First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process

UNIVERSITÀ DEGLI STUDI DI TORINO

ALMA UNIVERSITAS TAURINENSIS

BAKUR PARSAMYAN

University of Turin and INFN section of Turin

on behalf of the COMPASS Collaboration

"25th International Workshop on Deep Inelastic Scattering and Related Topics"

University of Birmingham
Birmingham, United Kingdom
3-7 April 2017

COMPASS collaboration

24 institutions from 13 countries – nearly 250 physicists

Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

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

Wide physics program

COMPASS-I

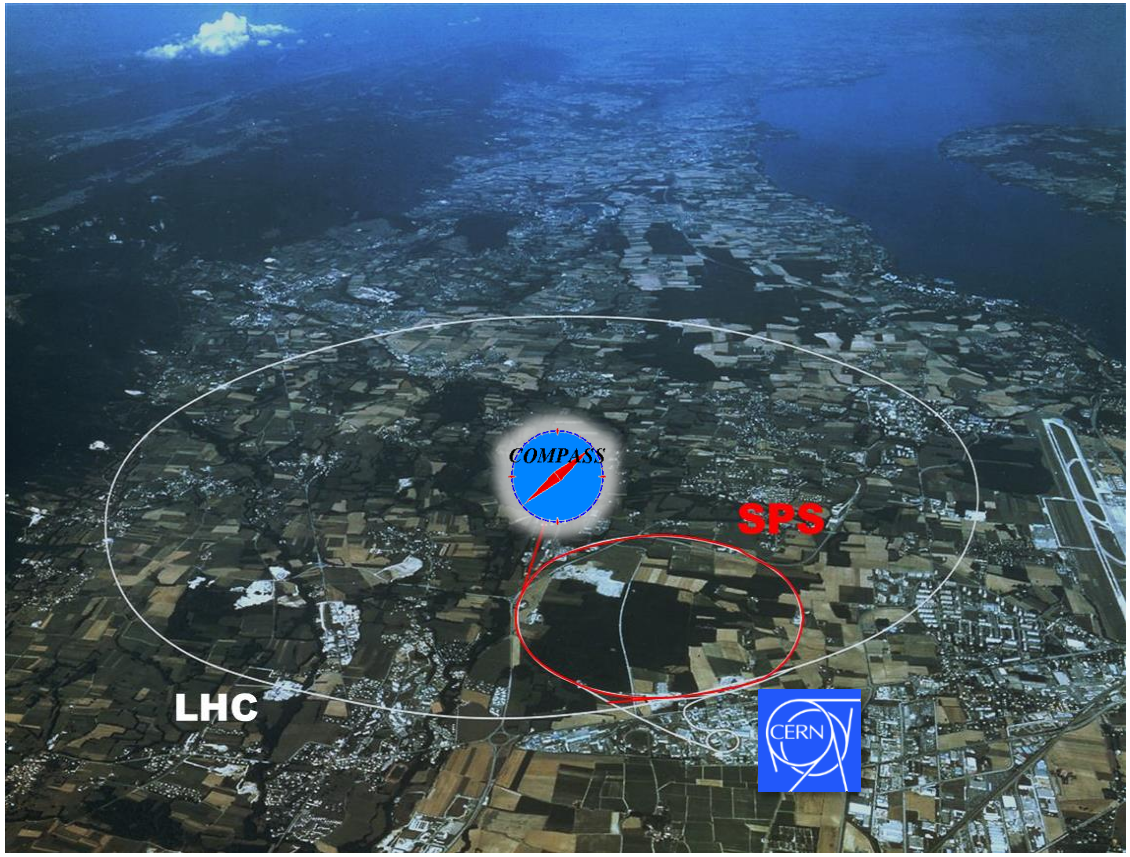
- **Data taking 2002-2011**
- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

See talks by B. Badelek, E. Kabuss, M. Stolarski, A. Szabelski and B.P.

COMPASS-II

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

Talk by A. Ferrero and this talk



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

If we were now in Tuscany for IWHSS-2017 COMPASS workshop…

Introduction: COMPASS setup, SIDIS and Drell-Yan

A glass of Prosecco for the start

COMPASS experimental setup: Phase I (muon program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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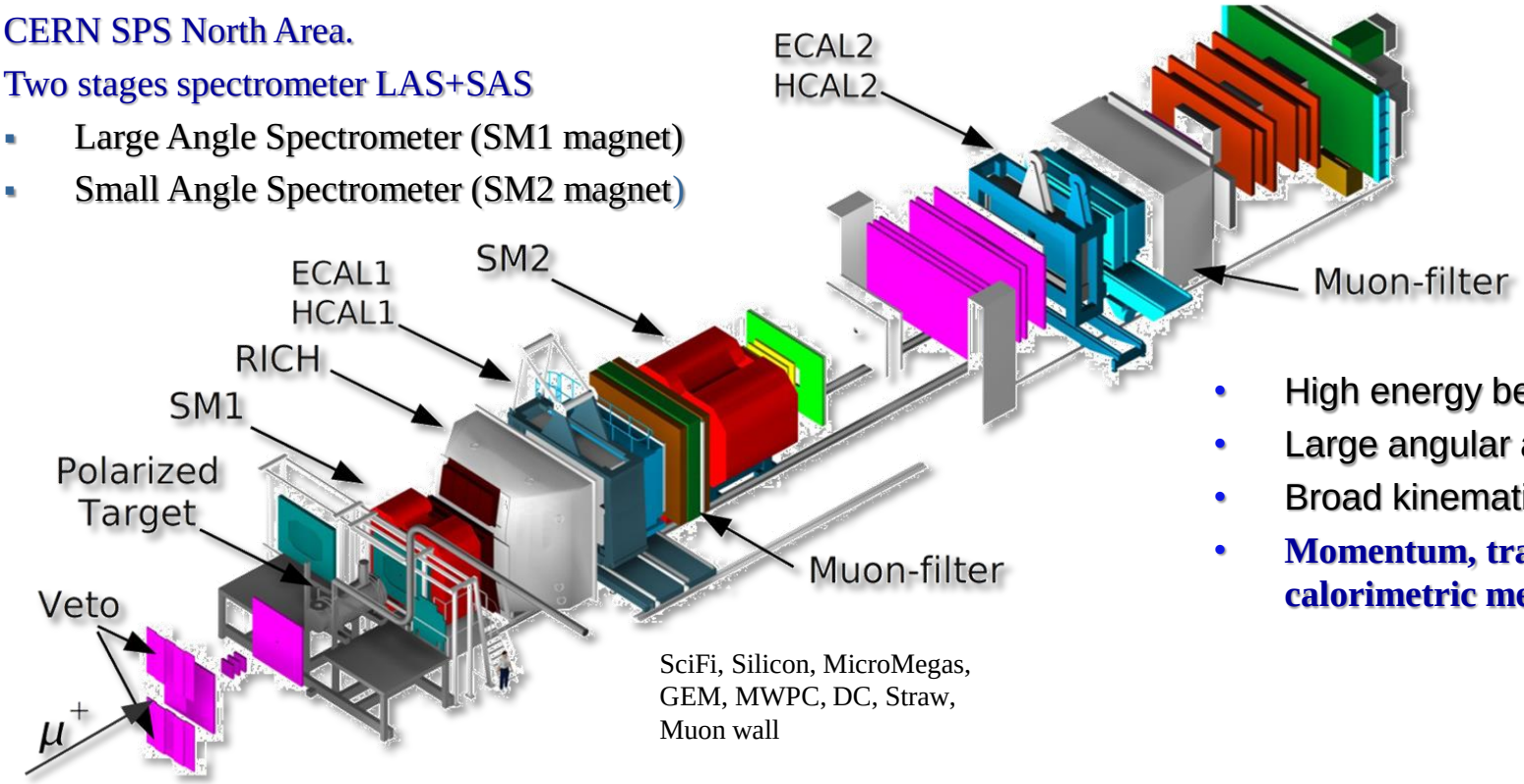


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

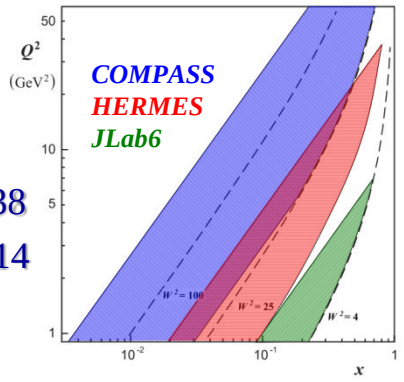
- High energy beam
- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking and calorimetric measurements, PID**

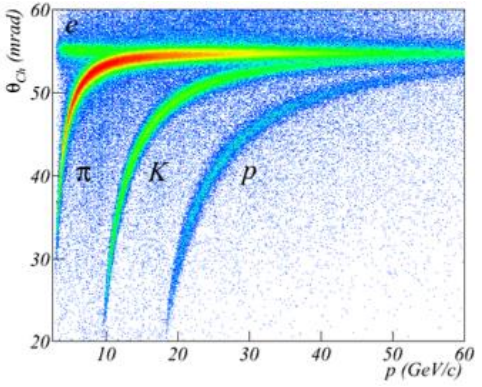
Longitudinally polarized (80%) μ^+ beam:
Energy: 160/200 GeV/c, Intensity: $2 \cdot 10^8$ μ^+/spill (4.8s).

Target: Solid state (*^{6}LiD or NH_3*)

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

Data-taking years: 2002-2011





COMPASS experimental setup: Phase II (DY program)

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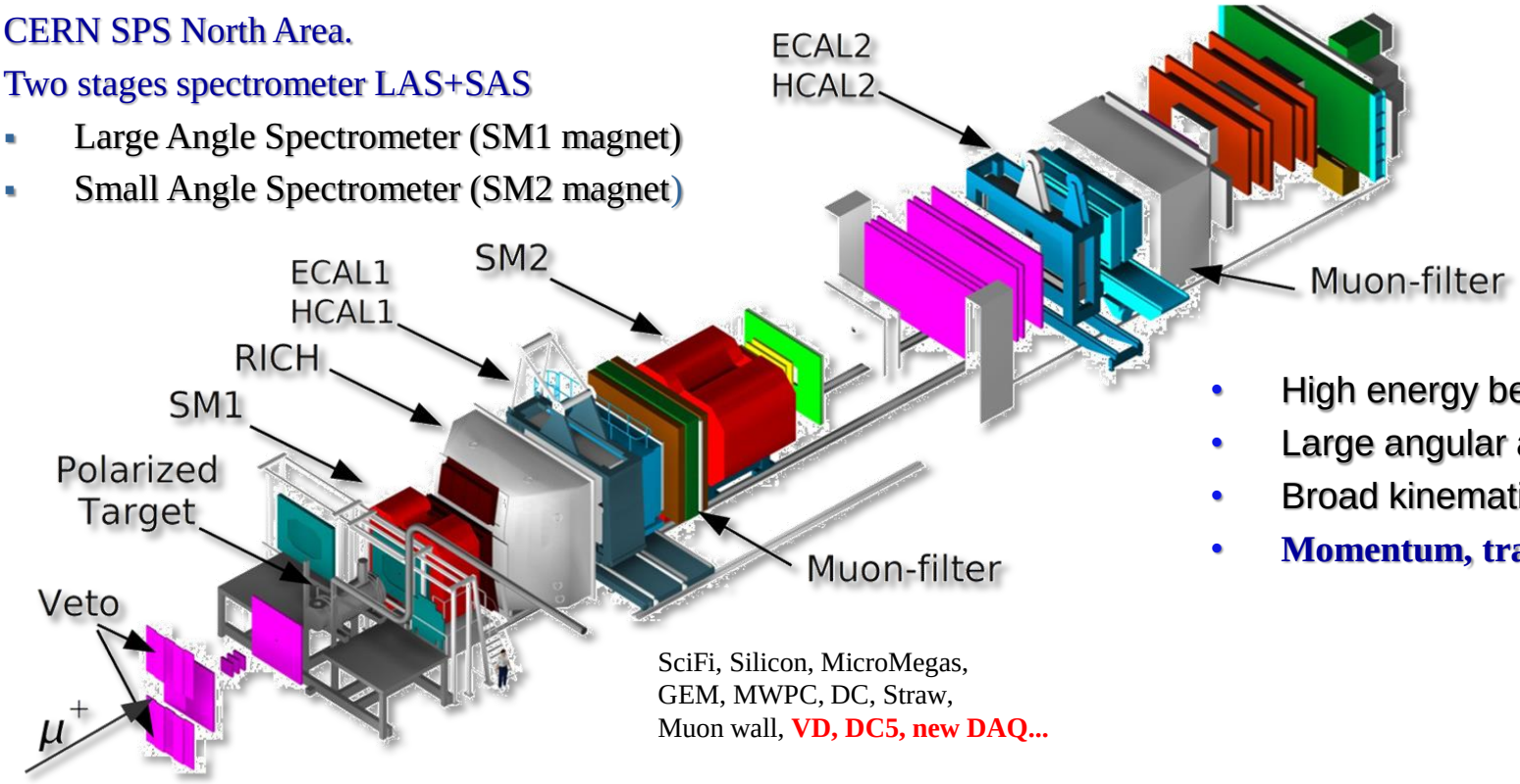

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- Large angular acceptance
- Broad kinematical range
- **Momentum, tracking**

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

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

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 80%, f ~ 0.22
- 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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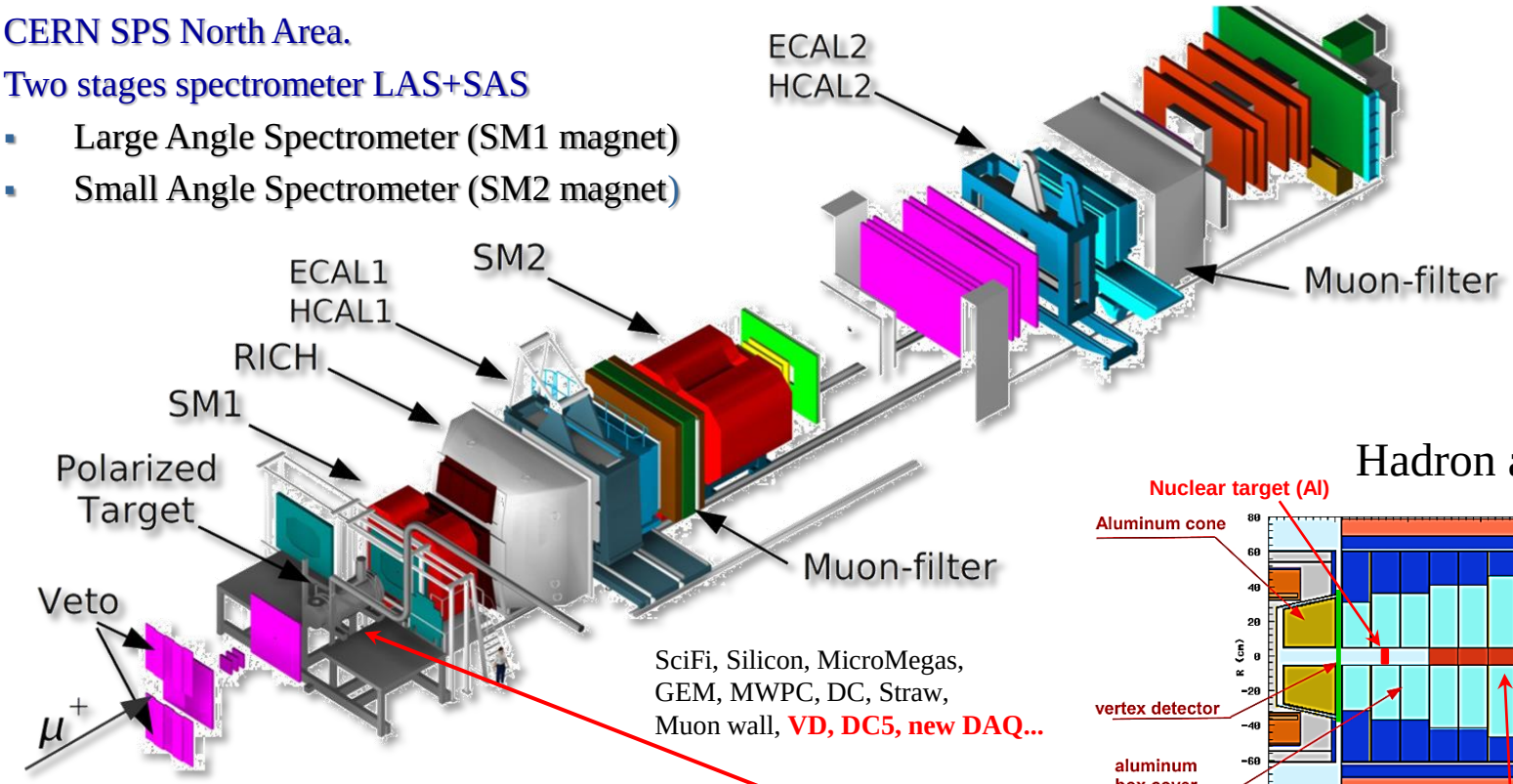

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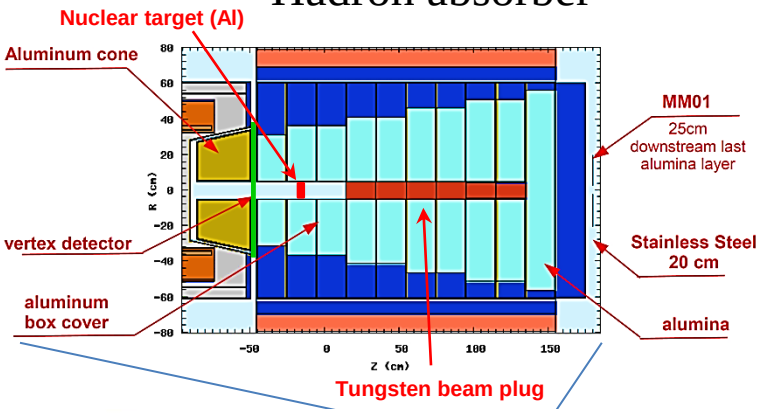
Hadron absorber



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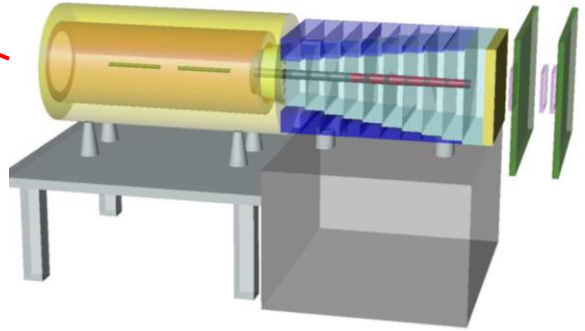

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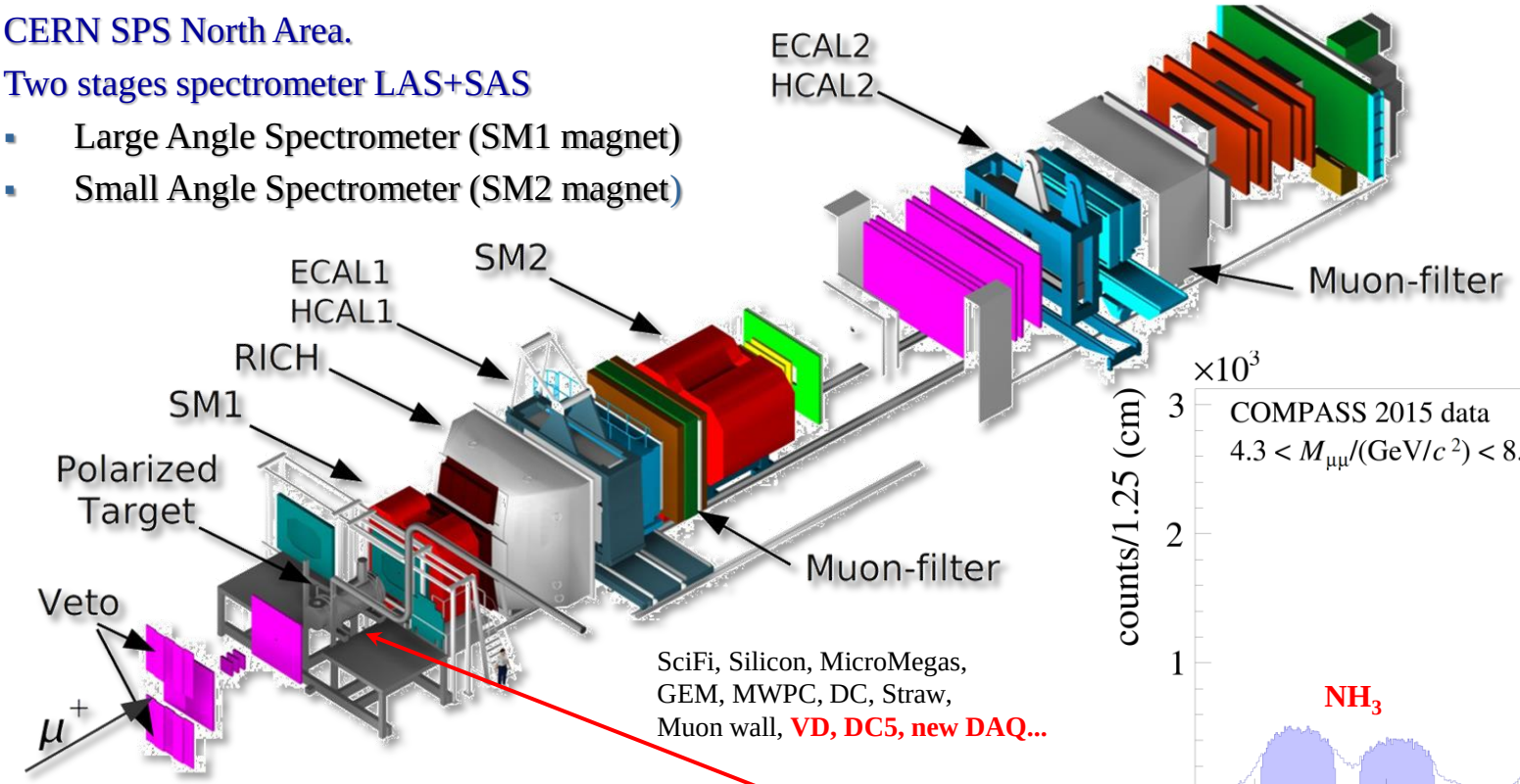

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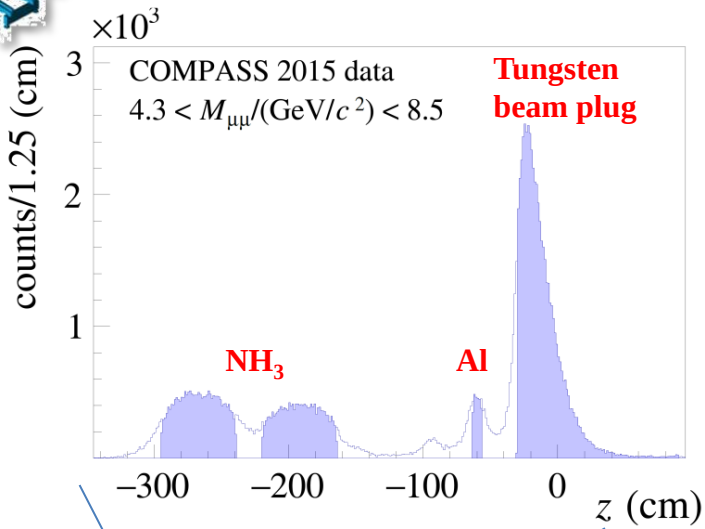

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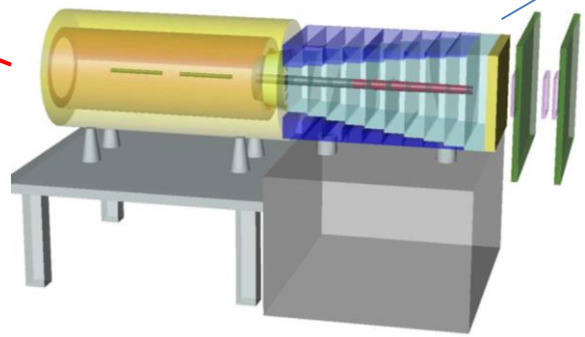

