



# The spin program of the COMPASS experiment: recent results and plans

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TAURINENSIS



*on behalf of the COMPASS Collaboration*

**QCD Evolution 2018**  
**International workshop**  
**Santa Fe, NM, US**  
**May 20 – 24, 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 (20 years)
- Taking data since 2002

### Wide physics program COMPASS-I

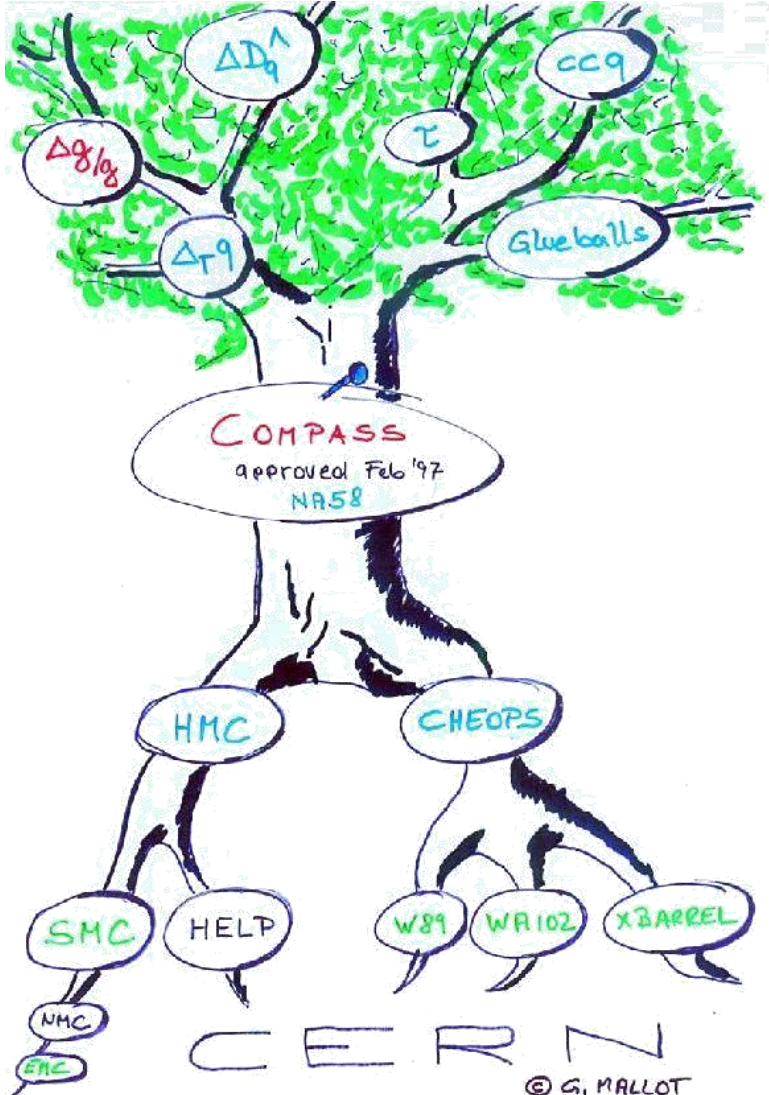
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

### 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...



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



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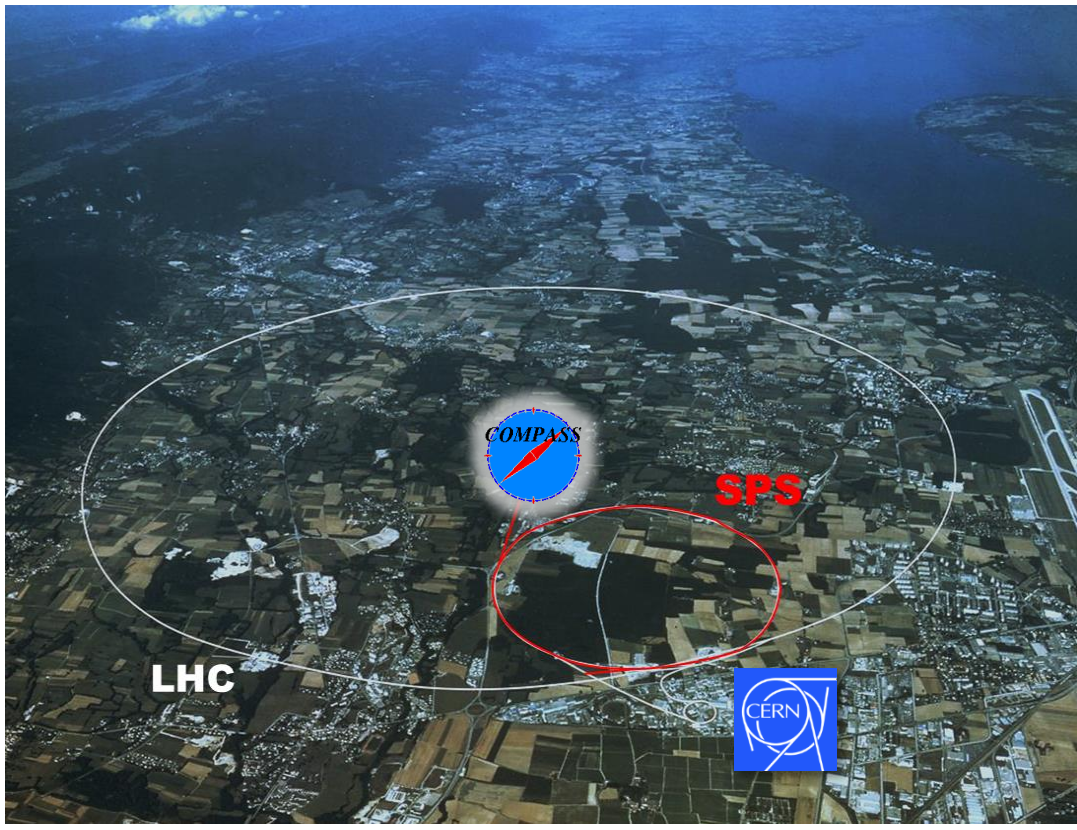
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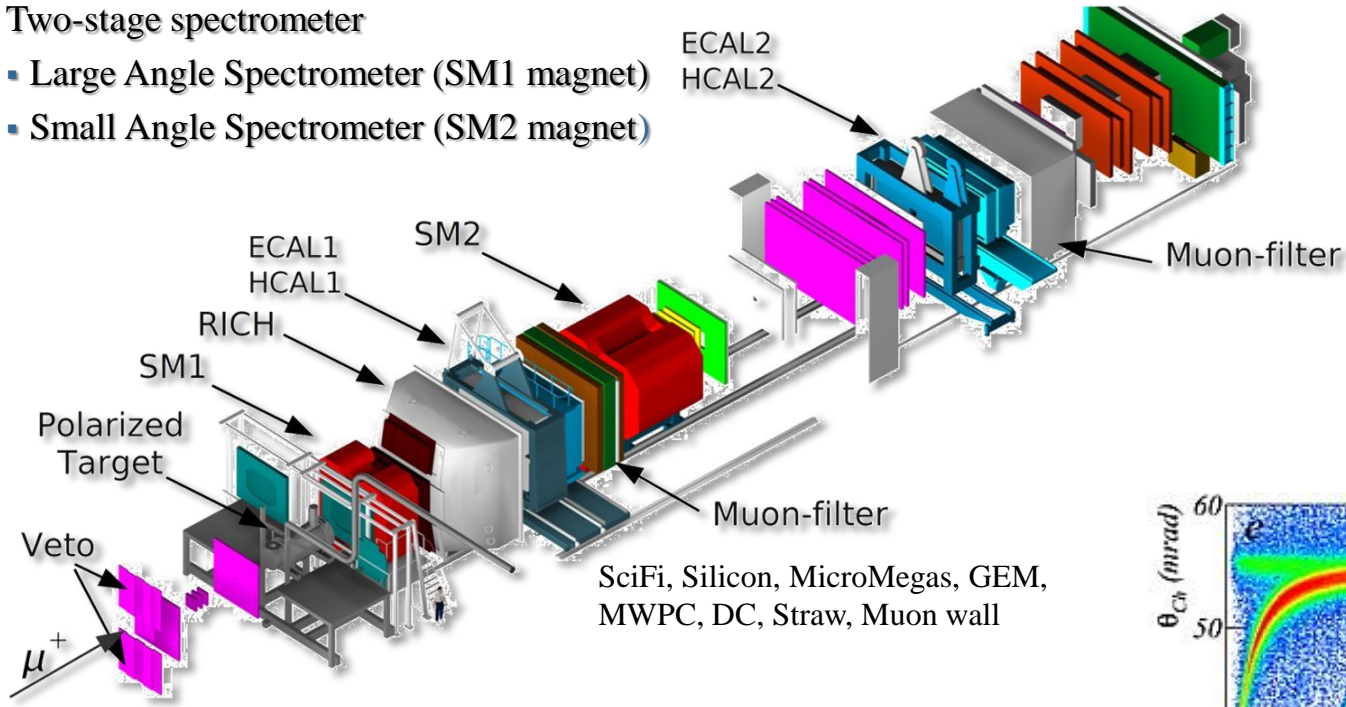
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# COMPASS experimental setup: Phase I (muon program)

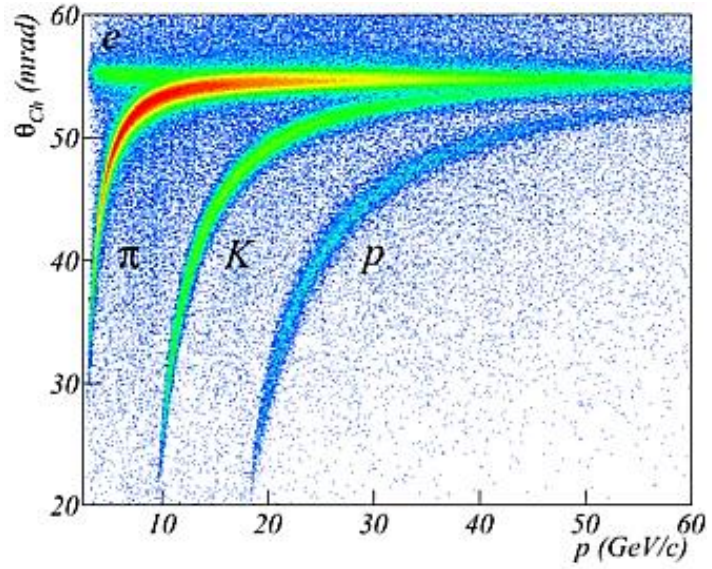
## Two-stage spectrometer

- 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

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



## 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  $\text{NH}_3$ )

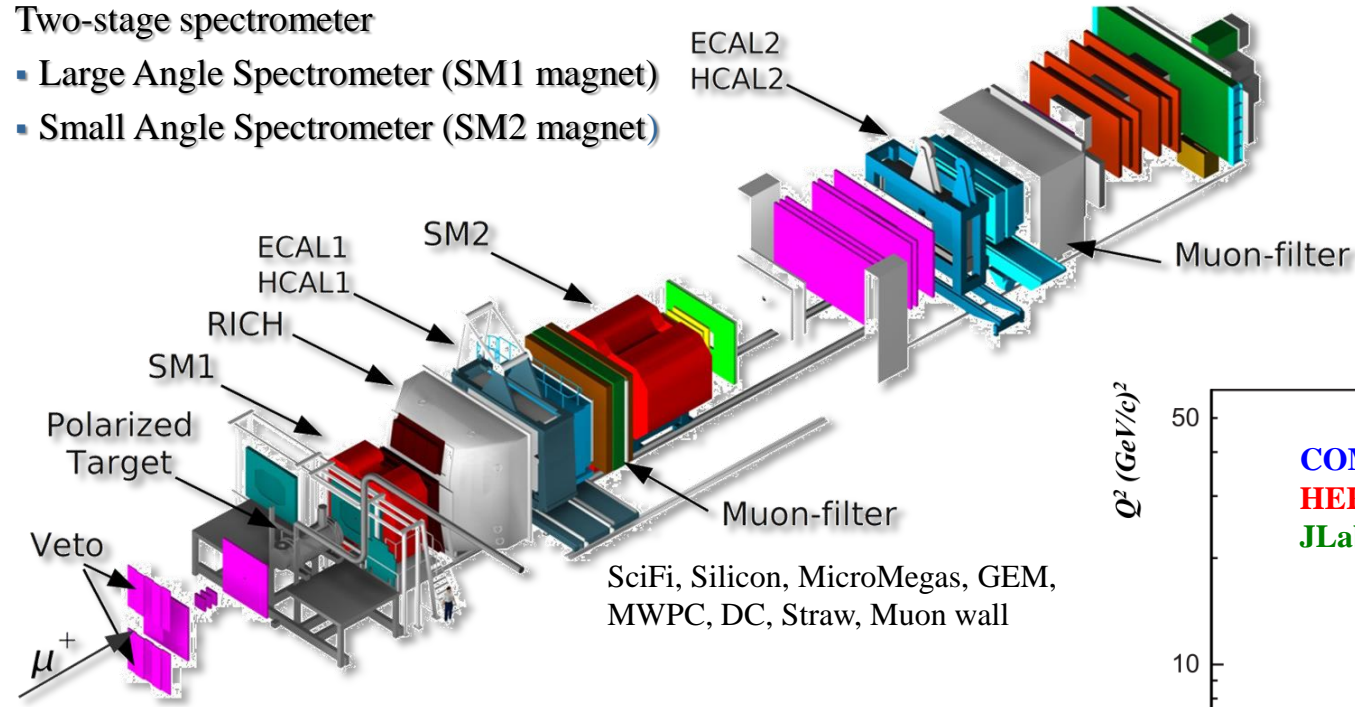
- ${}^6\text{LiD}$  2-cell configuration. Polarization (L & T)  $\sim 50\%$ ,  $f \sim 0.38$
- $\text{NH}_3$  3-cell configuration. Polarization (L & T)  $\sim 80\%$ ,  $f \sim 0.14$



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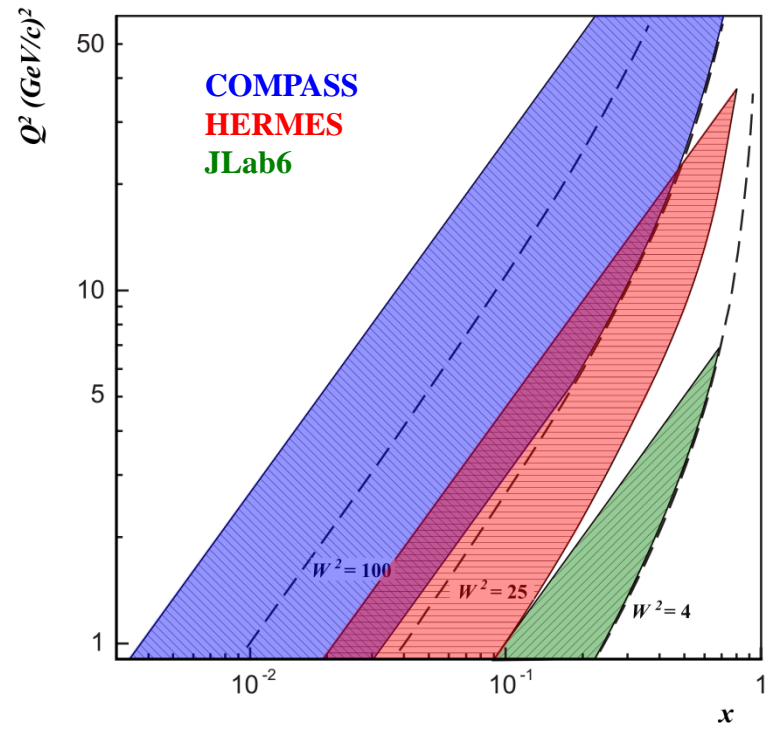


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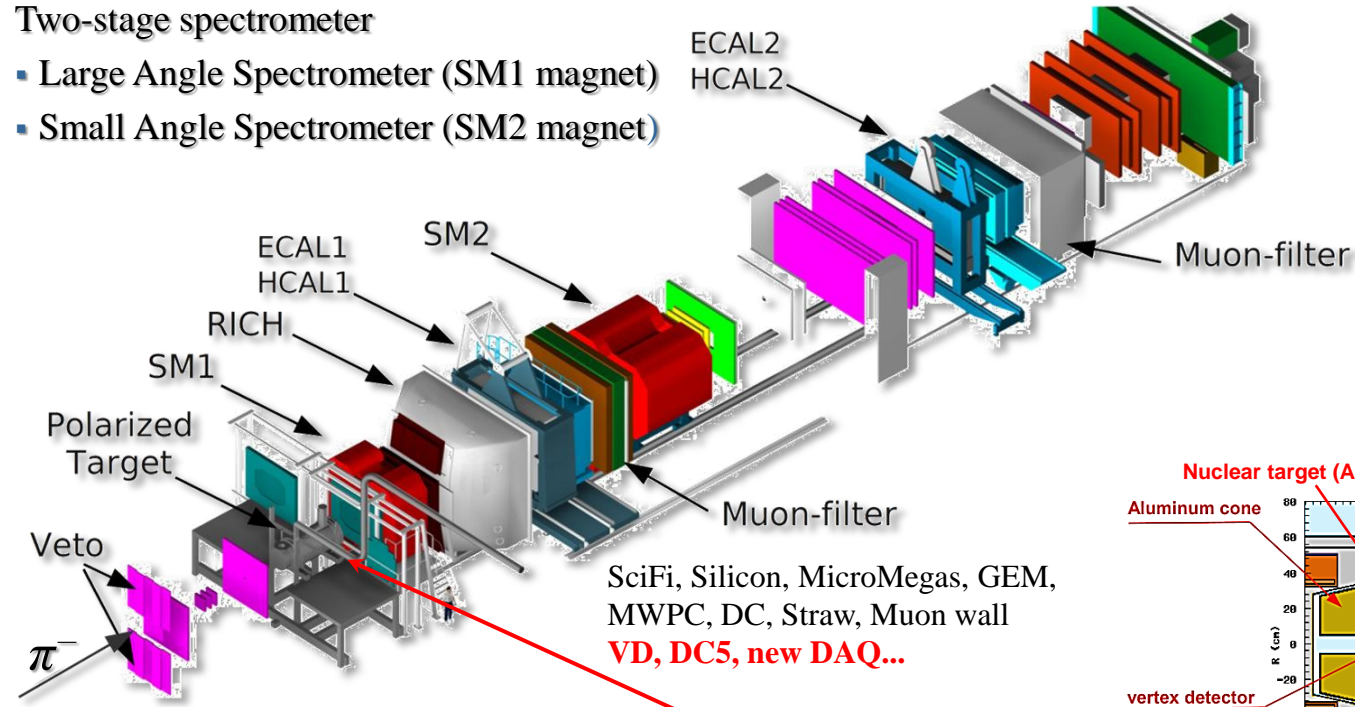




# COMPASS experimental setup: Phase II (DY program)

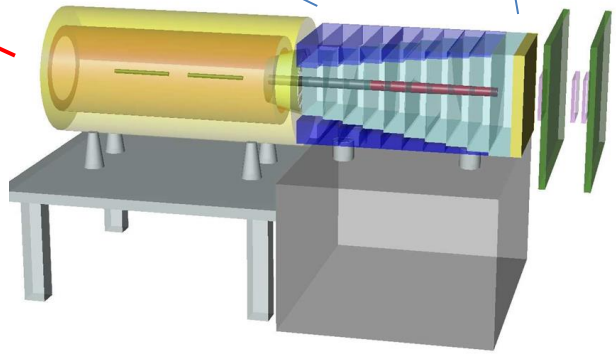
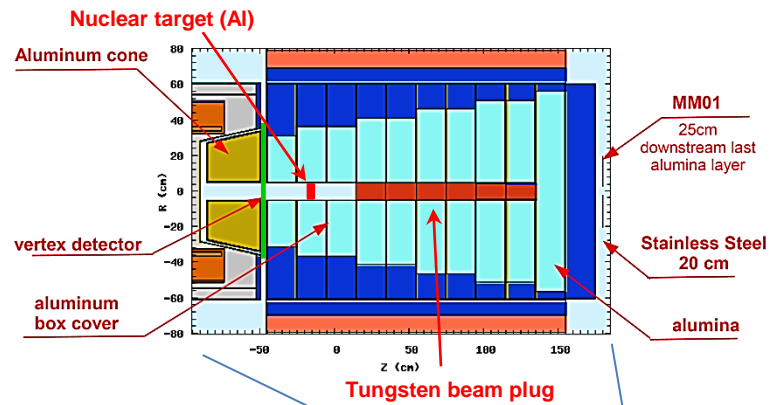
## Two-stage spectrometer

- 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

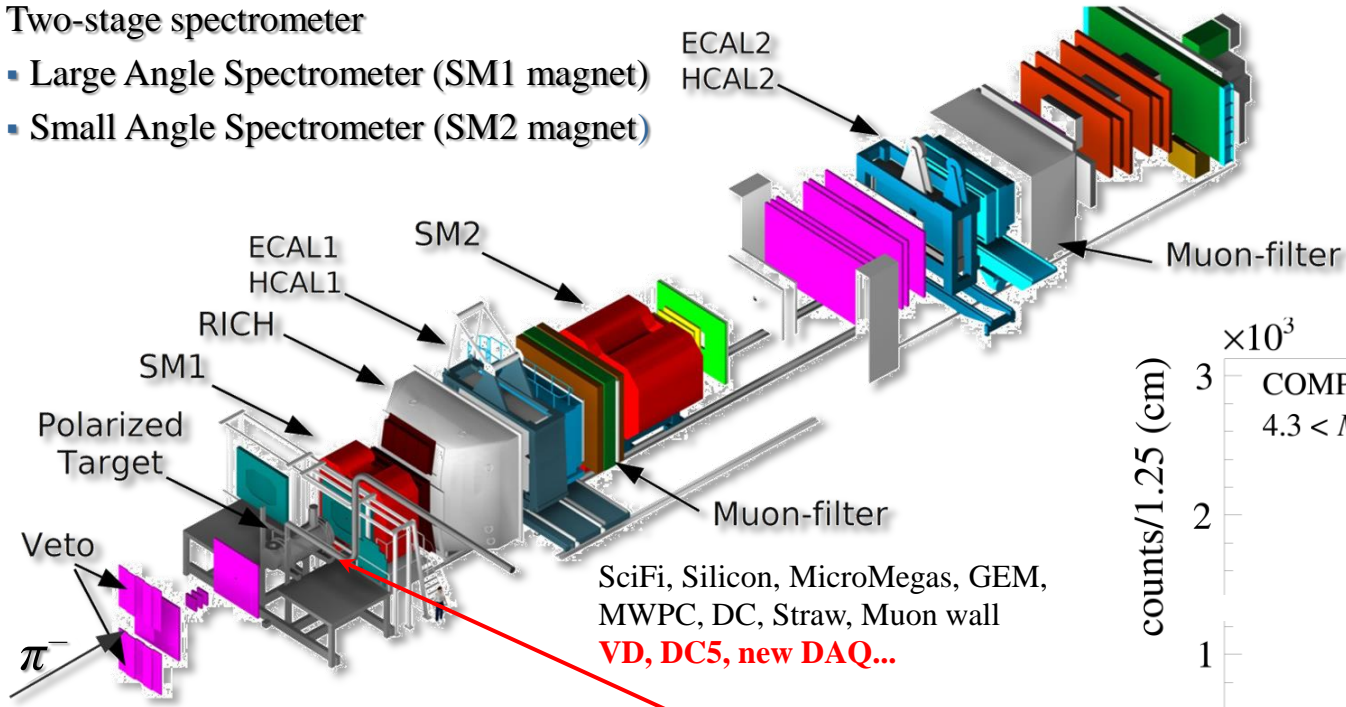
- $NH_3$  2-cell configuration. Polarization  $T \sim 73\%$ ,  $f \sim 0.18$



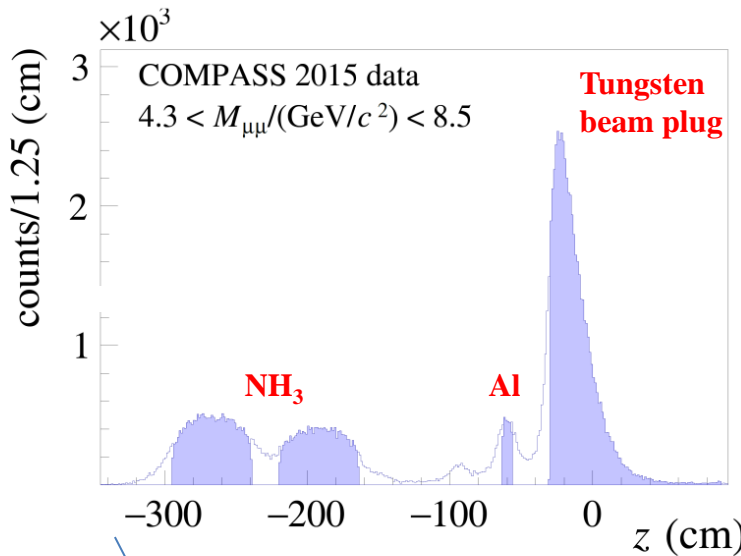
# COMPASS experimental setup: Phase II (DY program)

## Two-stage spectrometer

- Large Angle Spectrometer (SM1 magnet)
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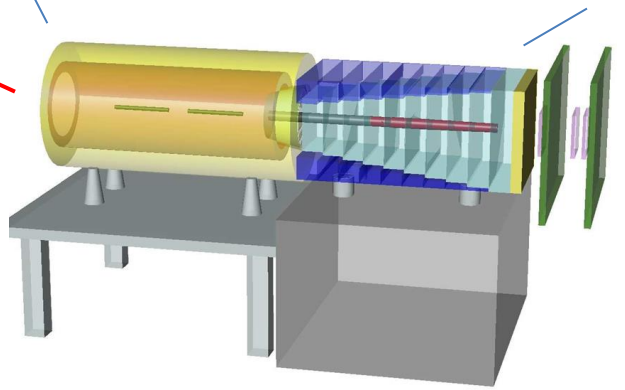
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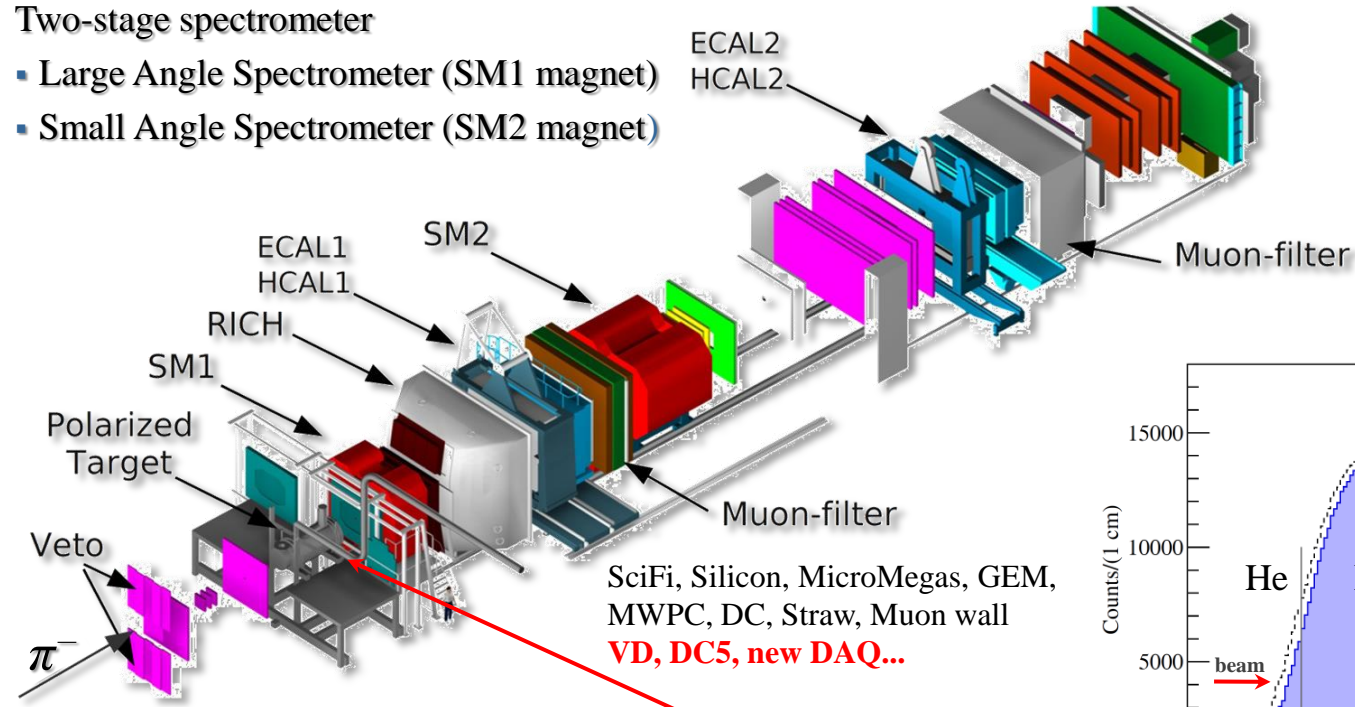




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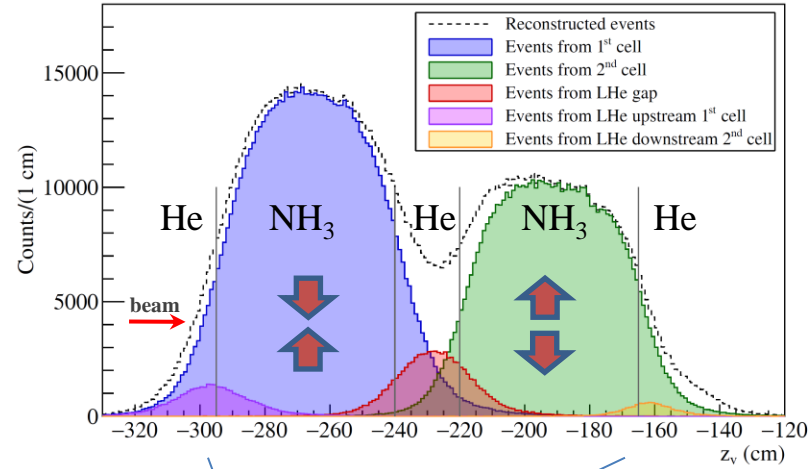
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SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall  
**VD, DC5, new DAQ...**



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

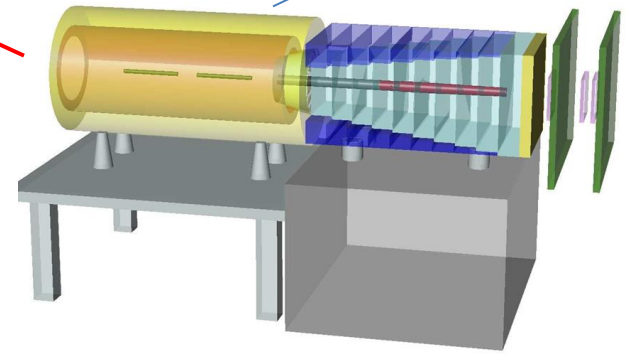
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Energy: 190 GeV/c, Intensity:  $10^8 \pi/s$

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• **Data is collected simultaneously with both target spin orientations**  
**Periodic polarization reversal to minimize systematic effects**





