Polarized Drell-Yan measurements at COMPASS

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on behalf of the COMPASS Collaboration

Excited QCD Conference
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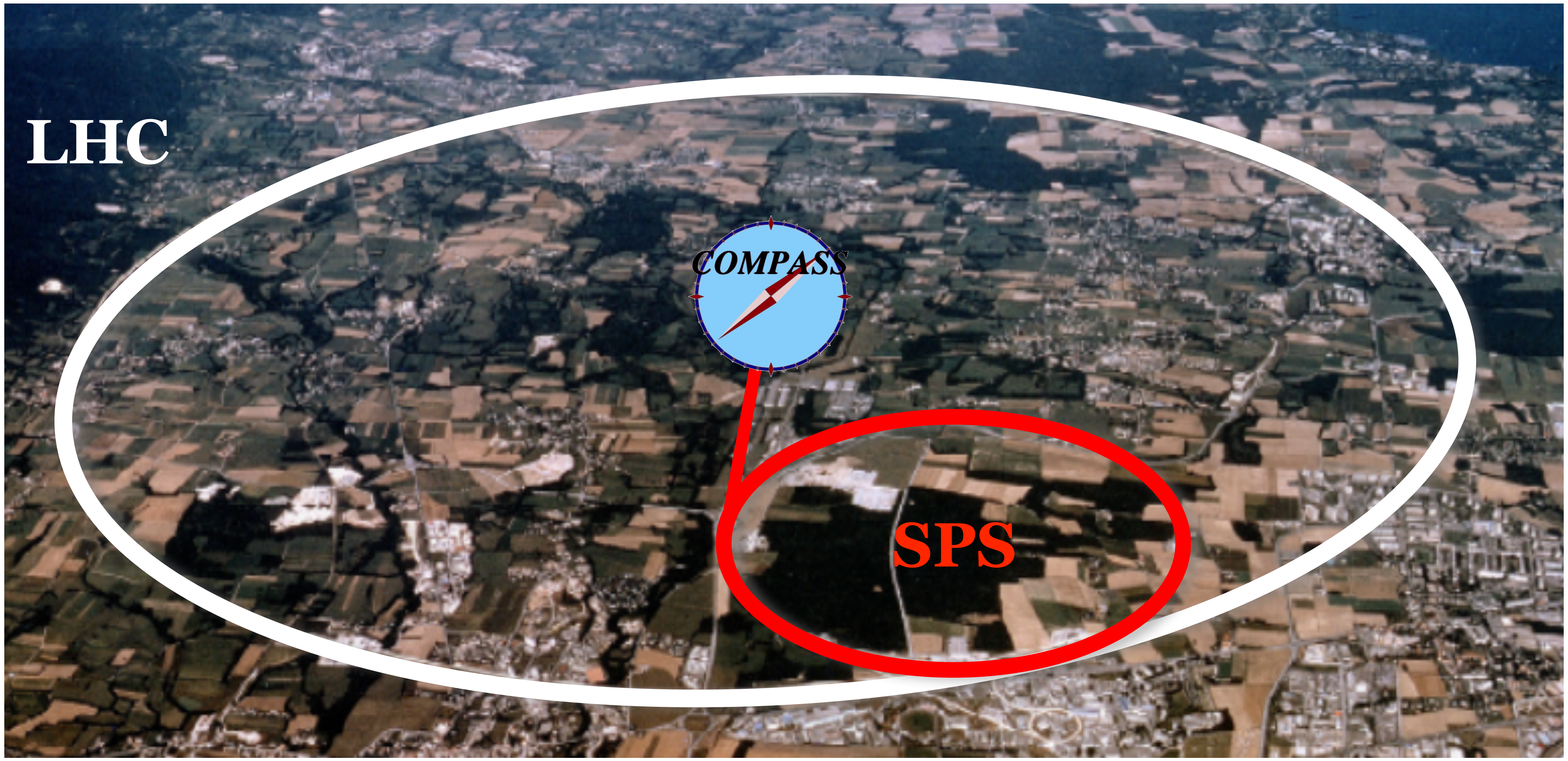
7 - 13 May 2017

COMPASS

Introduction

The COMPASS collaboration



- SPS North Area
- Fixed target experiment
- First data taking in 2002

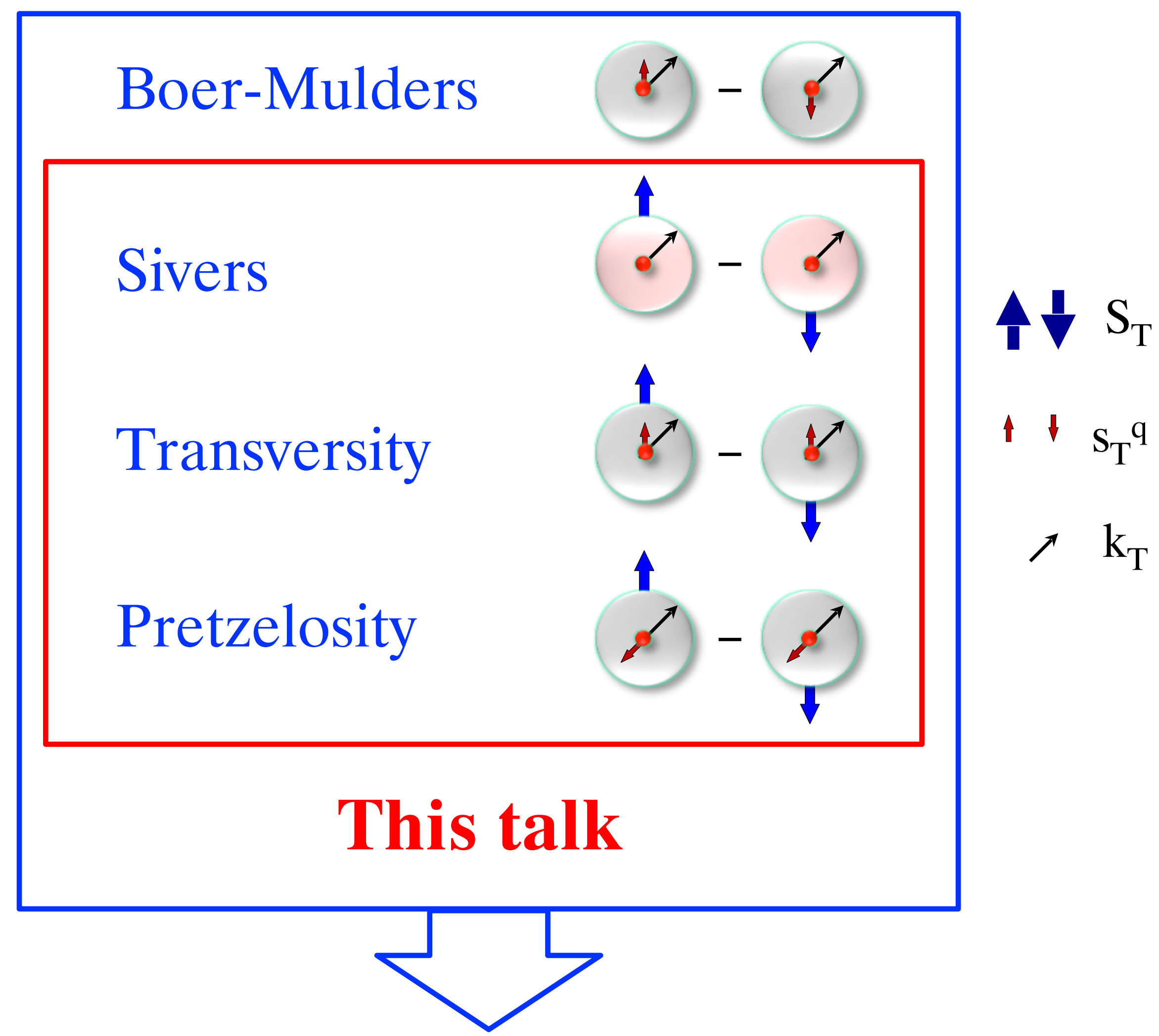
Phase I
- 2002 – 2011
- Hadron spectroscopy
- Nucleon spin structure (L/T P/D Targets)

Phase II
- 2012 – 2018
- Primakoff + DVCS pilot run (2012)
- Drell-Yan (2015, 2018)
- DVCS + Unpolarized SIDIS(2016-2017)

Transverse Momentum Dependent Parton Distribution Functions, TMD PDFs

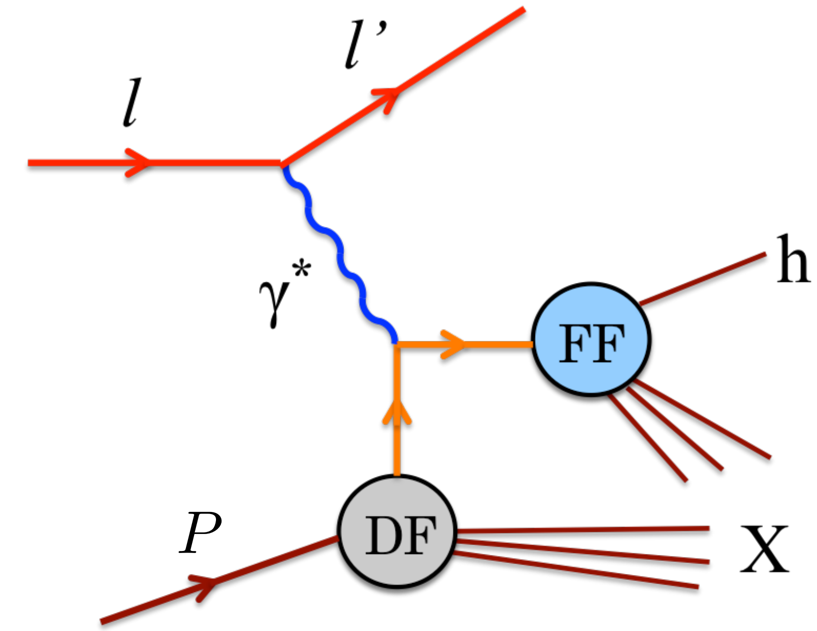
In the leading order QCD parton model nucleon spin-structure can be parametrized in terms of 8 twist-2 quark intrinsic transverse momentum (k_T) dependent TMD PDFs.

Quark \ Nucleon	U	L	T
U	$f_1^q(x,k_T^2)$ Number density		$f_{1T}^{q\perp}(x,k_T^2)$ Sivers
L		$g_1^q(x,k_T^2)$ Helicity	$g_{1T}^{q\perp}(x,k_T^2)$ Kotzinian-Mulders or Worm-gear T
T	$h_1^{q\perp}(x,k_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x,k_T^2)$ Worm-gear L	$h_1^q(x,k_T^2)$ Transversity; $h_{1T}^{q\perp}(x,k_T^2)$ Pretzelosity



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

Single T-polarized SIDIS cross section at LO



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

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

$$A_{U,T}^{w(\phi_h,\phi_S)} = \frac{F_{U,T}^{w(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}; \quad \gamma = \frac{2Mx}{Q};$$

Standard SIDIS kinematic variables:

- Photon virtuality

$$Q^2 = -q^2 = -(l-l')^2$$

- Bjorken scaling variable

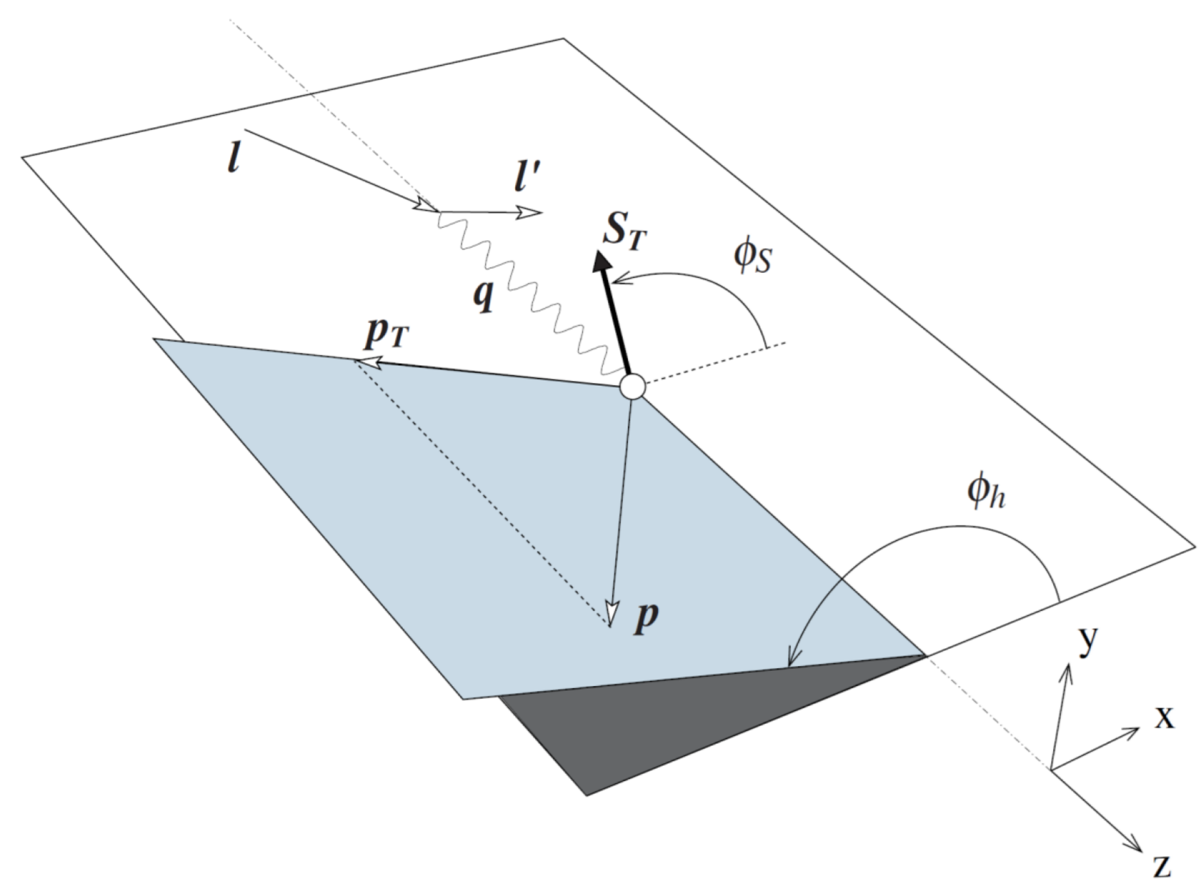
$$x = \frac{Q^2}{2P\cdot q}$$

- Fractional energy of the virtual photon

$$y = \frac{P\cdot q}{P\cdot l}$$

- Fractional energy of the observed final state hadron

$$z = \frac{P\cdot P_h}{P\cdot q}$$



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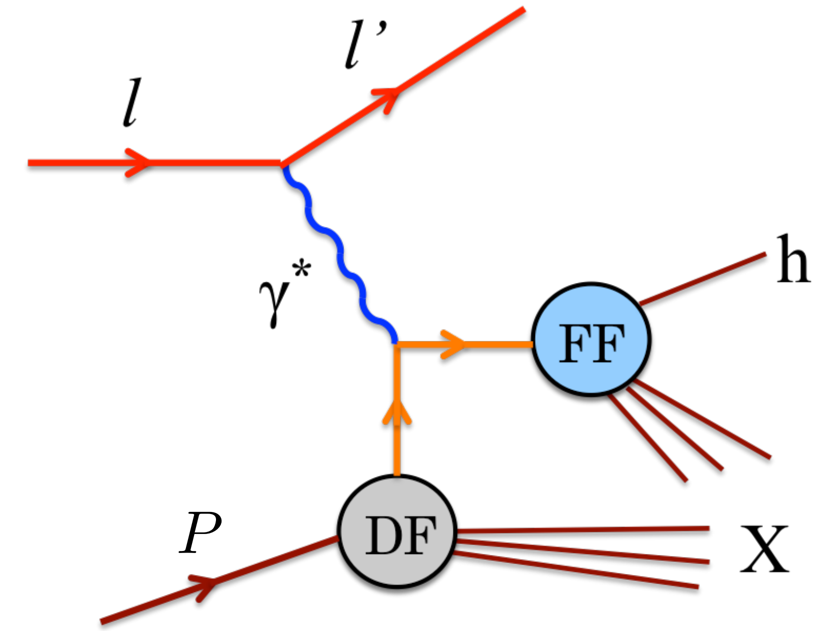

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Measuring the azimuthal asymmetries of the transversely polarized SIDIS process, specific convolutions of TMD PDFs of the target (p) and TMD Fragmentation Functions can be accessed

1 Unpolarized Asymmetry

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

3 Single Spin Asymmetries

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

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

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

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

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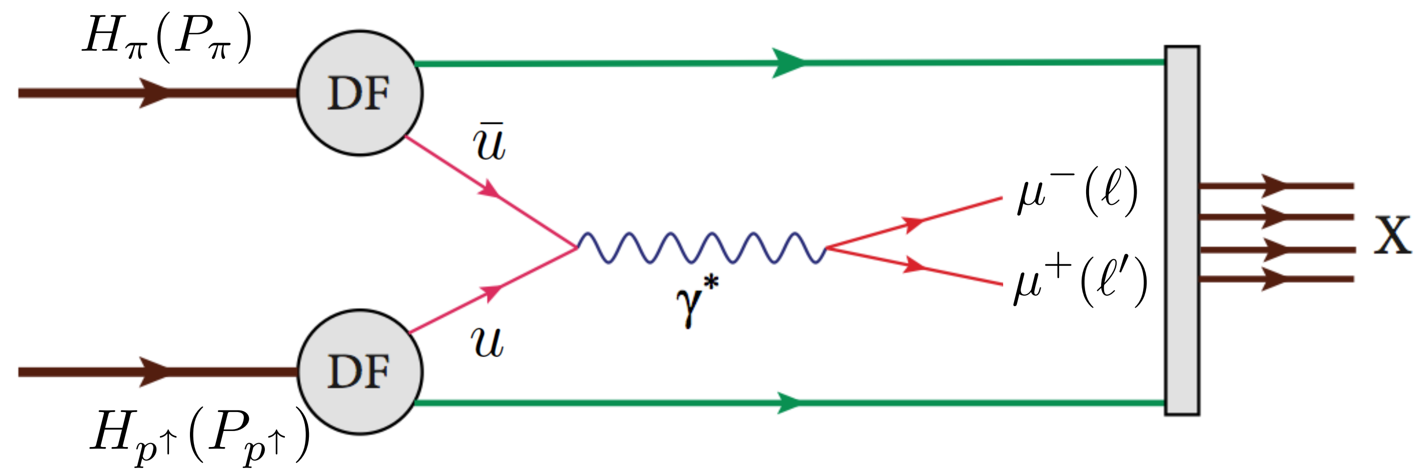
Single Polarized Drell-Yan process



General leading order QCD parton model expression of the Single Polarized (SP) DY cross-section

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

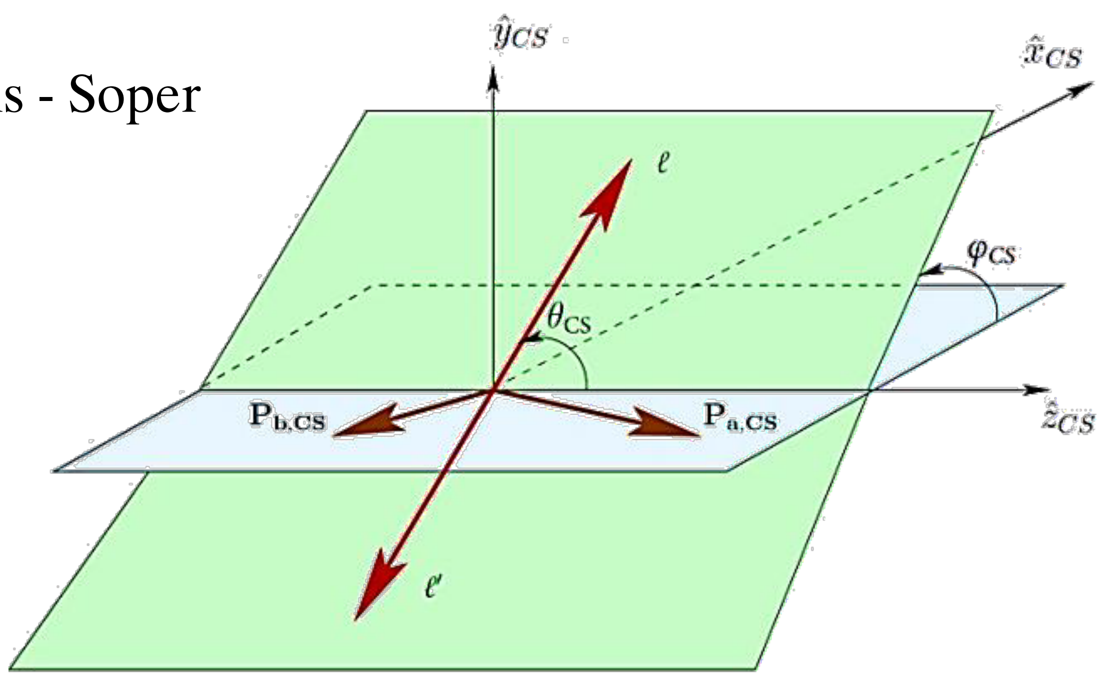
D-factors

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

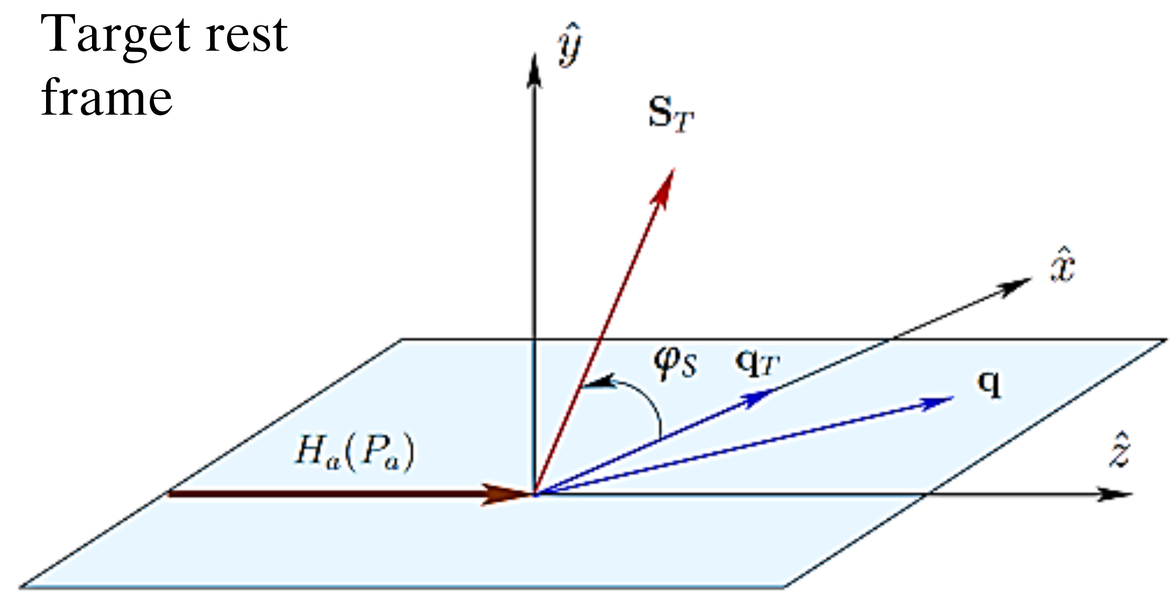
Azimuthal asymmetries

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

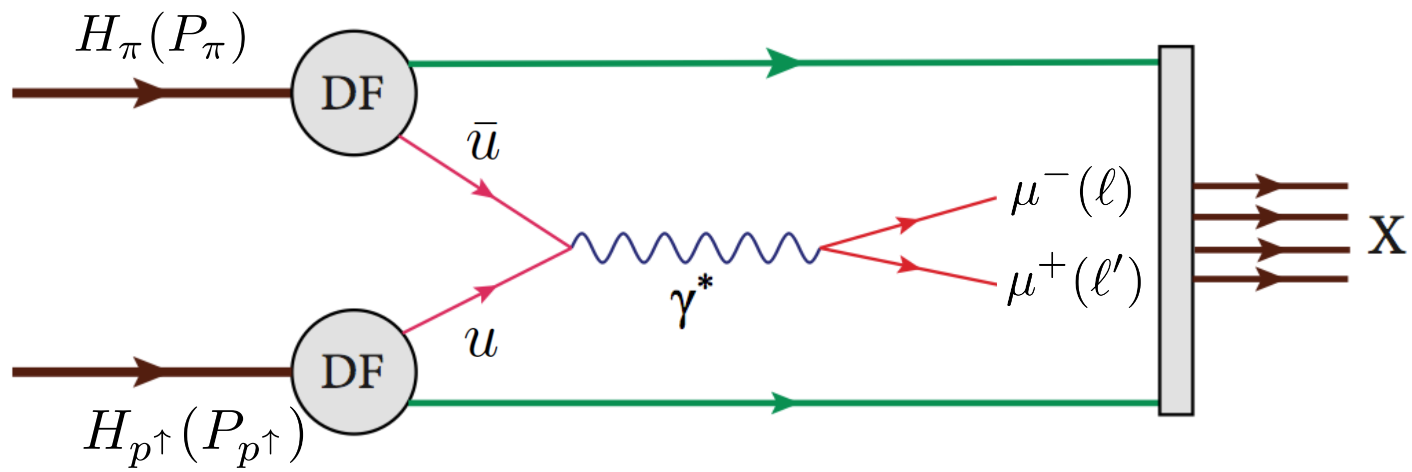
Collins - Soper frame



Target rest frame



Single Polarized Drell-Yan process



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Measuring the azimuthal asymmetries of the SP DY process, specific convolutions of TMD PDFs of the beam (π^-) and of the target (p) can be accessed

