

# Transversely polarized Drell-Yan measurements at COMPASS



**BAKUR PARSAMYAN**

CERN, University of Turin  
and INFN-Turin

*on behalf of the COMPASS Collaboration*

UNIVERSITÀ  
DEGLI STUDI  
DI TORINO

ALMA UNIVERSITAS  
TAURINENSIS



“XXVII International Workshop on  
Deep Inelastic Scattering  
and Related Topics”

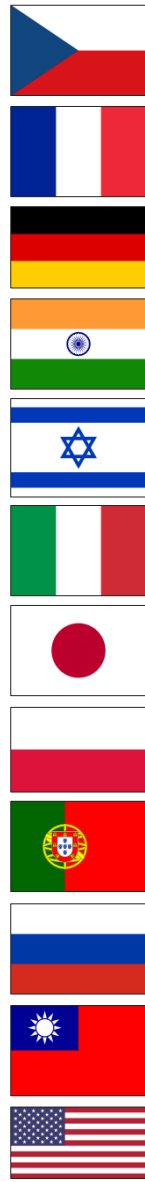
Università degli Studi di Torino,  
Turin, Italy  
8-12 April 2019





# COMPASS collaboration

## Common Muon and Proton Apparatus for Structure and Spectroscopy



24 institutions from 13 countries – nearly 250 physicists

- COMPASS is a fixed target experiment operating on the M2-beamline (CERN SPS north area)
- Approved in 1997 (**22 years**)
- Taking data since 2002

### Wide physics program

#### COMPASS-I

- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

See talks by F. Bradamante and M. Stolarski

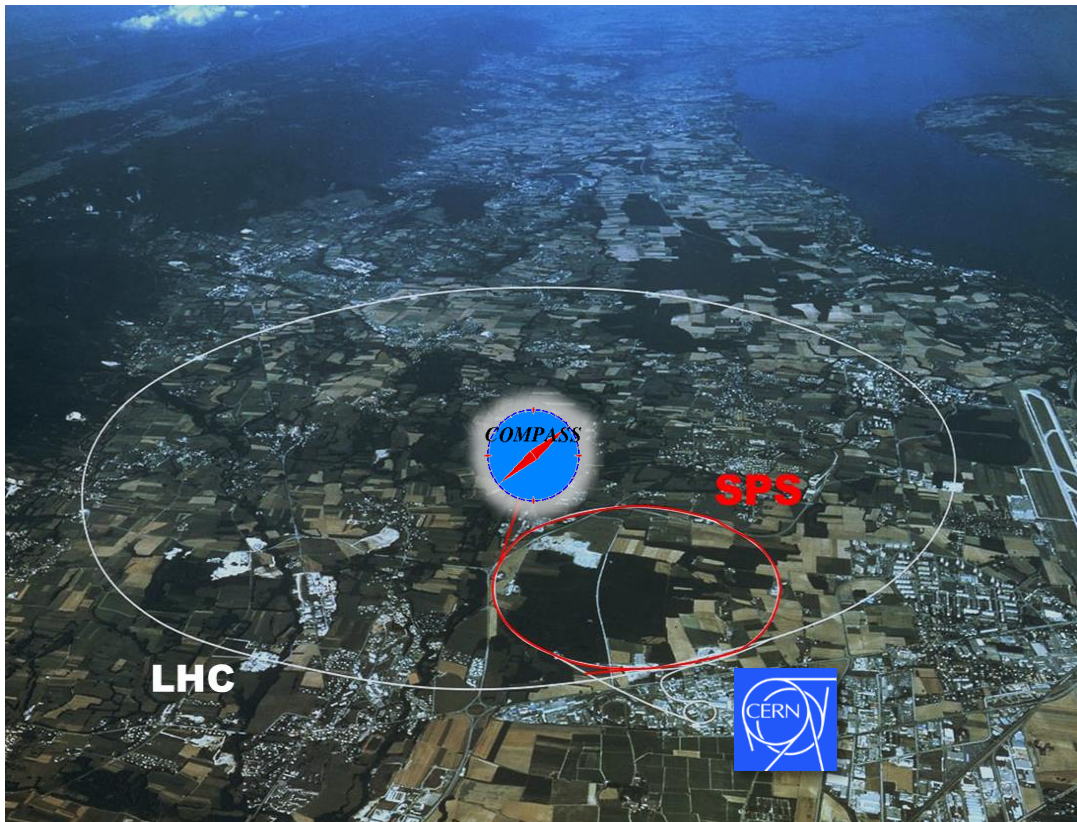
#### COMPASS-II

- Data taking 2012-2018 (**2021**)
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan
- **Transverse deuteron SIDIS**

See talks by A. Martin, J. Matousek, A. Moretti, R. Longo, N. Pierre, A. Vidon and this talk

#### Many “beyond 2021” ideas:

Proton-radius, Drell-Yan, spectroscopy...  
see COMPASS++/AMBER talks



COMPASS web page: <http://wwwcompass.cern.ch>



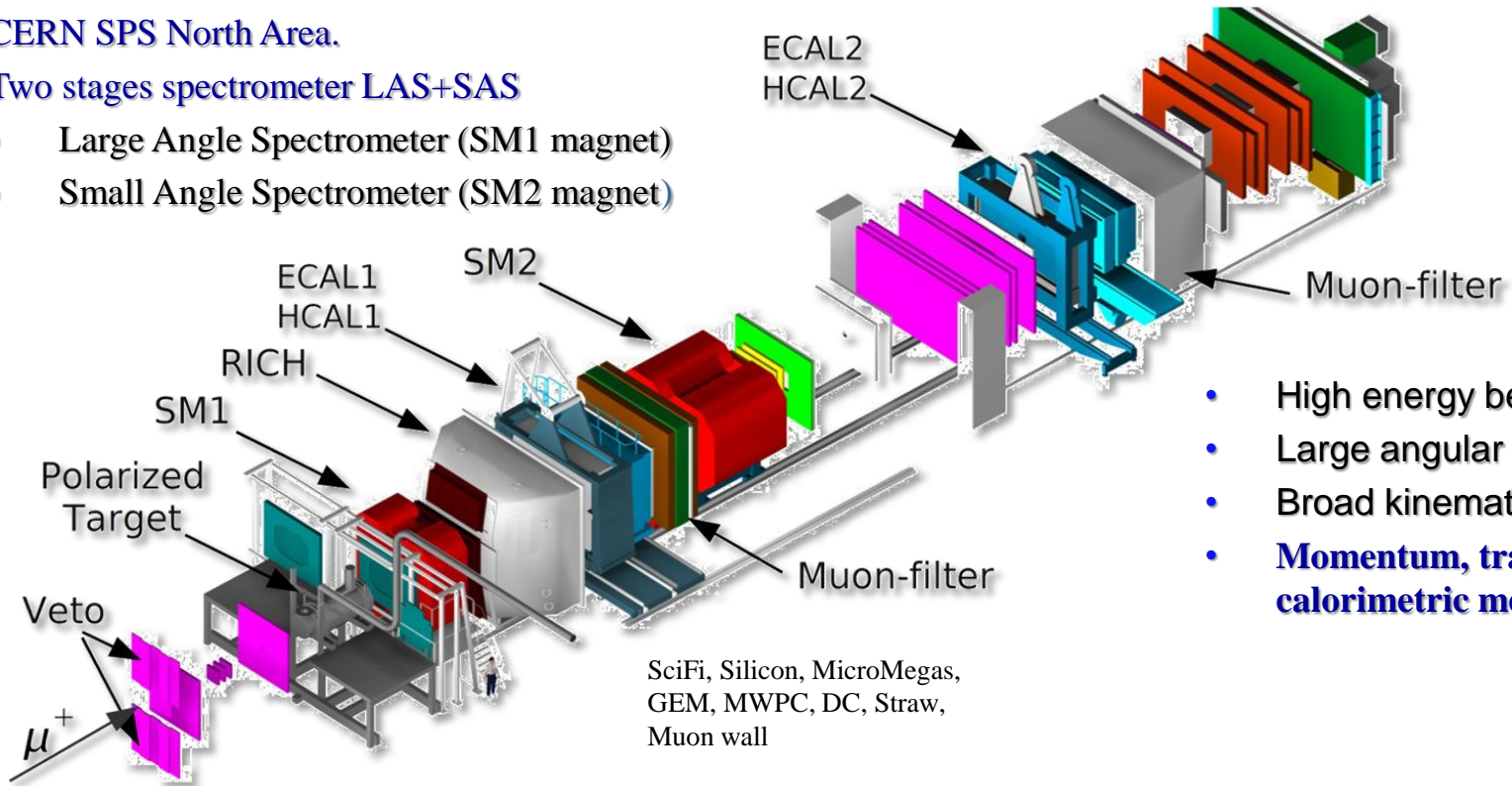
# COMPASS experimental setup: Phase I (muon program)

## COmmon MUon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



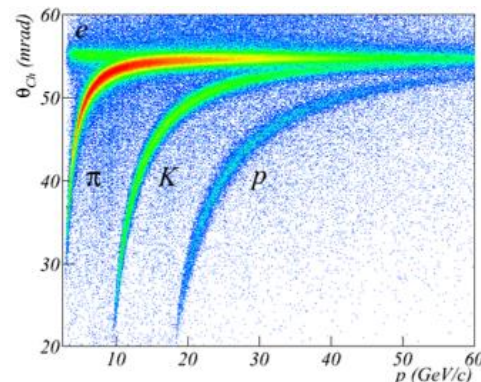
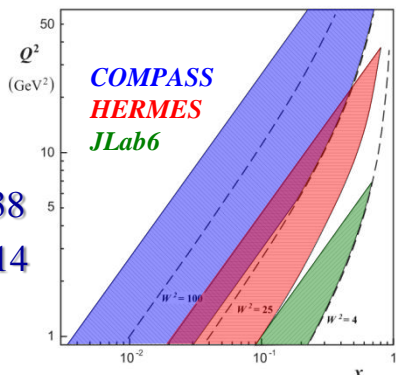
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

Longitudinally polarized (80%)  $\mu^+$  beam:  
 Energy: 160/200 GeV, Intensity:  $2 \cdot 10^8 \mu^+$ /spill (4.8s).  
 Target: Solid state ( ${}^6\text{LiD}$  or  $\text{NH}_3$ )

- ${}^6\text{LiD}$  2-cell configuration. Polarization (L & T)  $\sim 50\%$ ,  $f \sim 0.38$
- $\text{NH}_3$  3-cell configuration. Polarization (L & T)  $\sim 80\%$ ,  $f \sim 0.14$

**Data-taking years: 2002-2011**



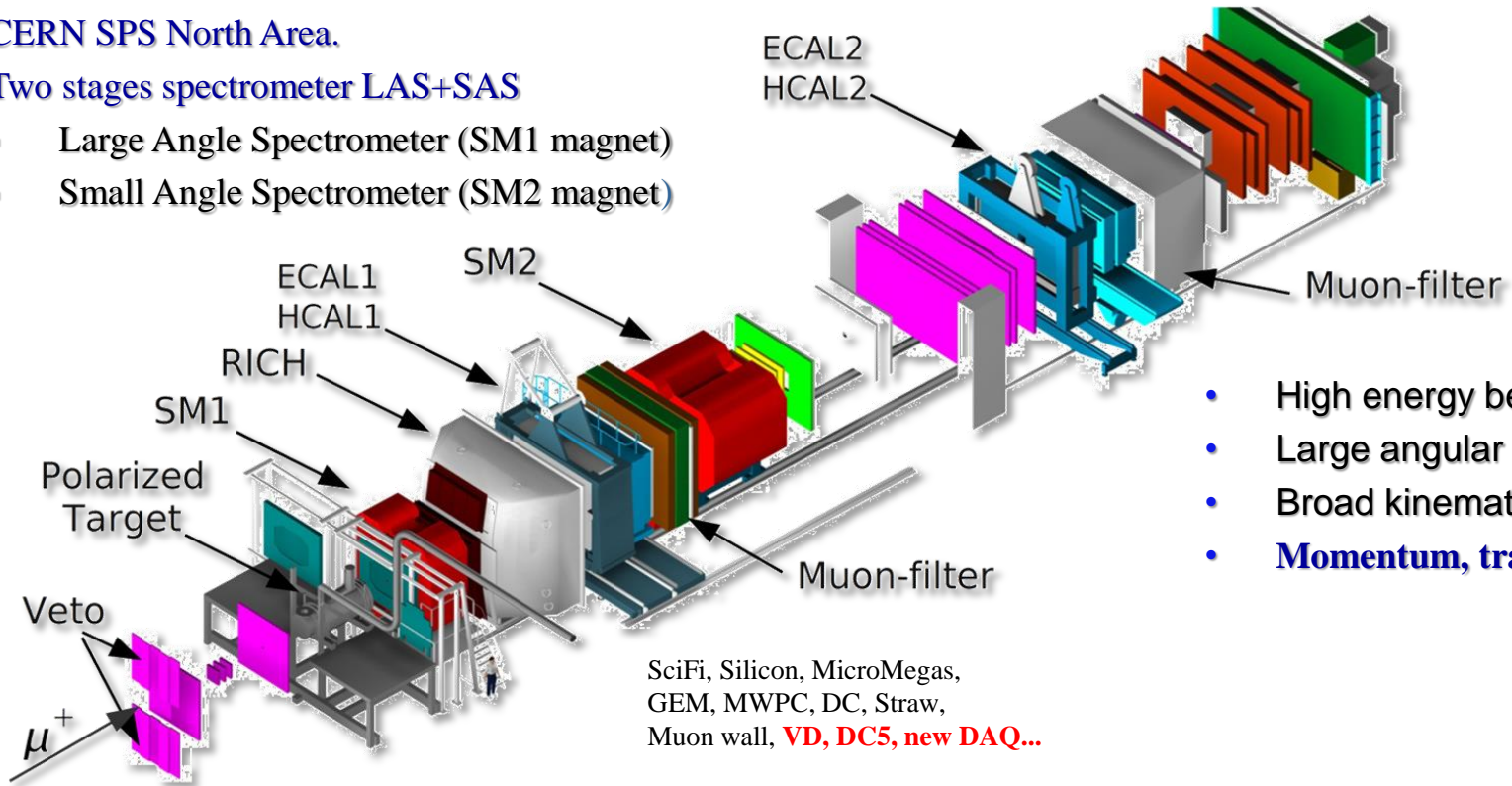
# COMPASS experimental setup: Phase II (DY program)

## COmmon MUon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking**

SciFi, Silicon, MicroMegas,  
GEM, MWPC, DC, Straw,  
Muon wall, **VD, DC5, new DAQ...**

High energy  $\pi^-$  beam:  
Energy: 190 GeV, Intensity:  $10^8 \pi/s$   
Target: Solid state

- $NH_3$  2-cell configuration. Polarization T ~ 80%, f ~ 0.19
- Data is collected simultaneously for the two target spin orientations. Periodic polarization reversal to minimize systematic effects

**Data-taking years: 2014(test), 2015 (~ 4 months), 2018 (~5 months)**



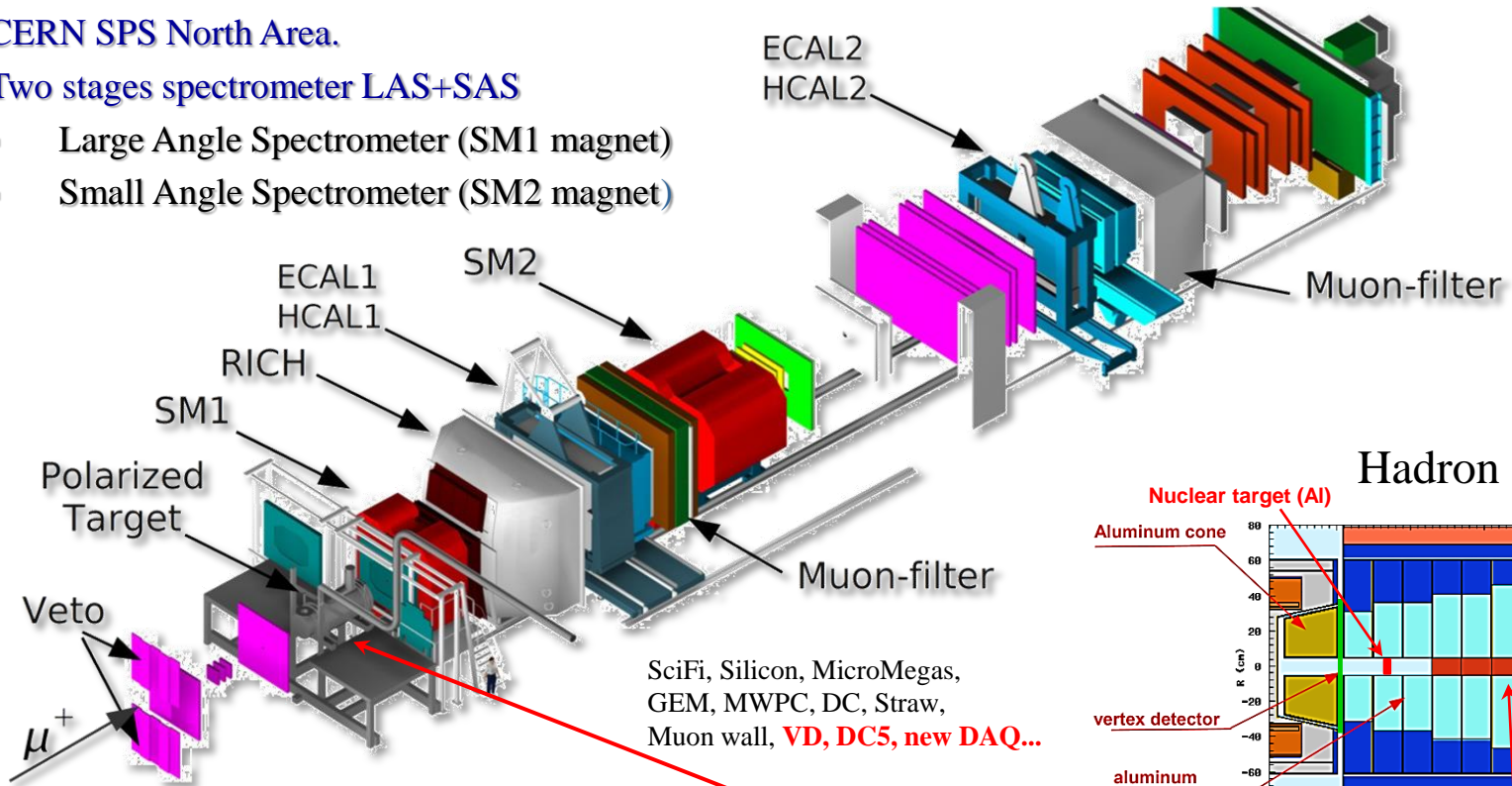
# COMPASS experimental setup: Phase II (DY program)

## COmmon MUon Proton Apparatus for Structure and Spectroscopy

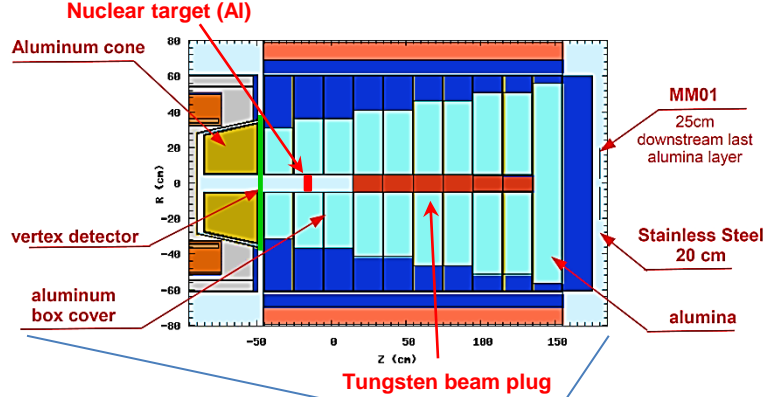
CERN SPS North Area.

Two stages spectrometer LAS+SAS

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### Hadron absorber

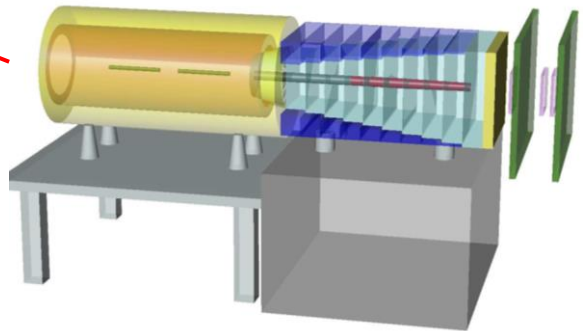


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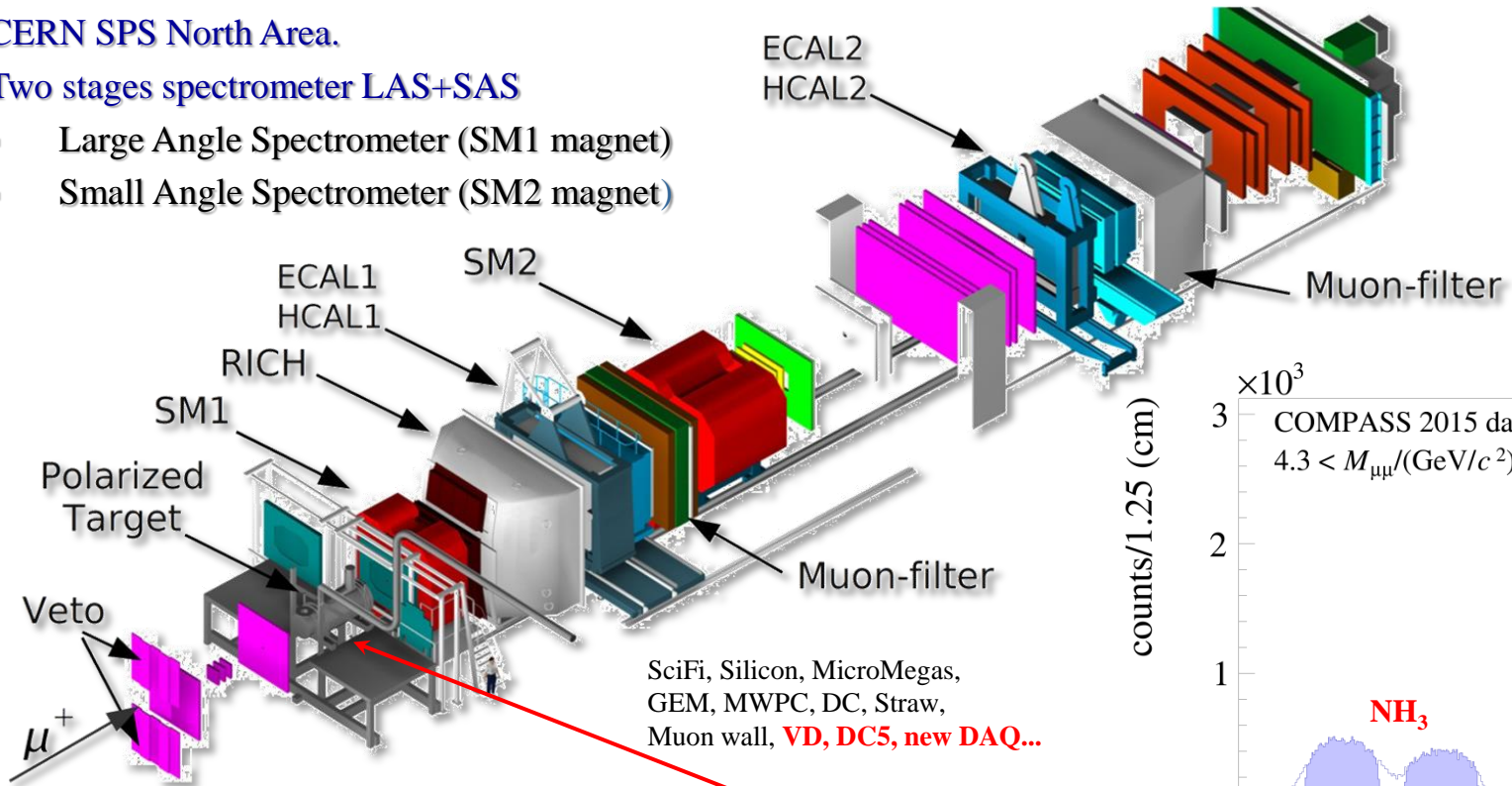
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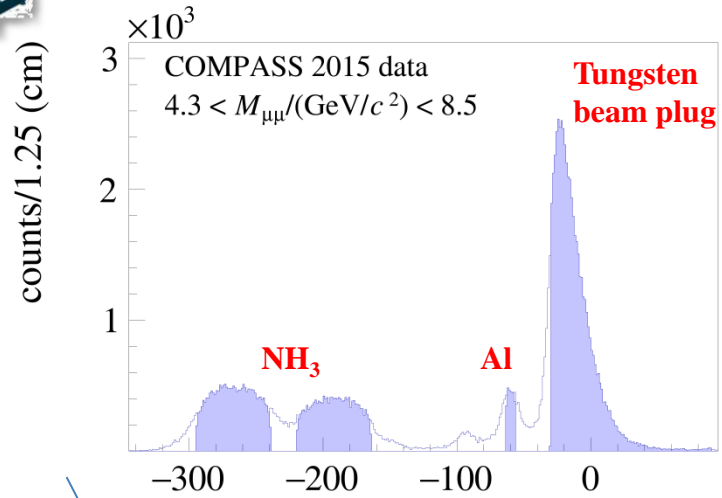
CERN SPS North Area.