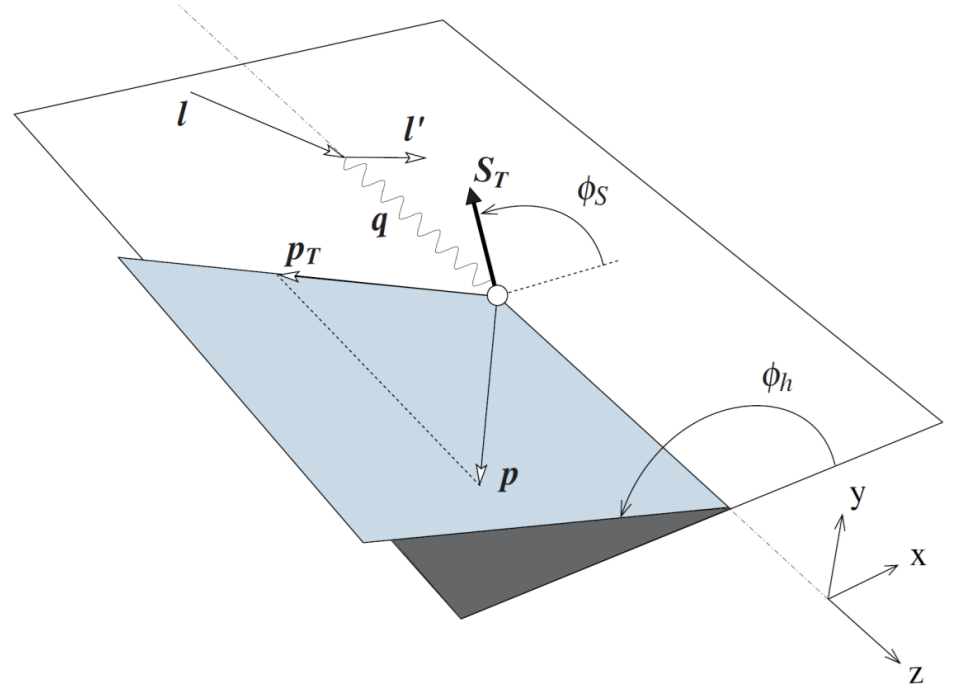
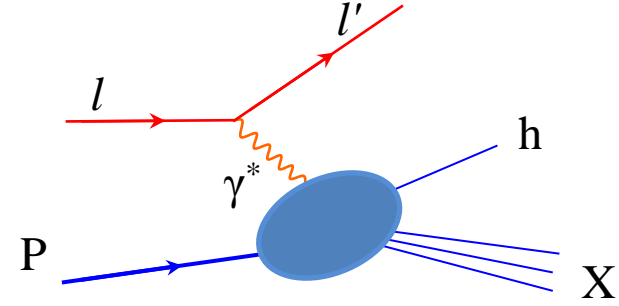


**All measured by COMPASS**

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

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

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



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



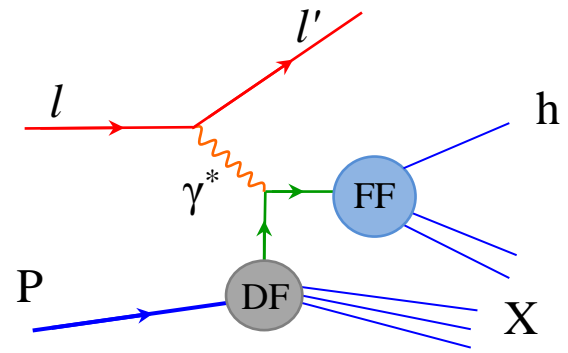
# SIDIS x-section and TMDs at twist-2

**All measured by COMPASS**

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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	$h_1^q(x, \mathbf{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \mathbf{k}_T^2)$ pretzelosity

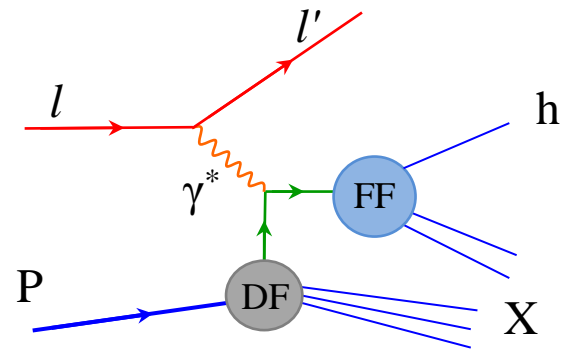
+ two FFs:  $D_{1q}^h(z, P_{\perp}^2)$  and  $H_{1q}^{\perp h}(z, P_{\perp}^2)$



# SIDIS x-section and TMDs at twist-2

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

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



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

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

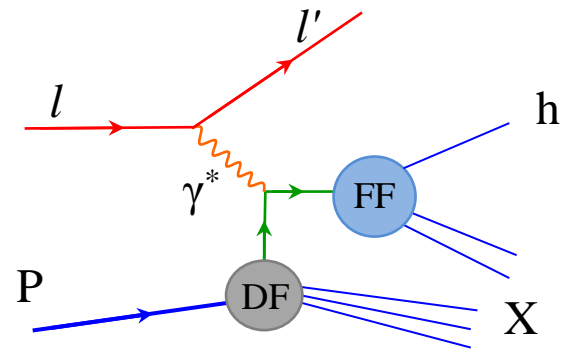
spin of the nucleon   
 spin of the quark   
 k<sub>T</sub>



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

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

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

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

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

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

Twist-2  
Twist-3

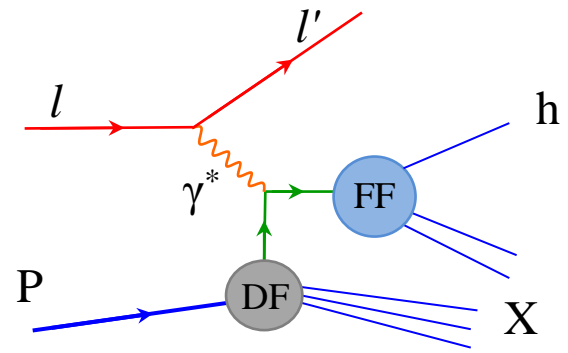
WW = Wandzura-Wilczek-type approximation  
See talk by S. Bastami



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

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

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

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

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

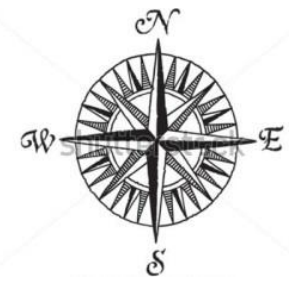
$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

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

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Twist-2  
Twist-3

COMPASS bridge



Drell-Pan

SIDS

# SIDIS and single-polarized DY x-sections

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

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

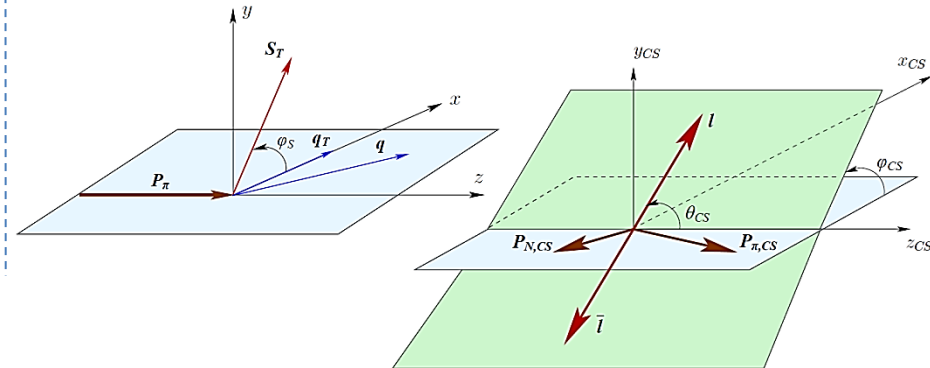
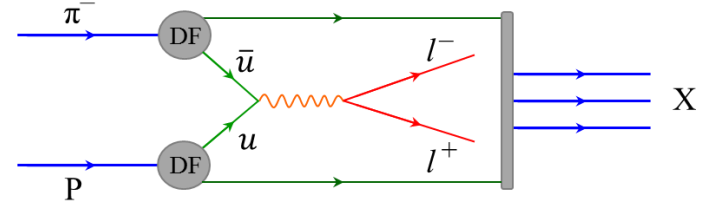
**SIDIS**

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

**DY**

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

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





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

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

**SIDIS**

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

**DY**

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



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

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





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

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

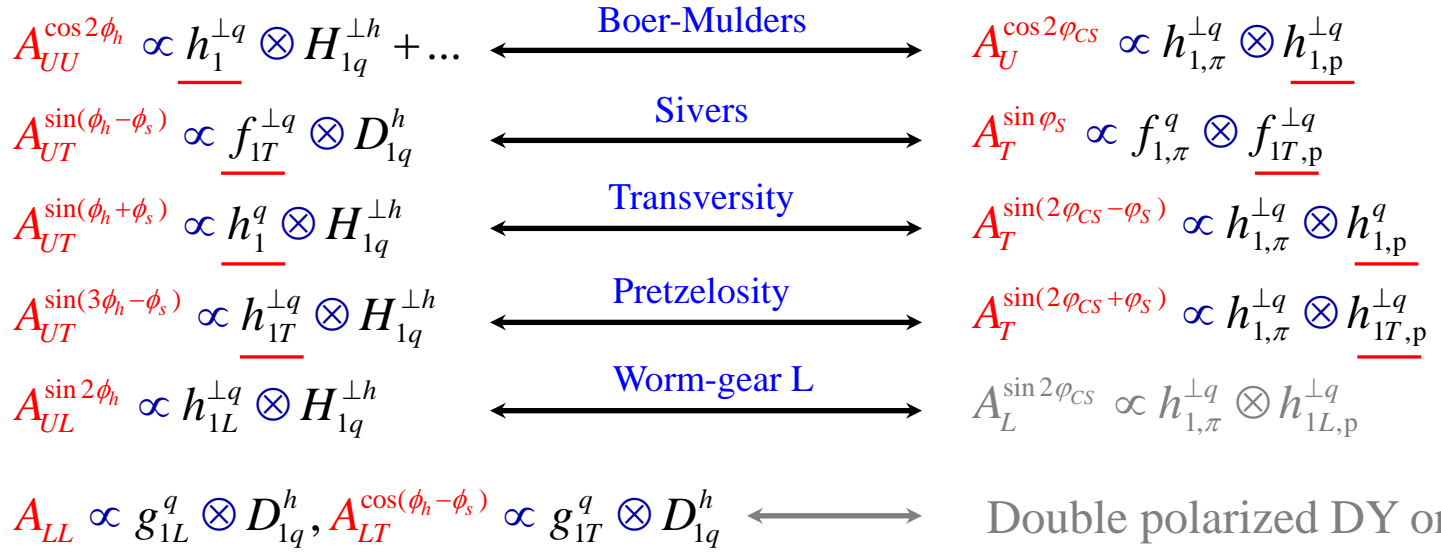
**SIDIS**

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

**DY**

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

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



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



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

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

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

within QCD TMD-framework:

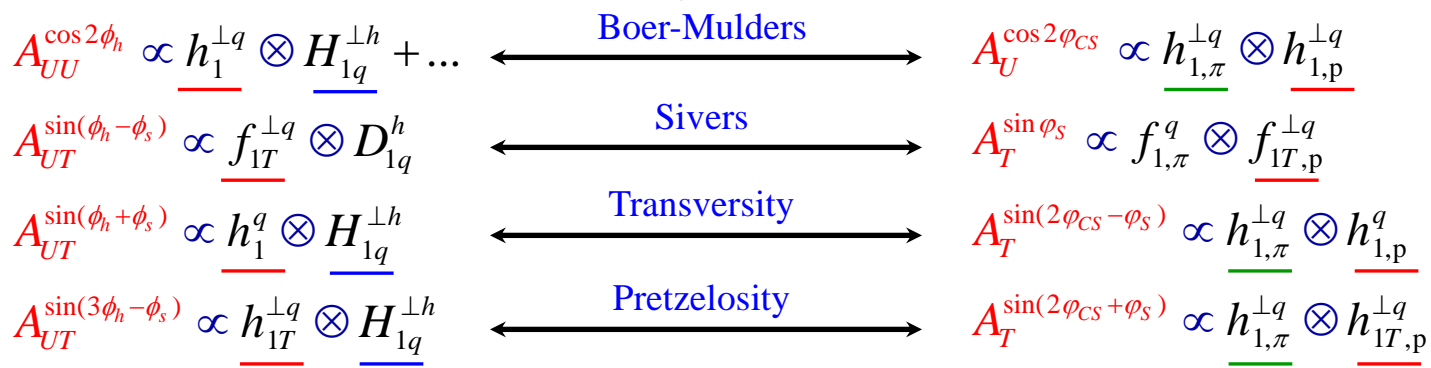
$h_1^{\perp q}$  &  $f_{1T}^{\perp q}$  TMD PDFs are expected to be "conditionally" universal (SIDIS  $\leftrightarrow$  DY: **sign change**)

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



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

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



Complementary information from different channels :

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



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

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

**SIDIS**

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

**DY**

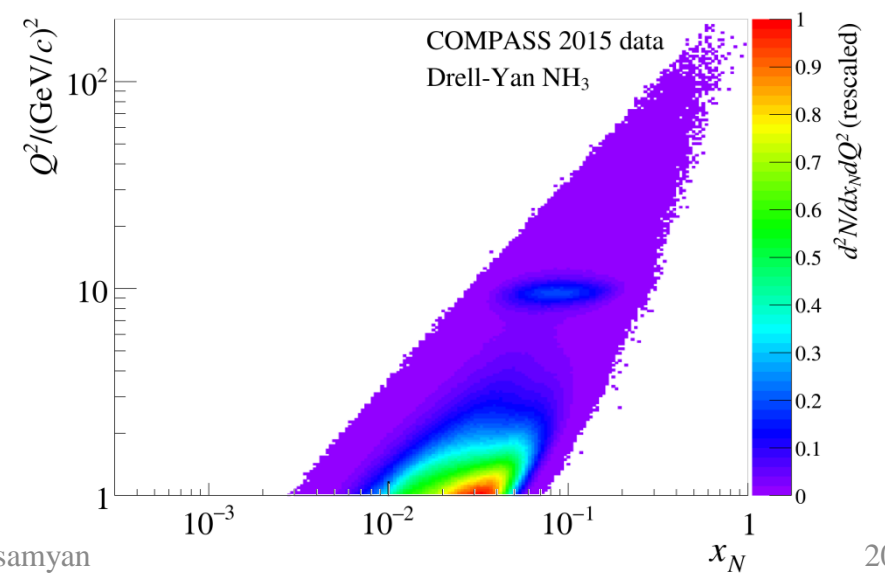
$$\begin{aligned}
 & \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right. \\
 & \quad \left. + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \right. \\
 & \times \left\{ \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S)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

**SIDIS-DY bridge**

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

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)

**SIDIS**

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

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

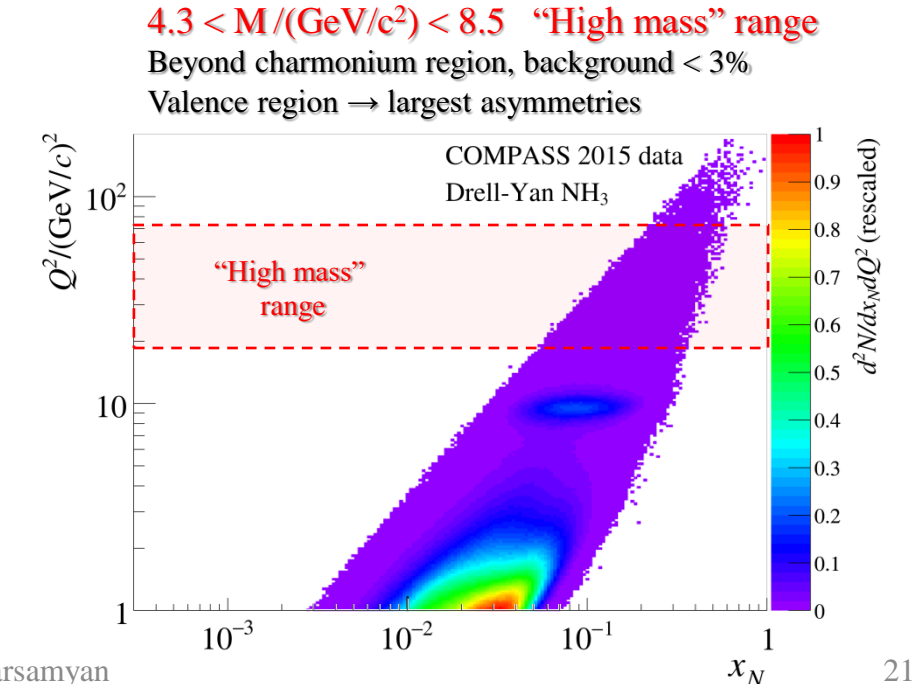
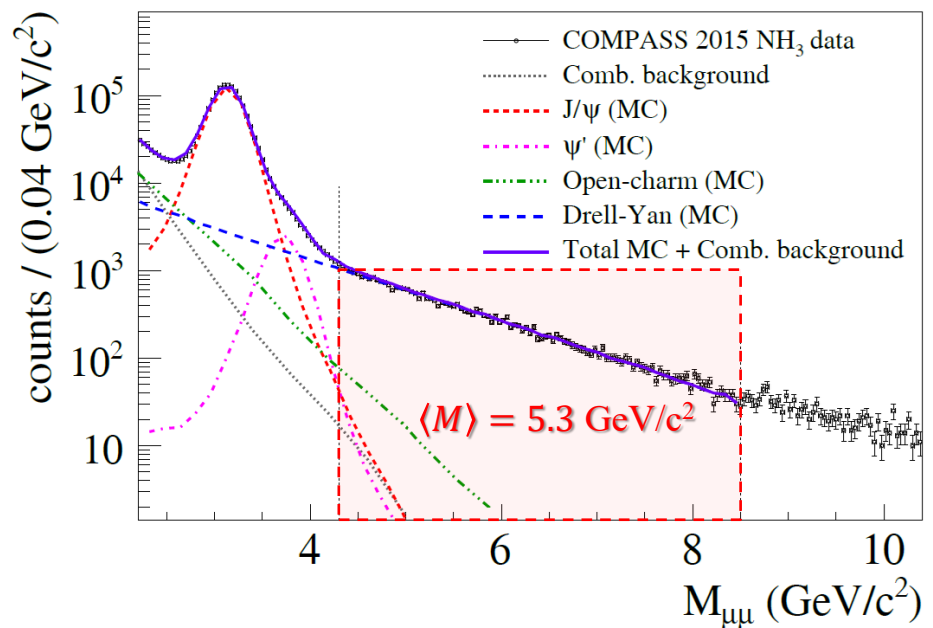
**SIDIS-DY  
bridge**

**DY**

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

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

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





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

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

**SIDIS**

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

**DY**

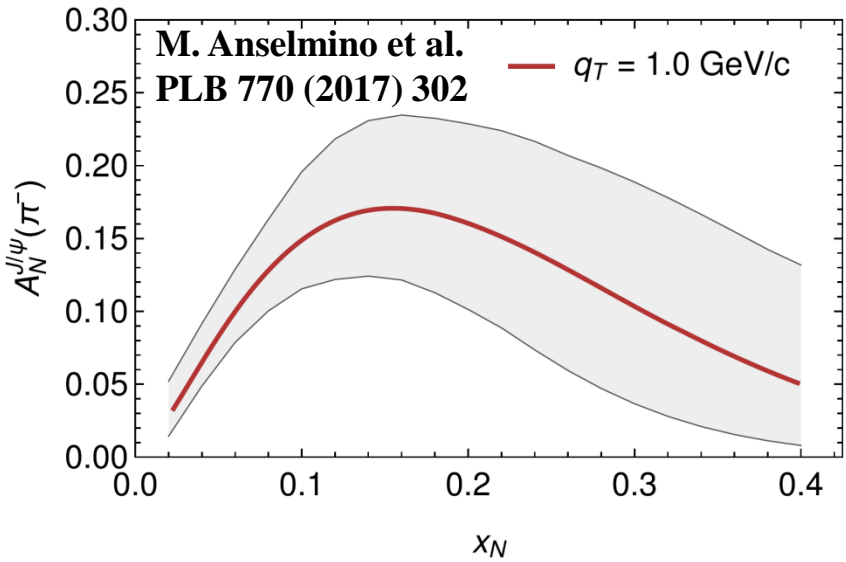
$$\left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\ & + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h +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



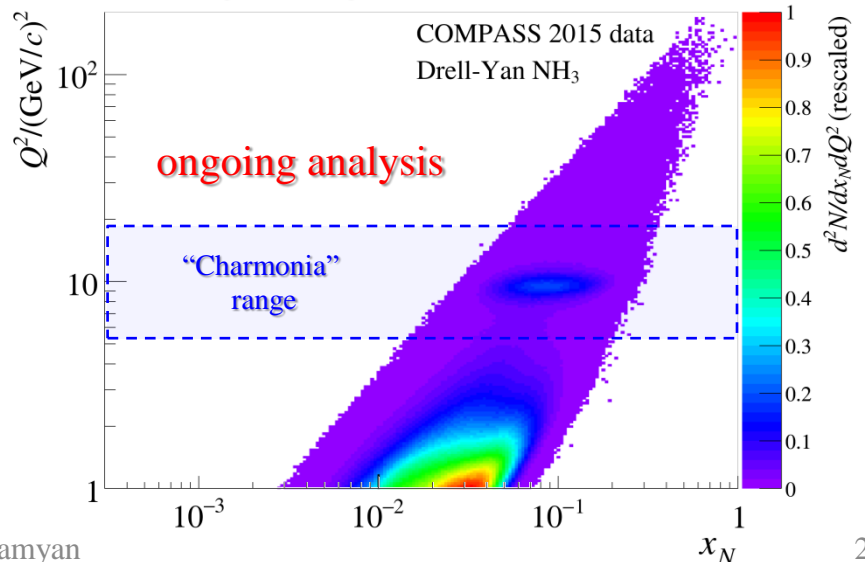
$$\left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ & + S_T \begin{bmatrix} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left( A_T^{\sin(2\varphi_{CS} -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

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

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



$2.5 < M / (\text{GeV}/c^2) < 4.3$  “Charmonia mass”  
 Strong J/ψ-signal → study of J/ψ physics  
 Good signal/background





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

**SIDIS**

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

$$\left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \end{aligned} \right\}$$

$$\times \left\{ \begin{aligned} & A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ & + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{aligned} \right\}$$

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

**SIDIS-DY  
bridge**

**DY**

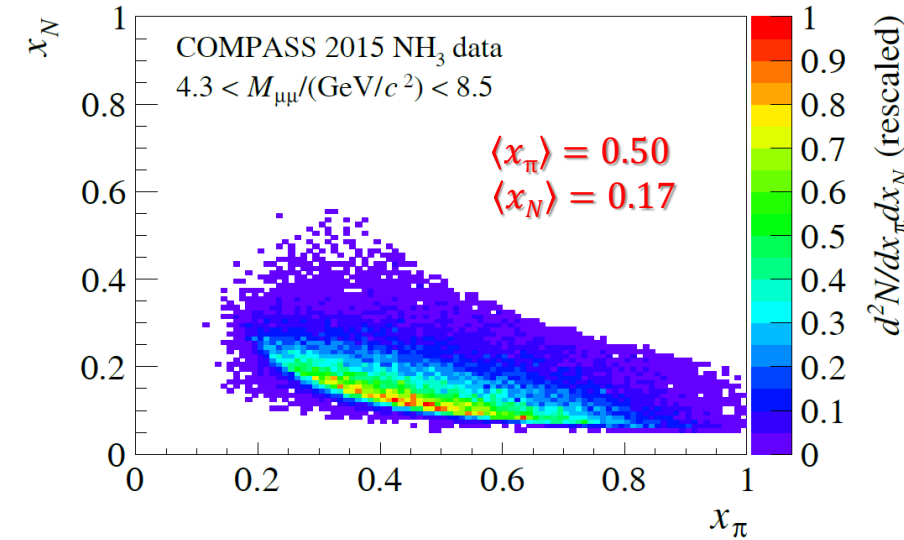
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$$\left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \end{aligned} \right\}$$

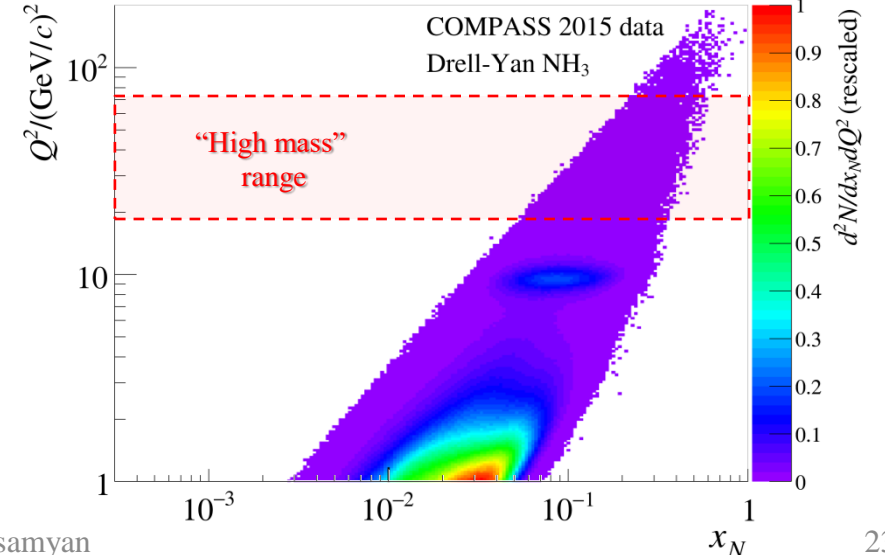
$$\times \left\{ \begin{aligned} & A_T^{\sin \varphi_S} \sin \varphi_S \\ & + D_{[\sin^2 \theta_{CS}]} \left( \begin{aligned} & A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ & + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{aligned} \right) \end{aligned}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

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

## HM events are in the valence quark range



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





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

**SIDIS**

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

**SIDIS**

**DY**

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

COMPASS

**SIDIS-DY bridge**

×

COMPASS

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

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

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

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

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

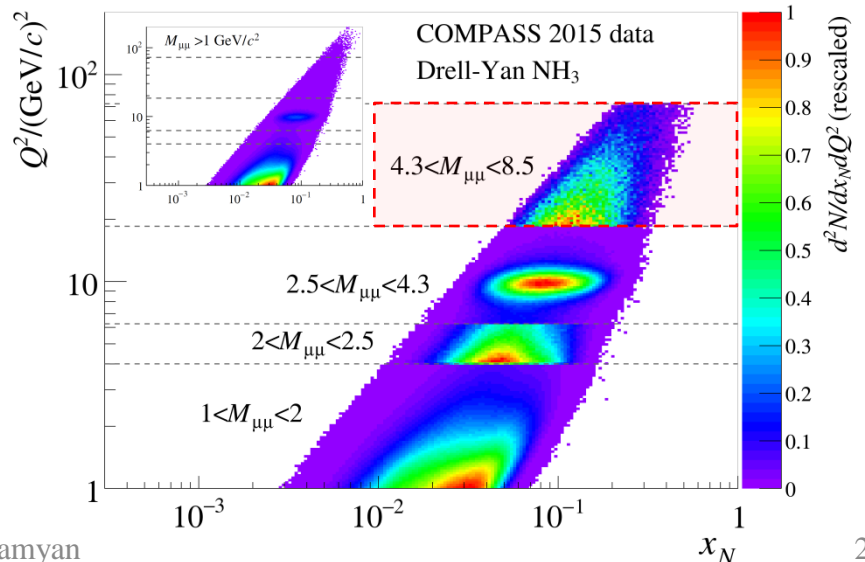
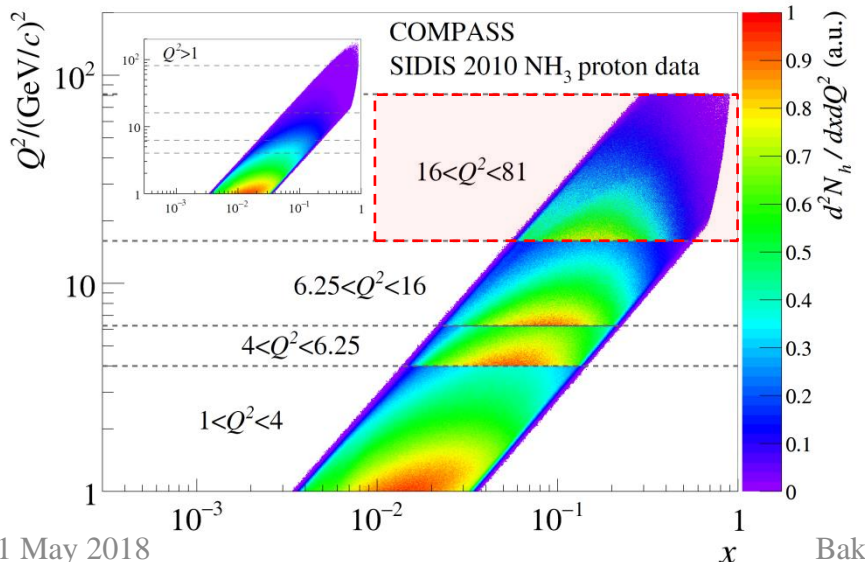
$$+ S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}$$
  

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

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

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







- Longitudinal target spin dependent azimuthal asymmetries

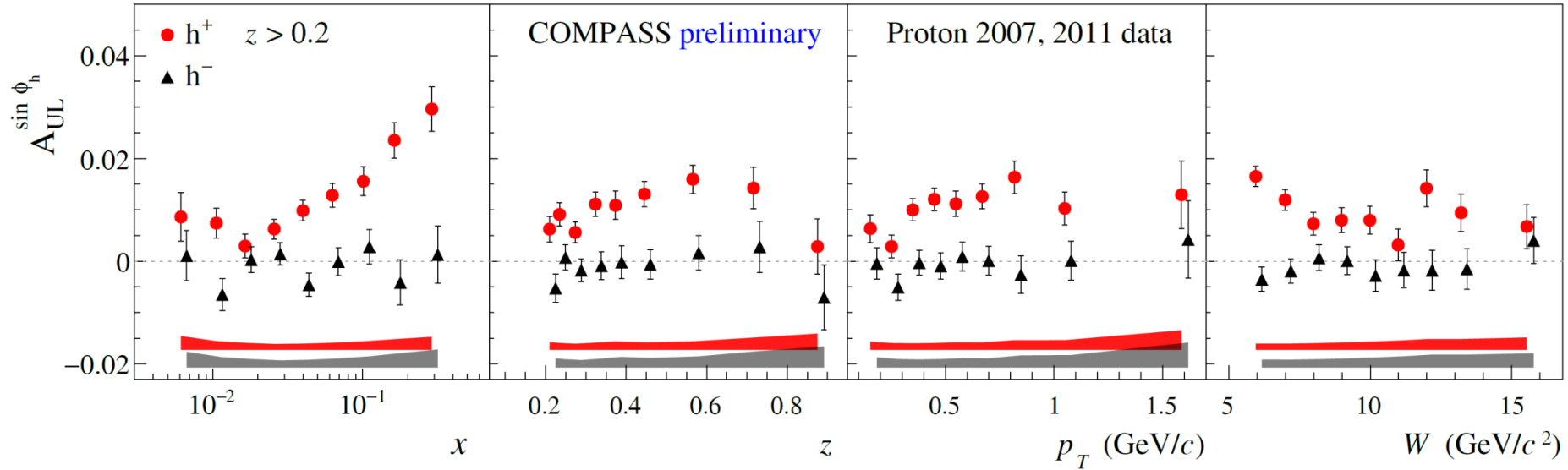


# SIDIS: target longitudinal spin dependent asymmetries

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

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

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



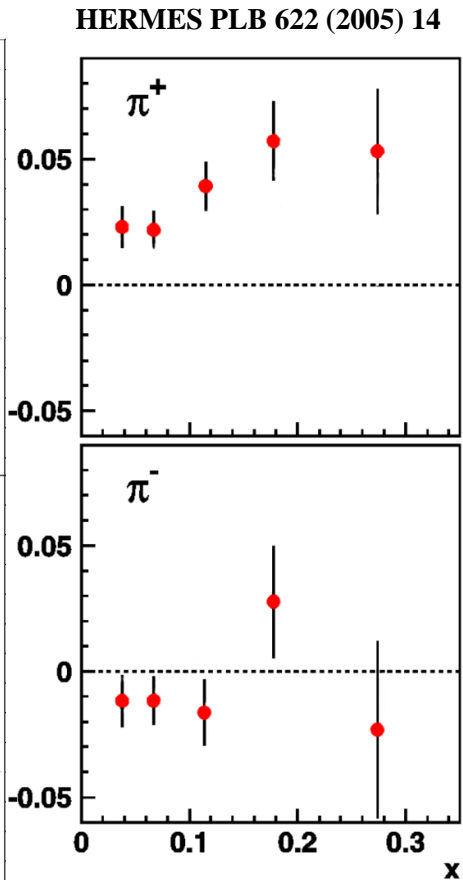
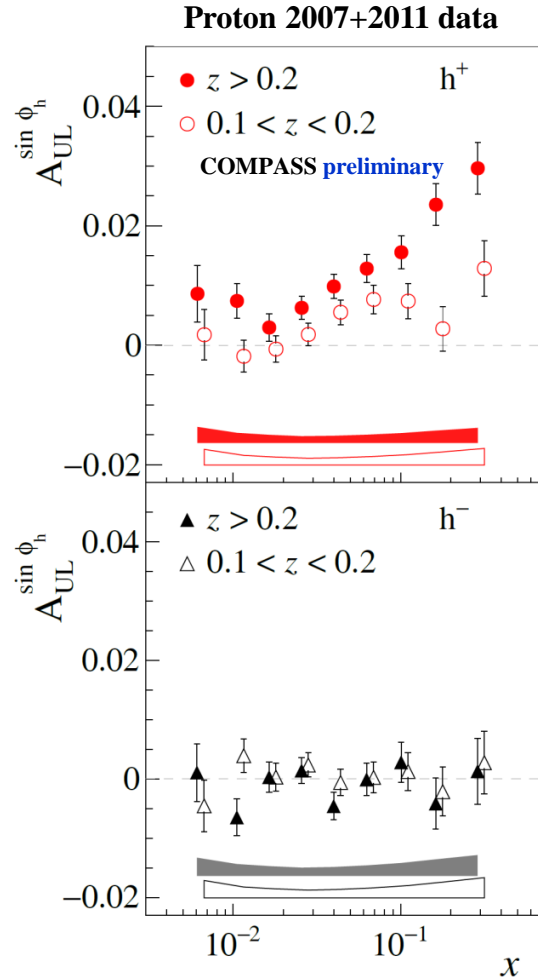
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+$ ,  $h^-$  compatible with zero**