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

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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DY and SIDIS x-sections at LO

This talk

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

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

$$A_{SIDIS} \propto PDF_p \otimes FF \qquad A_{DY} \propto PDF_\pi \otimes PDF_p$$

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 are expected to be "genuinely" universal (no sign change between SIDIS and DY)
- Boer Mulders and Sivers TMD PDFs are expected to be "conditionally" universal (sign change between SIDIS and DY)

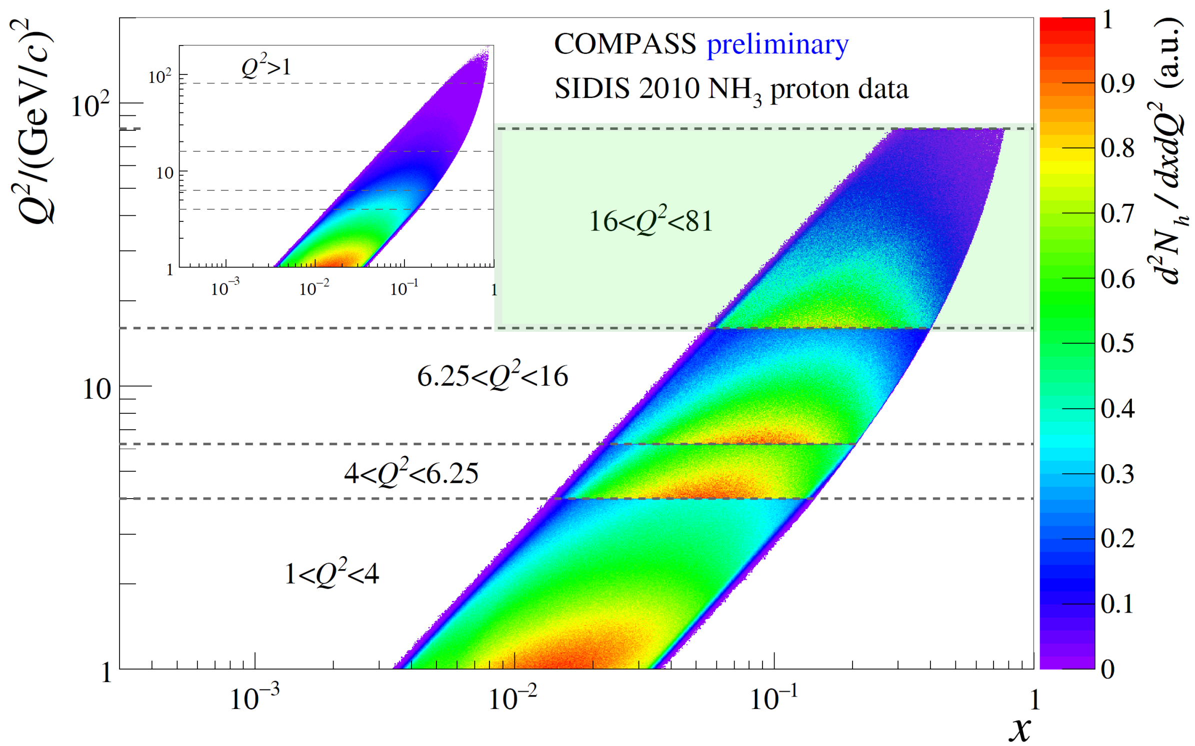
$$h_1^{\perp q}|_{SIDIS} = -h_1^{\perp q}|_{DY}$$
$$f_{1T}^{\perp q}|_{SIDIS} = -f_{1T}^{\perp q}|_{DY}$$

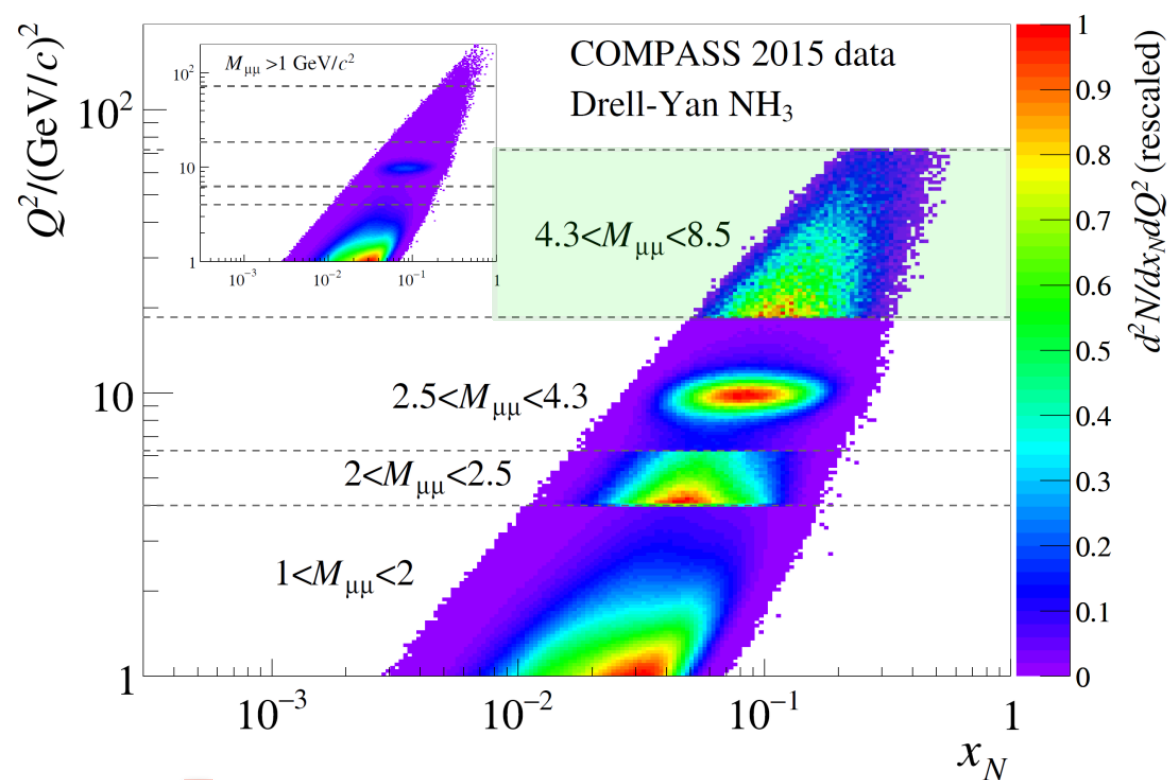
COMPASS SIDIS-DY bridge

This talk

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

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





comparable x:Q² kinematic coverage

minimization of possible Q² evolution effects

Unique experimental environment to test TMD universality and Sivers and Boer Mulders sign change

COMPASS DY mass ranges

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

- Large background contamination: combinatorial, open charm (bottom) $D\overline{D},\ B\overline{B}$, π and K decays.

II. $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$, "Intermediate mass"

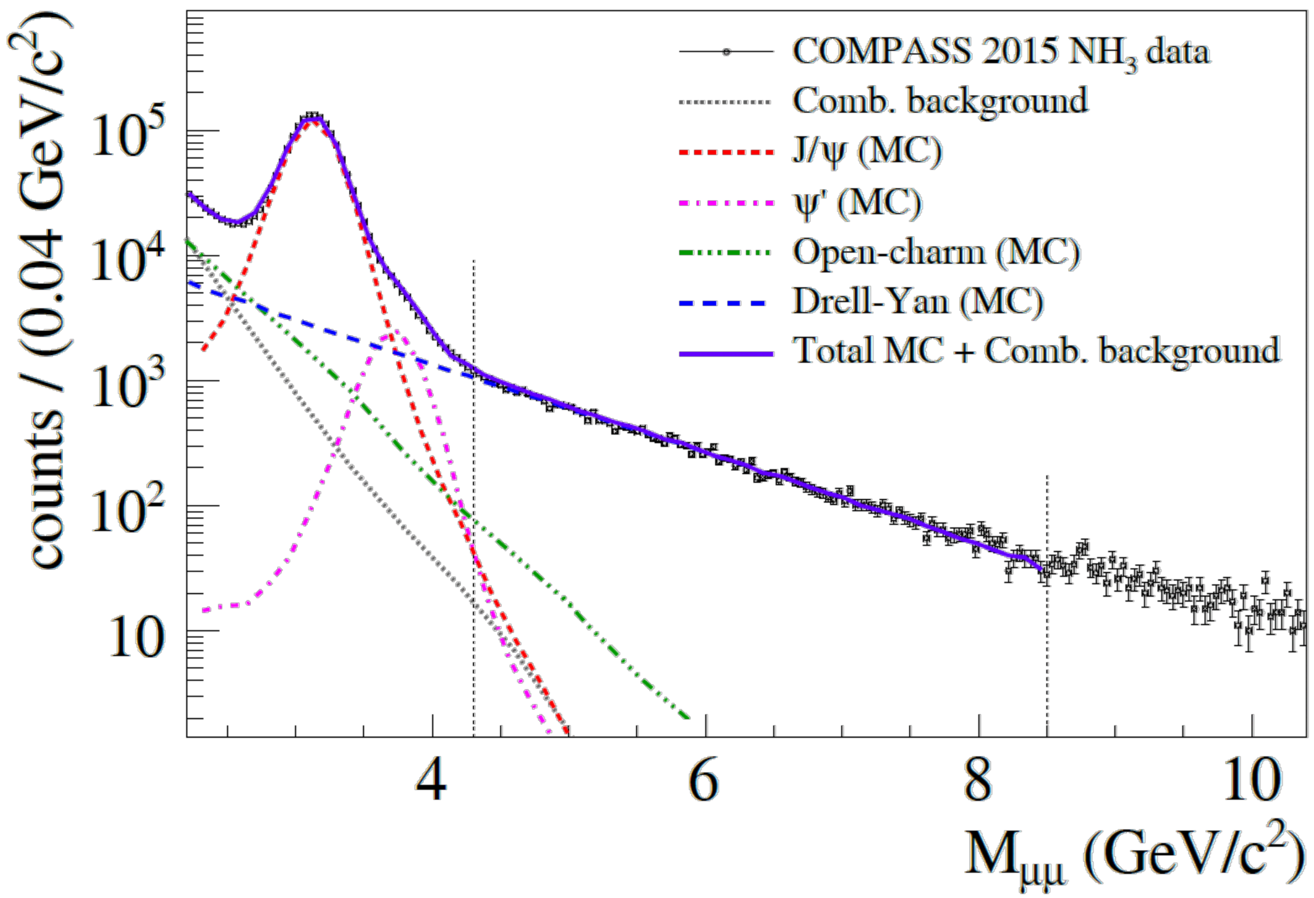
- High DY cross section.
- Still low DY-signal/background ratio.

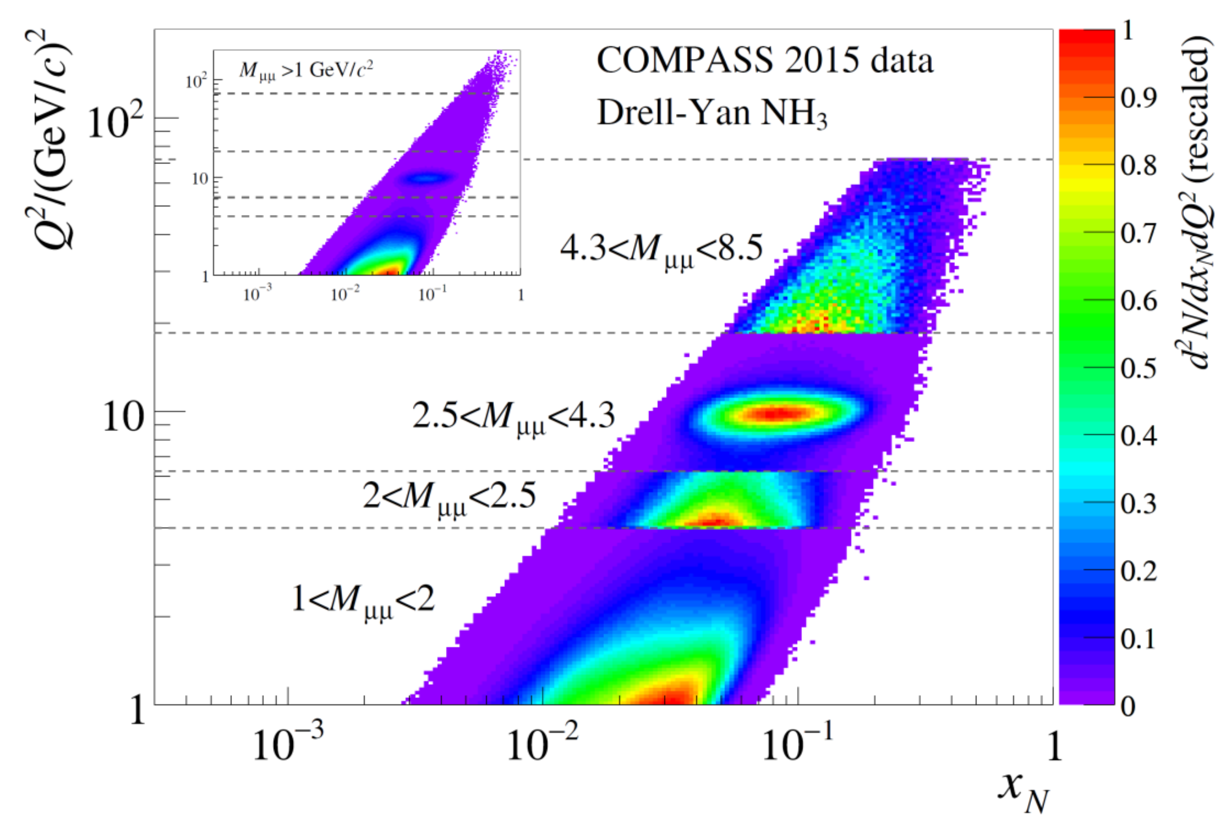
III. $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$, "Charmonia mass"

- 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 < 3%.
- Valence quark region → Largest asymmetries!
- Low DY cross-section





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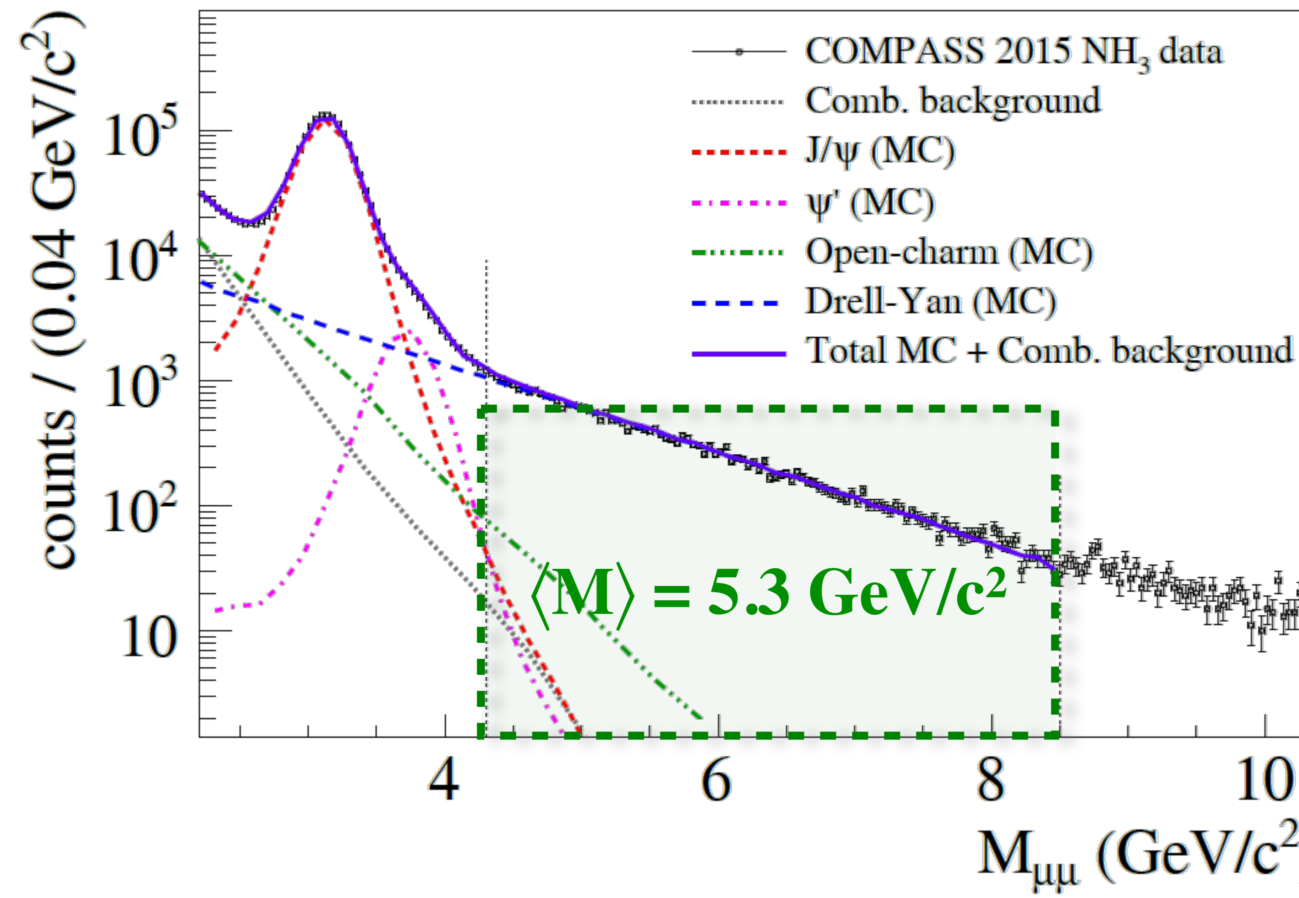

