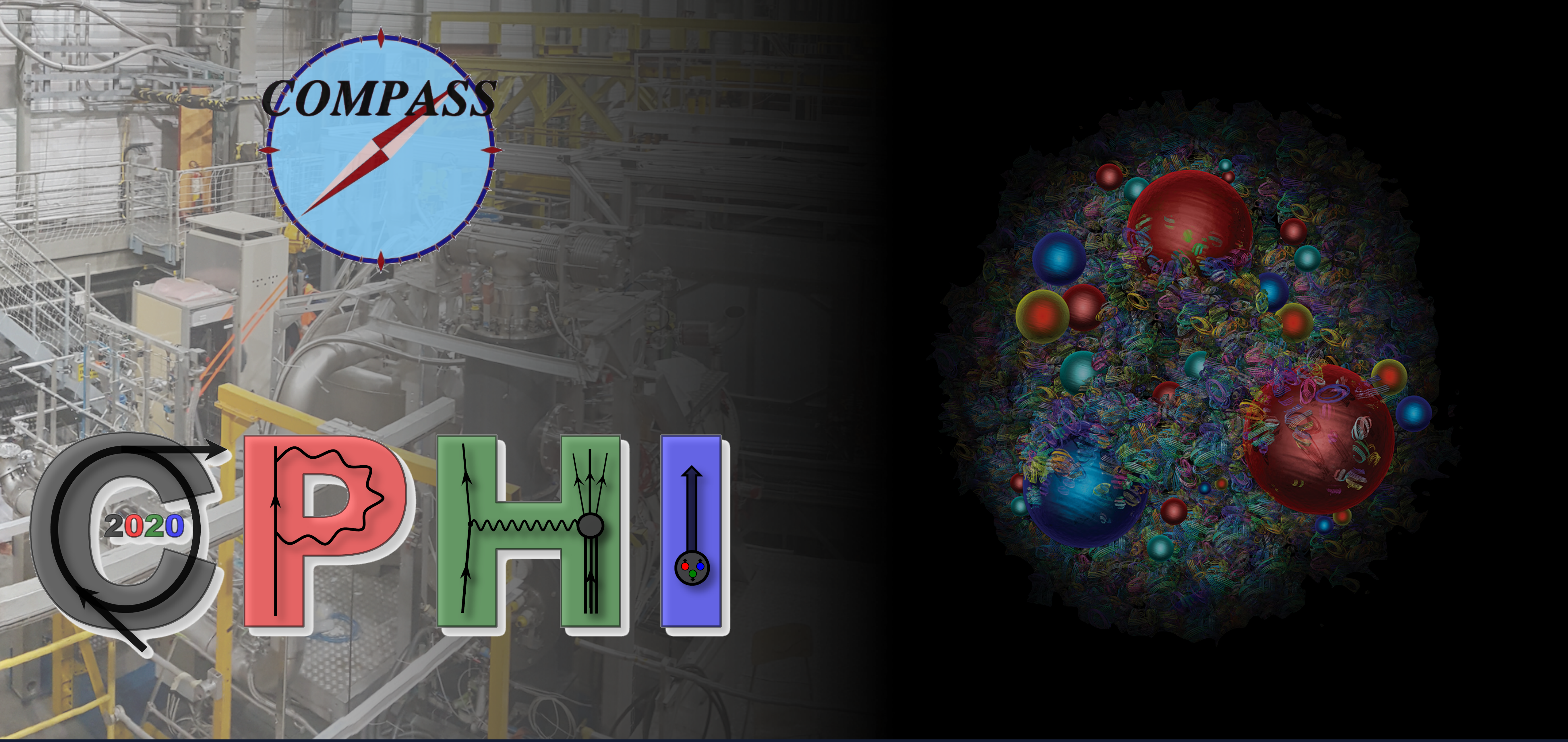


COMPASS DRELL-YAN PROGRAMME

Riccardo Longo
on behalf of the COMPASS Collaboration
4th February 2020

NSF

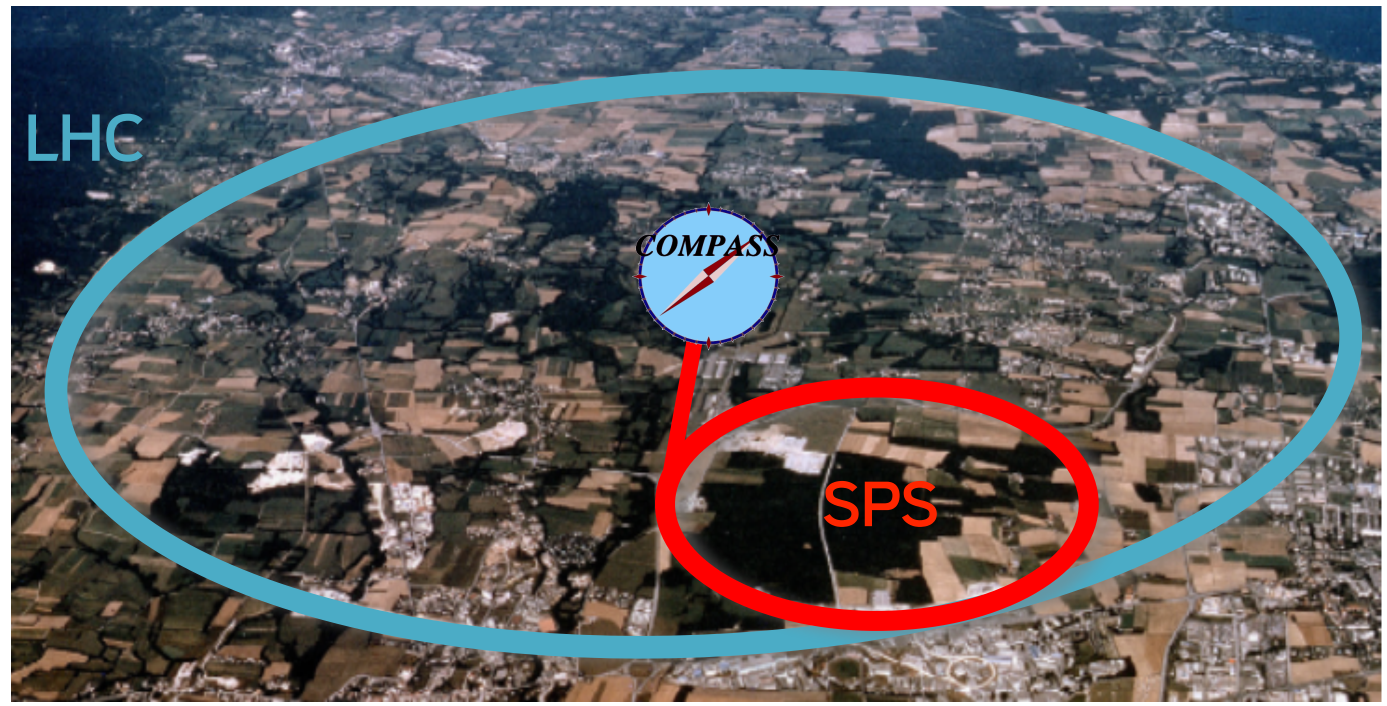
ILLINOIS

OUTLINE

- Introduction
- COMPASS Drell-Yan measurements
- COMPASS Drell-Yan Transverse Spin Asymmetries results
- COMPASS Drell-Yan “future arrivals”
- Summary

THE COMPASS COLLABORATION

- Fixed target experiment
- CERN SPS North-Area (M2 beam-line)
- First data taking in 2002
- Will run again in 2021



Phase I

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

See talks by A.Martin and F.Kunne

Phase II

See talks by J. Matoušek, N.D'Hose, F.Kunne and A.Moretti

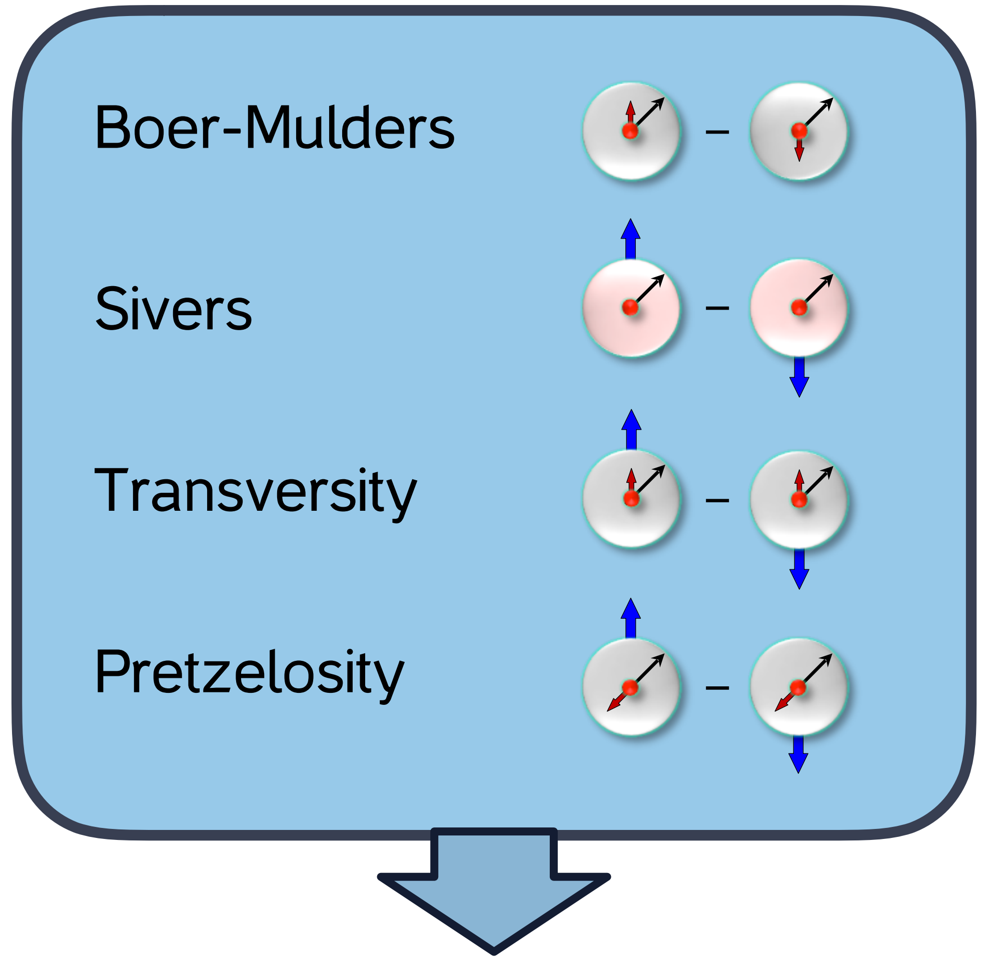
- 2012 - 2021
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018) → This talk
- DVCS + Unpolarized SIDIS(2016-2017)
- Transversely polarized SIDIS on D target (2021)

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

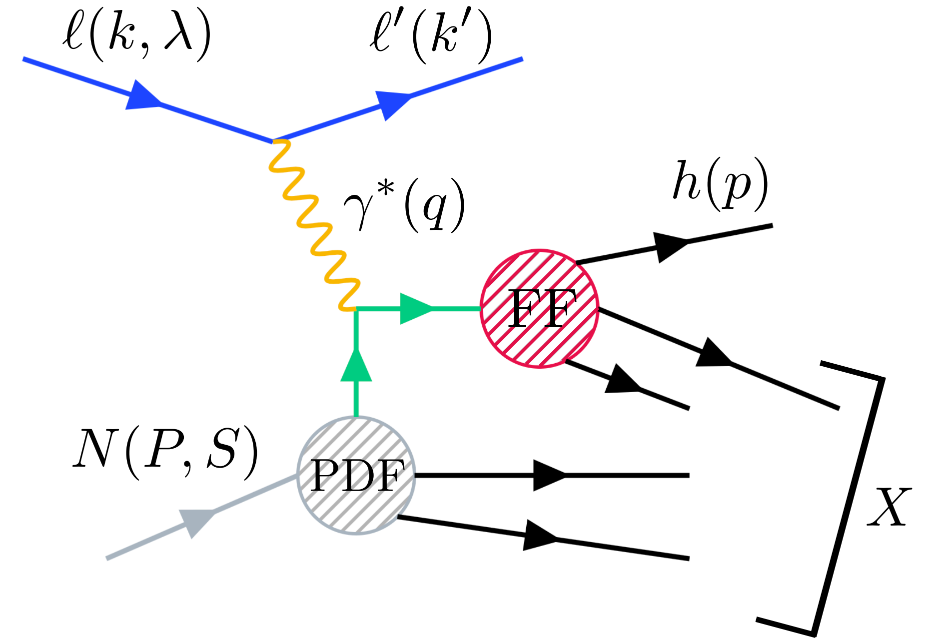
Nucleon | Nucleon spin | quark | quark spin | $\mathbf{k_T}$



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

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

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

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

See talks by A.Martin, A.Moretti and J.Matousek

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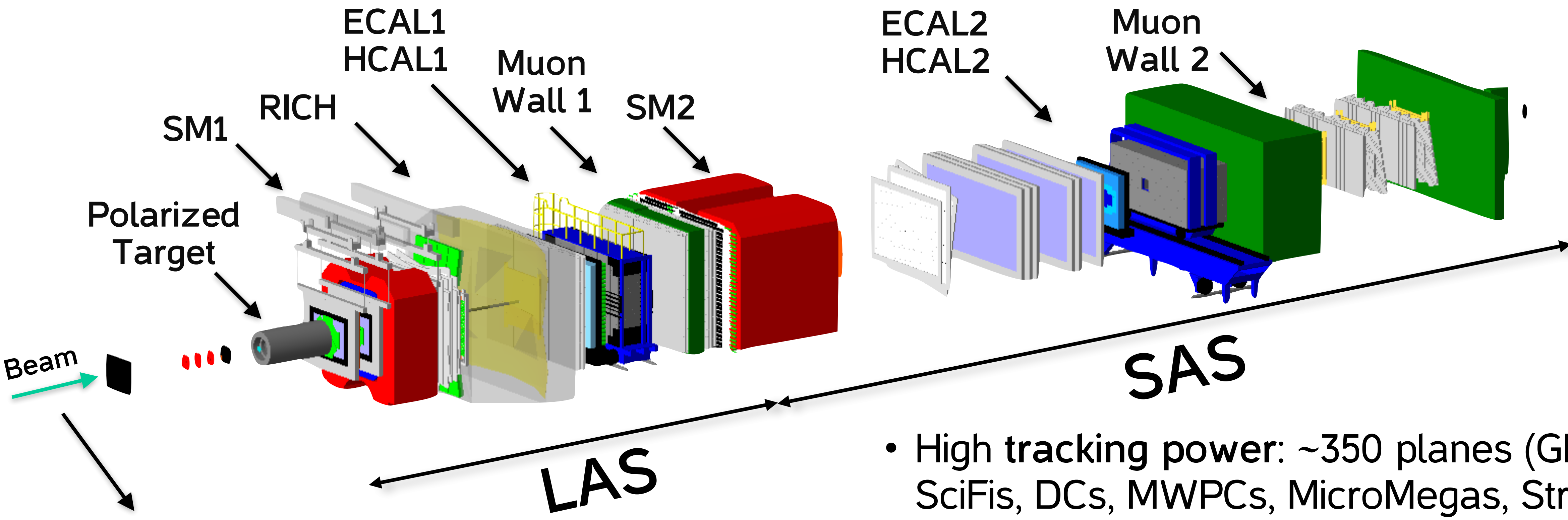
	T	$h_1^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ Worm-Gear L	$h_{1T}^{q}(x,\mathbf{k}_T^2)$ Transversity $h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Pretzelosity

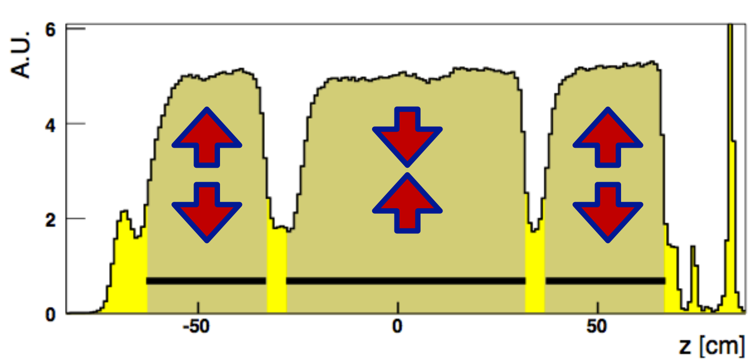
COMPASS SETUP (PHASE I)



μ^+ beam

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

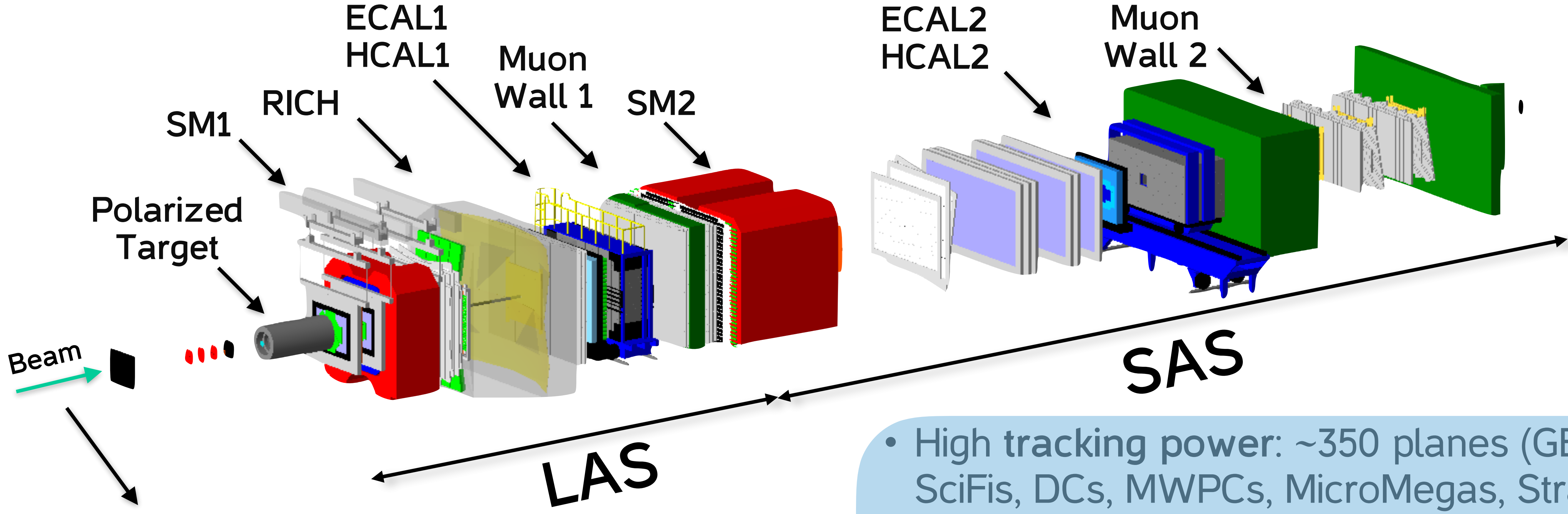
Target	# of cells	Polarization
NH_3	3	T, ~80-90 %



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 programme, the polarization was **reversed** after each 4-5 days

COMPASS SETUP (PHASE I)



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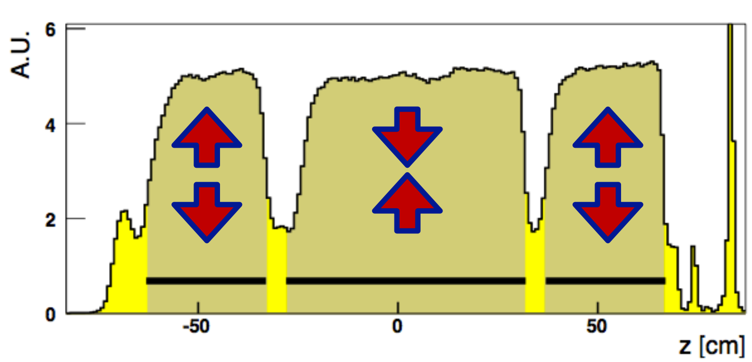

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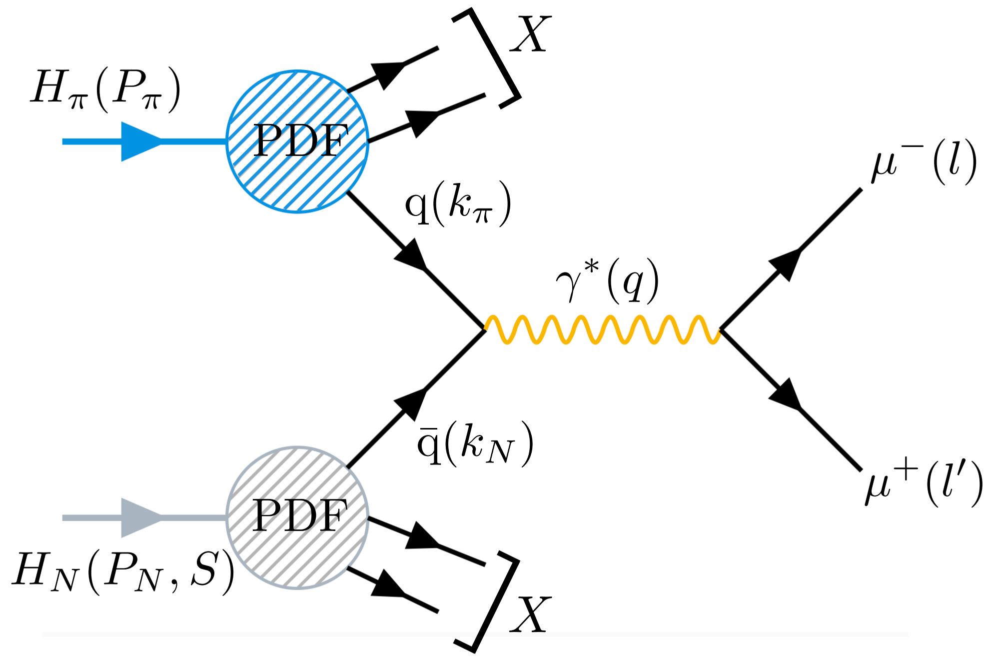
VISIT ON FRIDAY!

