



Polarized SIDIS and Drell-Yan measurements at COMPASS

BAKUR PARSAMYAN

University of Turin and INFN section of Turin
on behalf of the COMPASS Collaboration



UNIVERSITÀ
DEGLI STUDI
DI TORINO

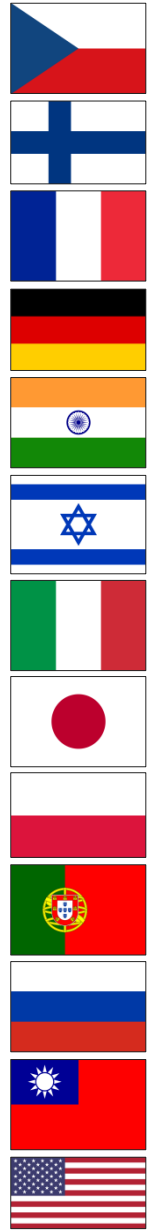
ALMA UNIVERSITAS
TAURINENSIS



QCD Evolution 2017 workshop
Jefferson Lab
Newport News, Virginia
May 22 – 26, 2017



COMPASS collaboration



24 institutions from 13 countries – nearly 250 physicists

Common Muon and Proton Apparatus for Structure and Spectroscopy

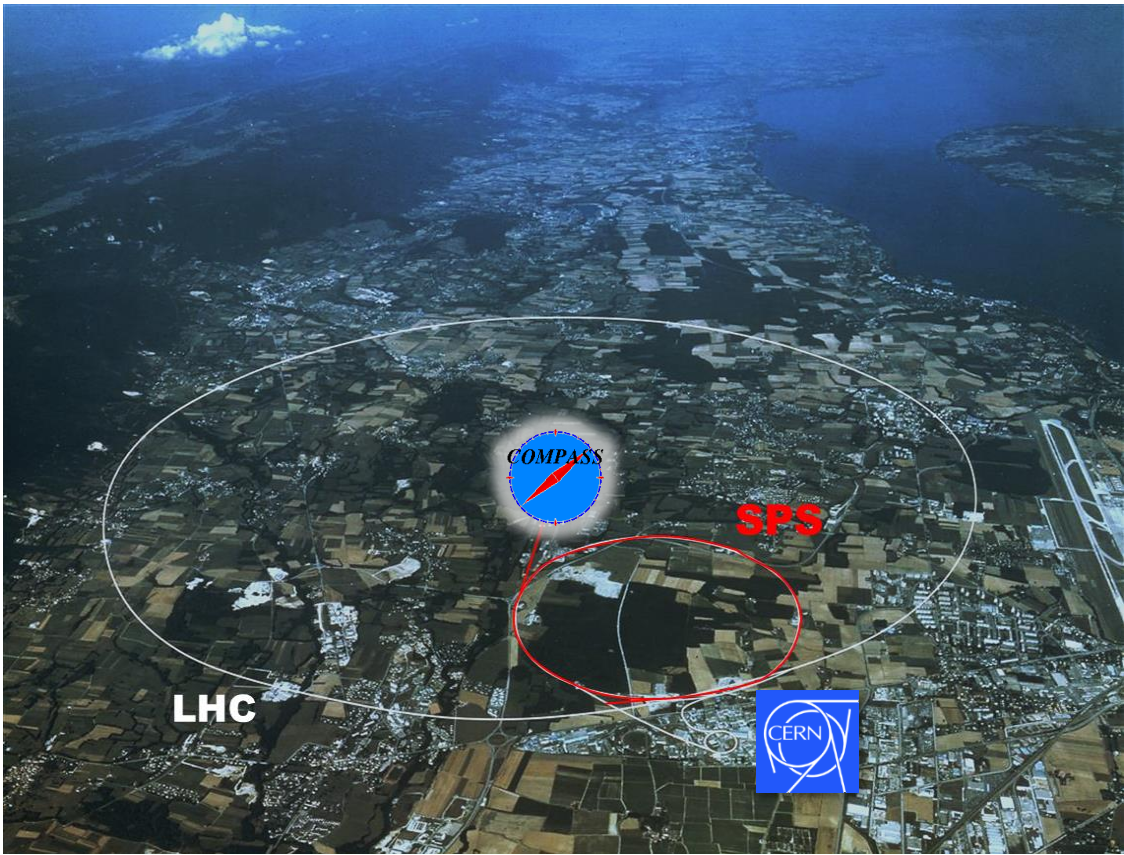
- CERN SPS north area
- Fixed target experiment
- Taking data since 2002

Wide physics program
COMPASS-I

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

COMPASS-II

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



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



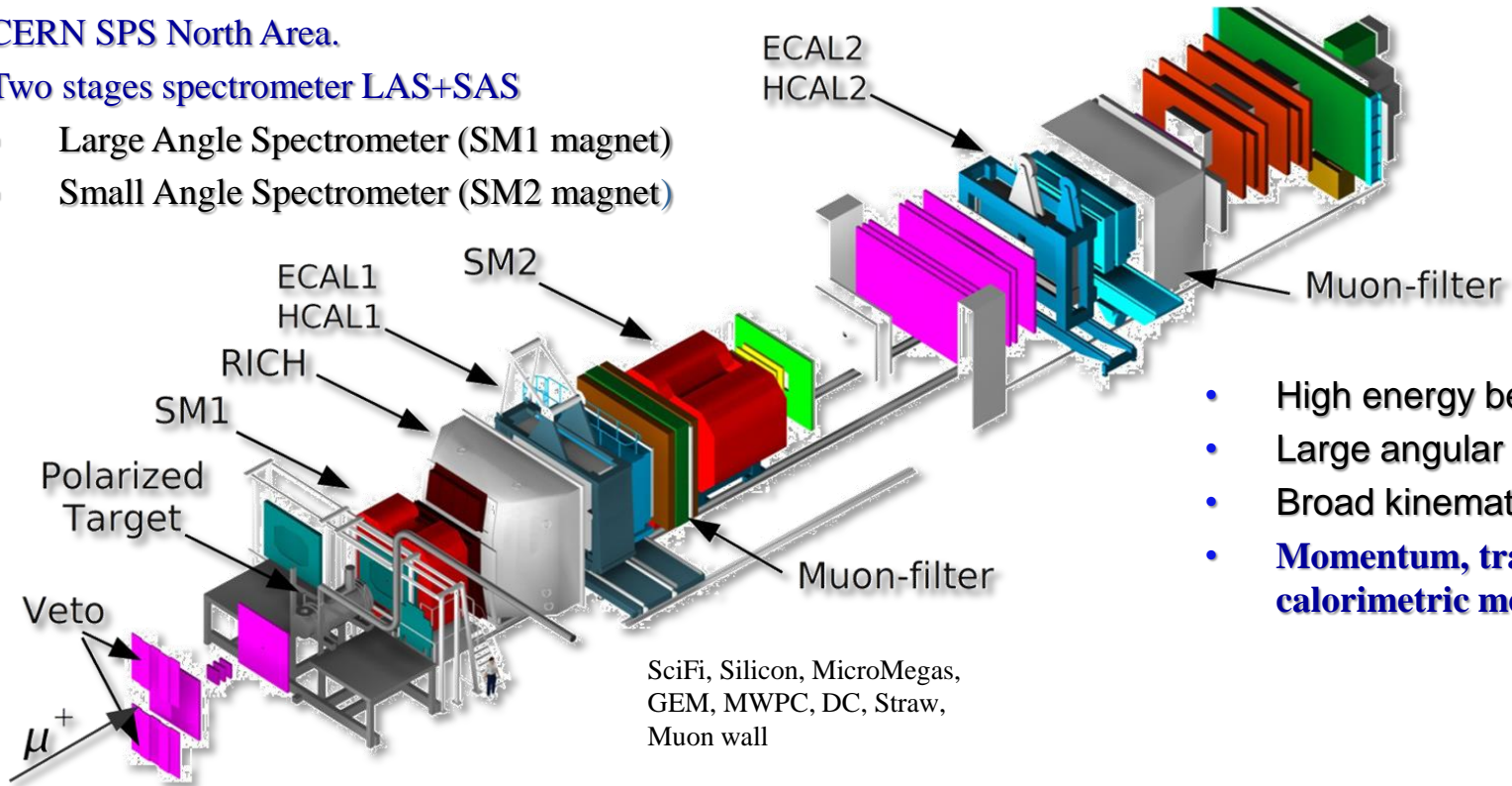
COMPASS experimental setup: Phase I (muon program)

COmmon MUon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area.

Two stages spectrometer LAS+SAS

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



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

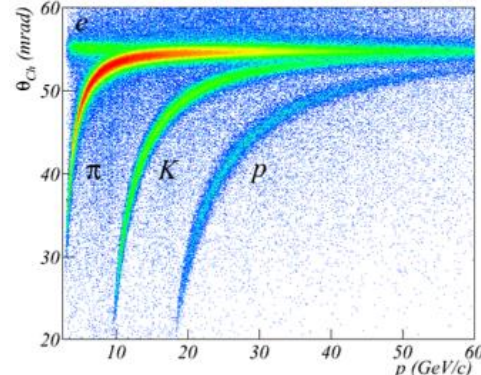
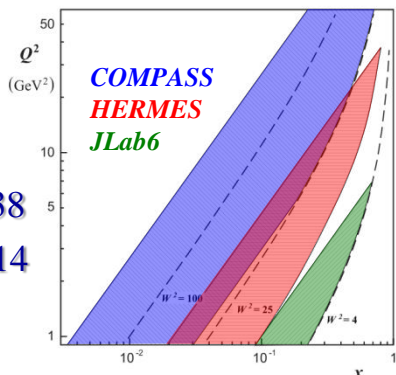
SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

Longitudinally polarized (80%) μ^+ beam:
 Energy: 160/200 GeV/c, Intensity: $2 \cdot 10^8 \mu^+$ /spill (4.8s).

Target: Solid state (${}^6\text{LiD}$ or NH_3)

- ${}^6\text{LiD}$ 2-cell configuration. Polarization (L & T) $\sim 50\%$, $f \sim 0.38$
- NH_3 3-cell configuration. Polarization (L & T) $\sim 80\%$, $f \sim 0.14$

Data-taking years: 2002-2011



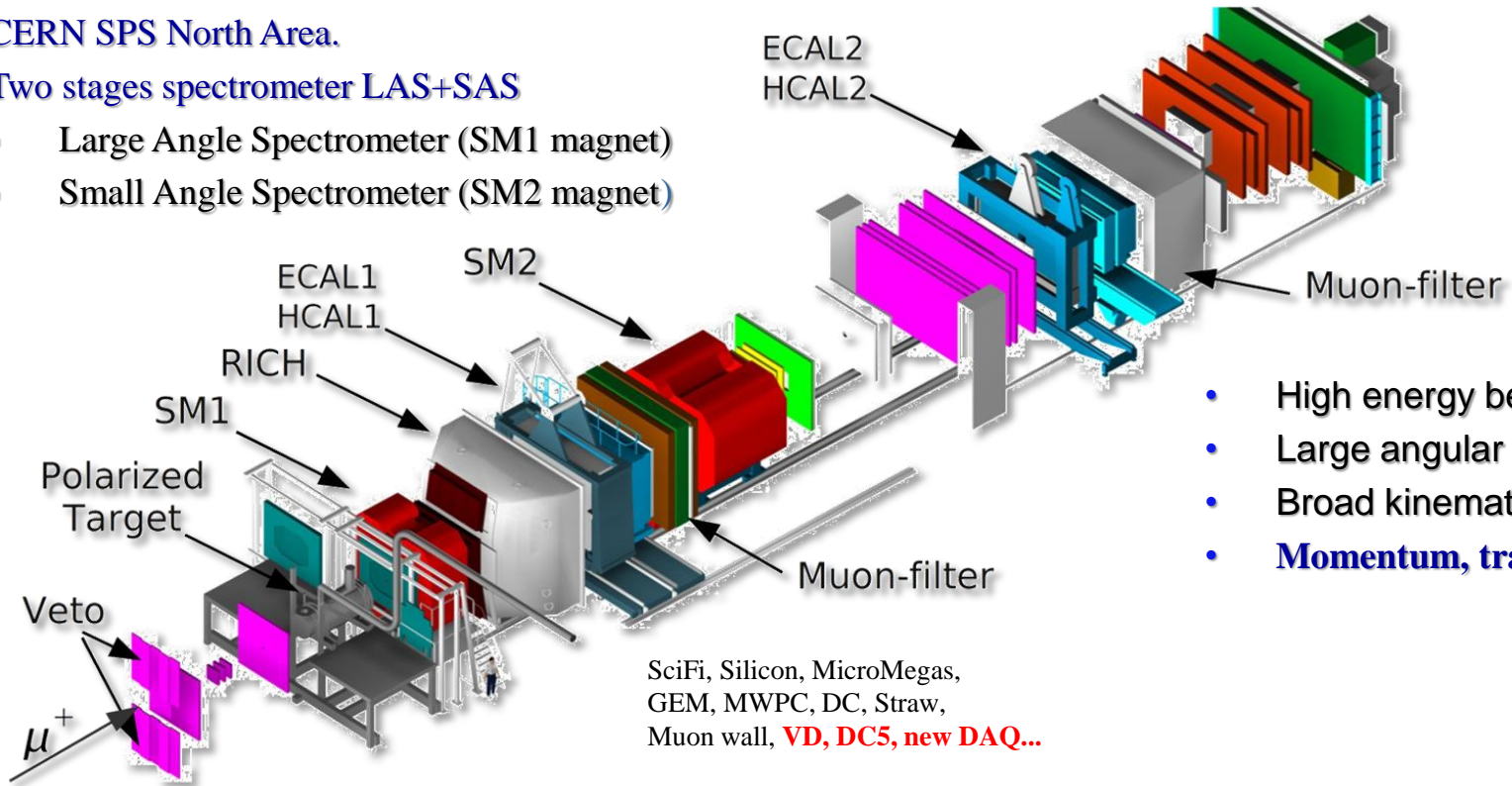
COMPASS experimental setup: Phase II (DY program)

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CERN SPS North Area.

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

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

High energy π^- beam:
Energy: 190 GeV/c, Intensity: $10^8 \pi/s$

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 73%, f ~ 0.18
- Data is collected simultaneously for the two target spin orientations. Periodic polarization reversal to minimize systematic effects

Data-taking years: 2014(test), 2015, 2018



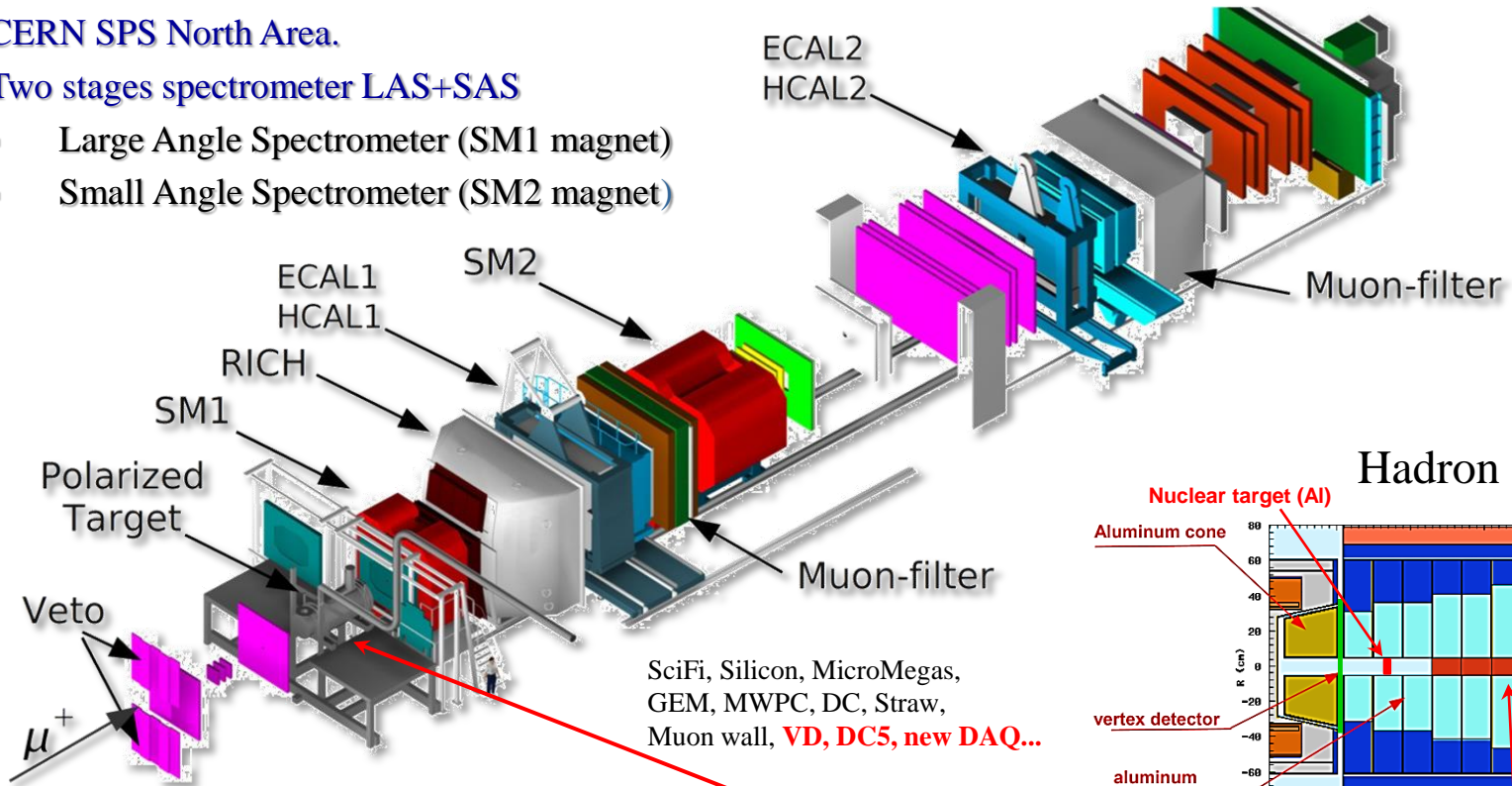
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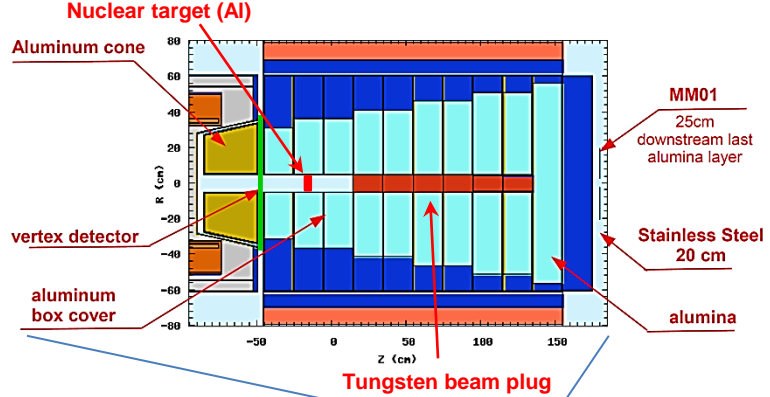
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Hadron absorber

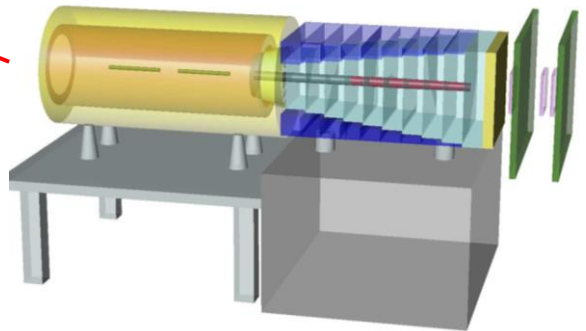


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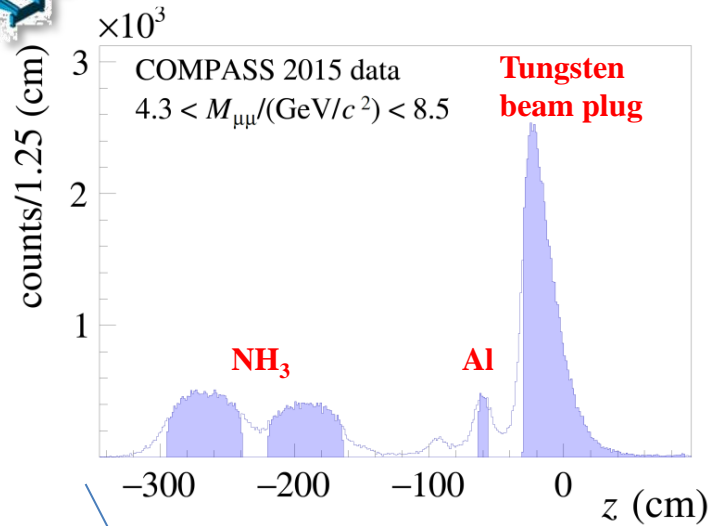
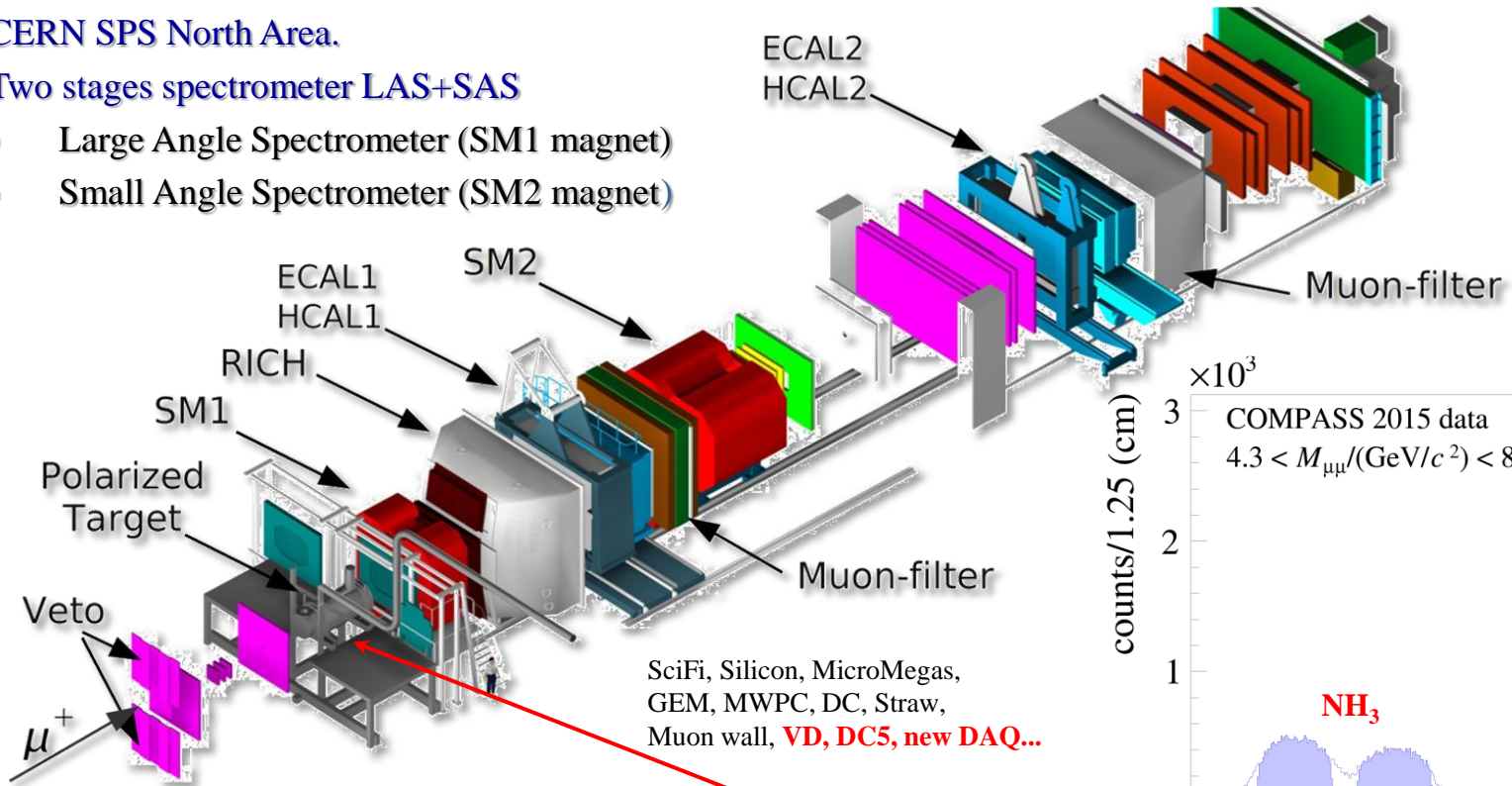
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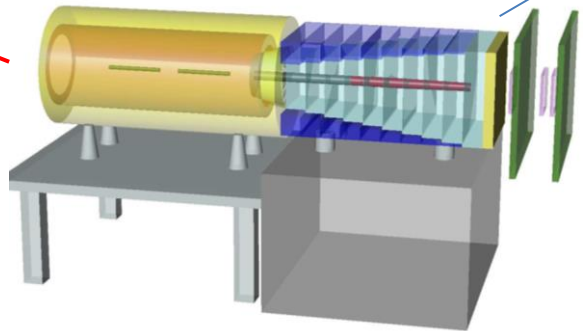


