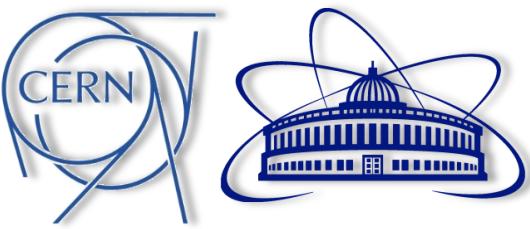




# Recent SIDIS and Drell-Yan results from the COMPASS experiment



**BAKUR PARSAMYAN**

CERN, JINR,  
University of Turin and INFN

*on behalf of the COMPASS Collaboration*

UNIVERSITÀ  
DEGLI STUDI  
DI TORINO  
  
ALMA UNIVERSITAS  
TAURINENSIS



International Workshop on Spin  
Physics Experiments at NICA  
  
(SPIN-Praha-2018)  
  
Charles University, Prague,  
Czech Republic  
  
July 9 – 13, 2018

# COMPASS collaboration

## Common Muon and Proton Apparatus for Structure and Spectroscopy



24 institutions from 13 countries  
– nearly 250 physicists

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (21 years)
- Taking data since 2002

### Wide physics program

#### COMPASS-I

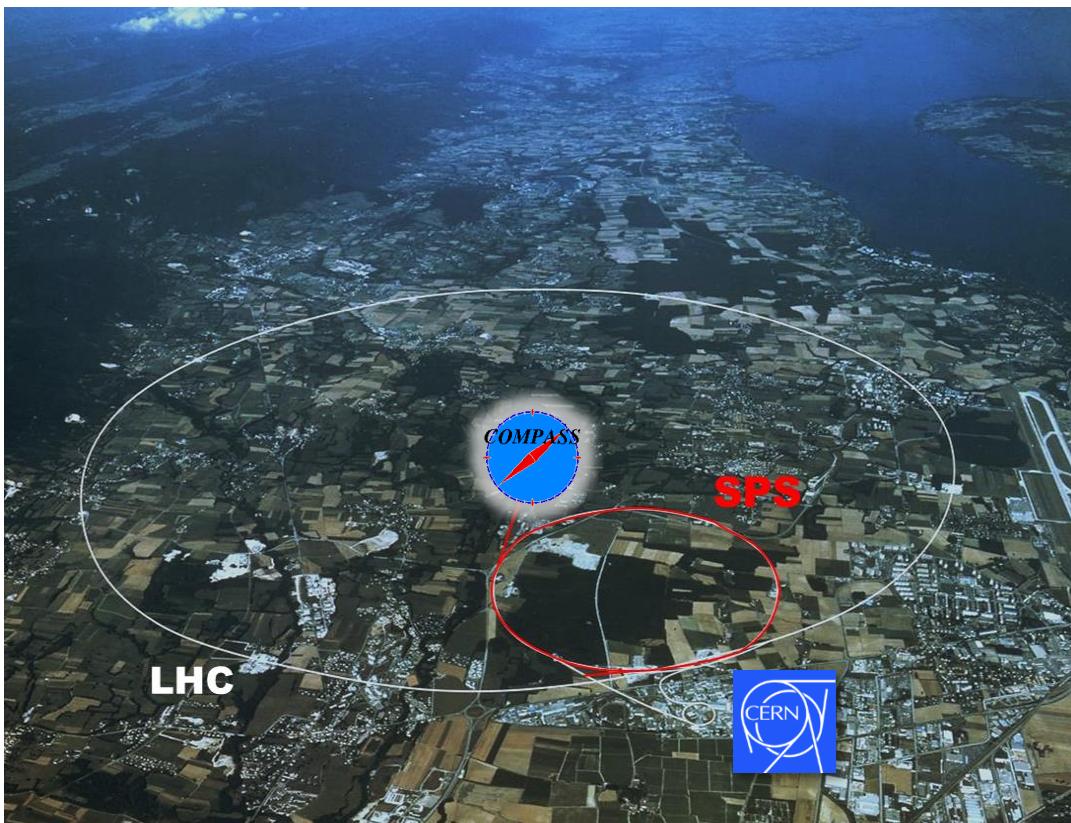
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

#### COMPASS-II

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

#### Many “beyond 2021” ideas:

Proton-radius, Drell-Yan,  
spectroscopy... see Oleg's talk



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

# SIDIS x-section

A.Kotzinian, Nucl. Phys. B441, 234 (1995).

Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

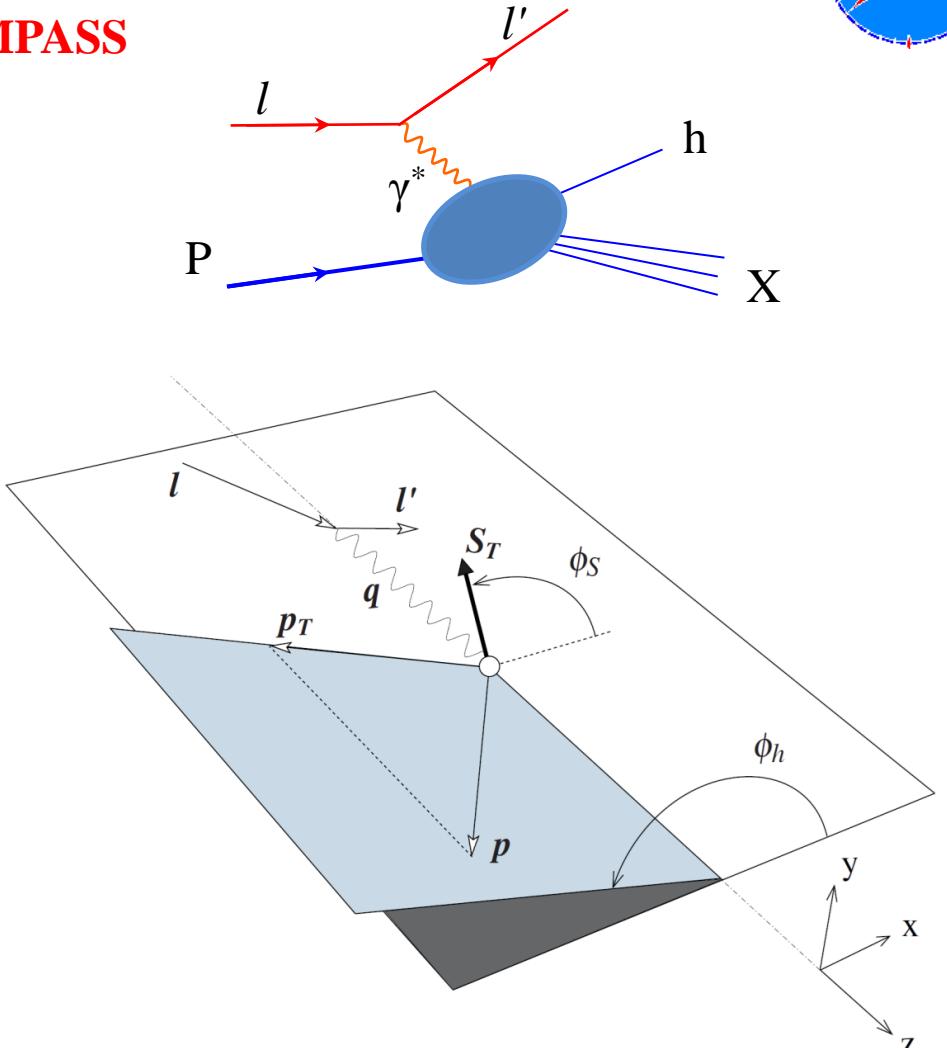


$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} =$$

All measured by COMPASS

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

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



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

# SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} =$$

All measured by COMPASS

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

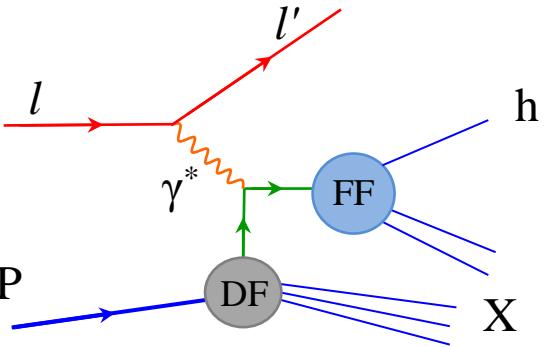
$$\left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right.$$

$$+ S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right]$$

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

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

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



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

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

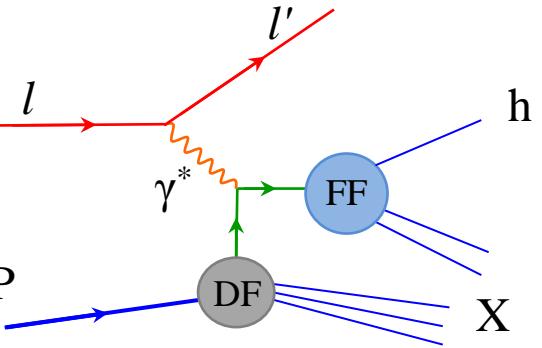
# SIDIS x-section and TMDs at twist-2

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All measured by COMPASS

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



Quark	U	L	T
Nucleon	number density		
U			
L			
T			

spin of the nucleon      spin of the quark       $k_T$

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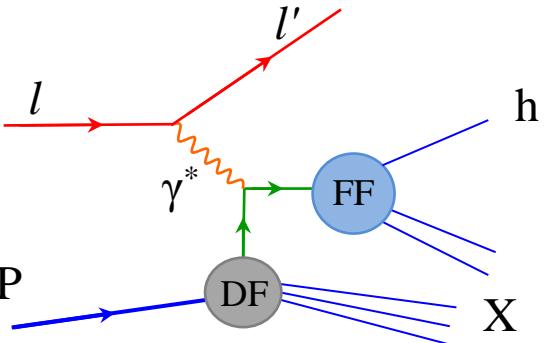
$$1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h$$

$$+ S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right]$$

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

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

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



$$A_{UU}^{\cos\phi_h} \stackrel{WW}{\propto} Q^{-1} (f_1^q \otimes D_{1q}^h + h_1^{\perp q} \otimes H_{1q}^{\perp h} \dots)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{UL}^{\sin\phi_h} \stackrel{WW}{\propto} Q^{-1} (h_{1L}^{\perp q} \otimes H_{1q}^{\perp h} + \dots)$$

$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h$$

$$A_{LL}^{\cos\phi_h} \stackrel{WW}{\propto} Q^{-1} (g_{1L}^q \otimes D_{1q}^h + \dots)$$

Twist-2

Twist-3

WW = Wandzura-Wilczek-type approximation ``

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

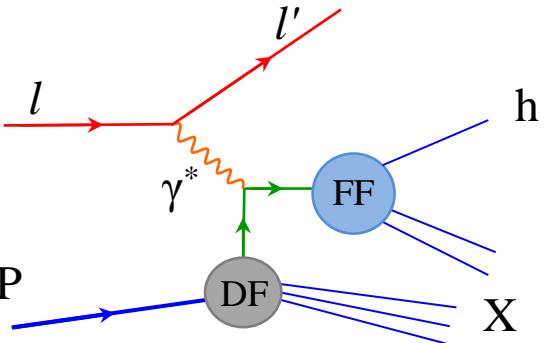
$$1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h$$

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

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

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

$$A_{UT}^{\sin(\phi_s)} \stackrel{WW}{\propto} Q^{-1} (h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots)$$

$$A_{UT}^{\sin(2\phi_h - \phi_s)} \stackrel{WW}{\propto} Q^{-1} (h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots)$$

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{LT}^{\cos(\phi_s)} \stackrel{WW}{\propto} Q^{-1} (g_{1T}^q \otimes D_{1q}^h + \dots)$$

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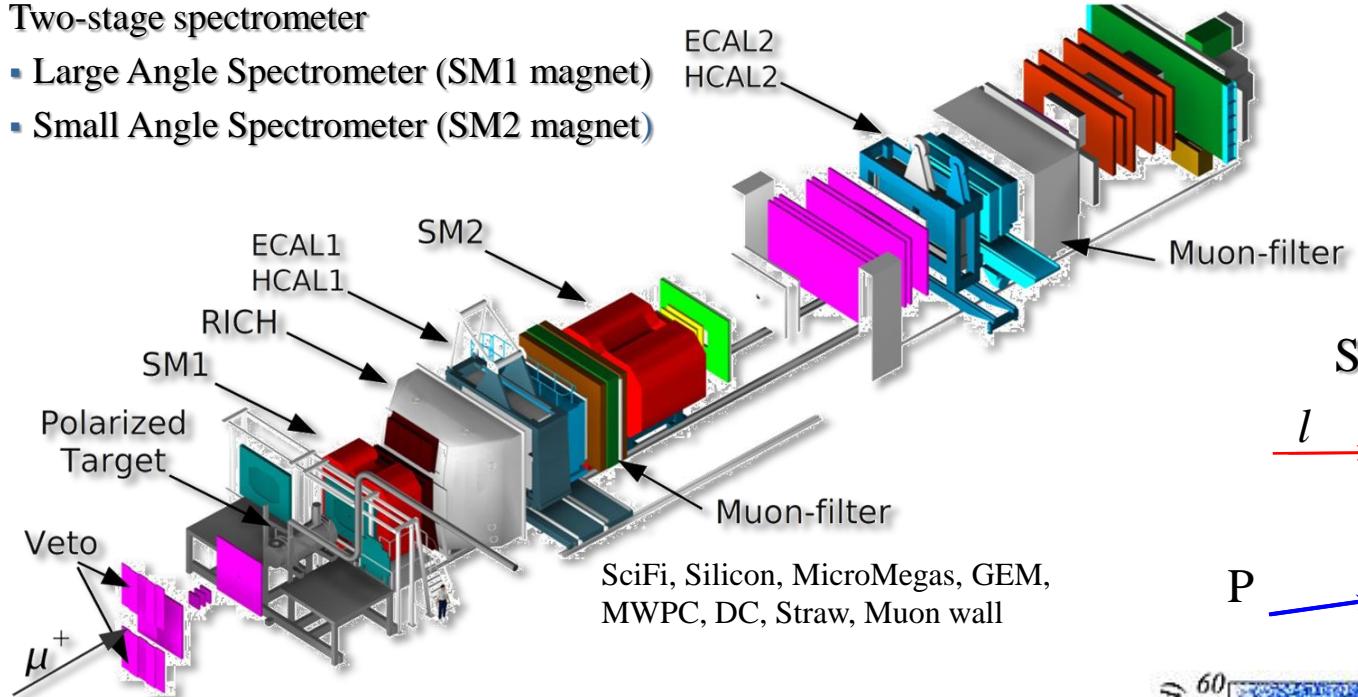
Twist-2

Twist-3

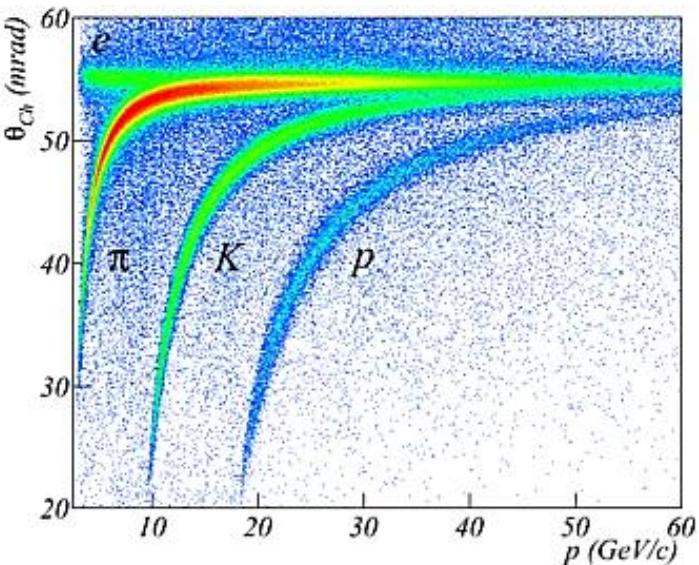
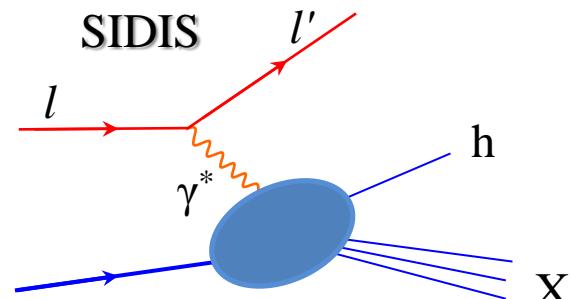
# COMPASS experimental setup: Phase I (muon program)

## Two-stage spectrometer

- 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



## Data-taking years: 2002-2011

Longitudinally polarized (80%)  $\mu^+$  beam:

Energy: 160/200 GeV/c, Intensity:  $2 \cdot 10^8 \mu^+$ /spill (4.8s).

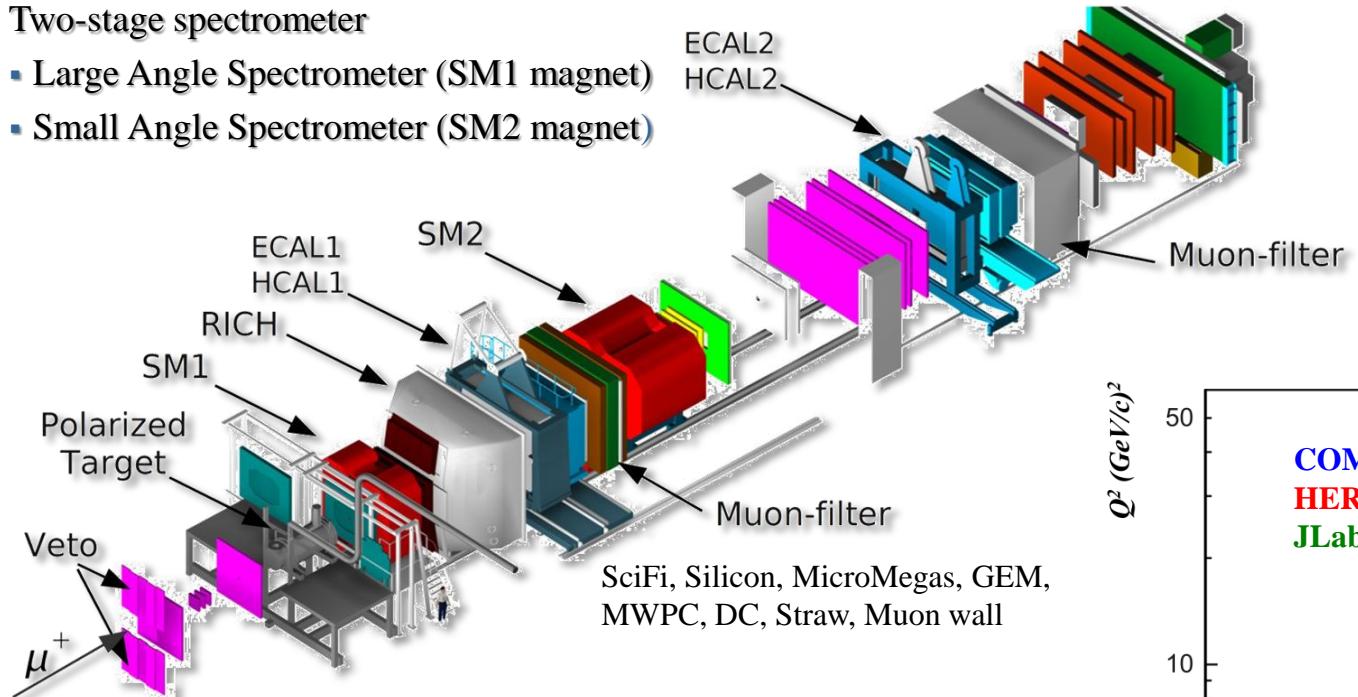
Target: Solid state ( ${}^6\text{LiD}$  or  $\text{NH}_3$ )

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

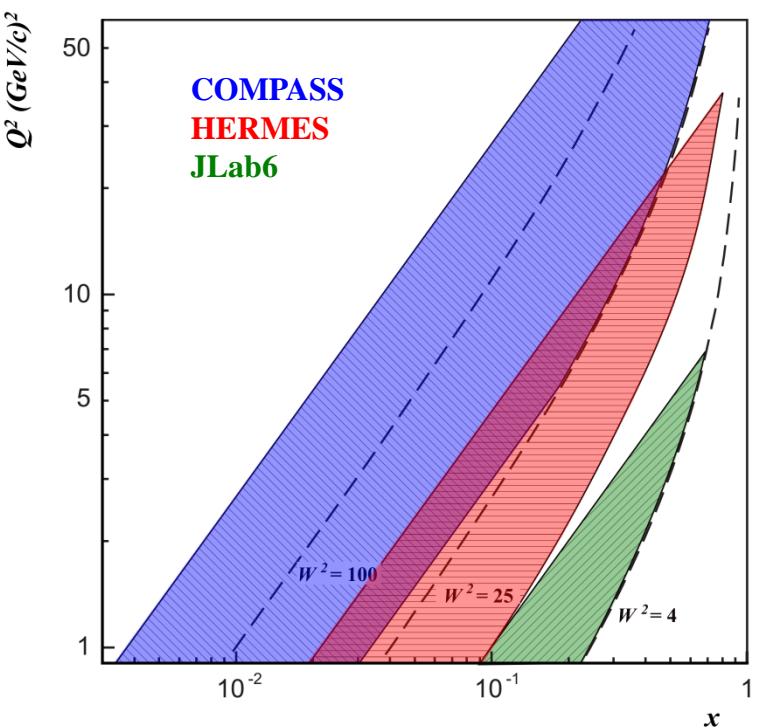
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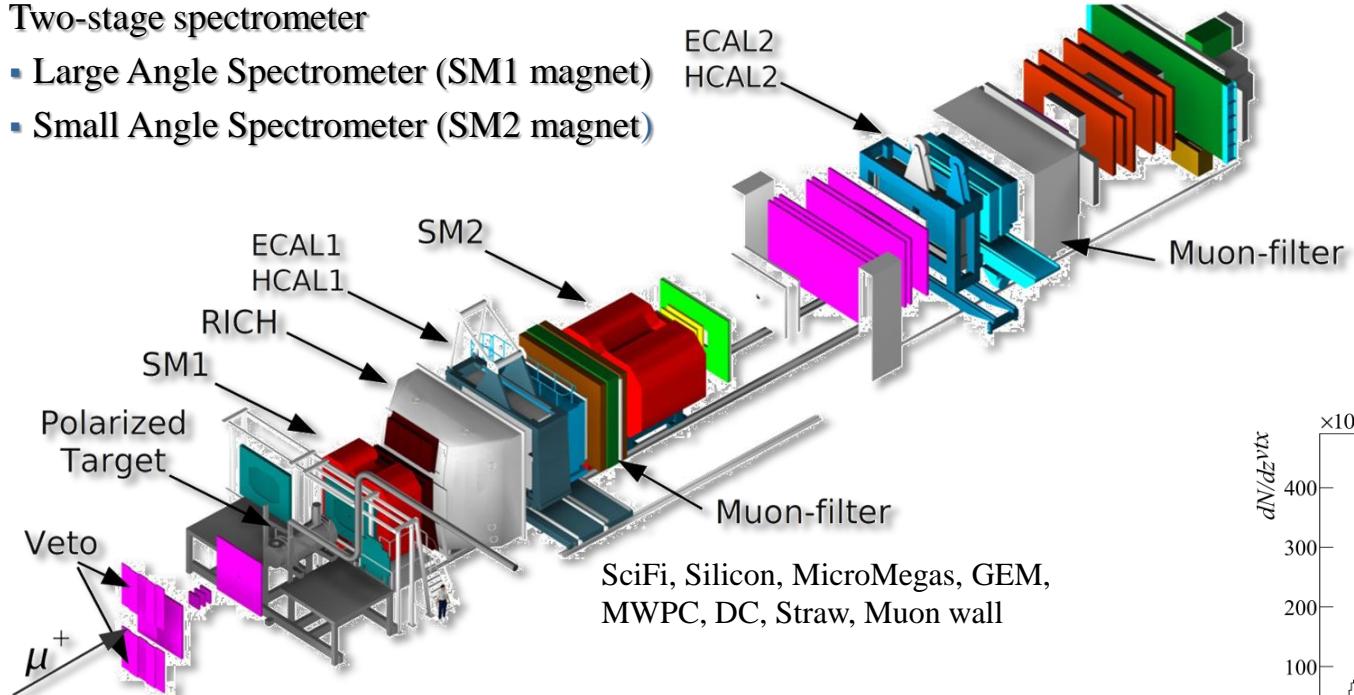
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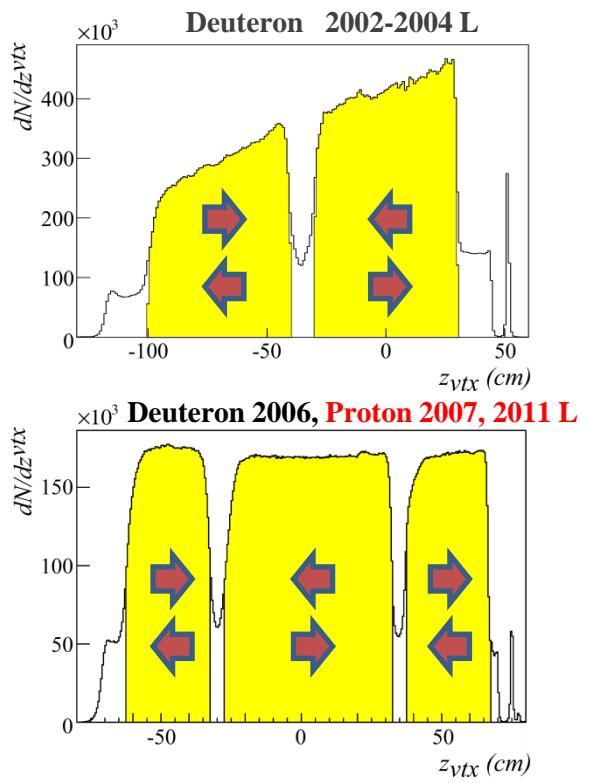
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- $\text{NH}_3$  3-cell configuration. Polarization (L & T)  $\sim 80\%$ , f  $\sim 0.14$
- Data is collected simultaneously with both target spin orientations.  
Periodic polarization reversal to minimize systematic effects



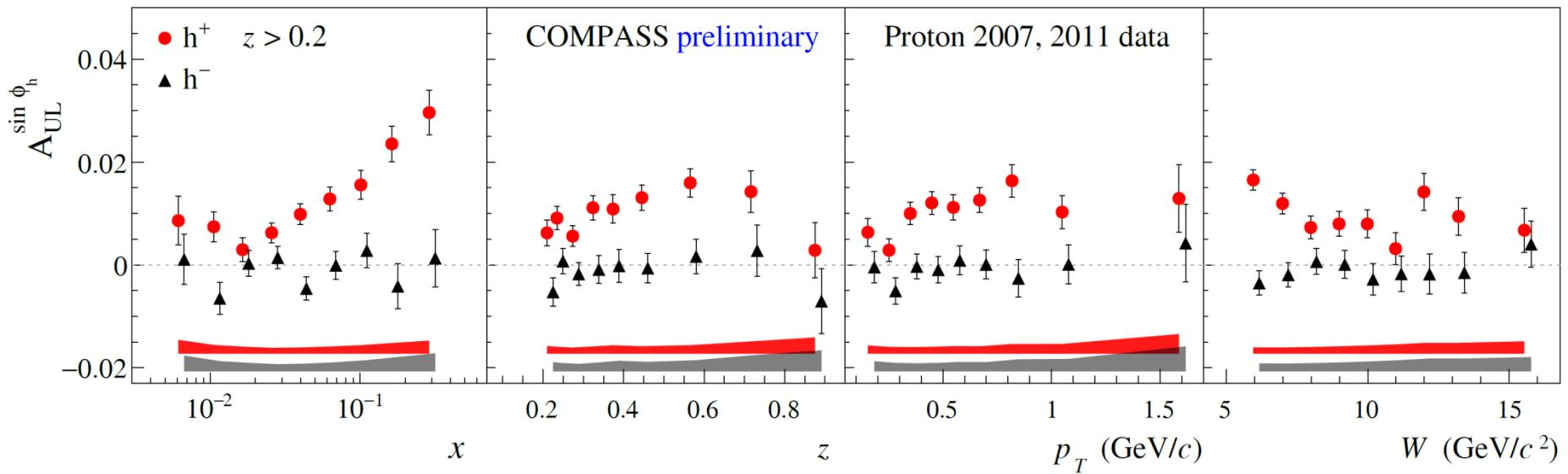
- Longitudinal target spin dependent azimuthal asymmetries

# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \dots \right\}$$

$$F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

B.Parsamyan (for COMPASS) [arXiv:1801.01488 \[hep-ex\]](https://arxiv.org/abs/1801.01488) (DIS-2017)

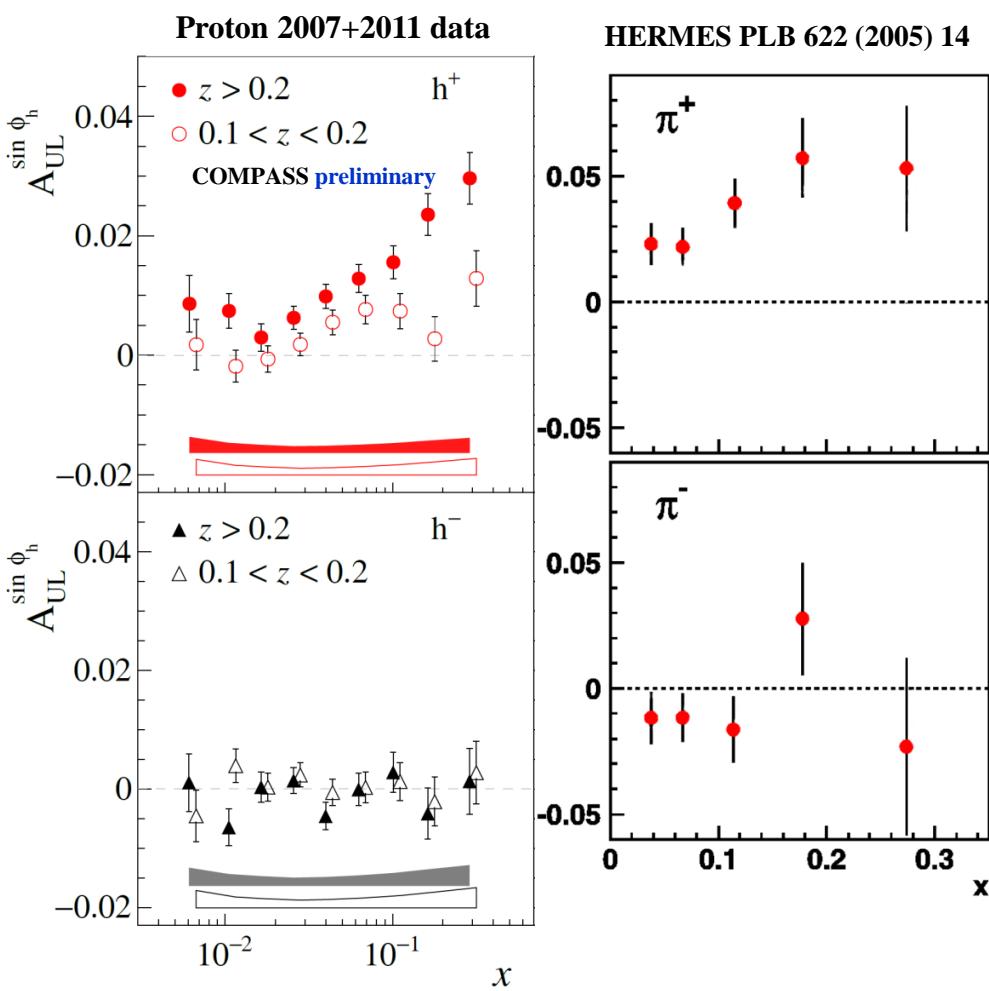


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+, h^-$  compatible with zero**

# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \dots \right\}$$

$$F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

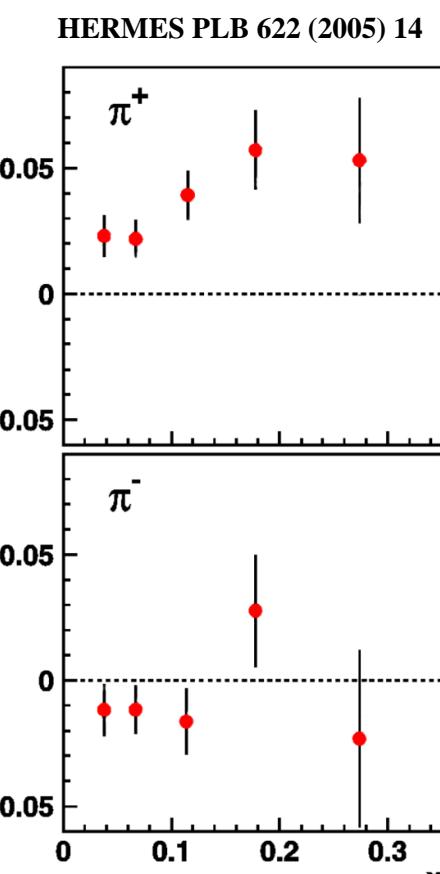
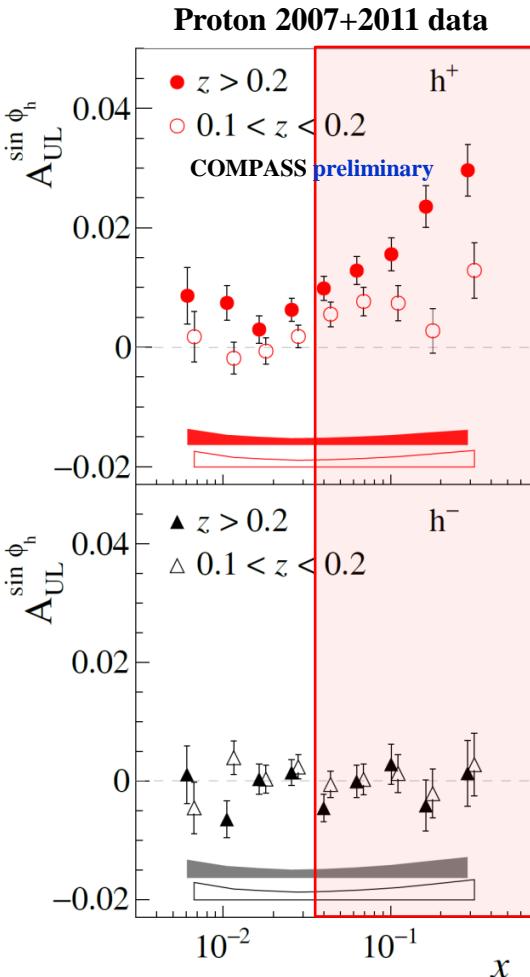
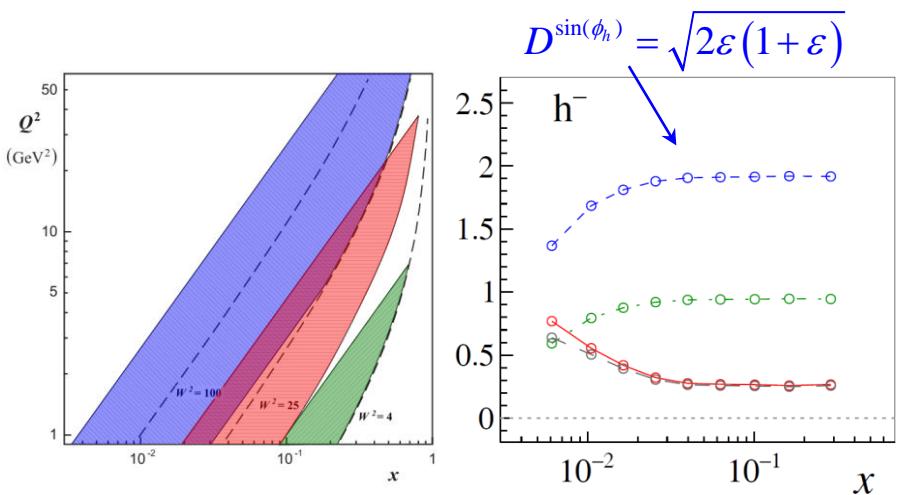