- Data were collected simultaneously for the two target spin orientation
- For transverse programme, 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

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



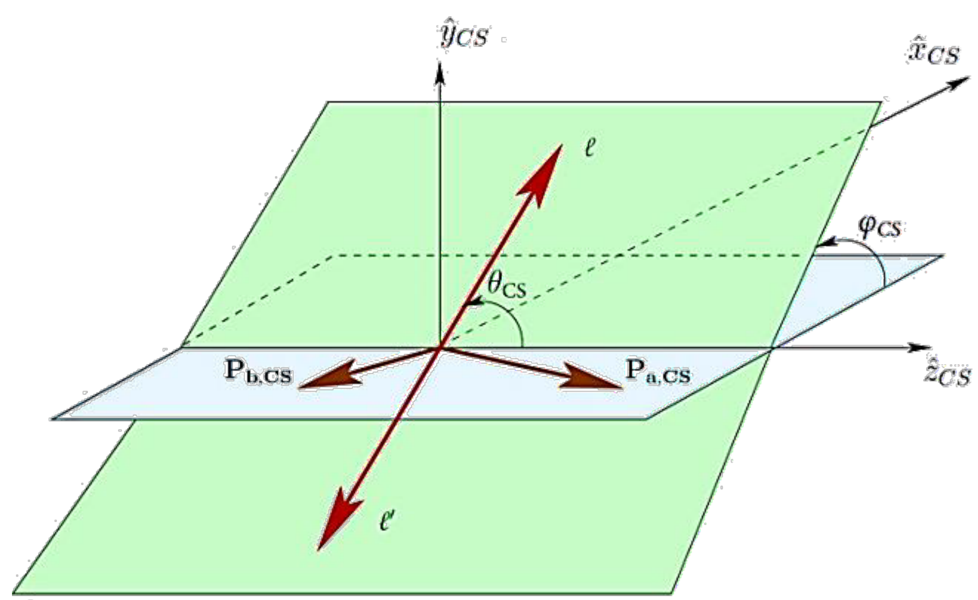
Pion induced polarized Drell-Yan $\quad \pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X \quad$ COMPASS 2015, 2018

D-factors

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

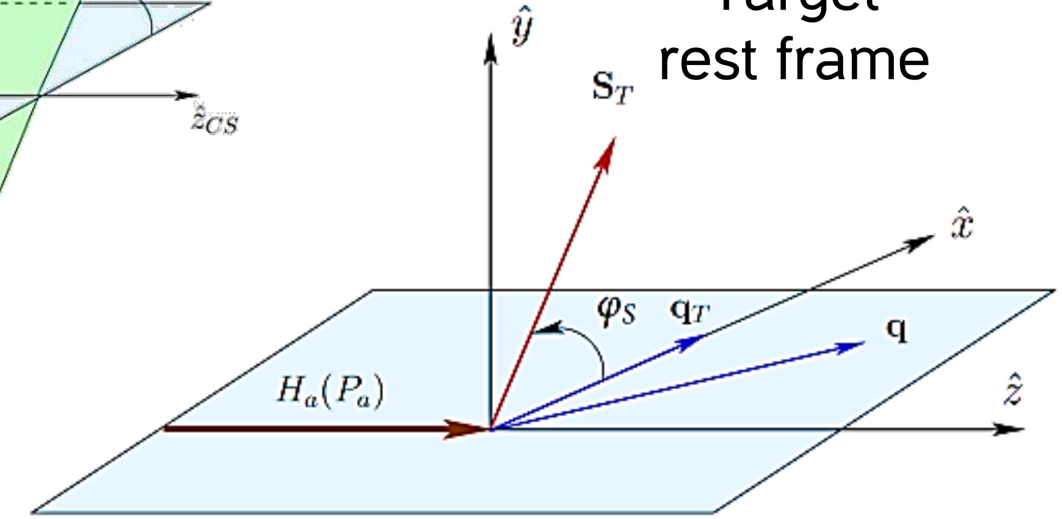
Azimuthal asymmetries

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



Collins-Soper frame

Target rest frame



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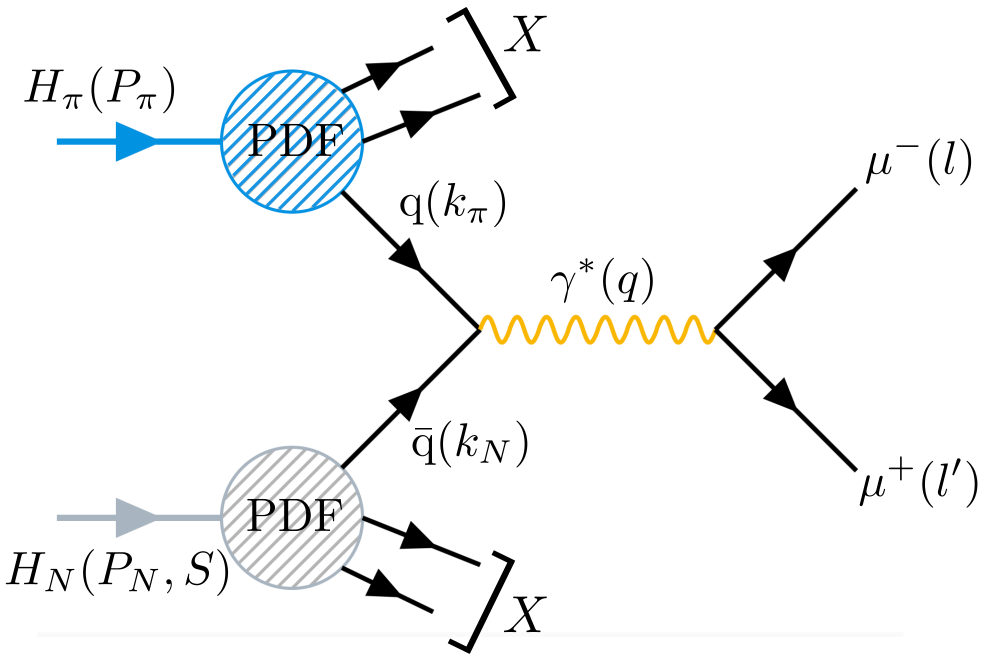

$$A_{DY} \propto PDF_\pi \otimes PDF_p$$

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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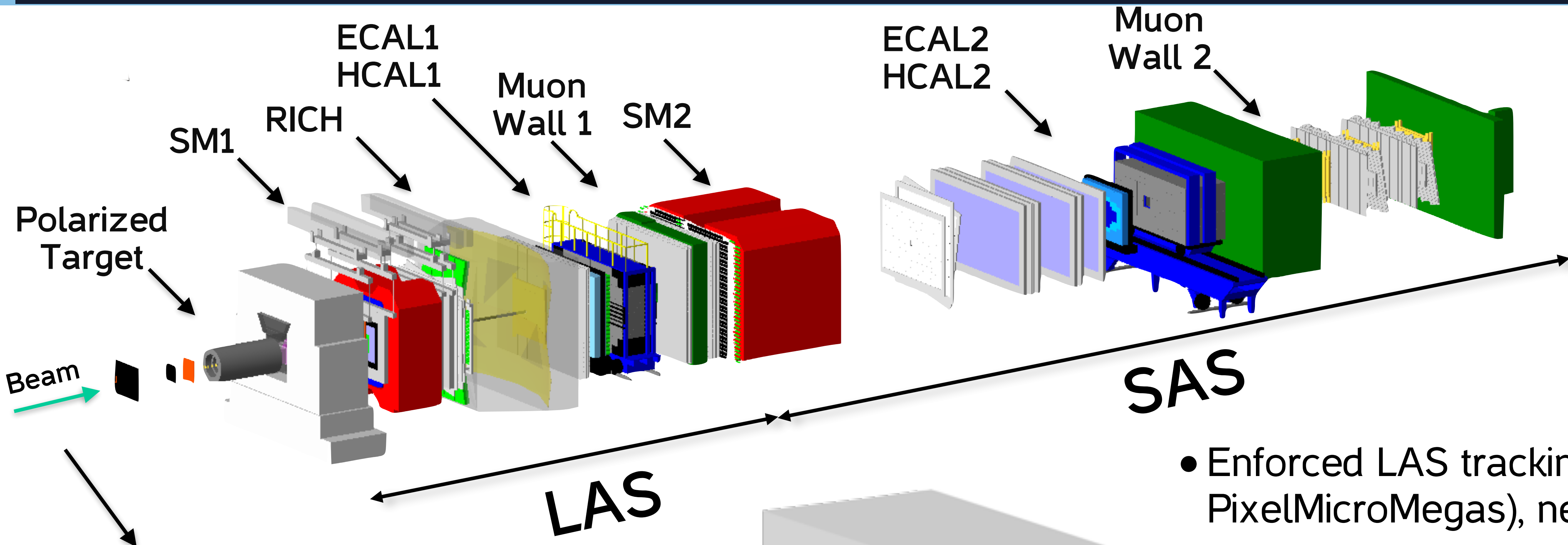
COMPASS SETUP (DY)

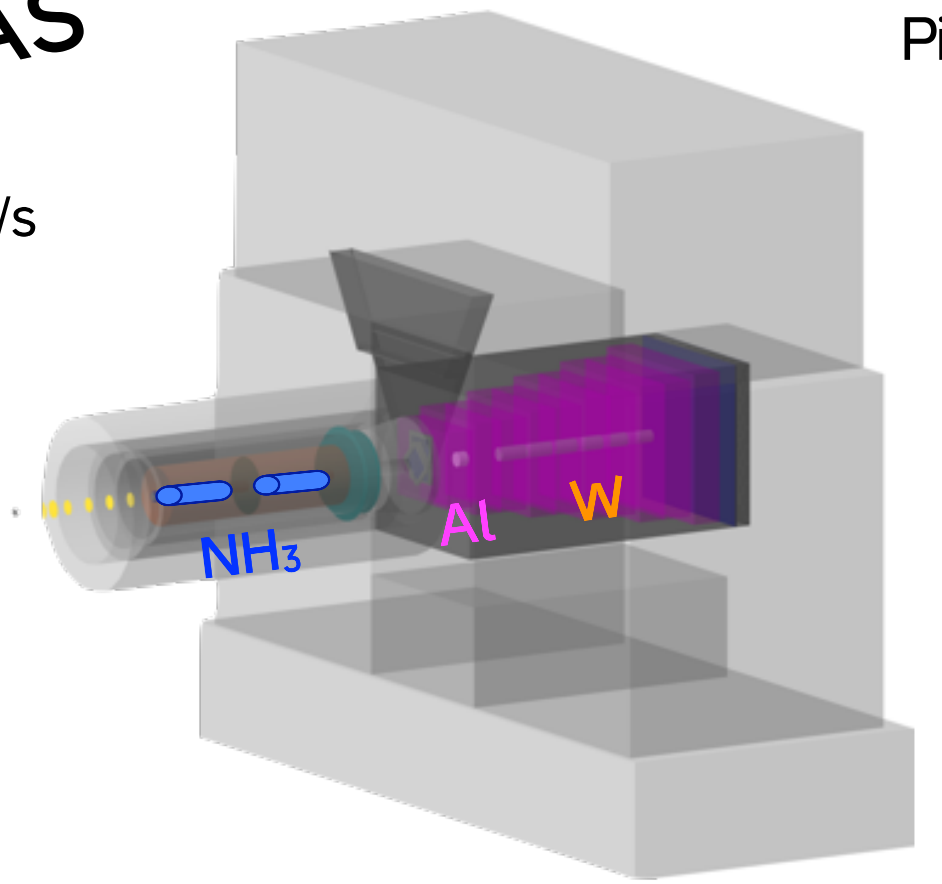


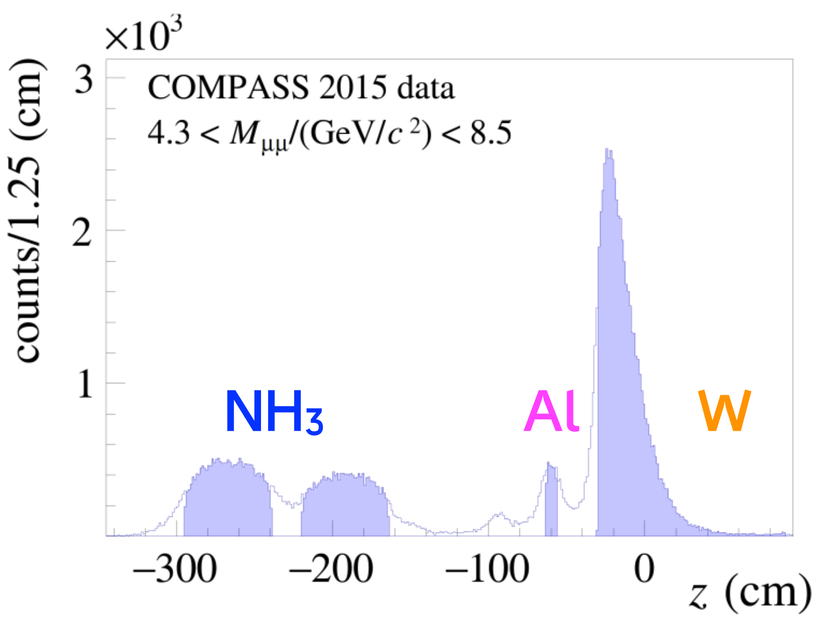
- Enforced LAS tracking (DC05, PixelMicroMegas), new DAQ …

π^- beam

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

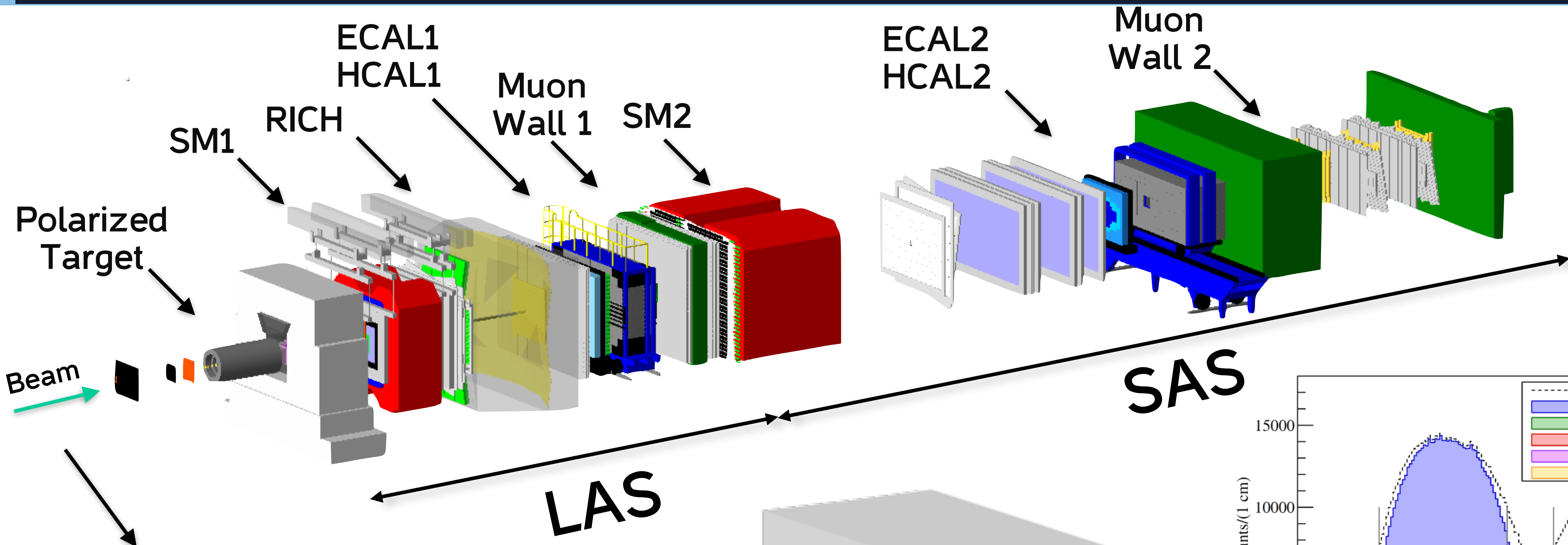
Target	# of cells	Polarization
NH_3	2	T, ~73 %





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

COMPASS SETUP (DY)



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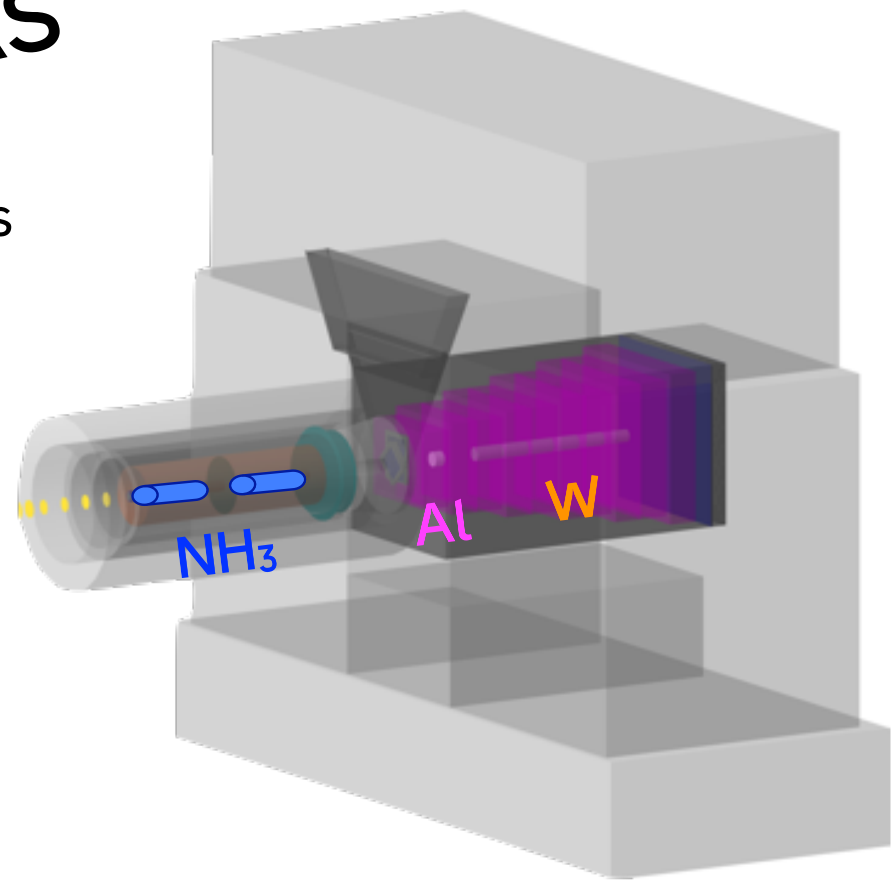

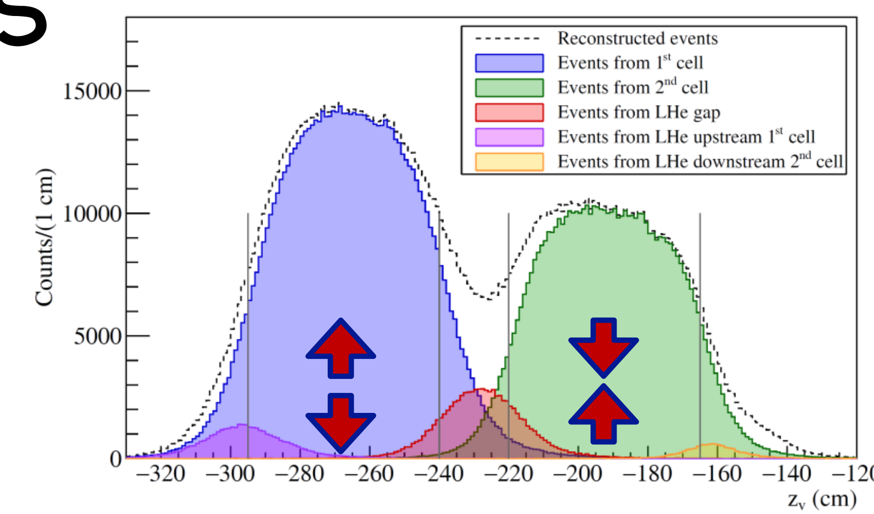

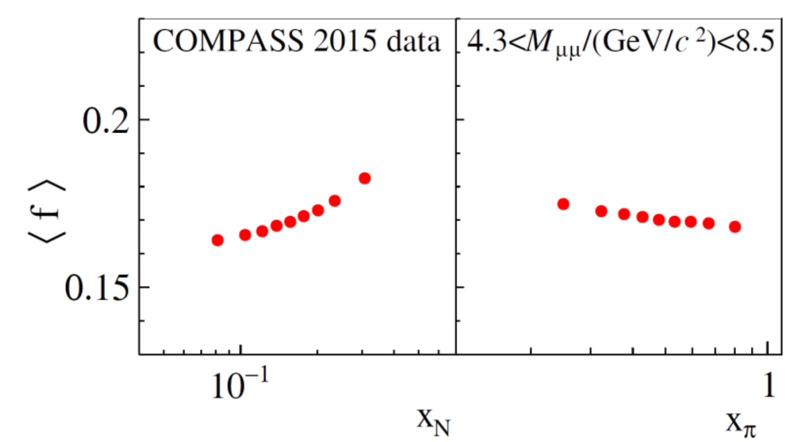

Fraction of polarizable material in the target

DY AND SIDIS CROSS-SECTIONS @ LO

SIDIS on transversely polarized nucleons

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

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

Pion induced polarized Drell-Yan

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

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 ⟷	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$	Pretzelosity ⟷	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$
$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$	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)

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

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

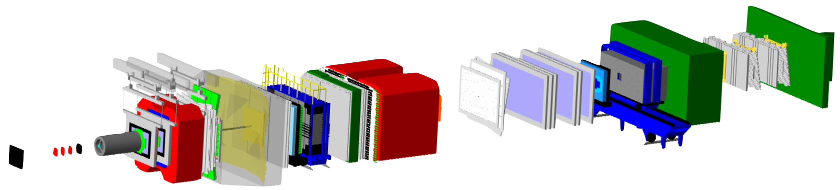
$$f_{1T,p}^{\perp q}|_{SIDIS} = -f_{1T,p}^{\perp q}|_{DY}$$

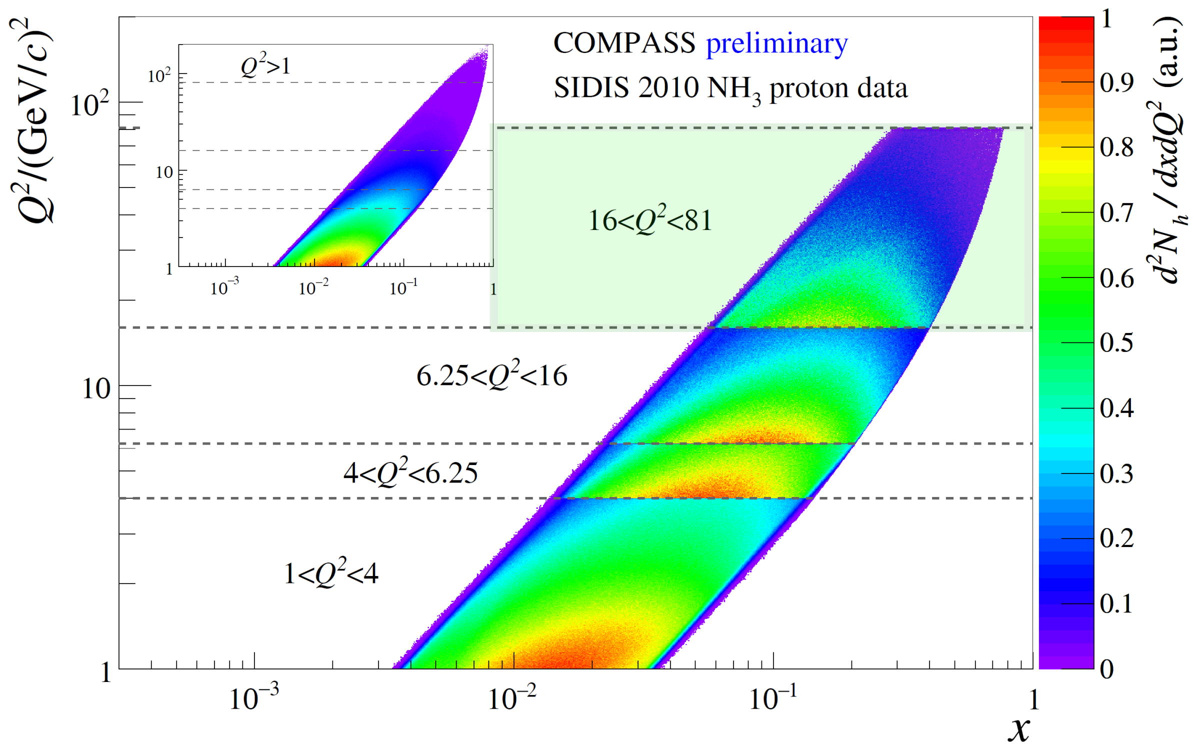
$$h_{1,p}^{\perp q}|_{SIDIS} = -h_{1,p}^{\perp q}|_{DY}$$

COMPASS SIDIS-DY BRIDGE

SIDIS on transversely polarized nucleons

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





Pion induced polarized Drell-Yan

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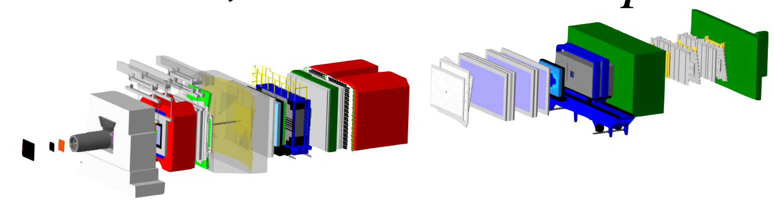
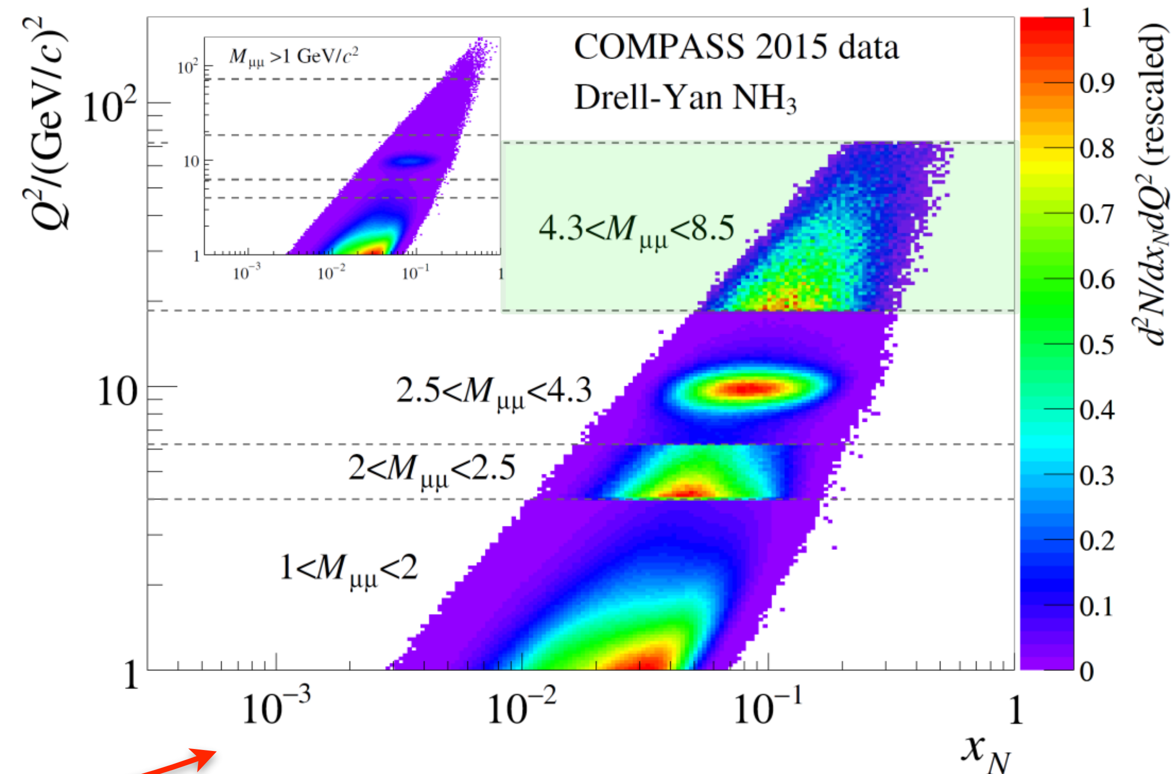




