Polarized Drell-Yan and SIDIS measurements at the COMPASS experiment

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CERN, University of Turin
and
INFN section of Turin

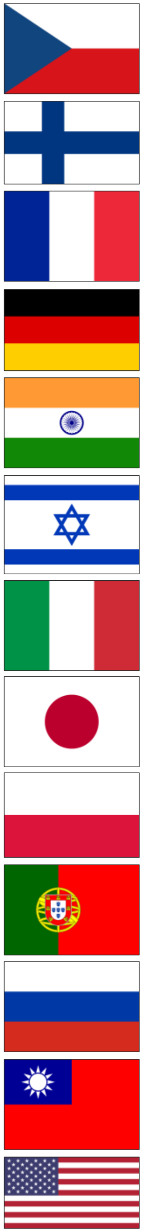
UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

on behalf of the COMPASS Collaboration

International workshop on
"Dilepton Productions with Meson and Antiproton Beams"
ECT*, Trento, Italy
November 6 – 10, 2017

COMPASS collaboration

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



24 institutions from 13 countries
– nearly 250 physicists

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997**
- **Taking data since 2002**

Wide physics program

COMPASS-I

- **Data taking 2002-2011**
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- **Nucleon spin structure**
- **Spectroscopy**

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- **Data taking 2012-2018 (2021?)**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
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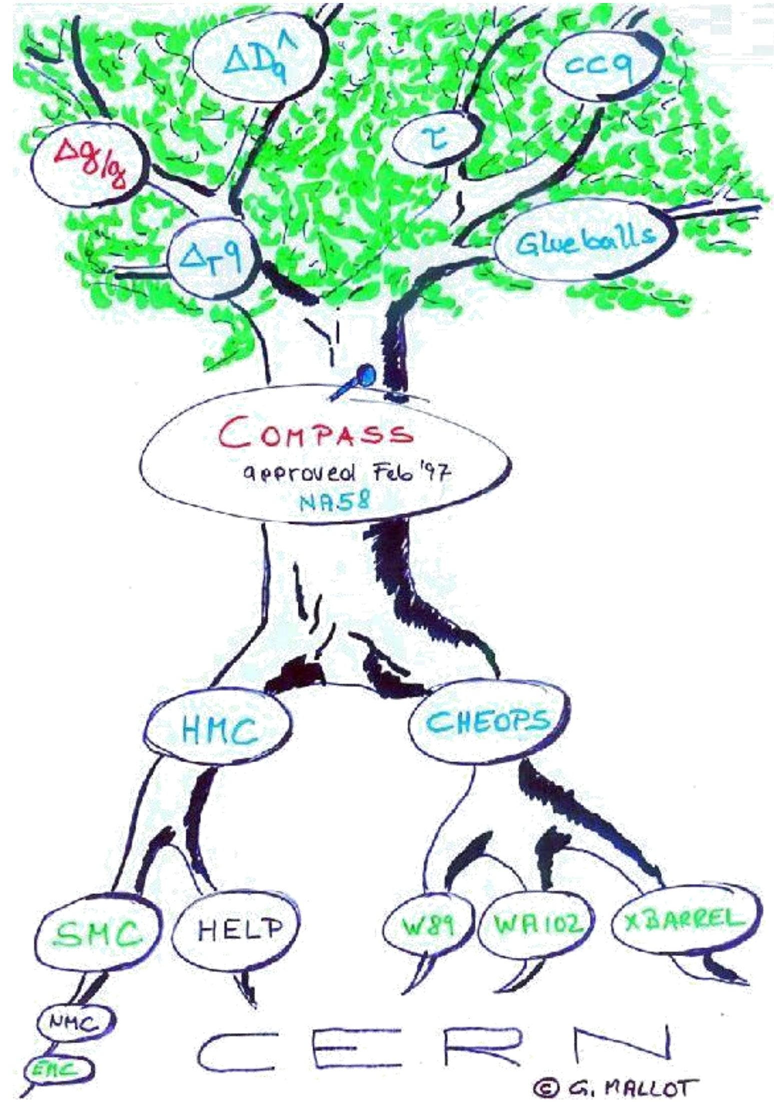
Many “beyond 2021” ideas:

See talks by V. Andrieux, B. Grube, A. Guskov, O. Denisov, C. Quintans, J. Berhnard



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

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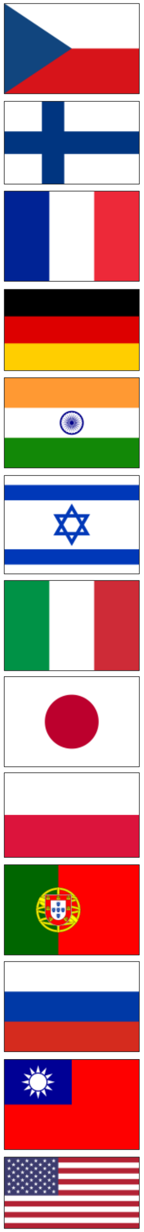

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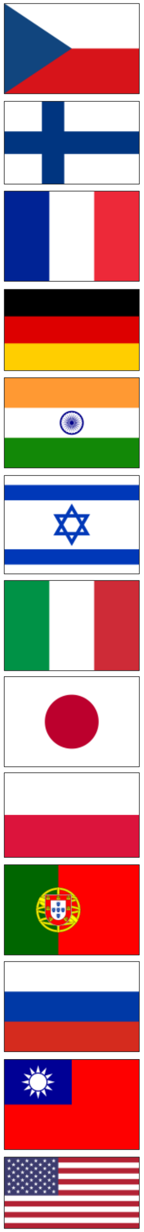

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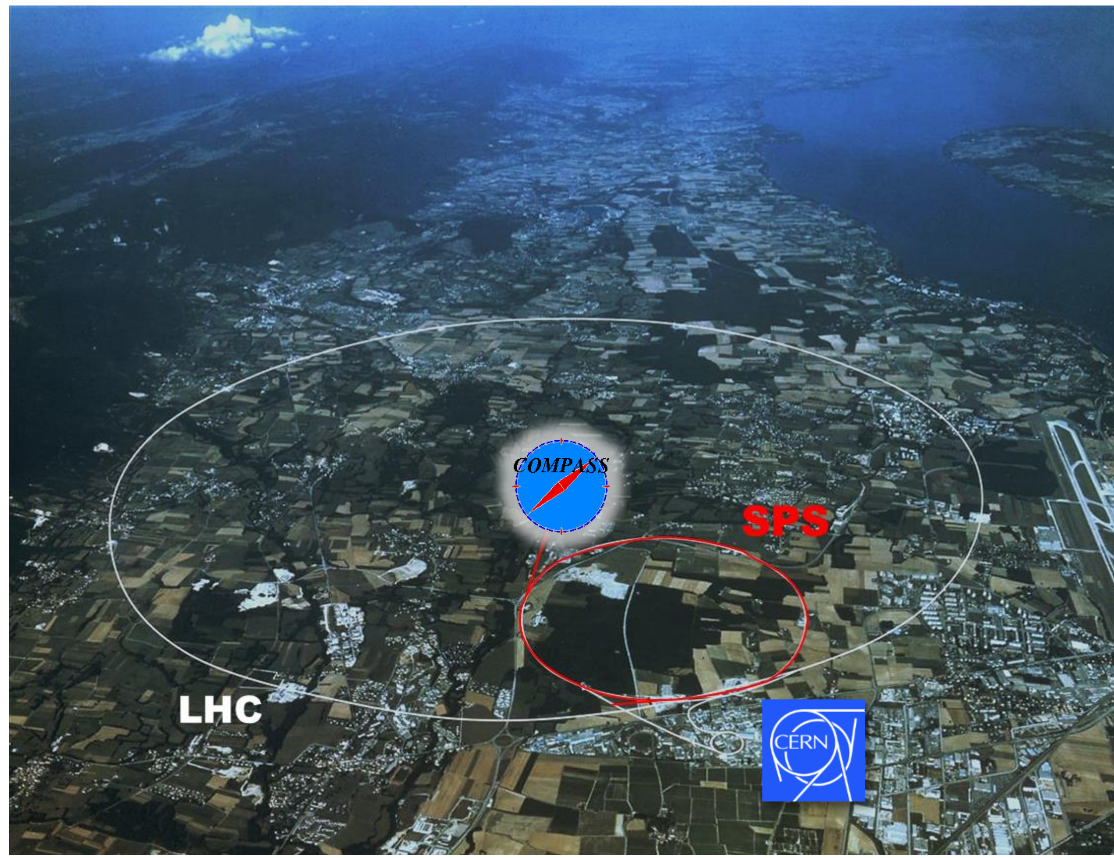

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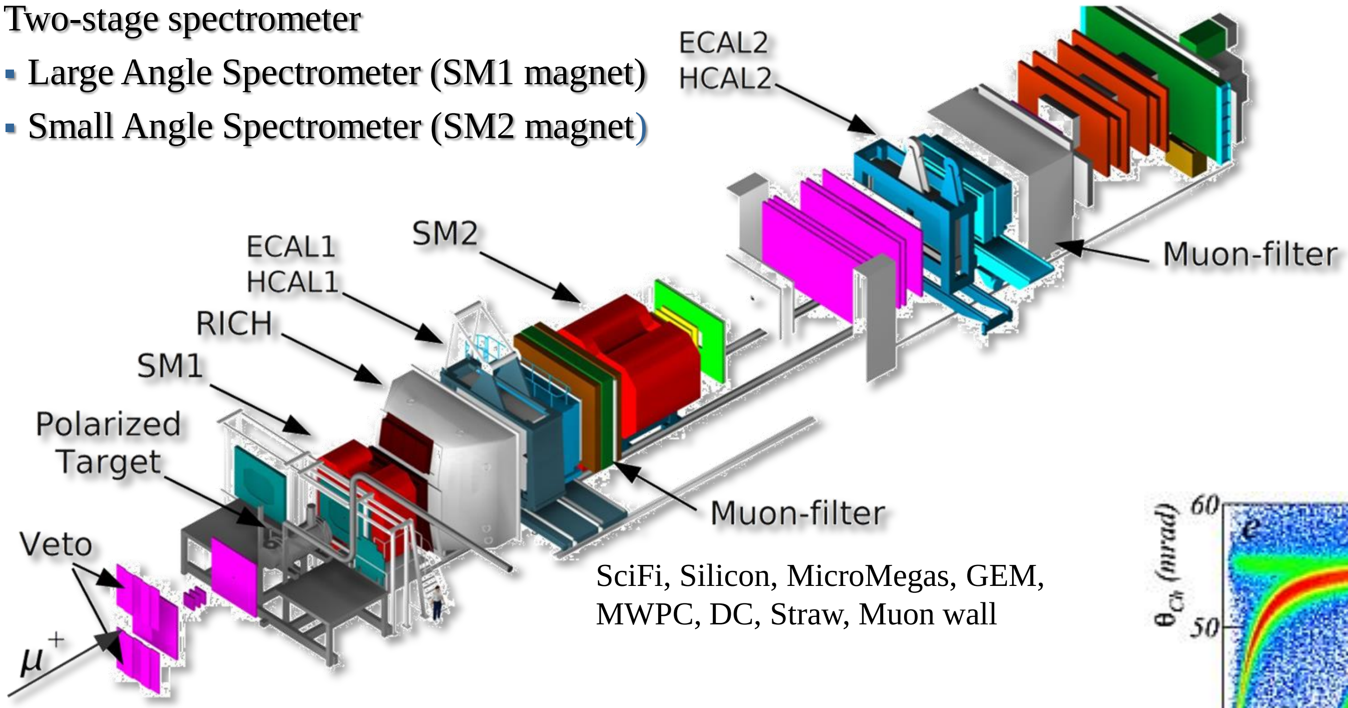

SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

- High energy beam
- Large angular acceptance
- Broad kinematical range
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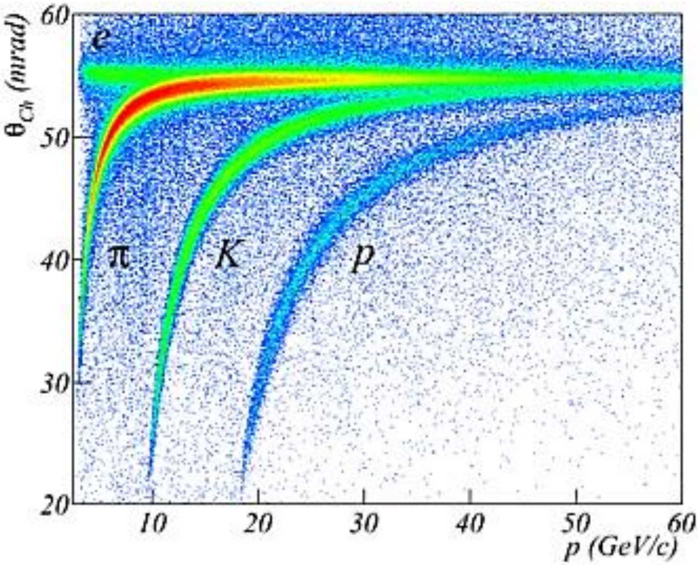

Data-taking years: 2002-2011

Longitudinally polarized (80%) μ^+ beam:

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

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

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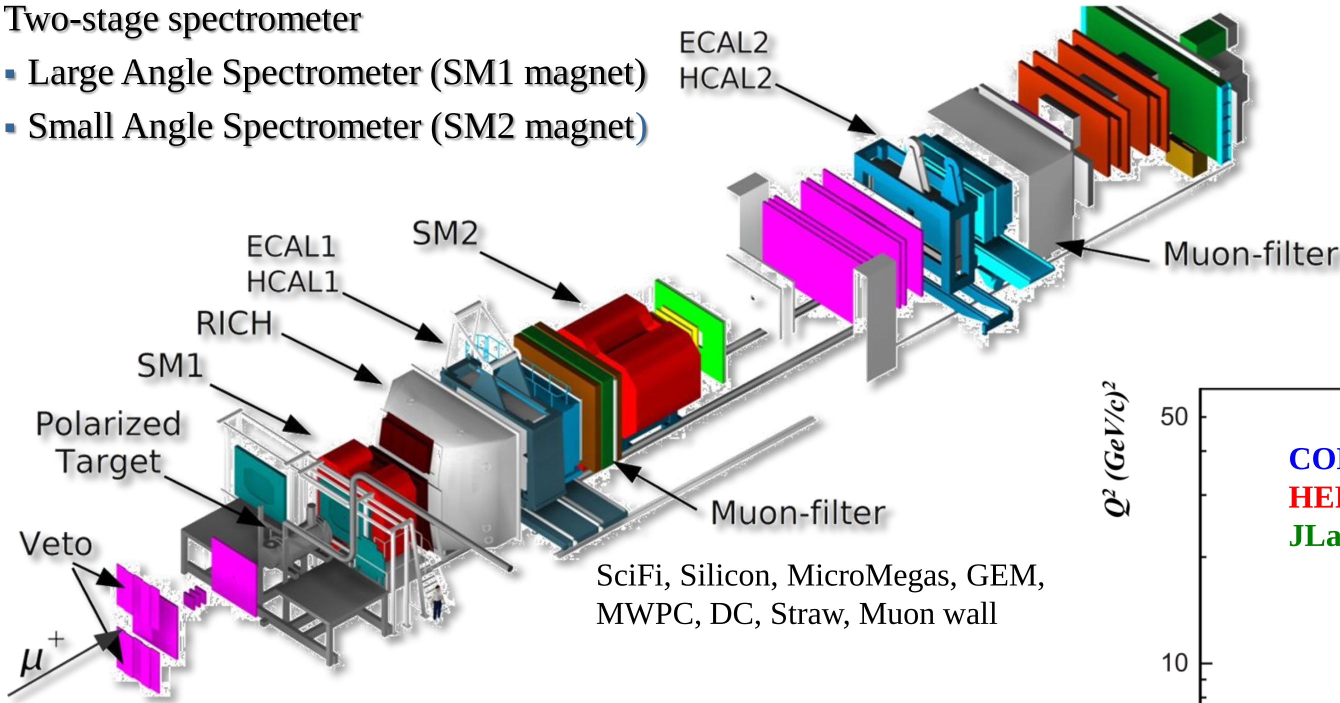

