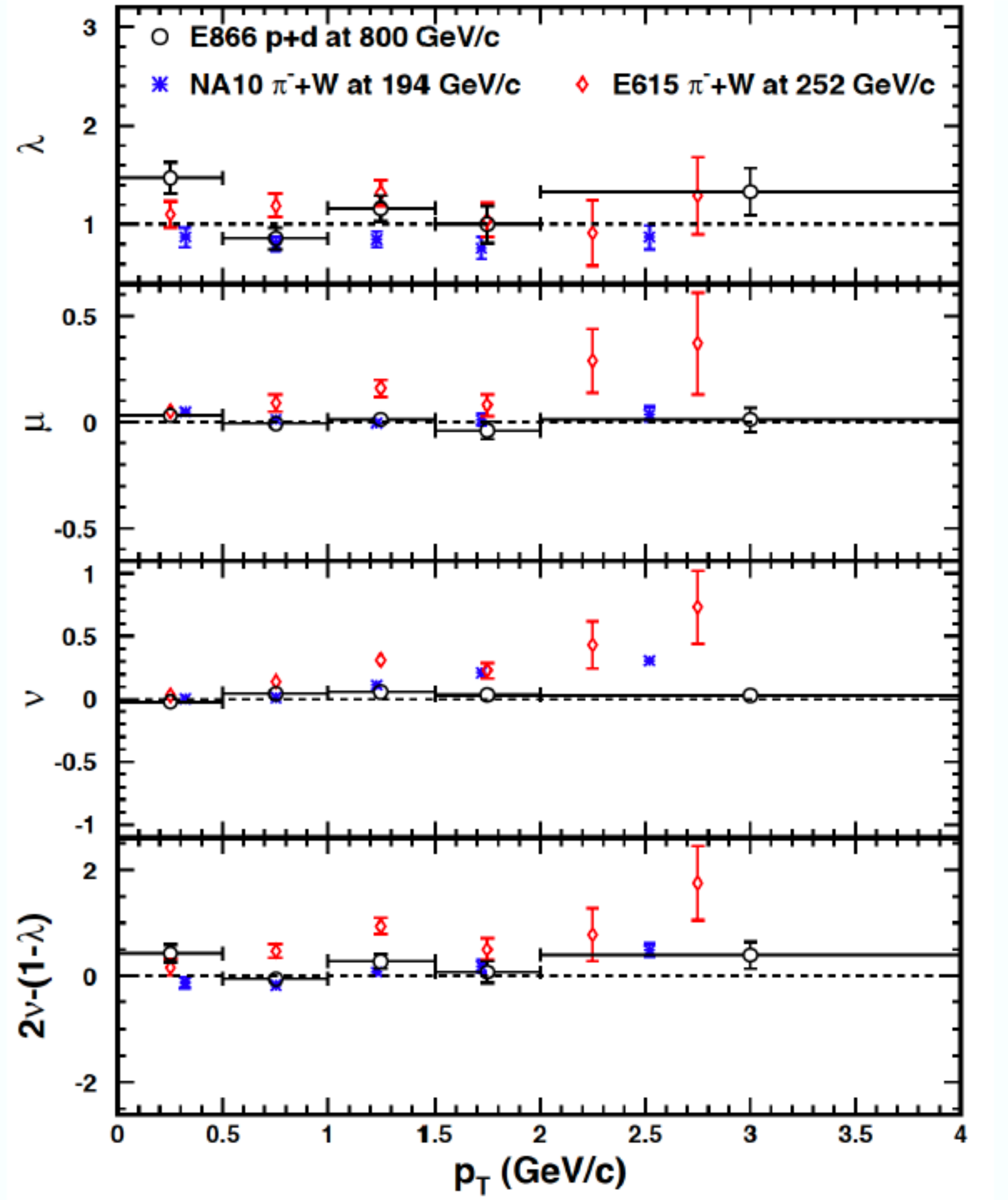


FNAL E772 Data (Ann. Rev. Nucl. Part. Sci. 49 (1999) 217-253)

UAs: NON-PERTURBATIVE EFFECT?

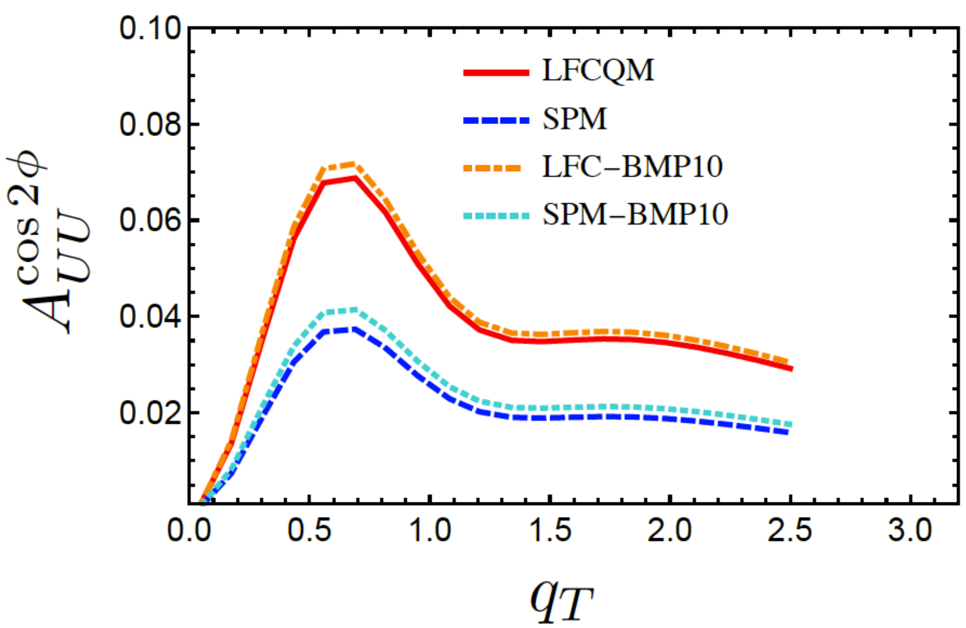
E615, π⁻ (252 GeV) + W, PRD 39, 92 (1989)
E866/NuSea, p (800 GeV) + d, Phys. Rev. Lett. 99, 082301
NA10, π⁻ (194 GeV) + W, Z.Phys.C 31, 513 (1986)





- 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;

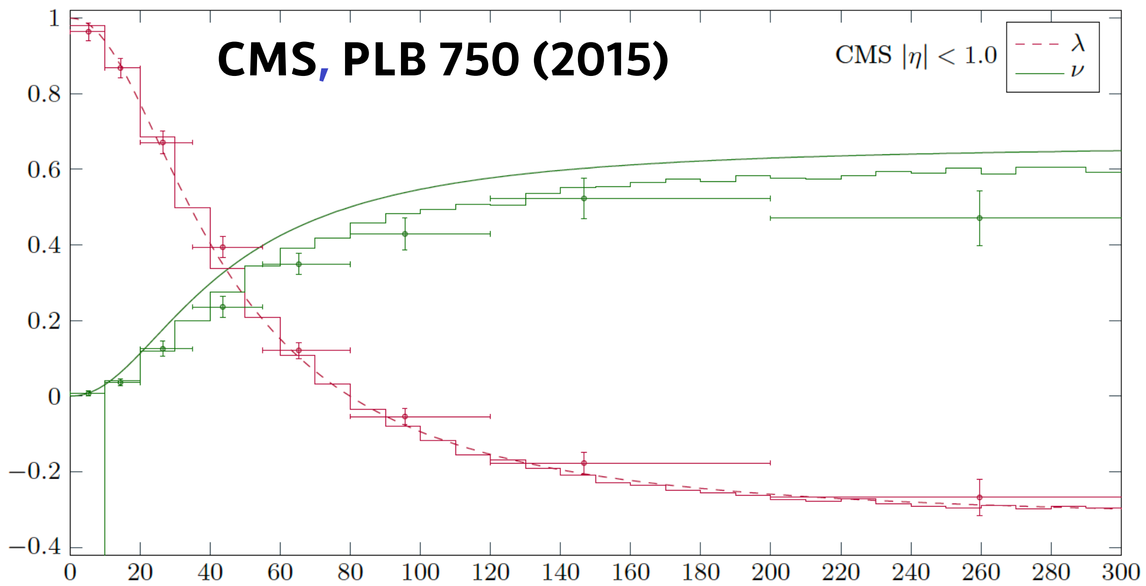
$$A_{UU}^{\cos 2\phi} = \frac{\nu}{2} \propto h_1^{\perp q}(p) \otimes h_1^{\perp \bar{q}}(\pi^-)$$

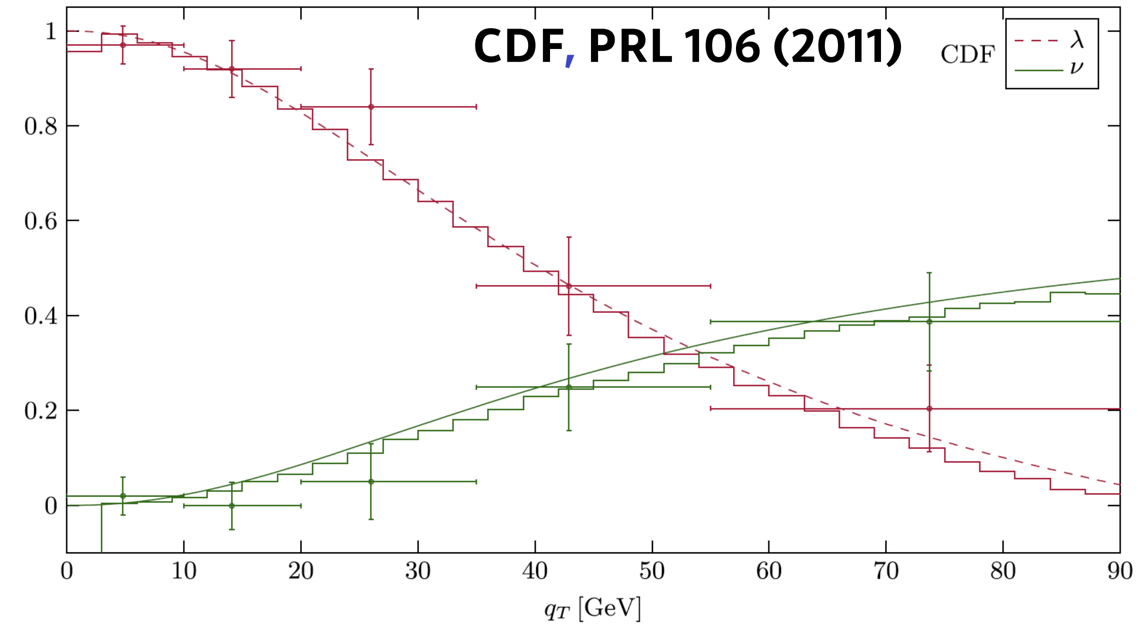


JHEP 02, 166 (2021)
$A_{UU}^{\cos 2\phi}$ prediction for COMPASS kinematics

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

UAs : NLO & NNLO EFFECTS?

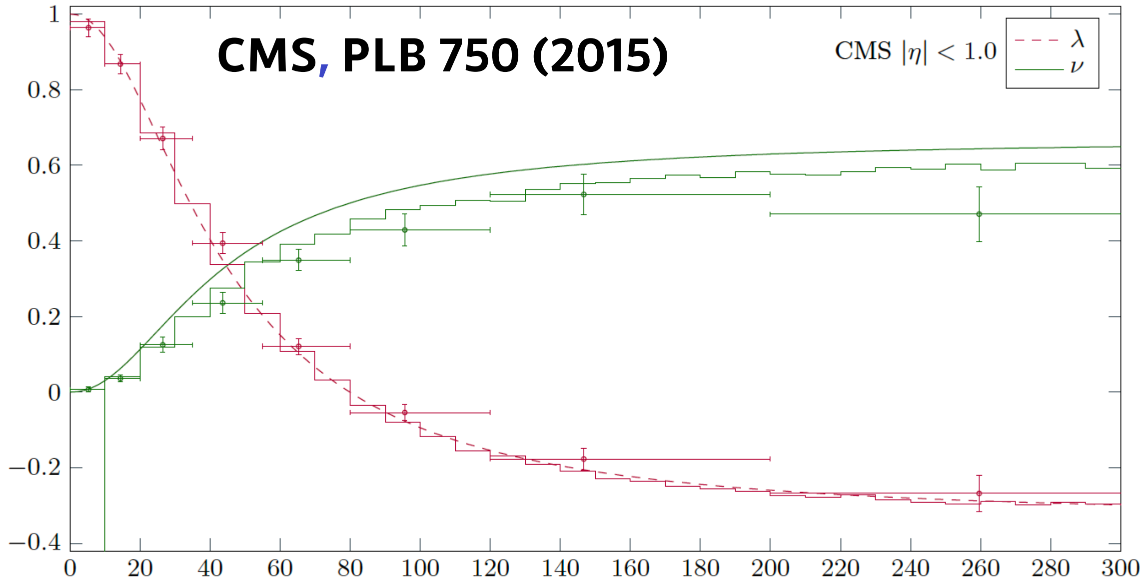


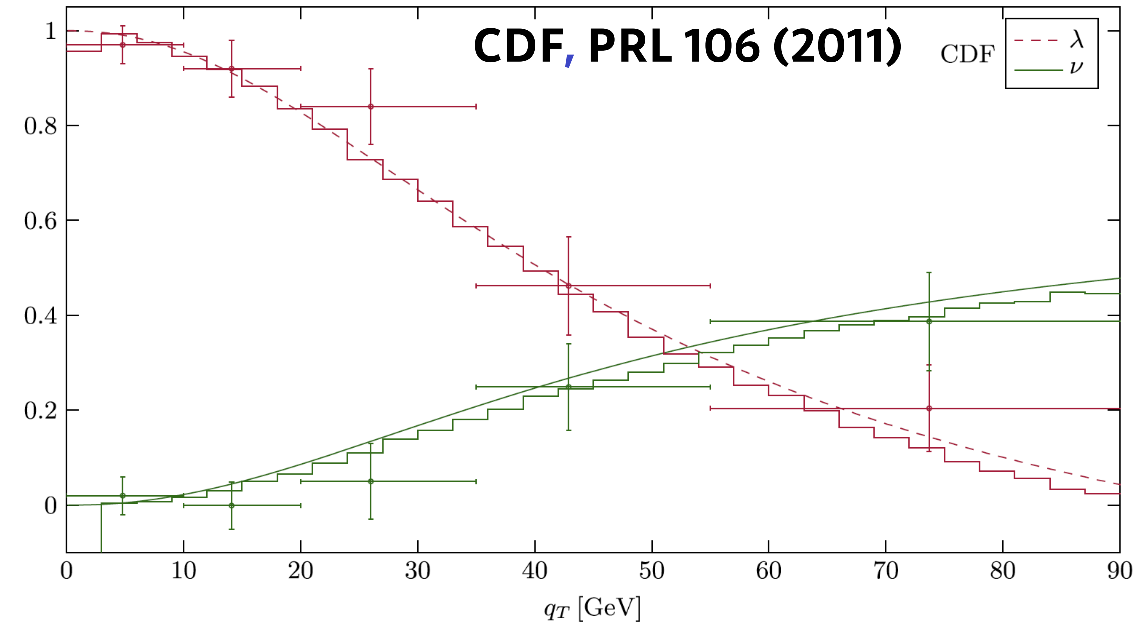


M.Lambertsen and W.Vogelsang
PRD 93 (2016)

- 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?

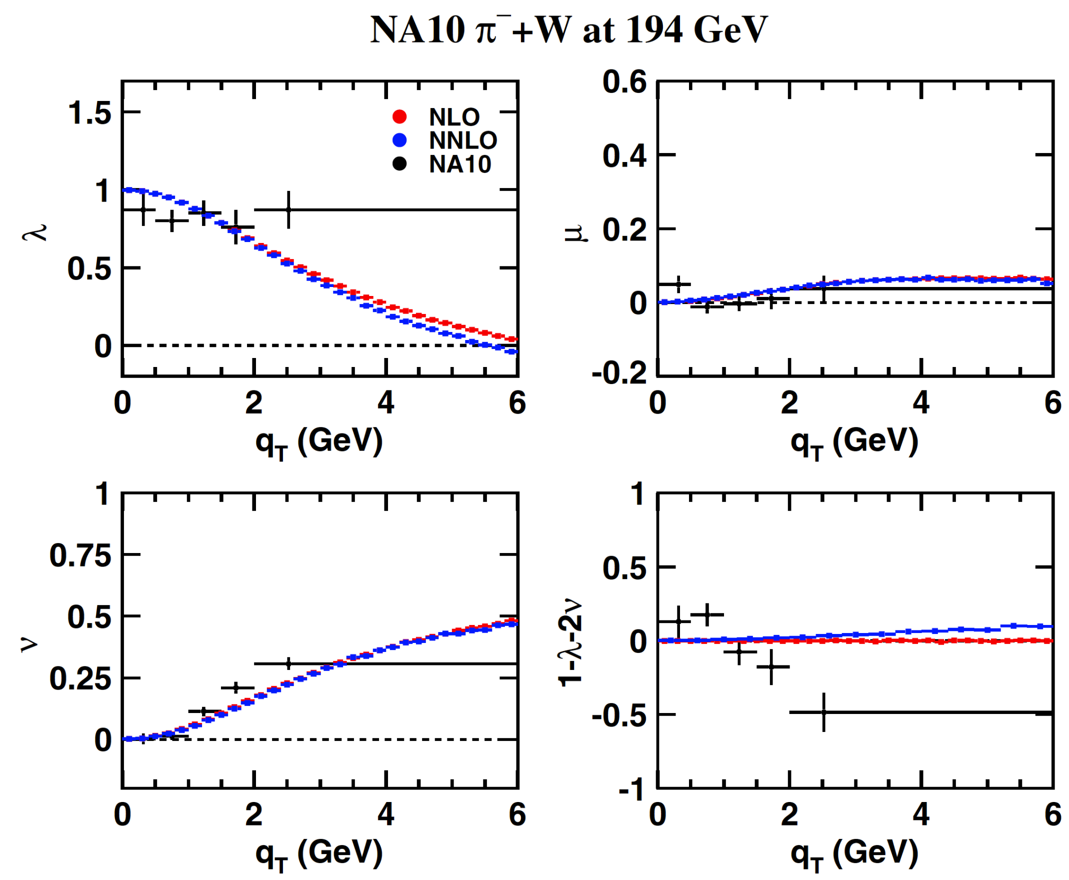
UAs : NLO & NNLO EFFECTS?