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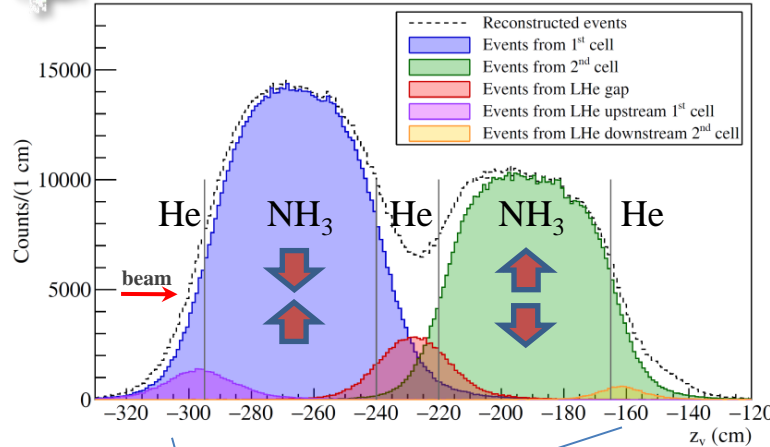
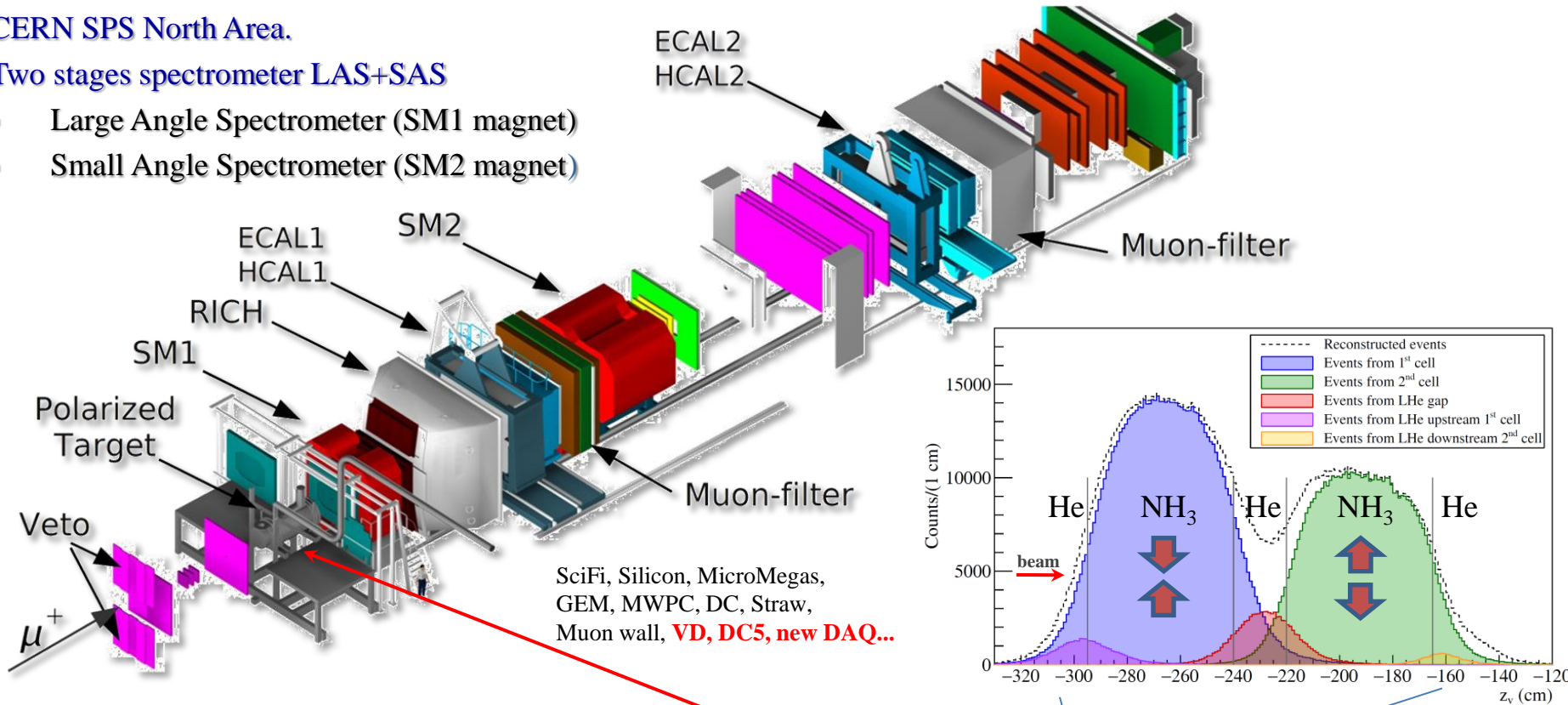
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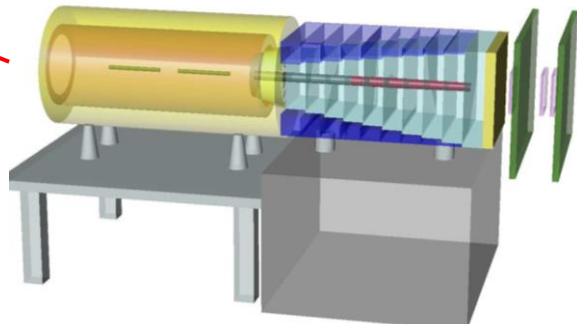


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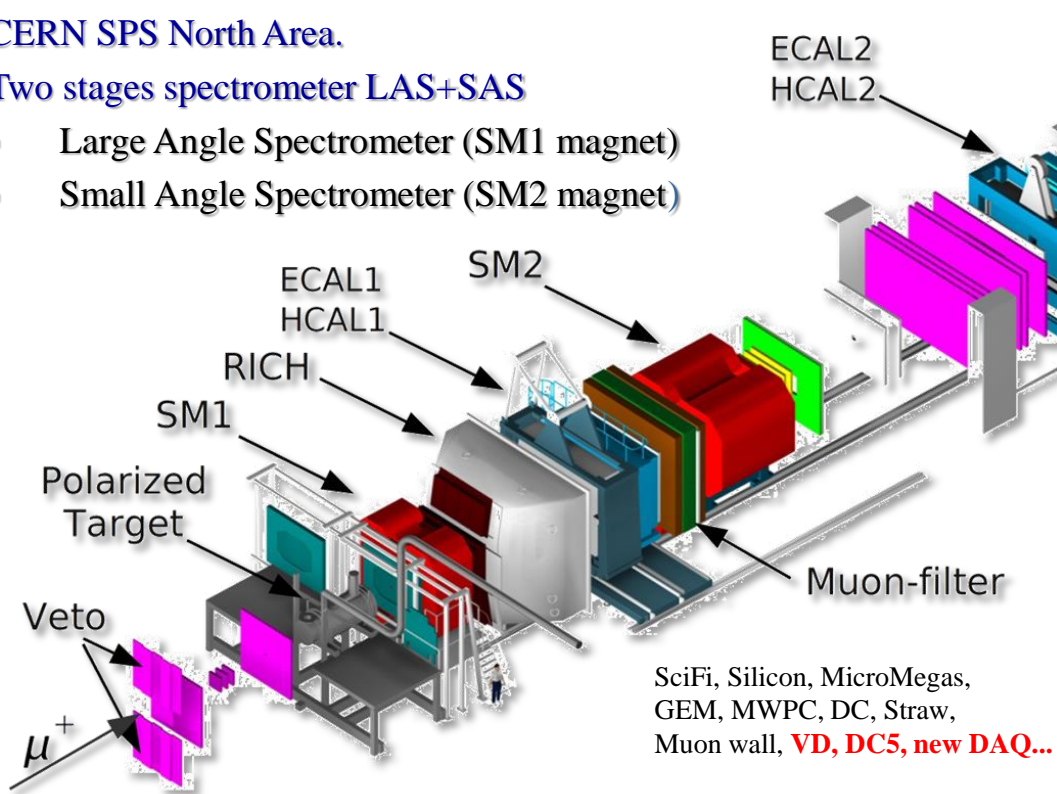
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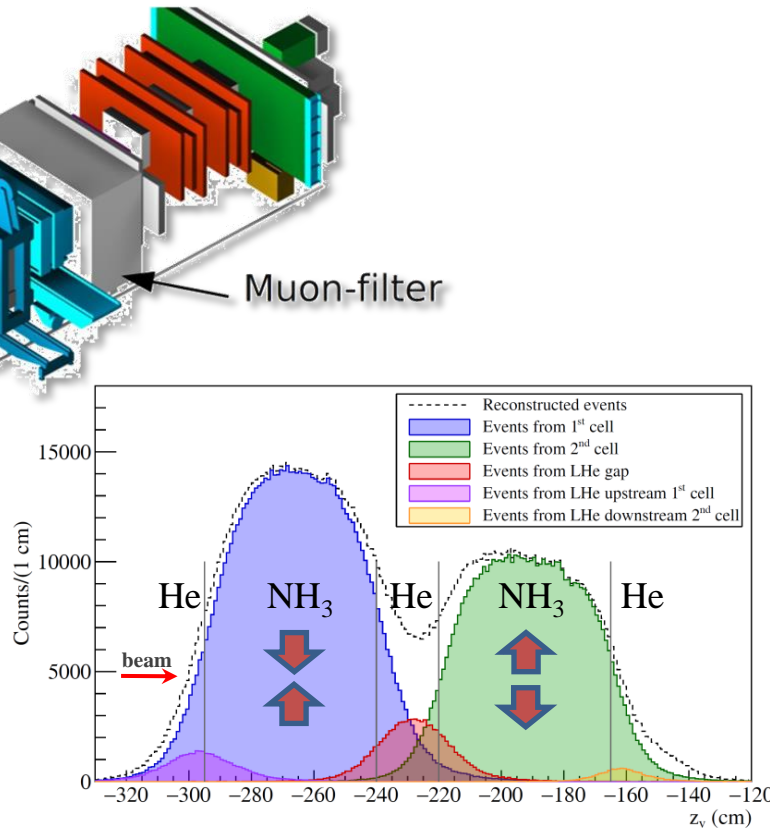
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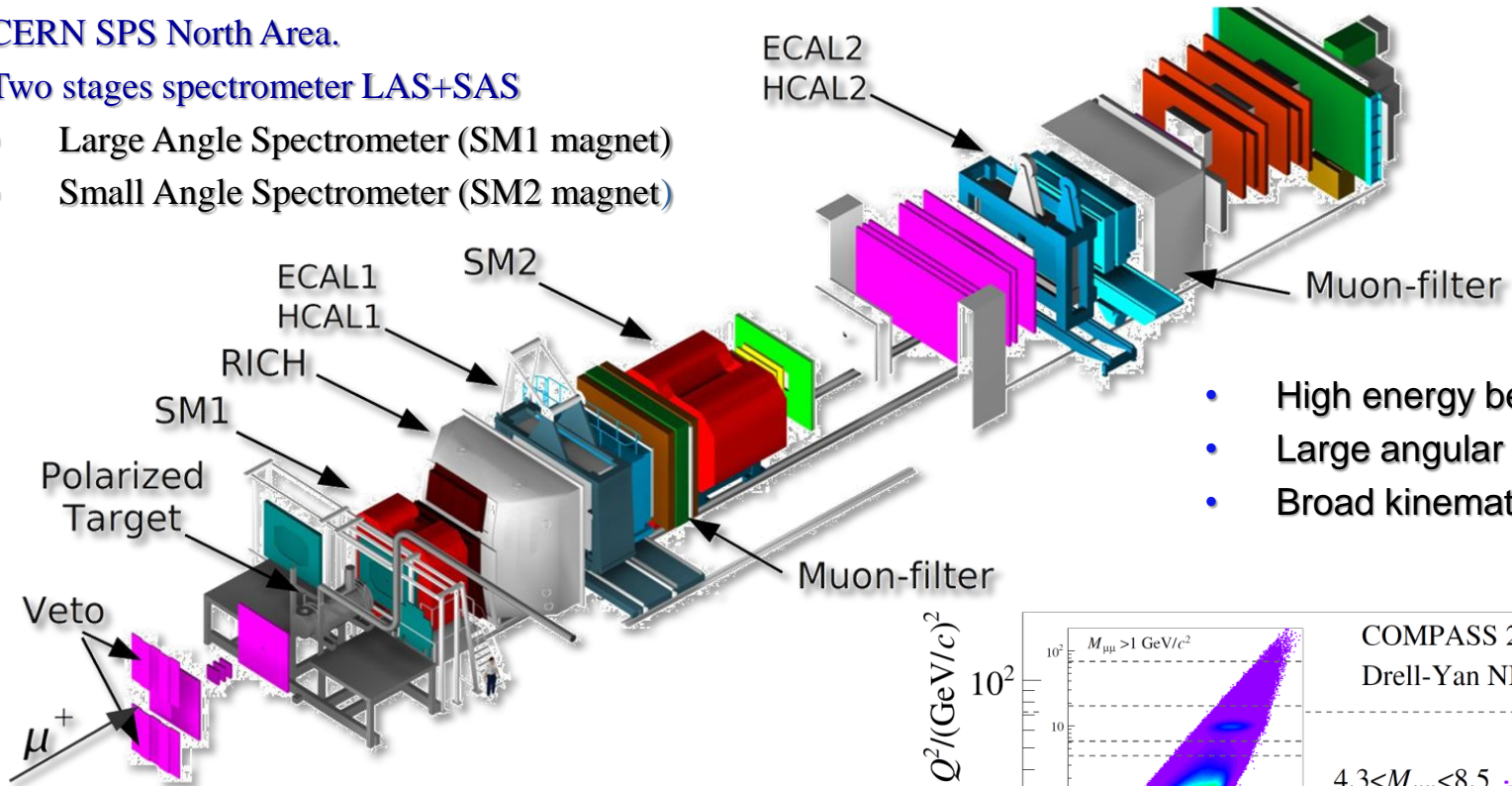
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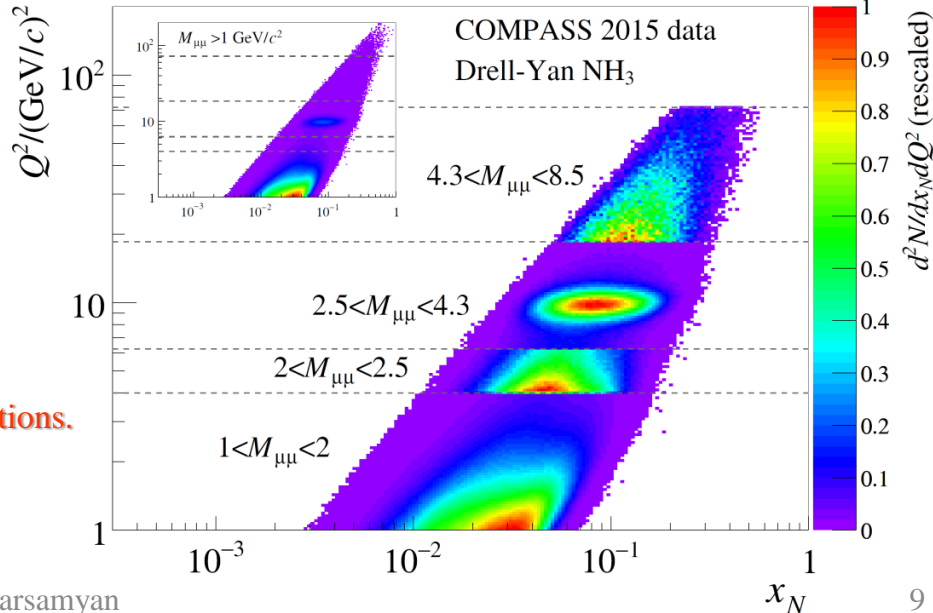


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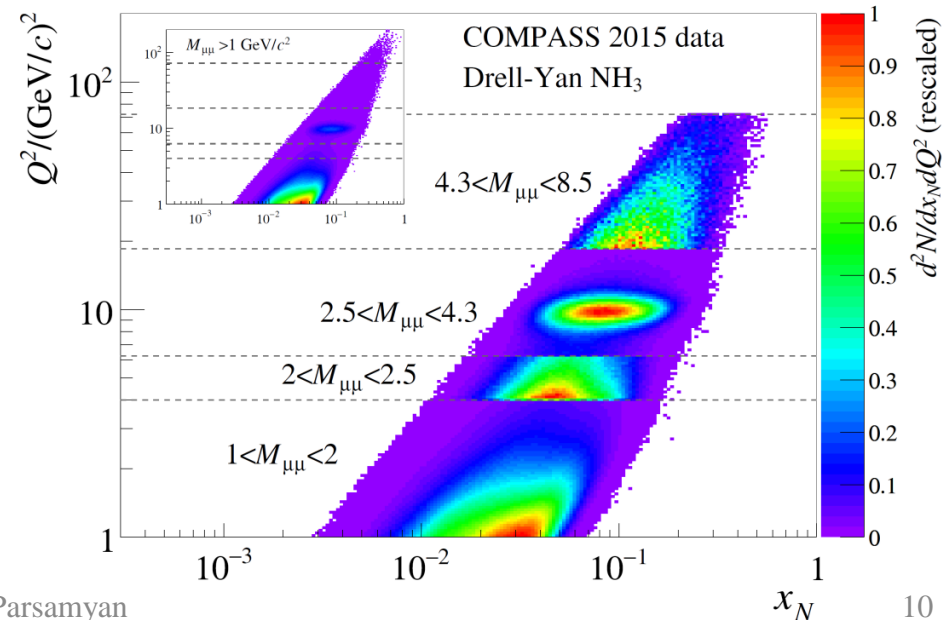
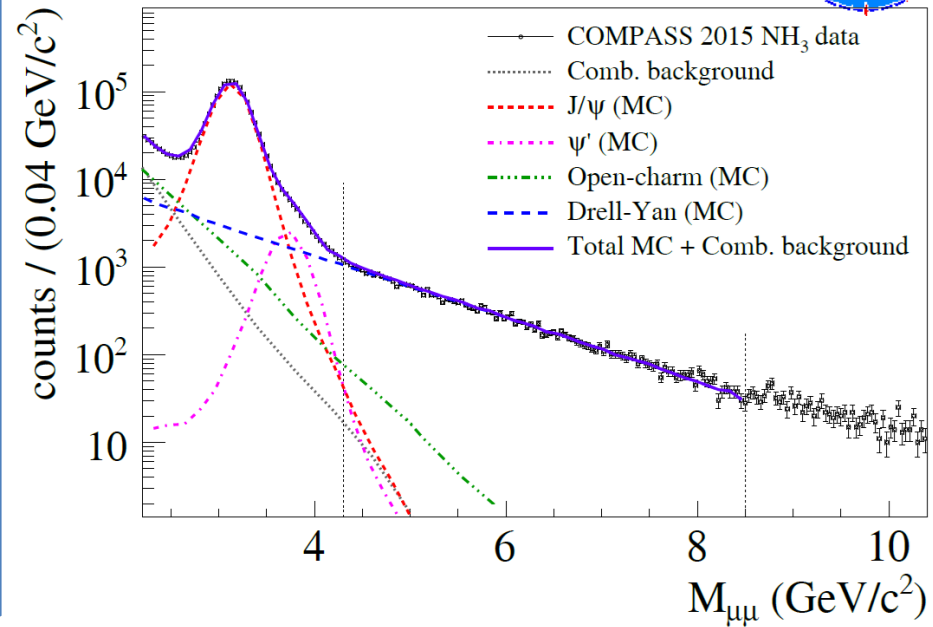
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COMPASS DY mass ranges

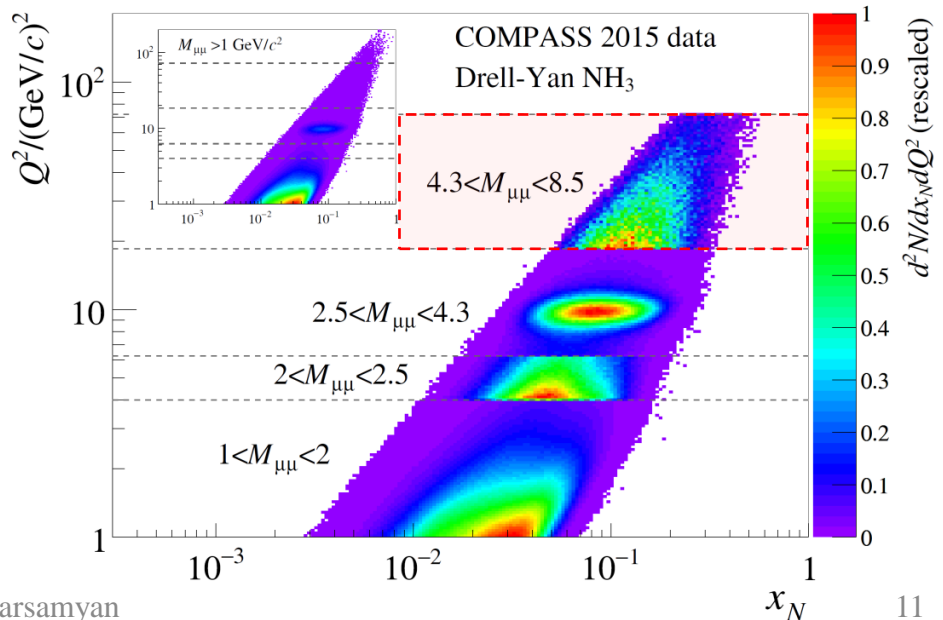
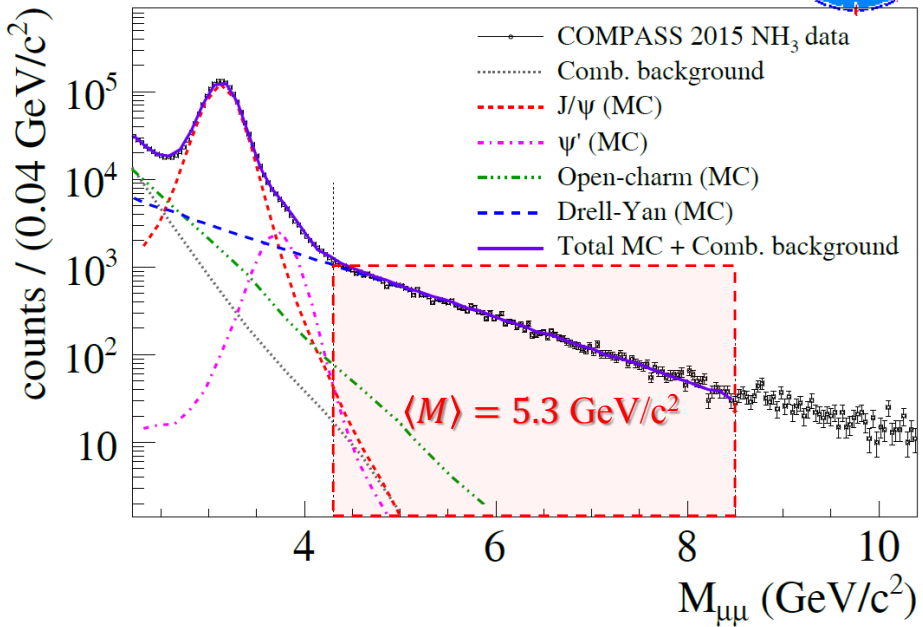
- $1.0 < M / (\text{GeV}/c^2) < 2.0$ “Low mass”
 - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π , K decays
- $2.0 < M / (\text{GeV}/c^2) < 2.5$ “Intermediate mass”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $2.5 < M / (\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ 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



COMPASS DY: high mass range

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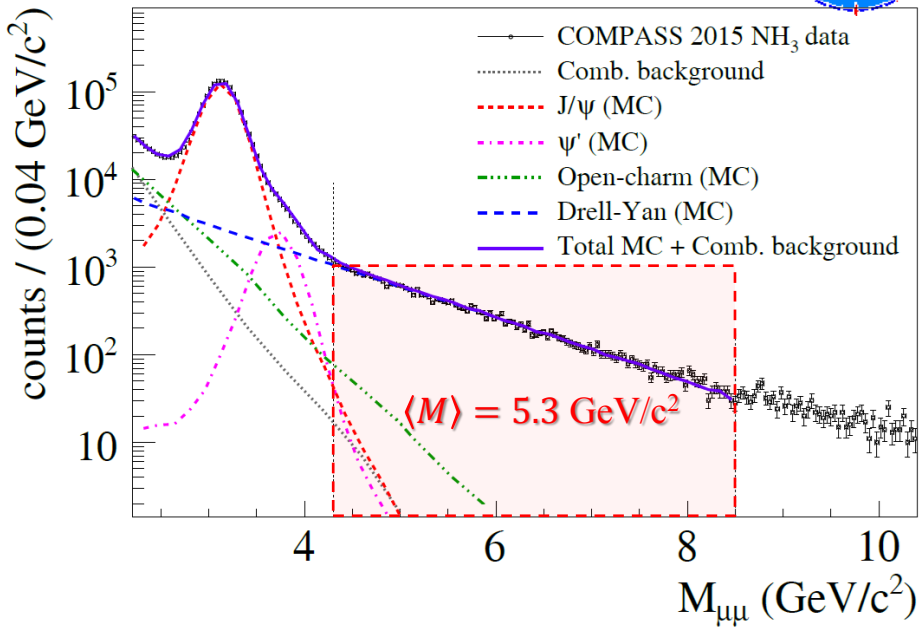
Final sample: 35 000 dimuons in HM



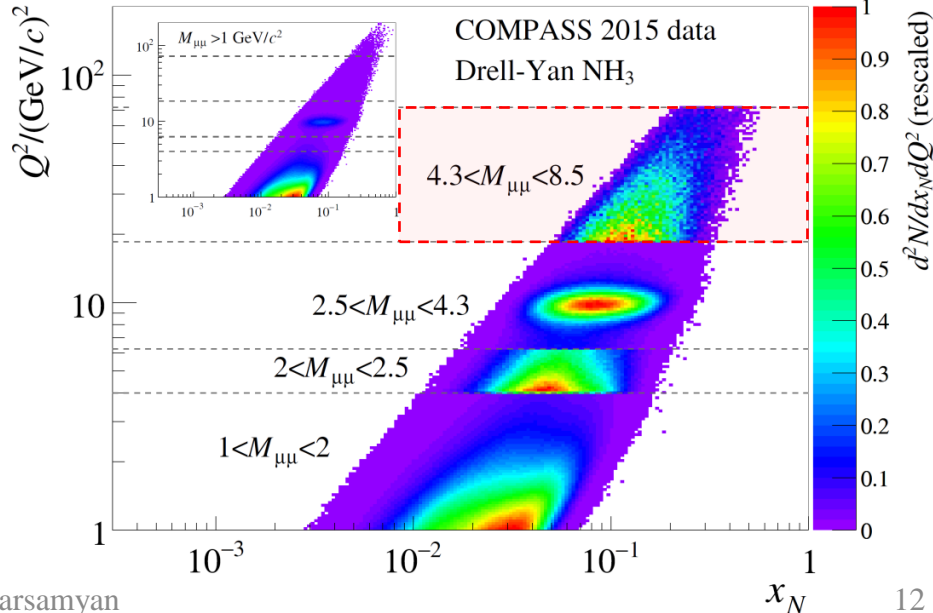
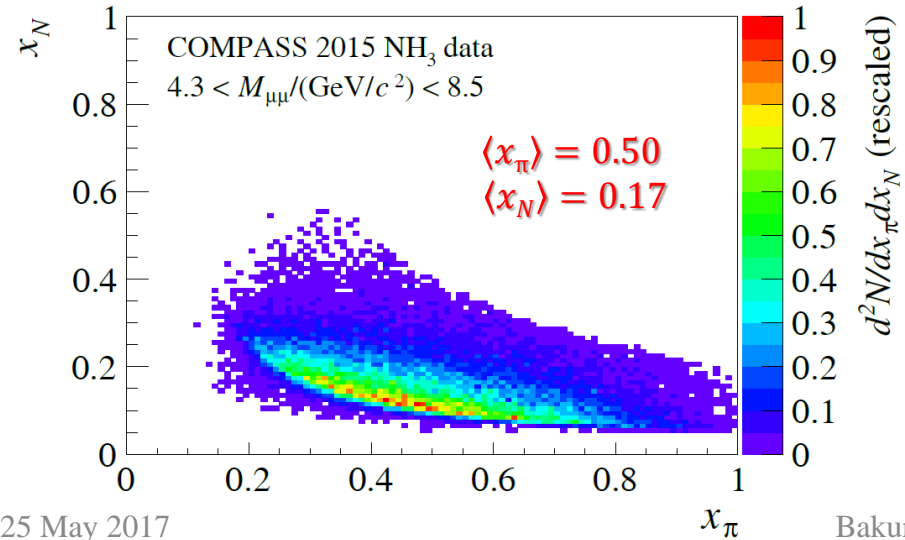
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HM events are in the valence quark range