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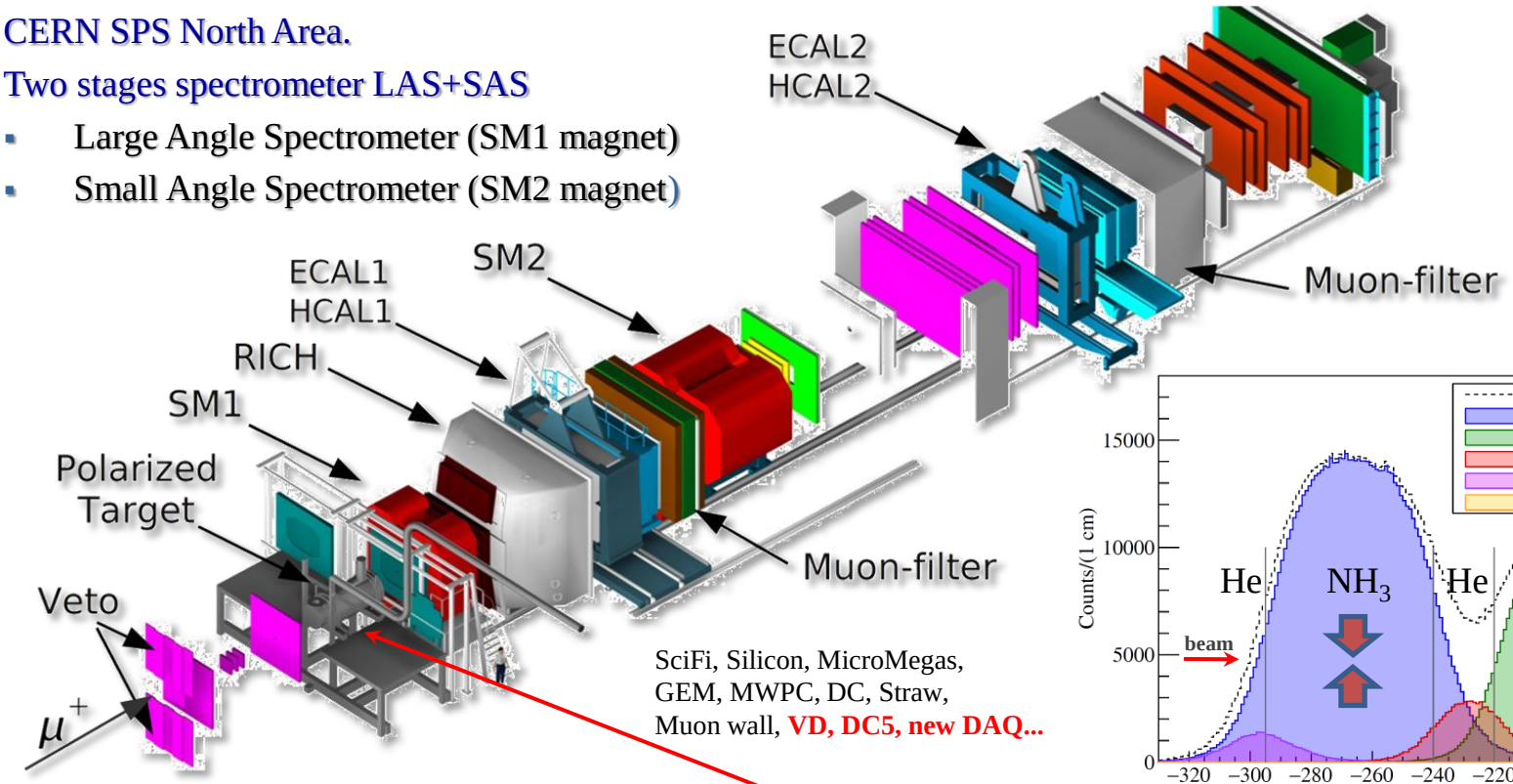

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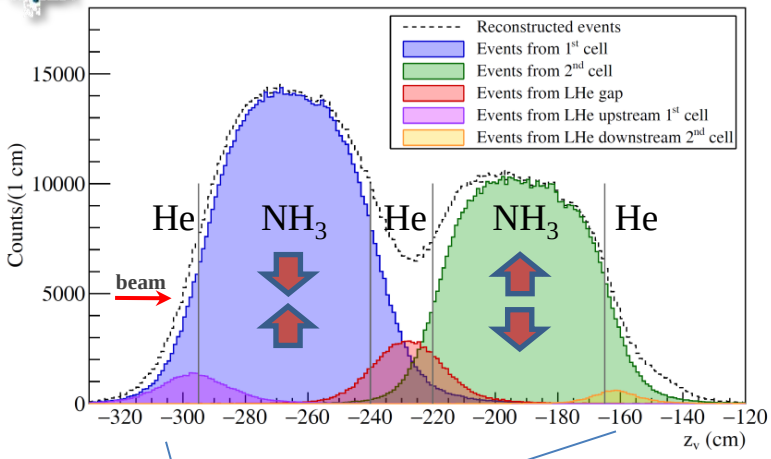

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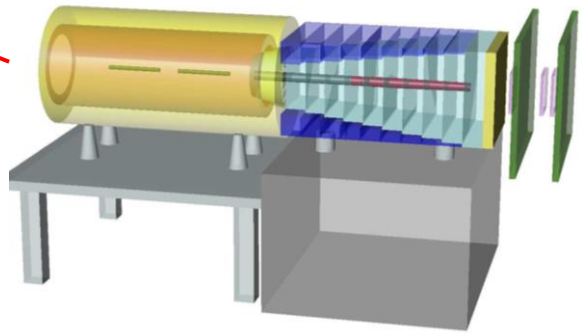

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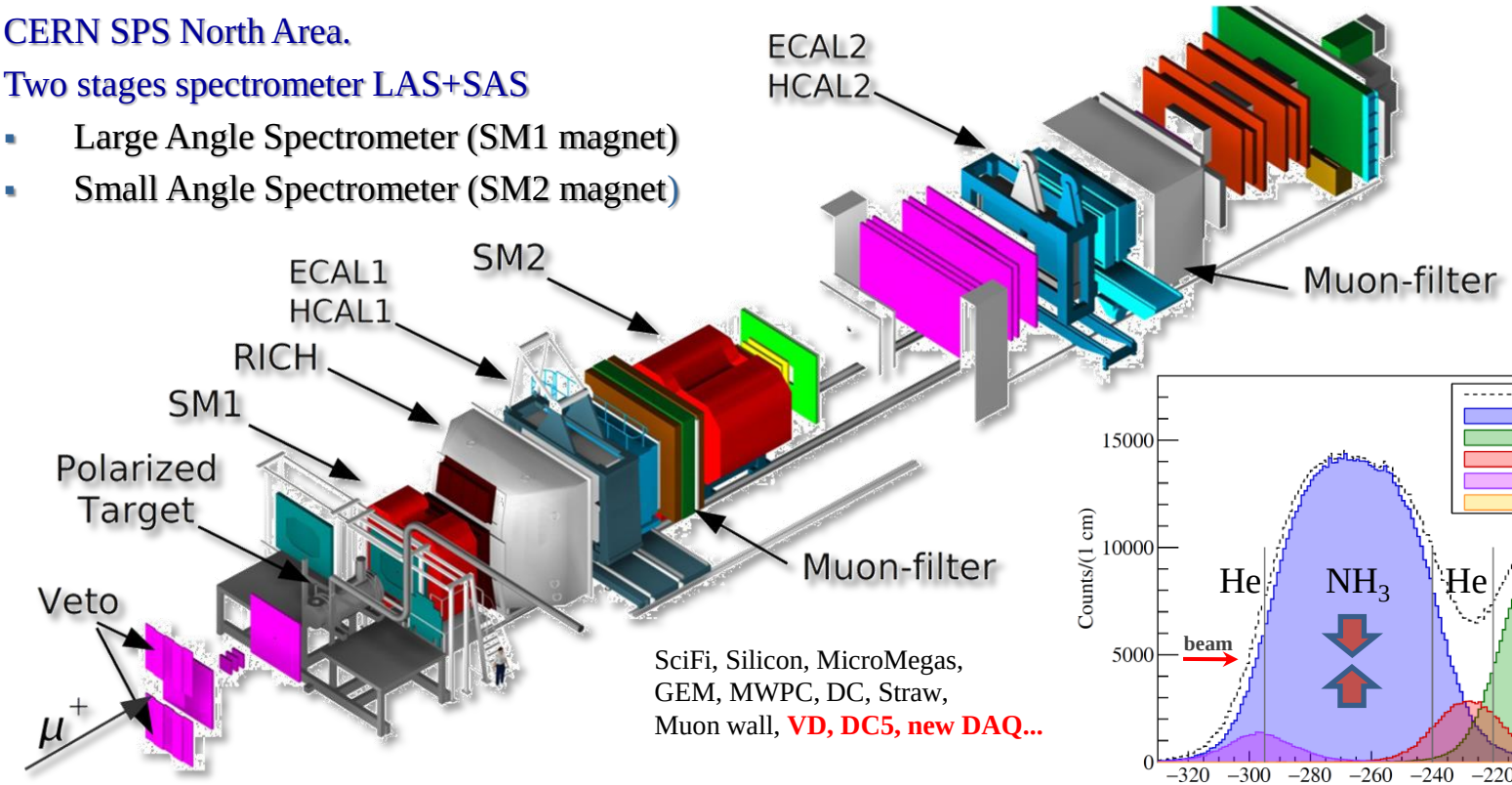

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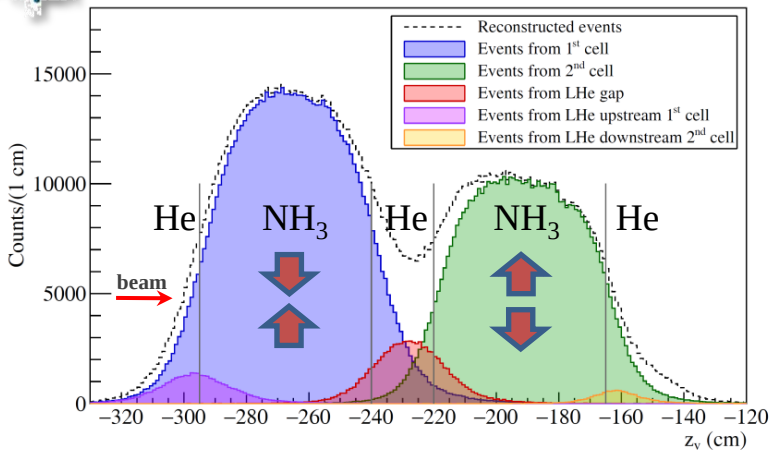

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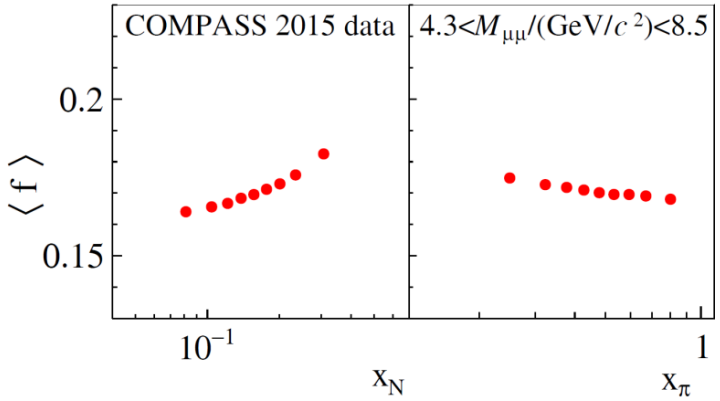

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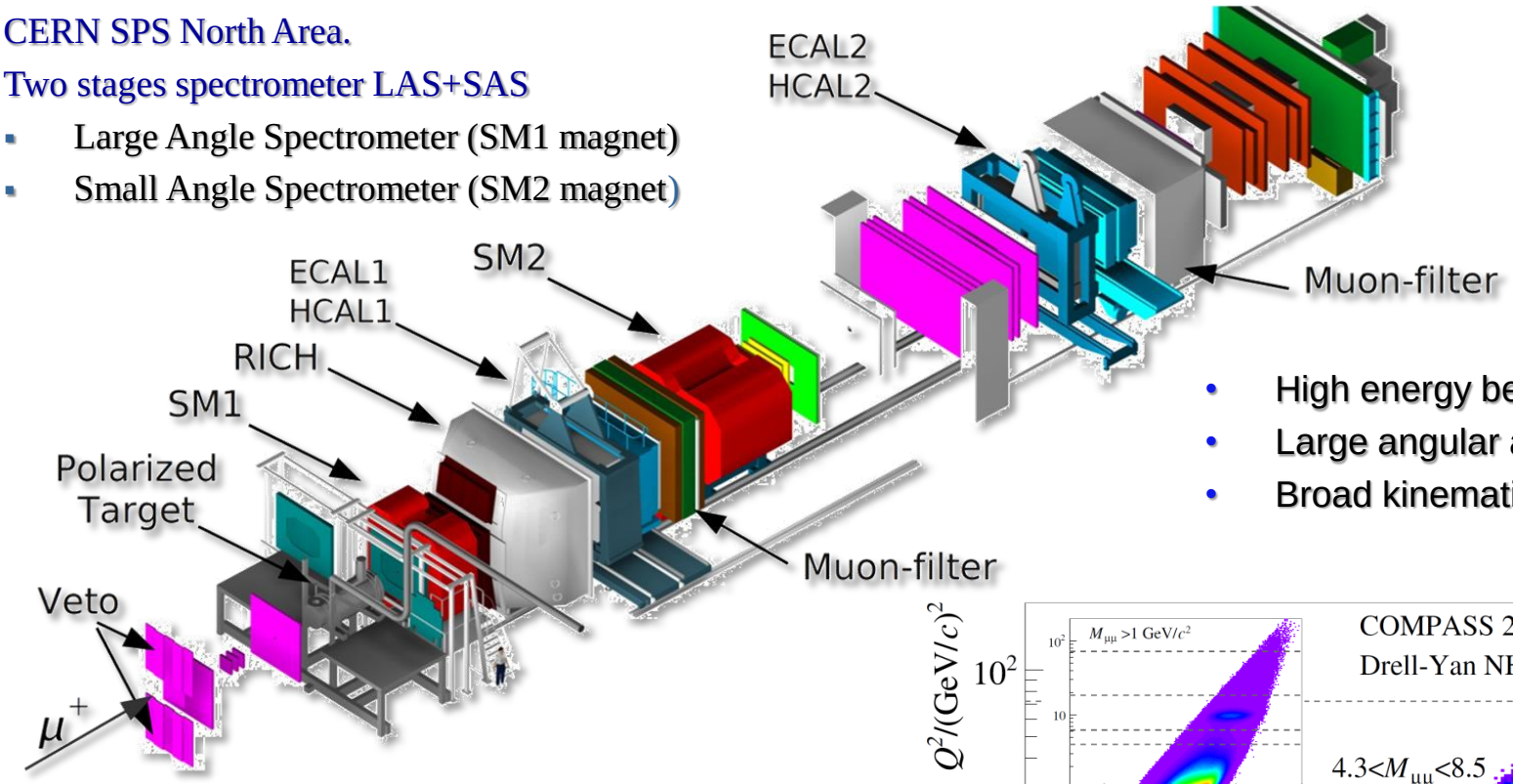

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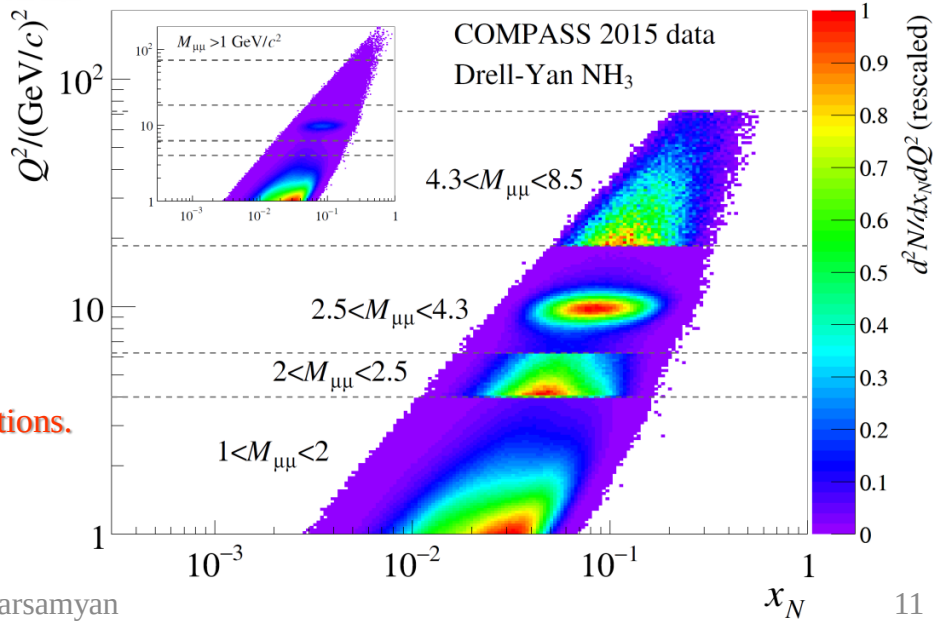

COMPASS DY mass ranges

- $1.0 < M/(GeV/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(GeV/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
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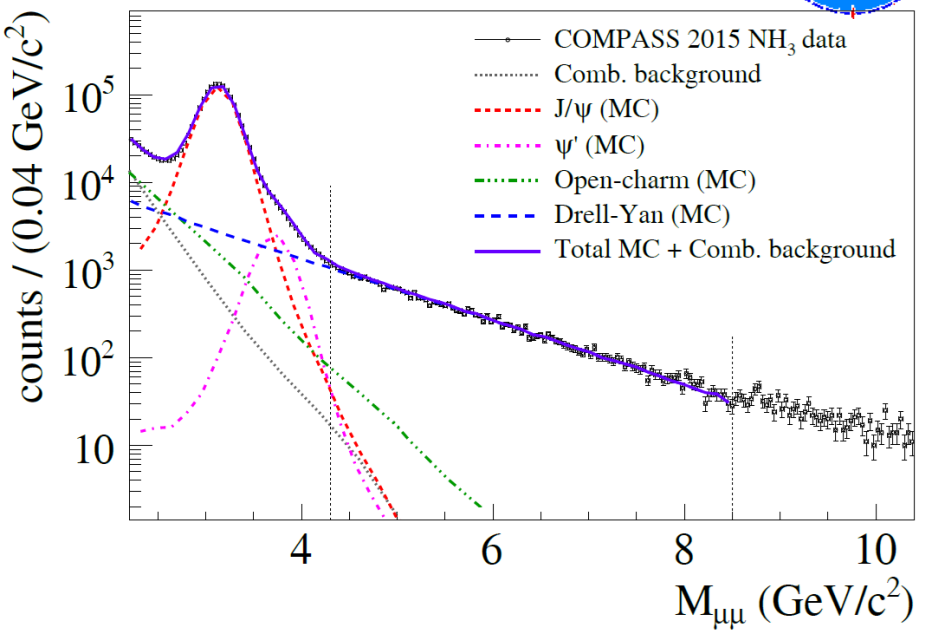

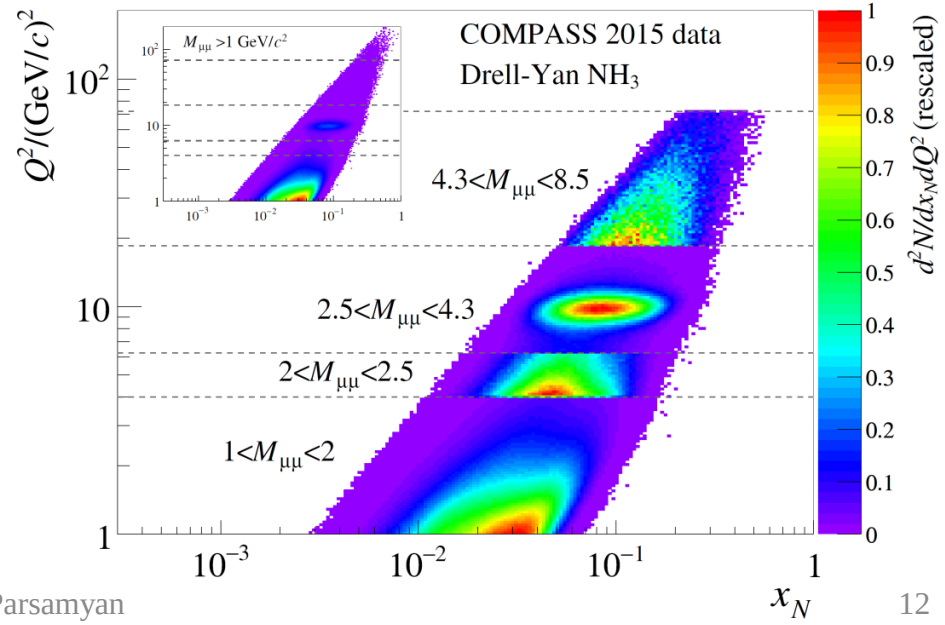

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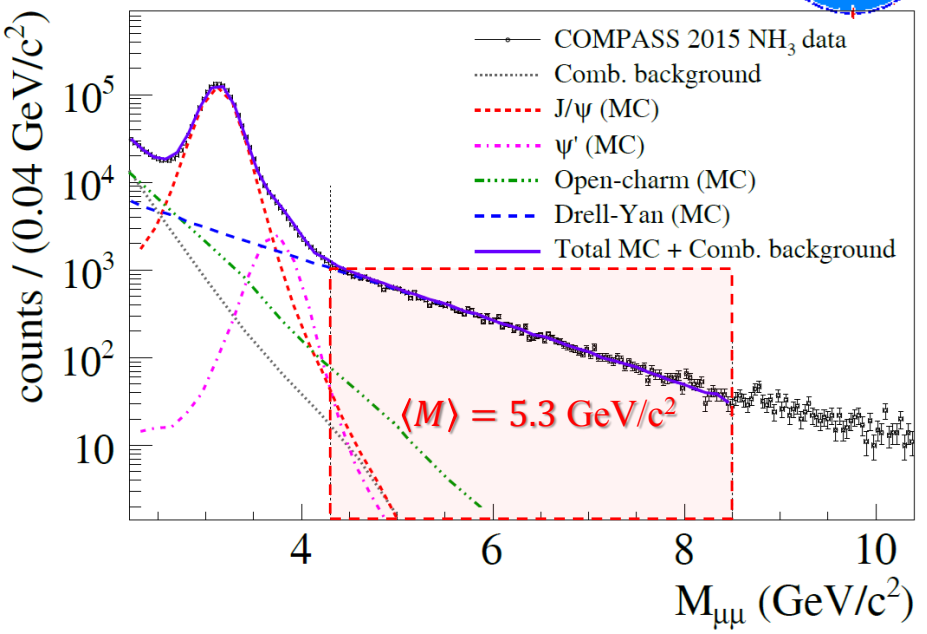
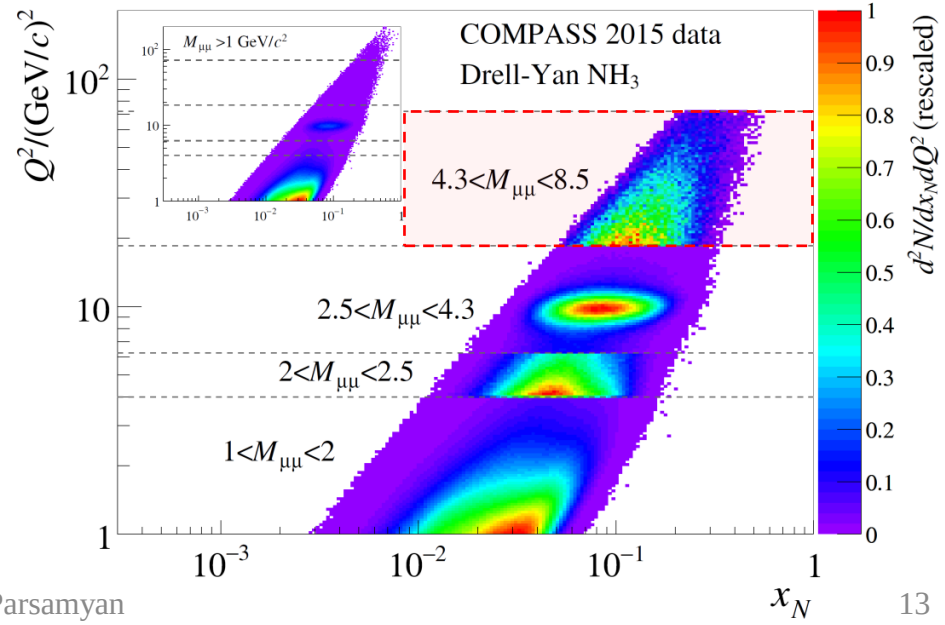
Final sample: 35 000 dimuons in HM