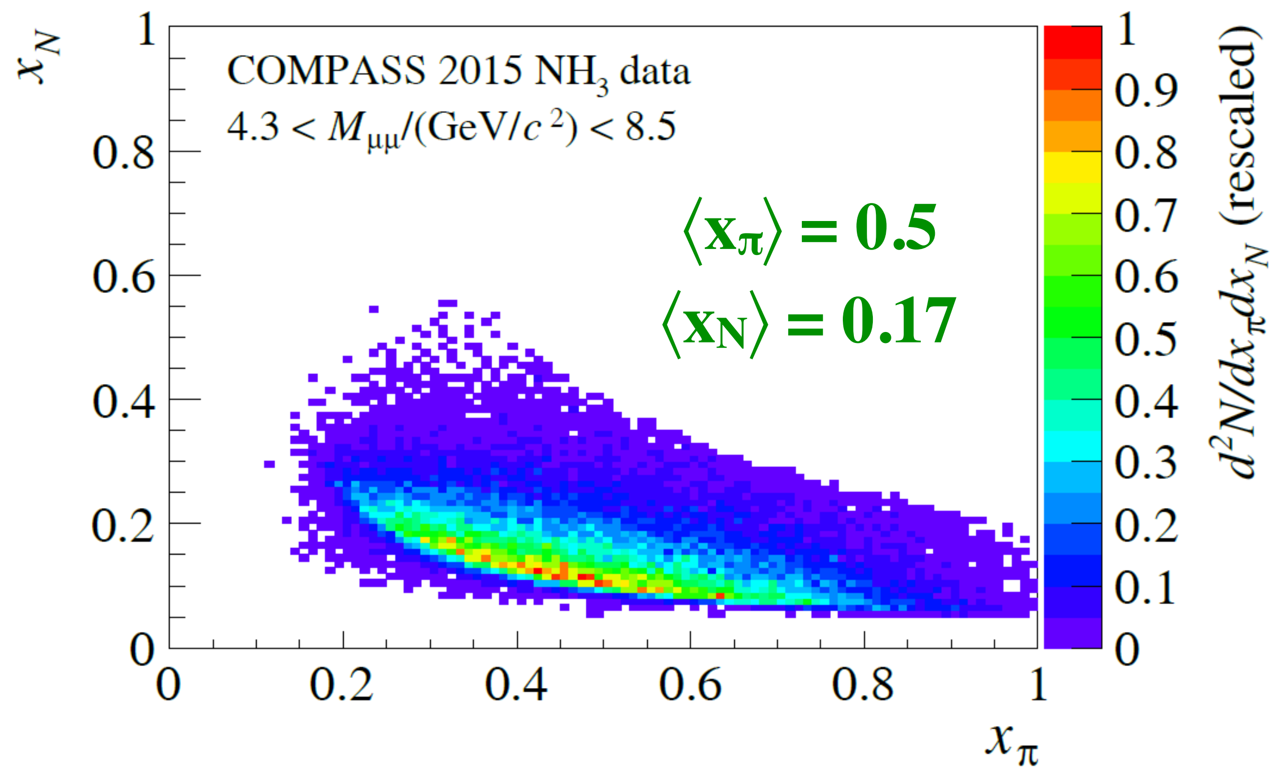

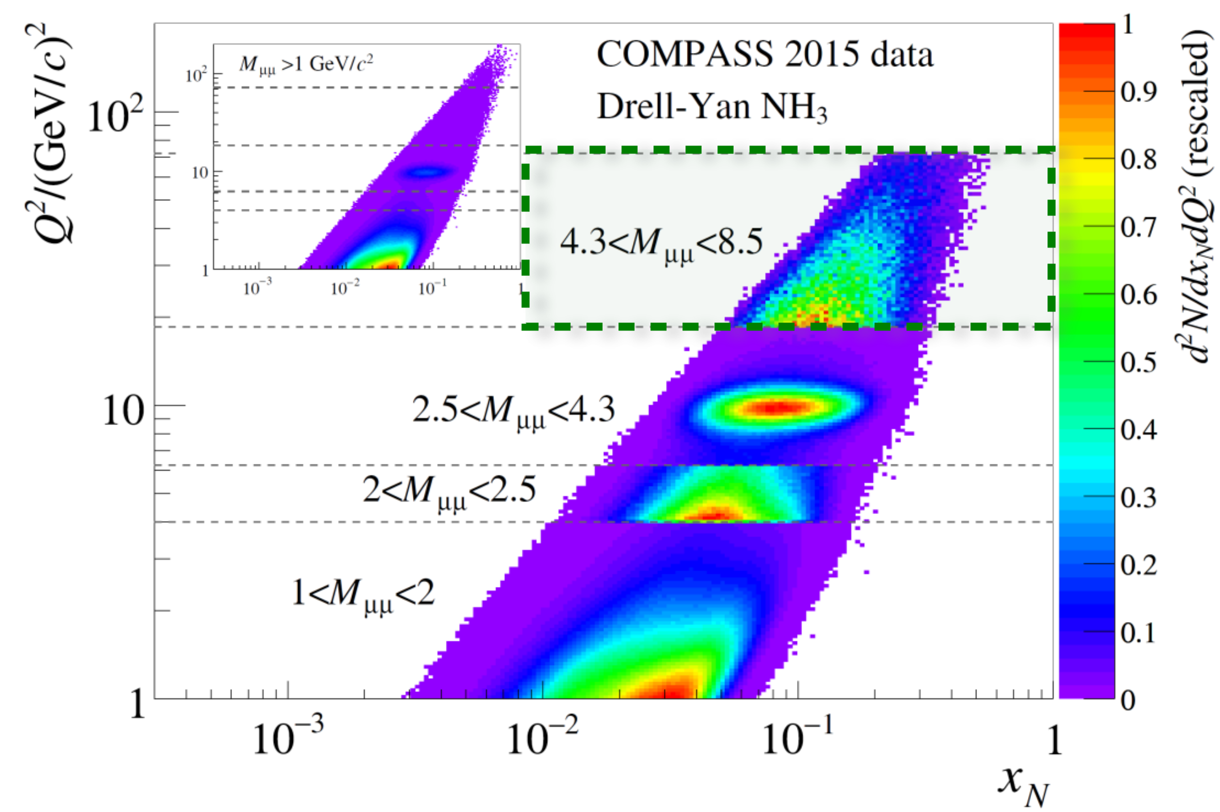

HM events are in the valence quark region

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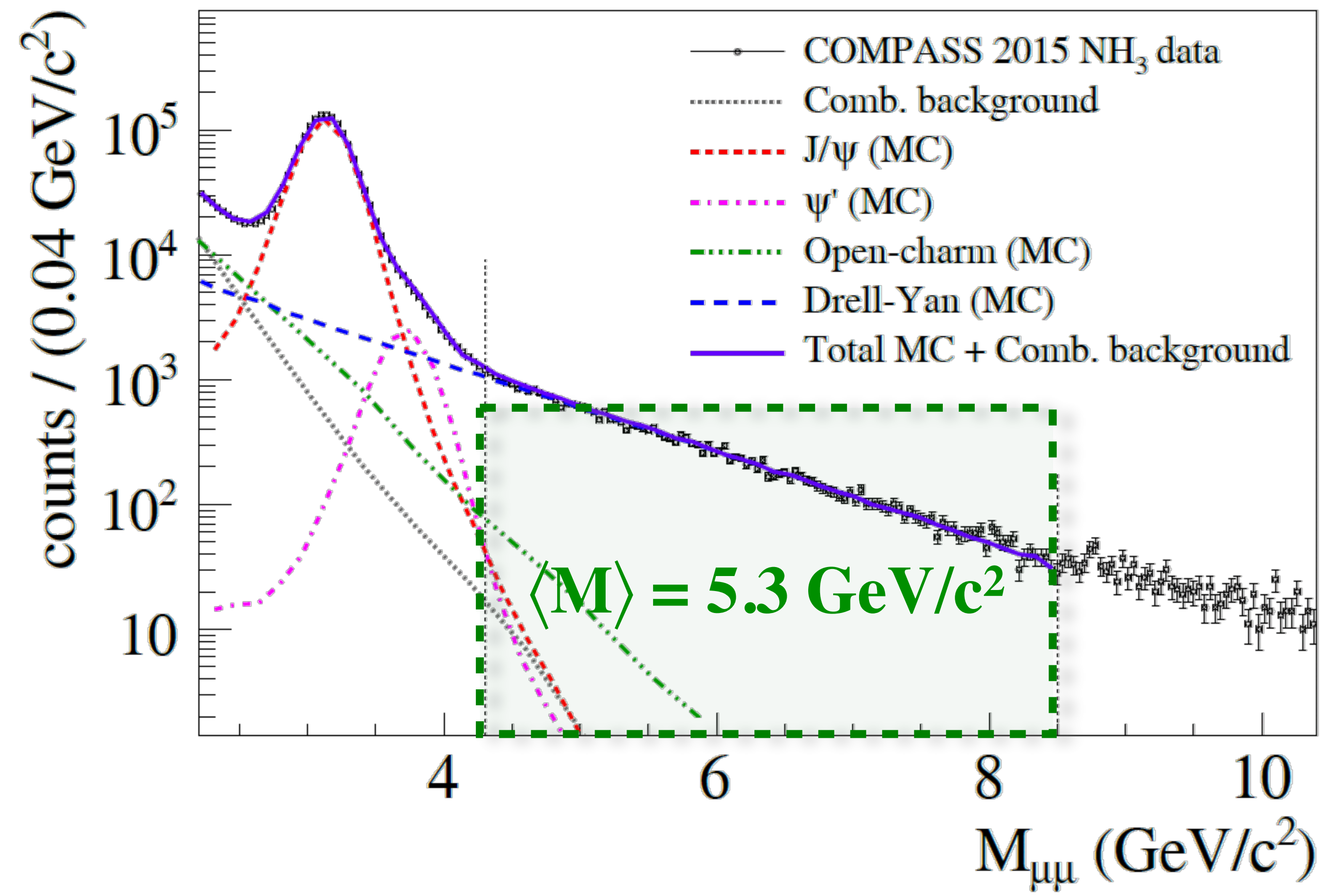
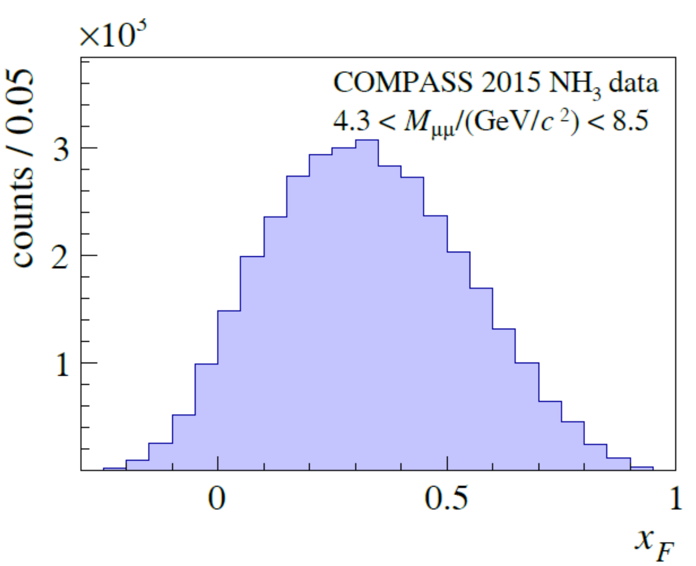
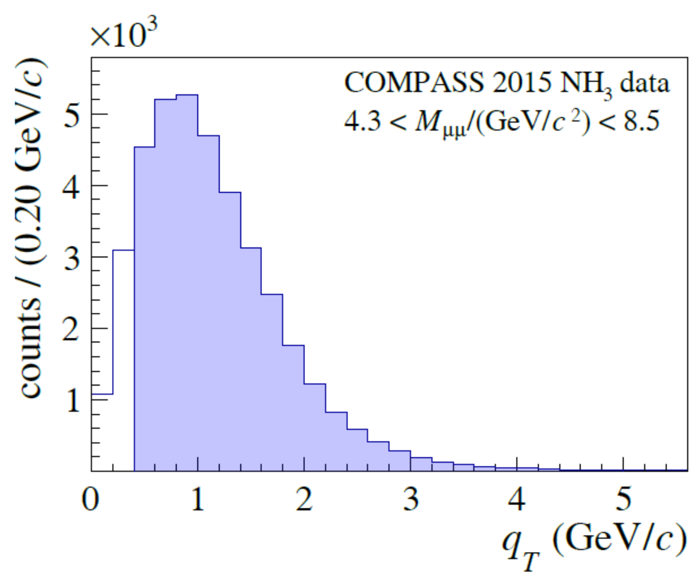


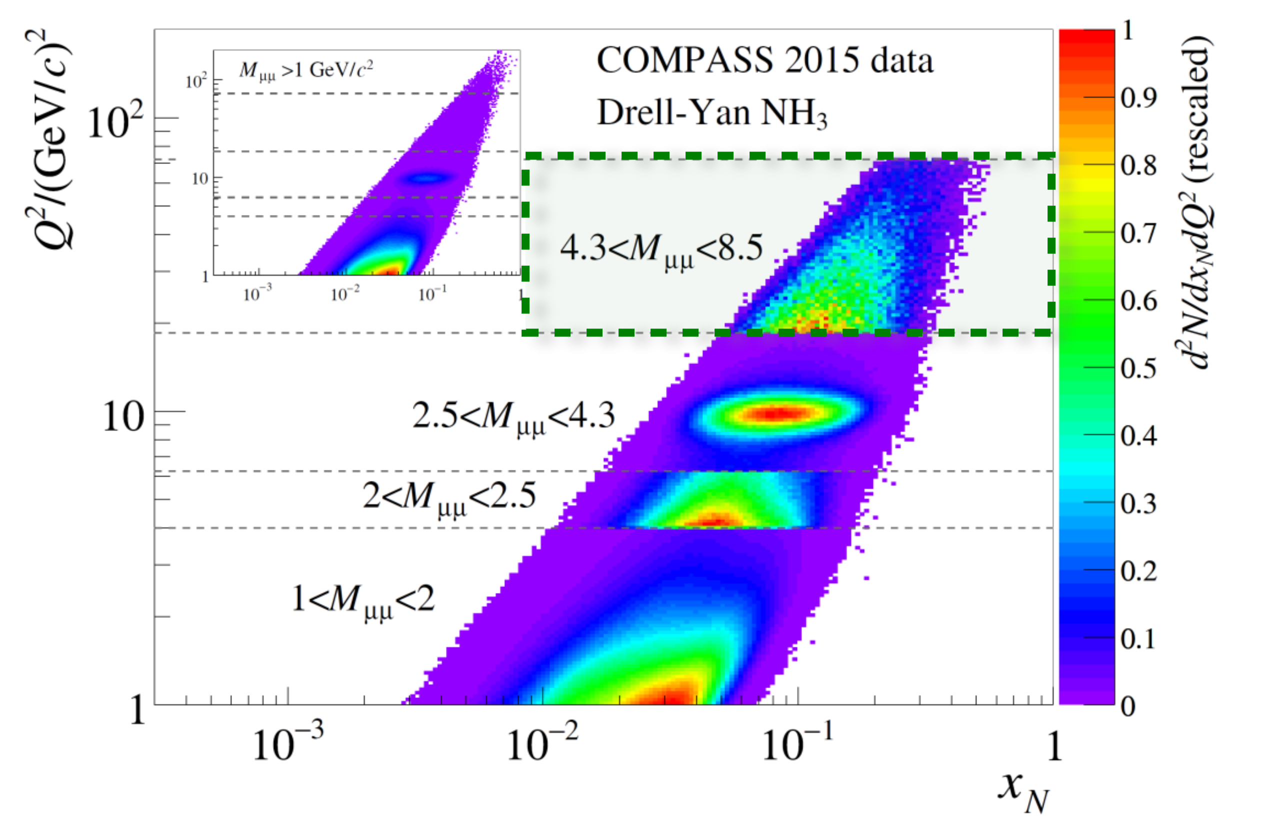
q_T > 0.4 GeV/c

⟨x_F⟩ = 0.33

⟨q_T⟩ = 0.17 GeV/c

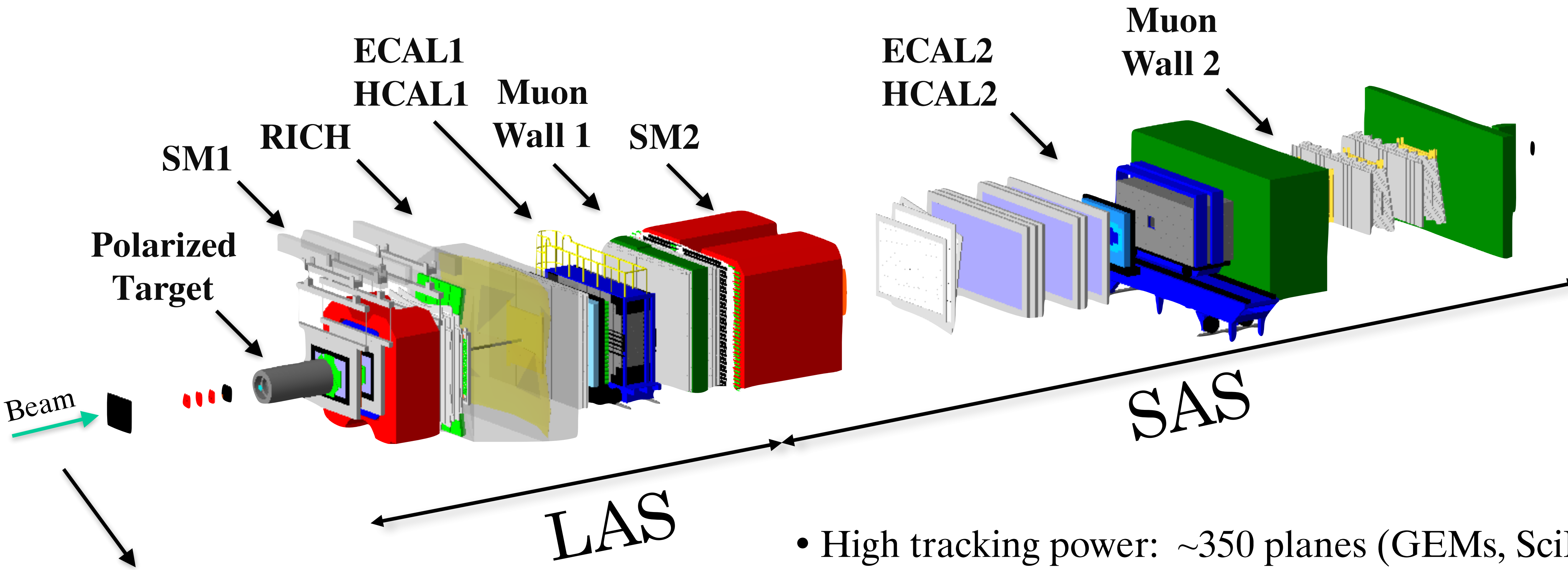






COMPASS-Setup

COMPASS experimental setup: Phase I (muon program)

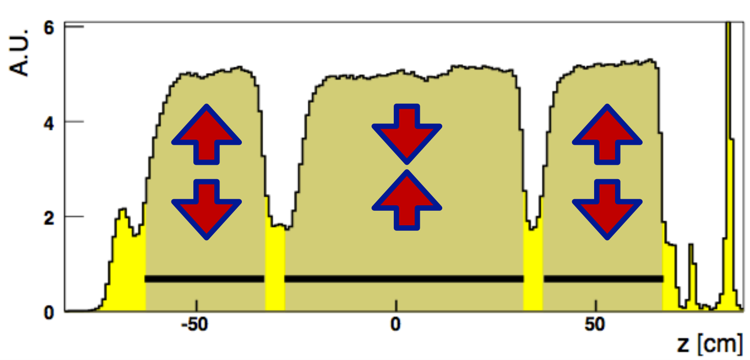


μ^+ beam

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

Solid state transversely polarized target (2007 , 2010)

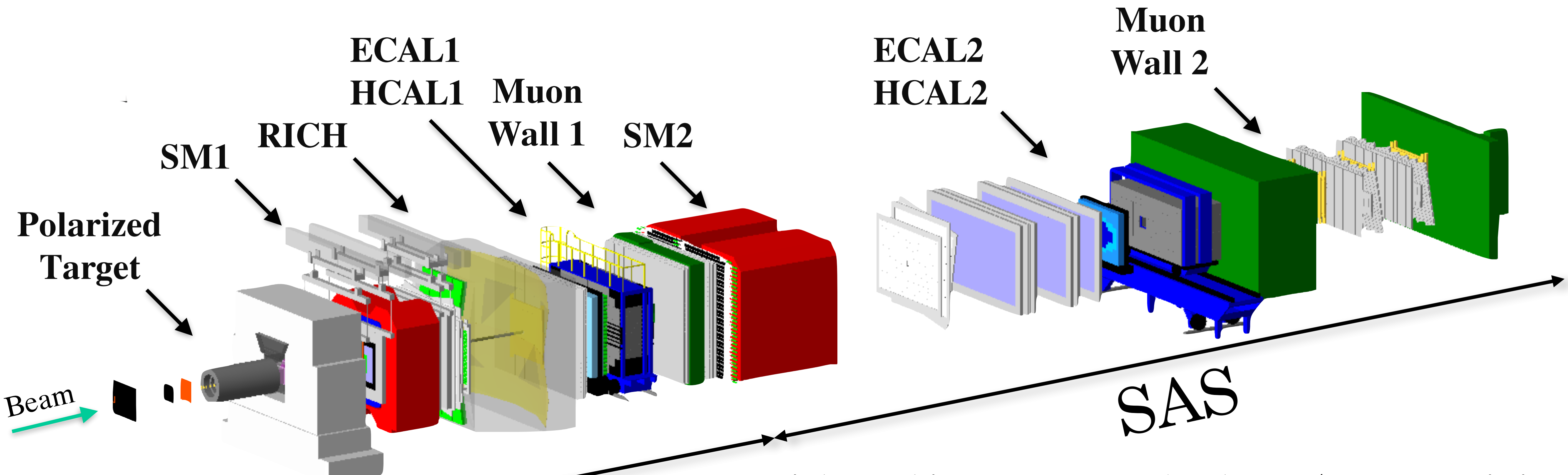
Target	# of cells	Polarization
NH_3	3	T, ~80-90 %



- High tracking power: ~350 planes (GEMs, SciFis, DCs, MWPCs, MicroMegas, Straws);
- PID via RICH and Calorimetric measurements;

- Two stages spectrometer
  - Large Angle Spectrometer (LAS)
    - 35 mrad $< \Theta <$ 180 mrad
    - SM1 magnet (1 T · m)
  - Small Angle Spectrometer (SAS)
    - 18 mrad $< \Theta <$ 35 mrad
    - SM2 magnet (4.4 T · m)
- Data were collected simultaneously for the two target spin orientation
- For transverse programme, the polarization was reversed after each 4-5 days

COMPASS experimental setup: Phase II (DY program)



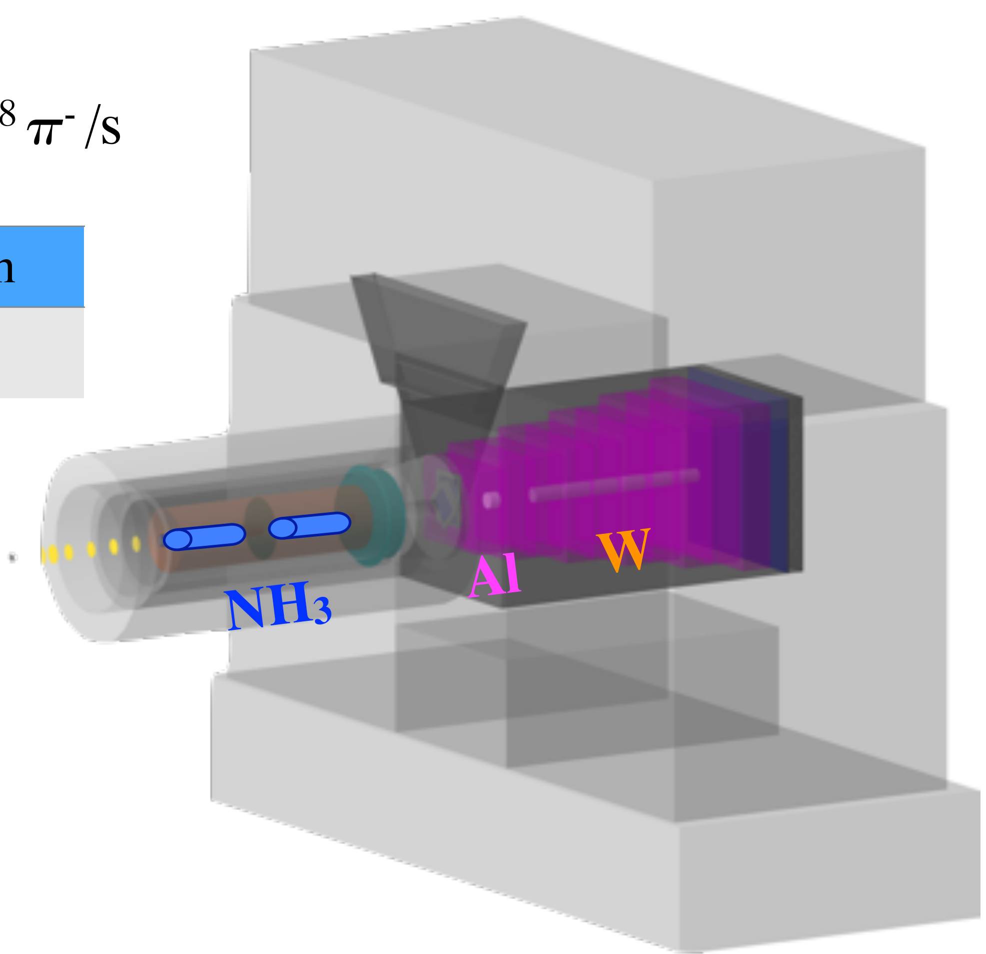
- High tracking power: ~350 planes (GEMs, SciFis, DCs, MWPCs, MicroMegas, Straws, DC05, VD, PixelMicroMegas, new DAQ …)