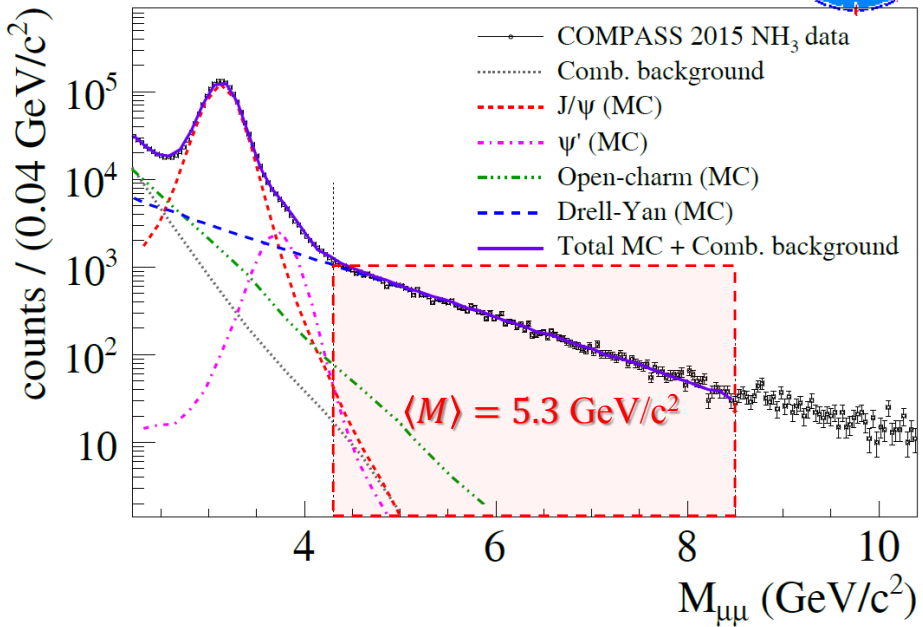




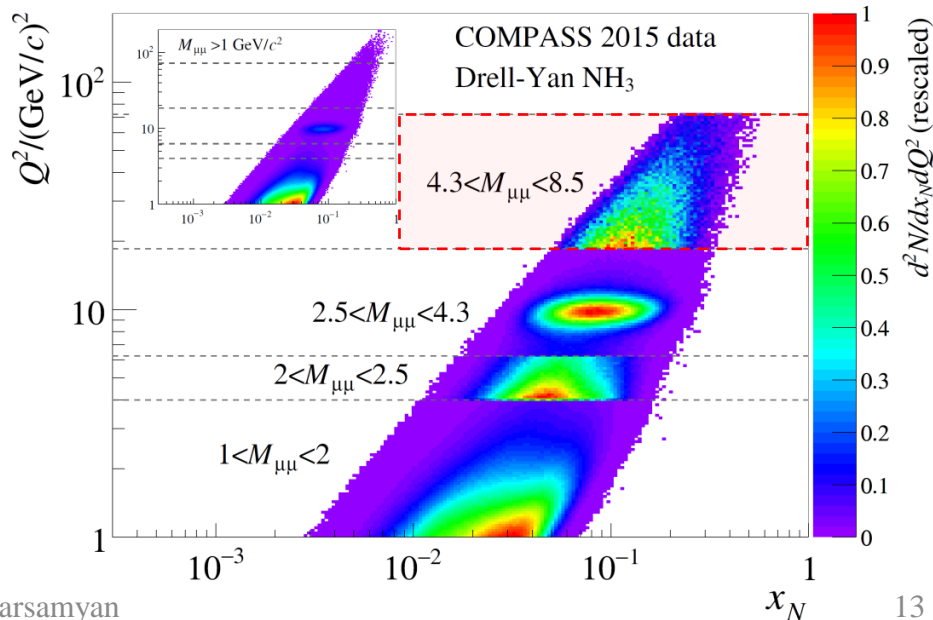
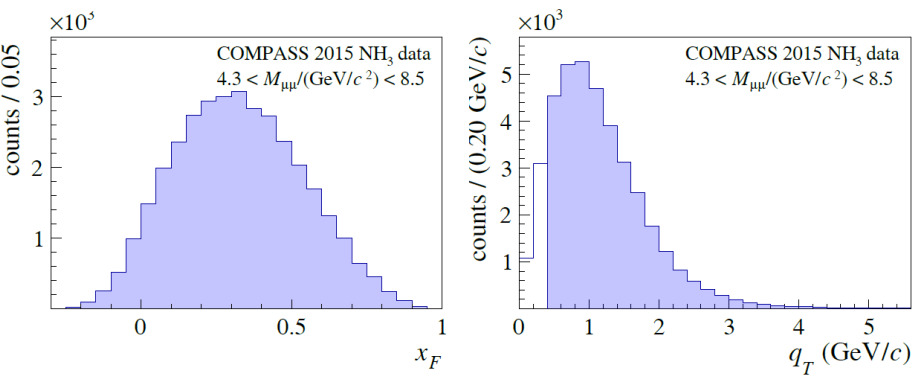
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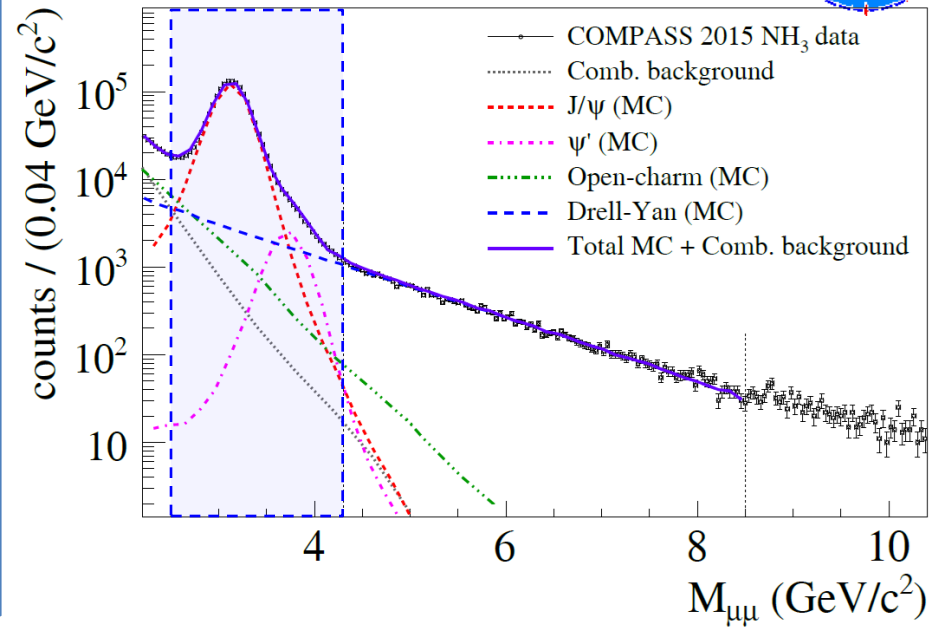


Dimuon transverse momentum $q_T > 0.4 \text{ GeV}/c$
 $\langle x_F \rangle = 0.33$, $\langle q_T \rangle = 1.2 \text{ GeV}/c$

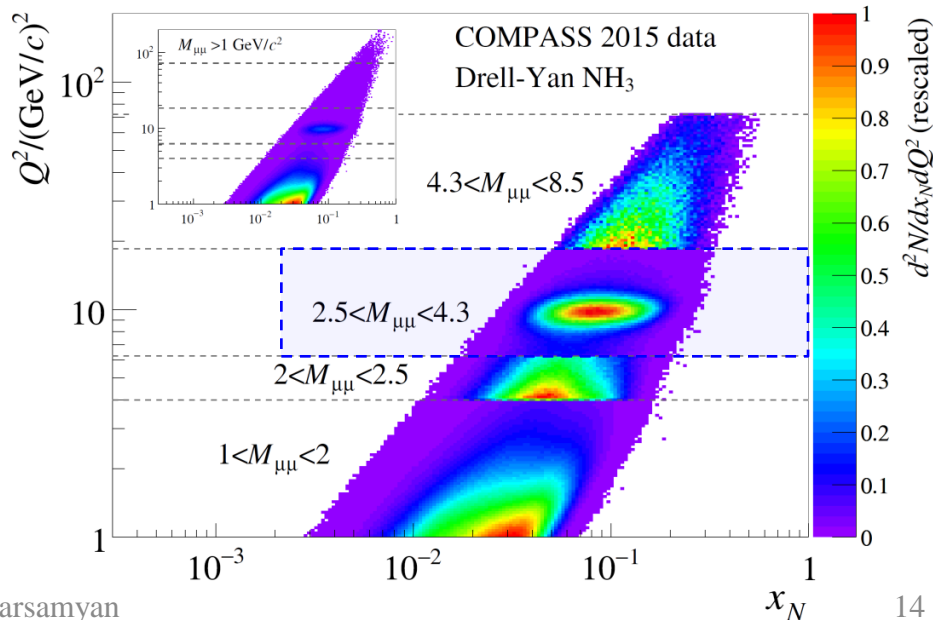
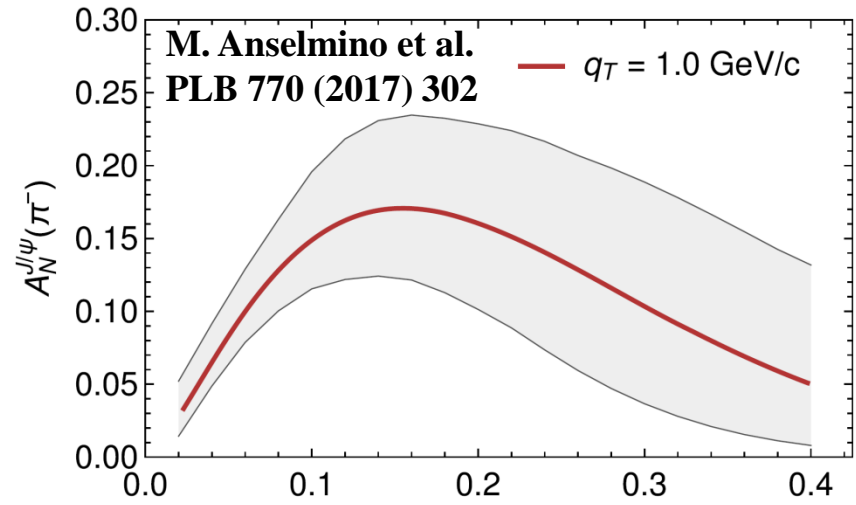


COMPASS DY: Charmonia mass range

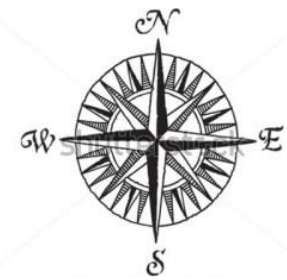
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$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1 \text{ GeV}/c$



COMPASS bridge



Drell-Van

SIDS



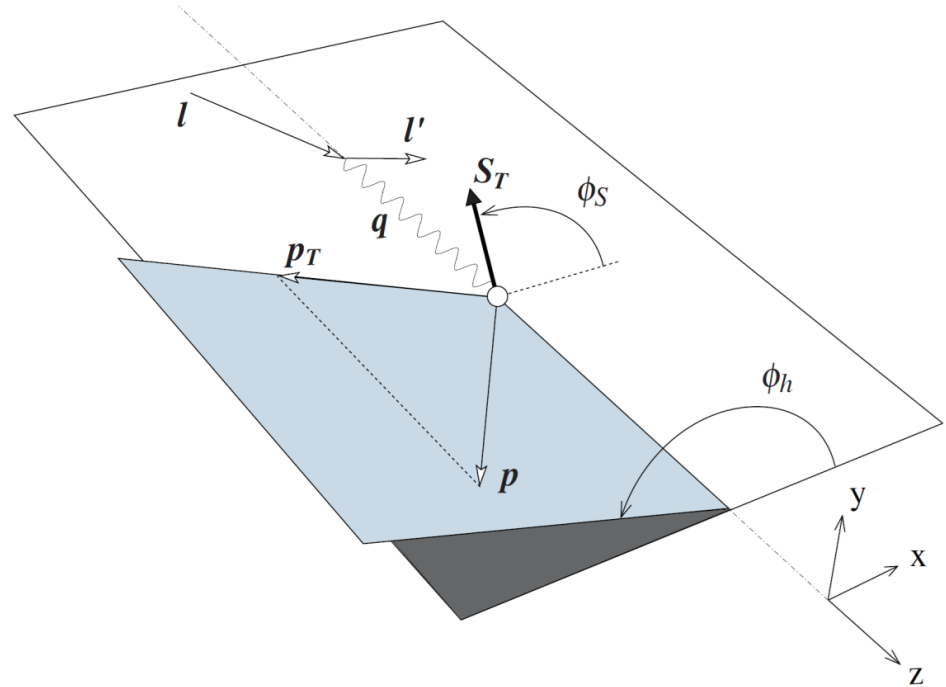
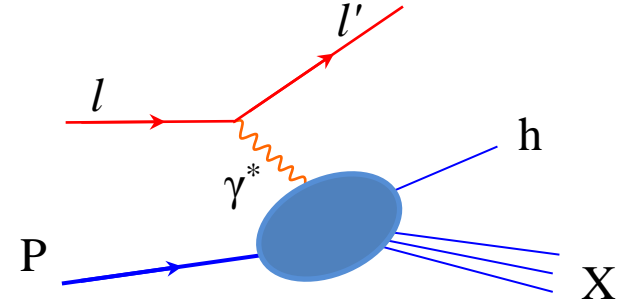
SIDIS x-section

All measured by COMPASS

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

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

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



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

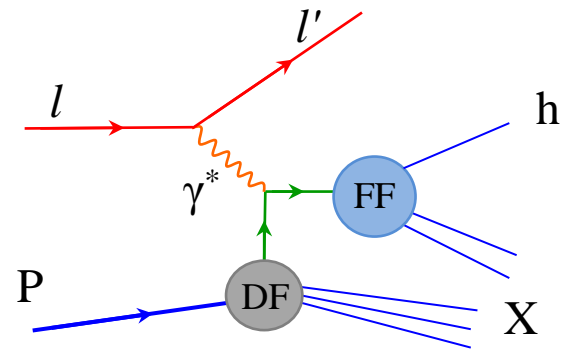


SIDIS x-section and TMDs at twist-2

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

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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 $H_{1q}^{\perp h}(z, P_{\perp}^2)$

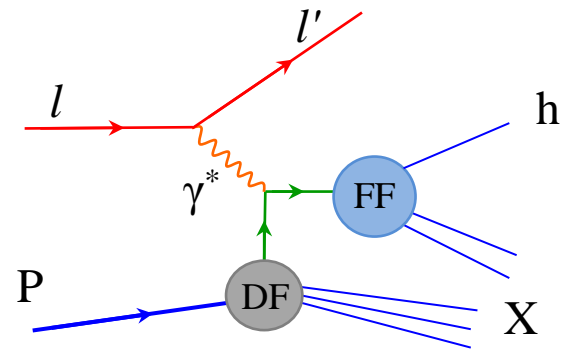


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$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \text{All measured by COMPASS}$$

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

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



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

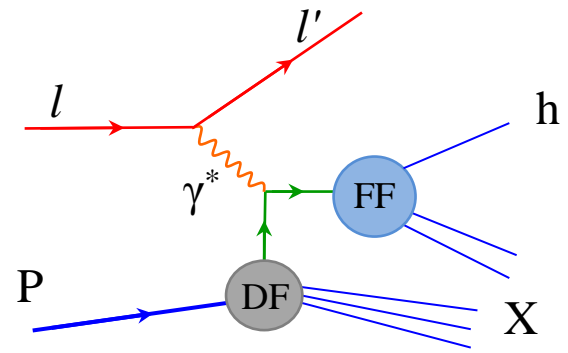
spin of the nucleon
 spin of the quark
 k_T



SIDIS x-section and TMDs at twist-2

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

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



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

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

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

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

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

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

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

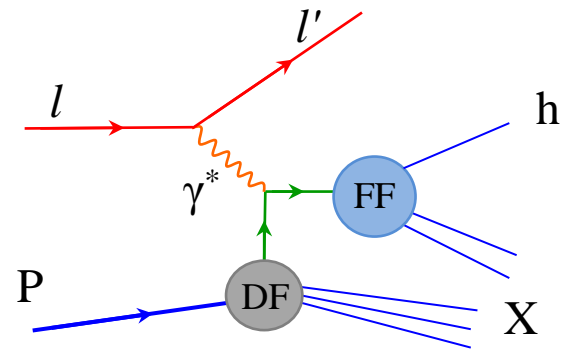
Twist-2
Twist-3



SIDIS x-section and TMDs at twist-2

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

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



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

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

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

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

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

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

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

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

$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right)$$

Twist-2
Twist-3

SIDIS and single-polarized DY x-sections

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

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

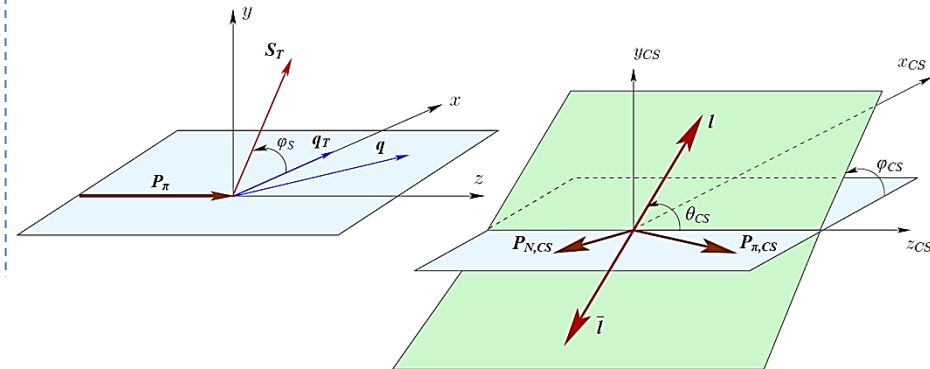
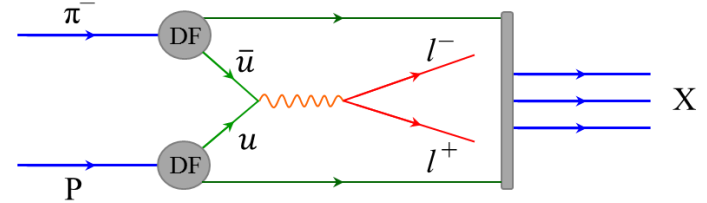
SIDIS

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

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

DY

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





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)

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

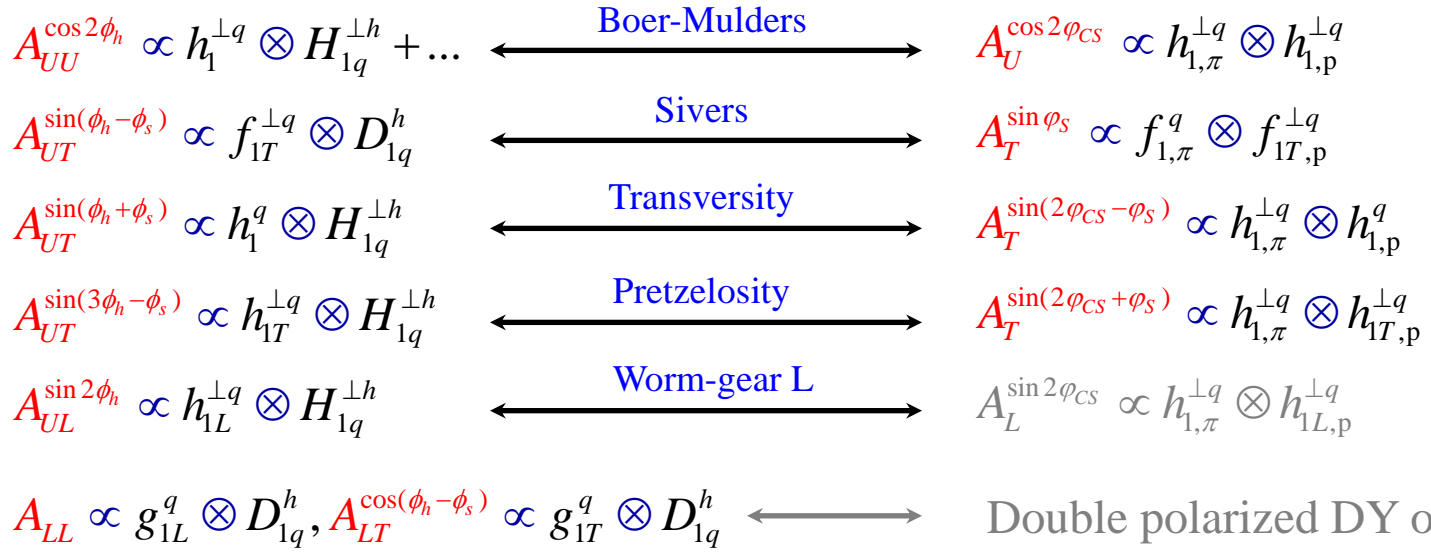
SIDIS

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

DY

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

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

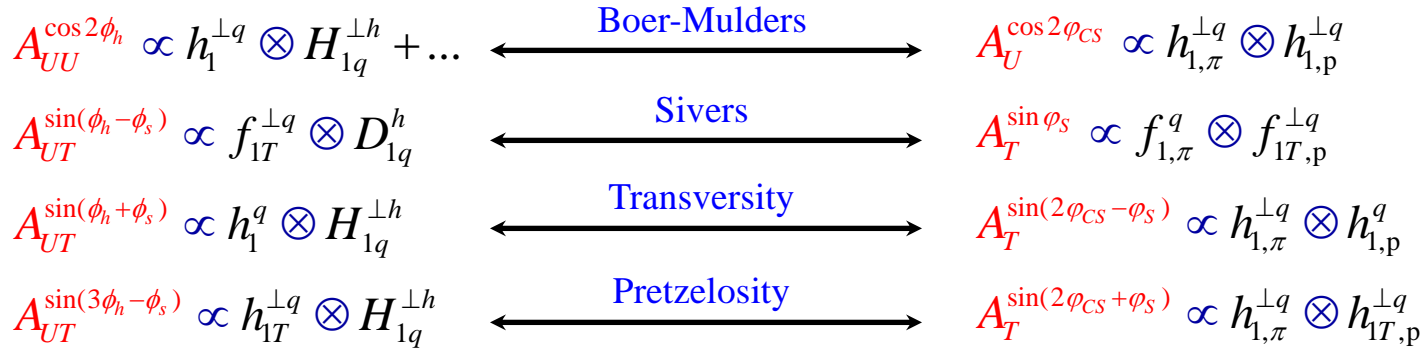


COMPASS accesses all 8 twist-2 nucleon TMD PDFs in SIDIS and 5 nucleon+2 pion TMD PDFs in DY



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

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



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}^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)

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**

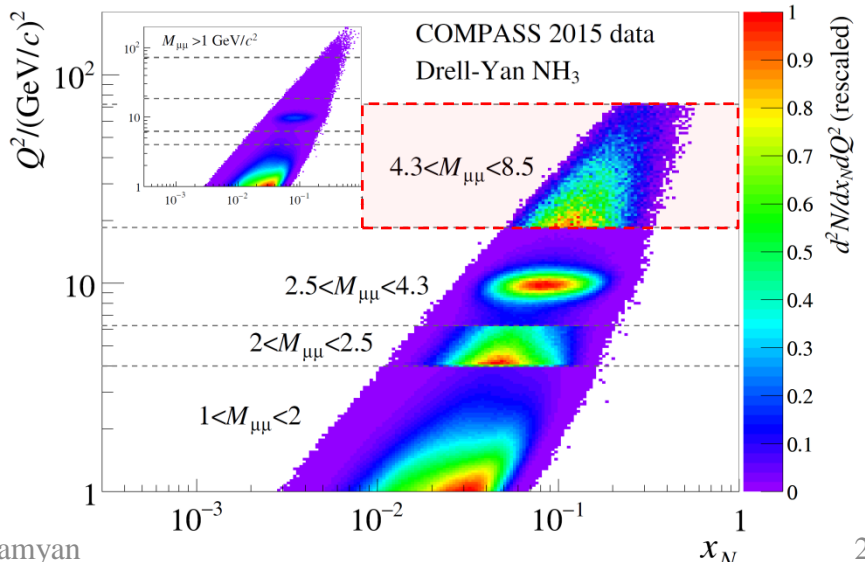
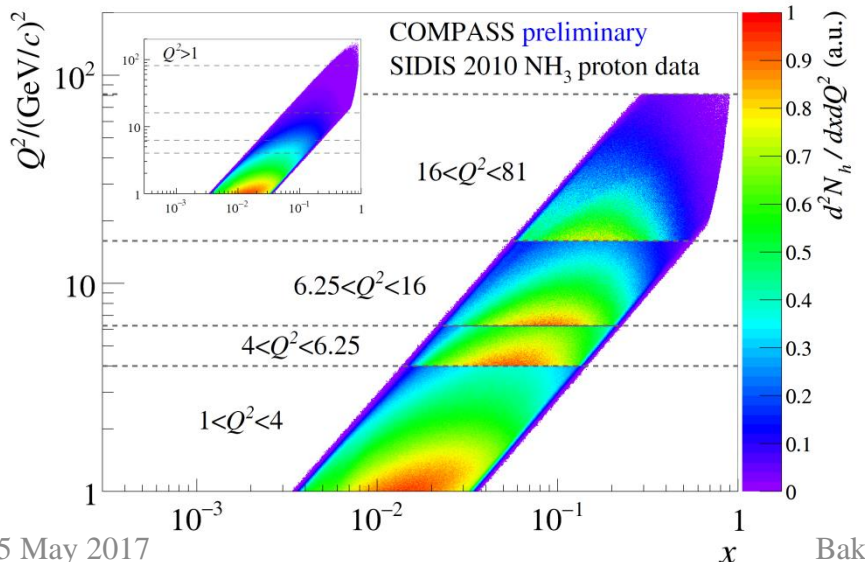
DY

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

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

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

Comparable x:Q² coverage – minimization of possible Q²-evolution effects





- Selected SIDIS results



SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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

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



SIDIS: target longitudinal spin dependent asymmetries

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

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

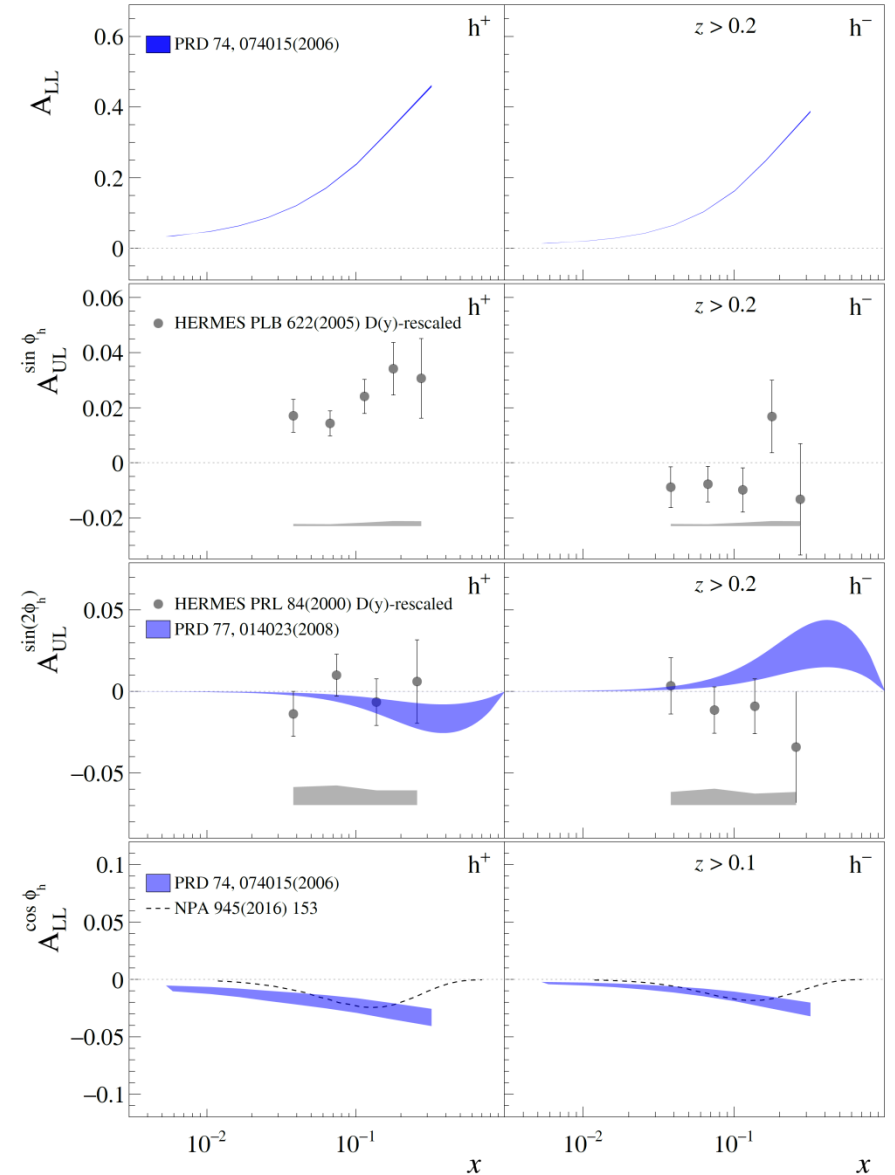
$$+ S_L \lambda \left[\begin{array}{l} \sqrt{1-\varepsilon^2} A_{LL} \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \end{array} \right]$$