# SIDIS: target longitudinal spin dependent asymmetries

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

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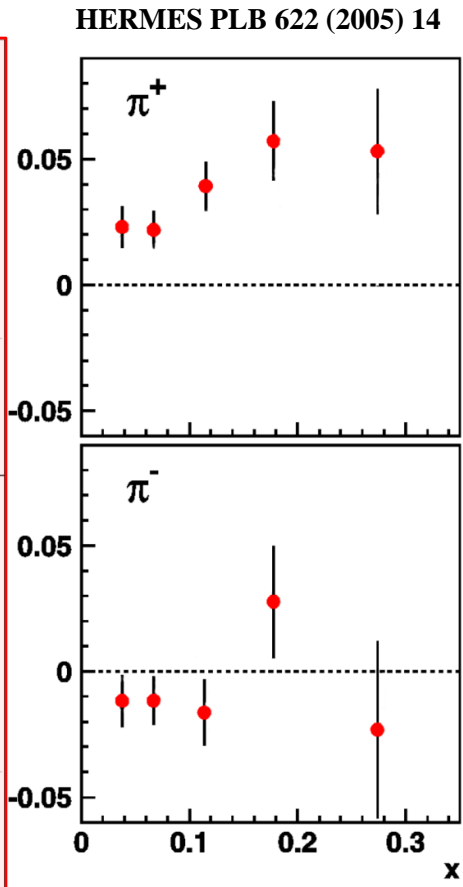
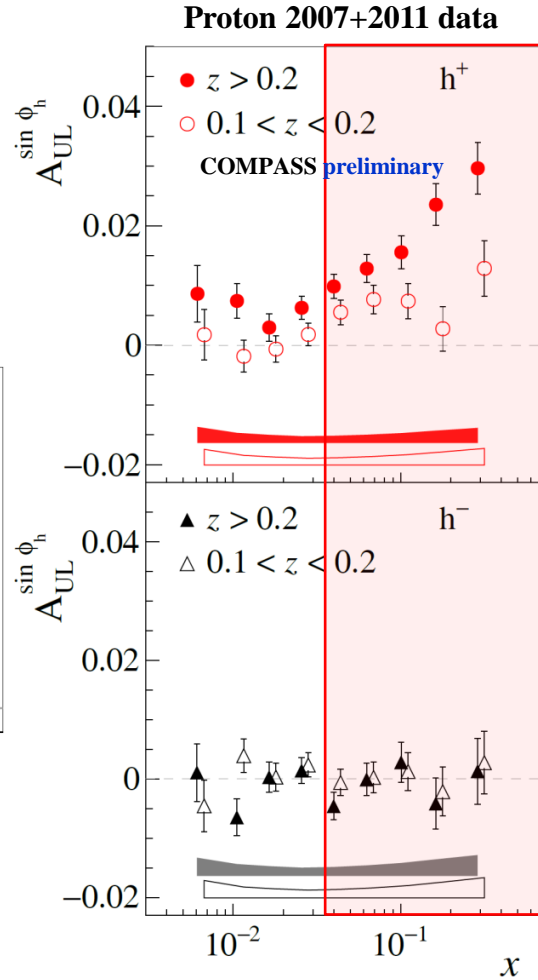
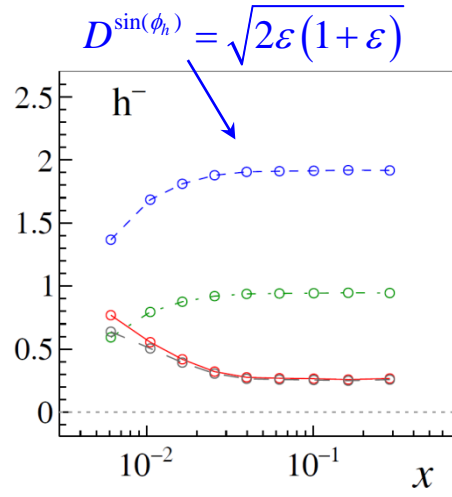
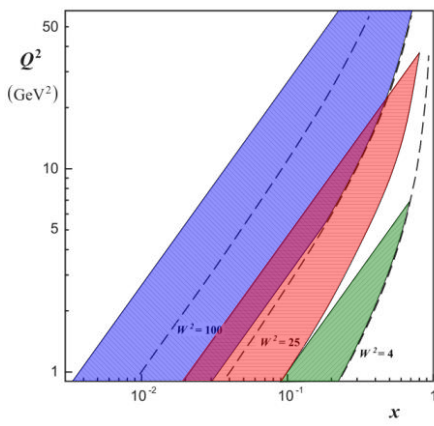
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
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# SIDIS: target longitudinal spin dependent asymmetries

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

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



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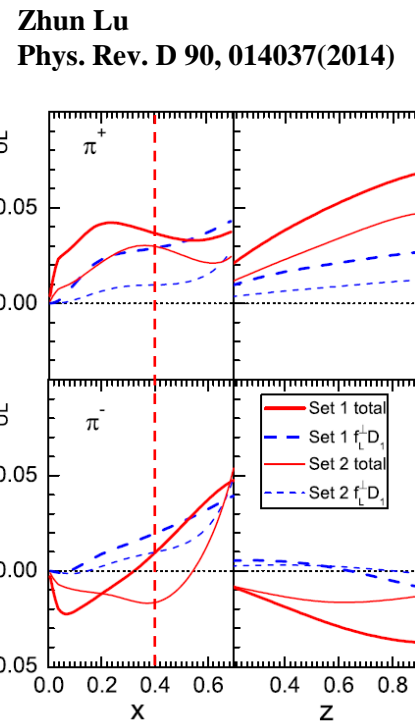
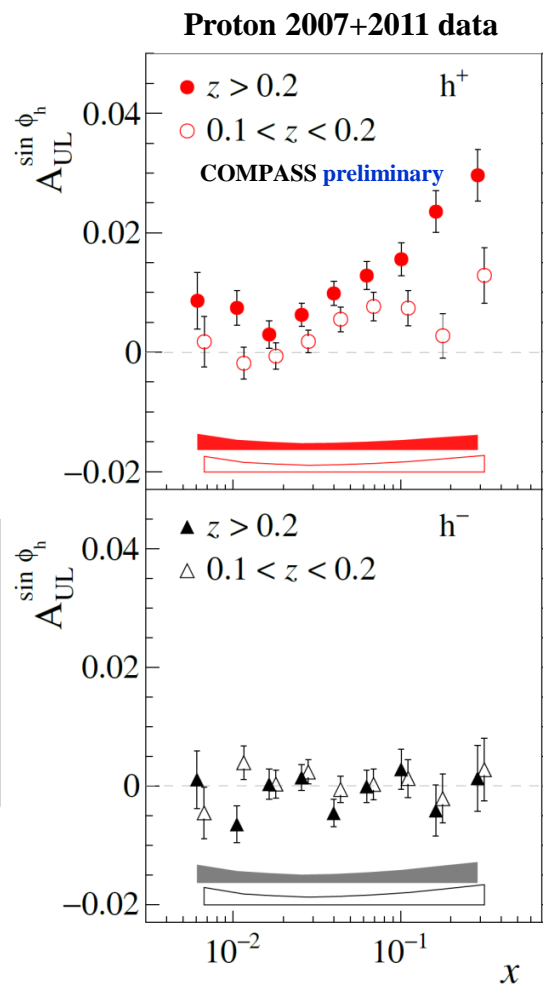
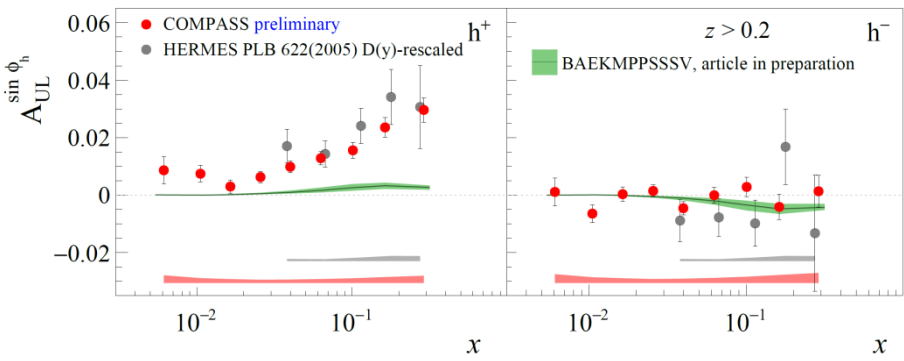


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S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang Article in preparation: “SIDIS in Wandzura-Wilczek-type approximation” → See talk by S. Bastami



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



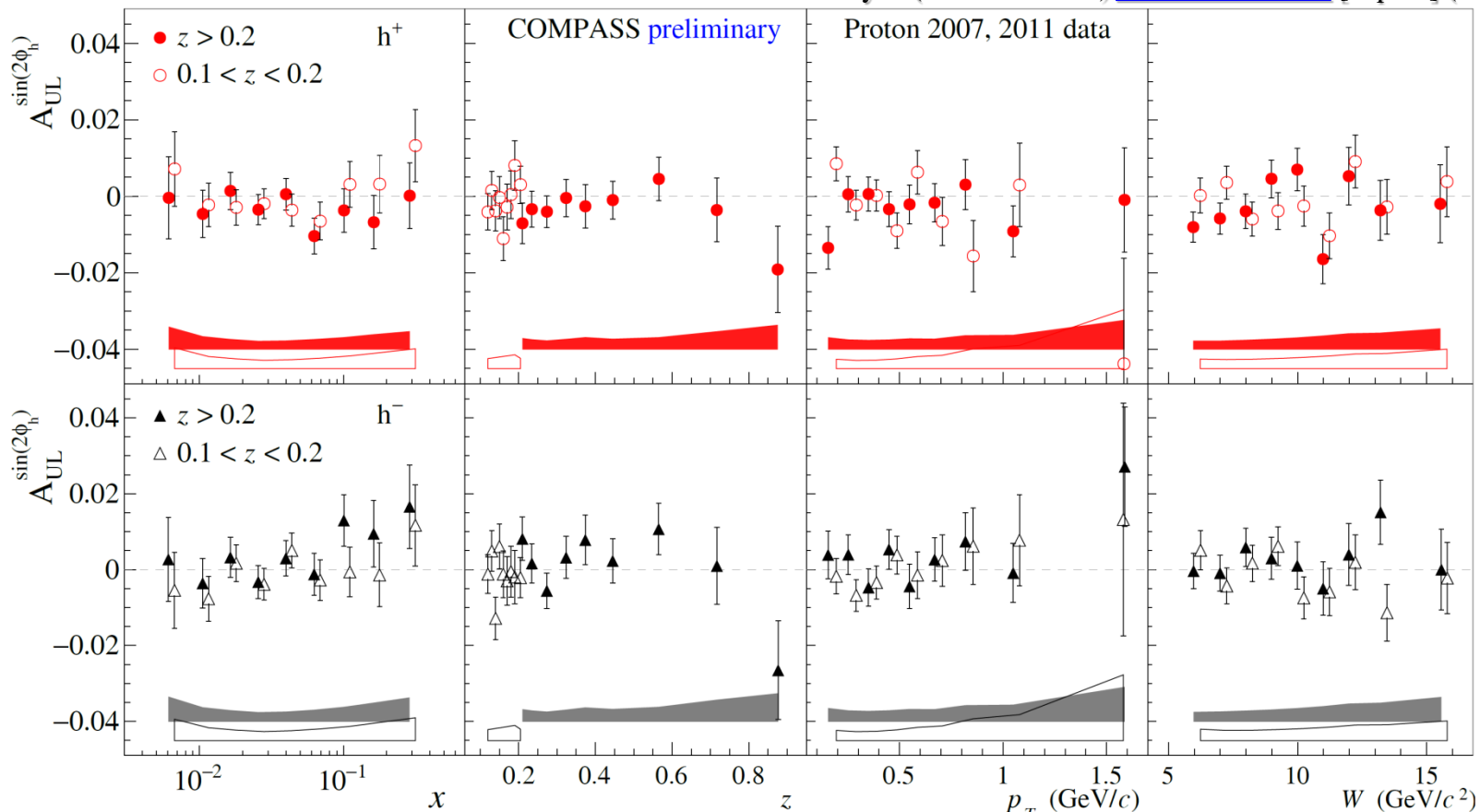
# SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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



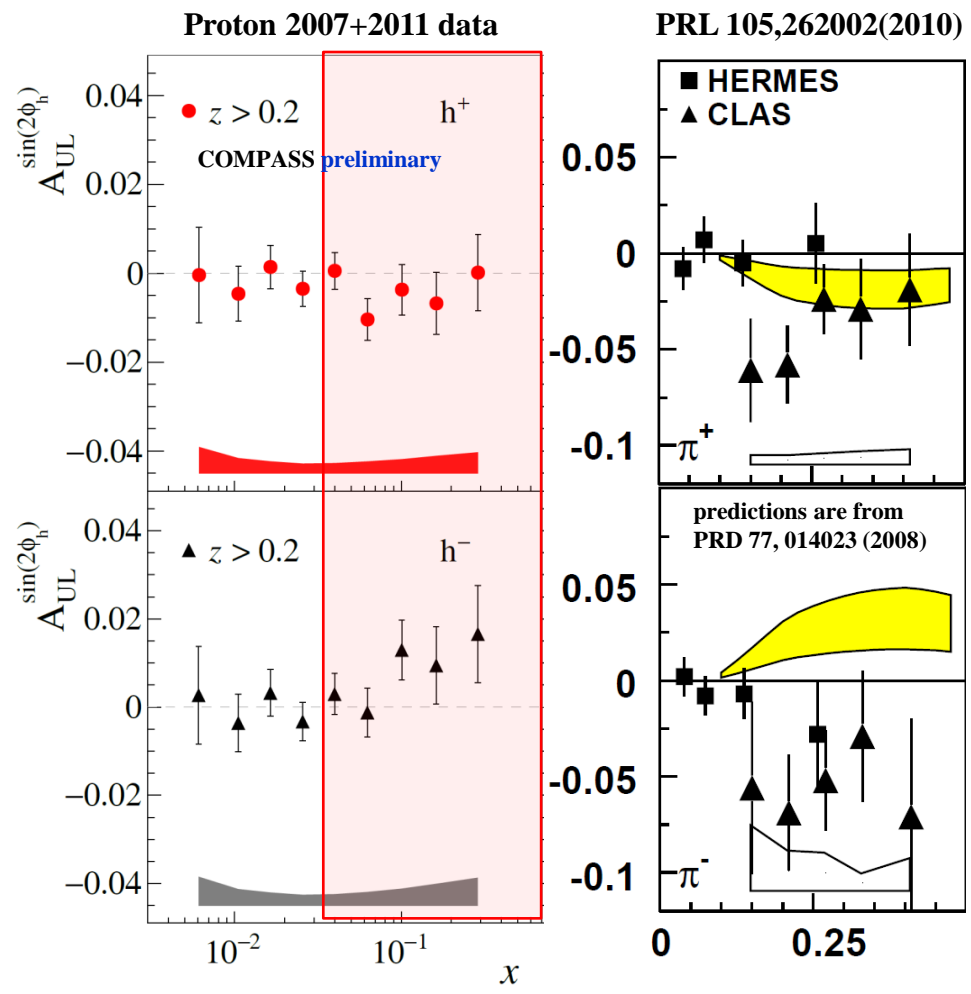


# SIDIS: target longitudinal spin dependent asymmetries

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

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

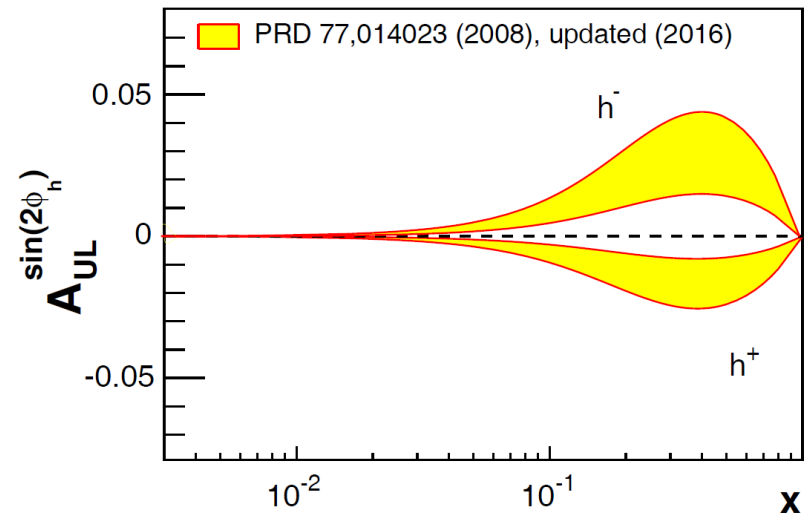




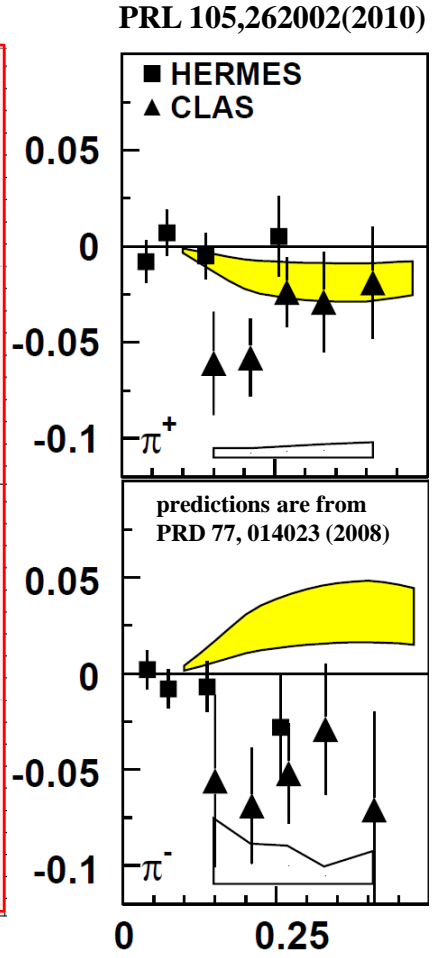
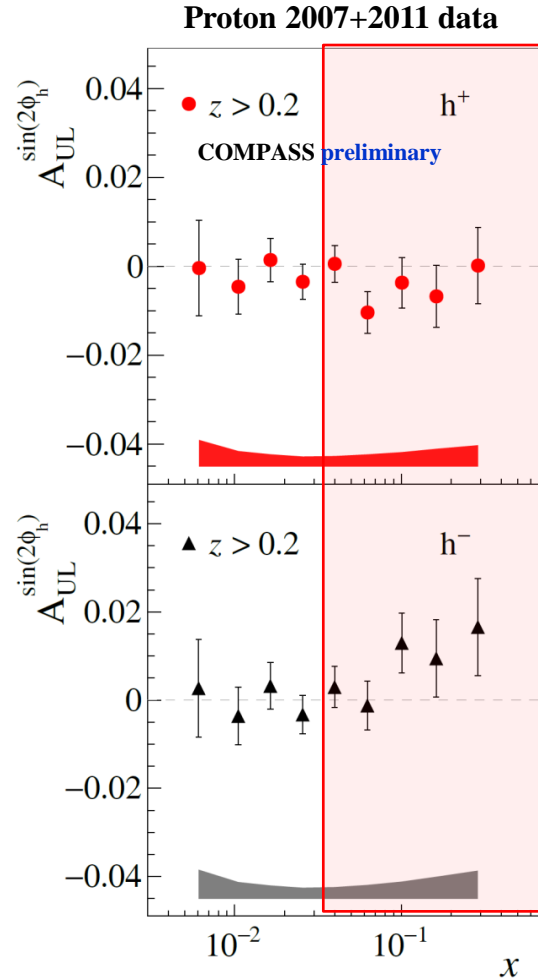
# SIDIS: target longitudinal spin dependent asymmetries

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

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- Only “twist-2” ingredients
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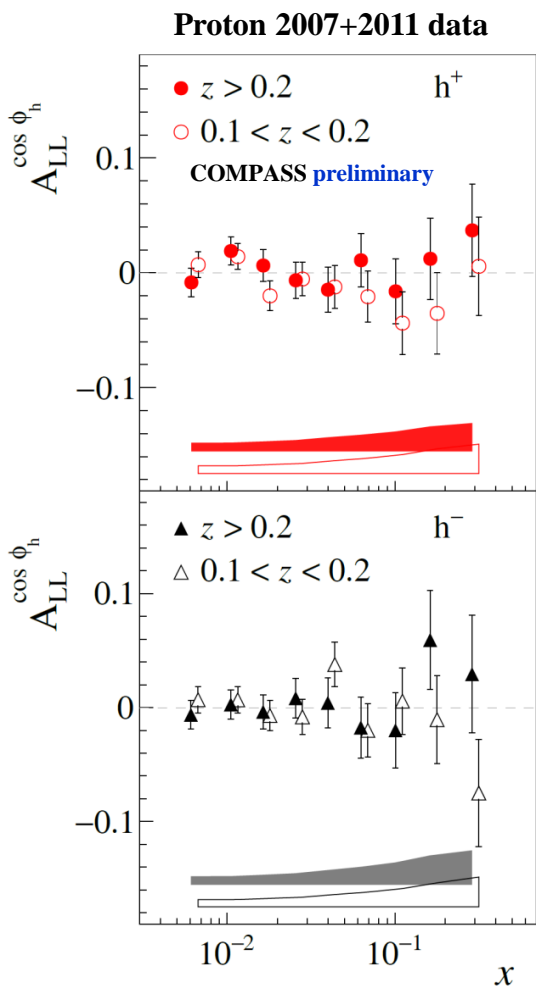
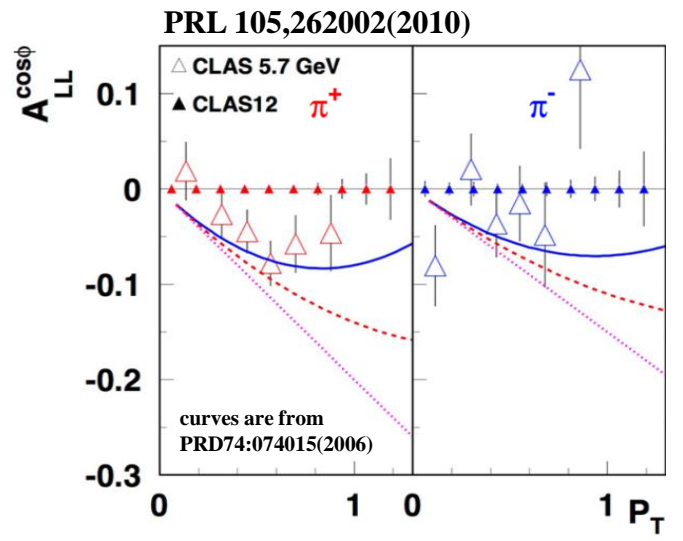




# SIDIS: target longitudinal spin dependent asymmetries

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

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



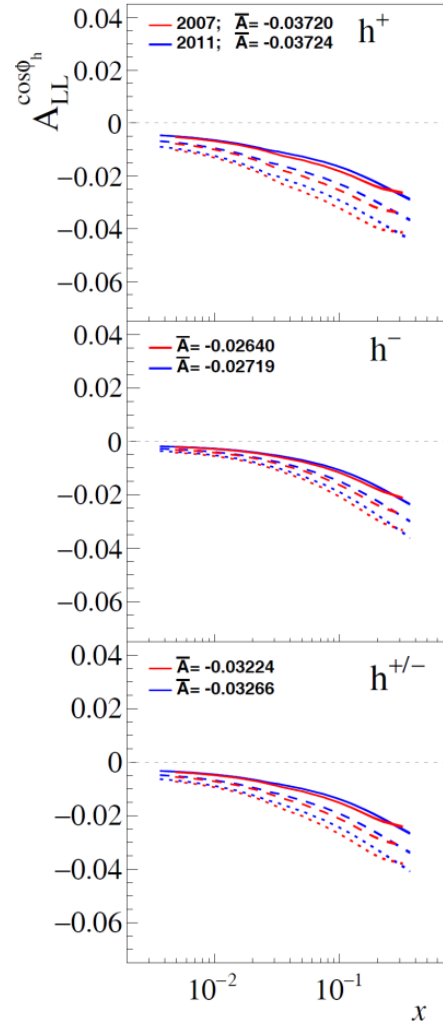
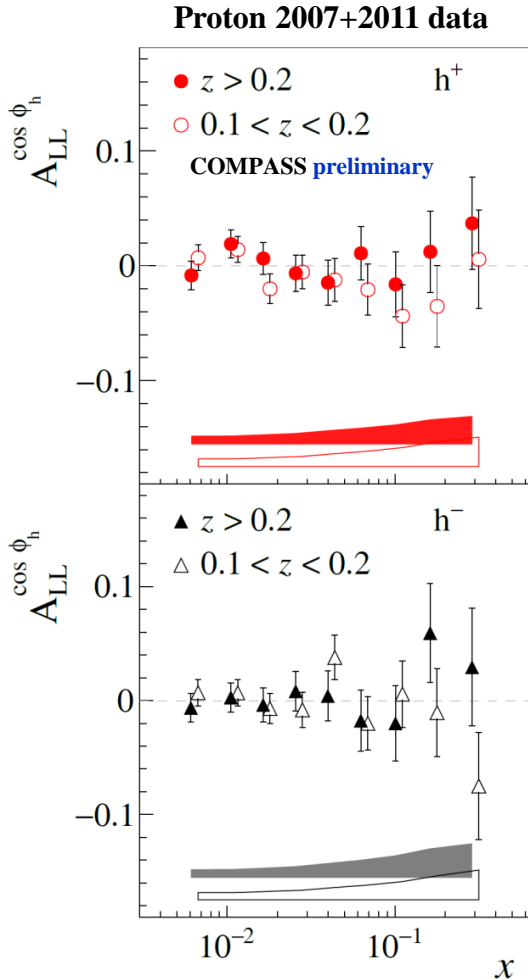
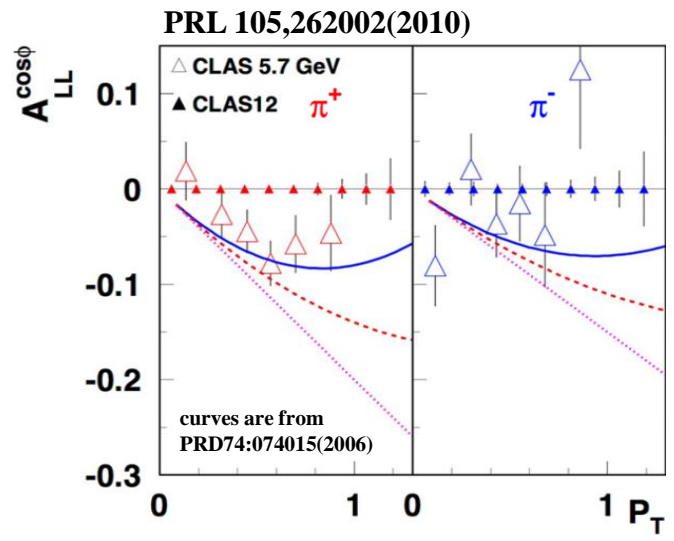
- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab



# SIDIS: target longitudinal spin dependent asymmetries

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- 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

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

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

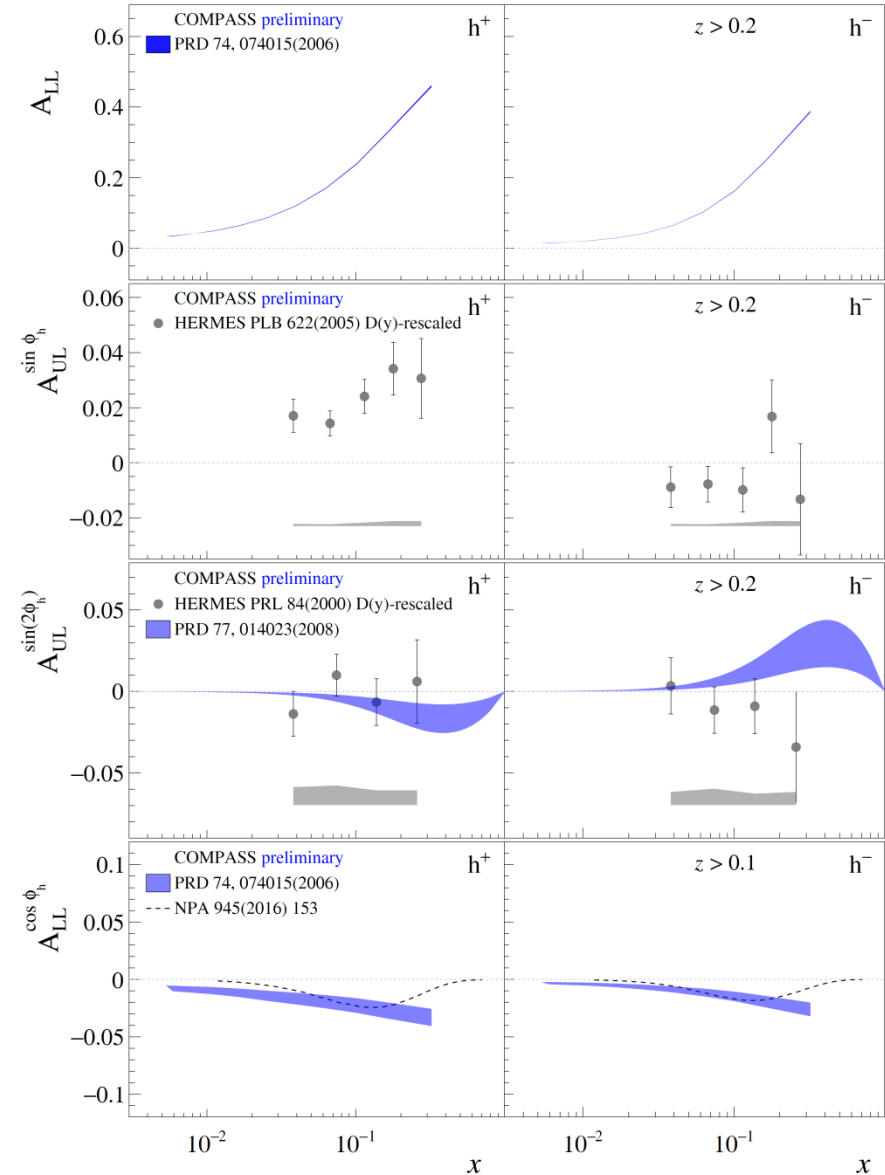
$$+ S_L \lambda \left[ \begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \end{array} \right] \left. \right\}$$