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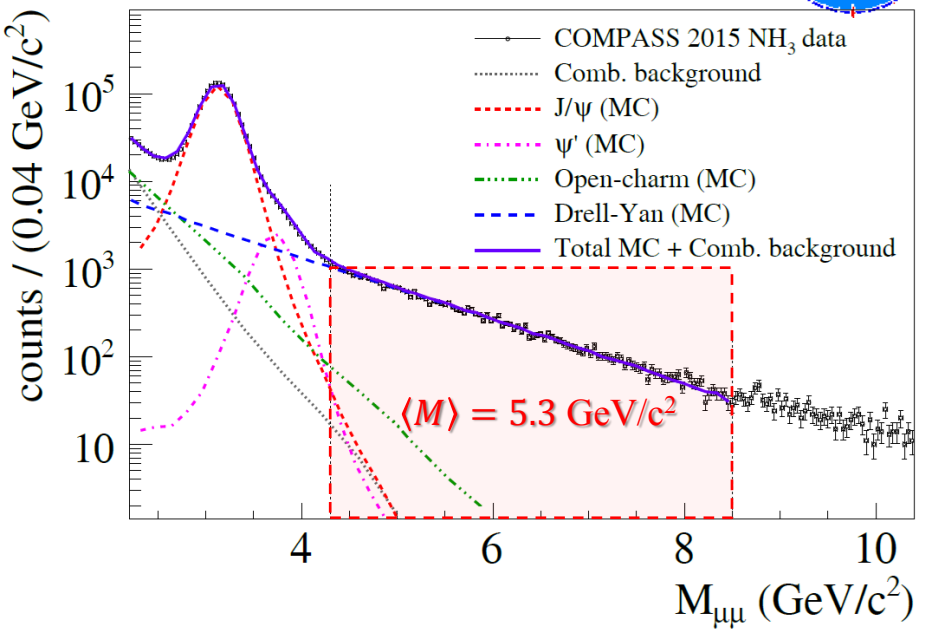
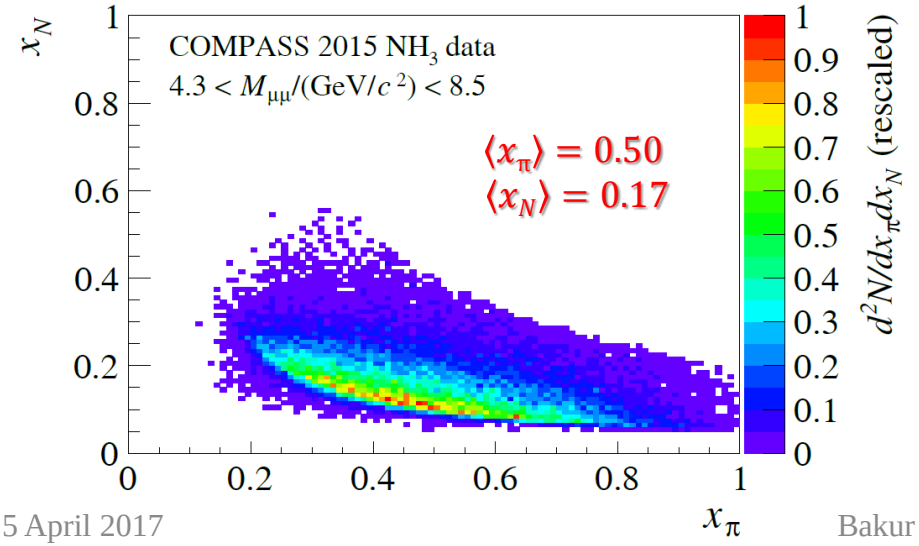
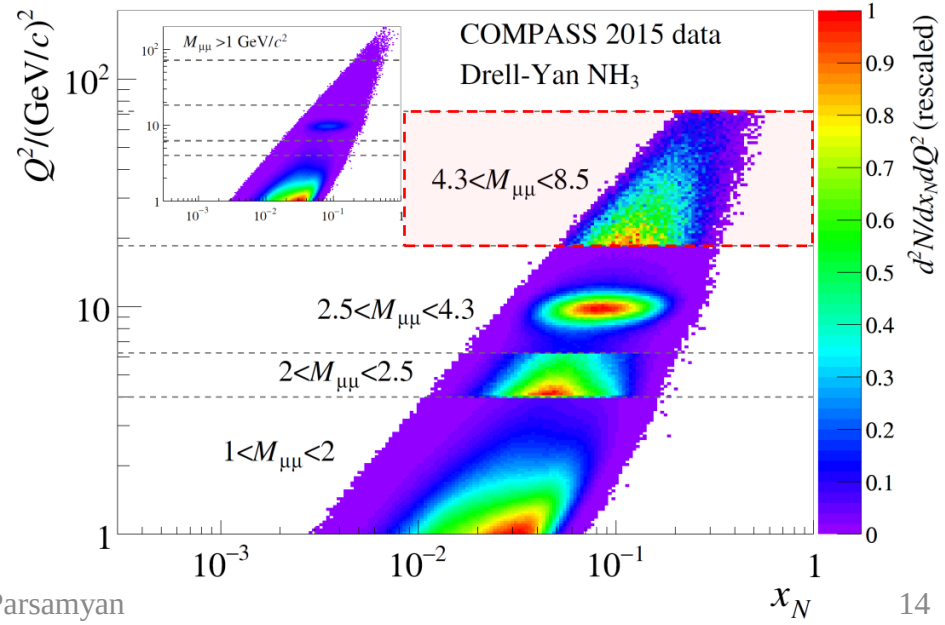


HM events are in the valence quark range





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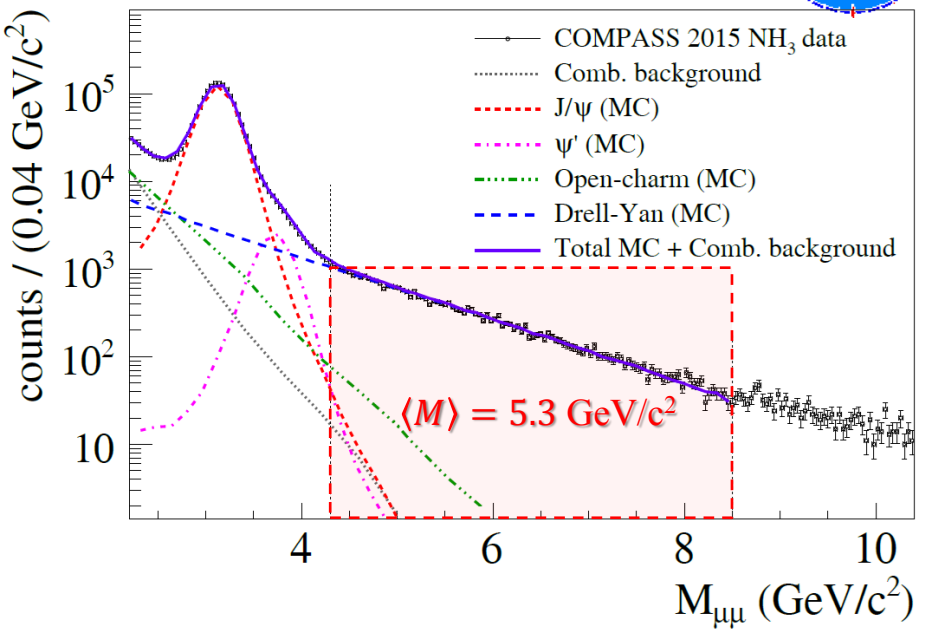
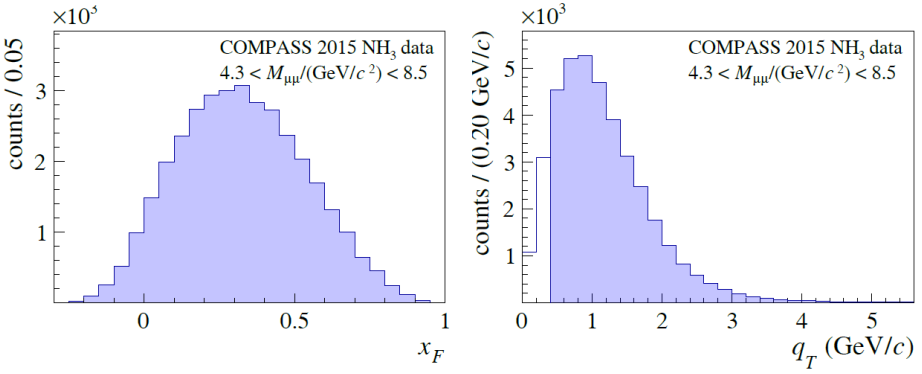
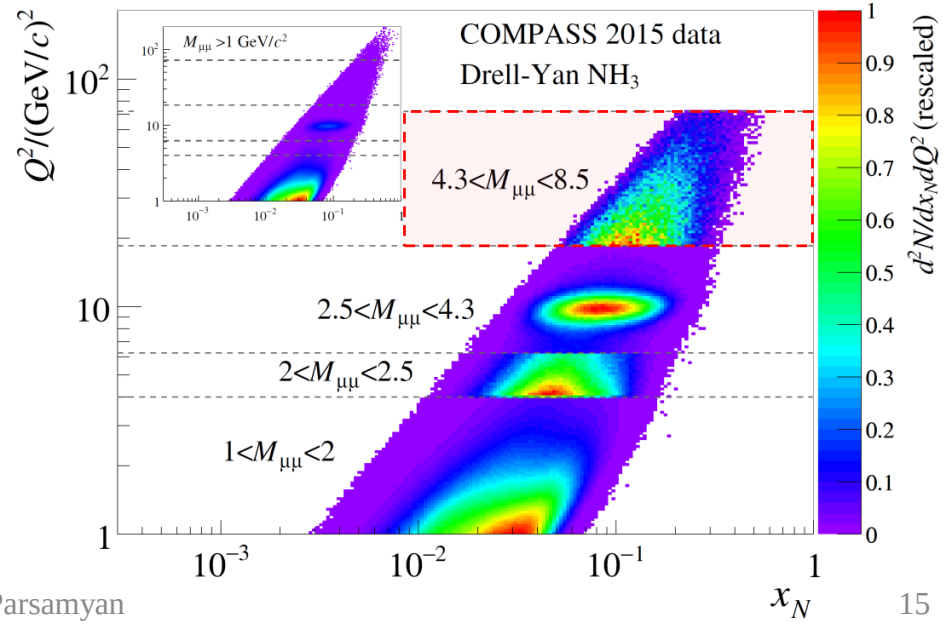


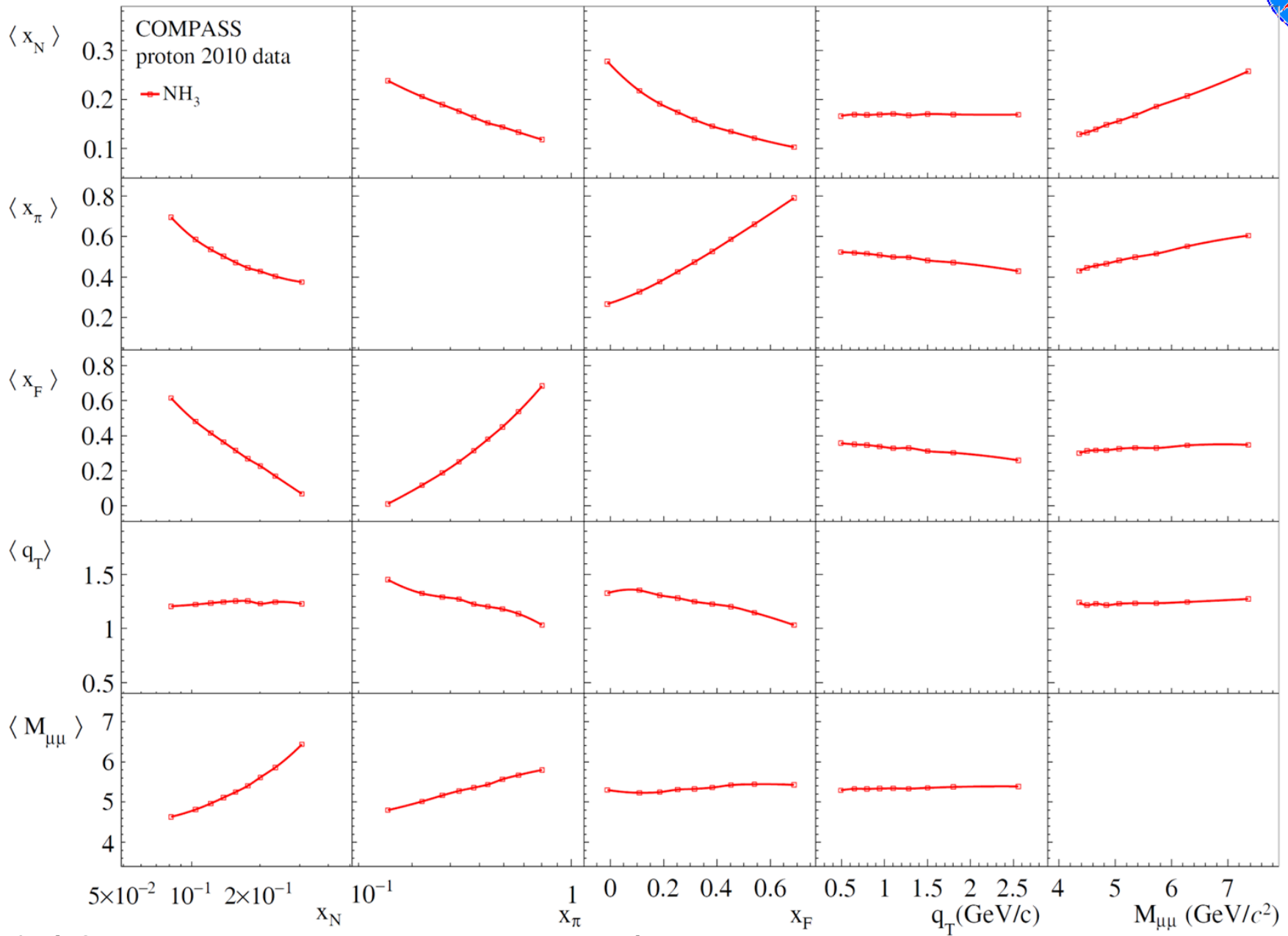
Dimuon transverse momentum $q_T > 0.4$ GeV/c

$\langle x_F \rangle = 0.33$, $\langle q_T \rangle = 1.2$ GeV/c





Kinematic map: high mass range



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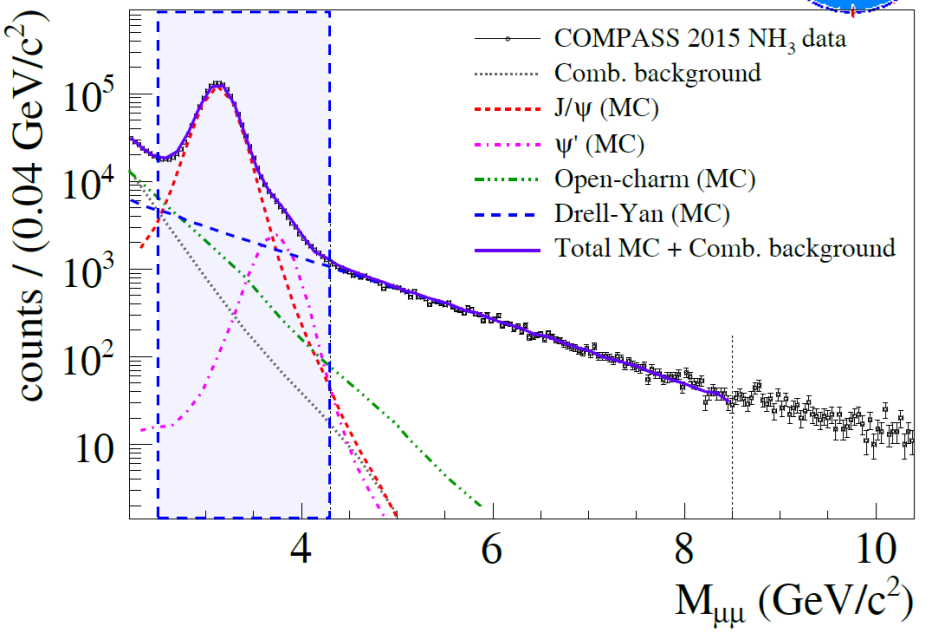
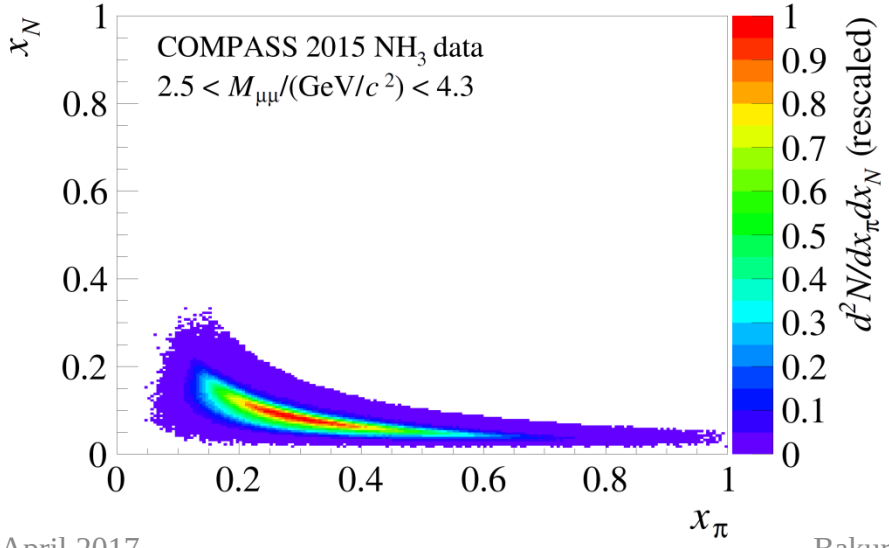
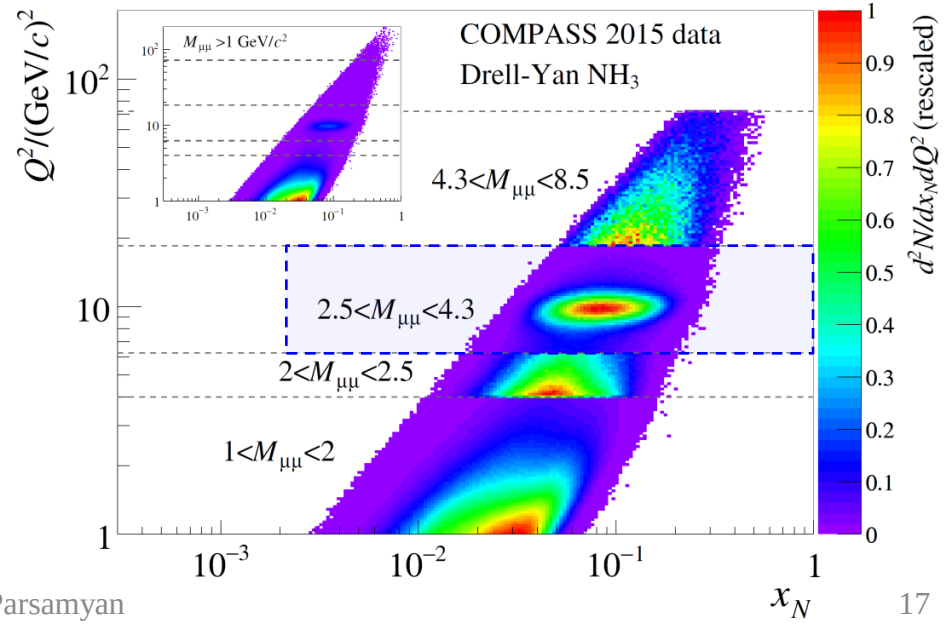


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c





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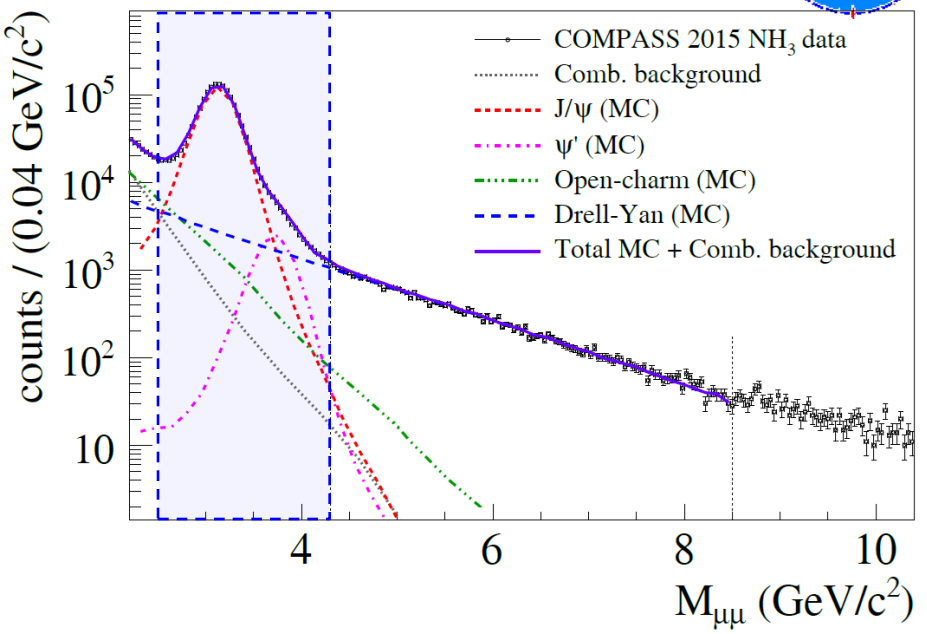
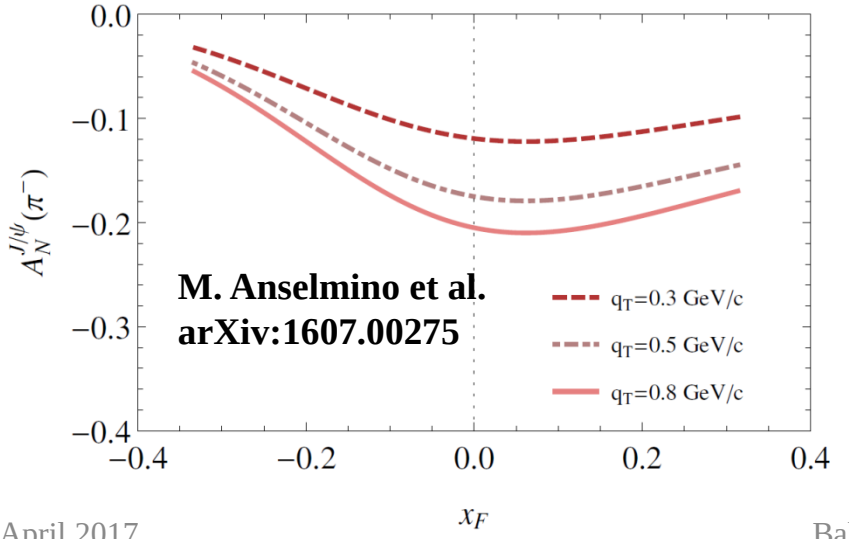
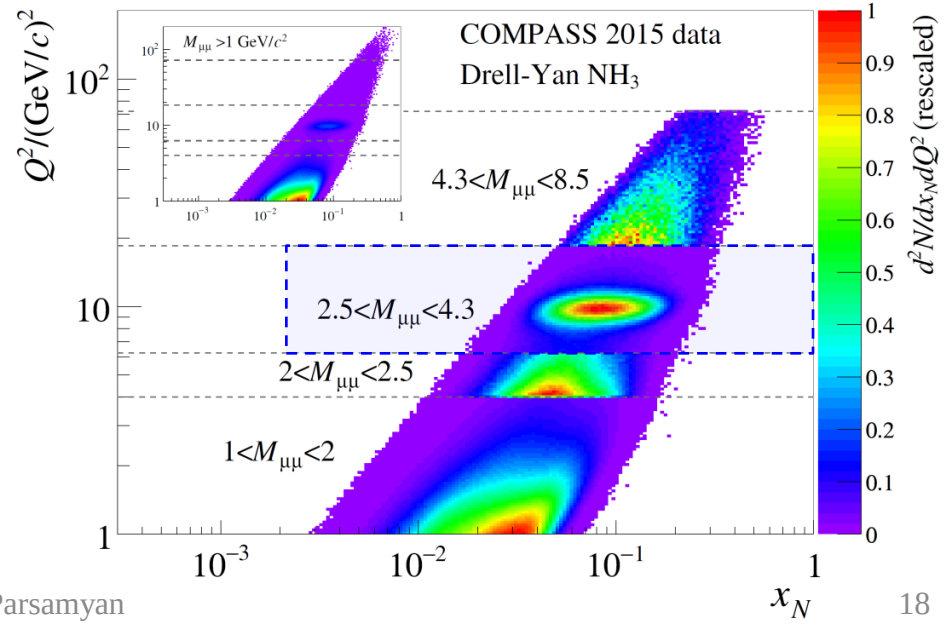
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries



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





COMPASS bridge
N
W
E
S
Drell-Yan
SIDIS

SIDIS x-section

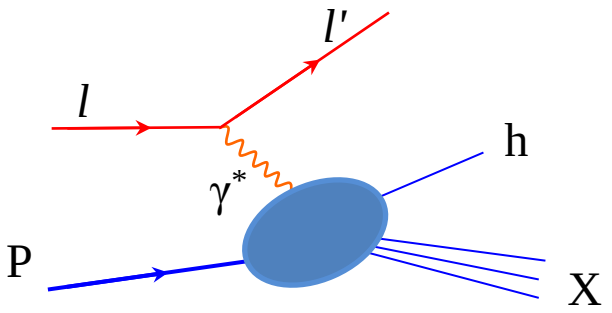
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

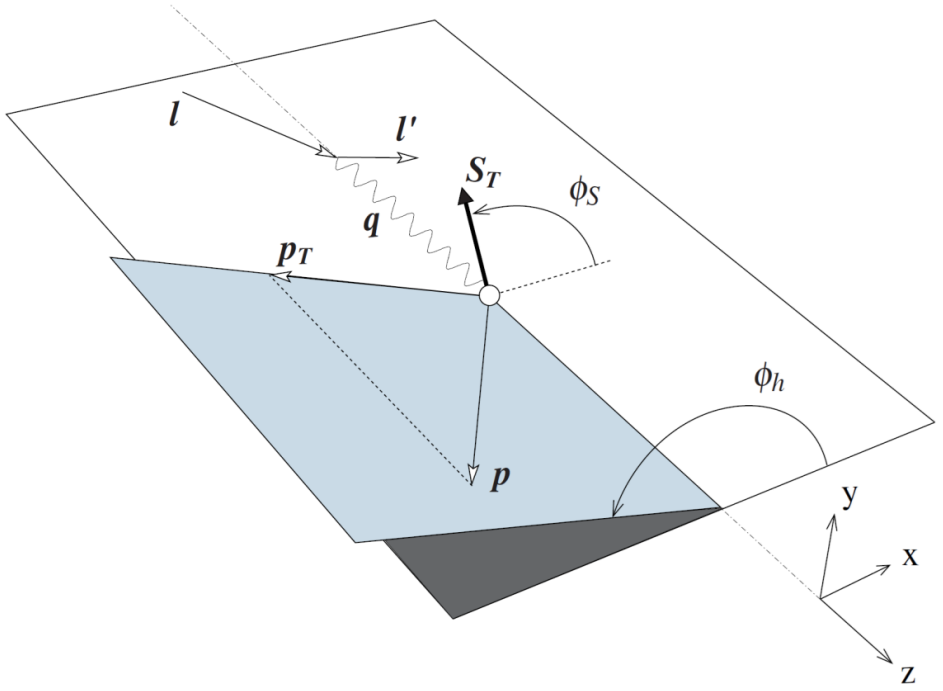
All measured by COMPASS

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

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

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





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

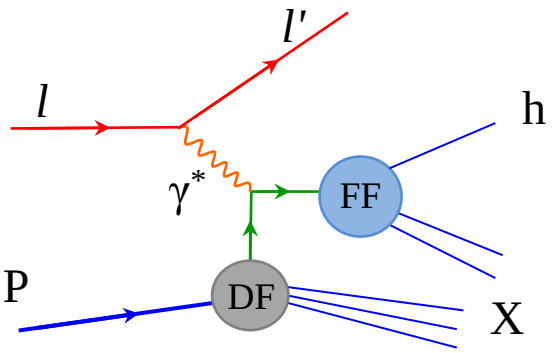
SIDIS x-section and TMDs at twist-2

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

All measured by COMPASS

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

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



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

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

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

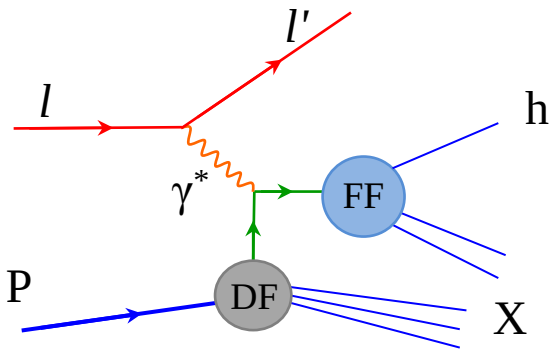
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

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

$$+ S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

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



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: transverse spin dependent part

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

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

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

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

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

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

Twist-2

Twist-3

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

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

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

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

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

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

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

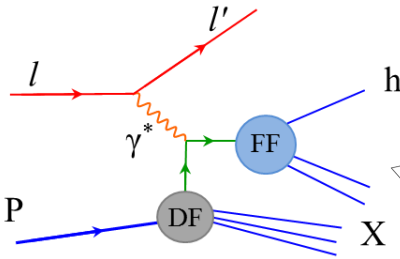
SIDIS and single-polarized DY x-sections

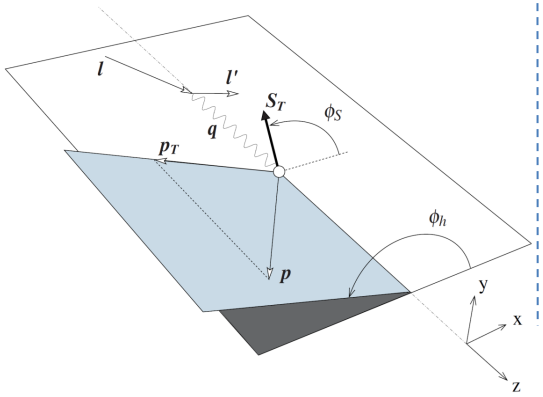
SIDIS

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

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

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





DY

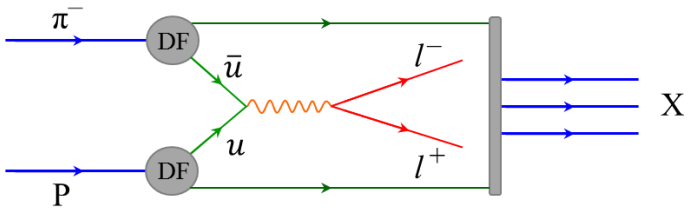
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)$$

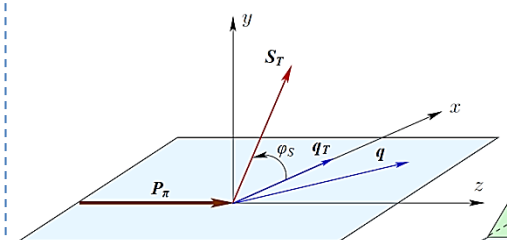
$$\times \Bigg\{ 1 + A_U^1 \cos^2\theta_{CS}$$

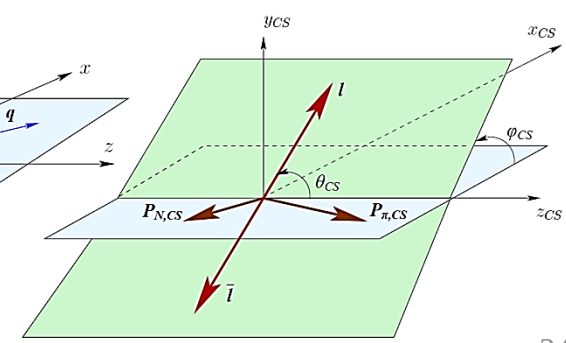
$$+\ \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$

$$+\ S_L \left[\sin 2\theta_{CS} A_L^{\sin\varphi_{CS}} \sin\varphi_{CS} + \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS}\right]$$

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







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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

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

SIDIS

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

SIDIS-DY bridge

DY

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

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

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

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$
$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,\mathrm{p}}^{\perp q}$
$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp q} \otimes H_{1q}^{\perp h}$	Worm-gear L	$A_L^{\sin 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1L,\mathrm{p}}^{\perp q}$
$A_{LL} \propto g_{1L}^{q} \otimes D_{1q}^{h}$, $A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$		Double polarized DY only

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

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

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

SIDIS

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

SIDIS-DY bridge

DY

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

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

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

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

within QCD TMD-framework:

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

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

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

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

SIDIS

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

SIDIS-DY bridge

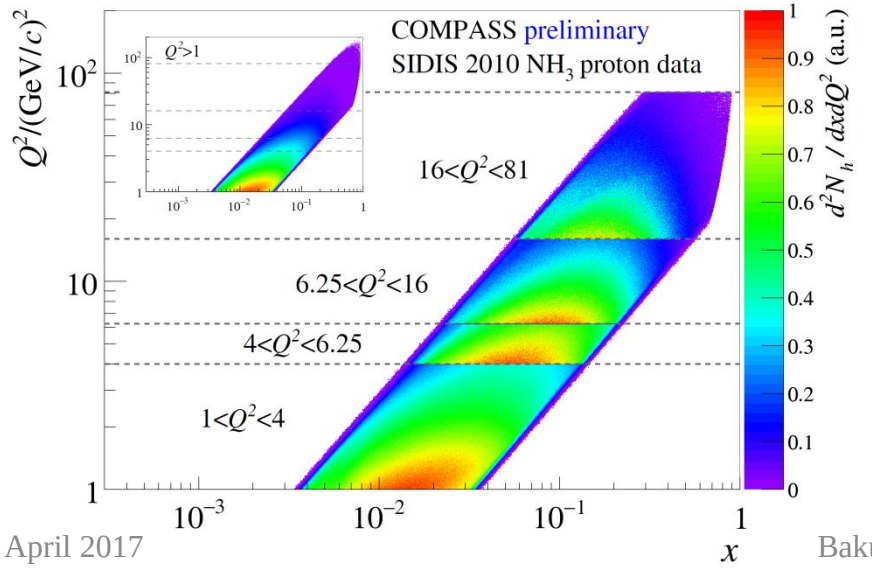
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)$$

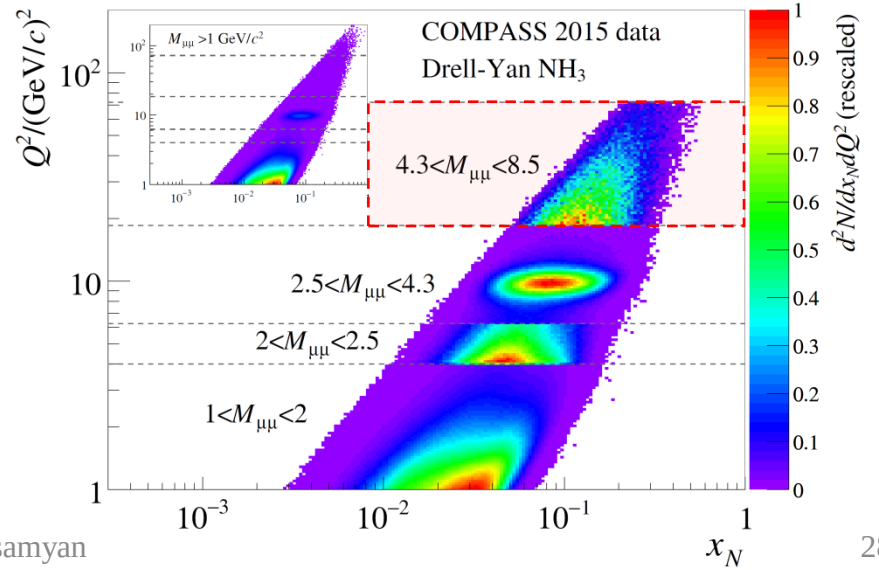
DY

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

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

Comparable x:Q^2 coverage – minimization of possible Q^2-evolution effects





Appetizers: selected COMPASS (and not only) results

Tuscan appetizers

SIDIS TSAs (Collins)

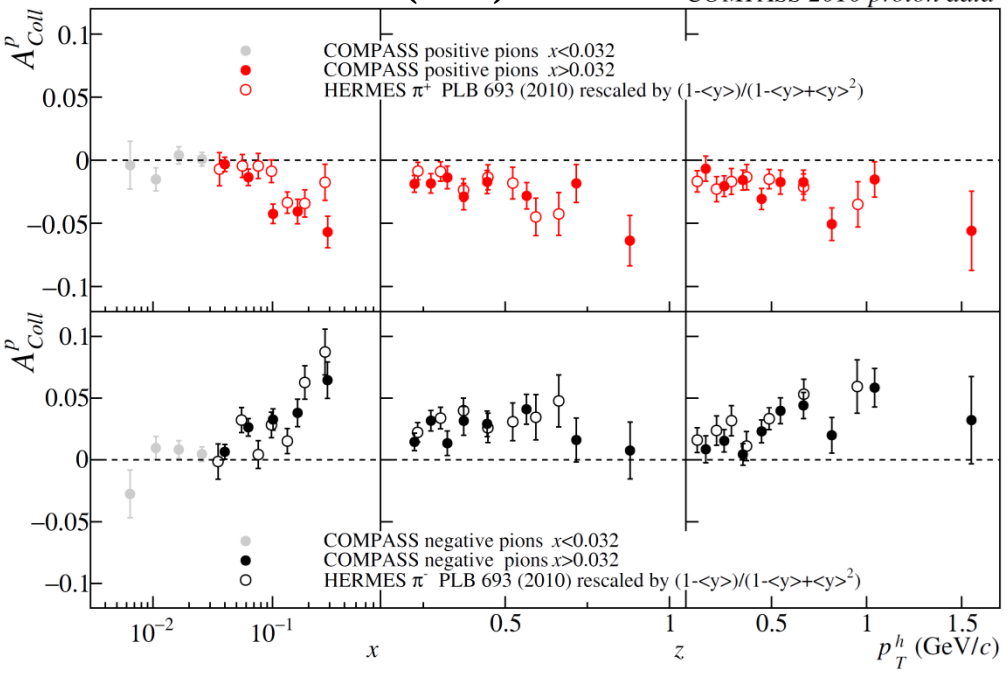
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ \quad 1+\ldots$$

$$+ S_T \Big[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \boxed{\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S)} + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

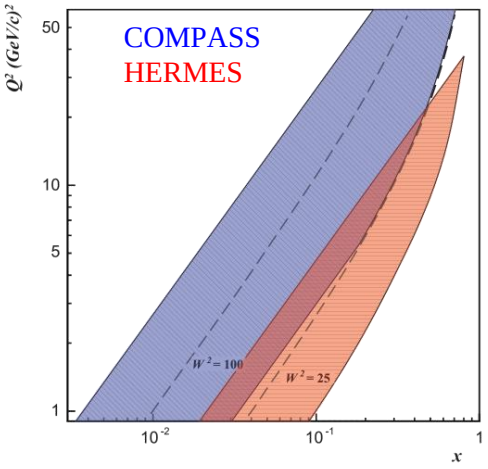
$$+ S_T\lambda \Big[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \Big]$$

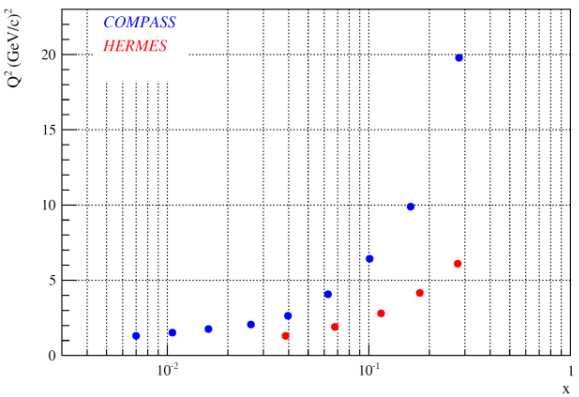
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$ SSA [twist-2]

PLB 744 (2015) 250 *COMPASS 2010 proton data*



- Measured on P/D in SIDIS and in dihadron SIDIS
  COMPASS and HERMES obtained compatible results on Collins TSA (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**





SIDIS TSAs (Collins)

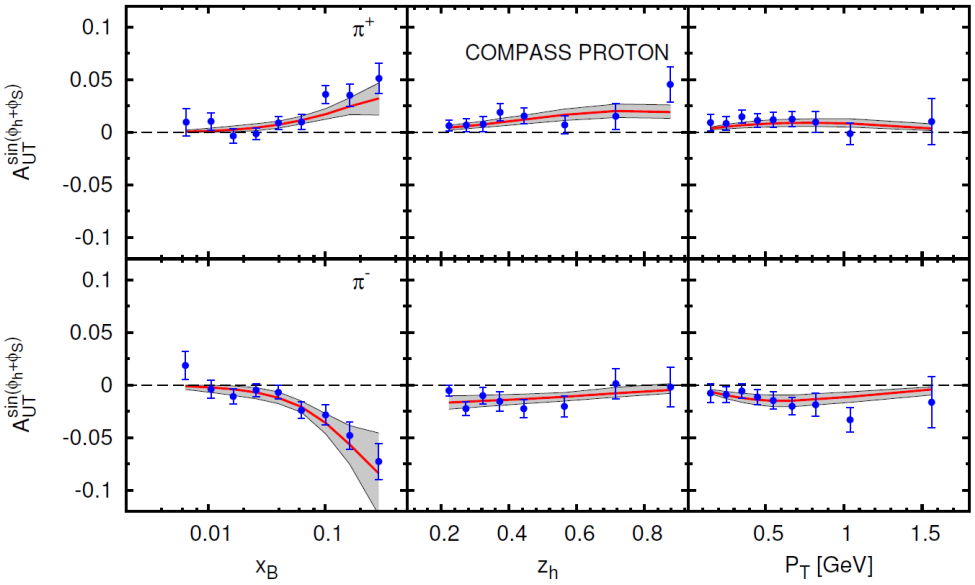
$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$ SSA [twist-2]

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

$$+ S_T \Big[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

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

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

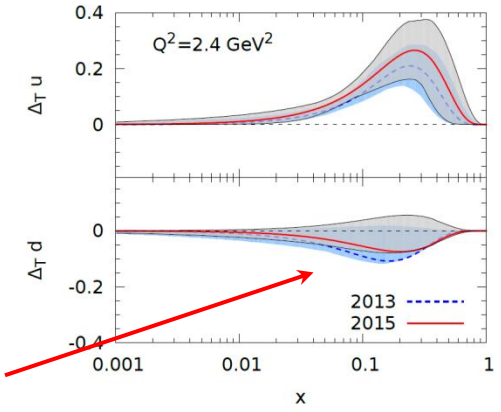


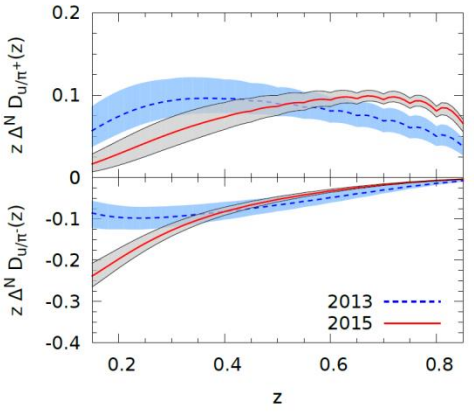
- Global fit of HERMES-COMPASS-BELLE data

Extensive phenomenological studies and various global fits by different groups

Ideas for COMPASS-III (>2020)

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





- Transversity PDF + Collins FF

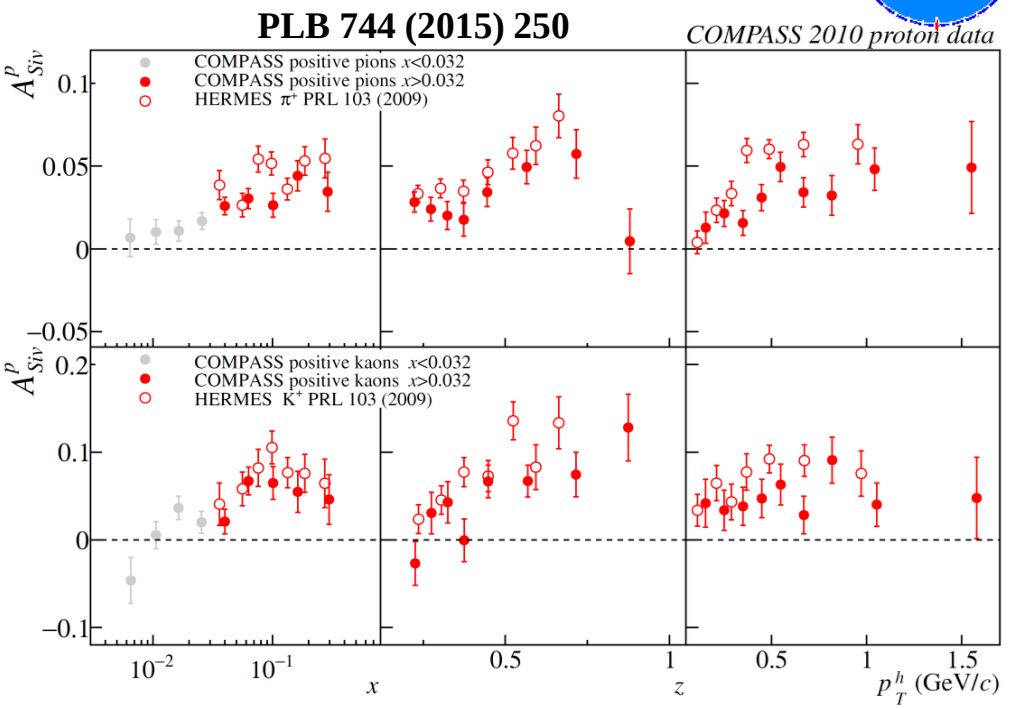
SIDIS TSAs (Sivers)

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

$$+ S_T \Big[\boxed{A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S)} + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

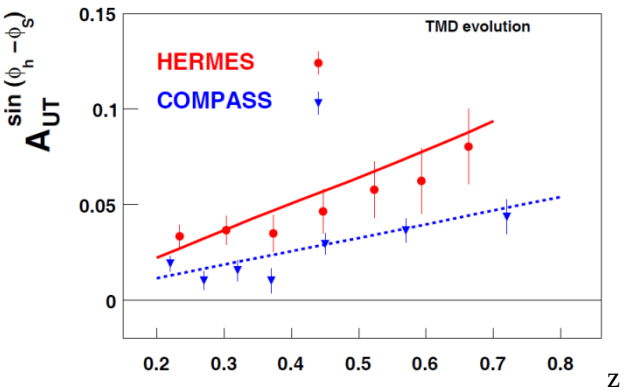
$$+ S_T\lambda \Big[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \Big]$$

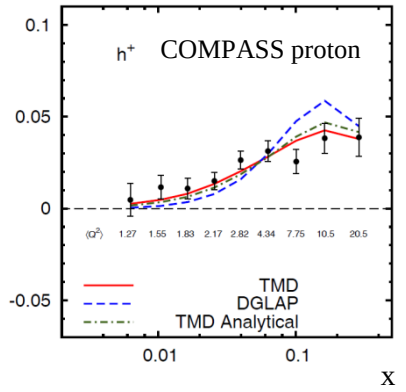
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h} \quad \text{SSA[twist-2]}$$



- Measured on proton and deuteron
- Gluon Sivers paper: submitted to PLB
  CERN-EP/2017-003, hep-ex/1701.02453

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results
  (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**