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

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

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

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





SIDIS: target longitudinal spin dependent asymmetries

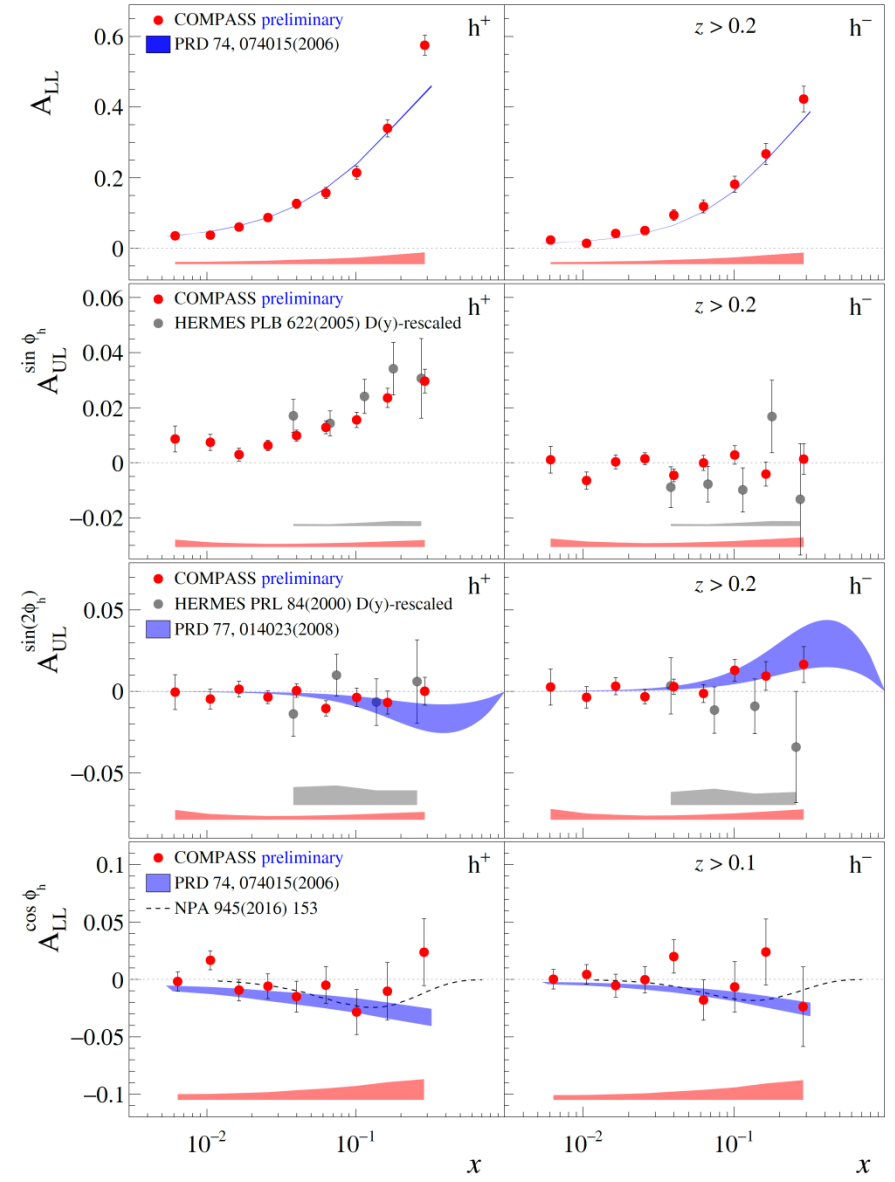
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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?**
- $A_{LL}^{\cos\phi_h}$
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SIDIS: target longitudinal spin dependent asymmetries

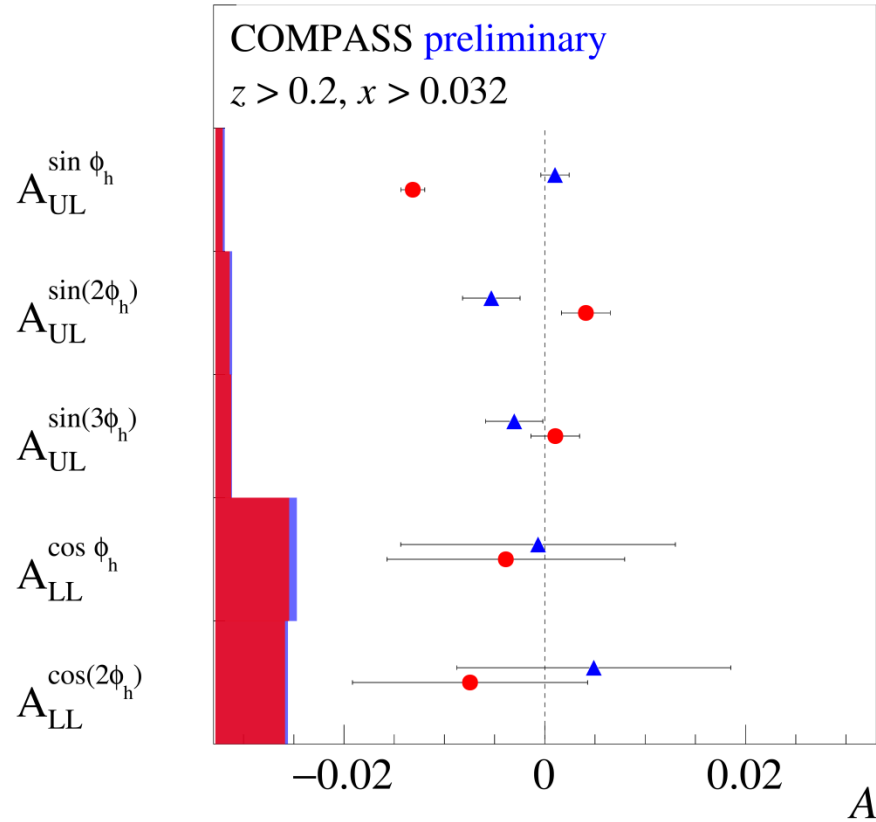
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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





SIDIS: target transverse spin dependent asymmetries

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

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

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

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

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

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

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

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

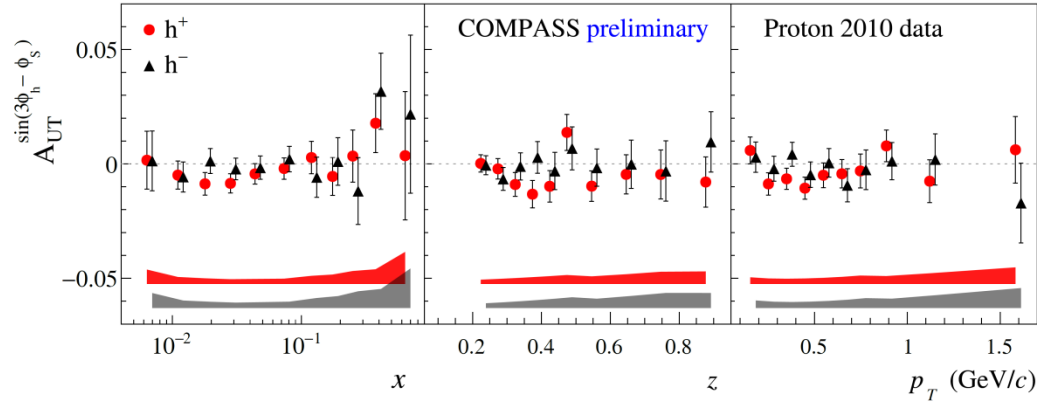


SIDIS: target transverse spin dependent asymmetries

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

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

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



COMPASS results

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

- Only “twist-2” ingredients, p_T^2 -suppression
- **Small, compatible with zero asymmetry**

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



SIDIS: target transverse spin dependent asymmetries

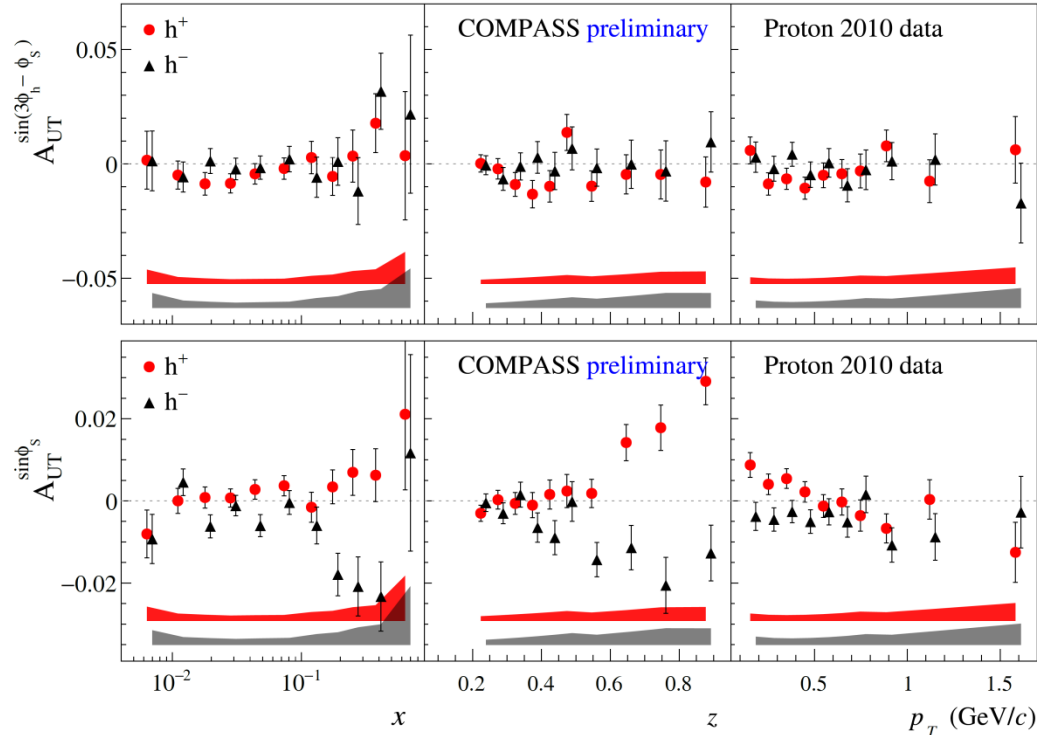
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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- $A_{UT}^{\sin(3\phi_h - \phi_S)}$
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 - Various different “twist” ingredients
 - Small asymmetry, non-zero signal for h^- ?**
- $A_{LT}^{\cos(\phi_h - \phi_S)}$
 - Only “twist-2” ingredients
 - Sizable non-zero effect for h^+ !**



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



SIDIS: target transverse spin dependent asymmetries

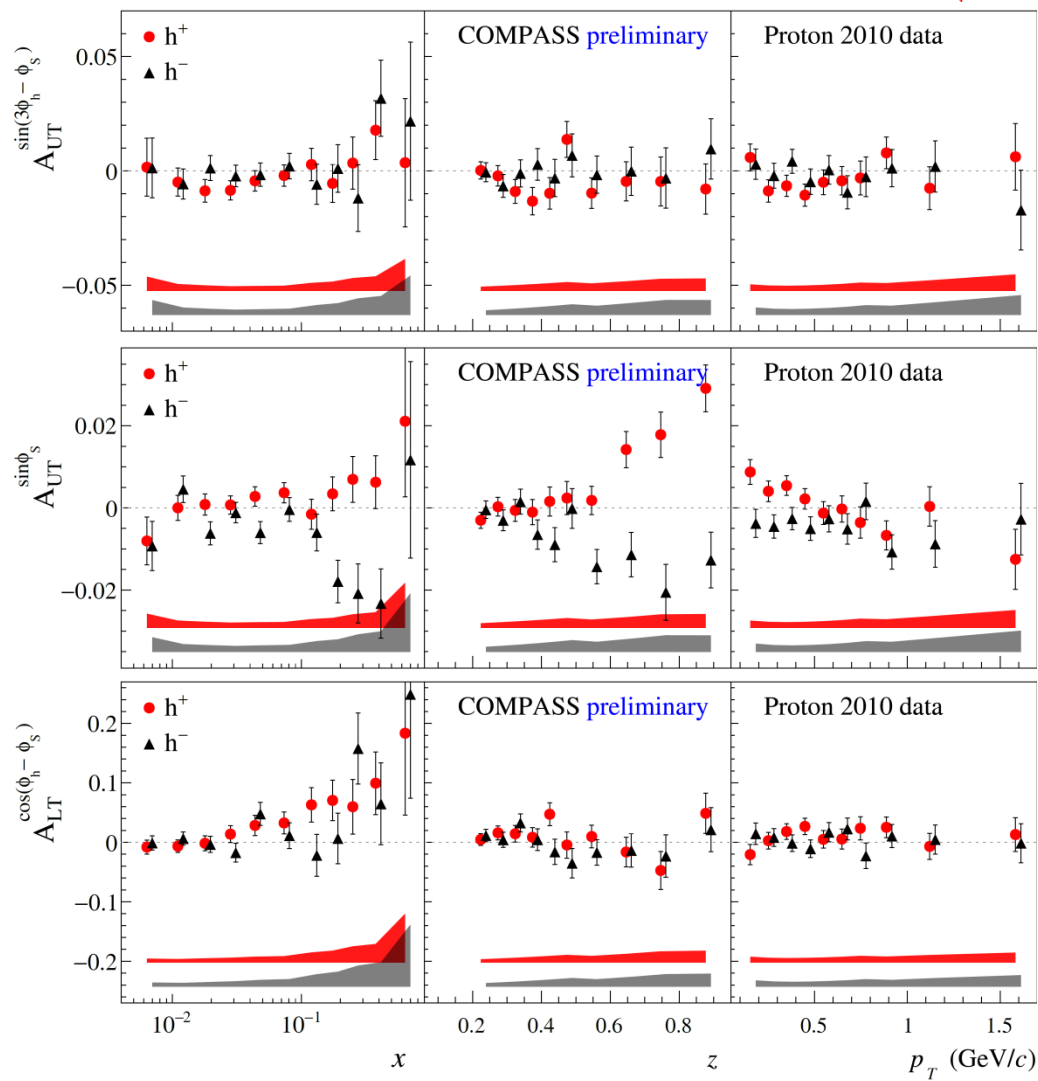
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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SIDIS TSAs (Collins)

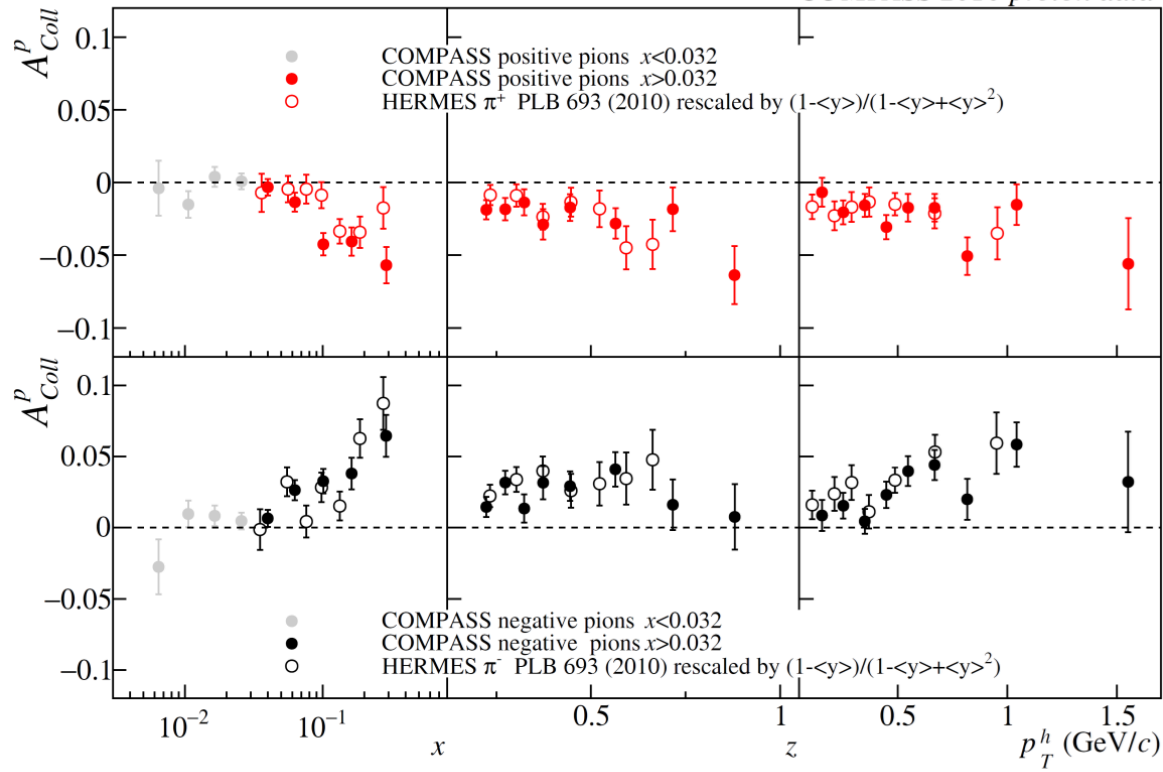
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

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

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data





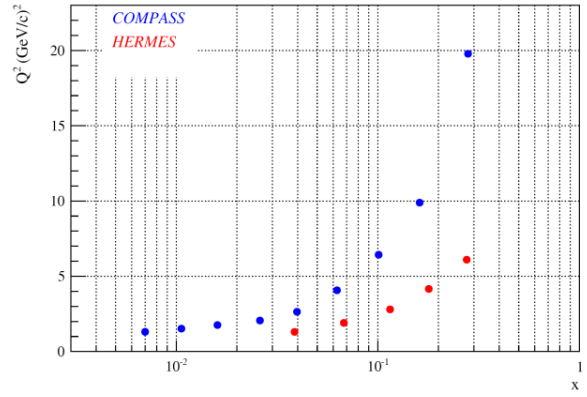
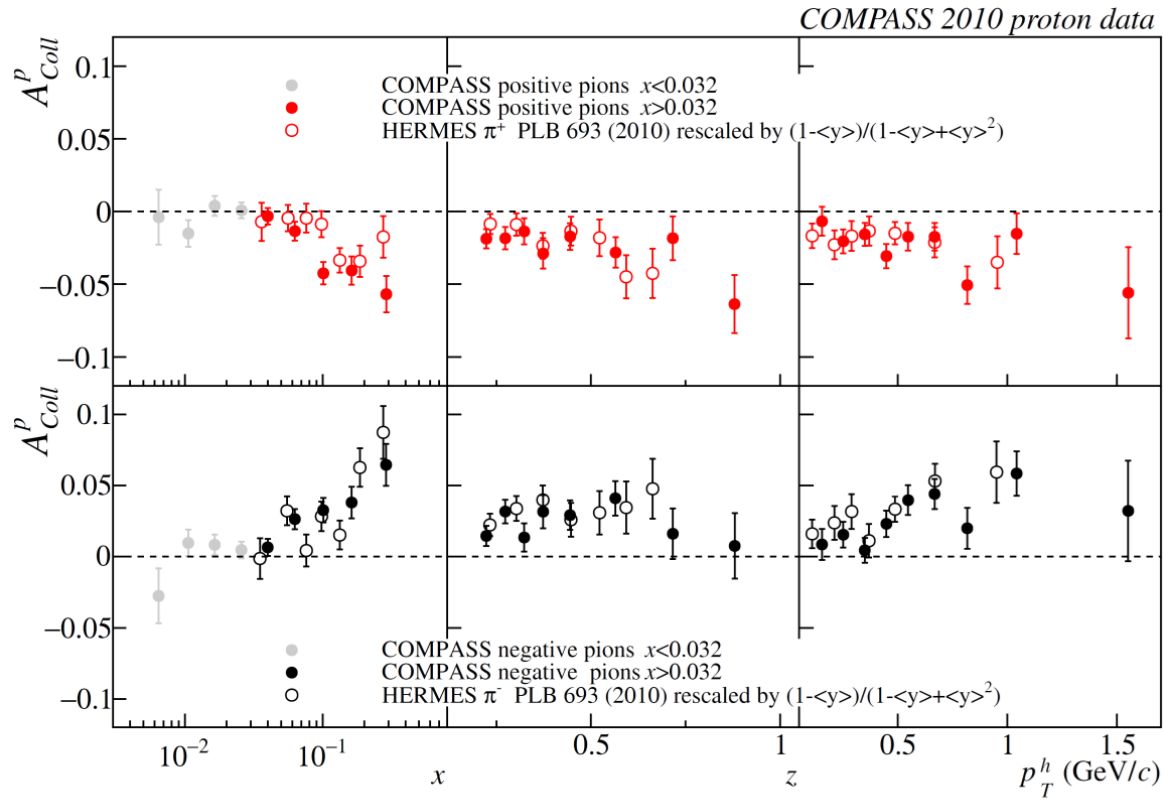
SIDIS TSAs (Collins)

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

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

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- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- **No Q²-evolution? Intriguing result!**

COMPASS PLB 744 (2015) 250



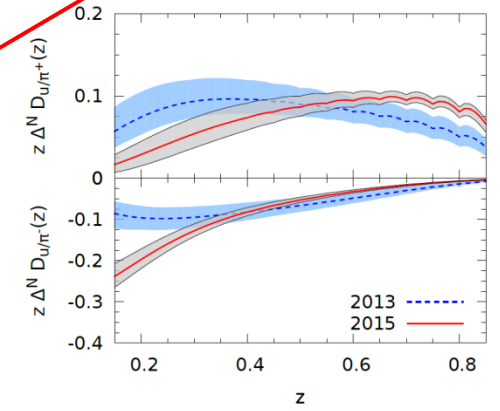
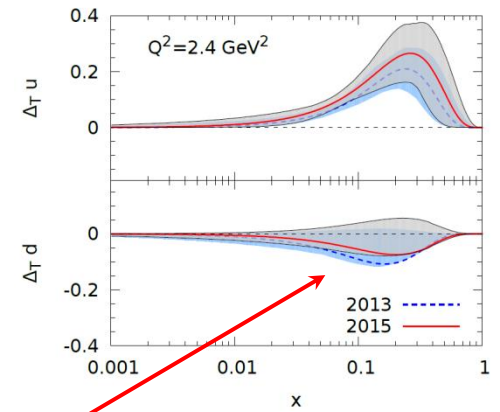
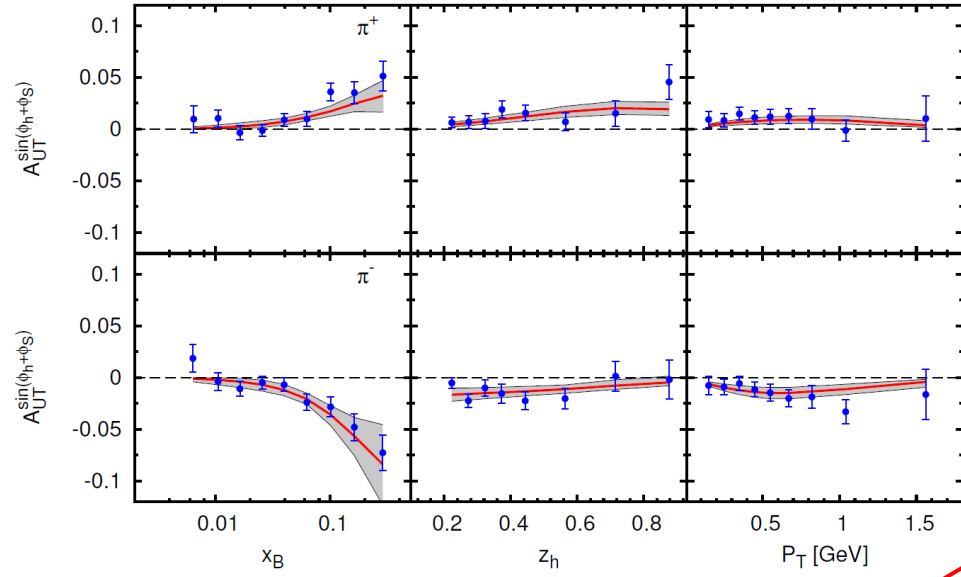
SIDIS TSAs (Collins)

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- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- **No Q²-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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



Ideas for COMPASS-III (>2020)

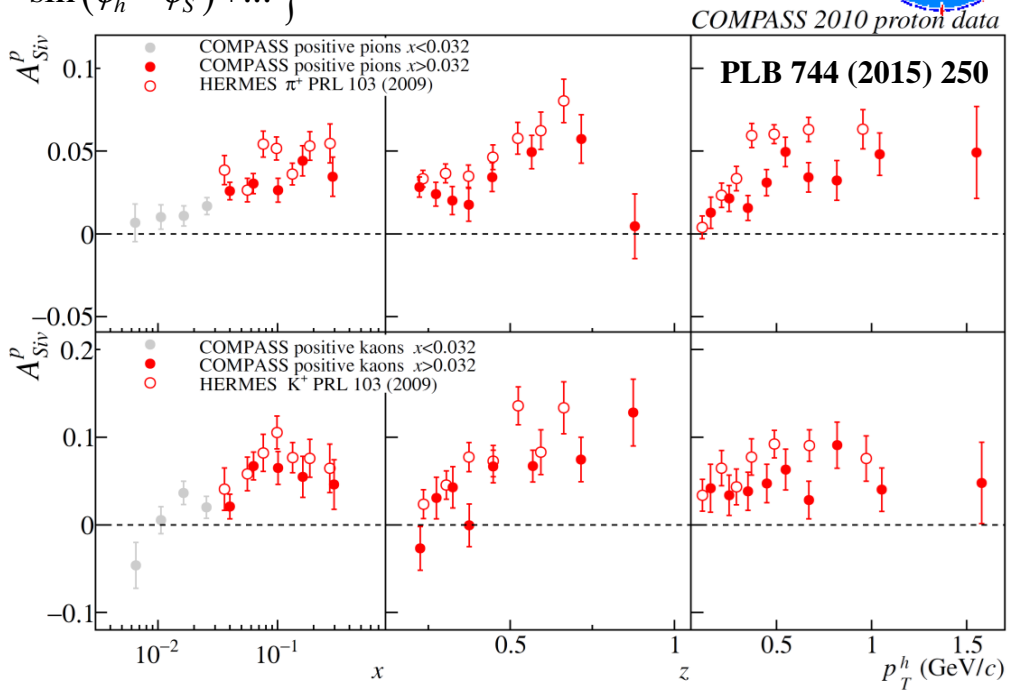
- Deuteron measurement to be repeated.
- Will be crucial to constrain the transversity TMD PDF for the d-quark