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+, h^-$  compatible with zero, clear  $z$ -dependence**

# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \dots \right\}$$

$$F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$



- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+$ ,  $h^-$  compatible with zero, clear  $z$ -dependence**

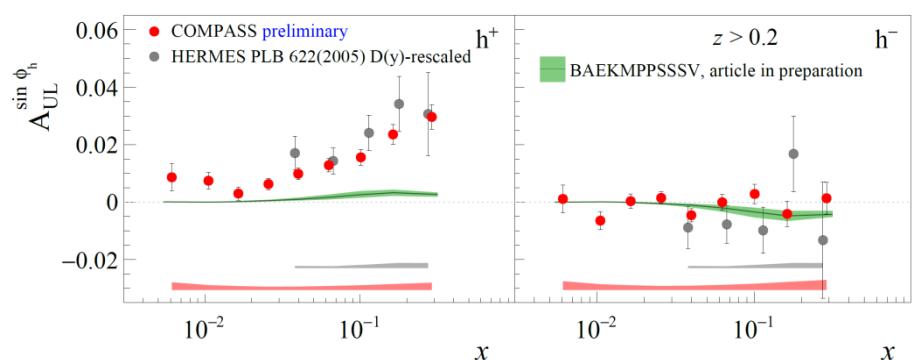
# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \dots \right\}$$

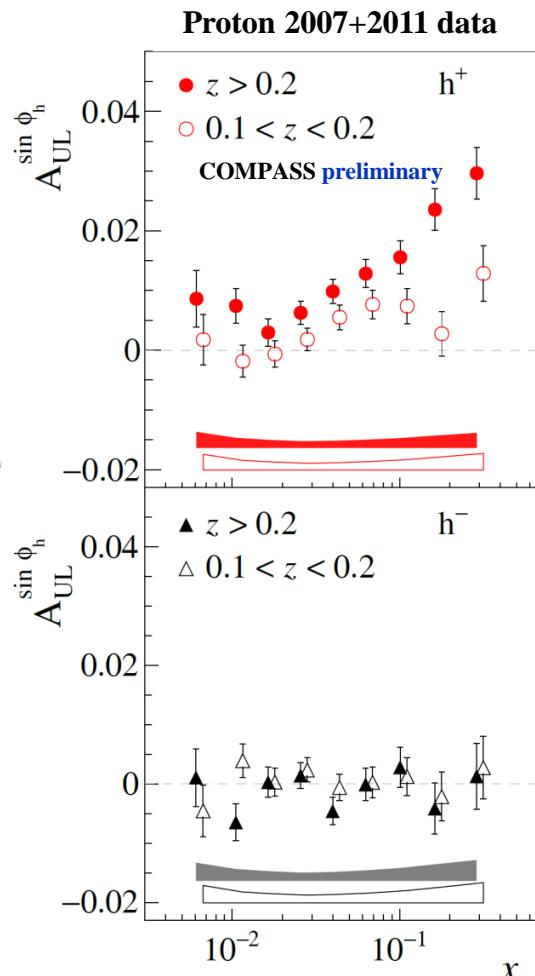
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch,  
B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer,  
W. Vogelsang

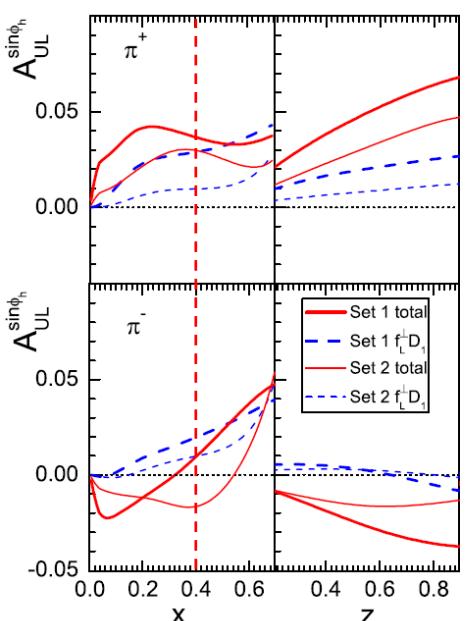
Article in preparation: “SIDIS in Wandzura-Wilczek-type approximation”



- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+$ ,  $h^-$  compatible with zero, clear  $z$ -dependence**



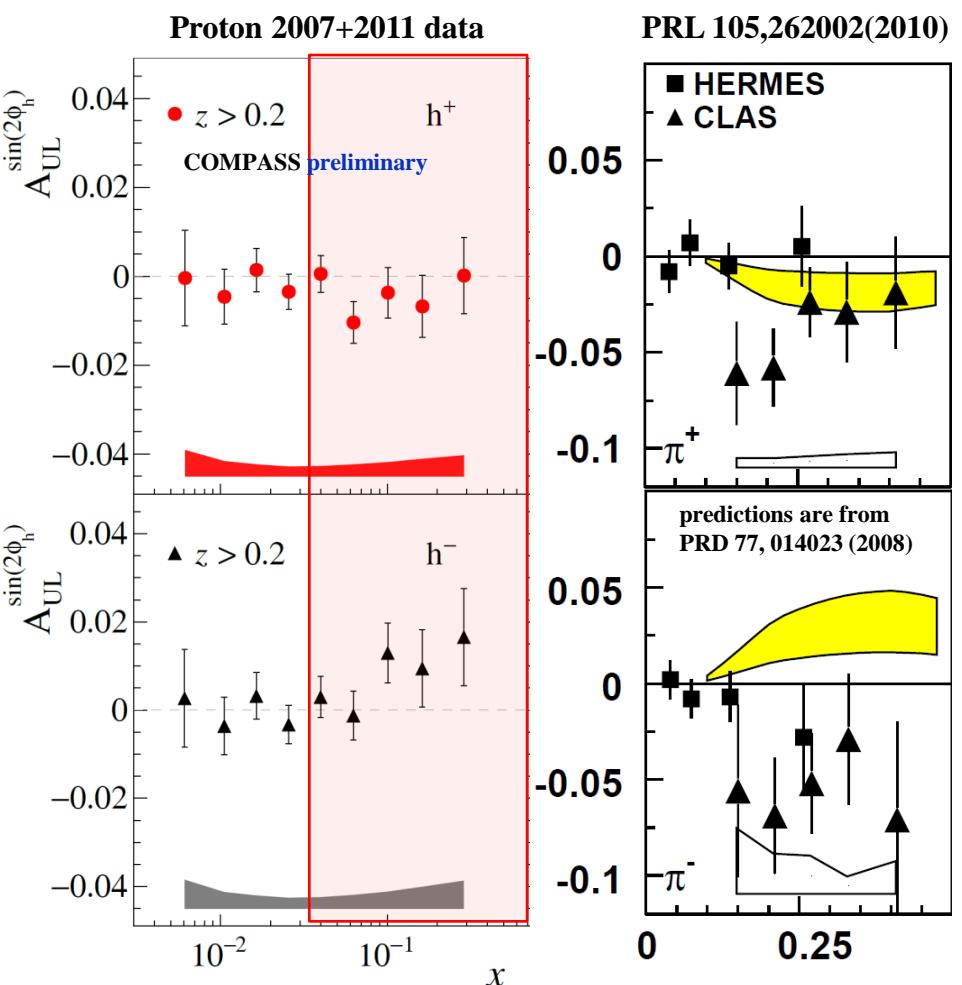
Zhun Lu  
Phys. Rev. D 90, 014037(2014)



# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + \dots \right\}$$

$$F_{UL}^{\sin 2\phi_h} = C \left\{ -\frac{2(\hat{h} \cdot \mathbf{p}_T)(\hat{h} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

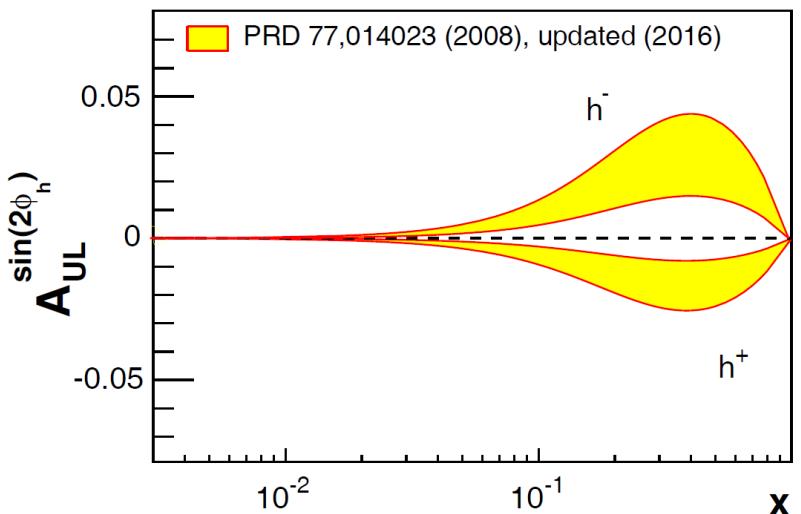


- Only “twist-2” ingredients
- Additional  $p_T$ -suppression
- **Collins-like behavior?**
- **In agreement with model predictions**
- **Discrepancy with HERMES and JLab?**

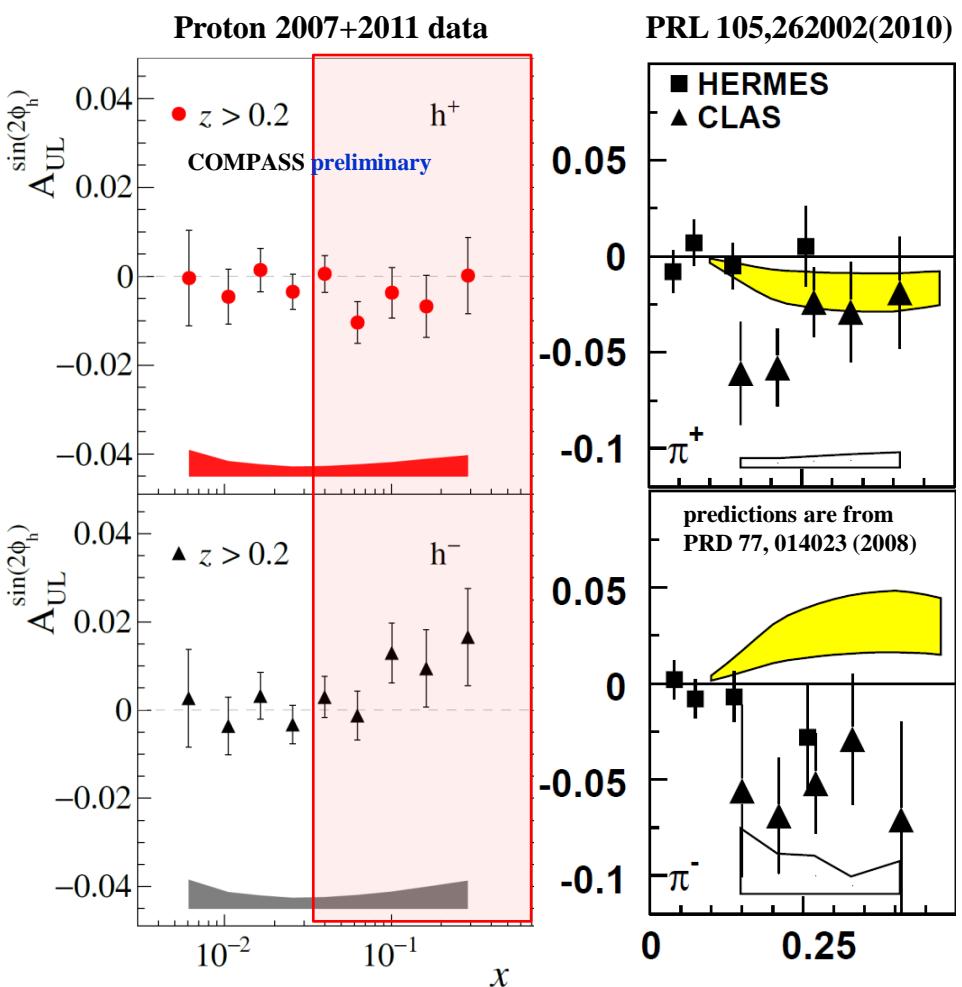
# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + \dots \right\}$$

$$F_{UL}^{\sin 2\phi_h} = C \left\{ -\frac{2(\hat{h} \cdot \mathbf{p}_T)(\hat{h} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$



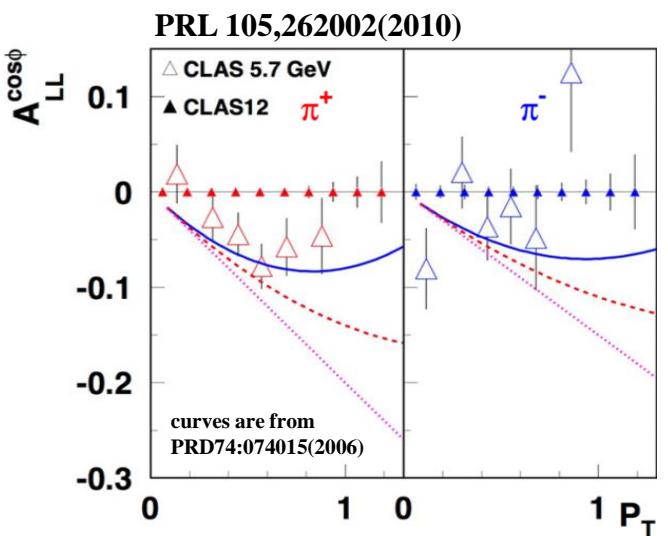
- Only “twist-2” ingredients
- Additional  $p_T$ -suppression
- **Collins-like behavior?**
- **In agreement with model predictions**
- **Discrepancy with HERMES and JLab?**



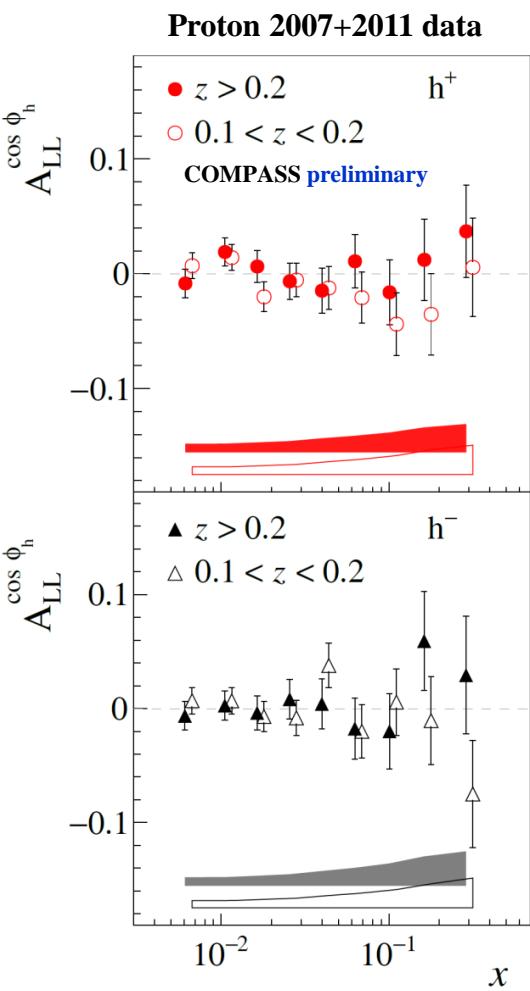
# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \dots \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



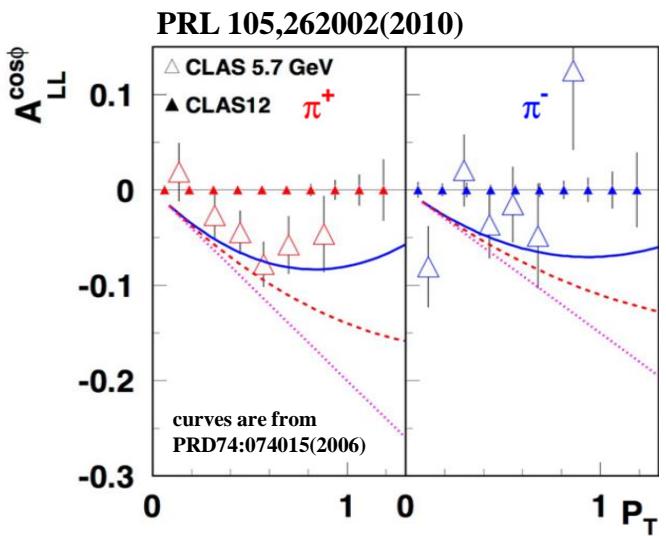
- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab



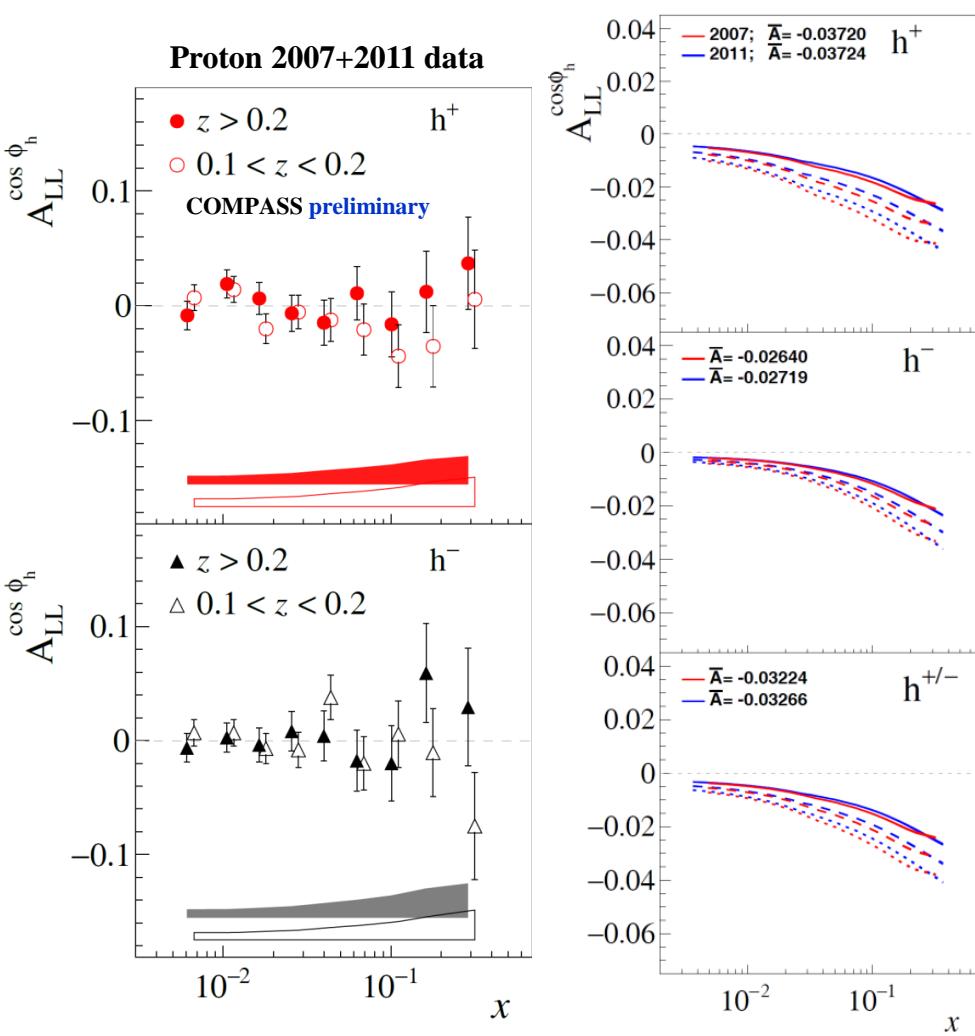
# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \dots \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab
- **Small and compatible with zero, in agreement with model predictions**



# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

$$+ S_L \left[ \begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \end{array} \right] \left. \right\}$$

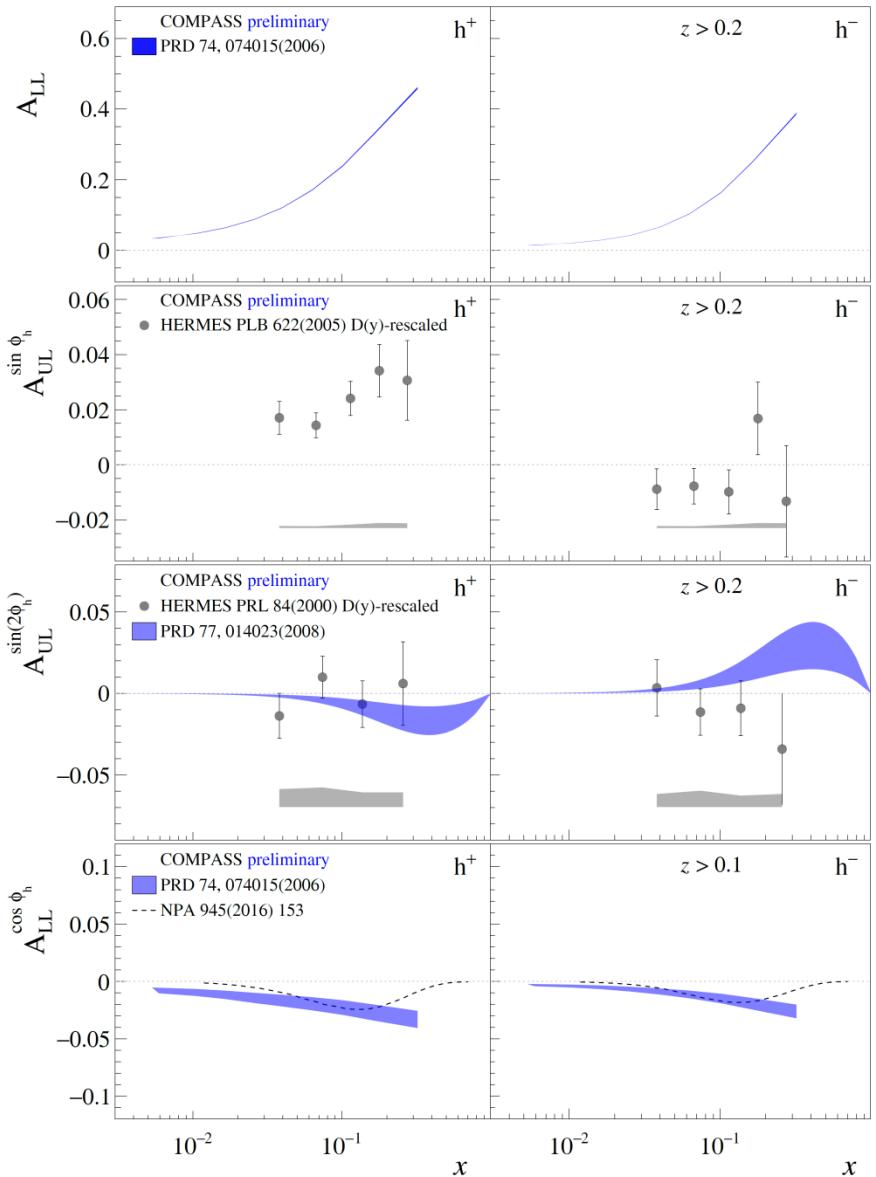
$$+ S_L \lambda \left[ \begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \end{array} \right]$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C} \left\{ -\frac{2(\hat{\mathbf{h}} \cdot \mathbf{p}_T)(\hat{\mathbf{h}} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

$$F_{LL}^1 = \mathcal{C} \left\{ g_{1L}^q D_{1q}^h \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



# SIDIS: target longitudinal spin dependent asymmetries

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

$$\left. + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \right] \right. \\ \left. + S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \right\}$$

**COMPASS collected large amount of L-SIDIS data  
Unprecedented precision!**

$$A_{UL}^{\sin\phi_h}$$

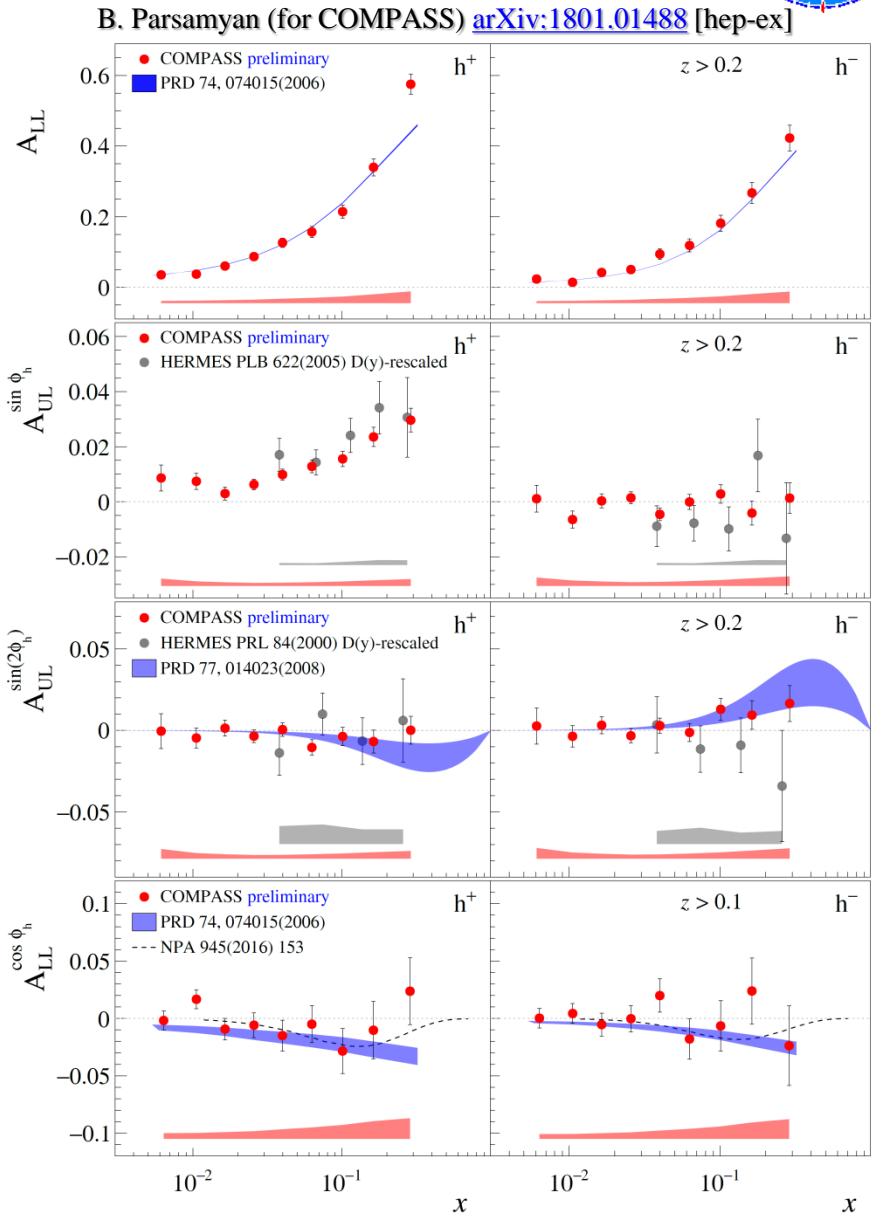
- Q-suppression, Various different “twist” ingredients
- Sizable TSA-mixing
- **Significant  $h^+$  asymmetry, clear  $z$ -dependence**
- **$h^-$  compatible with zero**

$$A_{UL}^{\sin 2\phi_h}$$

- Only “twist-2” ingredients
- Additional  $p_T$ -suppression
- **Compatible with zero, in agreement with models**
- **Collins-like behavior?**

$$A_{LL}^{\cos\phi_h}$$

- Q-suppression, Various different “twist” ingredients
- **Compatible with zero, in agreement with models**





- Transverse target spin dependent azimuthal asymmetries

# SIDIS TSAs (Collins)

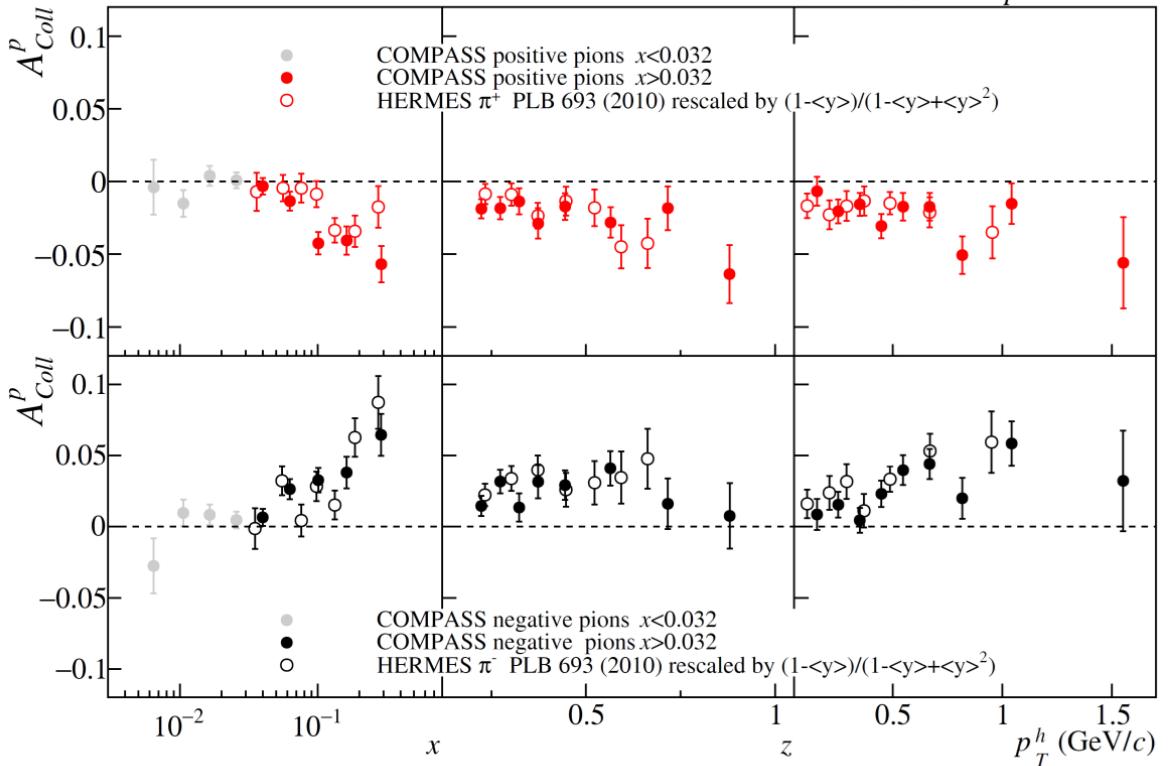
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

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

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data



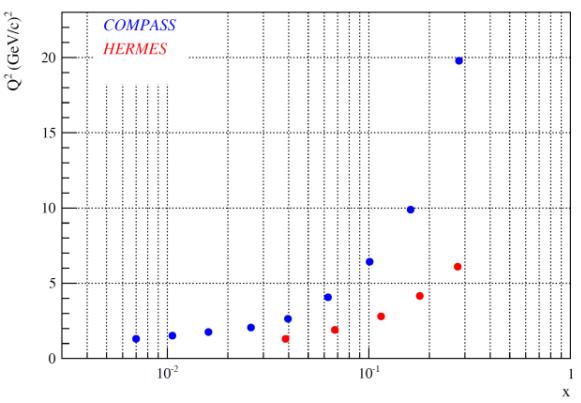
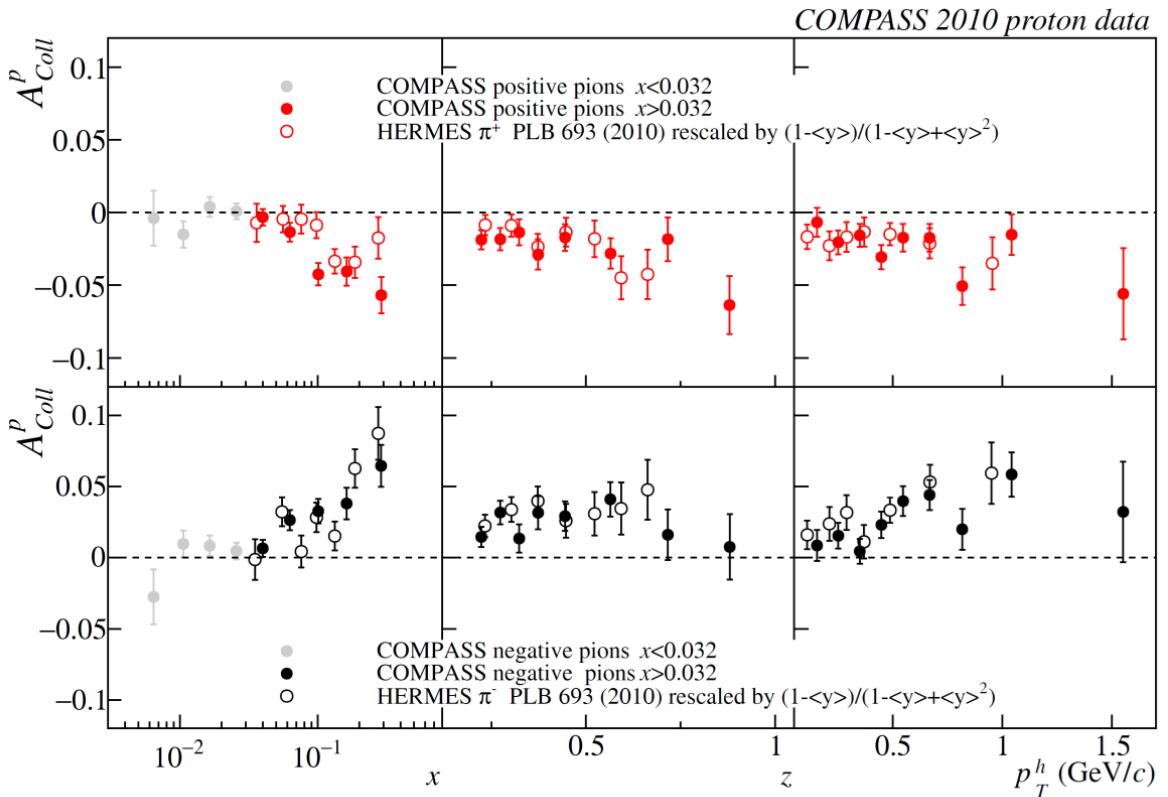
# SIDIS TSAs (Collins)

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

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

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES  
( $Q^2$  is different by a factor of  $\sim 2$ -3)
- **No  $Q^2$ -evolution? Intriguing result!**