Comparable x:Q² kinematic coverage

minimization of possible Q² evolution effects

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

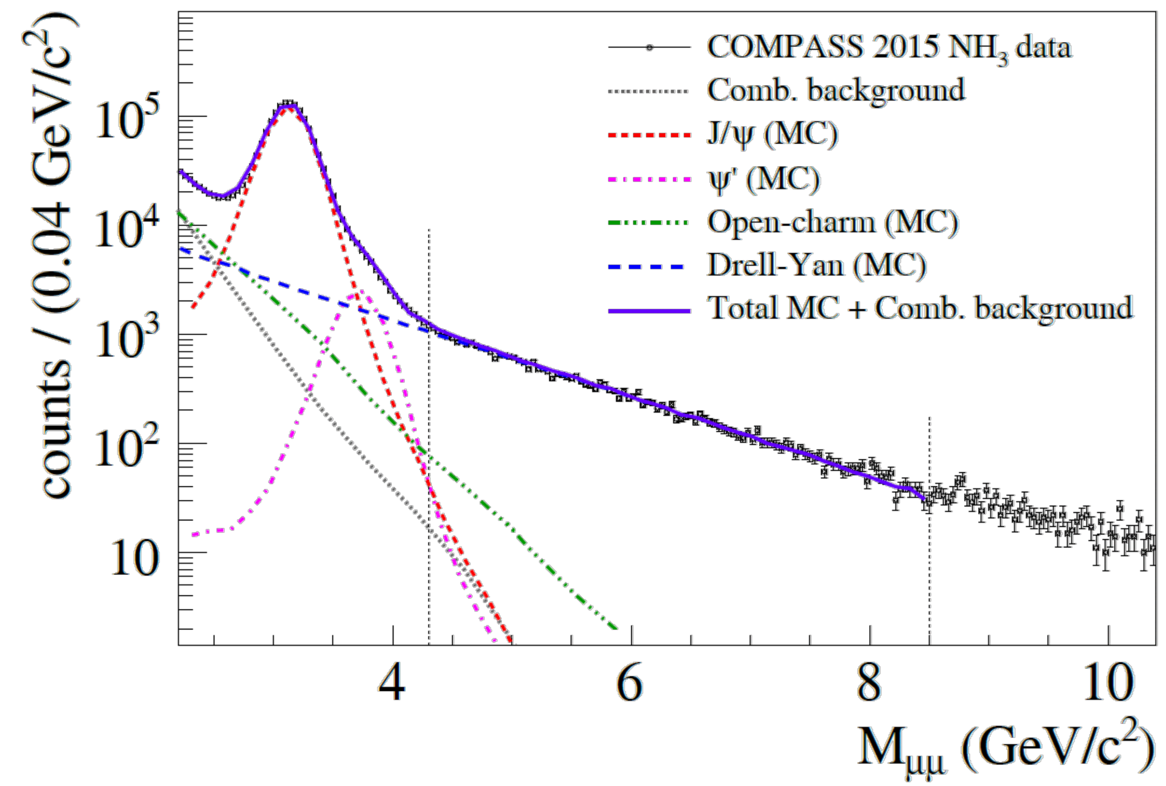
DRELL-YAN MEASUREMENTS AT COMPASS

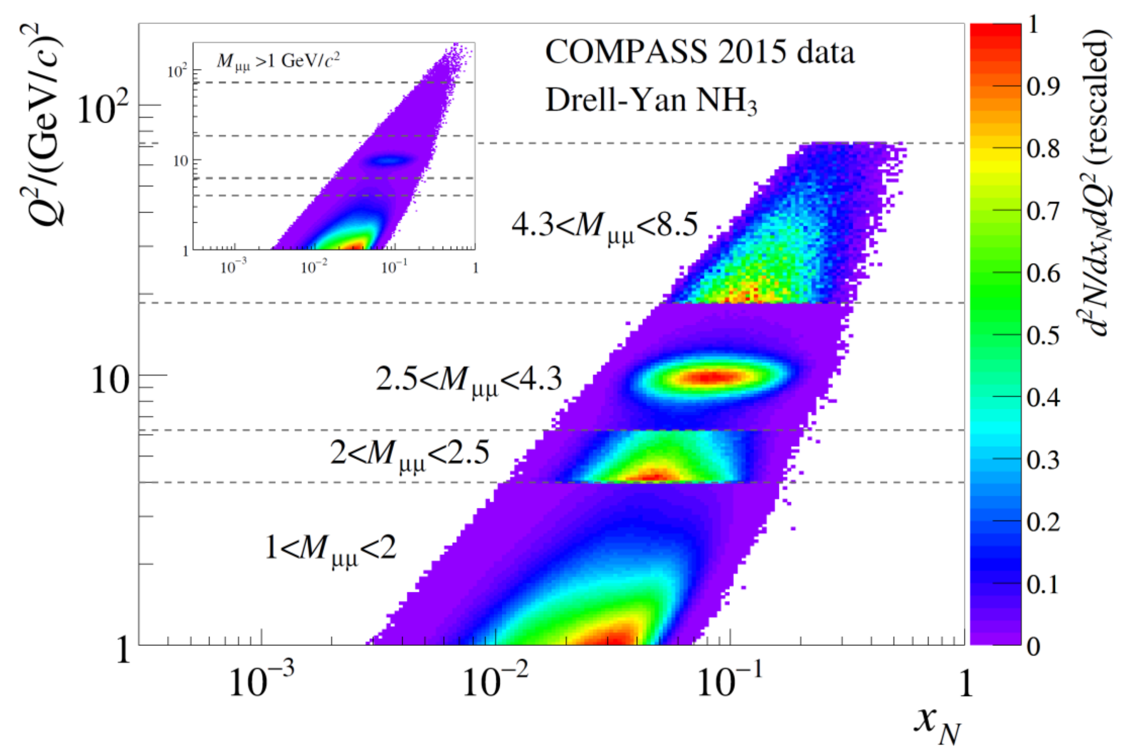
I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
- Large background contamination

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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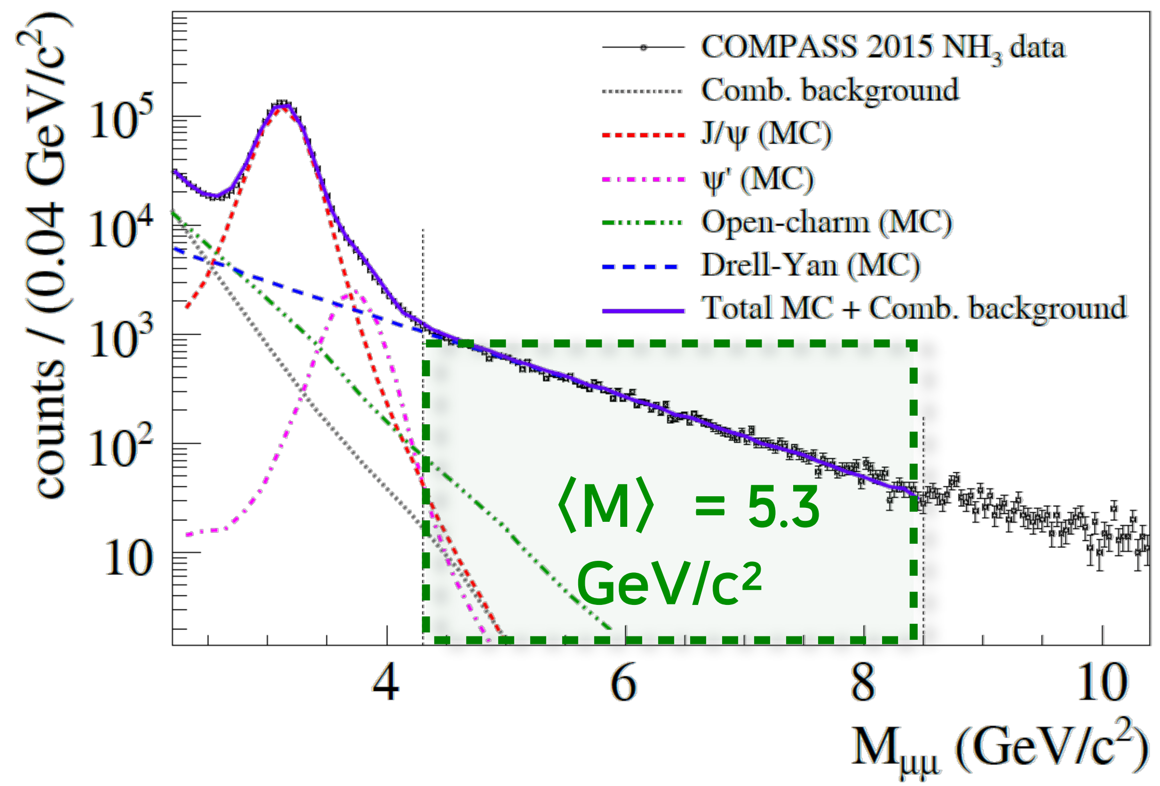
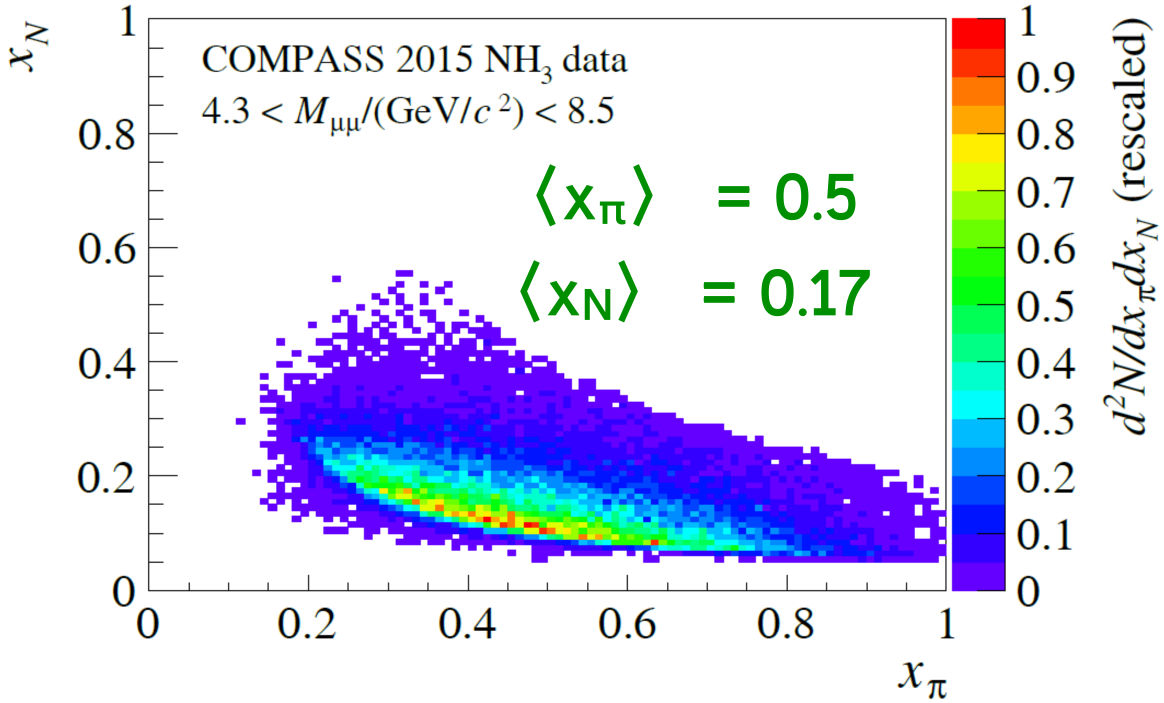
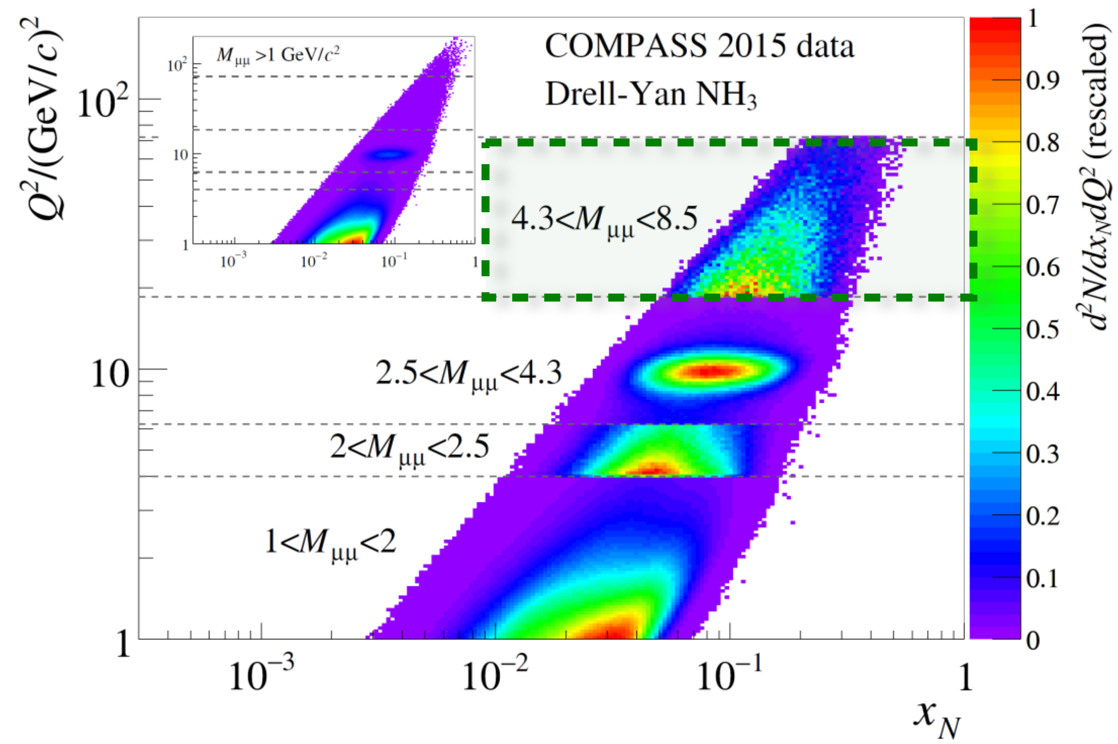




HM events are in the valence quark region



Drell-Yan measurements at COMPASS

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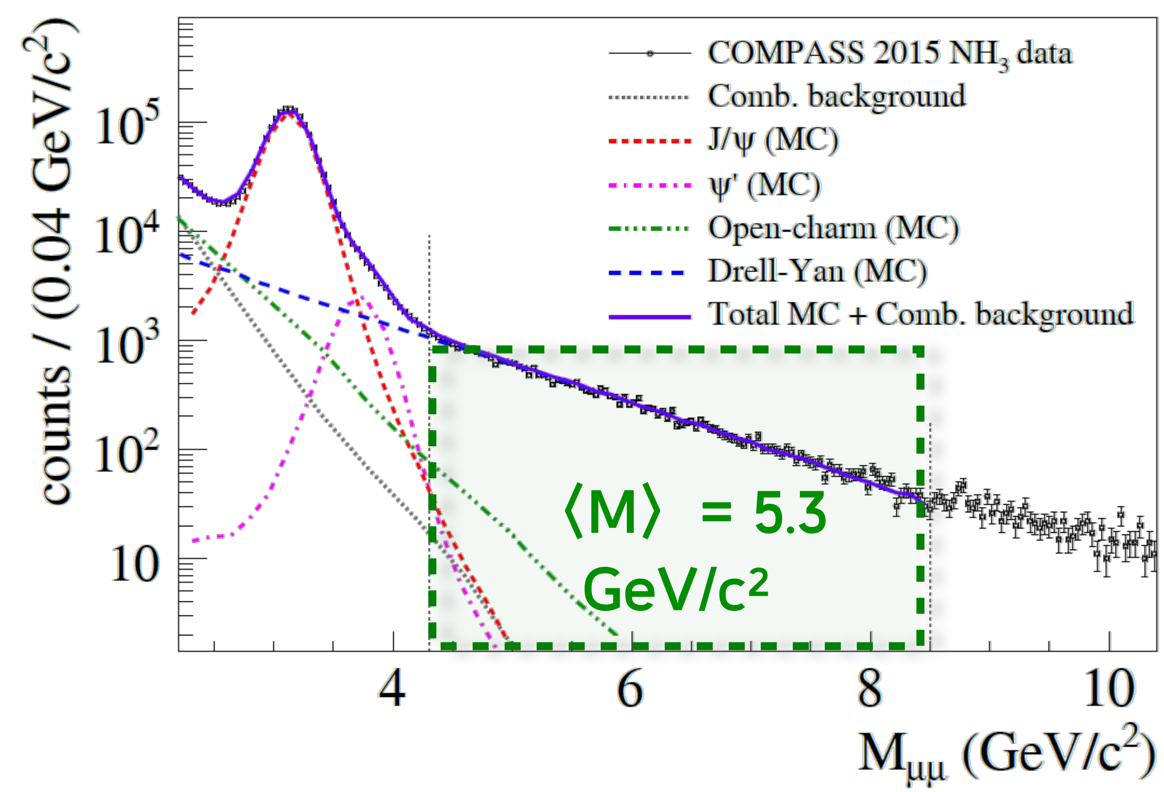
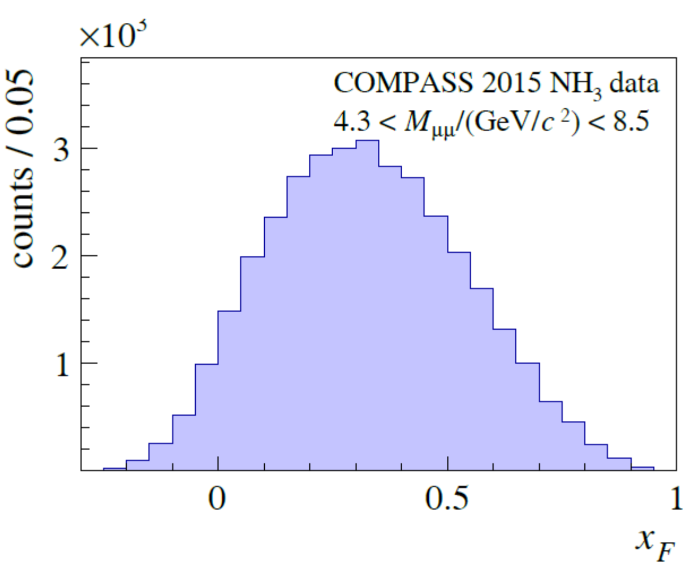
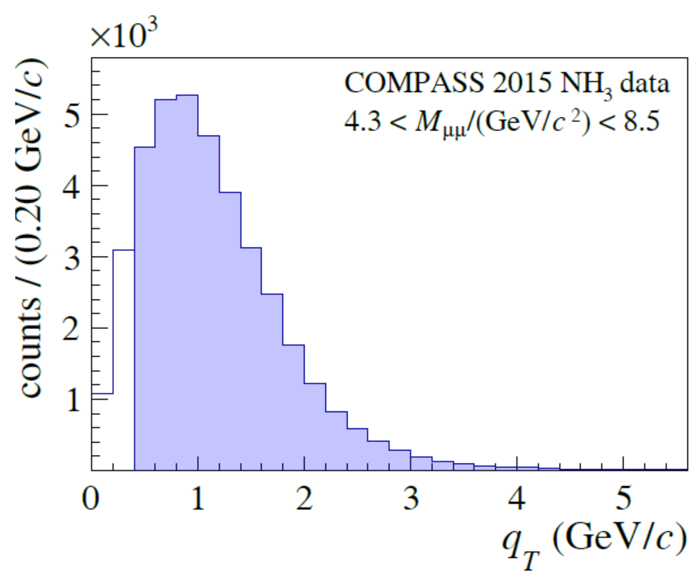