Two stages spectrometer LAS+SAS

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Muon wall, **VD, DC5, new DAQ...**

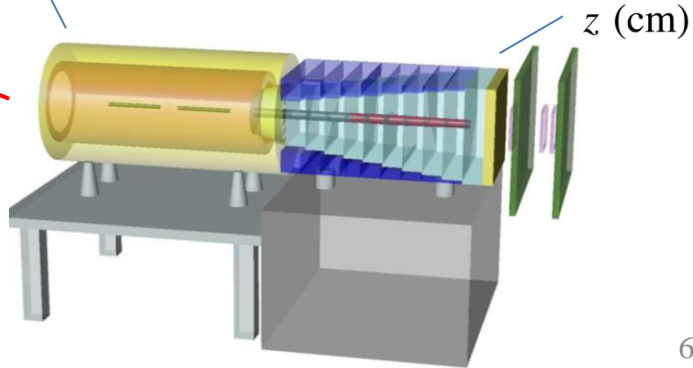


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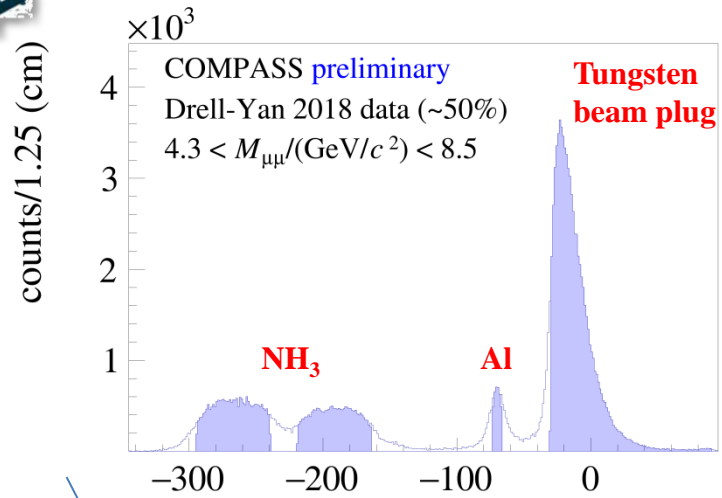
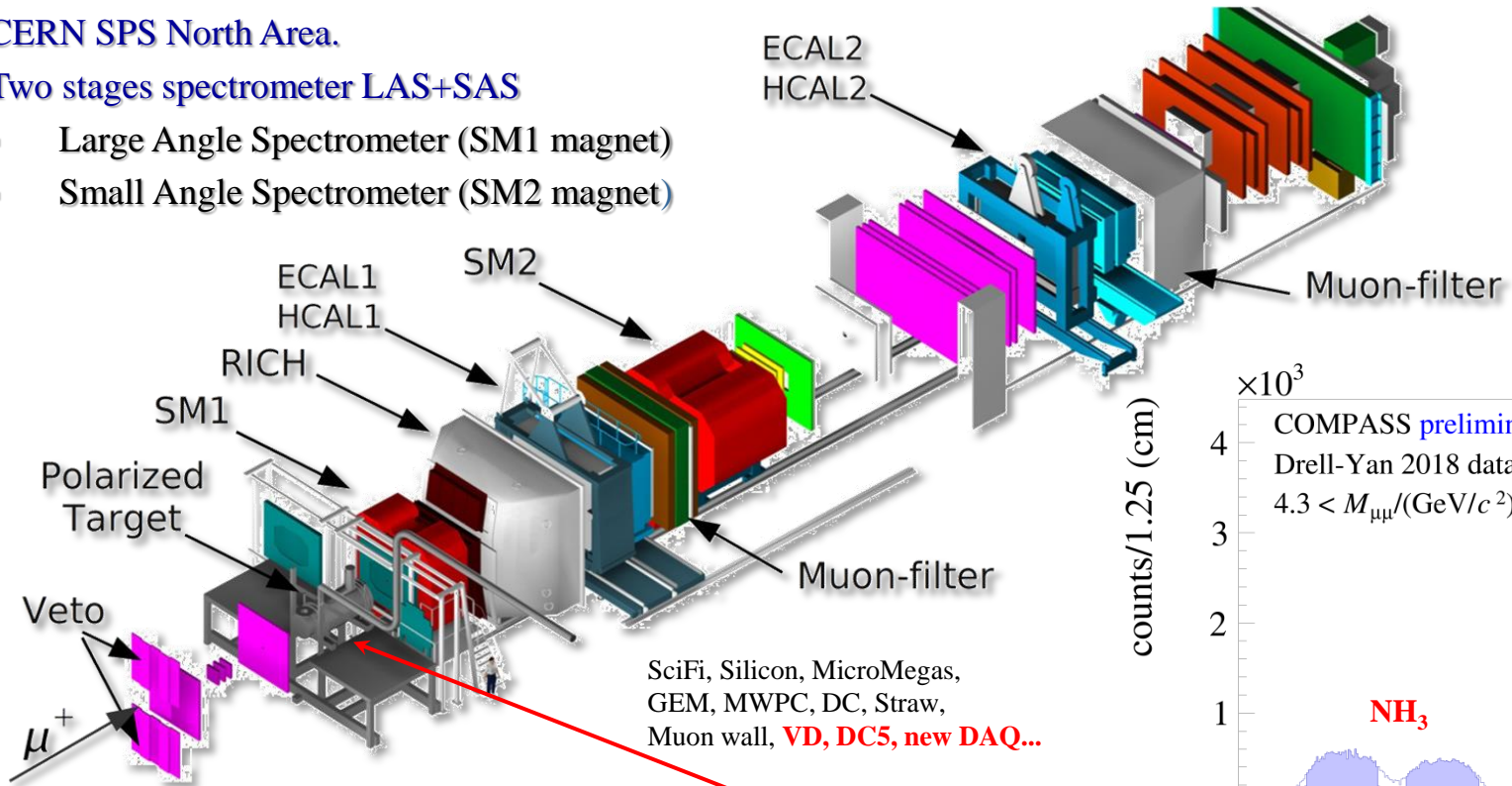
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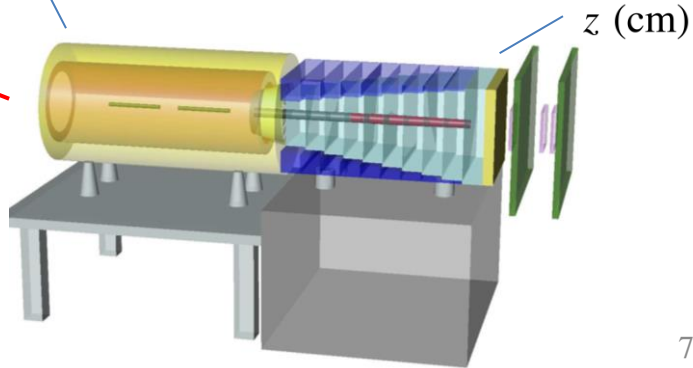


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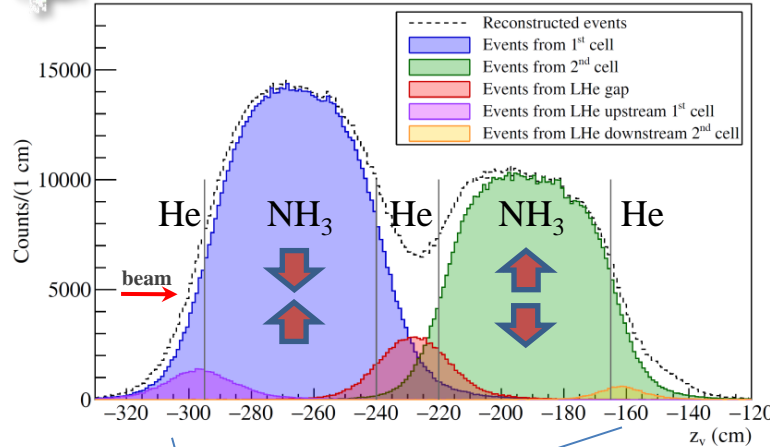
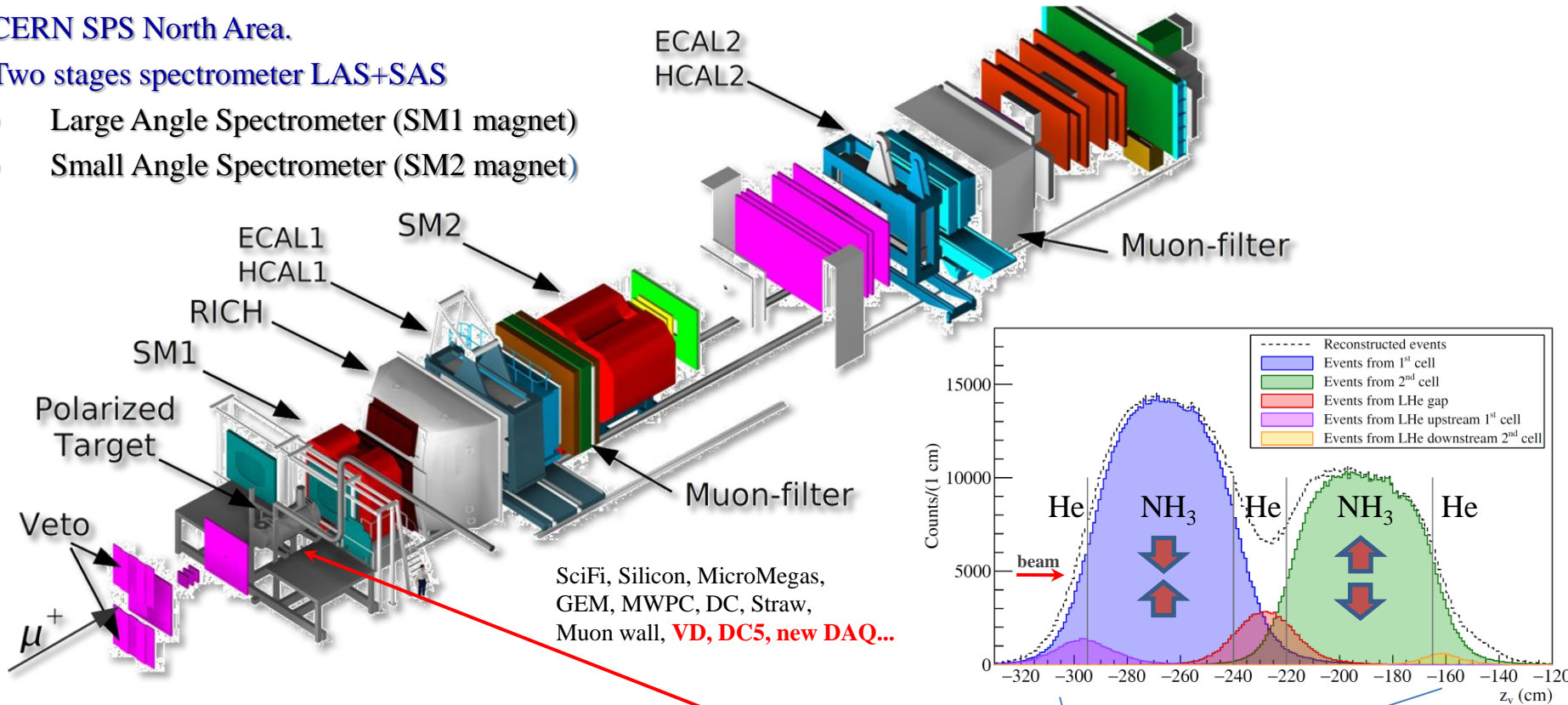
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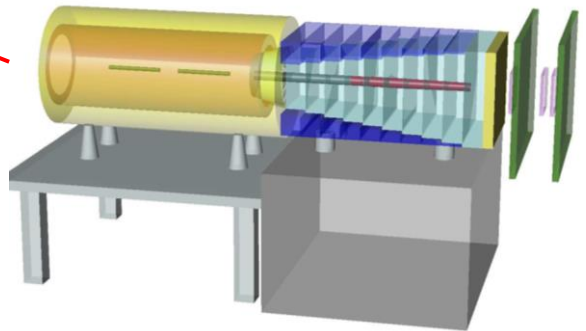


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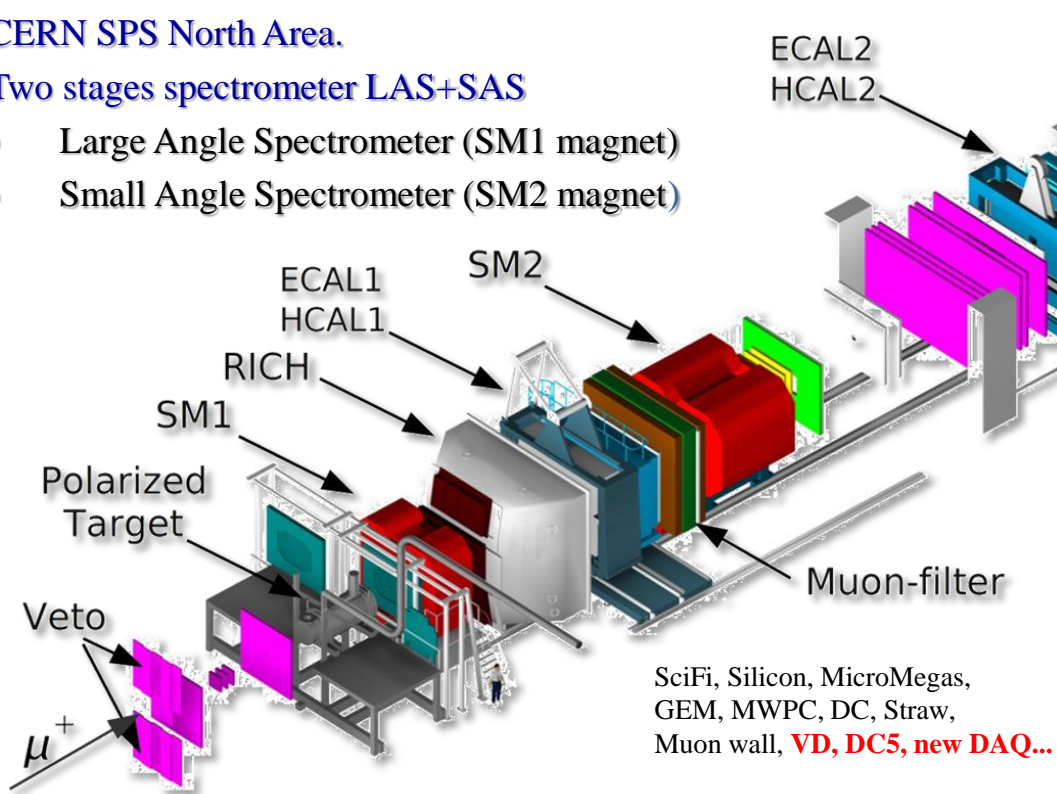
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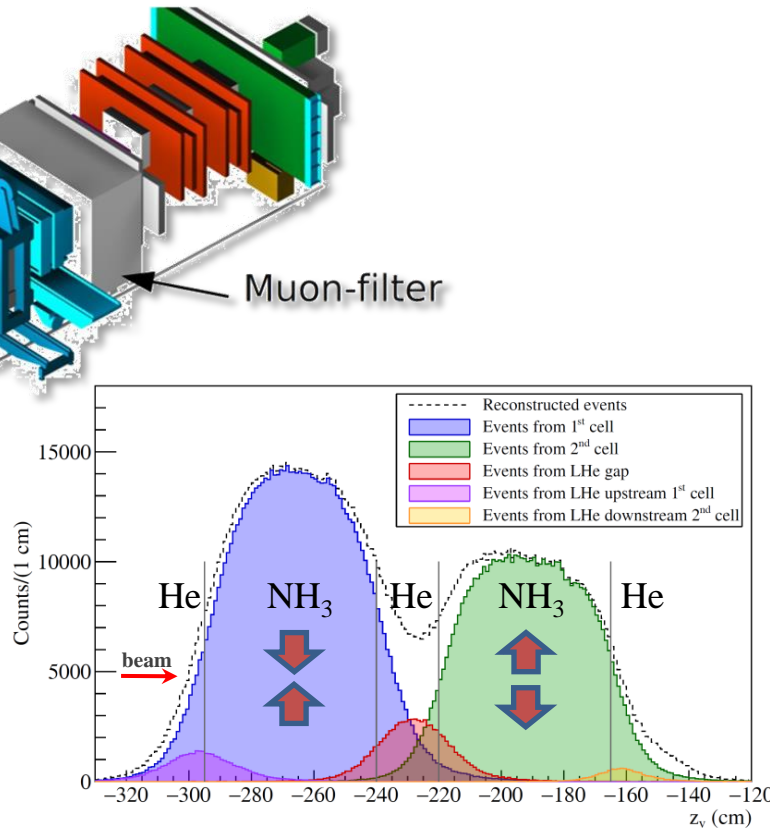
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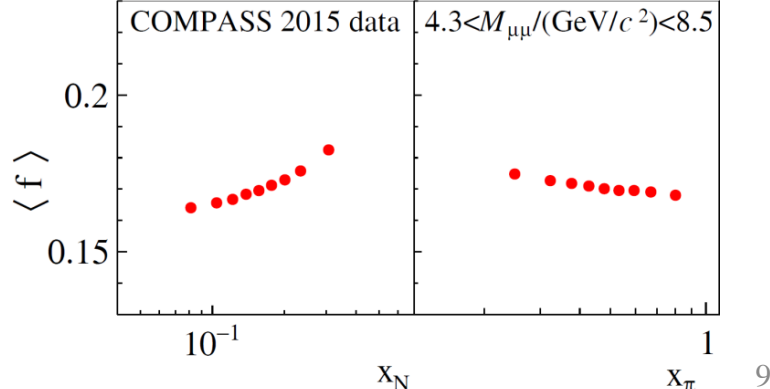


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Target: Solid state

- $NH_3$  2-cell configuration. Polarization  $T \sim 80\%$ ,  $f \sim 0.19$
- **Data is collected simultaneously for the two target spin orientations. Periodic polarization reversal to minimize systematic effects**

**Data-taking years: 2014(test), 2015 (~ 4 months), 2018 (~5 months)**



# COMPASS 2018 data production and analysis

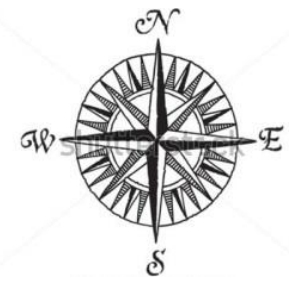


- About 1.8 PB data was collected during ~5 months of data taking
- A special care was taken to ensure stable detector conditions during the data-taking
- Already during the run the data started to be transferred to the Blue Waters supercomputer storage system (NCSA, US)
- Between December 2018 and March 2019 two full mass data-productions were performed at Blue Waters
- About ~50% of data was considered to be ready for the physics analyses
- For the remaining 50% some further alignment and calibration fixes are needed