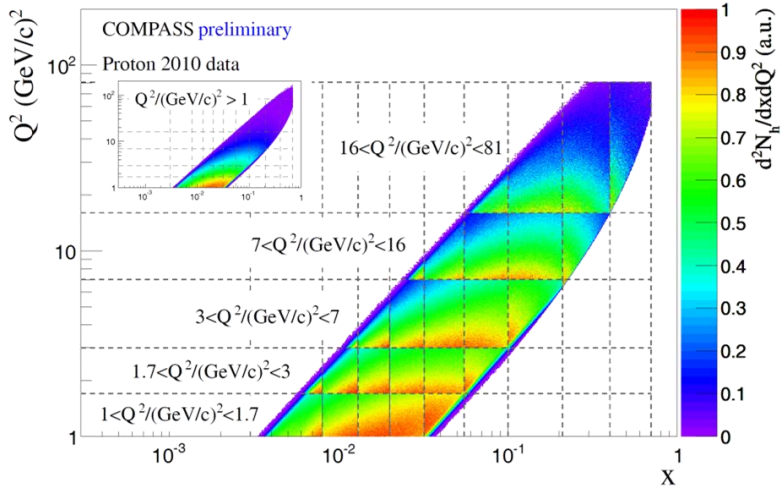
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

Multi-D TSA analysis

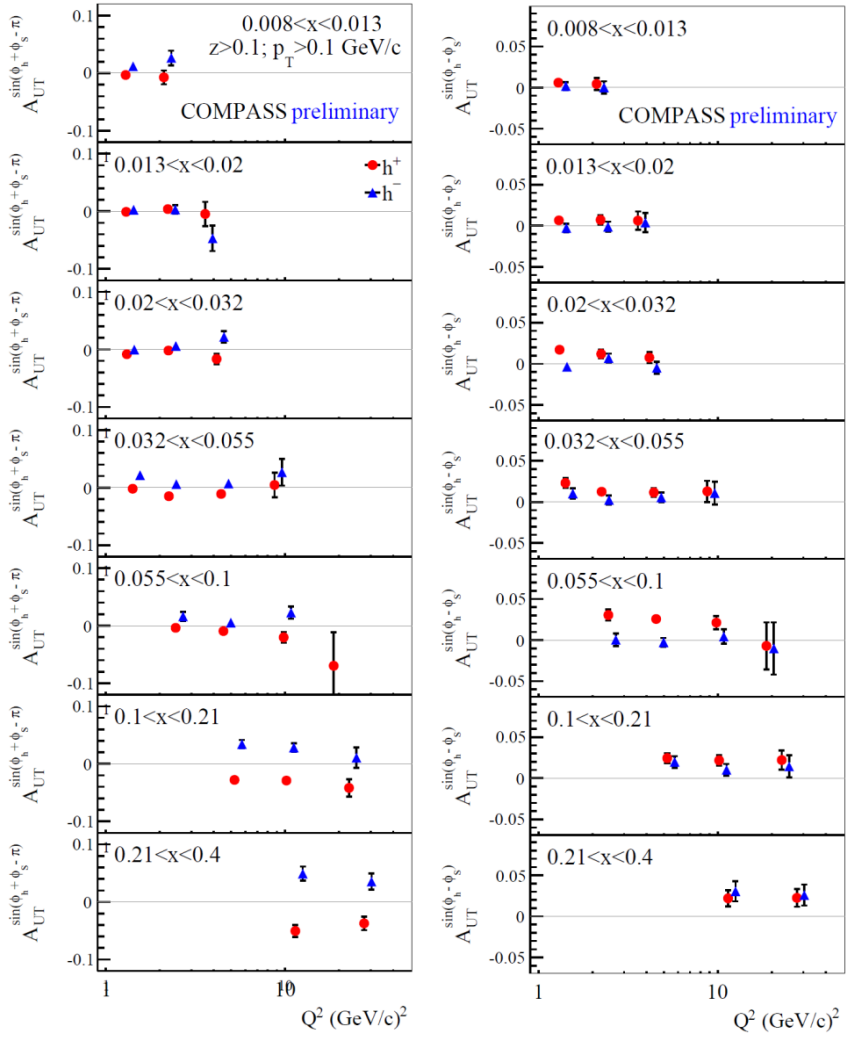
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ \quad 1 + \ldots$$

$$+ \; S_T \Big[A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \Big]$$

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



Results first shown at the SPIN-2014 conference
arXiv:1504.01599 [hep-ex]



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

Sivers TSA SIDIS→DY

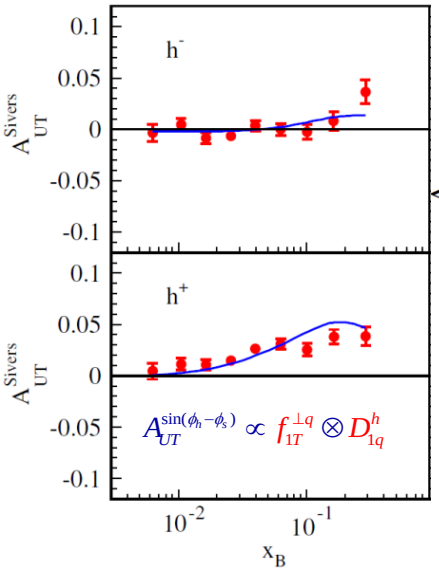
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

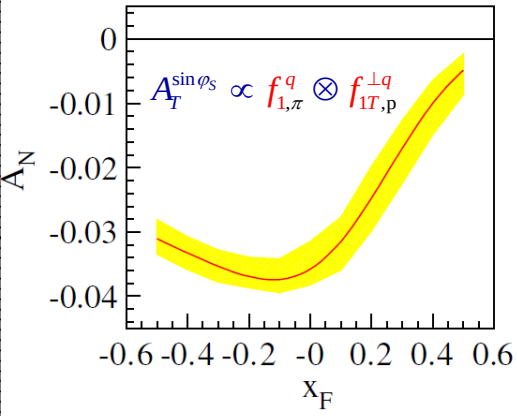
$$+ S_T \left[\begin{array}{l} \boxed{A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S)} \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)}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

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

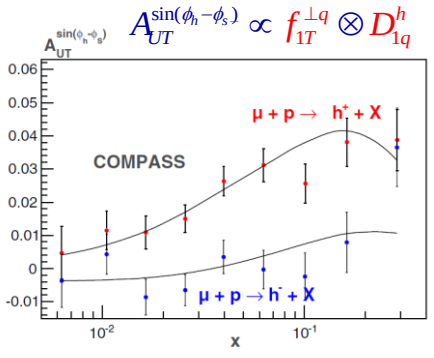
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

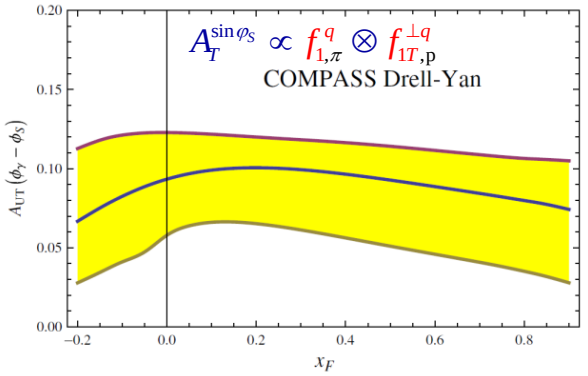
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev,
"QCD Evolution of the Sivers Asymmetry"
PRD 89 074013 (2014)





P. Sun and F. Yuan,
"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".
PRD 88 11, 114012 (2013)





Sivers TSA SIDIS→DY

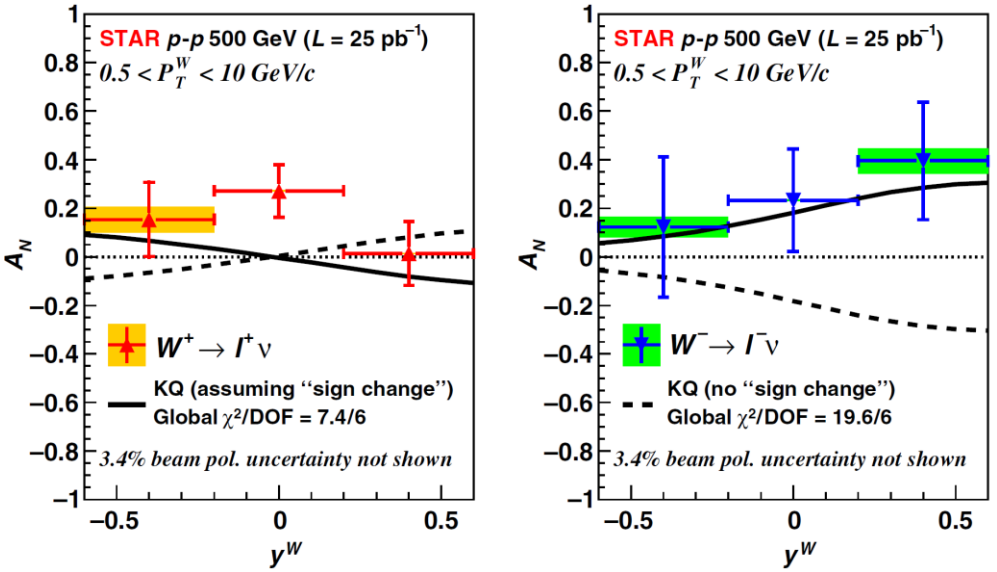
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

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

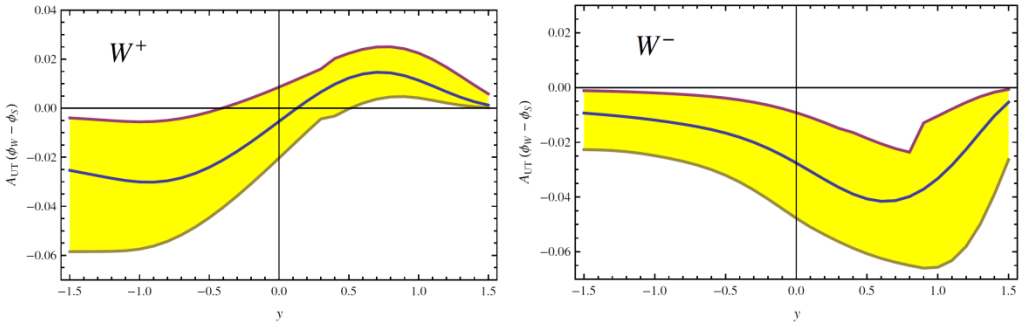
$$+ S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \end{array} \right] \Bigg\}$$

- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- First experimental investigation of Sivers-nonuniversality 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,
"Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production".
PRD 88 11, 114012 (2013)

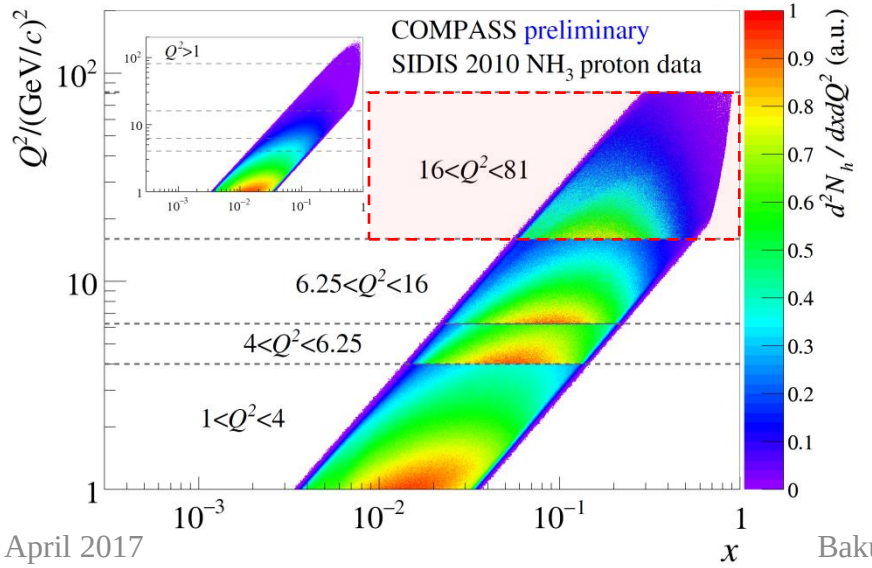


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

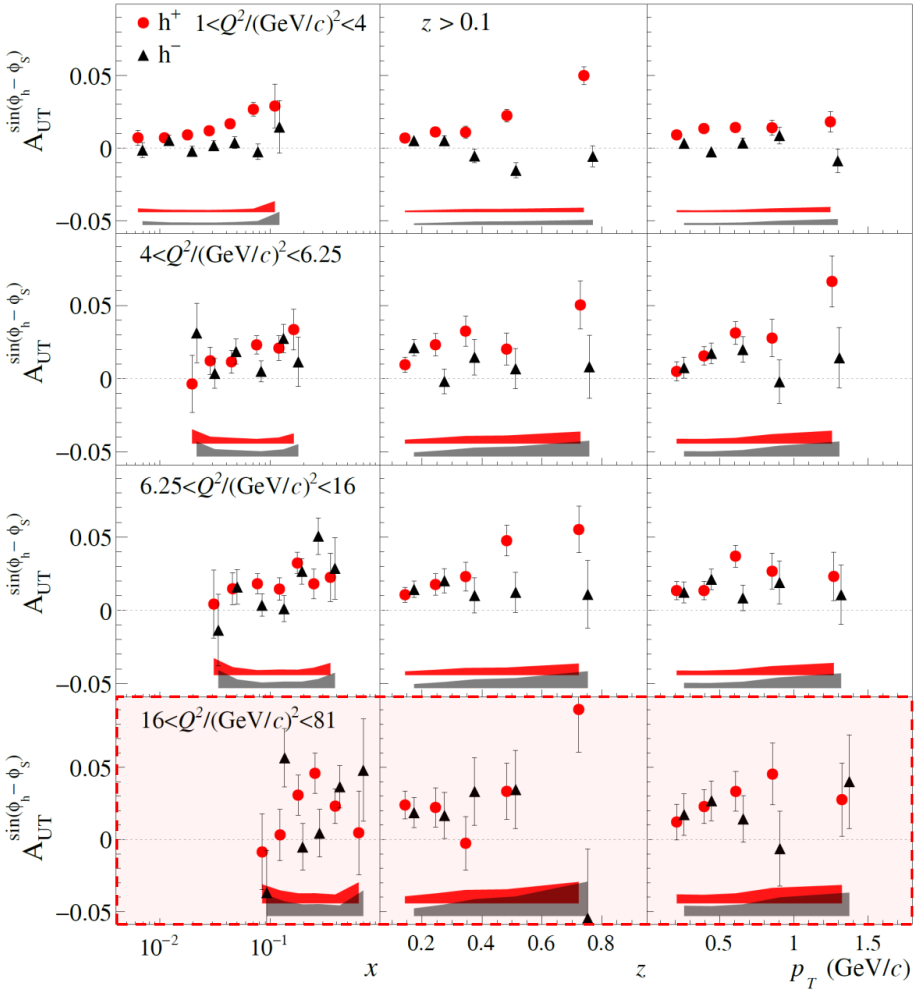
$$+ S_T \Big[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

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



Soon in PLB

CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]

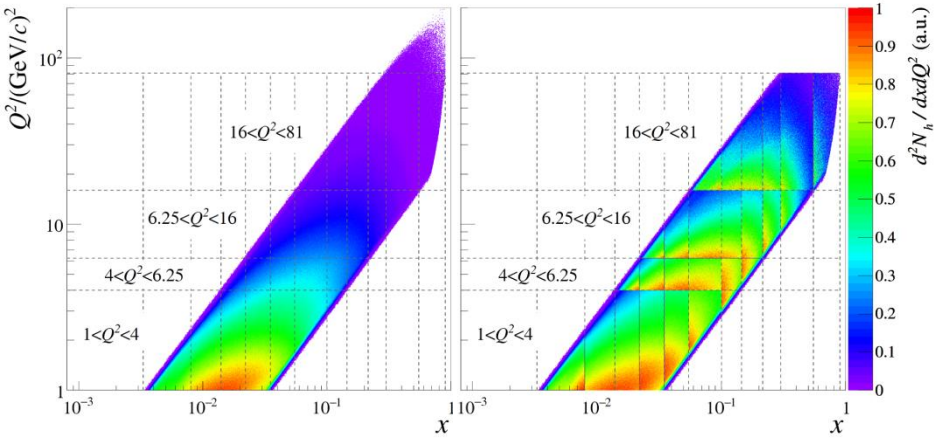


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

$$+ \; S_T \Big[A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \Big]$$

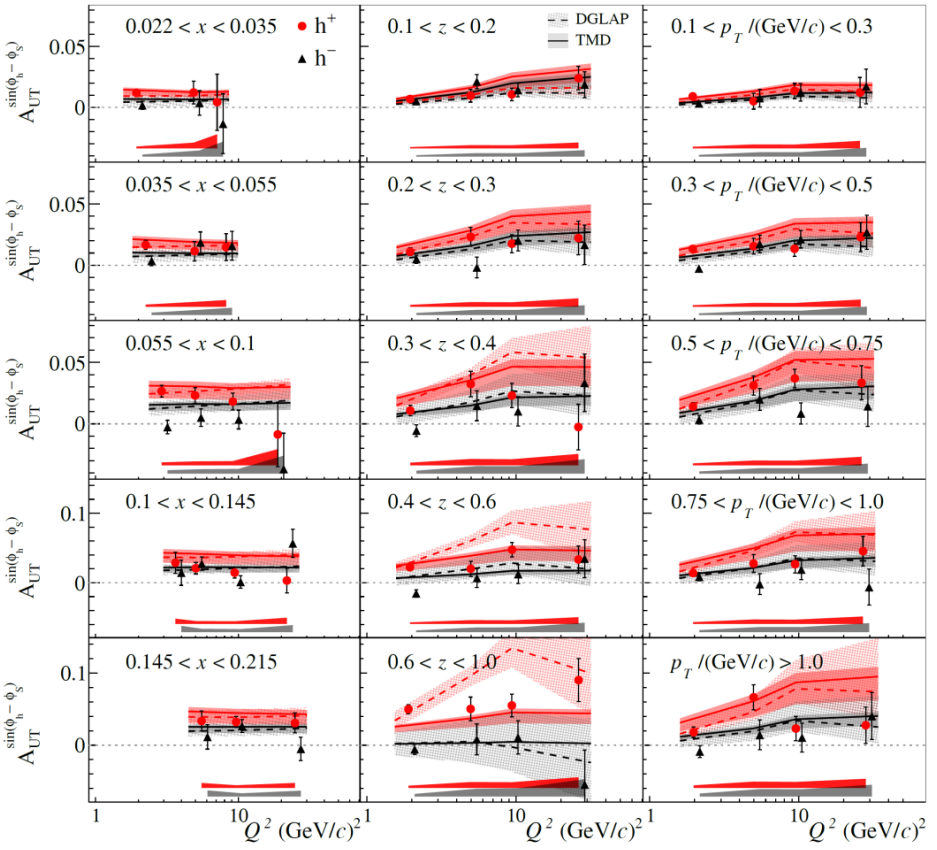
$$+ \; S_T \lambda \Big[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h - \phi_S)} \cos(2\phi_h - \phi_S) \Big]$$



A multi-dimensional input for TMD evolution studies

Soon in PLB

CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]



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.

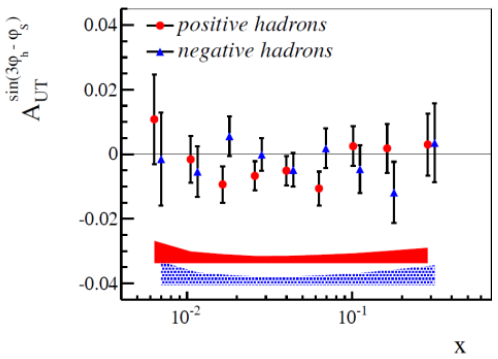
SIDIS TSAs (Pretzelosity and Kotzinian-Mulders)

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

$$+ S_T \Big[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

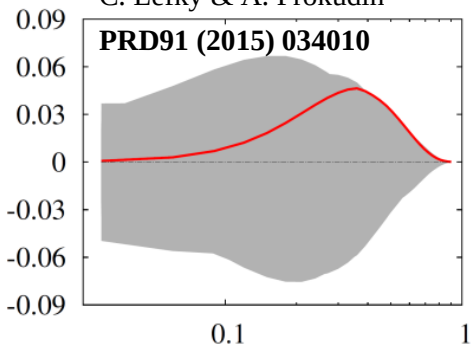
$$+ S_T\lambda \Big[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \Big]$$

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$ SSA[twist-2]



C. Lefky & A. Prokudin

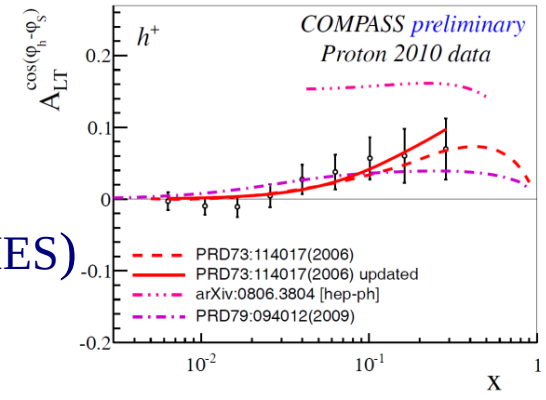
PRD91 (2015) 034010

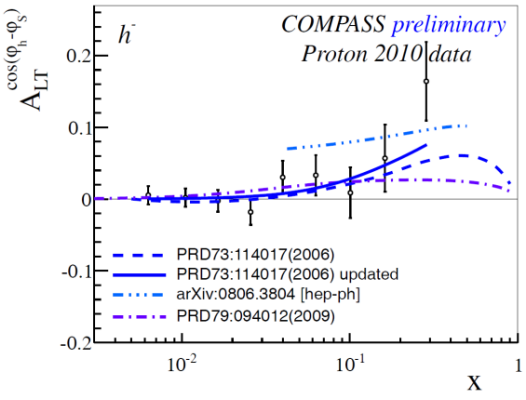


- All compatible with zero within uncertainties (P/D)
- Suppressed by a factor of $\sim|p_T|^2$ w.r.t the Collins and Sivers TSAs

$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$ DSA[twist-2]

- Not accessible in single-polarized DY
- Gives access to g_{1T} "twist-2" PDF (Kotzinian-Mulders or worm-gear-T)
- Clear signal for h^+ (*preliminary* confirmation also by HERMES)
- In agreement with several models





The $A_{UT}^{\sin\phi_S}$ asymmetry

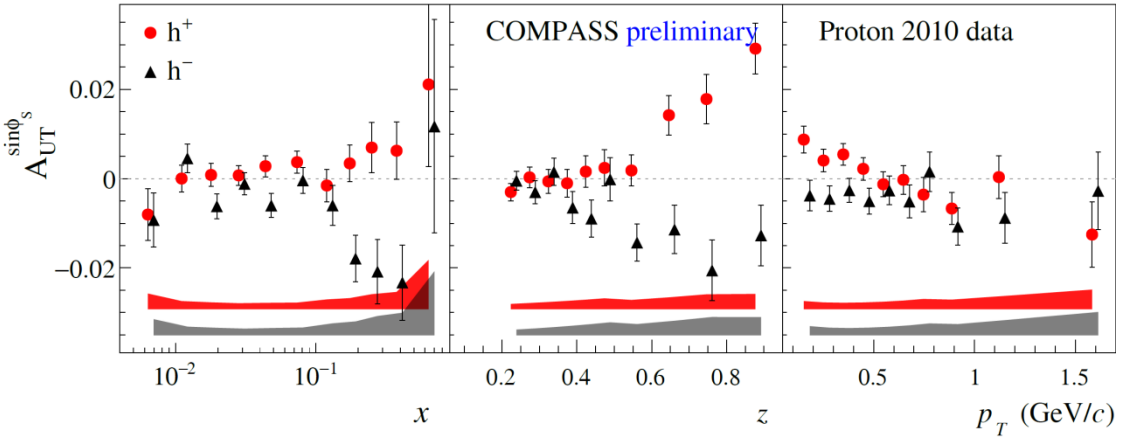
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ 1 + \ldots$$