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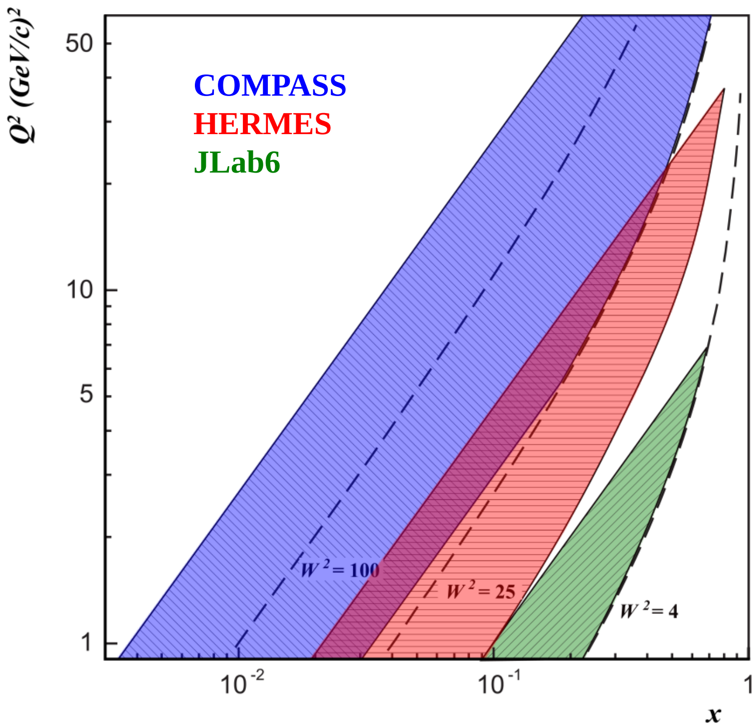

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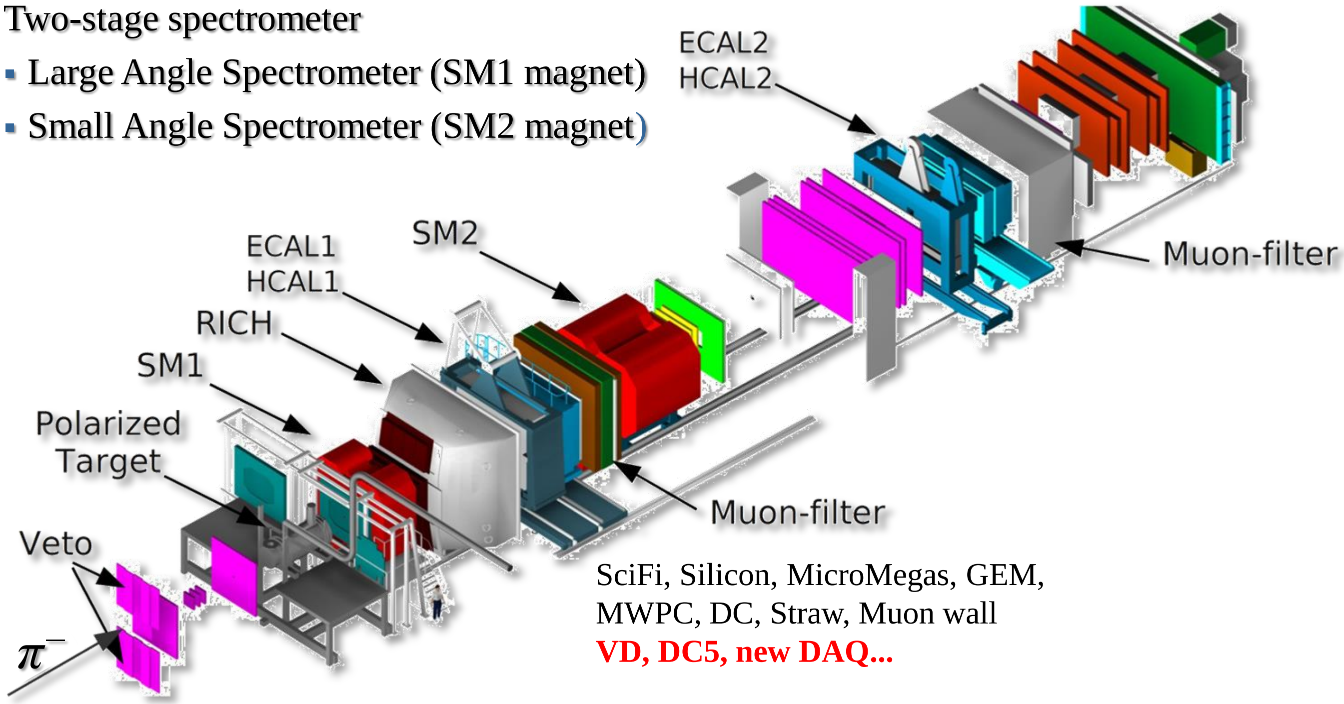

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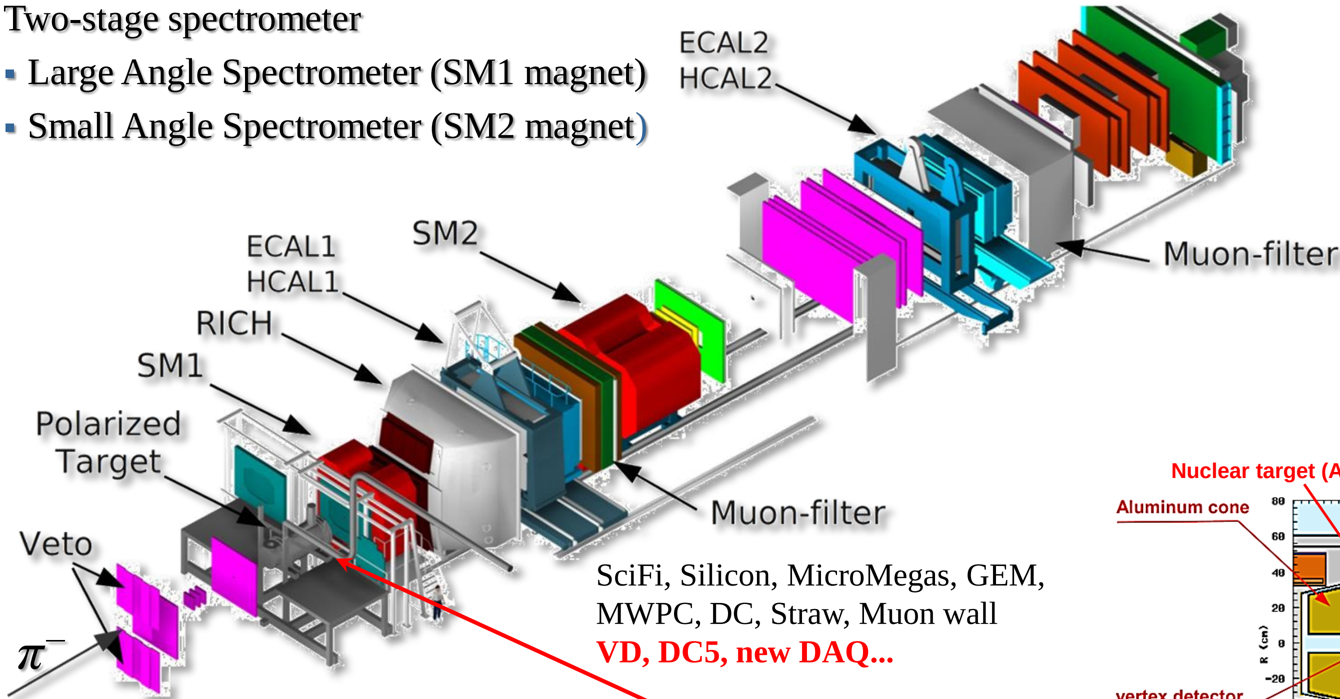

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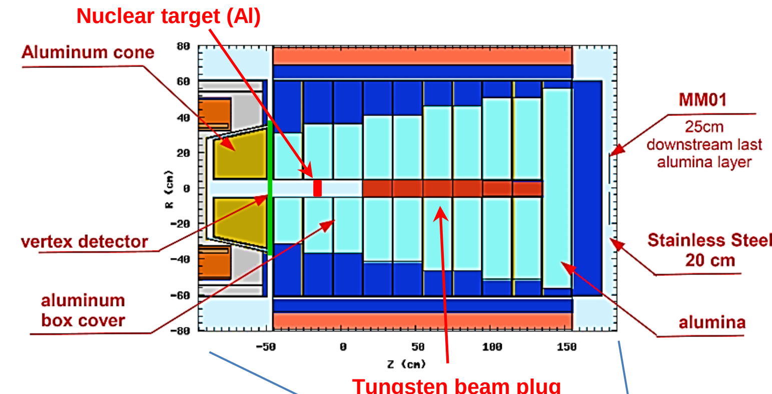
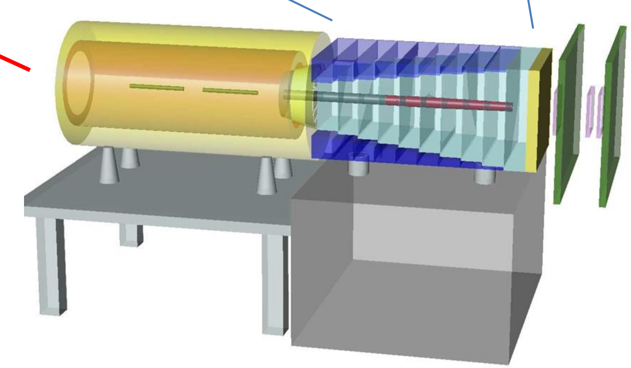
Hadron absorber





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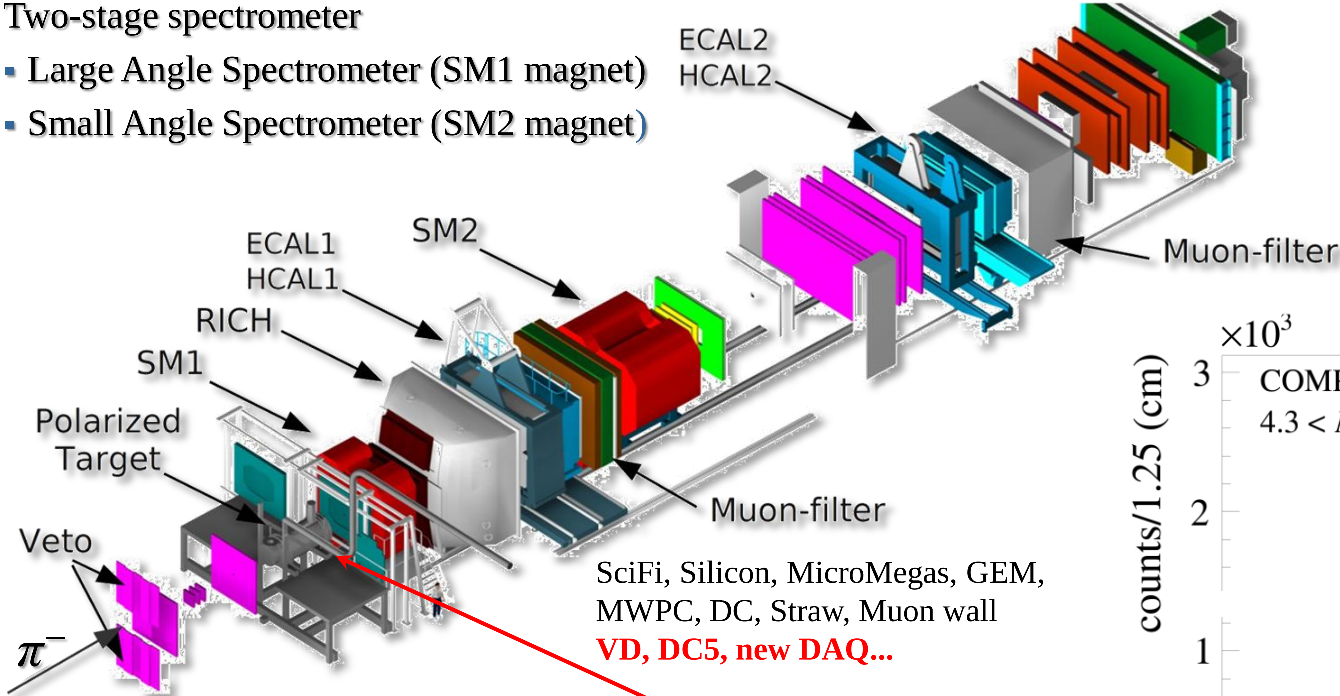

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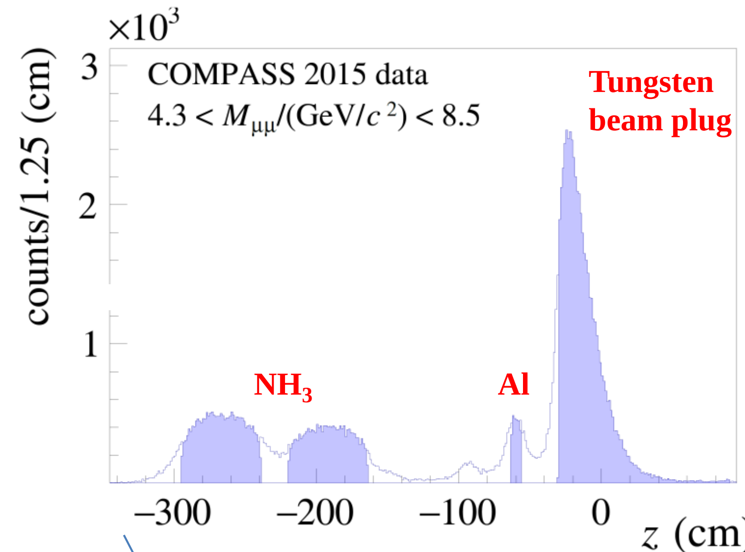