COMPASS PLB 744 (2015) 250



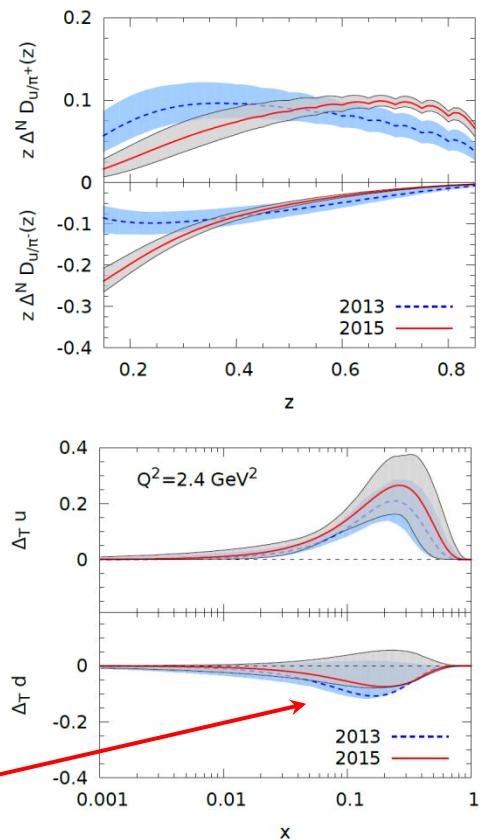
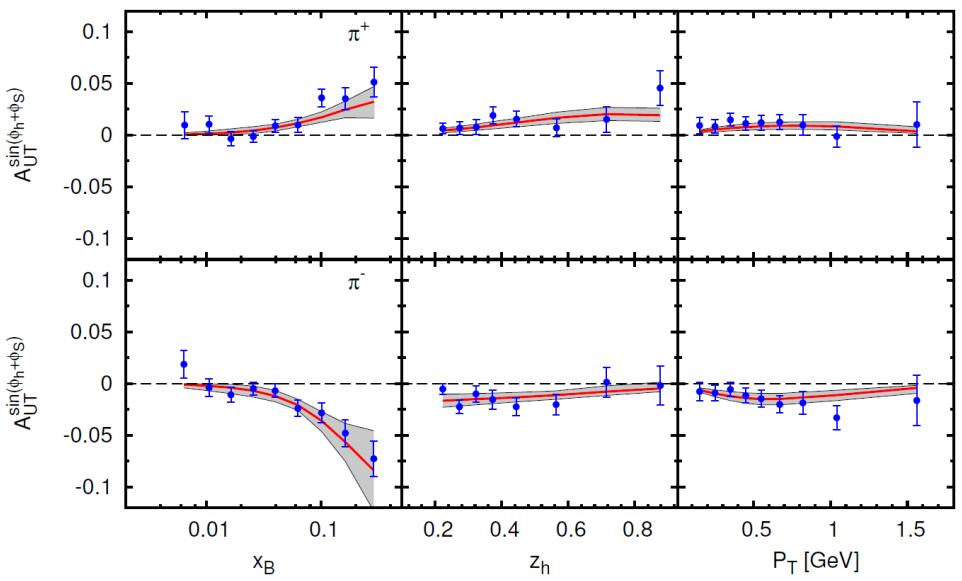
# SIDIS TSAs (Collins)

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

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

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

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



## COMPASS-II (2021)

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

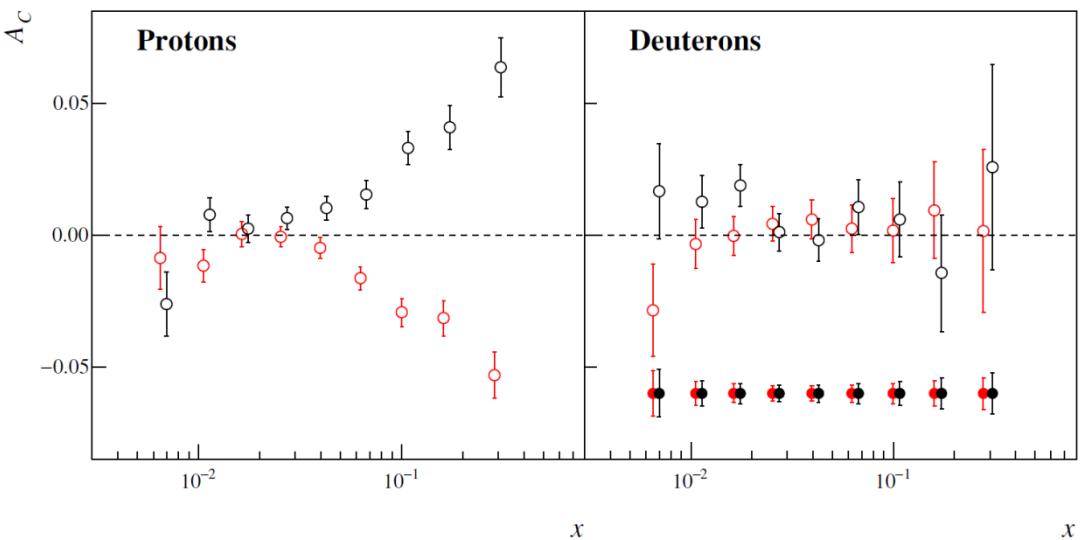
# SIDIS TSAs (Collins)

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

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

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES  
( $Q^2$  is different by a factor of  $\sim 2$ -3)
- No  $Q^2$ -evolution? Intriguing result!**
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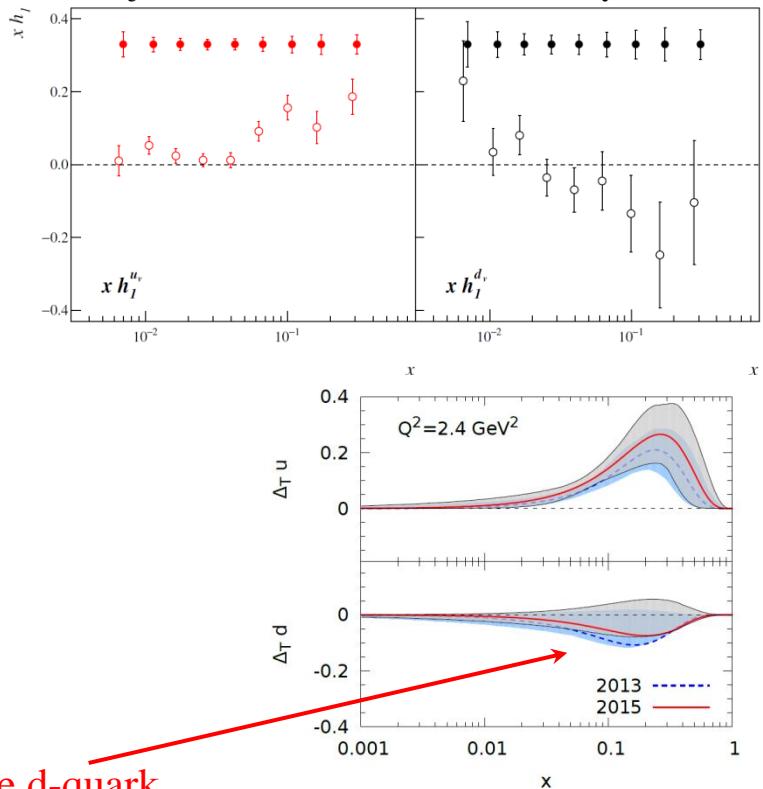
Addendum to the COMPASS-II Proposal  
Projected uncertainties for Collins asymmetry



## COMPASS-II (2021 run – approved!)

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

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

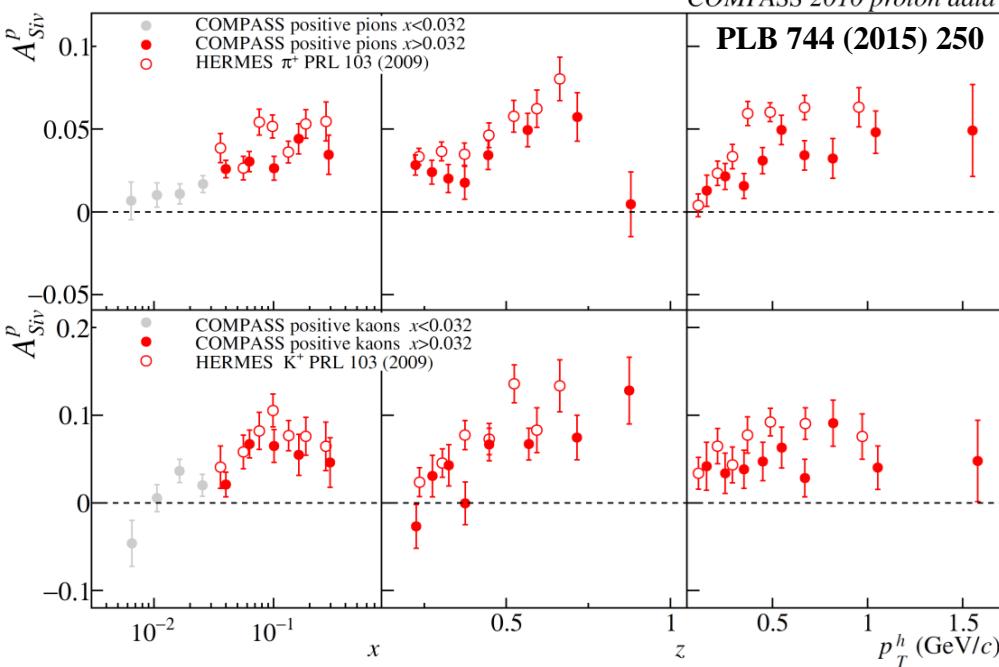


# SIDIS TSAs (Sivers)

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

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

- 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  
( $Q^2$  is different by a factor of  $\sim 2-3$ )
- **$Q^2$ -evolution? Intriguing result!**

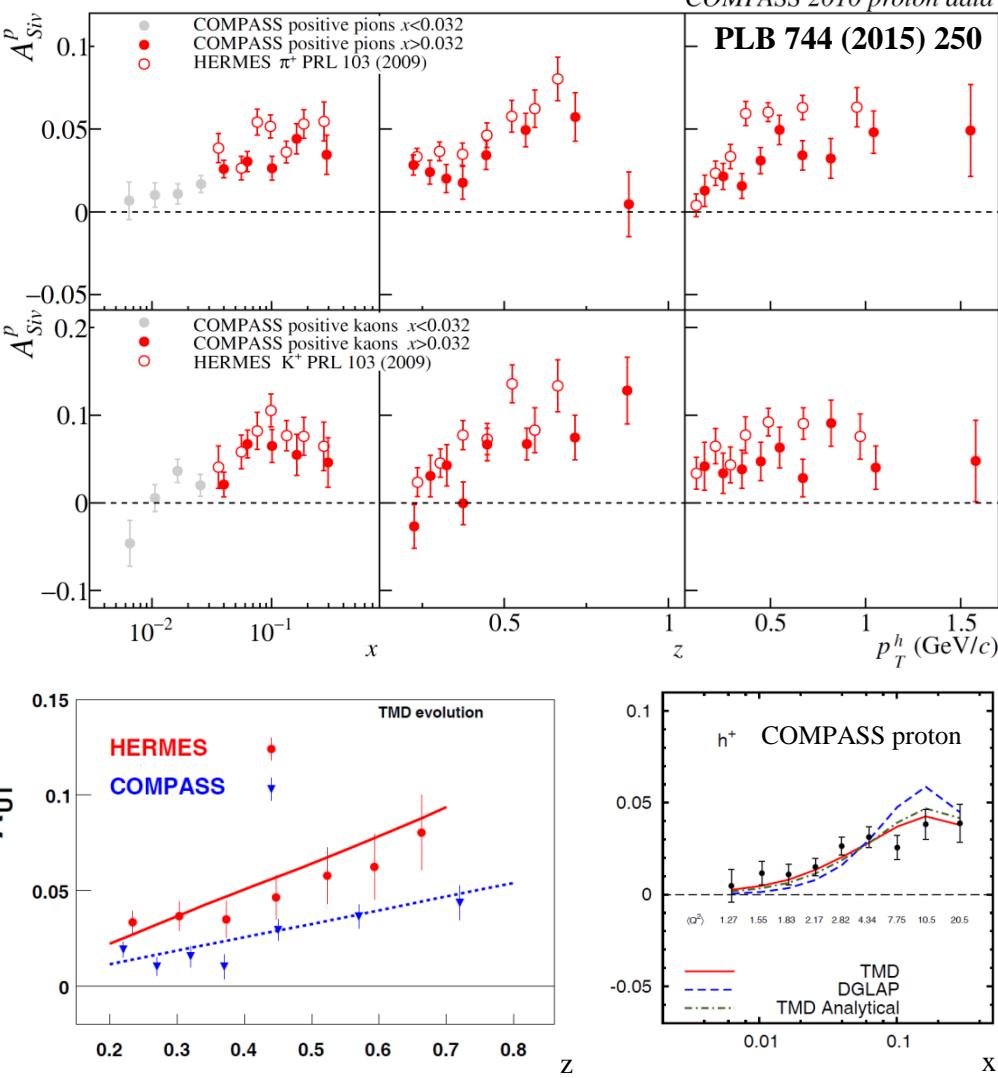


# SIDIS TSAs (Sivers)

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

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

- 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  
( $Q^2$  is different by a factor of  $\sim 2$ - $3$ )
- $Q^2$ -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**



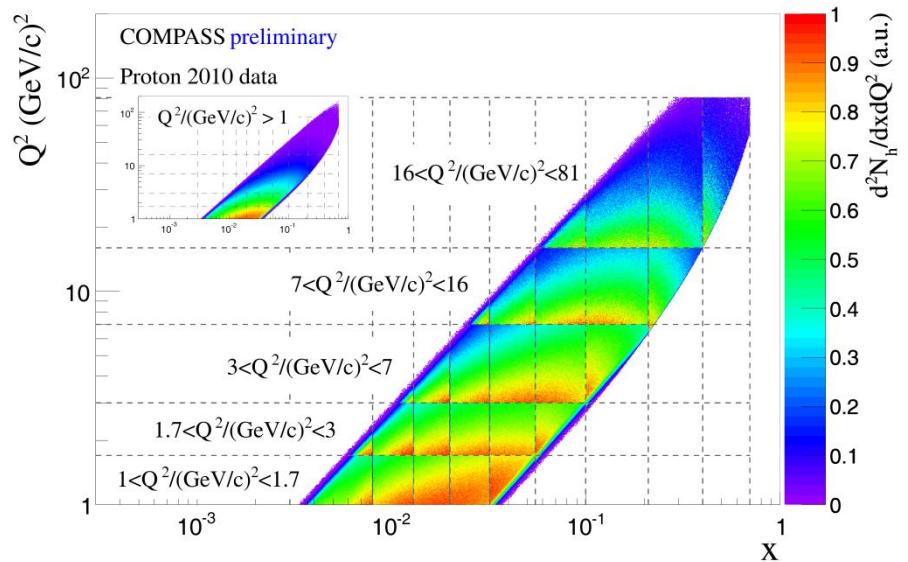
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**  
 M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

# Multi-D TSA analysis

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

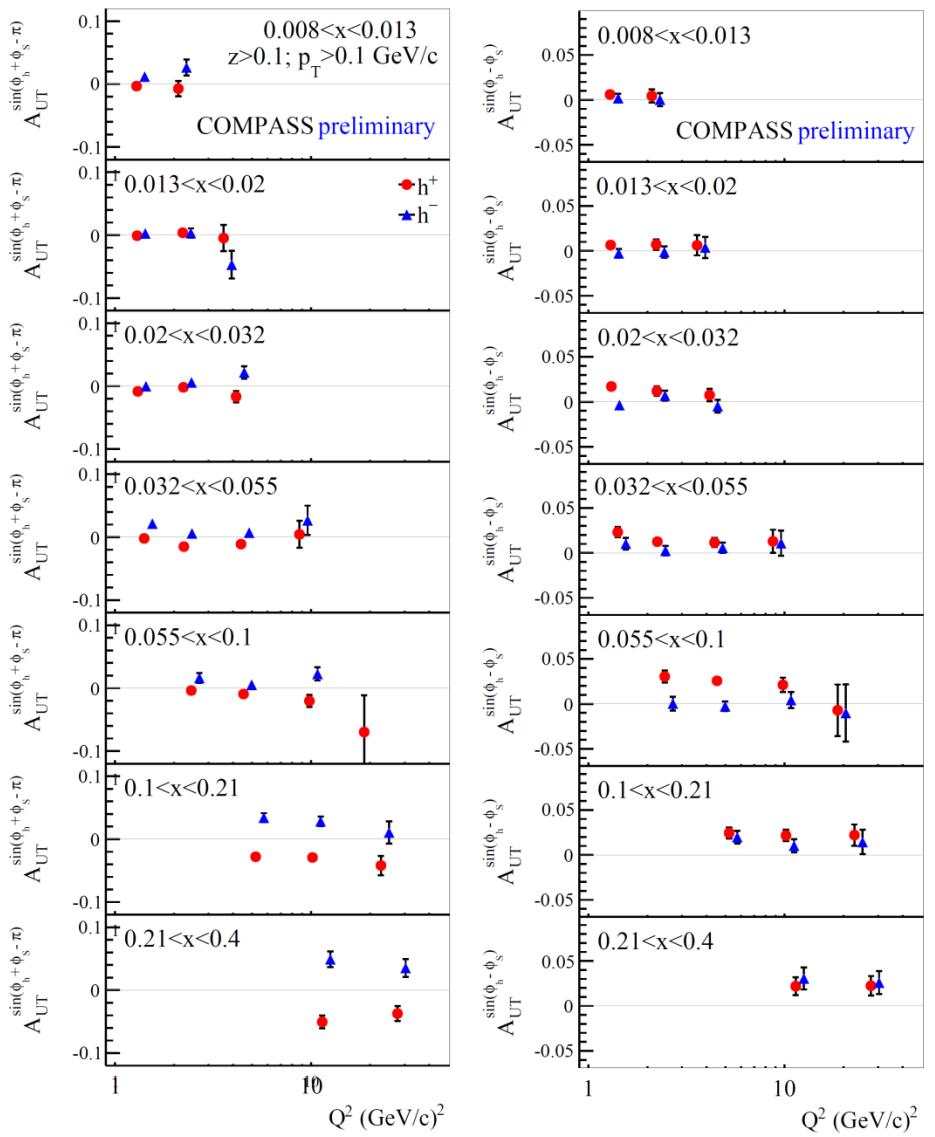
$$F_{UT,T}^{\sin(\phi_h - \phi_s)} = C \left[ -\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_s)} = 0$$

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



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

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



“ID”



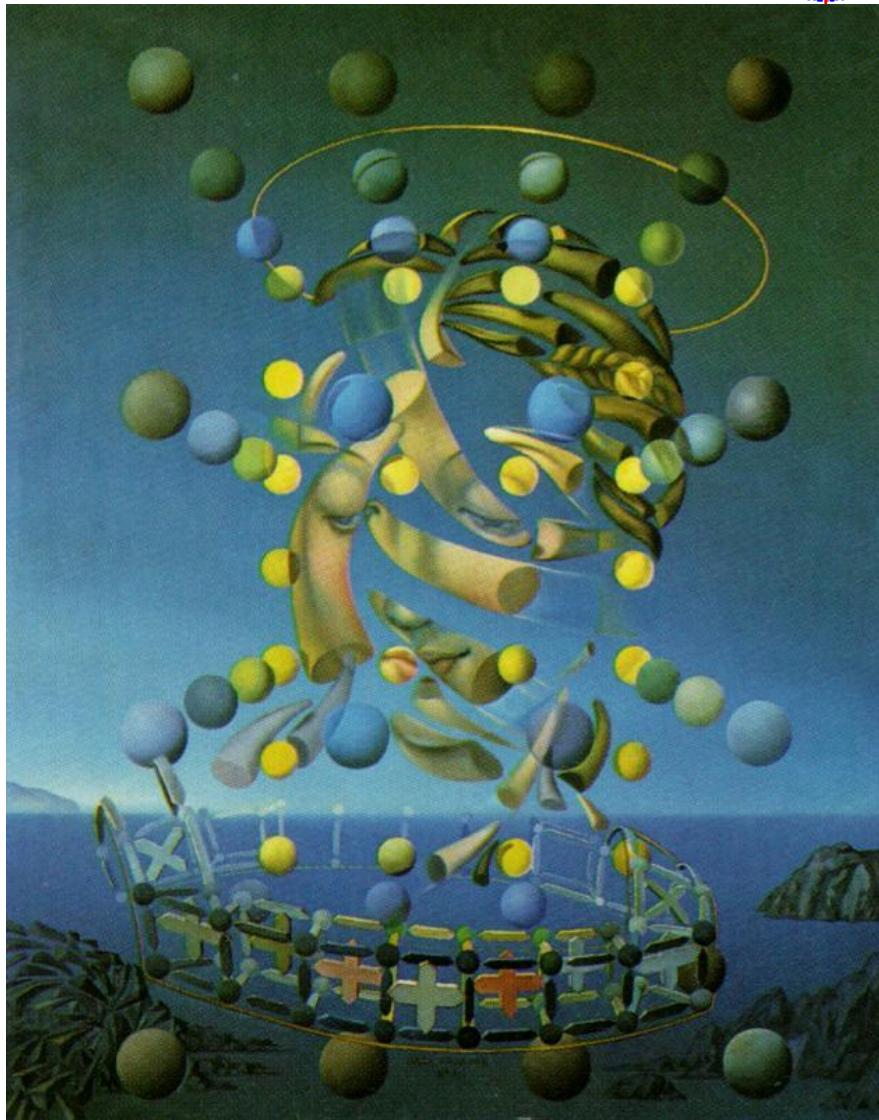
*Salvador Dalí “Maximum Speed of Raphael's Madonna”*

“Nature”



Raphael “Madonna del Prato”

“ID”



Salvador Dali “Maximum Speed of Raphael's Madonna”

“Nature”



Raphael “Madonna del Prato”

“multi-D” with available statistics



Raphael “Madonna del Prato” (poor resolution)

# SIDIS: target transverse spin dependent asymmetries

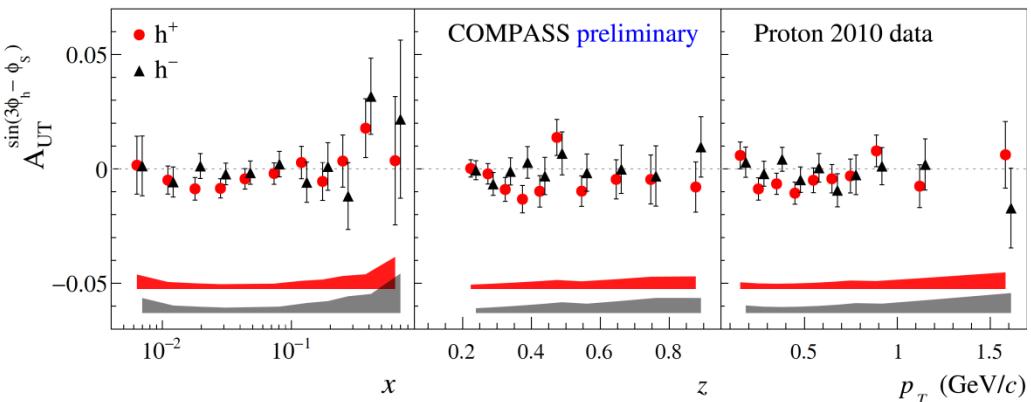
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

## 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**

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



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

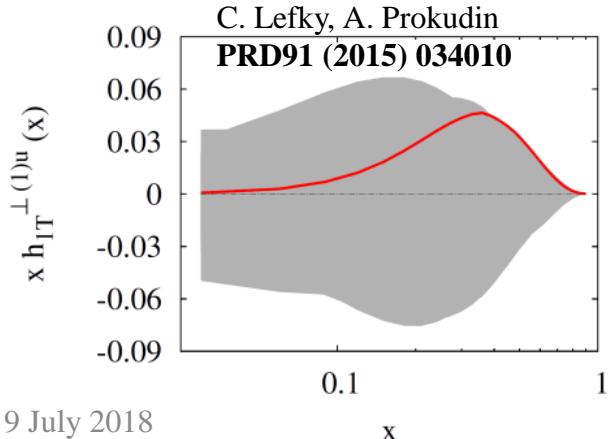
# SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

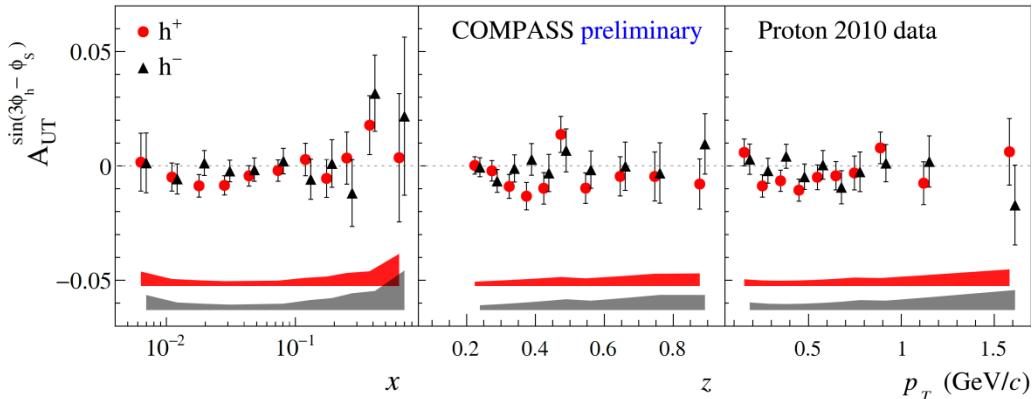
## COMPASS results

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

- 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**

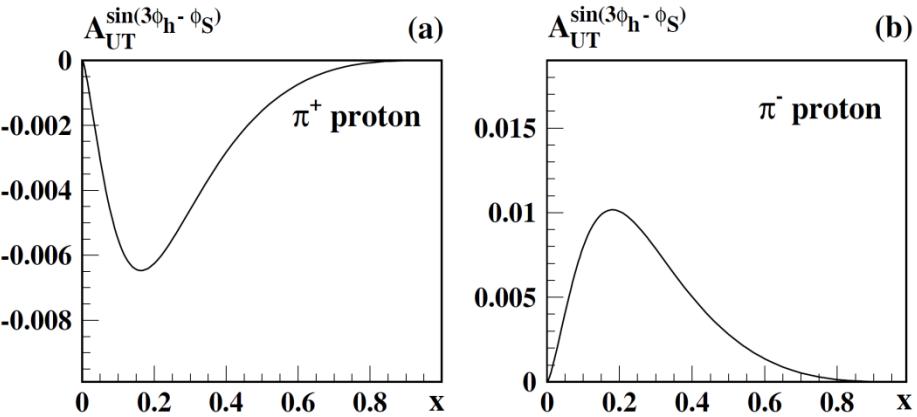


B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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

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



# SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

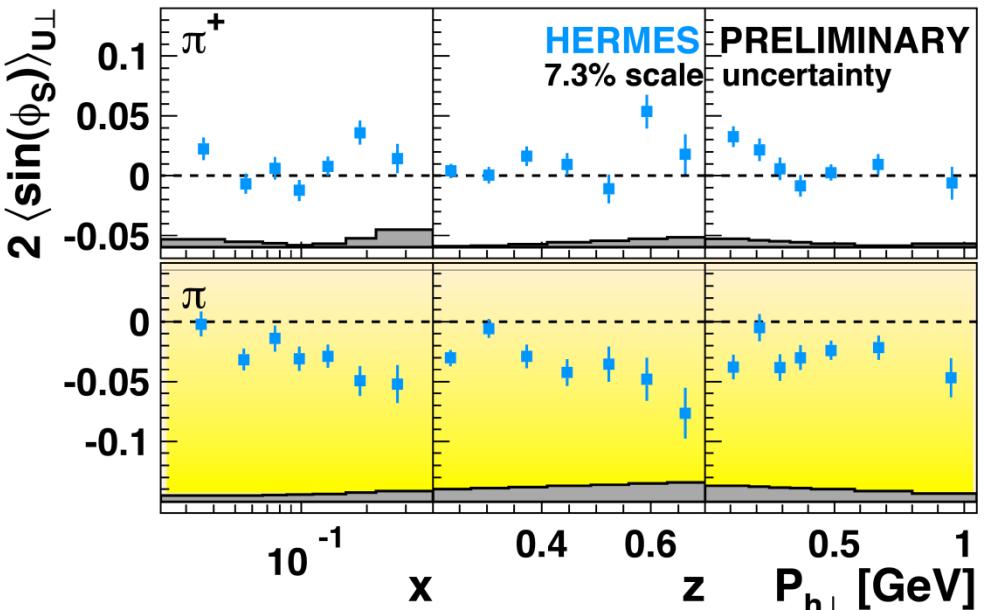
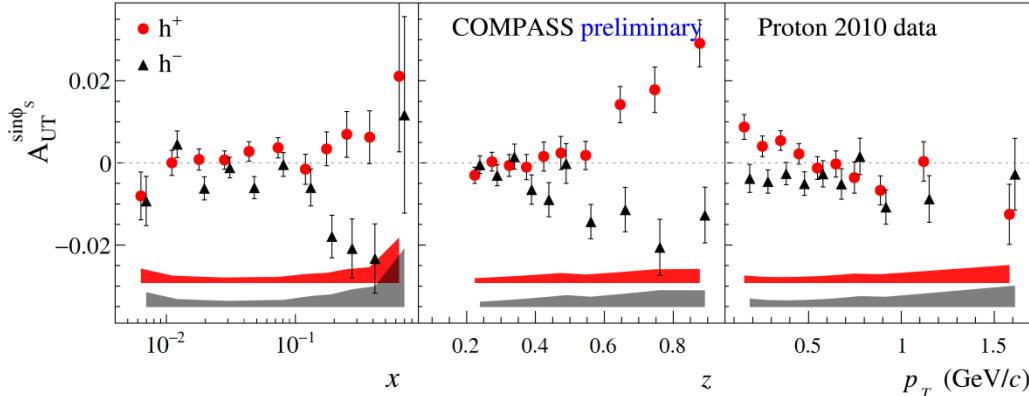
## COMPASS results

$$A_{UT}^{\sin\phi_s}$$

- Q-suppression
- Various different “twist” ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for  $h^-$ ?**

$$F_{UT}^{\sin\phi_s} = \frac{2M}{Q} C \left\{ \left( xf_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) \right. \\ \left. - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[ \left( xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \right. \\ \left. \left. - \left( xh_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

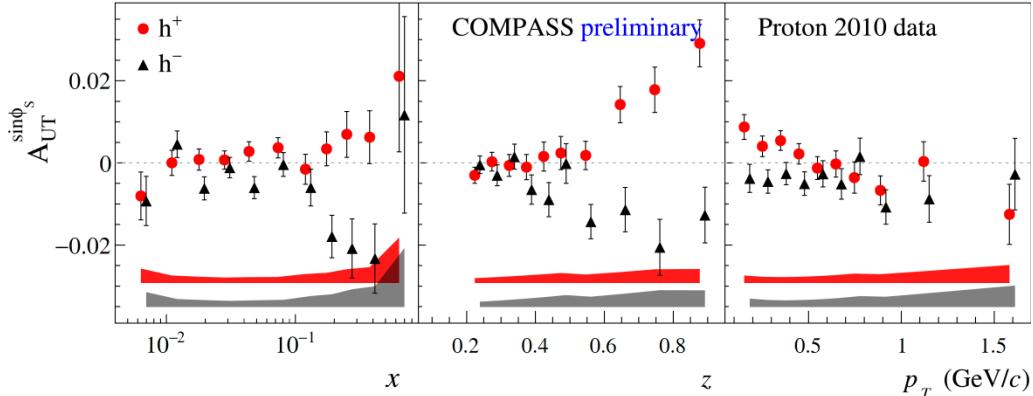
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



# SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

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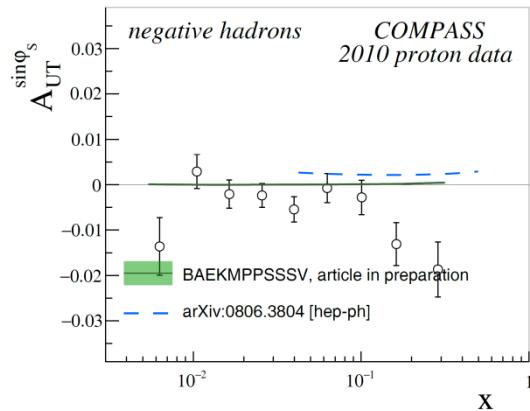
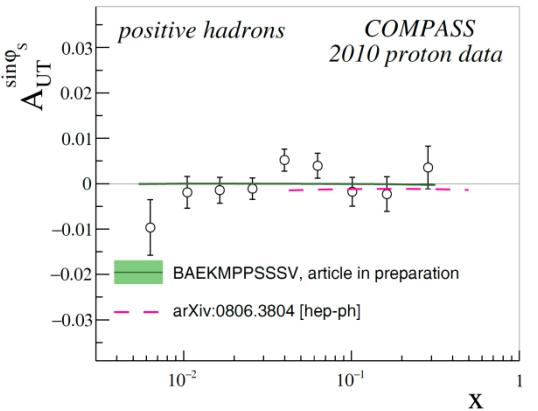


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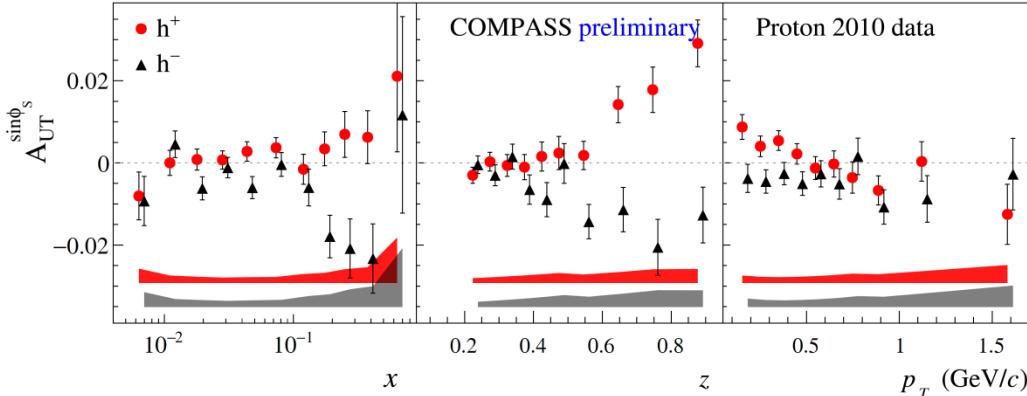
$$F_{UT}^{\sin\phi_s} = \frac{2M}{Q} C \left\{ \left( xf_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) \right. \\ \left. - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[ \left( xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \right. \\ \left. \left. - \left( xh_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$