SIDIS TSAs (Sivers)

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

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- Measured on proton and deuteron
- Gluon Sivers paper: submitted to PLB [CERN-EP/2017-003](https://arxiv.org/abs/1701.02453), [hep-ex/1701.02453](https://arxiv.org/abs/1701.02453)

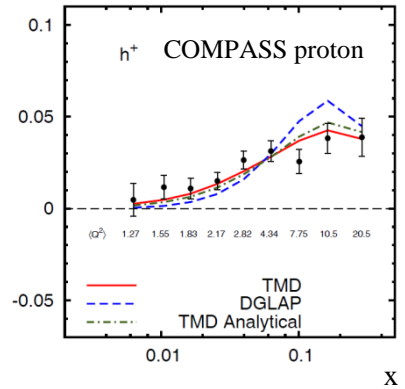
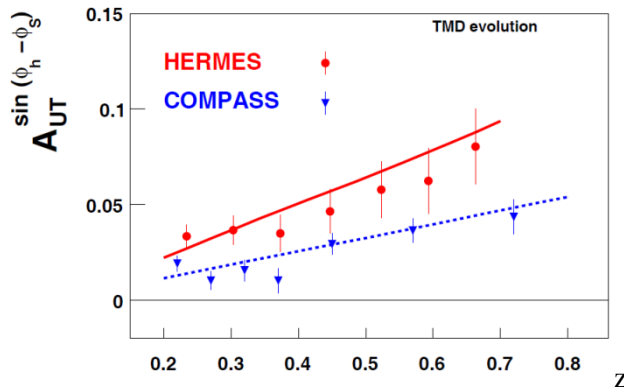
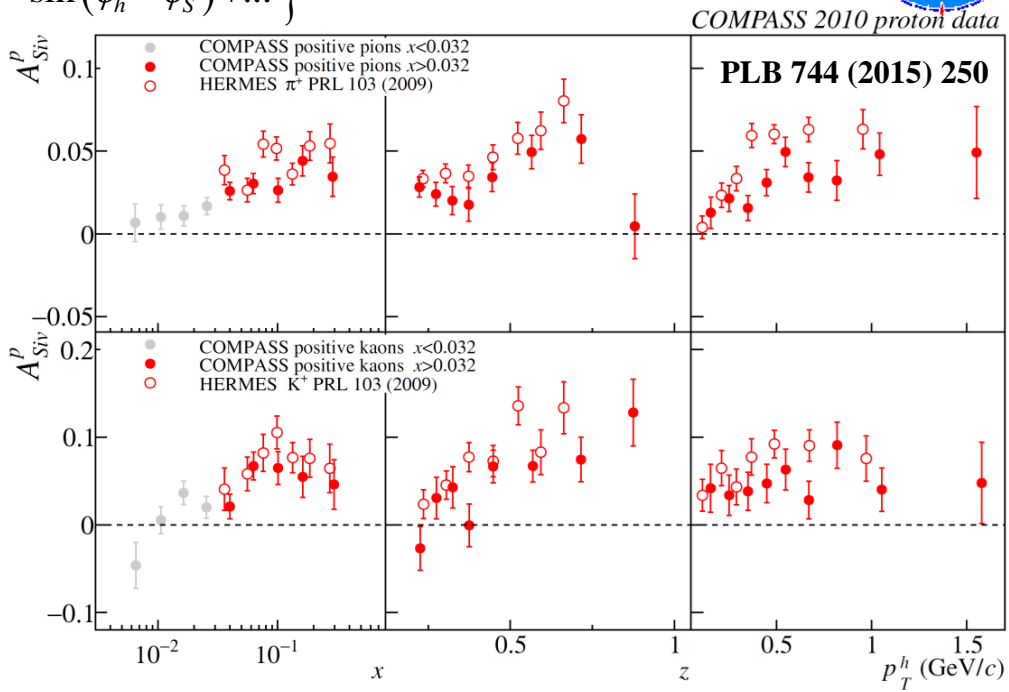


SIDIS TSAs (Sivers)

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- **Q^2 -evolution? Intriguing result!**



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



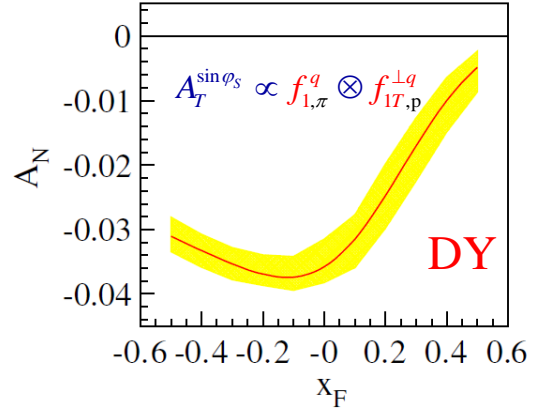
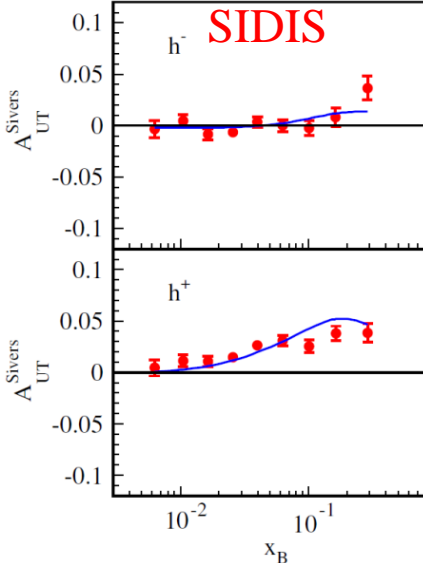
SIDIS TSAs (Sivers)

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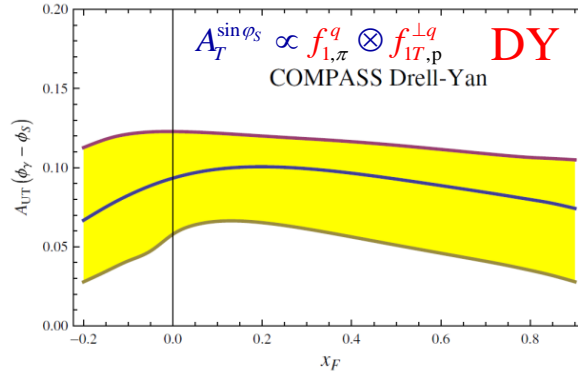
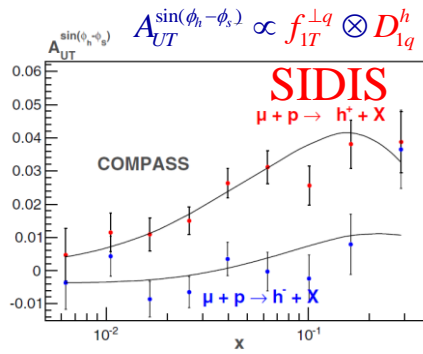
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

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)**





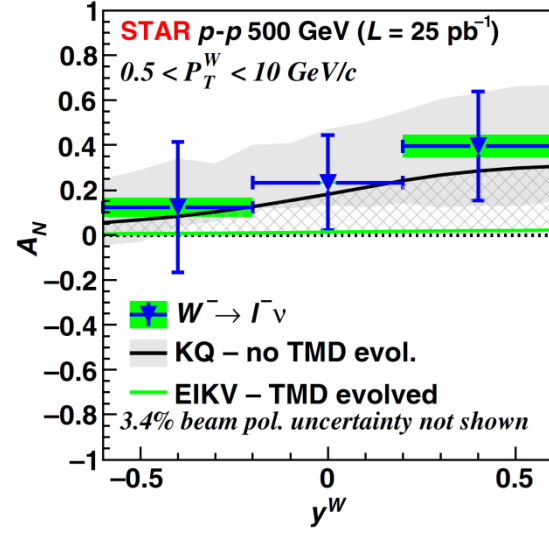
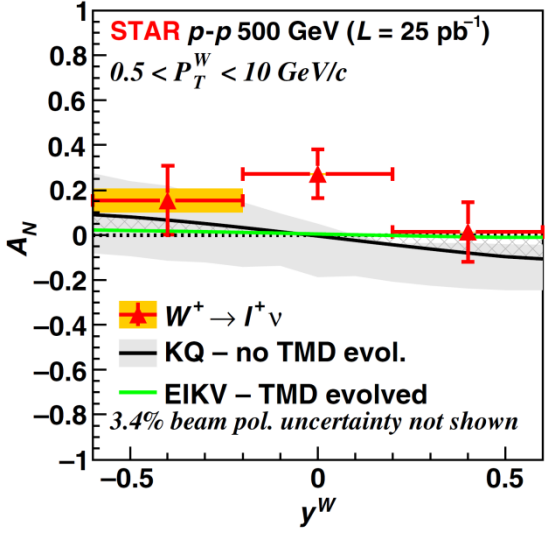
SIDIS TSAs (Sivers)

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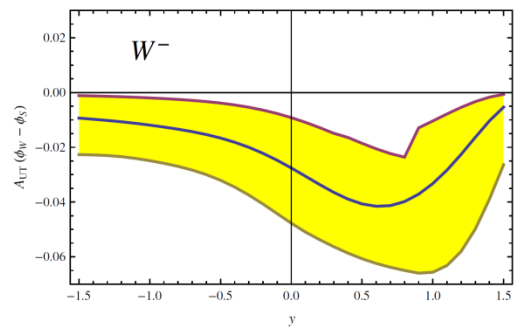
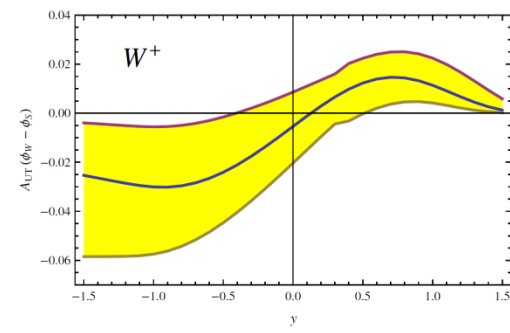
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- **Q^2 -evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- First experimental investigation of Sivers-non-universality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

STAR collaboration: PRL 116, 132301 (2016)



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



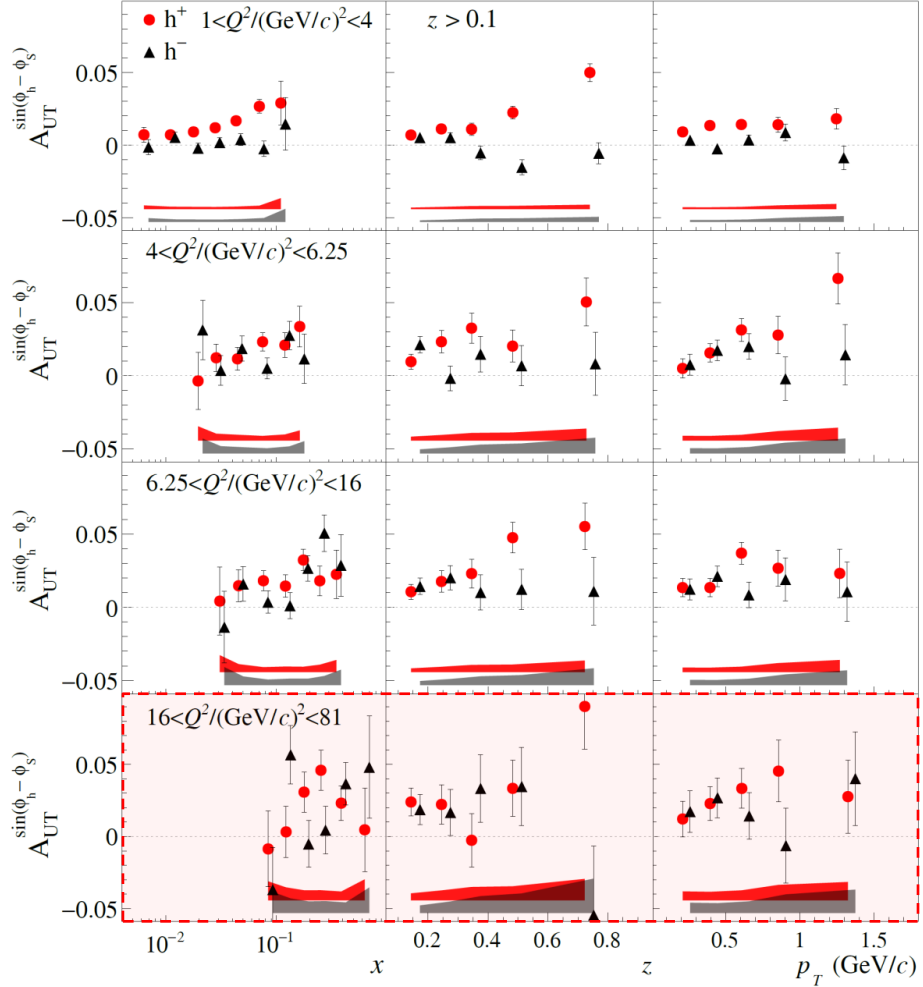
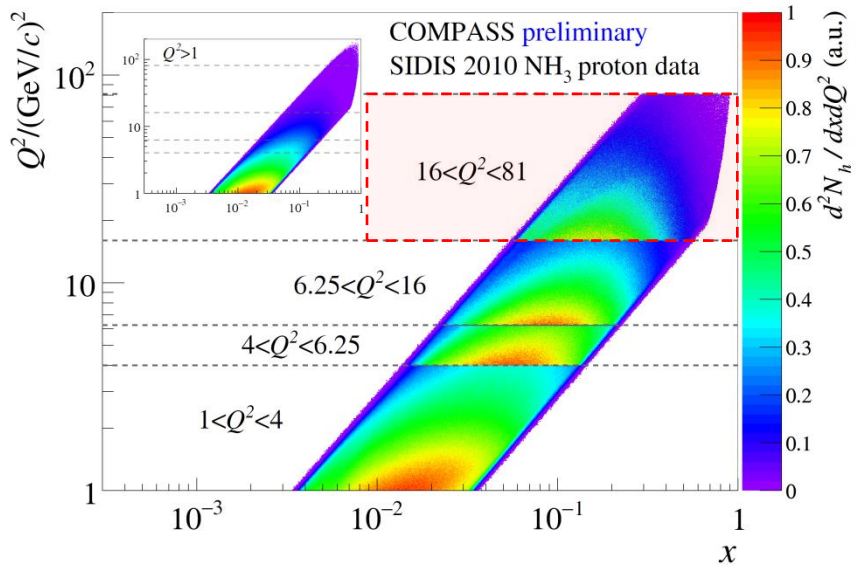


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

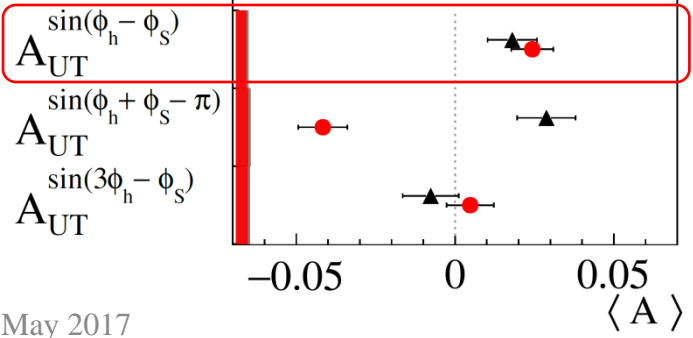
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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COMPASS PLB 770 (2017) 138



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



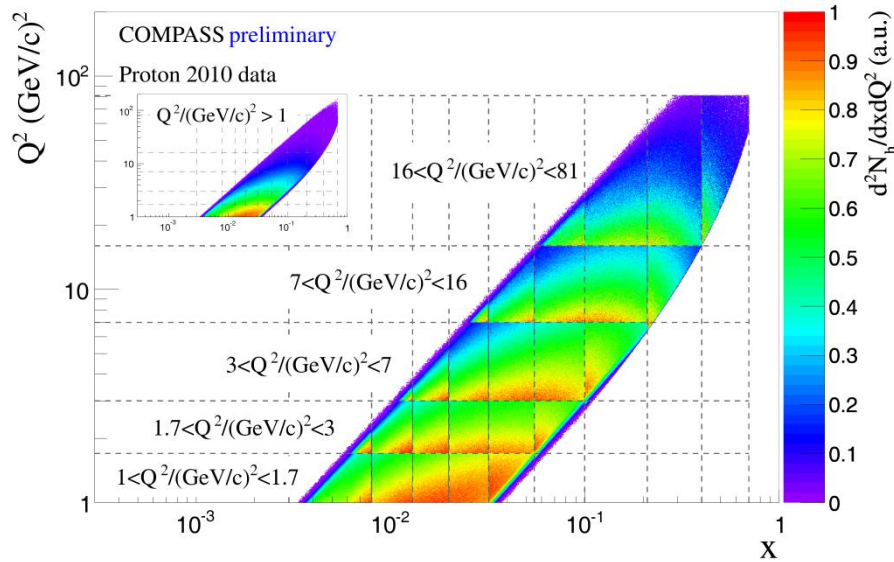
Multi-D TSA analysis

First shown at the SPIN-2014

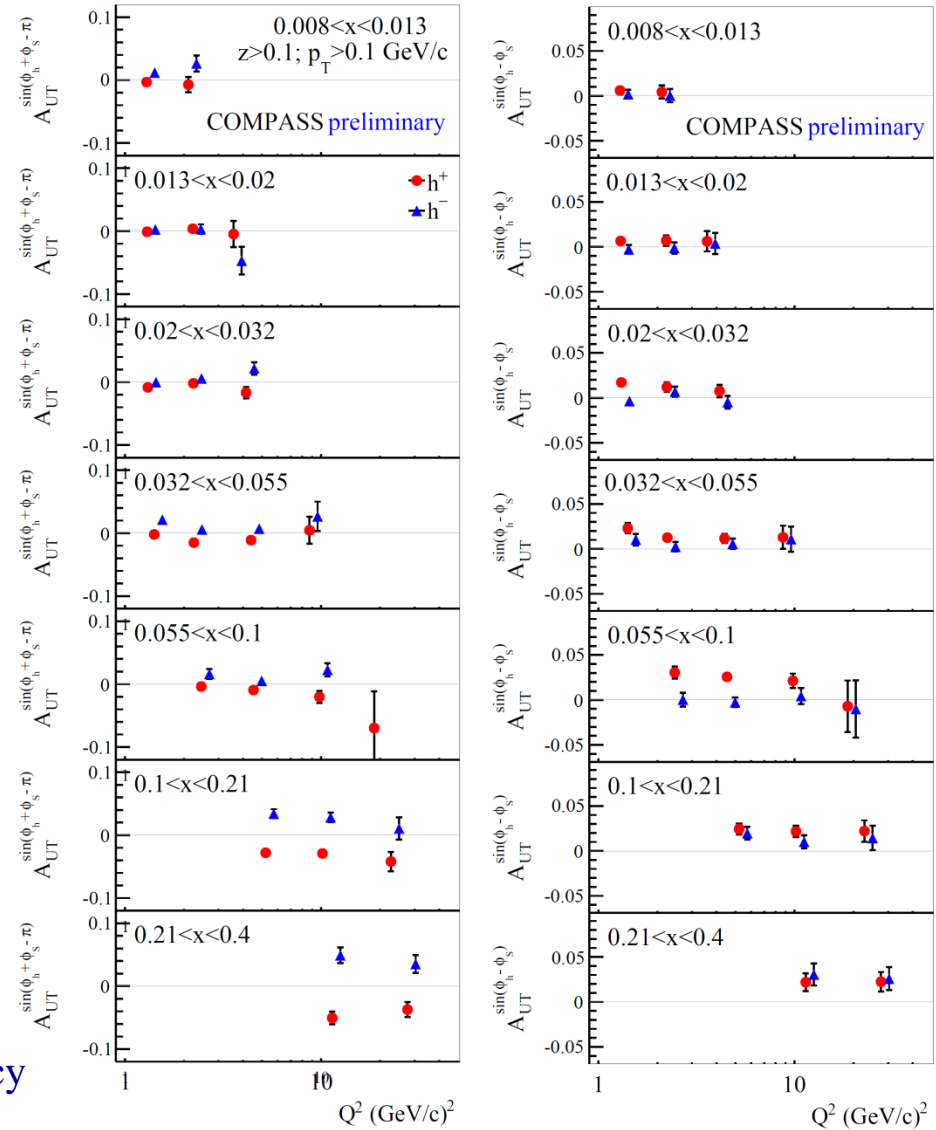
[arXiv:1504.01599](https://arxiv.org/abs/1504.01599) [hep-ex]

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

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



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





- Results from first ever measurement of Drell-Yan TSAs



Single-polarized DY x-section: transverse part

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

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

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

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

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



Single-polarized DY x-section: transverse part

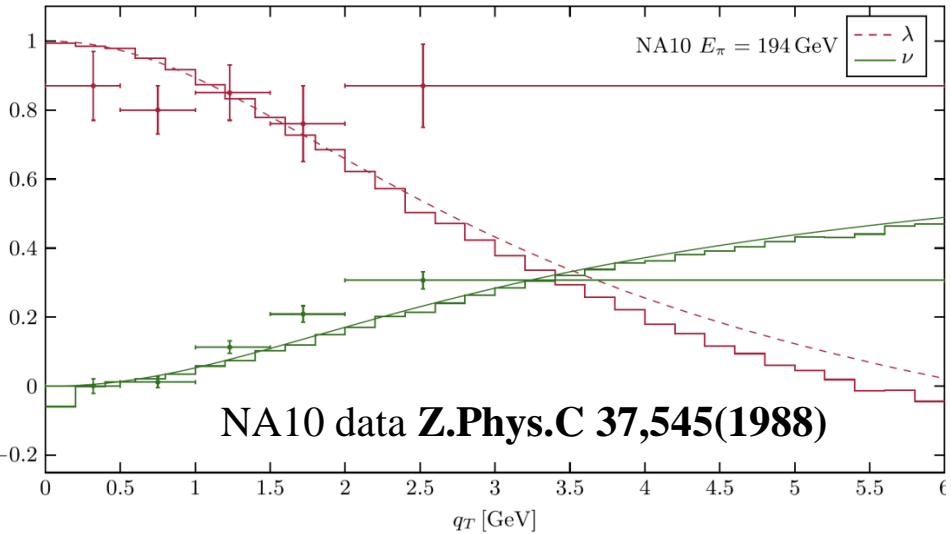
$$\lambda = A_U^1, \mu = A_U^{\cos \varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

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

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

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

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



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

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



Single-polarized DY x-section: transverse part

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

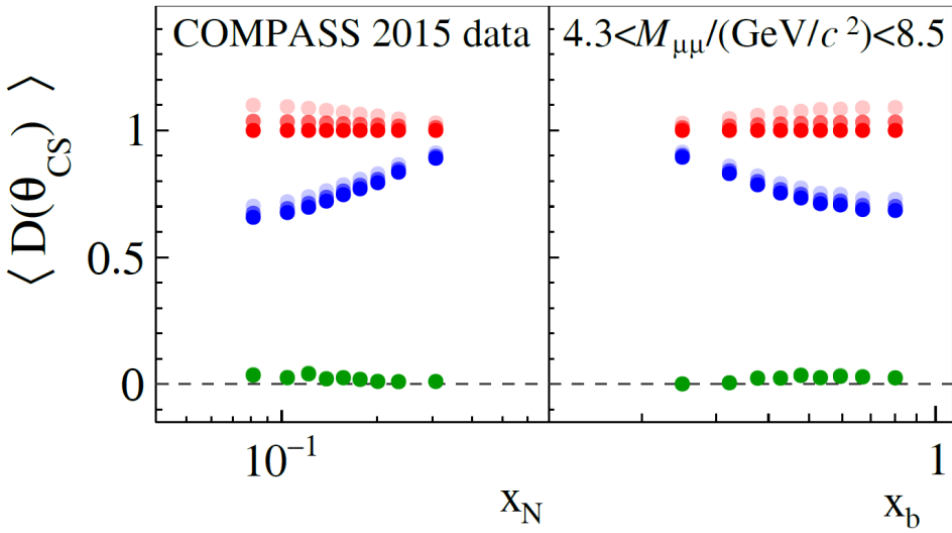
- “naive” Drell–Yan model
collinear ($k_T=0$) LO pQCD no rad. processes
 $\lambda=1, (F_U^2=0), \mu=\nu=0$
- Intrinsic transverse motion + QCD effects
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- Experiment,
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

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

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





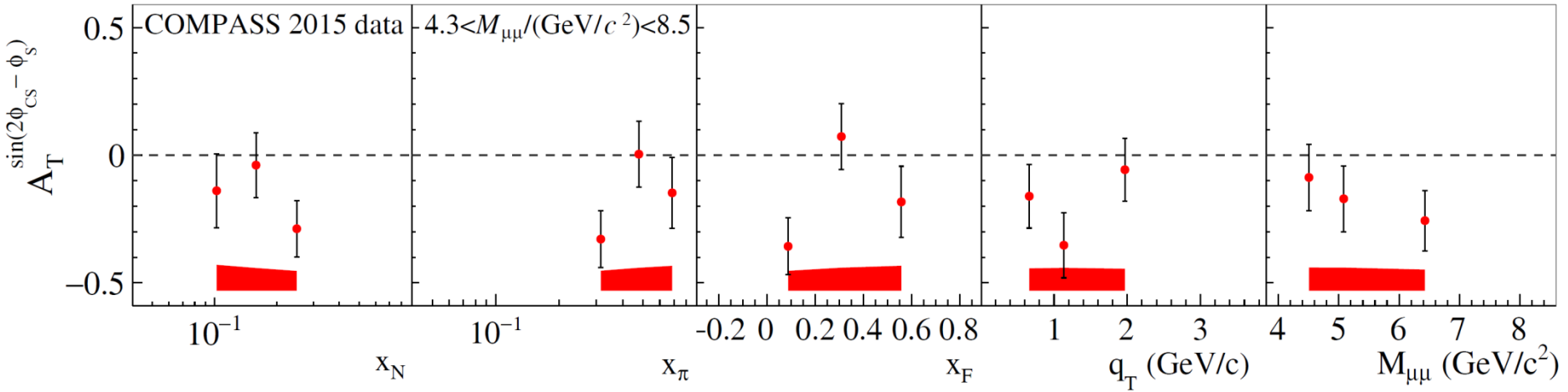
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