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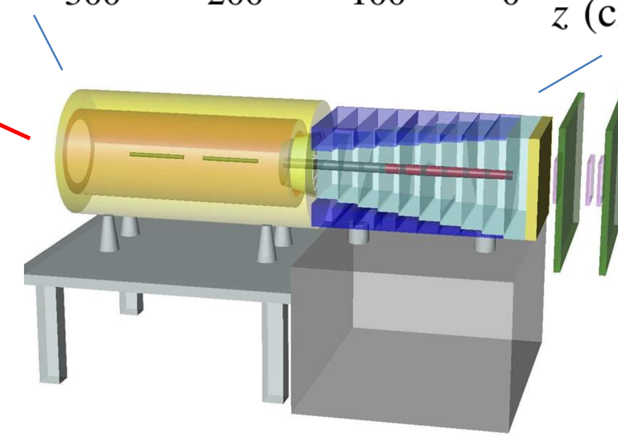

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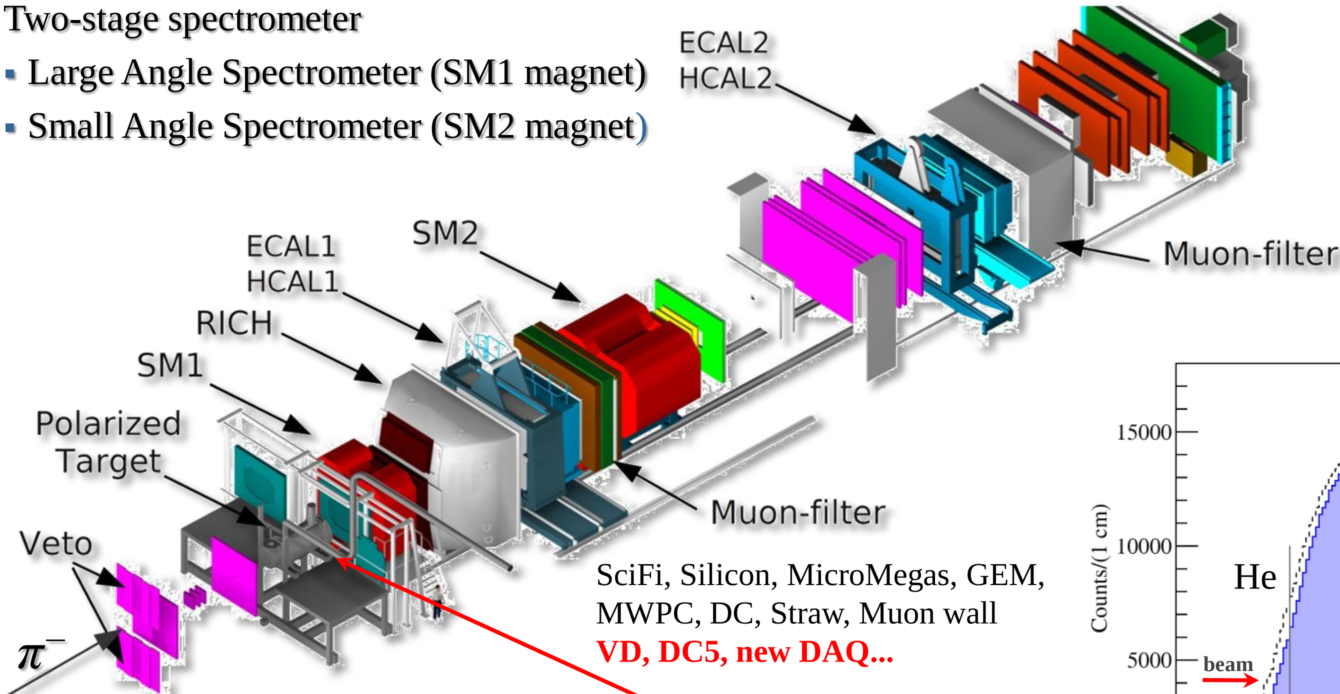

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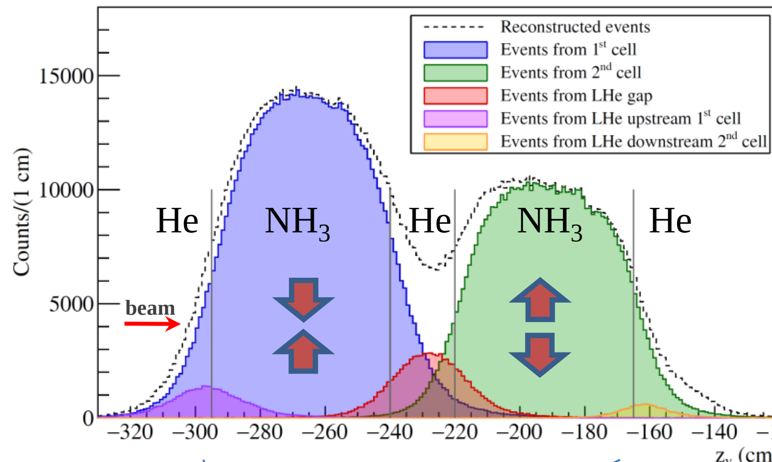

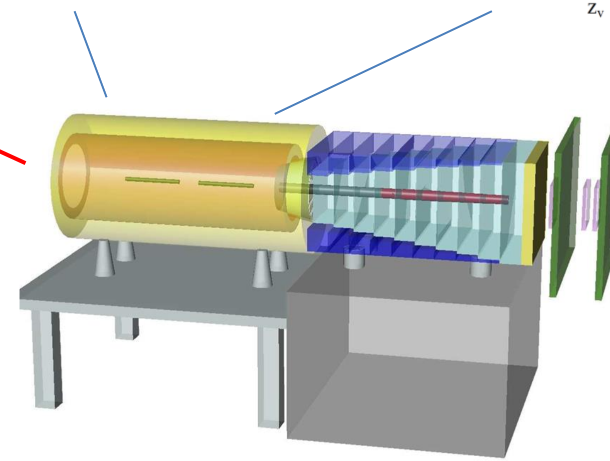

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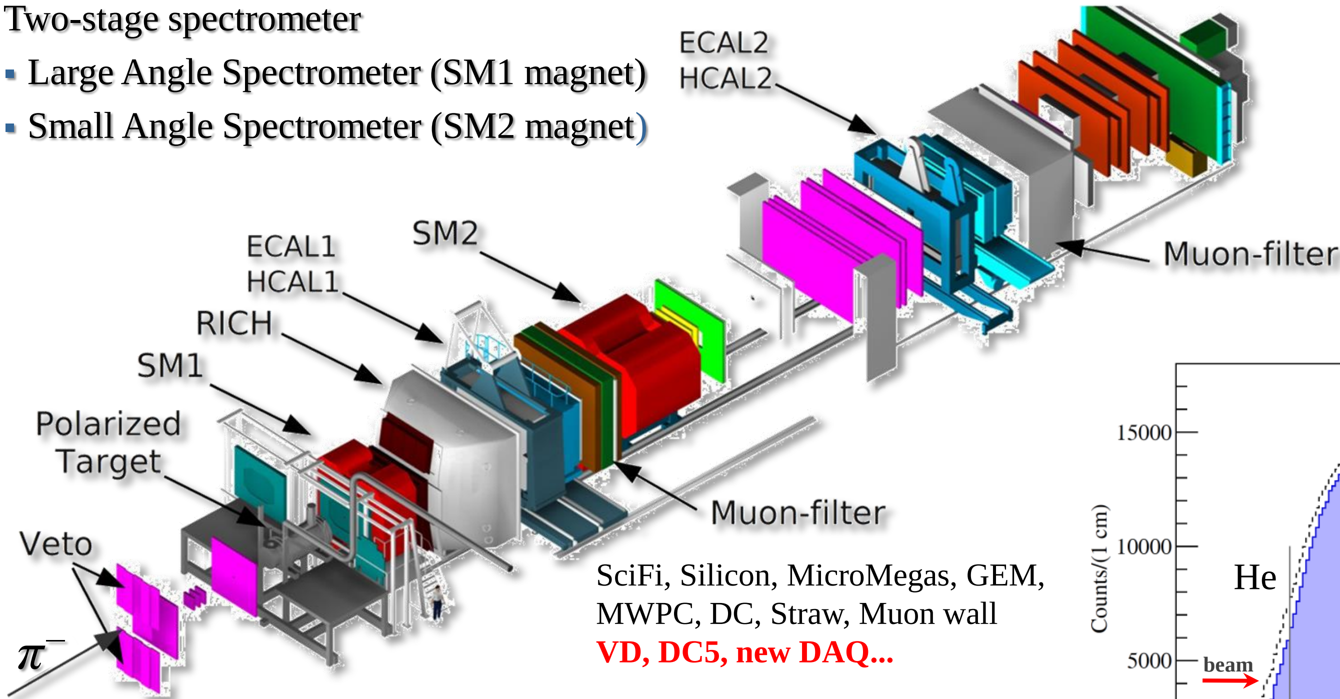

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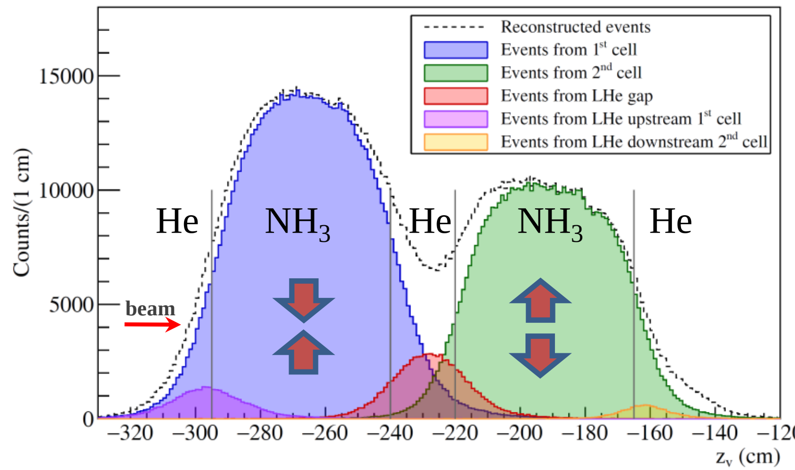

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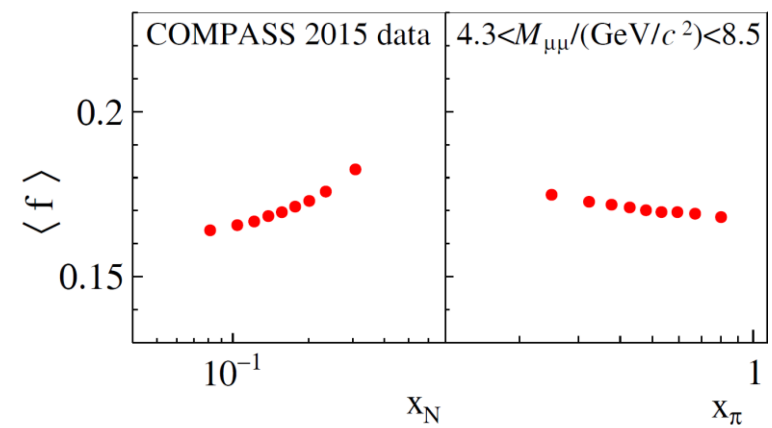

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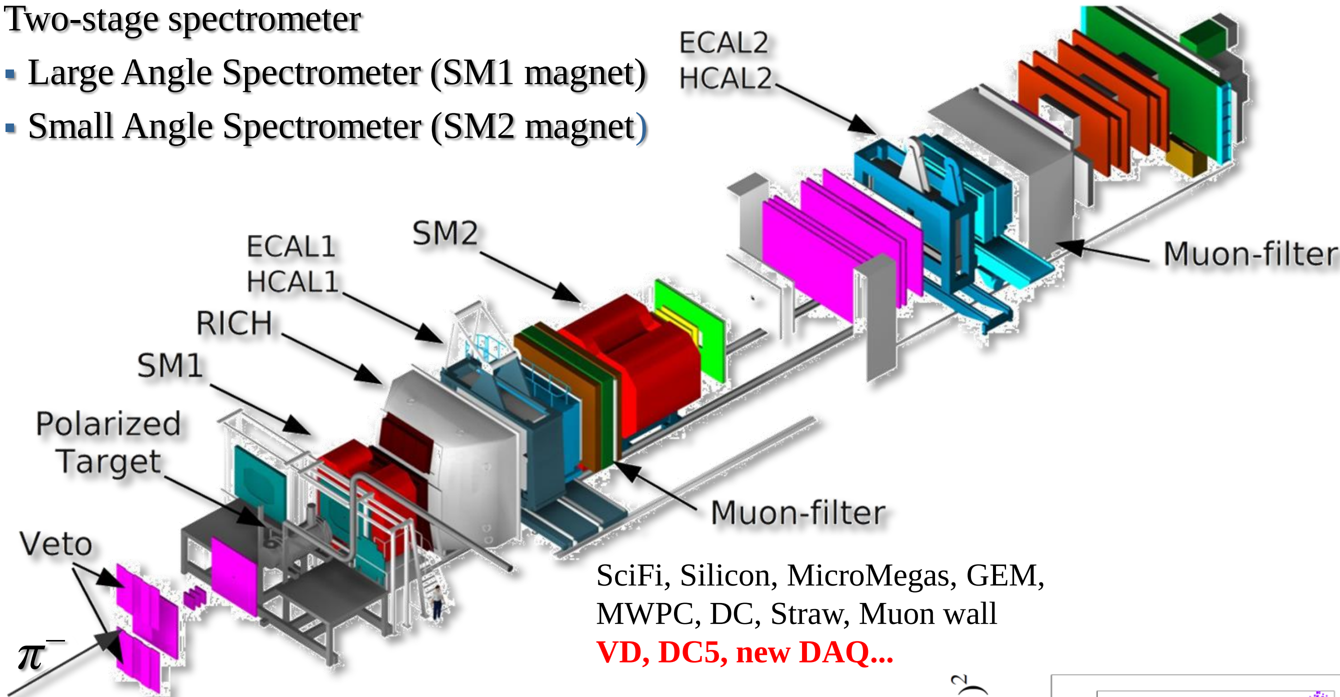