## BLUE WATERS

*This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).*

COMPASS bridge



Drell-Pan

SIDS

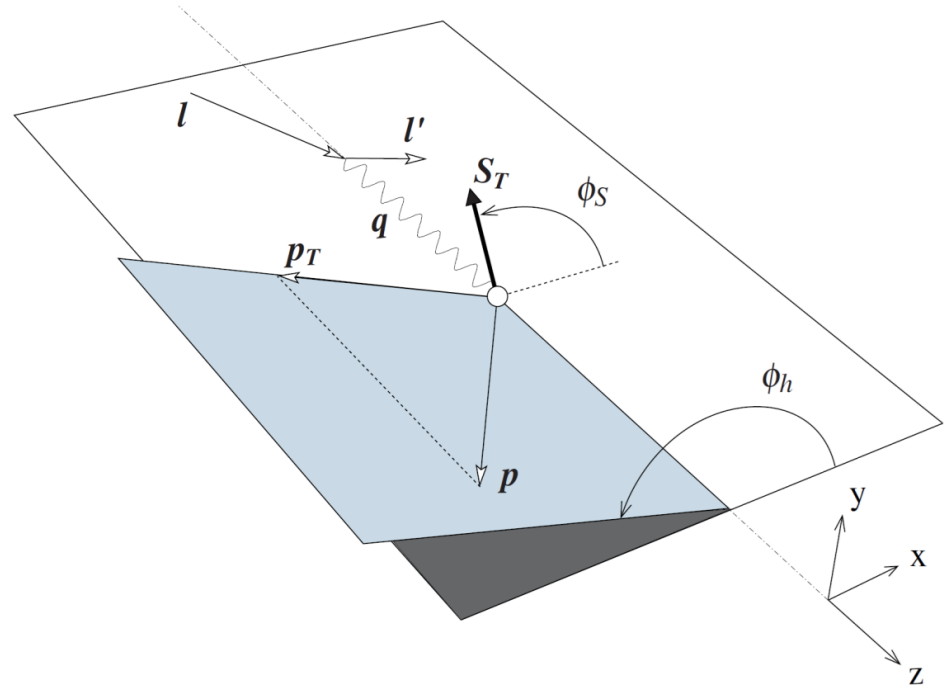
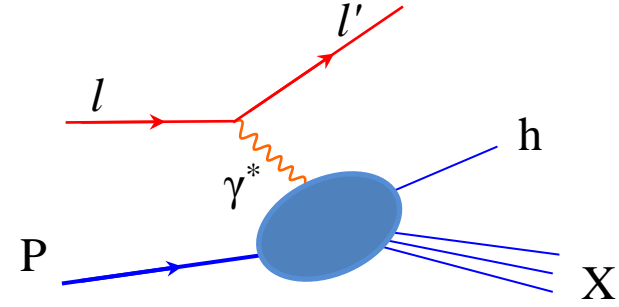


**All measured by COMPASS**

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} =$$

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

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



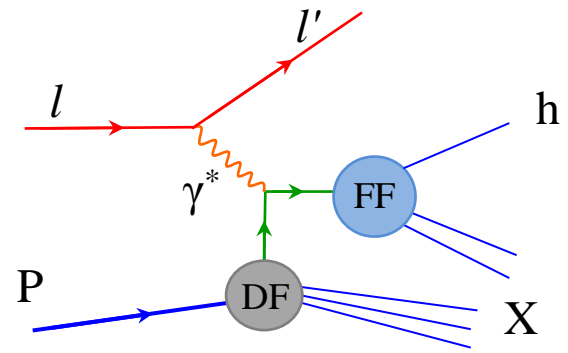
$$A_{U(L),T}^{w(\phi_h,\phi_S)} = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T} + \varepsilon F_{UU,L}}; \quad \varepsilon = \frac{1-y-\frac{1}{4}\gamma^2 y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2 y^2}, \quad \gamma = \frac{2Mx}{Q}$$



# SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \text{All measured by COMPASS}$$

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



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

Quark \ Nucleon	U	L	T
U	$f_1^q(x, \mathbf{k}_T^2)$ number density		$h_1^{q\perp}(x, \mathbf{k}_T^2)$ Boer-Mulders
L		$g_1^q(x, \mathbf{k}_T^2)$ helicity	$h_{1L}^{q\perp}(x, \mathbf{k}_T^2)$ worm-gear L
T	$f_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Sivers	$g_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x, \mathbf{k}_T^2)$ transversity $h_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ pretzelosity

+ two FFs:  $D_{1q}^h(z, P_\perp^2)$  and  $H_{1q}^{\perp h}(z, P_\perp^2)$



# SIDIS x-section: transverse spin dependent part

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} =$$

**All measured by COMPASS**

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

Eight transverse-spin-dependent azimuthal asymmetries (TSA) appear in SIDIS x-section

- Four “twist-2” TSAs (Sivers, Collins, pretzelosity, Kotzinian-Mulders)
- Four “higher-twist”
- All measured at COMPASS (P/D)

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

See talk by K. Tezgin

Twist-2  
Twist-3

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

# SIDIS and single-polarized DY x-sections

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} =$$

**SIDIS**

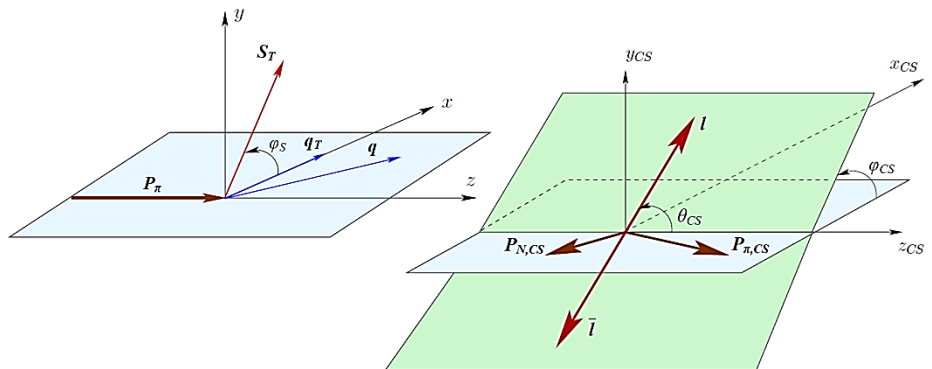
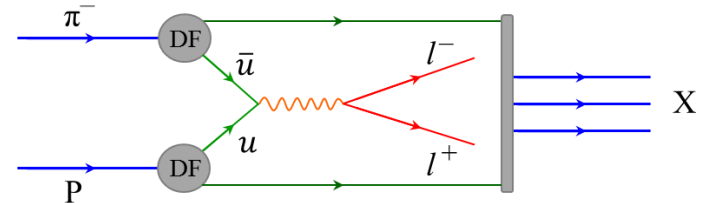
$$\left[ \frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

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

$$\frac{d\sigma}{dq^4 d\Omega} \propto (F_U^1 + F_U^2)$$

**DY**

$$\times \left\{ \begin{array}{l} \left[ \begin{array}{l} 1 + A_U^1 \cos^2 \theta_{CS} \\ + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \end{array} \right] \\ + S_L \left[ \begin{array}{l} \sin \theta_{CS} A_L^{\sin\varphi_{CS}} \sin\varphi_{CS} + \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \end{array} \right] \\ + S_T \left[ \begin{array}{l} \left( A_T^{\sin\varphi_s} + \cos^2 \theta_{CS} \tilde{A}_T^{\sin\varphi_s} \right) \sin\varphi_s \\ + \sin^2 \theta_{CS} \left( \begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_s)} \sin(2\varphi_{CS}-\varphi_s) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_s)} \sin(2\varphi_{CS}+\varphi_s) \end{array} \right) \\ + \sin 2\theta_{CS} \left( \begin{array}{l} A_T^{\sin(\varphi_{CS}-\varphi_s)} \sin(\varphi_{CS}-\varphi_s) \\ + A_T^{\sin(\varphi_{CS}+\varphi_s)} \sin(\varphi_{CS}+\varphi_s) \end{array} \right) \end{array} \right] \end{array} \right\}$$





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

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

**SIDIS**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

**DY**

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



$$\times \left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ & + S_T \begin{bmatrix} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\ \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \end{bmatrix} \end{aligned} \right\}$$

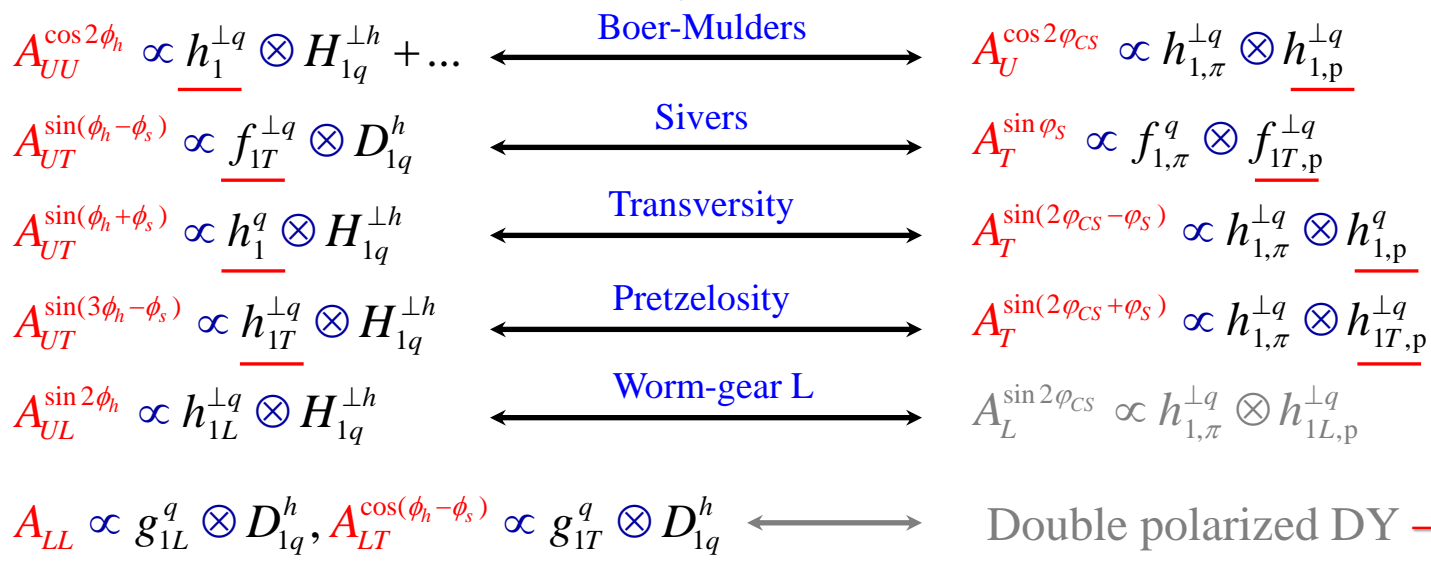
where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

$$\begin{aligned}
 \frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} &\propto (F_{UU,T} + \varepsilon F_{UU,L}) & \text{SIDIS} & \frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) & \text{DY} \\
 & \left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\ & \times \left[ \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{aligned} \right] \\ & + S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{aligned} \right. & \times & \left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ & \times \left[ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + S_T \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\ & \left. + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \right) \end{aligned} \right] \end{aligned} \right. \\
 & \text{where } D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})
 \end{aligned}$$



COMPASS accesses all 8 twist-2 nucleon TMD PDFs in SIDIS and 5 nucleon+2 pion TMD PDFs in DY



# SIDIS and single-polarized DY x-sections at twist-2 (LO)

$$\begin{aligned}
 \frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} &\propto (F_{UU,T} + \varepsilon F_{UU,L}) & \text{SIDIS} & \frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) & \text{DY} \\
 & \left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\ & \times \left[ \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{aligned} \right] \\ & + S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{aligned} \right. & \text{COMPASS} & \left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ & \times \left[ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + S_T \left( \begin{aligned} & + D_{[\sin^2 \theta_{CS}]} \left( \begin{aligned} & A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ & + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{aligned} \right) \end{aligned} \right) \end{aligned} \right. \\ & \text{where } D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})
 \end{aligned}
 \end{aligned}$$

$$\begin{aligned}
 A_{UU}^{\cos 2\phi_h} &\propto \underline{h_1^{\perp q}} \otimes H_{1q}^{\perp h} + \dots & \text{Boer-Mulders} & A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1,p}^{\perp q}} \\
 A_{UT}^{\sin(\phi_h - \phi_s)} &\propto \underline{f_{1T}^{\perp q}} \otimes D_{1q}^h & \text{Sivers} & A_T^{\sin \varphi_S} \propto f_{1,\pi}^q \otimes \underline{f_{1T,p}^{\perp q}} \\
 A_{UT}^{\sin(\phi_h + \phi_s)} &\propto \underline{h_1^q} \otimes H_{1q}^{\perp h} & \text{Transversity} & A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1,p}^q} \\
 A_{UT}^{\sin(3\phi_h - \phi_s)} &\propto \underline{h_{1T}^{\perp q}} \otimes H_{1q}^{\perp h} & \text{Pretzelosity} & A_T^{\sin(2\varphi_{CS} + \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1T,p}^{\perp q}}
 \end{aligned}$$

within QCD TMD-framework:

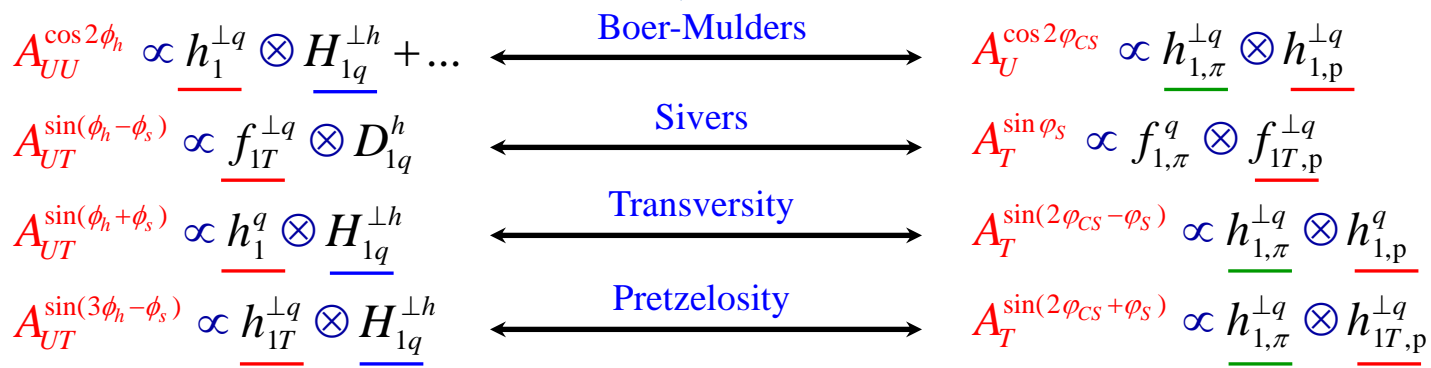
$\underline{h_1^{\perp q}}$  &  $\underline{f_{1T}^{\perp q}}$  TMD PDFs are expected to be "conditionally" universal (SIDIS  $\leftrightarrow$  DY: **sign change**)

$\underline{h_1^q}$  &  $\underline{h_{1T}^{\perp q}}$  TMD PDFs are expected to be "genuinely" universal (SIDIS  $\leftrightarrow$  DY: **no sign change**)



# SIDIS and single-polarized DY x-sections at twist-2 (LO)

$$\begin{aligned}
 & \frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \quad \text{SIDIS} \quad \frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \quad \text{DY} \\
 & \left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \end{aligned} \right\} \times \left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \end{aligned} \right\} \\
 & \times \left\{ \begin{aligned} & \left[ \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{aligned} \right] \\ & + S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{aligned} \right\} \times \left\{ \begin{aligned} & \left[ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + D_{[\sin^2 \theta_{CS}]} \left( \begin{aligned} & A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ & + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{aligned} \right) \end{aligned} \right] \end{aligned} \right\} \\
 & \text{where } D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})
 \end{aligned}$$



Complementary information from different channels :

- SIDIS-DY bridging of nucleon TMD PDFs
- Multiple access to Collins FF  $H_{1,q}^{\perp h}$  and pion Boer-Mulders PDF  $h_{1,\pi}^{\perp q}$



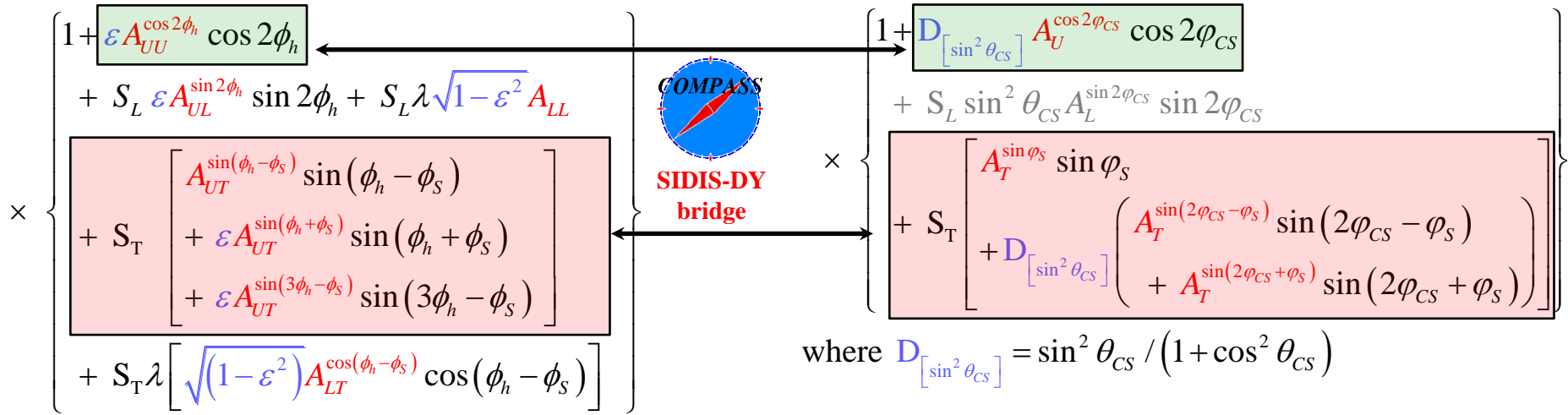
# SIDIS and single-polarized DY x-sections at twist-2 (LO)

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

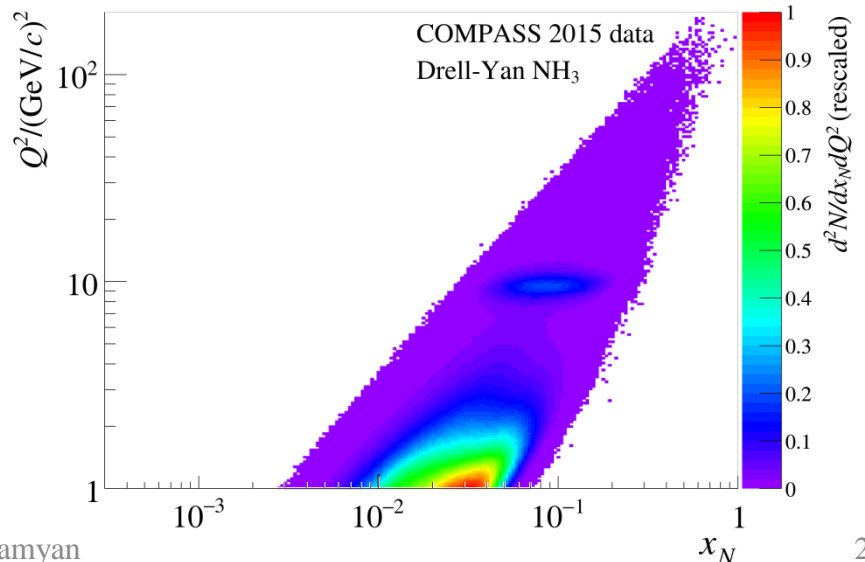
**SIDIS**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

**DY**



COMPASS x:Q<sup>2</sup> phase space (DY 2015 data)





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

**SIDIS**

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

**SIDIS**

**DY**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

←

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

$$+ S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}$$

←

←

**SIDIS-DY bridge**

←

$$1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$

$$+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

×

$$\begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{bmatrix}$$

×

×

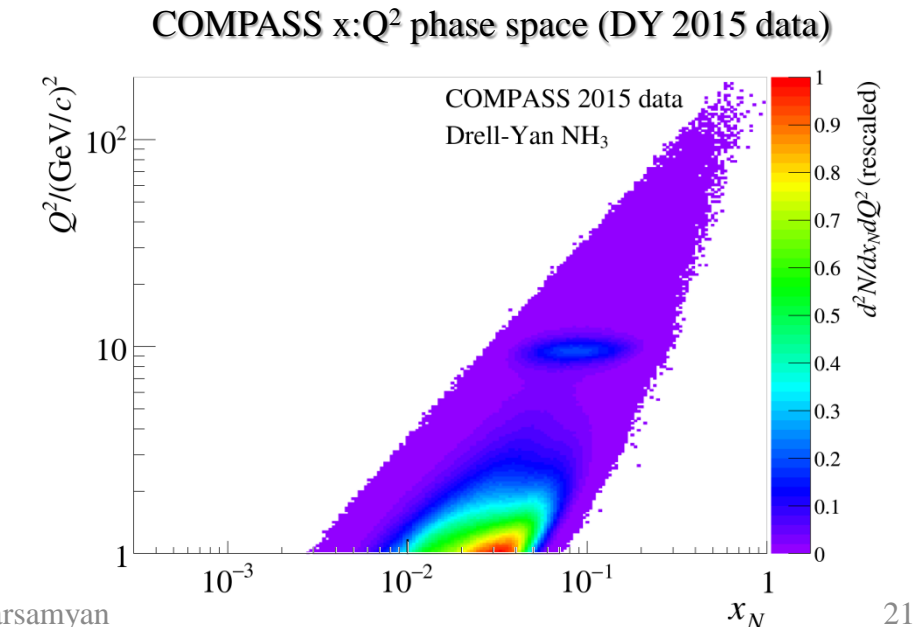
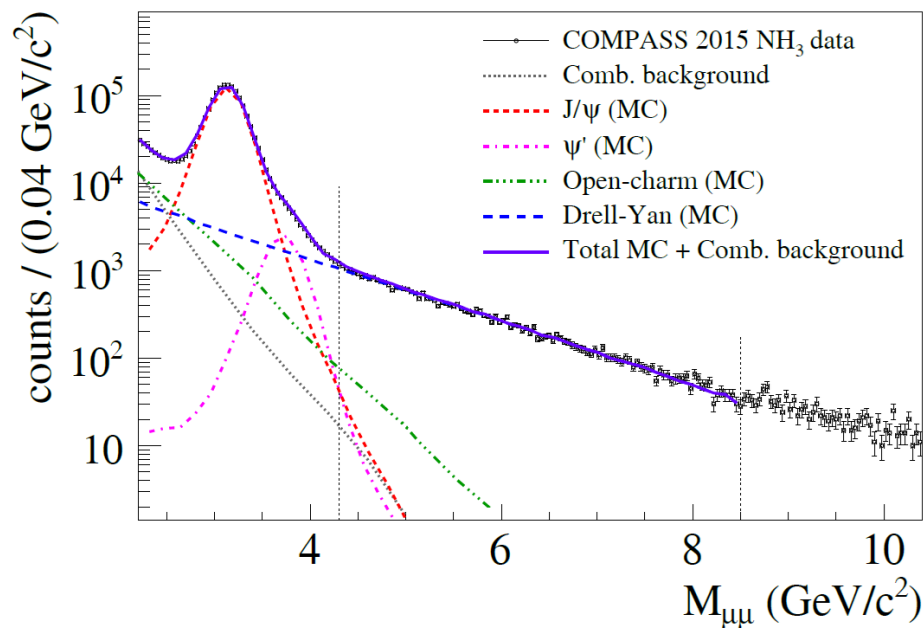
$$\begin{bmatrix} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\ \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \end{bmatrix}$$