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

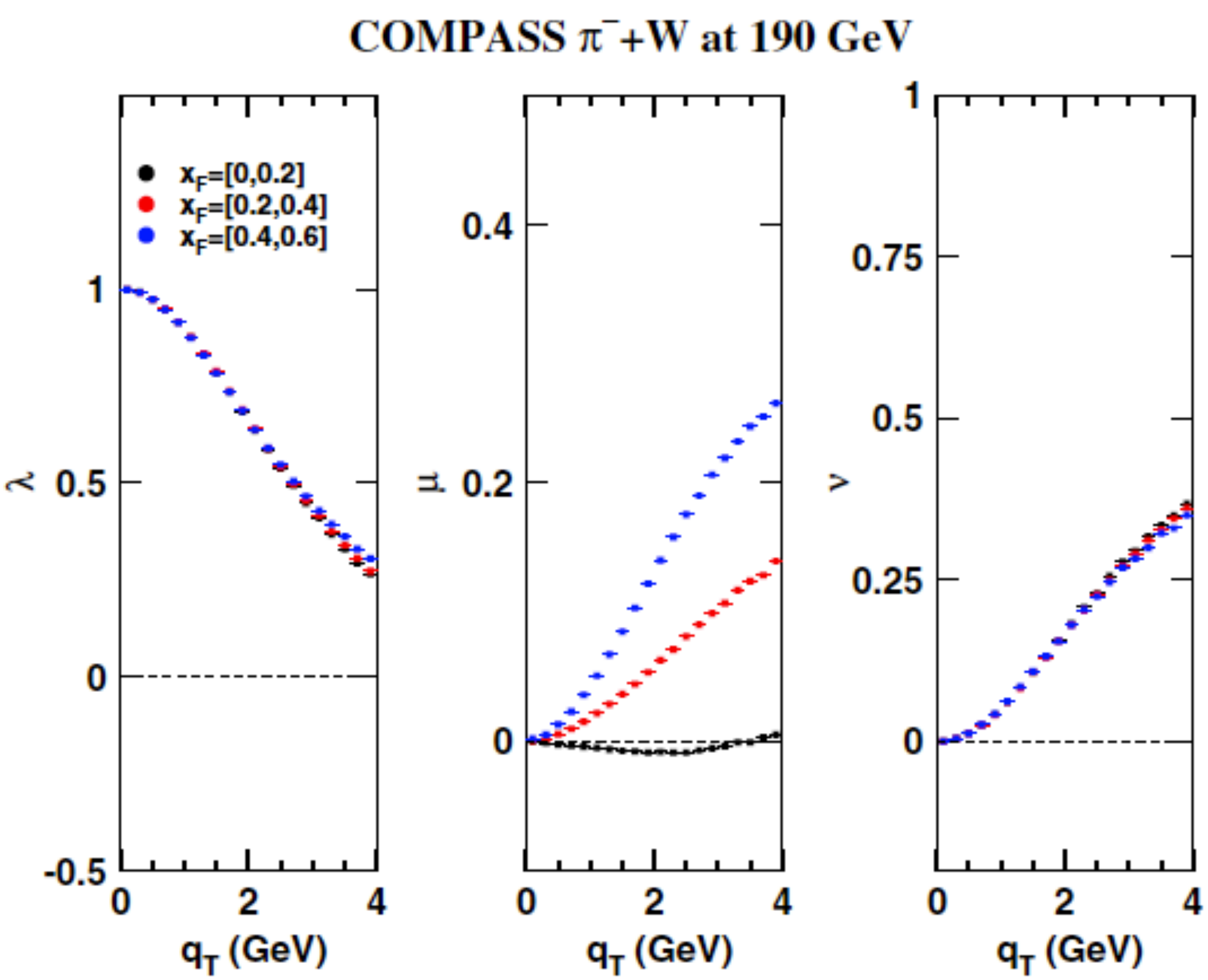
- Sizable ν asymmetry strongly dependent on q_T also measured by different experiments at colliders (CMS, CDF)
- Room for explanation in terms of NLO and NNLO effects
- Still room for non-perturbative Boer-Mulders effect?
- At lower energies - and much lower <q_T> - the picture is far to be clear - more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

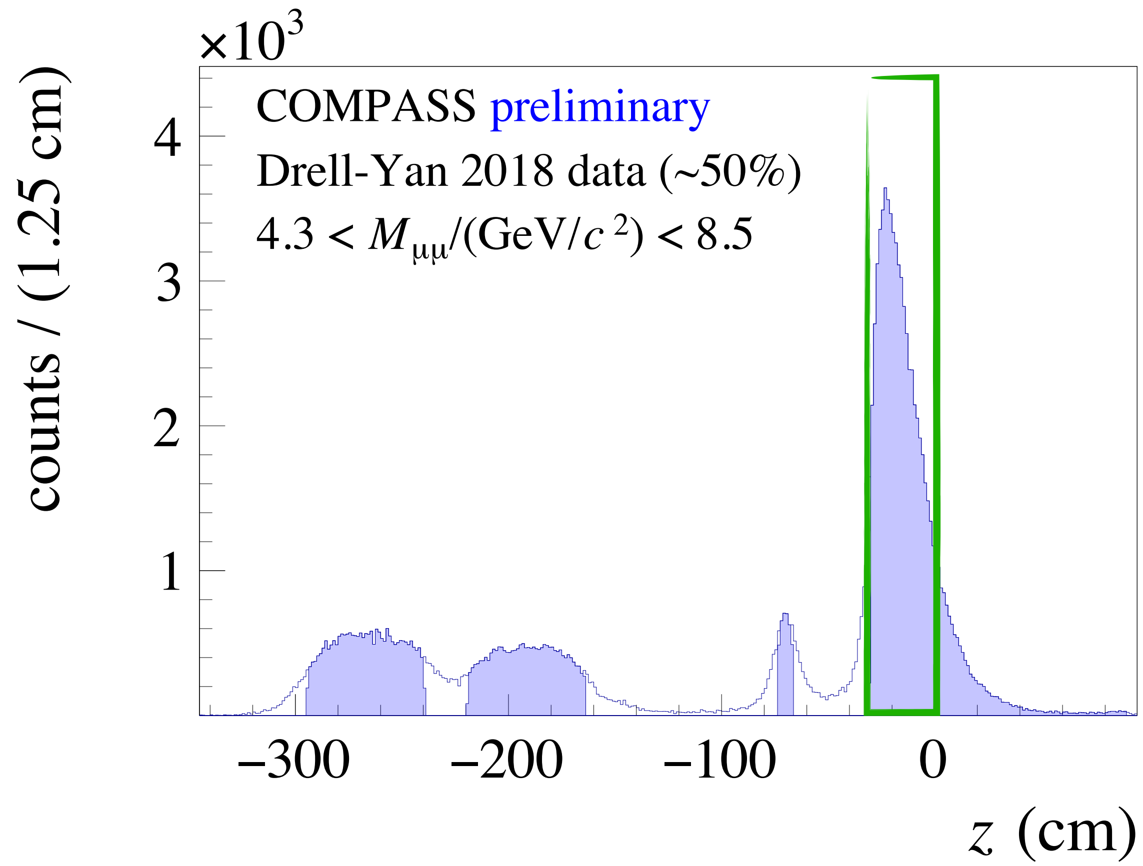


W.Chang, R. McClellan, J.C.Peng, O.Teryaev
PRD 99, 014032 (2019)

UAs : COMPASS INPUT

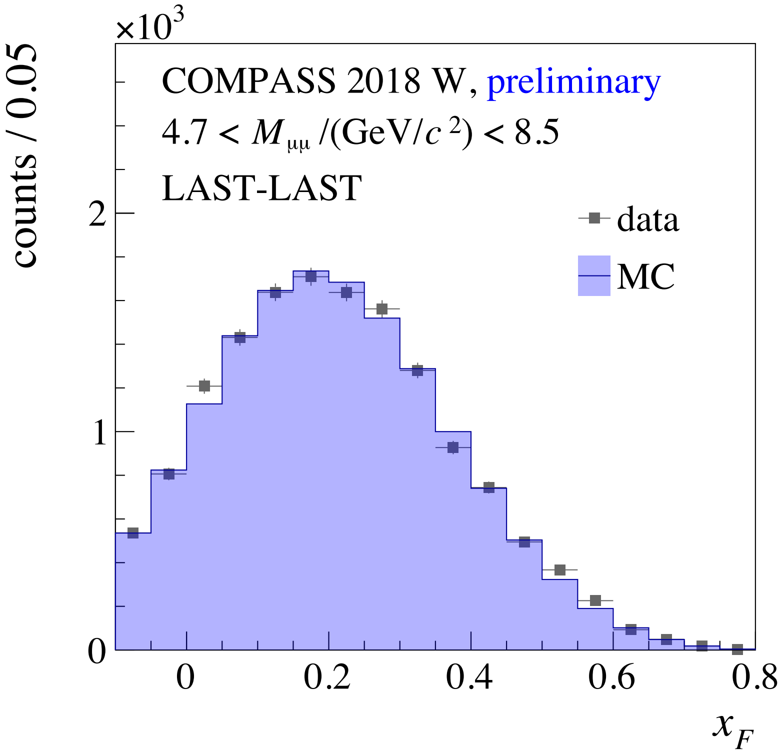
NLO pQCD prediction for COMPASS
W.Chang,R. McClellan, J.C.Peng, O.Teryaev
PRD 99, 014032 (2019)

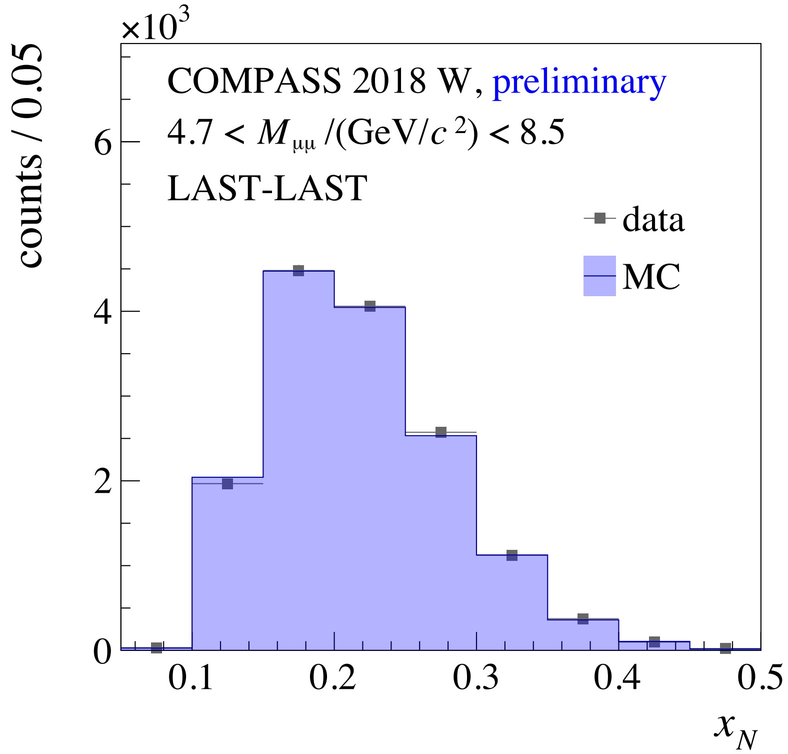


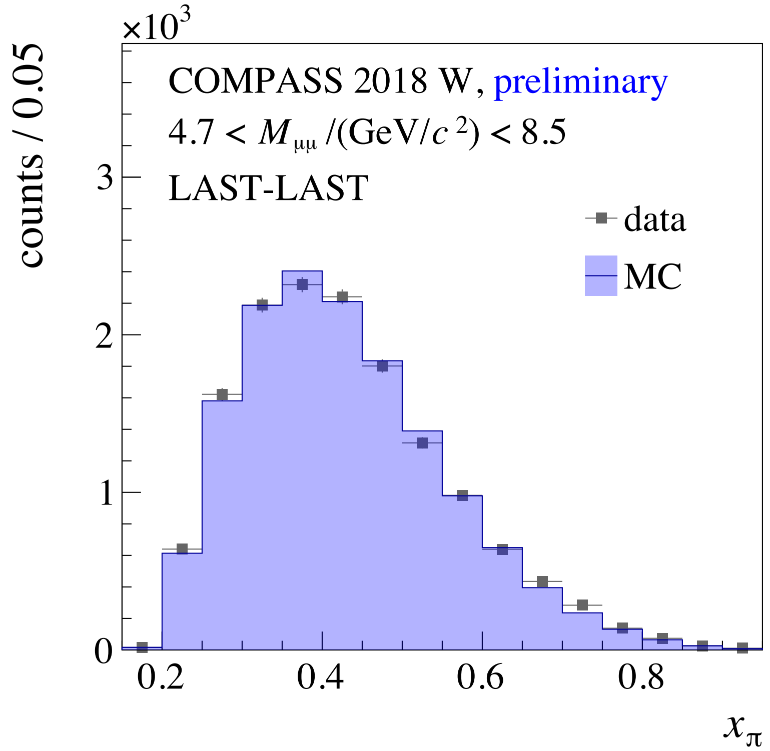


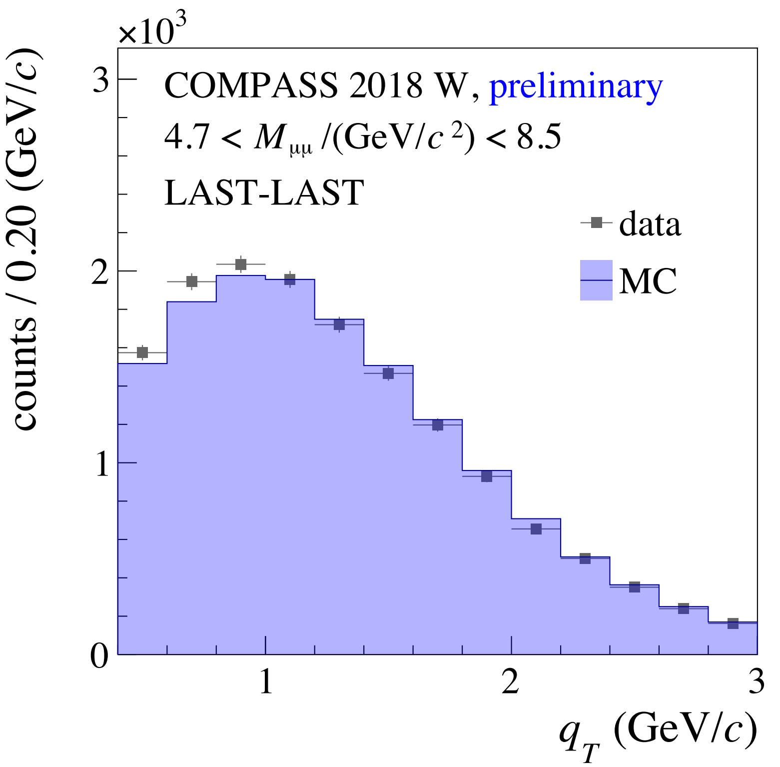
- **π⁻ (190 GeV) + NH_3:** analysis ongoing
- **π⁻ (190 GeV) + W: preliminary results**
  - 70% of 2018 data
  - "reduced" HM range due lower mass resolution for events in W, $4.7 < M_{\mu\mu}/(GeV/c^2) < 8.5$
  - First 20 cm of W to minimize effects of reinteraction of secondaries

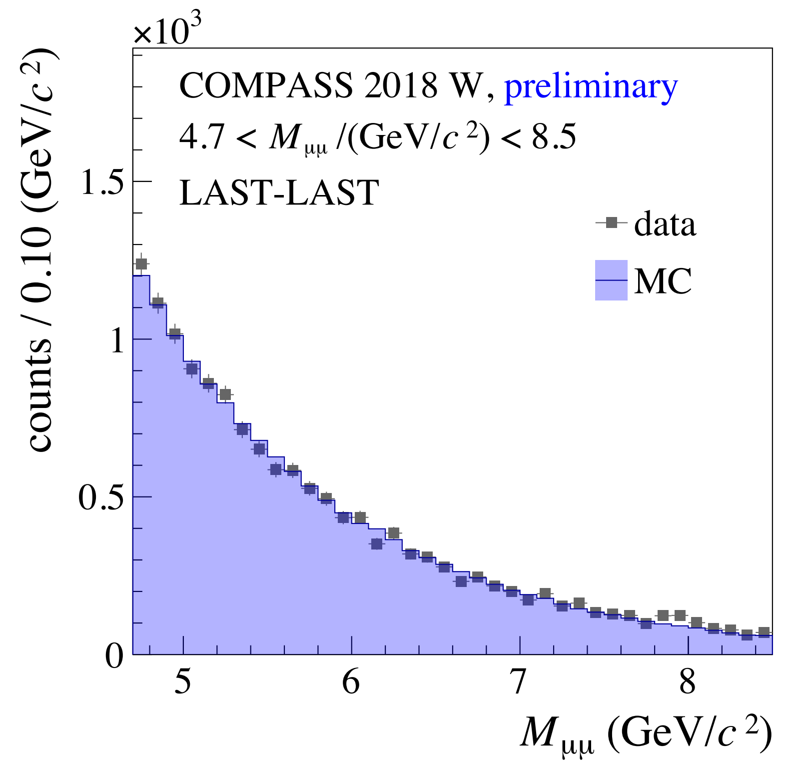
MONTECARLO FOR ACCEPTANCE CORRECTION







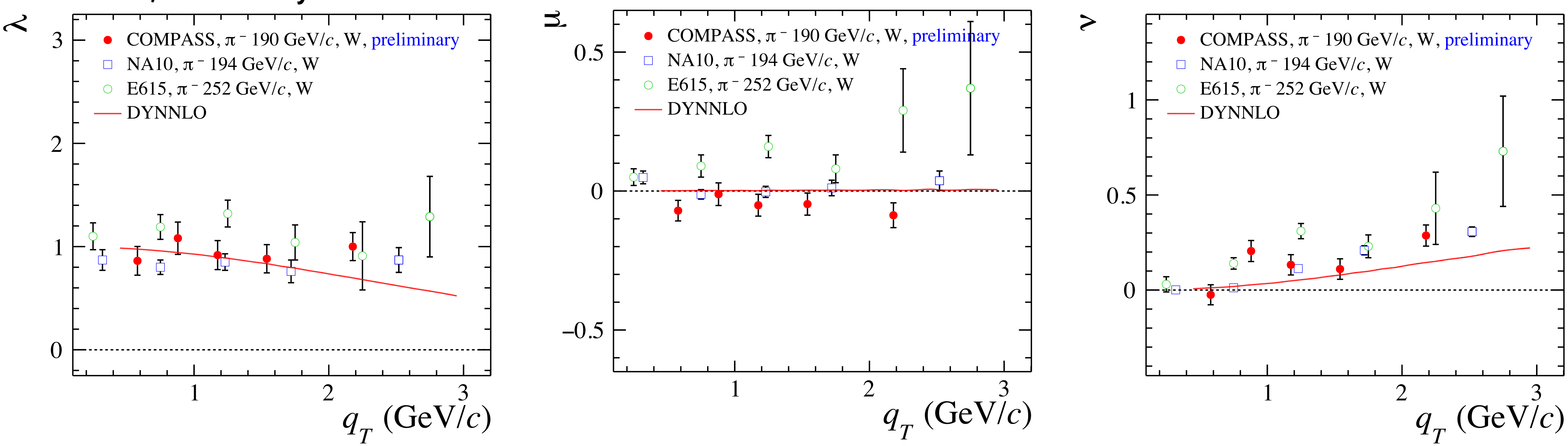




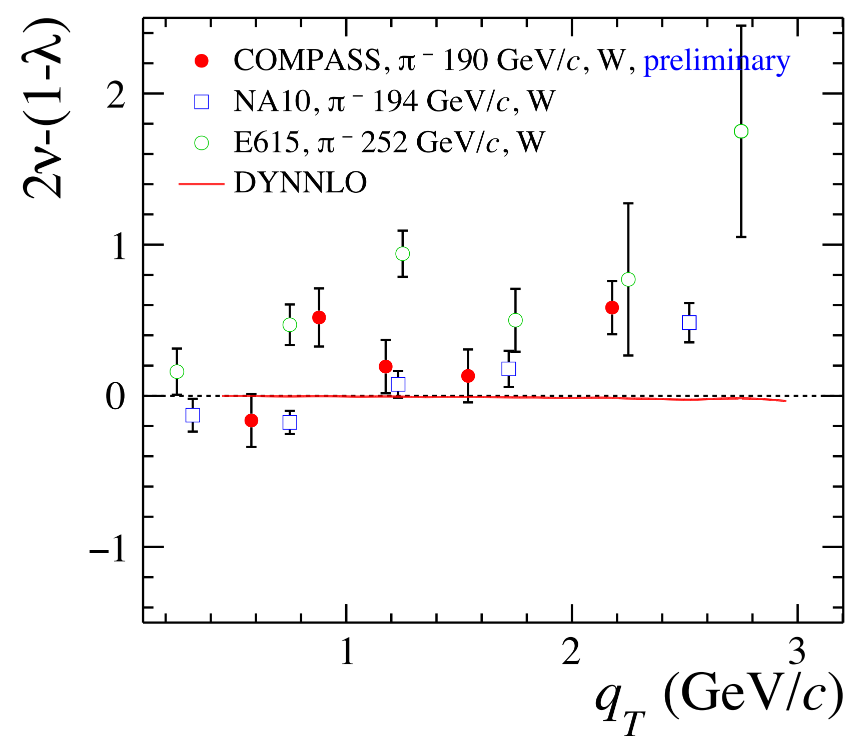
- Angular distribution of unpolarized Drell-Yan event corrected for acceptance making use of Monte Carlo (MC)
- Good MC/data agreement achieved for all the MC distributions related to the W target