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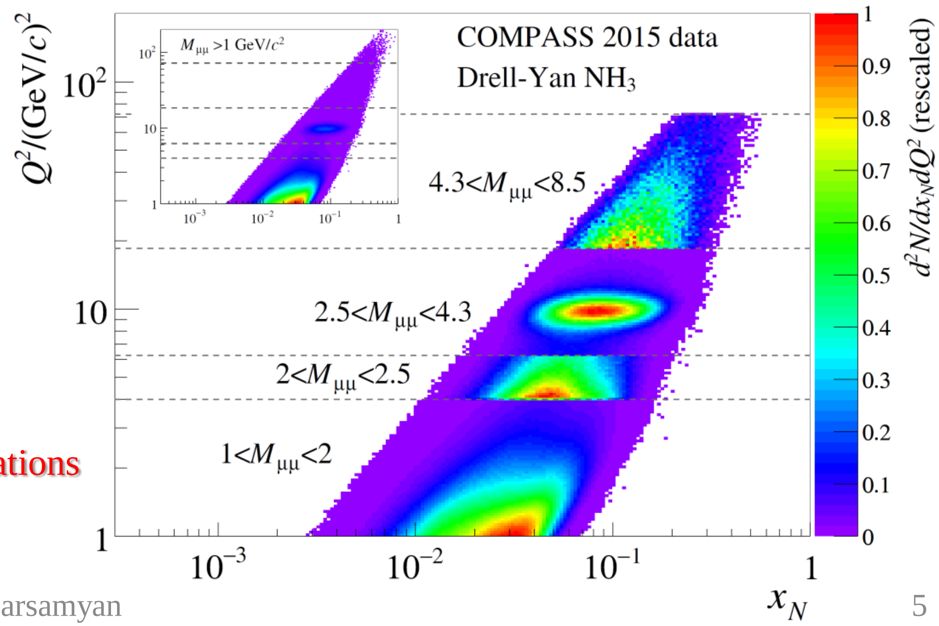

COMPASS DY mass ranges

- $1.0 < M/(GeV/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
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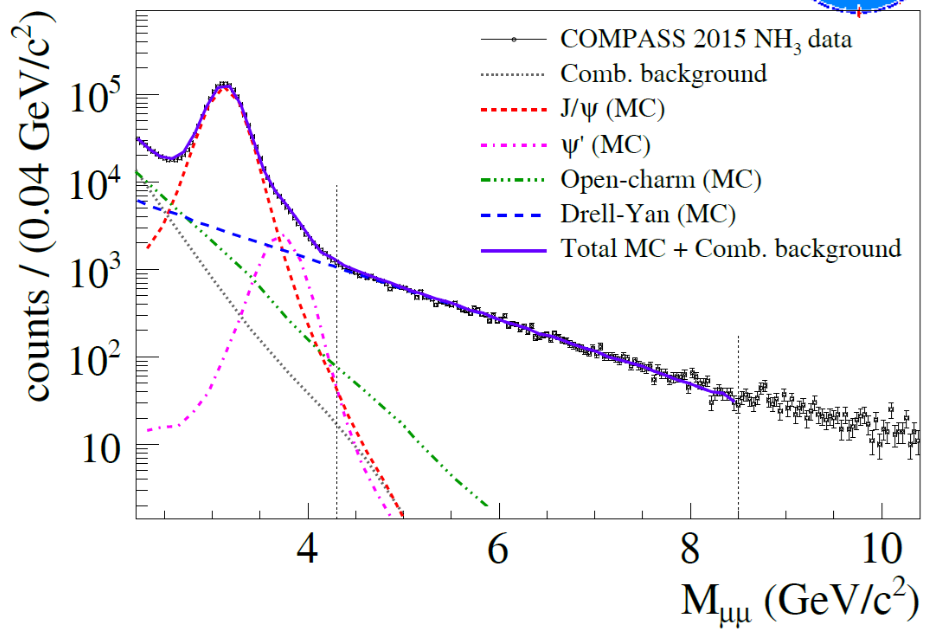

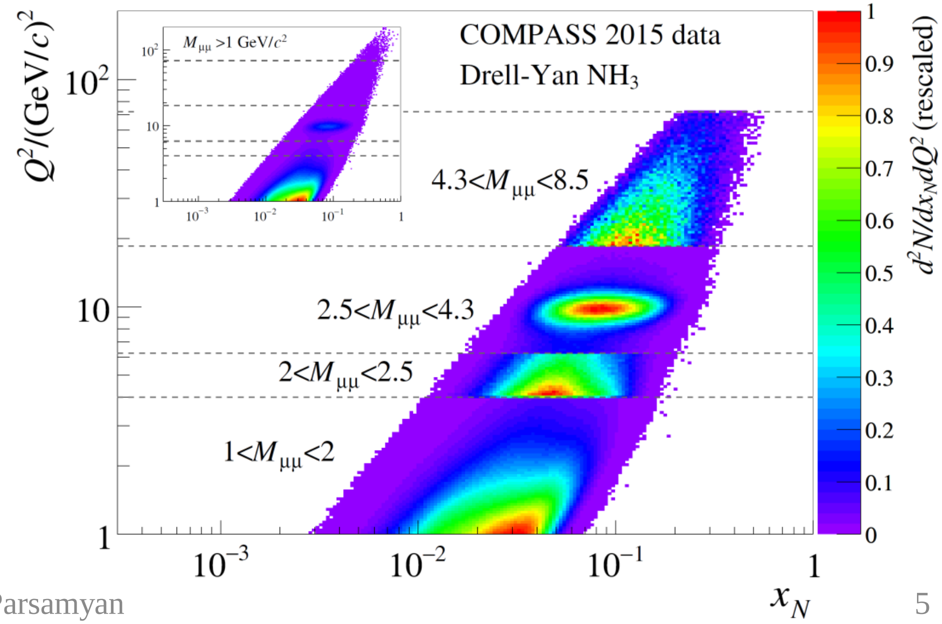

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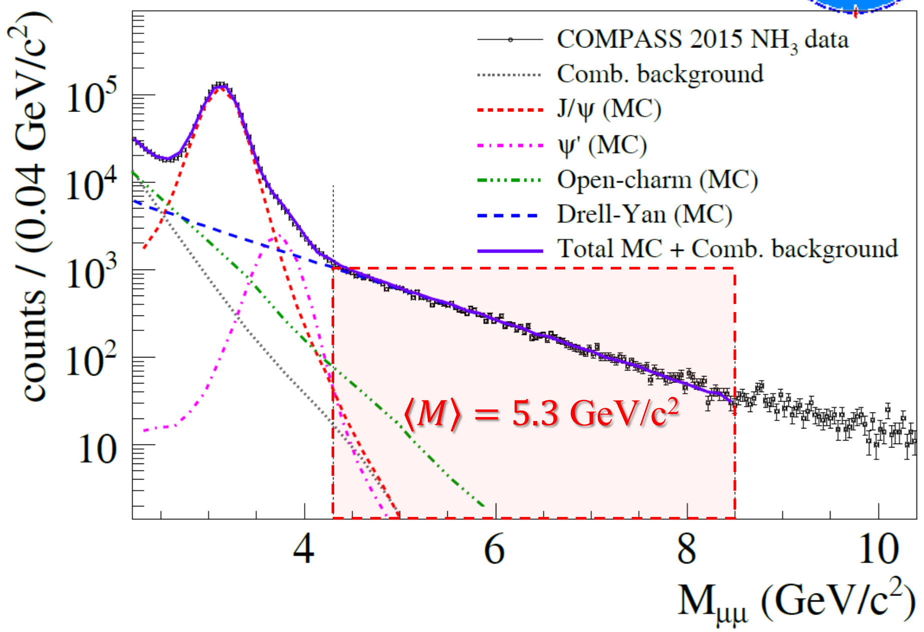
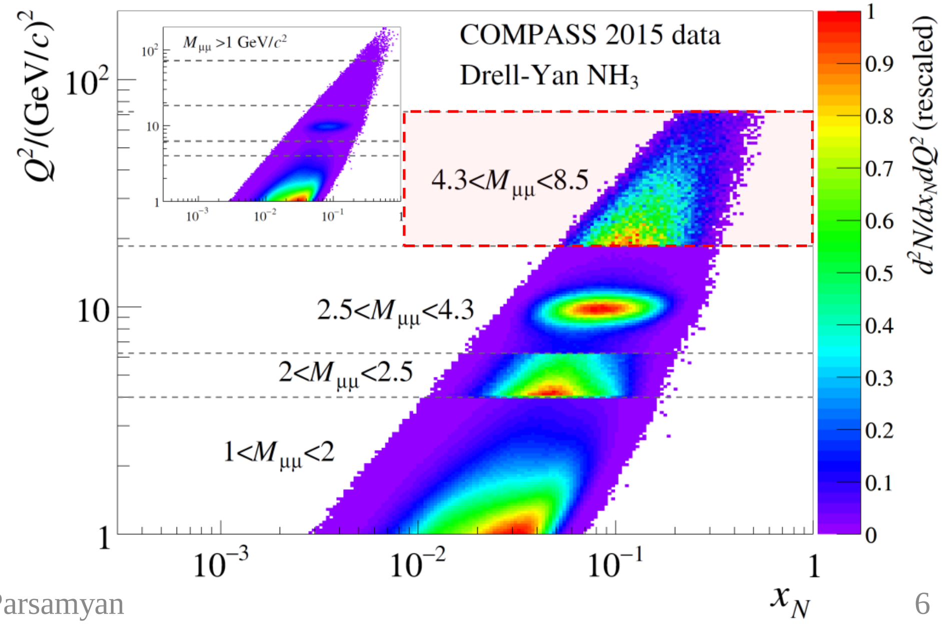
Final sample: 35 000 dimuons in HM





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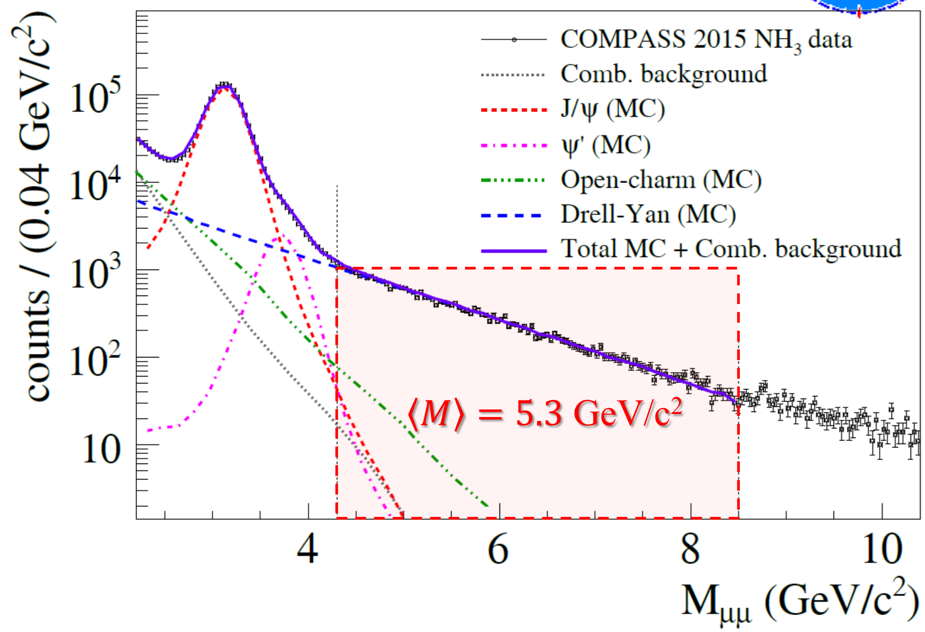
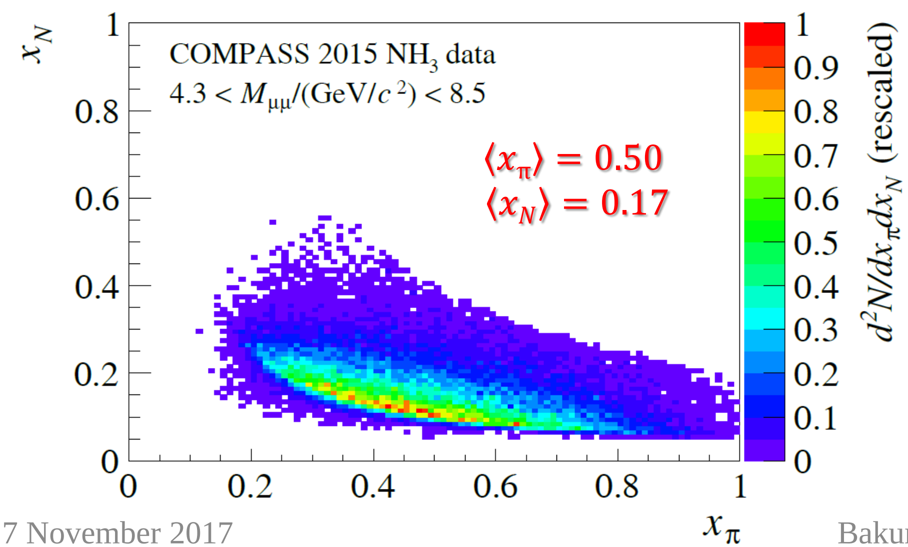
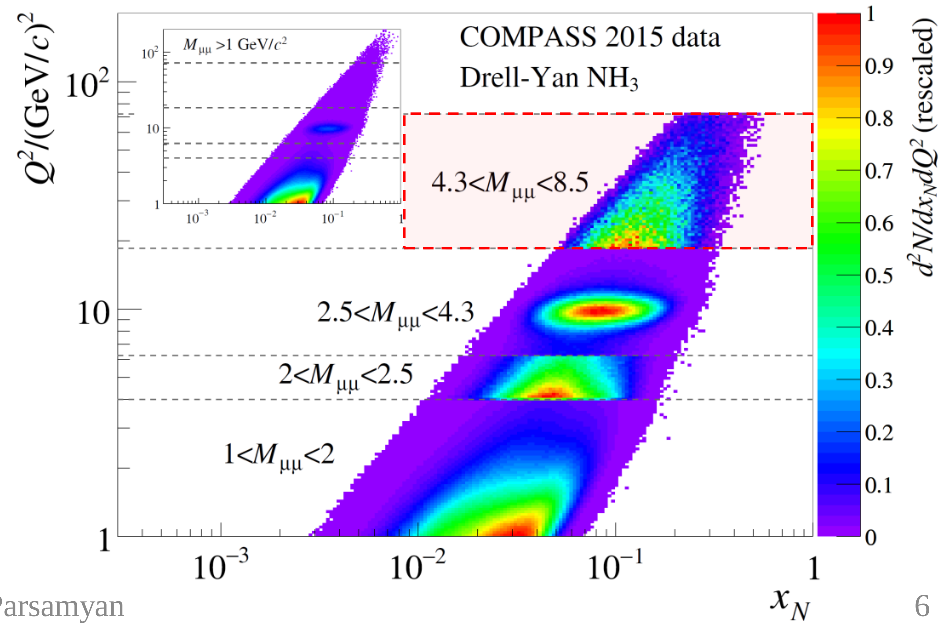