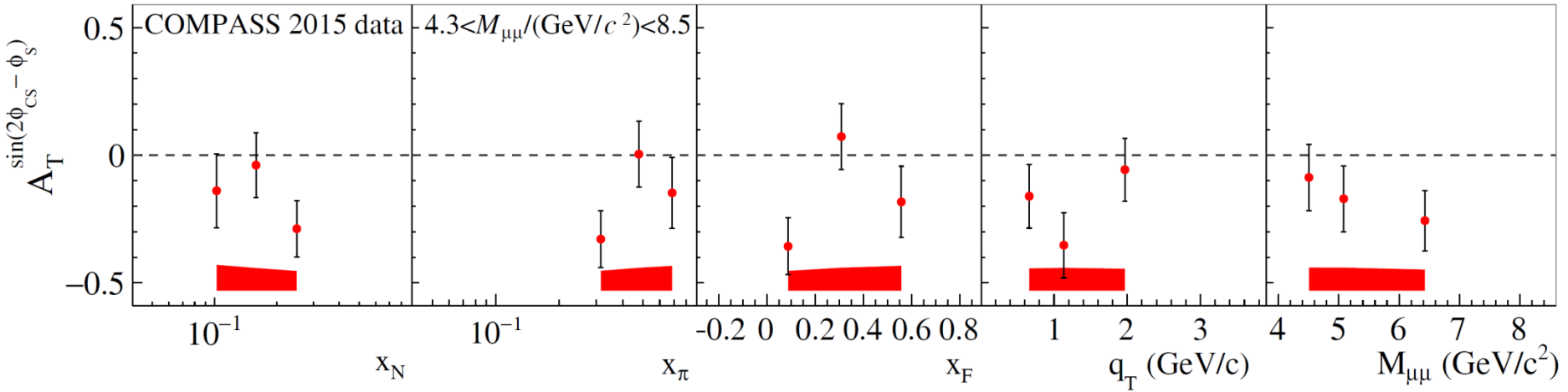
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Transversity DY TSA

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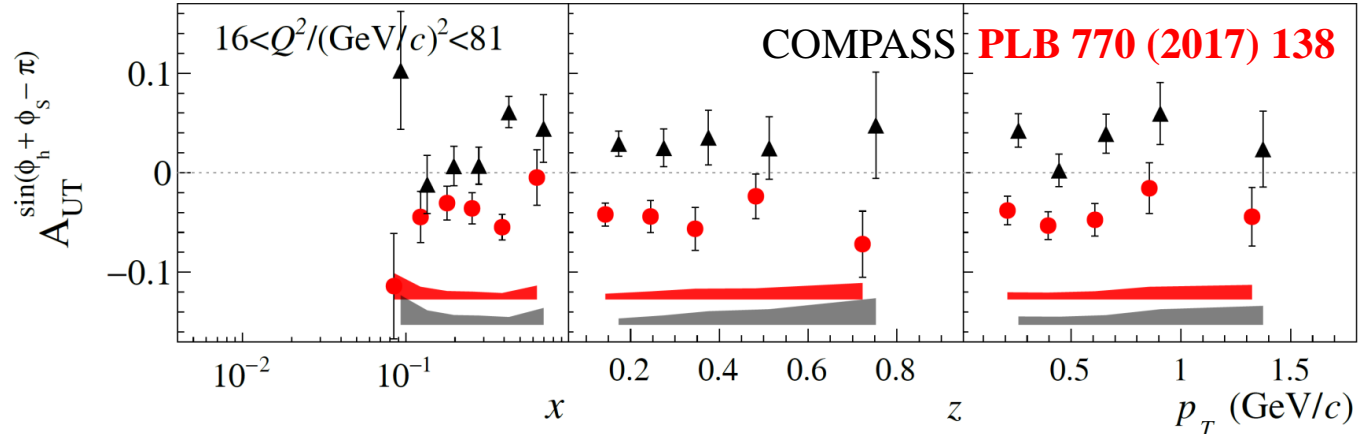
New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)



SIDIS in Drell-Yan high-mass range

Collins SIDIS TSA

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





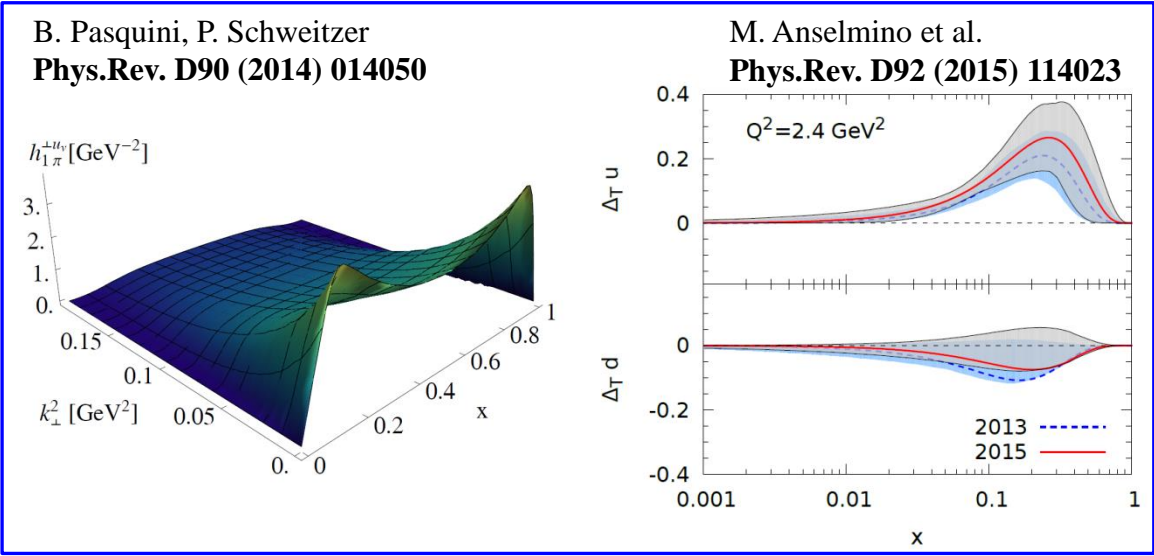
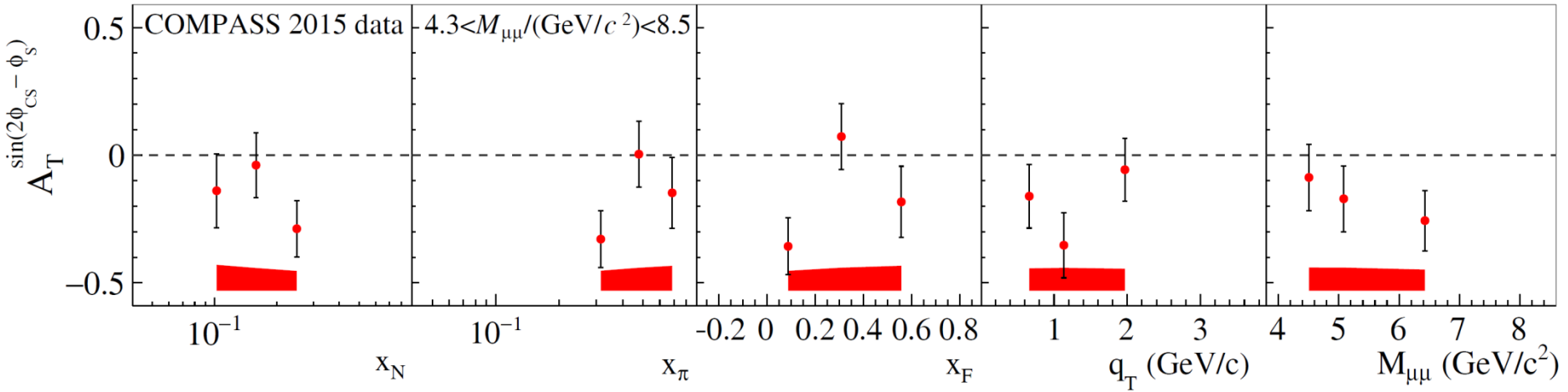
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





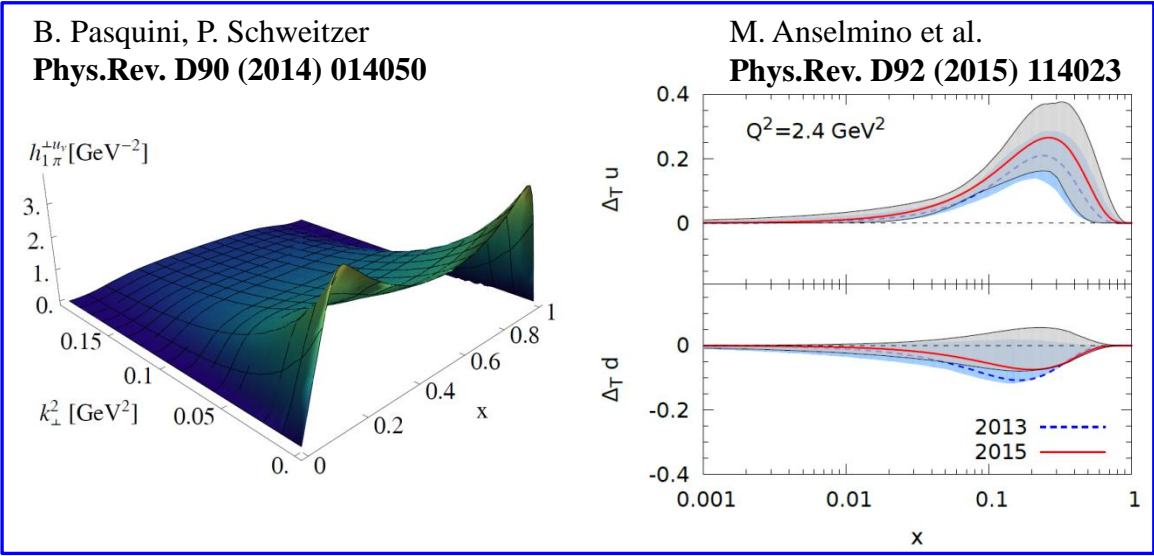
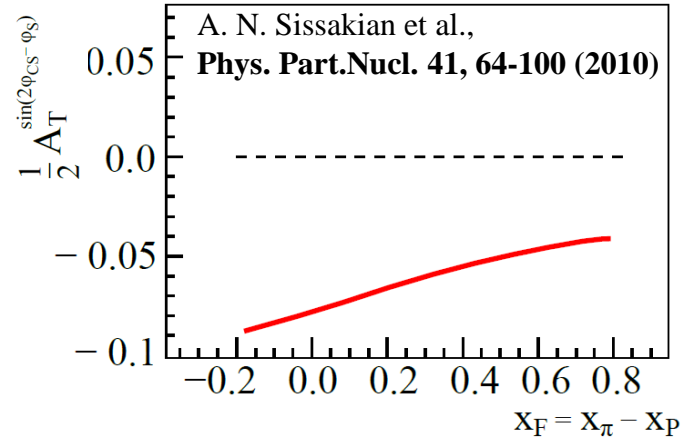
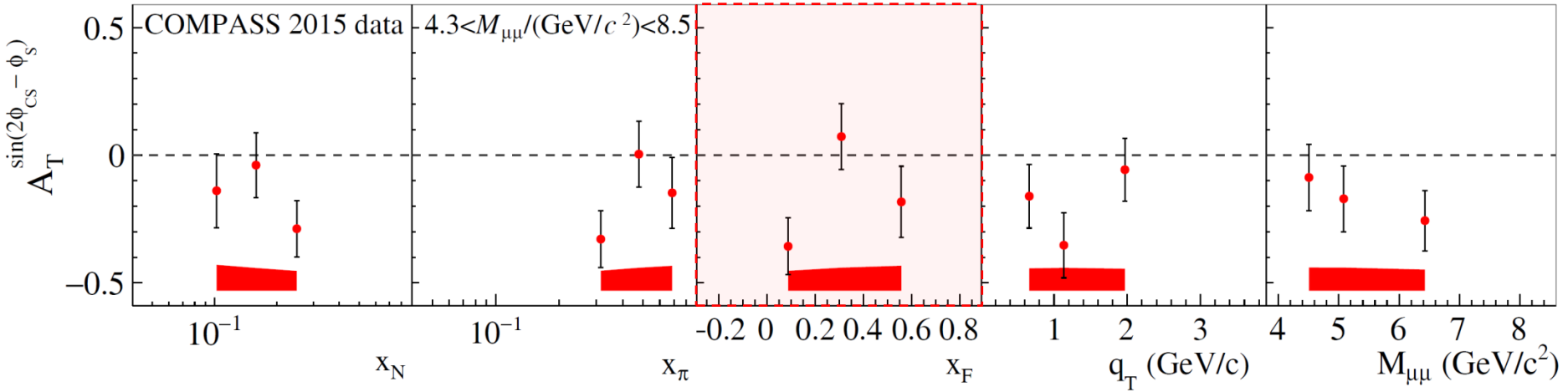
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





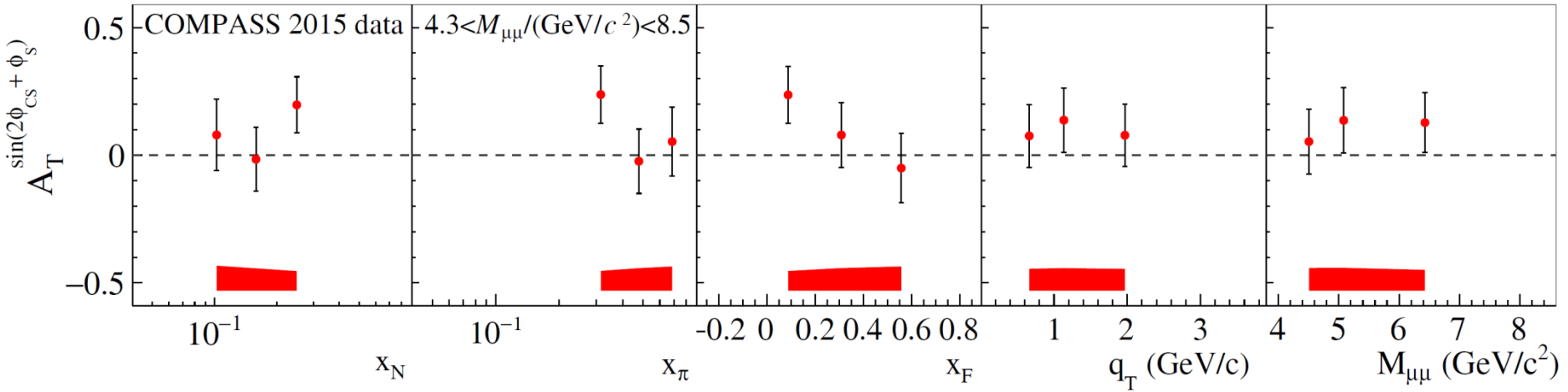
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





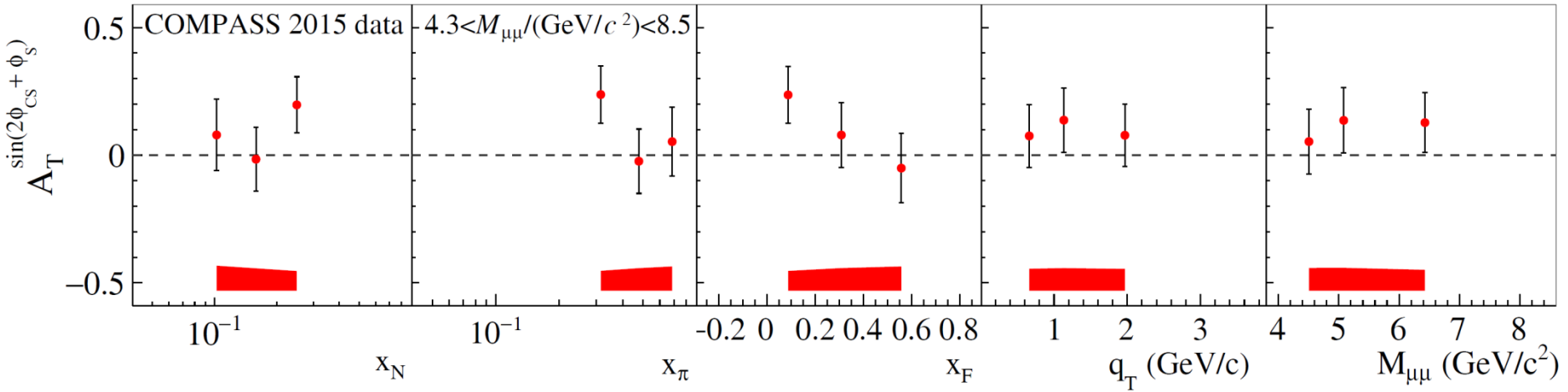
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

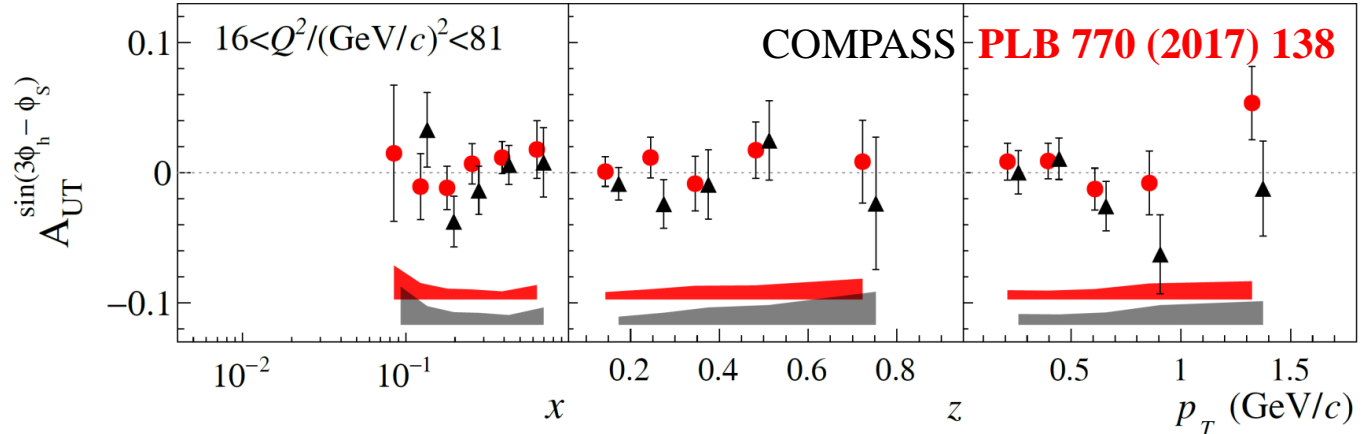
New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)



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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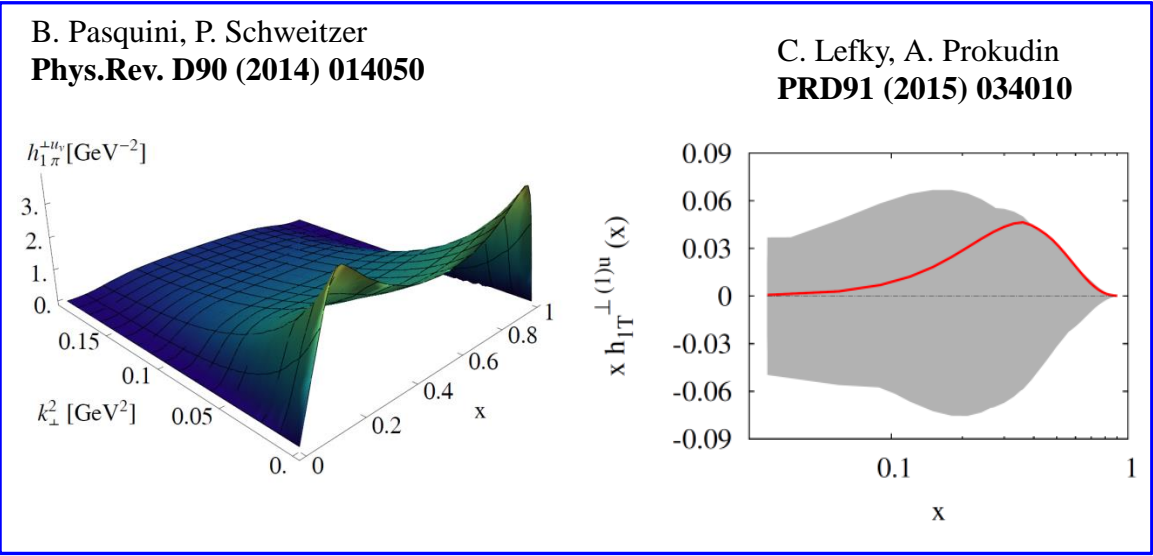
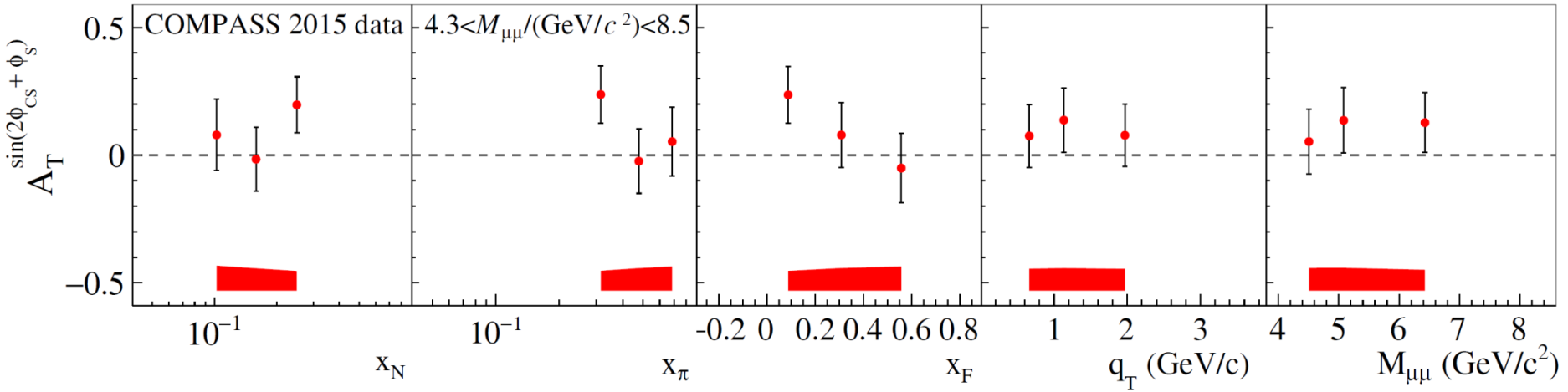
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





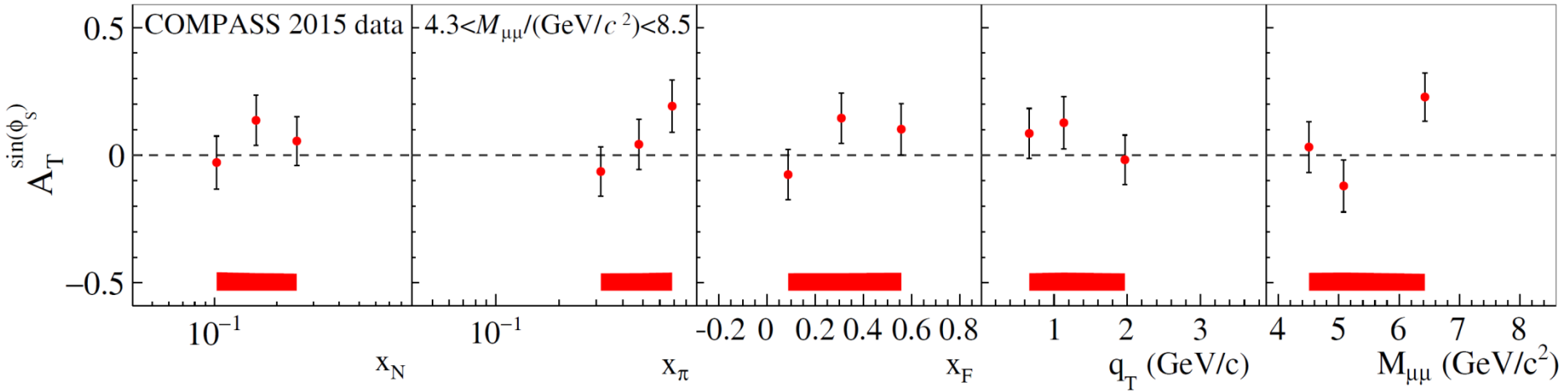
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





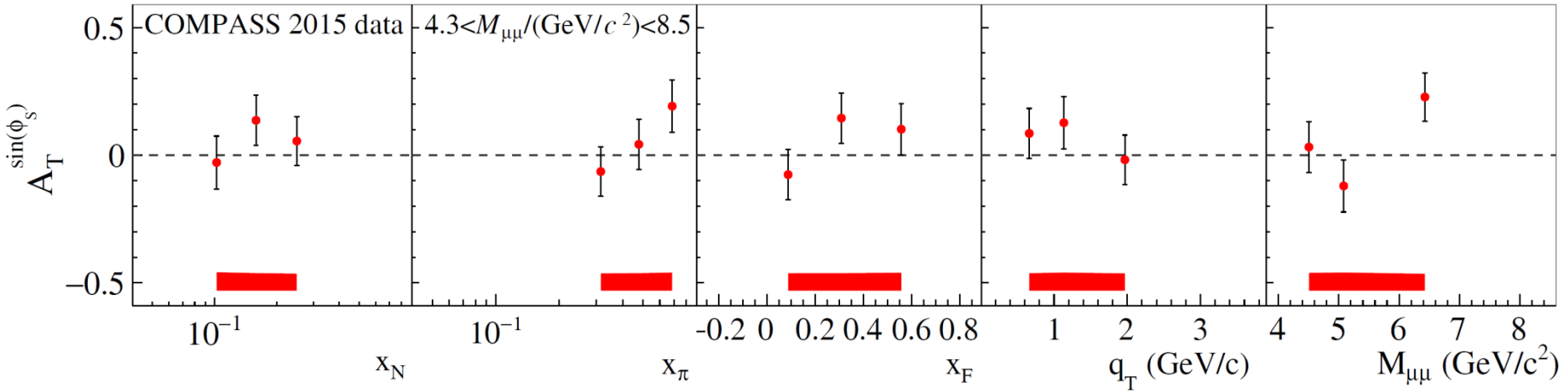
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Sivers DY TSA

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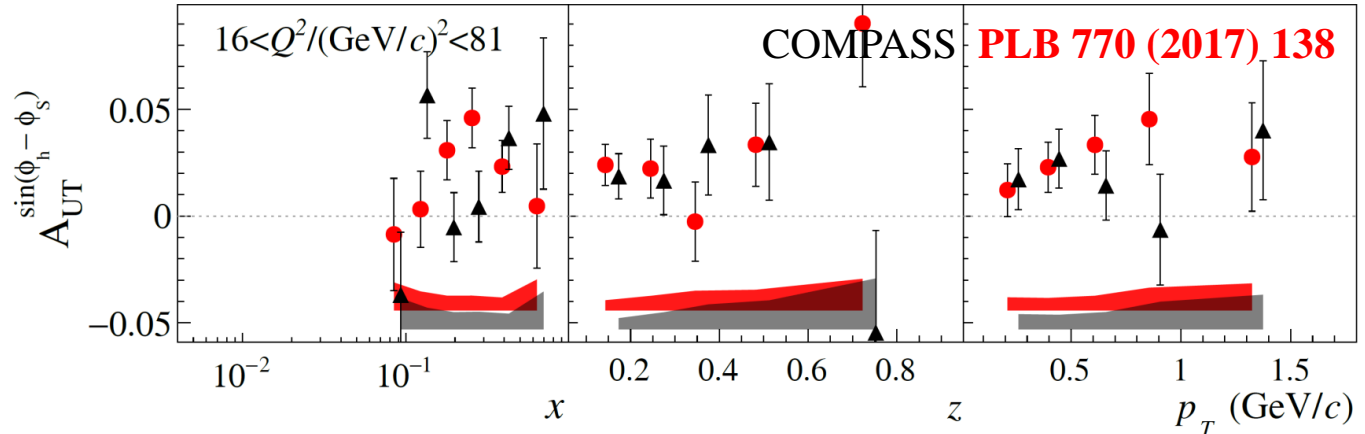
New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)