π⁻ + 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



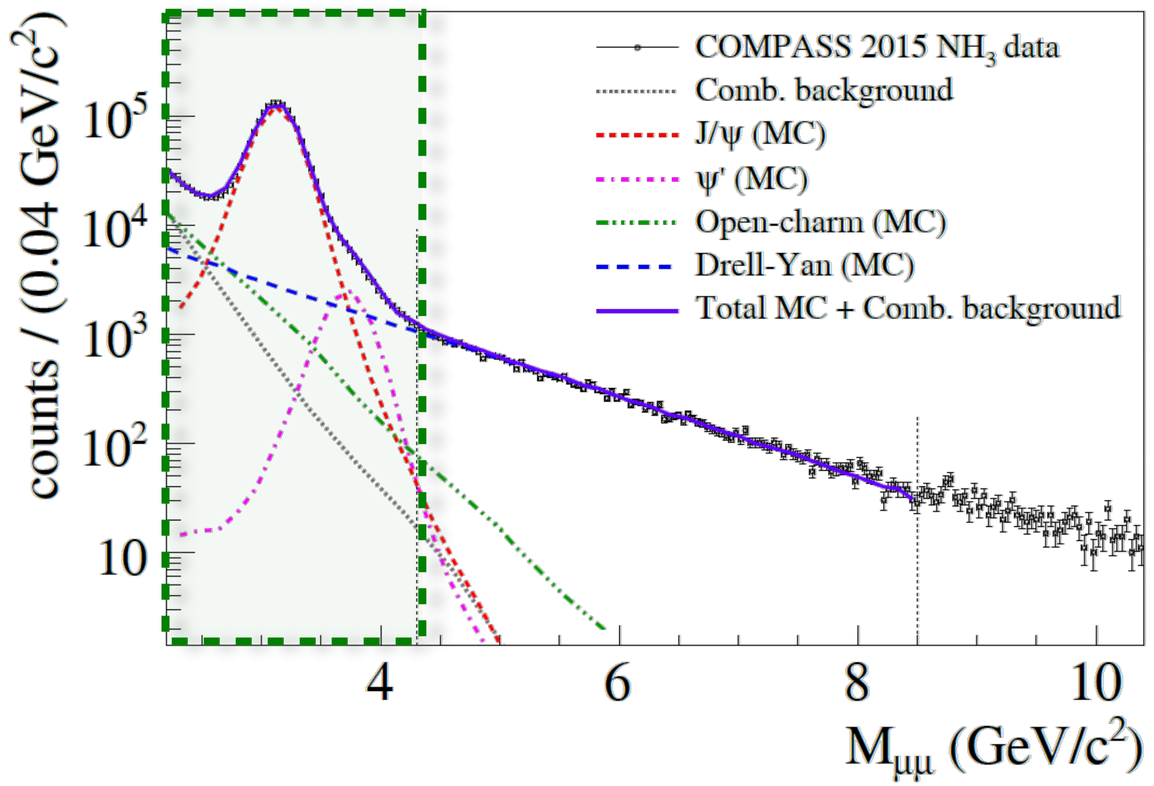
TSAs & A_N IN J/Ψ RANGE

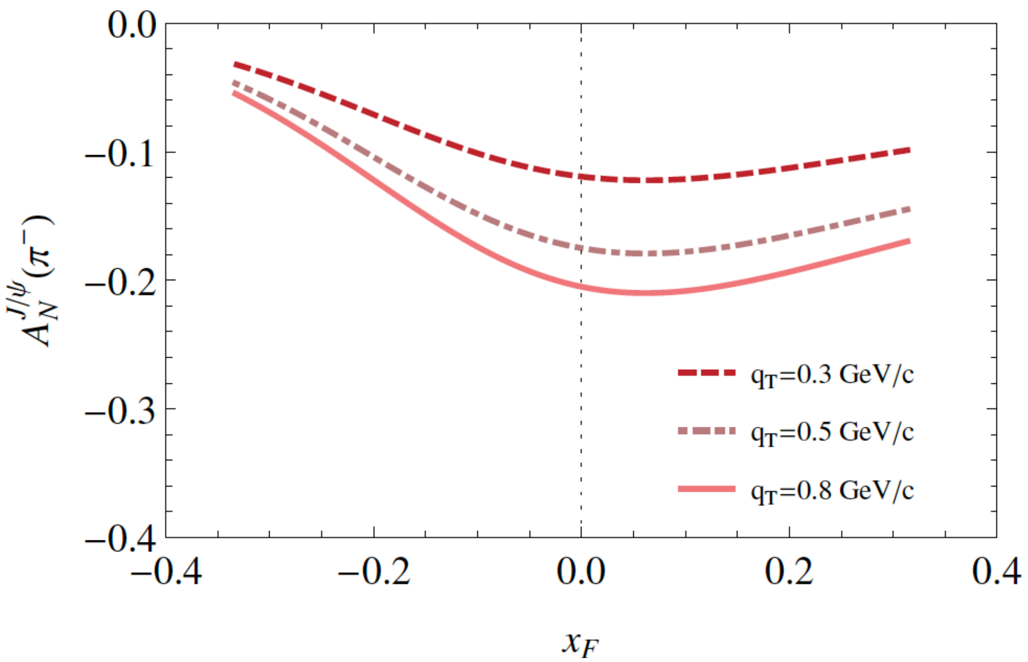
I. $1 < M_{\mu\mu}/(\text{GeV}/c^2) < 2$, "Low mass"
- Large background contamination

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

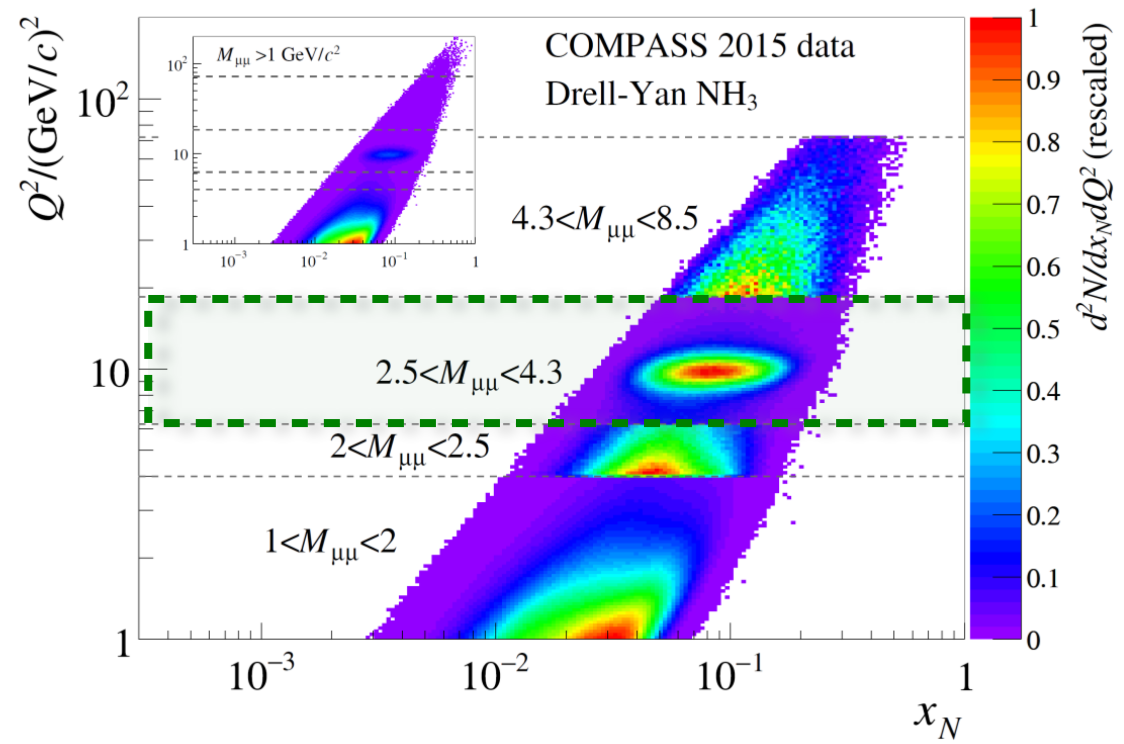
III. $2.5 < M_{\mu\mu}/(\text{GeV}/c^2) < 4.3$, "Charmonia mass"
- Strong J/ψ signal → Studies of J/ψ physics.
- Good signal/background.

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





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



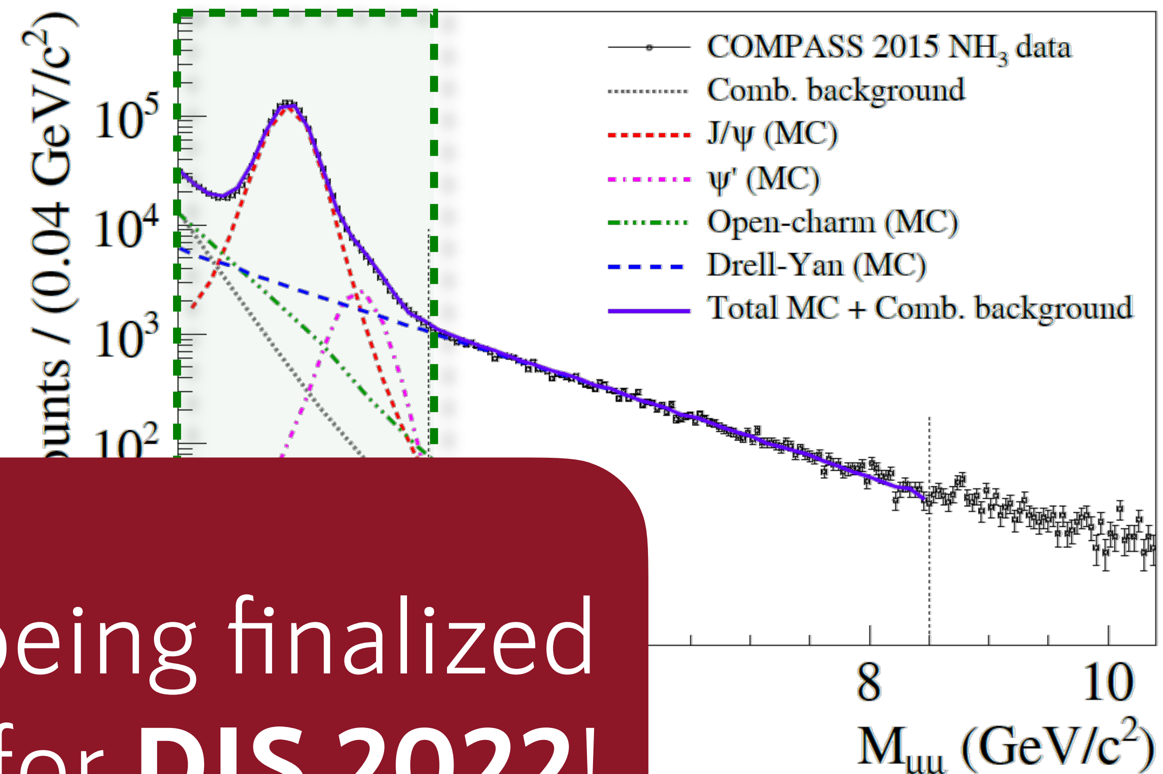
TSAs & A_N IN J/Ψ RANGE @ DIS!

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

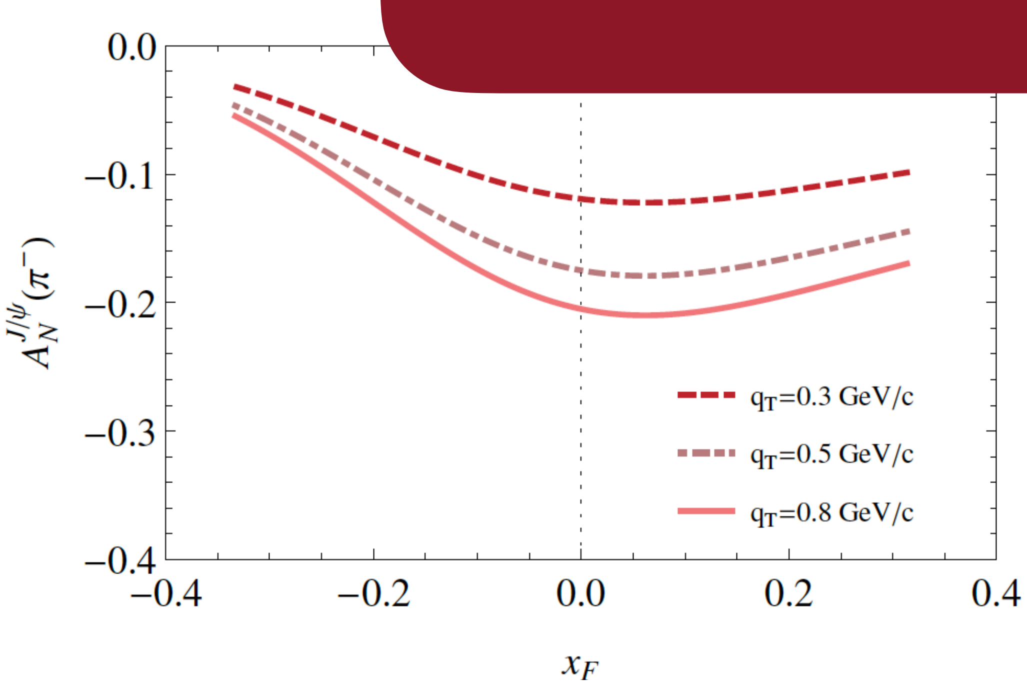
II. $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$, "Intermediate mass"
- High DY cross section.
- Still low DY-signal/background ratio.

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

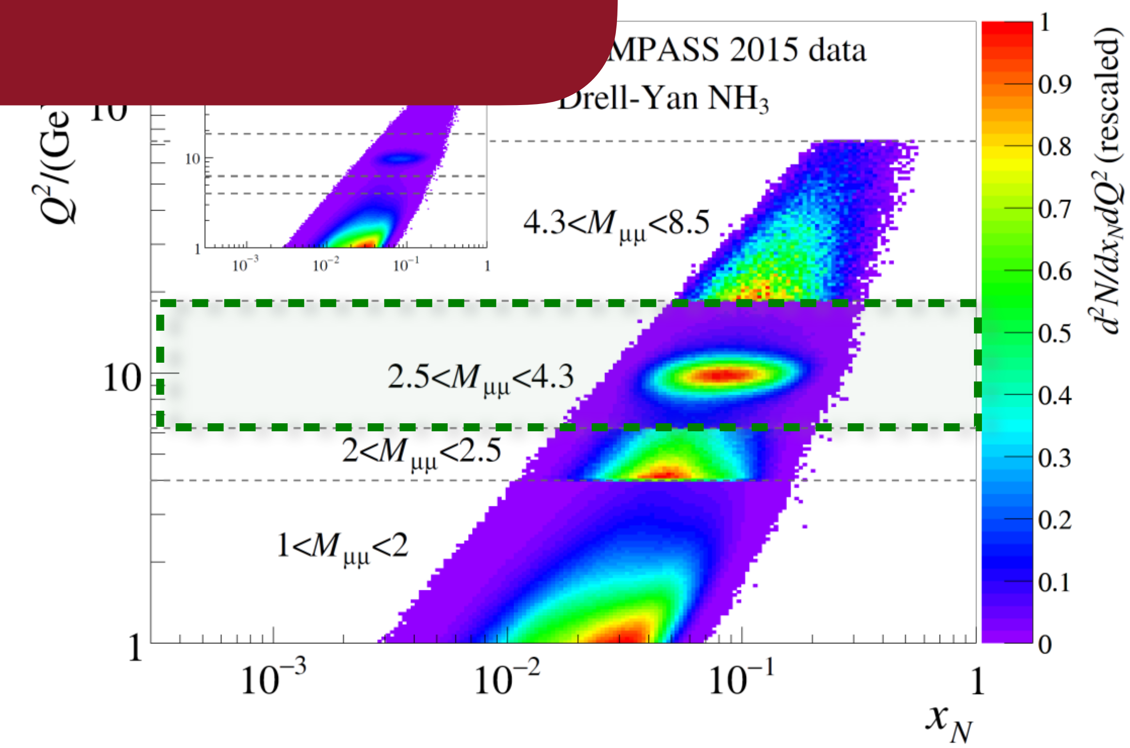
IV. 4.3 < $M_{\mu\mu}$/(GeV
- Beyond J/ψ and
- Valence quark re
- Low DY cross-se



Results currently being finalized
Release expected for **DIS 2022**!