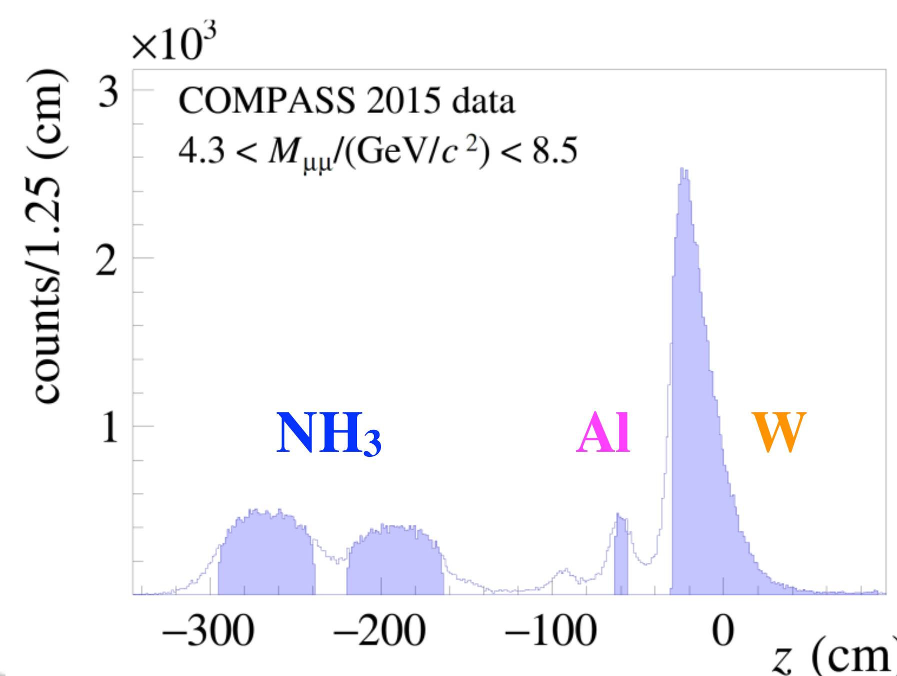
π^- beam

- P_{π^-} : 191 GeV/c, intensity $10^8\ \pi^-$/s

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

- 2015 Polarized DY run ~4 months of data taking;
- The polarization was reversed after each week;





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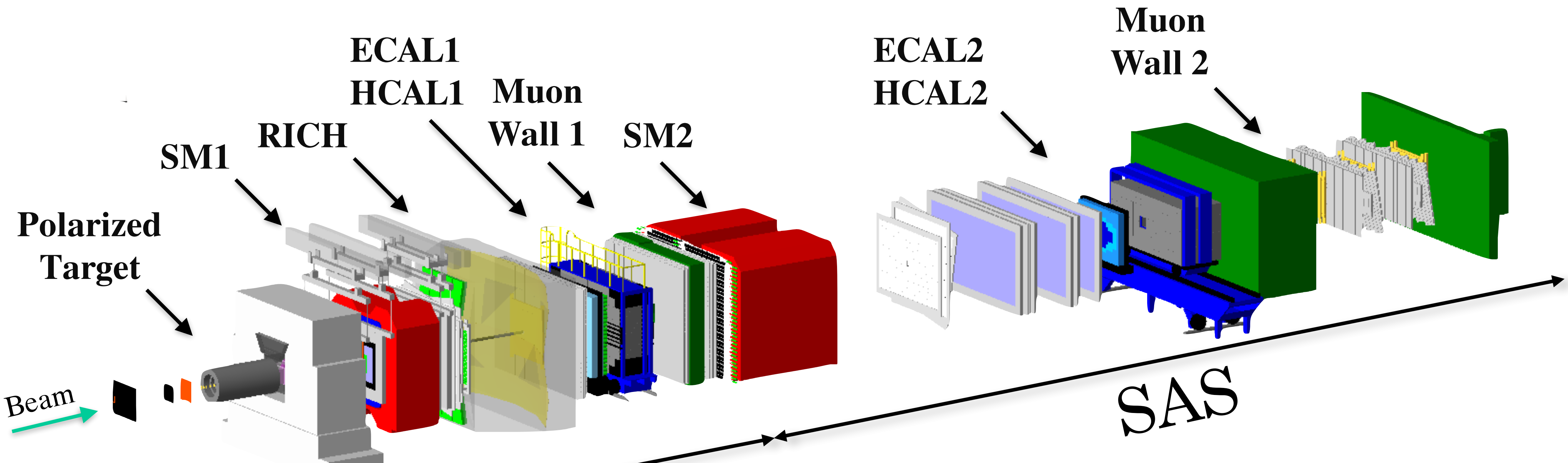

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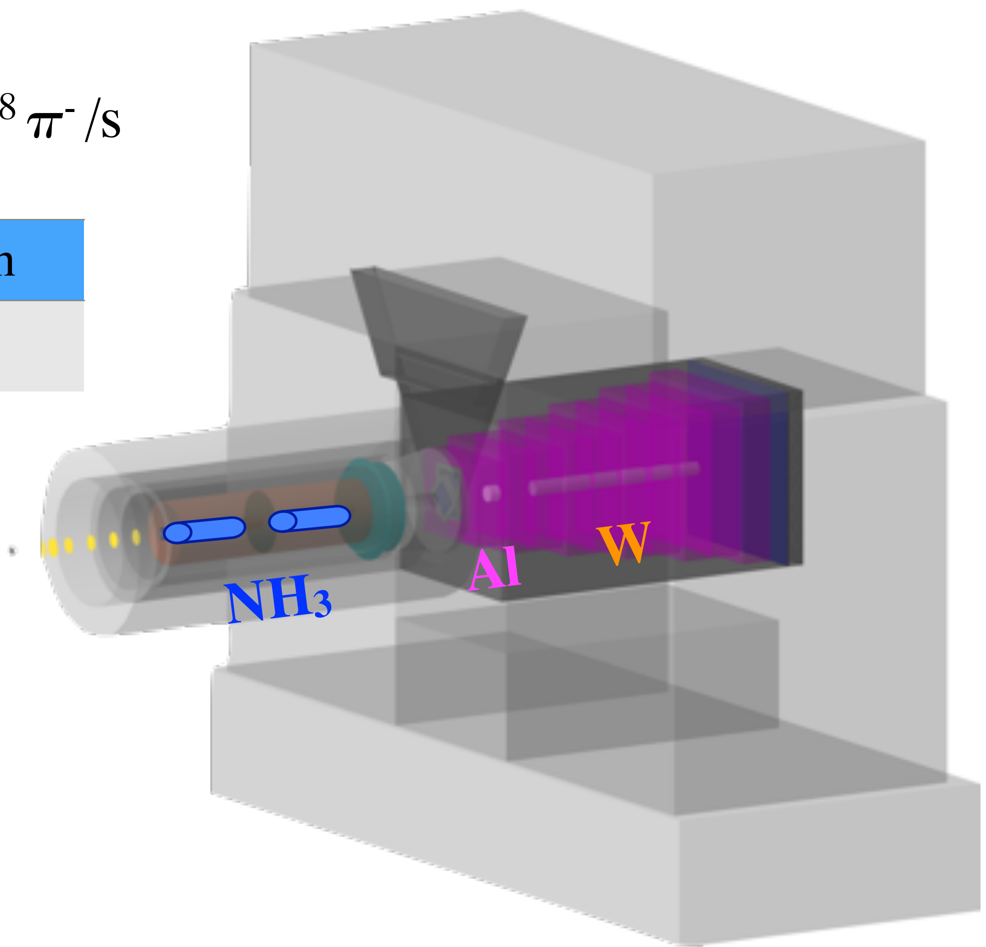
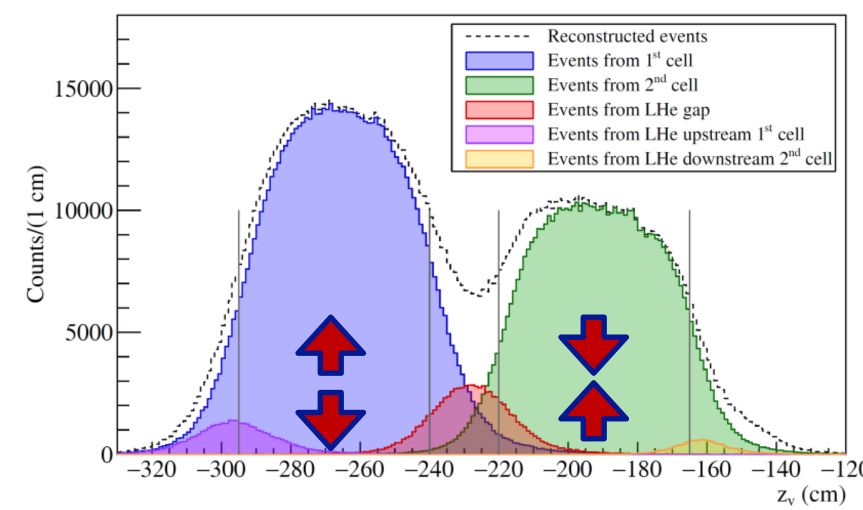
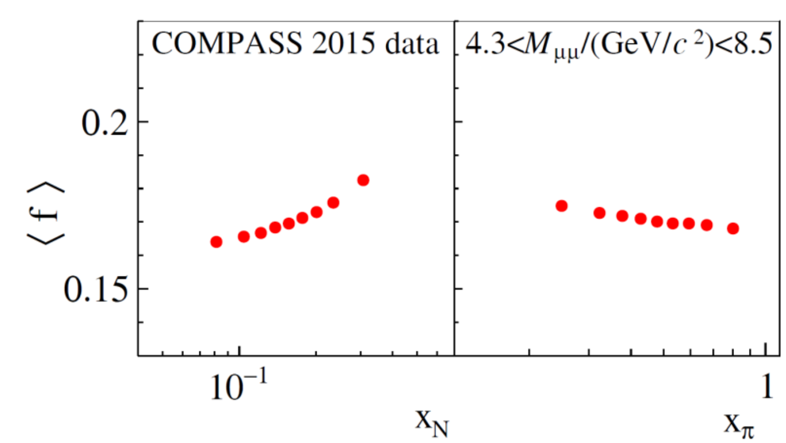


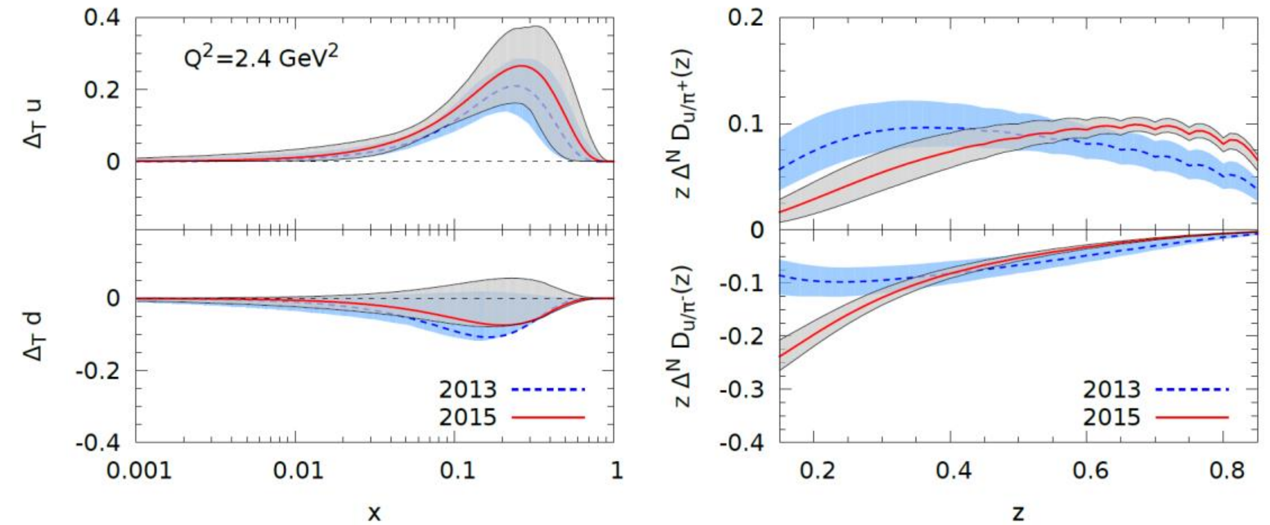




Selected SIDIS results on the Transverse Spin Asymmetries

COMPASS SIDIS results: Collins TSA

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

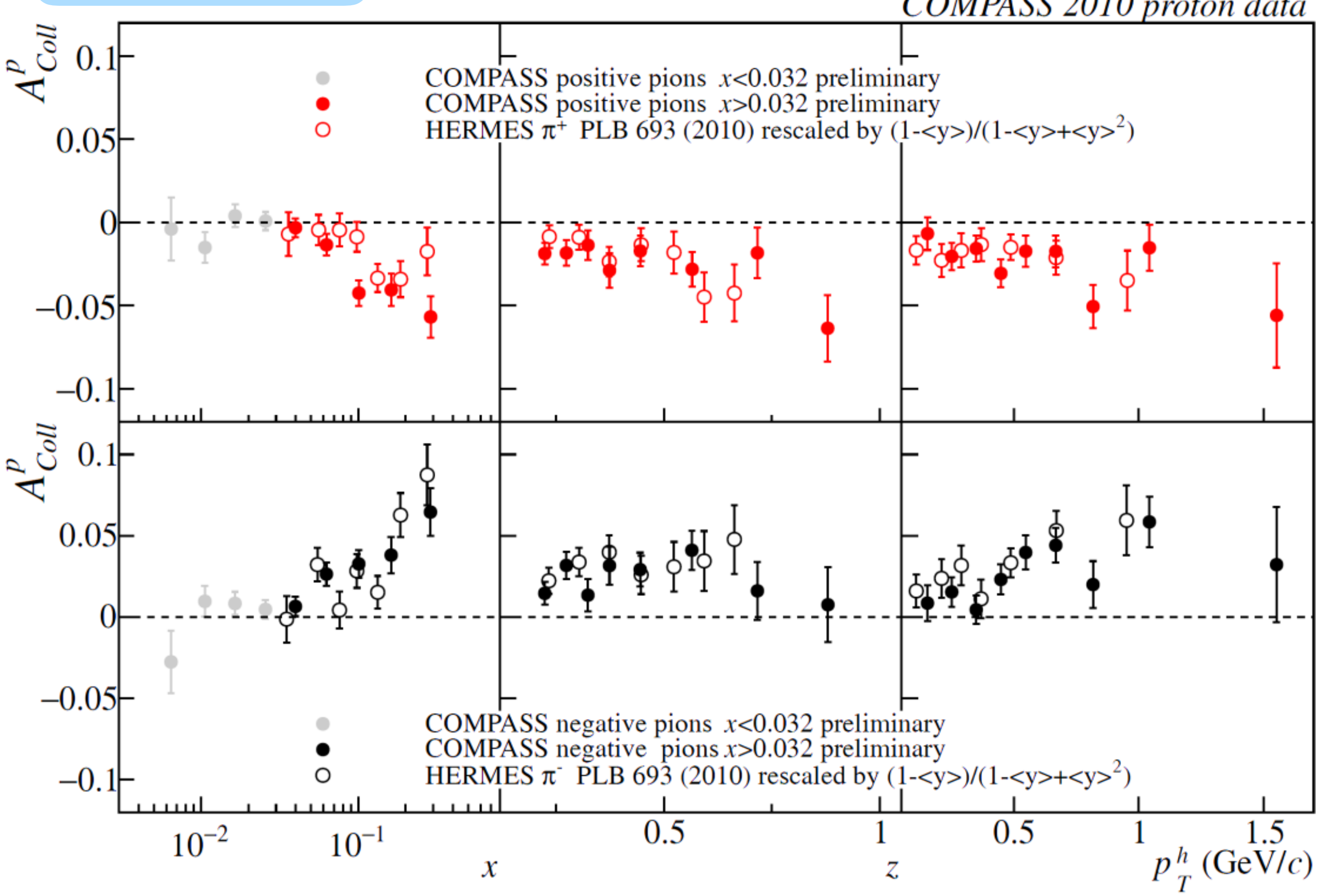


Anselmino et al., Phys.Rev. D92 (2015) 114023
Global fit of HERMES - COMPASS - BELLE data

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

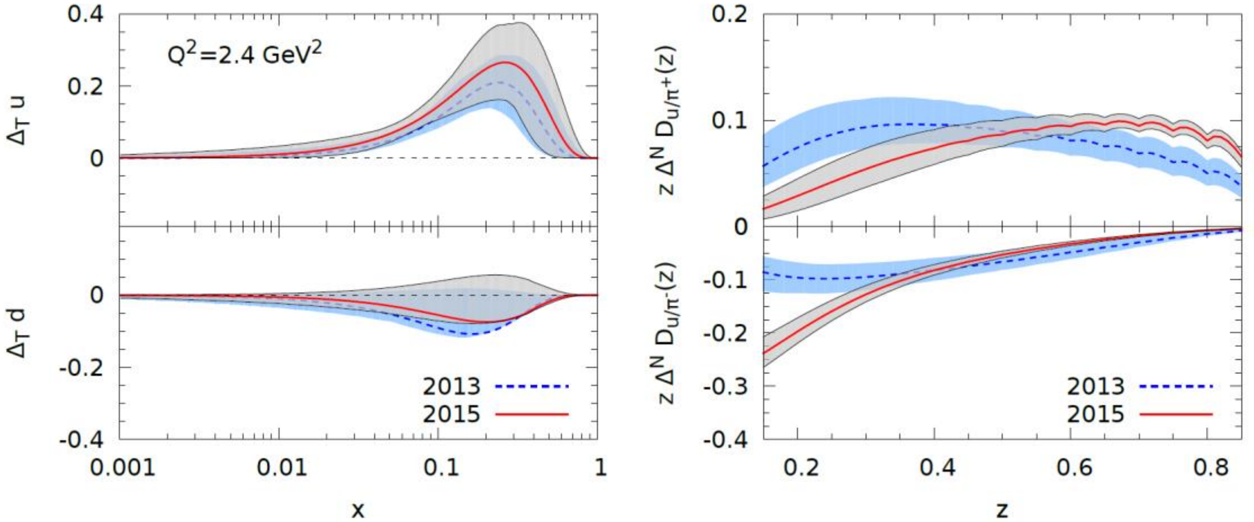
PLB 744 (2015) 250

COMPASS 2010 proton data



COMPASS SIDIS results: Collins TSA

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



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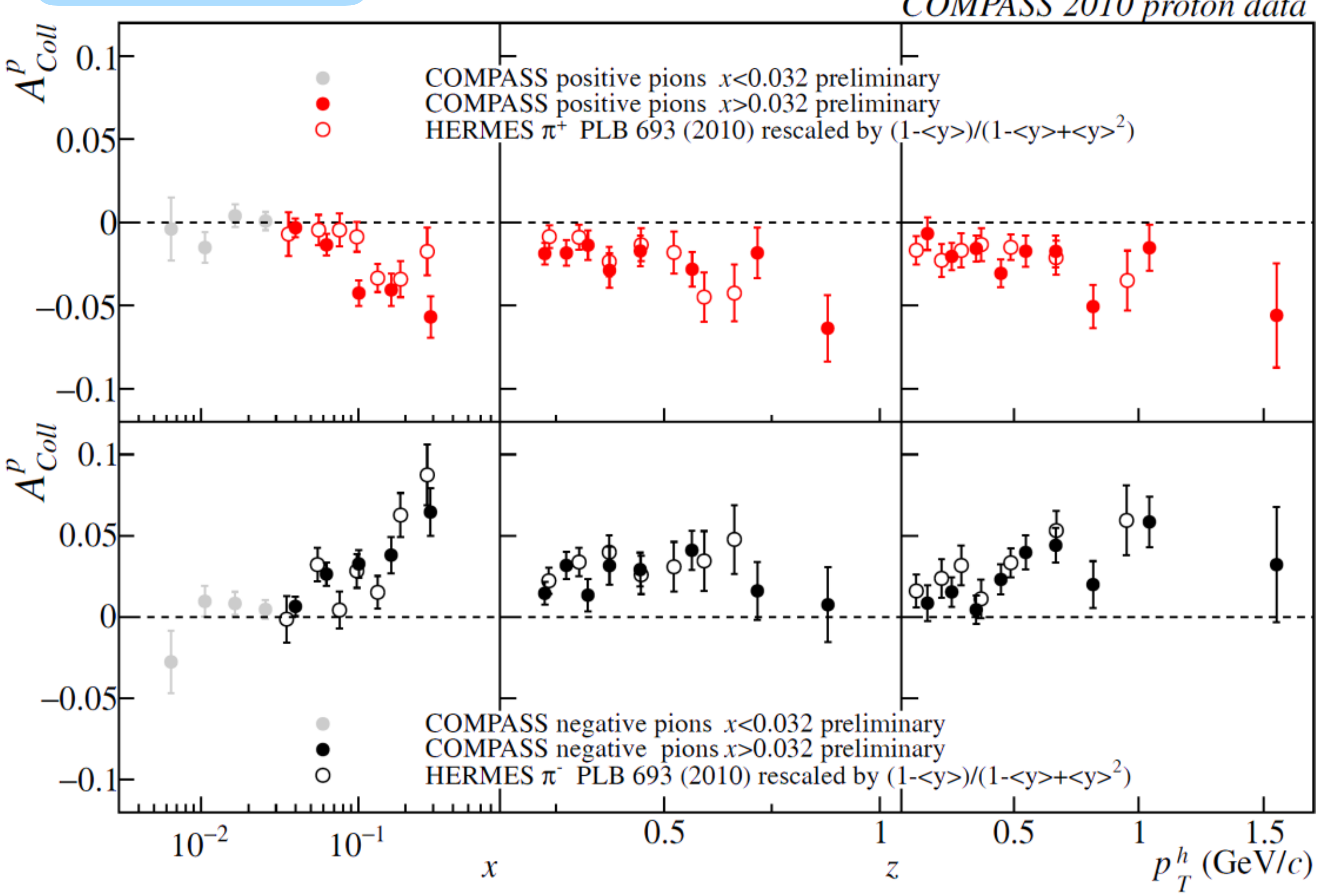
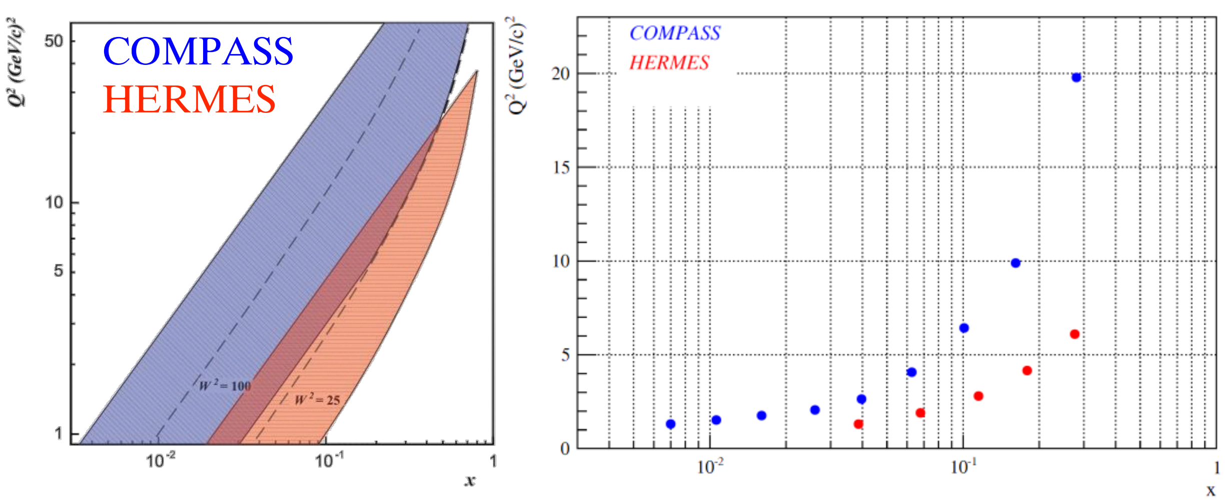
PLB 744 (2015) 250