SIDIS in Drell-Yan high-mass range

Sivers SIDIS TSA

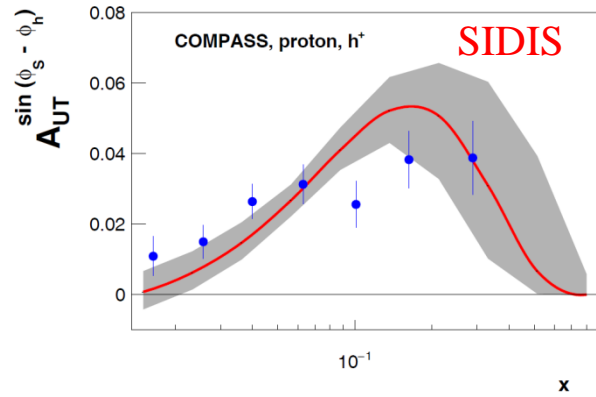
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$



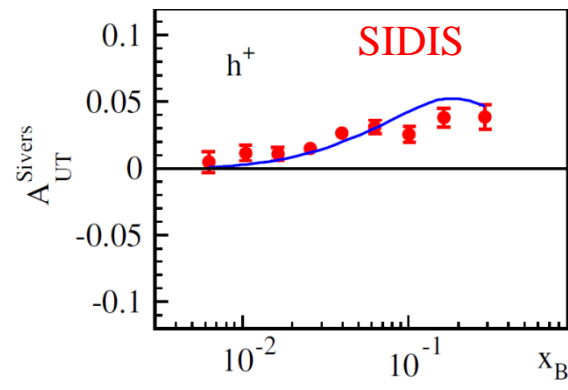


Sivers asymmetry in Drell-Yan: sign change

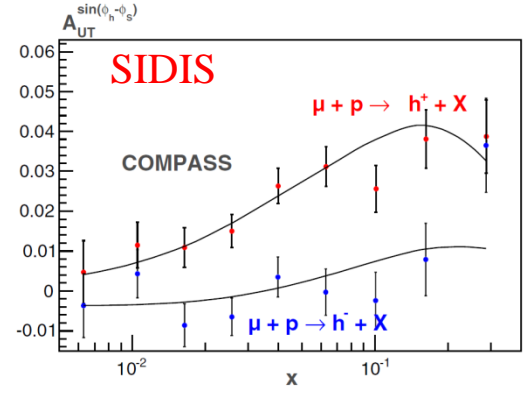
DGLAP (2016)
M. Anselmino et al., [arXiv:1612.06413](#)



TMD-1 (2014)
M. G. Echevarria et al. [PRD89,074013](#)



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

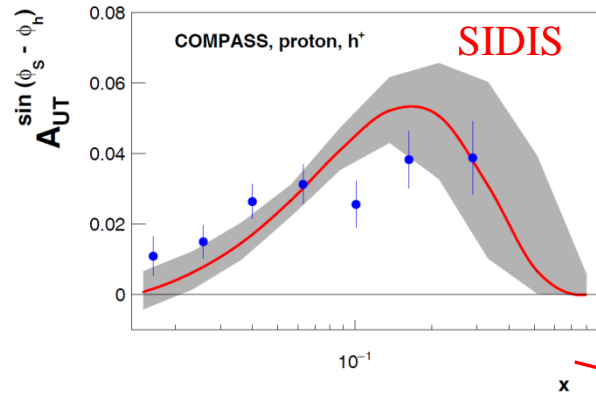




Sivers asymmetry in Drell-Yan: sign change

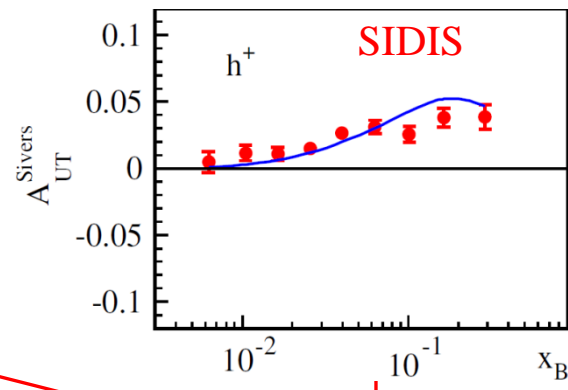
DGLAP (2016)

M. Anselmino et al., arXiv:1612.06413



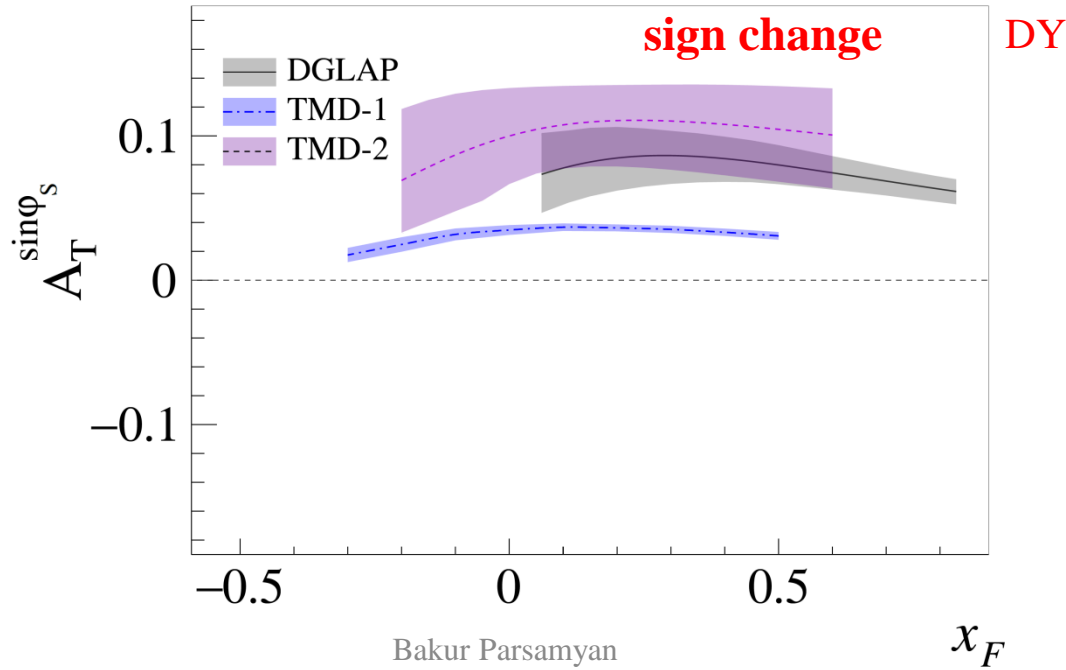
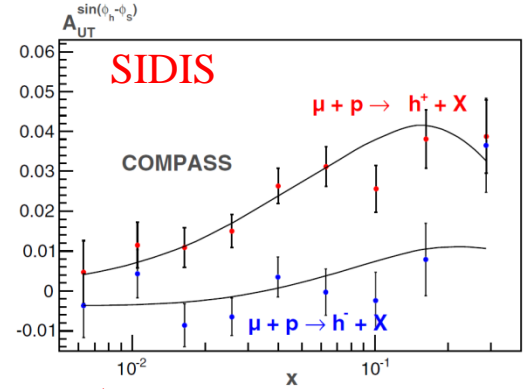
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



TMD-2 (2013)

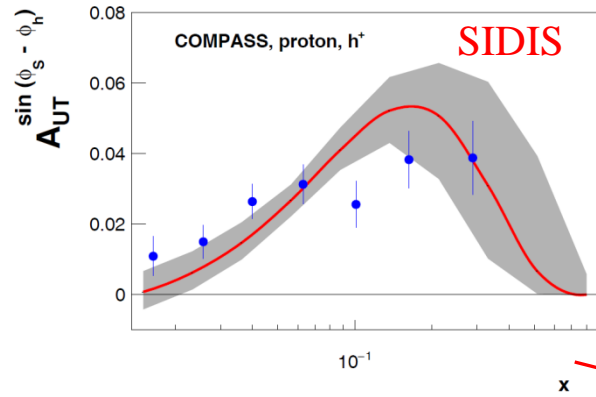
P. Sun, F. Yuan, PRD88, 114012



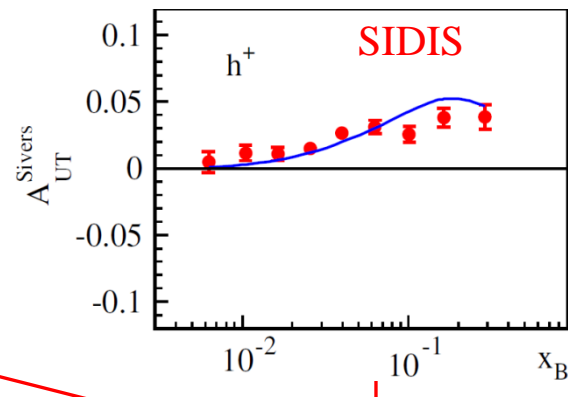


Sivers asymmetry in Drell-Yan: sign change

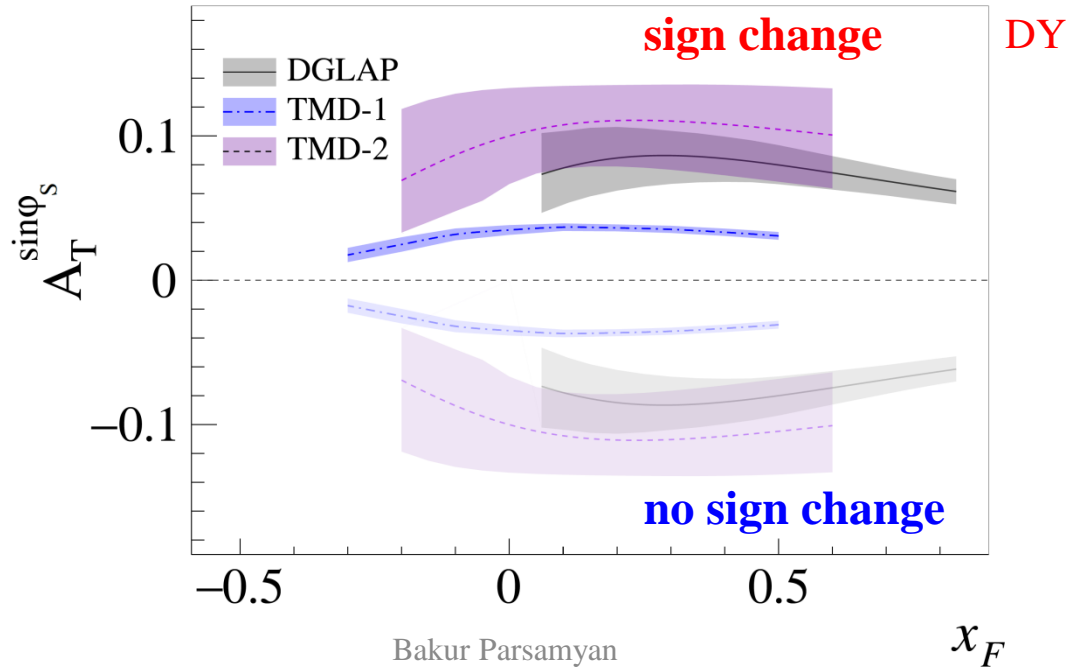
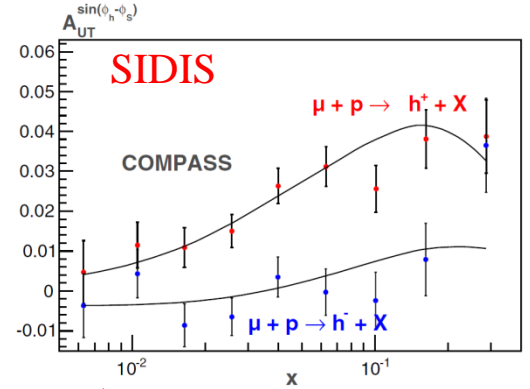
DGLAP (2016)
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TMD-1 (2014)
M. G. Echevarria et al. [PRD89,074013](https://arxiv.org/abs/1403.0001)



TMD-2 (2013)
P. Sun, F. Yuan, [PRD88, 114012](https://arxiv.org/abs/1303.0001)

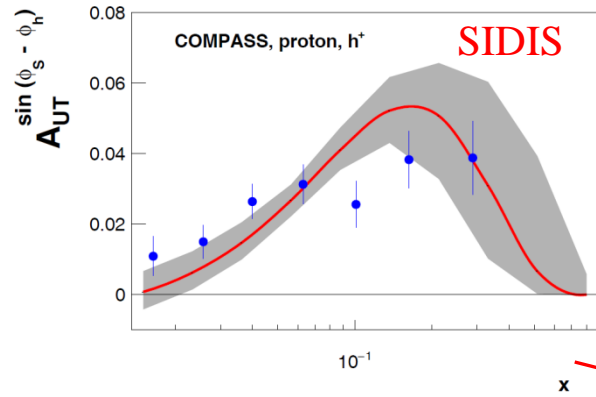




Sivers asymmetry in Drell-Yan: sign change

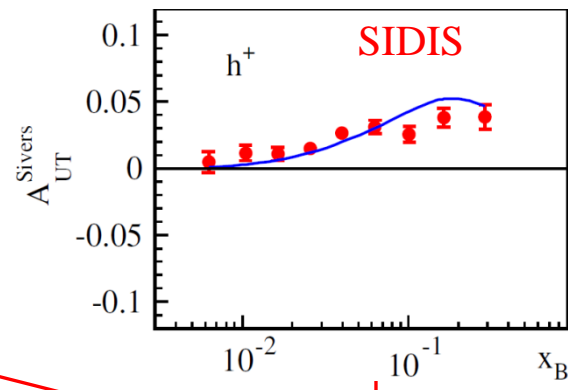
DGLAP (2016)

M. Anselmino et al., arXiv:1612.06413



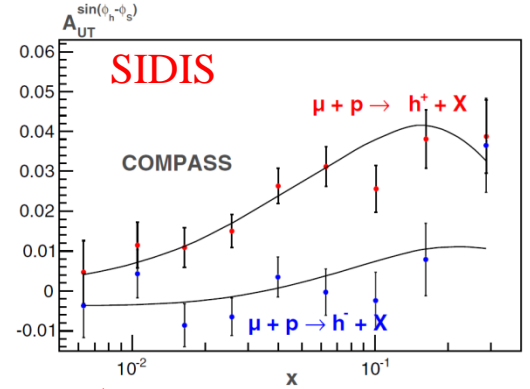
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



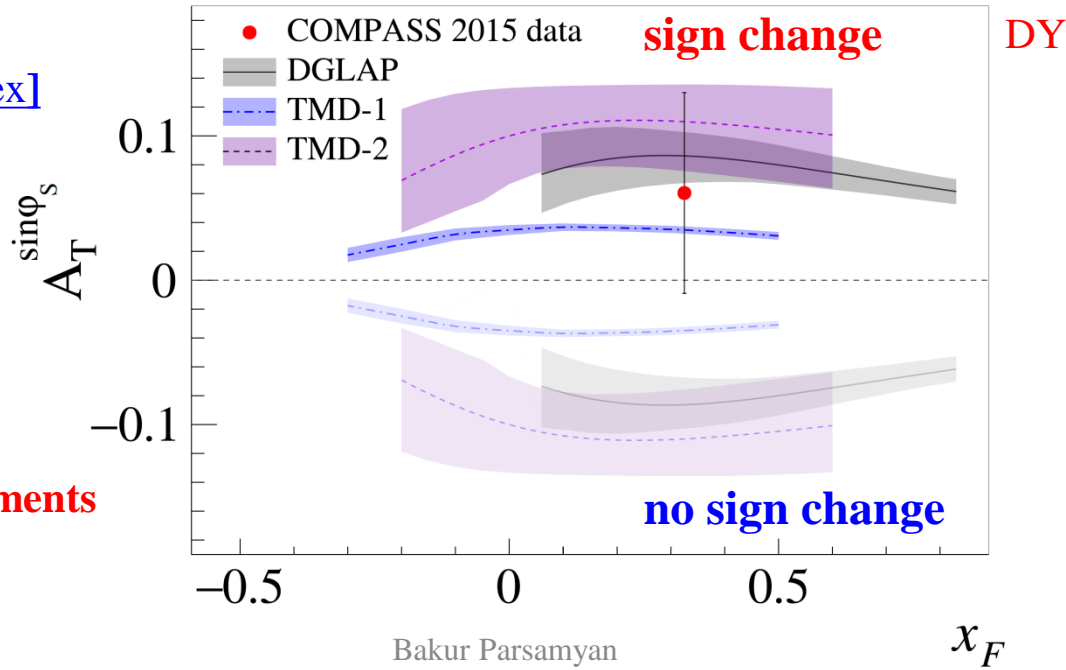
TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012



New! COMPASS
[CERN-EP-2017-059](#)
[arXiv:1704.00488\[hep-ex\]](#)

In 2018 – 2nd round of polarized DY measurements at COMPASS





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

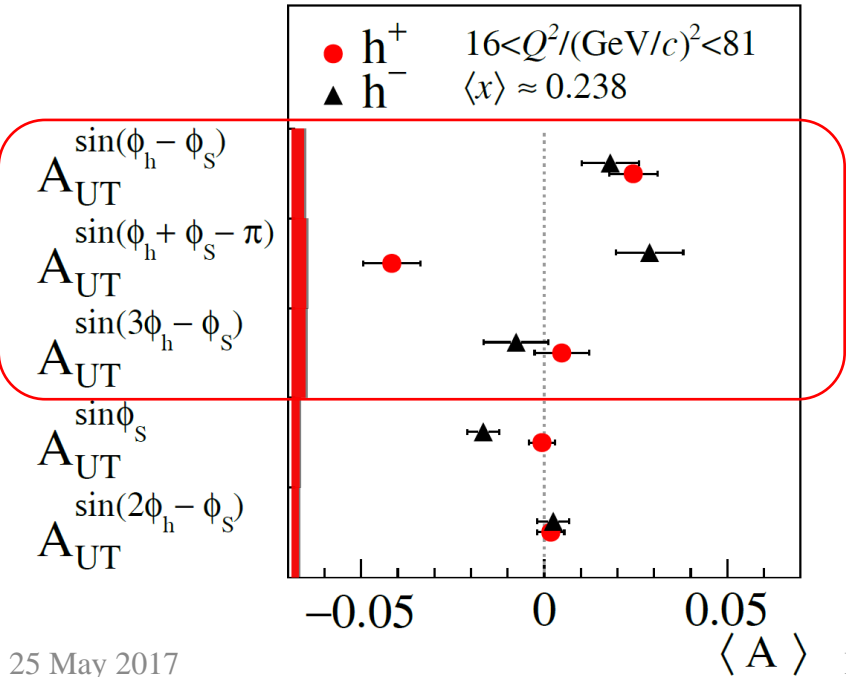
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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

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

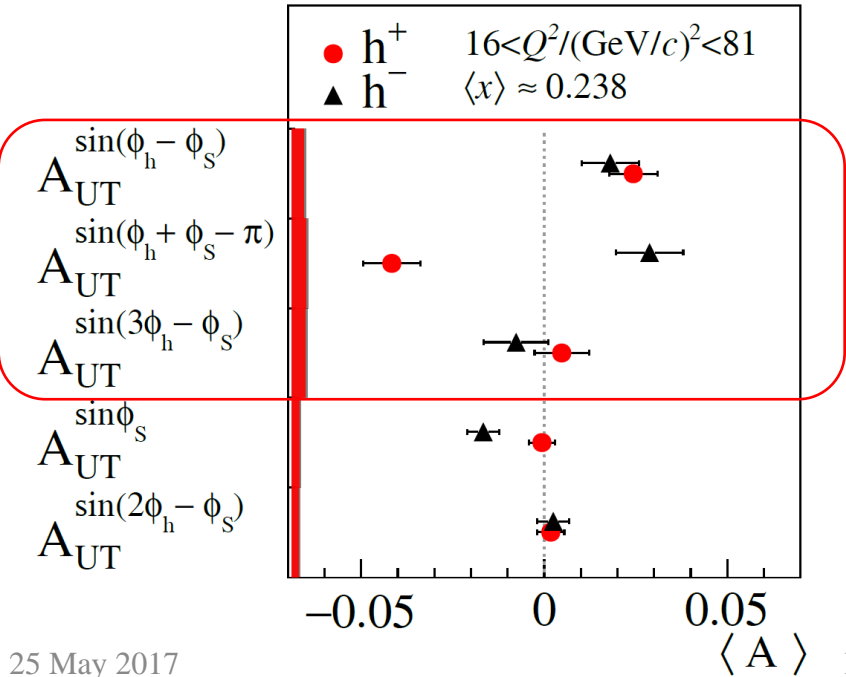
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

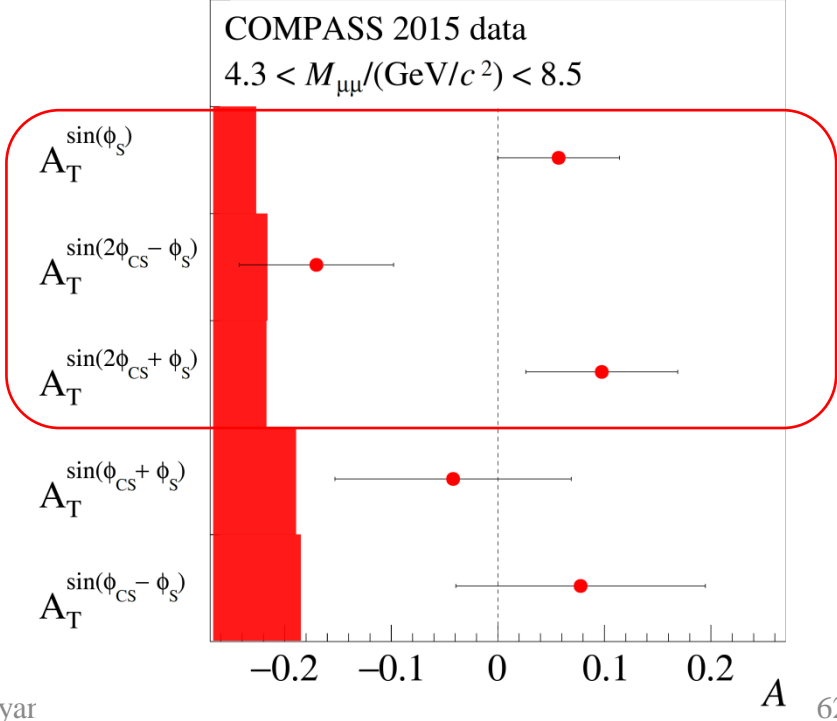
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

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COMPASS [arXiv:1704.00488 \[hep-ex\]](https://arxiv.org/abs/1704.00488)





Conclusions

- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs.
 - COMPASS has measured SIDIS proton TSAs at Drell-Yan mass-ranges
 - The Sivers and Collins SIDIS-TSAs are measured to be non-zero at high-mass range **PLB 770 (2017) 138**
- In 2015 COMPASS has successfully collected **first ever polarized DY data** becoming the first experiment to measure both SIDIS and DY TSAs and giving a unique opportunity to compare the TMD PDFs obtained from two processes [CERN-EP-2017-059](#), [arXiv:1704.00488\[hep-ex\]](#)
 - Sivers asymmetry is found to be above zero at about one s.d.
 - **1st measurement of the DY Sivers asymmetry is consistent with the predicted change of sign for the Sivers function**
 - Transversity asymmetry is found to be below zero at about two s.d.
 - **A second year of polarized DY data-taking will take place in 2018**
- **COMPASS phase-III is being discussed to take place after 2020**
 - Particular attention is given to possible SIDIS and Drell-Yan measurements

Spare slides



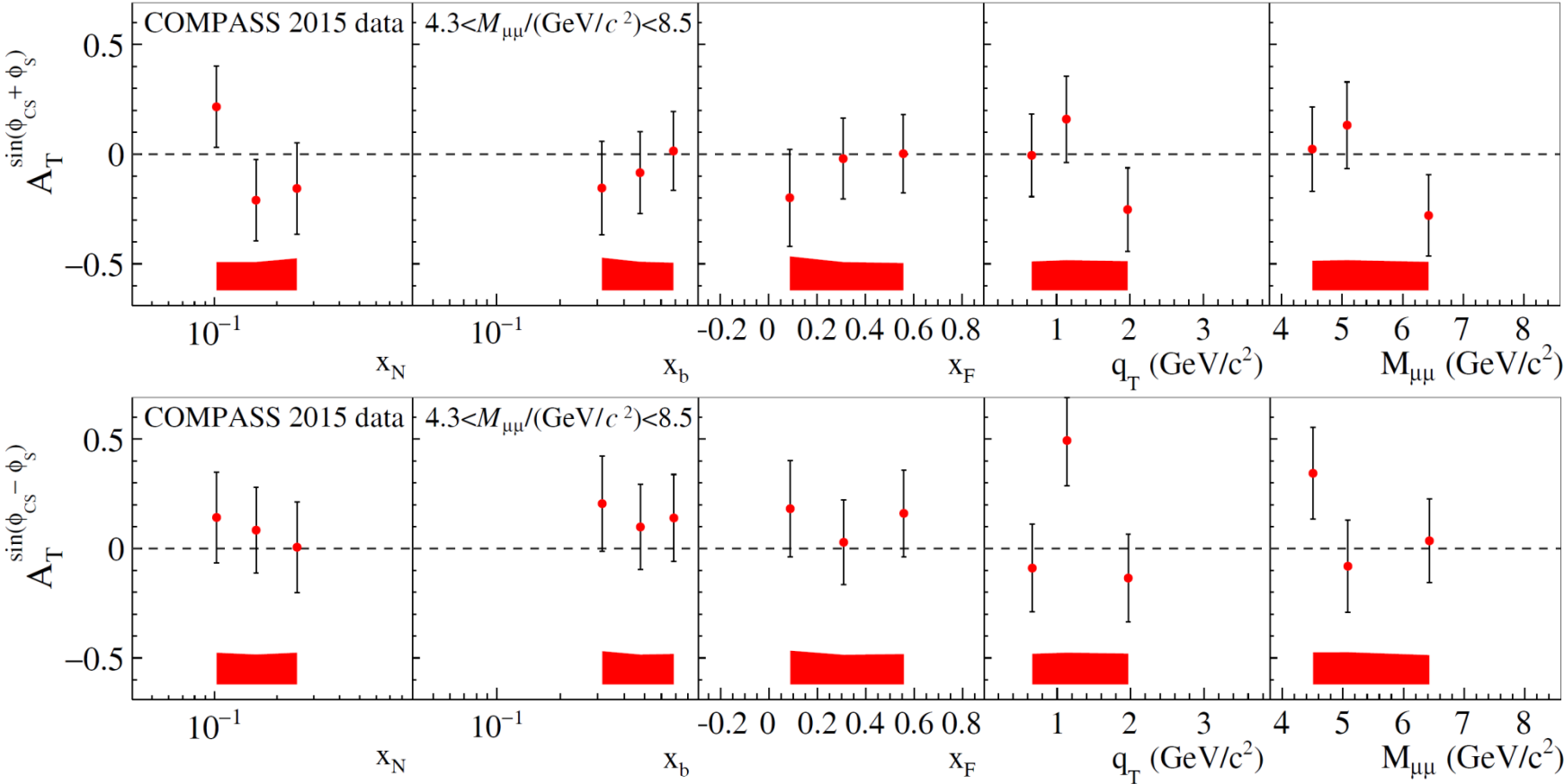


quark nucleon	U	L	T	FF
U	f_1		h_1^\perp	D_1
L		g_1	h_{1L}^\perp	H_1^\perp
T	f_{1T}^\perp	g_{1T}	h_1, h_{1T}^\perp	