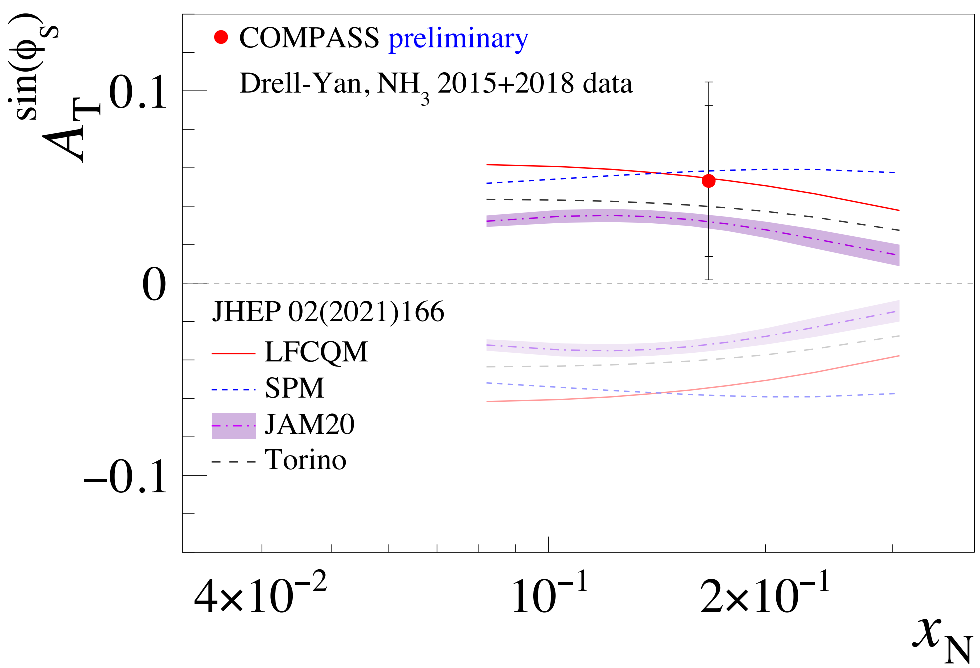


Anselmino et al., Phys.Lett. B770 (2017) 302-306



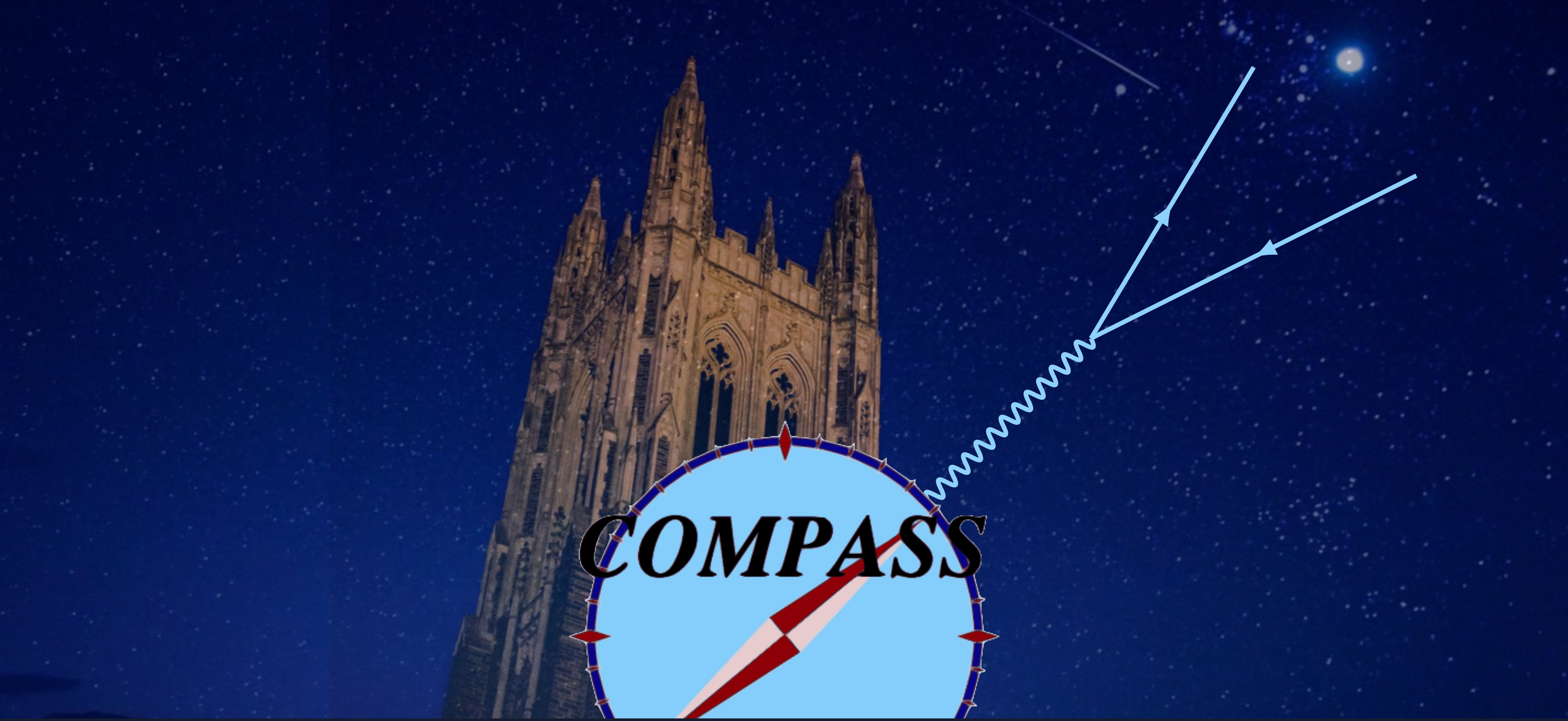
SUMMARY

- COMPASS successfully collected polarized Drell-Yan data in 2015 and 2018
- **Full 2015+2018 combined Drell-Yan TSA data analysis is now completed!**
  FIRST SHOWN TODAY!
  - 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

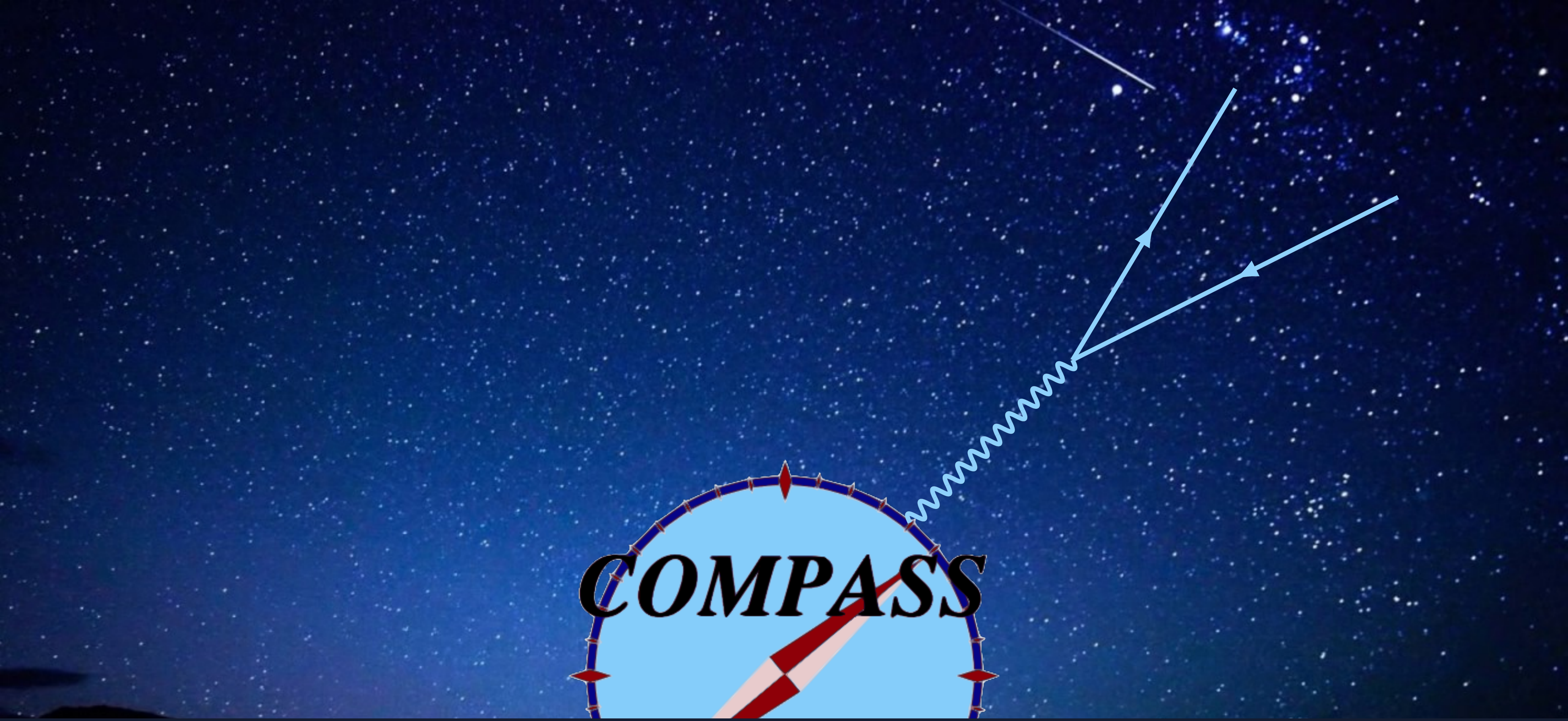


- **COMPASS** SIDIS and Drell-Yan TSAs **measurements** represent a **unique experimental input** to study the universality of TMD PDFs

- COMPASS is investigating the TMD PDFs also using weighted asymmetries in SIDIS and Drell-Yan and the A_N in Drell-Yan
- **TSAs and A_N in J/ψ region will be presented at DIS 2022**
- COMPASS is also extracting the unpolarized asymmetries of the Drell-Yan cross section. First results from the analysis of 2018 W data already available, and more to come in the future!



THANKS FOR YOUR ATTENTION!



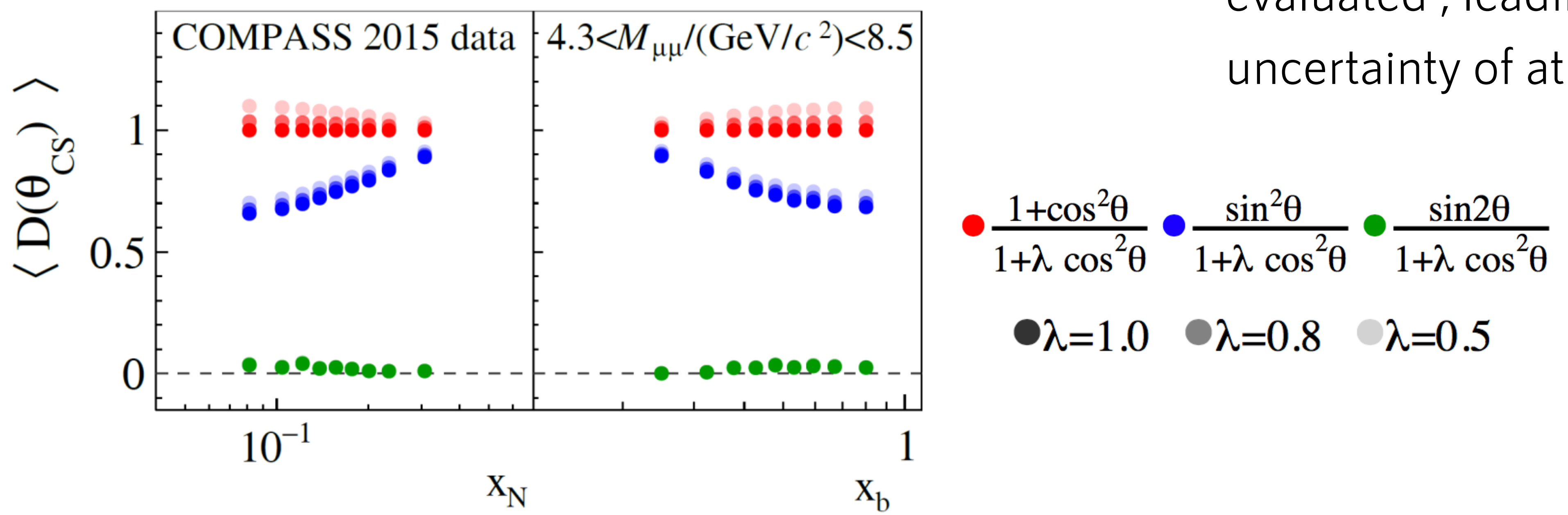
BACKUP SLIDES

TSAs EXTRACTION

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

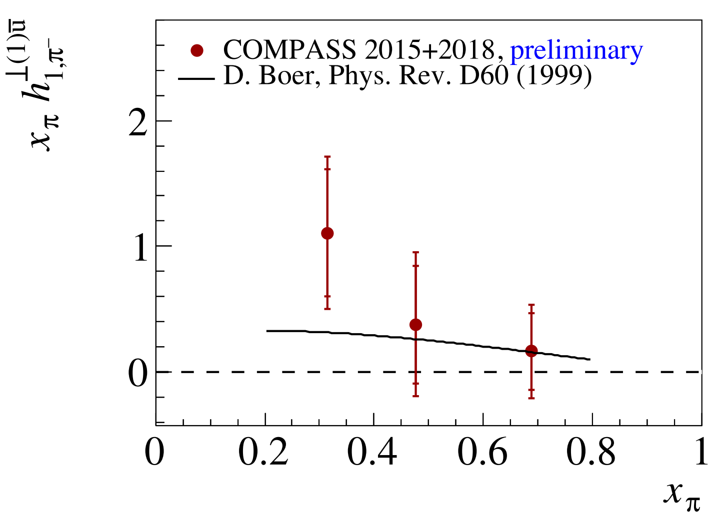
$$D_{[f(\theta_{CS})]} = \frac{f(\theta_{CS})}{1 + A_U^1 \cos^2\theta_{CS}}$$

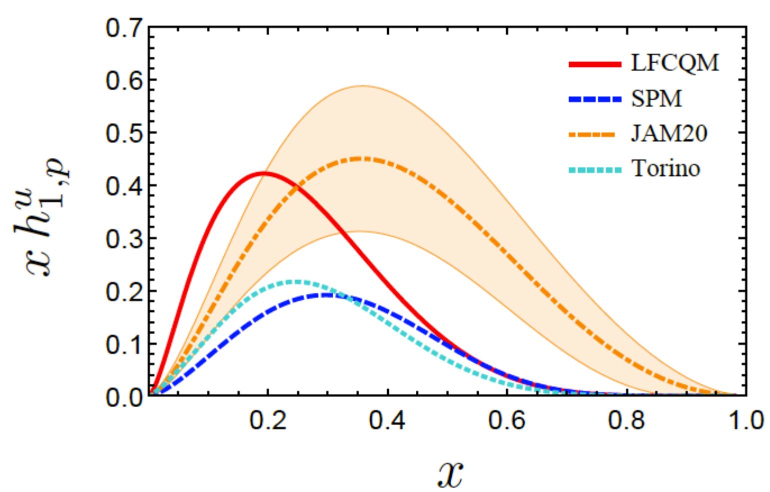
- All five DY TSAs are extracted simultaneously using an extended Unbinned Maximum Likelihood estimator;
- Depolarization factors are evaluated under assumption $A_U^1 = 1$;
- Possible scenarios with $A_U^1 \neq 1$ were evaluated , leading to a normalization uncertainty of at most 5 %;



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**

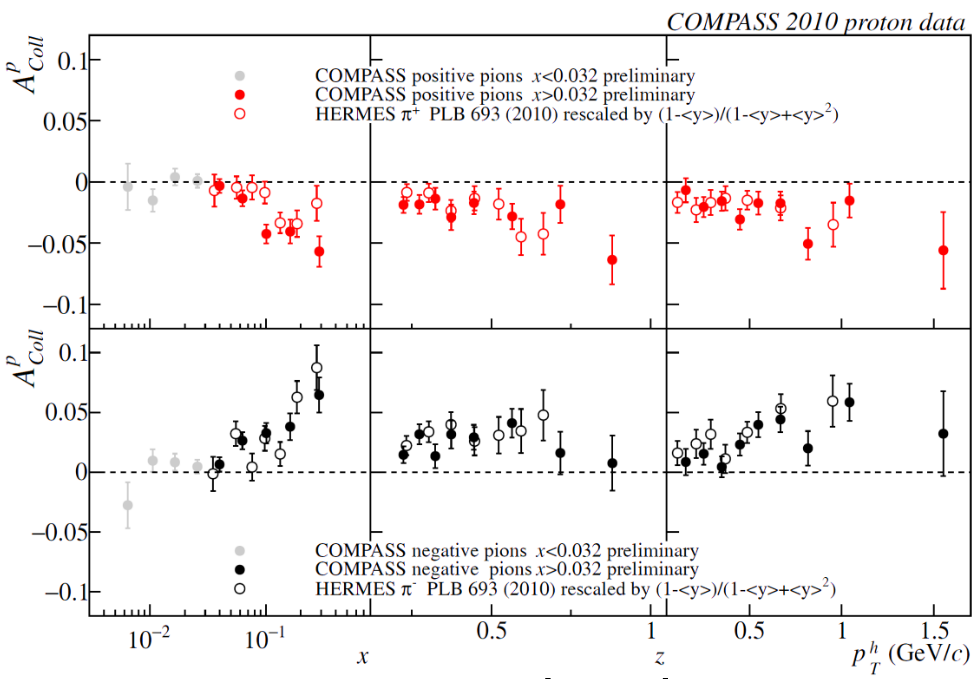




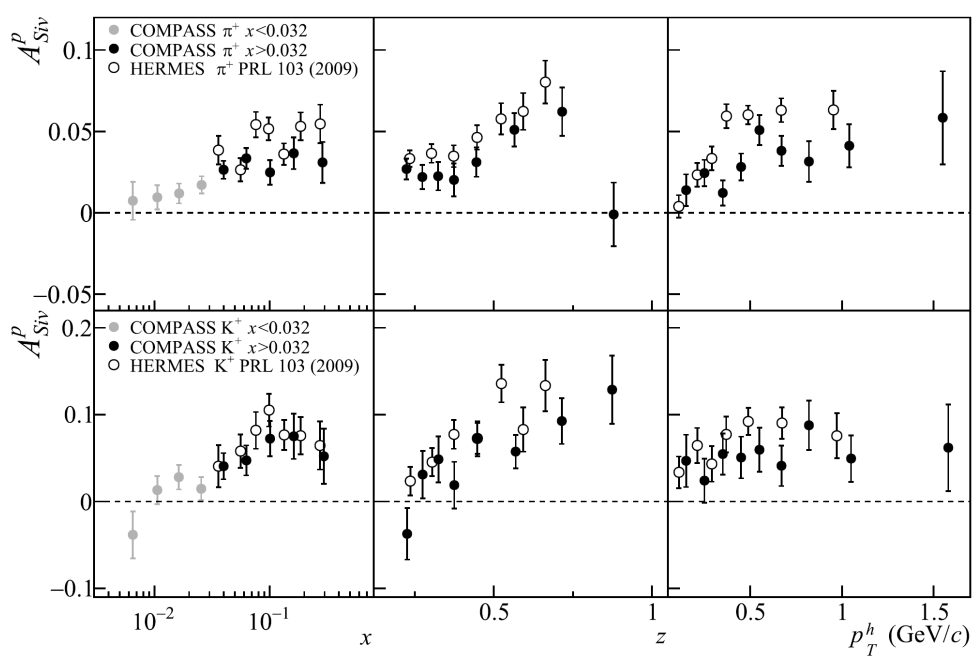
$$A_{UT}^{\sin(2\phi-\phi_S)} \propto -\, h_{1,\pi^-}^{\perp(1)\bar{u}}(x_\pi) h_{1,p}^{u}(x_p)$$