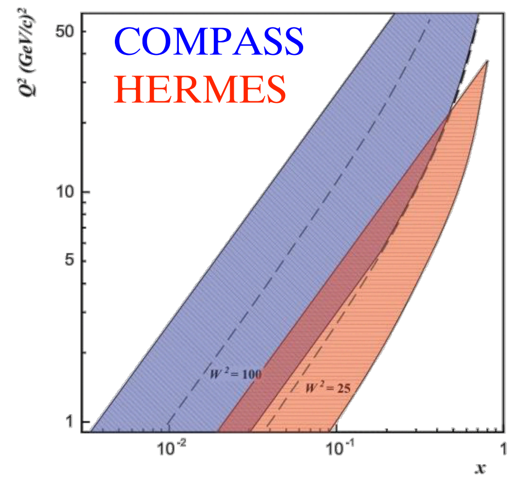


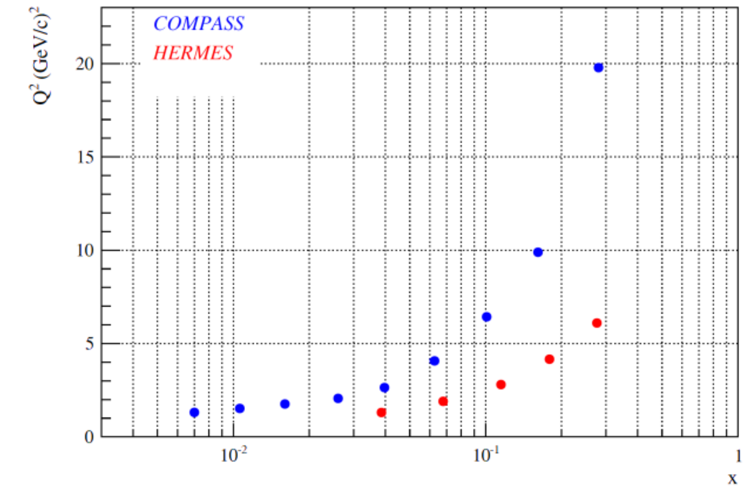
- COMPASS and HERMES obtained compatible results on Collins TSA (Q^2 is different by a factor of ~2-3)
- No Q^2 evolution?



COMPASS SIDIS results: Sivers

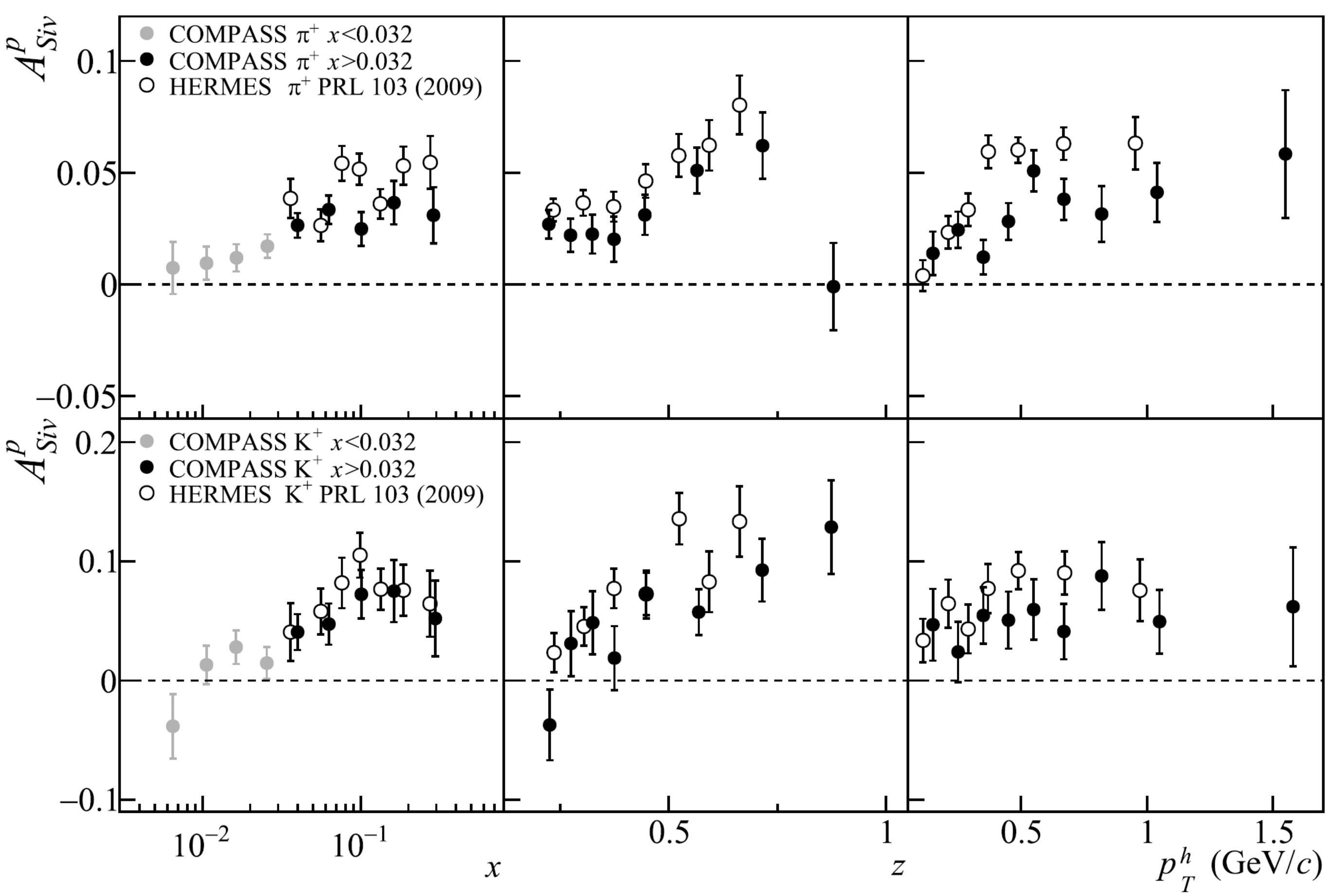
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2d\varphi_h d\psi} \propto \left\{ \begin{array}{l} 1+\cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ +S_T \left[\begin{array}{l} \sin(\phi_h-\phi_S) A_{UT}^{\sin(\phi_h-\phi_s)} \\ +\sin(\phi_h+\phi_S)\varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \\ +\sin(3\phi_h-\phi_S)\varepsilon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

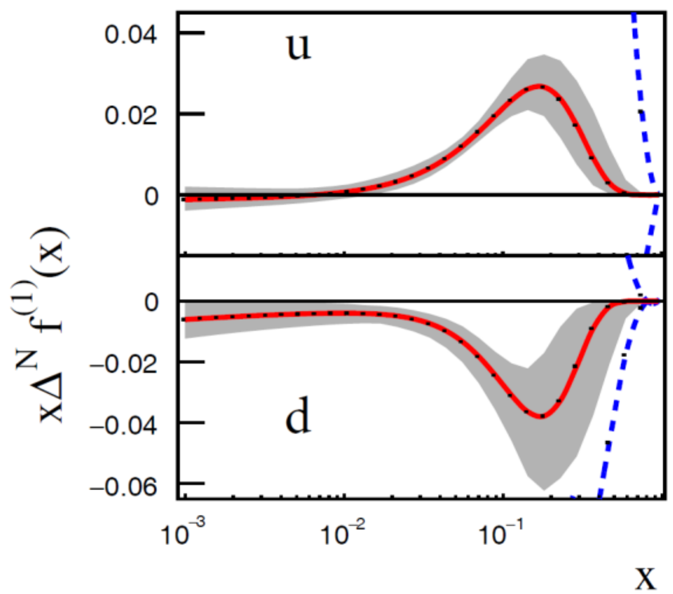




$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^h$$

PLB 744 (2015) 250



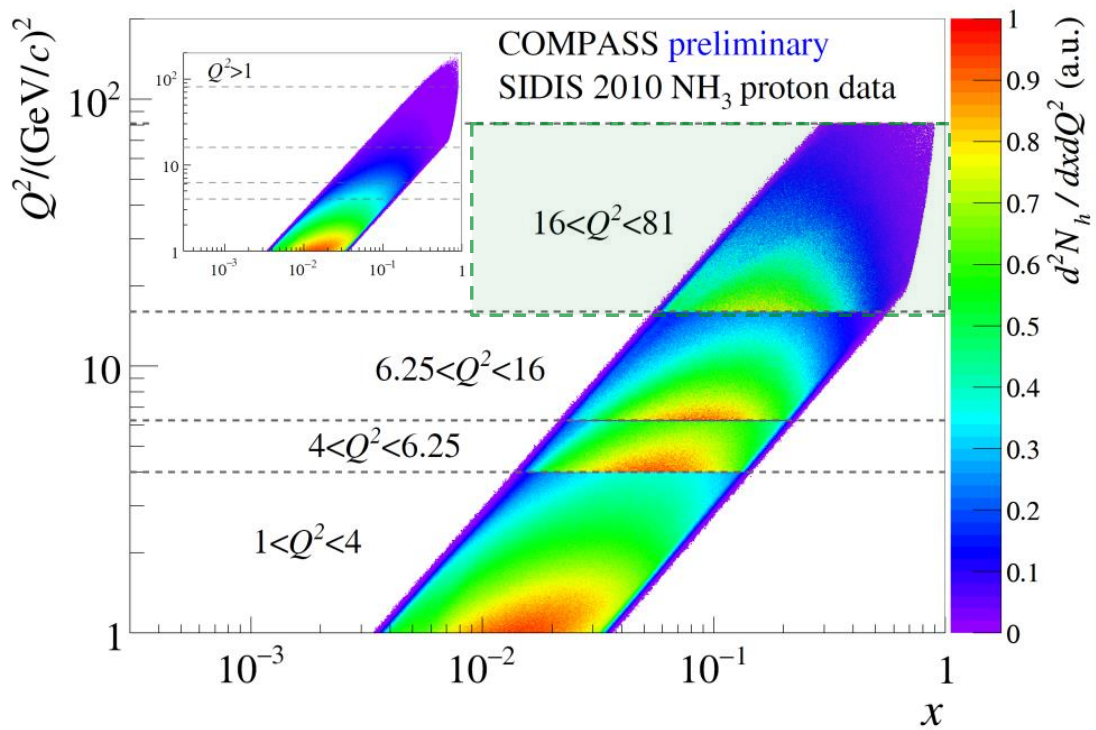


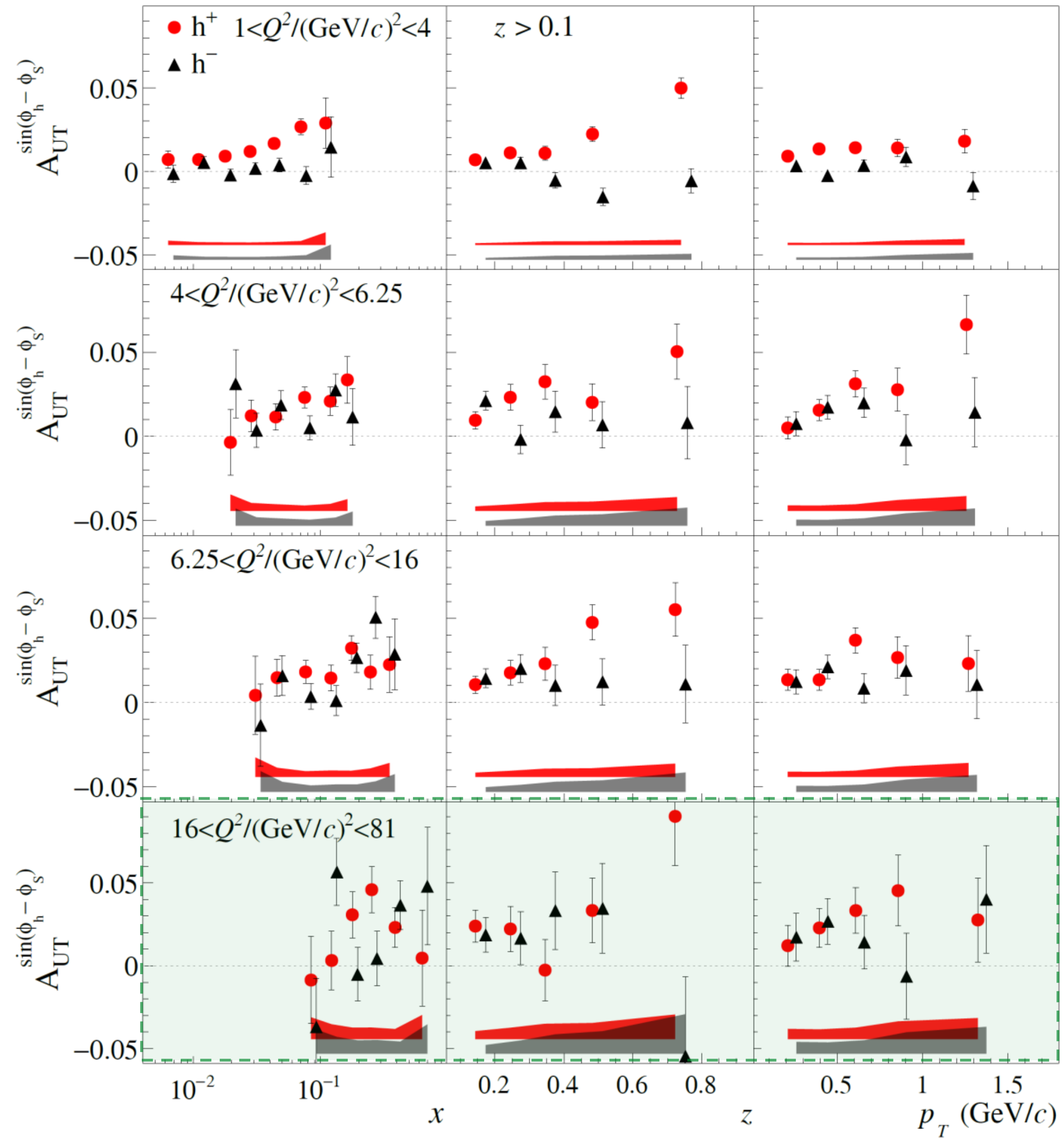
M. Anselmino et al., Arxiv:1612:06413 [hep-ph]

- Sivers asymmetry for π^+ and K^+ : COMPASS proton 2010 vs Hermes proton 2002-2005.
- Sivers asymmetry measured in COMPASS is lower than the one from HERMES, for both π^+ and K^+.
- For given x COMPASS operates with larger mean Q^2 values (factor 2-3).
- Q^2 evolution?

COMPASS SIDIS results: Sivers

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





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

Published last week on PLB

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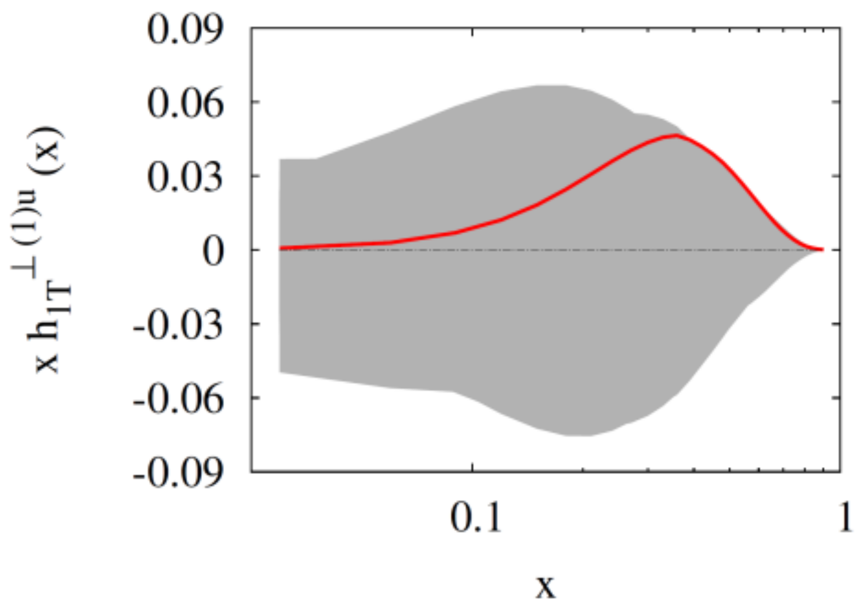
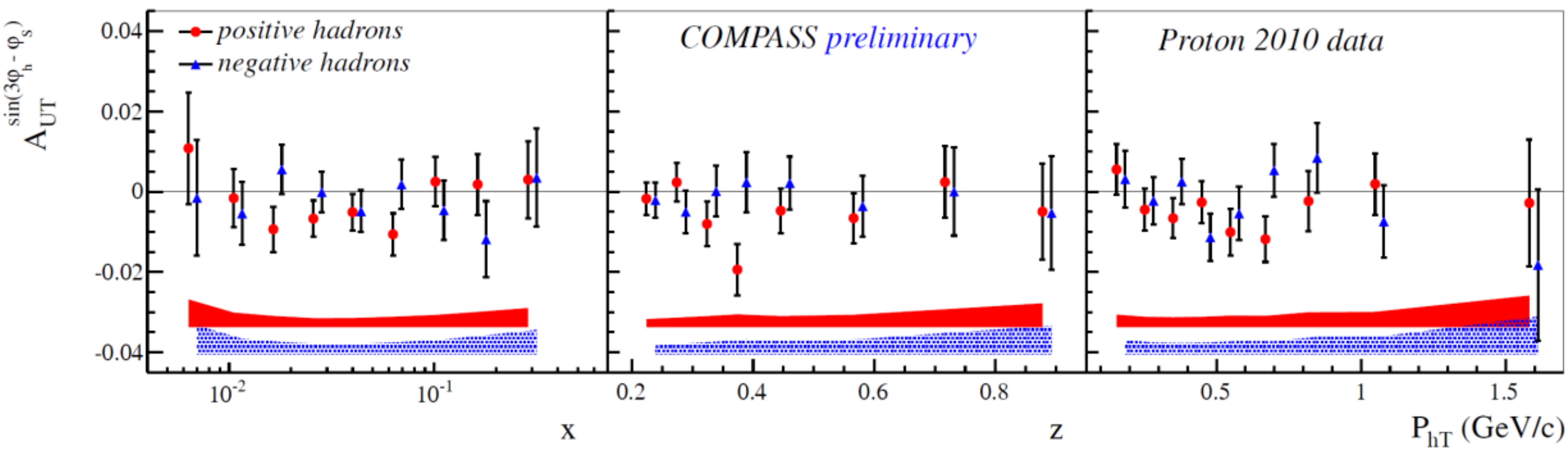
COMPASS SIDIS results: Pretzelosity TSA

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



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

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



B.Parsamyan, PoS DIS2013 (2013)

Results from polarized Drell-Yan: Transverse Spin Asymmetries

Drell-Yan TSAs : Transversity

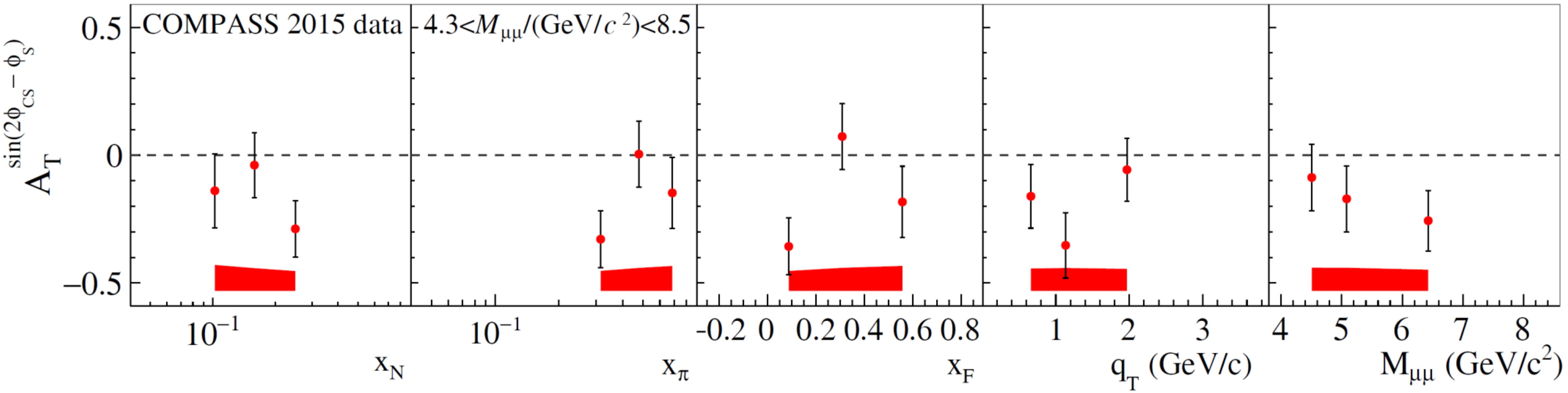
$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