# SIDIS: target transverse spin dependent asymmetries

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



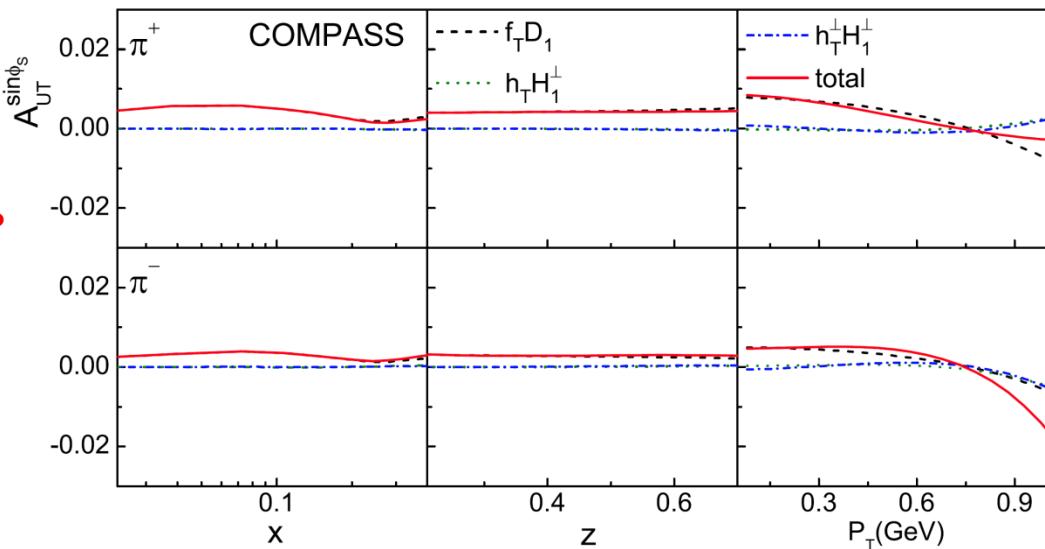
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W. Mao, Z. Lu and B.Q. Ma Phys.Rev. D 90 (2014) 014048



# SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

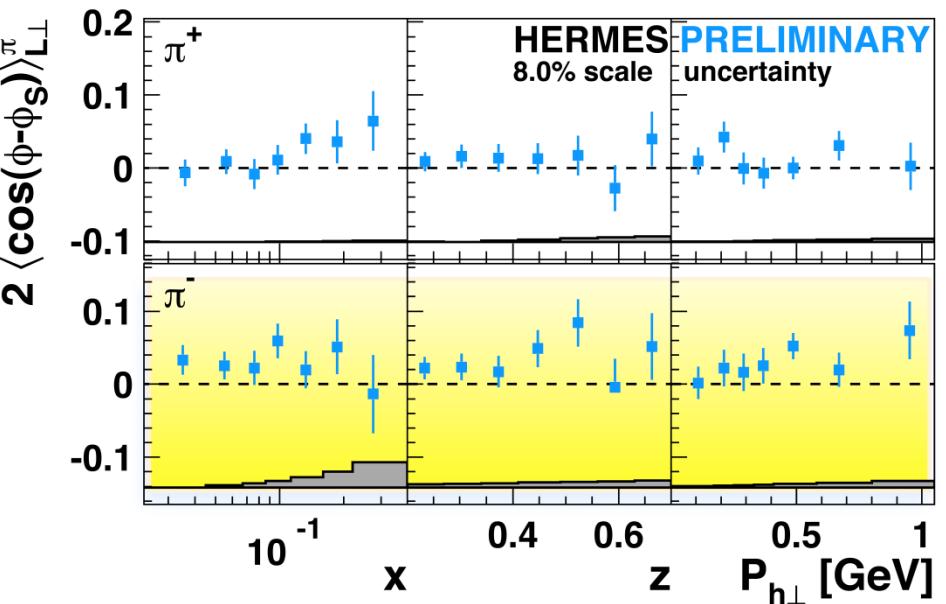
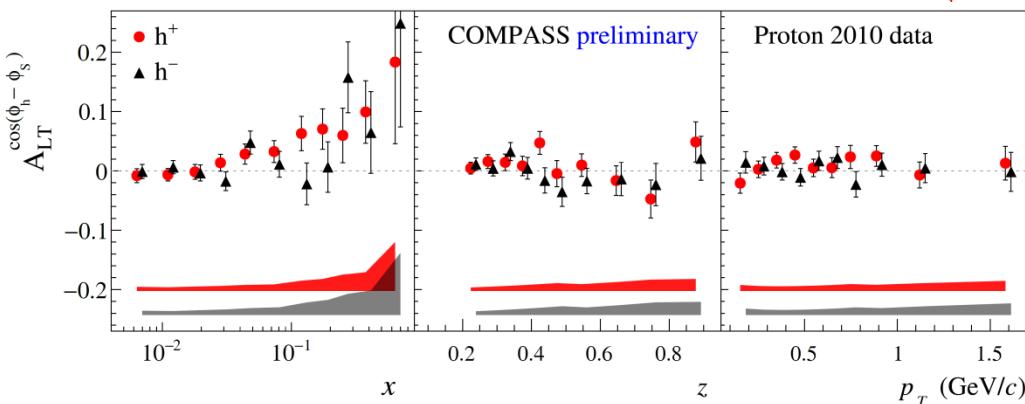
## COMPASS results

$$A_{LT}^{\cos(\phi_h - \phi_s)}$$

- Only “twist-2” ingredients
- Sizable non-zero effect for  $h^+$  !**
- Similar effect at HERMES

$$F_{LT}^{\cos(\phi_h - \phi_s)} = C \left[ \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} g_{1T}^q D_{1q}^h \right]$$

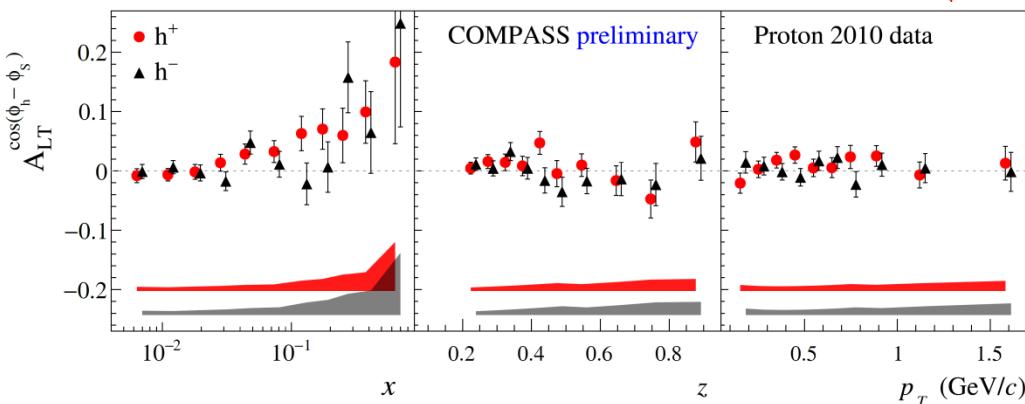
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



# SIDIS: target transverse spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ \begin{array}{l} 1 + \dots \\ \\ + S_T \left[ \begin{array}{l} + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ + \dots \end{array} \right] \\ \\ + S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \dots \end{array} \right] \end{array} \right\}$$

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



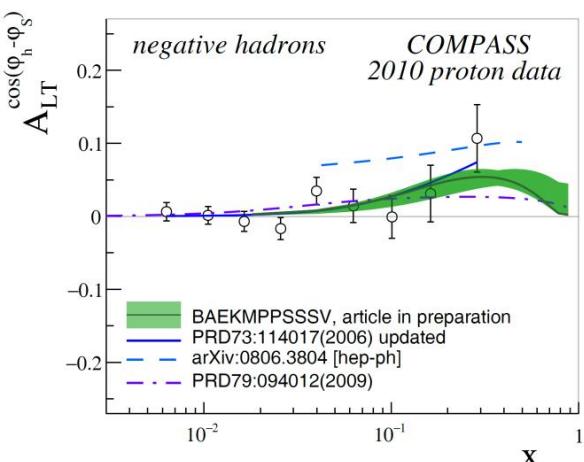
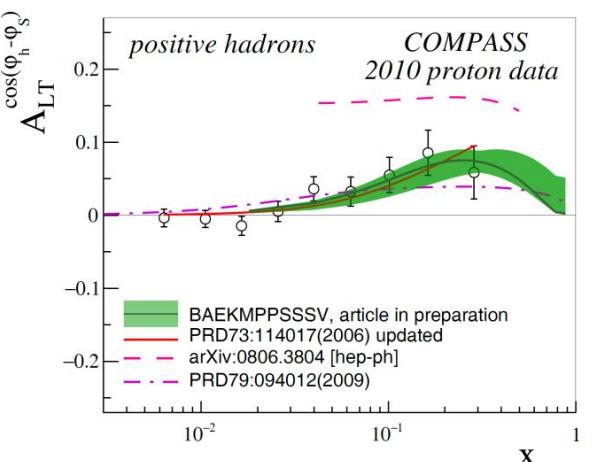
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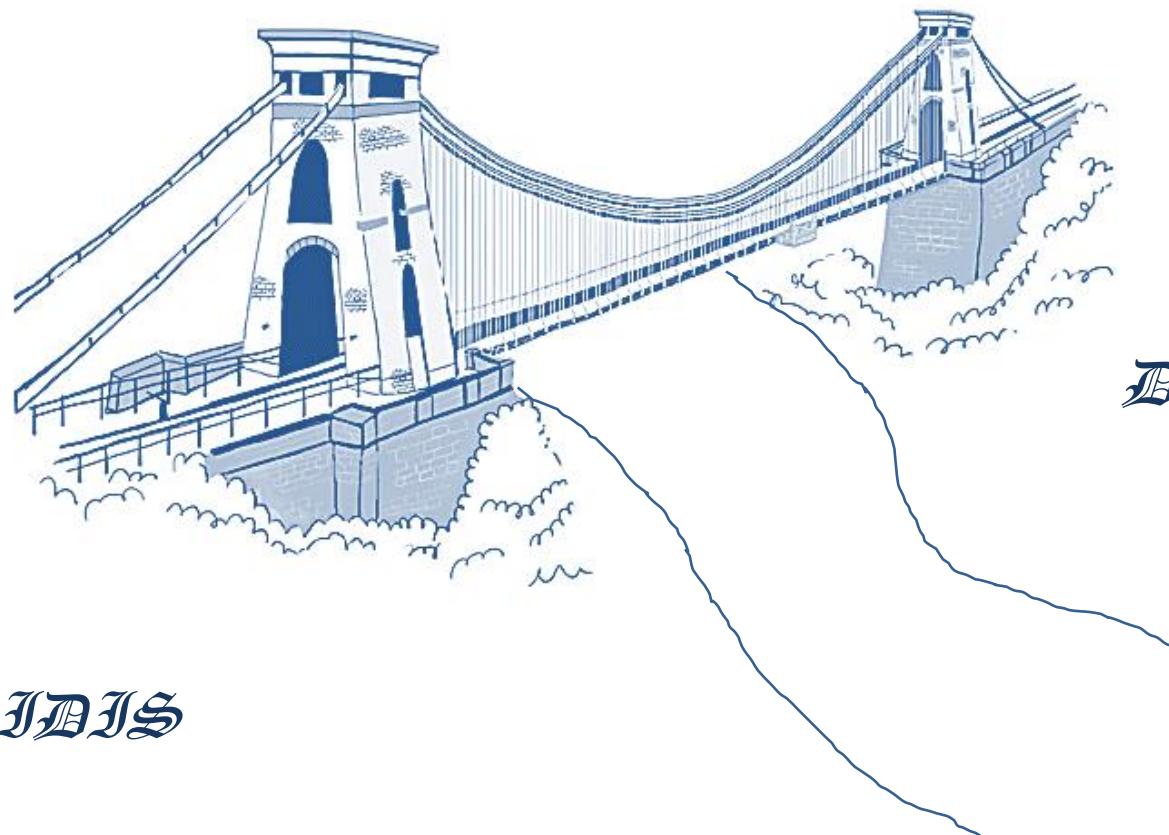
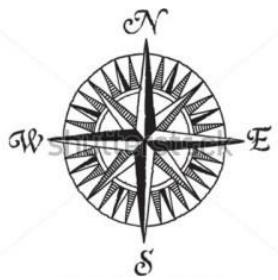
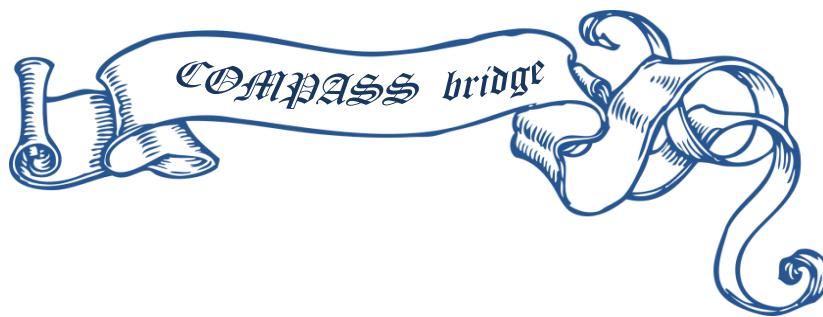
$$A_{LT}^{\cos(\phi_h - \phi_s)}$$

- Only “twist-2” ingredients
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$$F_{LT}^{\cos(\phi_h - \phi_s)} = C \left[ \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} g_{1T}^q D_{1q}^h \right]$$

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang  
Article in preparation: “SIDIS in Wandzura-Wilczek-type approximation“





Drell-Pan

SIDS

# SIDIS and single-polarized DY x-sections

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_s} =$$

SIDIS

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

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

$$+ \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h$$

$$+ S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right]$$

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

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

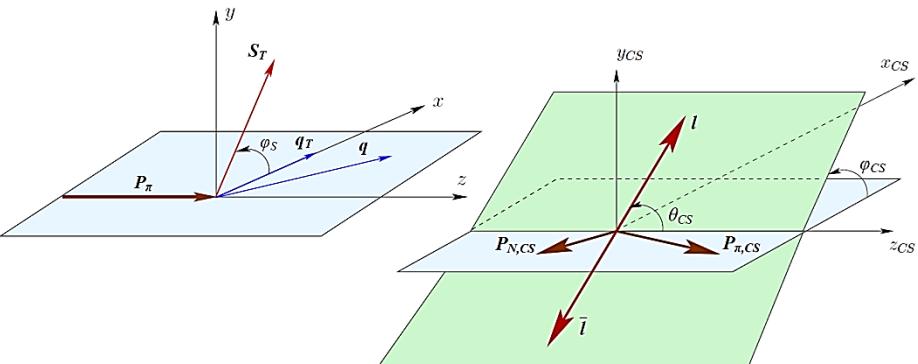
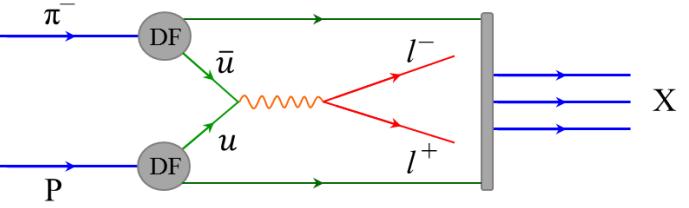

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$$+ S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h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

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

DY

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



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

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

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

**SIDIS**

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

**DY**



**SIDIS-DY bridge**

$$\left\{ \begin{array}{l} 1 + \boxed{D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}} \\ + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( \begin{array}{l} A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \\ + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

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)

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

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

**DY**

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

  
**SIDIS-DY bridge**

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

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

$$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes H_{1q}^{\perp h} + \dots$$

Boer-Mulders

$$A_U^{\cos 2\phi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1,p}^{\perp q}}$$

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

Sivers

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

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

Transversity

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

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

Pretzelosity

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

$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$$

Worm-gear L

$$A_L^{\sin 2\phi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1L,p}^{\perp q}}$$

$$A_{LL} \propto g_{1L}^q \otimes D_{1q}^h, A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

Double polarized DY → 

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)

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

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

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

  
**SIDIS-DY bridge**

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

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

$$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes H_{1q}^{\perp h} + \dots$$

Boer-Mulders

$$A_U^{\cos 2\phi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes \underline{h_{1,p}^{\perp q}}$$

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

Sivers

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

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

Transversity

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

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

Pretzelosity

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

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)

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

**SIDIS**

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

**DY**

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

  
**SIDIS-DY bridge**

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

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

$$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes \underline{H_{1q}^{\perp h}} + \dots$$

Boer-Mulders

$$A_U^{\cos 2\phi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$$

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

Sivers

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

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

Transversity

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

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

Pretzelosity

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

Complementary information from different channels :

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

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

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

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

**SIDIS**

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

**DY**

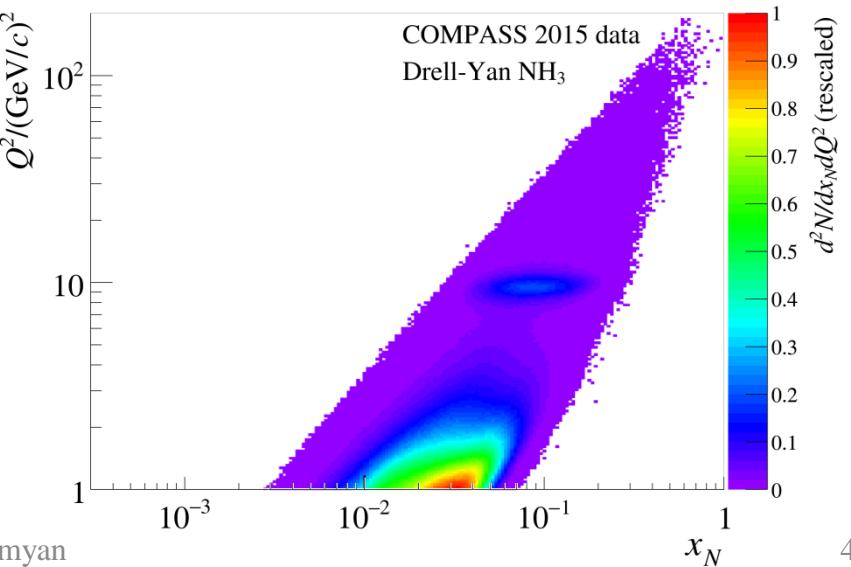
$$1 + \boxed{D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}}$$

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

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

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

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



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

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

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

**SIDIS**

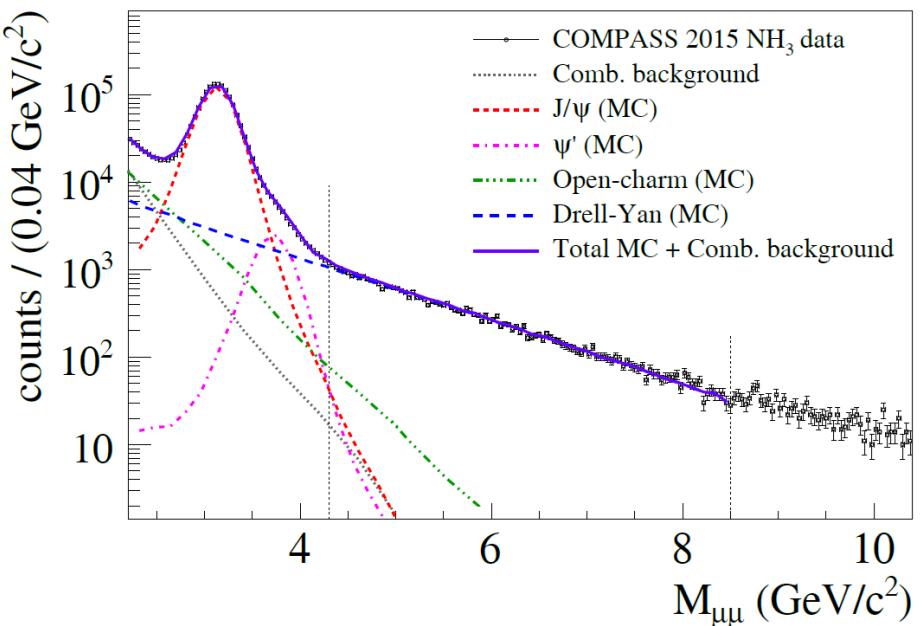
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

**DY**

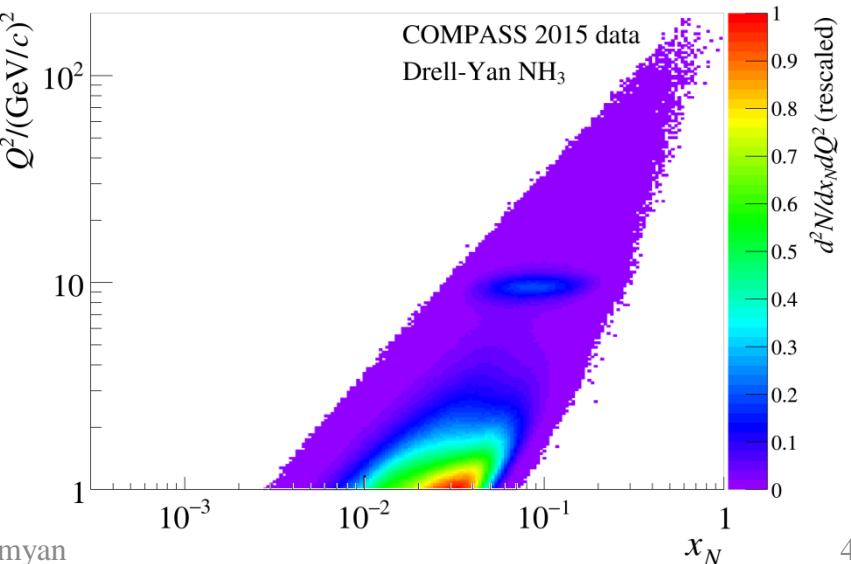
  
**SIDIS-DY bridge**

$$\begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ & + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( \begin{array}{l} A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \\ + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \end{array} \right) \end{array} \right] \end{aligned}$$

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



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



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

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

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

SIDIS

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

DY

  
SIDIS-DY bridge

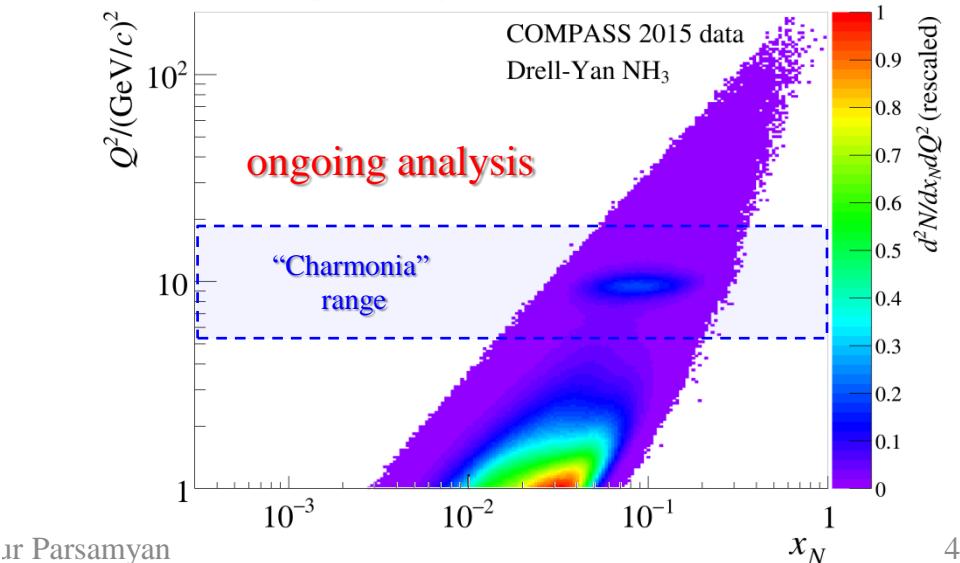
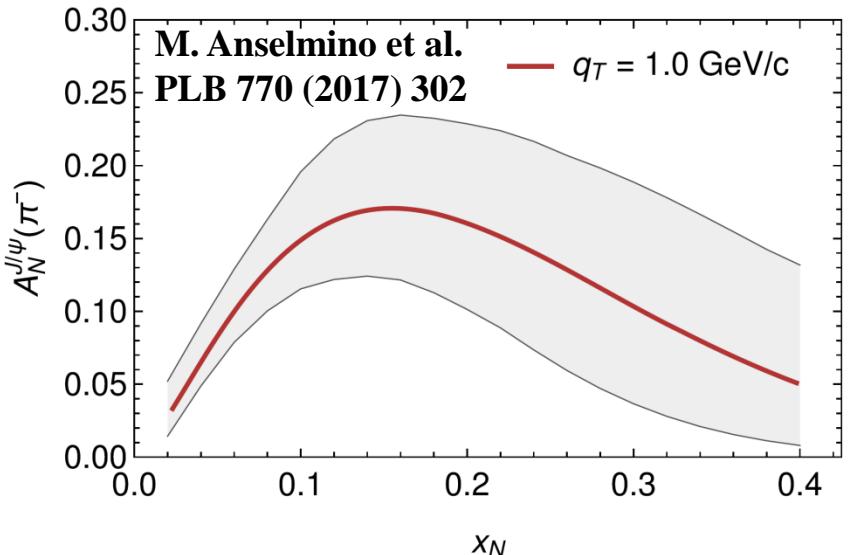
$$\left\{ \begin{array}{l} 1 + \boxed{D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS}} \\ + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ \\ + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right. \\ \left. + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right) \end{array} \right] \end{array} \right\}$$

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

$2.5 < M / (\text{GeV}/c^2) < 4.3$  “Charmonia mass”

Strong J/ψ-signal → study of J/ψ physics  
Good signal/background

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



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



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

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

**SIDIS**

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

**DY**

COMPASS  
SIDIS-DY  
bridge

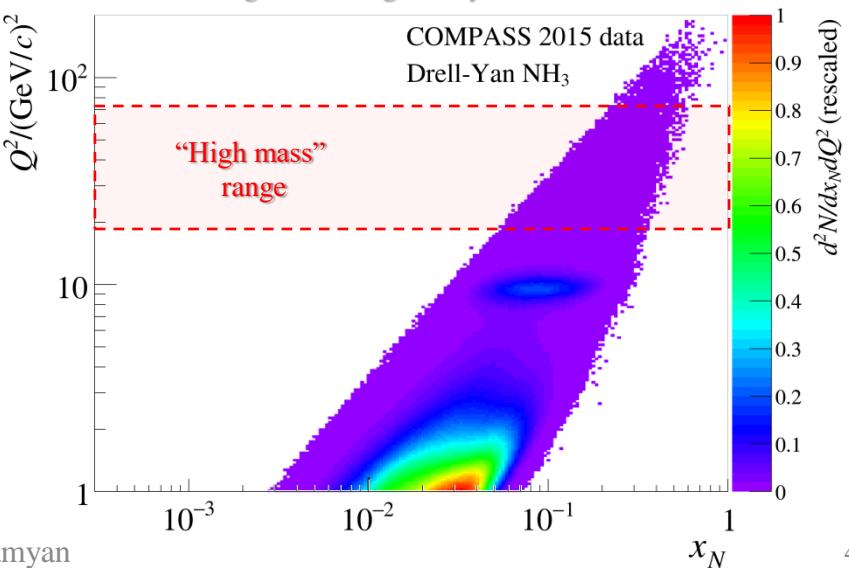
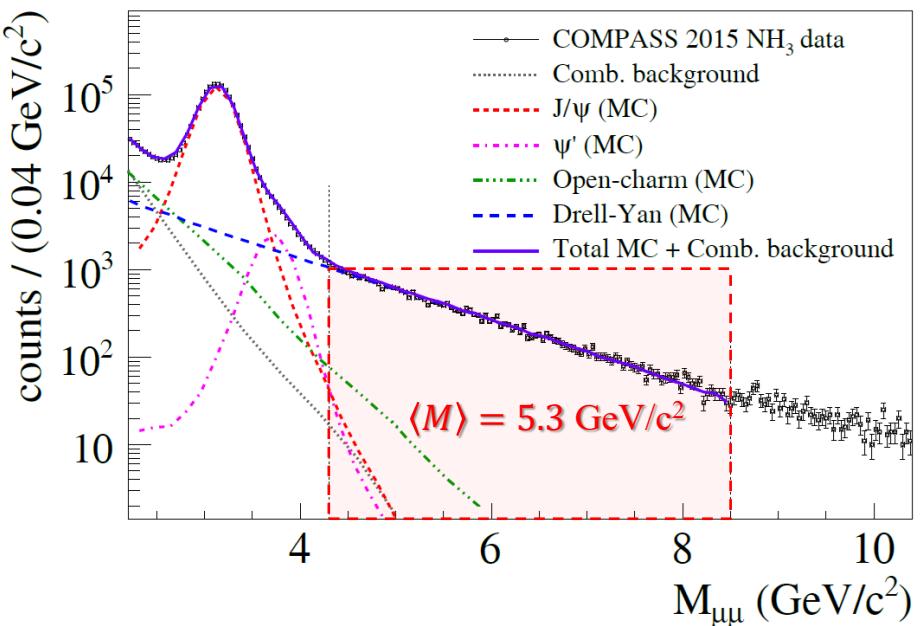
$$\begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ & + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right. \\ \left. + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right) \end{array} \right] \end{aligned}$$

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

**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)

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

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

**SIDIS**

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

**DY**

  
**SIDIS-DY bridge**

$$\begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ & + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right. \\ \left. + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right) \end{array} \right] \end{aligned}$$

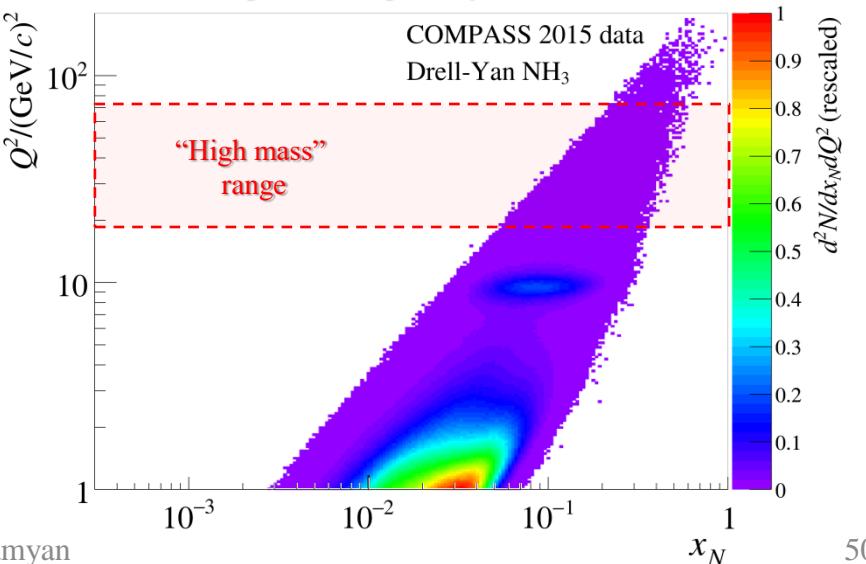
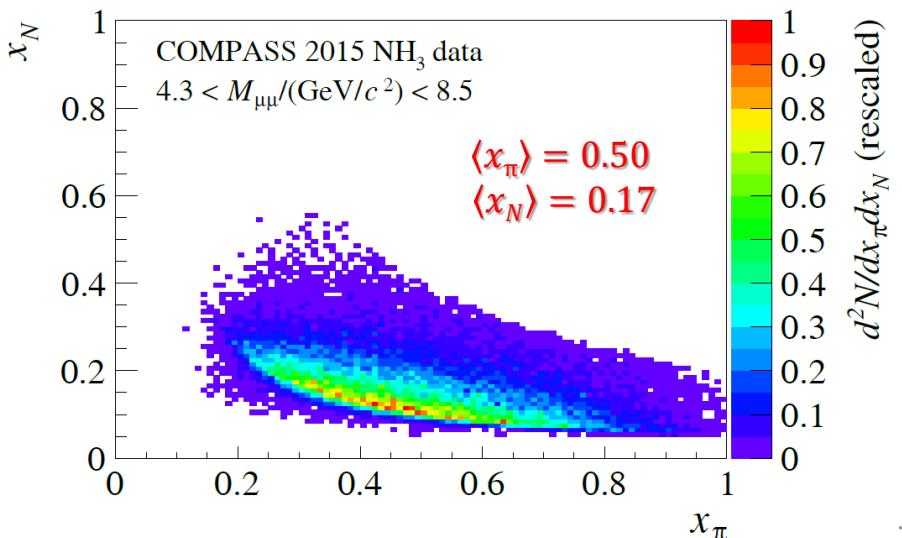
$$\text{where } D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$$

$4.3 < M / (\text{GeV}/c^2) < 8.5$  “High mass” range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries

HM events are in the valence quark range



Parsamyan

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

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

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

**SIDIS**

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

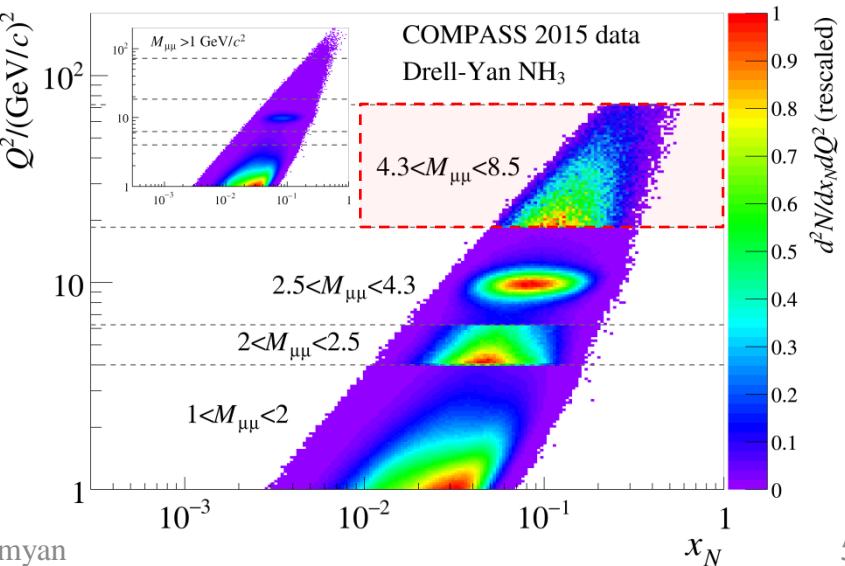
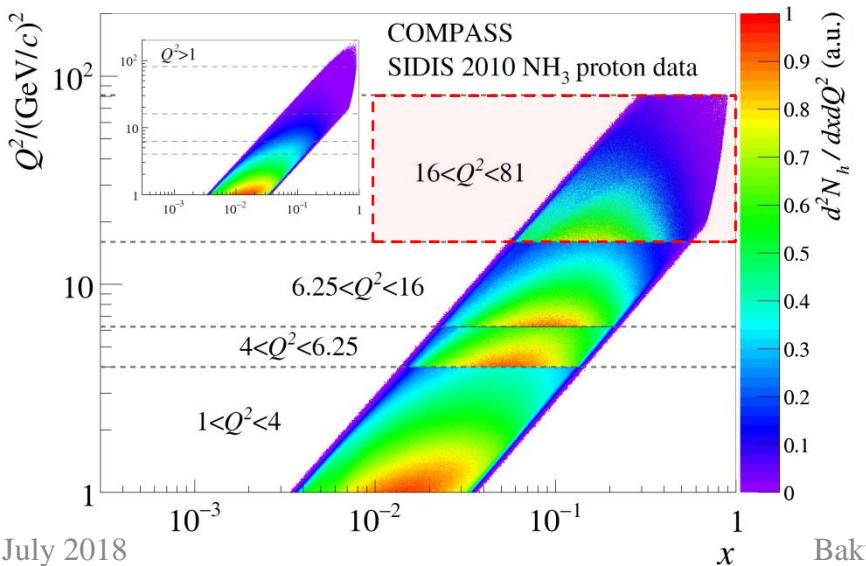
**DY**