HM events are in the valence quark range





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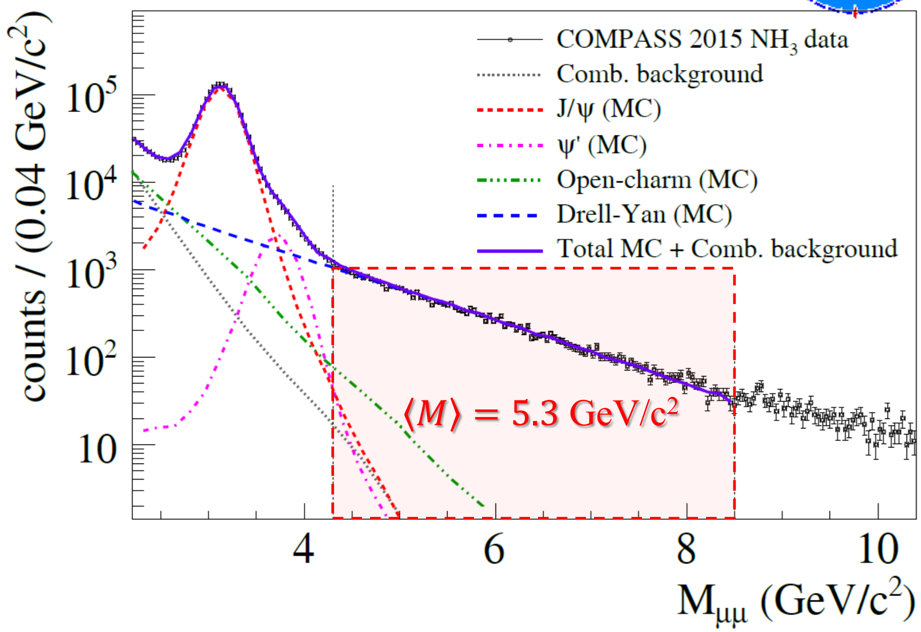
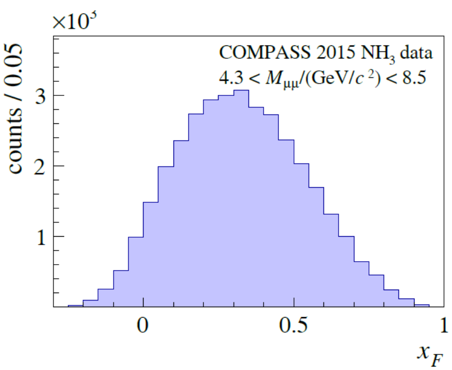
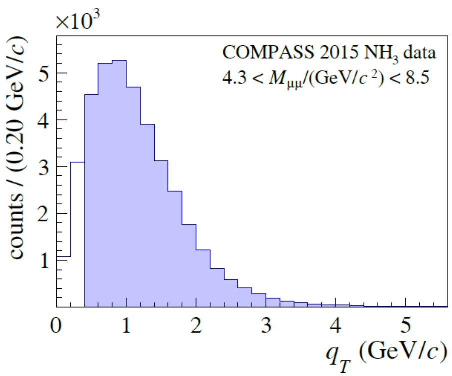
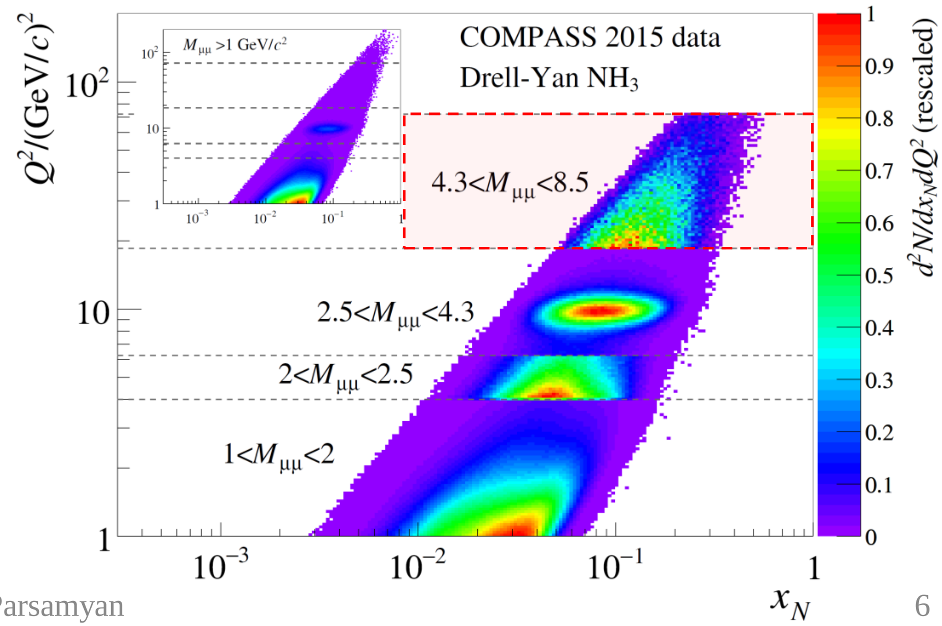


Dimuon transverse momentum $q_T > 0.4$ GeV/c

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







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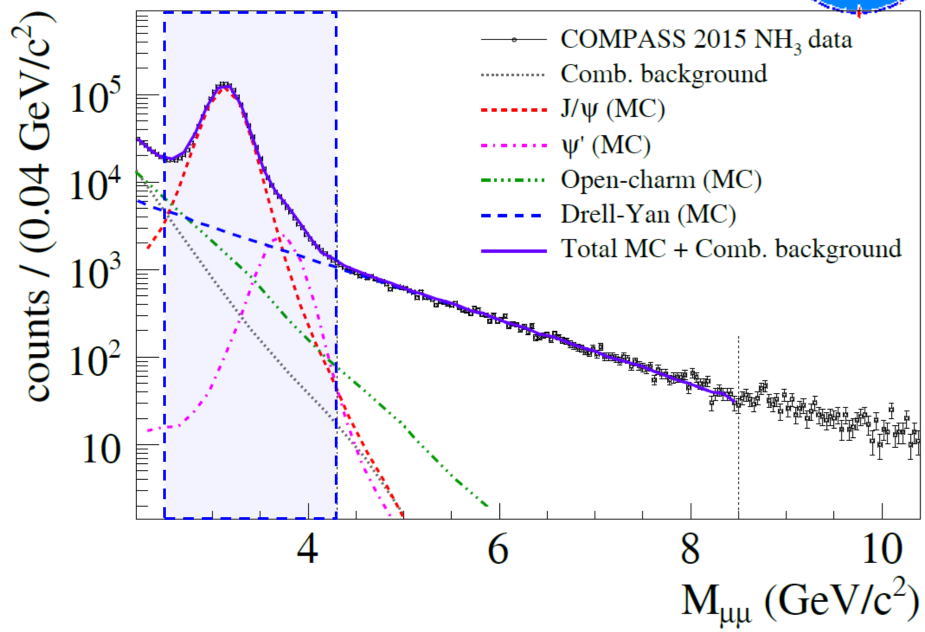
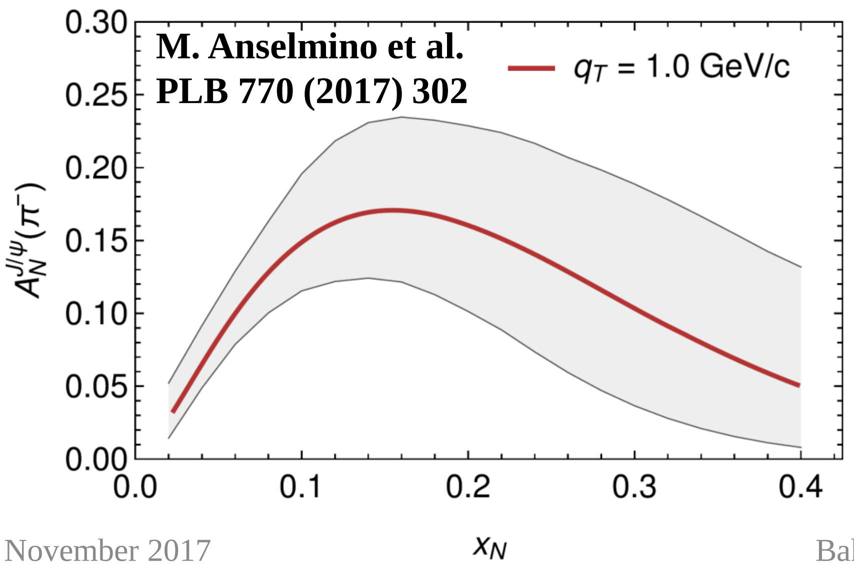
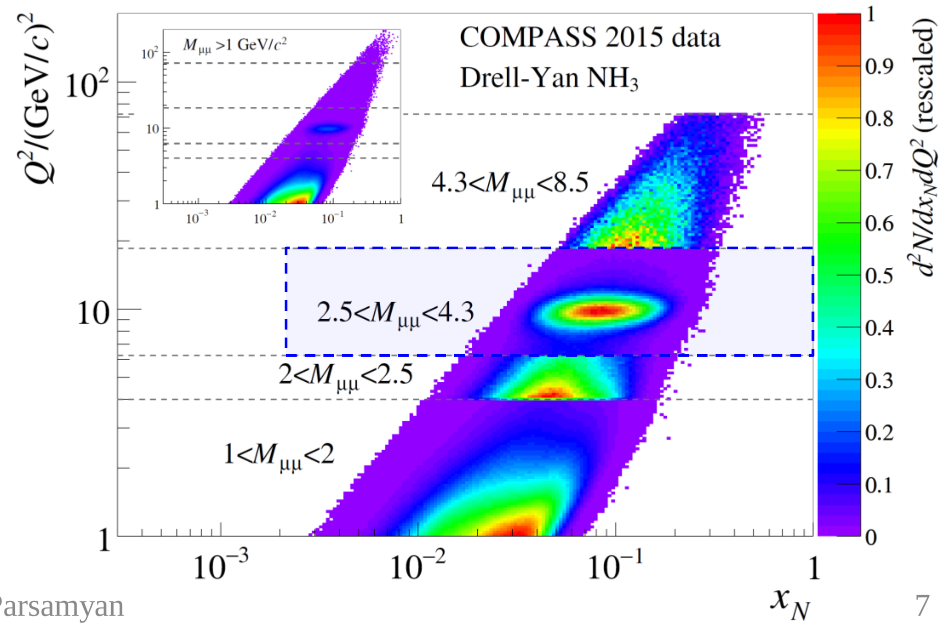


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c





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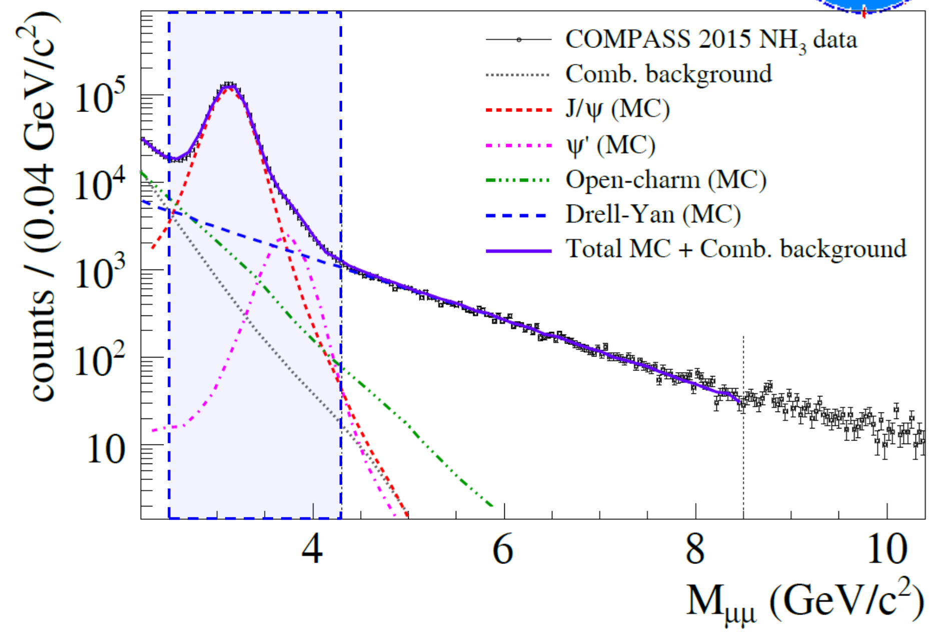
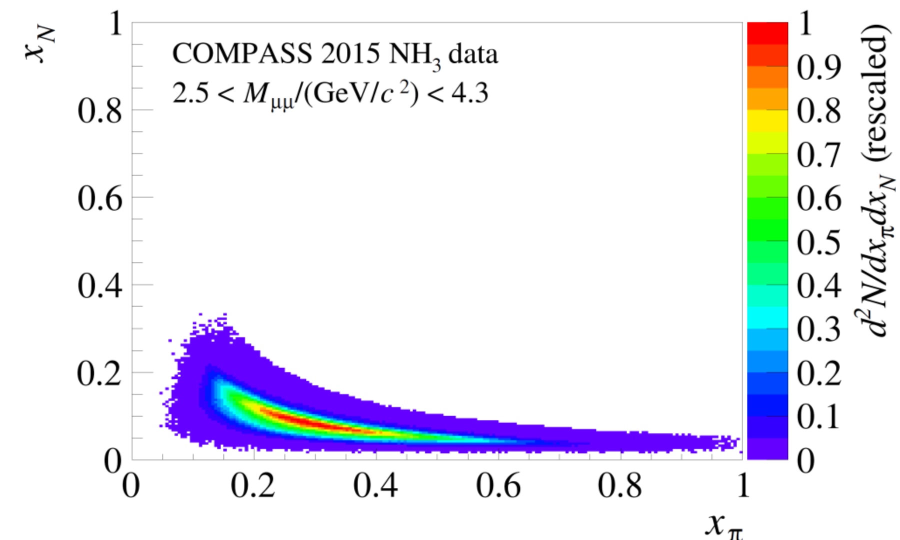
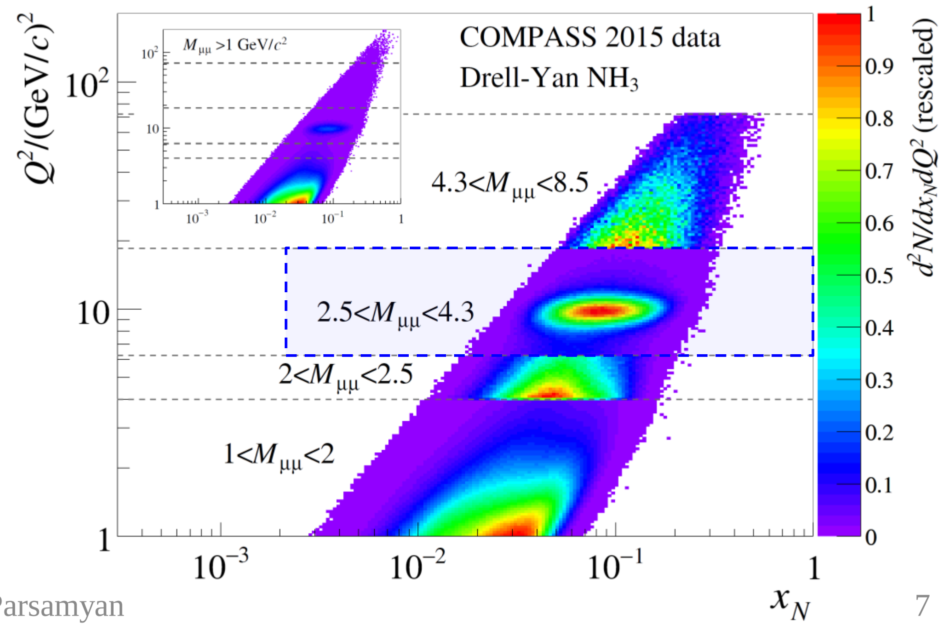