COMPASS: FROM SIDIS TO DY

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

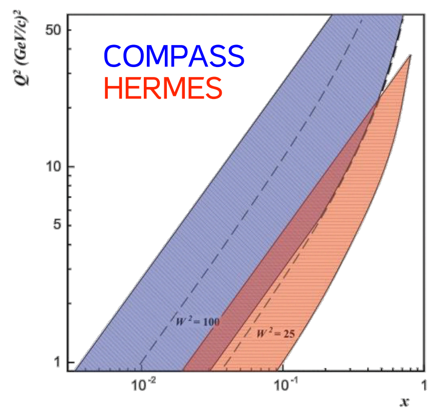


PLB 744 (2015) 250



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

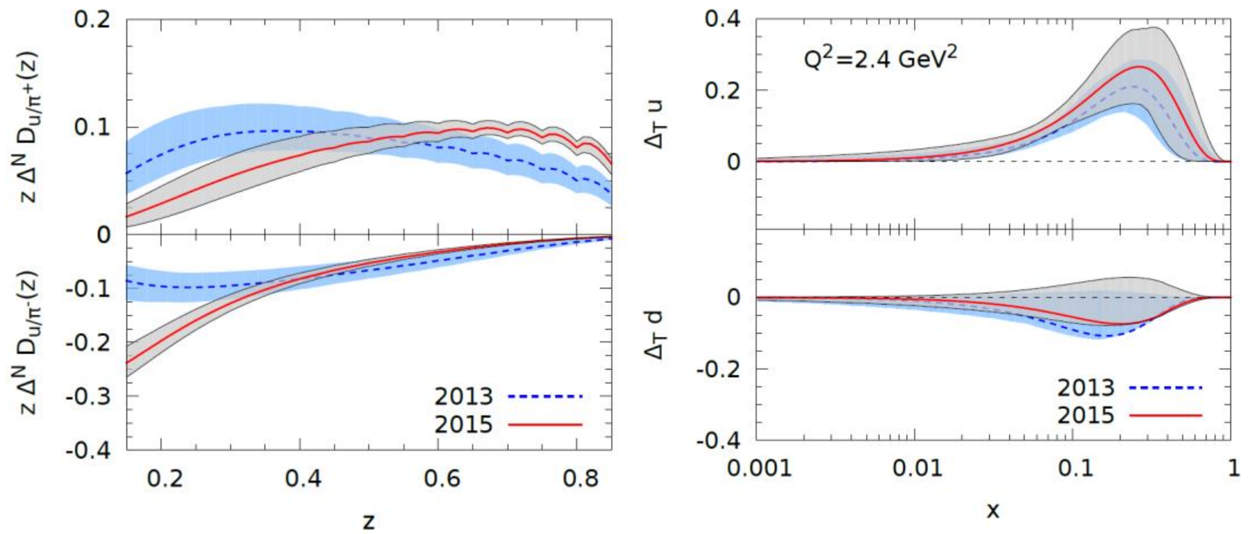
- Compatible results COMPASS/ HERMES for Collins effect
- No Q^2 evolution effects?

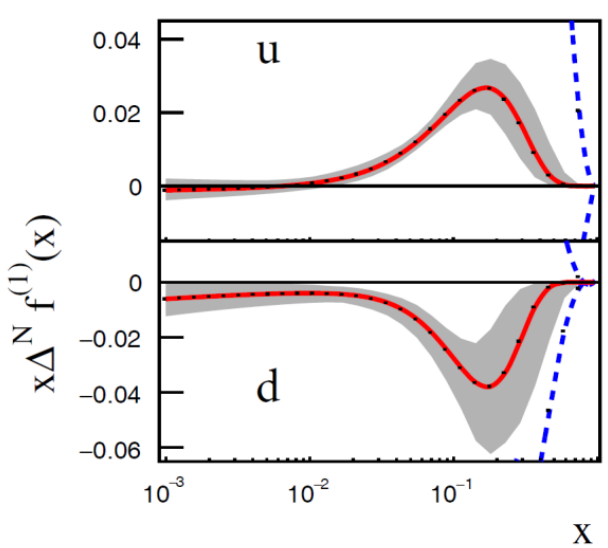


- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
- Q^2 evolution effects?

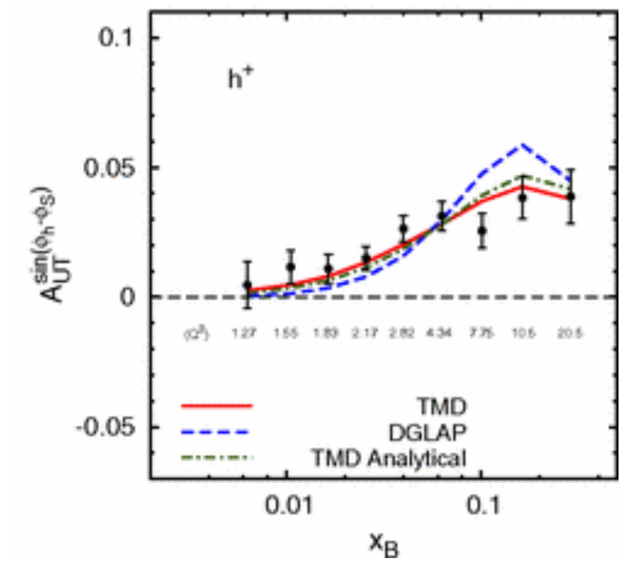
Anselmino et al., Phys.Rev. D92 (2015) 114023

Global fit of HERMES - COMPASS - BELLE data





Anselmino et al., JHEP 1704 (2017)046

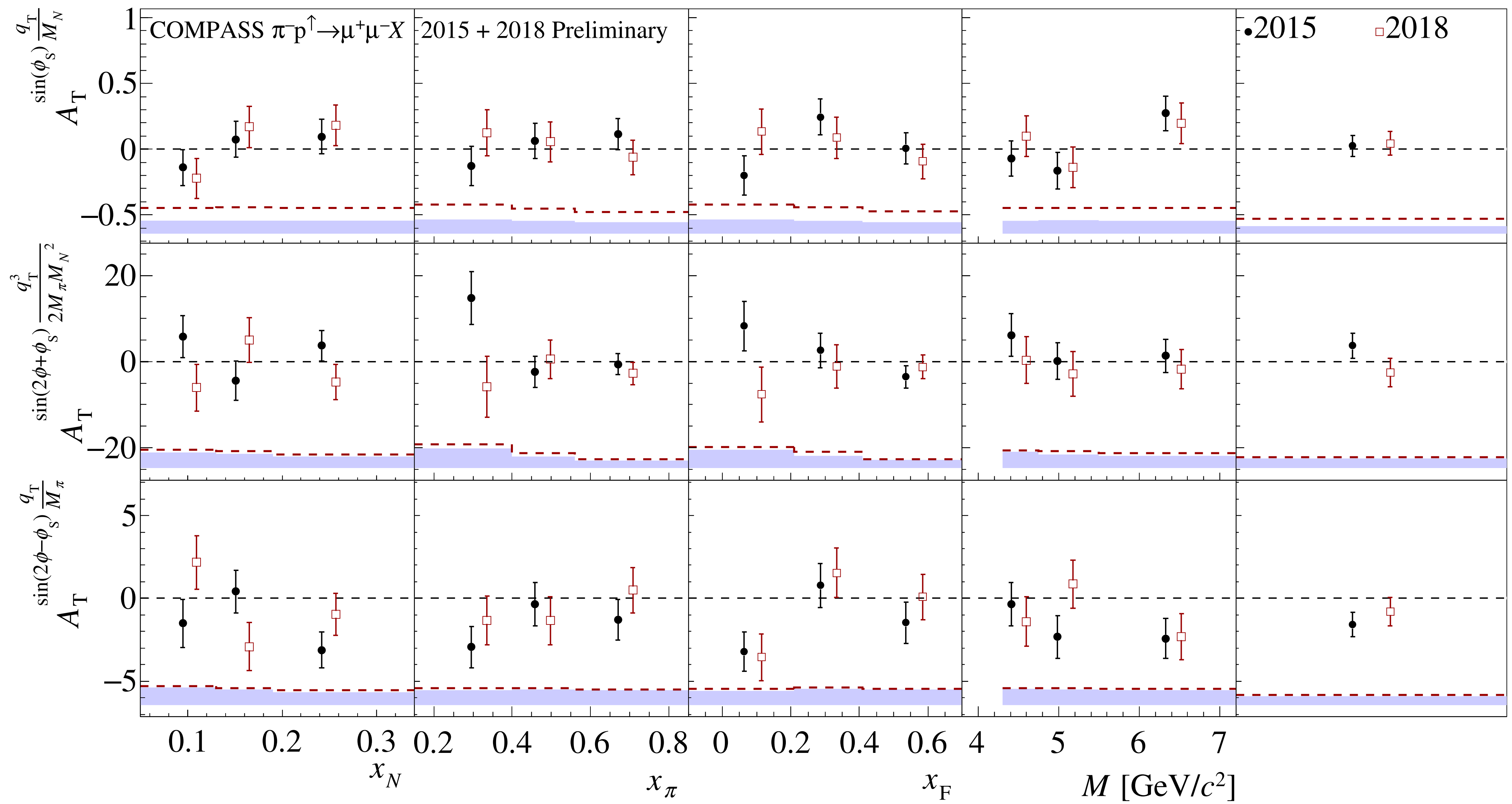


Anselmino et al., PRD 86 (2012) 014028

DY WEIGHTED TSAs

- 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: complementary way to test the Sivers sign-change!

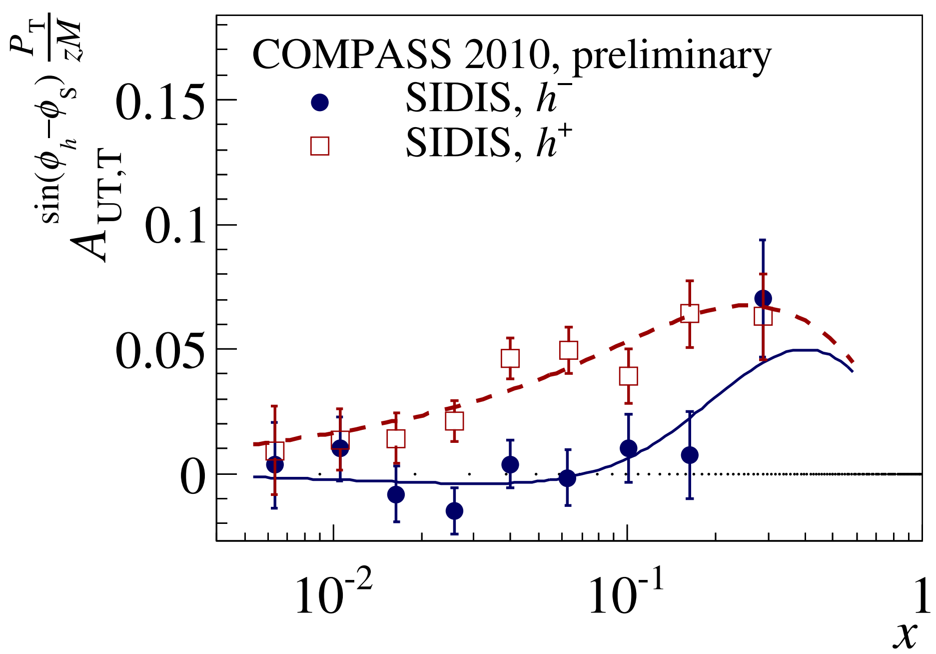
R.Longo, **PoS (DIS2019) 186**



- Preliminary analysis using only ~50% of 2018 data

TESTING SIVERS SIGN CHANGE W/ WEIGHTED TSA

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

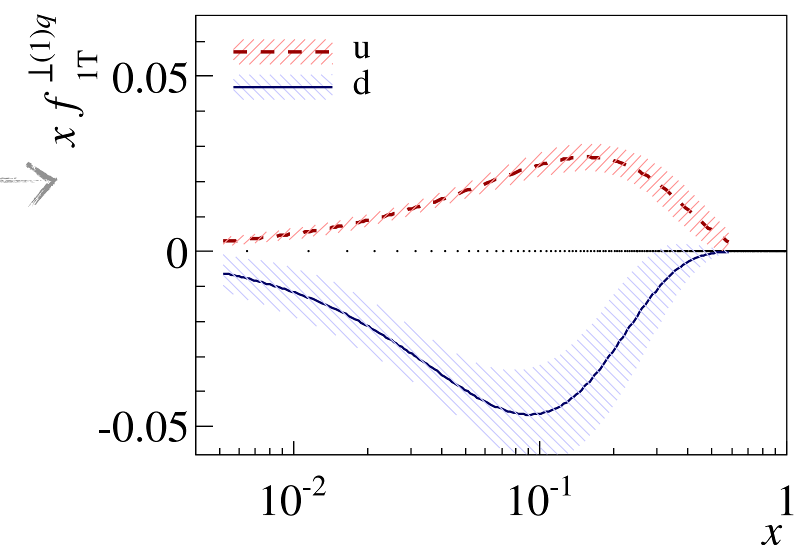


- COMPASS has also measured the p_T weighted TSAs in SIDIS;
- Alternative way to compare TMD PDFs from SIDIS and DY;

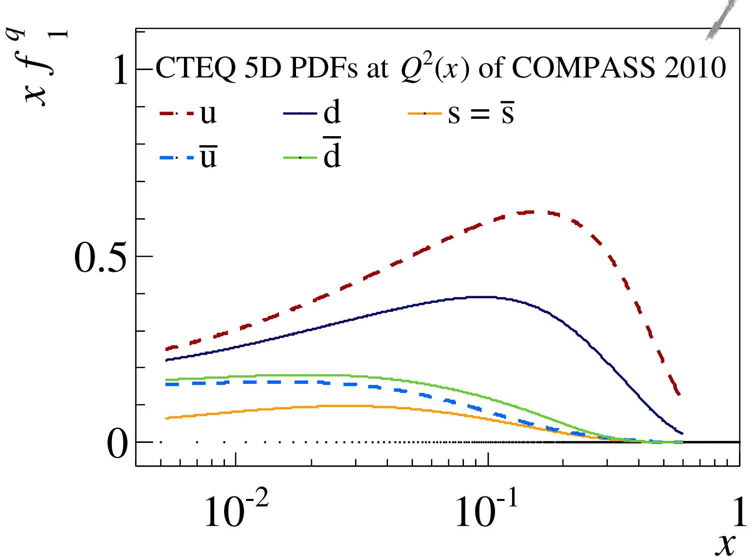
  - Sivers TSA in SIDIS $\quad A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$
  - Sivers wTSA in SIDIS $\quad A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}} \propto f_{1T}^{\perp q(1)} \times D_{1q}^h$

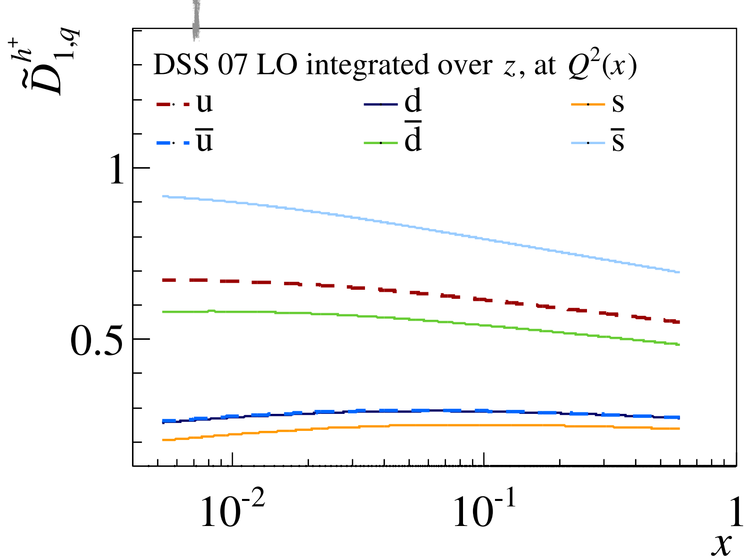
$$A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}}(x,z) = 2\frac{\sum_q e_q^2 f_{1T}^{\perp q(1)}(x) D_1^q(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

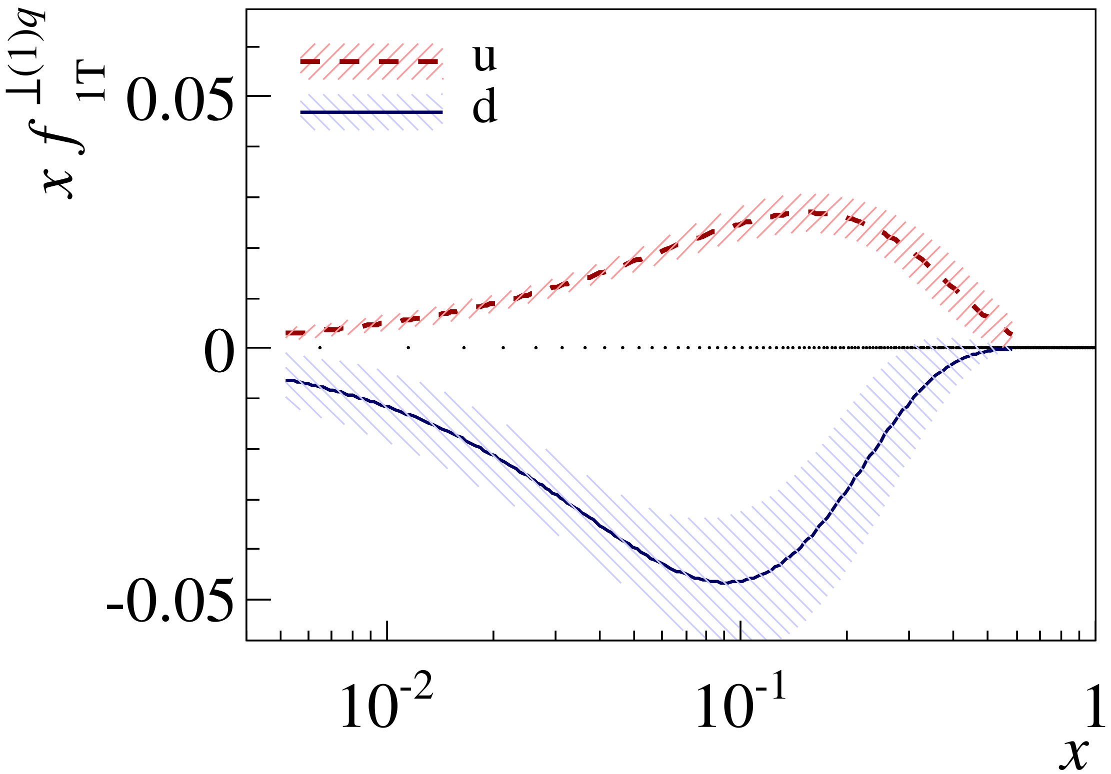
$$x f_{1T}^{\perp(1)q}(x) = a_q x^{b_q}(1-x)^{c_q}$$