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

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

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

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





# SIDIS: target longitudinal spin dependent asymmetries

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

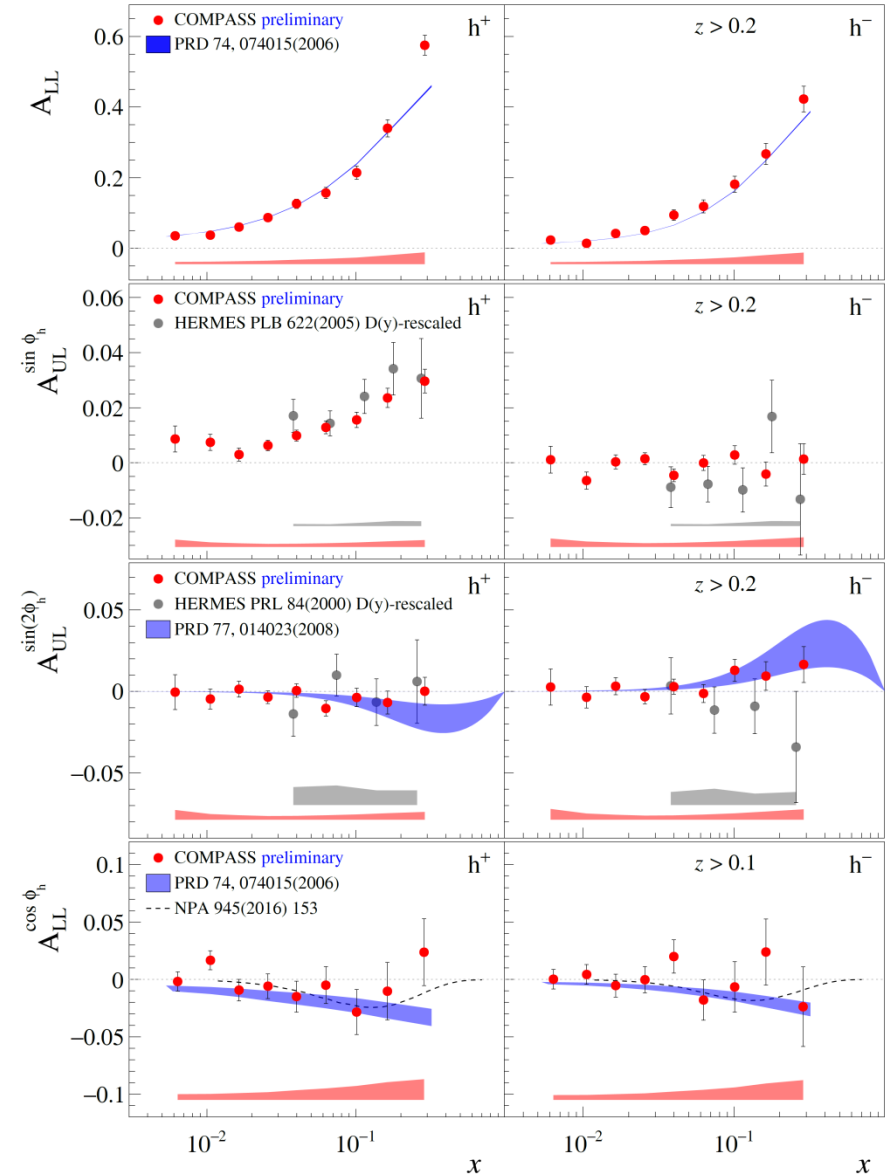
$$+ S_L \left[ \begin{array}{l} \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h \\ + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \end{array} \right]$$

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

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





# SIDIS: target longitudinal spin dependent asymmetries

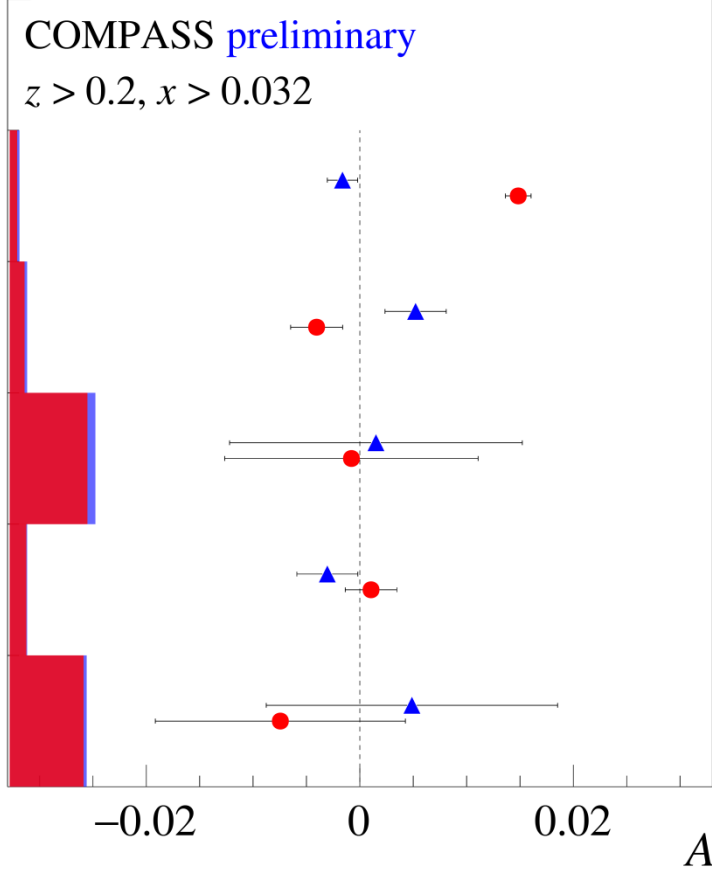
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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- **h<sup>-</sup> compatible with zero**
- Only “twist-2” ingredients
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- **Collins-like behavior?**
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- **Compatible with zero, in agreement with models**





- Transverse target spin dependent azimuthal asymmetries



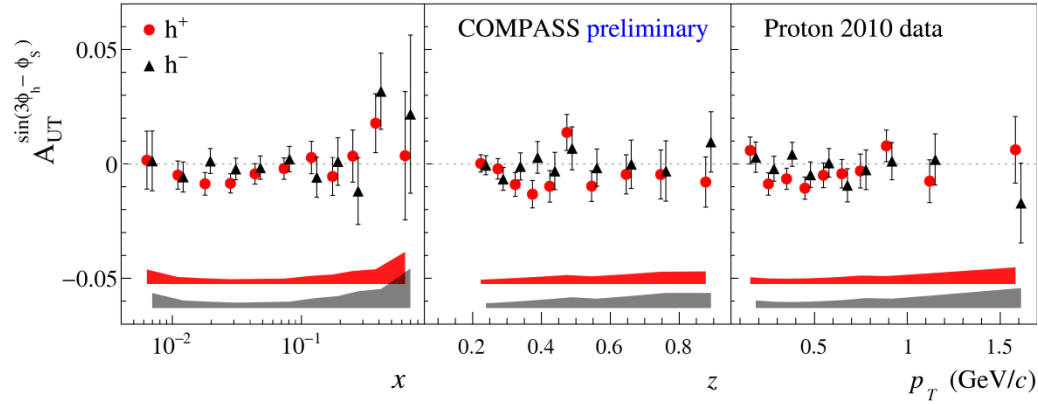
# SIDIS: target transverse spin dependent asymmetries

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

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

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

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



## COMPASS results

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

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

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



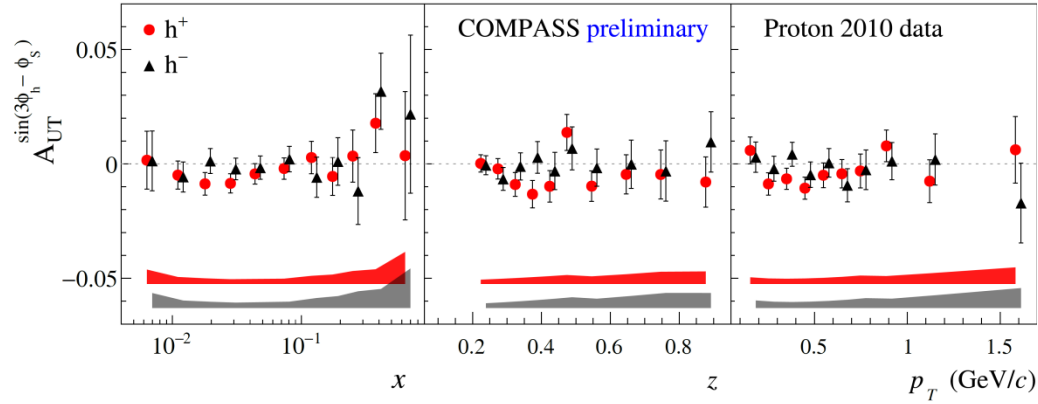
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



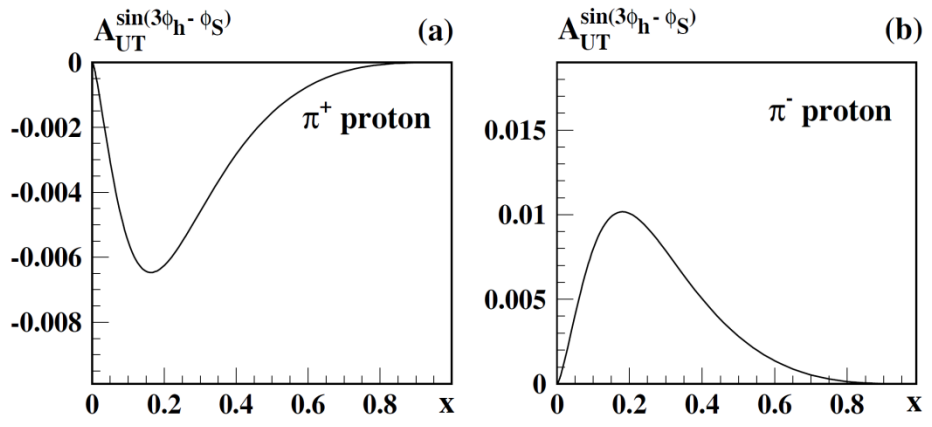
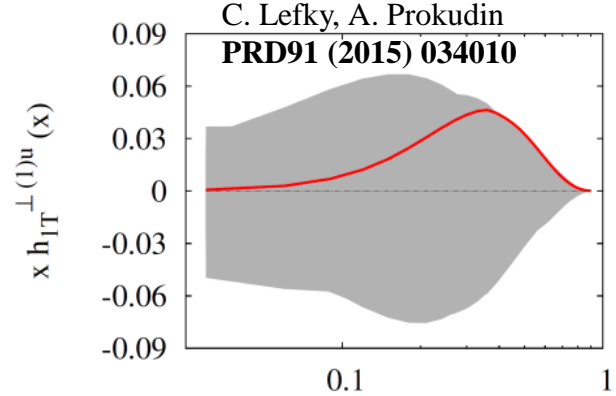
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$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C \left[ \frac{2(\hat{h} \cdot k_T)(k_T \cdot p_T) + k_T^2(\hat{h} \cdot p_T) - 4(\hat{h} \cdot k_T)^2(\hat{h} \cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$

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







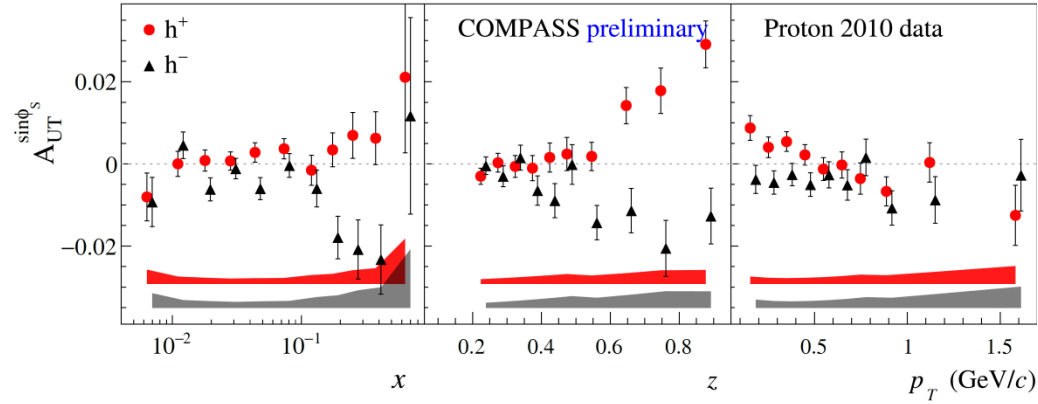
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$$+ S_T \lambda \left[ \begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \dots \end{array} \right]$$

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



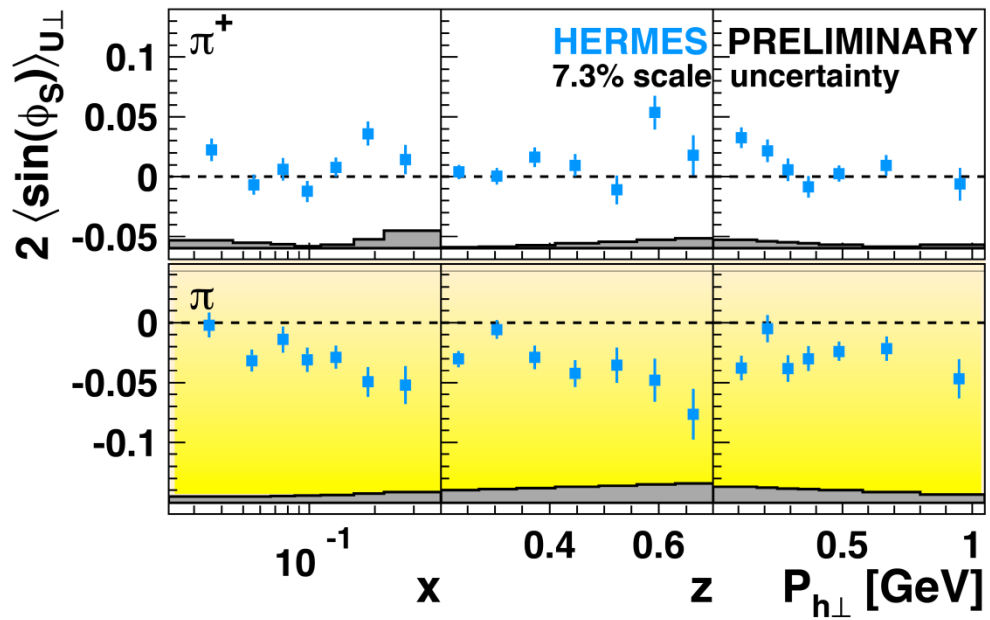
## COMPASS results

- $A_{UT}^{\sin\phi_S}$
- Q-suppression
- Various different “twist” ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h<sup>-</sup> ?**

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left( x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) \right.$$

$$\left. - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[ \left( x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right] \right\}$$

$$\left. - \left( x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right\}$$





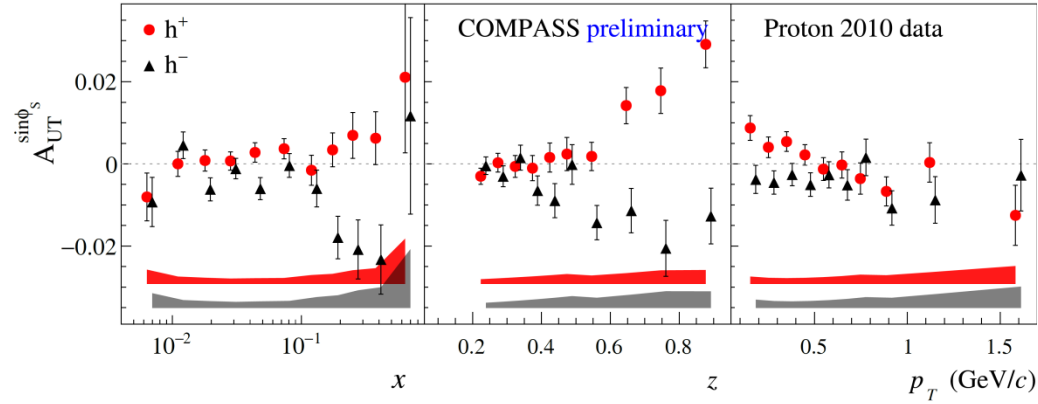
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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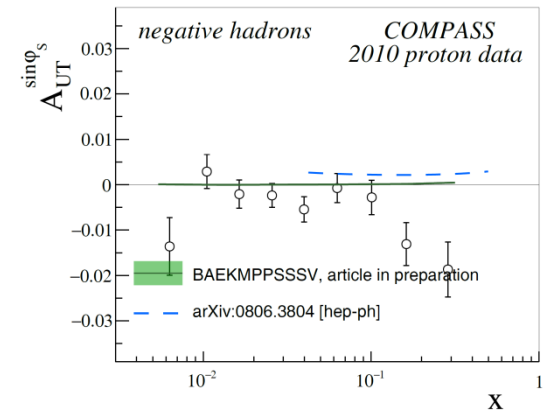
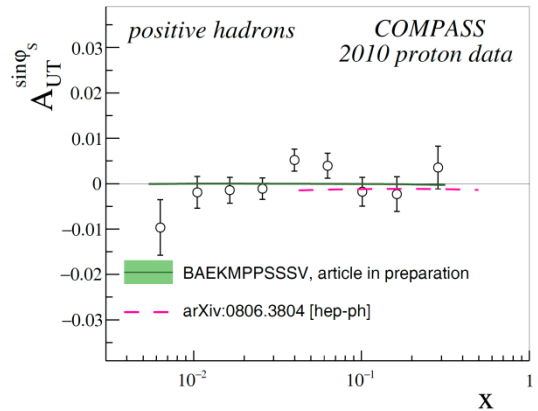
$$A_{UT}^{\sin(\phi_S)} \propto Q^{-1} \left( h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right)$$

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” → See talk by S. Bastami

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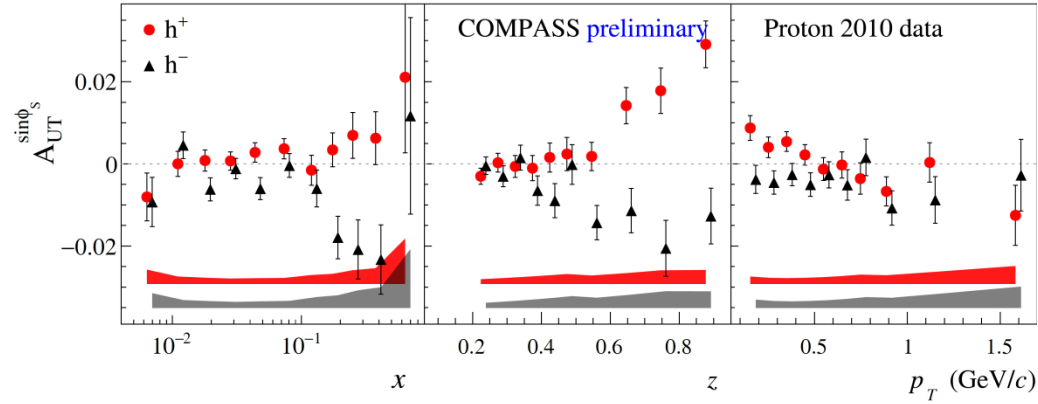
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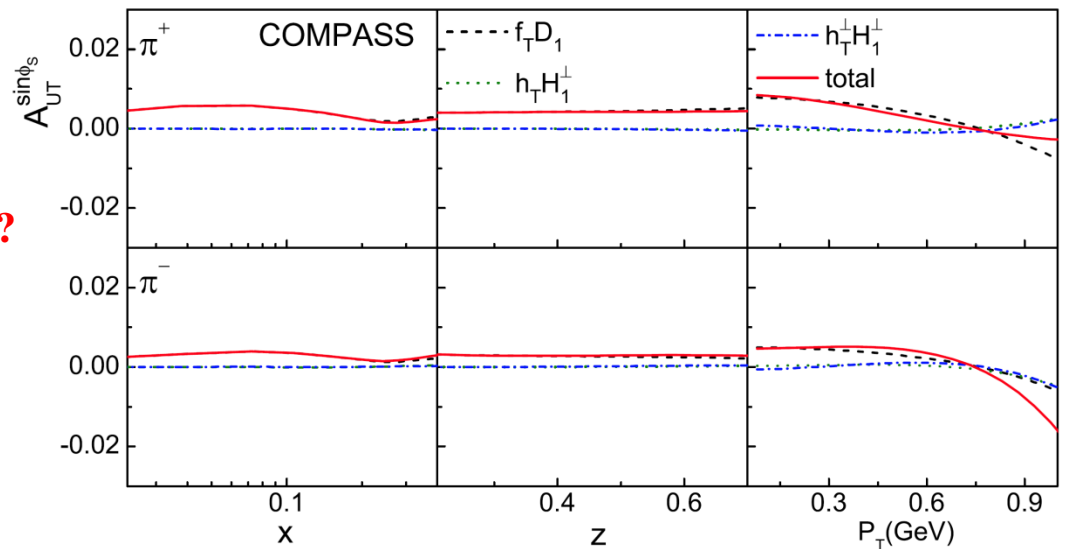
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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



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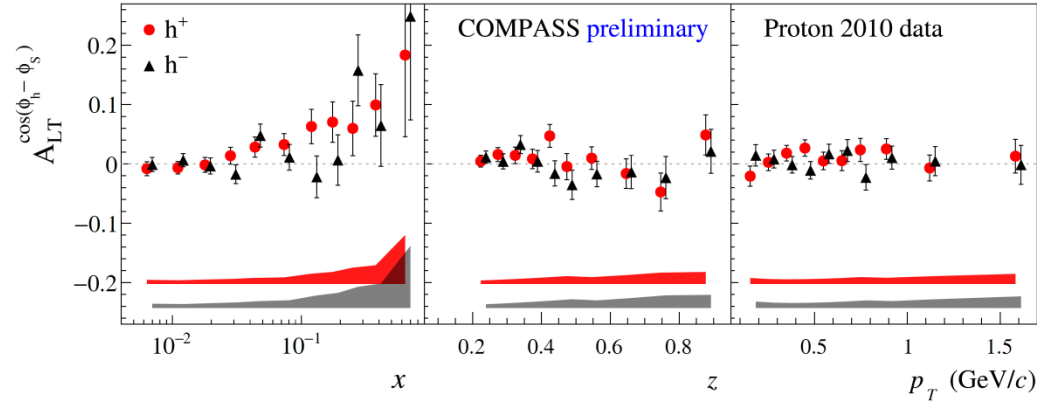
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042

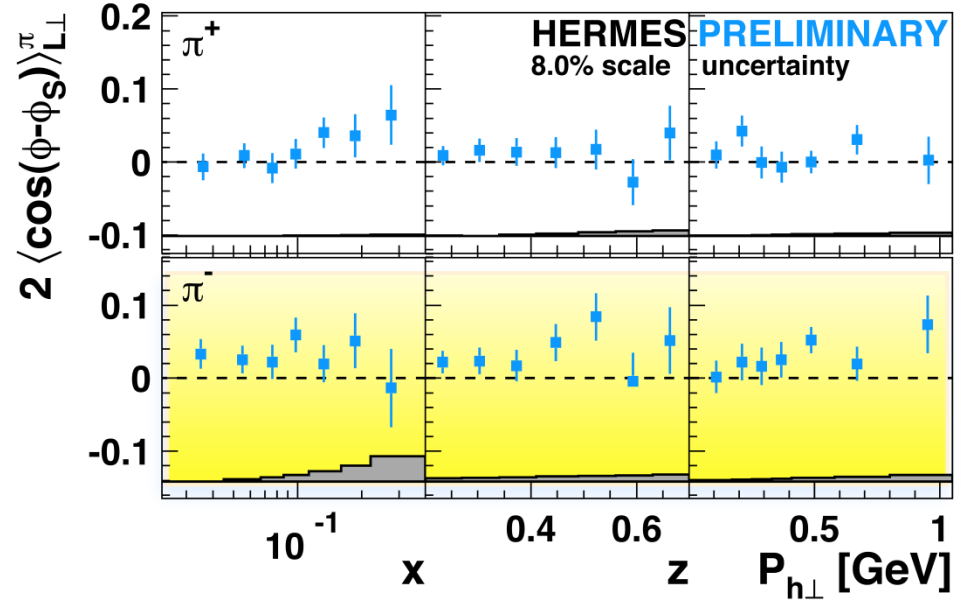


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$$A_{LT}^{\cos(\phi_h - \phi_S)}$$

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





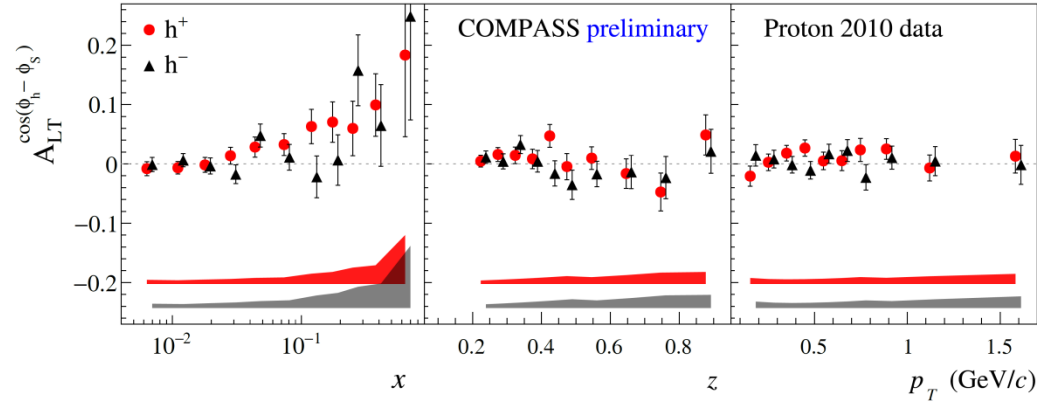
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B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



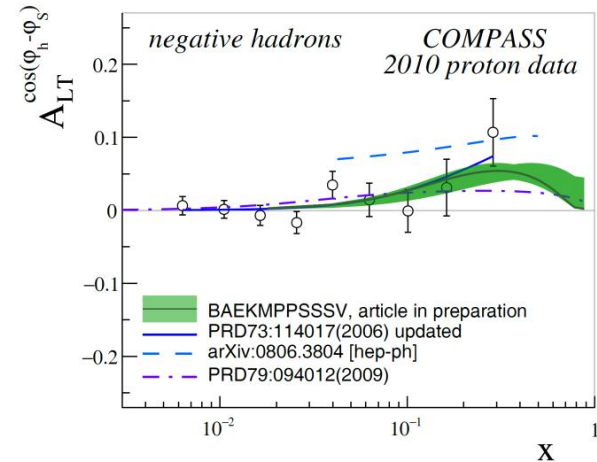
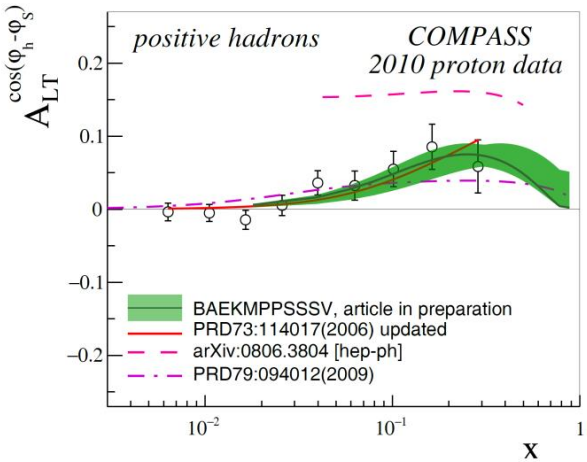
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S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang Article in preparation: “SIDIS in Wandzura-Wilczek-type approximation” → **See talk by S. Bastami**

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# SIDIS TSAs (Collins)

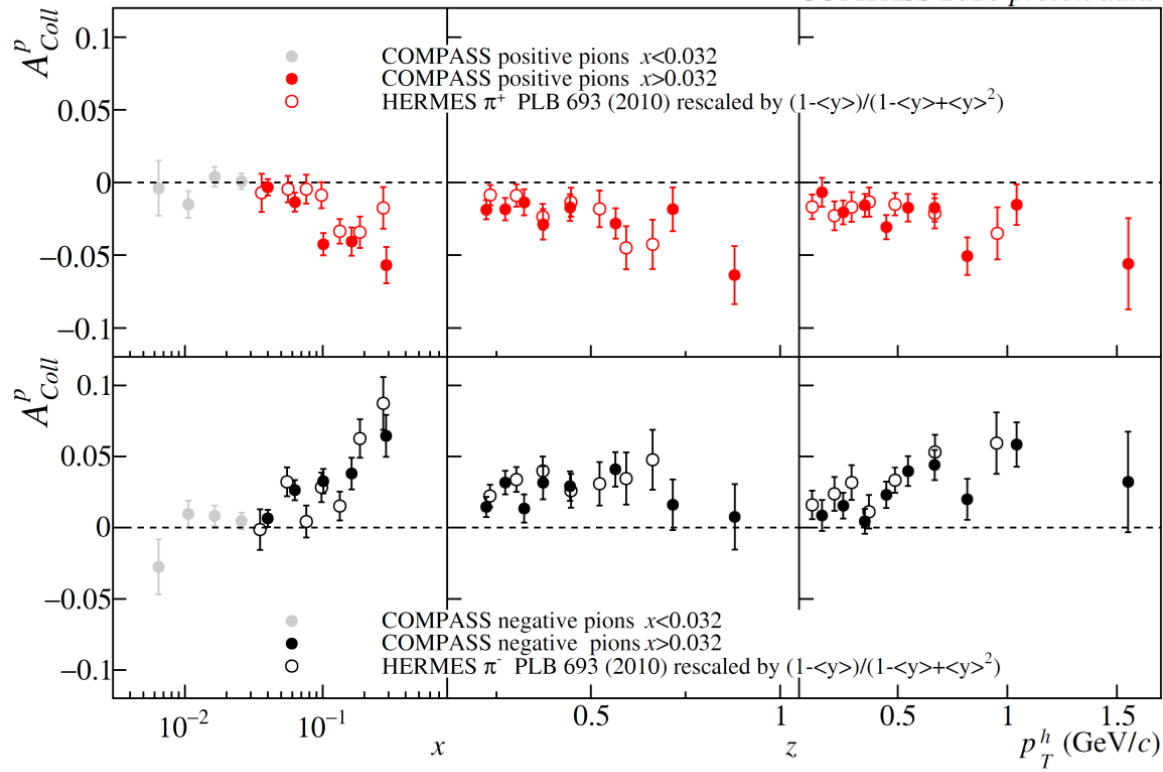
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data