New! 03 April 2017! COMPASS

CERN-EP-2017-059, arXiv:1704.00488[hep-ex]

DY - HM range



Drell-Yan TSAs : Transversity

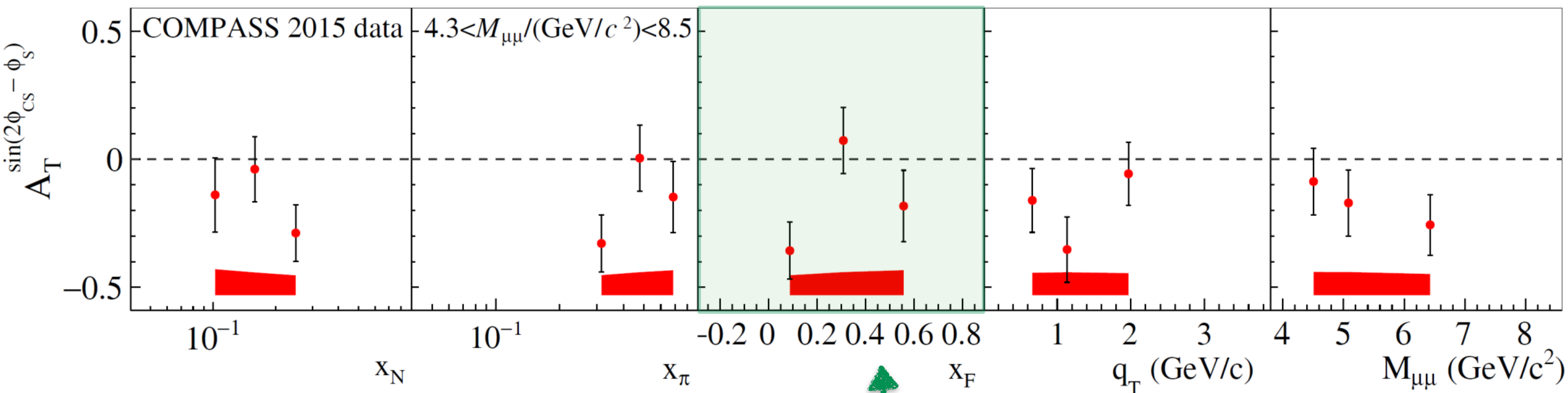
$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

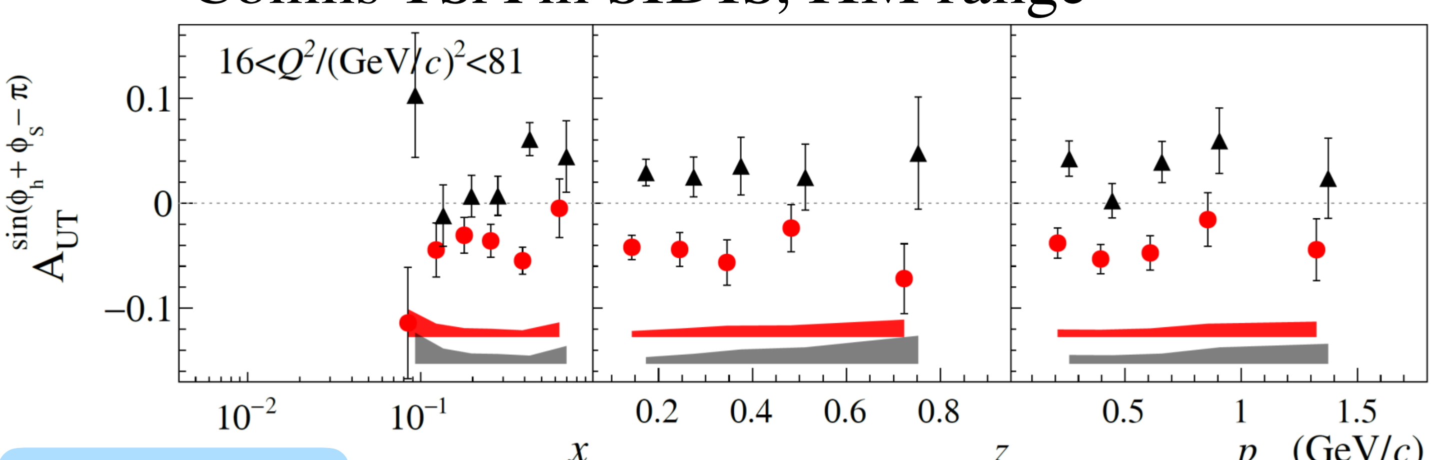
New! 03 April 2017! COMPASS

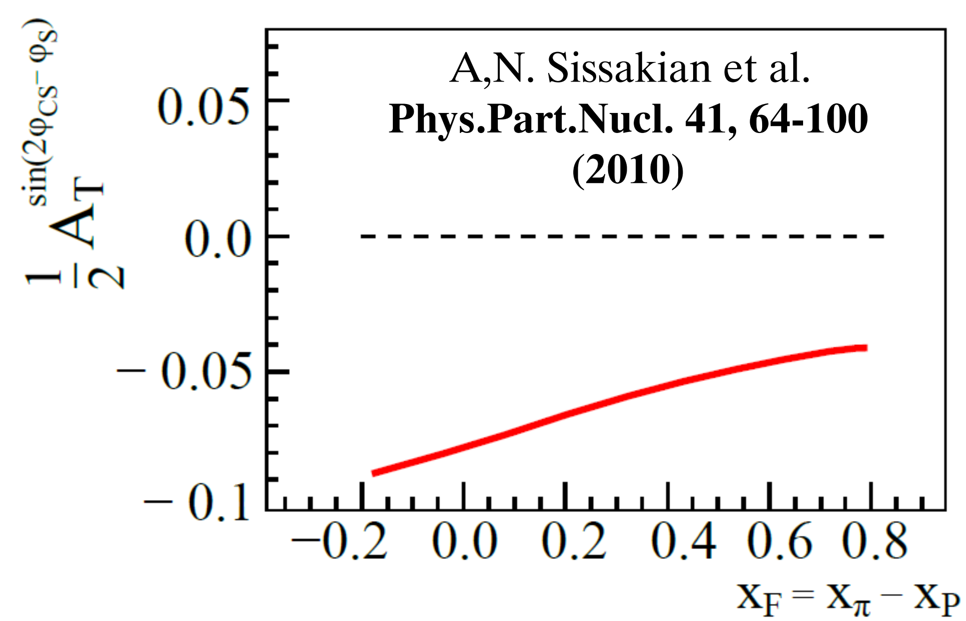
CERN-EP-2017-059, arXiv:1704.00488[hep-ex]

DY - HM range



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**

Drell-Yan TSAs : Pretzelosity

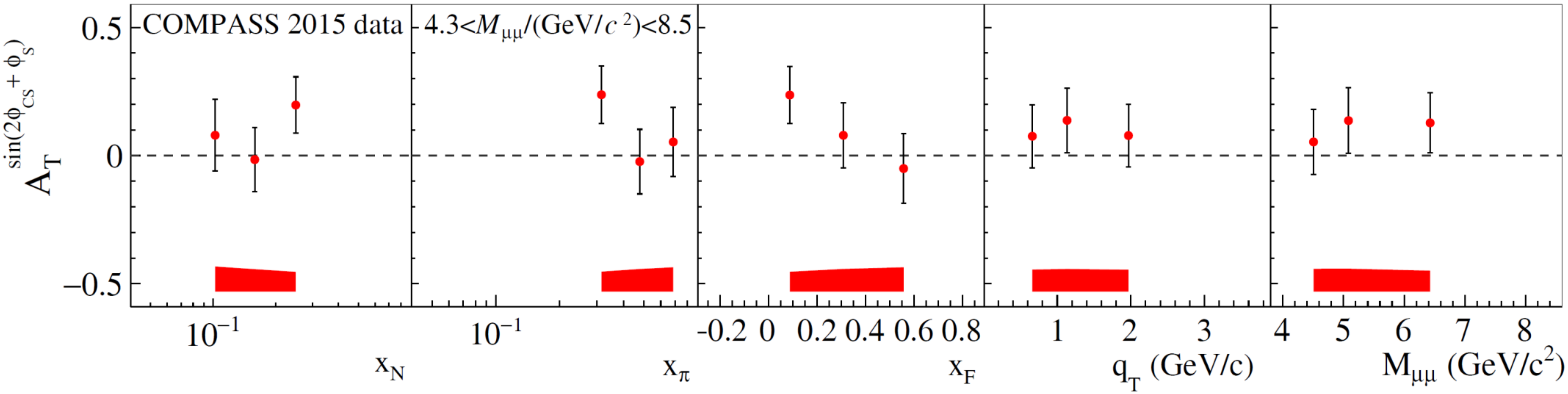
$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

New! 03 April 2017! COMPASS

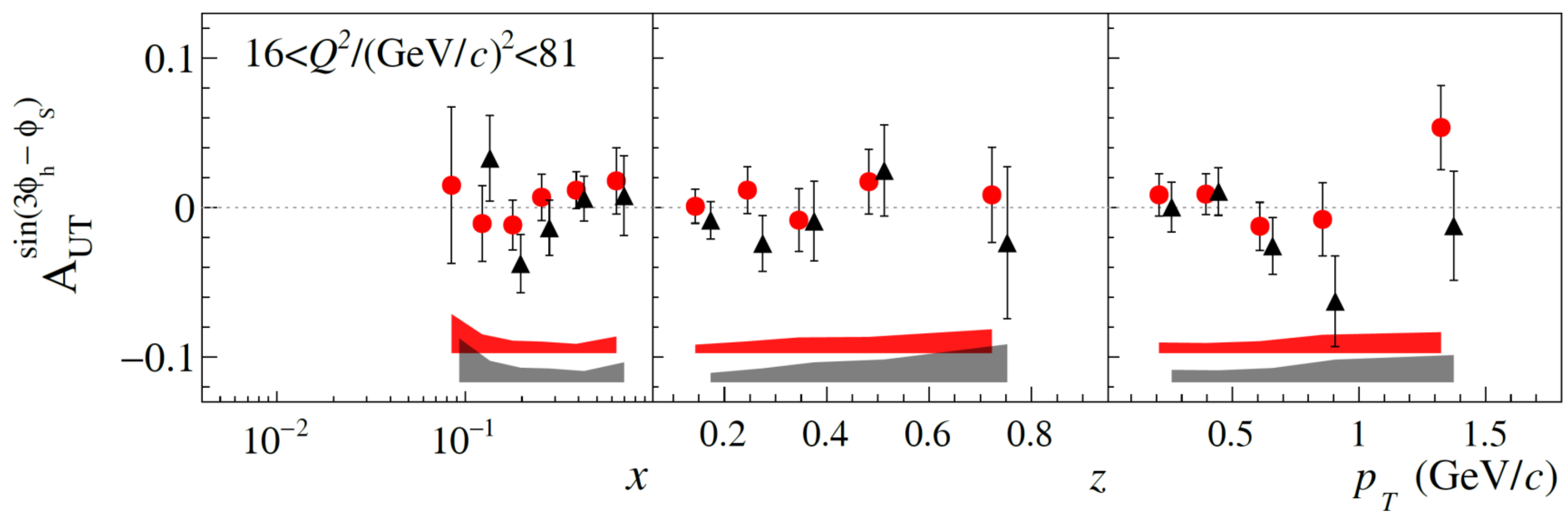
CERN-EP-2017-059, arXiv:1704.00488[hep-ex]

DY - HM range



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**

Drell-Yan TSAs : Sivers

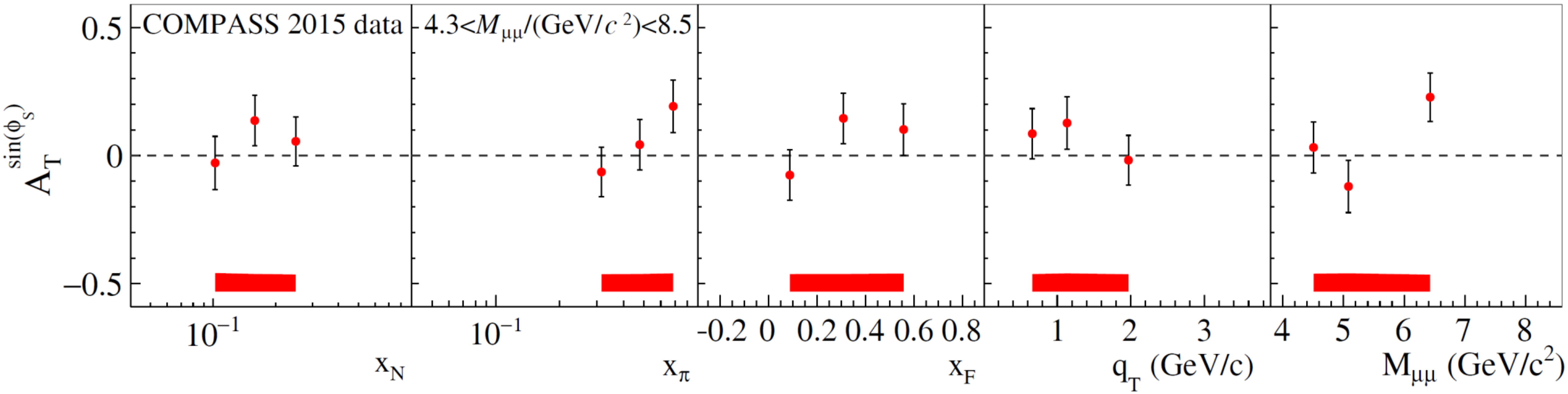
$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]} \cos(2\varphi_{CS}) A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

New! 03 April 2017! COMPASS

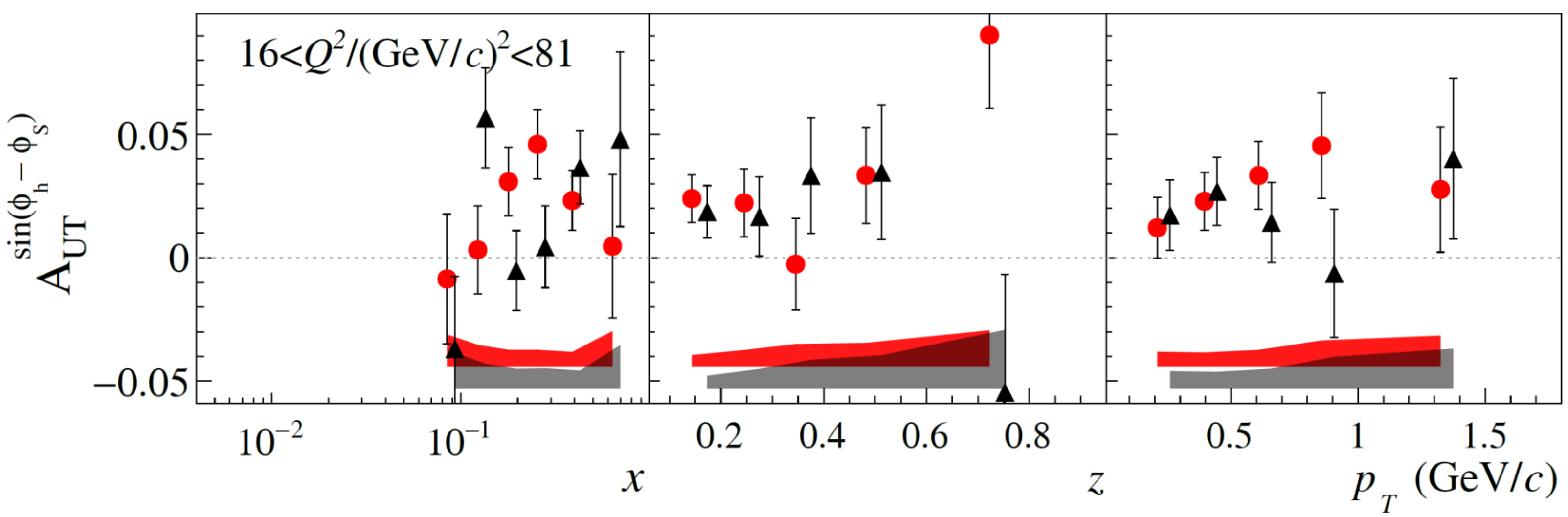
CERN-EP-2017-059, arXiv:1704.00488[hep-ex]

DY - HM range



Sivers TSA in SIDIS, HM range

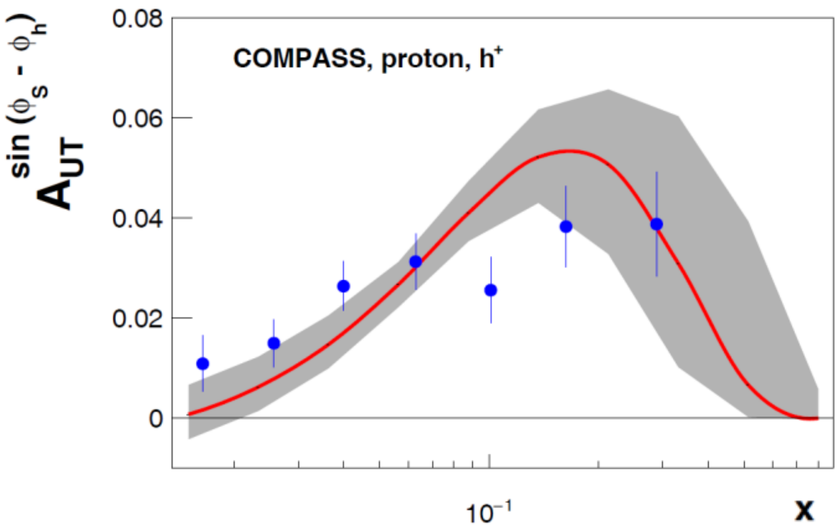
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$$



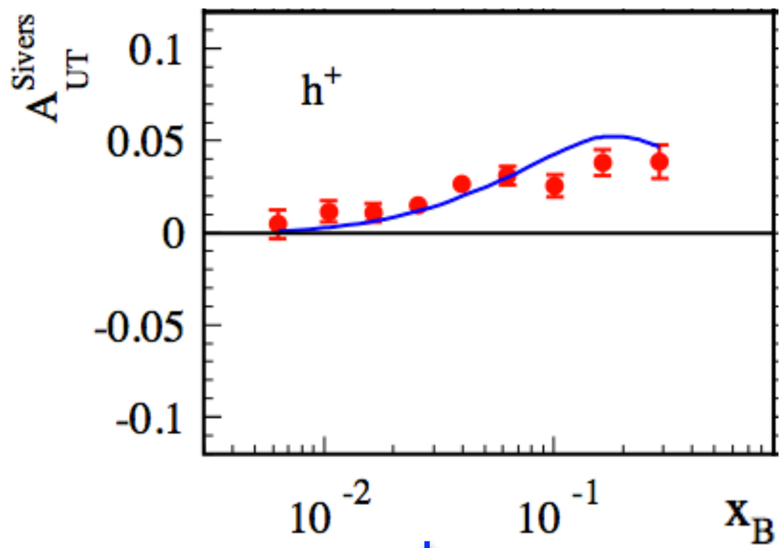
COMPASS **PLB 770 (2017) 138**

Sivers sign change test

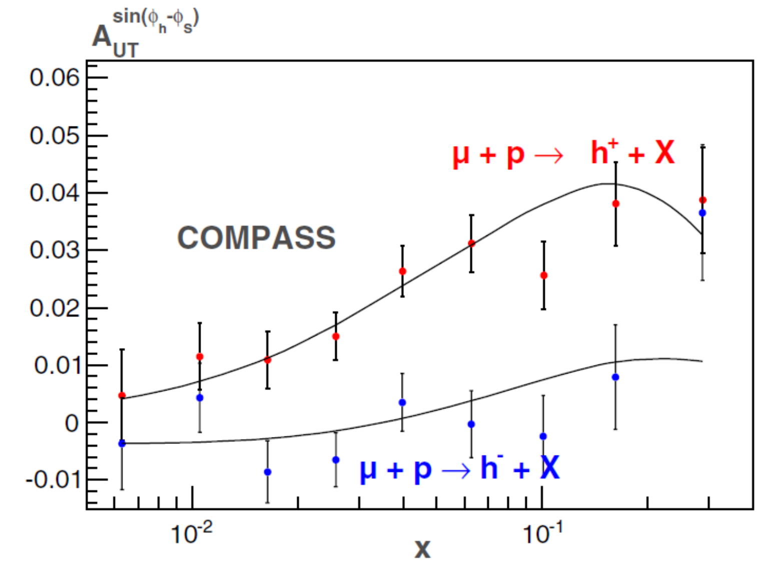
DGLAP (2016)
M. Anselmino et al., arXiv:1612.06413