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c



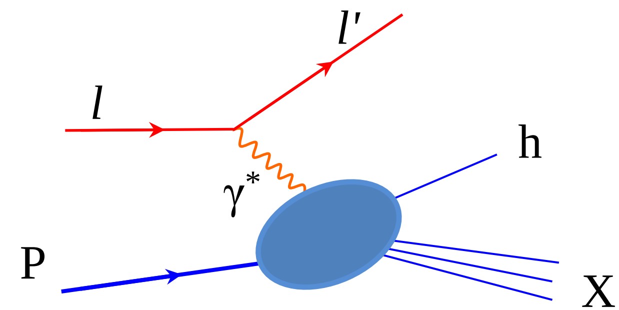


COMPASS bridge

SIDIS x-section

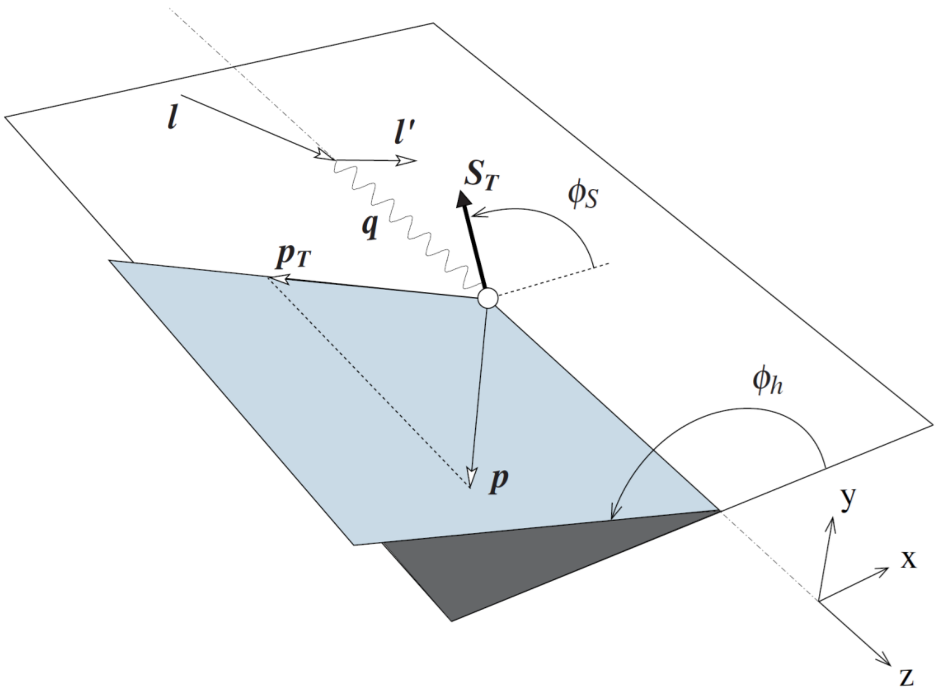
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

All measured by COMPASS



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

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



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

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

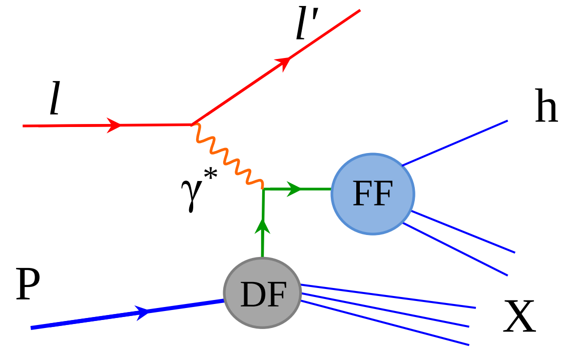
$$\times \Bigg\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

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

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



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

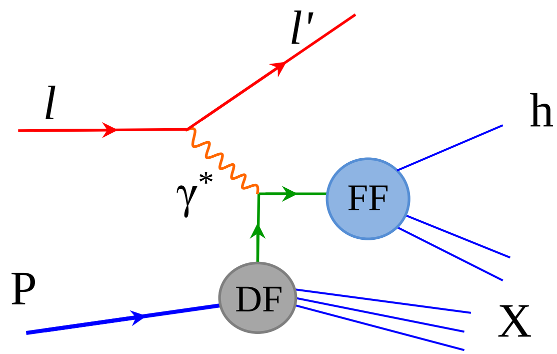
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

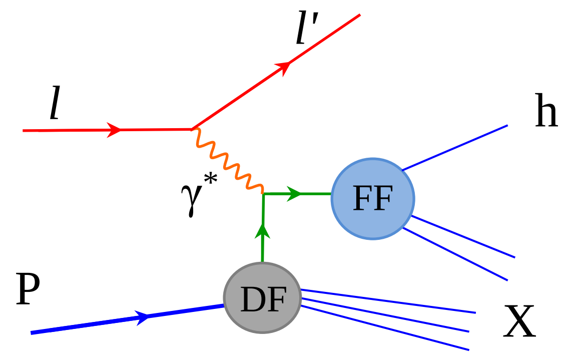
spin of the nucleon **spin of the quark** **k_T**

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

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

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

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

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

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

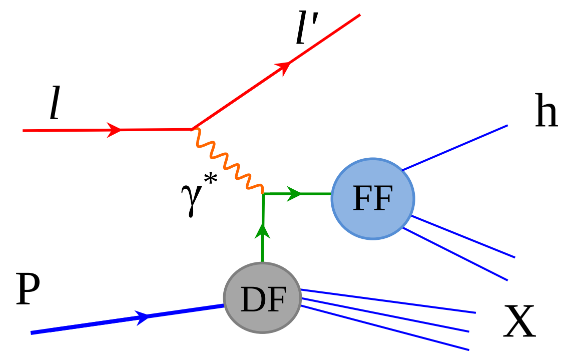
Twist-2

Twist-3

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

See talks by F. Bradamante and O. Denisov



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

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

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

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

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

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

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

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

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

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

Twist-2

Twist-3

SIDIS and single-polarized DY x-sections

SIDIS

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

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

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

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

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

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

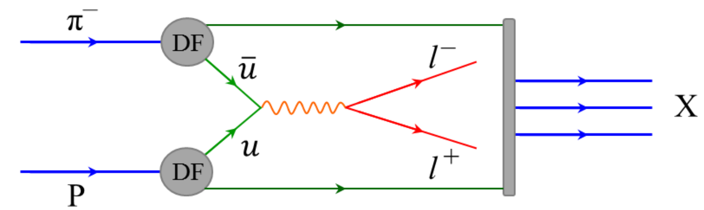
DY

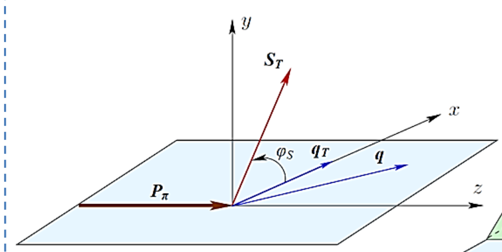
$$\frac{d\sigma}{d\Omega}\propto\left(F_U^1+F_U^2\right)$$

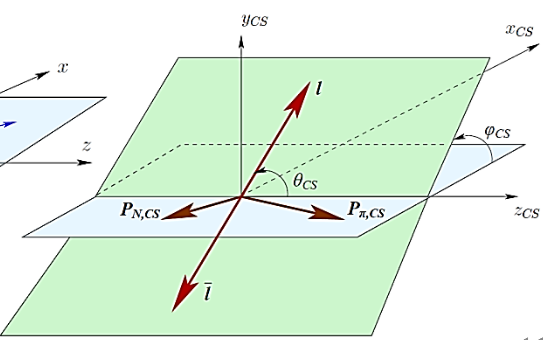
$$\times\Bigg\{1+A_U^1\cos^2\theta_{CS} + \sin 2\theta_{CS}A_U^{\cos\varphi_{CS}}\cos\varphi_{CS}+\sin^2\theta_{CS}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS}$$

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

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







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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

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)

SIDIS

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

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

DY

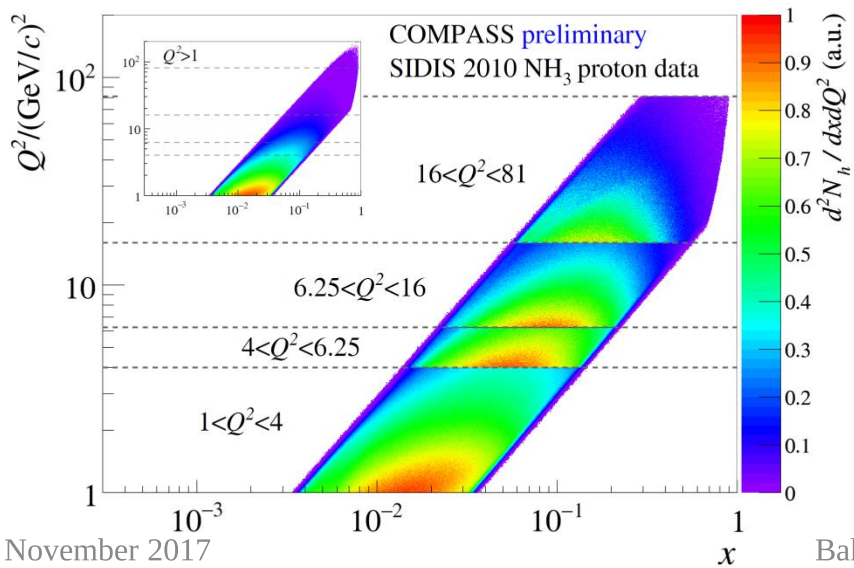
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

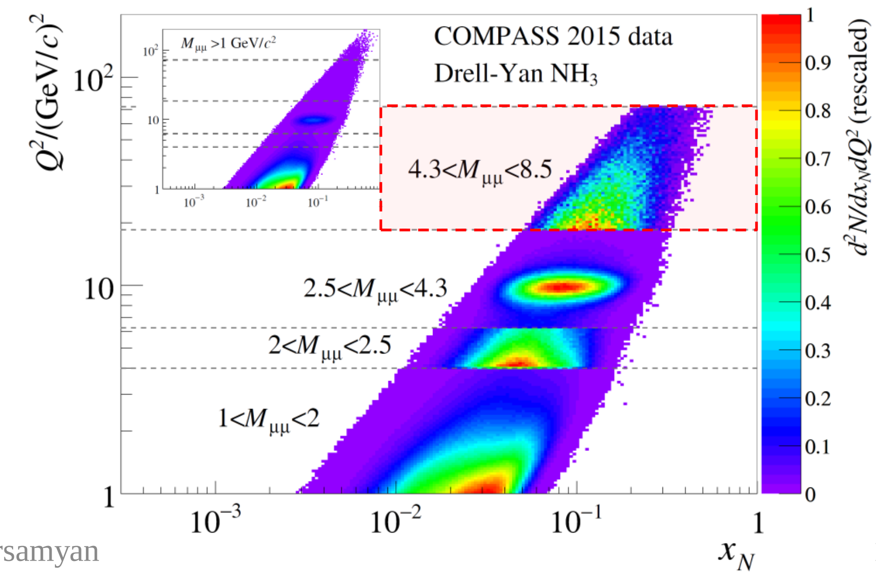
$$\times \left\{ \begin{array}{l} 1+\boxed{D_{[\sin^2\theta_{CS}]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS}} \\ + S_L\sin^2\theta_{CS}\,A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ \boxed{+ S_T\left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{[\sin^2\theta_{CS}]}\left(\begin{array}{l}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

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

SIDIS-DY bridge

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





- Selected SIDIS results

SIDIS: target longitudinal spin dependent asymmetries

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

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

$$F_{UL}^{\sin 2\phi_h} = \mathbb{C} \left\{ -\frac{2\left(\hat{\boldsymbol{h}} \cdot \boldsymbol{p_T}\right)\left(\hat{\boldsymbol{h}} \cdot \boldsymbol{k_T}\right) - \boldsymbol{p_T} \cdot \boldsymbol{k_T}}{M M_h} h_{1L}^{\perp q} H_{1q}^{\perp h} \right\}$$

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

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

SIDIS: target longitudinal spin dependent asymmetries

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

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

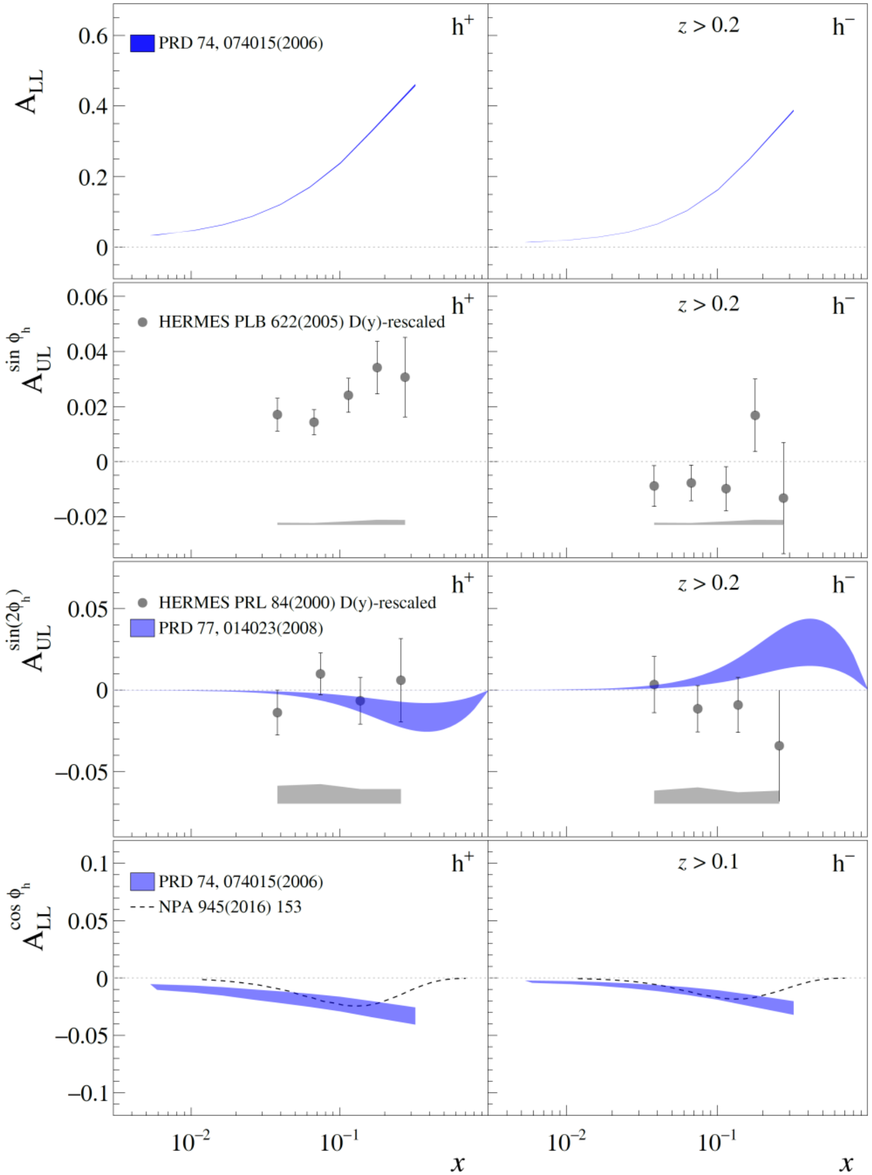
$$+\; S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\cos\phi_h\right]\Bigg\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