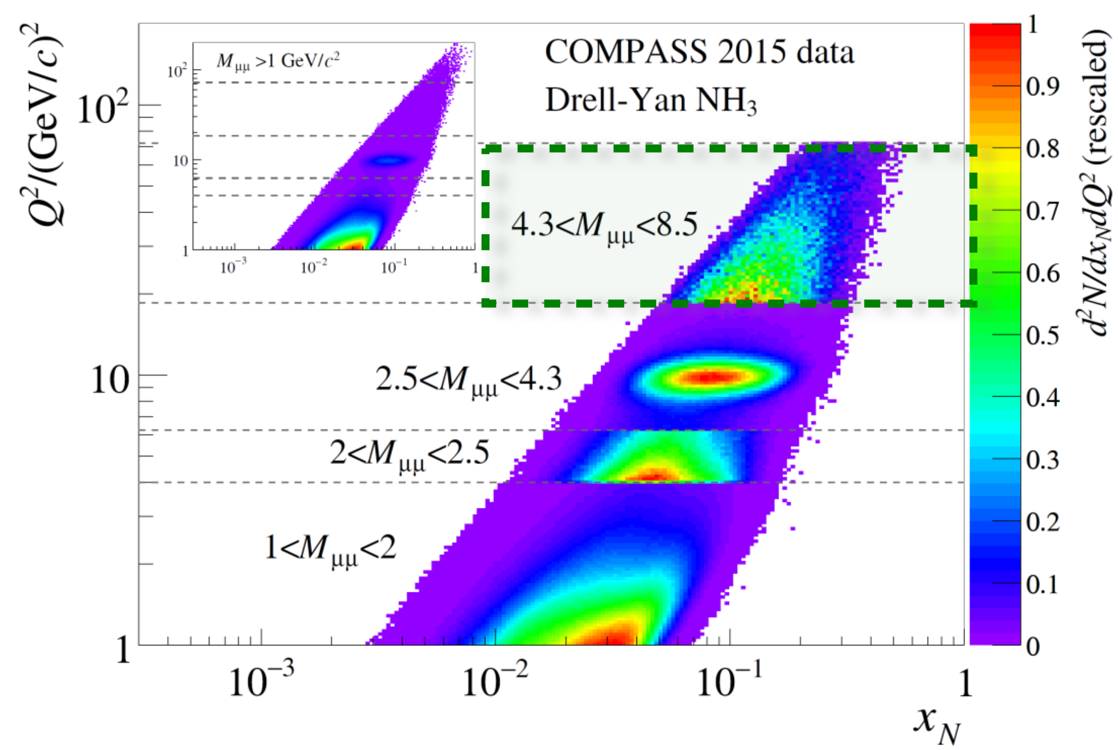
$q_T > 0.4$ GeV/c

$\langle x_F \rangle = 0.33$

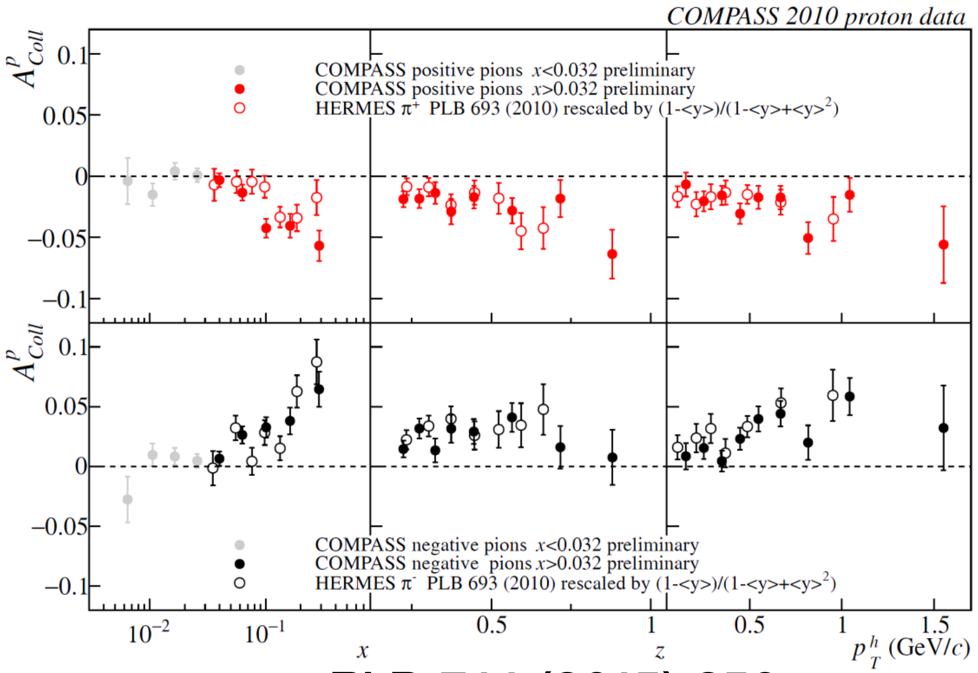
$\langle q_T \rangle = 1.17$ GeV/c



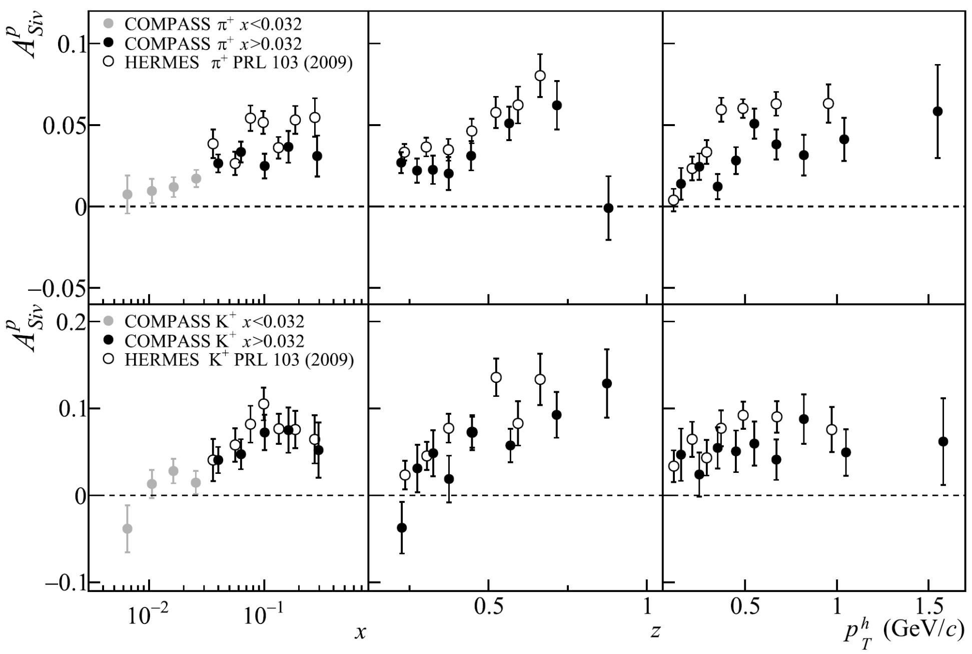




$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$$



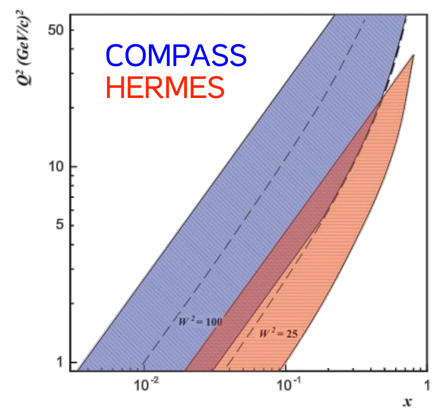
PLB 744 (2015) 250



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

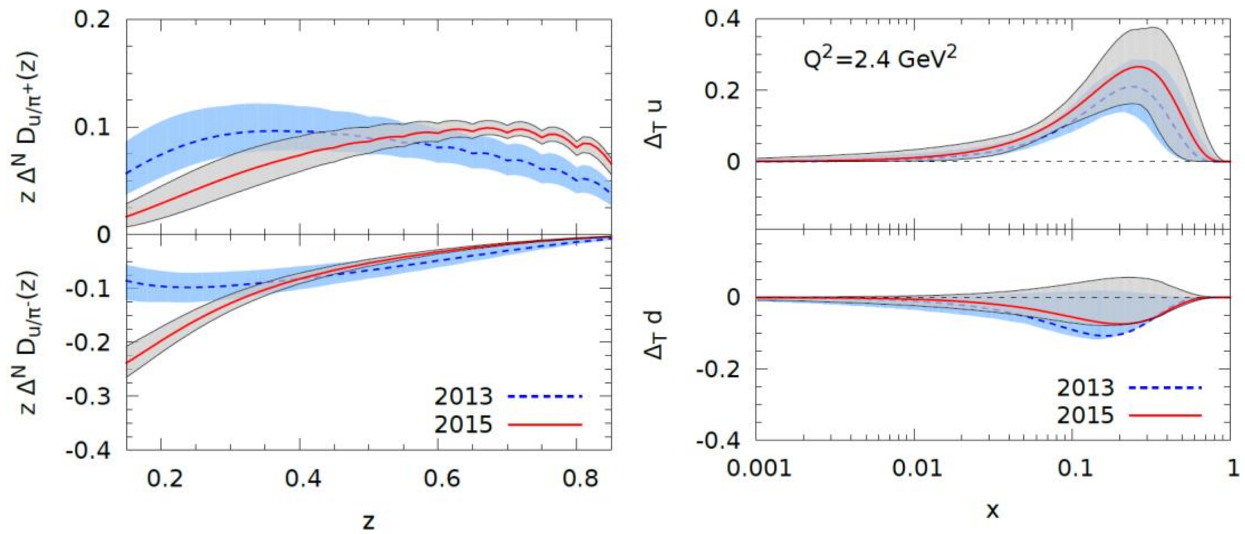
See talk by A.Martin

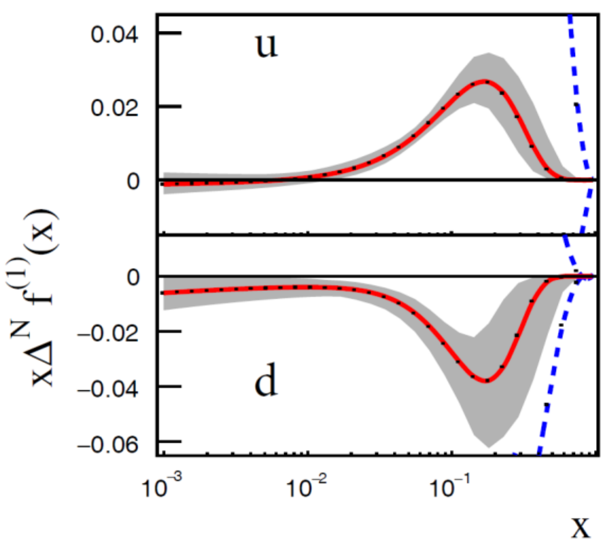
- Compatible results COMPASS/ HERMES for Collins effect
- No Q^2 evolution effects?



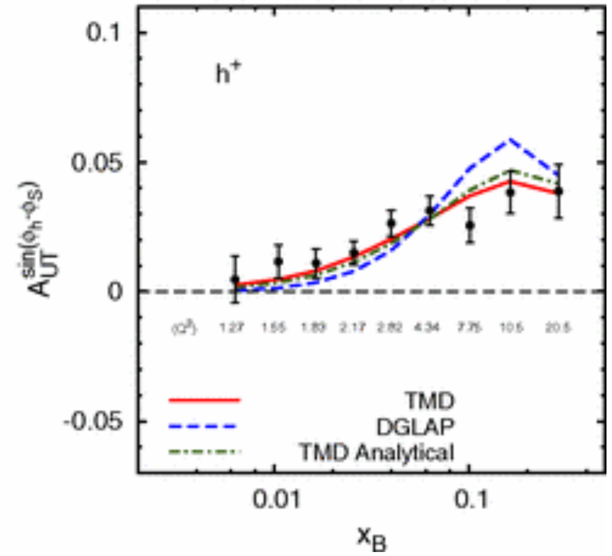
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
- Q^2 evolution effects?

Anselmino et al., Phys.Rev. D92 (2015) 114023
Global fit of HERMES - COMPASS - BELLE data



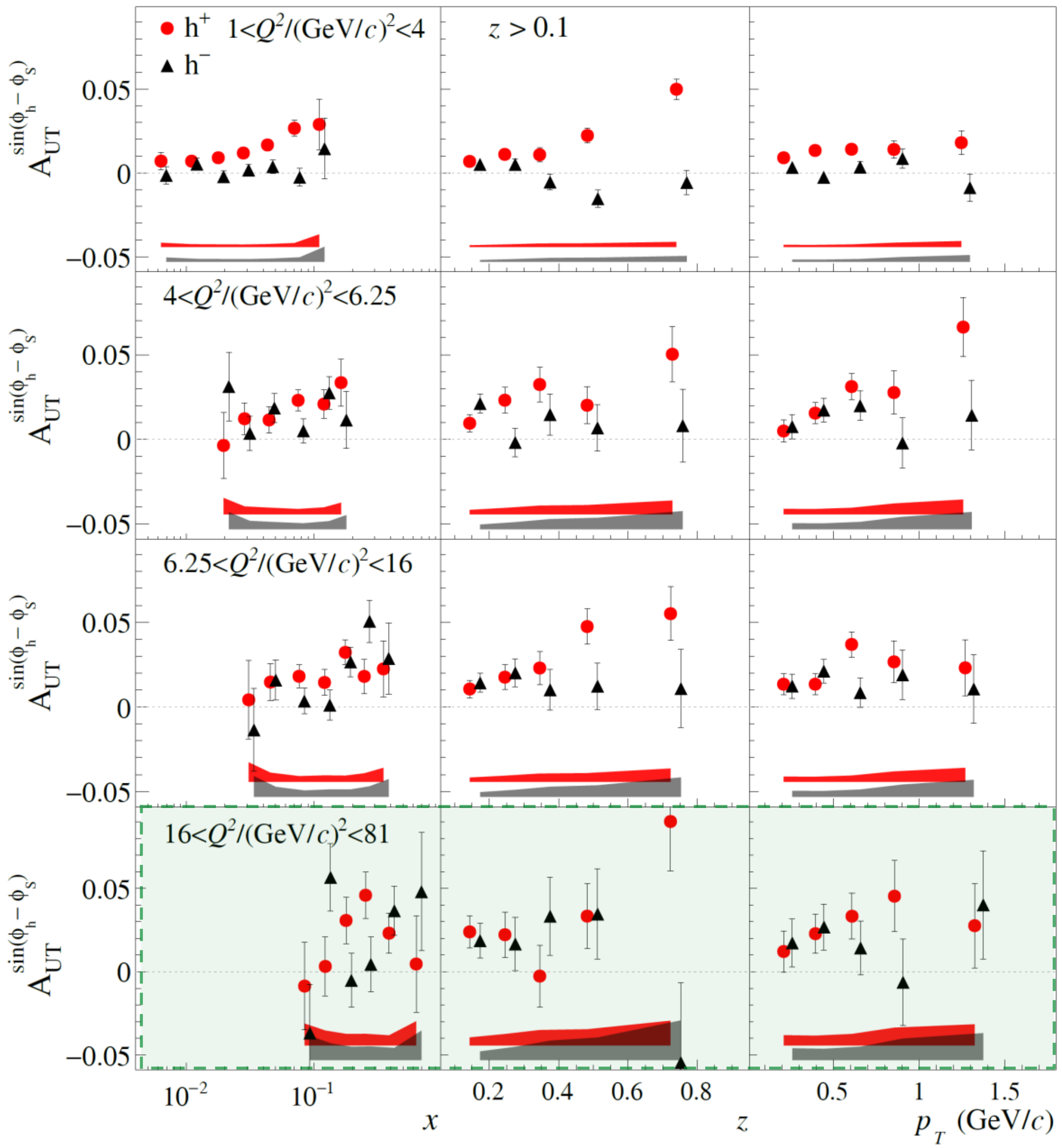


Anselmino et al.,
JHEP 1704 (2017)046

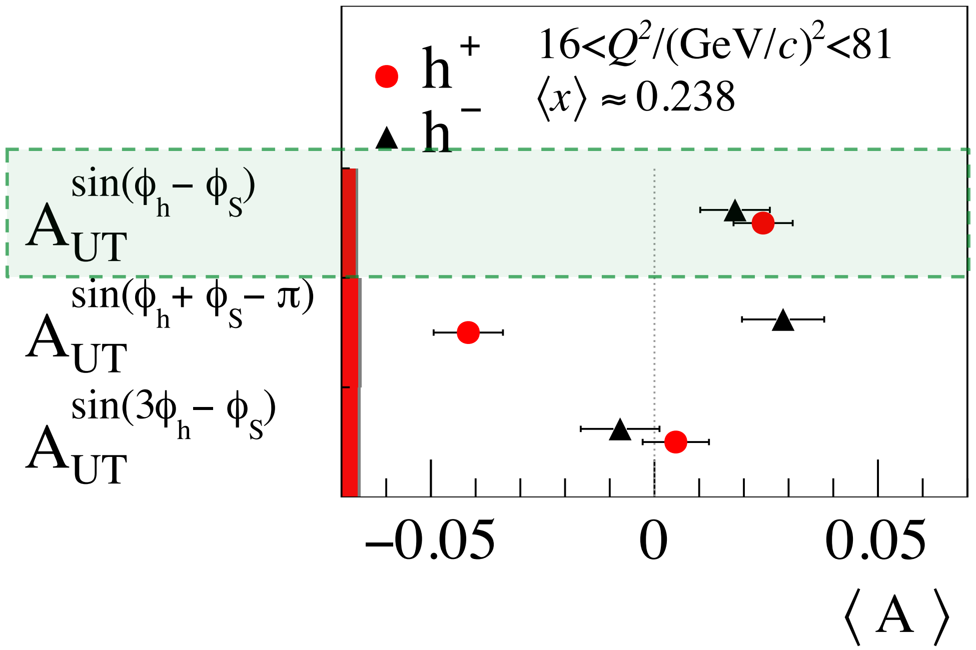


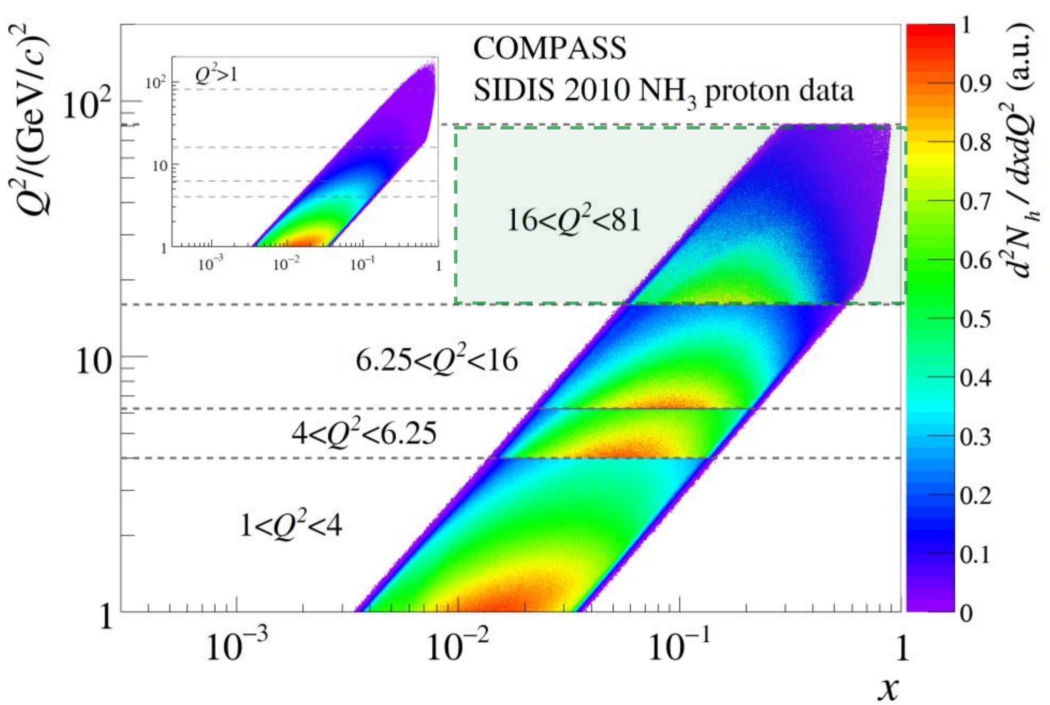
Anselmino et al.,
PRD 86 (2012) 014028

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+;

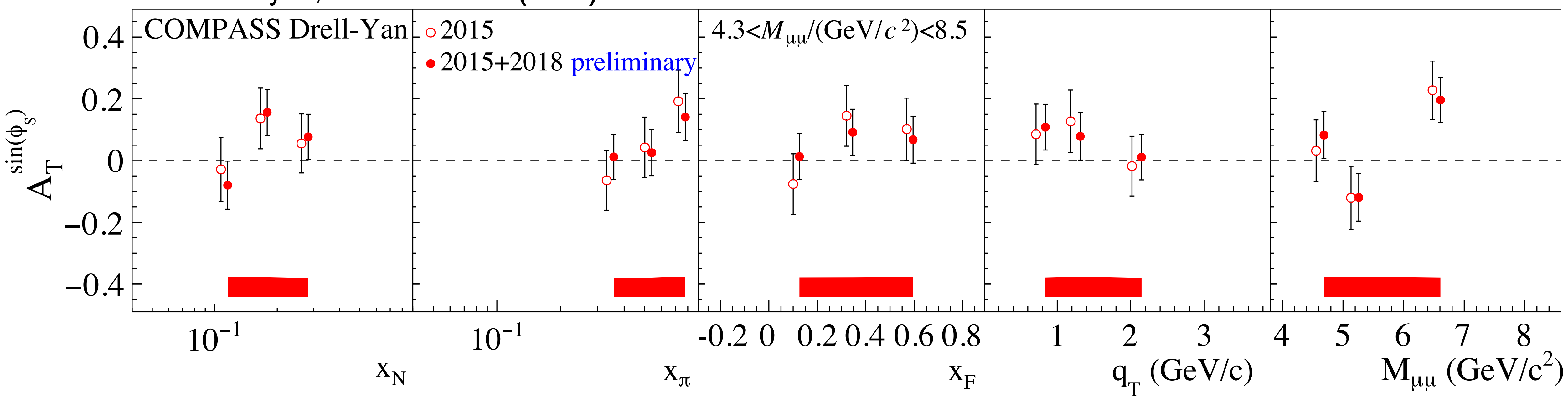
DY HM TSA RESULTS: SIVERS

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

DY - HM range

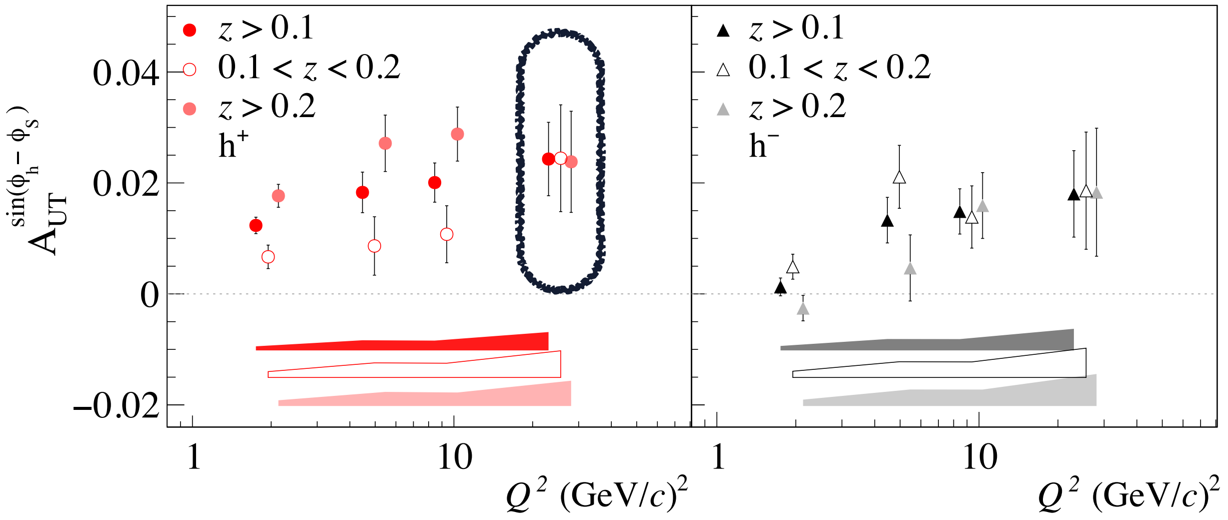
- ○ COMPASS, PRL 119 112002 (2017)
- ● COMPASS, **2015 + 2018 (~50%) preliminary**

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



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

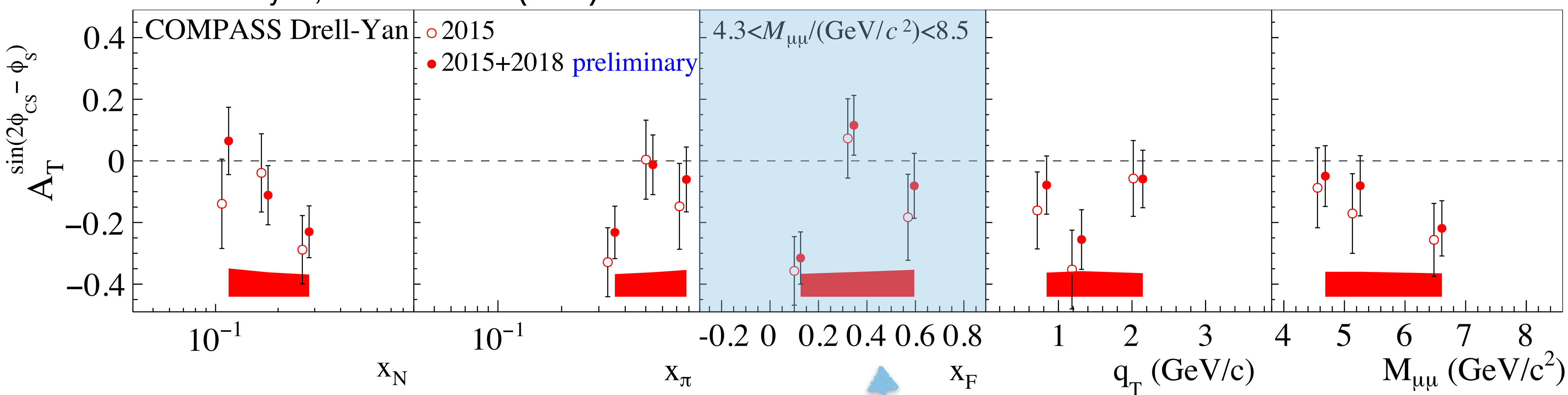
Full 2018 DY data analysis ongoing!