COMPASS  
SIDIS-DY  
bridge

$$\begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\phi_{CS}} \sin 2\phi_{CS} \\ & + S_T \left[ \begin{array}{l} A_T^{\sin \phi_S} \sin \phi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\phi_{CS} - \phi_S)} \sin(2\phi_{CS} - \phi_S) \right. \\ \left. + A_T^{\sin(2\phi_{CS} + \phi_S)} \sin(2\phi_{CS} + \phi_S) \right) \end{array} \right] \end{aligned}$$

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

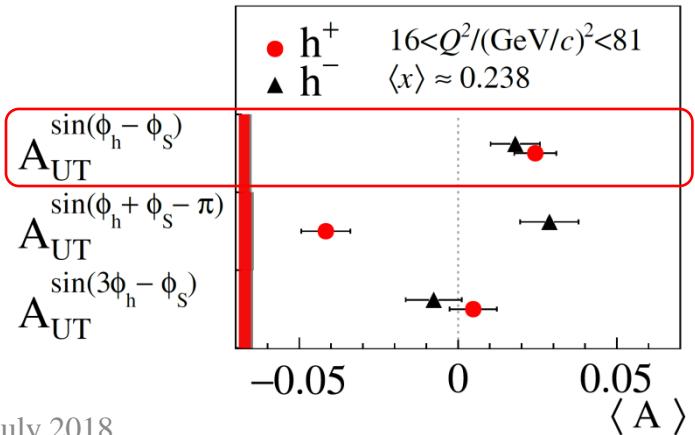
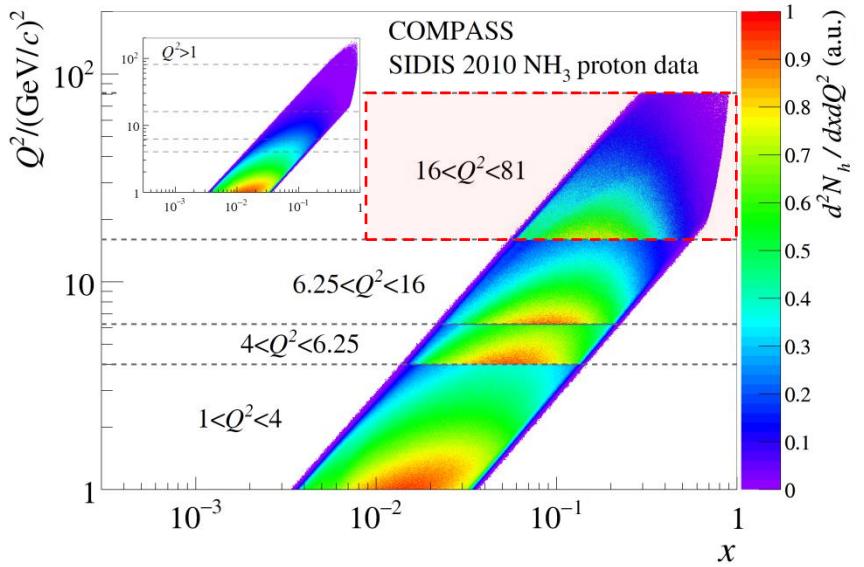
Comparable x:Q<sup>2</sup> coverage – minimization of possible Q<sup>2</sup>-evolution effects



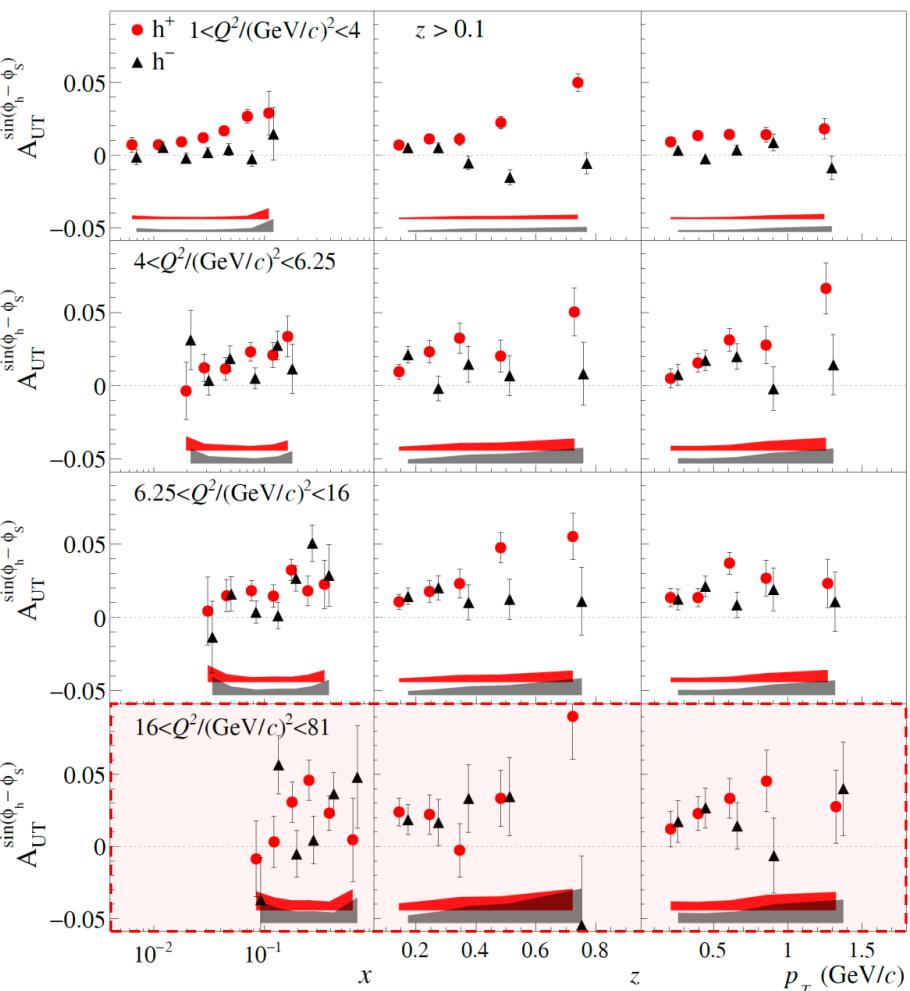
# SIDIS Sivers TSA in COMPASS Drell-Yan Q<sup>2</sup>-ranges

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

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



**COMPASS PLB 770 (2017) 138**

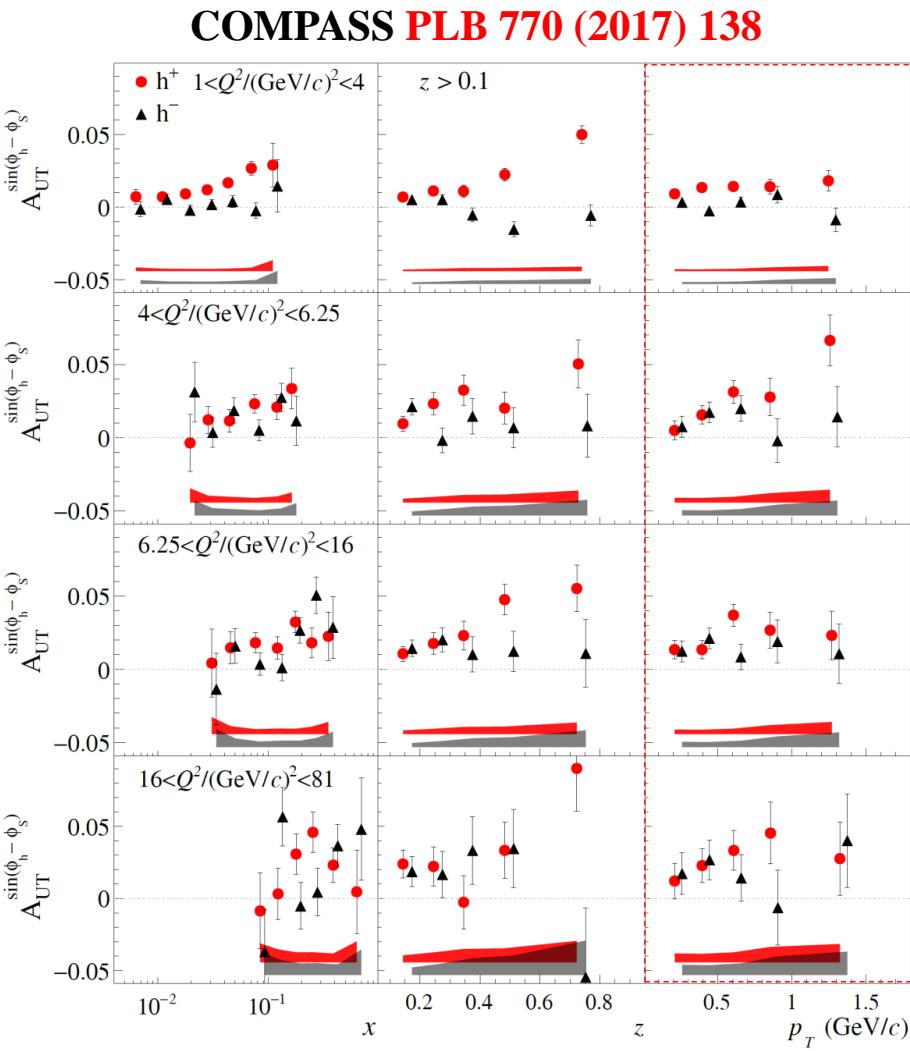
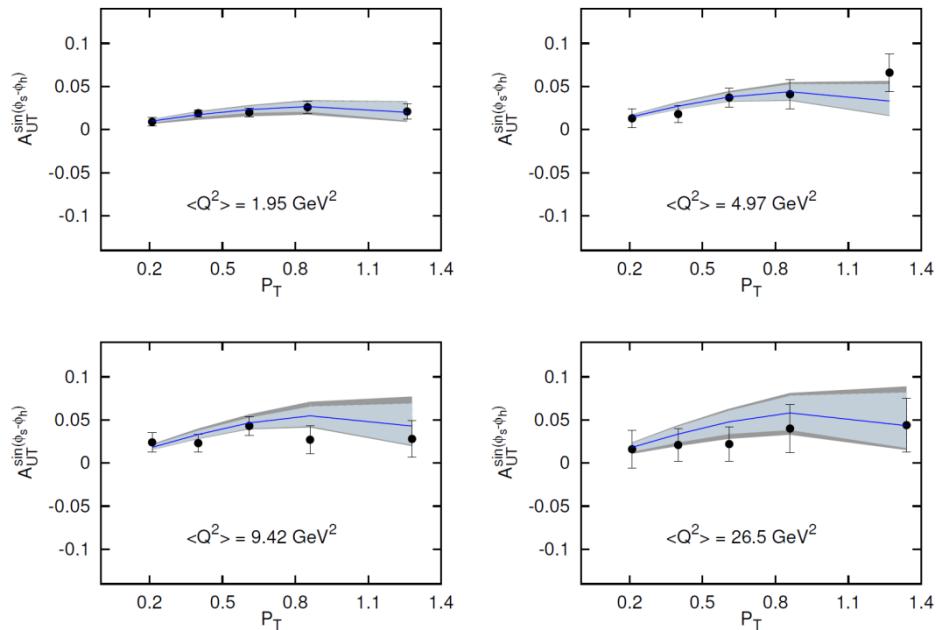


# SIDIS Sivers TSA in COMPASS Drell-Yan Q<sup>2</sup>-ranges



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

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



Courtesy of M. Boglione, J.O. Gonzalez-Hernandez  
(ongoing study)

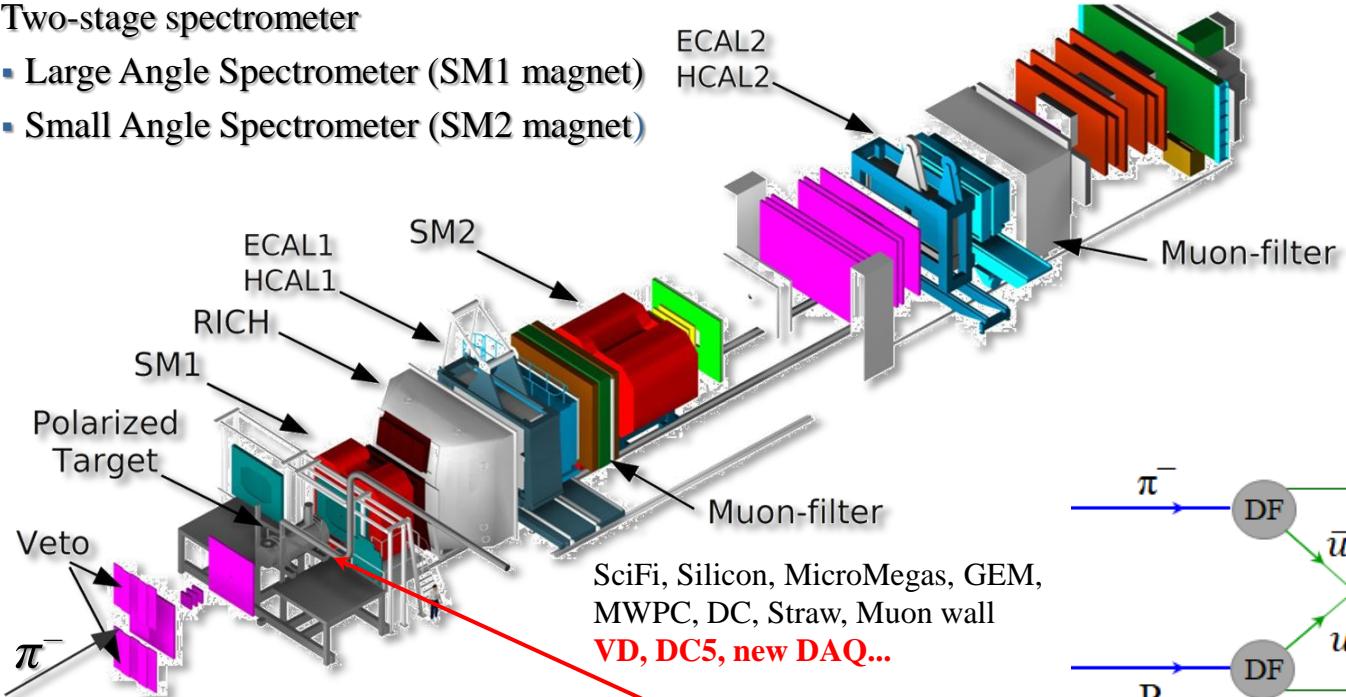


- Results from first ever measurement of Drell-Yan TSAs

# COMPASS experimental setup: Phase II (DY program)

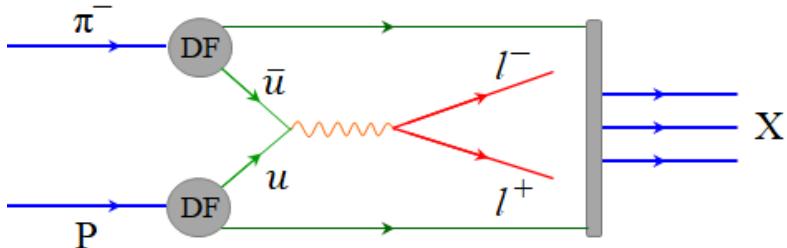
## Two-stage spectrometer

- 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

## Drell-Yan



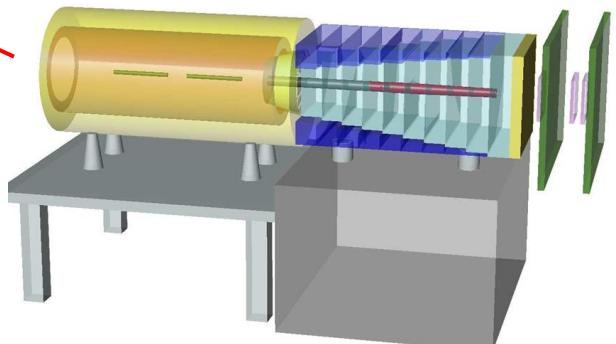
**Data-taking years: 2014 (test) 2015 and 2018**

High energy  $\pi^-$  beam:

Energy: 190 GeV/c, Intensity:  $10^8 \pi/s$

Target: Solid state

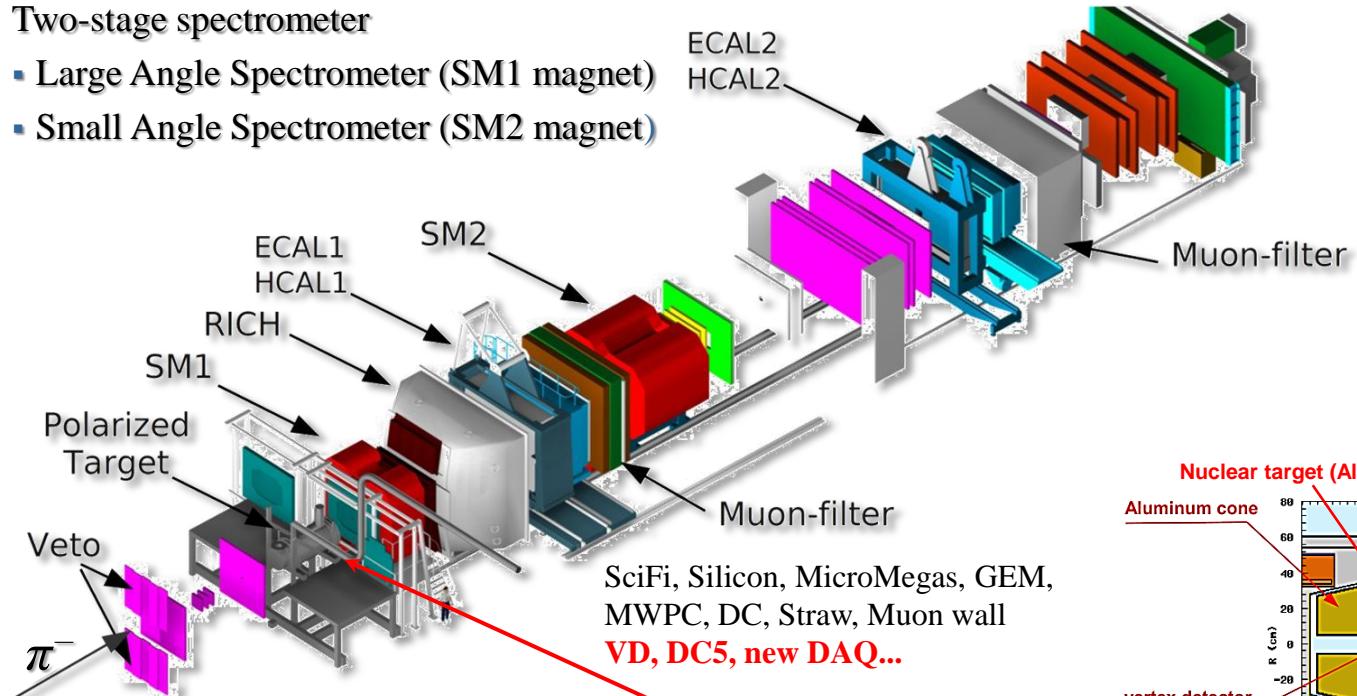
- NH<sub>3</sub> 2-cell configuration. Polarization T ~ 73%, f ~ 0.18



# COMPASS experimental setup: Phase II (DY program)

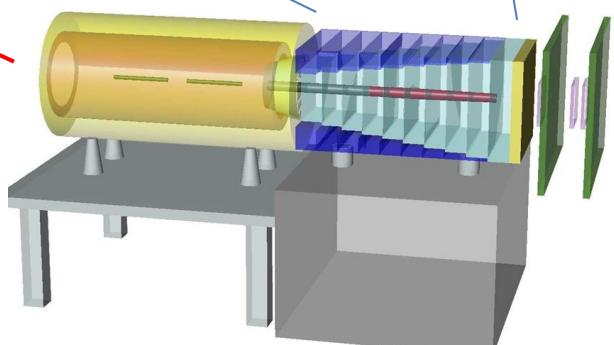
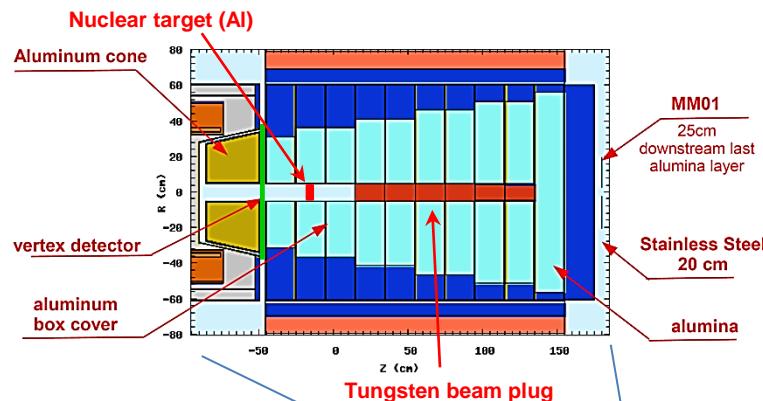
## Two-stage spectrometer

- 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

## Hadron absorber



## Data-taking years: 2014 (test) 2015 and 2018

High energy  $\pi^-$  beam:

Energy: 190 GeV/c, Intensity:  $10^8 \pi/s$

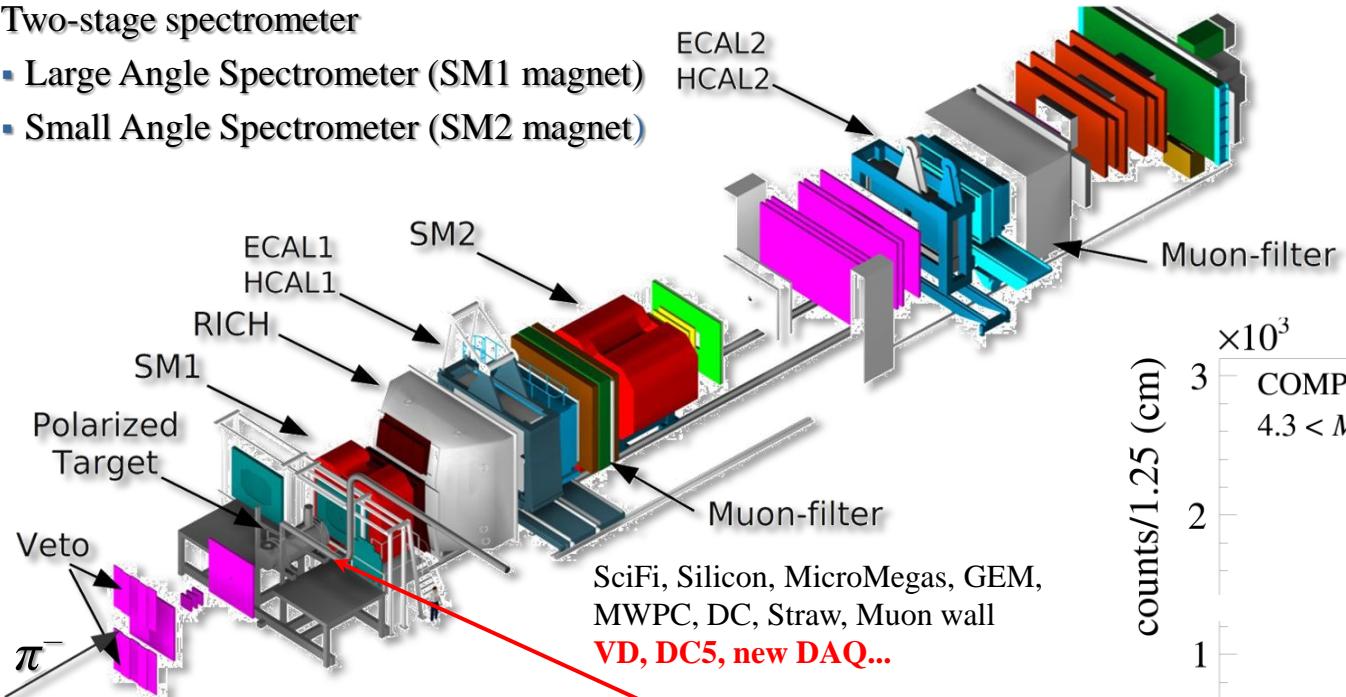
Target: Solid state

- NH<sub>3</sub> 2-cell configuration. Polarization T ~ 73%, f ~ 0.18

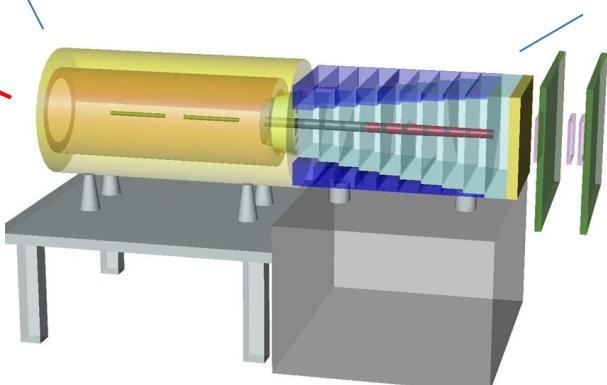
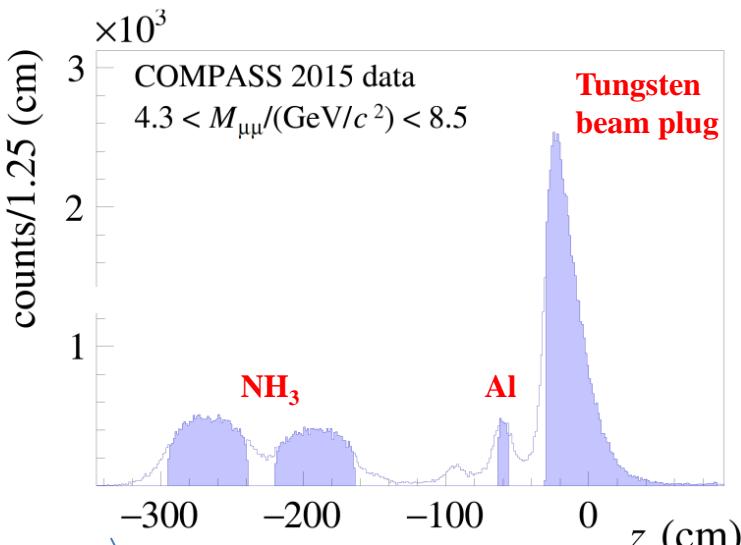
# COMPASS experimental setup: Phase II (DY program)

## Two-stage spectrometer

- 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



**Data-taking years: 2014 (test) 2015 and 2018**

High energy  $\pi^-$  beam:

Energy: 190 GeV/c, Intensity:  $10^8 \pi/\text{s}$

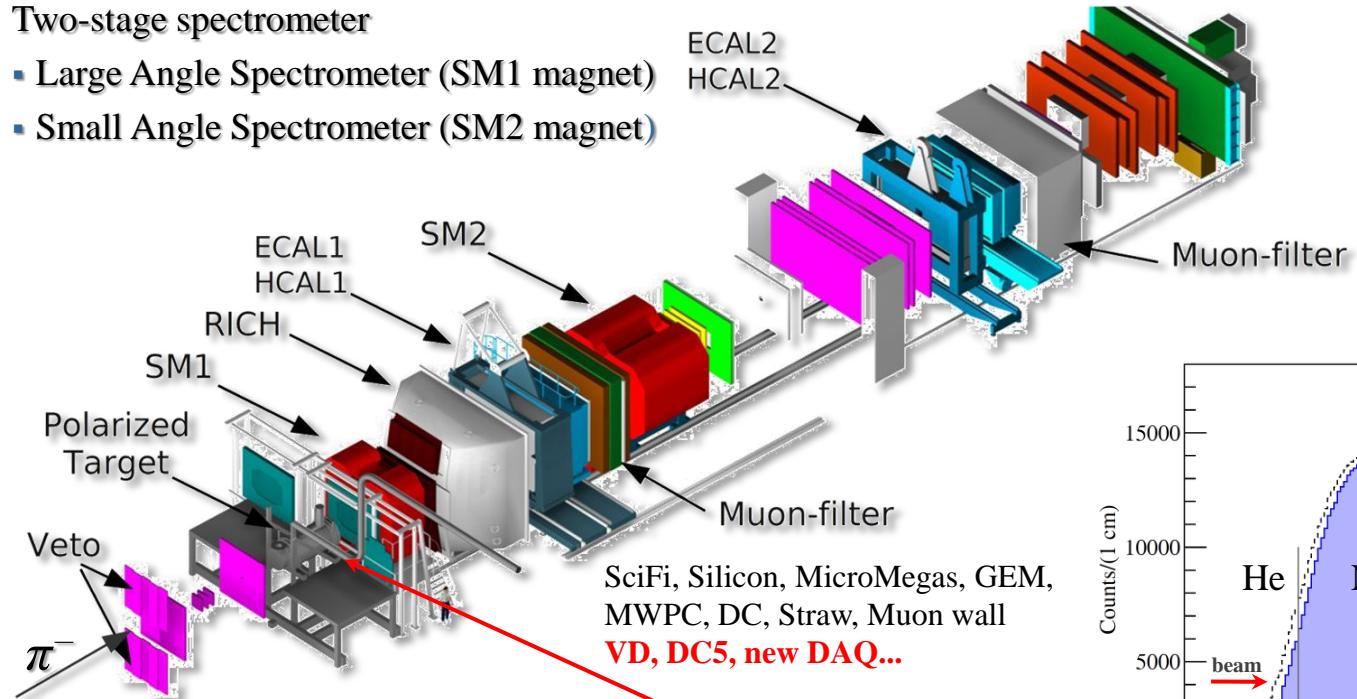
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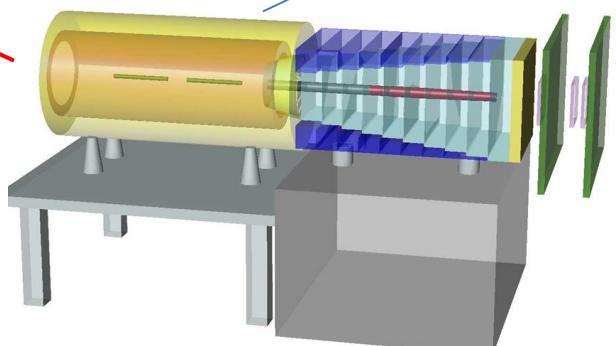
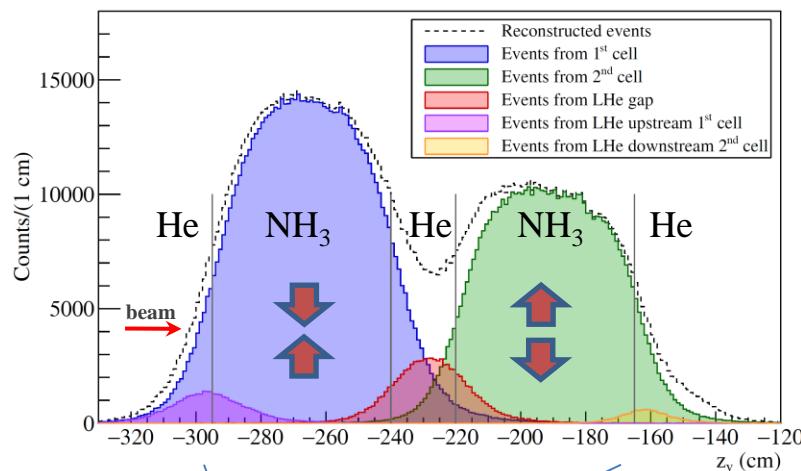
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High energy  $\pi^-$  beam:

Energy: 190 GeV/c, Intensity:  $10^8 \pi/s$

Target: Solid state

- $\text{NH}_3$  2-cell configuration. Polarization  $T \sim 73\%$ ,  $f \sim 0.18$
- Data is collected simultaneously with both target spin orientations  
Periodic polarization reversal to minimize systematic effects



# Single-polarized DY x-section: unpolarized part

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

- “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,  
 $\lambda \neq 1$ ,  $\mu \neq 0$ ,  $\nu \neq 0$

$$\frac{d\sigma}{dq^4 d\Omega} \propto \left( F_U^1 + F_U^2 \right) \\ \times \left\{ 1 + A_U^1 \cos^2 \theta_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} \right\}$$

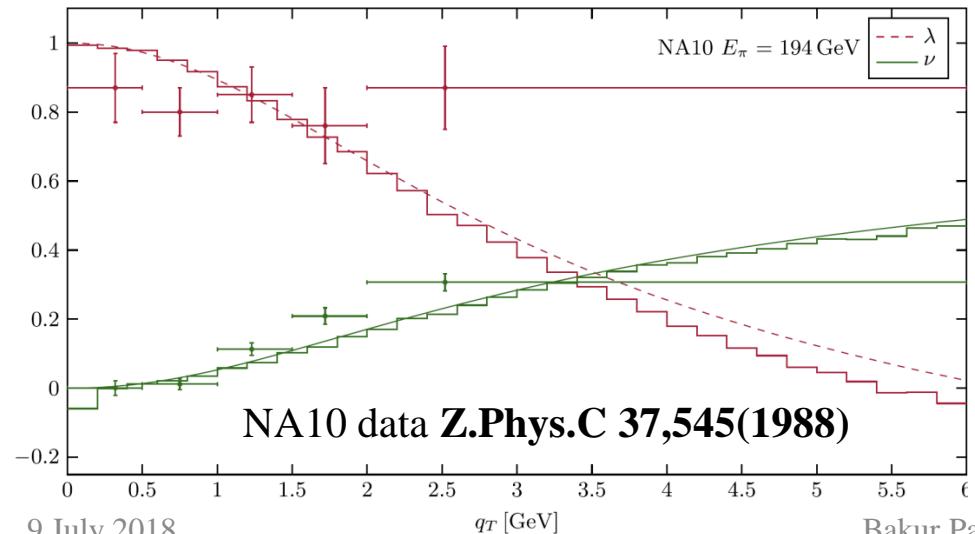
COMPASS ongoing analysis

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- Experiment,  
 $\lambda \neq 1$ ,  $\mu \neq 0$ ,  $\nu \neq 0$
- $\nu \neq 0$  - Energy and quark flavour dependence,  
QCD radiative effects, non-coplanarity  
(PRD93, 114013 (2016), PLB 758 (2016) 384)

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

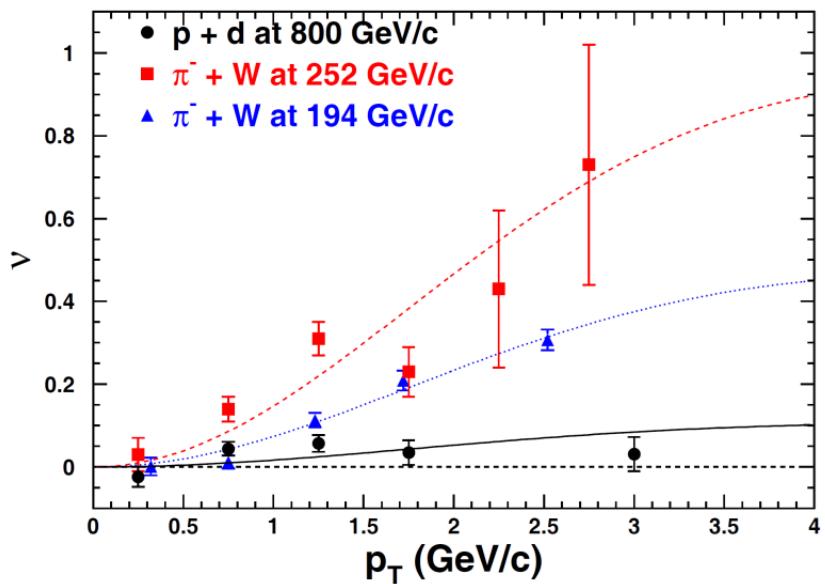


$$\frac{d\sigma}{dq^4 d\Omega} \propto (F_U^1 + F_U^2)$$

$$\times \left\{ 1 + A_U^1 \cos^2 \theta_{CS} + \right.$$

$$\left. \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} \right\}$$

COMPASS ongoing analysis



# Single-polarized DY x-section: transverse part

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

- “naive” Drell–Yan model  
collinear ( $k_T=0$ ) LO pQCD no rad. processes  
 $\lambda=1$ , ( $F_U^2=0$ ),  $\mu=\nu=0$
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 $\lambda \neq 1$ ,  $\mu \neq 0$ ,  $\nu \neq 0$  but  $1-\lambda=2\nu$  (Lam-Tung)
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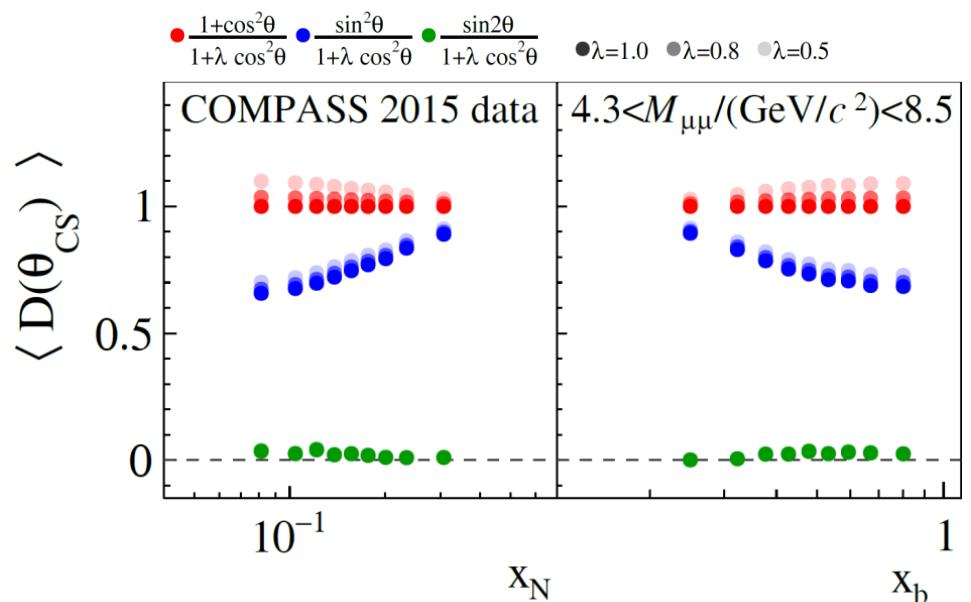
$$\frac{d\sigma}{dq^4 d\Omega} \propto (F_U^1 + F_U^2) (1 + A_U^1 \cos^2 \theta_{CS})$$

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

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

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

- 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  $-5\%$ .