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







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

Assuming:

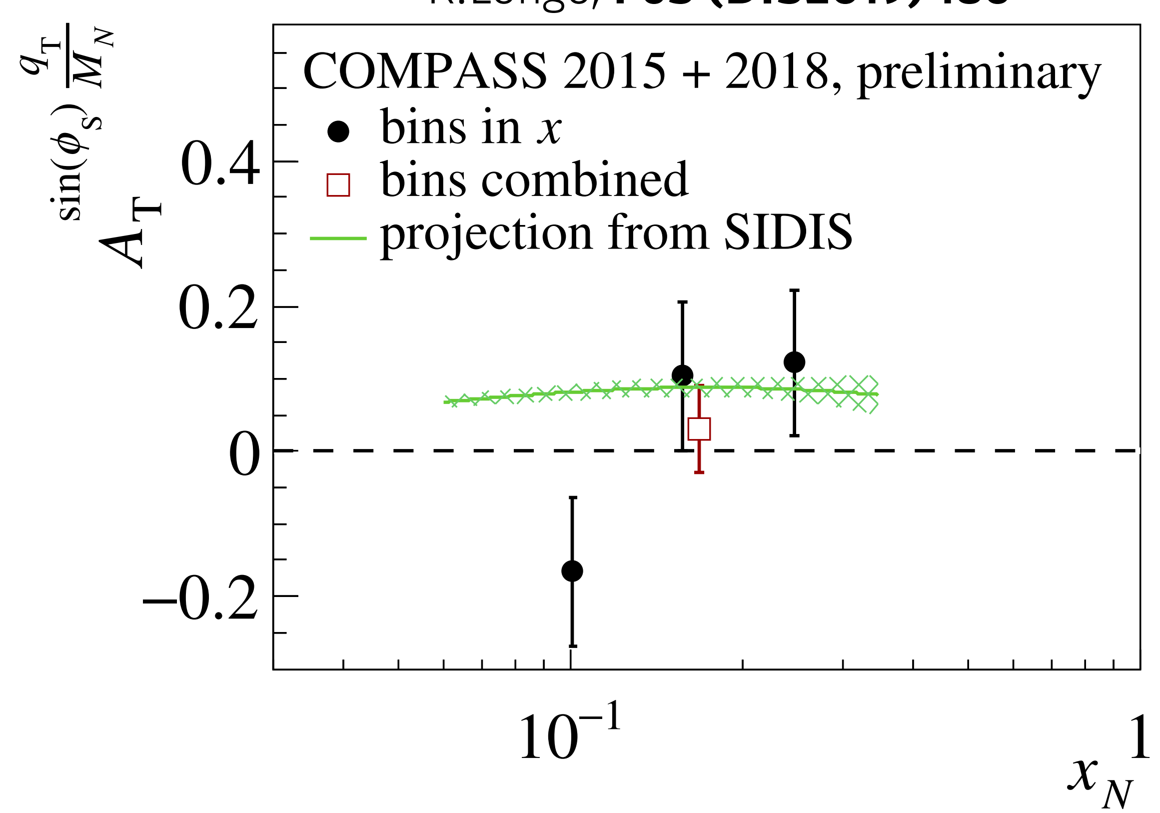
- u quark dominance

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

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

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

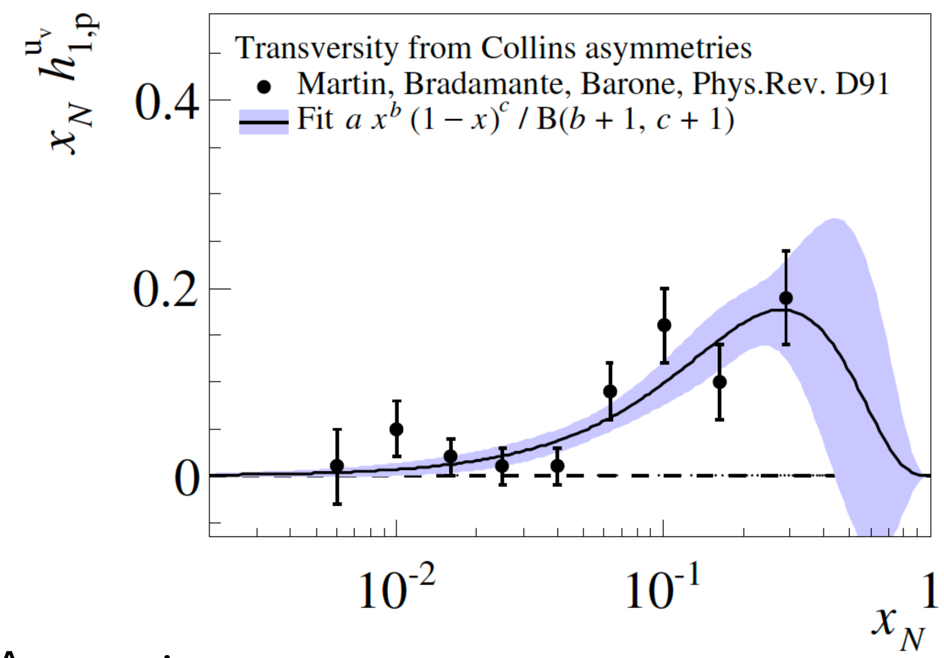
R.Longo, **PoS (DIS2019) 186**

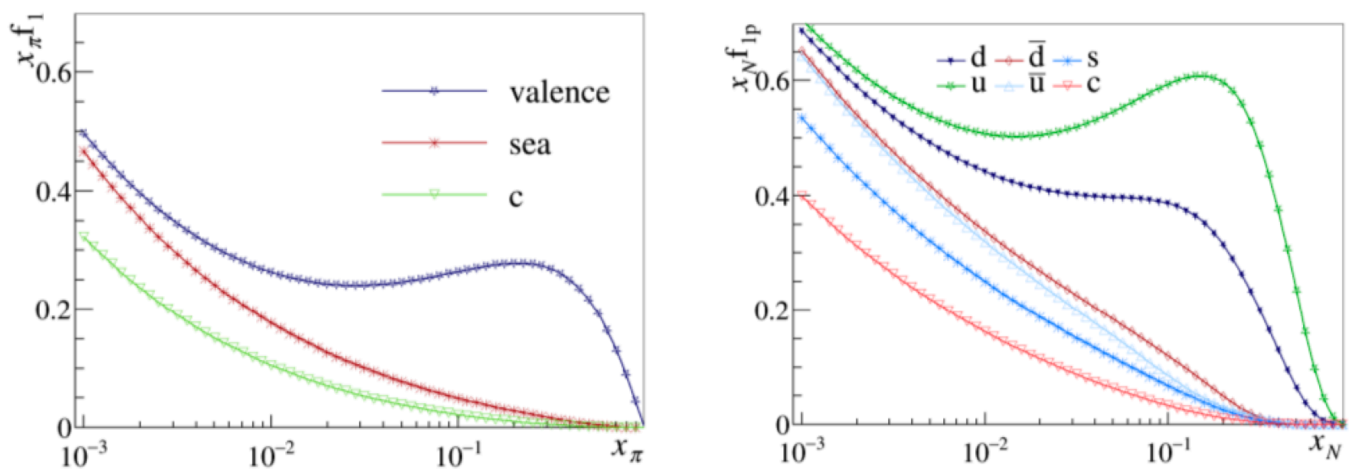


- Preliminary 2015 results, full data sample;
- Preliminary 2018 results, 50% of the sample;
- Analysis will be repeated with the full 2018 sample (same as standard TSAs)

WEIGHTED ASYMMETRIES: FROM SIDIS TO DY

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



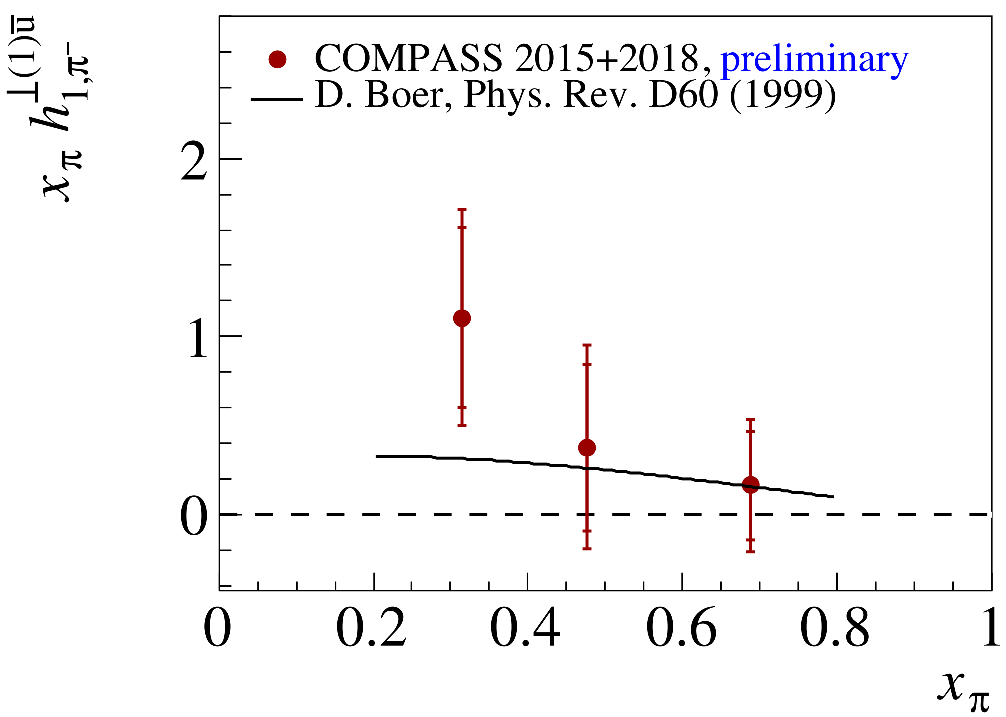


GRV-PI pion PDF
at Q^2 = 25 $(GeV/c^2)^2$

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

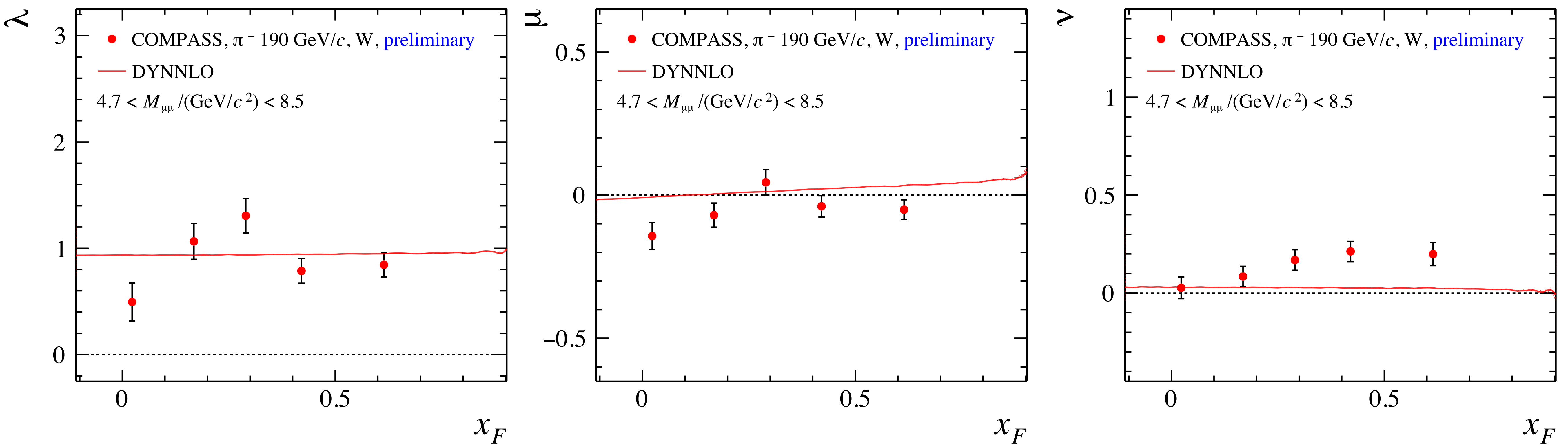
Assuming:

- u quark dominance
- no Q^2 evolution



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

UAs VS x_F


λ
μ
ν
COMPASS, π⁻ 190 GeV/c, W, preliminary
DYNNLO
4.7 < M_μμ /(GeV/c²) < 8.5
COMPASS, π⁻ 190 GeV/c, W, preliminary
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4.7 < M_μμ /(GeV/c²) < 8.5
COMPASS, π⁻ 190 GeV/c, W, preliminary
DYNNLO
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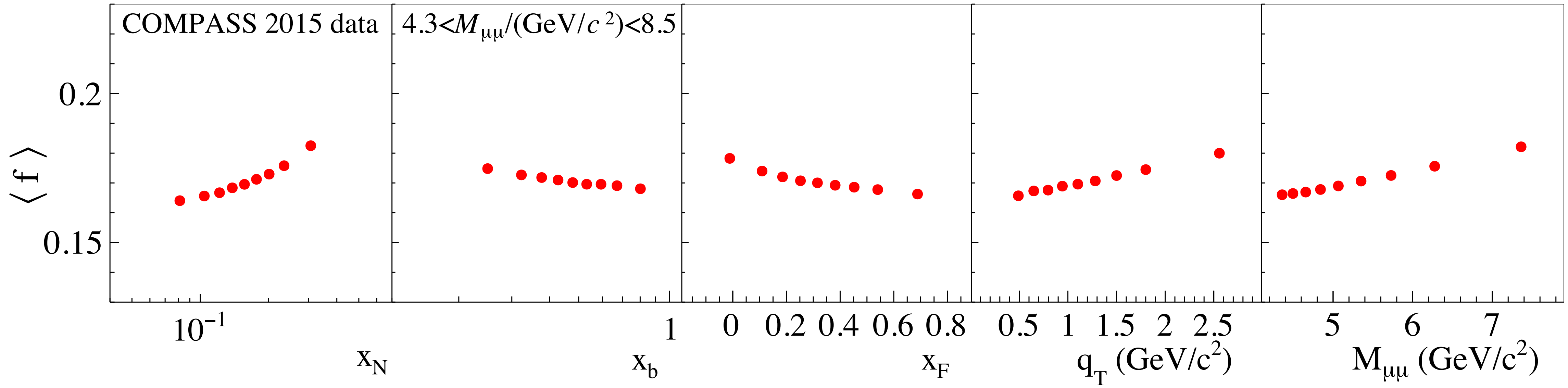
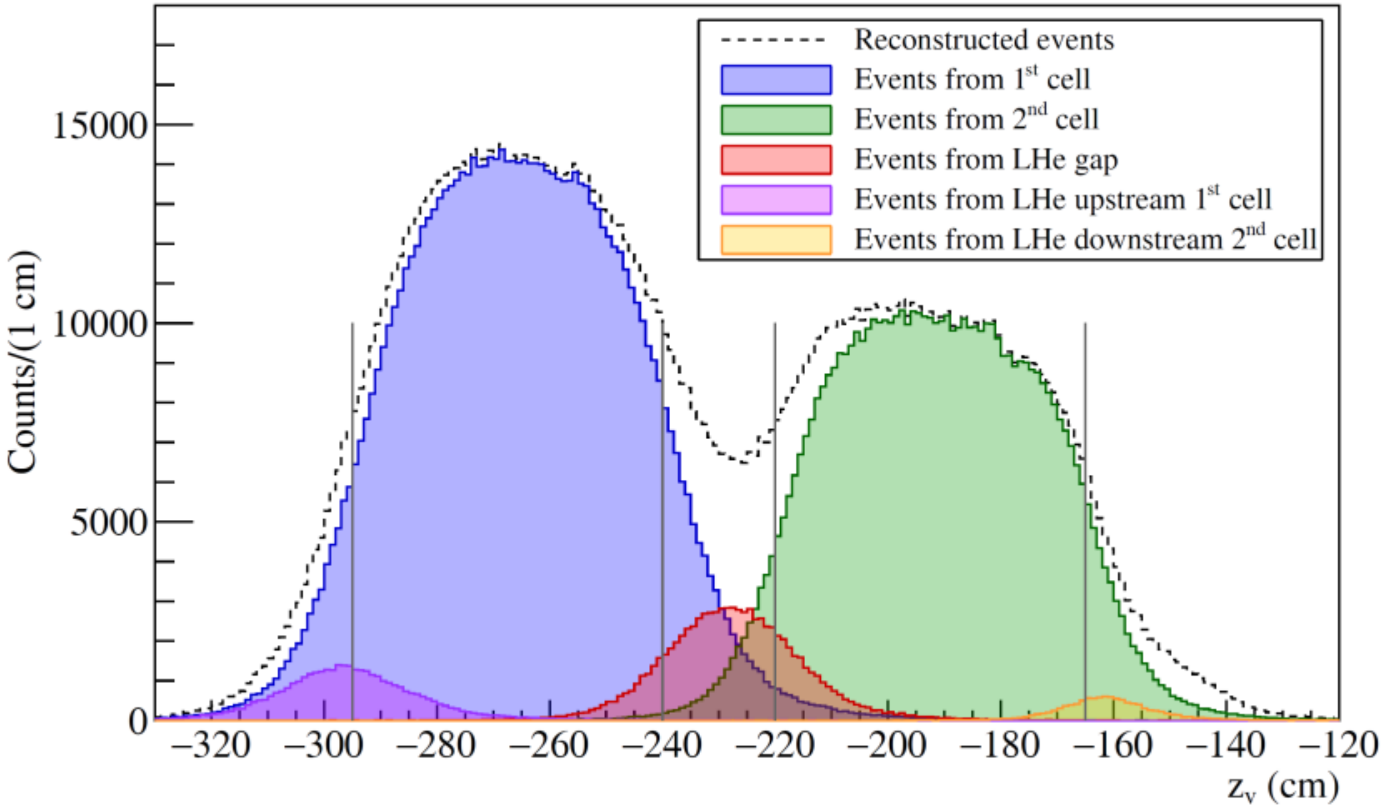
x_F
x_F
x_F