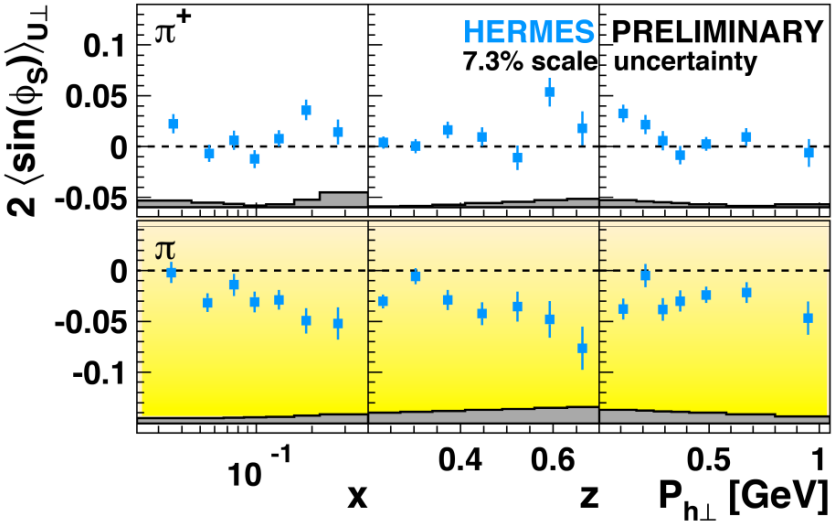
$$+ S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \boxed{\sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S} \\ + \sqrt{2\varepsilon(1+\varepsilon)}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

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

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

SSA[higher-twist]





- Higher twist effect..
- Within WW-approximation can be related to Sivers and Collins TSAs
- Non-zero trend for negative hadrons both at COMPASS and HERMES
- Compatible with zero on deuteron

The $A_{UT}^{\sin\phi_S}$ asymmetry

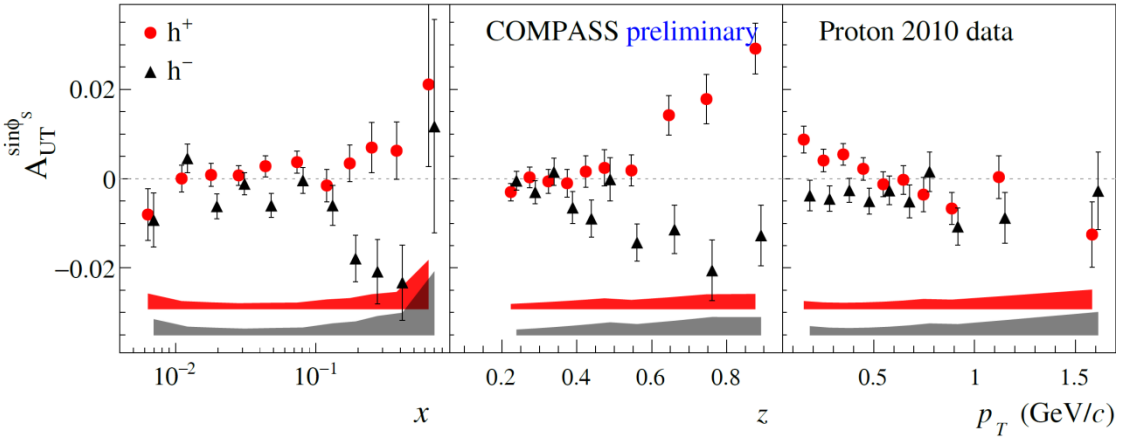
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ \quad 1+\ldots$$

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

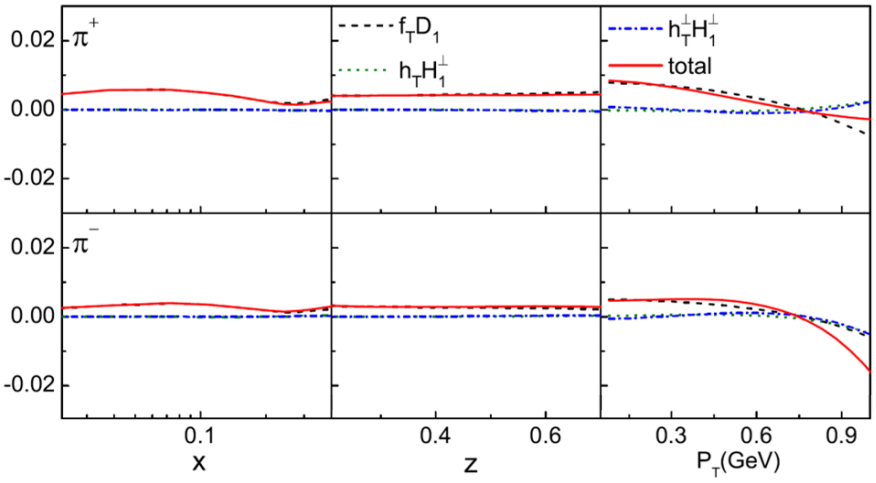
$$+\ S_T\lambda \Bigg[\begin{aligned} & \sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h-\phi_S)} \cos\left(\phi_h-\phi_S\right) \\ & + \sqrt{2\varepsilon(1-\varepsilon)}\, A_{LT}^{\cos\phi_S} \cos\phi_S \\ & + \sqrt{2\varepsilon(1-\varepsilon)}\, A_{LT}^{\cos(2\phi_h-\phi_S)} \cos\left(2\phi_h-\phi_S\right)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

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

SSA[higher-twist]



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



- Higher twist effect..
- Within WW-approximation can be related to Sivers and Collins TSAs
- Non-zero trend for negative hadrons both at COMPASS and HERMES
- Compatible with zero on deuteron

Main course: Results from first ever measurement of Drell-Yan TSAs. Shown for the first time!

Tuscan meat "bistecca alla Fiorentina"

in case you are vegetarian

Single-polarized DY x-section: transverse part

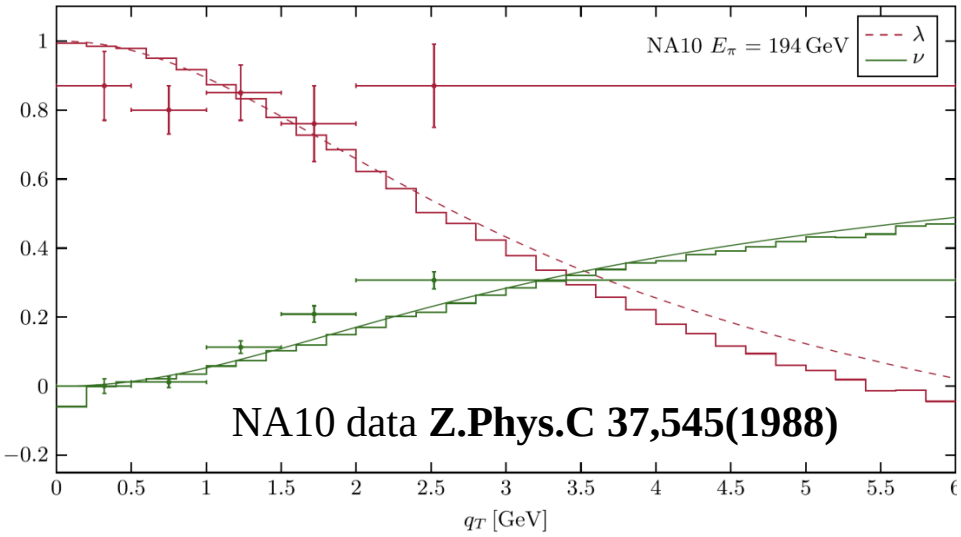
$$\lambda = A_U^1,\ \mu = A_U^{\cos\varphi_{CS}},\ \nu = 2A_U^{\cos 2\varphi_{CS}}$$

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

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

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

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



NA10 data **Z.Phys.C 37,545(1988)**

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

- 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

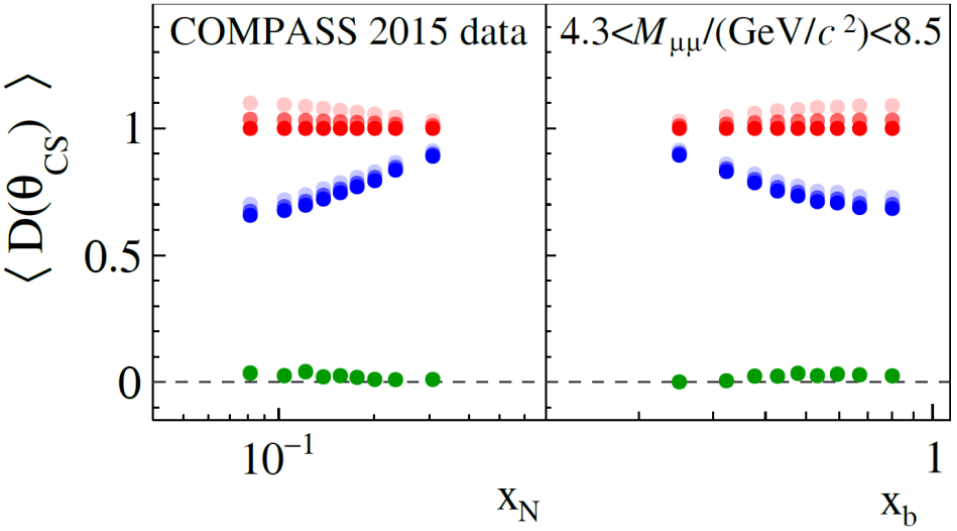
$$\lambda = A_U^1,\ \mu = A_U^{\cos\varphi_{CS}},\ \nu = 2A_U^{\cos 2\varphi_{CS}}$$

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

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

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

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



- 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%.

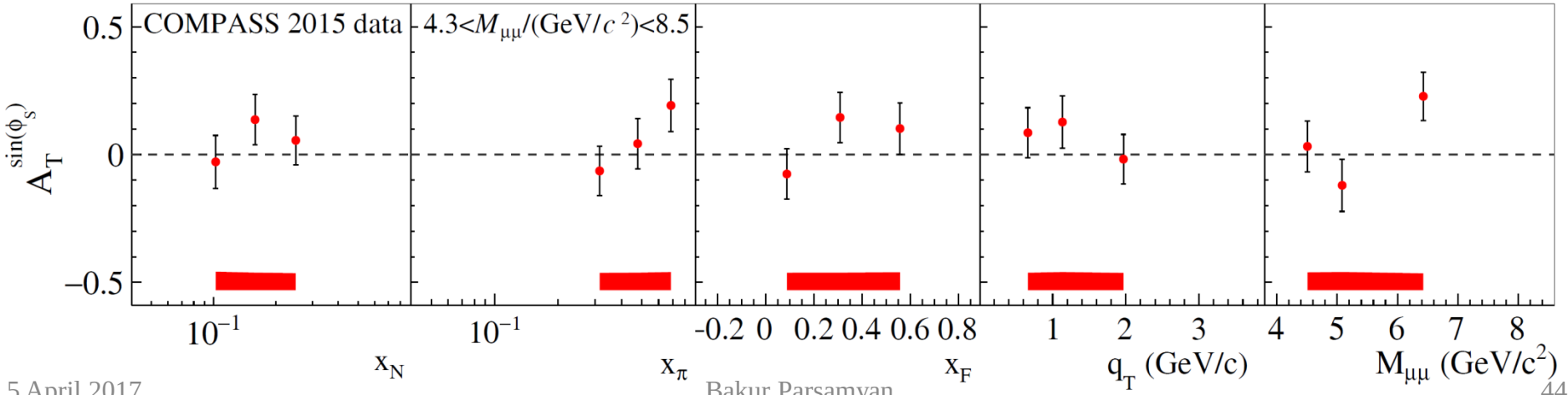
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

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



Drell-Yan TSAs – Sivers

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

Sivers SIDIS TSA

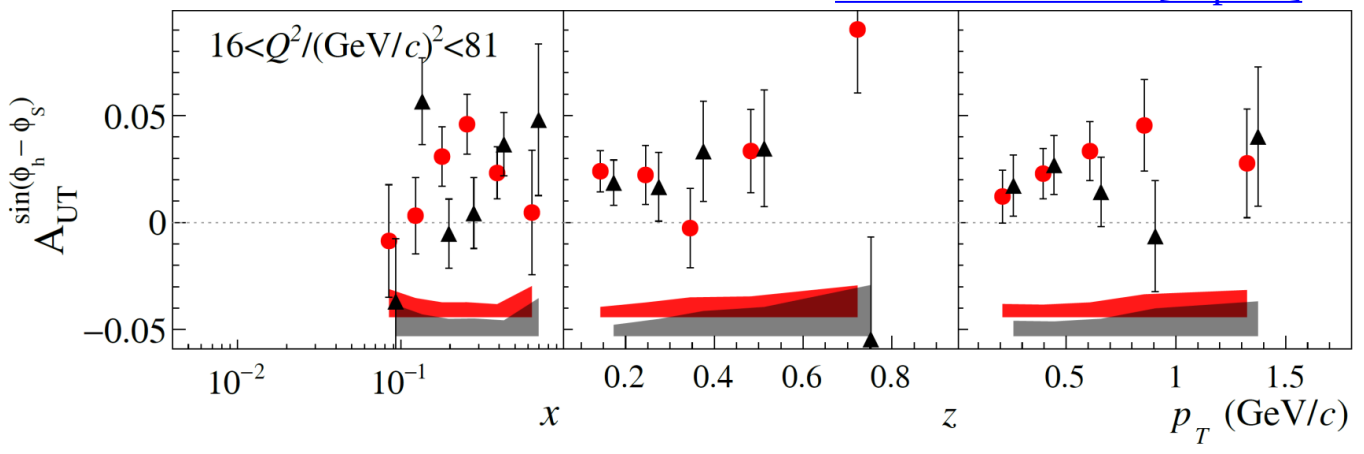
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

Sivers DY TSA

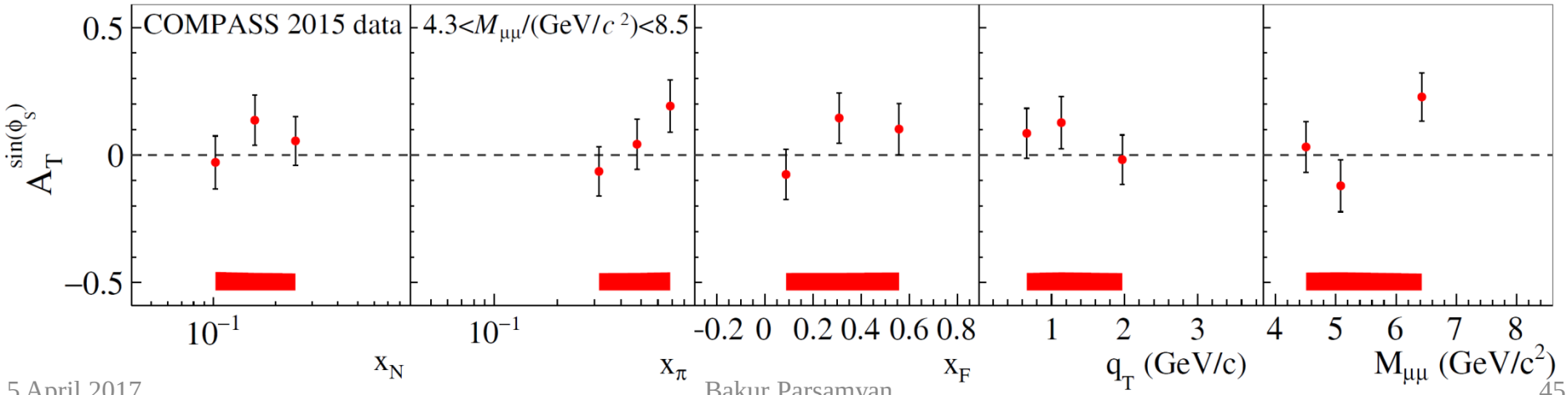
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$$

SIDIS in Drell-Yan high-mass range: Sivers TSA

COMPASS arXiv:1609.07374 [hep-ex]



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

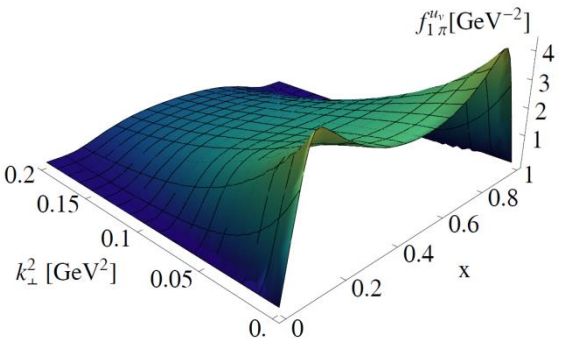


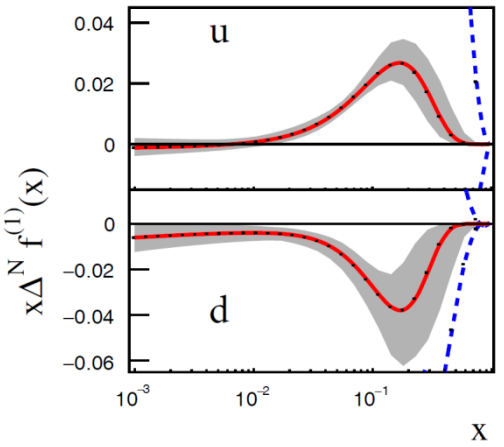
Drell-Yan TSAs – Sivers

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

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

M. Anselmino et al.
arXiv:1612.06413[hep-ph]

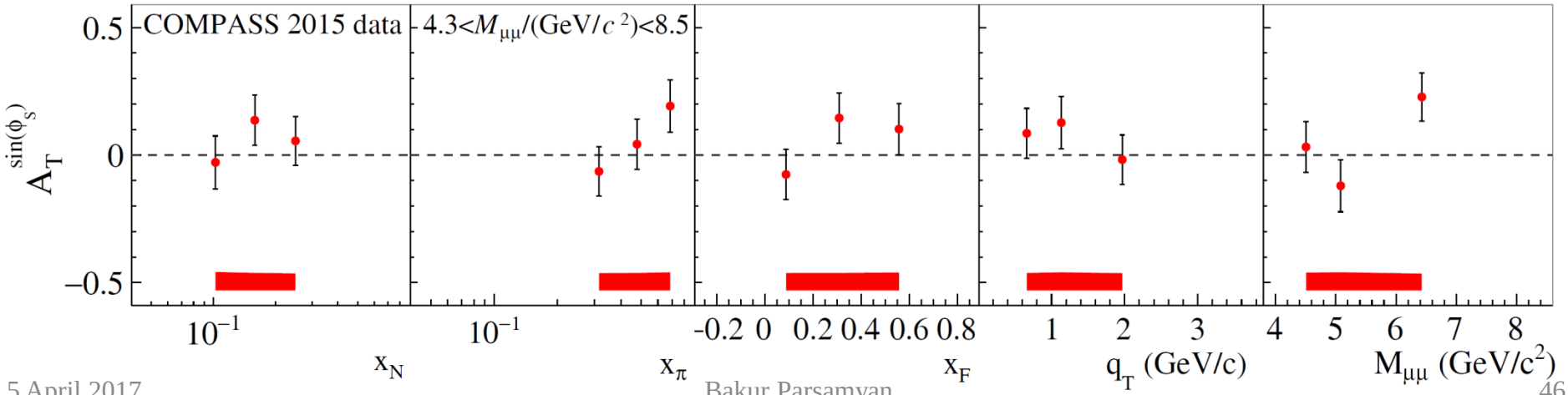




Sivers DY TSA

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

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



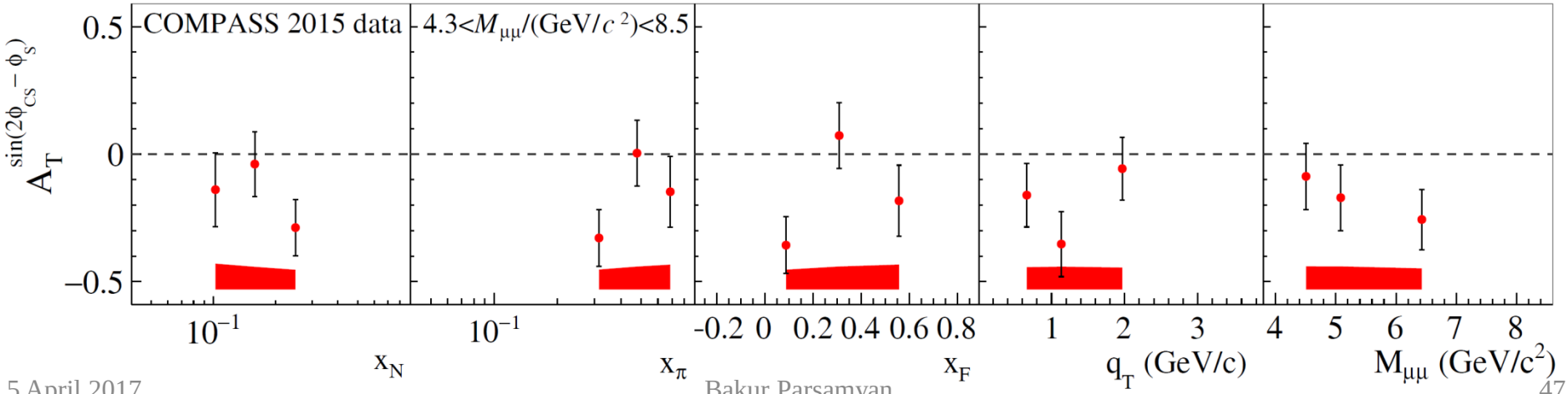
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

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



Drell-Yan TSAs – Transversity

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Collins SIDIS TSA

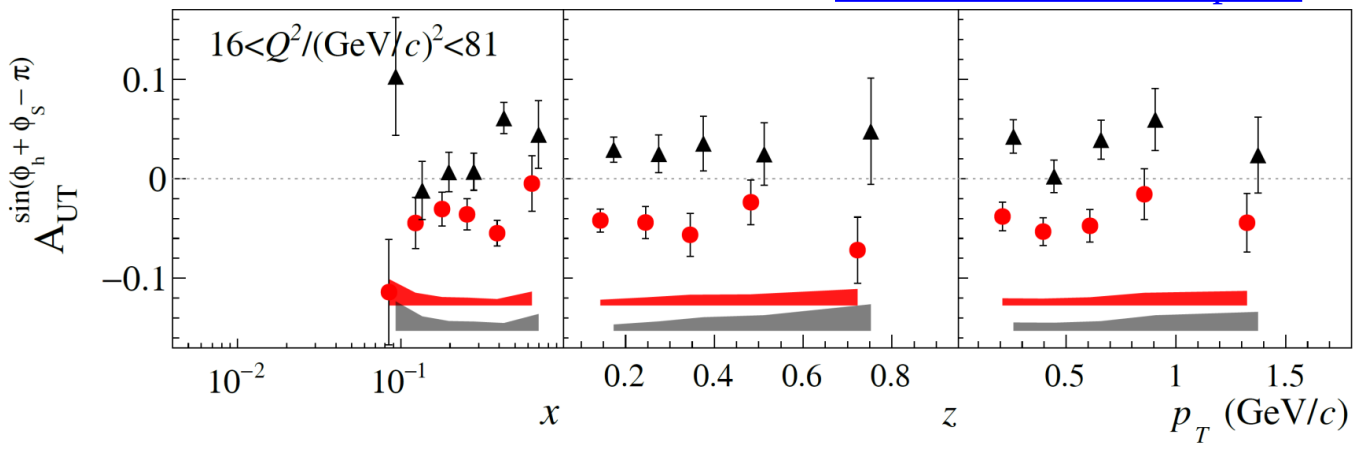
$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

Transversity DY TSA

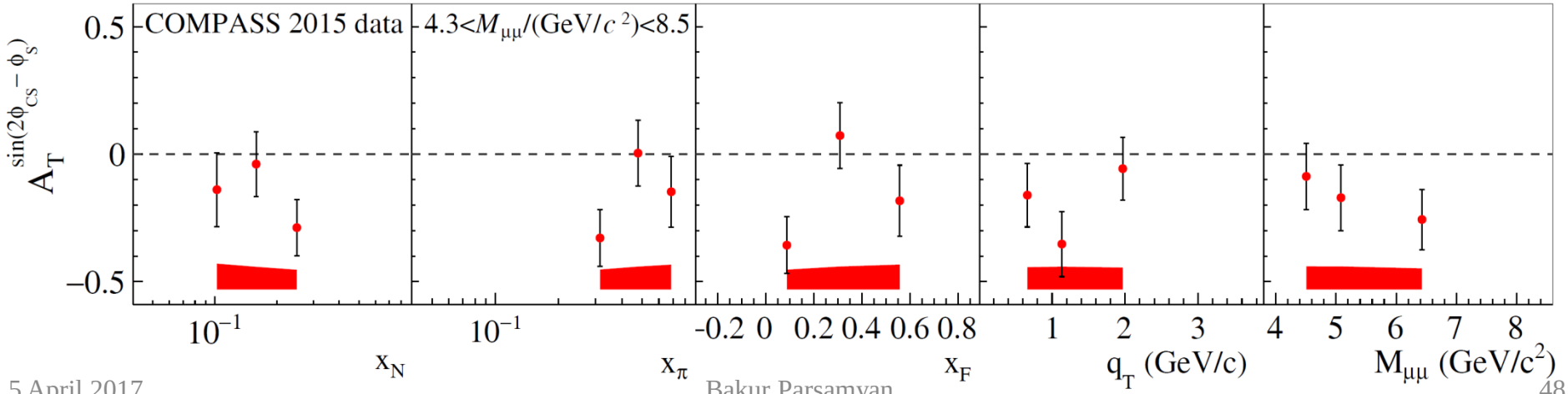
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