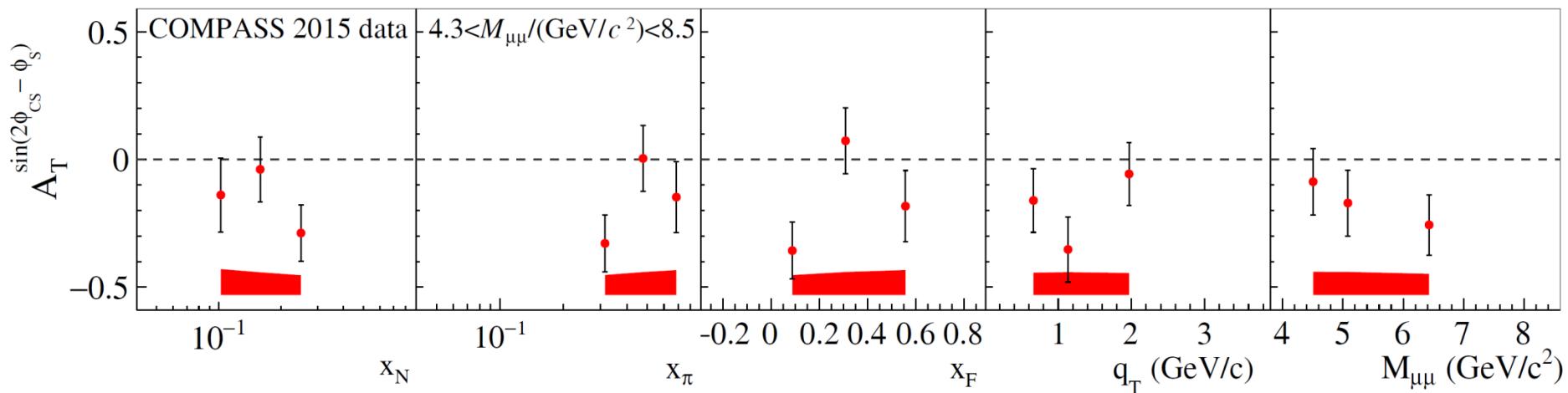
# Drell-Yan TSAs – Transversity

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

**COMPASS PRL 119, 112002 (2017)**

Transversity DY TSA

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



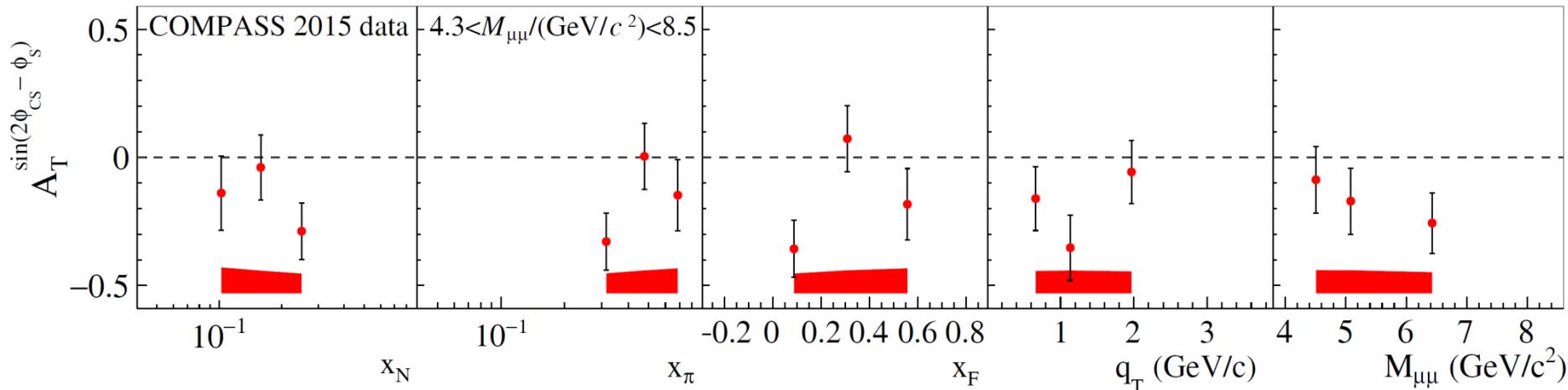
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**COMPASS PRL 119, 112002 (2017)**

Transversity DY TSA

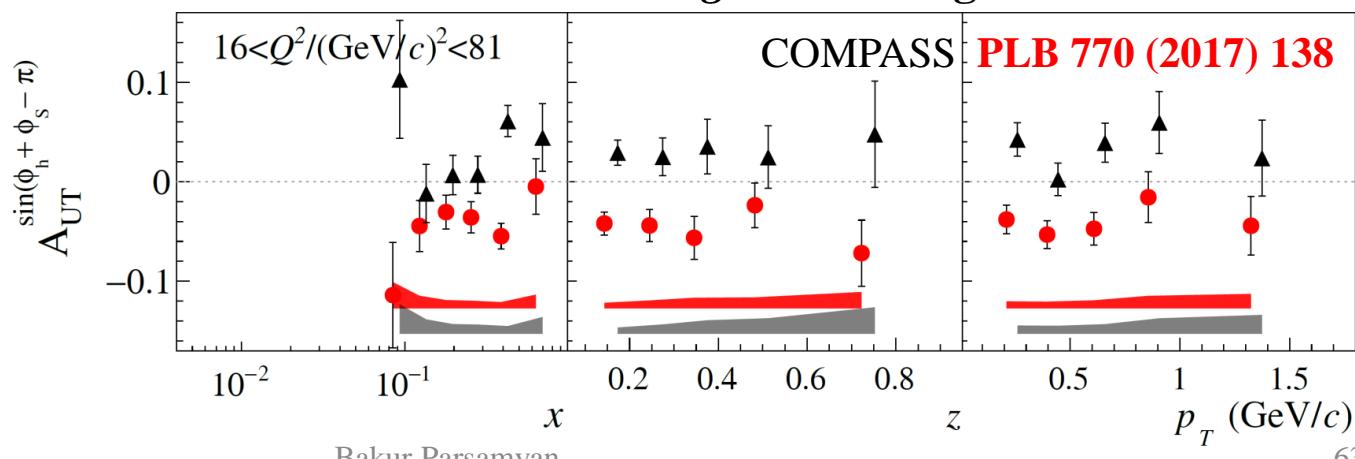
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Collins SIDIS TSA

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

SIDIS in Drell-Yan *high-mass range*



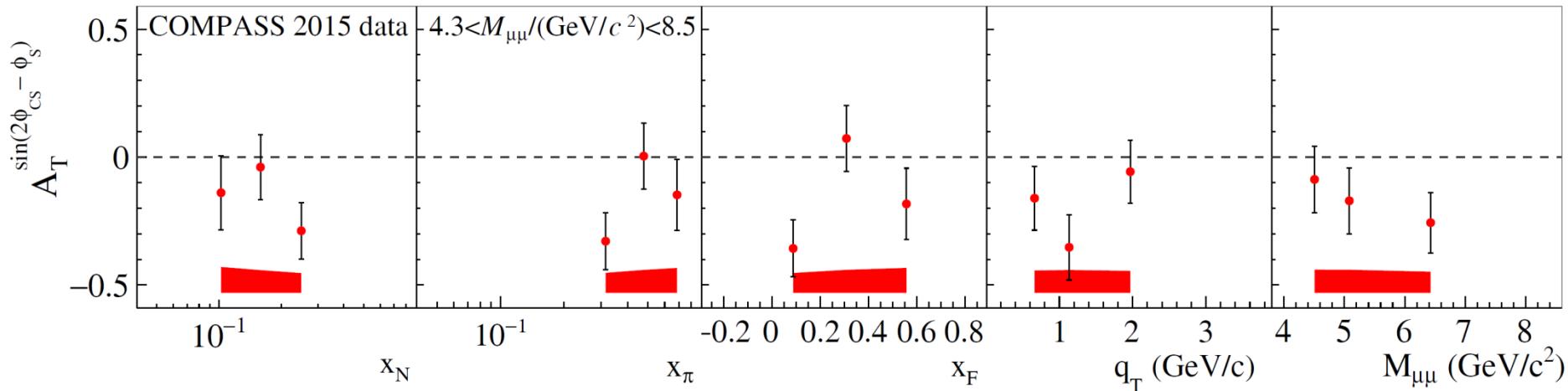
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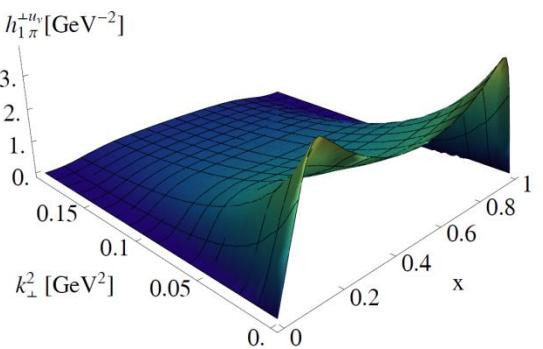
**COMPASS PRL 119, 112002 (2017)**

Transversity DY TSA

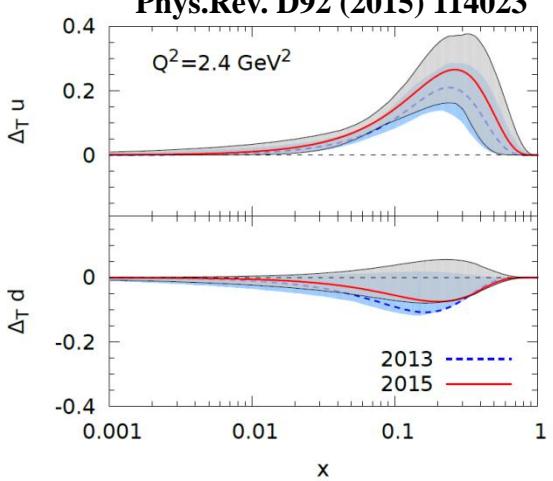
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B. Pasquini, P. Schweitzer  
Phys.Rev. D90 (2014) 014050



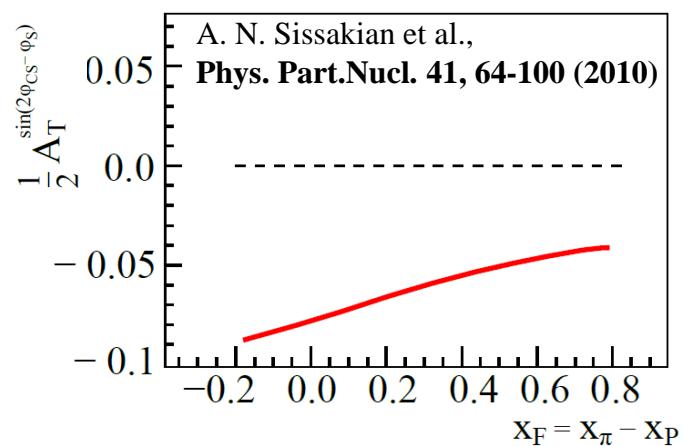
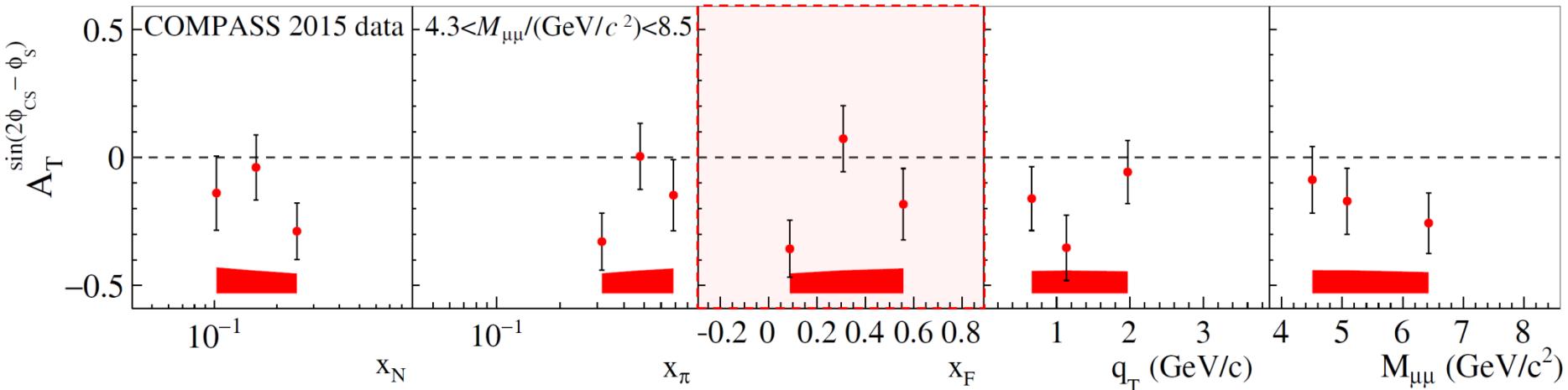
M. Anselmino et al.  
Phys.Rev. D92 (2015) 114023



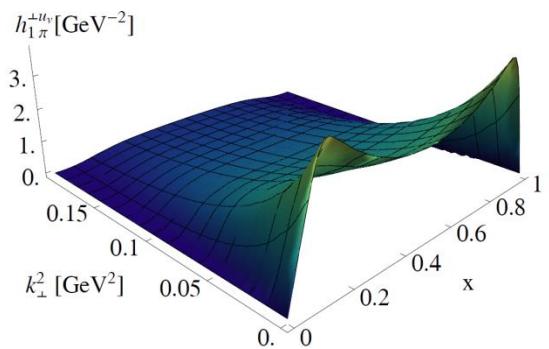
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**COMPASS PRL 119, 112002 (2017)**

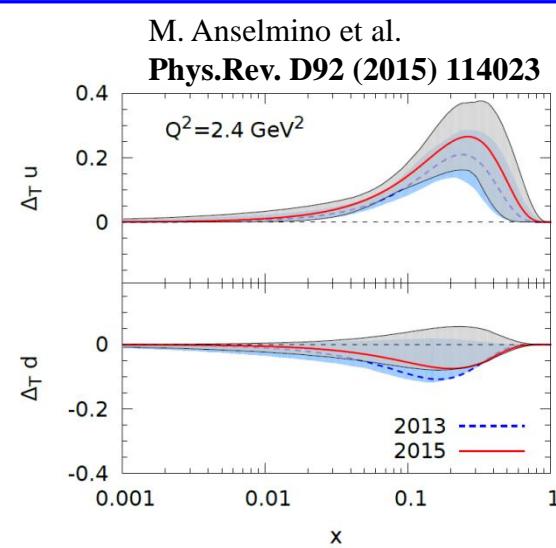


B. Pasquini, P. Schweitzer  
Phys. Rev. D90 (2014) 014050



Transversity DY TSA

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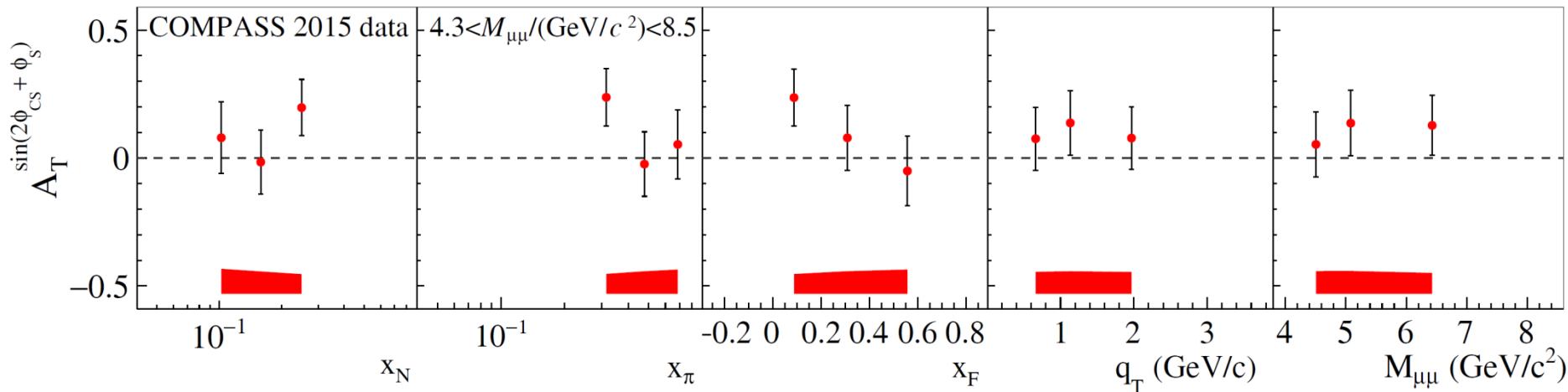
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$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[ D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\phi_{CS} + \phi_s)} \sin(2\phi_{CS} - \phi_s) + \dots \right]$$

**COMPASS PRL 119, 112002 (2017)**

Pretzelosity DY TSA

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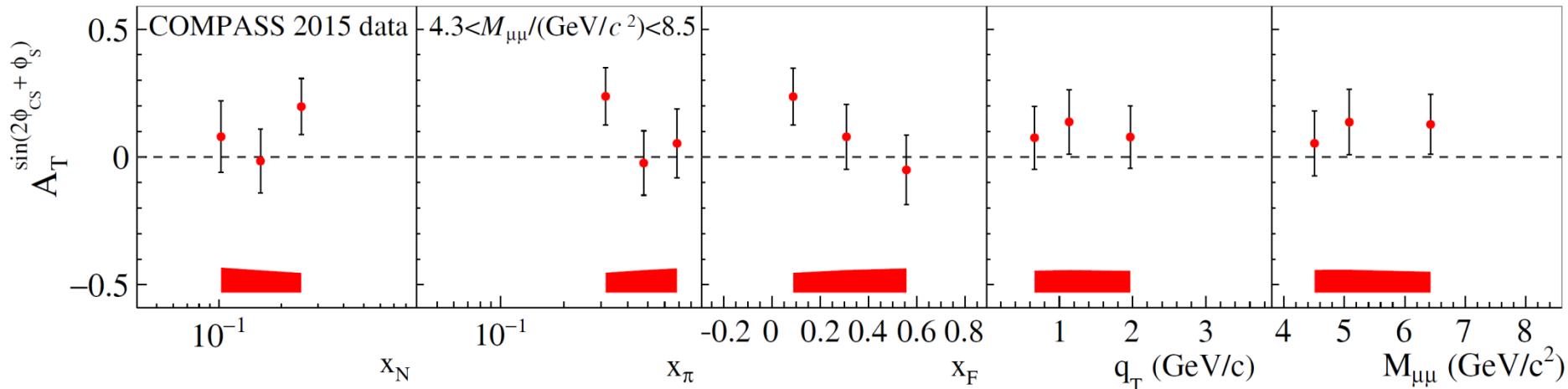
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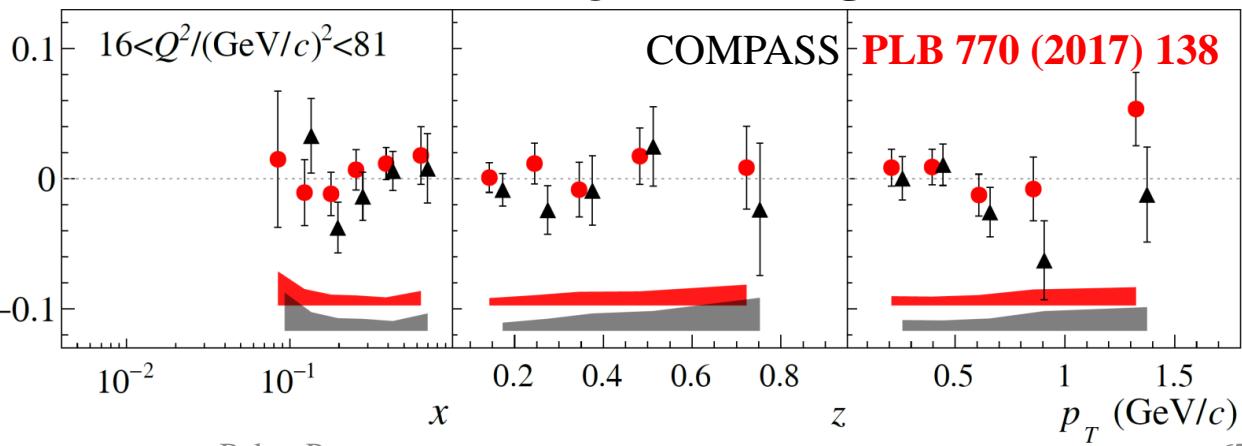


SIDIS in Drell-Yan *high-mass* range

Pretzelosity SIDIS TSA

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

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



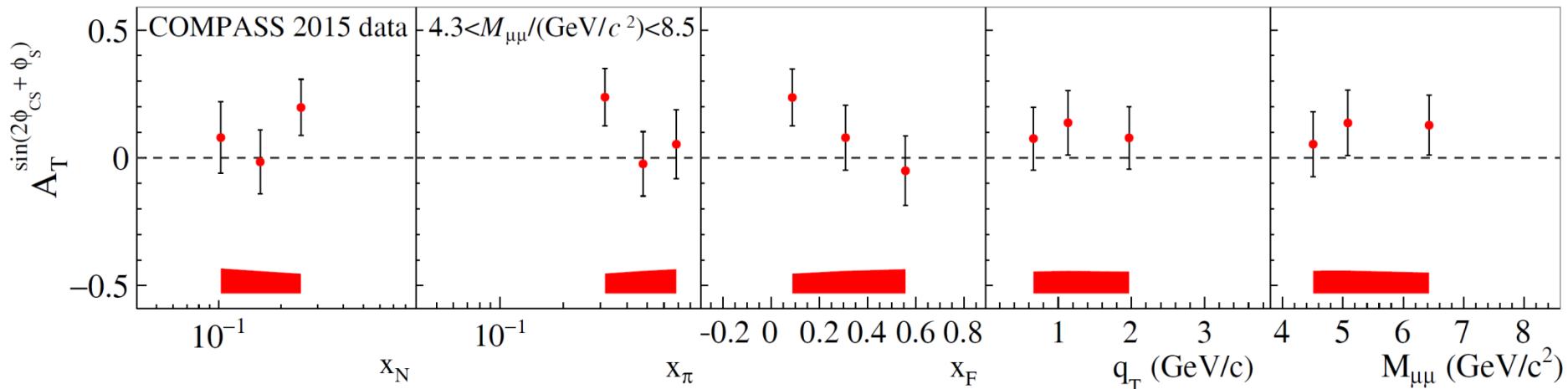
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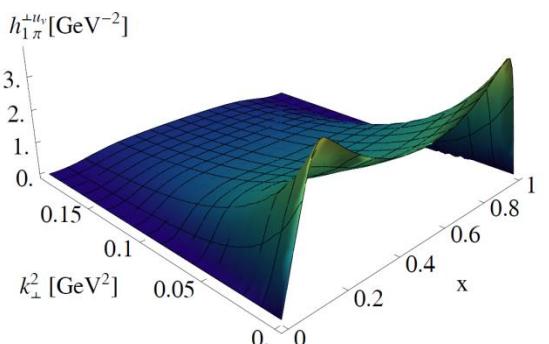
COMPASS PRL 119, 112002 (2017)

Pretzelosity DY TSA

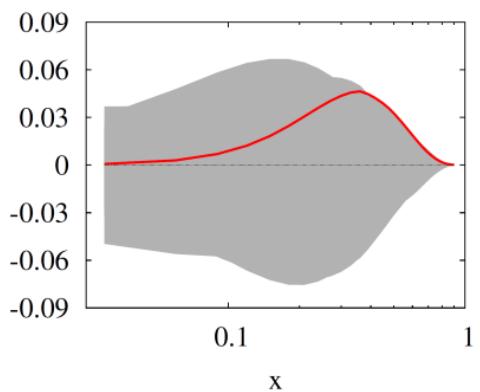
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B. Pasquini, P. Schweitzer  
Phys.Rev. D90 (2014) 014050



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



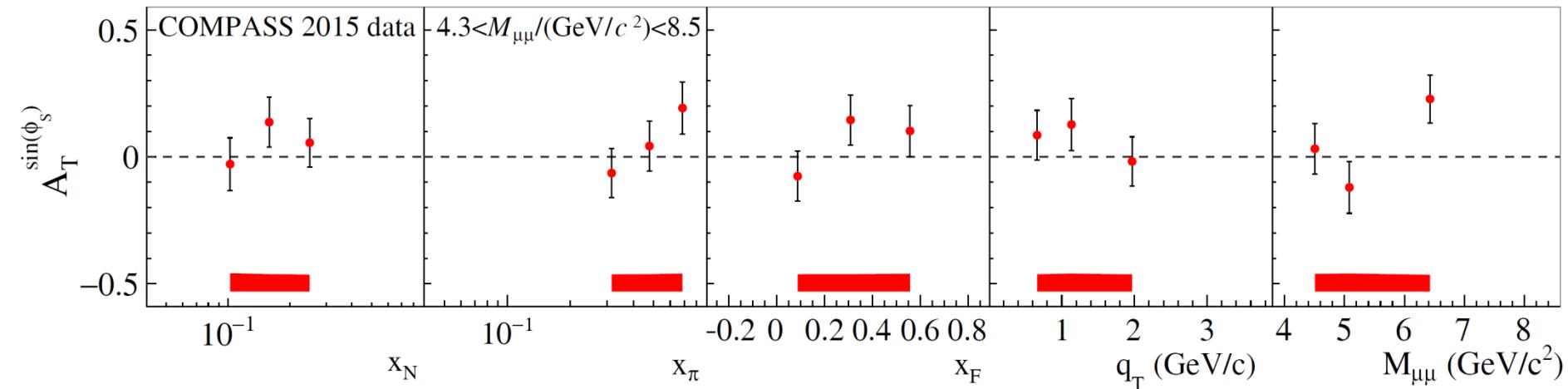
# Drell-Yan TSAs – Sivers

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

**COMPASS PRL 119, 112002 (2017)**

Sivers DY TSA

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



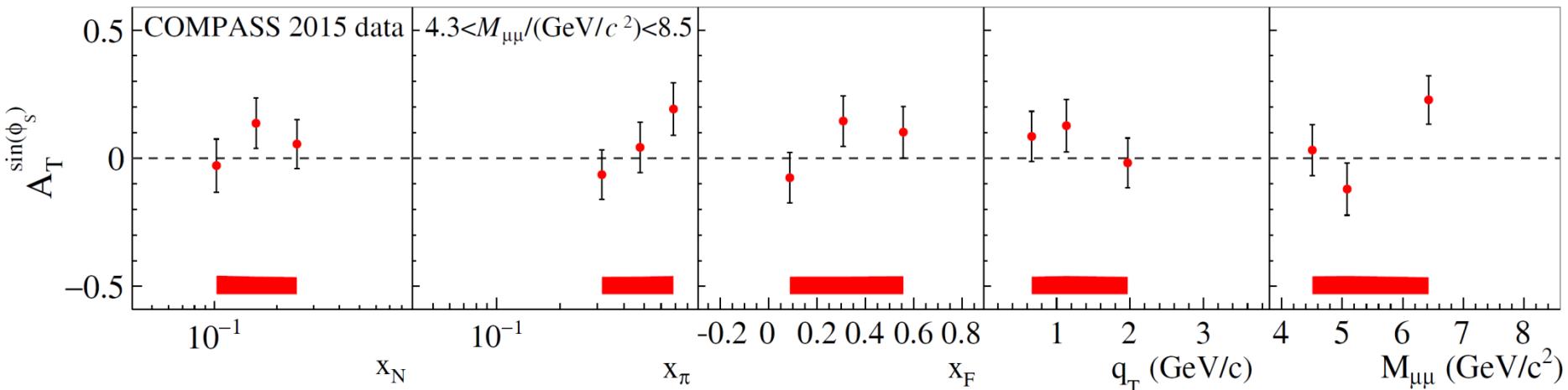
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COMPASS PRL 119, 112002 (2017)

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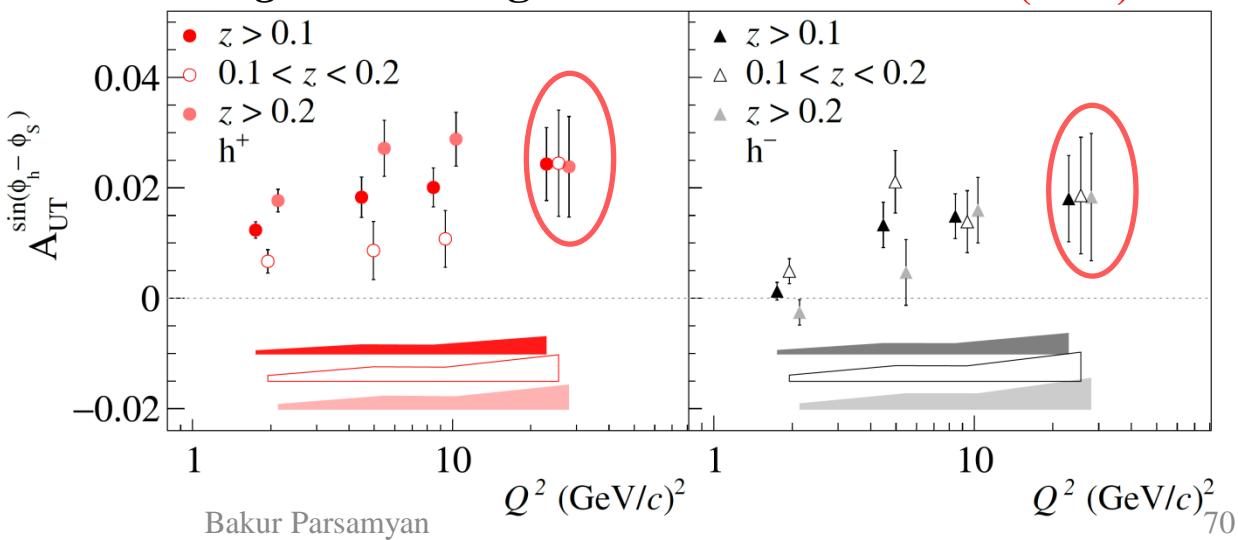


SIDIS in Drell-Yan *high-mass* range

COMPASS PLB 770 (2017) 138

Sivers SIDIS TSA

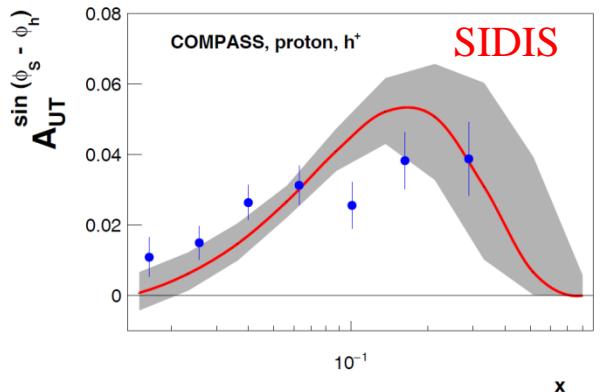
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# Sivers asymmetry in Drell-Yan: sign change

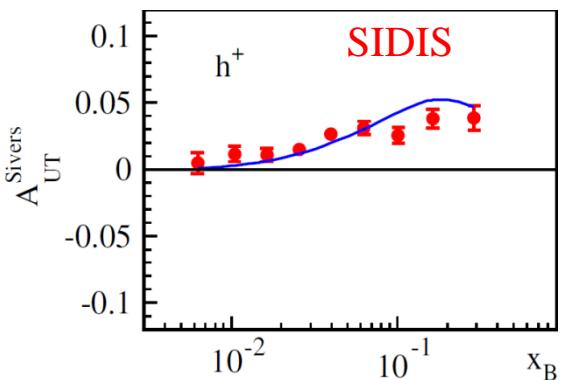
DGLAP (2016)

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



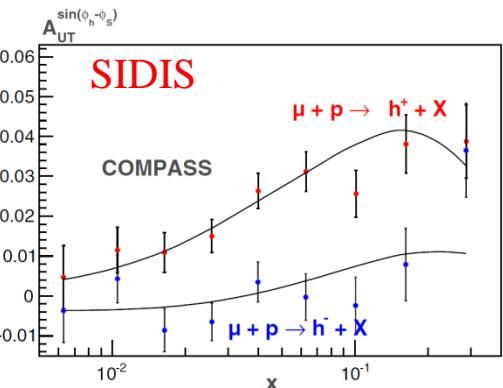
TMD-1 (2014)

M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)