DY HM TSA RESULTS: TRANSVERSITY

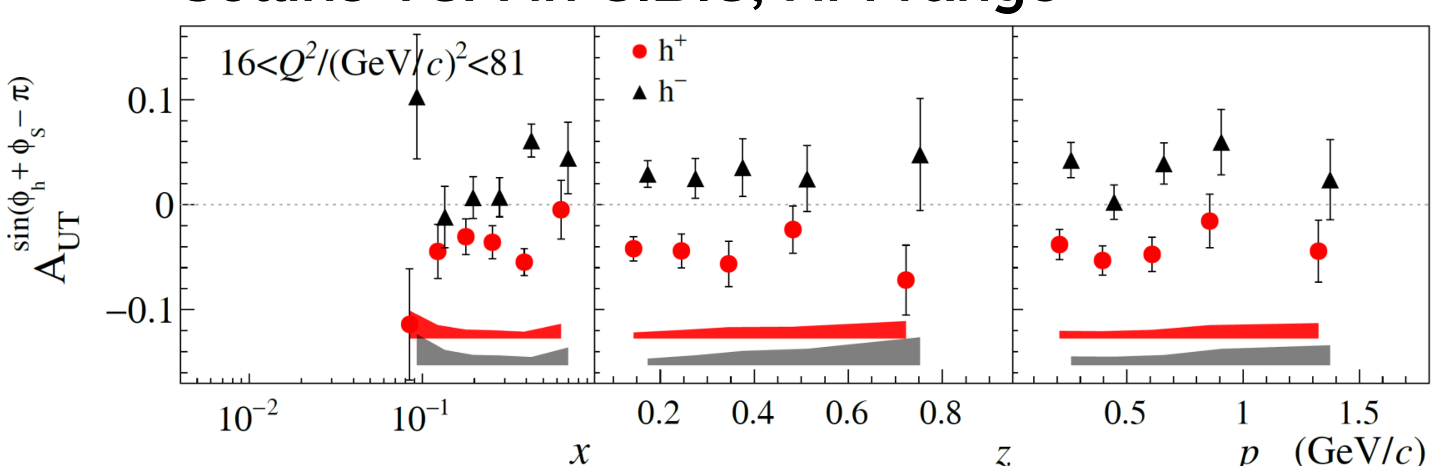
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$ **DY - HM range**

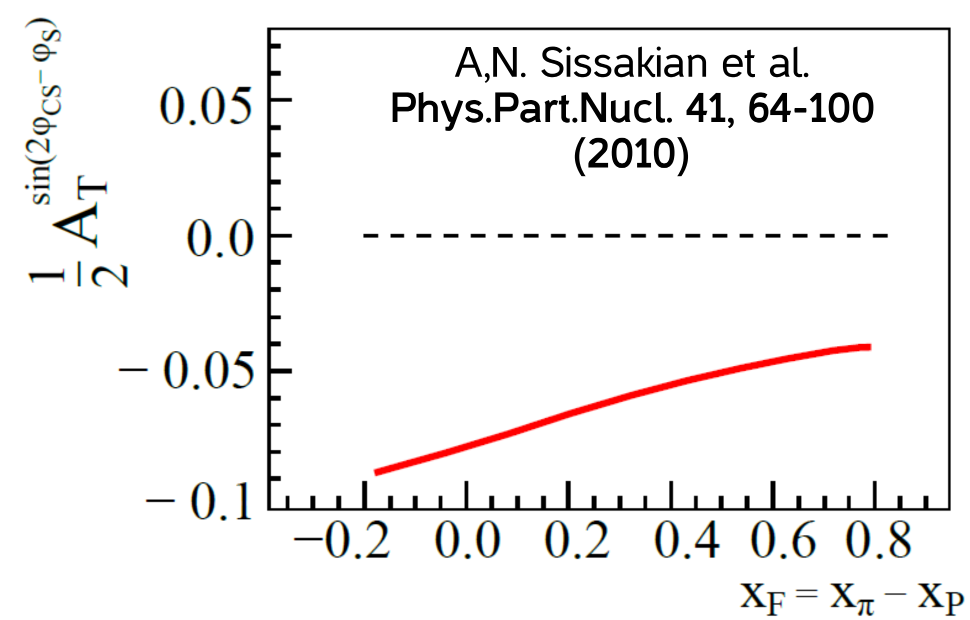
- ○ COMPASS, PRL 119 112002 (2017)
- ● COMPASS, **2015 + 2018 (~50%) preliminary**

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



Collins TSA in SIDIS, HM range





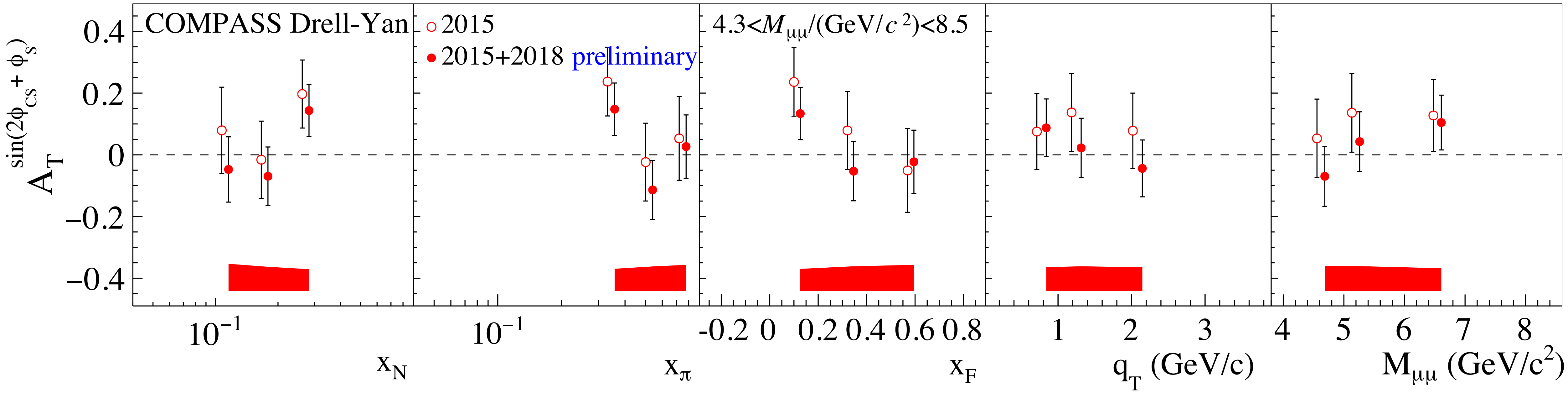
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$ COMPASS, PLB 770 (2017) 138

DY HM TSA RESULTS: PRETZELOSITY

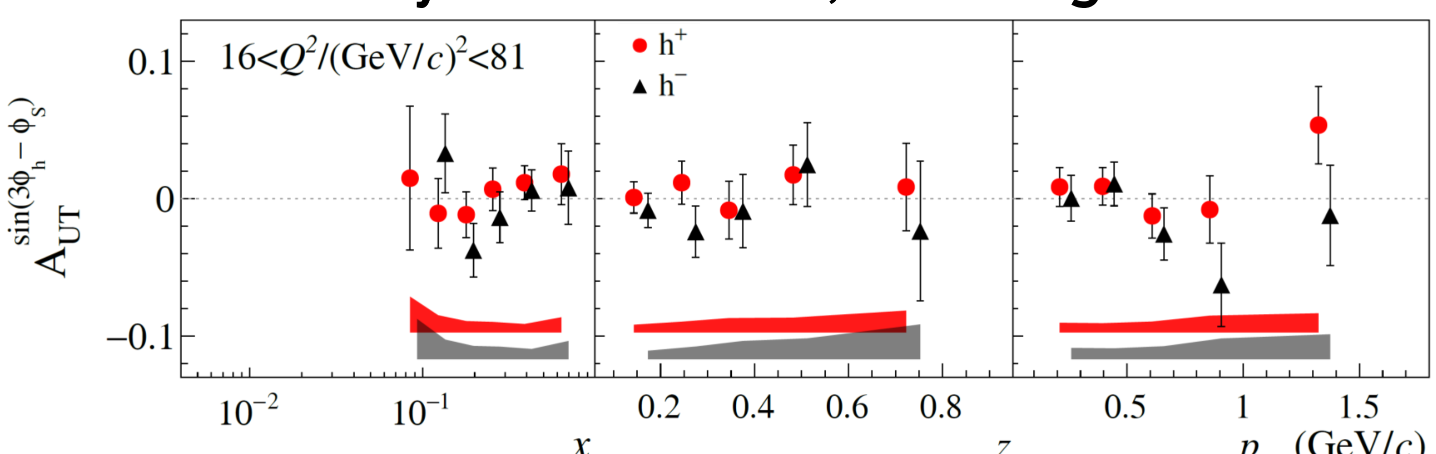
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$ **DY - HM range**

- ○ COMPASS, PRL 119 112002 (2017)
- ● COMPASS, **2015 + 2018 (~50%) preliminary**

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

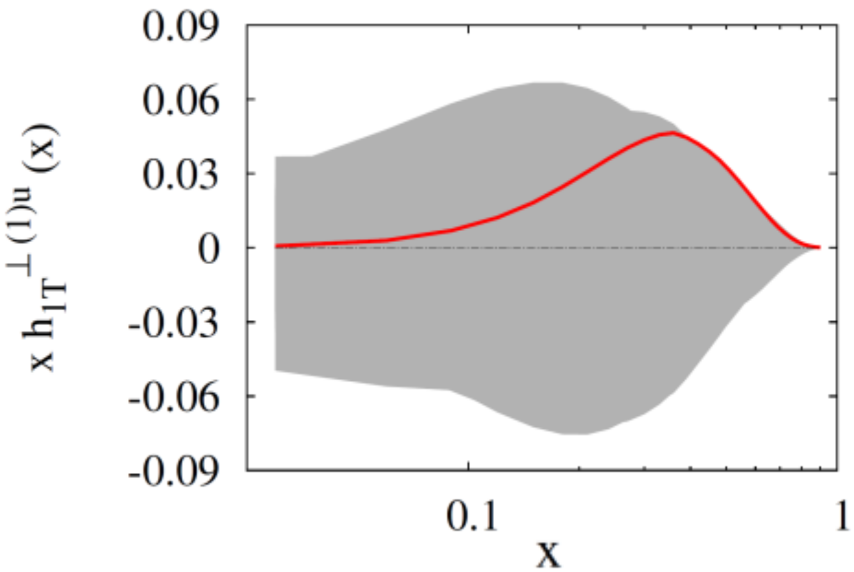


Pretzelosity TSA in SIDIS, HM range



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

COMPASS, PLB 770 (2017) 138

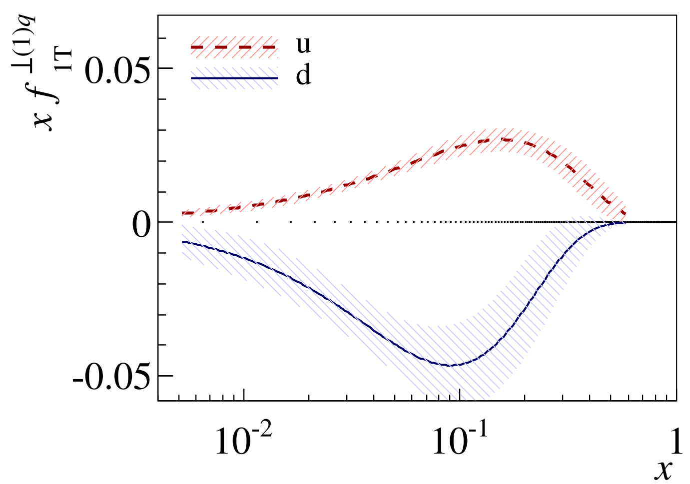


C.Lefky, A.Prokudin
PRD91 (2015) 034010

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);
- Recently measured in SIDIS by COMPASS;
- Complementary way to test the Sivers sign-change!

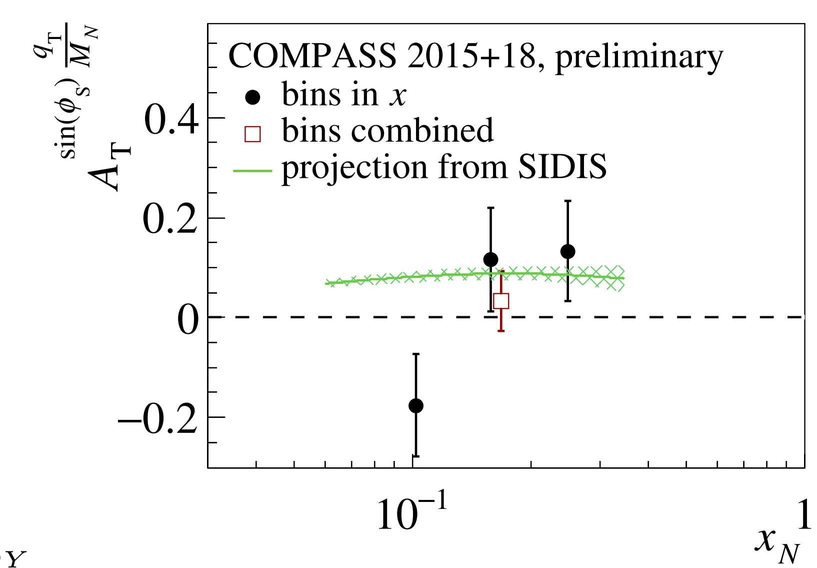
	SIDIS	Drell-Yan
TSA	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
wTSA	$A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM}} \propto f_{1T}^{\perp q(1)} \times D_{1q}^{h}$	$A_T^{\sin\varphi_S\frac{q_T}{M_N}} \propto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



1[st] 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

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



See dedicated talk by J.Matoušek!

COMPASS DY FUTURE ARRIVALS

ARRIVALS – 2020/2021

- TRANSVERSE SPIN ASYMMETRIES IN J/PSI
- DY & J/PSI UNPOLARIZED ASYMMETRIES
- DY & J/PSI ABSOLUTE CROSS-SECTION
- NUCLEAR DEPENDENCE OF DY

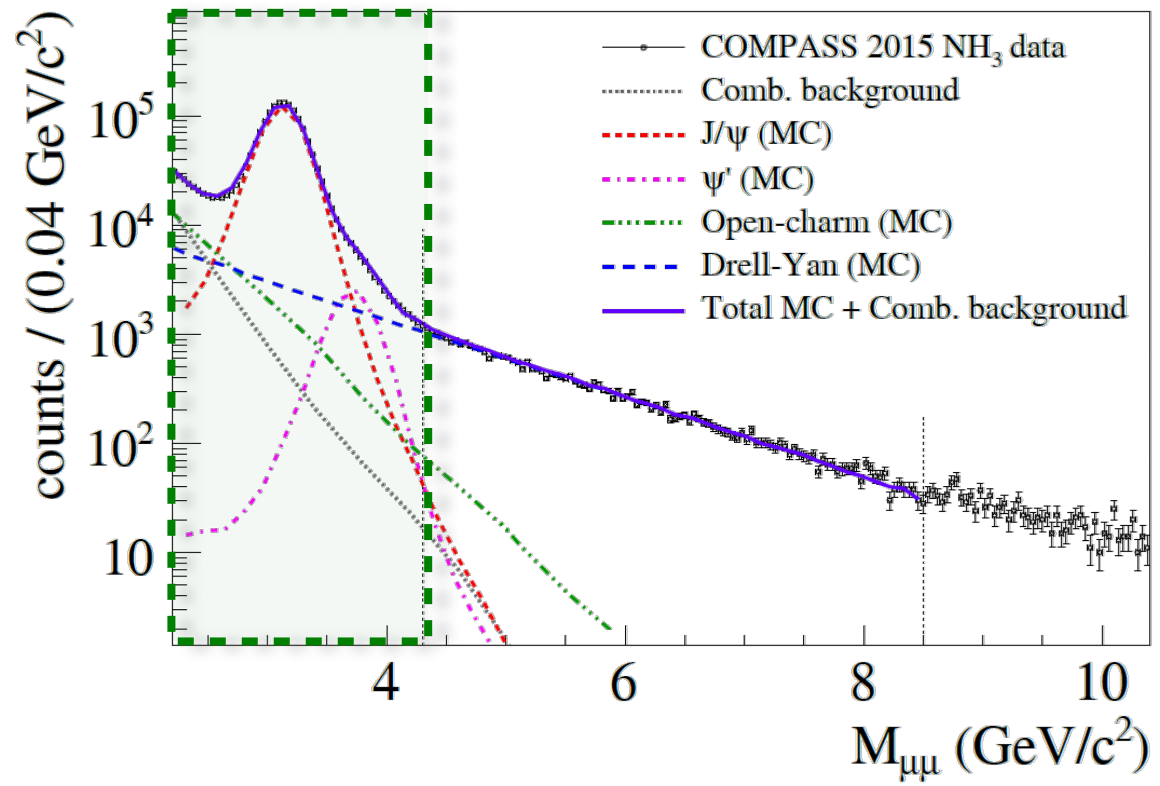
TSAs IN J/ψ RANGE

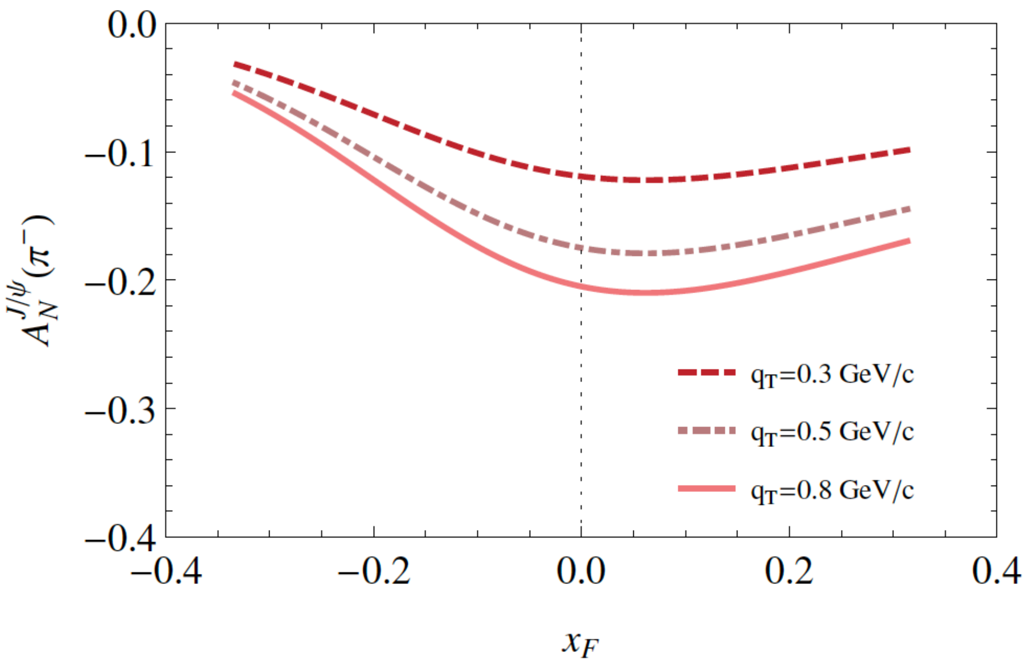
I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
  - Large background contamination

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

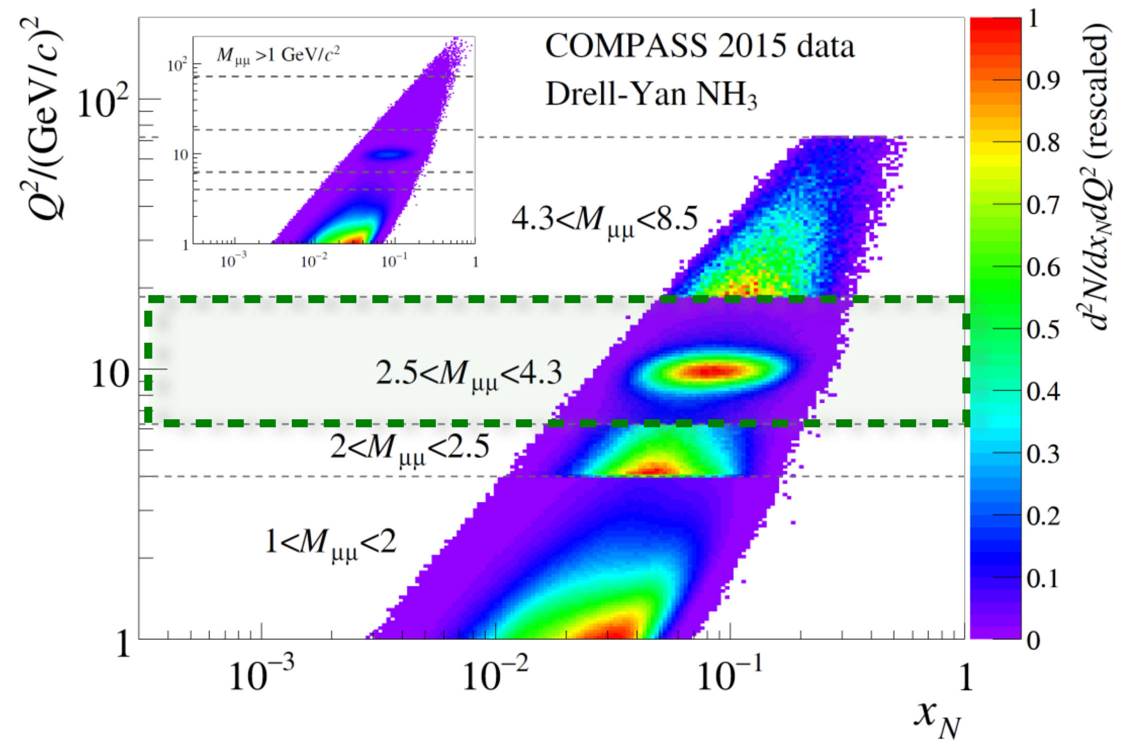
III. $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$, "Charmonia mass"
  - Strong J/ψ signal → Studies of J/ψ physics.
  - Good signal/background.

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





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

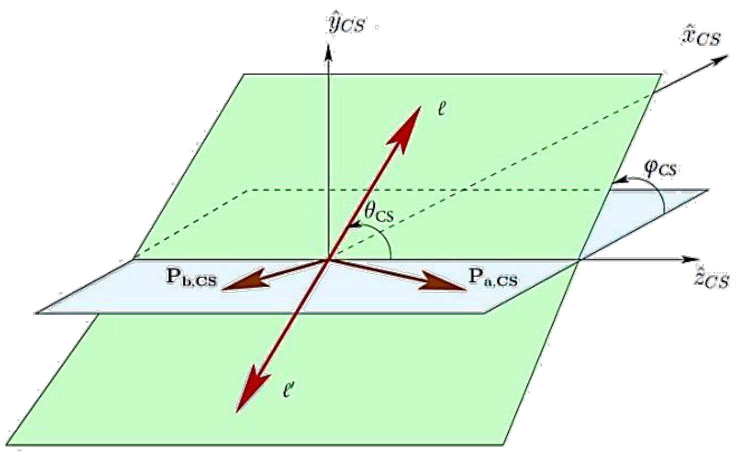


DY UNPOLARIZED CROSS-SECTION

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

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

Collins-Soper Frame



3 Unpolarized Asymmetries (UAs)

$$\lambda = A_U^1 \quad , \quad \mu = A_U^{\cos\varphi_{CS}} \quad , \quad \nu = 2A_U^{\cos 2\varphi_{CS}}$$

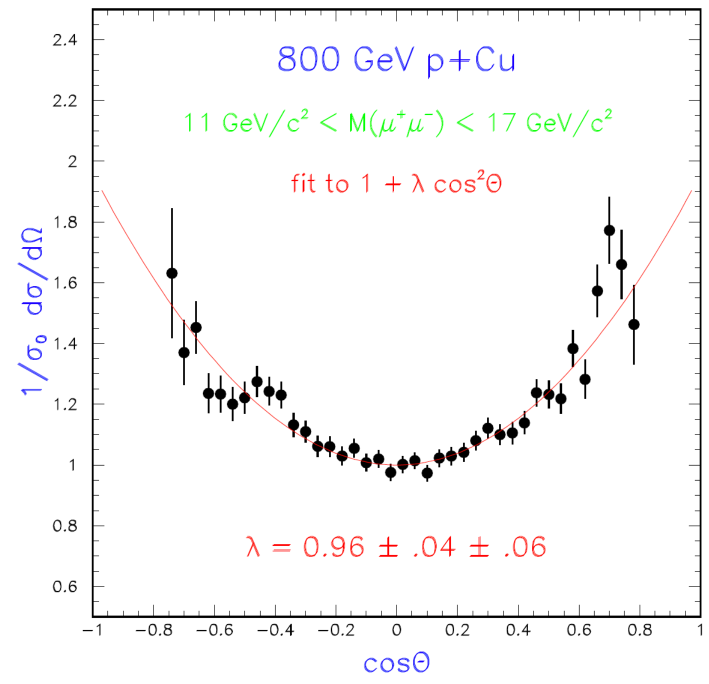
- Values of λ, μ and ν depends on the reference frame definition.
- In the naive Drell-Yan process, the virtual photon is produced purely by the electromagnetic $q+\bar{q}$ annihilation.

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

- 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;

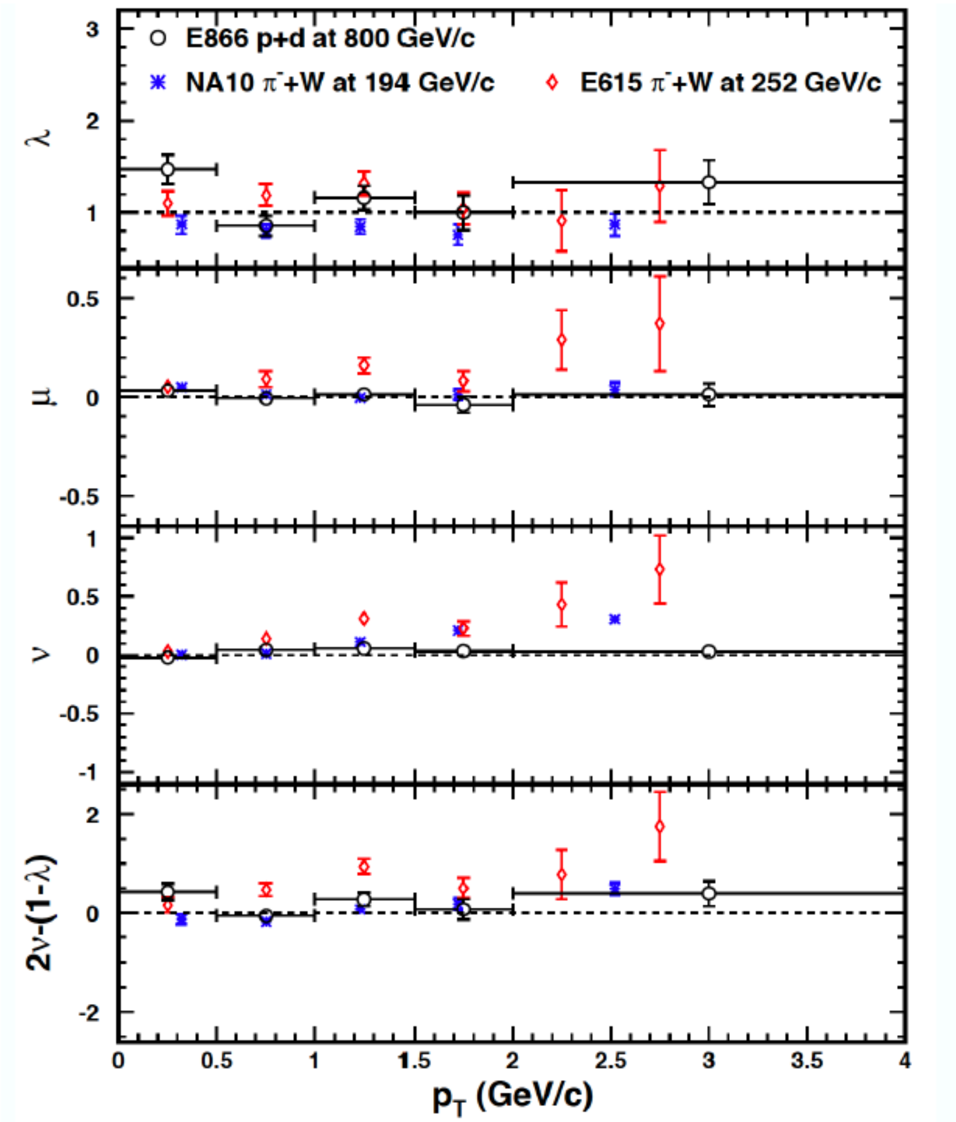


FNAL E772 Data (Ann. Rev. Nucl. Part. Sci. 49 (1999) 217-253)

UAs: NON-PERTURBATIVE EFFECT?