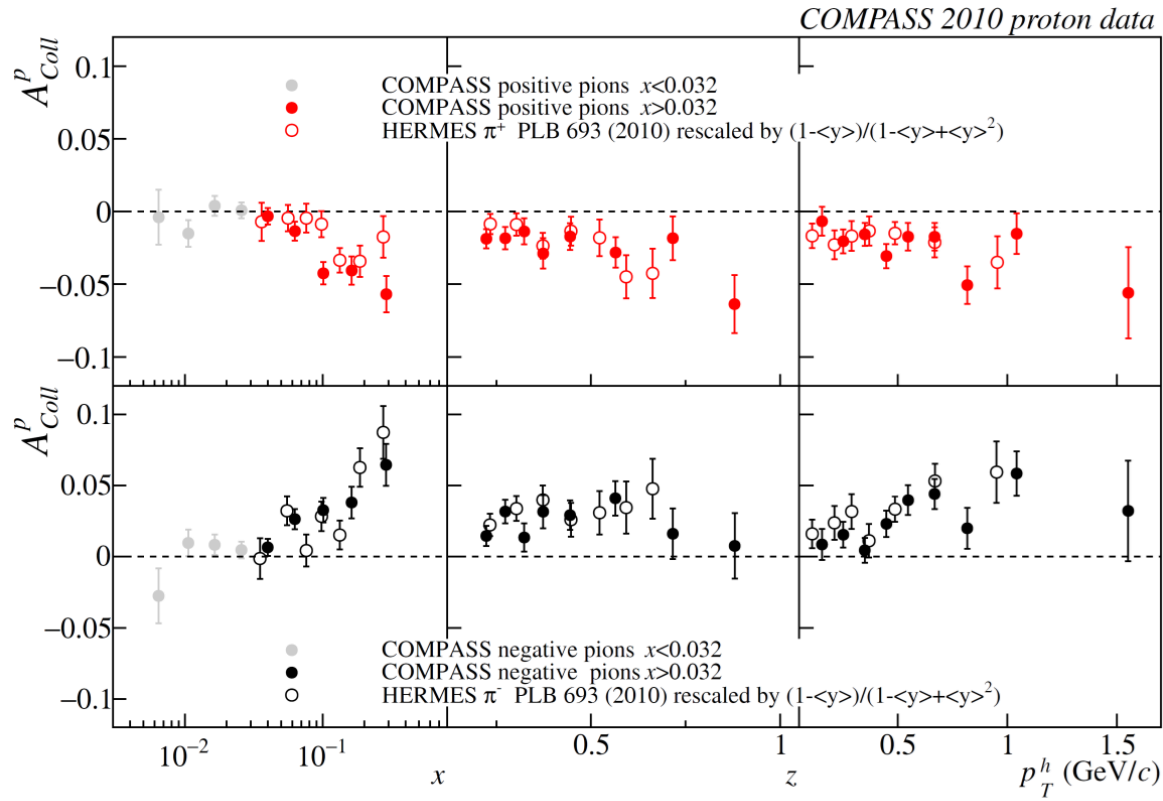
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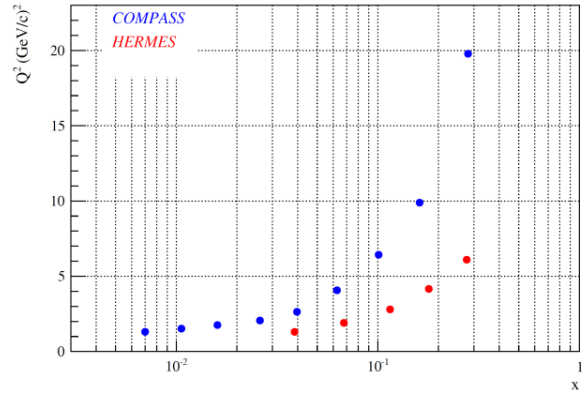
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COMPASS PLB 744 (2015) 250



COMPASS 2010 proton data





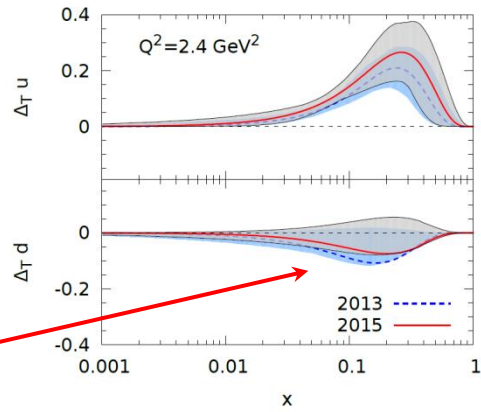
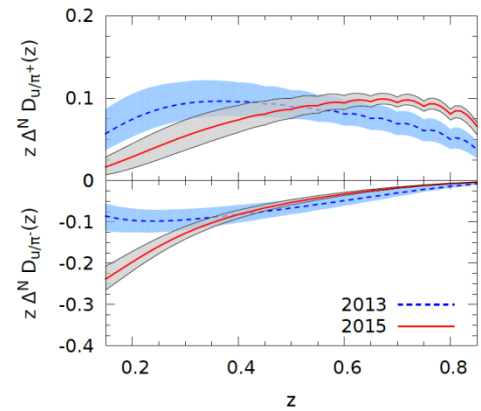
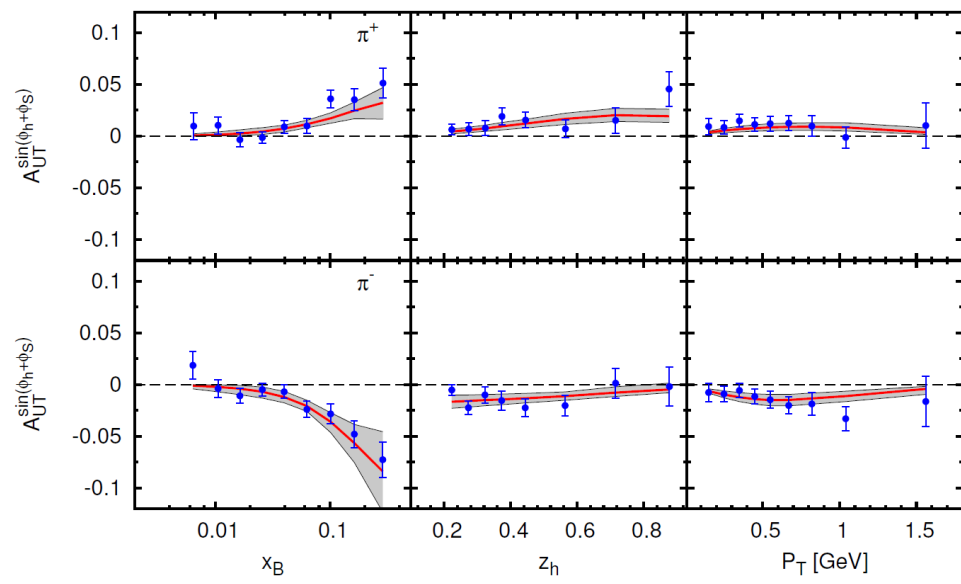
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- Extensive phenomenological studies and various global fits by different groups

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





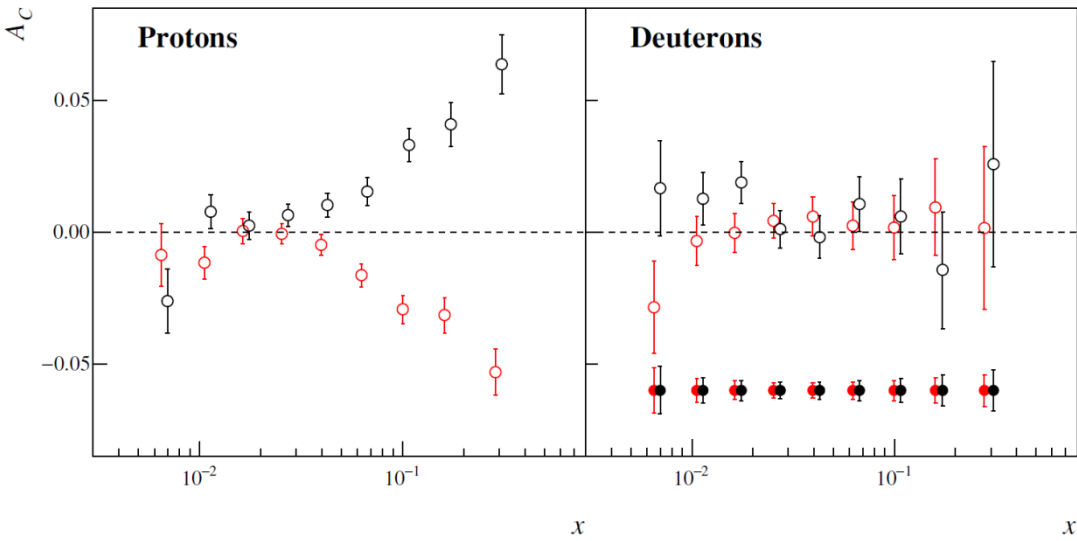
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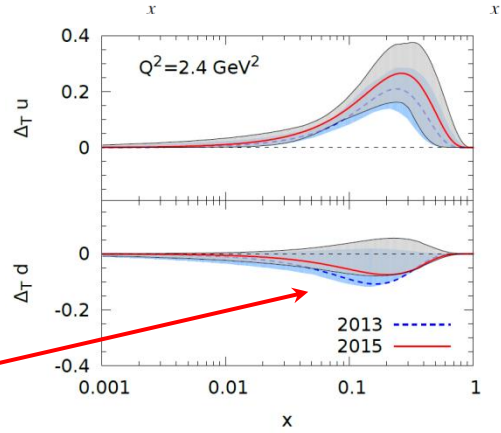
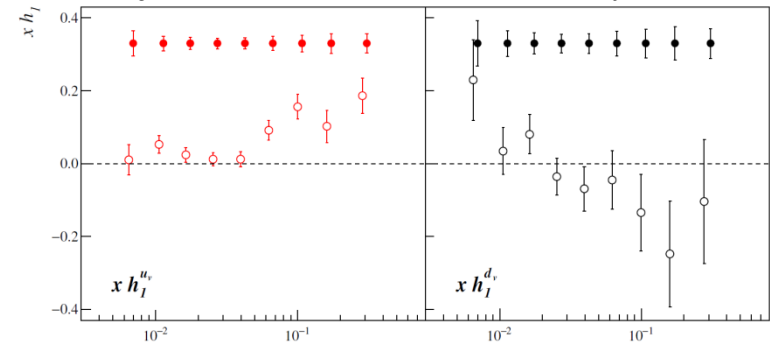
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Addendum to the COMPASS-II Proposal  
Projected uncertainties for Collins asymmetry



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



## COMPASS-II (2021)

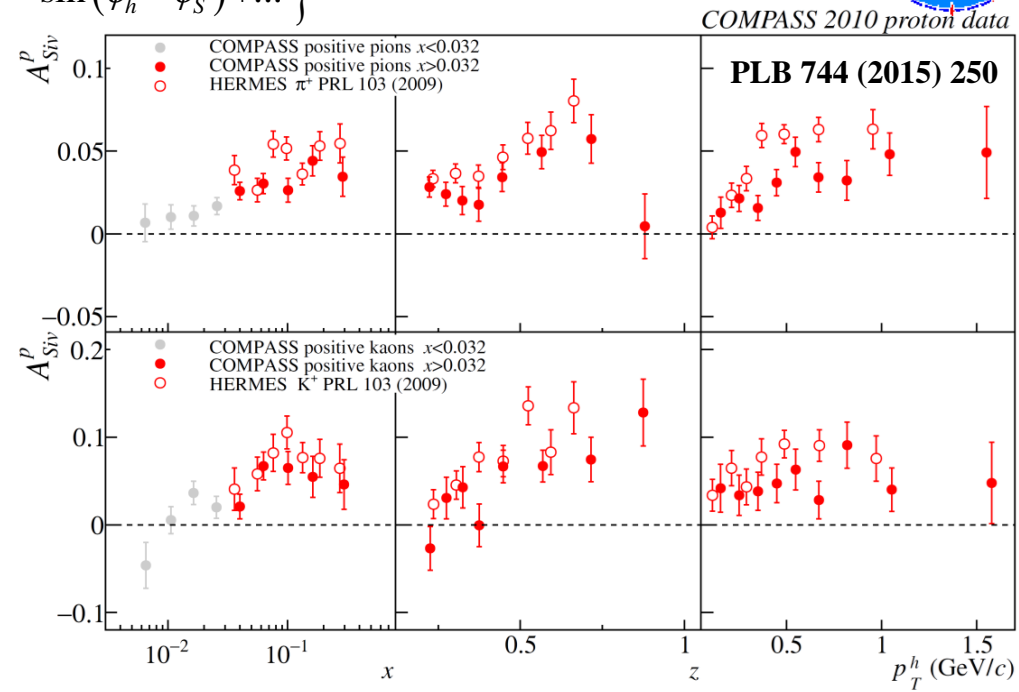
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# SIDIS TSAs (Sivers)

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

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

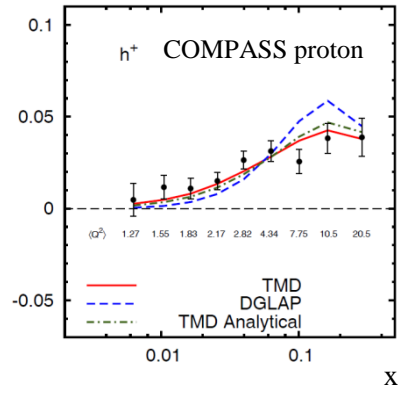
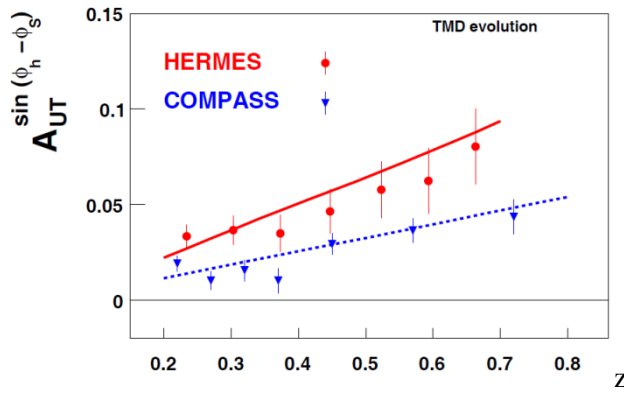
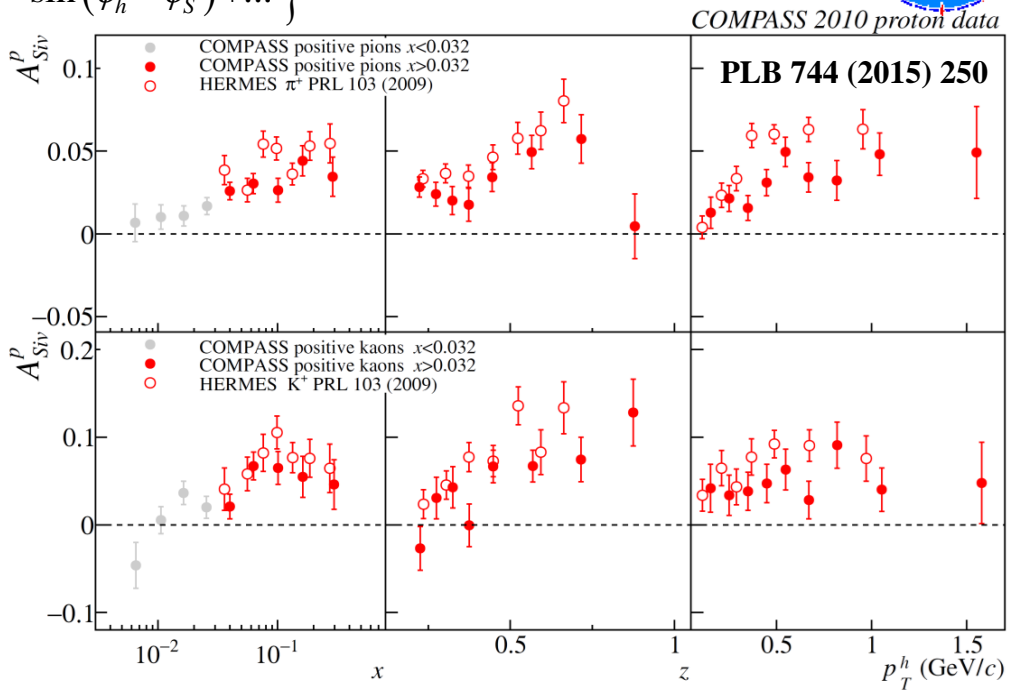


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$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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- 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**

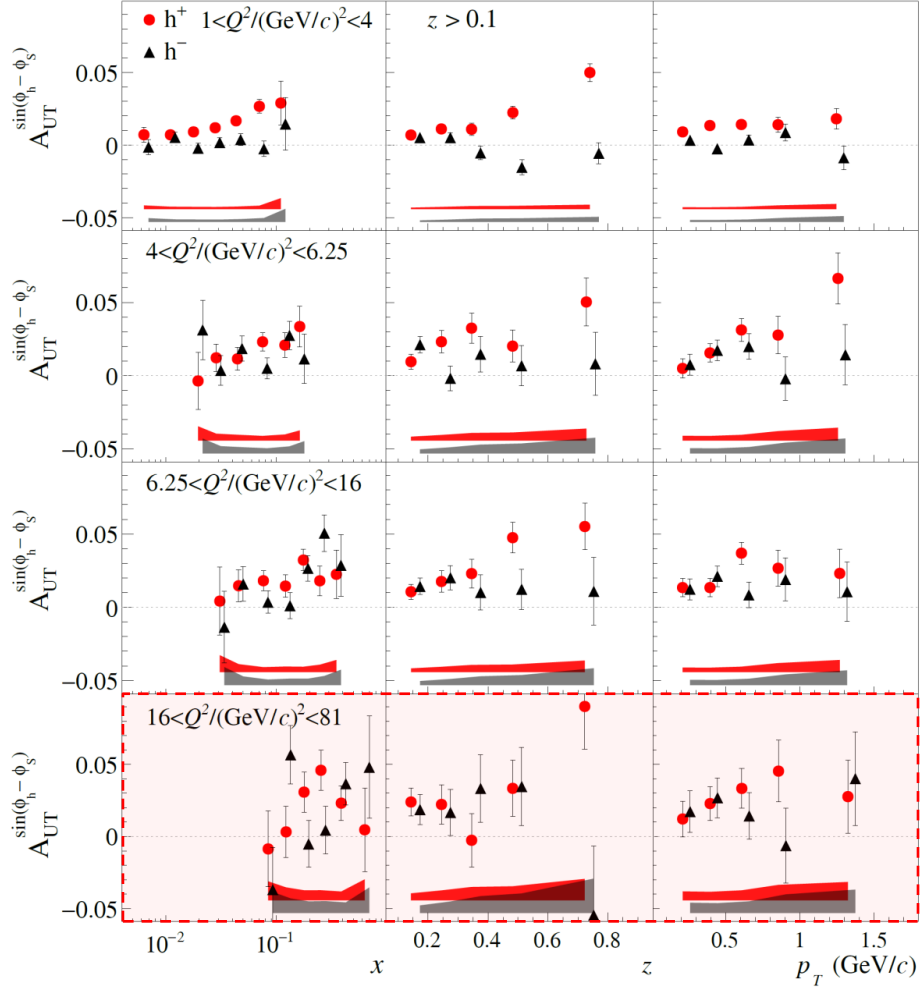
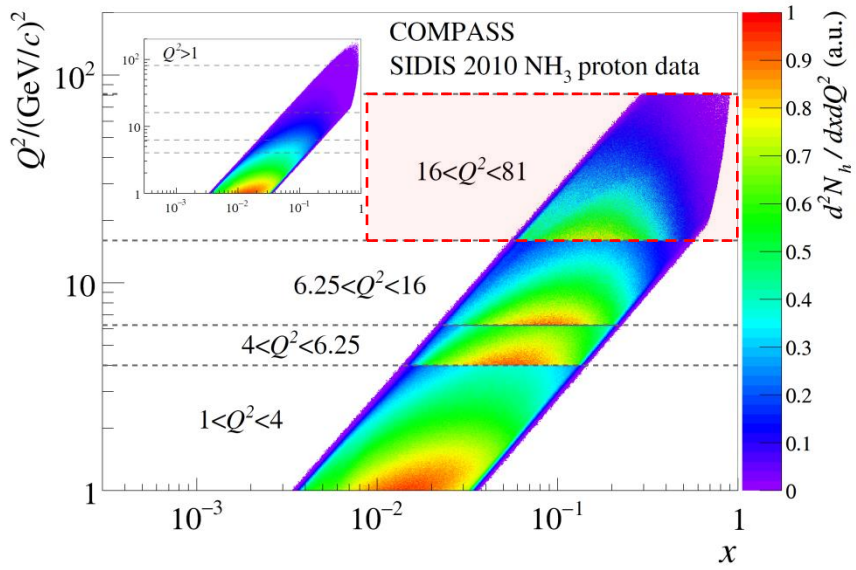


# SIDIS Sivers TSA in COMPASS Drell-Yan $Q^2$ -ranges

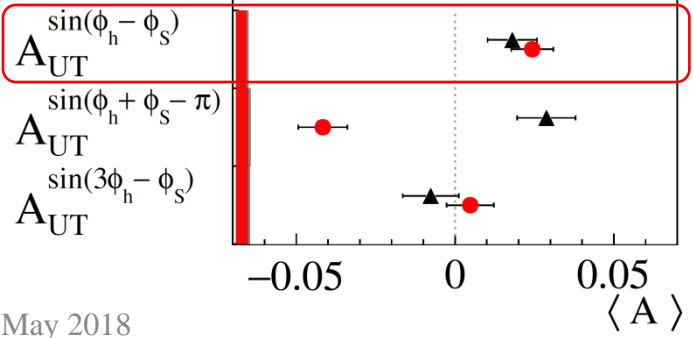
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COMPASS **PLB 770 (2017) 138**



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



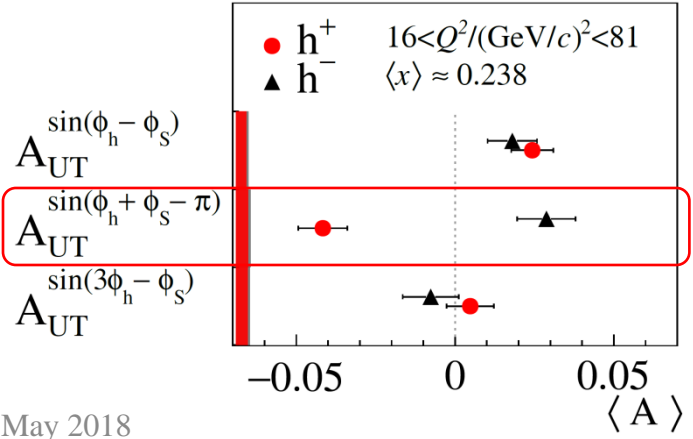
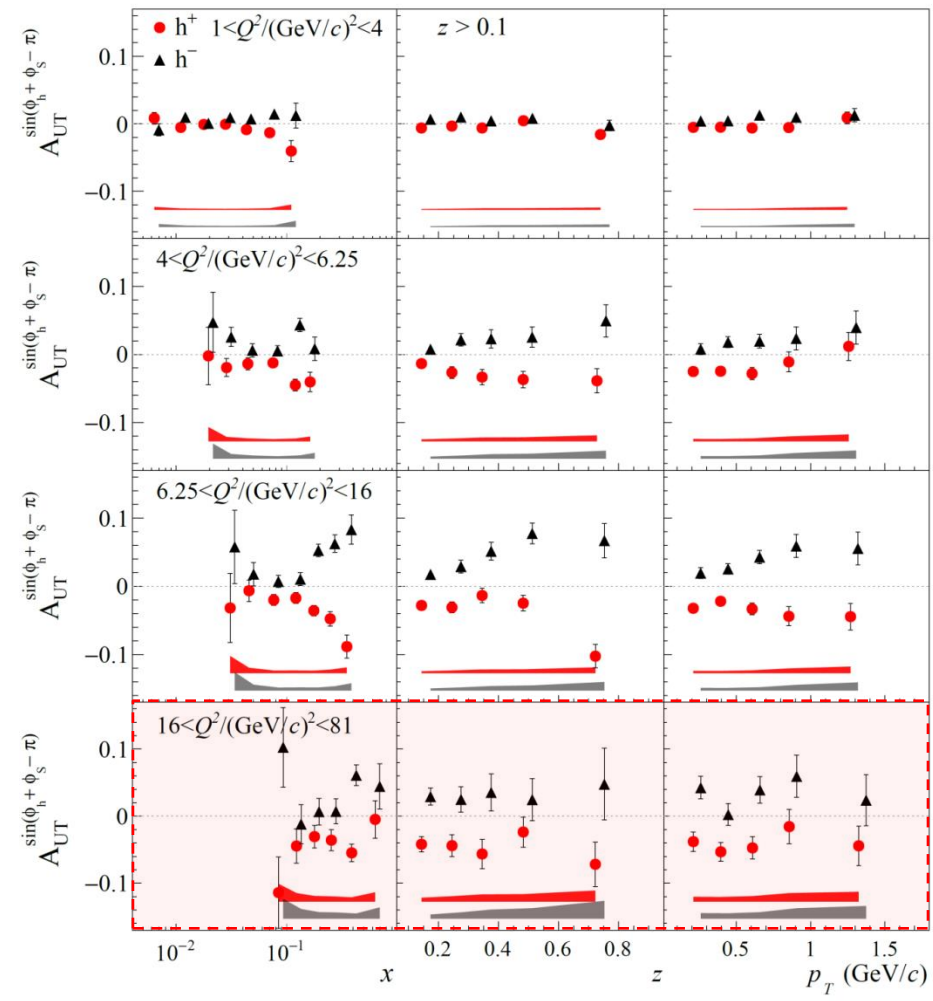
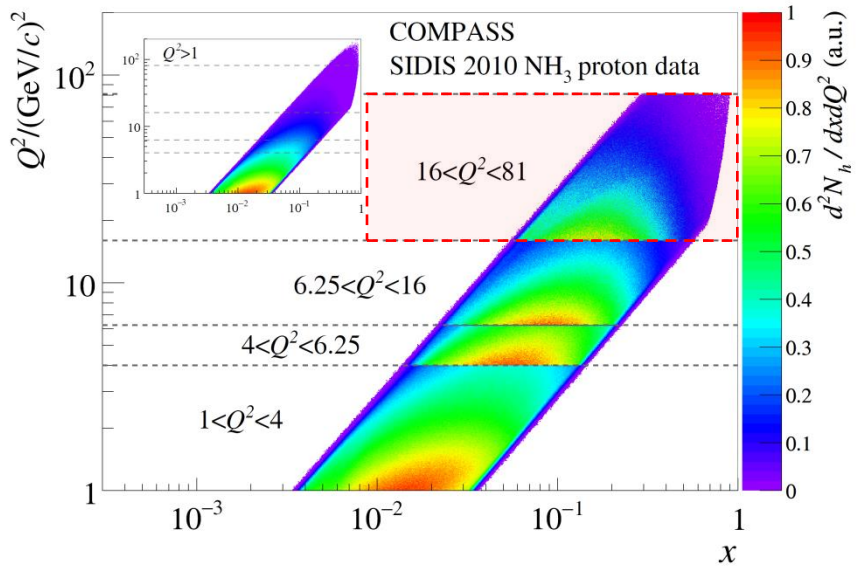


# SIDIS Collins TSA in COMPASS Drell-Yan $Q^2$ -ranges

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

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

COMPASS **PLB 770 (2017) 138**

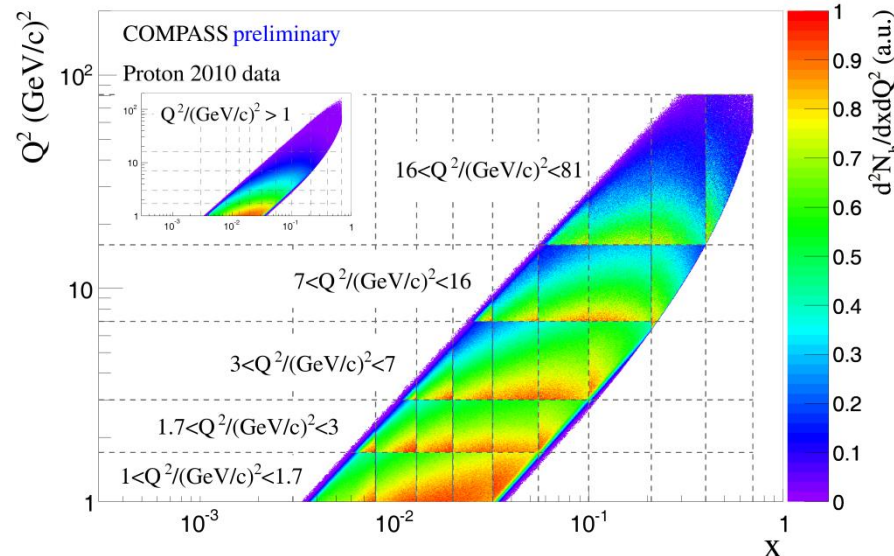


# Multi-D TSA analysis

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

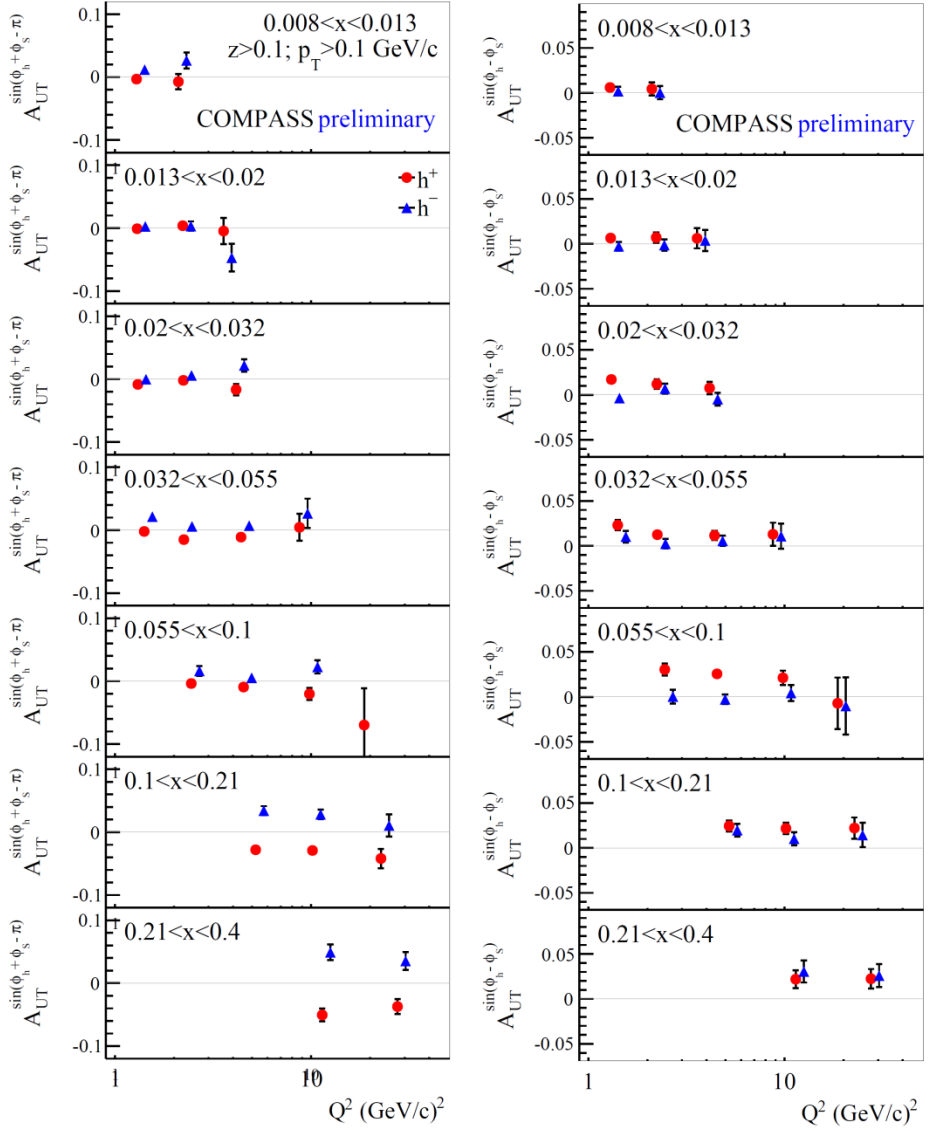
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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