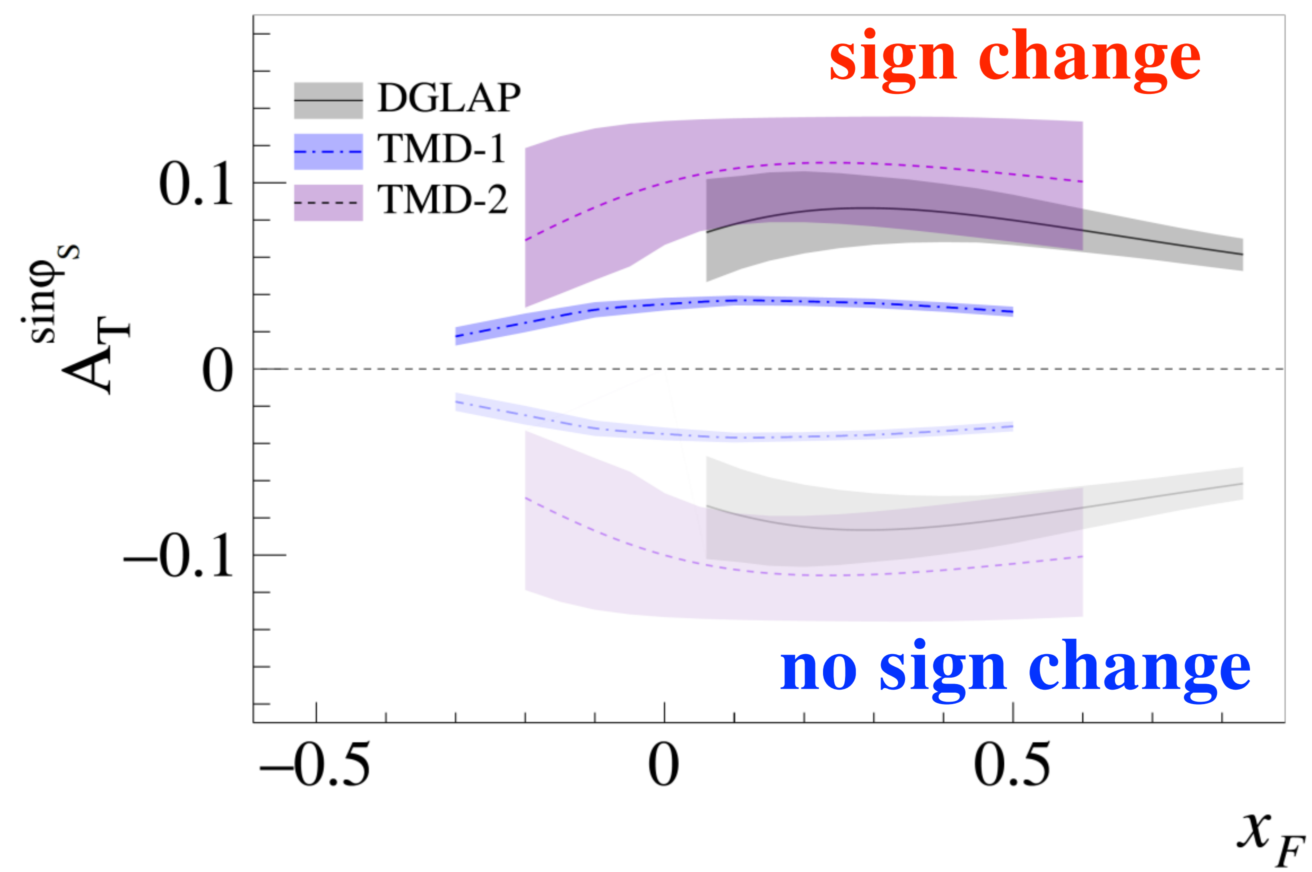


TMD-1 (2014)
M.G. Echevarria et al.,
PRD 89 074013



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





Sivers sign change test

DGLAP (2016)
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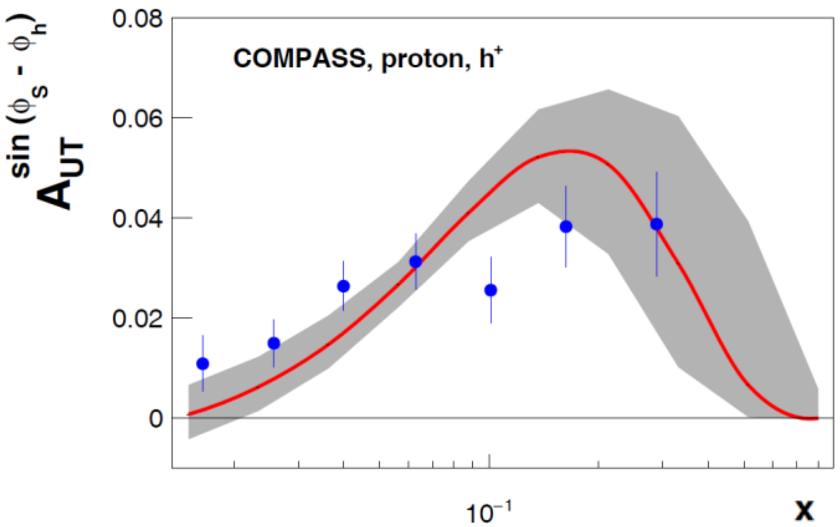

TMD-1 (2014)
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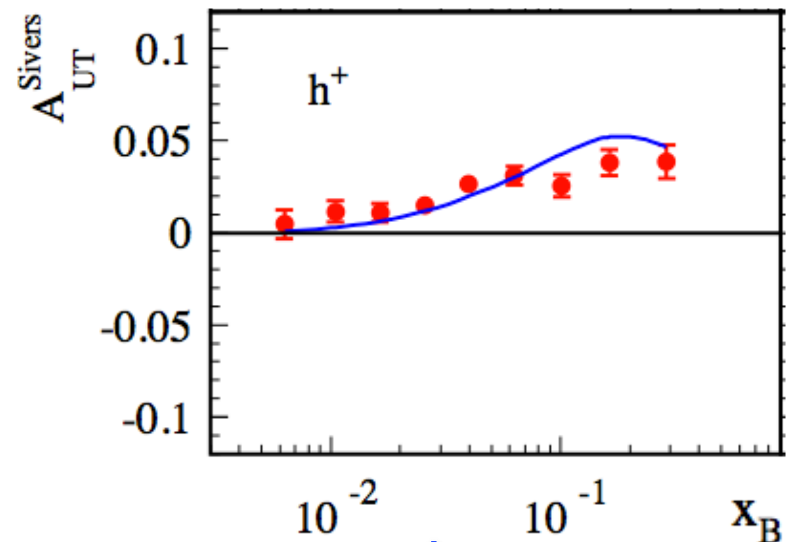
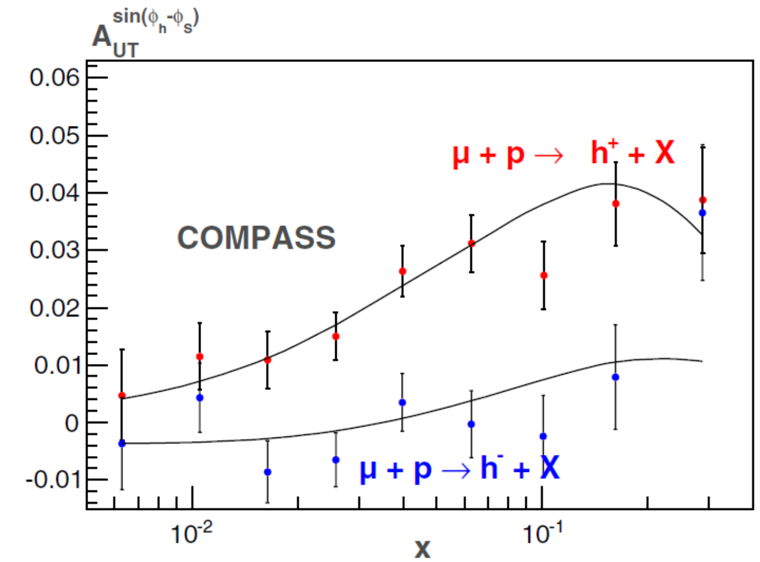
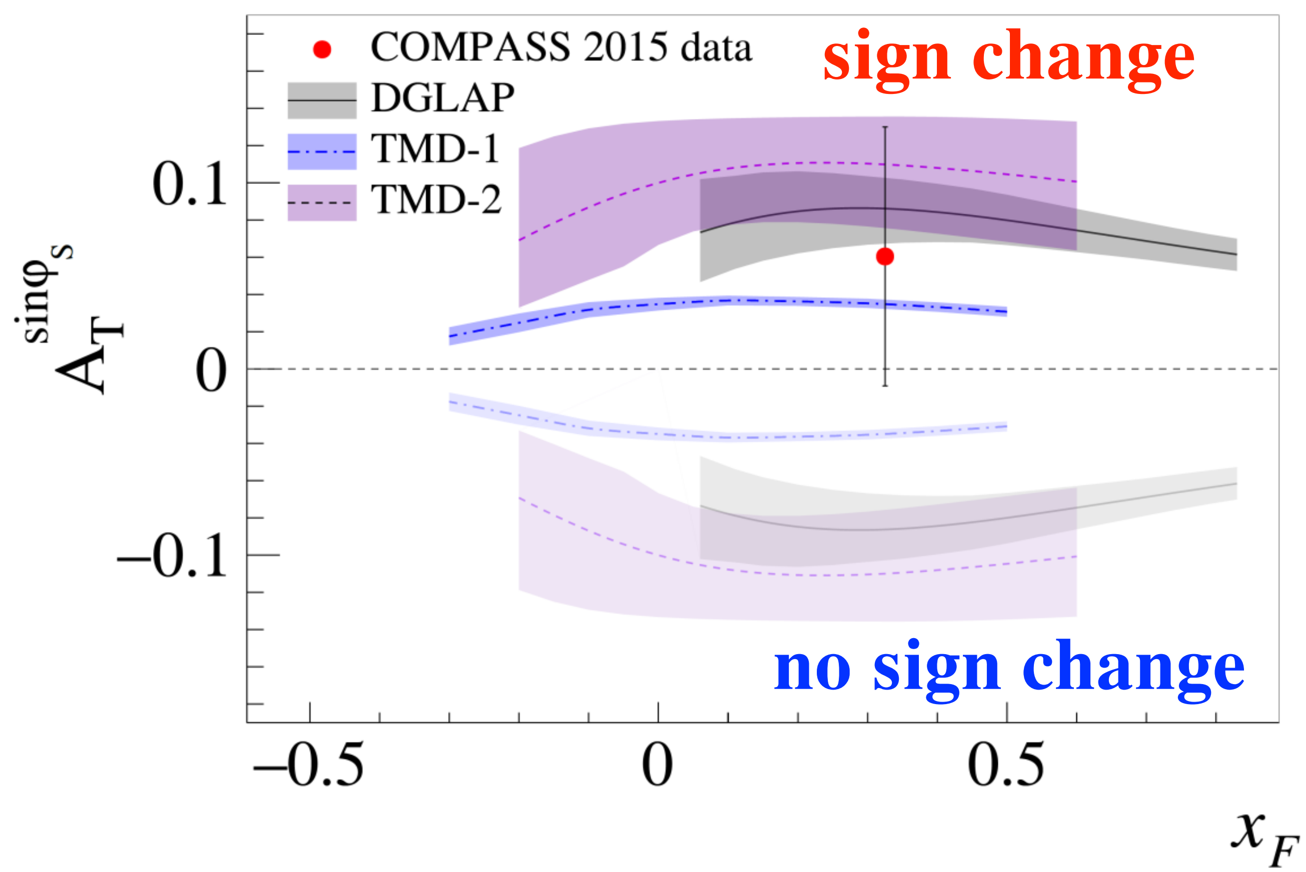


TMD-2 (2013)
P. Sun, F. Yuan, PRD88, 114012



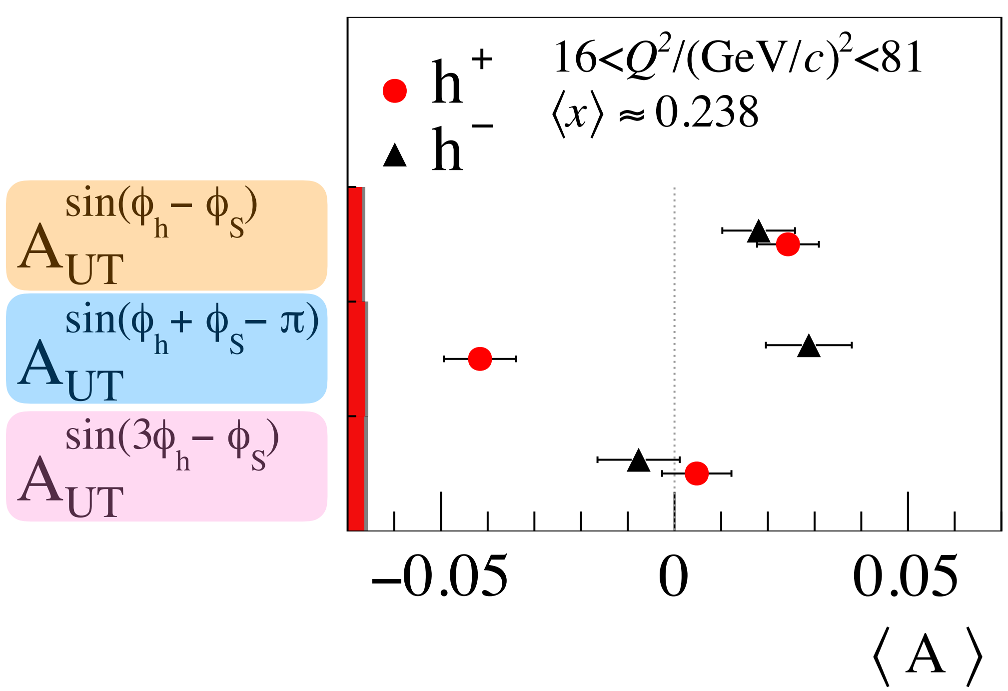


New!
03 April 2017, COMPASS
CERN-EP-2017-059
arXiv:1704.00488[hep-ex]

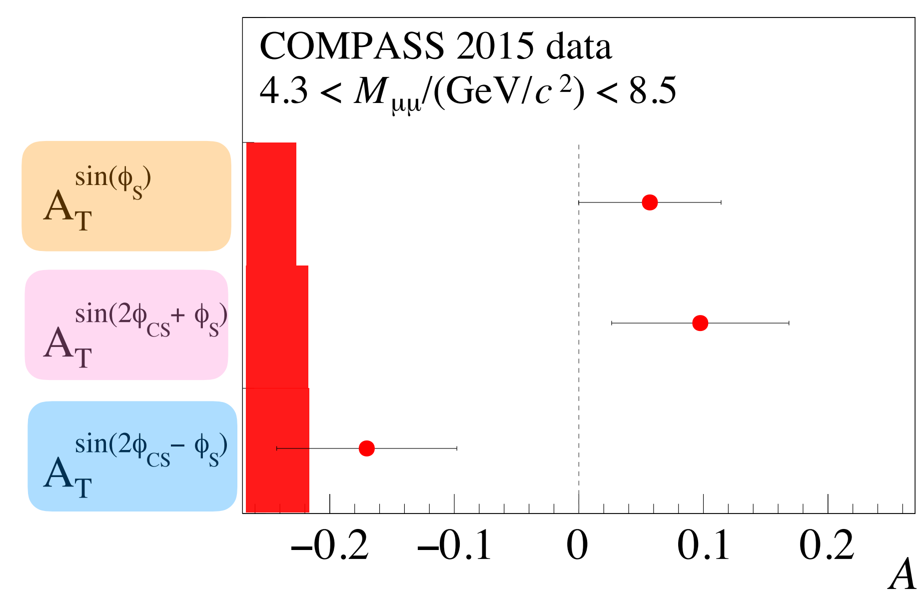
COMPASS DY run 2018 will improve the statistical precision

Summary

- The COMPASS Collaboration took a considerable amount of SIDIS data during its Phase I:
  - COMPASS has measured SIDIS proton TSAs at Drell-Yan mass ranges.
  - In the HM range Sivers and Collins TSAs are measured to be significant (> 3 s.d. away from zero for h+).
  - The Pretzelosity related asymmetry is compatible with zero.
- COMPASS has taken the first ever polarized DY data in 2015, becoming the first experiment to measure TSAs both in SIDIS and in DY and allowing to compare TMD PDFs obtained from the two processes.
  - Sivers TSA is above zero by about one standard deviation and it is consistent with the predicted change of sign for the Sivers function.
  - Transversity and Pretzelosity TSAs are found about 2 and 1 s.d. away from zero, respectively.
  - In 2018 a 2nd year of DY data taking will take place.



PLB 770 (2017) 138



CERN-EP-2017-059
arXiv:1704.00488[hep-ex]

Summary - 2

Before 2015 DY run…

Summary - 2

Before 2015 DY run…

After 2015 DY run!

Summary - 2

Before 2015 DY run…

After 2015 DY run!

But 2018 run has yet to come…

Summary - 2

Before 2015 DY run…

After 2015 DY run!

But 2018 run has yet to come…

And maybe even more, beyond 2020… !

Thank you for your attention!

Spare Slides

COMPASS SIDIS results: Boer-Mulders

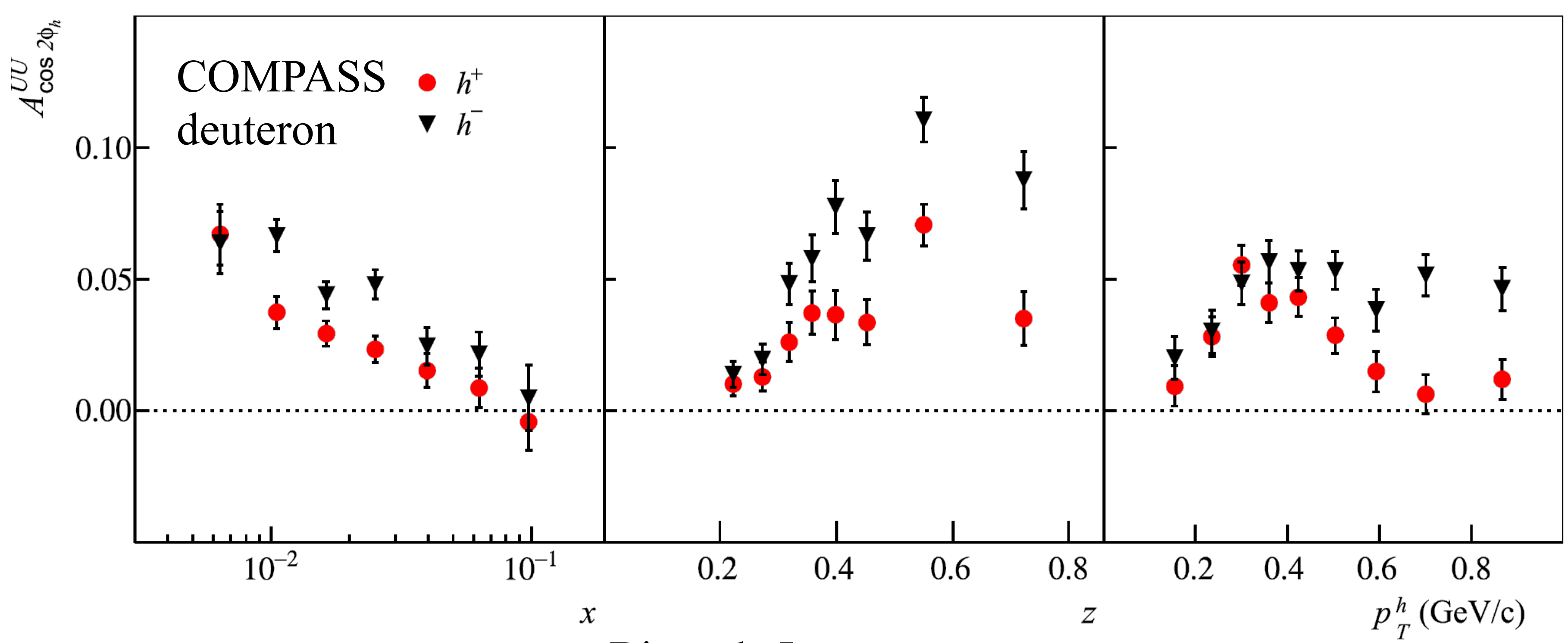
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\varphi_h\,d\psi} \propto \left\{ \begin{array}{l} 1 + \cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ + S_T \left[\begin{array}{l} \sin(\phi_h - \phi_S) A_{UT}^{\sin(\phi_h - \phi_s)} \\ + \sin(\phi_h + \phi_S)\varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \\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

- Large positive amplitudes decreasing with x for both h⁺/h⁻.
- Clear differences between h⁺/h⁻
- Slightly larger amplitude for h⁻
- Similarity between proton and deuteron results for $A_{UU}^{\cos(2\phi_h)}$ has been previously observed at HERMES collaboration.

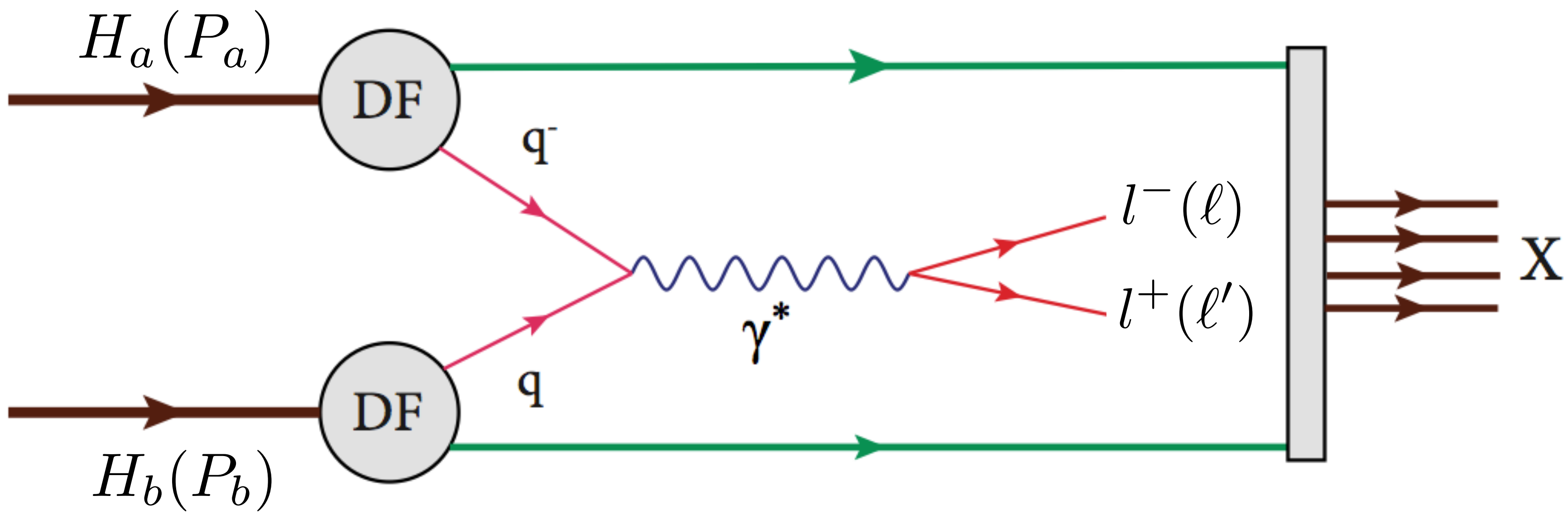
Boer-Mulders effect + "twist-4" Cahn effect

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

NPB 886 (2014) 1046



Drell-Yan process



Standard DY kinematic variables:

- 4-momenta of the virtual photon

$$q = \ell + \ell'$$

- Photon virtuality (~squared dimuon invariant mass)

$$Q^2 = q^2 \sim M_{\mu\mu}^2$$

- Bjorken variables of beam and target hadrons

$$x_a = \frac{q^2}{2P_a \cdot q}$$

$$x_b = \frac{q^2}{2P_b \cdot q}$$

- Feynman variable

$$x_F = x_a - x_b$$

- Quark-antiquark annihilation with two leptons in the final state.