DILUTION FACTOR



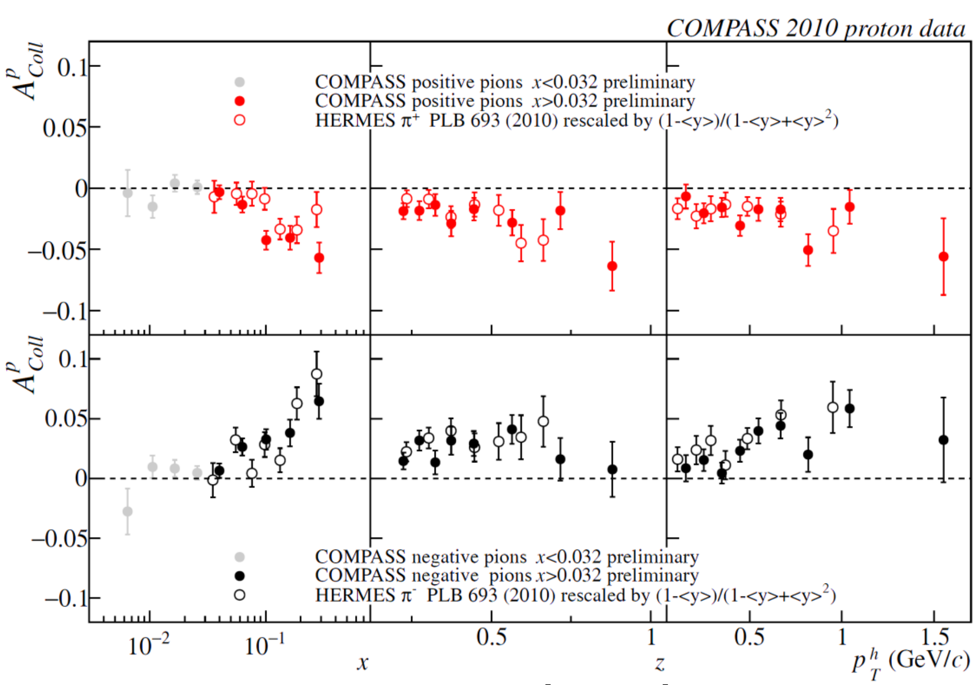


$$f = \frac{n_H \sigma^{DY}_{\pi-H}}{n_H \sigma^{DY}_{\pi-H} + \Sigma_A n_A \sigma^{DY}_{\pi-A}}$$

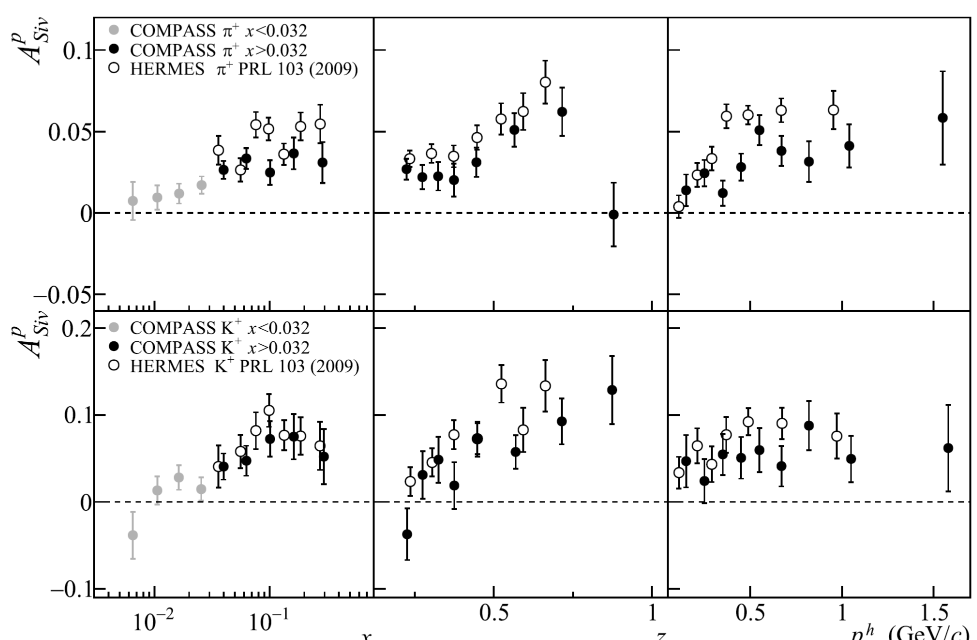
- The dilution factor accounts for the fraction of polarizable material inside the target volume.
- It is corrected to account for the migration of events from one cell to the other (obtained with MC simulation);

COMPASS: FROM SIDIS TO DY

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



PLB 744 (2015) 250



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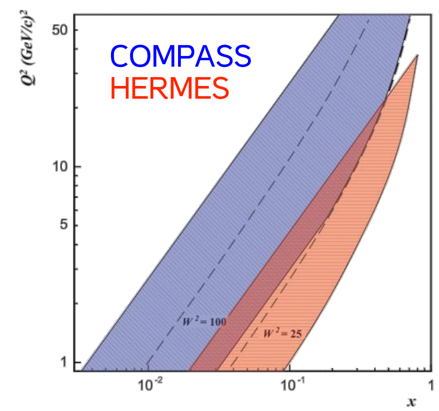
- Compatible results COMPASS/ HERMES for Collins effect
- No Q^2 evolution effects?



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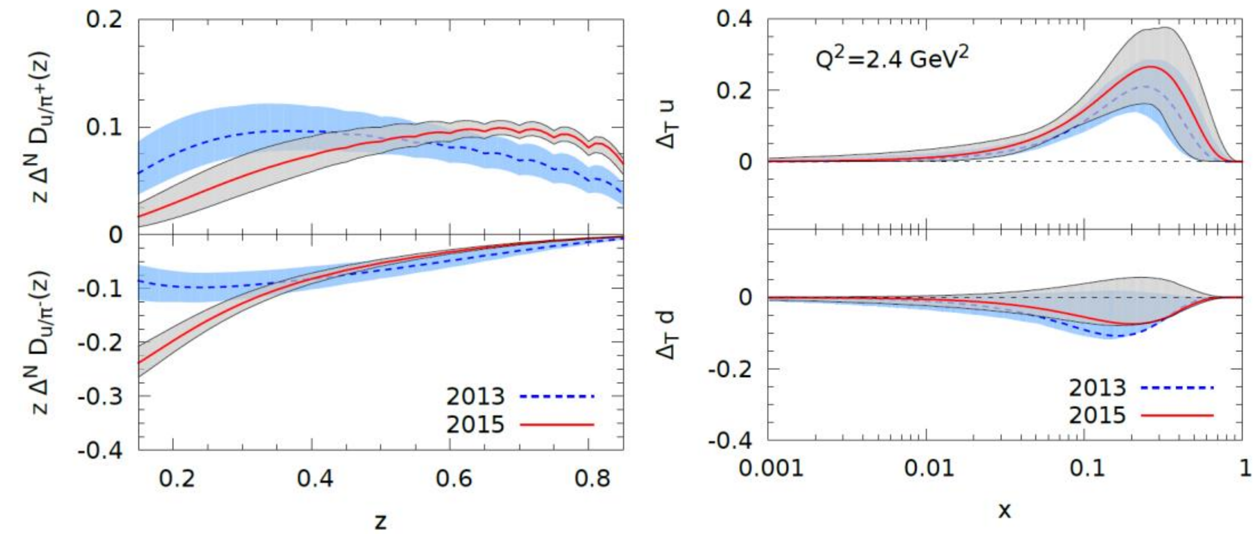
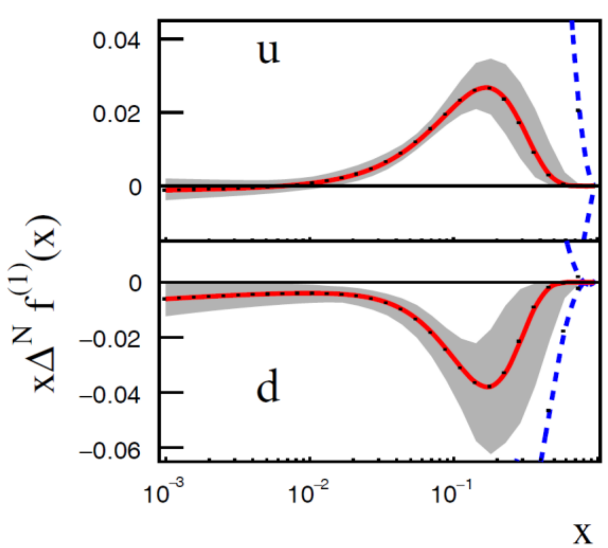
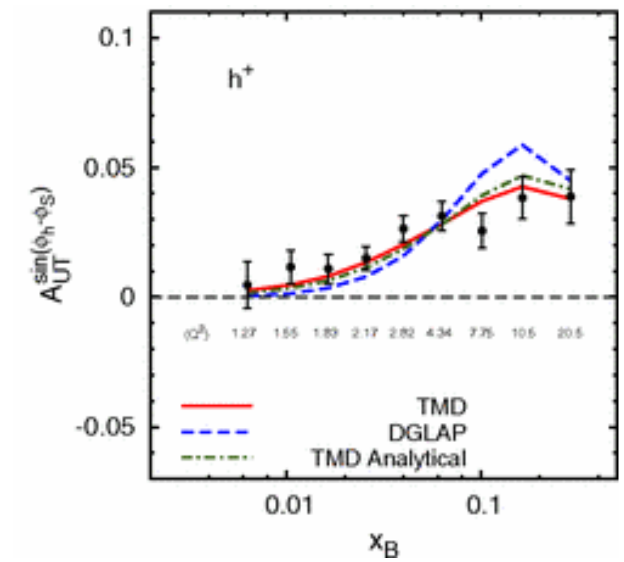
Anselmino et al., Phys.Rev. D92 (2015) 114023

Global fit of HERMES - COMPASS - BELLE data



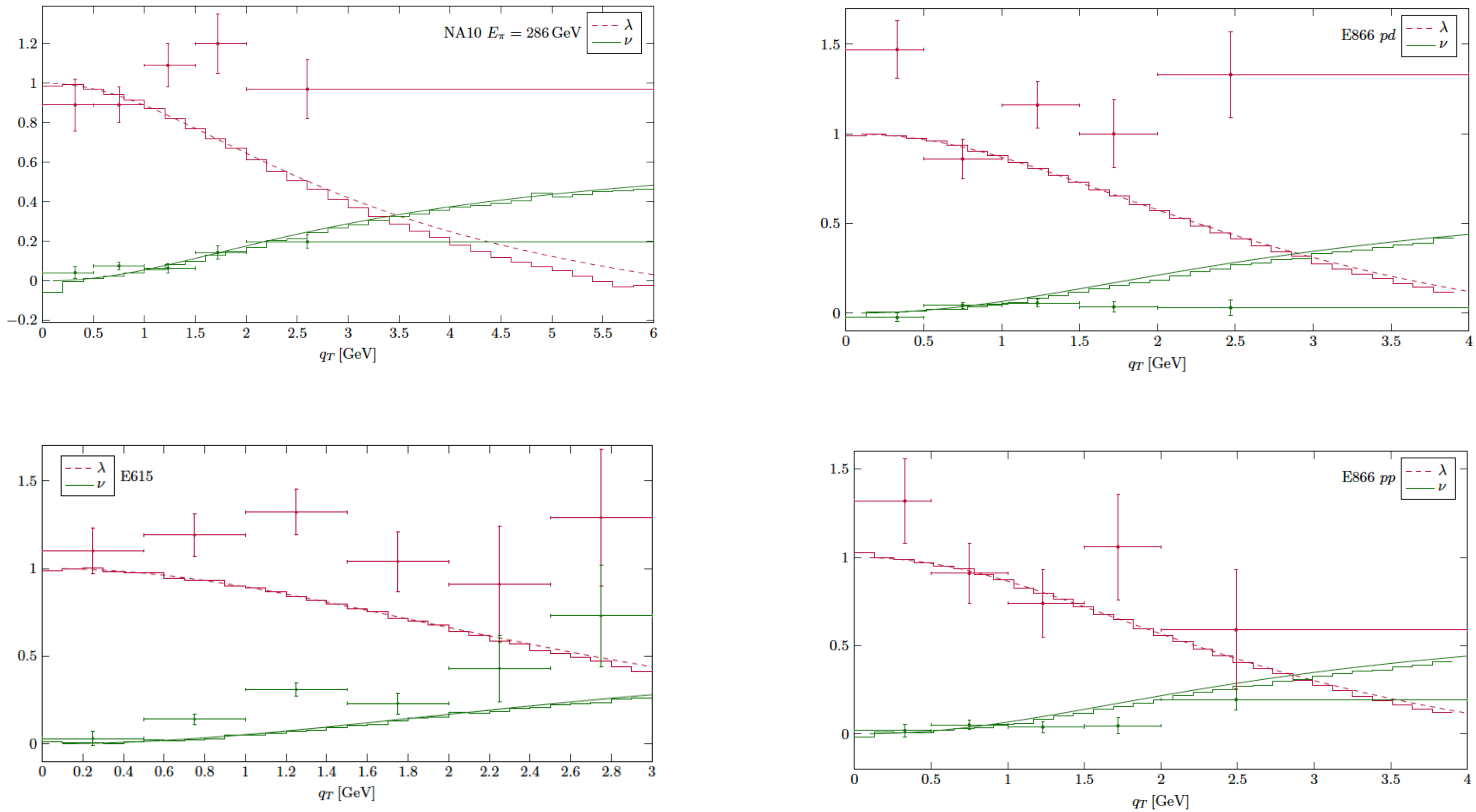


Anselmino et al., JHEP 1704 (2017)046



Anselmino et al., PRD 86 (2012) 014028

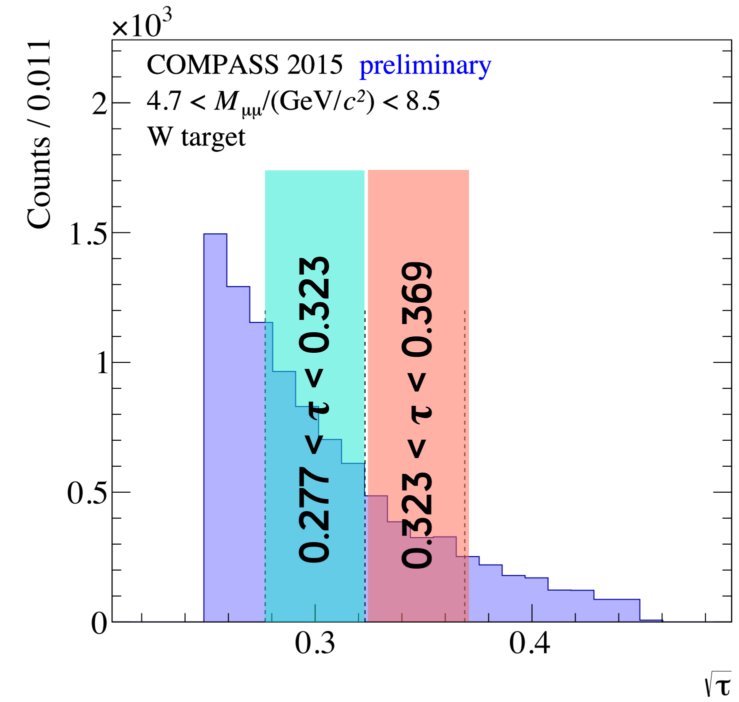
NLO ISSUES AT LOW q_T

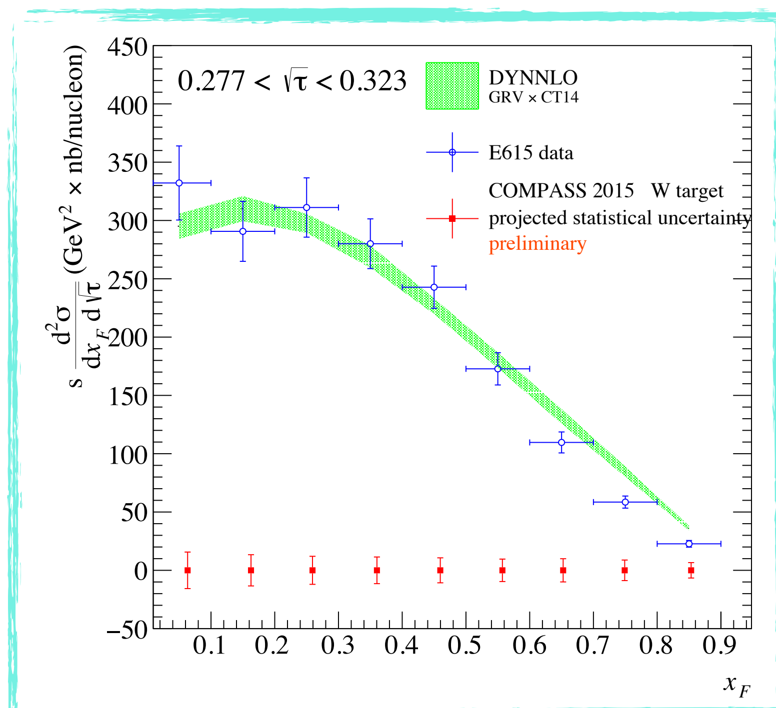


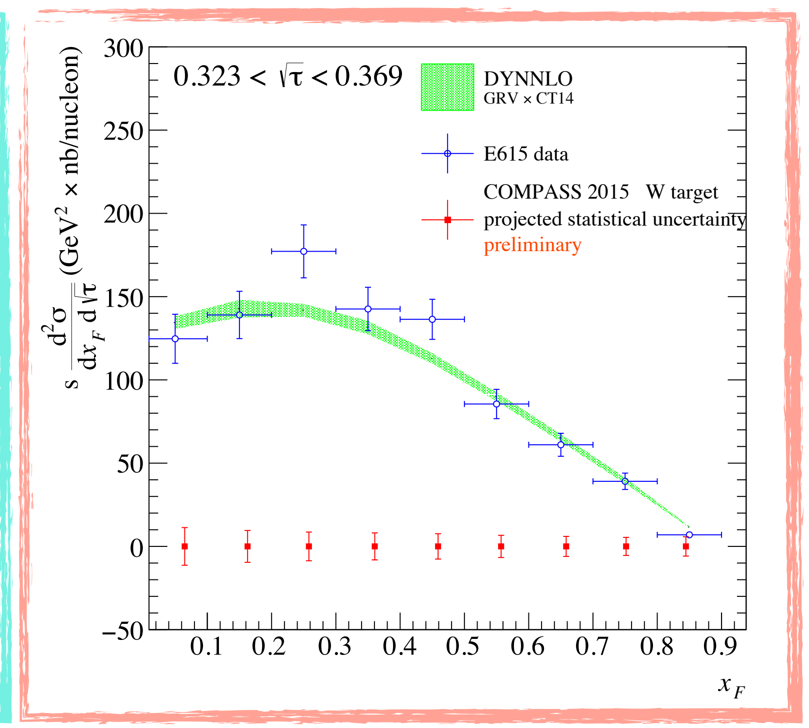
Vogelsang and Lambertsen
PRD 93 (2016)

ABSOLUTE DY CROSS-SECTION MEASUREMENT

- Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  - Absolute DY cross-section measurement:
    - Input for p_T dependence fit of the DY cross-section in global extraction of TMD PDFs (e.g. **Bacchetta et al., JHEP 06 (2017) 081**)
    - Input for the extraction of the pion PDF (e.g. **JAM 2018, PRL 121, 152001**)
    - Comparison with DY cross-section simulations and previous experiments
      - Statistical uncertainties recently in 2020
      - **W data:** projected statistical uncertainties vs DYNNLO simulation and E615 data (after energy rescaling) in same bins of $\sqrt{\tau}$
      - **NH_3 data:** projected statistical uncertainties vs DYNNLO simulation