Drell-Yan TSAs – “higher twists”

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

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





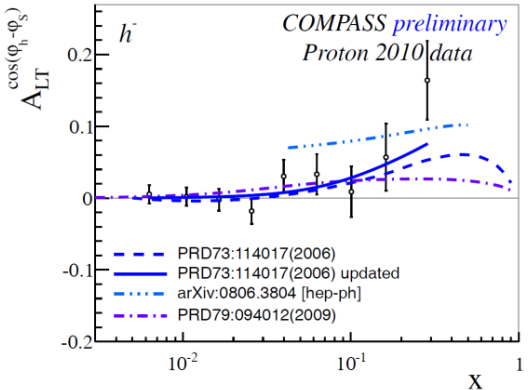
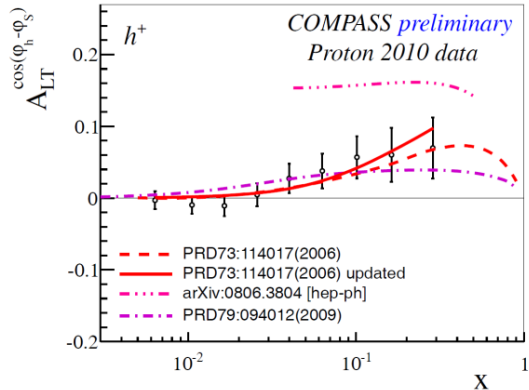
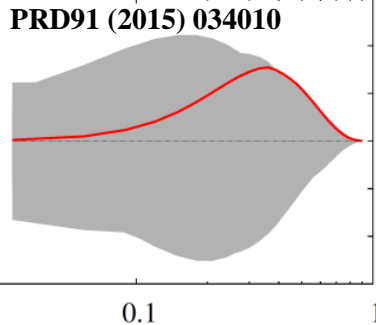
SIDIS: target transverse spin dependent asymmetries

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

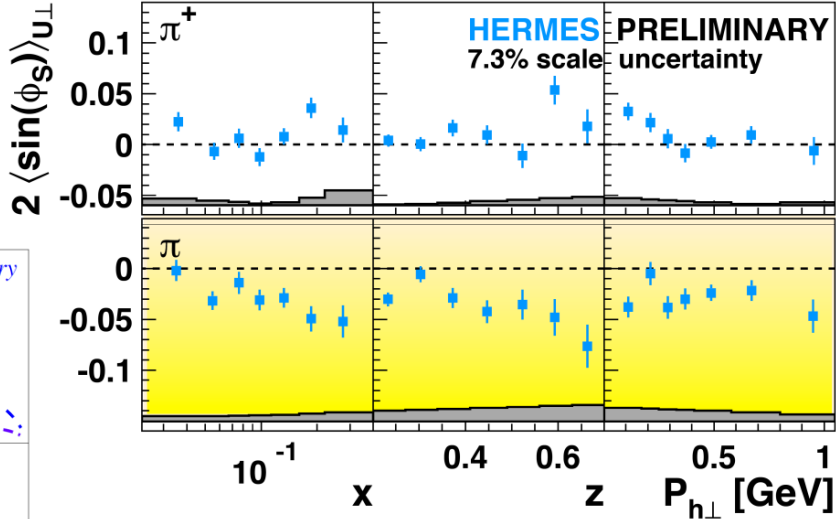
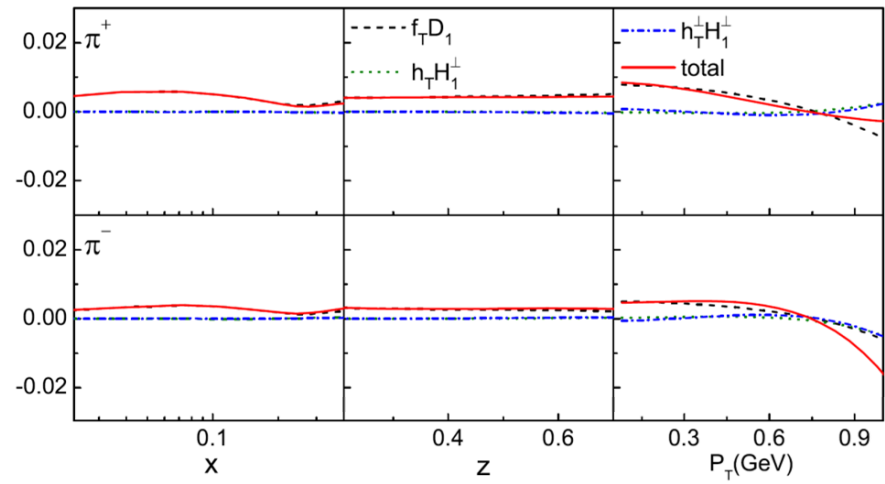
$$+ S_T \left[\begin{aligned} &+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ &+ \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ &+ \dots \end{aligned} \right]$$

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

C. Lefky & A. Prokudin



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



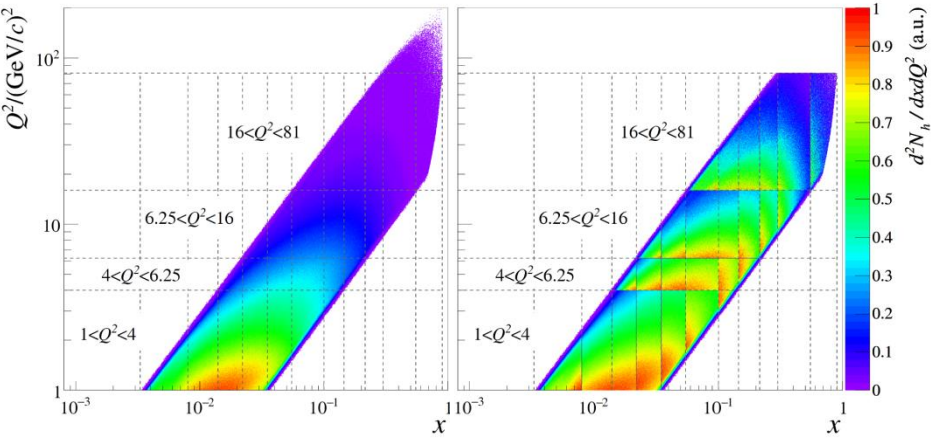


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

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

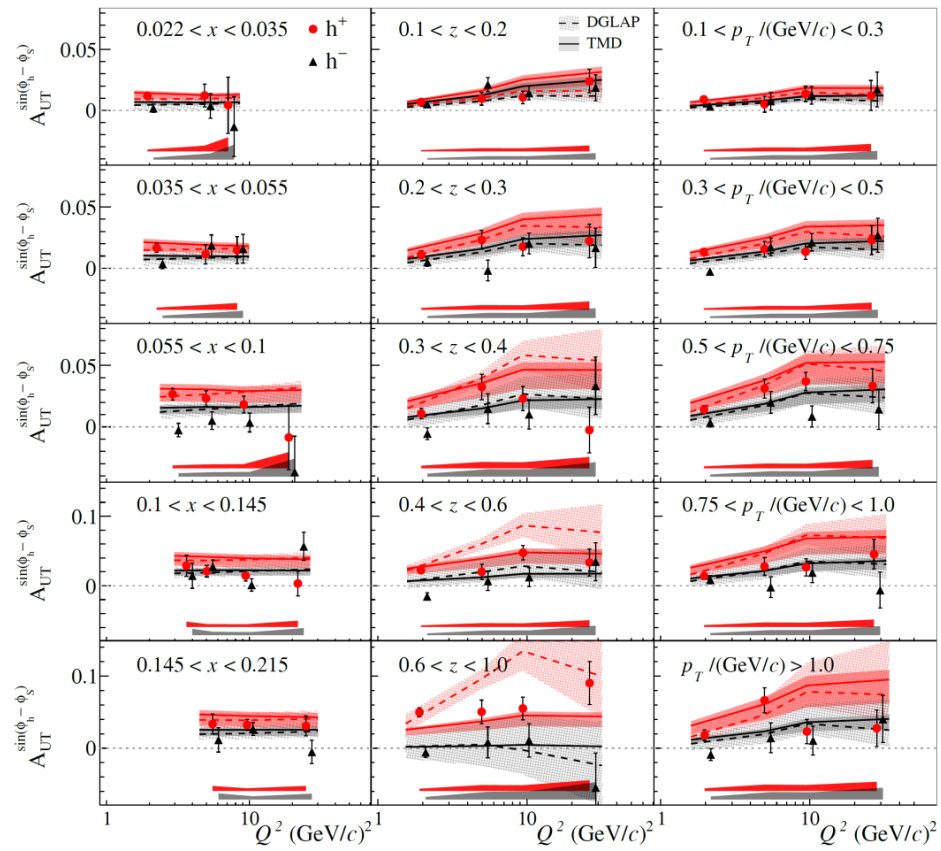
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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Multi-dimensional input for TMD evolution studies

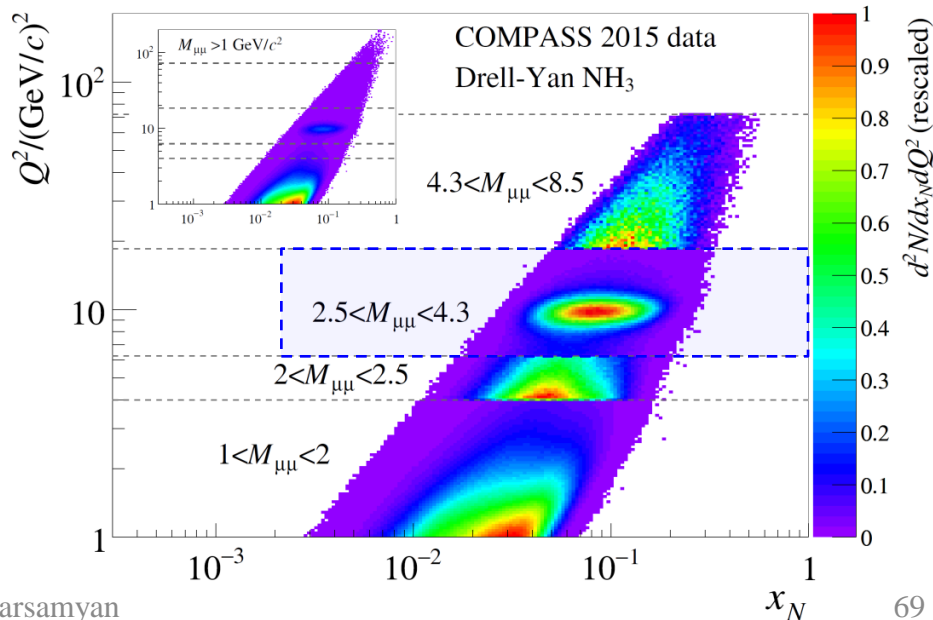
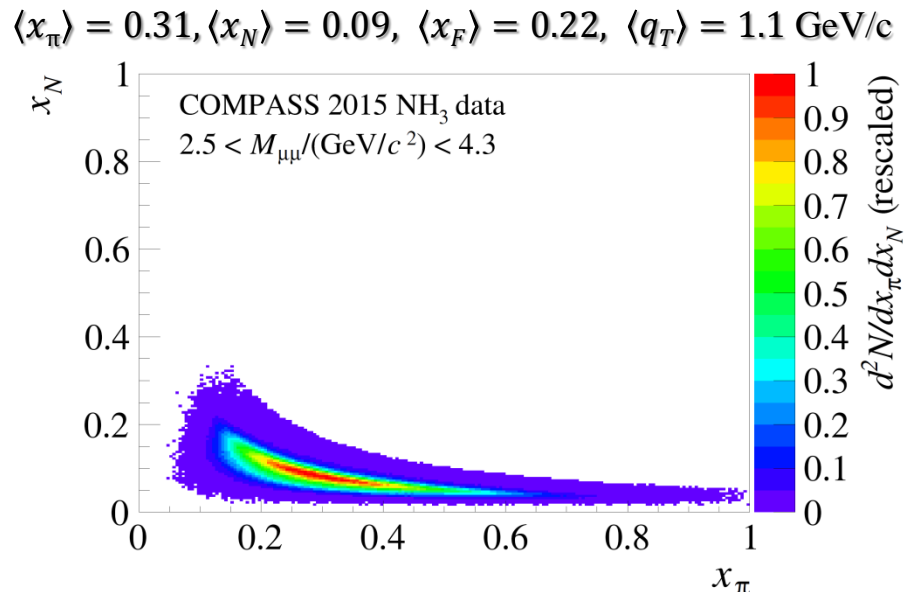
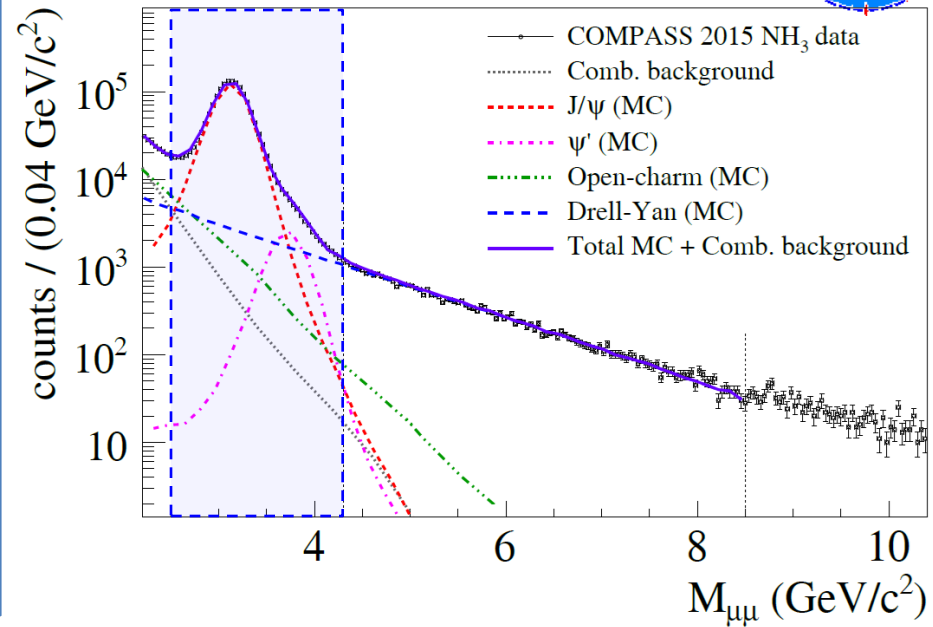
- No clear Q^2 -dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?



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.

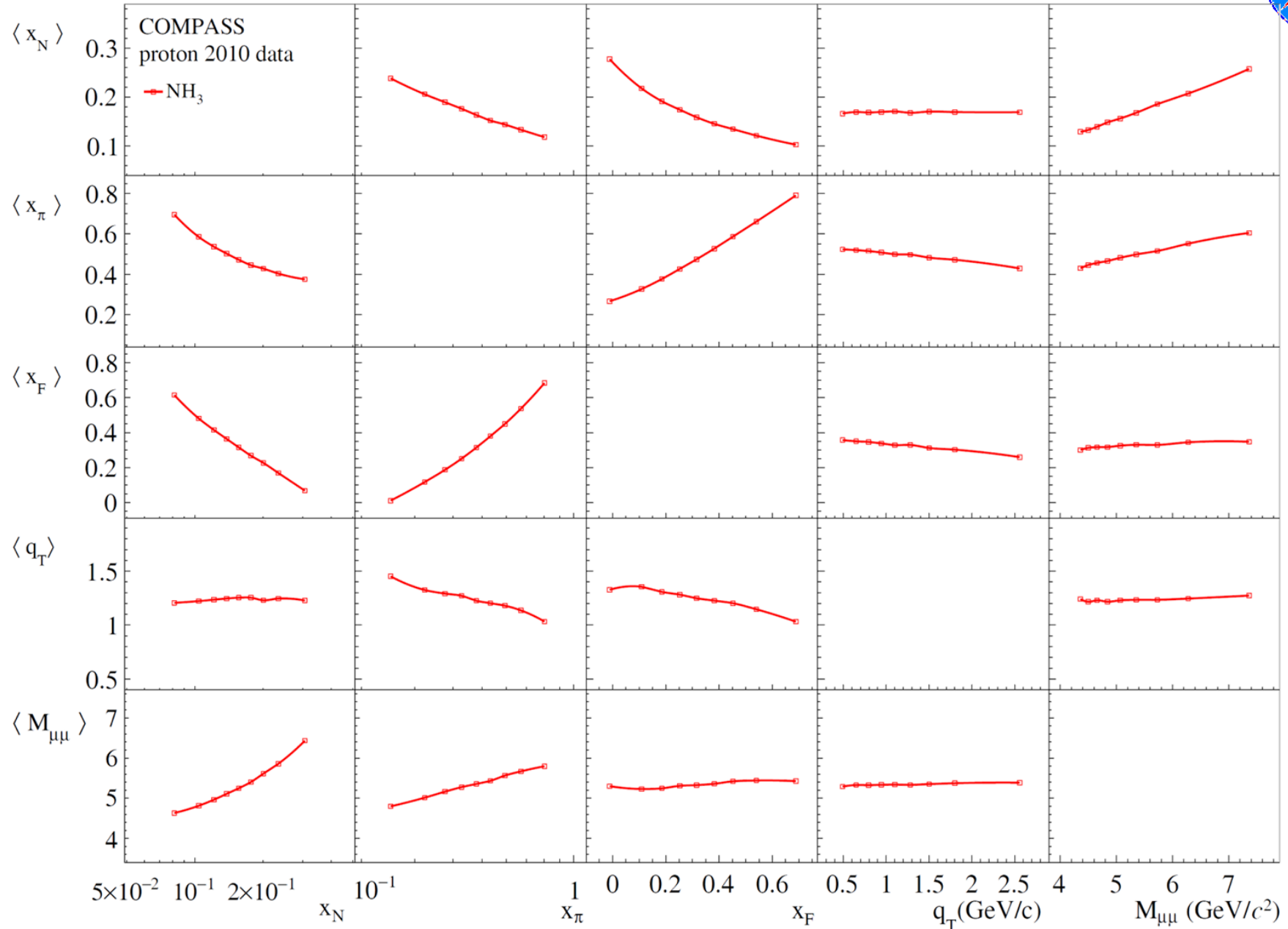
COMPASS DY: Charmonia mass range

- $1.0 < M / (\text{GeV}/c^2) < 2.0$ “Low mass”
 - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π , 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/ψ -signal \rightarrow study of J/ψ 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





Kinematic map: high mass range





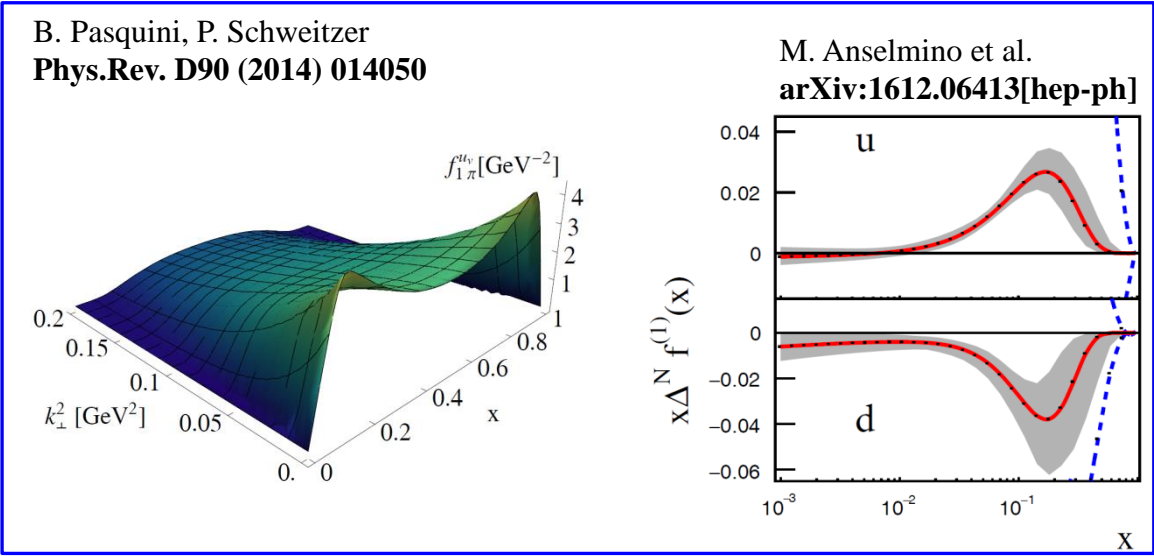
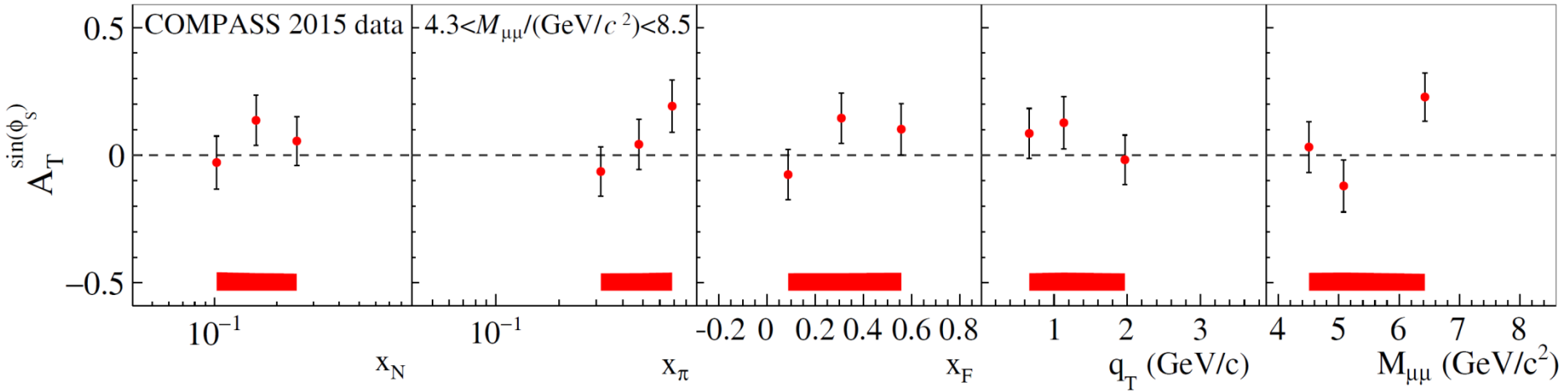
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

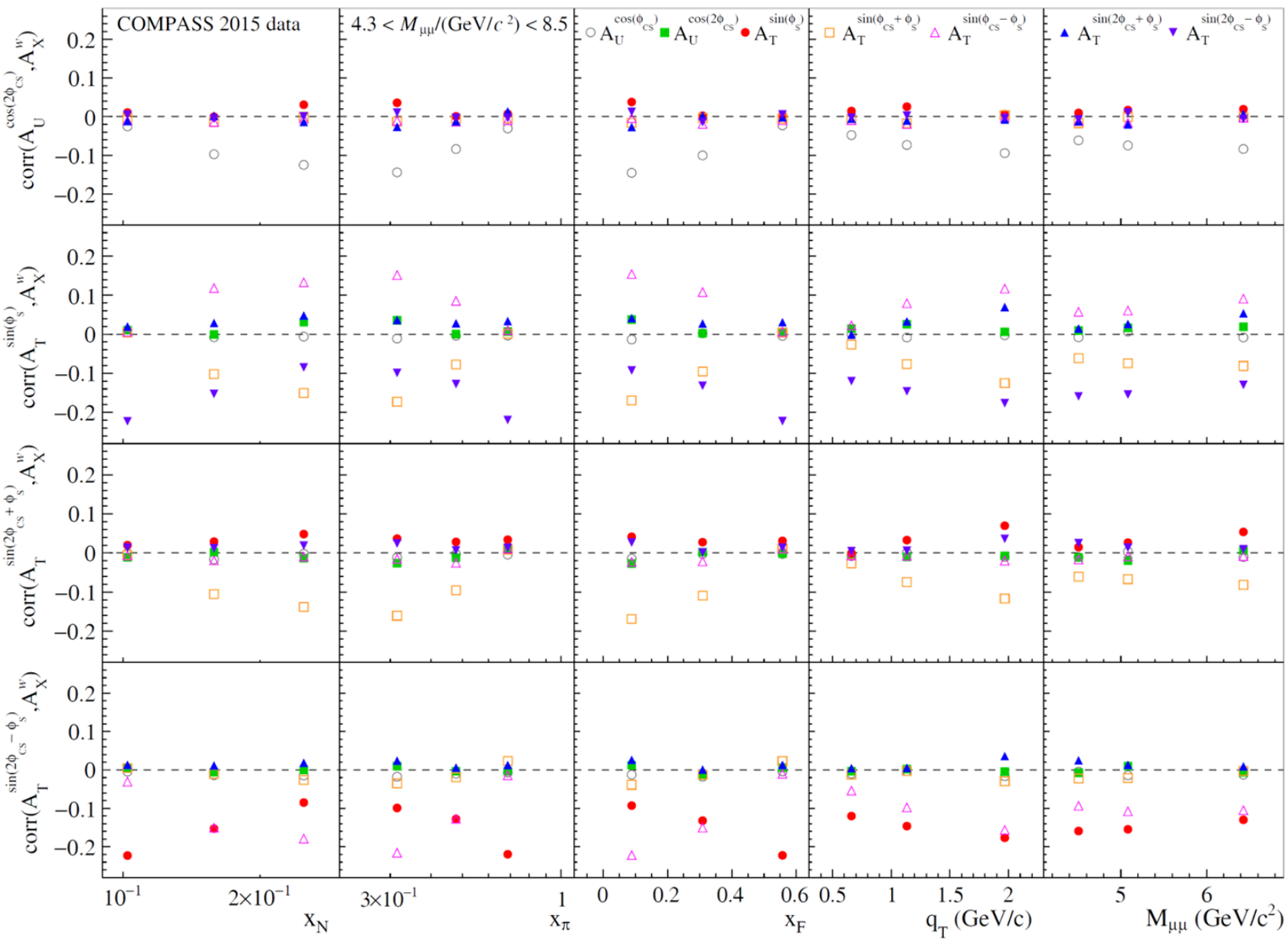
$$A_T^{\sin\phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

New! COMPASS [arXiv:1704.00488\[hep-ex\]](https://arxiv.org/abs/1704.00488)





Correlation coefficients



Maximum correlations are about ~0.2