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

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

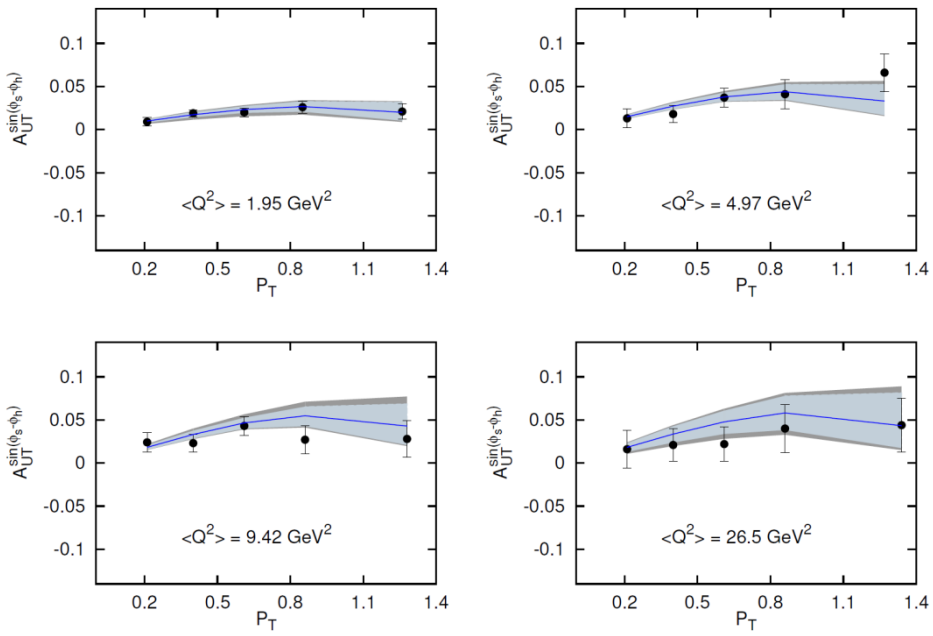




# SIDIS Sivers TSA in COMPASS Drell-Yan $Q^2$ -ranges

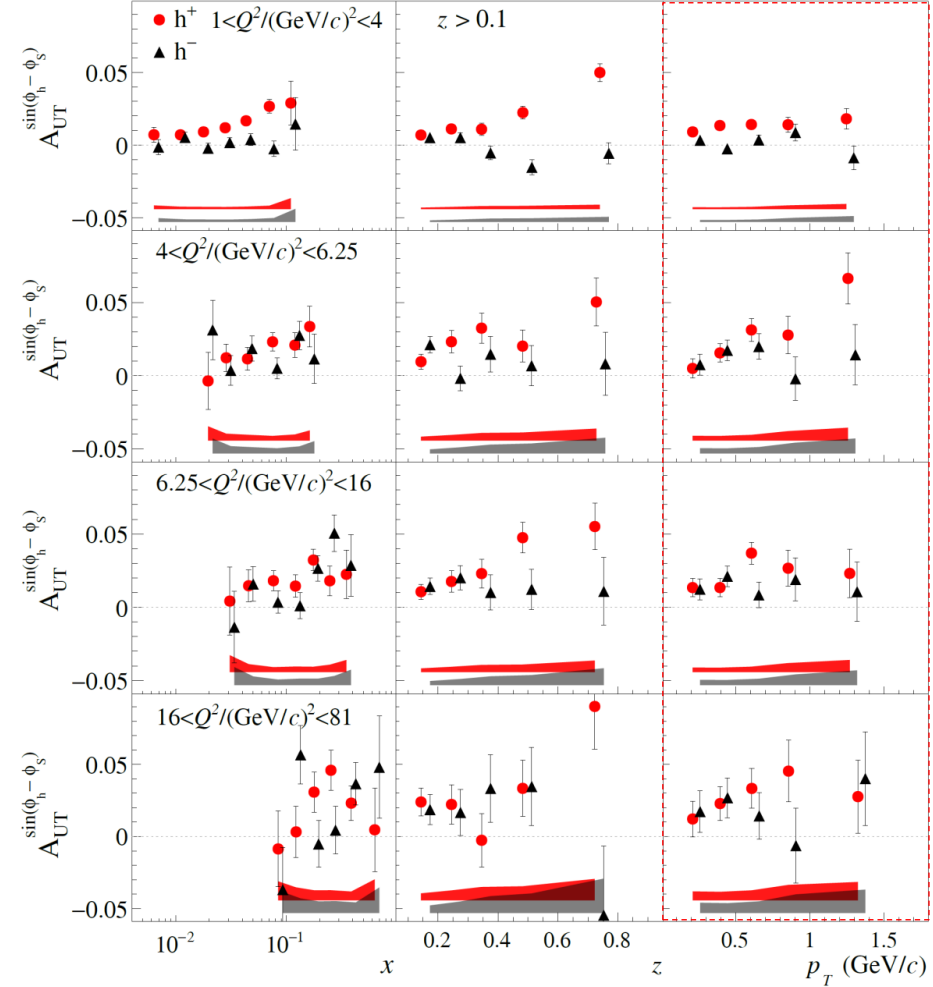
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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



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

COMPASS **PLB 770 (2017) 138**

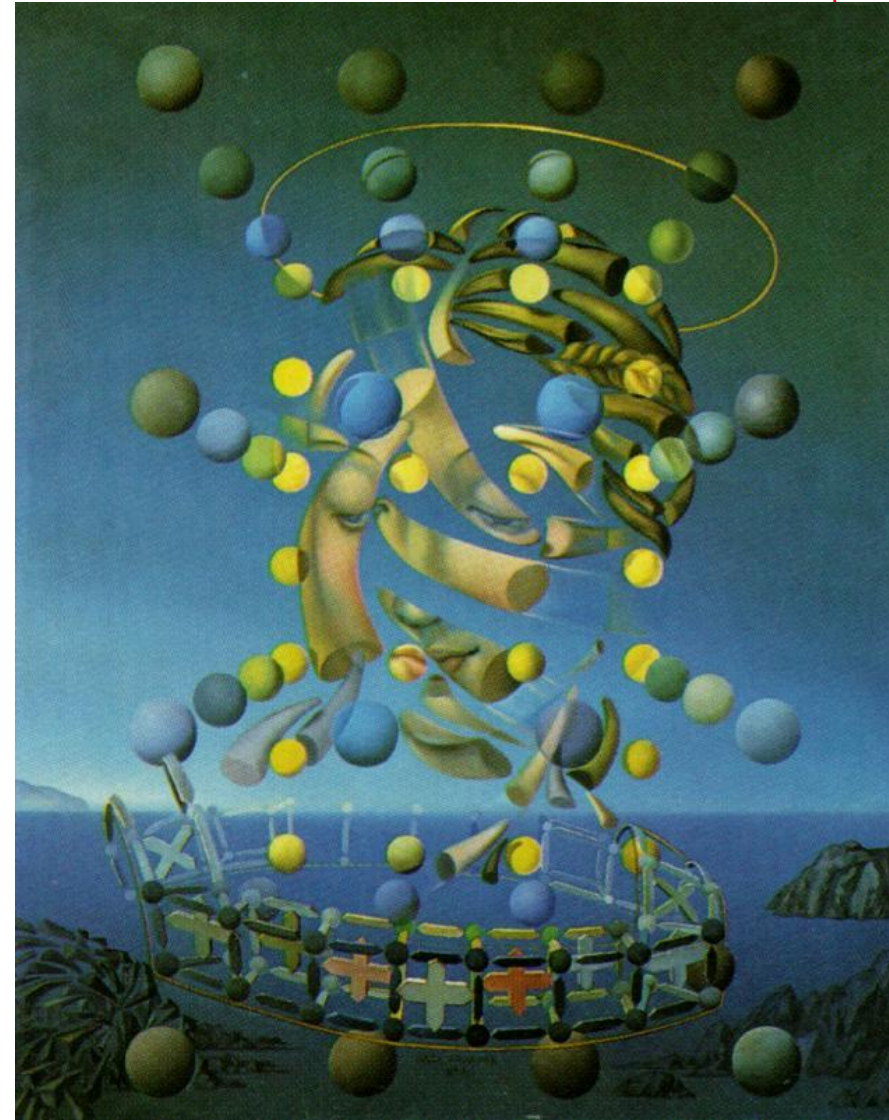


*“Nature”*



*Raphael “Madonna del Prato”*

*“ID”*



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



*“Nature”*



**Raphael** *“Madonna del Prato”*

*“multi-D” with available statistics*



**Raphael** *“Madonna del Prato”* (poor resolution)



- Results from first ever measurement of Drell-Yan TSAs



# 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,**  
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

COMPASS ongoing analysis



# Single-polarized DY x-section: unpolarized part

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

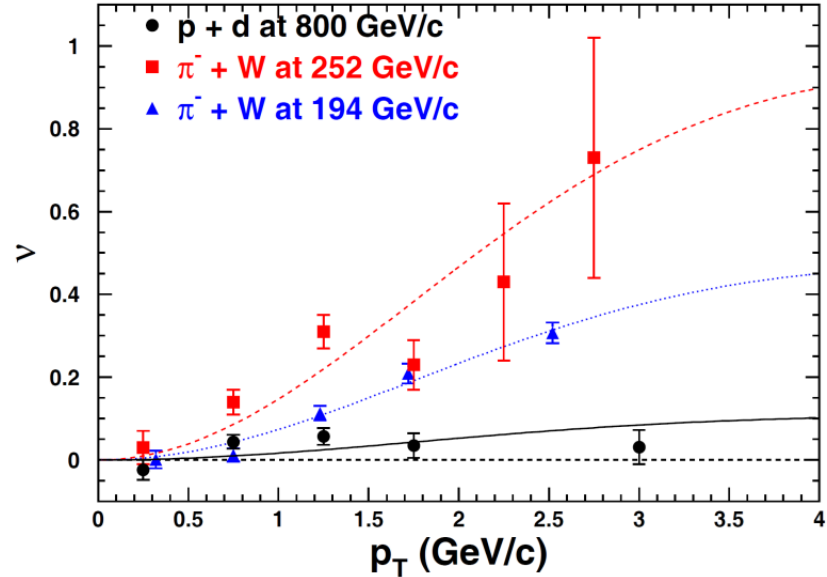
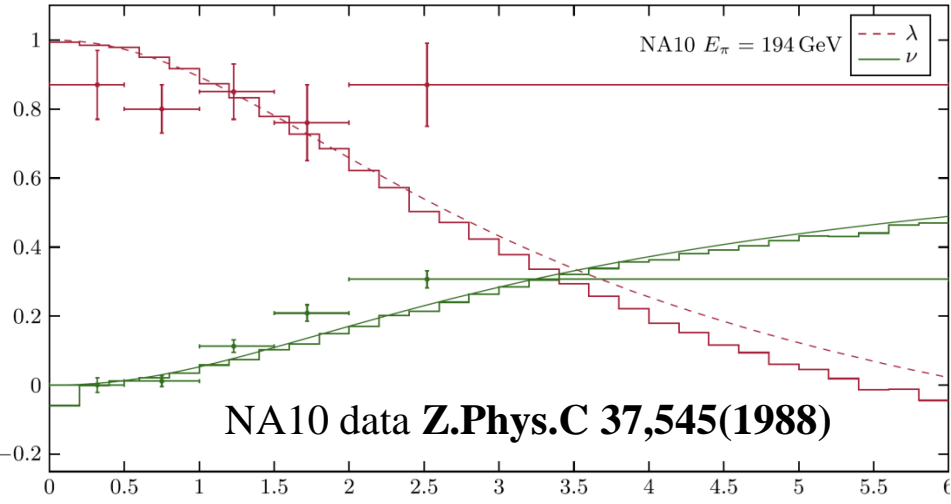
- “naive” Drell–Yan model  
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 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$  but  $1-\lambda=2\nu$  (Lam-Tung)
- Experiment,  
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$
- $\nu \neq 0$  - Energy and quark flavour dependence,  
QCD radiative effects, non-coplanarity  
(PRD93, 114013 (2016), PLB 758 (2016) 384)

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

COMPASS ongoing analysis

See talk by J.-C. Peng

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





# Single-polarized DY x-section: transverse part

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

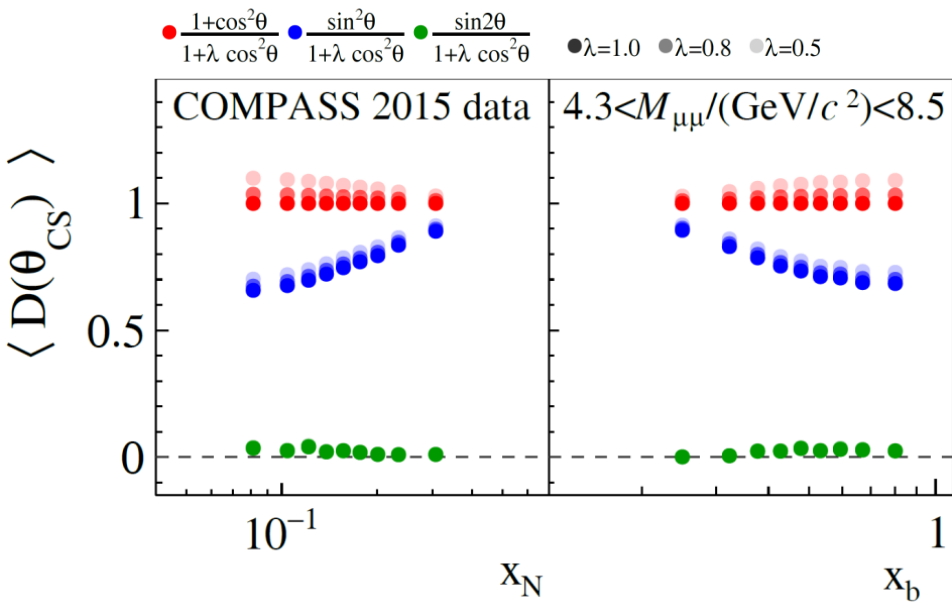
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- **Experiment,**  
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

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

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





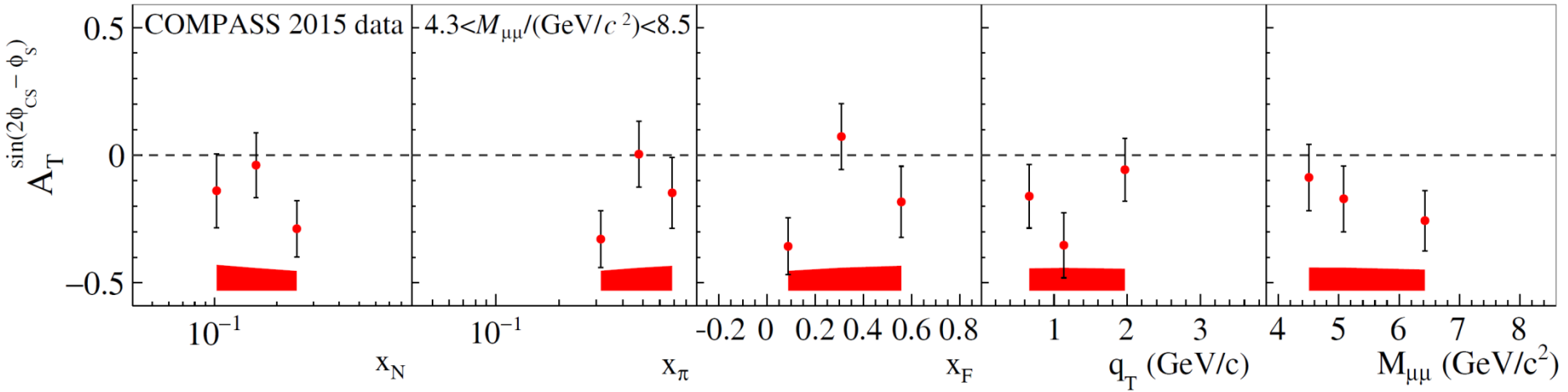
# Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

COMPASS PRL 119, 112002 (2017)





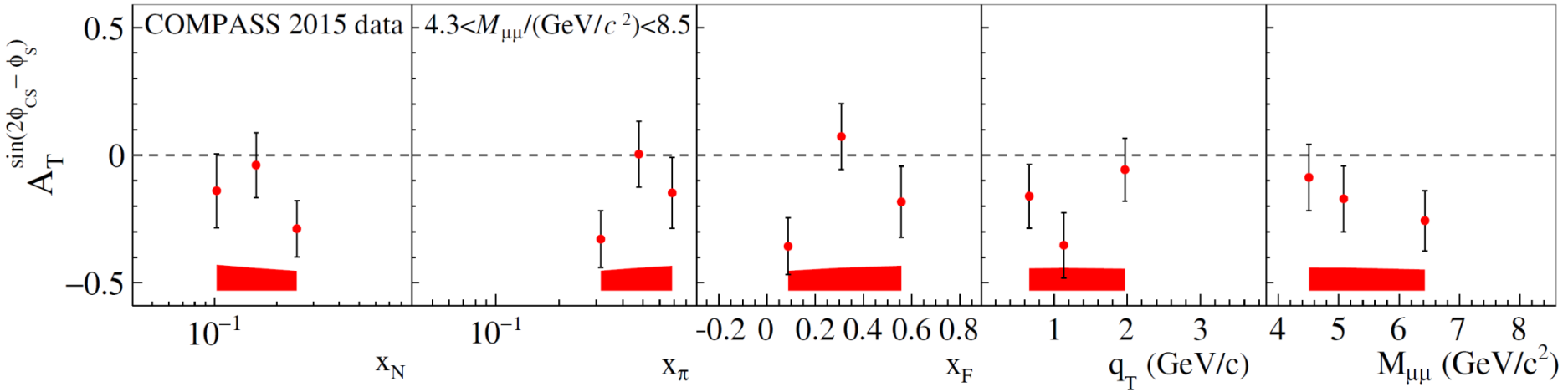
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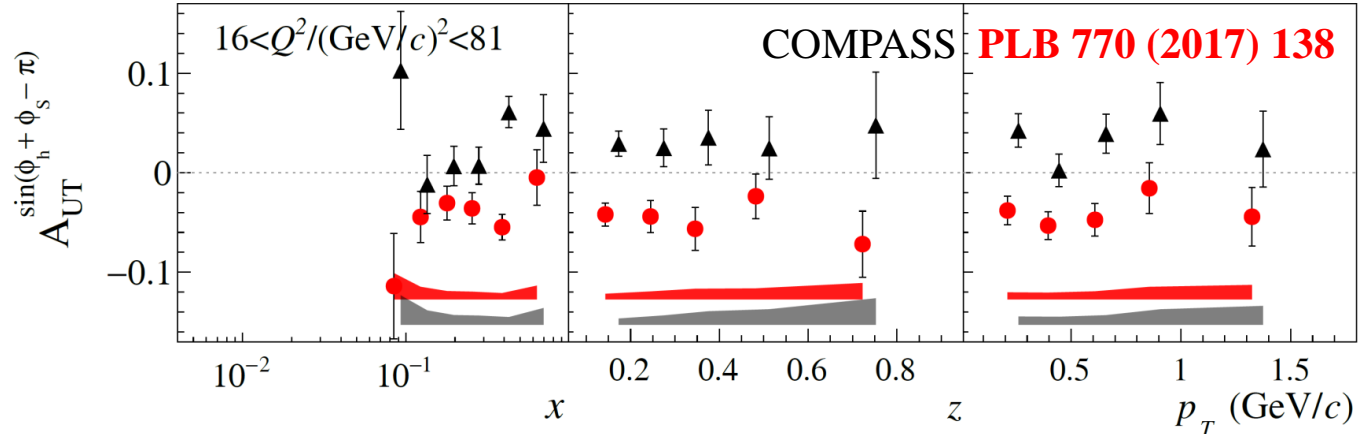
COMPASS PRL 119, 112002 (2017)



## SIDIS in Drell-Yan high-mass range

Collins SIDIS TSA

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





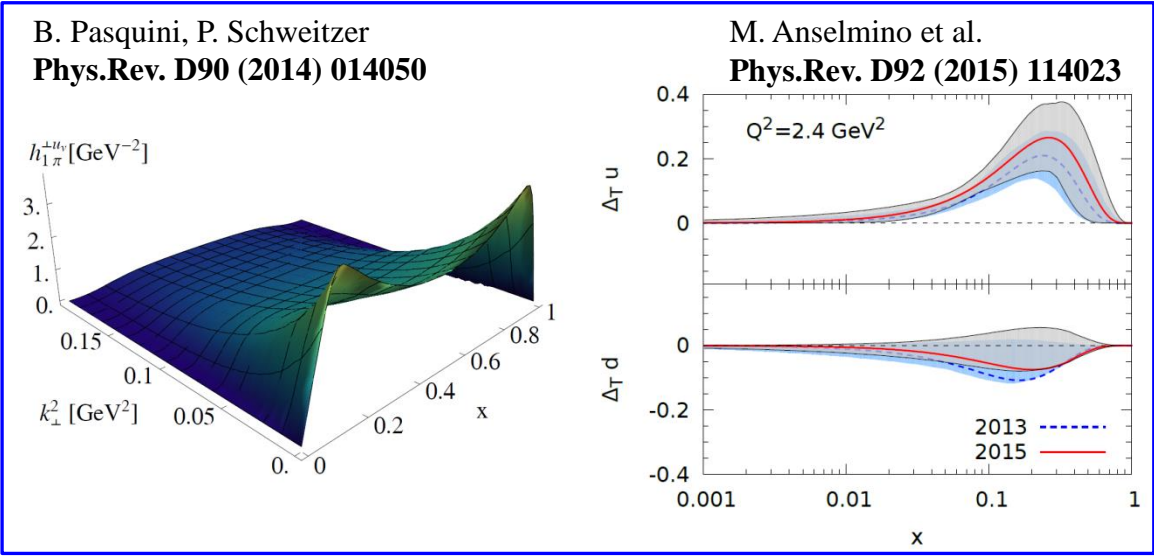
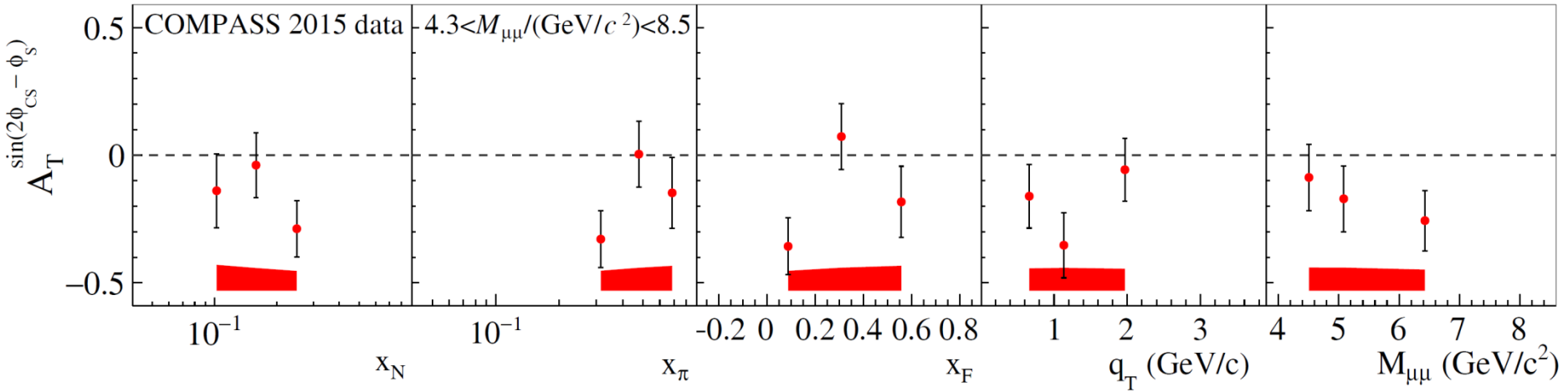
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Transversity DY TSA

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COMPASS PRL 119, 112002 (2017)







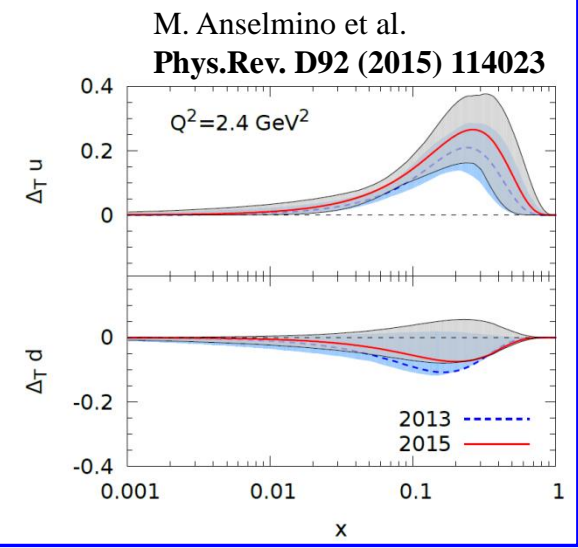
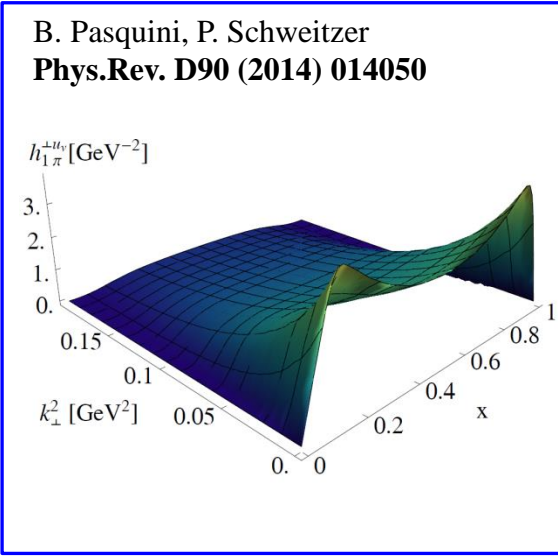
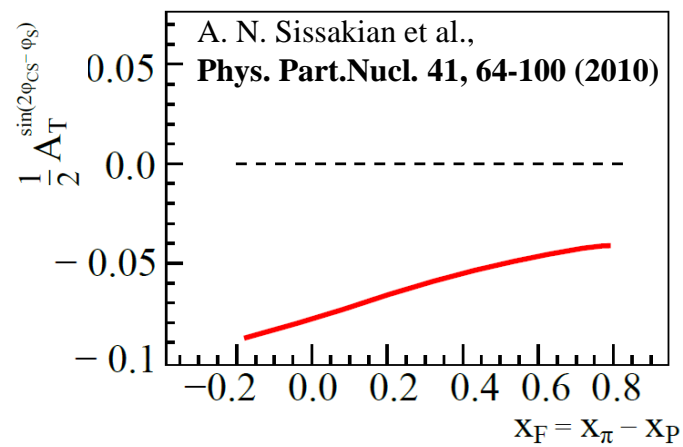
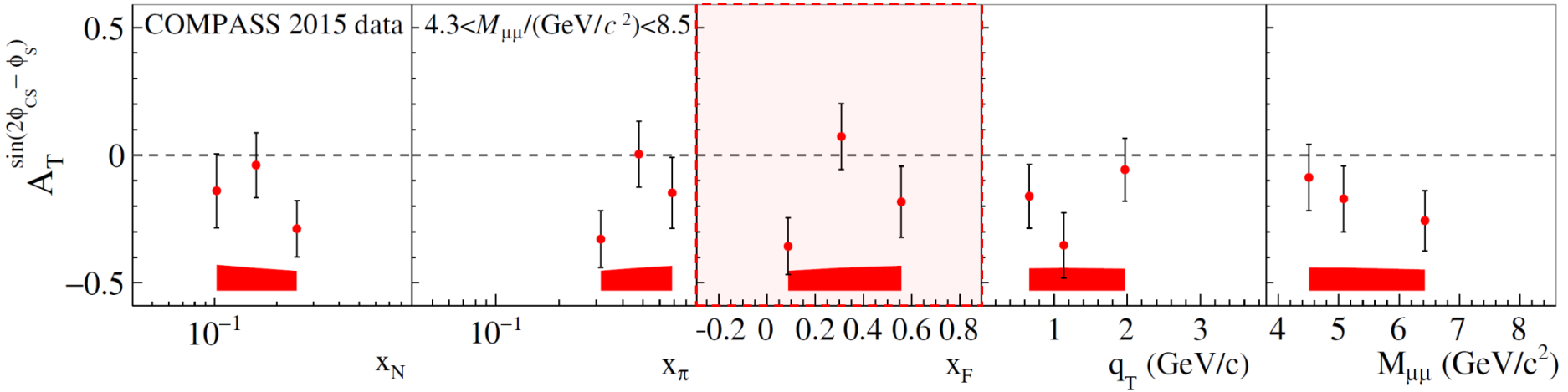
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COMPASS PRL 119, 112002 (2017)





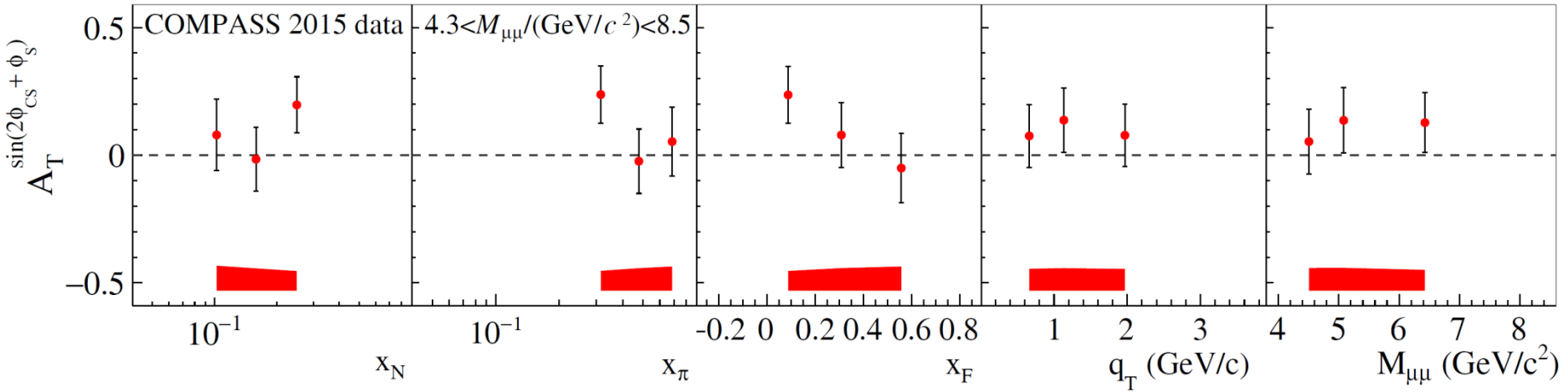
# Drell-Yan TSAs – Pretzelosity

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

## Pretzelosity DY TSA

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

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





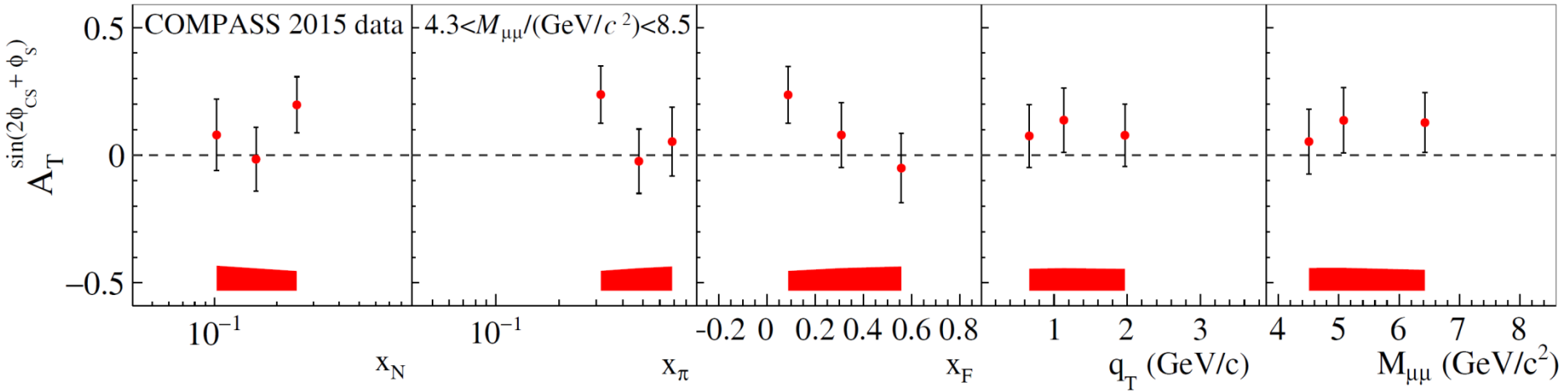
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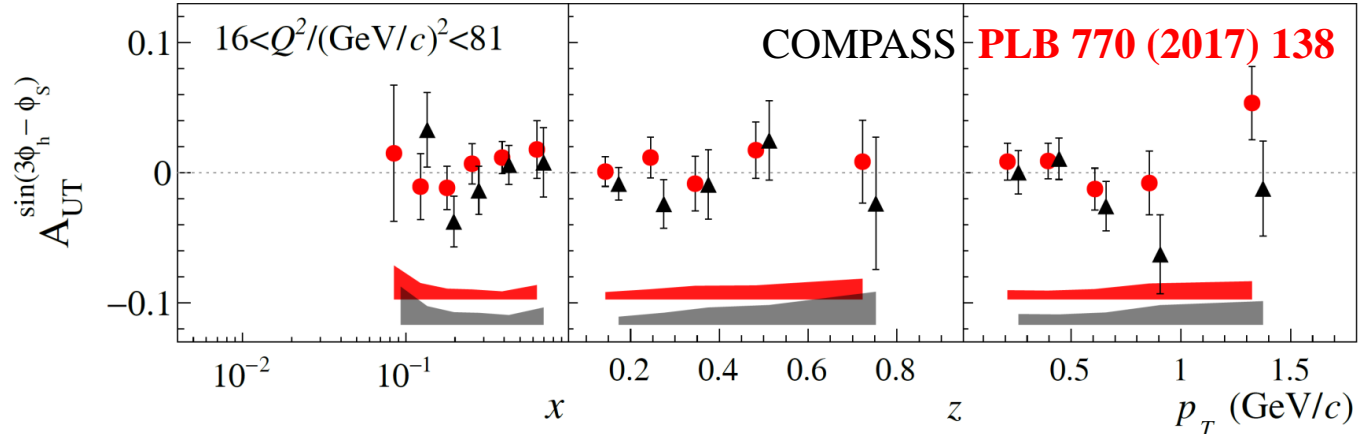
COMPASS PRL 119, 112002 (2017)