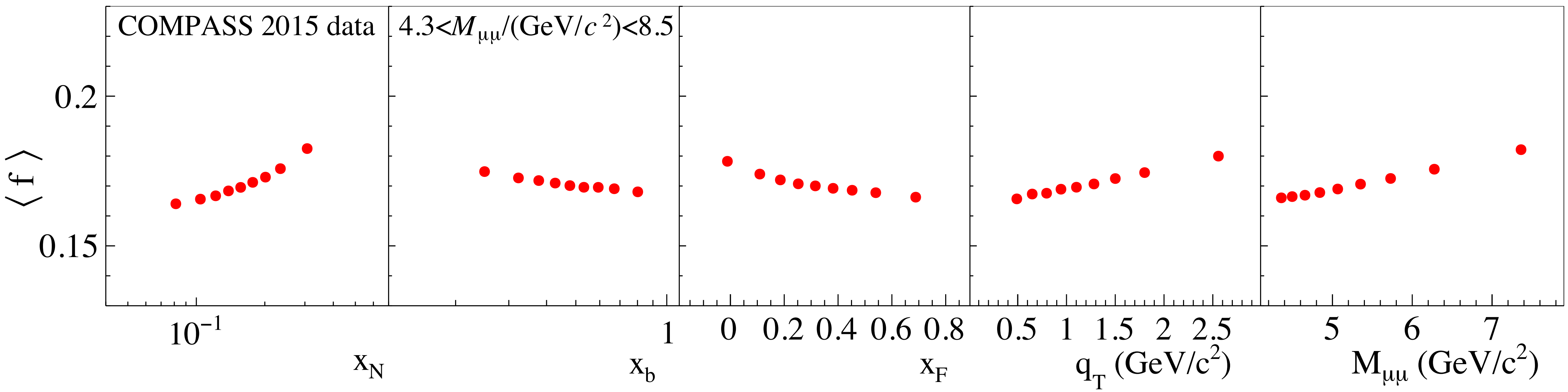
$$H_a(P_a) + H_b(P_b) \rightarrow \gamma^*(q) + X \rightarrow l^-(\ell) + l^+(\ell') + X$$

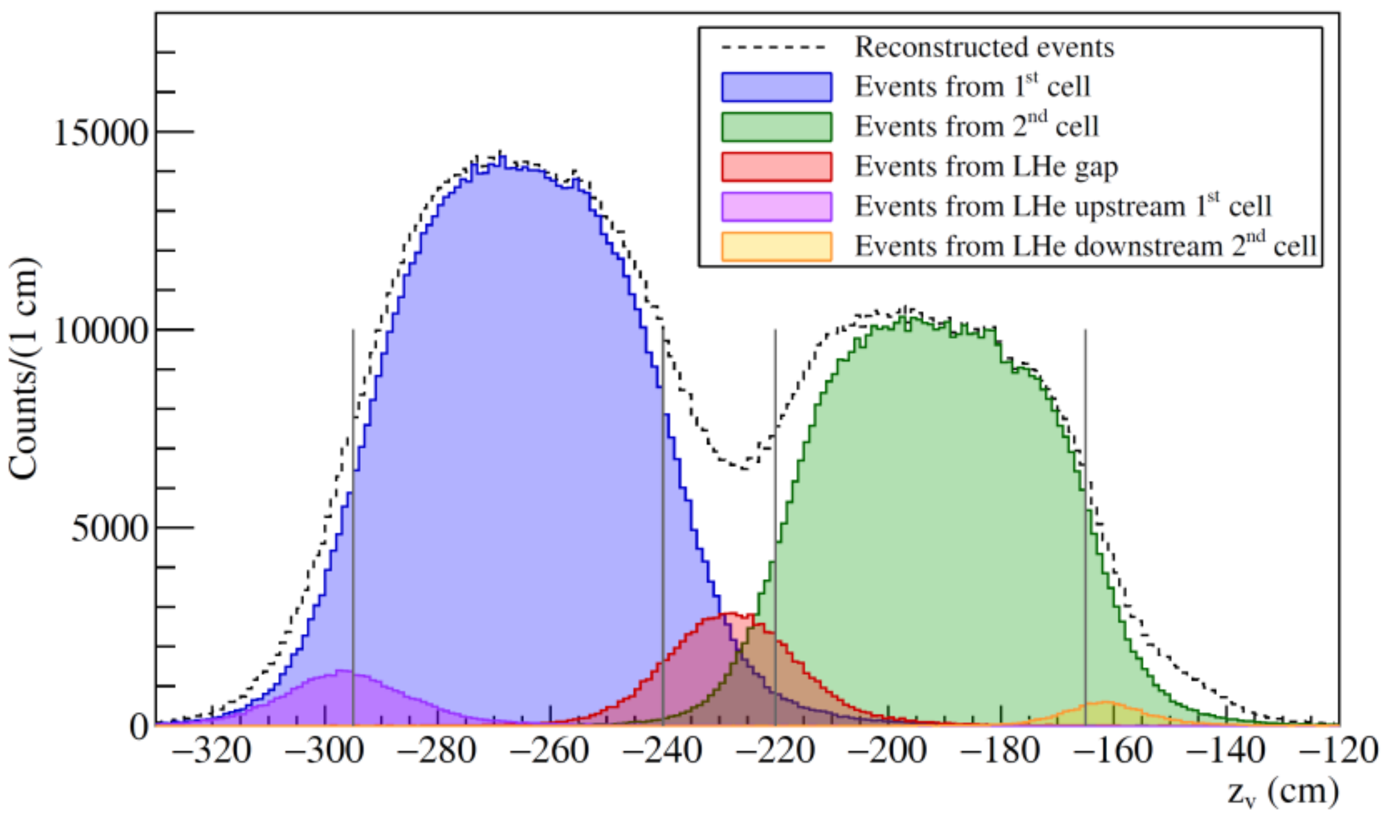
- Experimentally challenging, because of the small cross section

$$\frac{d\sigma}{dM_{\mu\mu}} \sim \frac{10^{-32}}{M_{\mu\mu}^5} \frac{cm^2}{GeV^2}$$

- Therefore DY measurement is a task for high luminosity experiments.
- Using different beams (p, π, K…) different quark flavors and phase space regions can be explored.

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);

Beyond LO: Single Polarized DY cross - section

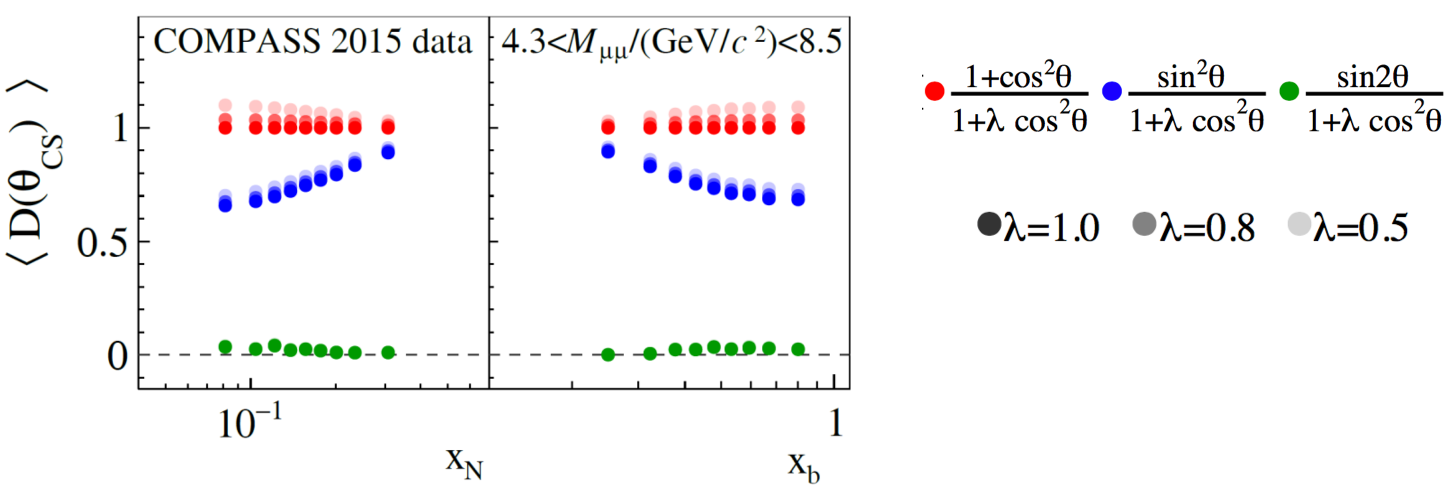
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right)$$
$$\times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} \\ + S_T \left[\begin{array}{l}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

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

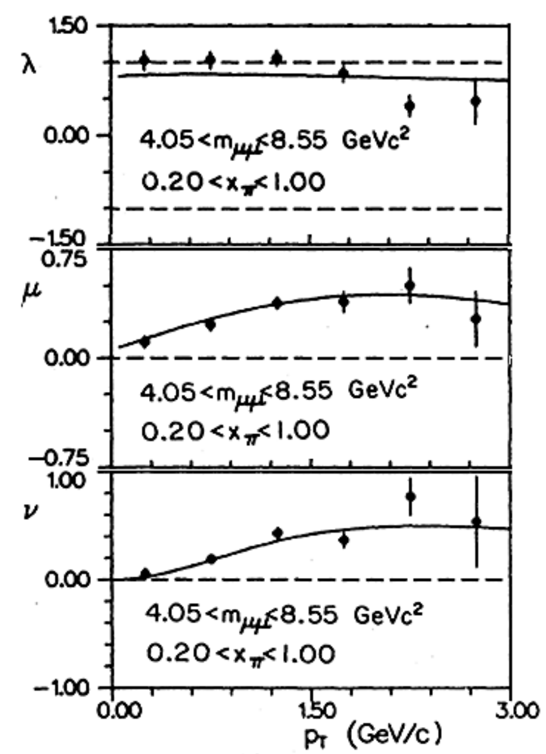
- Collinear LO pQCD ($k_T = 0$), no radiative processes:
  $\lambda = 1, \mu = \nu = 0$
- Intrinsic transverse moments motion ($k_T \neq 0$) + QCD effects:
  $\lambda \neq 1, \mu \neq 0, \nu \neq 0$
  $1-\lambda = 2\nu$ (Lam Tung sum-rule)
- Experiment
  $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

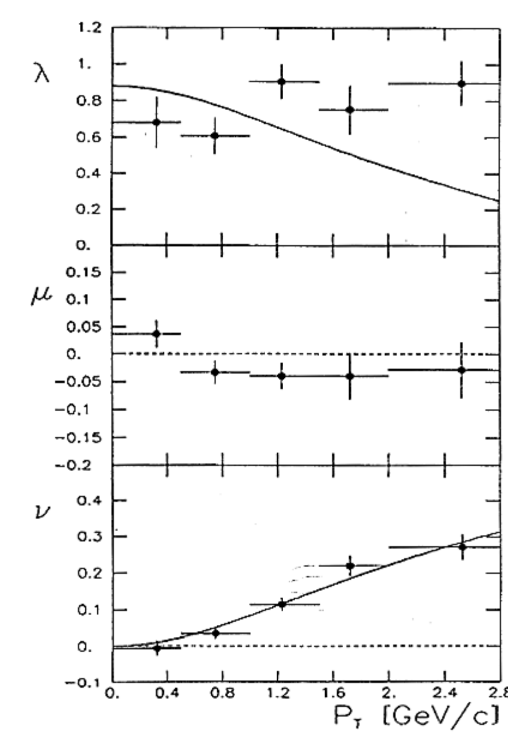
- All five DY TSAs are extracted simultaneously using an extended Unbinned Maximum Likelihood estimator;
- Depolarization factors are evaluated under assumption $A_U^1 = 1$;
- Possible scenarios with $A_U^1 \neq 1$ were evaluated , leading to a normalization uncertainty of at most 5 %;



E252 615 (π^-W GeV)
PRD 39, 92 (1989)



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



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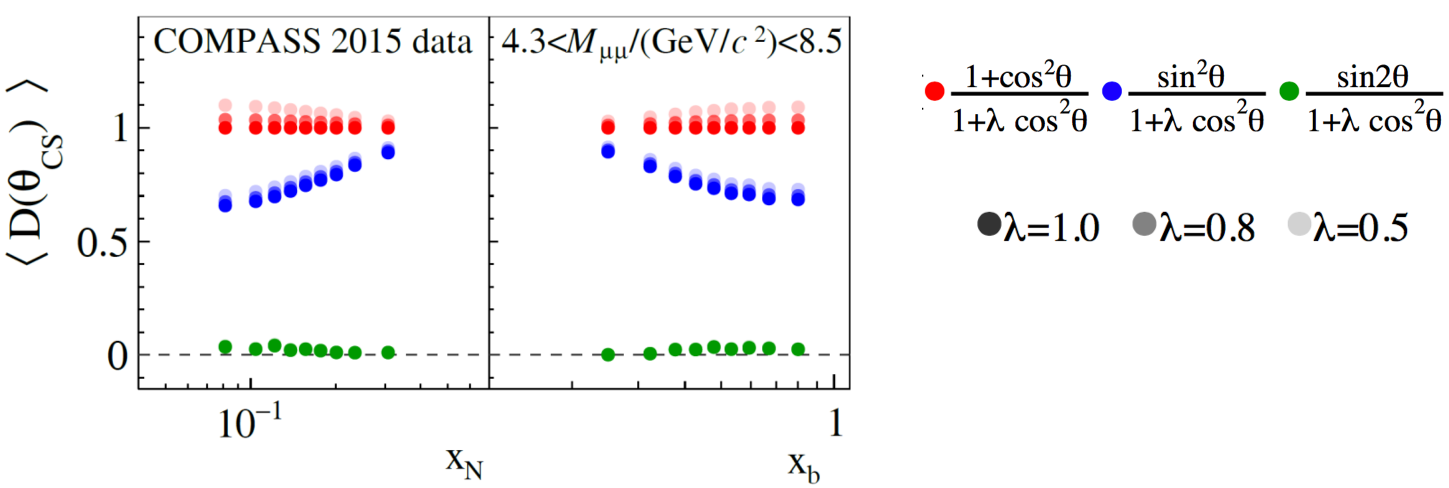
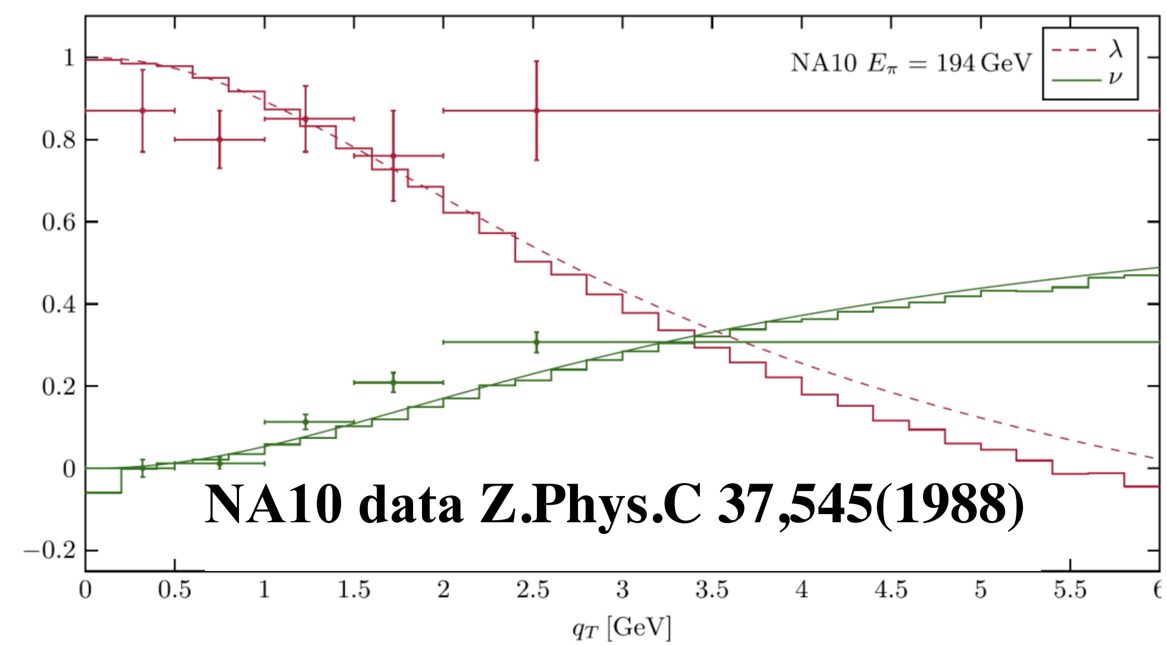
M.Lambertsen,W.Vogelsang,
PRD93,114013(2016)



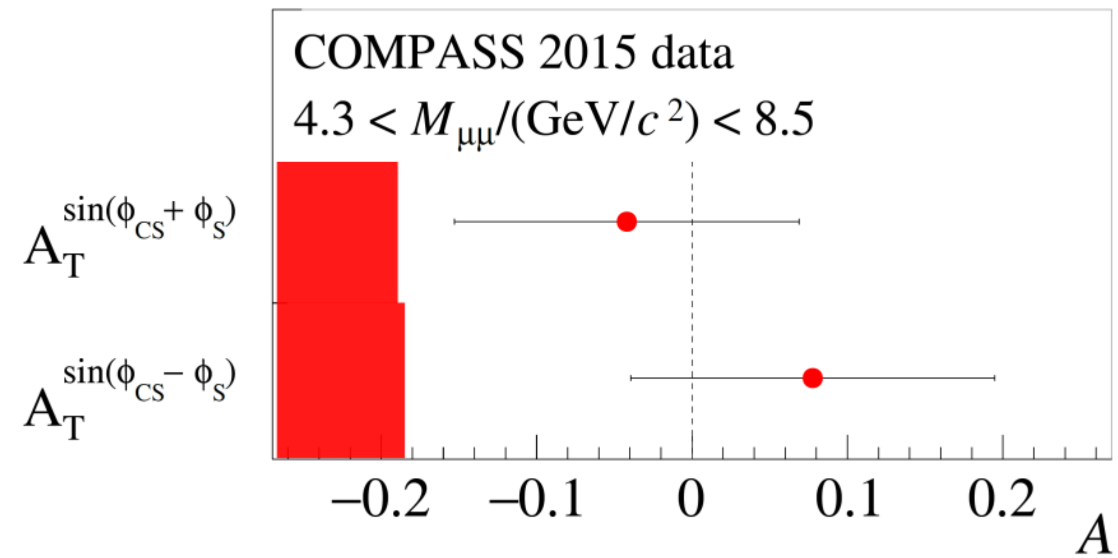


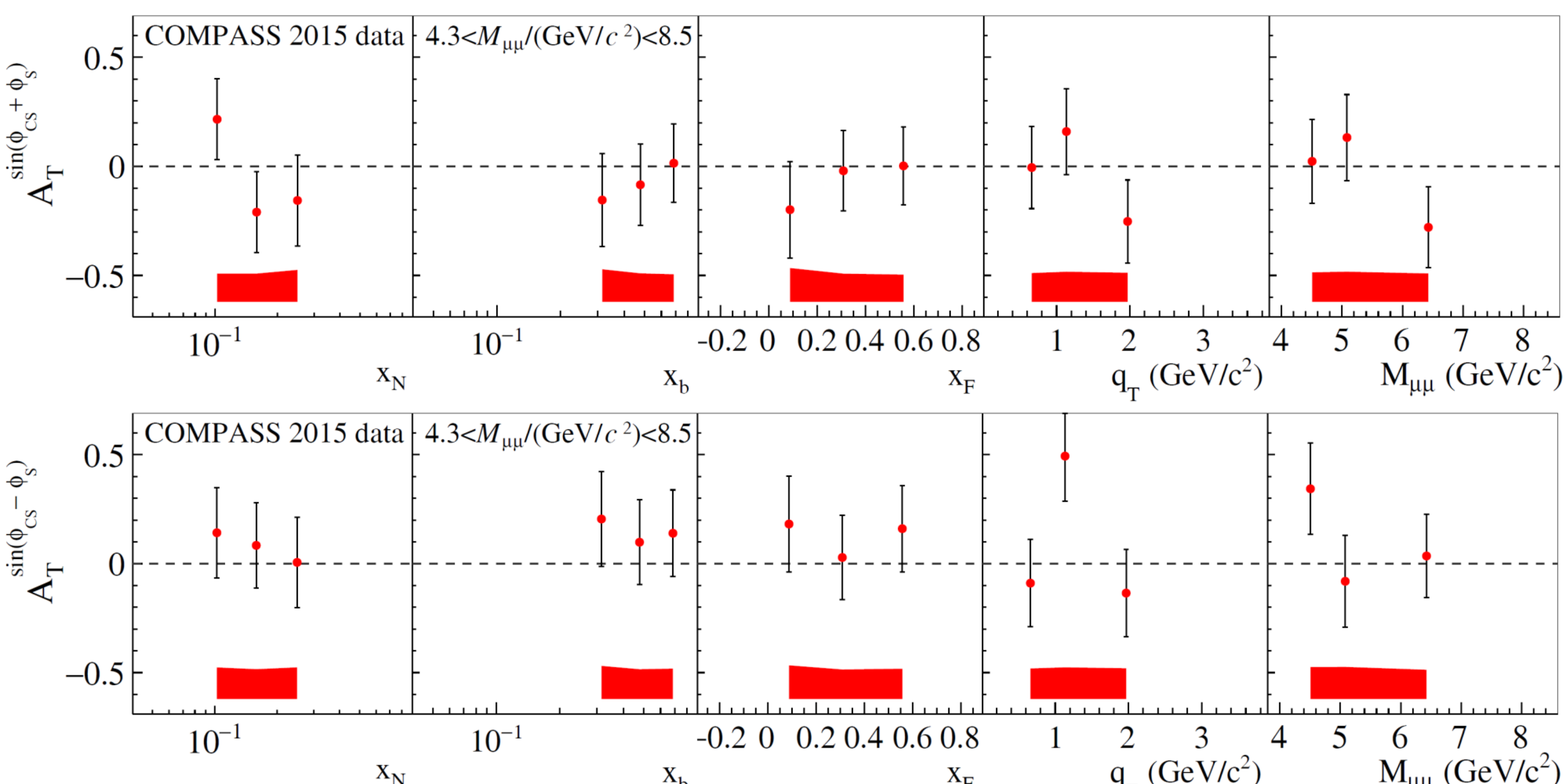
Higher twist TSAs

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

$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right)$$

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





Correlation coefficients