SIDIS in Drell-Yan high-mass range: Collins TSA

COMPASS arXiv:1609.07374 [hep-ex]



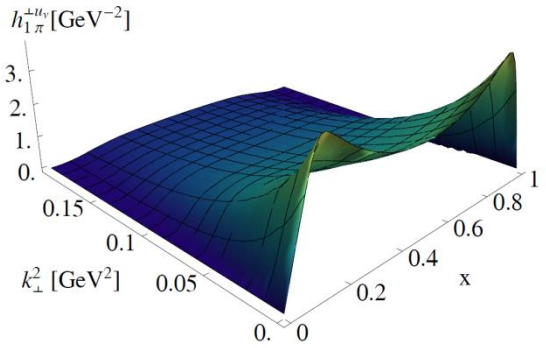
New! 03 April 2017! COMPASS CERN-EP-2017-059, arXiv:1704.00488[hep-ex]



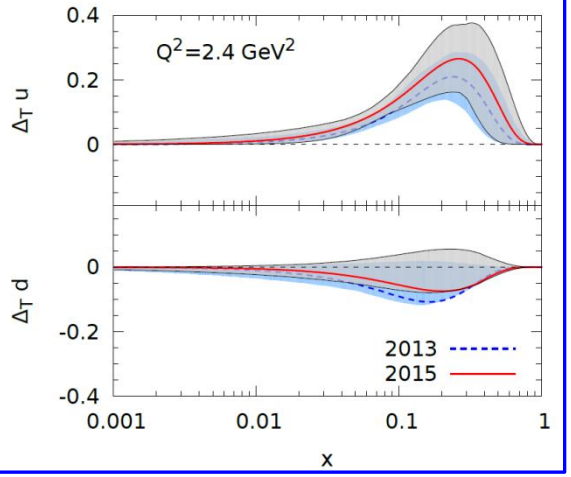
Drell-Yan TSAs – Transversity

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

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



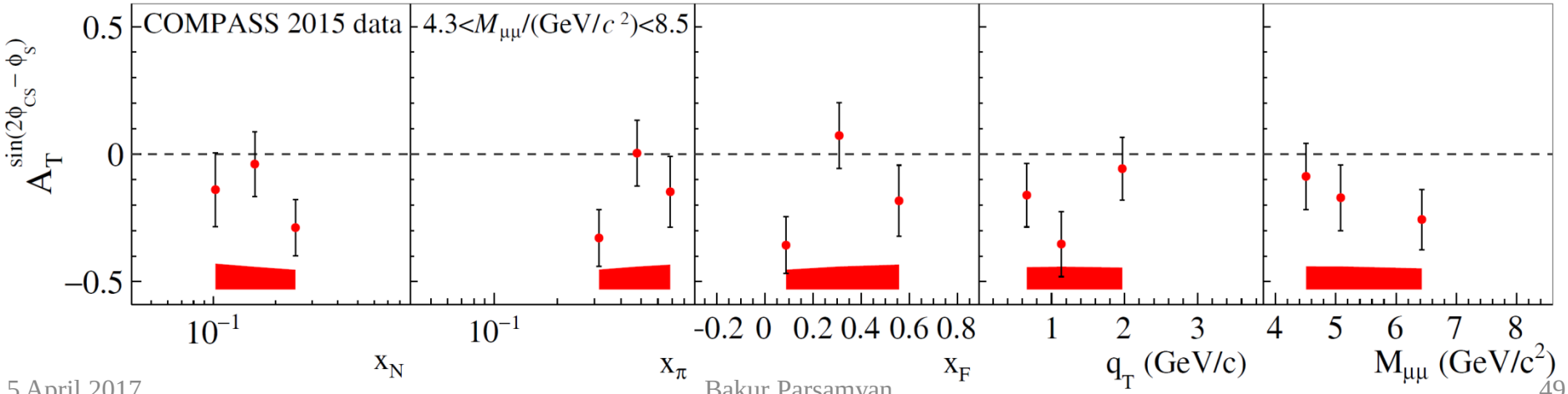
M. Anselmino et al.
Phys.Rev. D92 (2015) 114023



Transversity DY TSA

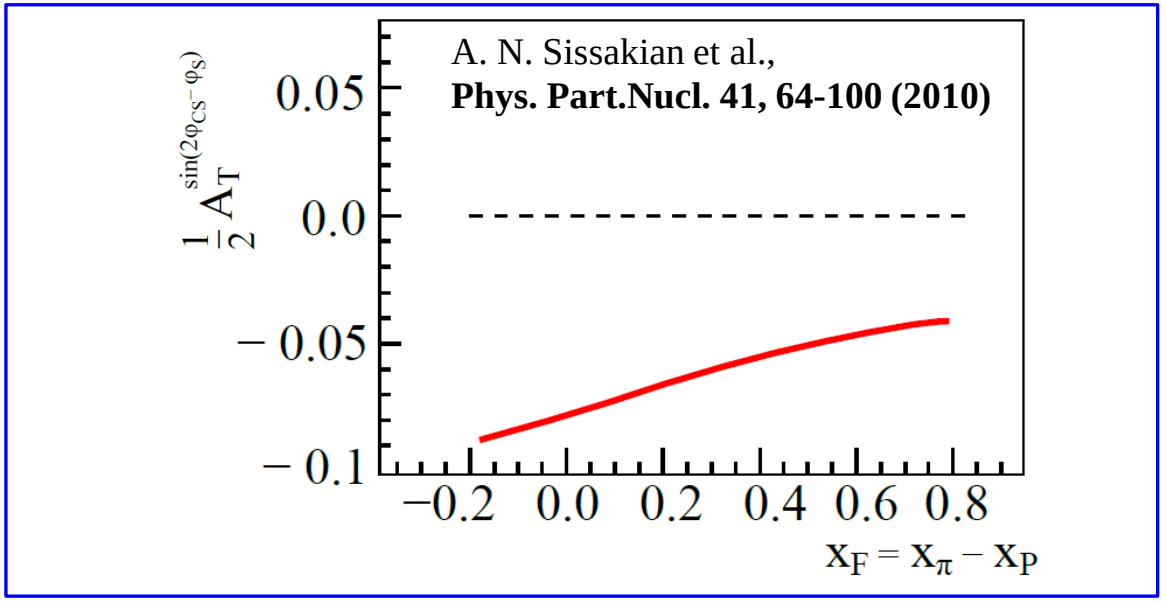
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$$

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



Drell-Yan TSAs – Transversity

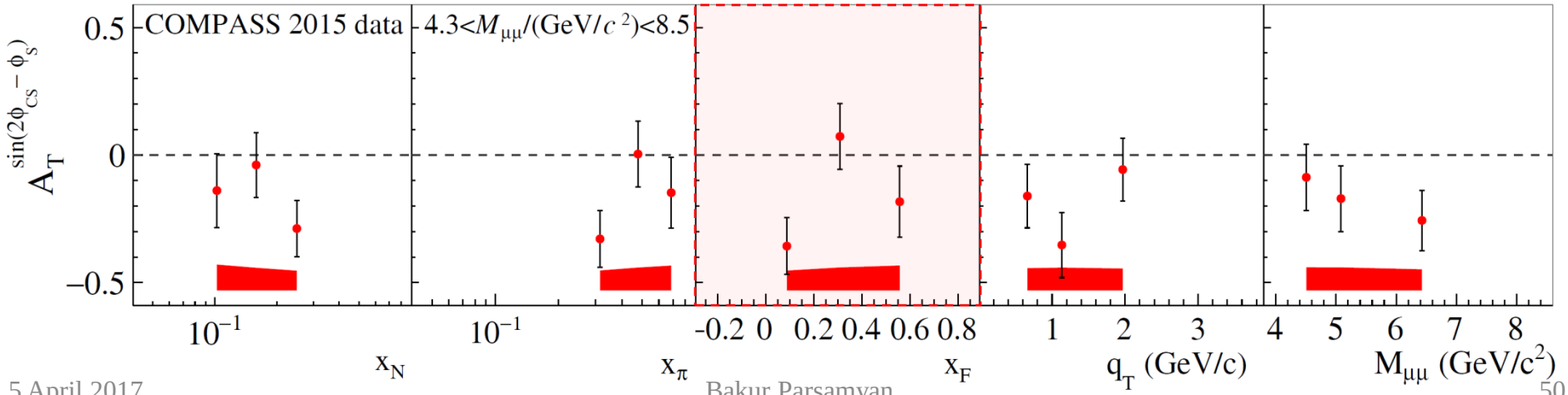
$$\frac{d\sigma}{d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + \ldots \right]$$



Transversity DY TSA

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

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



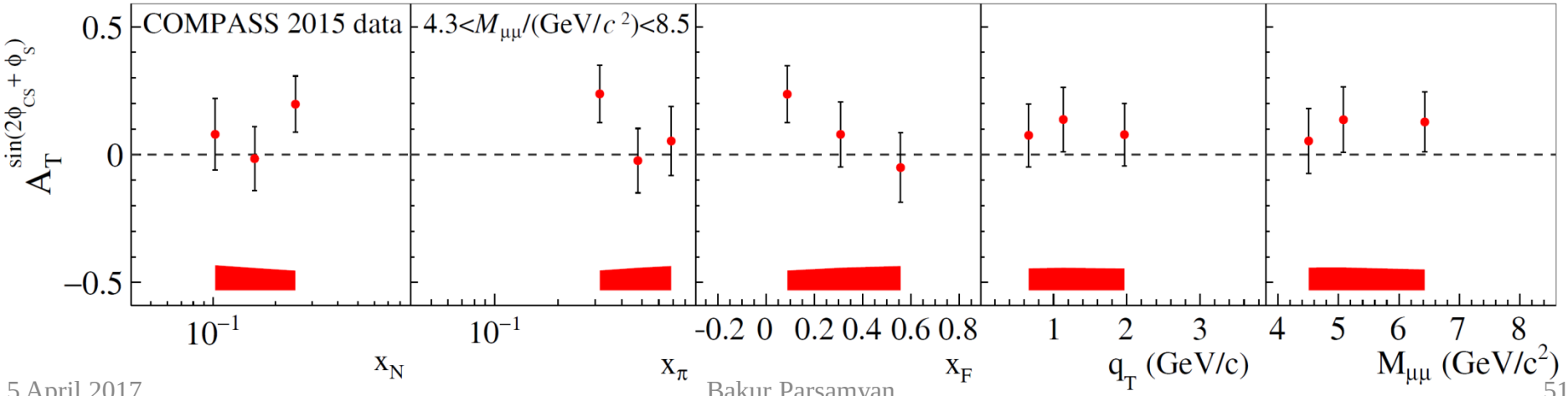
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

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



Drell-Yan TSAs – Pretzelosity

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

Pretzelosity SIDIS TSA

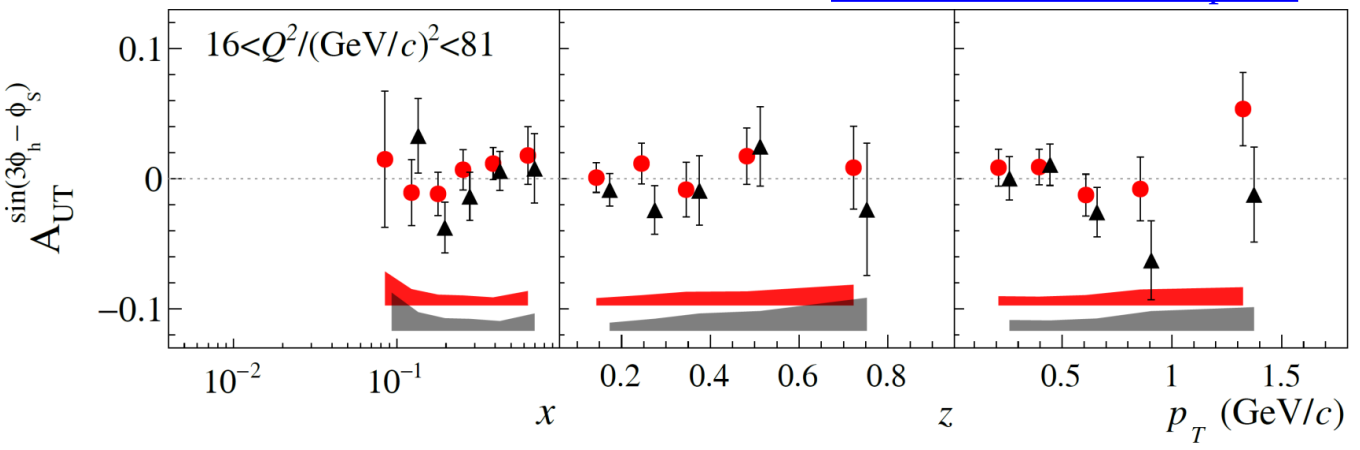
$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

Pretzelosity DY TSA

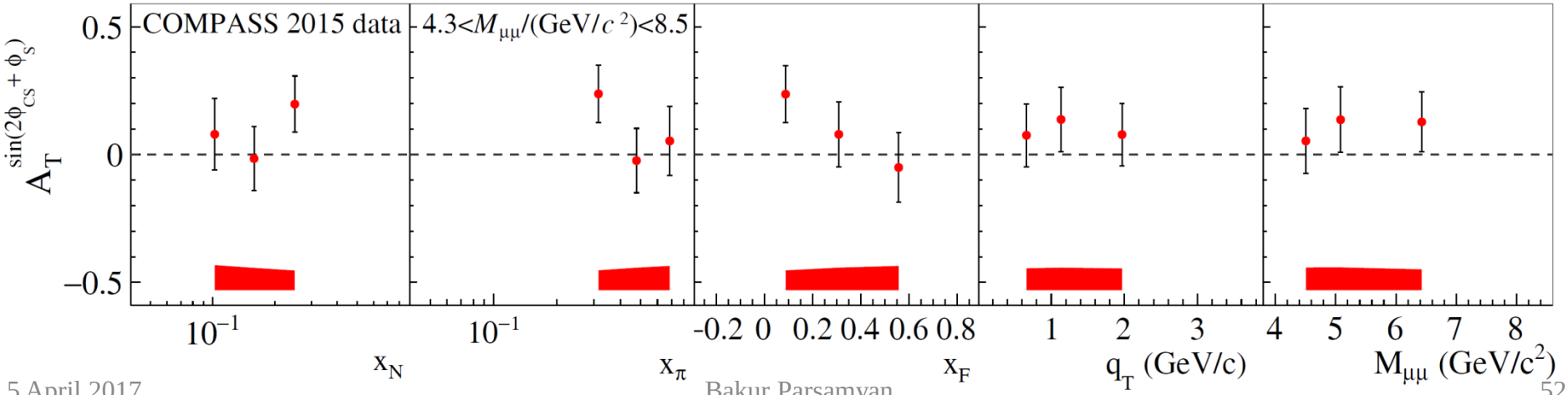
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

SIDIS in Drell-Yan high-mass range: Pretzelosity TSA

COMPASS arXiv:1609.07374 [hep-ex]



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

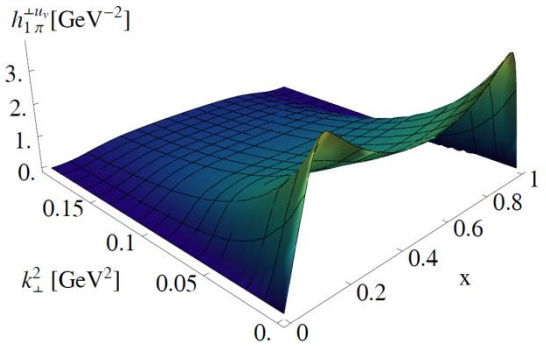


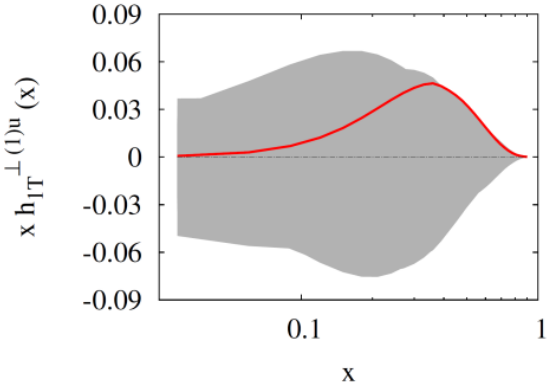
Drell-Yan TSAs – Pretzelosity

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

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

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

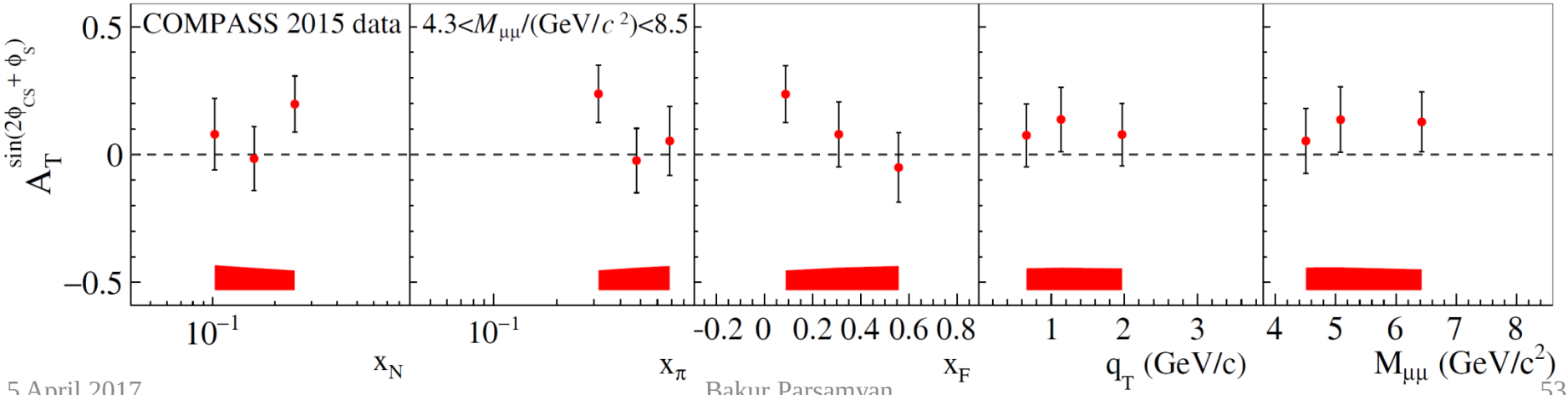




Pretzelosity DY TSA

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

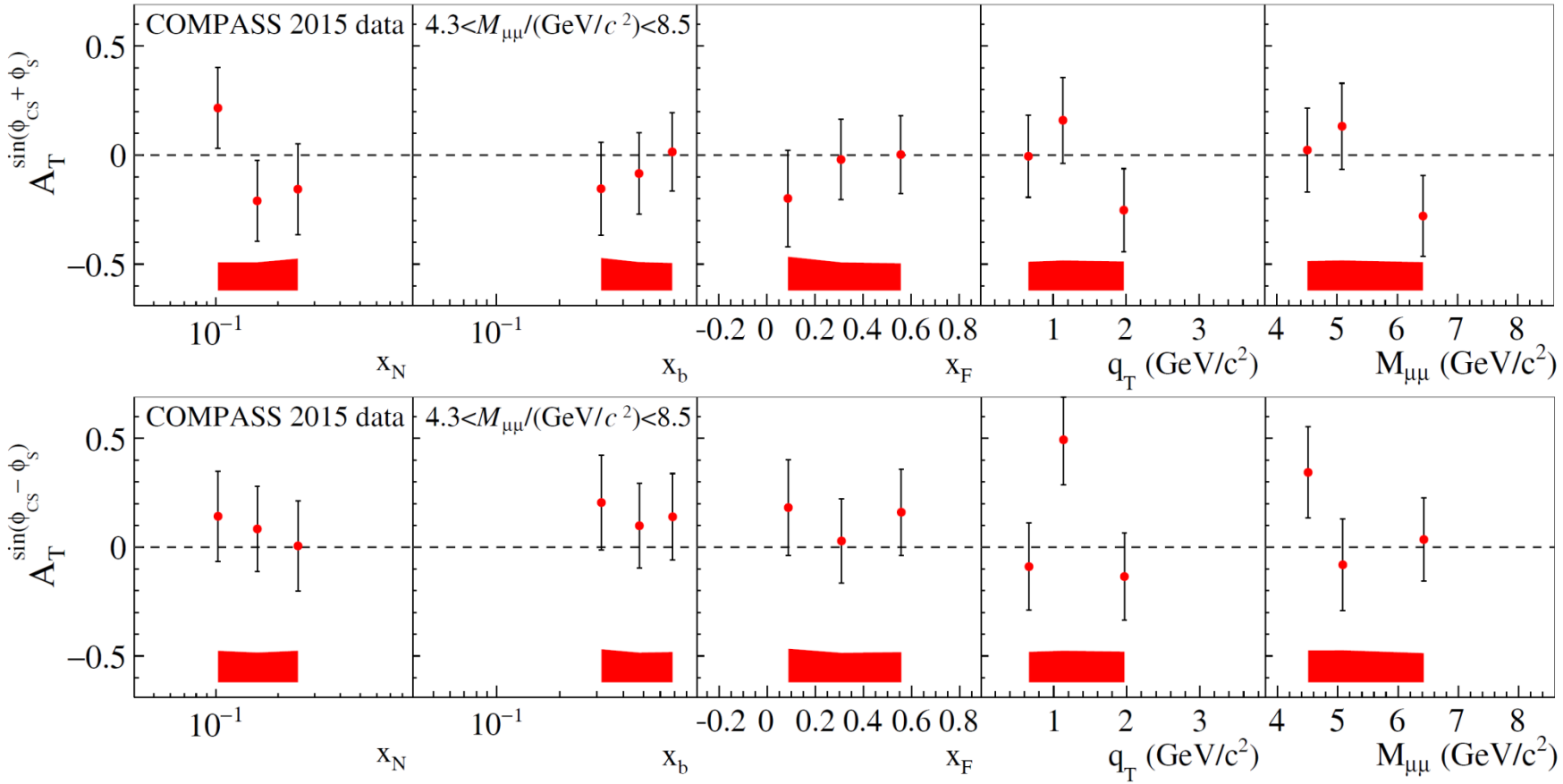
New! 03 April 2017! COMPASS CERN-EP-2017-059, arXiv:1704.00488[hep-ex]