## SIDIS in Drell-Yan high-mass range

Pretzelosity SIDIS TSA

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





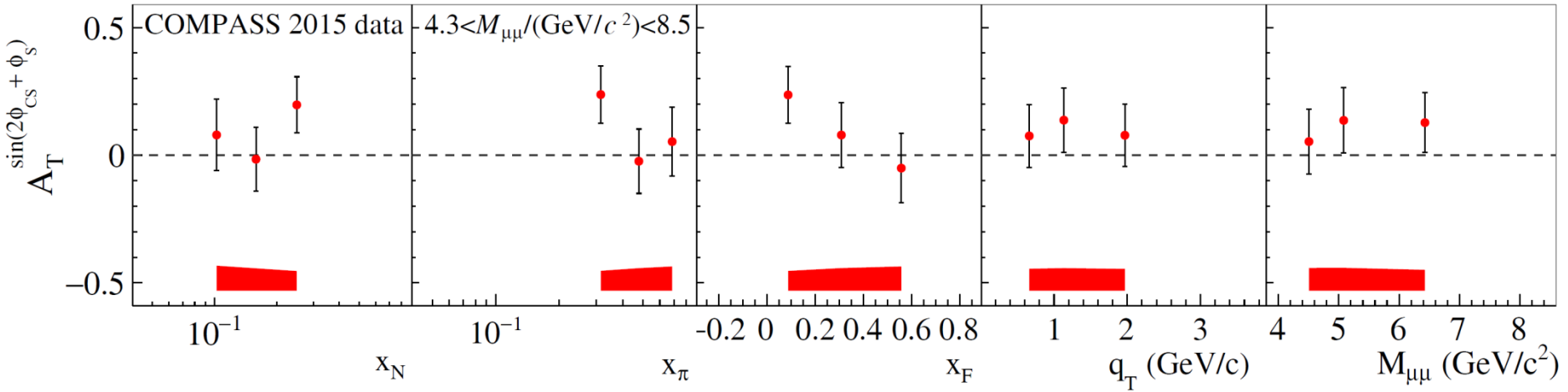
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**COMPASS PRL 119, 112002 (2017)**



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

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



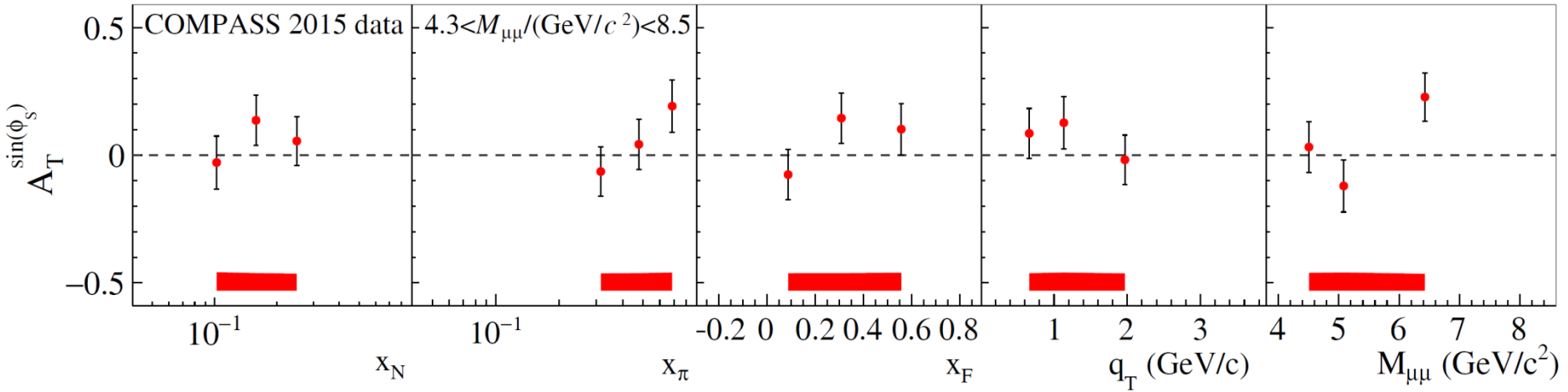
# Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)





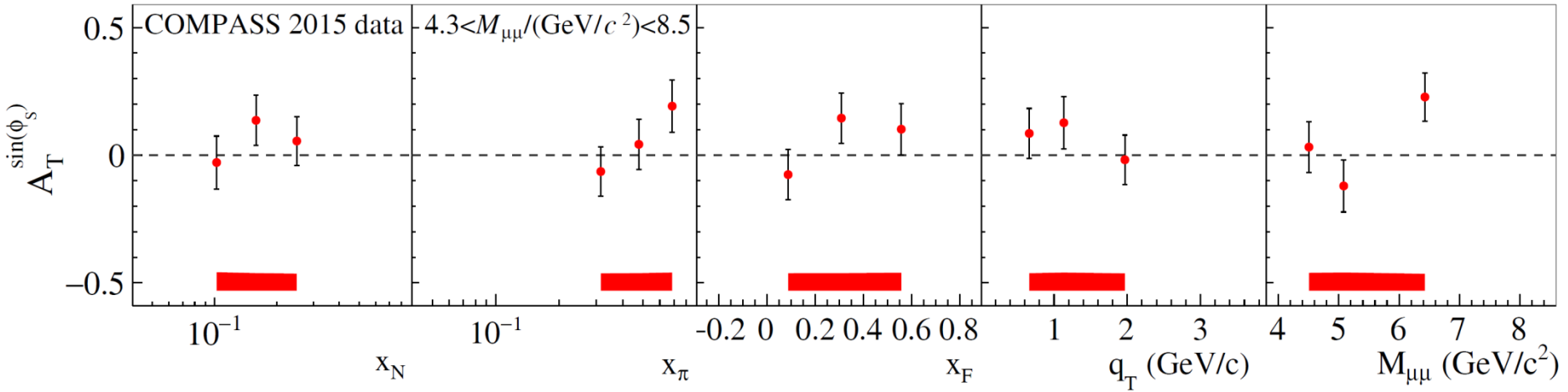
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COMPASS PRL 119, 112002 (2017)

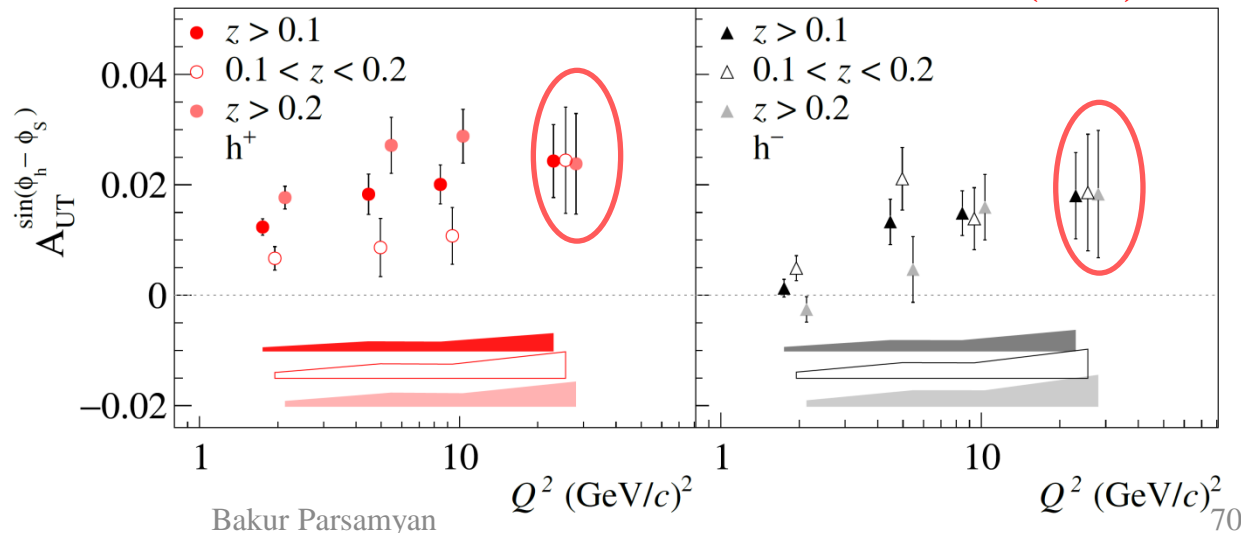


## SIDIS in Drell-Yan high-mass range

COMPASS PLB 770 (2017) 138

## Sivers SIDIS TSA

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

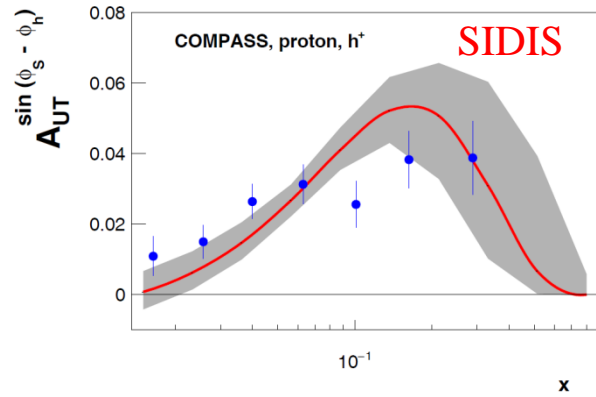




# Sivers asymmetry in Drell-Yan: sign change

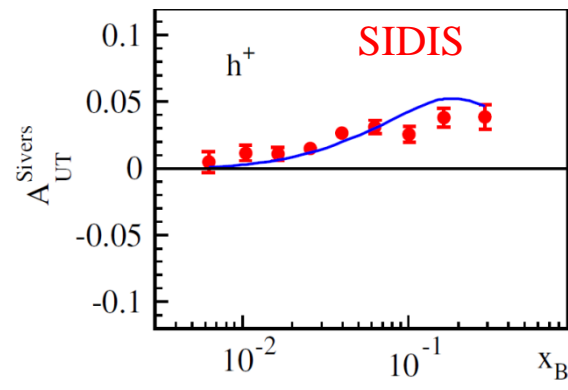
DGLAP (2016)

M. Anselmino et al., arXiv:1612.06413



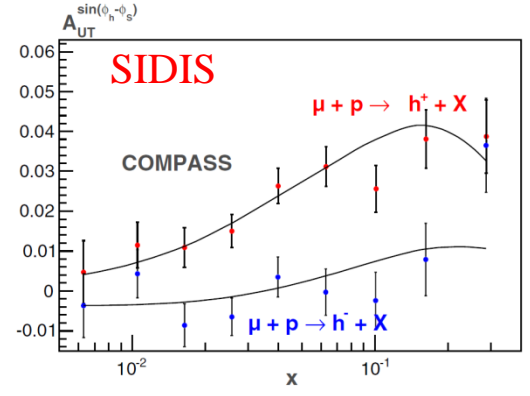
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012





# Sivers asymmetry in Drell-Yan: sign change

DGLAP (2016)

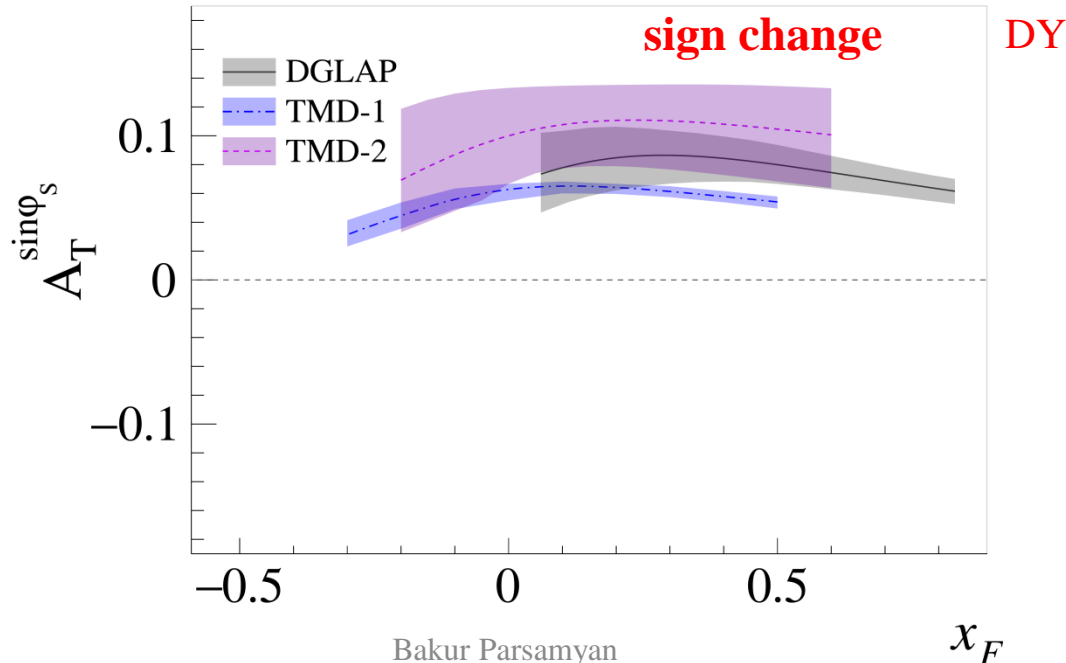
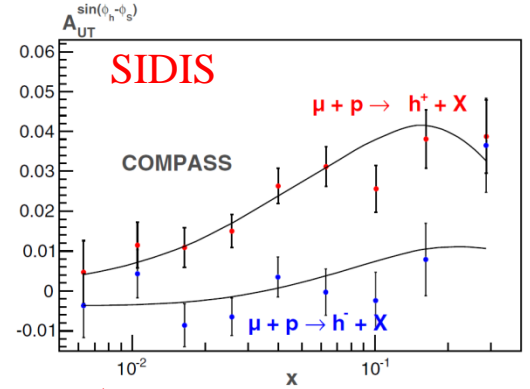
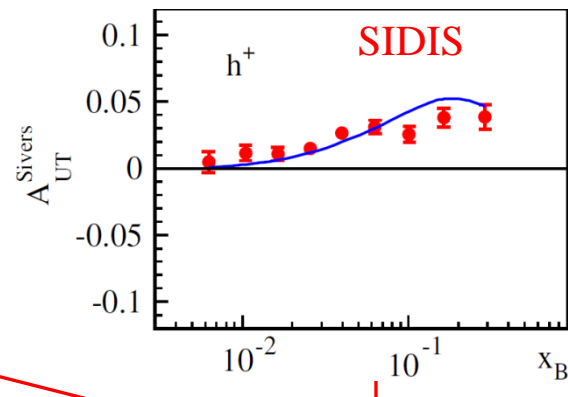
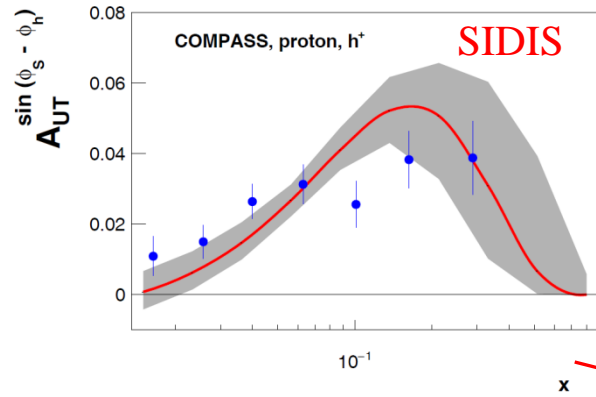
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# Sivers asymmetry in Drell-Yan: sign change

DGLAP (2016)

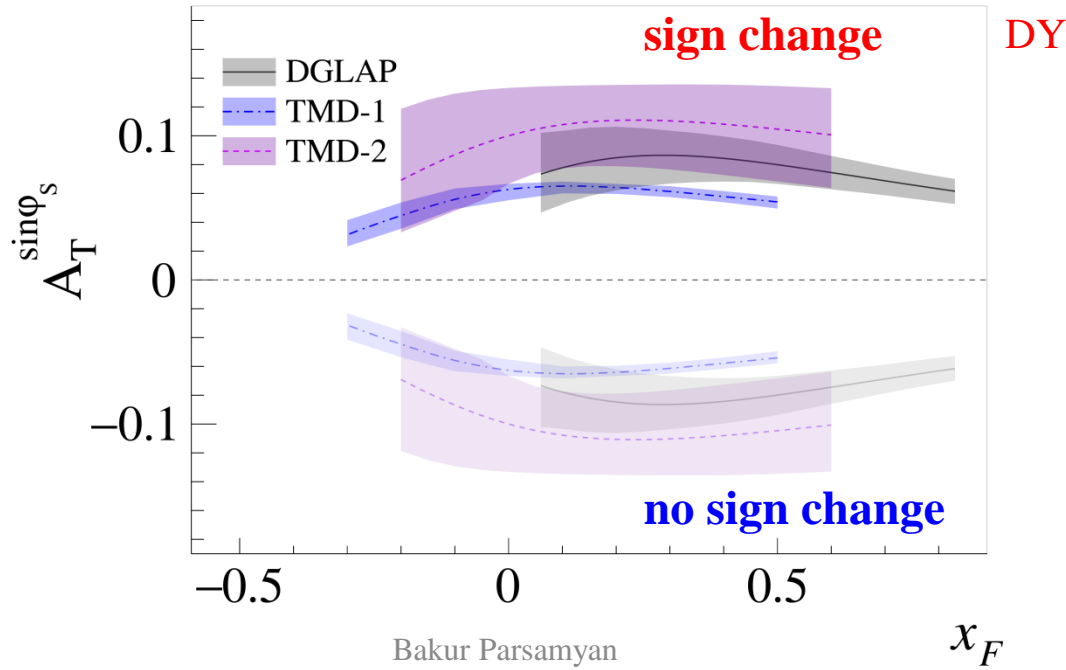
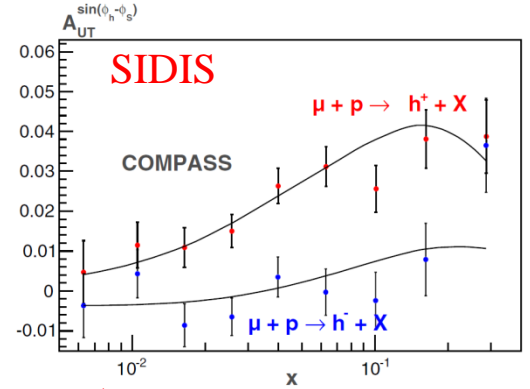
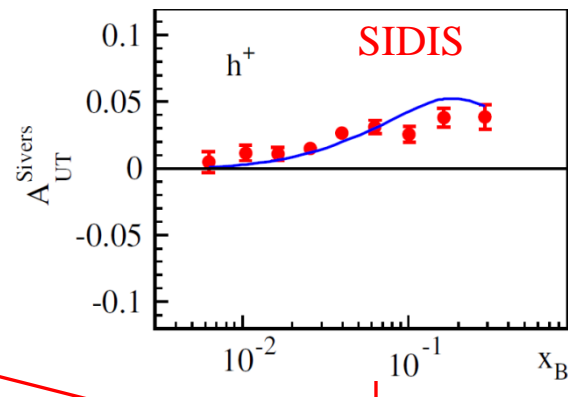
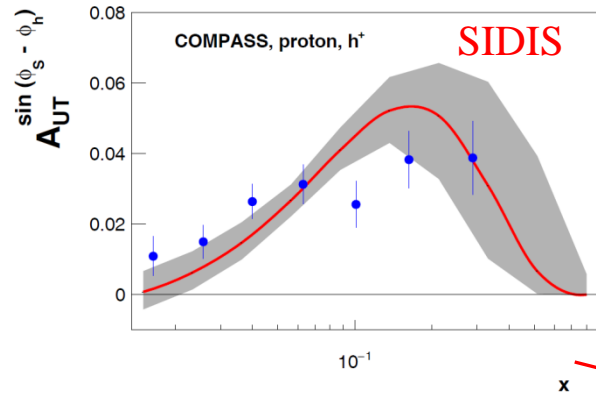
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TMD-1 (2014)

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TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012



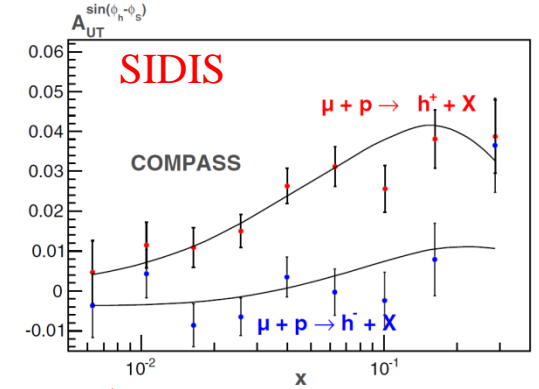
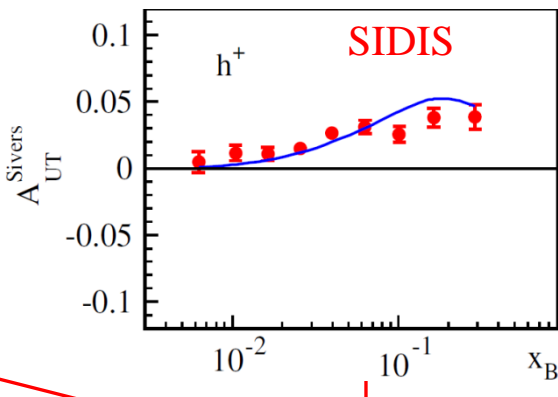
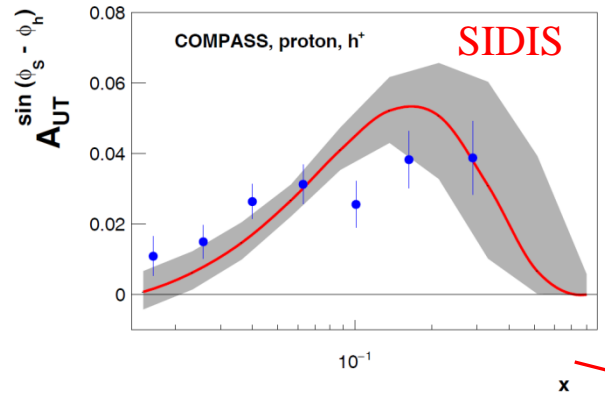


# Sivers asymmetry in Drell-Yan: sign change

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

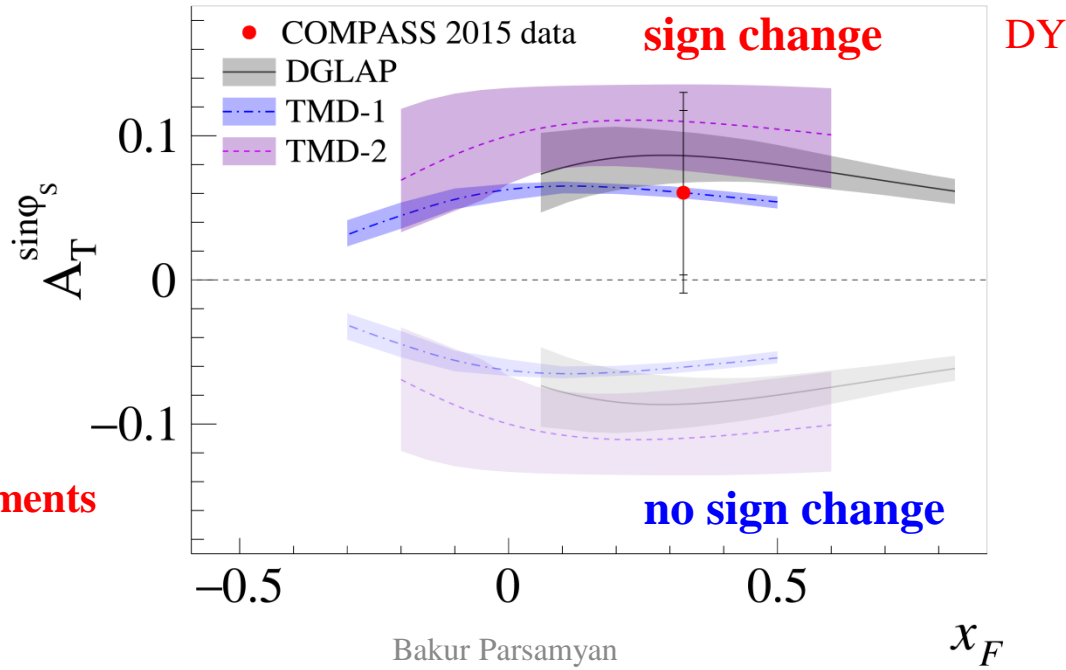
**TMD-1 (2014)**  
M. G. Echevarria et al. **PRD89,074013**

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



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

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

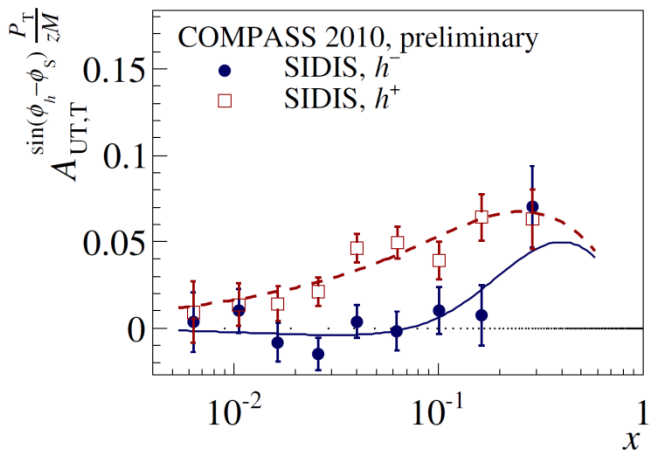




# The $p_T$ ( $q_T$ ) – weighted SIDIS(DY) Siverson asymmetry

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



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

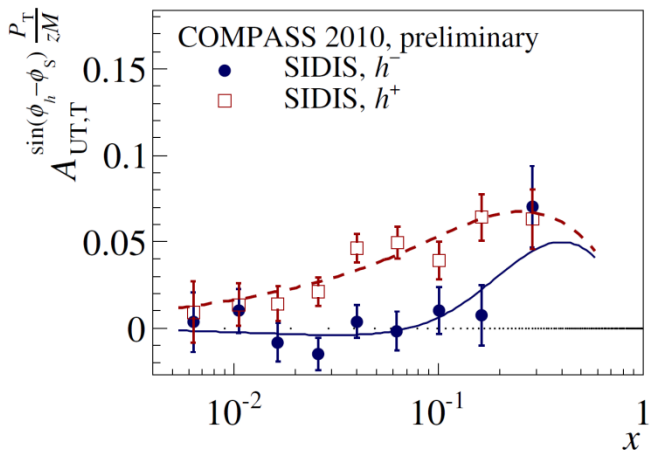
Sivers wTSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$



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

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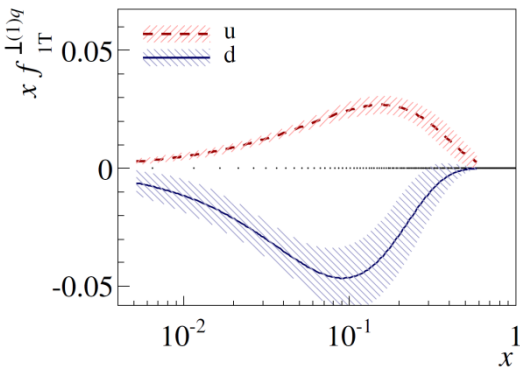


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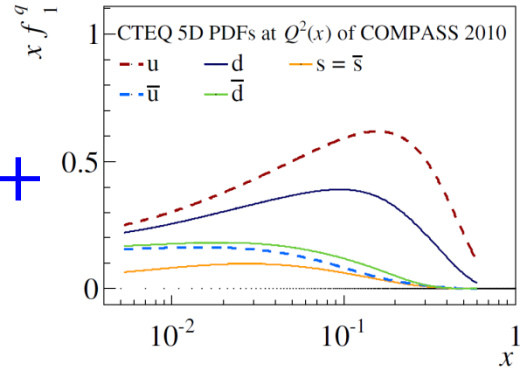
Sivers wTSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$

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

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



+



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

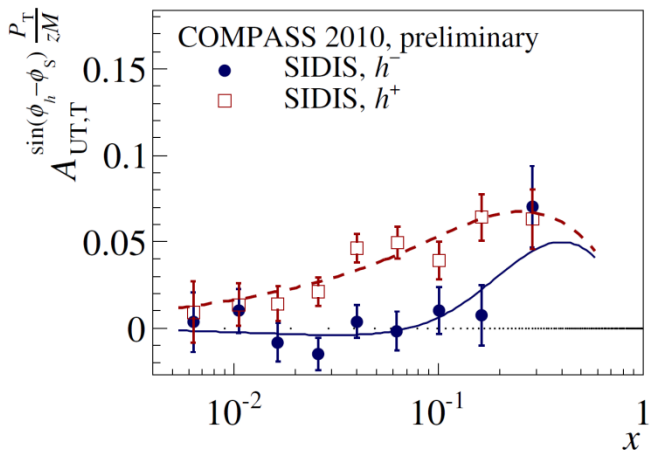
$$A_T^{\sin \phi_S} \frac{q_T}{M_P} \approx \frac{f_{1T,p}^{\perp u (1)}}{f_{1,p}^u}$$