+

$$S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]$$

where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$





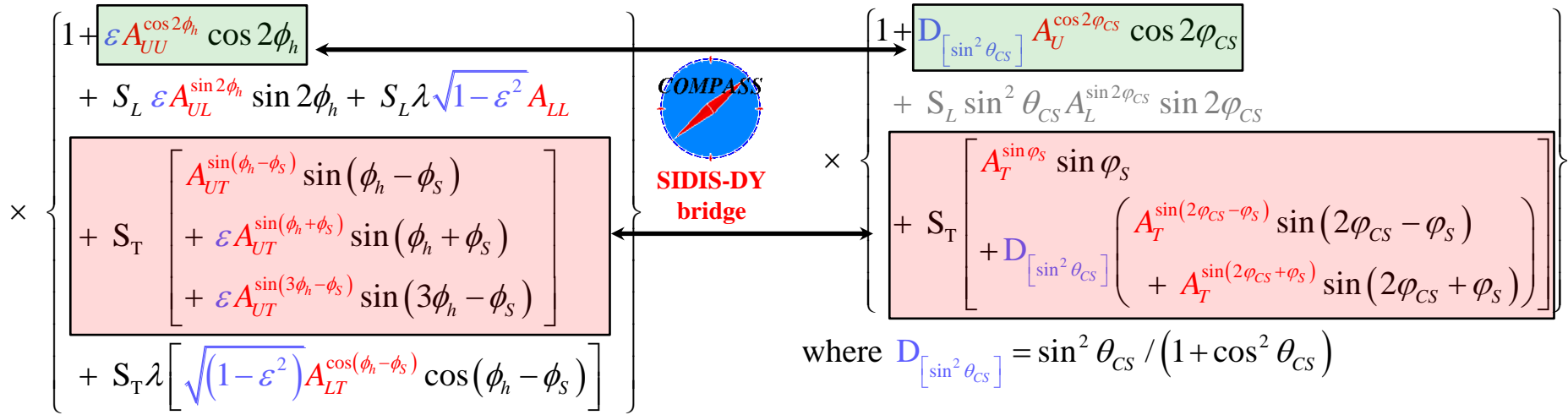
# SIDIS and single-polarized DY x-sections at twist-2 (LO)

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

**SIDIS**

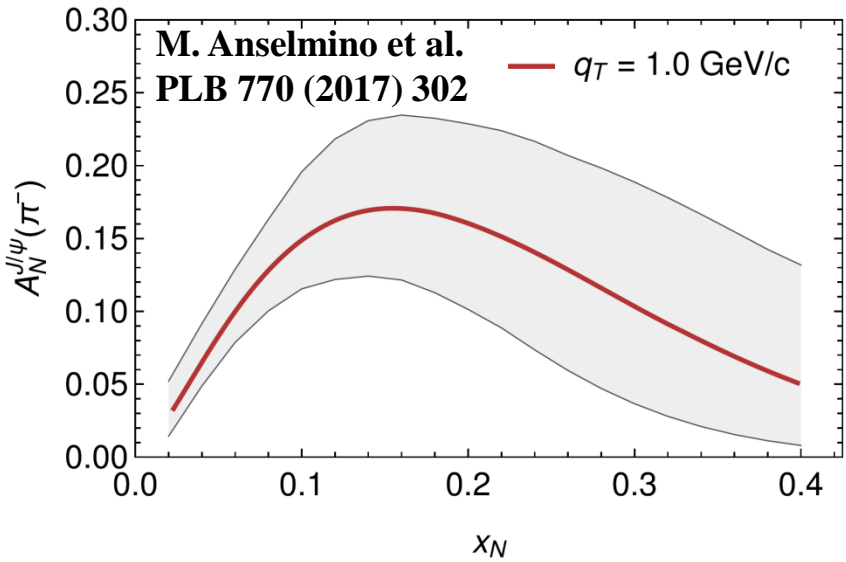
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

**DY**

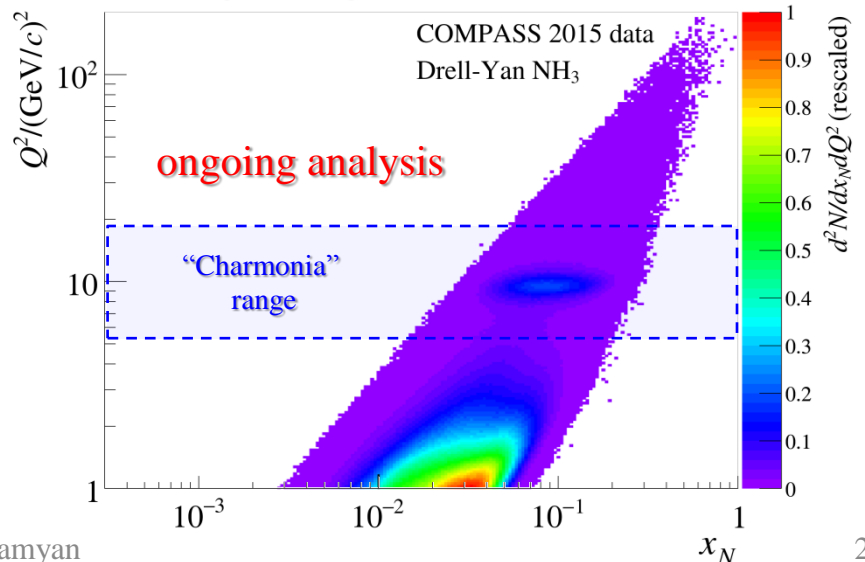


where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1 \text{ GeV}/c$



$2.5 < M / (\text{GeV}/c^2) < 4.3$  "Charmonia mass"  
 Strong  $J/\psi$ -signal  $\rightarrow$  study of  $J/\psi$  physics  
 Good signal/background





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

**SIDIS**

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

**DY**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

← COMPASS →

**SIDIS-DY bridge**

×

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$$

$$+ S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}$$
  

$$+ S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{bmatrix}$$
  

$$+ S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]$$

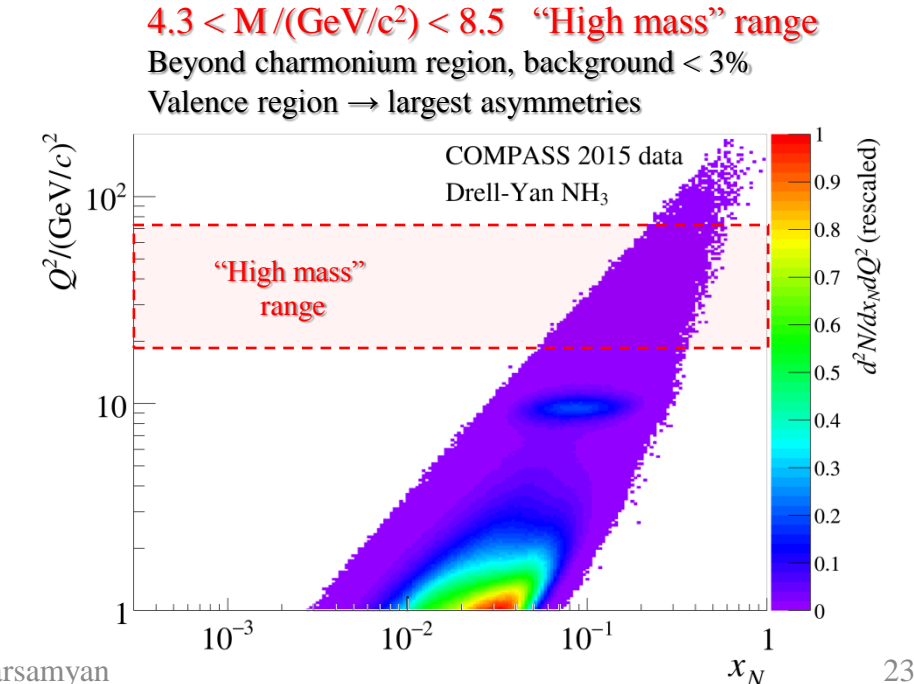
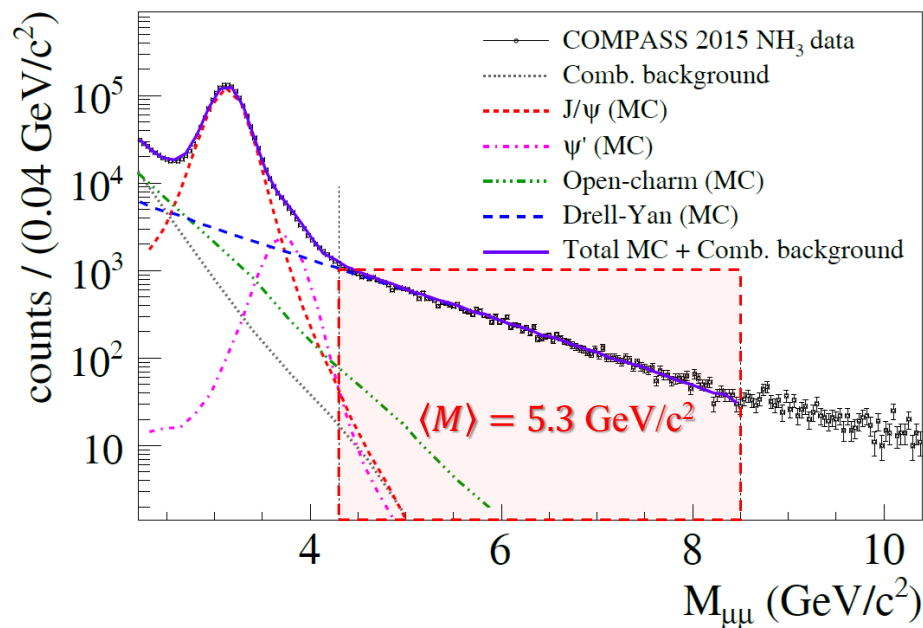
$$1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$

$$+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$
  

$$+ S_T \begin{bmatrix} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \right. \\ \left. \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \end{bmatrix}$$

where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

**SIDIS**

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

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL}$$

$$\times \left[ \begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right]$$

$$+ S_T \lambda \left[ \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]$$

**SIDIS-DY  
bridge**

**DY**

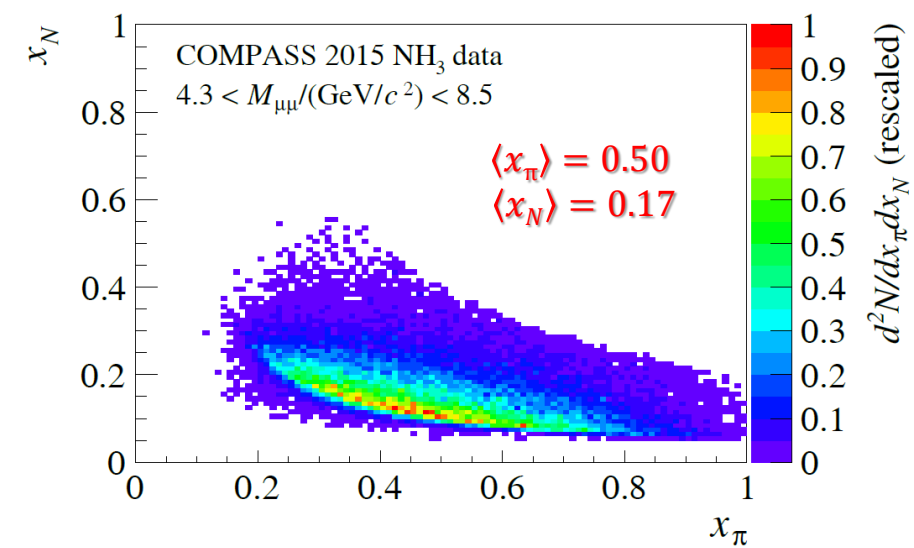
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$$1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

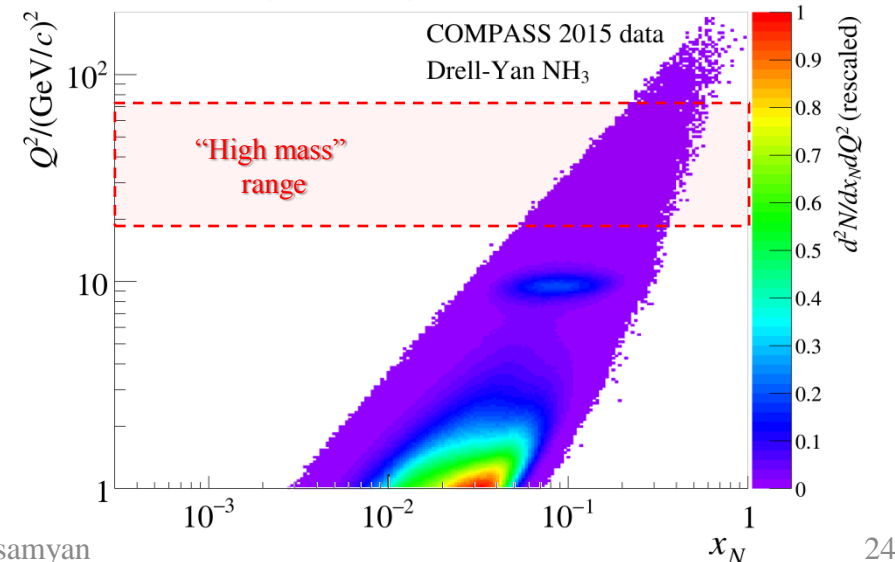
$$\times \left[ \begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \right. \\ \left. \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \right]$$

where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

## HM events are in the valence quark range



**4.3 < M/(GeV/c<sup>2</sup>) < 8.5** “High mass” range  
 Beyond charmonium region, background < 3%  
 Valence region → largest asymmetries







# SIDIS and single-polarized DY x-sections at twist-2 (LO)

**SIDIS**

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

**SIDIS-DY bridge**

**DY**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}$$

$$\times \left[ \begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right]$$

$$+ S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right]$$

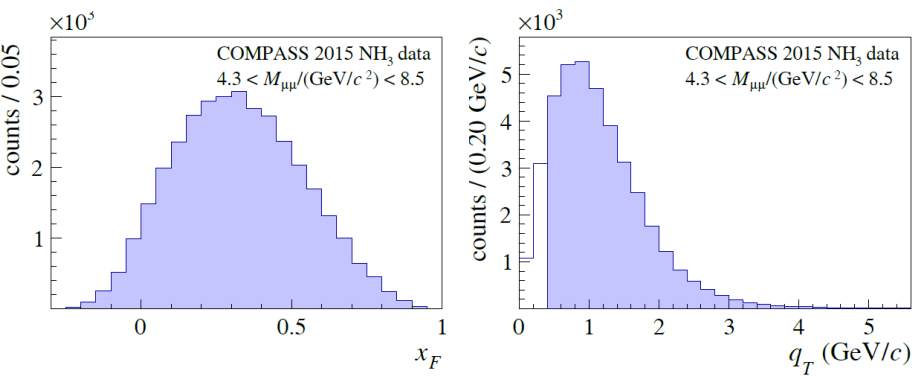
$\times$

$$1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$

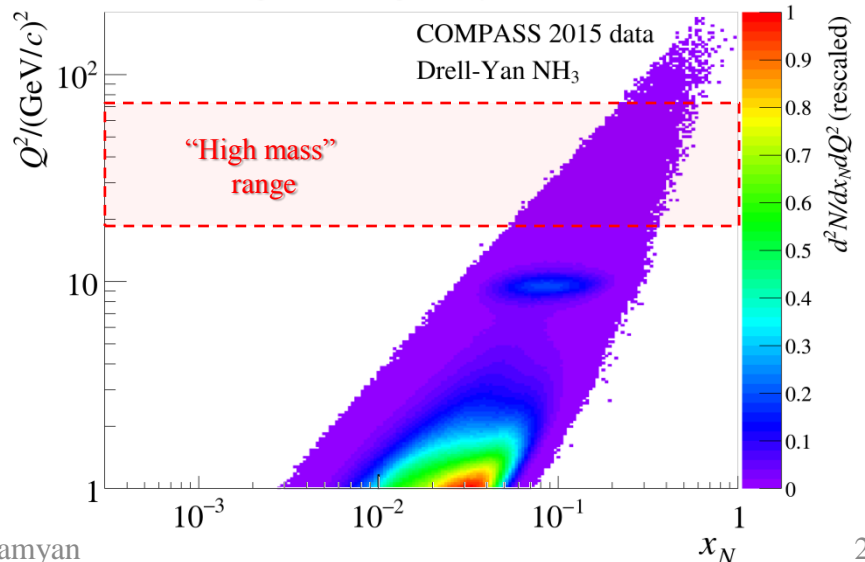
$$\times \left[ \begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( \begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right]$$

where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

Dimuon transverse momentum  $q_T > 0.4 \text{ GeV}/c$   
 $\langle x_F \rangle = 0.33, \langle q_T \rangle = 1.2 \text{ GeV}/c$



**4.3 < M/(GeV/c^2) < 8.5** “High mass” range  
 Beyond charmonium region, background < 3%  
 Valence region → largest asymmetries





# SIDIS and single-polarized DY x-sections at twist-2 (LO)

**SIDIS**

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$

**SIDIS-DY bridge**

**DY**

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h$   
 $+ S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL}$

$\times \left[ \begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{array} \right]$

$+ S_T \lambda \left[ \sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right]$

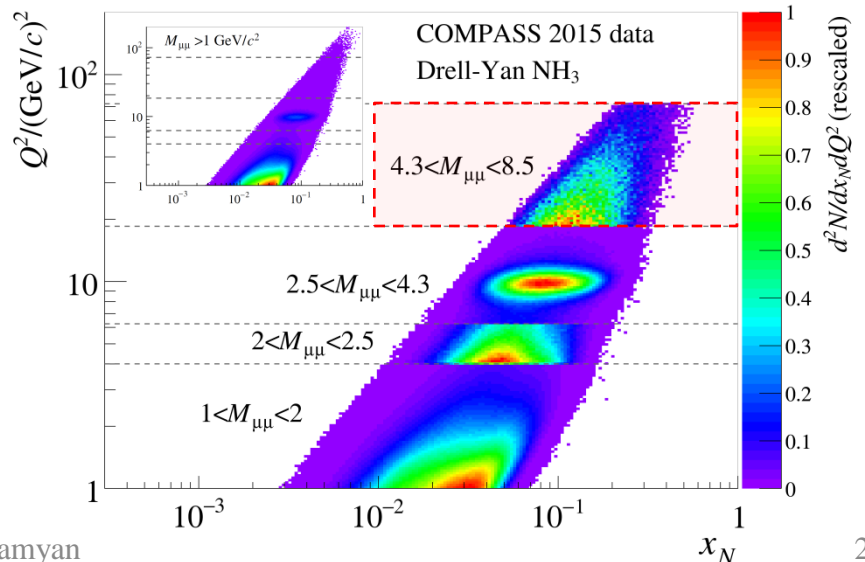
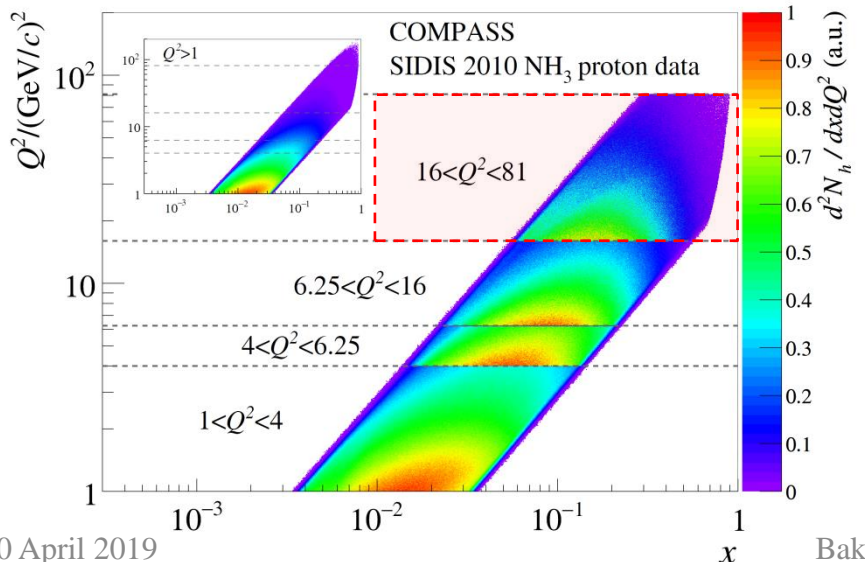
$\times$

$1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$   
 $+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$

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

where  $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$

## Comparable x:Q<sup>2</sup> coverage – minimization of possible Q<sup>2</sup>-evolution effects



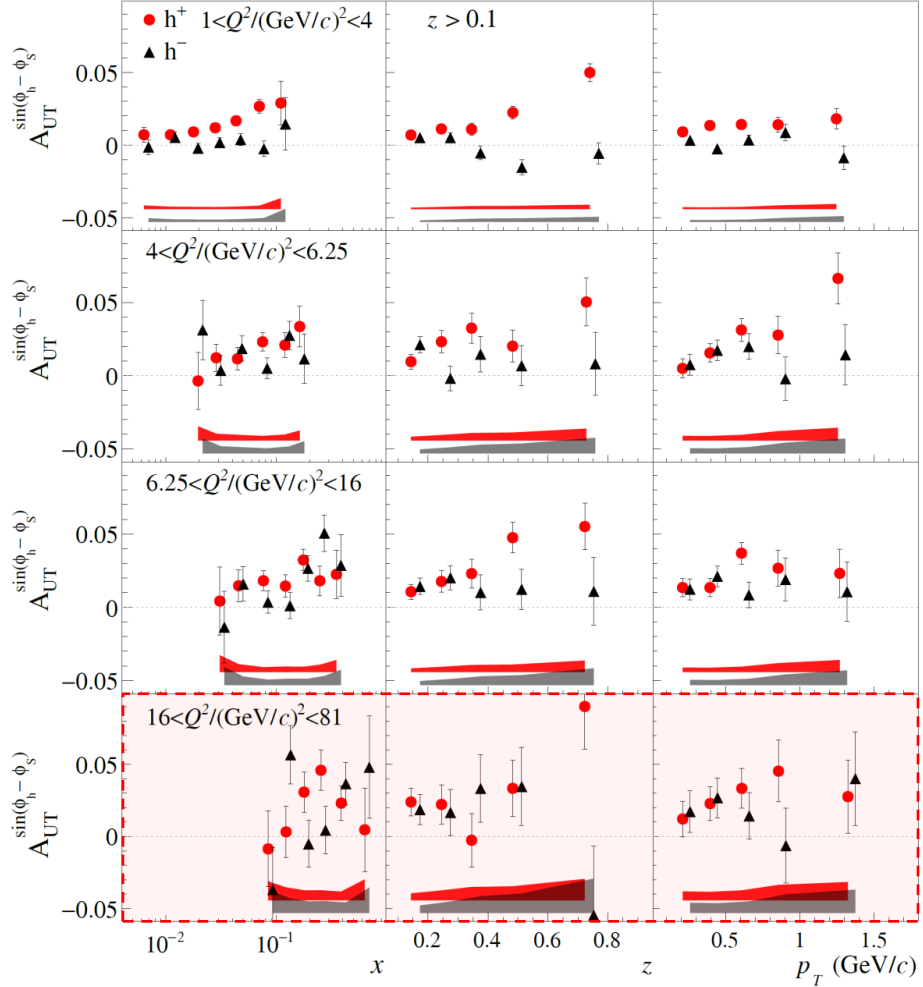
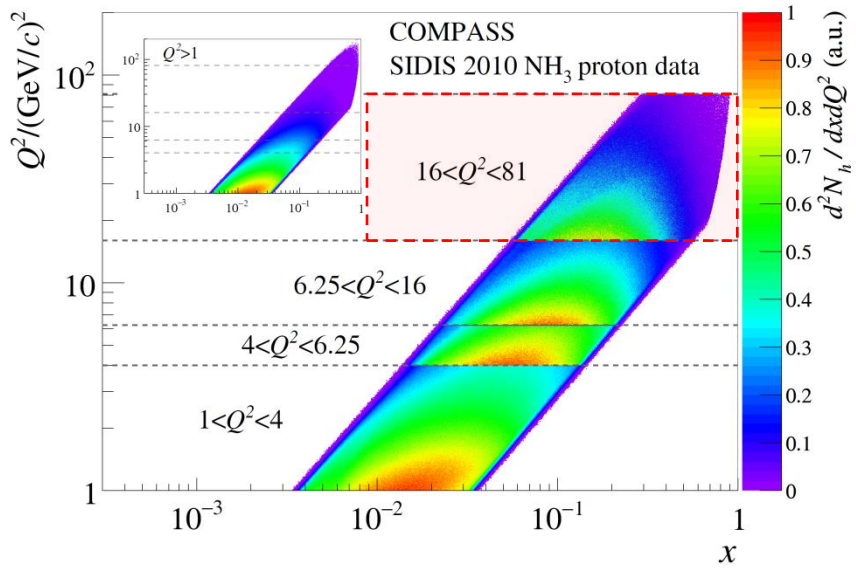