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

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

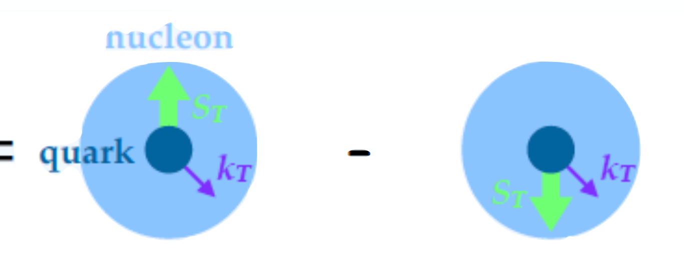


E615,
π⁻ (252 GeV) + W
PRD 39, 92 (1989)

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

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

- Sizable ν (cos 2φ) 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;

$h_1^{\perp q} =$ 

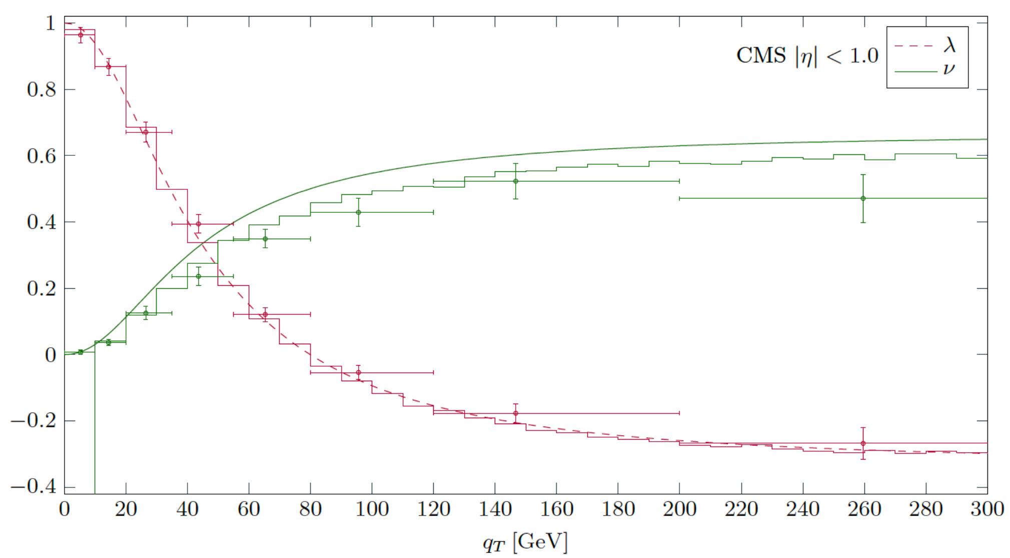
$$\frac{\nu}{2} \propto h_1^{\perp q}(p) \otimes h_1^{\perp \bar{q}}(\pi^-)$$

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

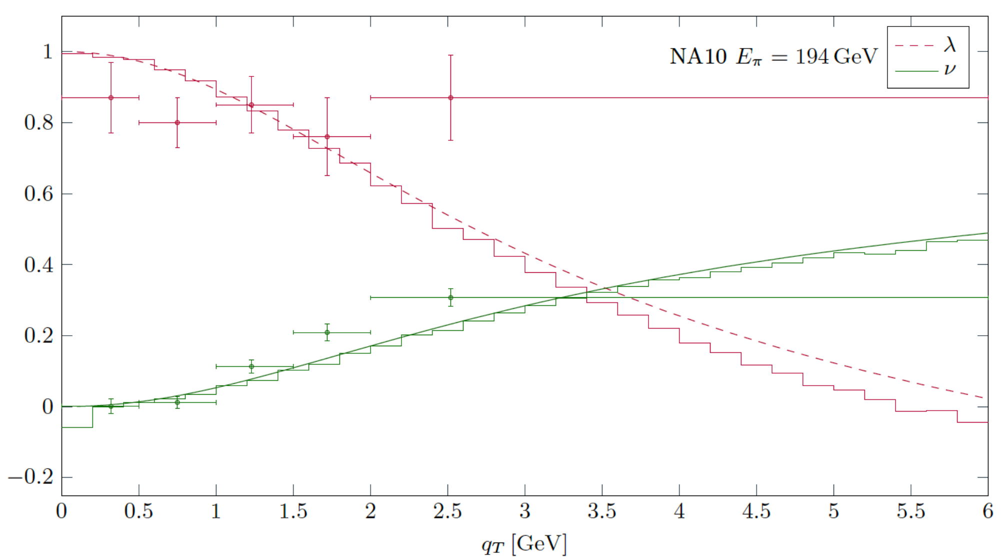
UAs: NLO EFFECT?

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

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



CMS, PLB 750 (2015)



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

Vogelsang and Lambertsen
PRD 93 (2016)

- Sizable ν (cos 2φ) asymmetry strongly dependent on q_T also measured by different experiments at colliders (CMS, CDF)
- Still room for non-perturbative Boer-Mulders effect?
- Room for explanation in terms of NLO effects
- At lower energies - and much lower $\langle q_T \rangle$ - the picture is far to be clear - more data are needed!

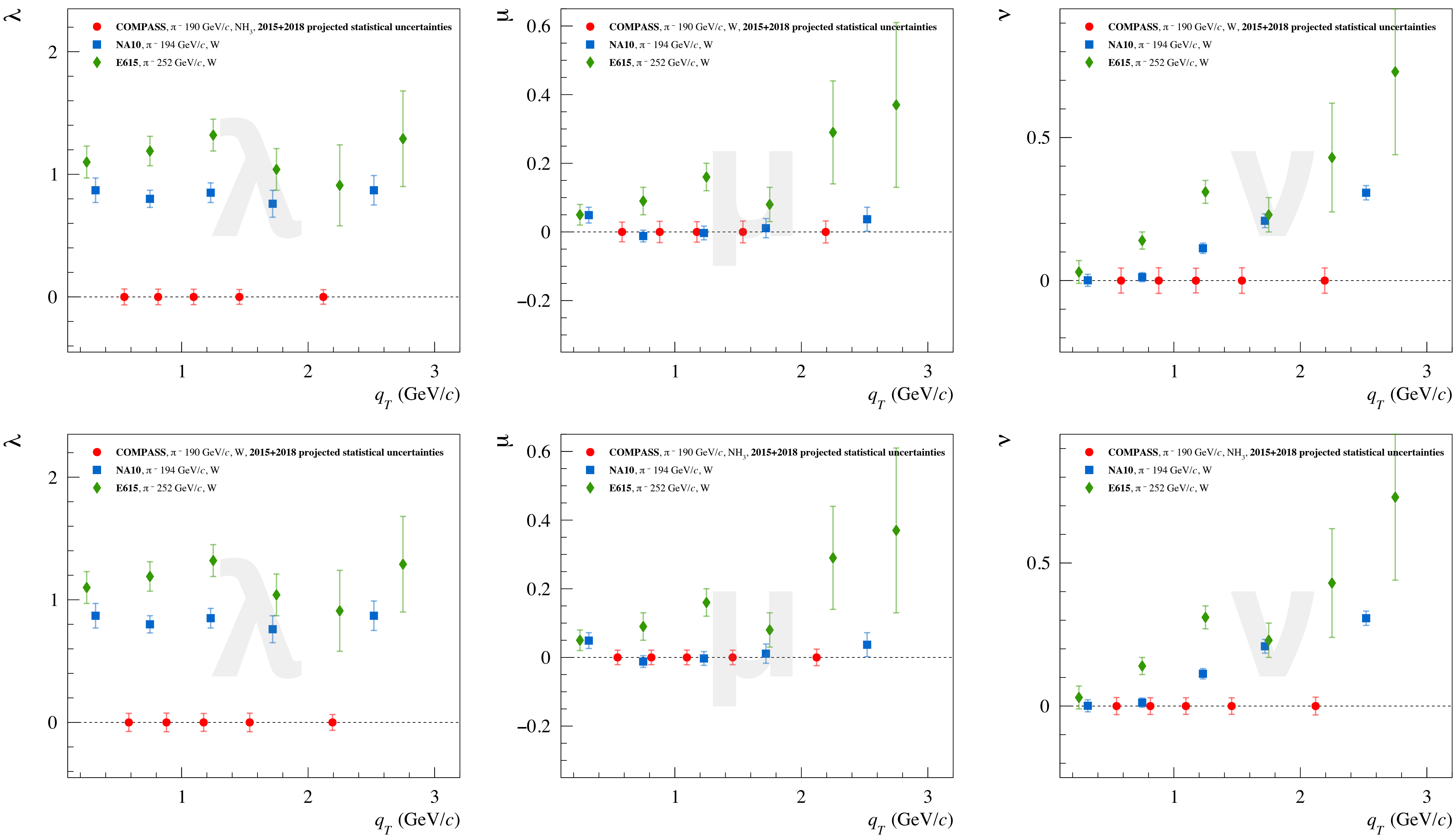
COMPASS

π^- (190 GeV) + NH_3

π^- (190 GeV) + W

UAs: COMPASS (future) input

- Unpolarized analysis requires detailed Montecarlo to correct for acceptance effect
- Constant work to improve MC description including important features (trigger efficiencies, detector efficiencies, etc.)

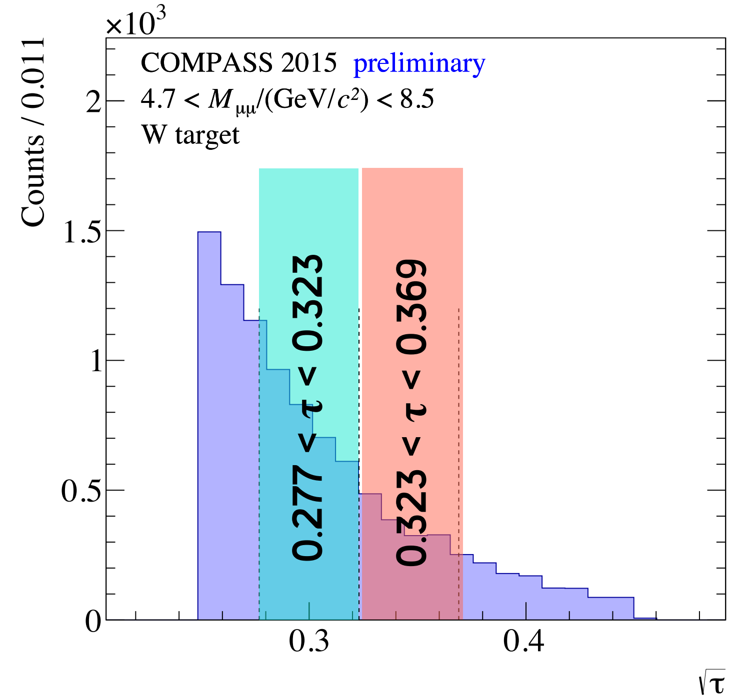


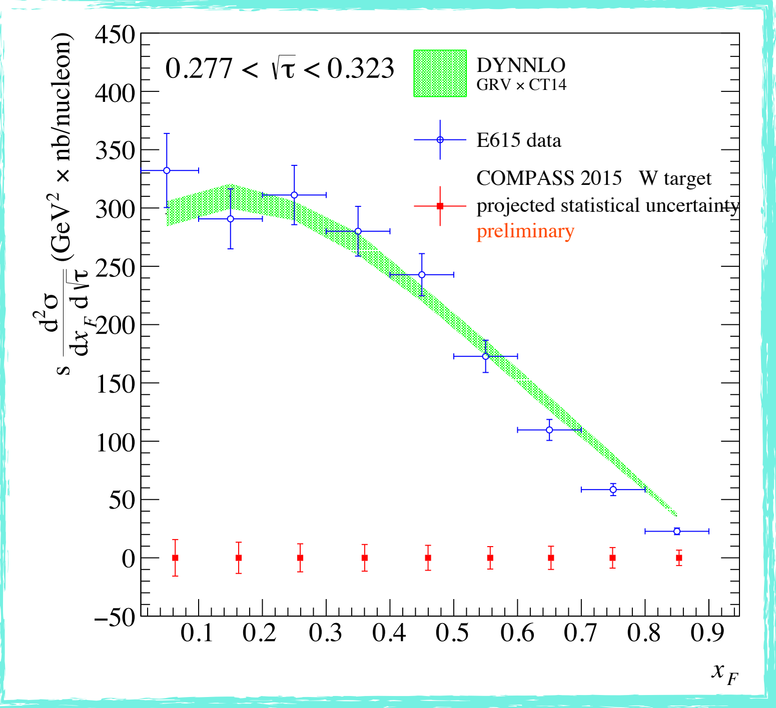
NH$_3$ target

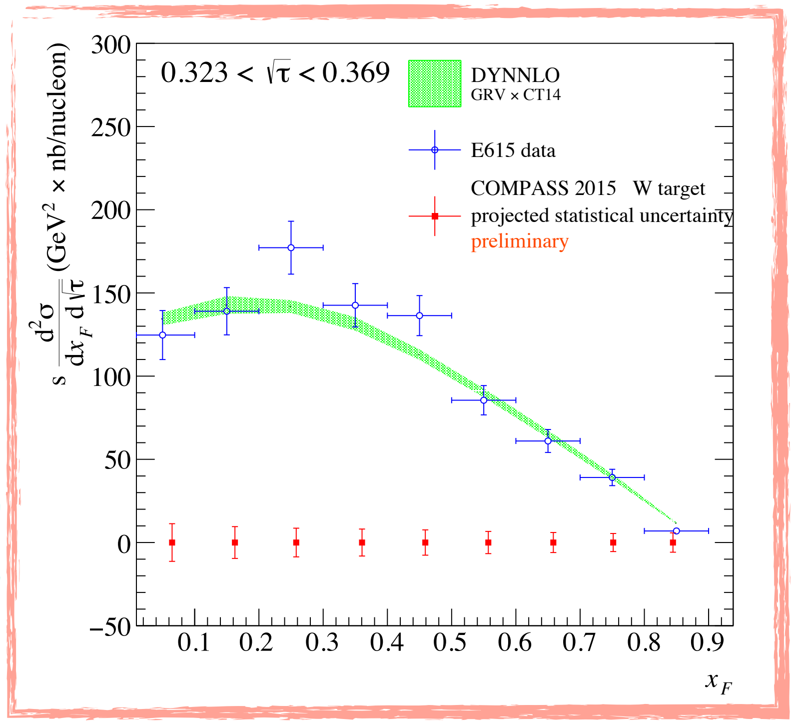
W target

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:
    - New 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**)
    - New 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 released
      - **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







ABSOLUTE DY CROSS-SECTION MEASUREMENT

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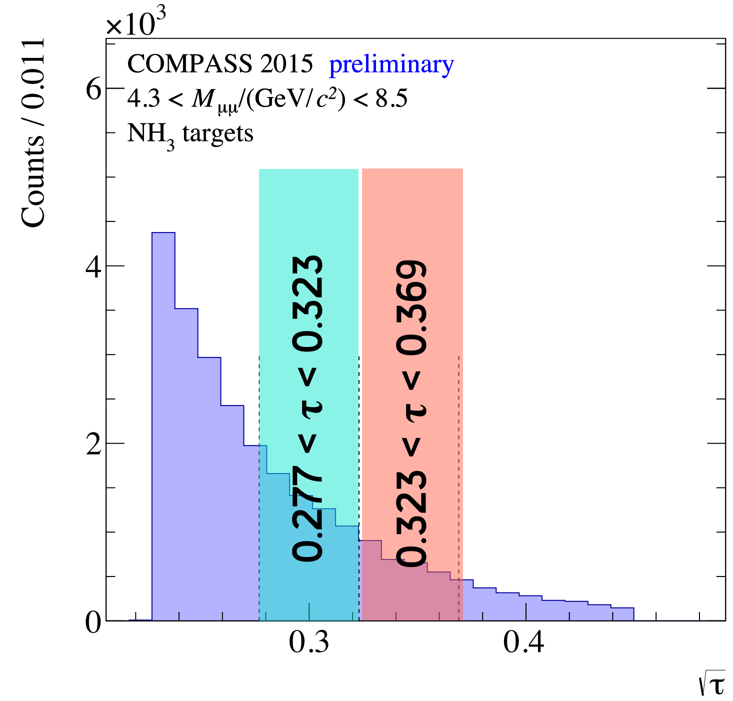
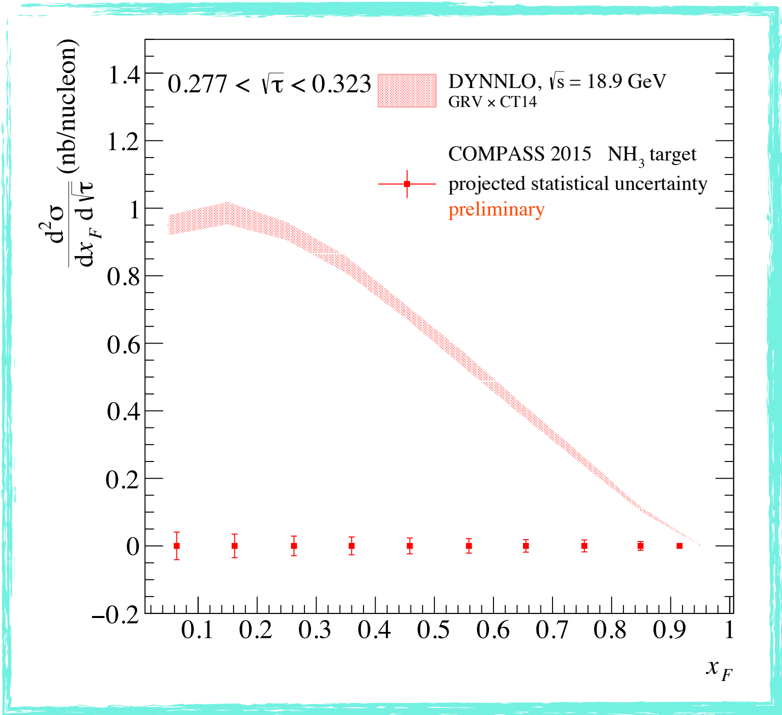
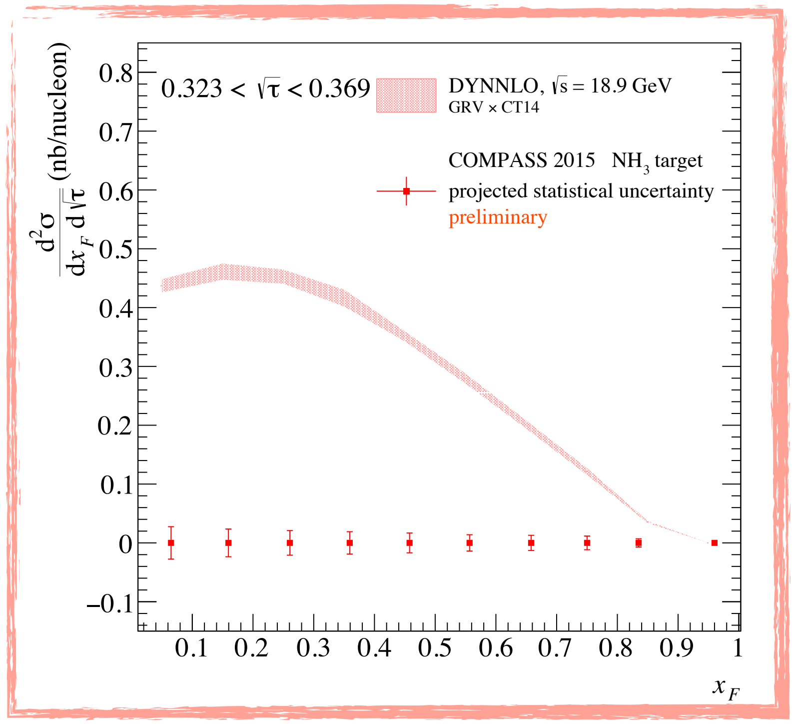
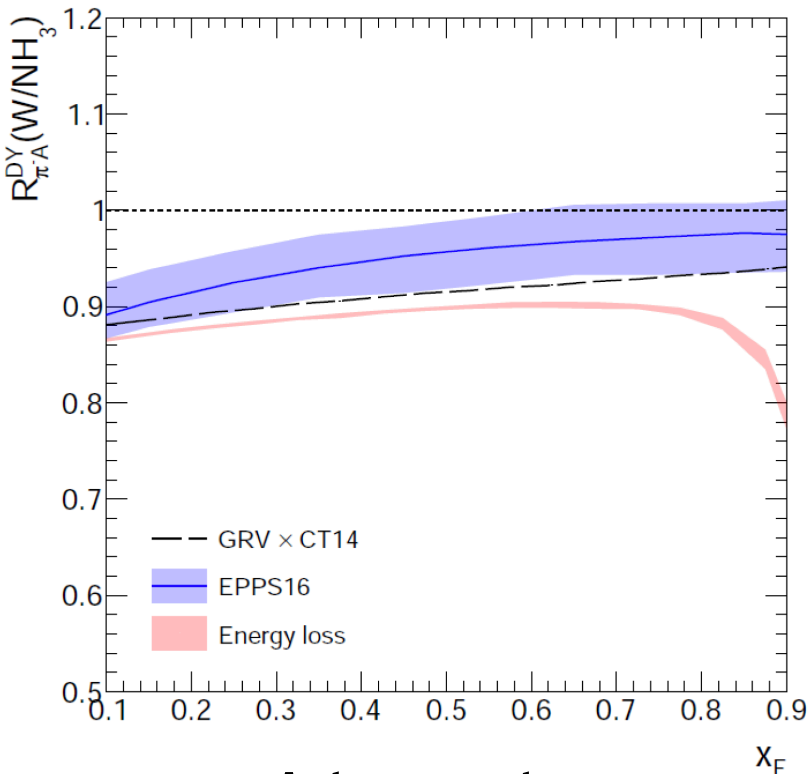




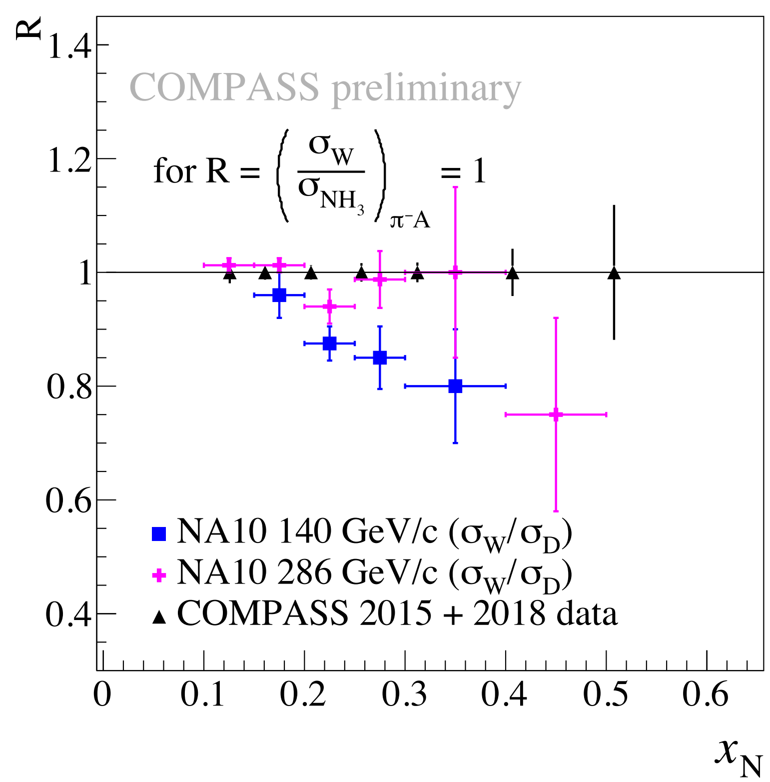


NUCLEAR DEPENDENCE OF DY PROCESS

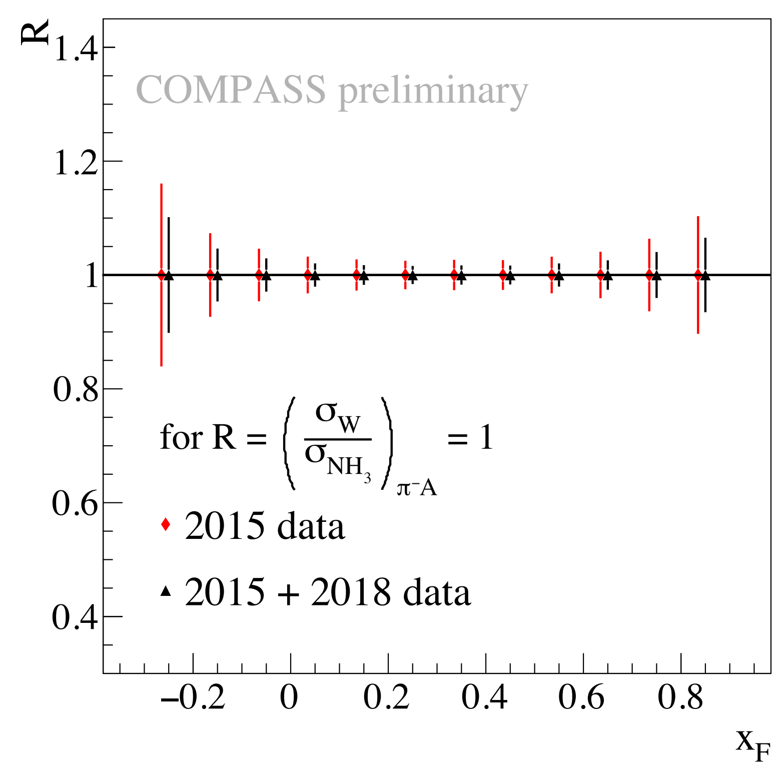
- Unpolarized data-sets from NH3 (summing over polarization states), Al (low statistics) and W targets open possibilities for further DY studies:
  - Absolute DY cross-section measurement
  - Nuclear dependence of the DY process:
    - **EMC effect**: nucleon PDFs modification when inside cold nuclear 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)