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

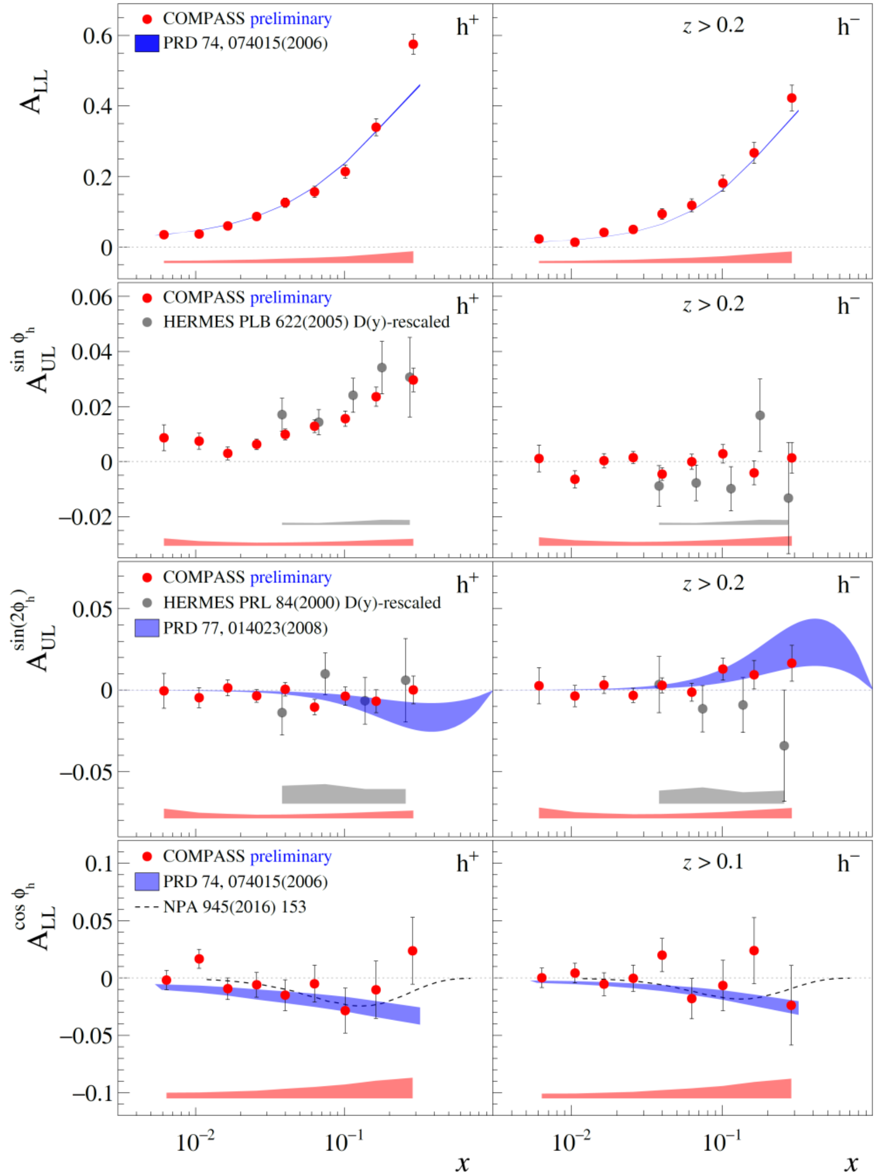
$$F_{LL}^1 = \mathcal{C}\left\{g_{1L}^q D_{1q}^h\right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$



SIDIS: target longitudinal spin dependent asymmetries

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

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

- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- **Significant h+ asymmetry, clear z-dependence,**
- **h– compatible with zero**

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

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

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

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

SIDIS: target transverse spin dependent asymmetries

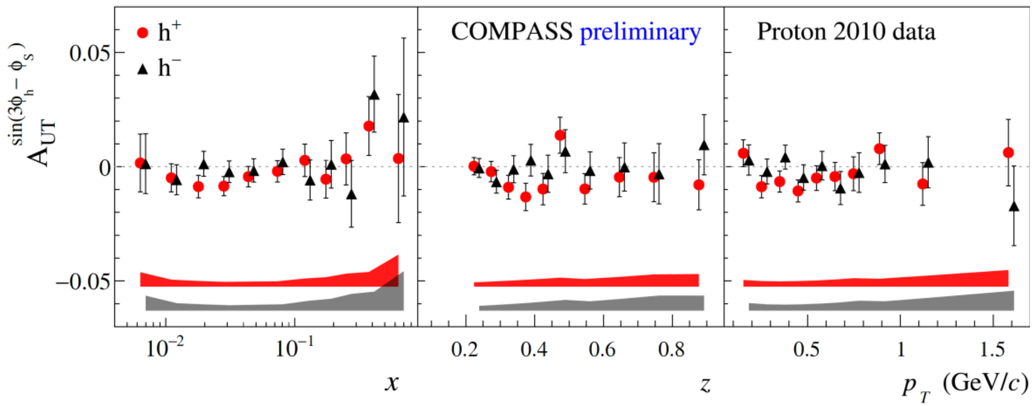
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \left\{ \begin{array}{l} 1 + \ldots \\ + \ S_T \left[\begin{array}{l} + \ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ + \ \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S}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

SIDIS: target transverse spin dependent asymmetries

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

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

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



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

COMPASS results

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

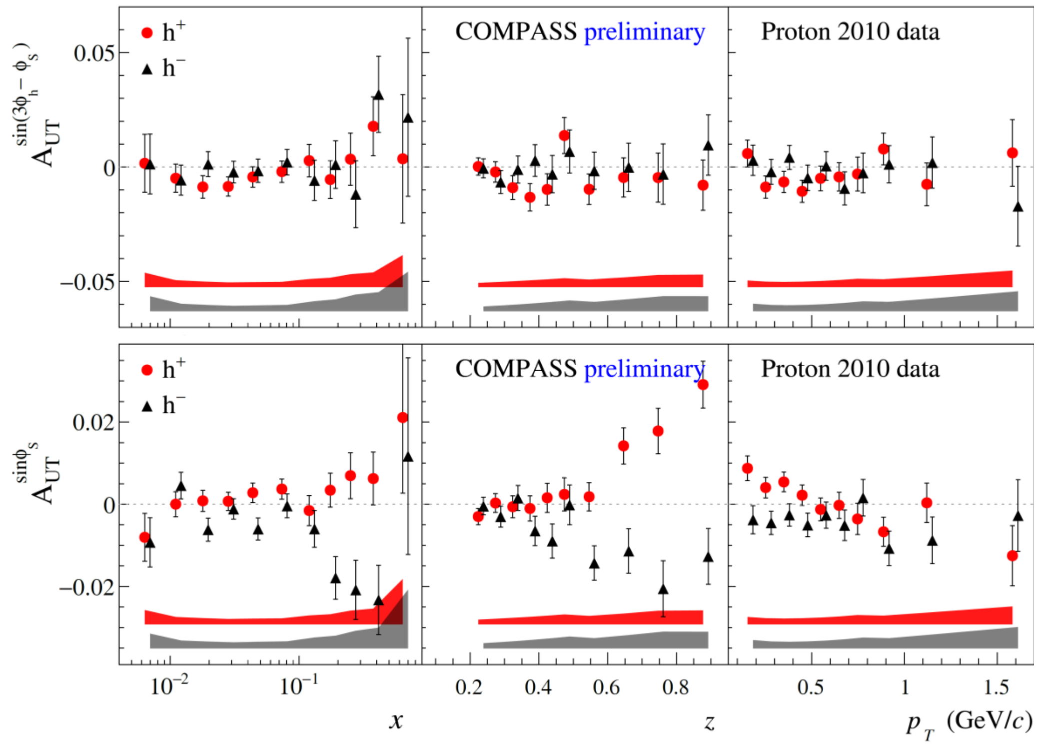
- Only "twist-2" ingredients, p_T^2-suppression
- **Small, compatible with zero asymmetry**

SIDIS: target transverse spin dependent asymmetries

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

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

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



COMPASS results

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

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

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

- Q-suppression
- 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⁺ !**

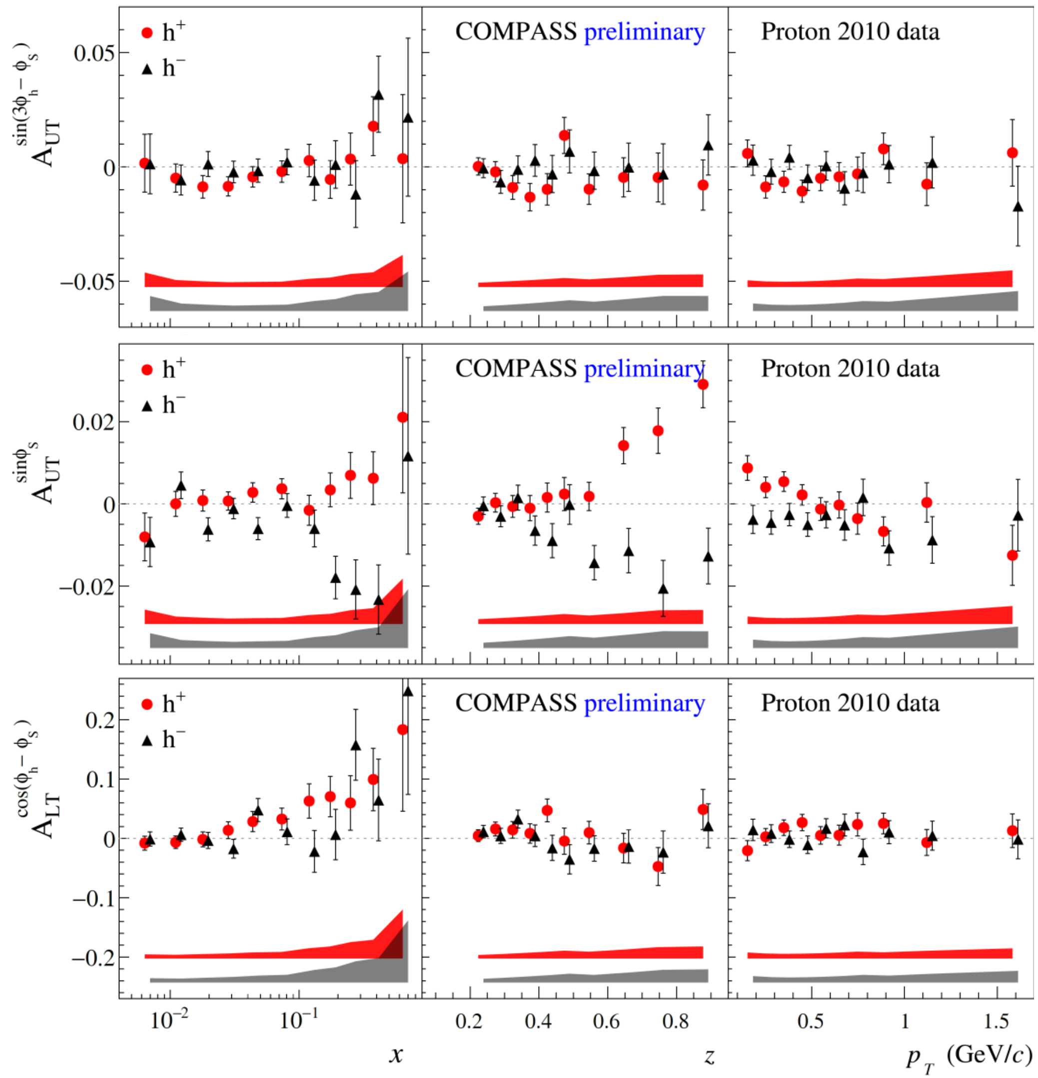
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\boldsymbol{p_T} \cdot \boldsymbol{k_T}}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp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