# SIDIS Sivers TSA in COMPASS Drell-Yan $Q^2$ -ranges

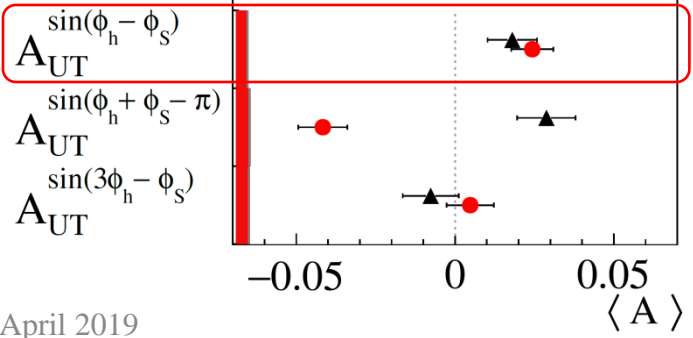
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

COMPASS PLB 770 (2017) 138



●  $h^+$   $16 < Q^2 / (\text{GeV}/c)^2 < 81$   
 ▲  $h^-$   $\langle x \rangle \approx 0.238$





# SIDIS TSAs (Collins)

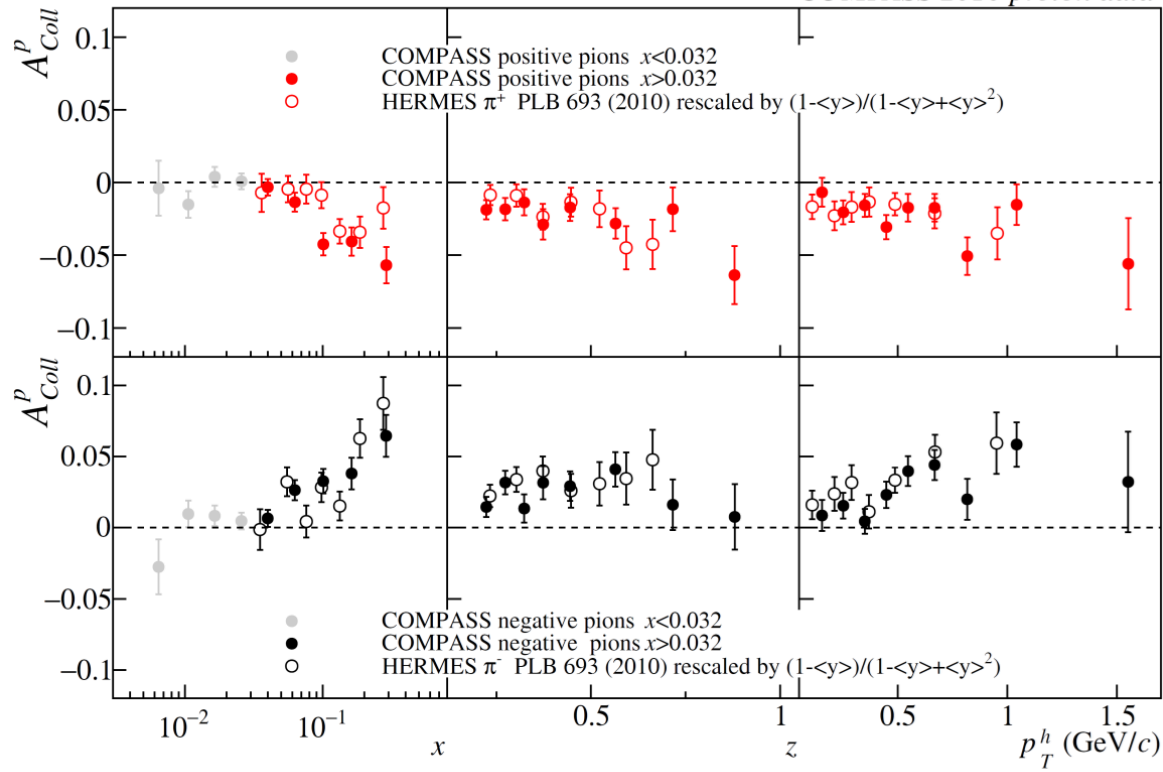
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data





See talk by F. Bradamante

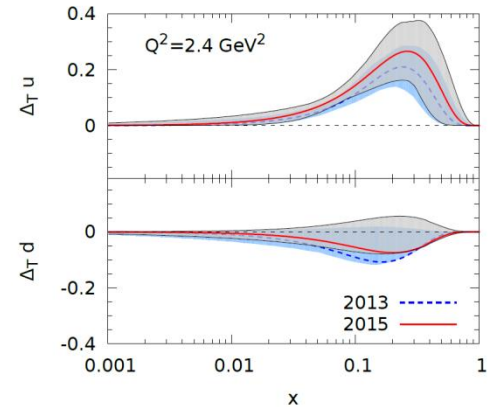
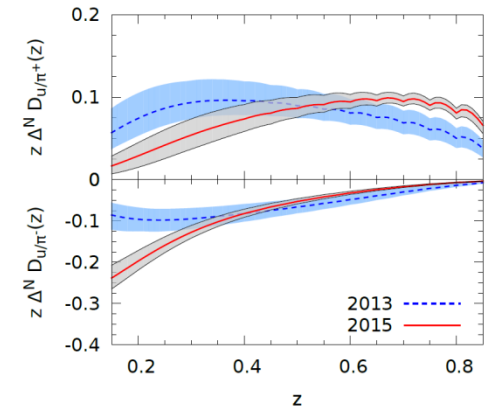
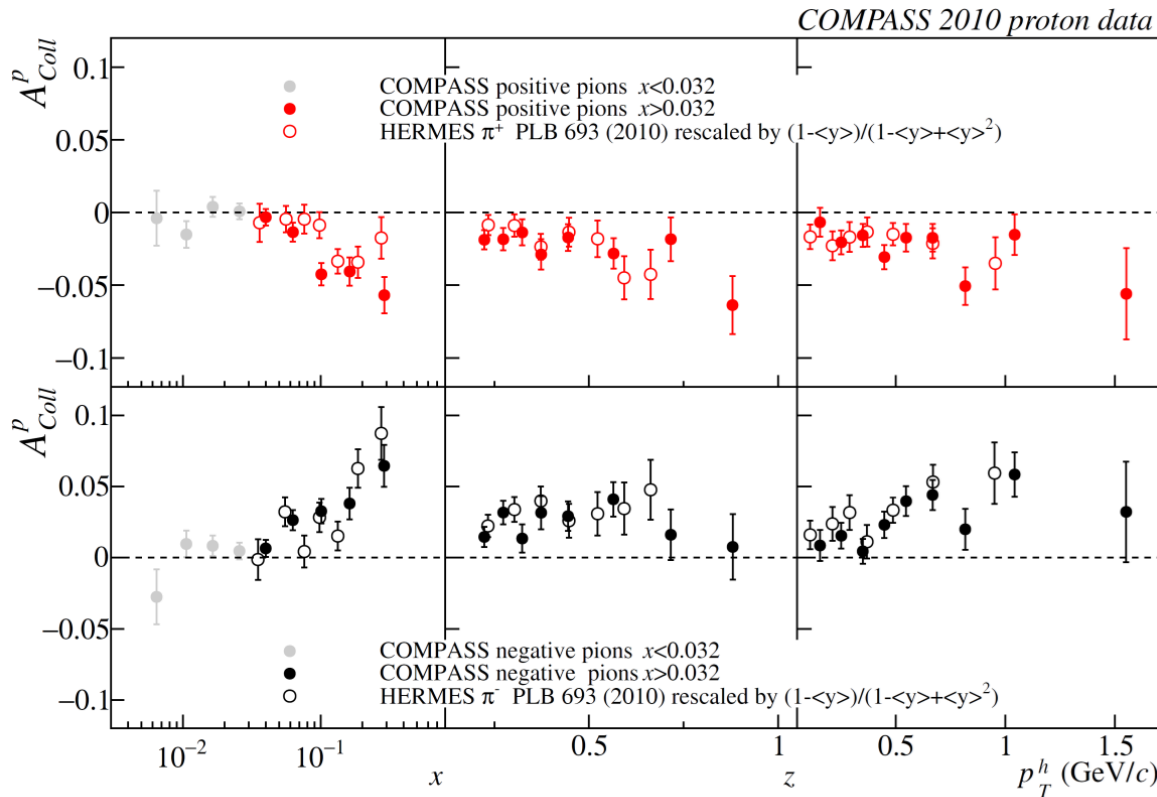
# SIDIS TSAs (Collins)

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

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q<sup>2</sup> is different by a factor of ~2-3)
- **No Q<sup>2</sup>-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

COMPASS PLB 744 (2015) 250





See talk by A. Martin

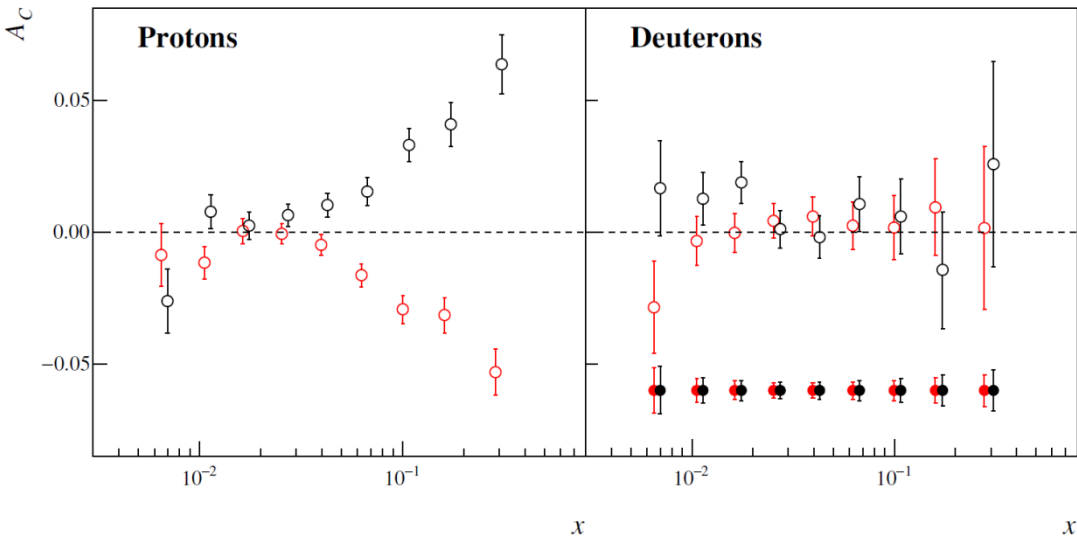
# SIDIS TSAs (Collins)

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

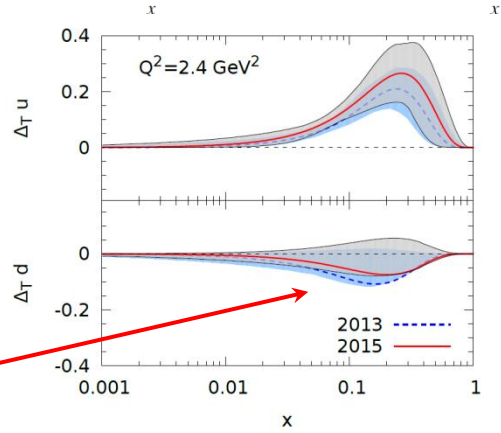
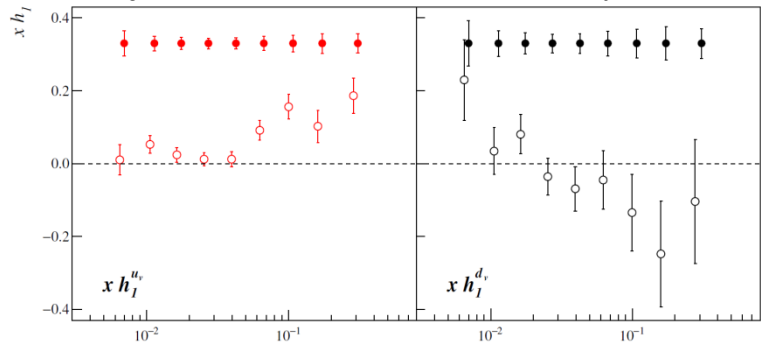
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[ -\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

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Addendum to the COMPASS-II Proposal  
Projected uncertainties for Collins asymmetry



Addendum to the COMPASS-II Proposal  
Projected uncertainties for transversity PDF



## COMPASS-II (2021 run)

- Deuteron measurement to be repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark

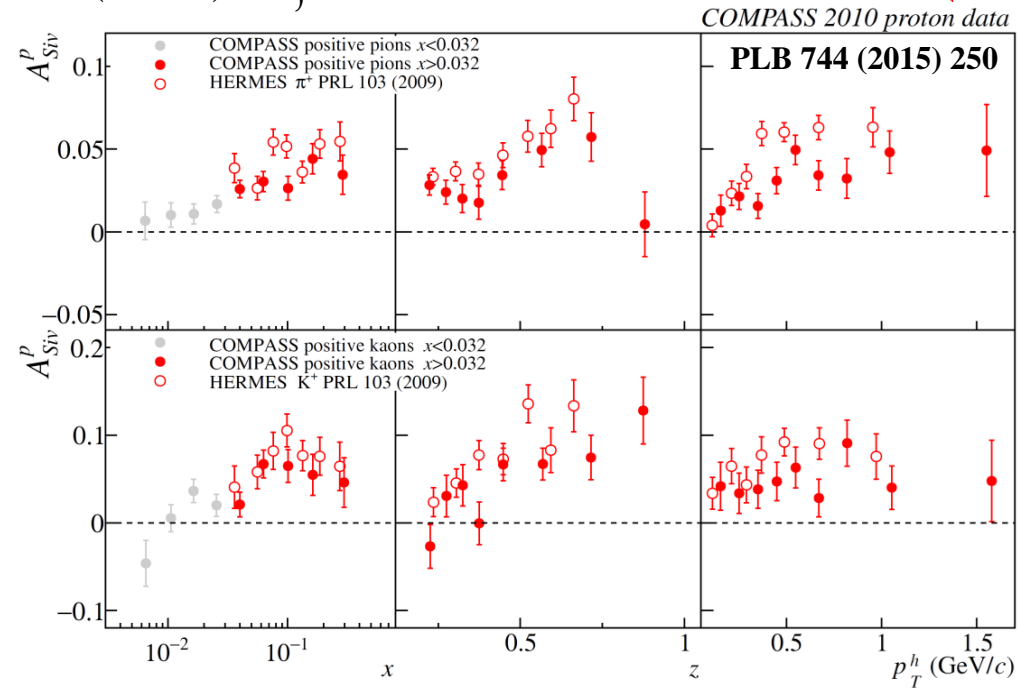


# SIDIS TSAs (Sivers)

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- Measured on proton and deuteron
- Recently - gluon Sivers paper  
PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q<sup>2</sup> is different by a factor of ~2-3)
- **Q<sup>2</sup>-evolution? Intriguing result!**



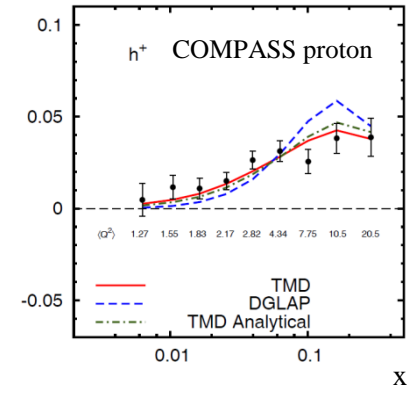
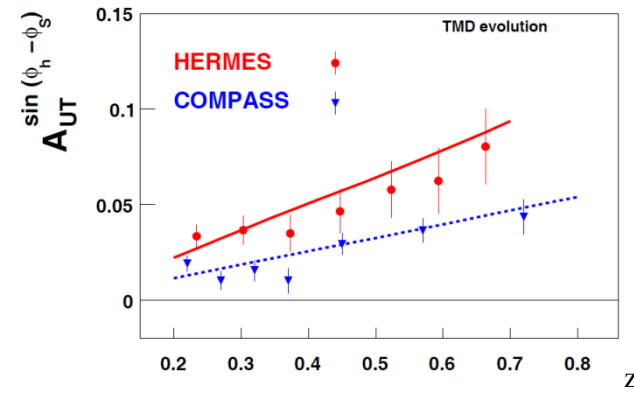
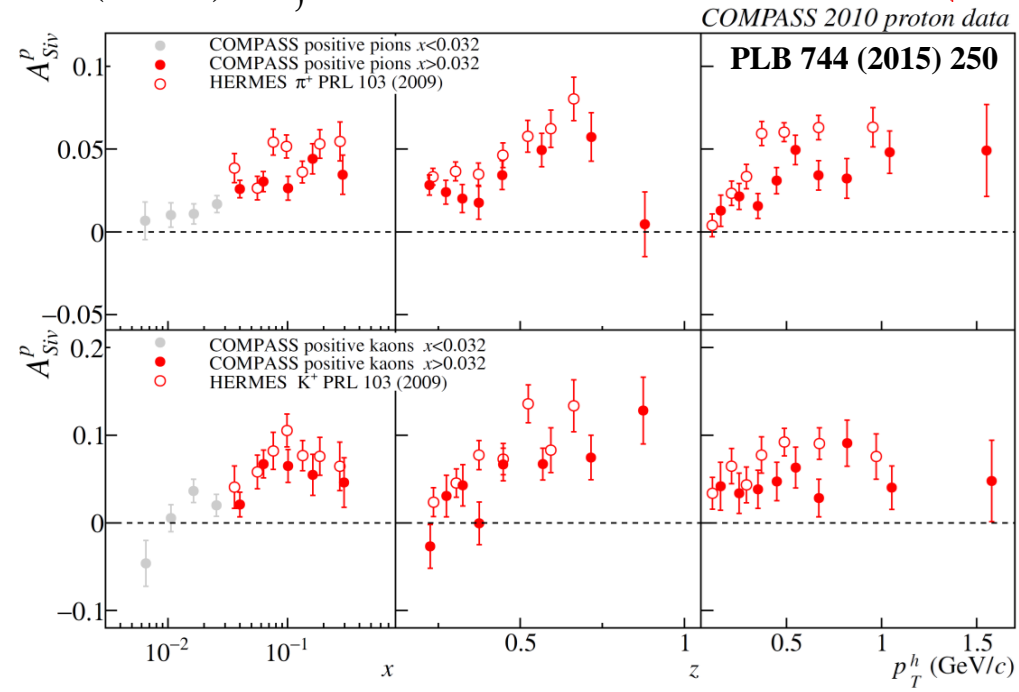


# SIDIS TSAs (Sivers)

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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- **Q<sup>2</sup>-evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- **Sivers TMD PDF is predicted to change the sign between SIDIS and DY**



S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**  
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