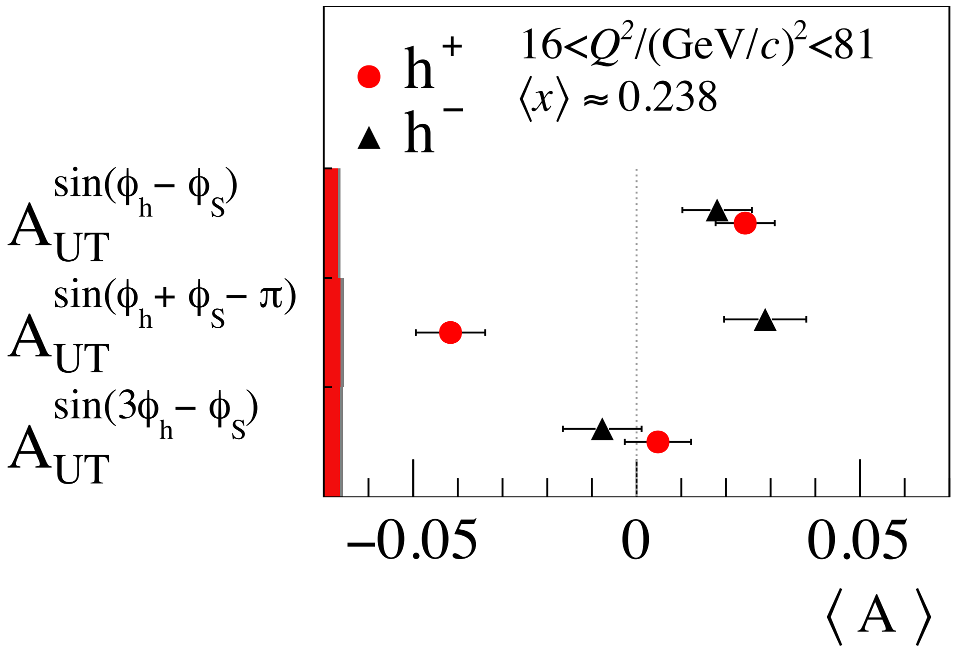
COMPASS **projected statistical error** for EMC effect (W/NH_3) compared with NA10 results



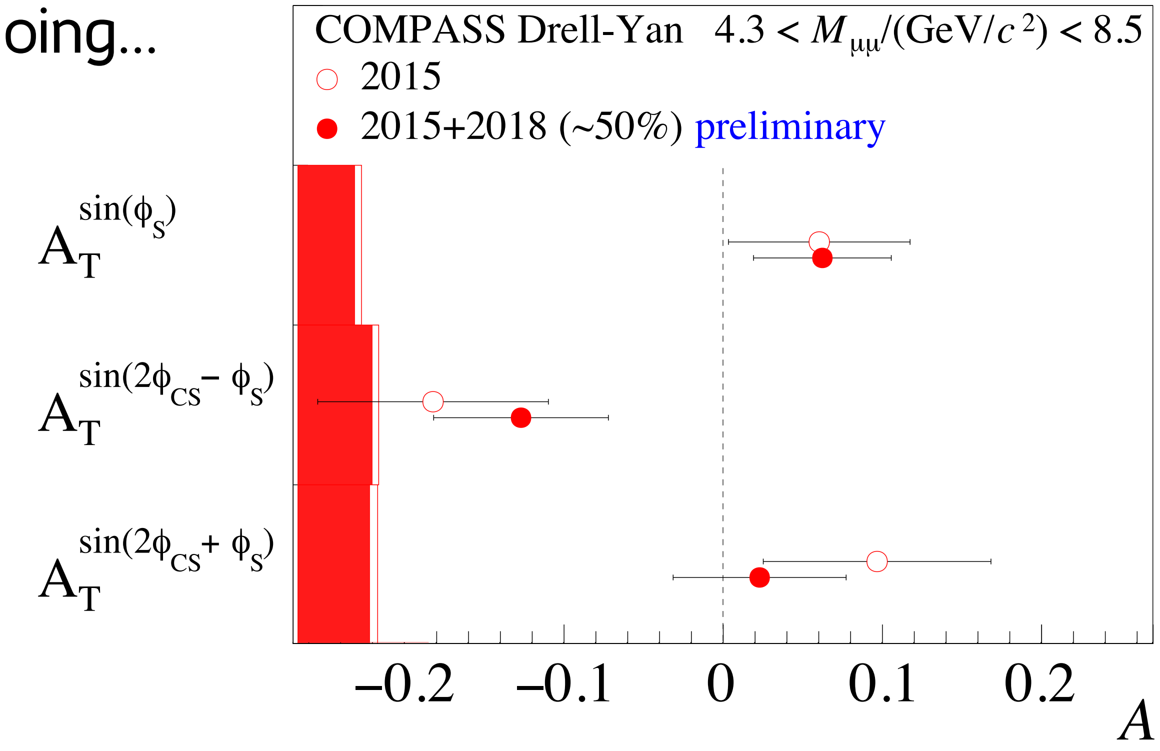
COMPASS **projected statistical error** for Energy Loss (W/NH_3)

SUMMARY

- COMPASS successfully collected Drell-Yan data in both 2015 and 2018.
  - 2015 TSAs analysis in HM published !
  - 2015+2018 combined TSAs analysis in HM ongoing…



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



- COMPASS, **PRL 119 112002 (2017)**
- COMPASS, **2015 + 2018 (~50%) preliminary**

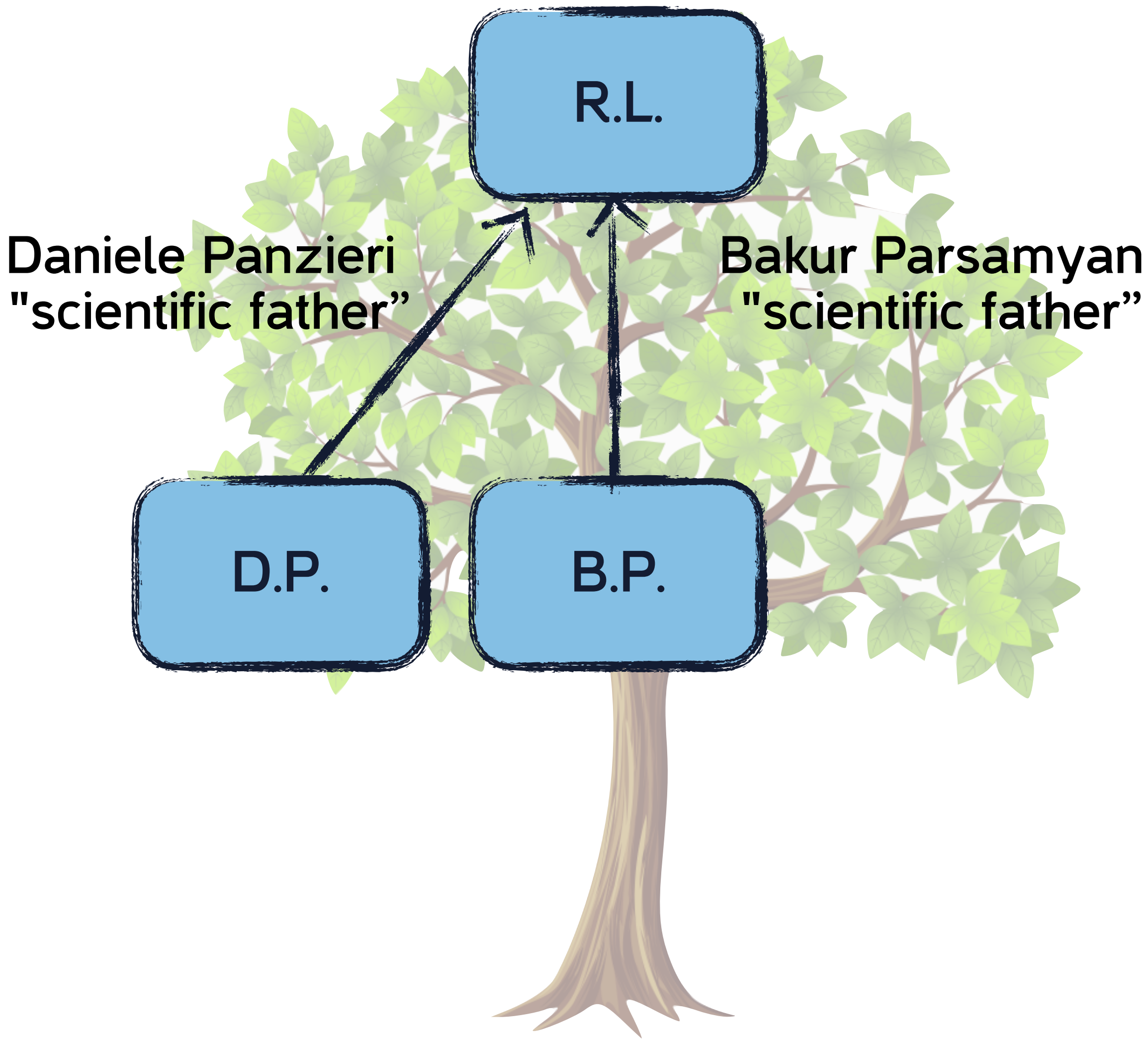
- COMPASS SIDIS and Drell-Yan TSAs measurements represent a unique experimental input to study the universality of TMD PDFs!

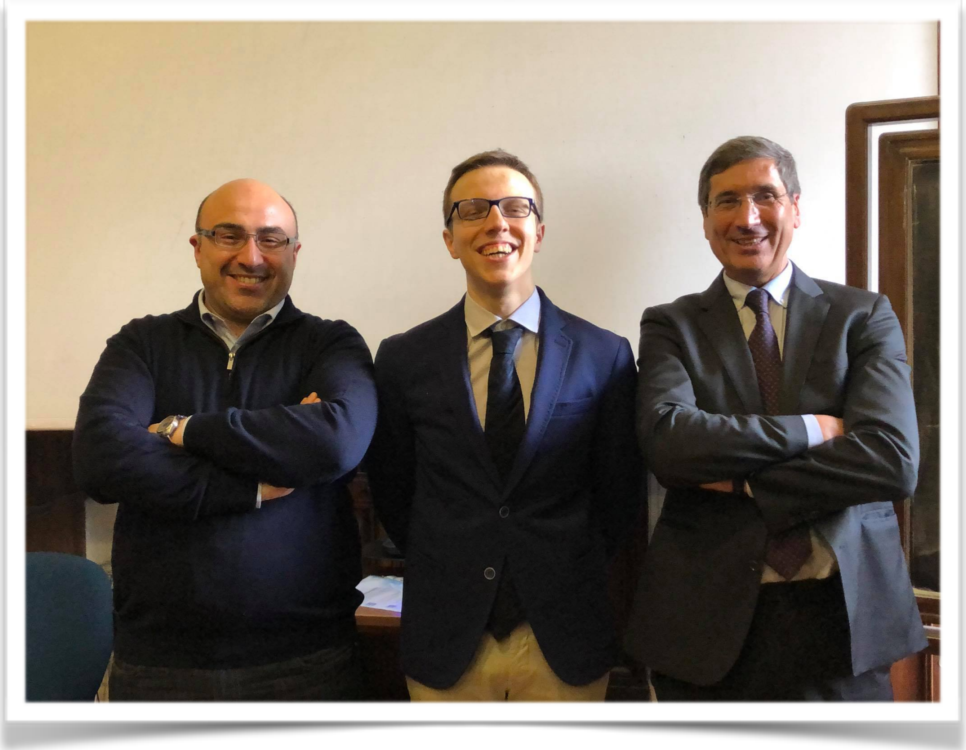
- Several other analyses currently ongoing (DY TSAs in J/ψ range, DY absolute cross-section, DY unpolarized asymmetries, nuclear effects in DY), bulk of new results expected in the next 2 years!

AKM 70

- Last, one personal thought…

My Scientific "family" tree

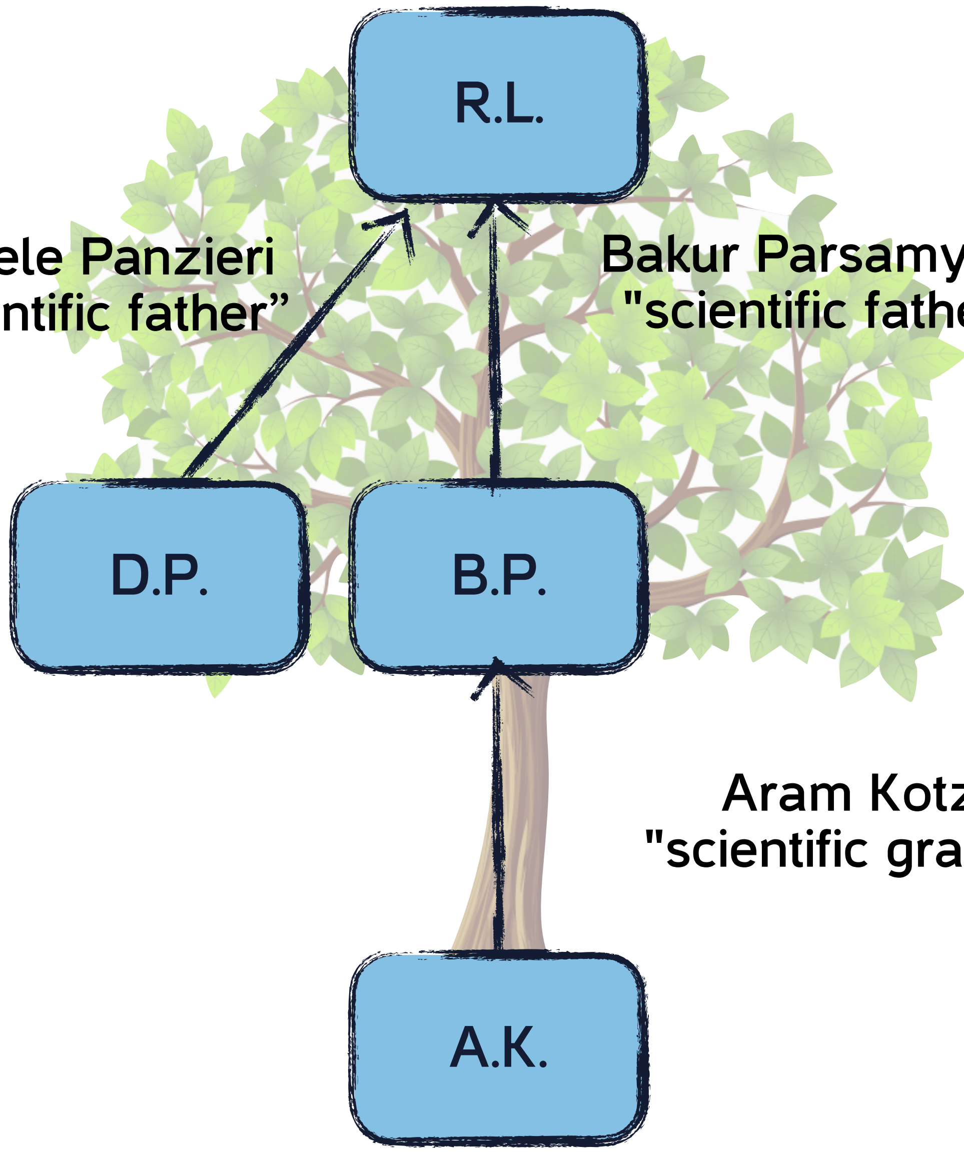




AKM 70

- Last, one personal thought…

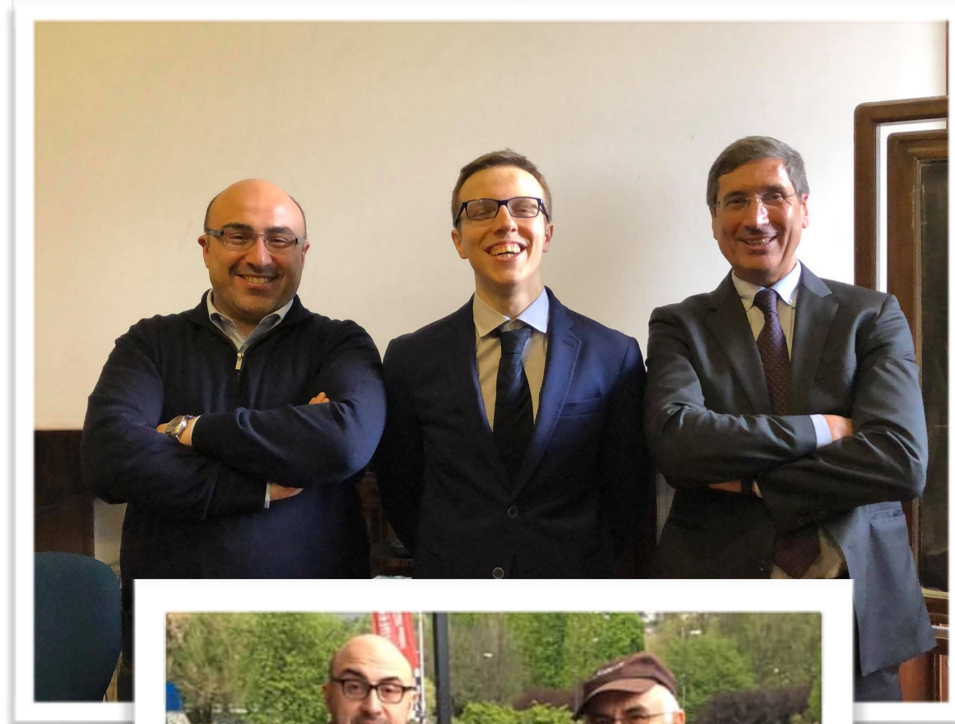
My Scientific "family" tree



Daniele Panzieri
"scientific father"

Bakur Parsamyan
"scientific father"

Aram Kotzinian
"scientific grandfather"



AKM 70

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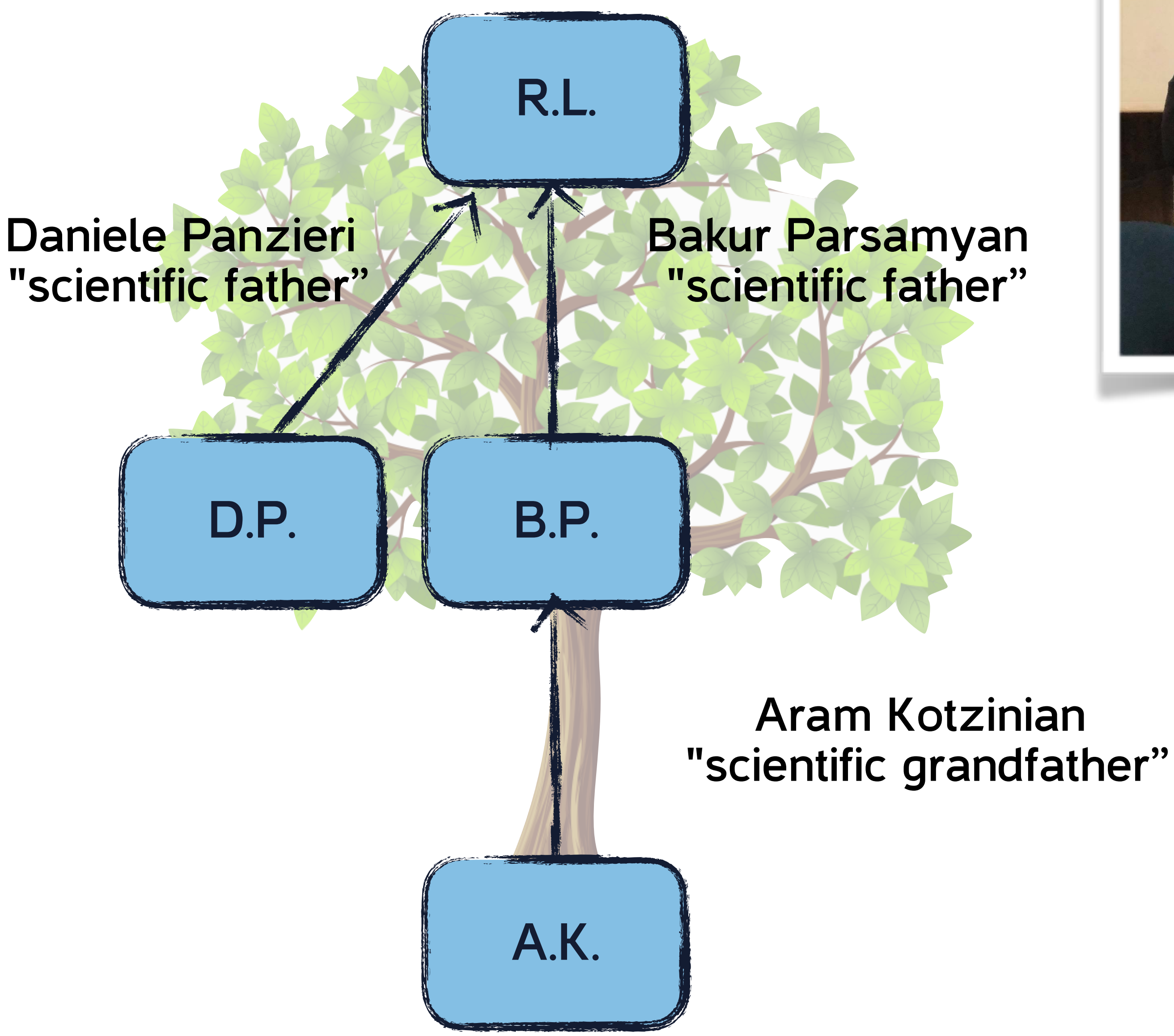
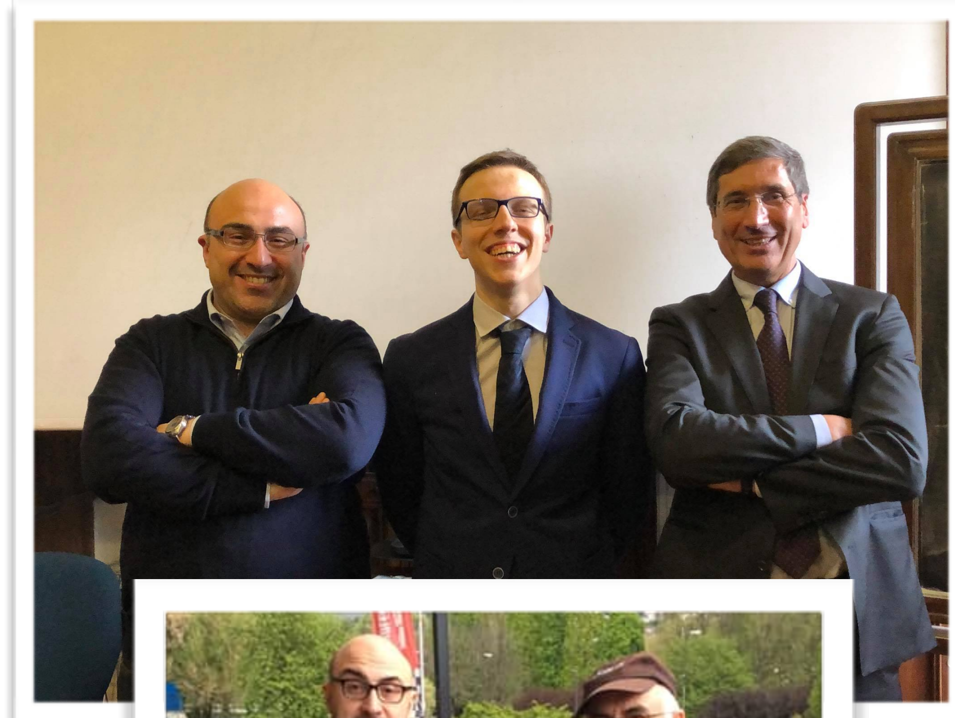
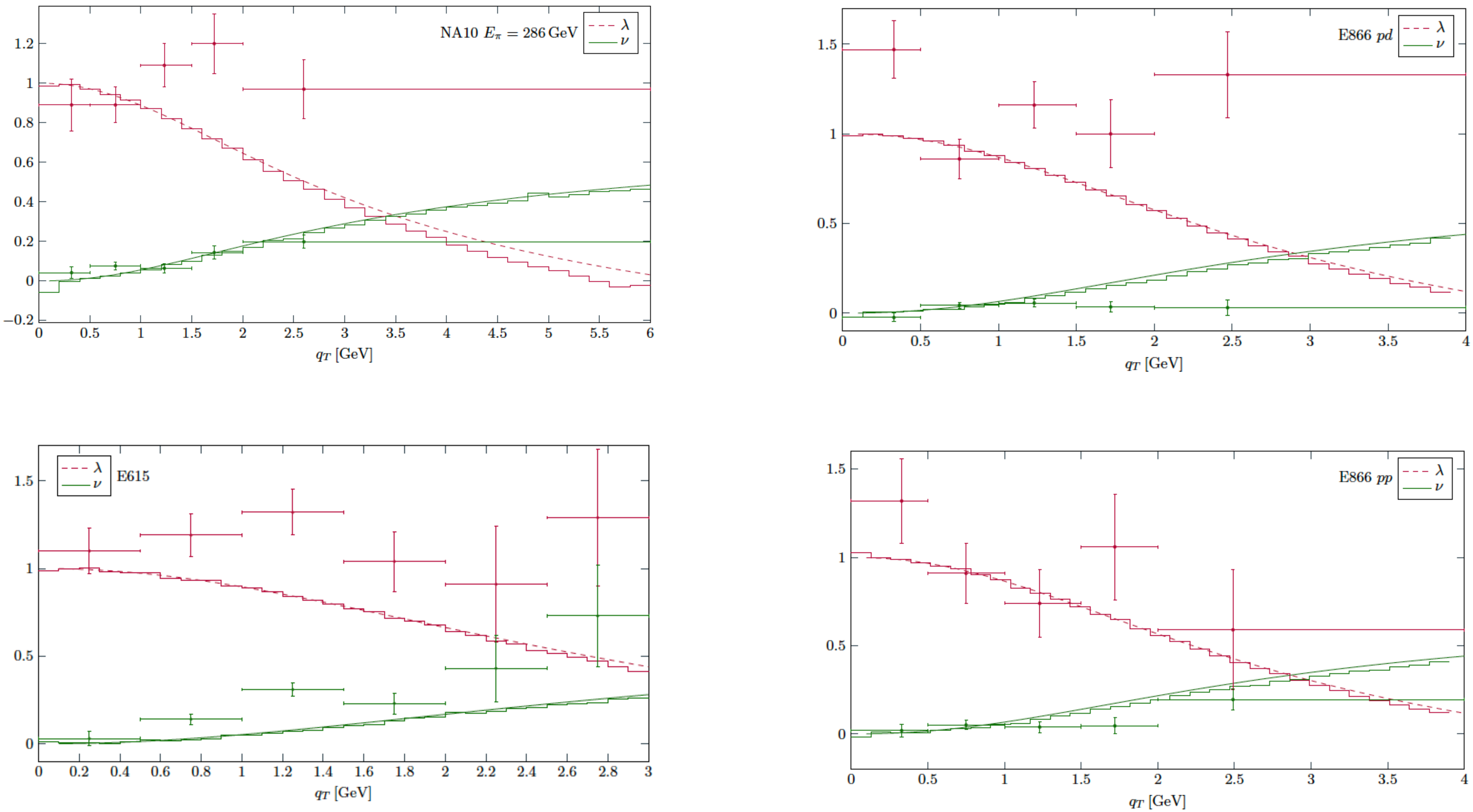




Happy Birthday Aram!