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

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



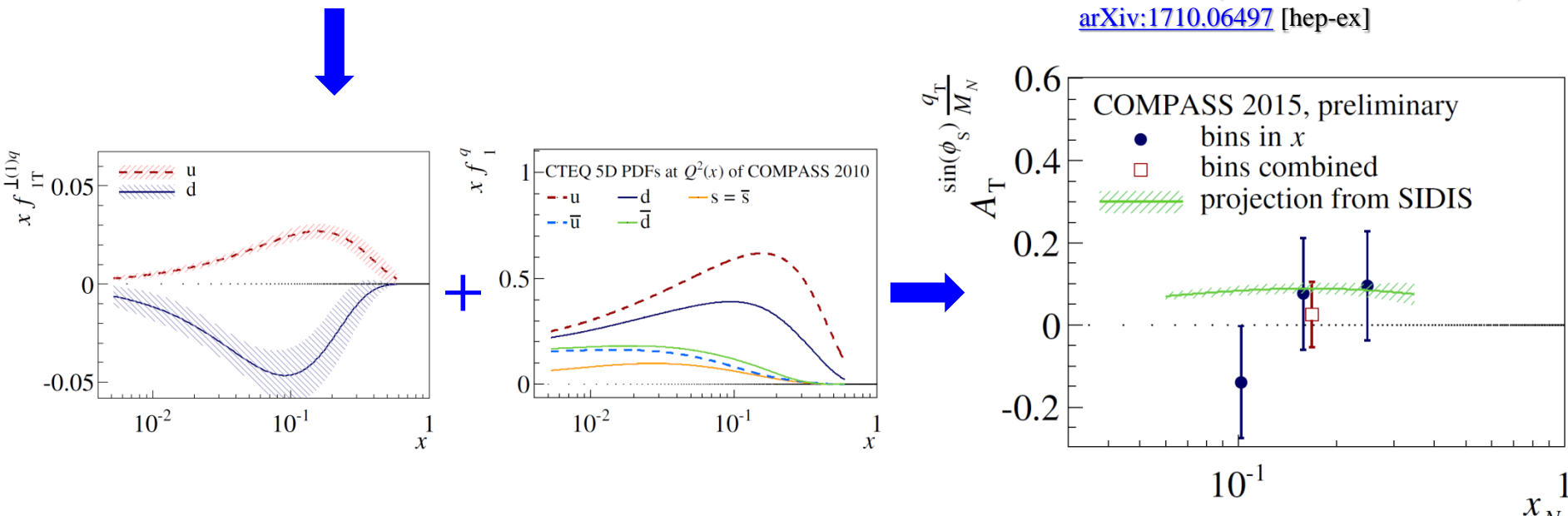
Siverts TSA in SIDIS:  $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$

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

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

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

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



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



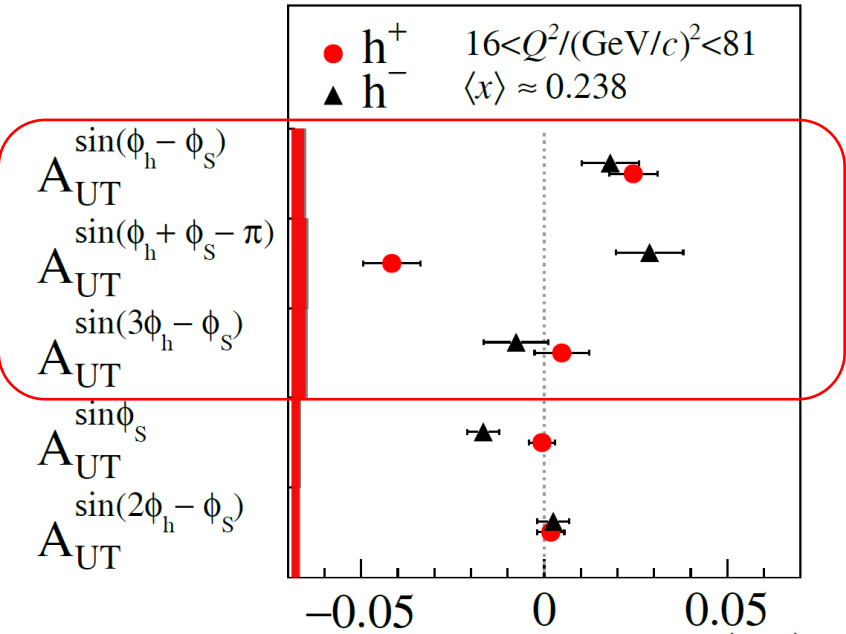
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

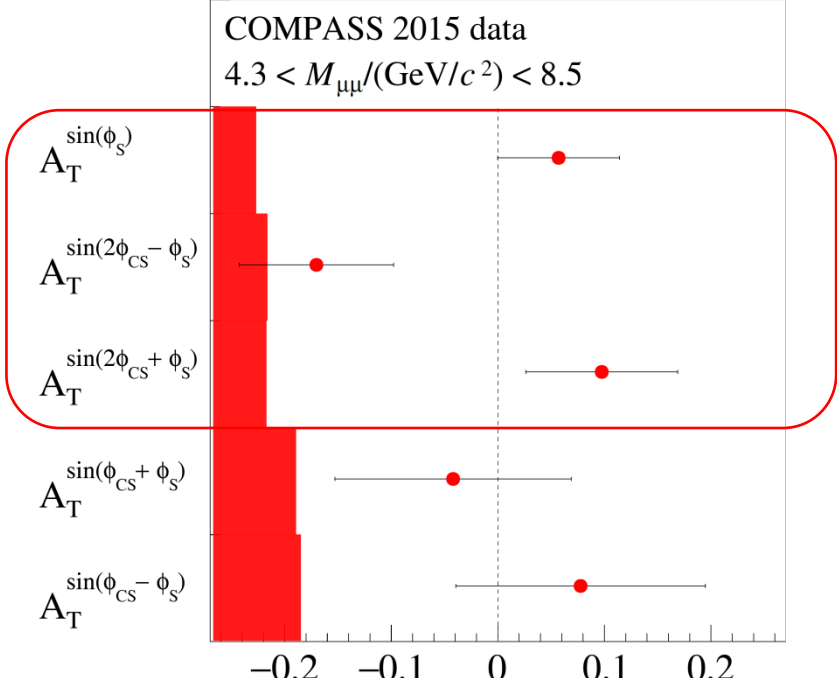
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

COMPASS PLB 770 (2017) 138



COMPASS PRL 119, 112002 (2017)





# “COMPASS-like” future long-term experiment

- [COMPASS beyond 2020](#) workshop, CERN, March 21-22, 2016
- [Physics Beyond Colliders](#) kick-off workshop CERN, September 6-7, 2016
- [IWHSS17](#) COMPASS workshop, Cortona, April 2-5, 2017
- [Dilepton Productions with Meson and Antiproton Beams](#) workshop, ECT\*, Trento, November 2017
- [Physics Beyond Colliders](#) annual workshop, CERN, November 21-22, 2017
- [IWHSS18](#) – COMPASS workshop, Bonn, March 19-21, 2018

### 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**

Masaru Anselmino  
Antonio Bacchetta  
Michaela C. Chiapparini  
Bianca Leung  
Daniela Pastorelli (Chair)  
Bakur Parsamyan

[iwhss17@to.infn.it](mailto:iwhss17@to.infn.it)  
[iwhss17.to.infn.it](https://iwhss17.to.infn.it)  
@iwhss17

**April 2-5, 2017**  
Cortona

**International Advisory Committee**

Masaru Anselmino (INFN/Univ.Torino, Italy)  
Haruo Asakura (KEK/SUUSA)  
Alessandro Bacchetta (INFN/Univ.Pavia, Italy)  
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Oleg Teresaev (JINR, Dubna, Russia)

**UPO**  
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EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS  
TRENTO, ITALY  
Institutional Member of the European Expert Committee NUPEC

Candelo di Trento ("Tiro"), watercolor 19.8 x 27.7, painted by A. Dier on his way back from Venice (1895), British Museum.

**Dilepton Production with Meson and Antiproton Beams**  
Trento, November 8-10, 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 pairs productions using meson and antiproton beams.

**Invited speakers**  
Vincent Andrieux (U. Illinois), Mauro Anselmino (U. Torino), Francois Arleo (Ecole Polytechnique), Johannes Bernhard (CERN), Daniel Boer (U. Groningen), Stan Brodsky (SLAC), Jian-Ping Chen (LJLAB), Alaa Deyoufi (Heinrich Heine), Alain Denisev (INFN, Torino), Matthias Grosser Perlekar (U. Illinois), Boris Gruber (Tech U. Munich), Alamy Goussor (JINR, Dubna), Cynthia Hadjiolaki (EPN, Orsay), Paul Hoyer (Helsinki U.), Xiangdong Ji (U. Maryland/Changshu Jiachong U.), Peter Kroll (U. Wuppertal), Shunzo Kumano (KEK), Wally Melnitchouk (LJLAB), Hiroyuki Nishi (Chiba U.), Bakur Parsamyan (U. Torino), Bogdan Povh (U. Frankfurt), Catarina Marques Quintana (LIP, Lisbon), Paul Reimer (ANL), Craig Roberts (ANL), Takahiro Sawada (U. Michigan), Ingo Schenker (LPGC, Grenoble), Shikharu Yoshida (LJLAB)

**Organizers**  
Jen-Christh Peng (Department of Physics, University of Illinois at Urbana-Champaign) jcpeng@illinois.edu  
Wen-Chen Chang (Institute of Physics, Academia Sinica, Taipei) stephsinca.edu.tw  
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Oleg Teresaev (Bogoliubov Laboratory of Theoretical Physics, JINR) teresaev@theor.jinr.ru

**Director of the ECT\* - Professor Jochen Wambach (ECT\*)**

The ECT\* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Associazione alla Cultura" (Provincia Autonoma di Trento), leading agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.  
For full organization please contact: Ivan Cavigio - ECT\* Secretariat - Villa Tarantini - Strada delle Tabacche, 28a - 38123 Villanuovo (Trento) - Italy  
Tel.: (+39-0461) 314721 Fax: (+39-0461) 314750. E-mail: [ect@ectstar.eu](mailto:ect@ectstar.eu) or visit <http://www.ectstar.eu>

## 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.

Following up on the mission of the study group, the workshop will discuss the opportunities offered by the CERN complex for future non-collider experiments that explore open questions in fundamental physics.

## IWHSS18

### XV International Workshop on Hadron Structure and Spectroscopy

March 19-21, 2018  
Bonn, Germany

[iwhss2018@physik.uni-bonn.de](mailto:iwhss2018@physik.uni-bonn.de)  
<https://cern.ch/iwhss-2018>

**COMPASS**

Transverse Spin Structure of the Nucleon  
TMD's and GTMD's  
Meson Structure  
Meson Spectroscopy  
Search for Exotics  
New Opportunities for fixed Target Physics

**Local Organizing Committee**

J. Barth  
O. Poghosyan  
N. Aizawa

P. Jorg  
B. Knieff (Co-Chair)  
F. Klein (Chair)

V. Negri  
J. Wagner  
P. Zundorf

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Craig D. Roberts (ANL, USA)  
Adam Szczepaniak (Univ. Indiana, USA)  
Oleg Teresaev (JINR Dubna, Russia)

**UNIVERSITÄT BONN**

present the progress and development of the COMPASS experiment and discuss new ideas.

Abstract submission, as well as the mandate for the workshop web site: <https://indico.cern.ch/event/644297>

Chair: Lamont, Connie Potter, Claude Vallée



# 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*  $A_{UT}^{\sin\phi_s}$  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
- The future of COMPASS collaboration is being currently actively discussed
  - SIDIS measurements with transversely polarized deuteron target in 2021
  - New experiment beyond 2021, the LOI will become public soon
    - Particular attention is given to possible Drell-Yan measurements



# Spare slides

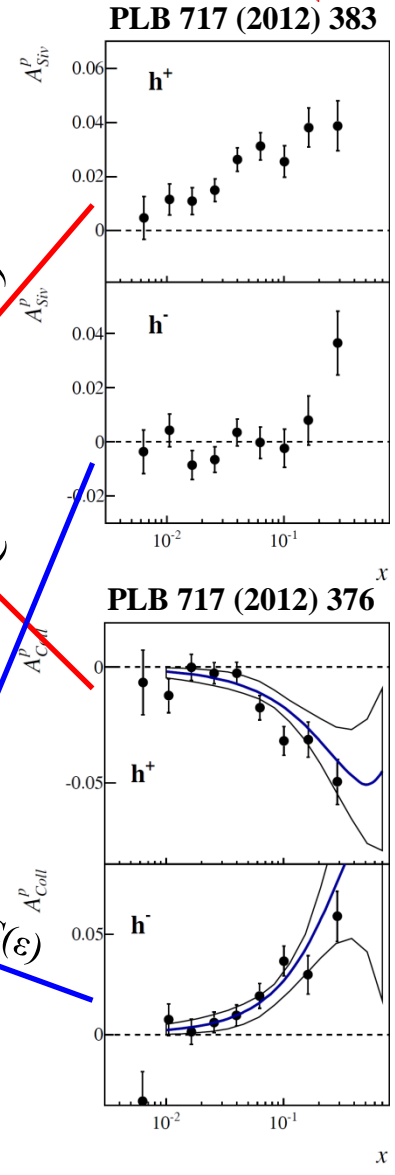
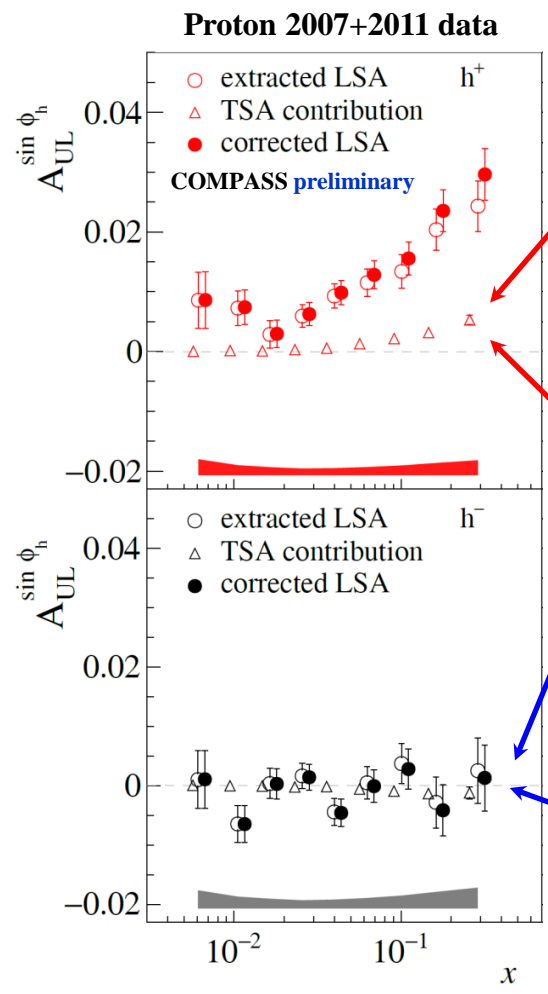
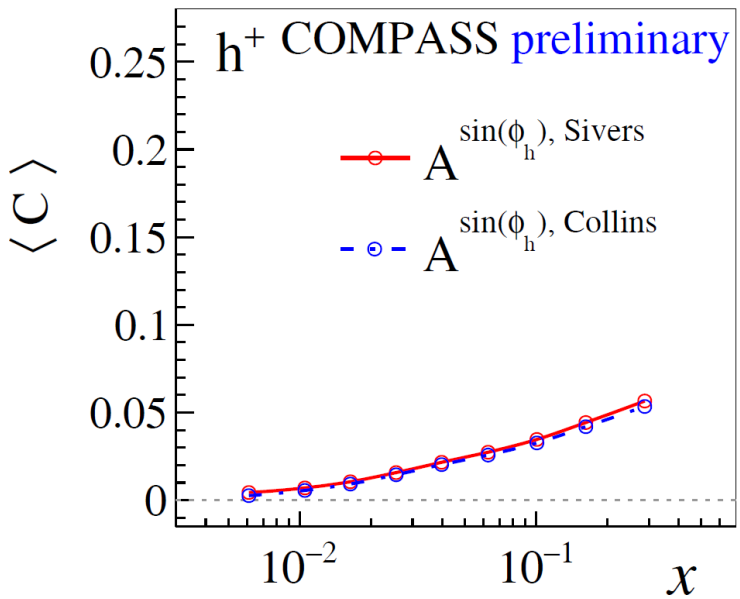




# The $A_{UL}^{\sin\phi_h}$ asymmetry

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

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

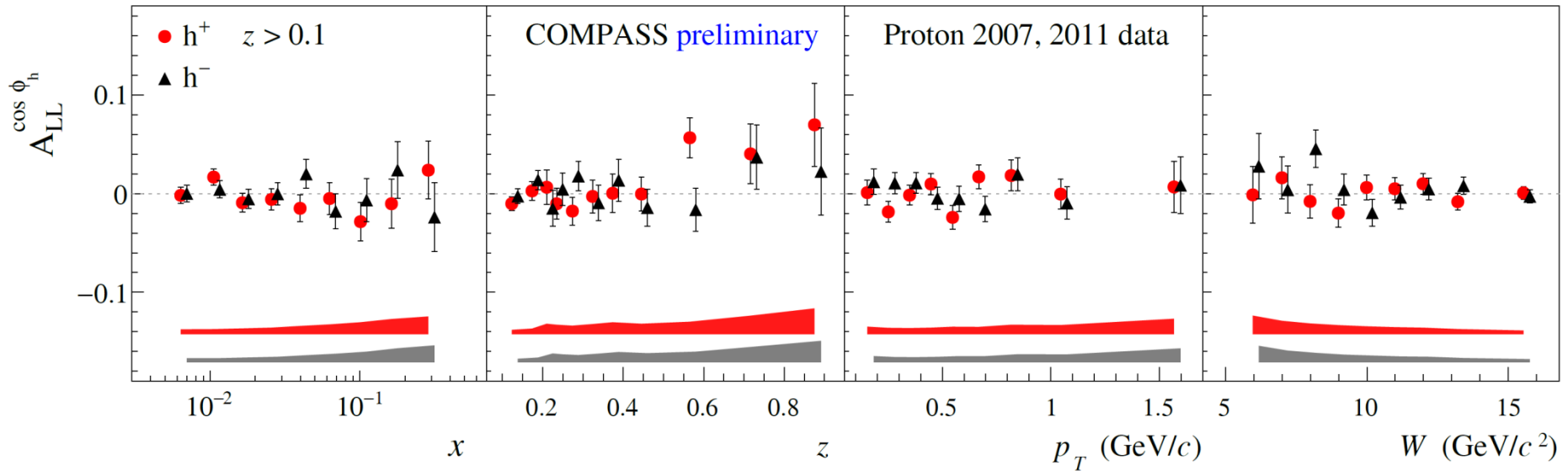


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for  $h^+$ ,  $h^-$  compatible with zero, clear  $z$ -dependence**

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

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

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



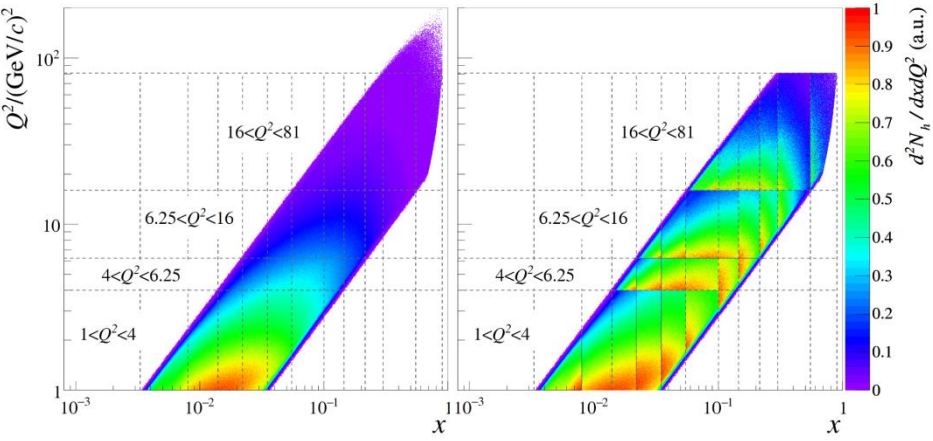
- Various different “twist” ingredients,
- Q-suppression

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

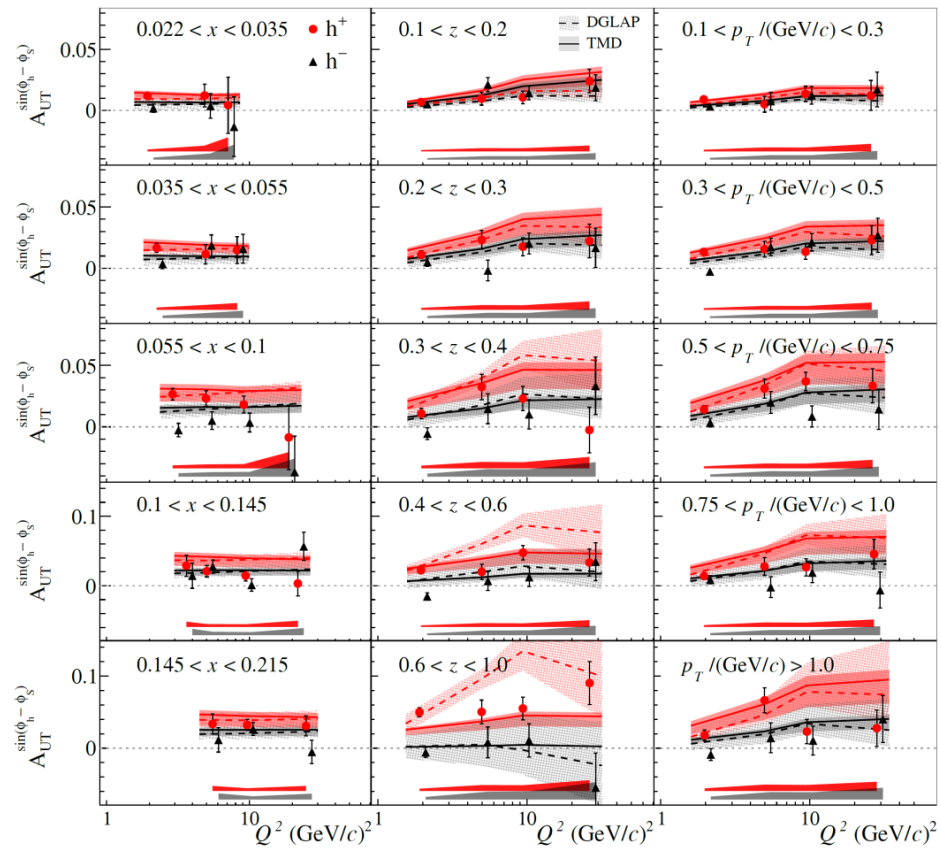
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

COMPASS **PLB 770 (2017) 138**



Multi-dimensional input for TMD evolution studies



- No clear  $Q^2$ -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.



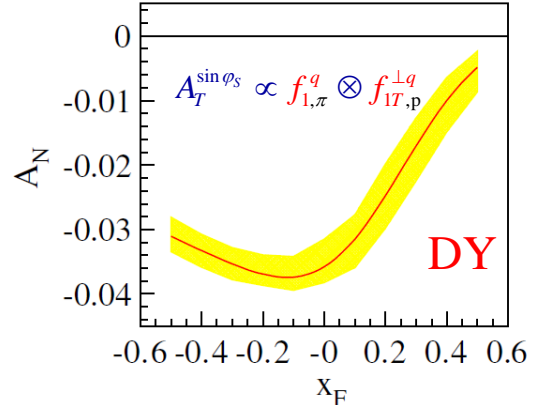
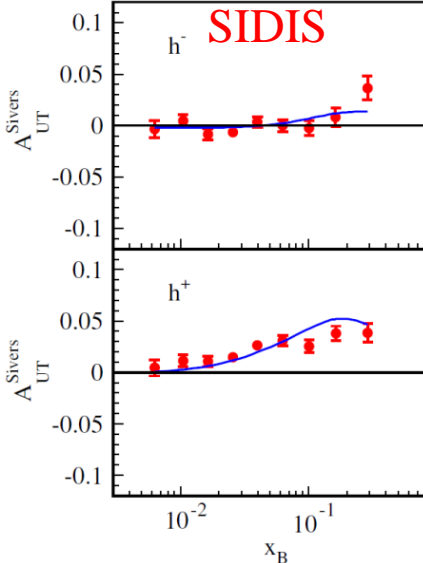
# SIDIS TSAs (Sivers)

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

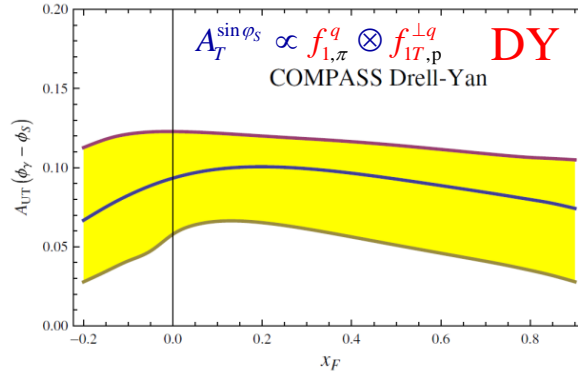
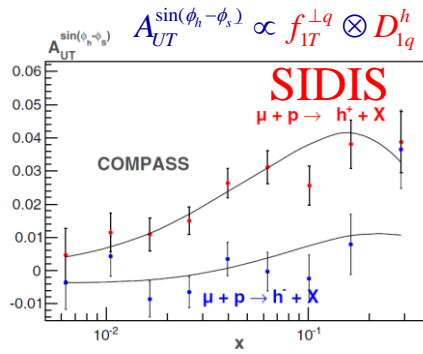
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[ -\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results ( $Q^2$  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)**



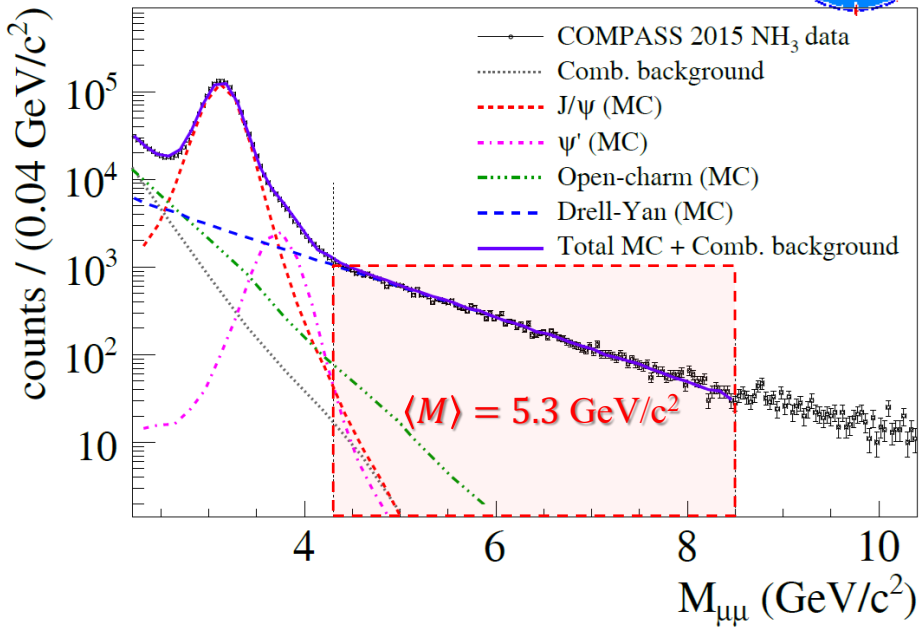
P. Sun and F. Yuan, **PRD 88 11, 114012 (2013)**



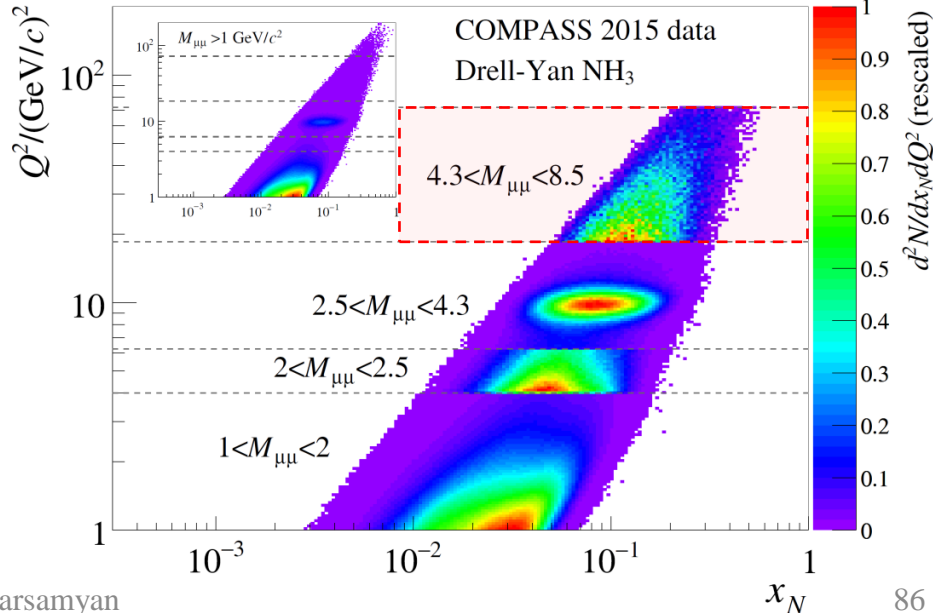
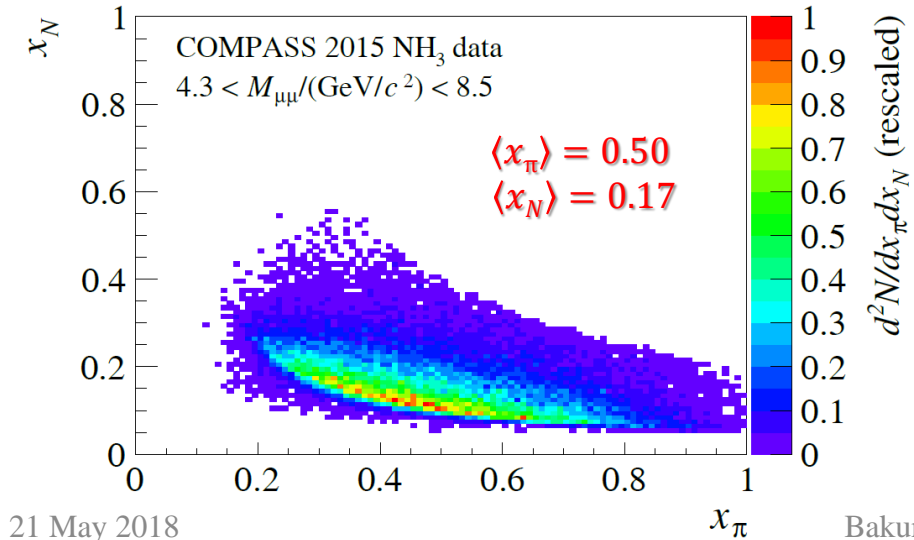
# COMPASS DY: high mass range

- $1.0 < M / (\text{GeV}/c^2) < 2.0$  “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  $\rightarrow$  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  $\rightarrow$  largest asymmetries

Final sample: 35 000 dimuons in HM



## HM events are in the valence quark range





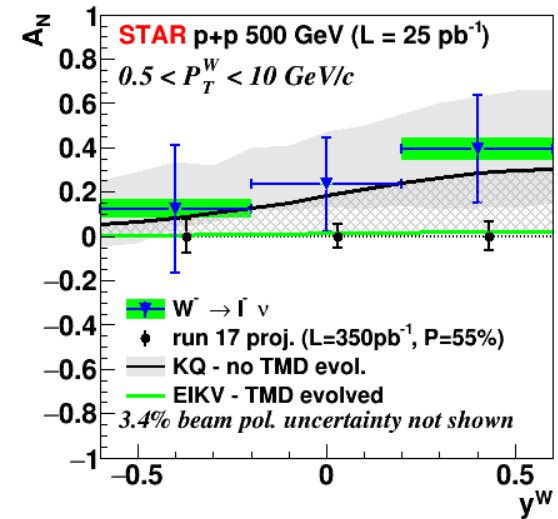
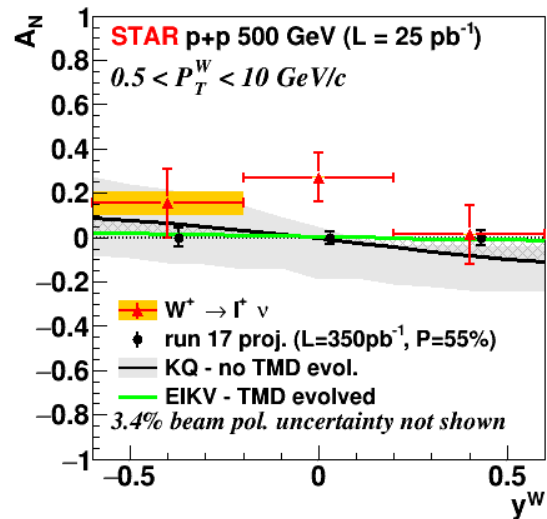
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- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- **Sivers TMD PDF is predicted to change the sign between SIDIS and DY**
- First experimental investigation of Sivers-non-universality 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)