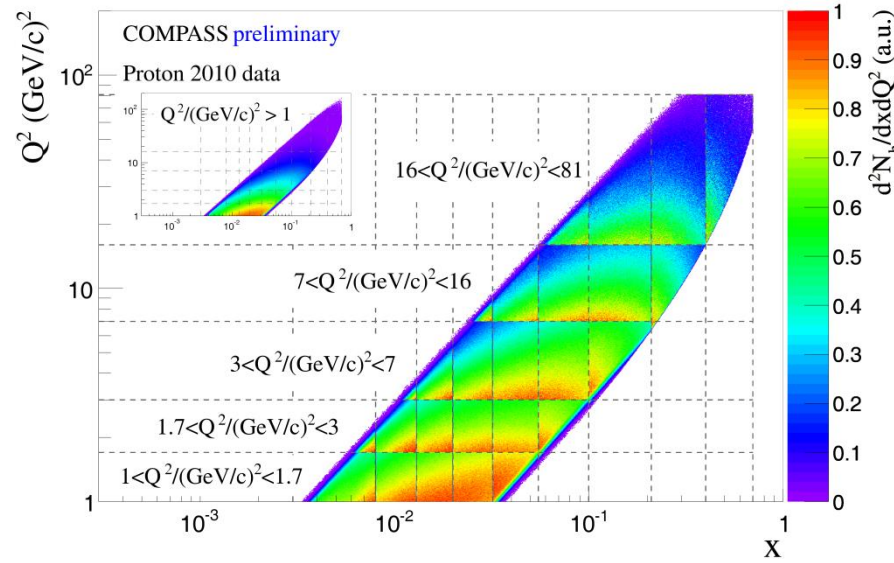


# Multi-D TSA analysis

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \dots \right\}$$

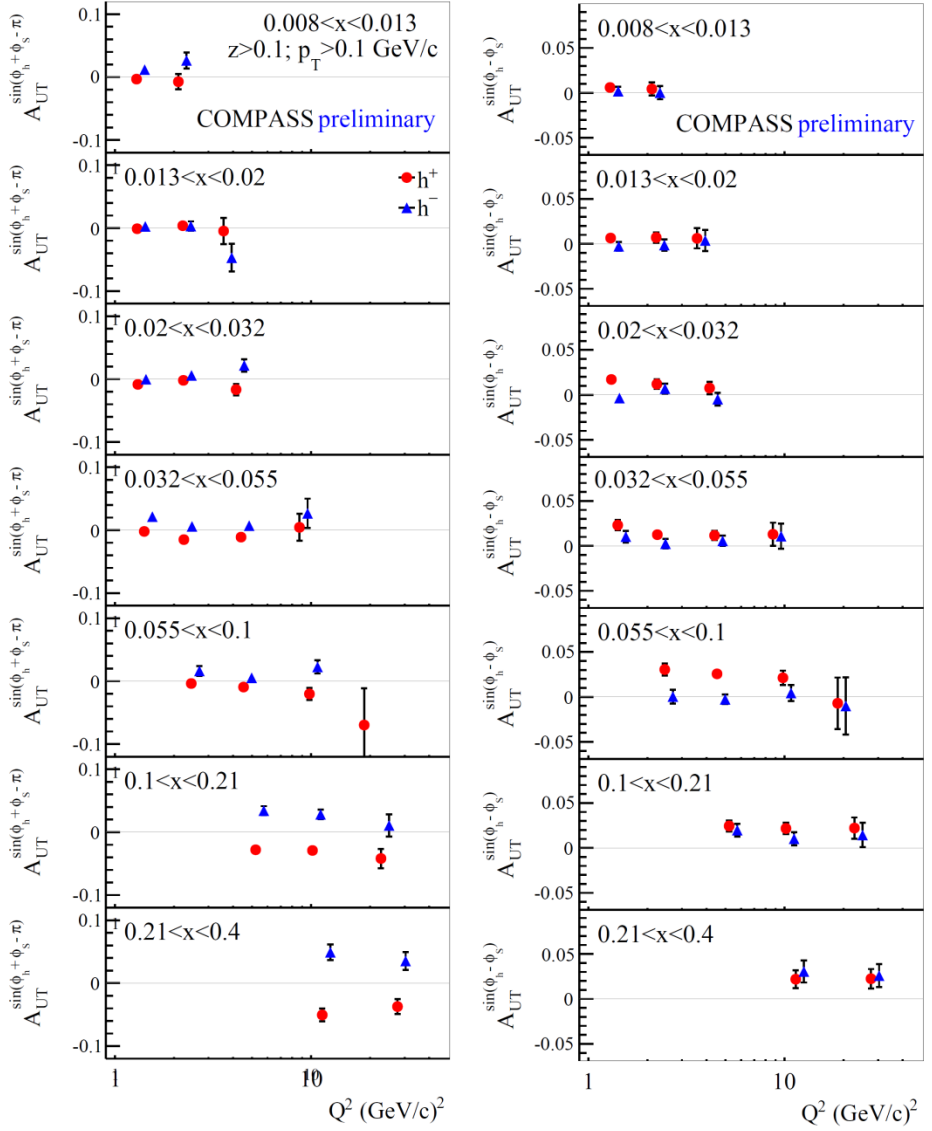
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



- No clear  $Q^2$ -dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

B. Parsamyan (for COMPASS) [arXiv:1504.01599](https://arxiv.org/abs/1504.01599) [hep-ex] (SPIN-2014)





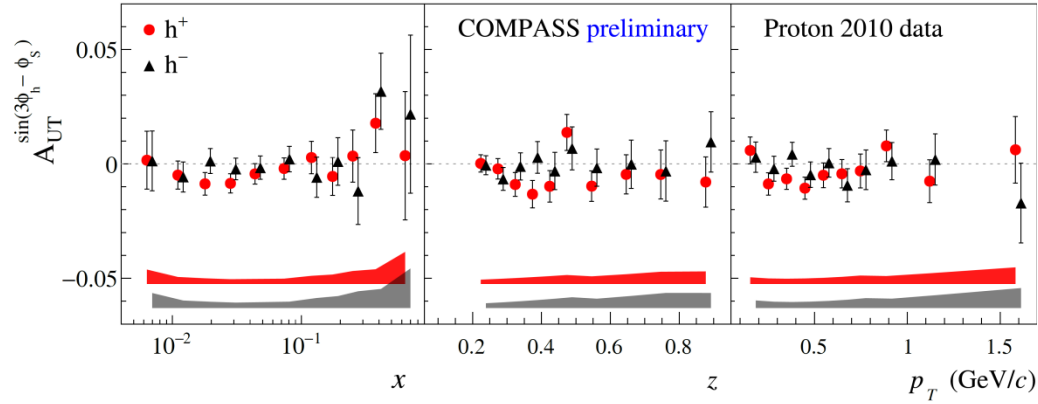
# SIDIS: target transverse spin dependent asymmetries

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

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

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



## COMPASS results

$$A_{UT}^{\sin(3\phi_h - \phi_S)}$$

- Only “twist-2” ingredients,  $p_T^2$ -suppression
- $h_{1T}^{\perp q}$  is also small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**

$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C \left[ \frac{2(\hat{h} \cdot k_T)(k_T \cdot p_T) + k_T^2(\hat{h} \cdot p_T) - 4(\hat{h} \cdot k_T)^2(\hat{h} \cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$



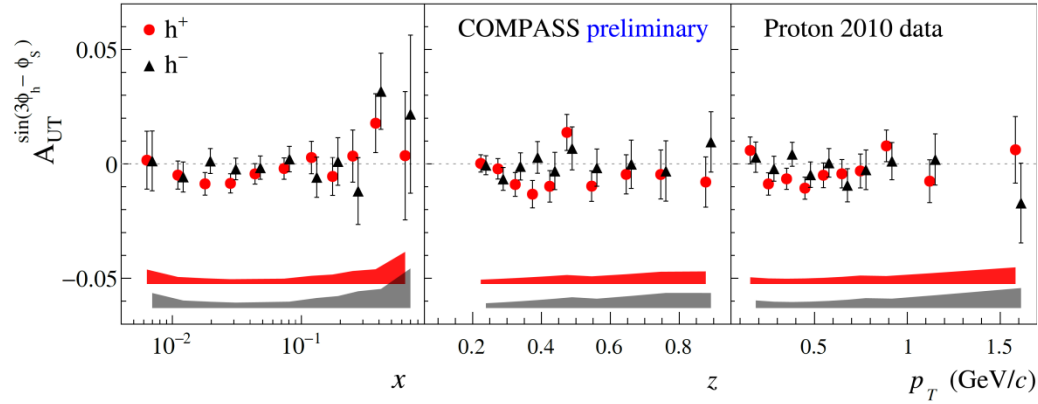
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



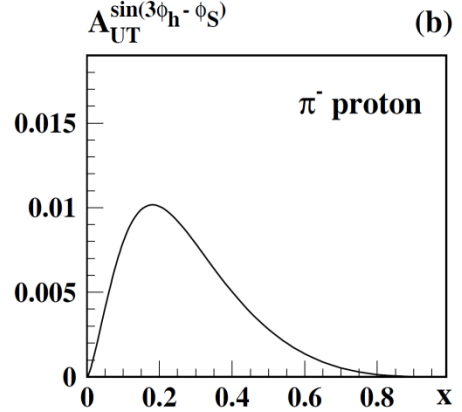
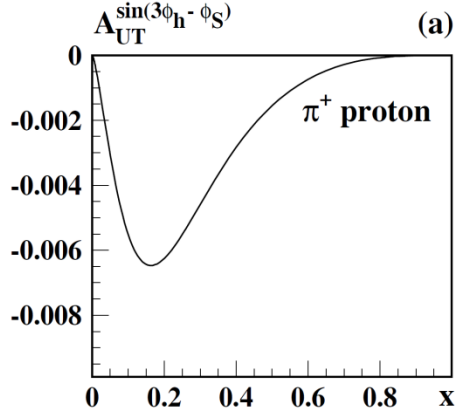
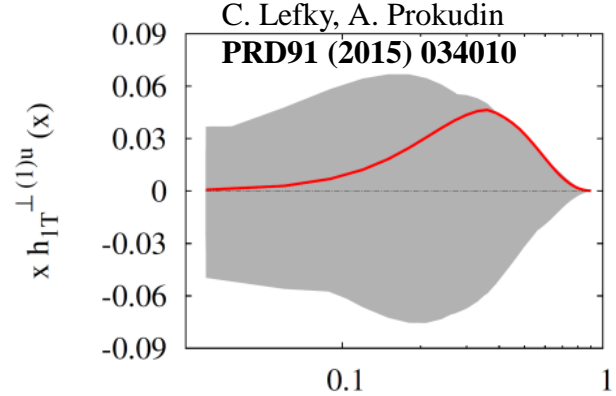
## COMPASS results

$$A_{UT}^{\sin(3\phi_h - \phi_S)}$$

- Only “twist-2” ingredients,  $p_T^2$ -suppression
- $h_{1T}^{\perp q}$  is also small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**
- **In agreement with models**

$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C \left[ \frac{2(\hat{h} \cdot k_T)(k_T \cdot p_T) + k_T^2(\hat{h} \cdot p_T) - 4(\hat{h} \cdot k_T)^2(\hat{h} \cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$

B. Pasquini, S. Boffi, A.V. Efremov, P. Schweitzer  
arXiv:0912.1761 [hep-ph]





# Single-polarized DY x-section: transverse part

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

- “naive” Drell–Yan model  
collinear ( $k_T=0$ ) LO pQCD no rad. processes  
 $\lambda=1, (F_U^2=0), \mu=\nu=0$
- Intrinsic transverse motion + QCD effects  
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$  but  $1-\lambda=2\nu$  (Lam-Tung)
- Experiment,  
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

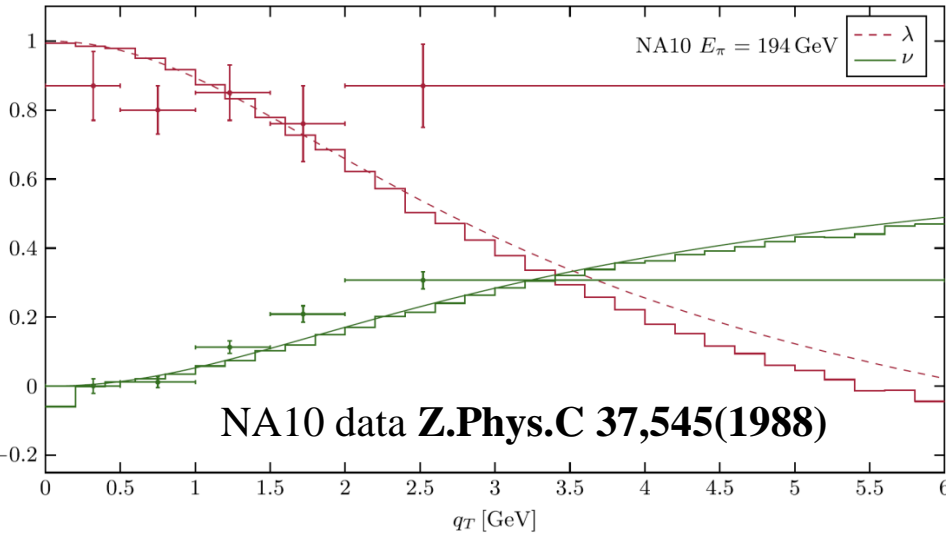
See talk by W-Ch. Chang

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

$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} \right\}$$

$$+ S_T \left[ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + D_{[\sin 2\theta_{CS}]} \left( \begin{aligned} & A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \\ & + A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) \end{aligned} \right) \\ & + D_{[\sin^2 \theta_{CS}]} \left( \begin{aligned} & A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ & + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{aligned} \right) \end{aligned} \right]$$

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



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

- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption  $A_U^1=1$



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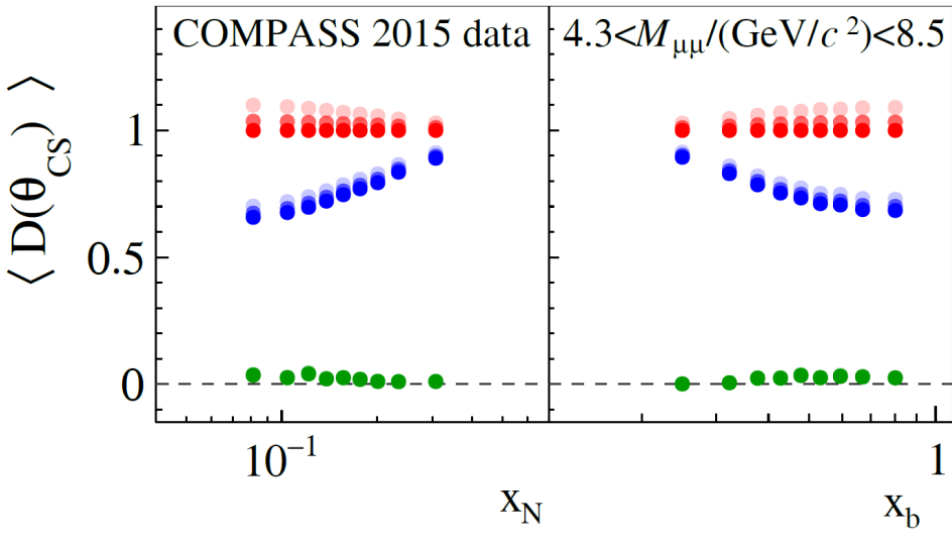
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- Experiment,  
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$$\frac{d\sigma}{d\Omega} \propto (F_U^1 + F_U^2) (1 + A_U^1 \cos^2 \theta_{CS})$$

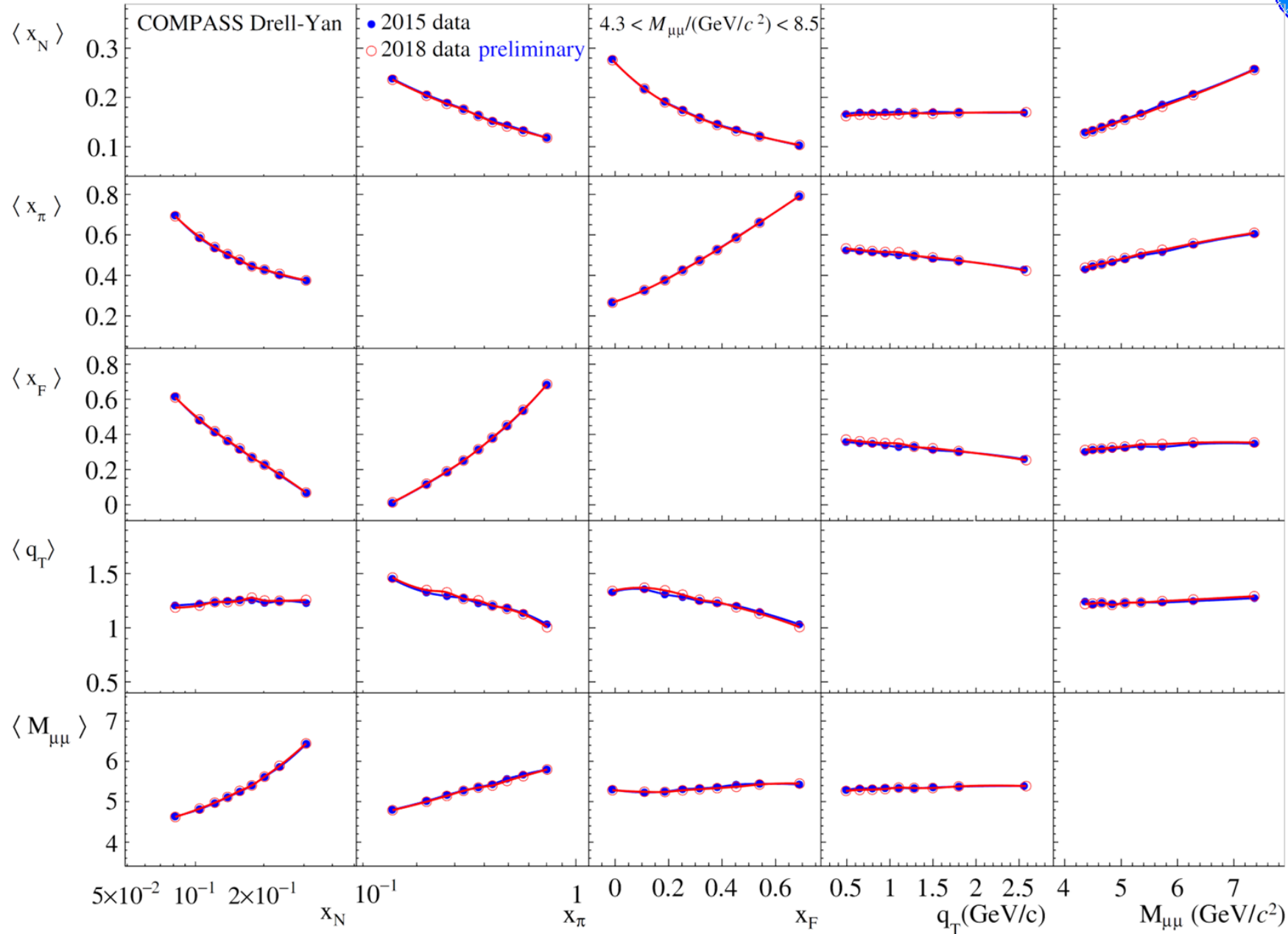
$$\times \left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} \right\} + S_T \left[ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + D_{[\sin 2\theta_{CS}]} \left( A_T^{\sin(\varphi_{CS}-\varphi_S)}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

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

- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption  $A_U^1=1$
- Possible impact of  $A_U^1 \neq 1$  scenarios lead to a normalization uncertainty of at most  $-5\%$ .



# Kinematic map: high mass range 2015 and 2018 data





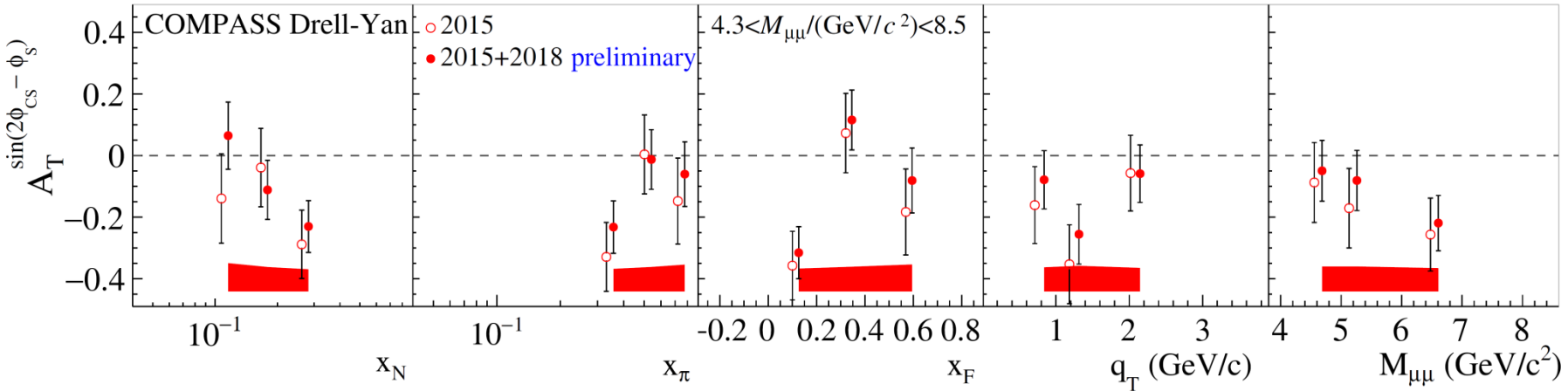
# Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$

Transversity DY TSA

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

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





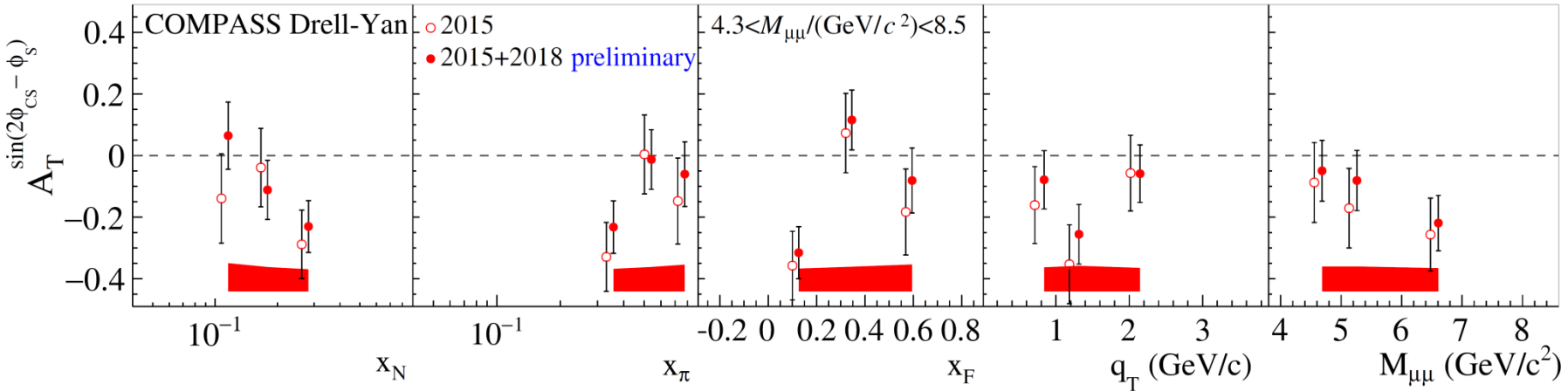
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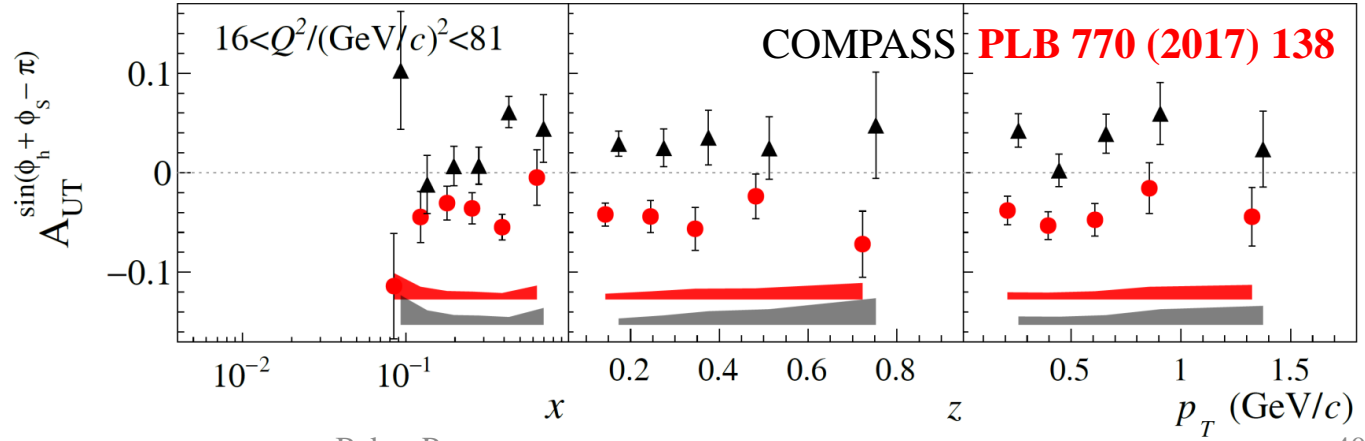
COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)