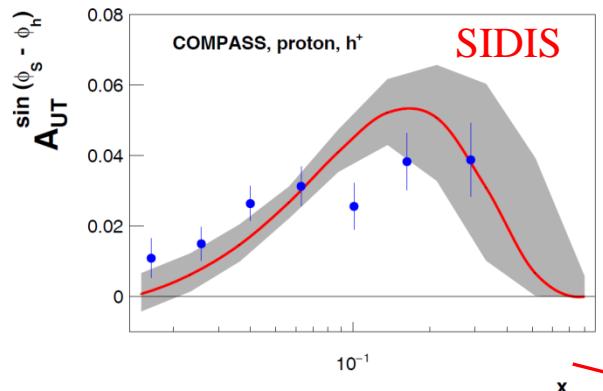
P. Sun, F. Yuan, **PRD88, 114012**



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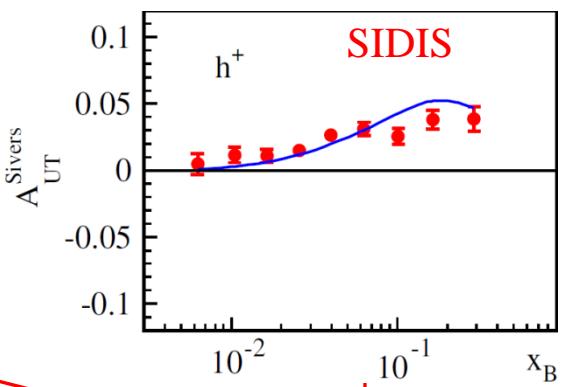
DGLAP (2016)

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



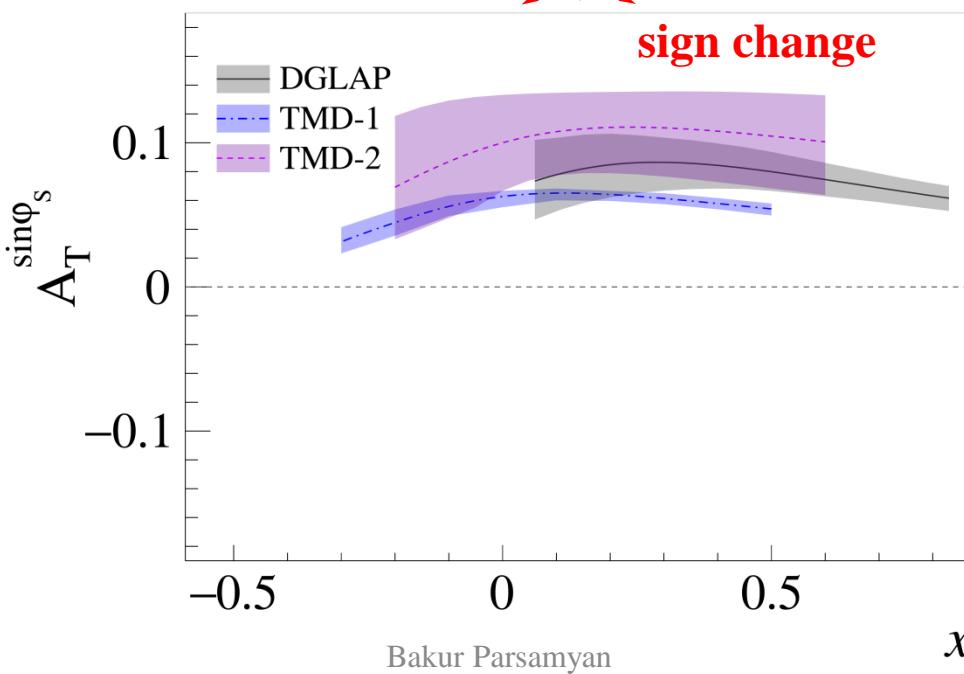
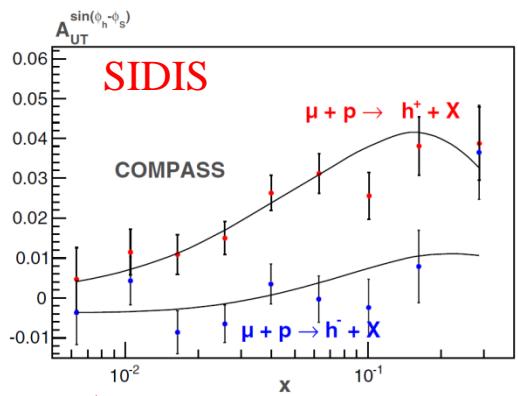
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012



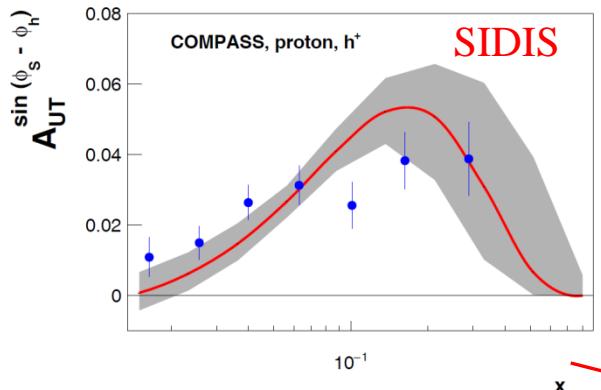
DY

sign change

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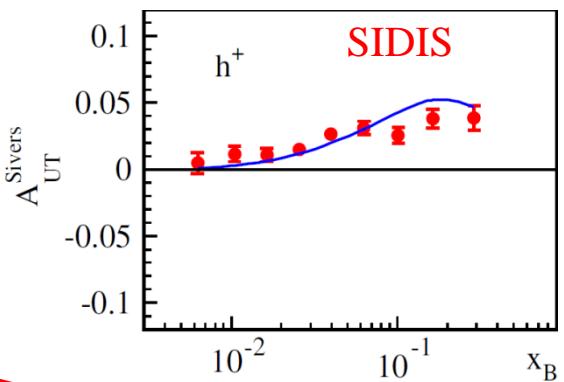
DGLAP (2016)

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



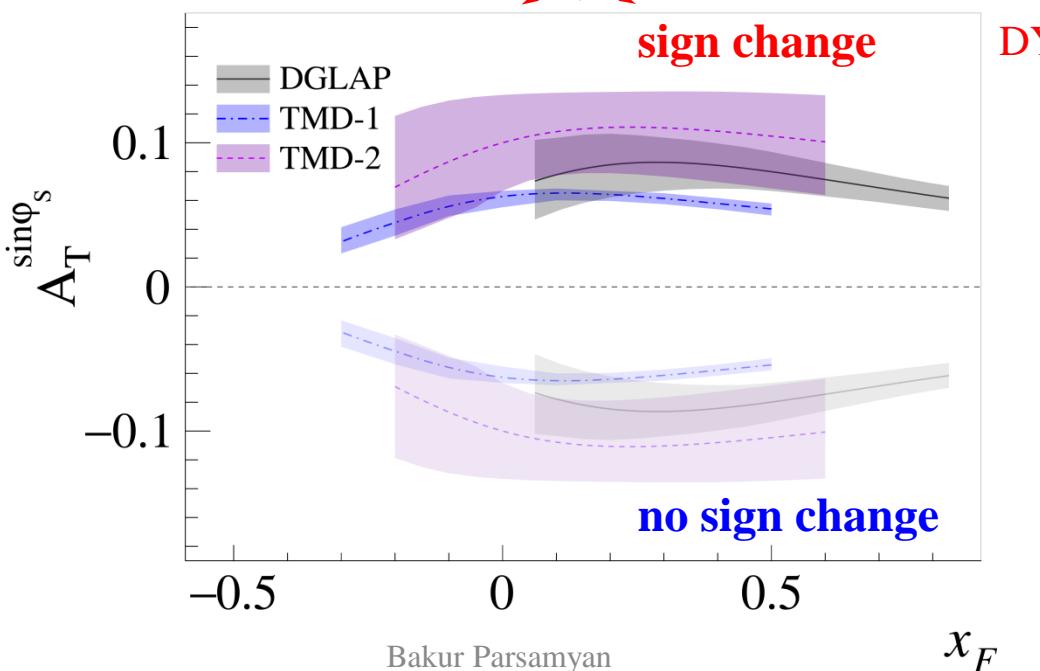
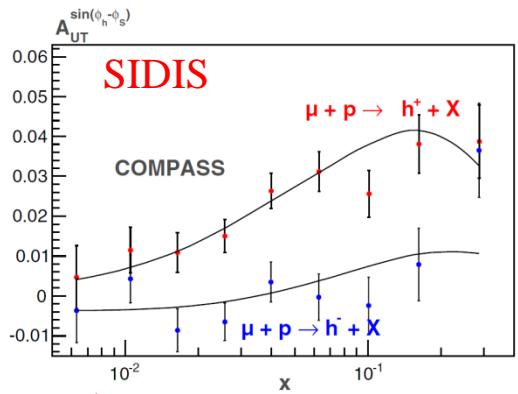
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



TMD-2 (2013)

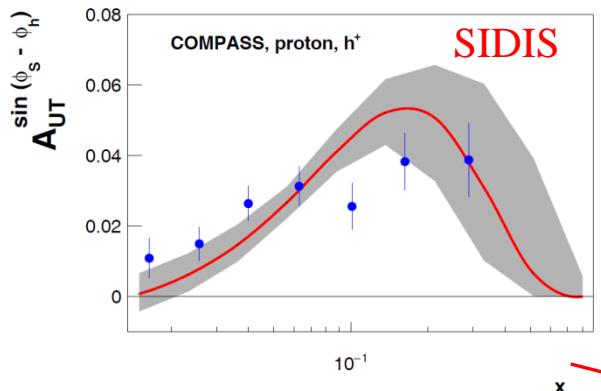
P. Sun, F. Yuan, PRD88, 114012



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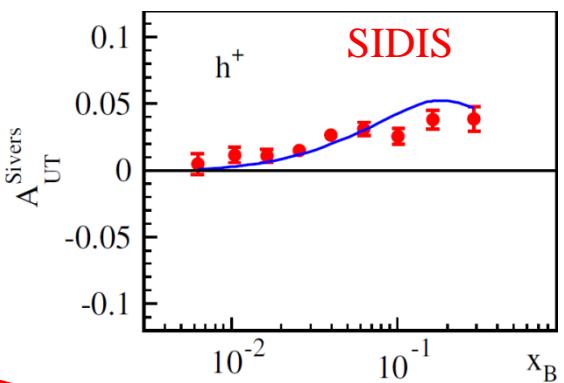
DGLAP (2016)

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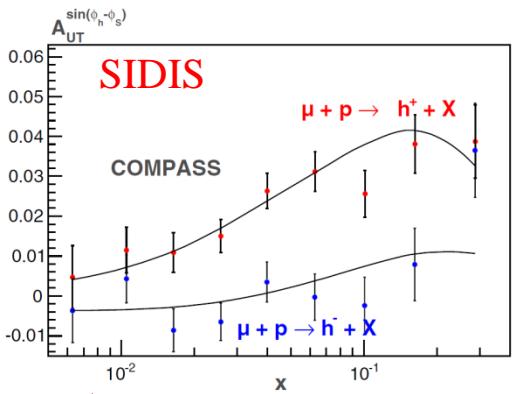
TMD-1 (2014)

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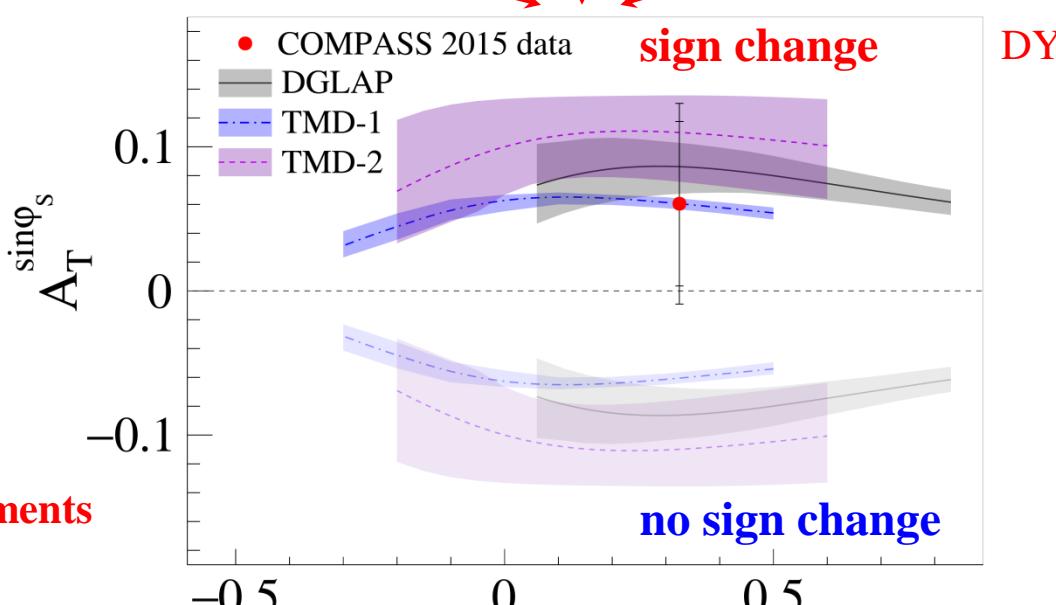
TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012



COMPASS

PRL 119, 112002 (2017)

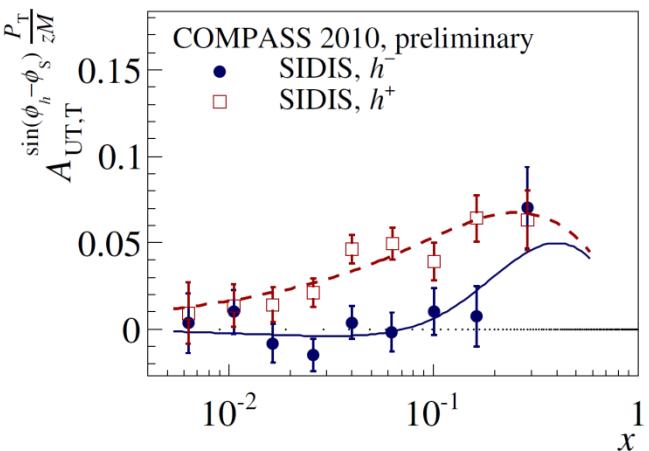


In 2018 – 2<sup>nd</sup> round of  
polarized DY measurements  
at COMPASS

# The $p_T$ ( $q_T$ ) – weighted SIDIS(DY) Sivers asymmetry

General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, PLB 406 (1997) 373)

F. Bradamante (COMPASS at SPIN-2016)  
[arXiv:1702.00621 \[hep-ex\]](https://arxiv.org/abs/1702.00621)



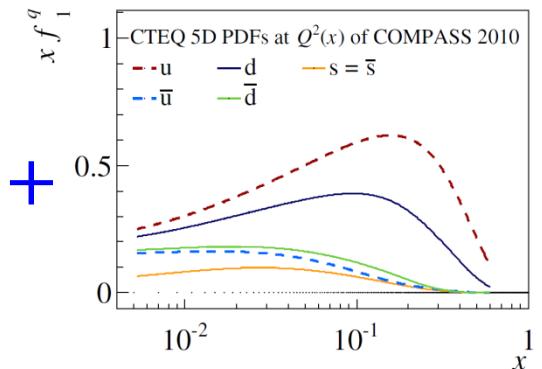
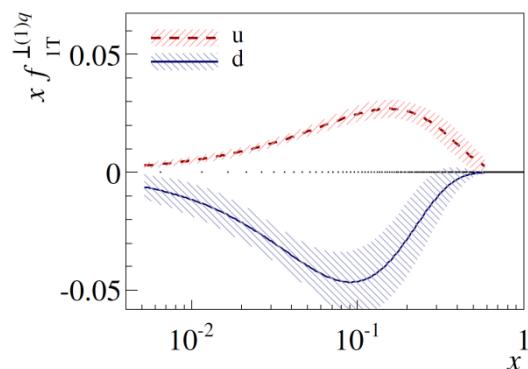
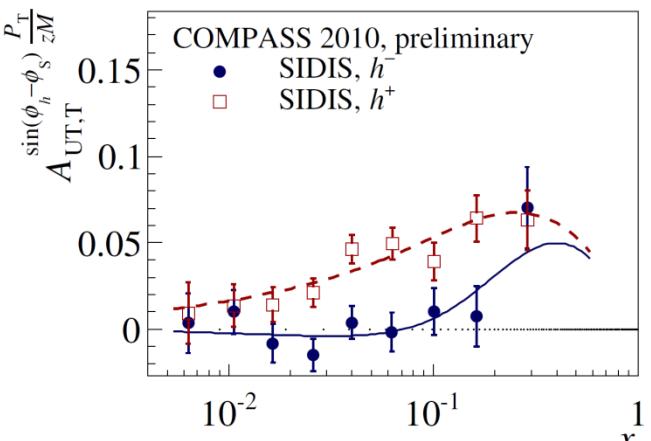
Sivers TSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

Sivers wTSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$

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[arXiv:1702.00621 \[hep-ex\]](https://arxiv.org/abs/1702.00621)



Sivers TSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

Sivers wTSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$

Sivers TSA in DY:  $A_T^{\sin \varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$

Sivers wTSA in DY:  $A_T^{\sin \varphi_S} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q (1)}$

Valence quark dominance  
 No  $Q^2$ -evolution for Sivers PDF

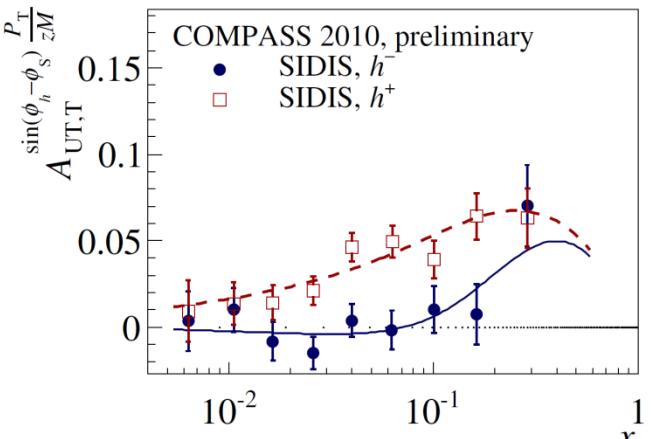


$$A_T^{\sin \varphi_S \frac{q_T}{M_P}} \approx \frac{f_{1T,p}^{\perp u (1)}}{f_{1,p}^u}$$

# The $p_T$ ( $q_T$ ) – weighted SIDIS(DY) Sivers asymmetry

General formalism was first introduced in 1997 (A. Kotzinian and P. Mulders, PLB 406 (1997) 373)

F. Bradamante (COMPASS at SPIN-2016)  
[arXiv:1702.00621 \[hep-ex\]](https://arxiv.org/abs/1702.00621)

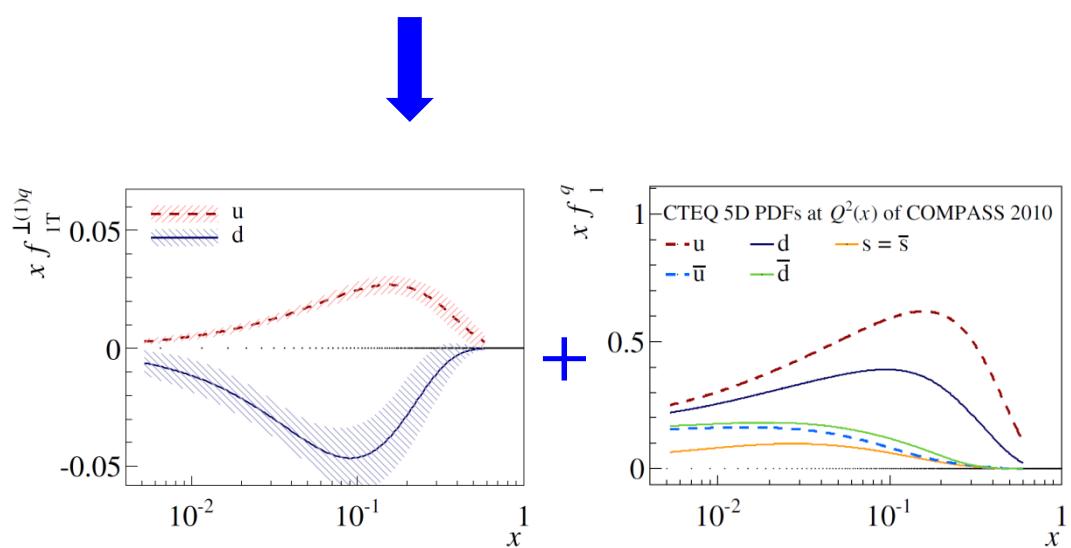


Sivers TSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

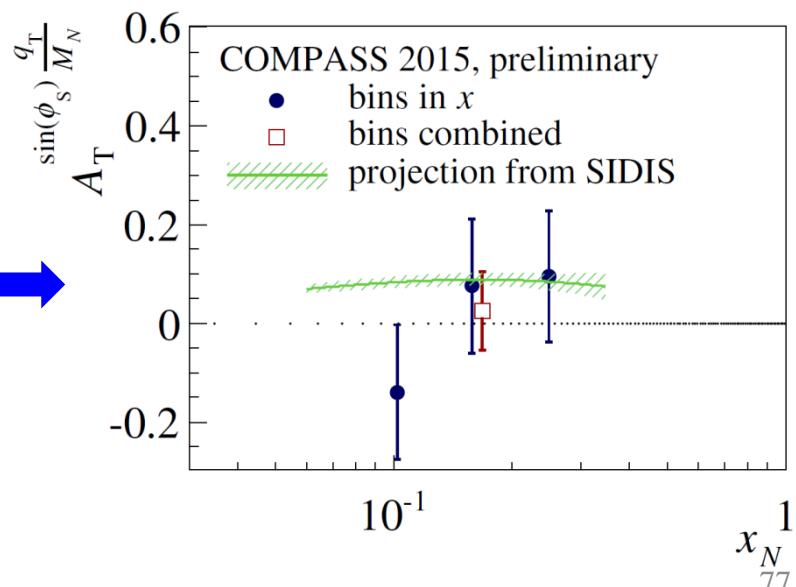
Sivers wTSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$

Sivers TSA in DY:  $A_T^{\sin \varphi_s} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$

Sivers wTSA in DY:  $A_T^{\sin \varphi_s} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q (1)}$



J. Matoušek (COMPASS at DSPIN-2017)  
[arXiv:1710.06497 \[hep-ex\]](https://arxiv.org/abs/1710.06497)



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

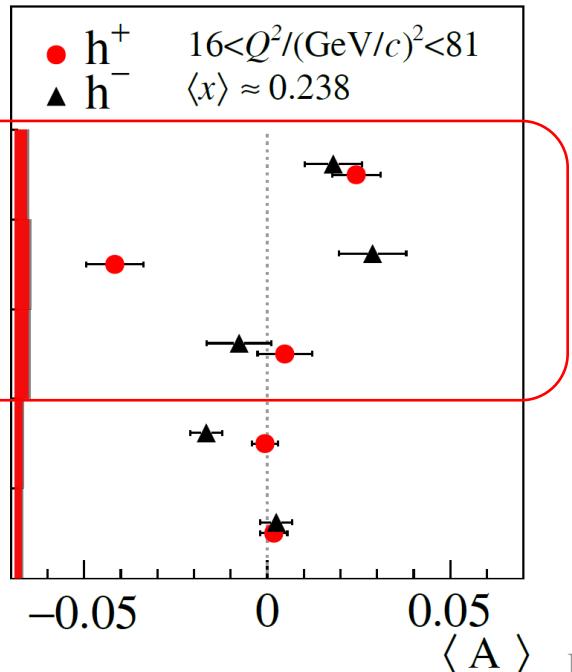
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

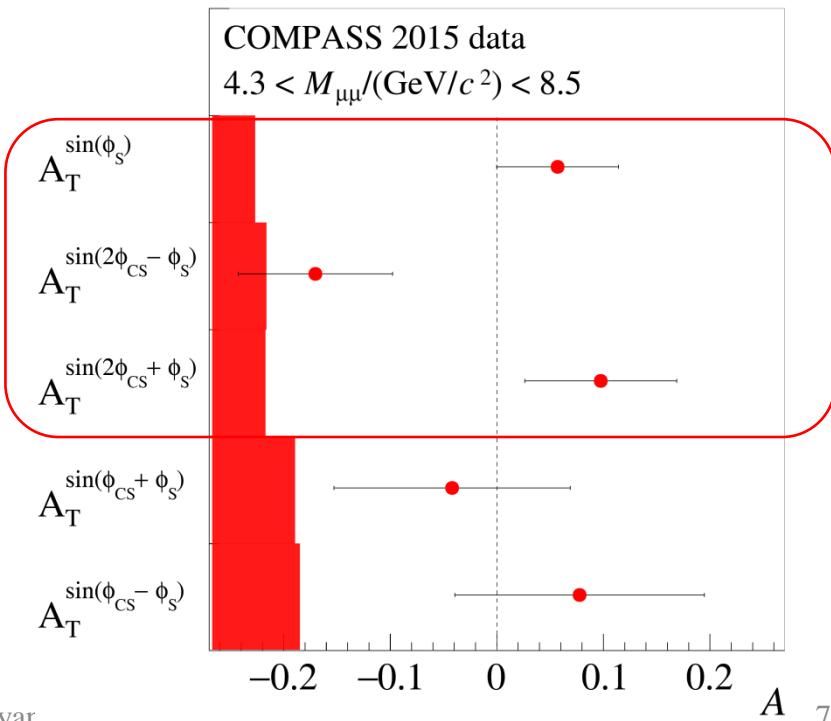
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

**COMPASS PLB 770 (2017) 138**



**COMPASS PRL 119, 112002 (2017)**





# Future long-term “COMPASS-like” experiment at the SPS-M2

[COMPASS beyond 2020](#) workshop, CERN, March 21-22, 2016

[Physics Beyond Colliders](#) kick-off workshop CERN, September 6-7, 2016

[IWHSS17](#) COMPASS workshop, Cortona, Italy, April 2-5, 2017

[Dilepton Productions with Meson and Antiproton Beams](#) workshop, ECT\*, Trento, Italy, November 2017

[Physics Beyond Colliders](#) annual workshop, CERN, November 21-22, 2017

[IWHSS18](#) – COMPASS workshop, Bonn, Germany, March 19-21, 2018

[Mini Workshop for a QCD Facility at the SPS after 2021](#) – CERN, 20 June 2018

[IWHSS19](#) – COMPASS workshop, Aveiro, Portugal, June 23-28, 2019

## XIV International Workshop on Hadron Structure and Spectroscopy

Longitudinal and Transverse Spin Structure of the Nucleon  
Fragmentation Functions  
Search for Glueballs, Hybrid Mesons and Multiquark States  
Meson Spectroscopy  
TMDs, GPDs and GTMDs  
New opportunities for physics beyond colliders  
Cosmic rays and accelerator physics



### Local Organizing Committee

Maxim Alexeev  
Antonio Amoroso  
Michela Antonini  
Riccardo Longo  
Danielle Panizzi (c.hat)  
Bakur Parsamyan

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@ iwhss17

**WHSS17**

April 2-5  
Cortona



### International Advisory Committee

Masao Anselmino (INFN/Uni/Torino, Italy)

Harut Avakian (JLAB, VA/USA)

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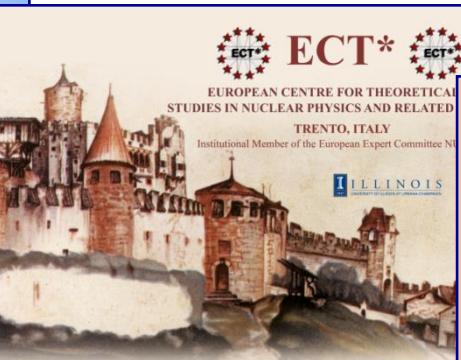
Jens Stephan Paul (TU München, Germany)

Jen-Cheh Peng (Univ. Illinois, USA)

Adam Schäfer (JGU Mainz, Germany)

Andrzej Sandacz (NCBI Warsaw, Poland)

Oleg Teryaev (JINR, Dubna, Russia)



Castello di Trento ("Trinità"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

### Dilepton Production with Meson and Antiproton Beams

Trento, November 6-10, 2017

#### Main Topics

Theoretical and experimental aspects of high-mass dilepton production with meson and antiproton beams.

Physics of partonic structures of pion and kaon.

Exclusive Drell-Yan process.

Opportunities to carry out new measurements on high-mass lepton pair productions using meson and antiproton beams.

#### Invited speakers

Vincenzo Andronico (Istituto ILLIUS, Italy); Mauro Anselmino (I.U.Torino, Italy); Enrico Polycarpou (CERN, Switzerland); Johannes Bernhard (CERN, Switzerland); Daniela Bozzo (INFN/Uni/Torino, Italy); Stan Brodsky (SLAC, USA); Jian-Ping Chen (IHEP, Beijing, China); Oleg Densler (CERN, Switzerland); Matja Grossi-Perdikaris (U Illinois); Boris Gruber (Tech U Munich); Aleksey Gusarov (JINR, Dubna); Cynthia Hajdukakis (IPN, Crete); Paul Helsinski (U. Xiangdong) & (U. Maryland/Shanghai Jiaotong U); Peter Kroll (U Wuppertal); Shunro Kumanou (KEK); Wally Meli (JLab); Hiroyuki Nomura (Chiba U); Bakur Parsamyan (U Turin); Bogdan Povh (U Heidelberg); Catalina Maniques Quintans (LPNHE, Paris); Paul Reimer (ANL); Craig Roberts (ANL); Takahiro Sawada (U Michigan); Ingo Schienbein (LPC/Paris); Rikardo Yoshida (U Tokyo)

#### Organizers

Jen-Cheh Peng (Department of Physics, University of Illinois at Urbana-Champaign); jcpeng@illinois.edu

Wen-Chang Lin (Institute of Physics, Academia Sinica); wclin@phys.sinica.edu.tw

Stephane Pritchcock (Nuclear Physics Division, BIFI, CEA Saclay); Stephane.Pritchcock@cea.fr

Oleg Teryaev (Bogoliubov Laboratory of Theoretical Physics, JINR); teryaev@theor.jinr.ru

Director of the ECT\*: Professor Joachim Wambach (ECT\*)

The ECT\* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento) and the funding agencies of EU Member and Associate States and has the support of the Department of Physics of the University of Trento. For local organization please contact: Drs. Carsten ECT\* Secretariat - Villa Tambosi - Strada delle Tollearie 26c - 38132 Viltellano (Trento) Tel. (+39-0461) 31421 Fax (+39-0461) 314276 E-mail: ect@ctesit.it or visit [www.ctesit.it](http://www.ctesit.it)

## IWHSS18

### XV International Workshop on Hadron Structure and Spectroscopy

March 19-21, 2018  
Bonn, Germany

@ iwhss18@physik.uni-bonn.de

✓ <https://cern.ch/iwhss-2018>

## Physics Beyond Colliders

The annual workshop of the Physics Beyond Colliders study group is to be held at CERN, Geneva, on 21-22 November, 2017.

mission of the study group, the workshop will highlight the opportunities offered by the CERN complex for future experiments that explore open questions in fundamental physics. The workshop will present the progress and development under investigation by the Physics-Beyond Colliders study group. It will stimulate and discuss new ideas.

Programme, registration and abstract submission, as well as the mandate can be found on the workshop web site: <https://indico.cern.ch/event/64428/>.