BACKUP SLIDES

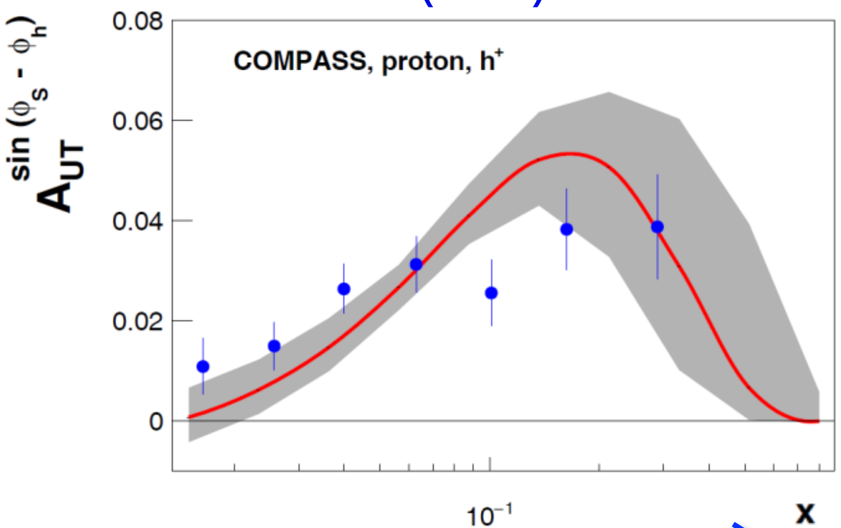
NLO ISSUES AT LOW q_T



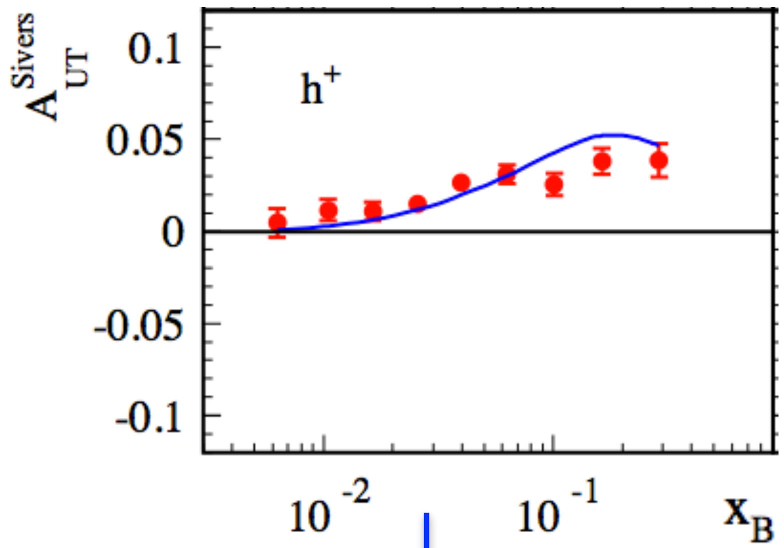
Vogelsang and Lambertsen
PRD 93 (2016)

SIVERS SIGN CHANGE?

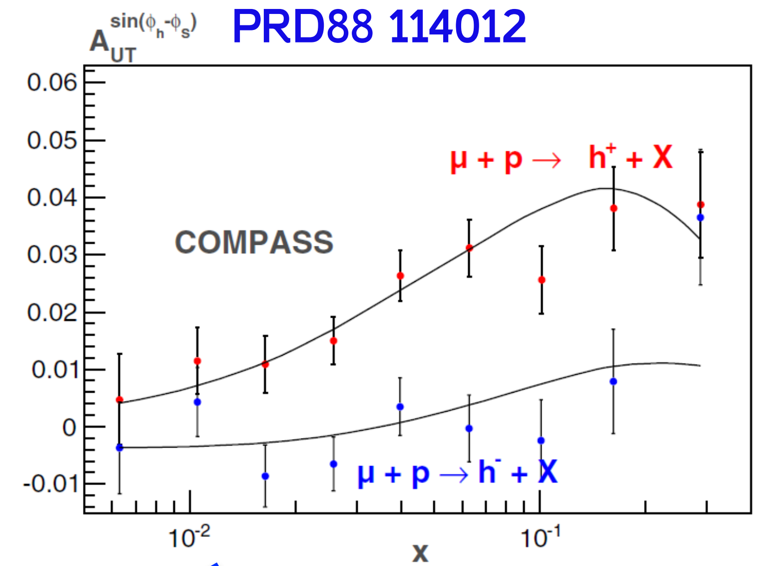
DGLAP (2016)
M. Anselmino et al.,
JHEP 1704 (2017) 046

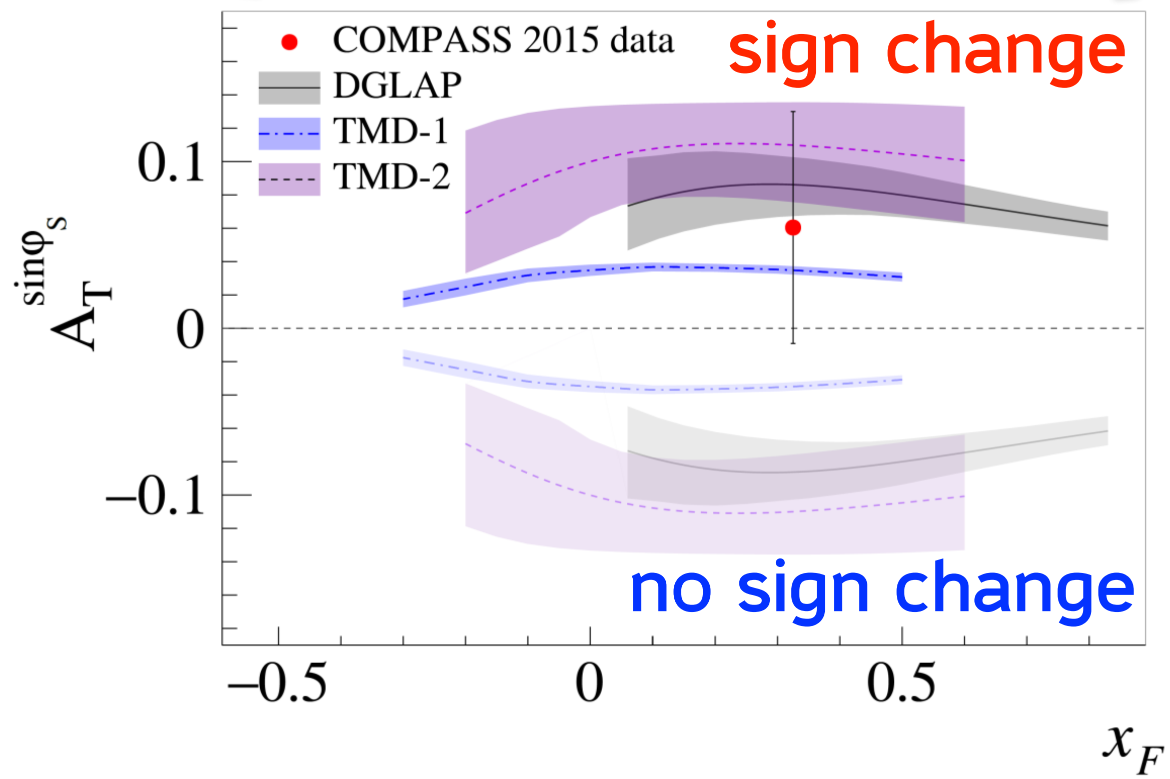


TMD-1 (2014)
M.G. Echevarria et al.,
PRD 89 074013



TMD-2 (2013)
P. Sun, F. Yuan,
PRD88 114012

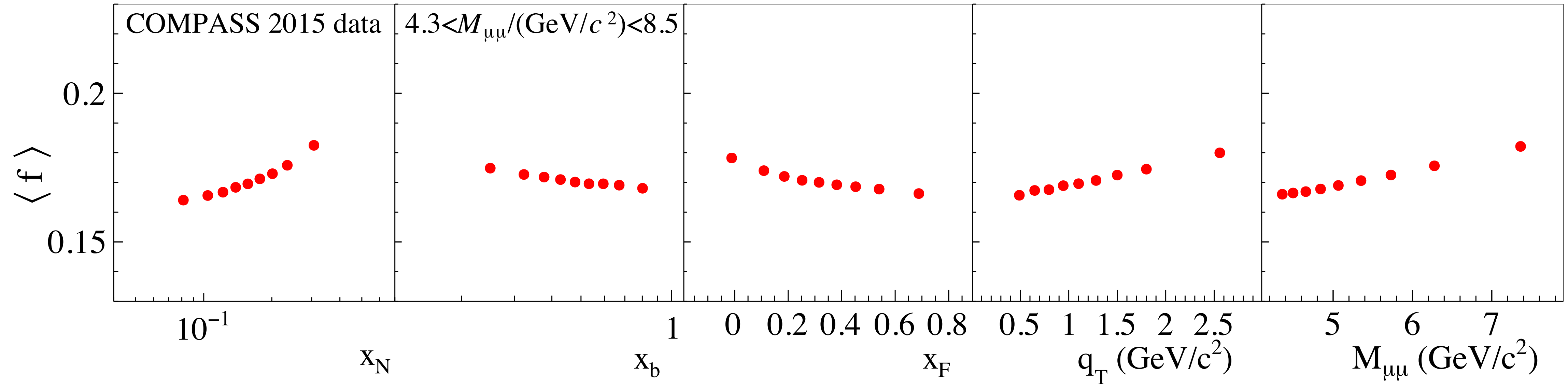


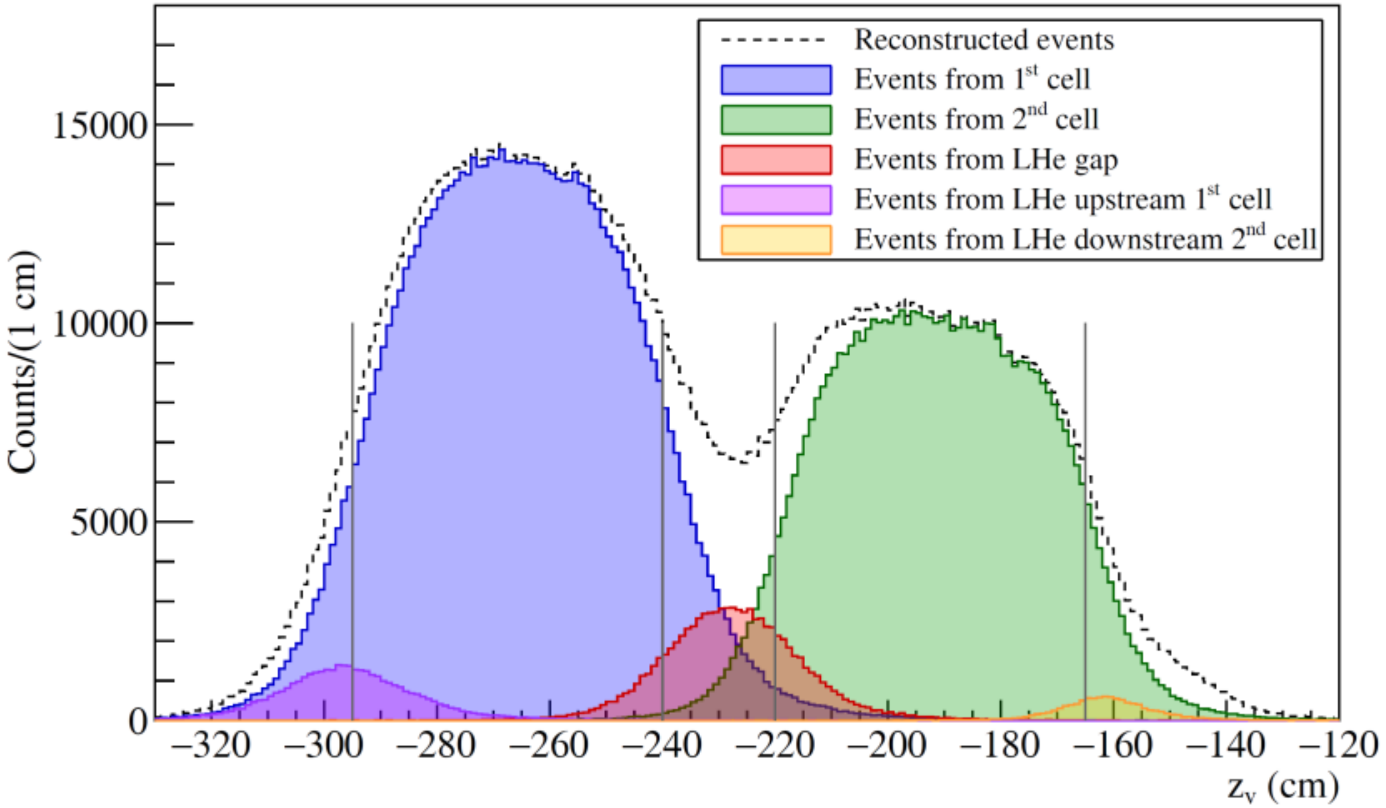


COMPASS
PRL 119 (2017) 112002

Full 2018 production to be started soon

DILUTION FACTOR





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

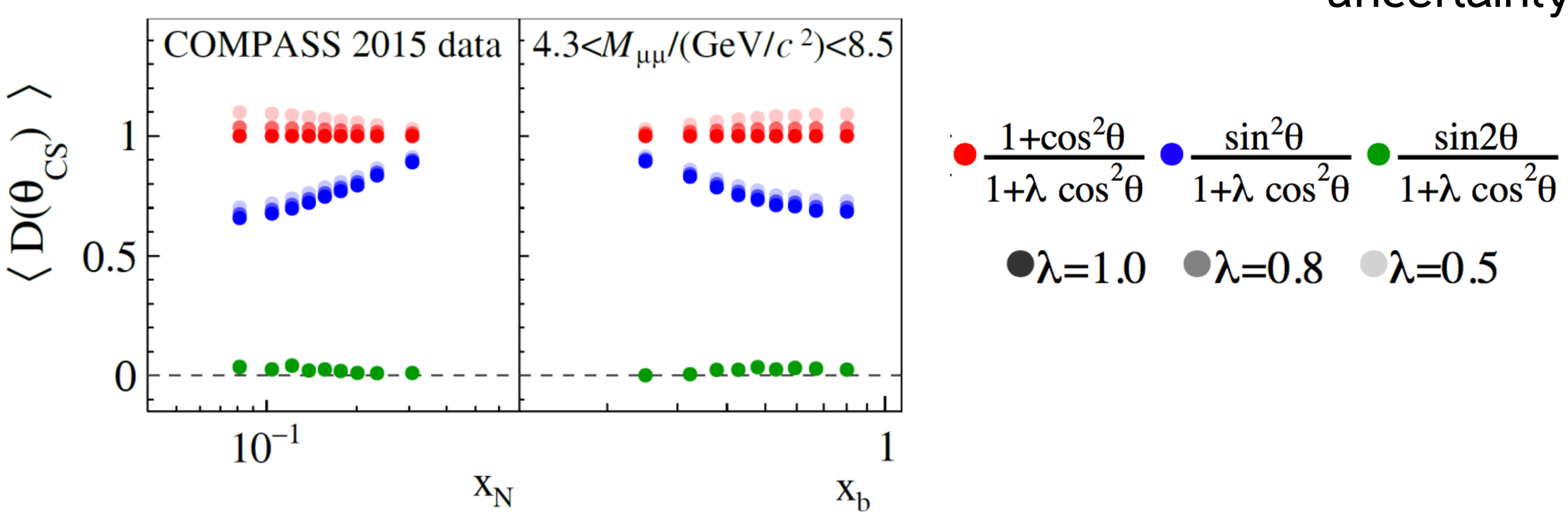
- The dilution factor accounts for the fraction of polarizable material inside the target volume.
- It is corrected to account for the migration of events from one cell to the other (obtained with MC simulation);

TSAs EXTRACTION

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

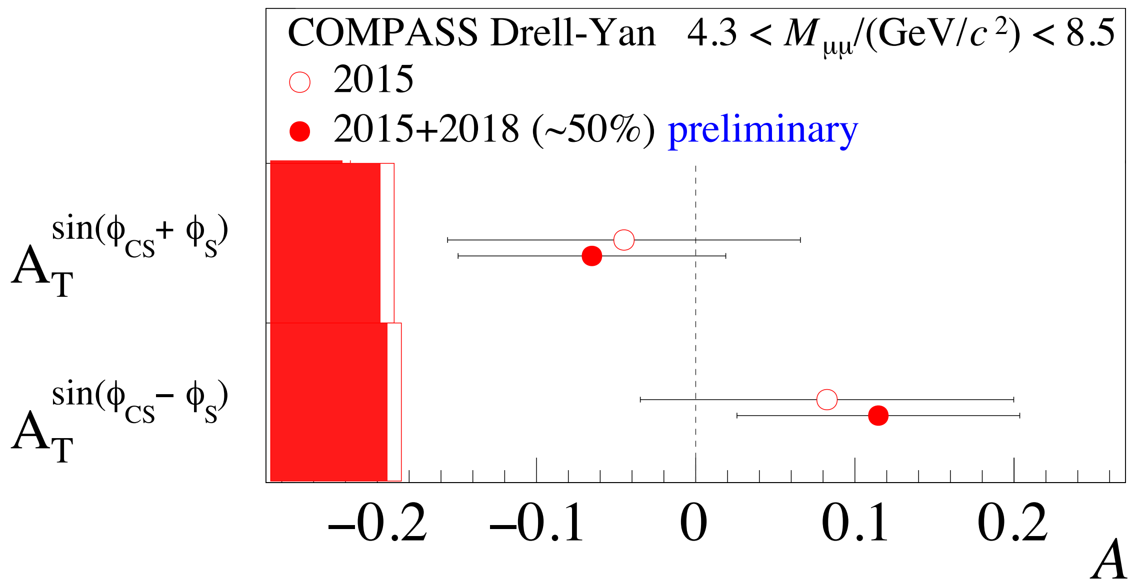
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right)$$
$$\times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \right.$$
$$+ S_T \left[A_T^{\sin\varphi_S}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

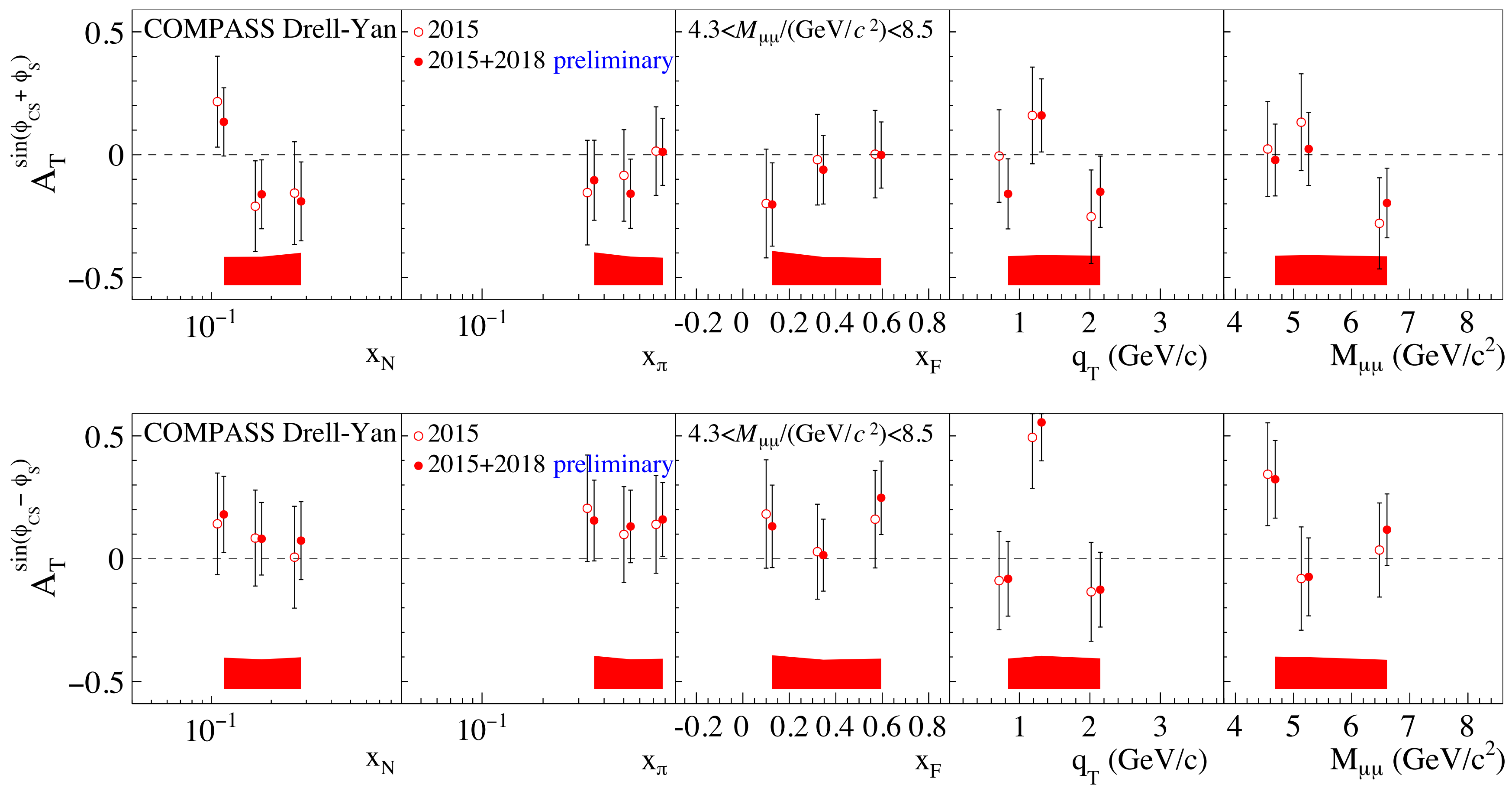
- All five DY TSAs are extracted simultaneously using an extended Unbinned Maximum Likelihood estimator;
- Depolarization factors are evaluated under assumption $A_U^1 = 1$;
- Possible scenarios with $A_U^1 \neq 1$ were evaluated , leading to a normalization uncertainty of at most 5 %;



TSAs : HIGHER TWIST

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





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