## SIDIS in Drell-Yan high-mass range

Collins SIDIS TSA

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







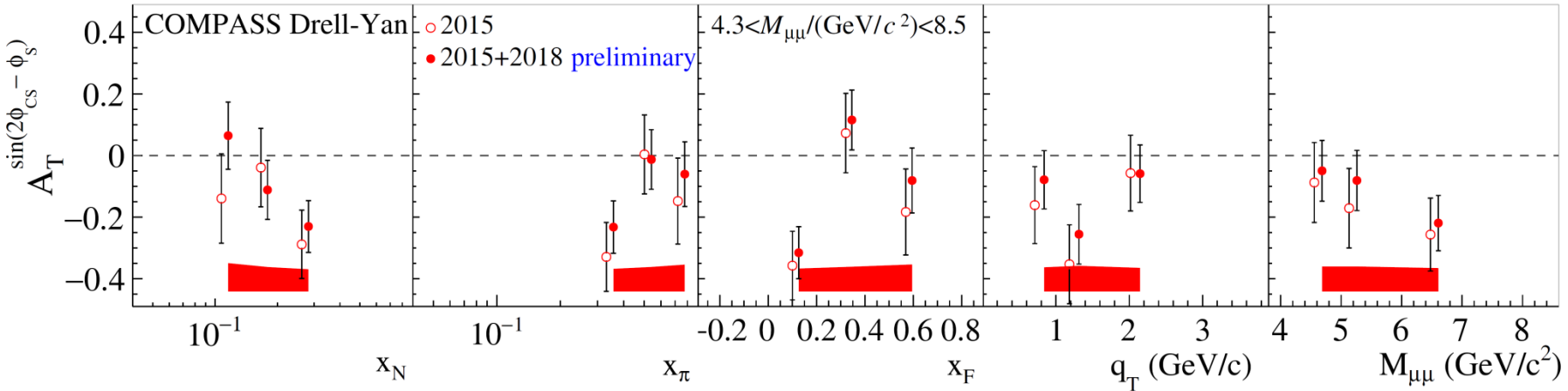
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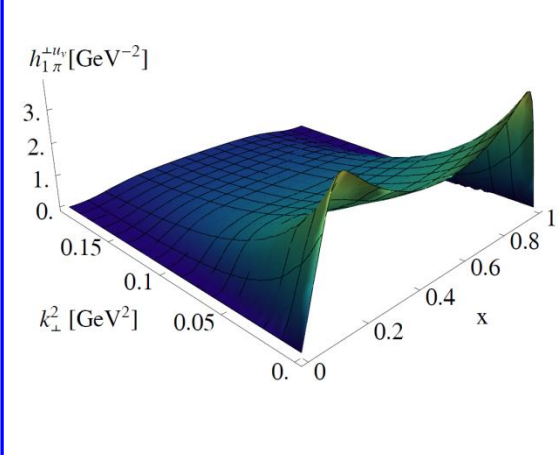
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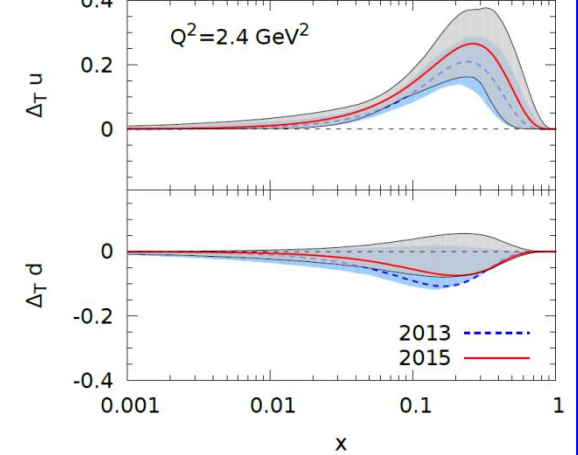
COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)



B. Pasquini, P. Schweitzer  
Phys.Rev. D90 (2014) 014050



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





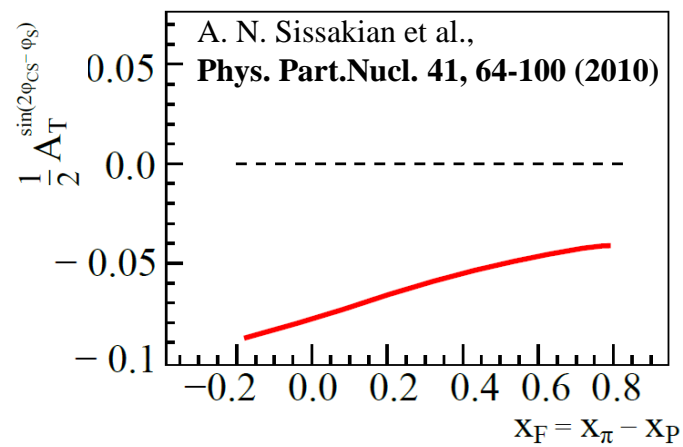
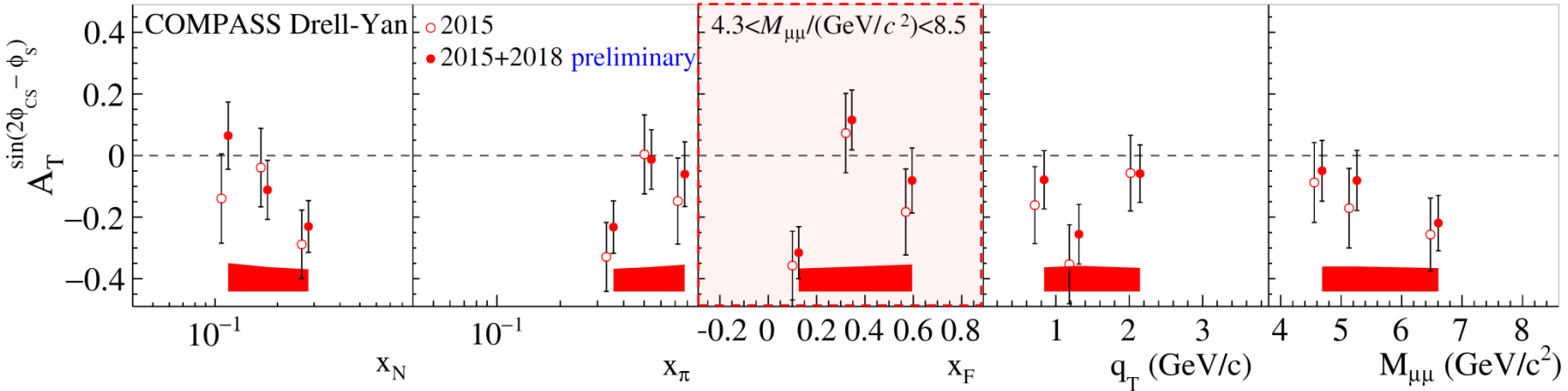
# Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$

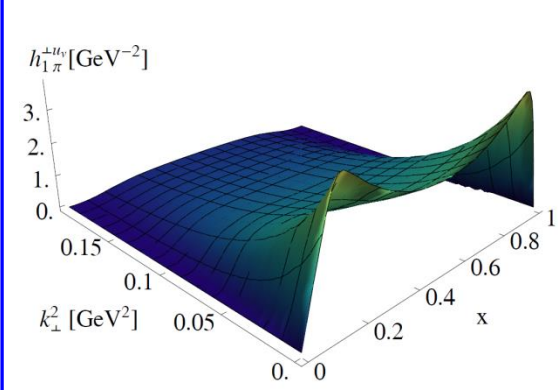
Transversity DY TSA

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

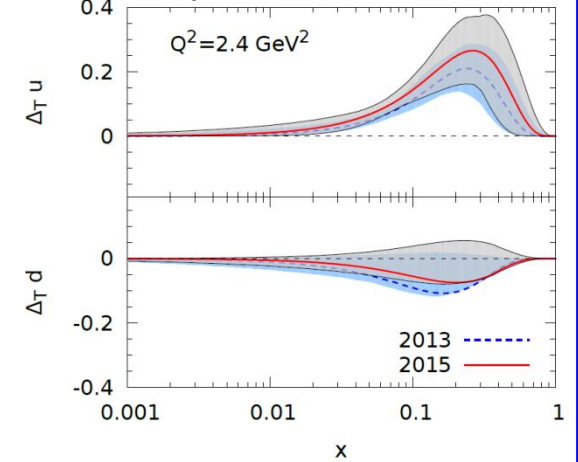
COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)



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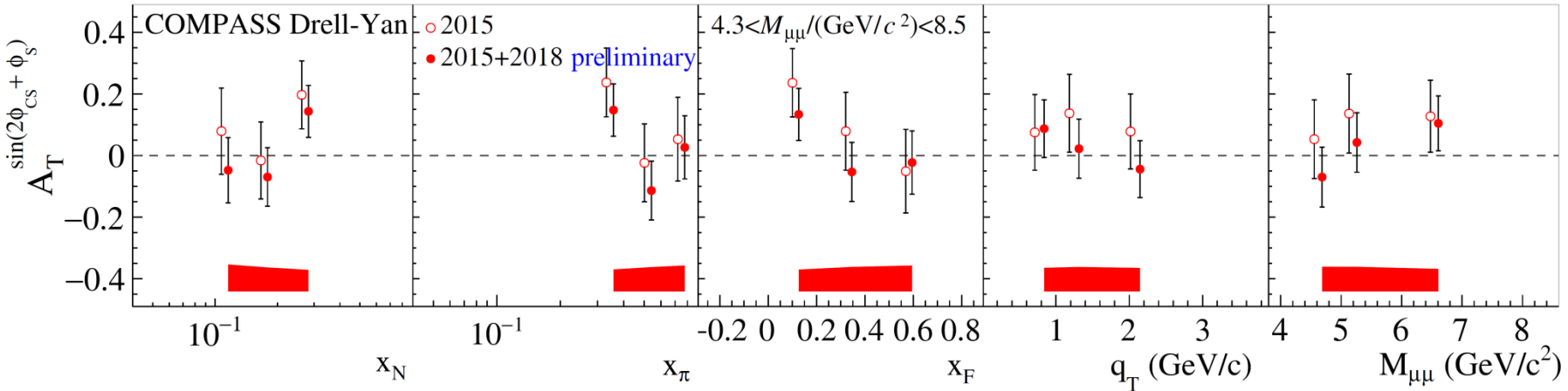
# Drell-Yan TSAs – Pretzelosity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$

Pretzelosity DY TSA

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

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





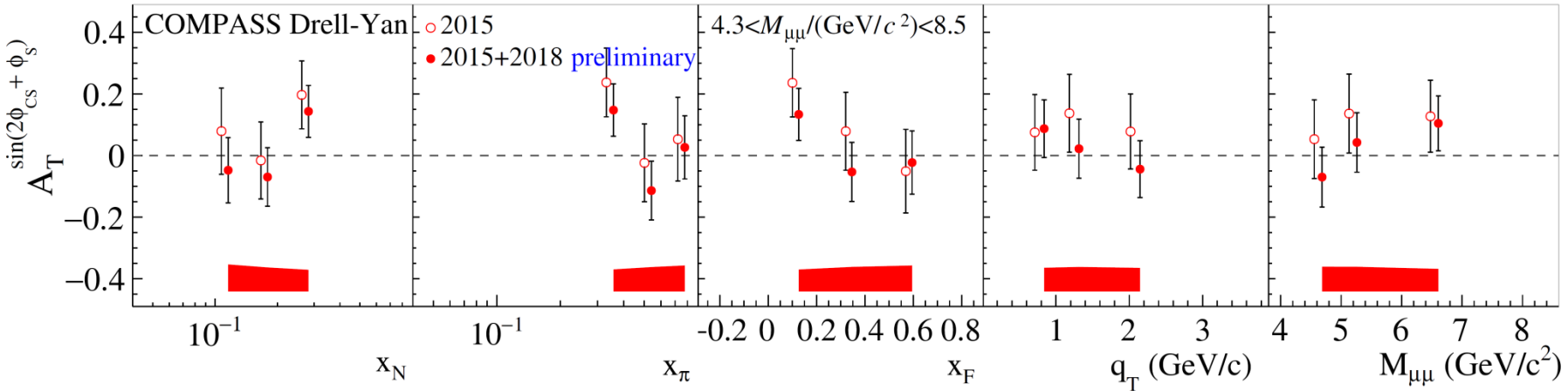
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Pretzelosity DY TSA

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

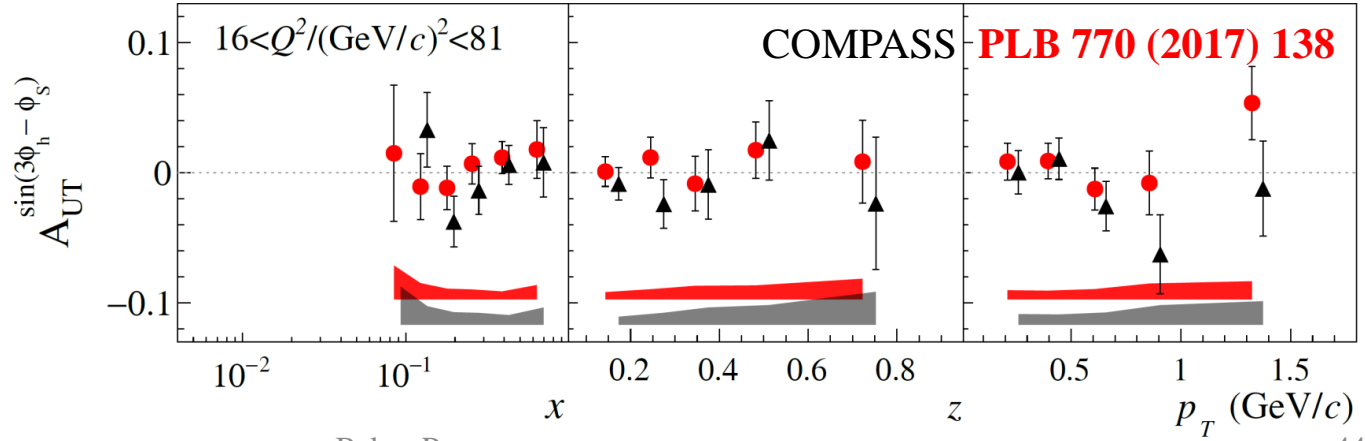
COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)



## SIDIS in Drell-Yan high-mass range

Pretzelosity SIDIS TSA

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





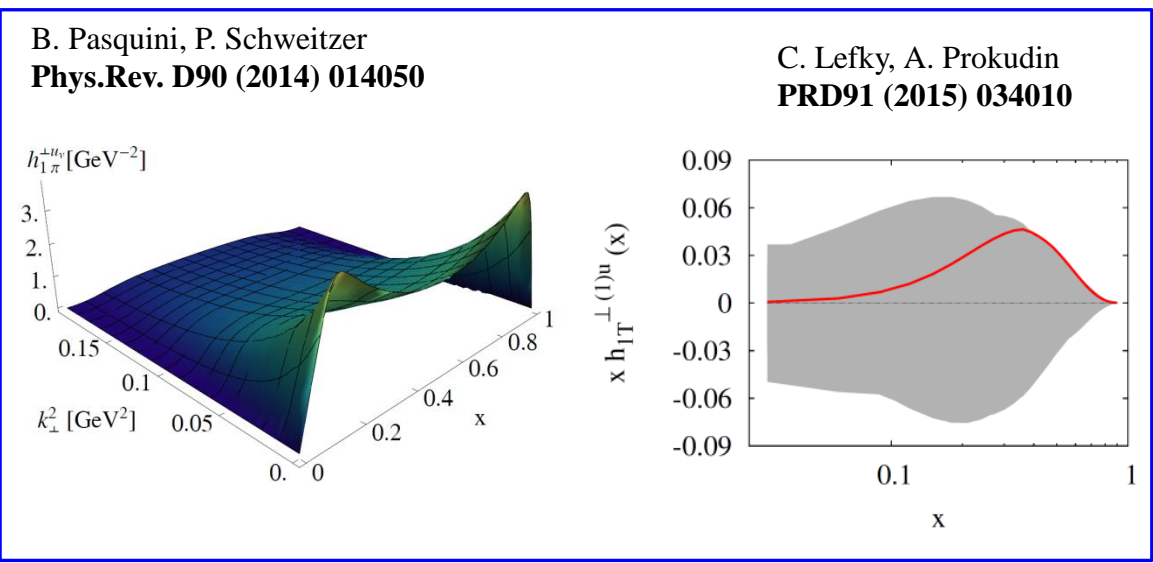
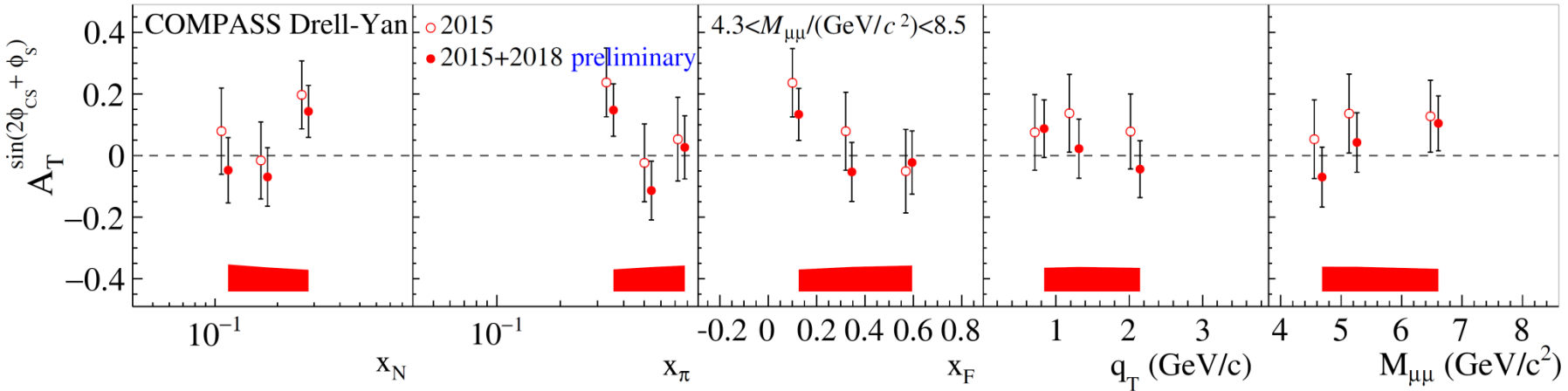
# Drell-Yan TSAs – Pretzelosity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$

Pretzelosity DY TSA

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

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



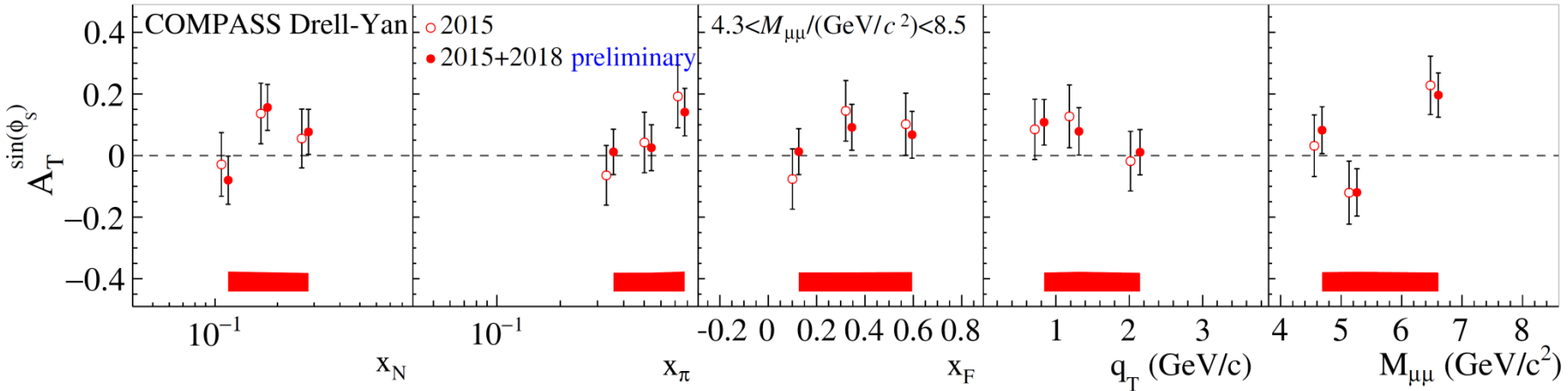
# Drell-Yan TSAs – Sivers

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ A_T^{\sin\phi_S} \sin\phi_S + \dots \right]$$

## Sivers DY TSA

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

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





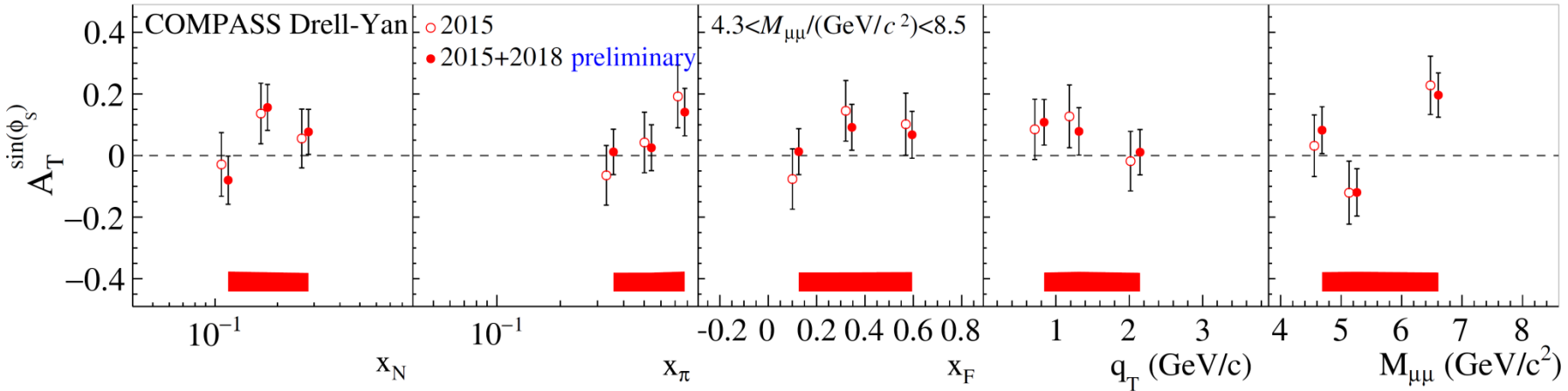
# Drell-Yan TSAs – Sivers

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ A_T^{\sin\phi_S} \sin\phi_S + \dots \right]$$