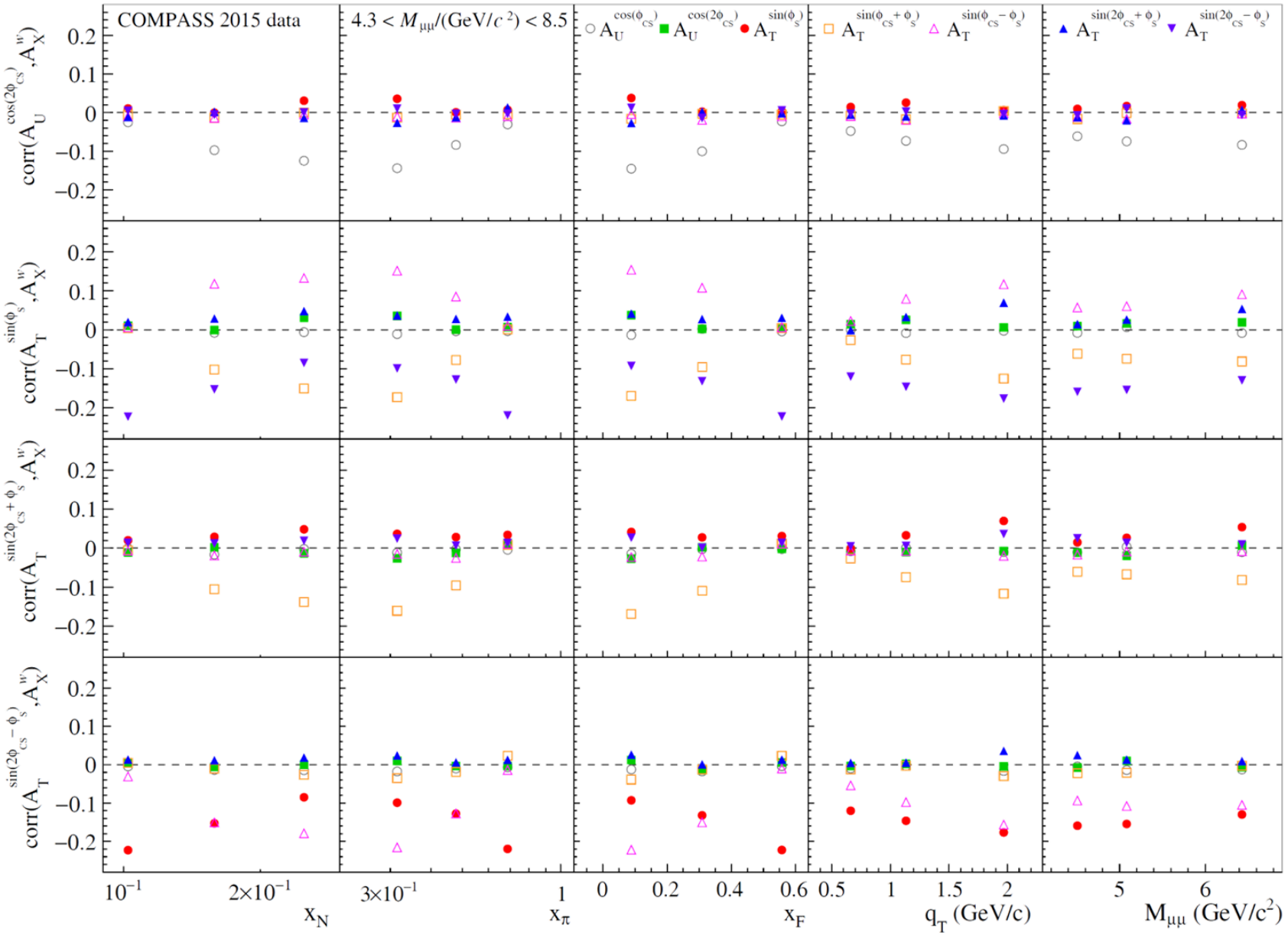
Drell-Yan TSAs – "higher twists"

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

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



Correlation coefficients



Maximum correlations are about ~0.2

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

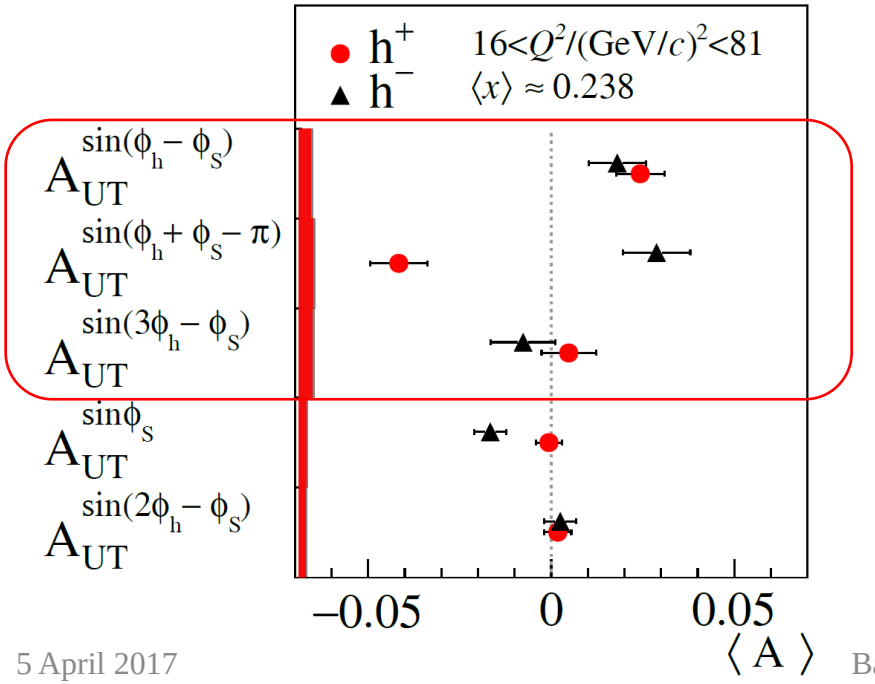
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ \; 1 + \ldots$$

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

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

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

COMPASS [arXiv:1609.07374 [hep-ex]]



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

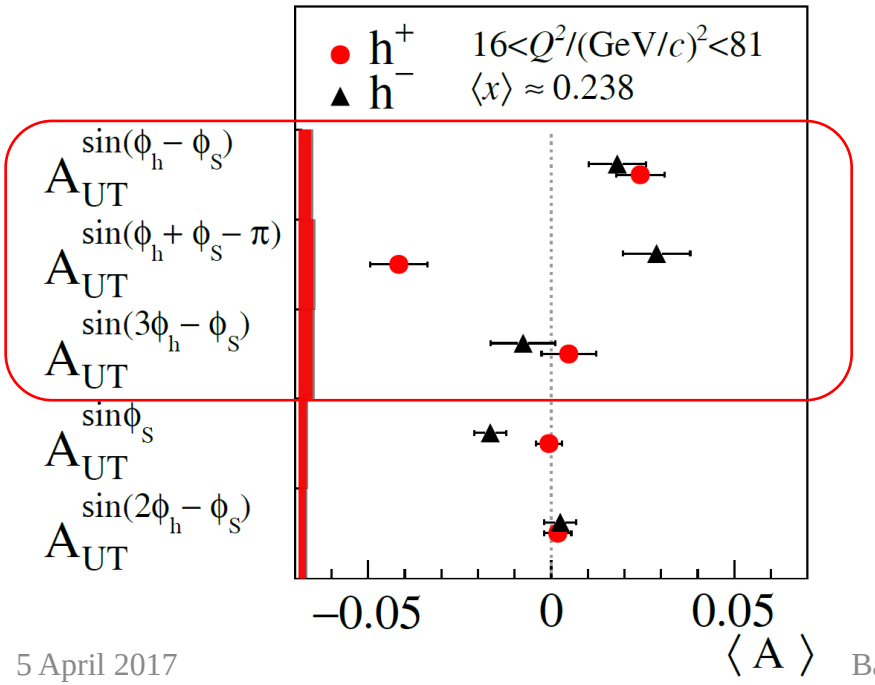
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ 1 + \ldots$$

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

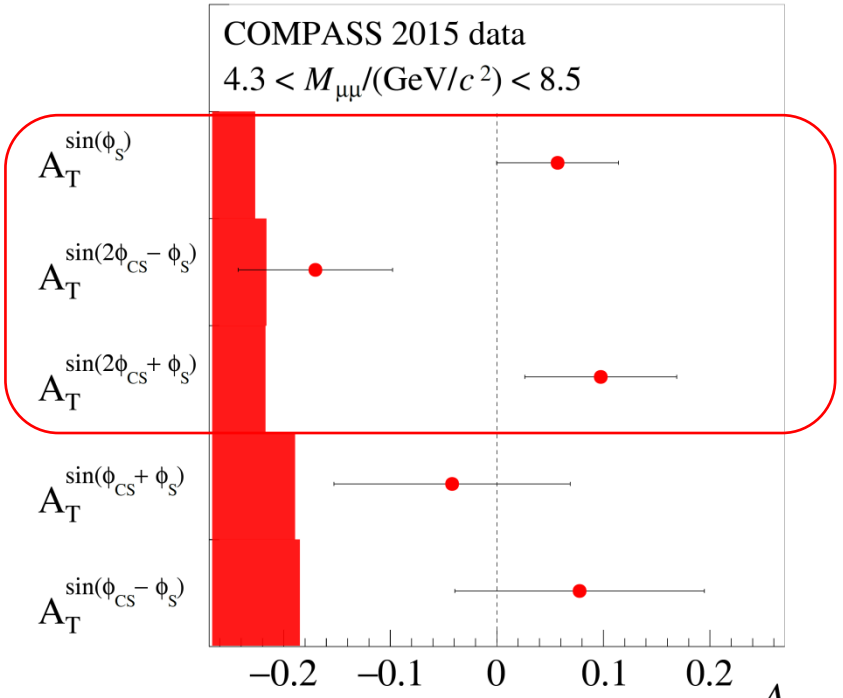
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)\Big\{ 1 + \ldots$$

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

COMPASS [arXiv:1609.07374 [hep-ex]]



COMPASS [arXiv:1704.00488 [hep-ex]]

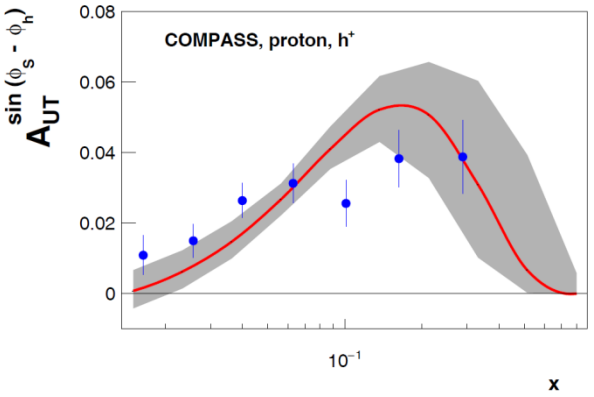


Dessert: Sivers sign change

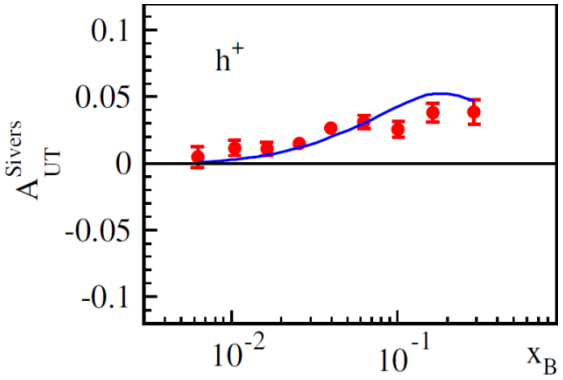
Wild berry panna cotta

Sivers asymmetry in Drell-Yan: sign change

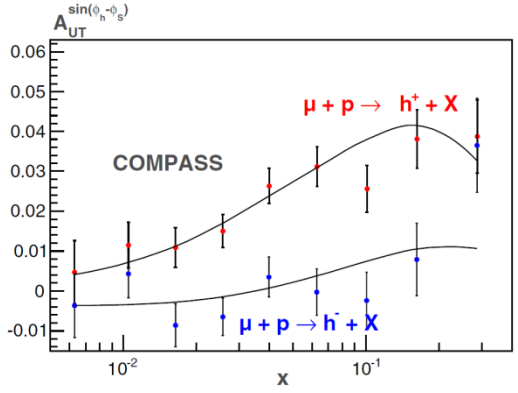
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.0641**3



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

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TMD-1 (2014)
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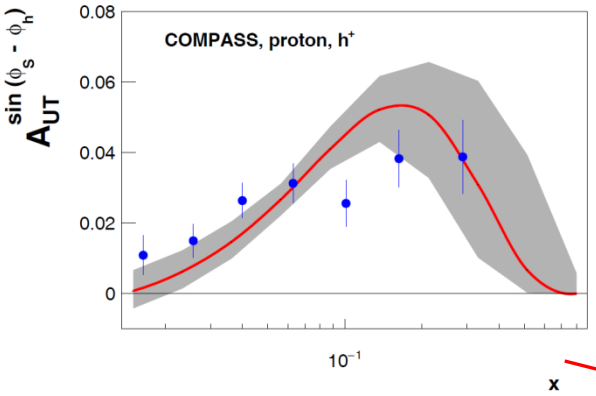
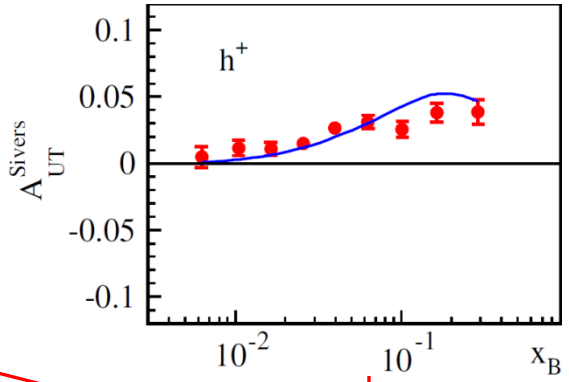
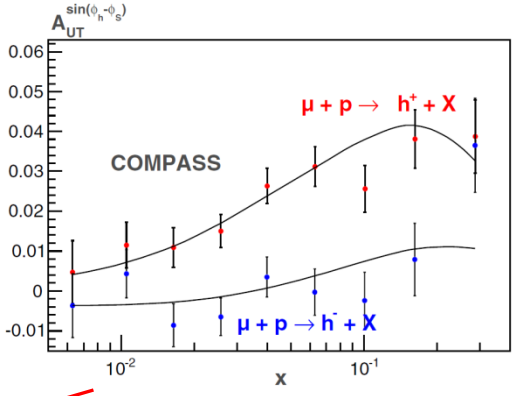
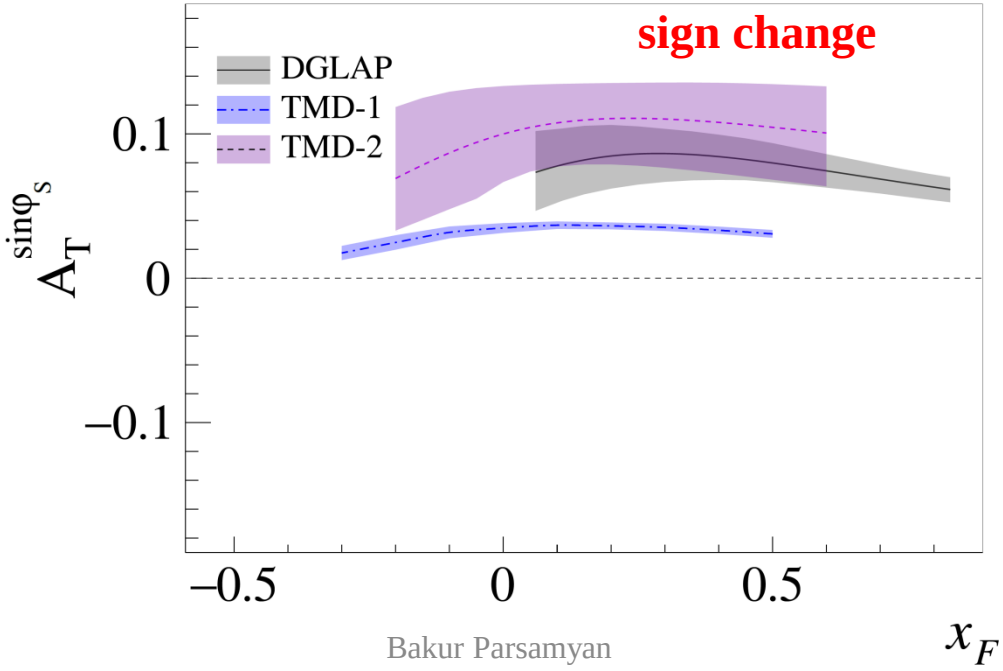
P. Sun, F. Yuan, **PRD88, 114012**









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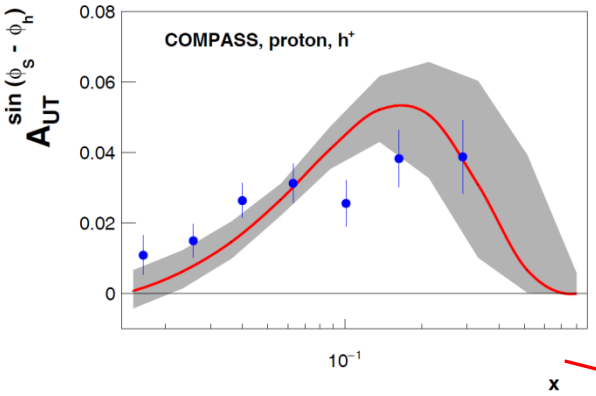

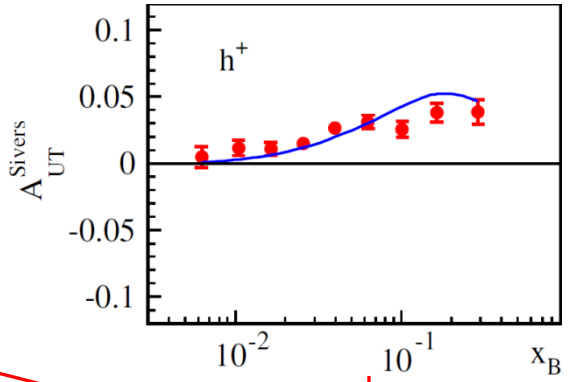

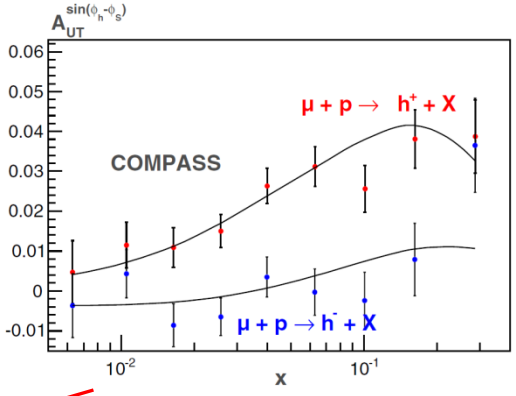

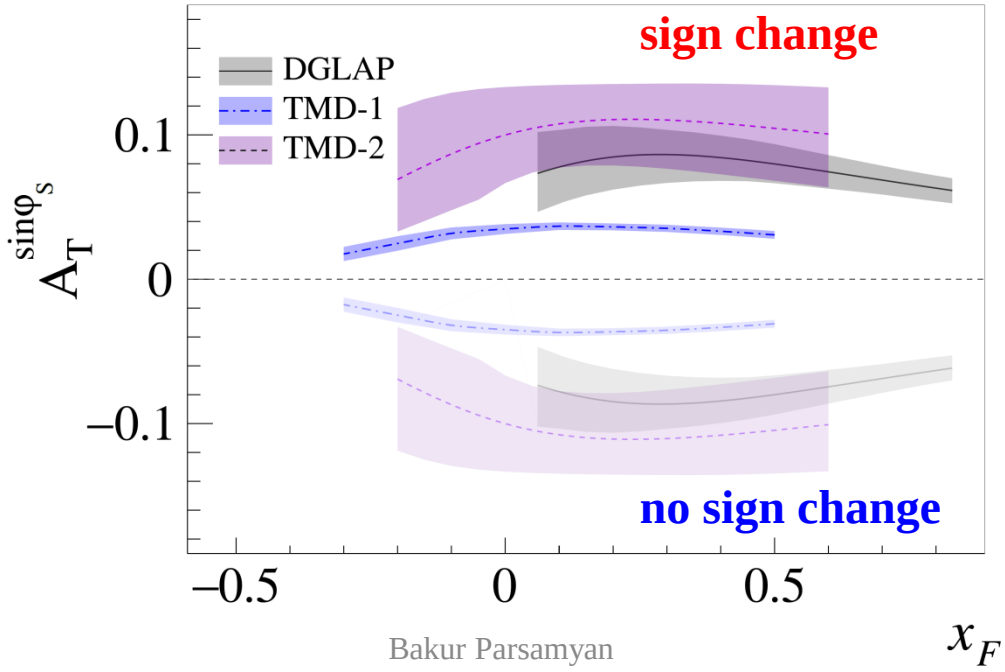

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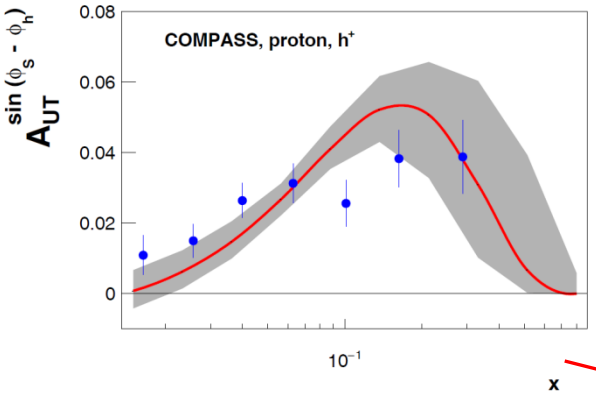
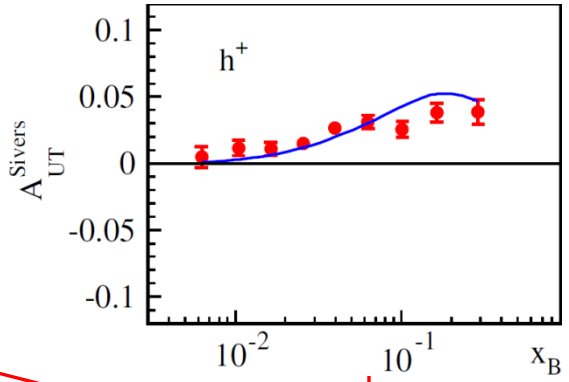
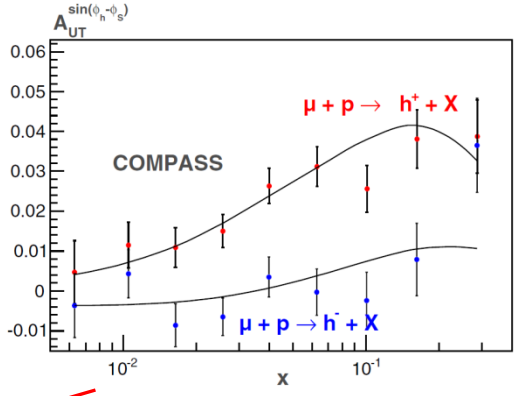
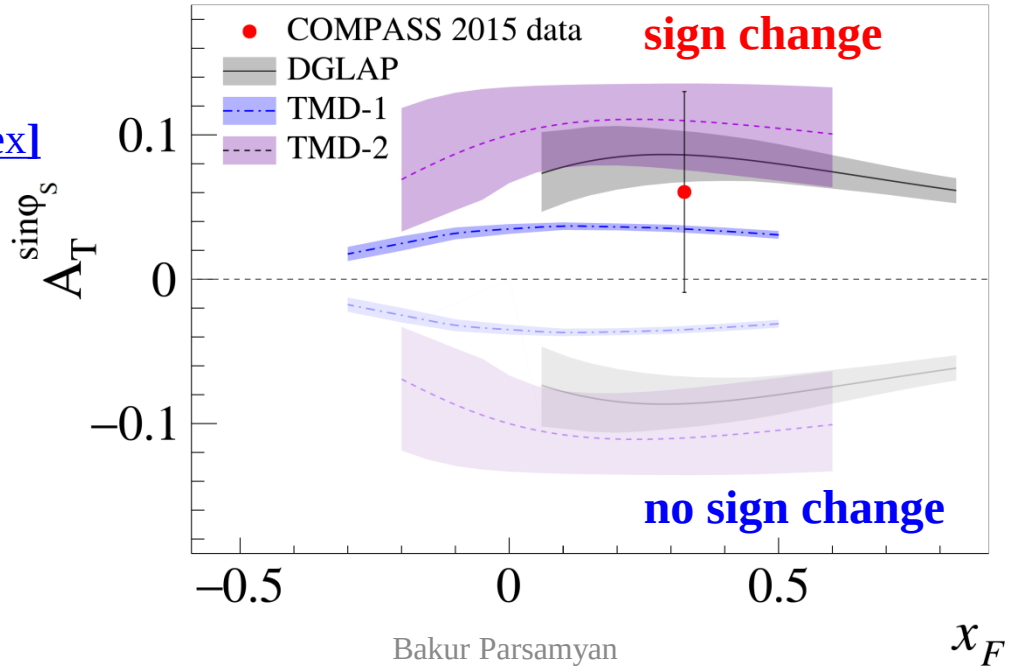






New! 03 April 2017
COMPASS
[CERN-EP-2017-059]
[arXiv:1704.00488[hep-ex]]



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 CERN-EP-2016-250, arXiv:1609.07374 [hep-ex]

- 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

Cold glass of Tuscan limoncello

Thank you!