Jaekel, Mike Lamont, Connie Potter, Claude Vallée,

Transverse Spin Structure of the Nucleon  
TMD's, GPD's and GTMD's  
Meson Structure  
Meson Spectroscopy  
Search for Exotics

New Opportunities for fixed Target Physics



see Oleg's talk

# Conclusions

- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs
  - Recently COMPASS has performed first multidimensional analysis of SIDIS proton TSAs: **PLB 770 (2017) 138**
    - No hints for significant  $Q^2$ -dependences of Sivers and Collins TSAs
    - Apart from Sivers and Collins effects non-zero signal was observed for *twist-2*  $A_{LT}^{\cos(\phi_h - \phi_S)}$  and *subleading-twist*  $A_{UT}^{\sin\phi_h}$  TSAs
  - COMPASS has measured SIDIS proton LSAs with unprecedented precision
    - *twist-2*  $A_{UL}^{\sin^2\phi_h}$  asymmetry seem to exhibit a Collins-like behavior
    - Significant effect was observed for *subleading-twist*  $A_{UL}^{\sin\phi_h}$  LSA
- In 2015 COMPASS has successfully collected first ever polarized DY data  
**PRL 119, 112002 (2017)**
  - A second year of polarized DY data-taking will take place in 2018
- COMPASS-II proposal addendum: SIDIS run in 2021 with transversely polarized deuteron target was recently **approved!**
- Possible future experiment at the SPS M2 beam line is being actively discussed
  - New experiment beyond 2021, the LOI will become public soon
    - Particular attention is given to possible Drell-Yan measurements

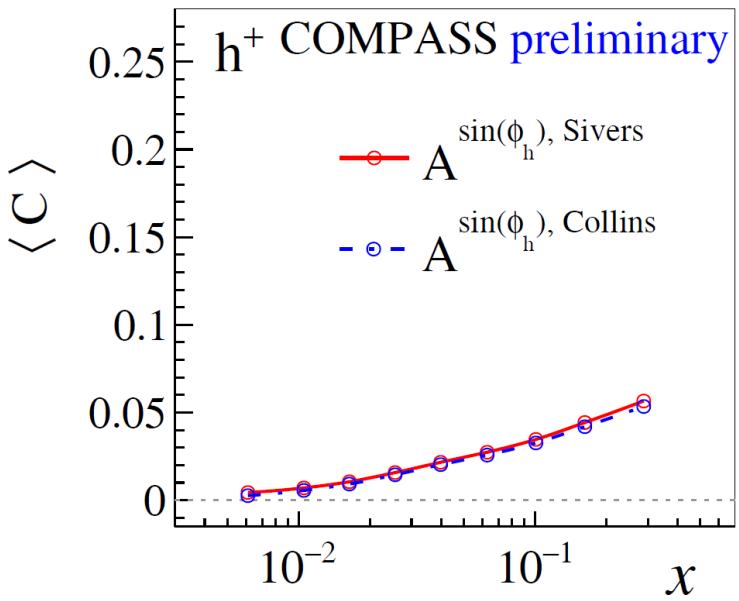


# Spare slides

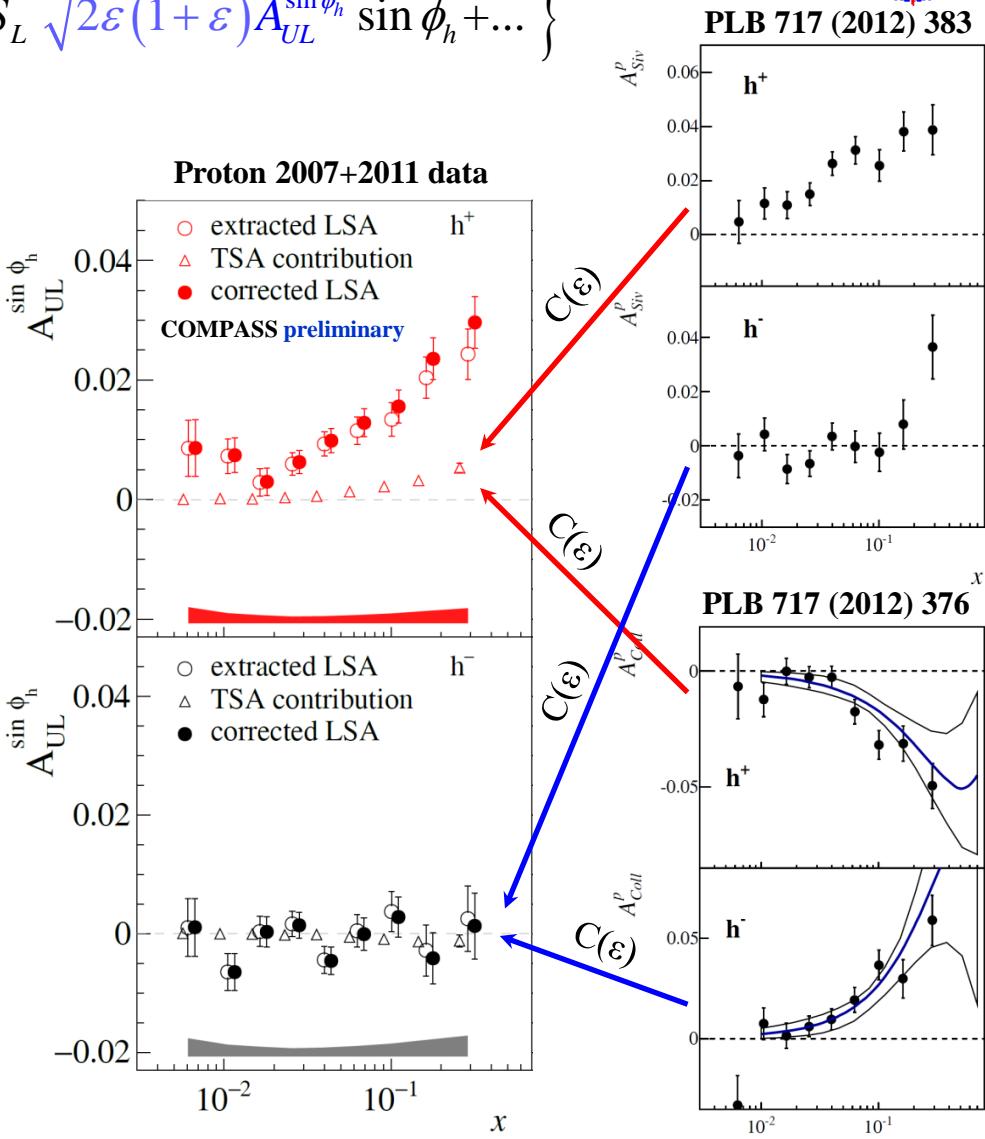
# The $A_{UL}^{\sin\phi_h}$ asymmetry

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \dots \right\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$



- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+$ ,  $h^-$  compatible with zero, clear  $z$ -dependence**



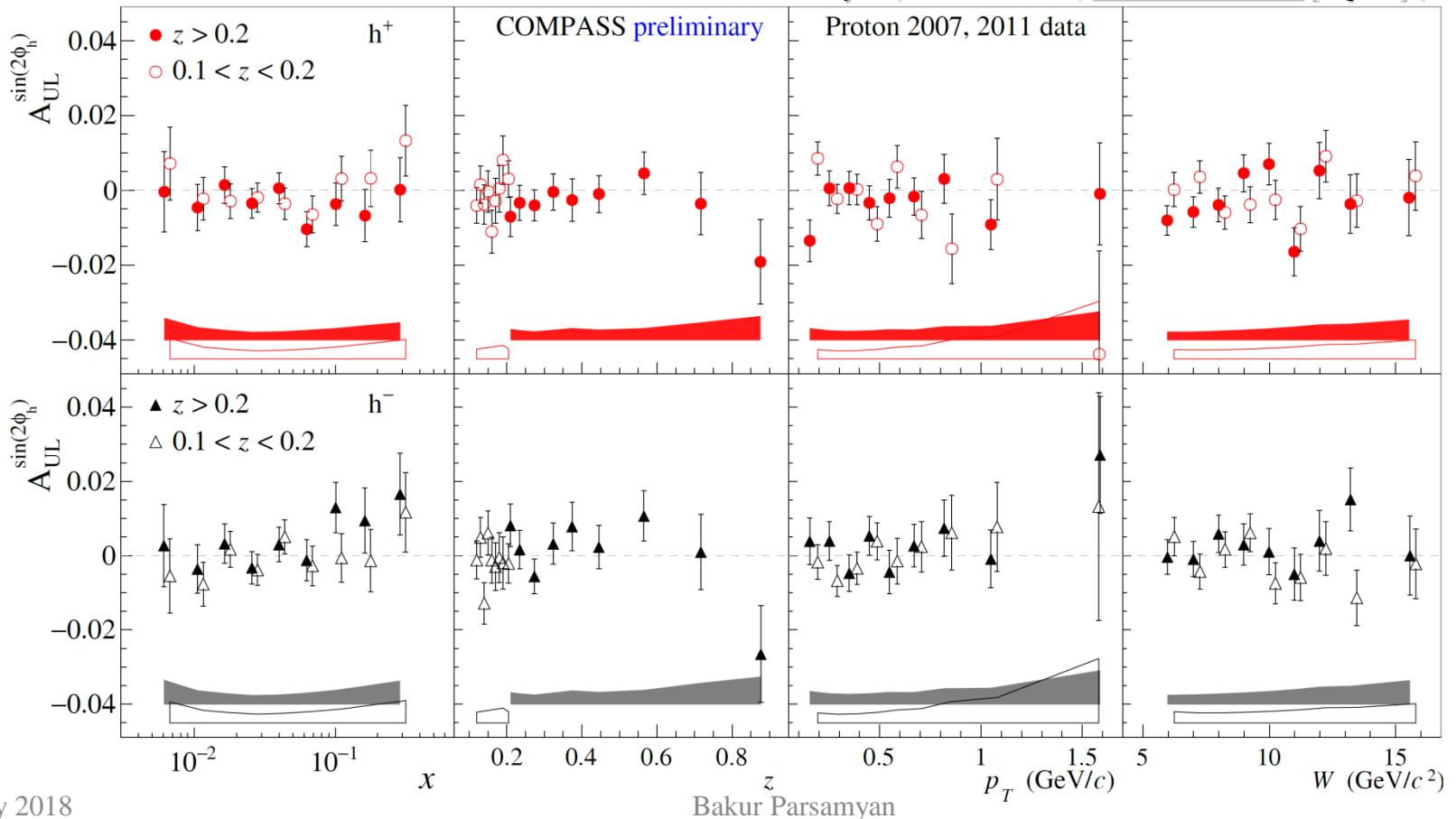
# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + \dots \right\}$$

$$F_{UL}^{\sin 2\phi_h} = C \left\{ -\frac{2(\hat{h} \cdot \mathbf{p}_T)(\hat{h} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

- Only “twist-2” ingredients
- Additional  $p_T$ -suppression

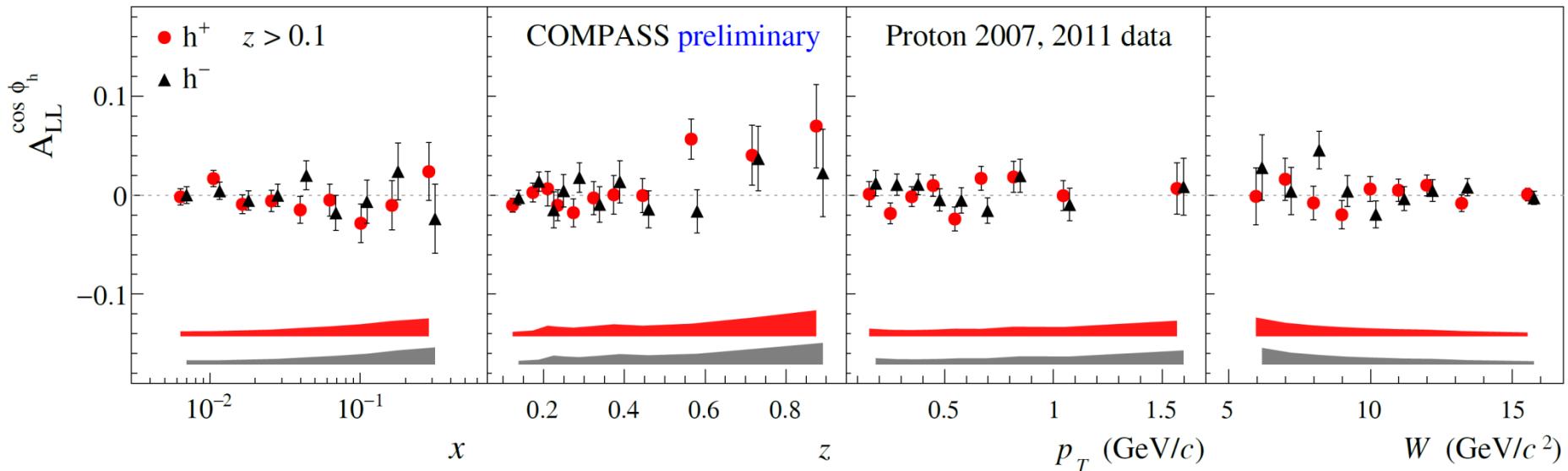
B. Parsamyan (for COMPASS) [arXiv:1801.01488 \[hep-ex\]](https://arxiv.org/abs/1801.01488) (DIS-2017)



# The $A_{LL}^{\cos\phi_h}$ asymmetry

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \dots \right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right. \\ \left. + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



- Various different “twist” ingredients,
- Q-suppression

# SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

$$\left. + S_L \begin{bmatrix} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \end{bmatrix} \right\}$$

$$+ S_L \lambda \begin{bmatrix} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \end{bmatrix} \right\}$$

**COMPASS collected large amount of L-SIDIS data  
Unprecedented precision!**

$A_{UL}^{\sin\phi_h}$

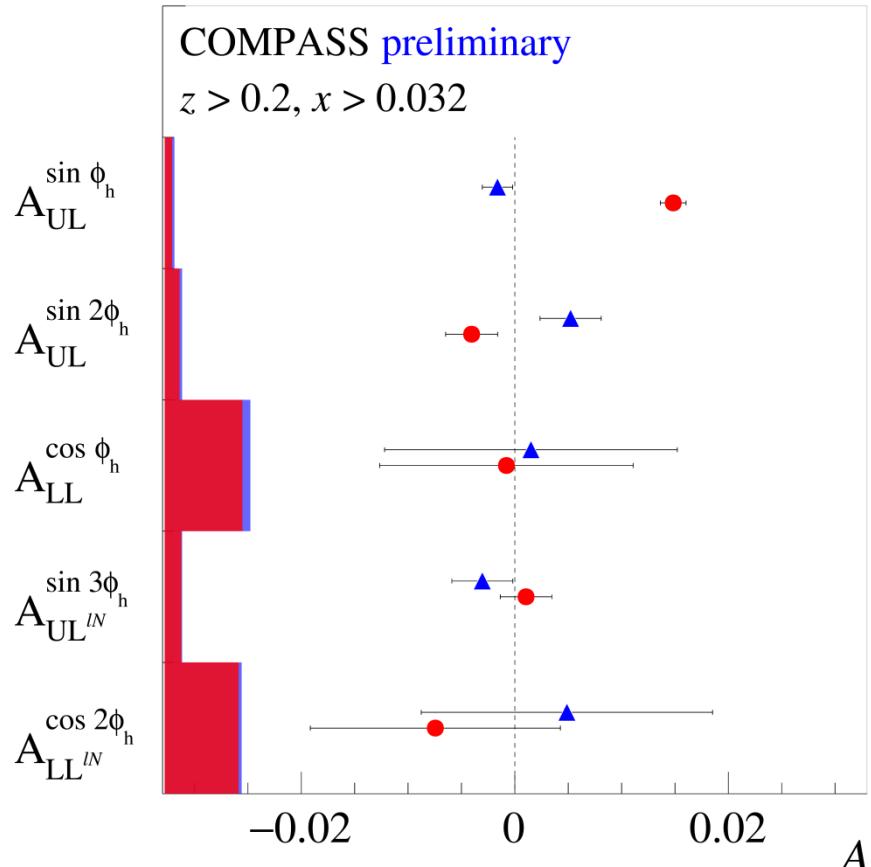
- Q-suppression, Various different “twist” ingredients
- Sizable TSA-mixing
- **Significant  $h^+$  asymmetry, clear  $z$ -dependence,**
- **$h^-$  compatible with zero**

$A_{UL}^{\sin 2\phi_h}$

- Only “twist-2” ingredients
- Additional  $p_T$ -suppression
- **Compatible with zero, in agreement with models**
- **Collins-like behavior?**

$A_{LL}^{\cos\phi_h}$

- Q-suppression, Various different “twist” ingredients
- **Compatible with zero, in agreement with models**

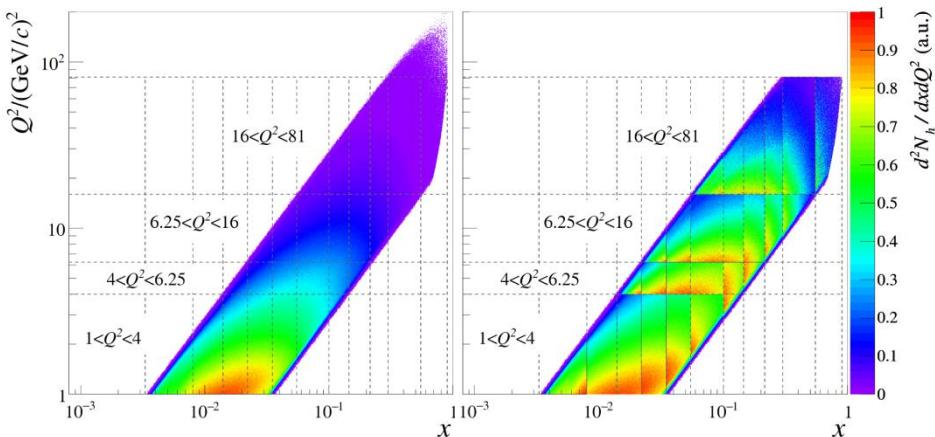
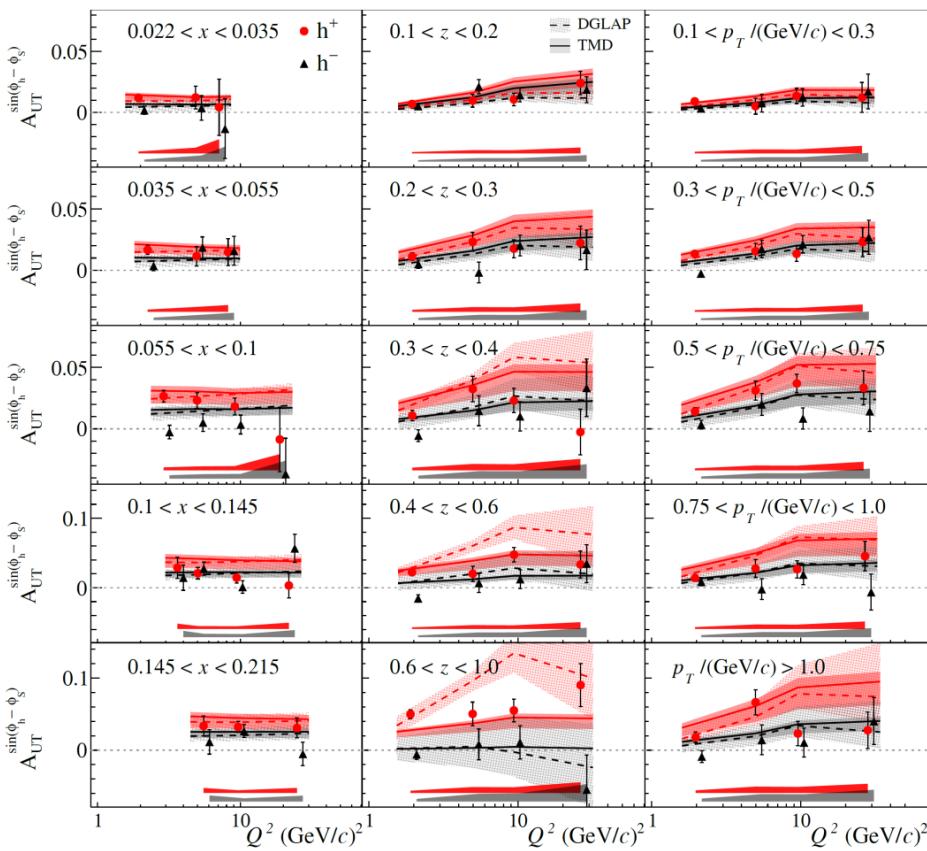


# SIDIS Sivers TSA in COMPASS Drell-Yan Q<sup>2</sup>-ranges

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

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

COMPASS PLB 770 (2017) 138



Multi-dimensional input for TMD evolution studies

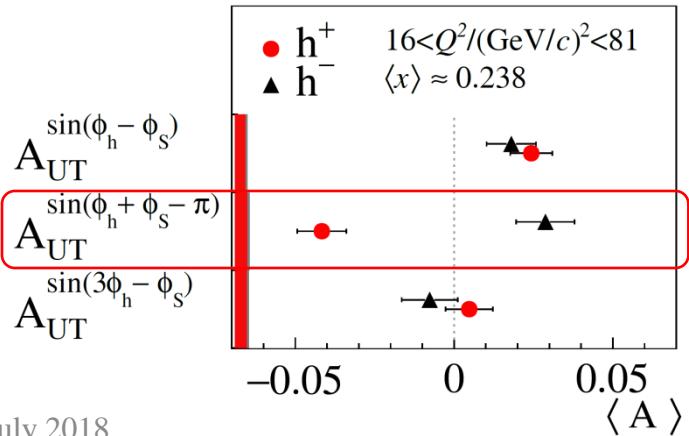
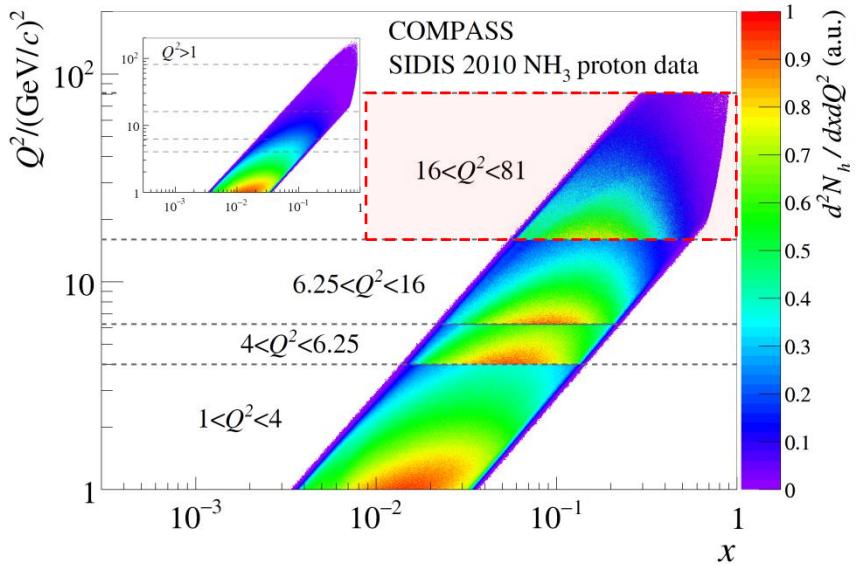
- No clear Q<sup>2</sup>-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

The solid (dashed) curves represent the calculations for TMD (DGLAP) evolution for the Sivers TSAs based on the best fit of 1D COMPASS and HERMES data from **Phys. Rev. D86 (2012) 014028** by M. Anselmino et al.

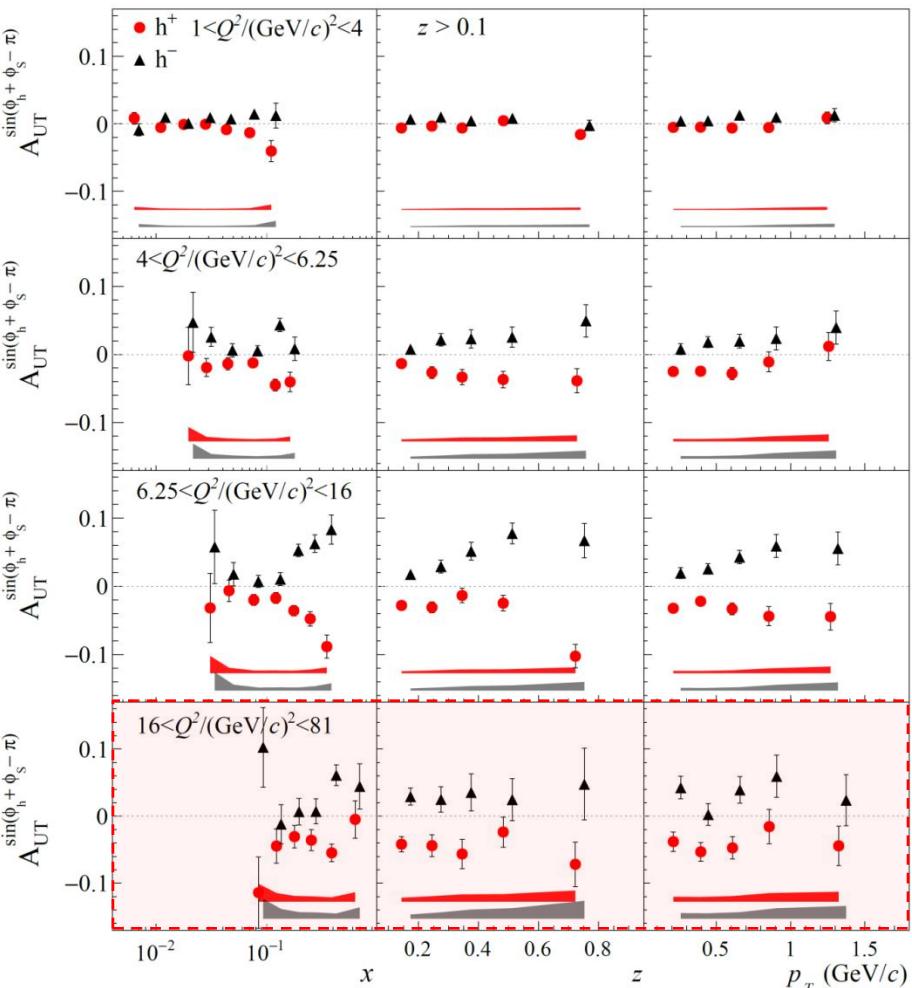
# SIDIS Collins TSA in COMPASS Drell-Yan Q<sup>2</sup>-ranges

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

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



**COMPASS PLB 770 (2017) 138**



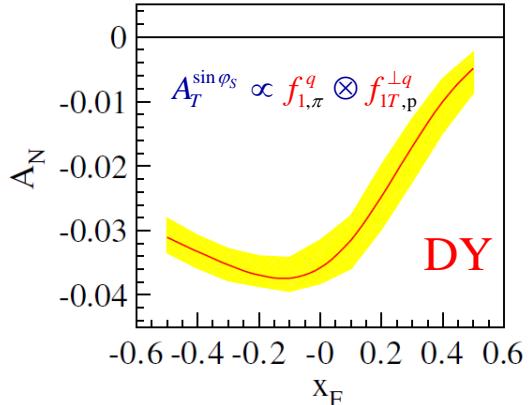
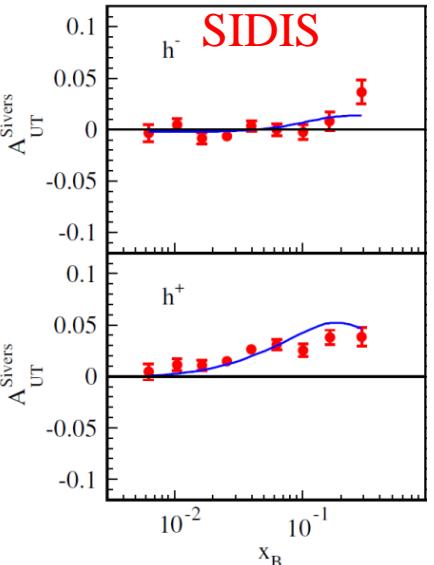
# SIDIS TSAs (Sivers)

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

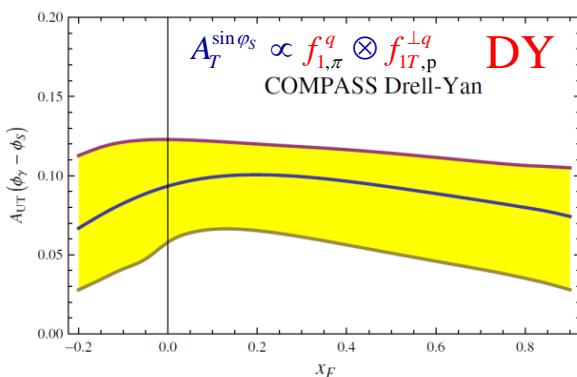
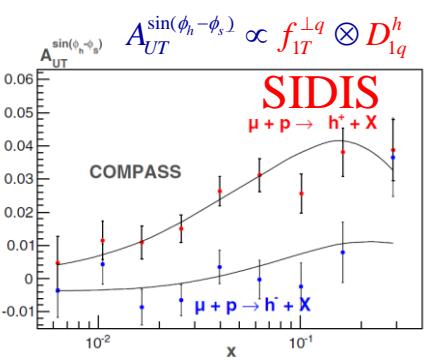
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- 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  
( $Q^2$  is different by a factor of  $\sim 2$ - $3$ )
- **$Q^2$ -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**

M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,  
**PRD 89 074013 (2014)**



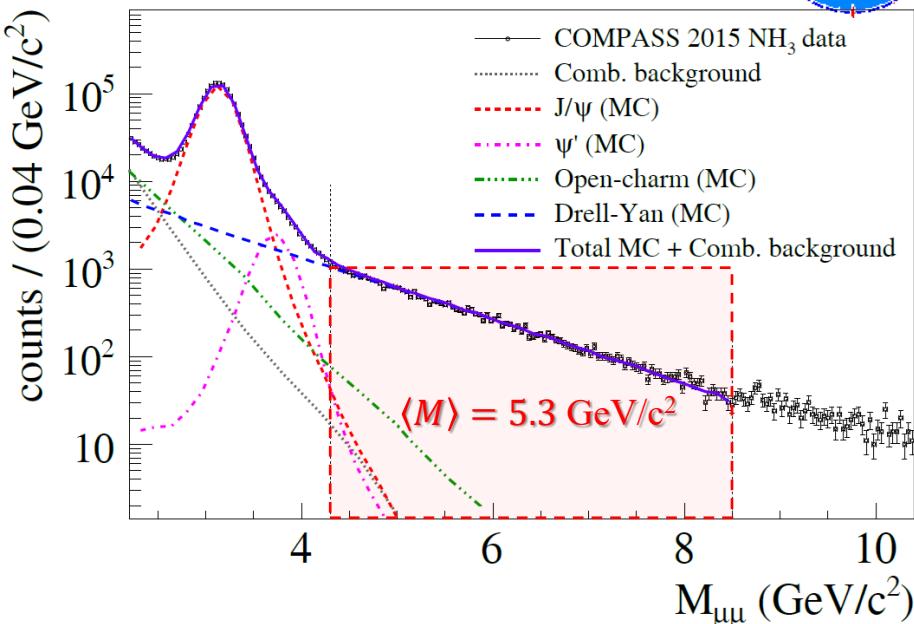
P. Sun and F. Yuan, **PRD 88 11, 114012 (2013)**



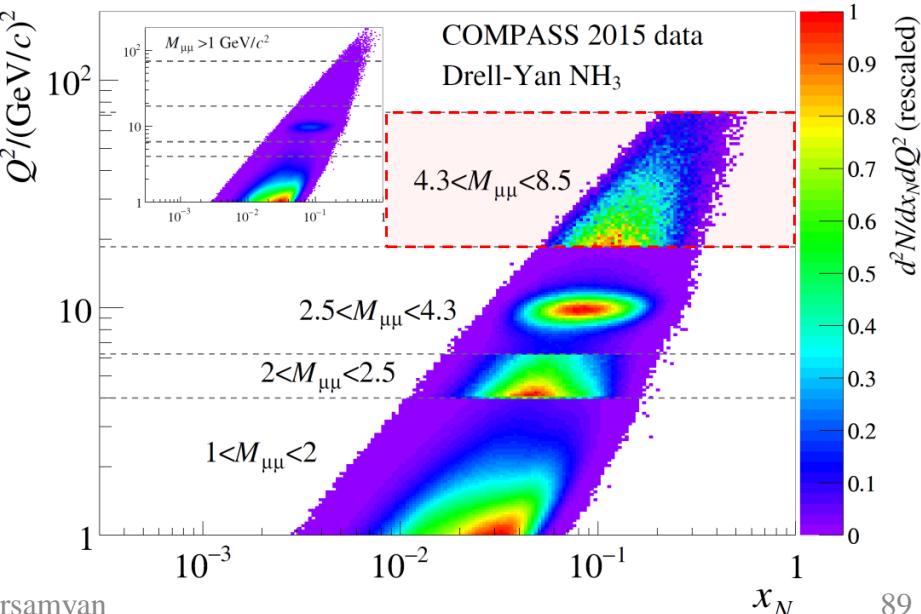
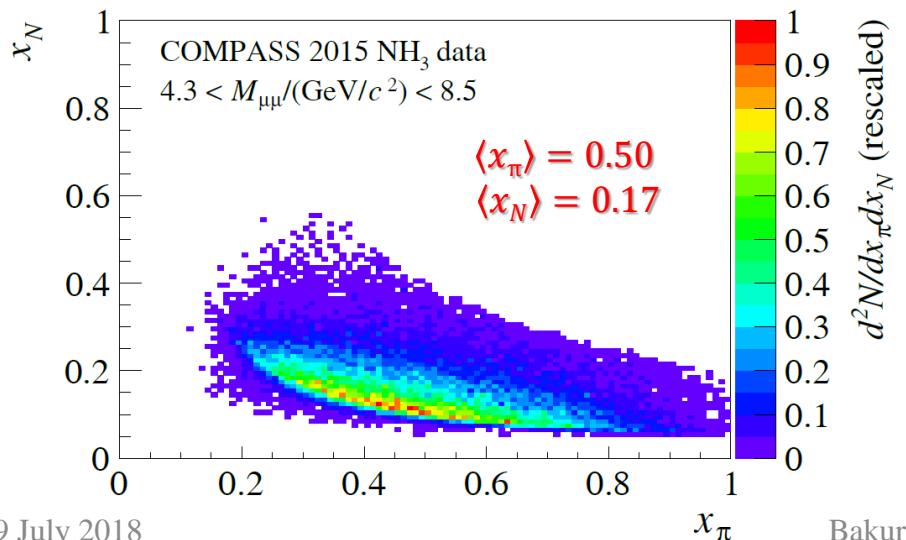
# COMPASS DY: high mass range

- $1.0 < M / (\text{GeV}/c^2) < 2.0$  “Low mass”
  - Large background contamination, combinatorial, Open-charm ( $B$ )  $D\bar{D}$ ,  $B\bar{B}$ ,  $\pi$ ,  $K$  decays
- $2.0 < M / (\text{GeV}/c^2) < 2.5$  “Intermediate mass”
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M / (\text{GeV}/c^2) < 4.3$  “Charmonia mass”
  - Strong  $J/\psi$ -signal → study of  $J/\psi$  physics
  - Good signal/background
- $4.3 < M / (\text{GeV}/c^2) < 8.5$  “High mass”
  - Low DY cross-section
  - Beyond charmonium region, background  $< 3\%$
  - Valence region → largest asymmetries

Final sample: 35 000 dimuons in HM



HM events are in the valence quark range



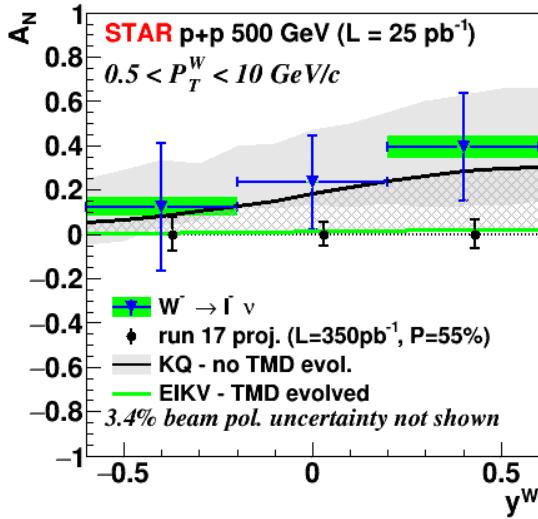
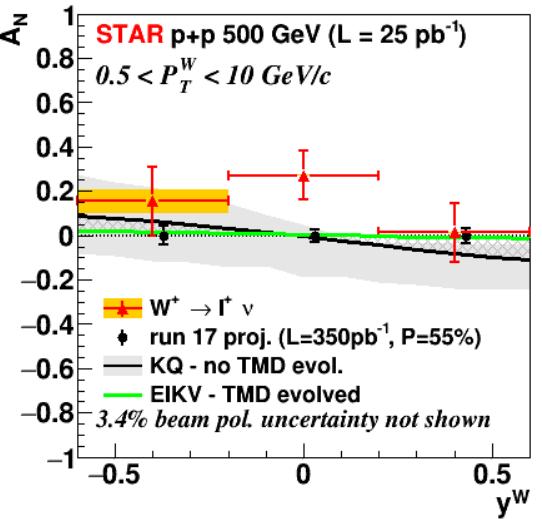
# SIDIS TSAs (Sivers)

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

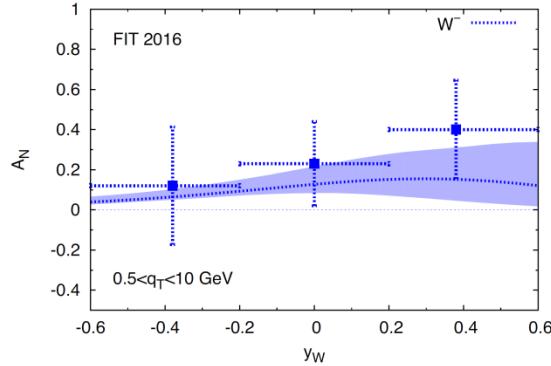
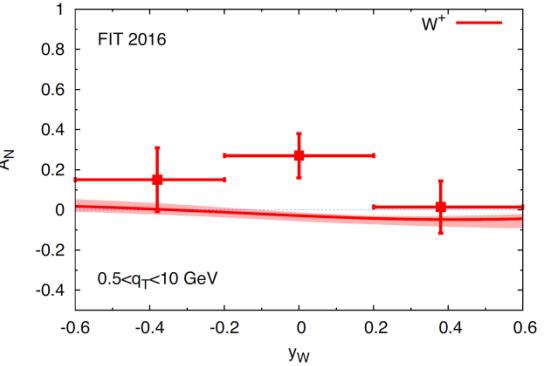
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- 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  
( $Q^2$  is different by a factor of  $\sim 2$ -3)
- **$Q^2$ -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**
- First experimental investigation of Sivers-non-universality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

STAR collaboration: PRL 116, 132301 (2016)



M. Anselmino et al., JHEP 1704 (2017) 046 (no TMD evolution)



Lorentz-invariance relations

The "bag" model, "spectator" model, "light-cone constituent quark" model, "chiral quark soliton" model, "covariant parton" model with intrinsic 3D-symmetric parton orbital motion, "quark-traget" model