## Sivers DY TSA

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

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

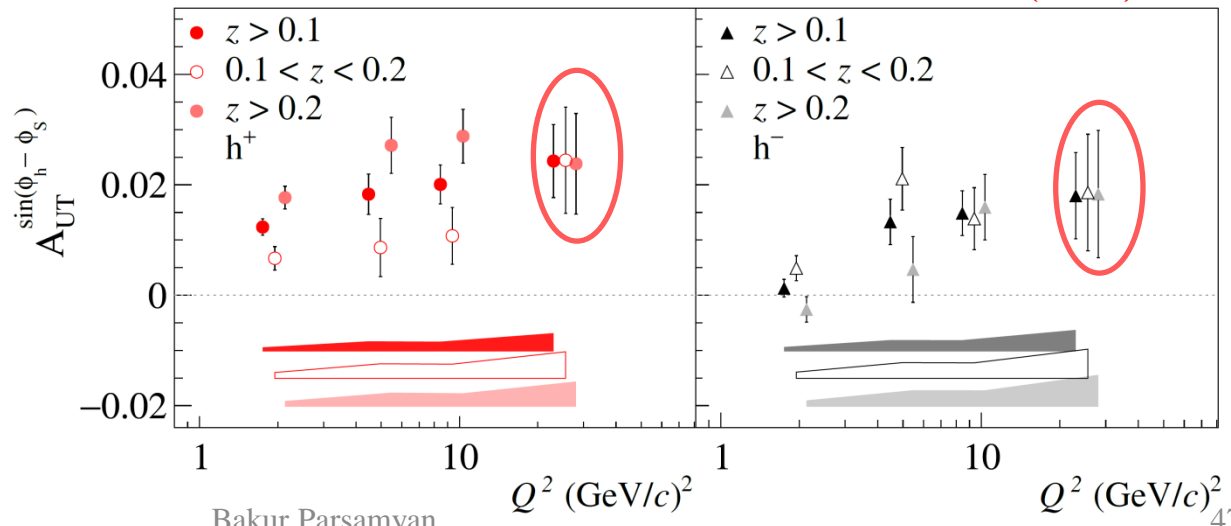


## SIDIS in Drell-Yan high-mass range

COMPASS PLB 770 (2017) 138

## Sivers SIDIS TSA

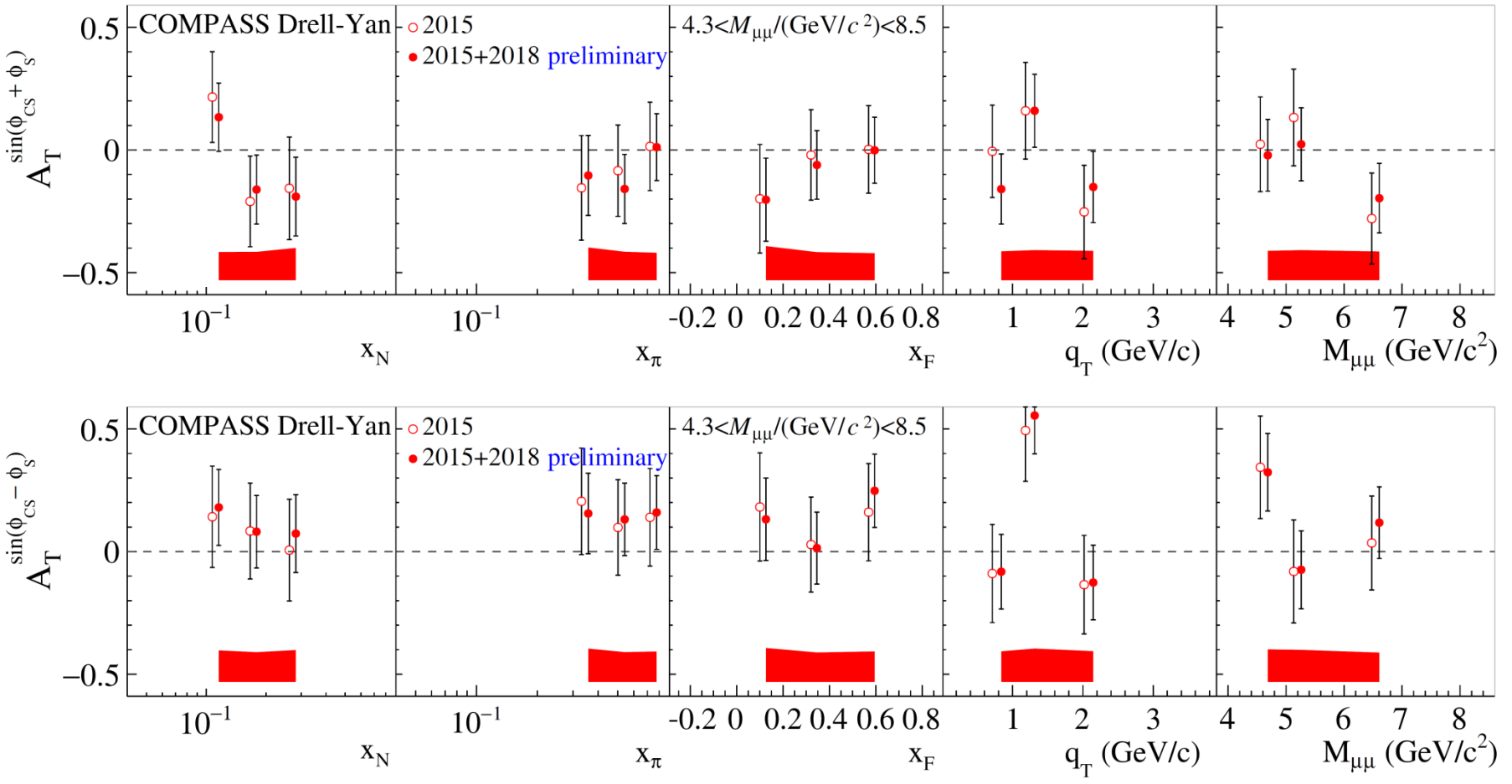
$$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$





# Drell-Yan TSAs – “higher twists”

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





# SIDIS and DY TSAs at COMPASS (high-mass range)



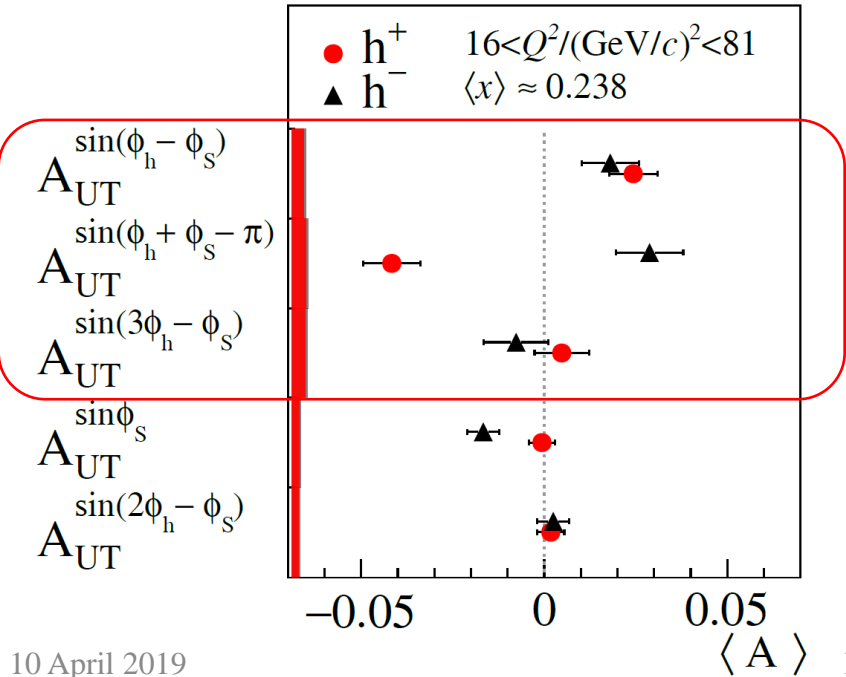
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

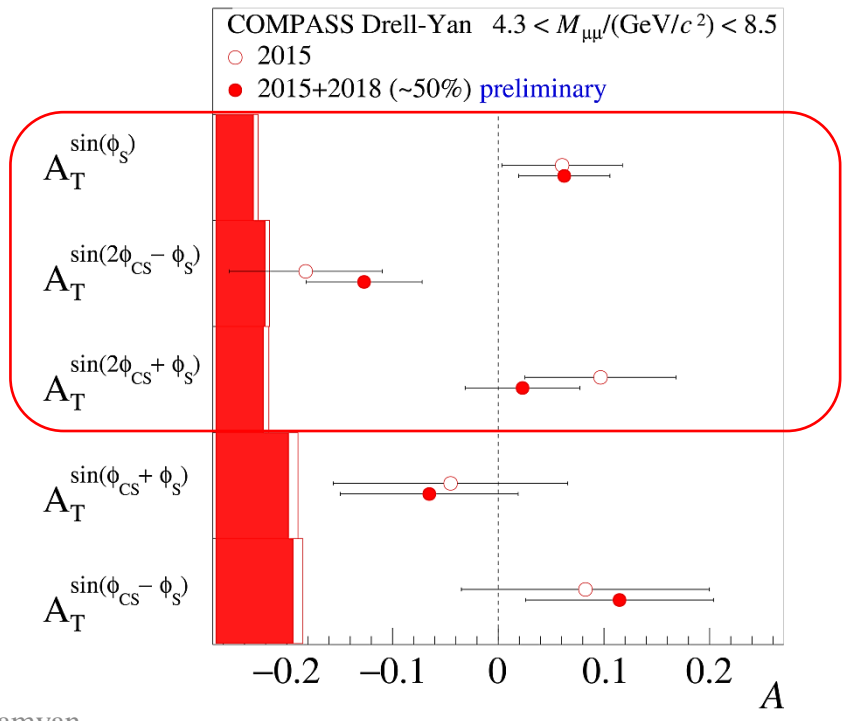
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

COMPASS PLB 770 (2017) 138



COMPASS 2015 + 2018 (~50%)





# Conclusions

- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs.
  - The Sivers and Collins SIDIS-TSAs were measured to be non-zero in particular at the  $Q^2$ -interval corresponding to the Drell-Yan “high-mass range”:  
PLB 770 (2017) 138
- In 2017 COMPASS has published the results for the **first polarized DY measurements**: PRL 119, 112002 (2017)
- The second year of polarized DY data-taking was performed in 2018
- The analysis of 2018 data is ongoing (~50% of the data has already been analyzed)
- Final results are expected to be out for autumn conferences

**Thank you!**

## BLUE WATERS

*This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).*

# Turin – the capital city of Piedmont

- ~200 BC: Taurini (an ancient Celto-Ligurian Alpine people)
- 1st century BC: Roman period (Augusta Taurinorum)
- From XI century: Savoy dynasty
- In 1861: First capital of united Italy and the residence of the king of Italy



*Palatine towers*



*Mole Antonelliana*



*Palazzo Reale*



*Duomo*



*Egyptian museum*



*Borgo medievale*

# Things invented in Turin

Vermouth, nutella, gianduiotti, Lavazza-coffee, tic-tac, grissini, the FIAT and etc.



# Turin football

Juventus F.C. (founded on 1 November 1897)

Torino F.C. (founded on 3 December 1906)

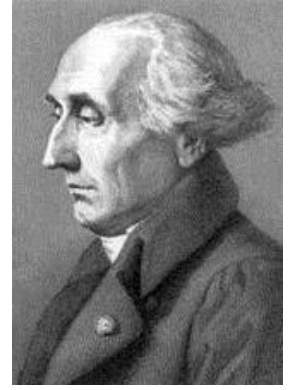


# Some of the Turin famous people

Amedeo Avogadro



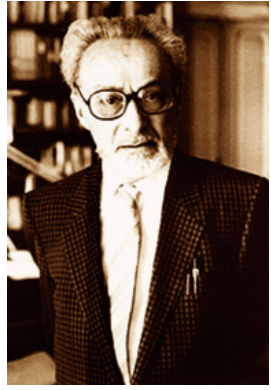
Joseph-Louis Lagrange



Vittorio Emanuele II



Primo Levi



Salvador Luria



Rita Levi-Montalcini



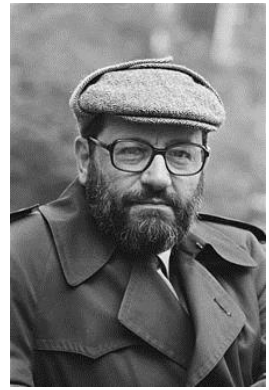
Tullio Regge



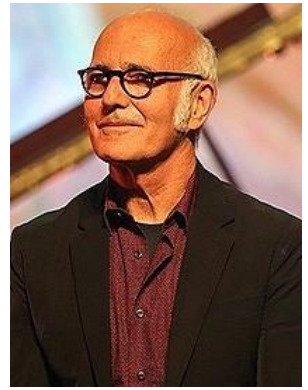
Ugo Fano



Umberto Eco



Ludovico Einaudi



Carla Bruni





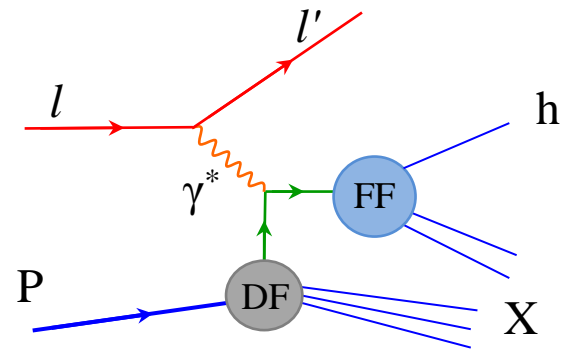


# SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \text{All measured by COMPASS}$$

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

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



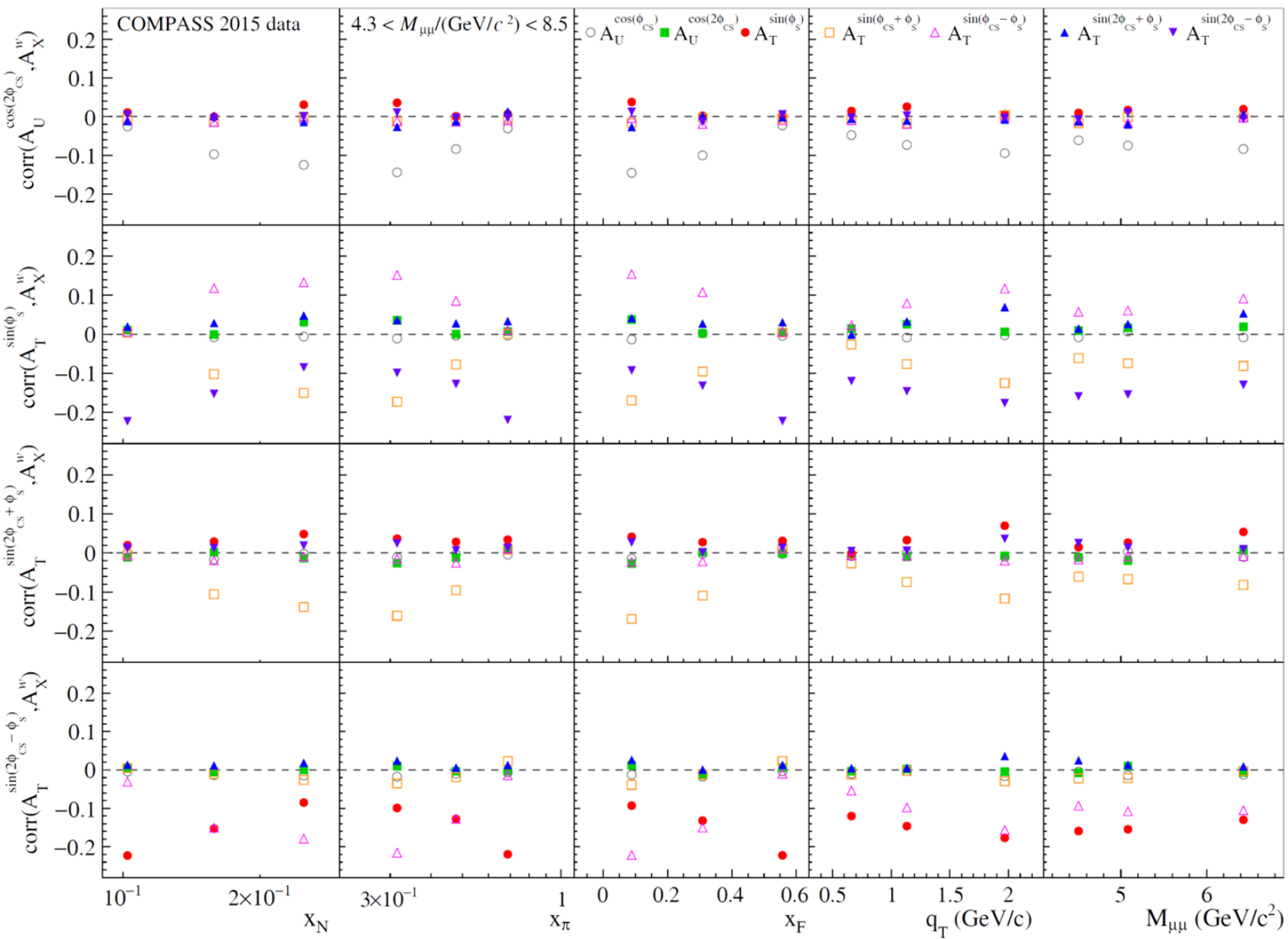
Quark \ Nucleon	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

spin of the nucleon    
 spin of the quark    
  $k_T$





# Correlation coefficients



Maximum correlations are about  $\sim 0.2$



# Sivers asymmetry in Drell-Yan: sign change

DGLAP (2016)

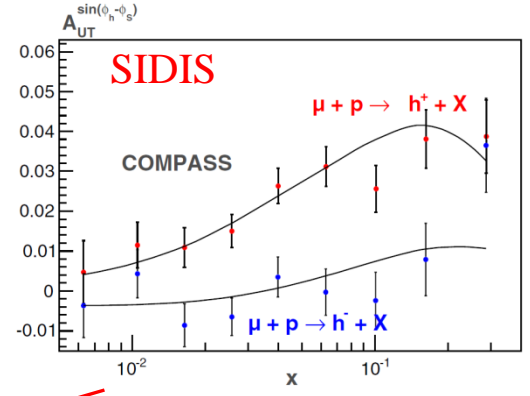
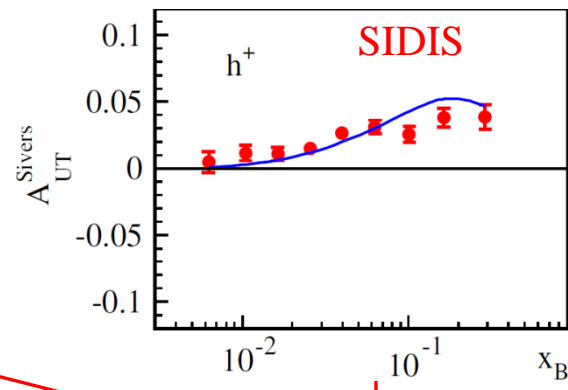
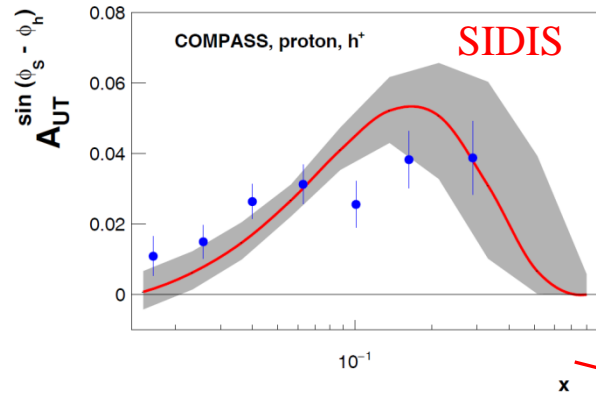
M. Anselmino et al., JHEP 1704 (2017) 046

TMD-1 (2014)

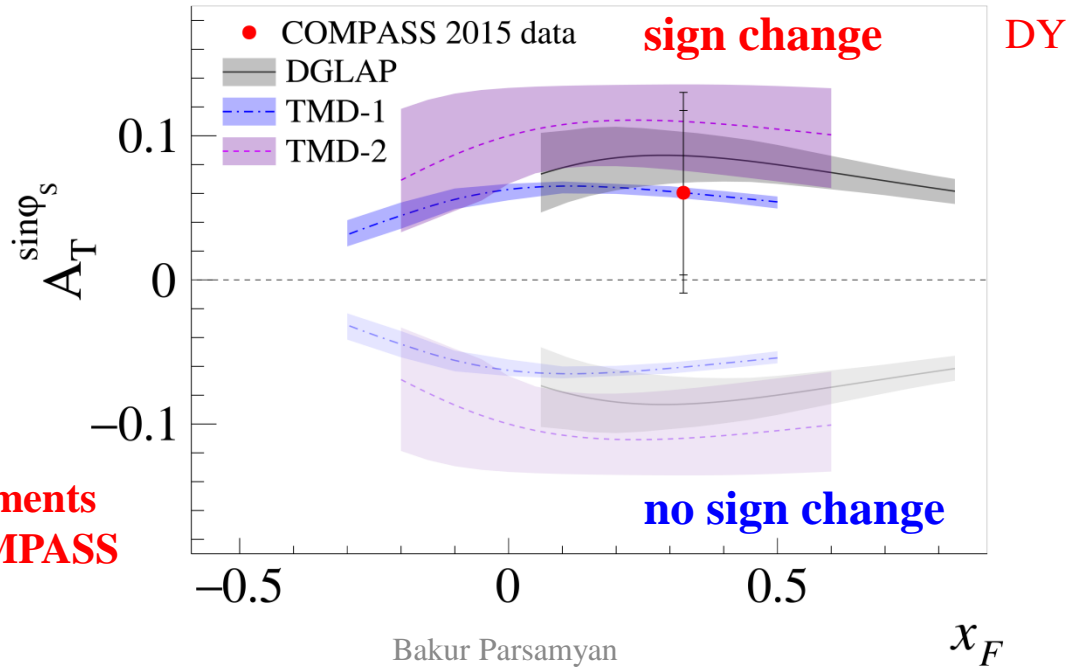
M. G. Echevarria et al. PRD89,074013

TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012



COMPASS  
PRL 119, 112002 (2017)



In 2018 – 2<sup>nd</sup> round of polarized DY measurements was performed at COMPASS