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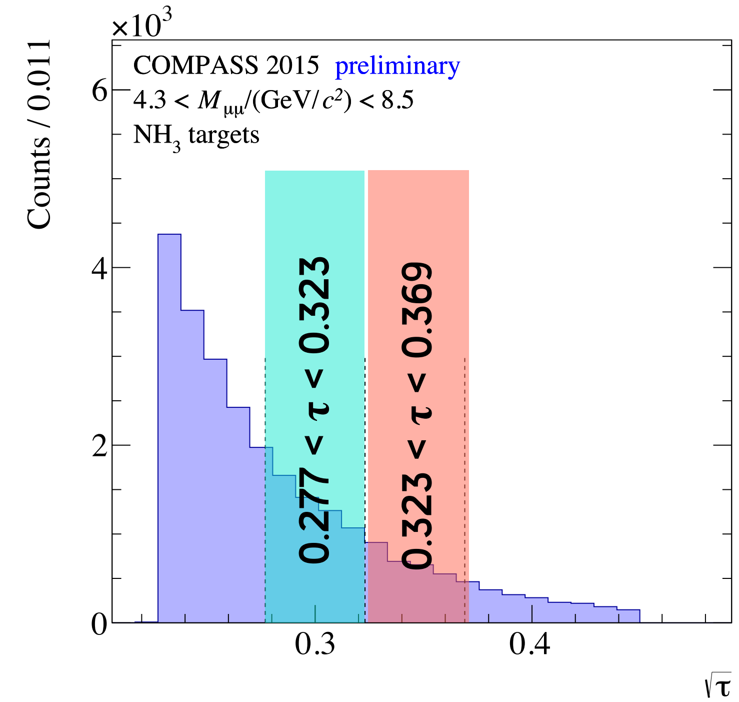
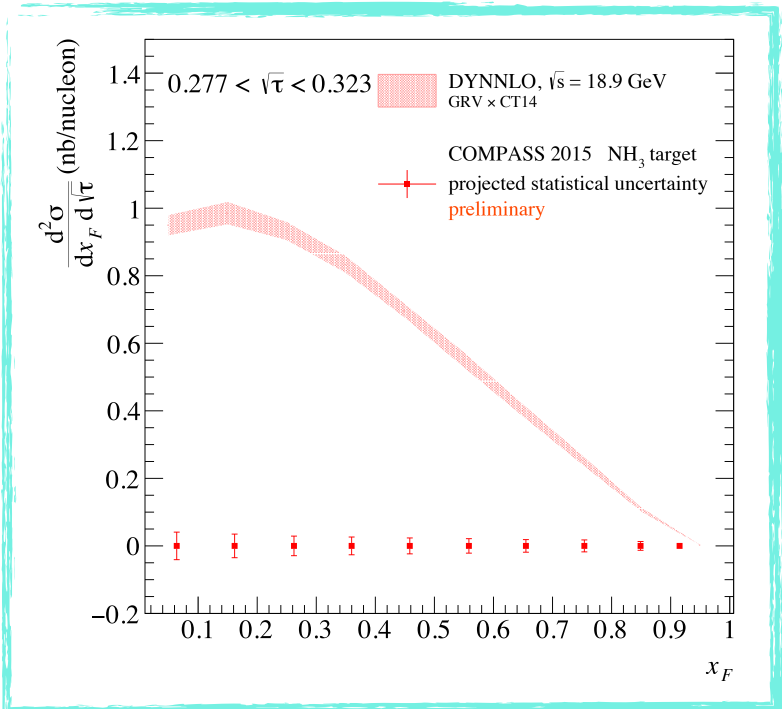
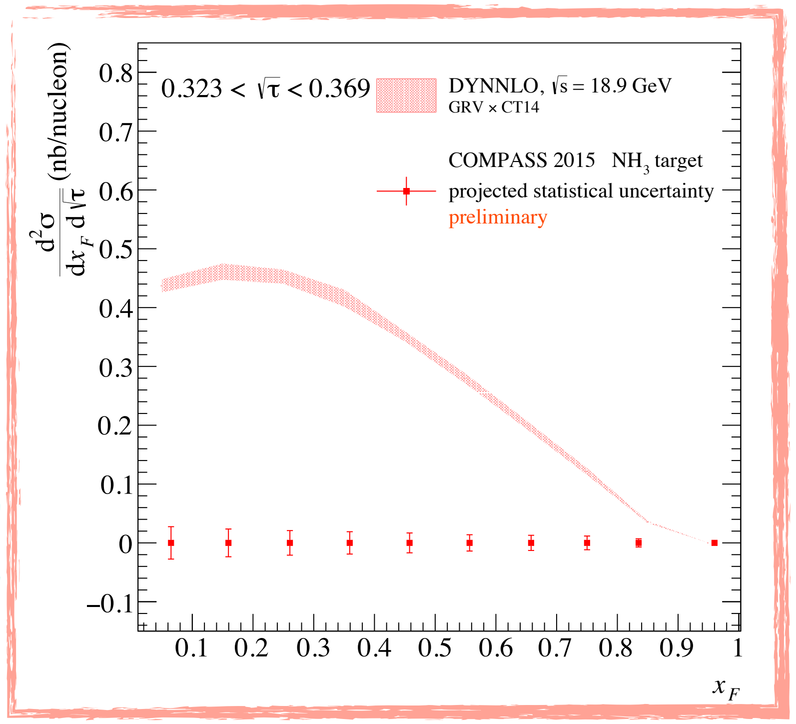
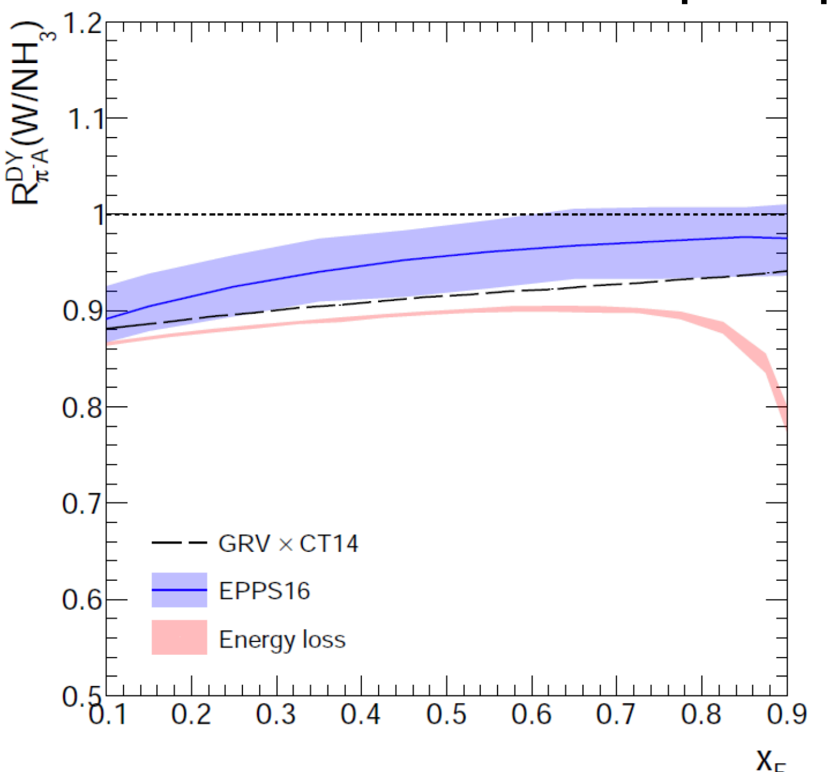




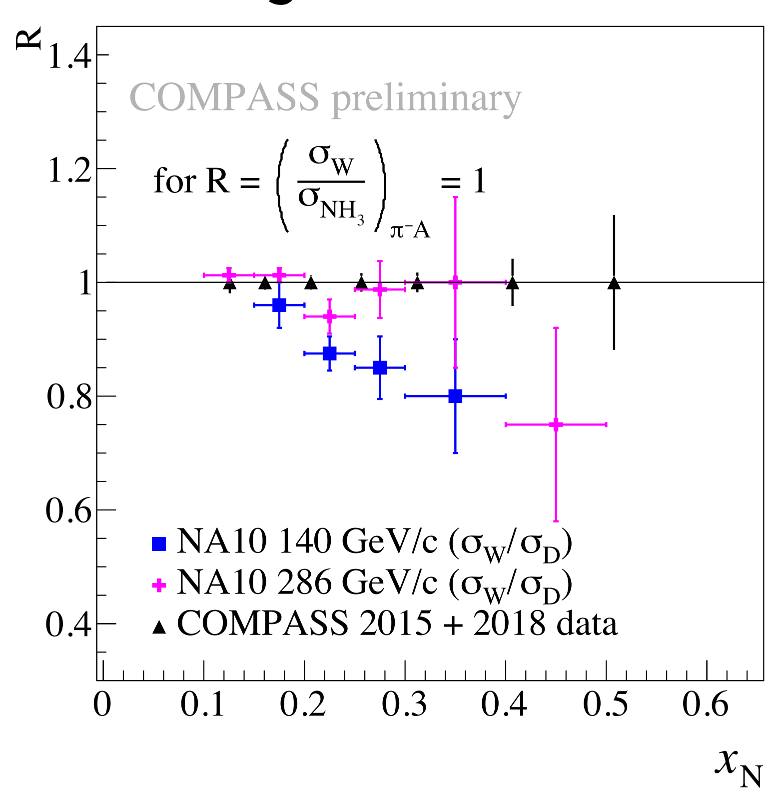


NUCLEAR DEPENDENCE OF DY PROCESS

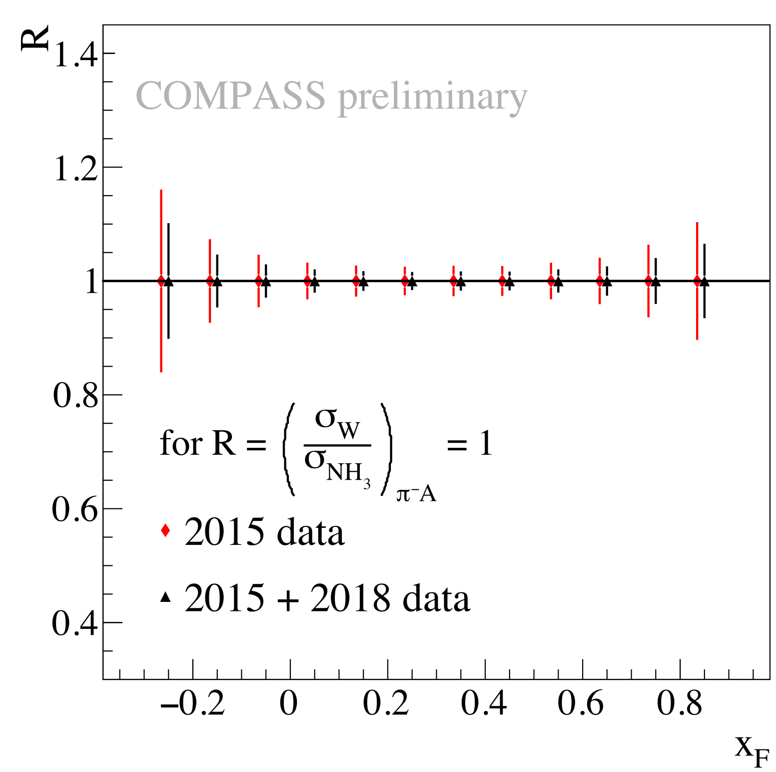
- Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  - Absolute DY cross-section measurement
  - Nuclear dependence of the DY process:
    - **EMC effect**: nucleon PDFs modification when inside cold nuclear matter (EMC collab., *Phys. Lett. B*. **123B** (3–4): 275–278, 1983);
    - **Energy loss** of the pion quarks when crossing cold nuclear matter
    - **Cronin effect**: dilepton p_T broadening in cold nuclear matter



Arleo et al. JHEP01(2019)129
EMC & Energy Loss effects predictions for COMPASS (W/NH_3)



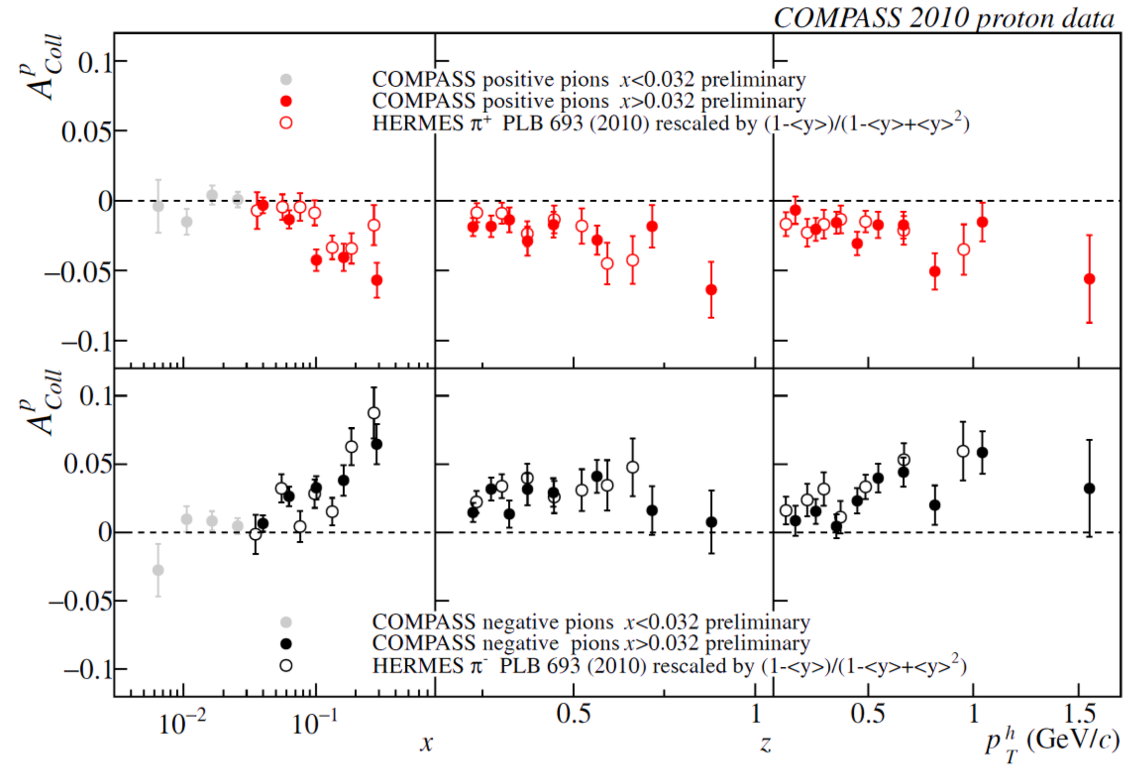
COMPASS **projected statistical error** for EMC effect (W/NH_3) compared with NA10 results



COMPASS **projected statistical error** for Energy Loss (W/NH_3)

COMPASS: FROM SIDIS TO DY

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



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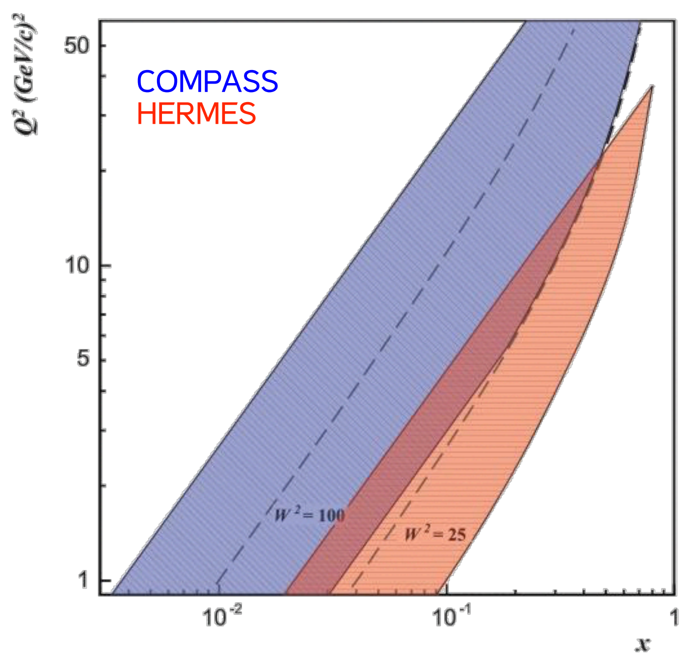
PLB 744 (2015) 250



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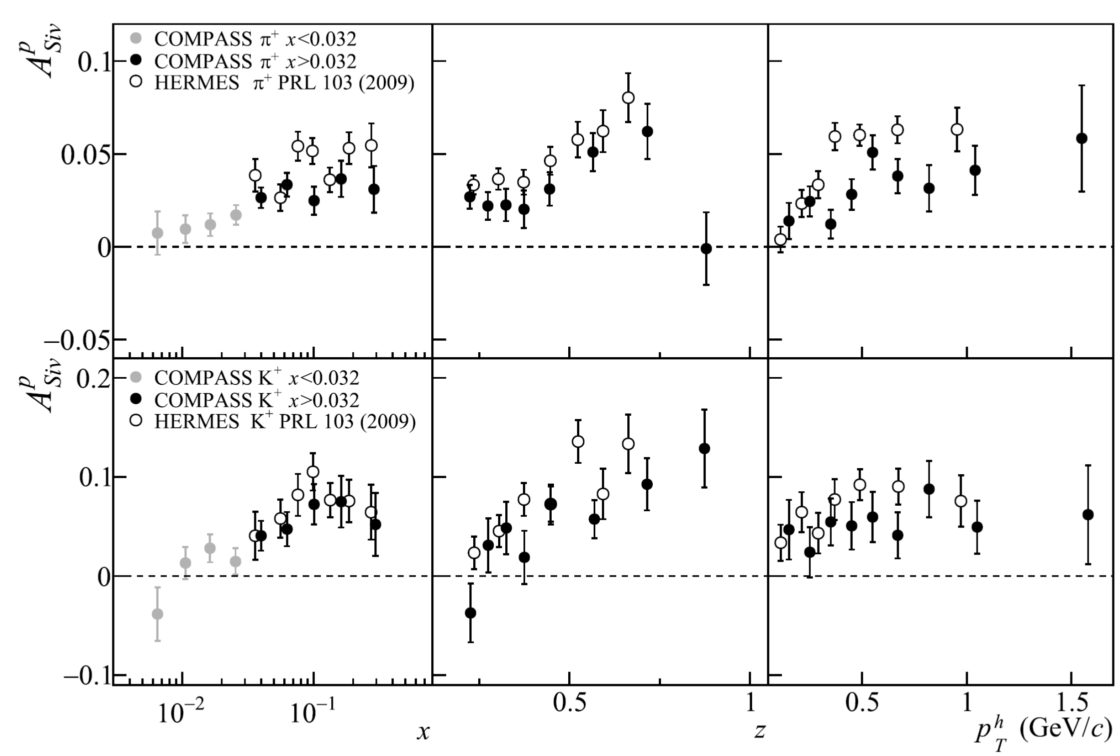
- Q² evolution effects?



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