SIDIS: target transverse spin dependent asymmetries

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

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

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



COMPASS results

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

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

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

- Q-suppression
- 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⁺ !**

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

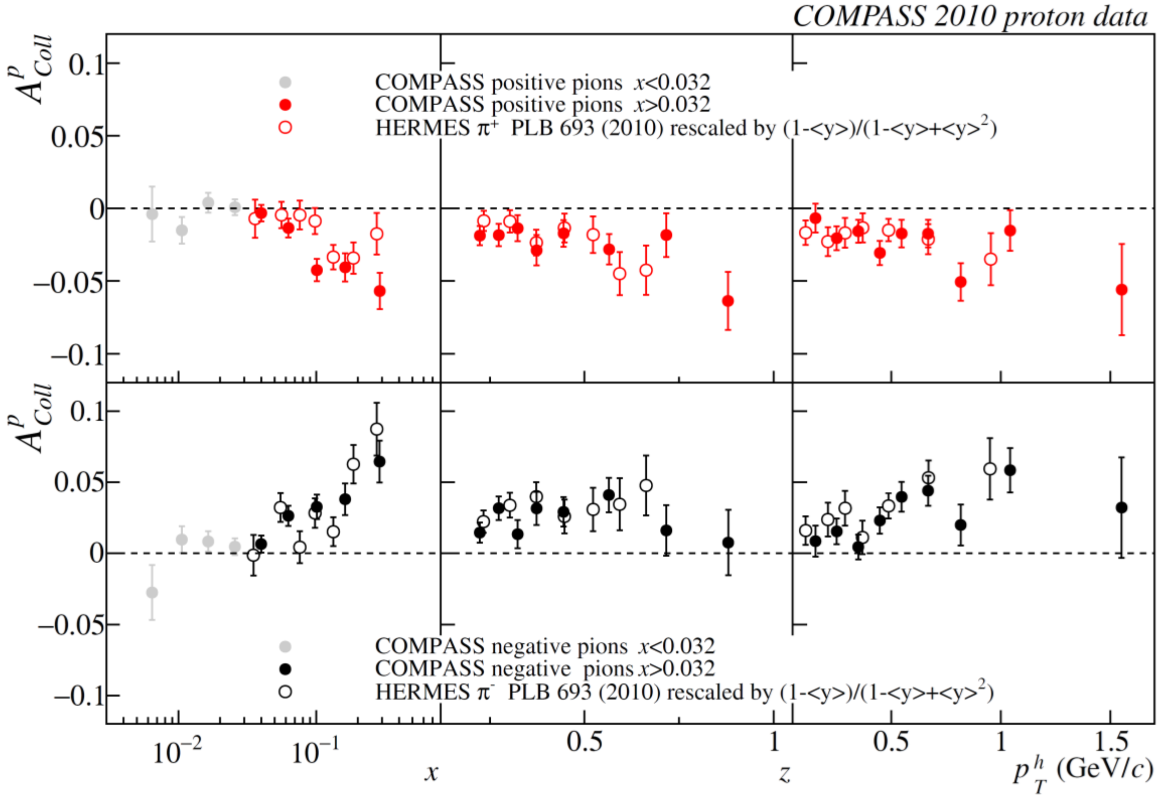
SIDIS TSAs (Collins)

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

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

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

COMPASS PLB 744 (2015) 250



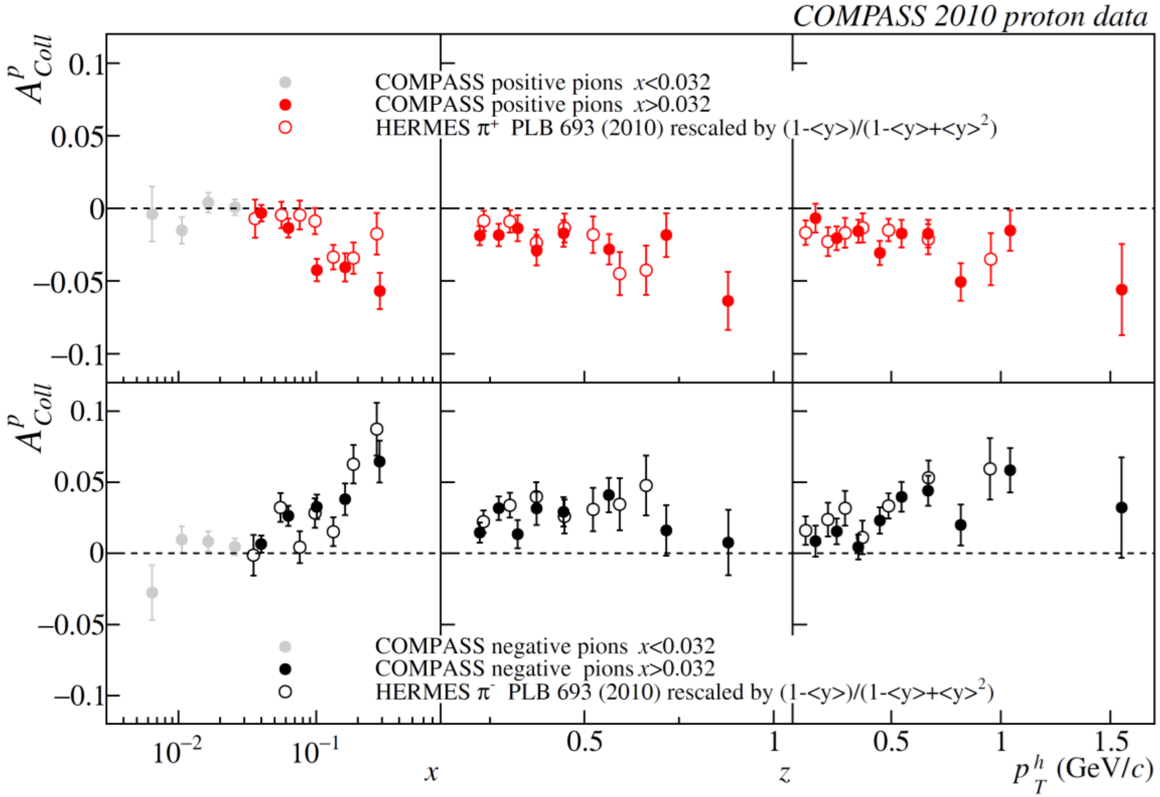
SIDIS TSAs (Collins)

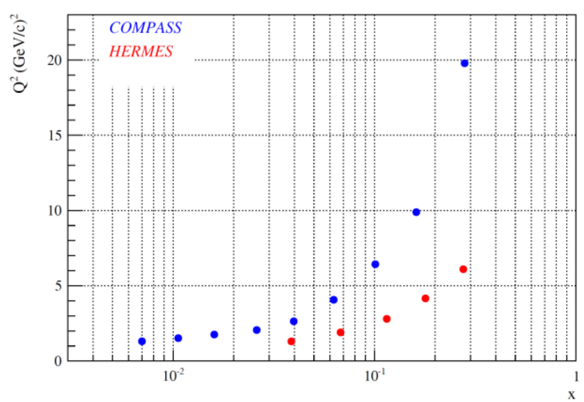
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \ldots\right\}$$

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

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

COMPASS PLB 744 (2015) 250





SIDIS TSAs (Collins)

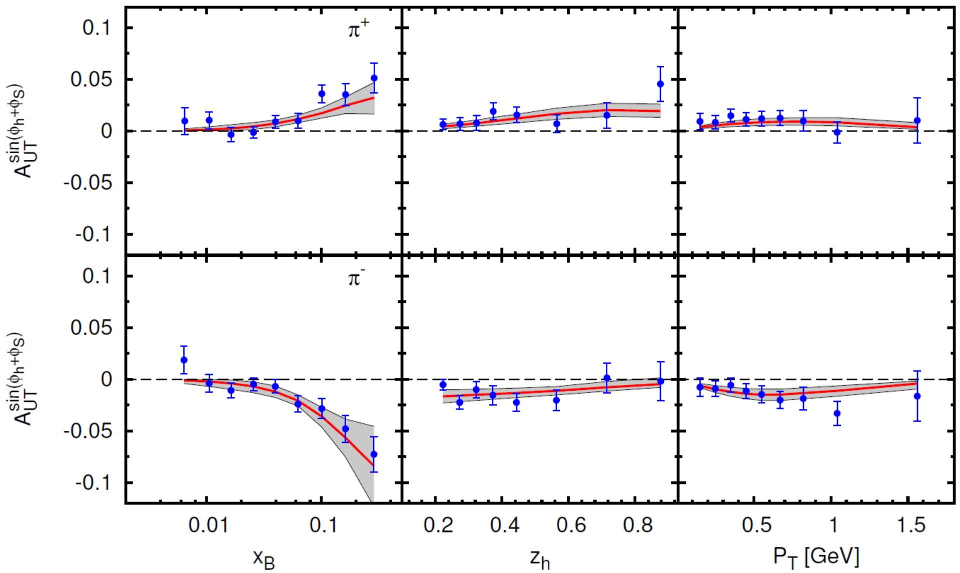
See talks by F. Bradamante and O. Denisov

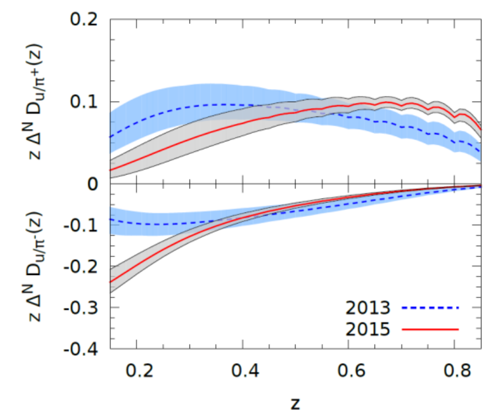
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right) + \ldots\right\}$$

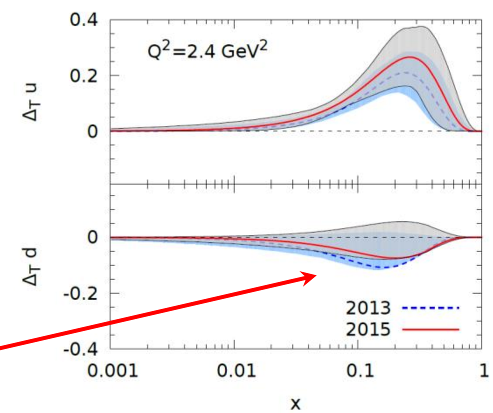
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

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







COMPASS-II (2021)

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

SIDIS TSAs (Collins)

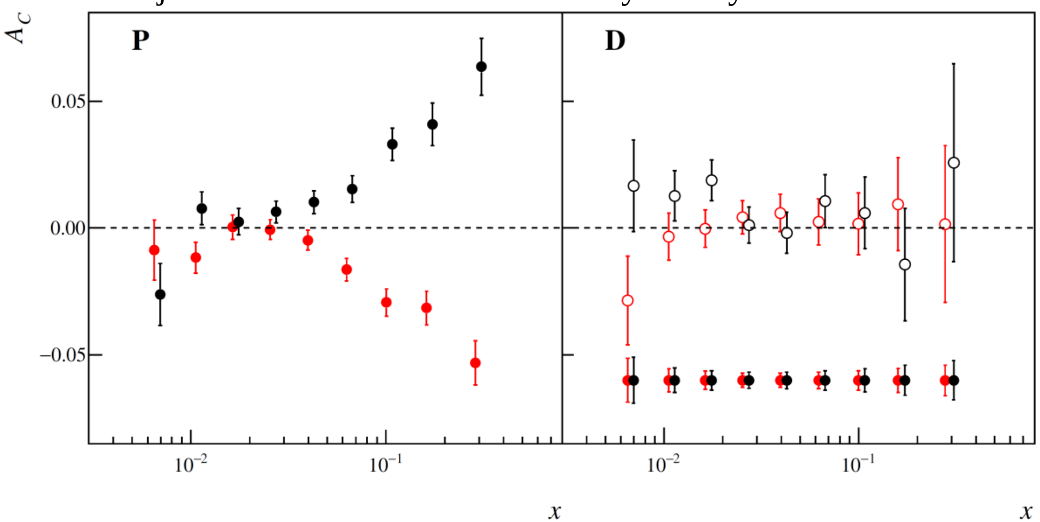
See talks by F. Bradamante and O. Denisov

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

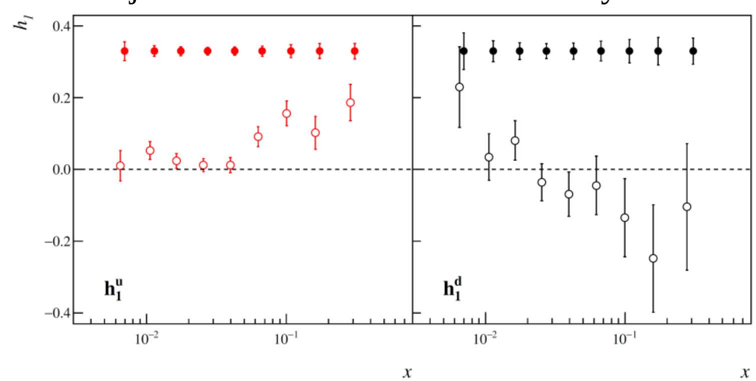
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

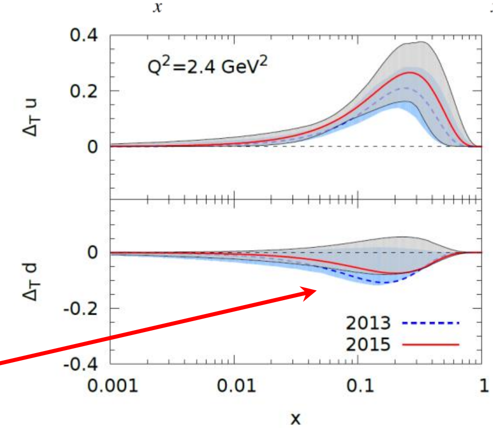
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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



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





COMPASS-II (2021)

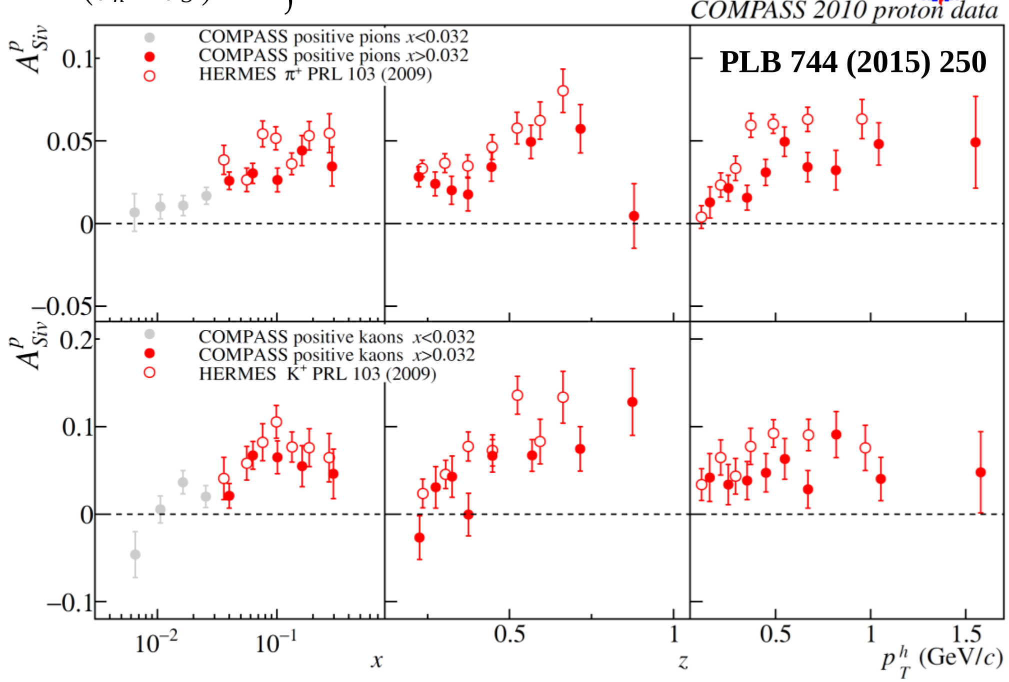
- Deuteron measurement to be repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark

SIDIS TSAs (Sivers)

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

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

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



SIDIS TSAs (Sivers)

See talk by F. Bradamante

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

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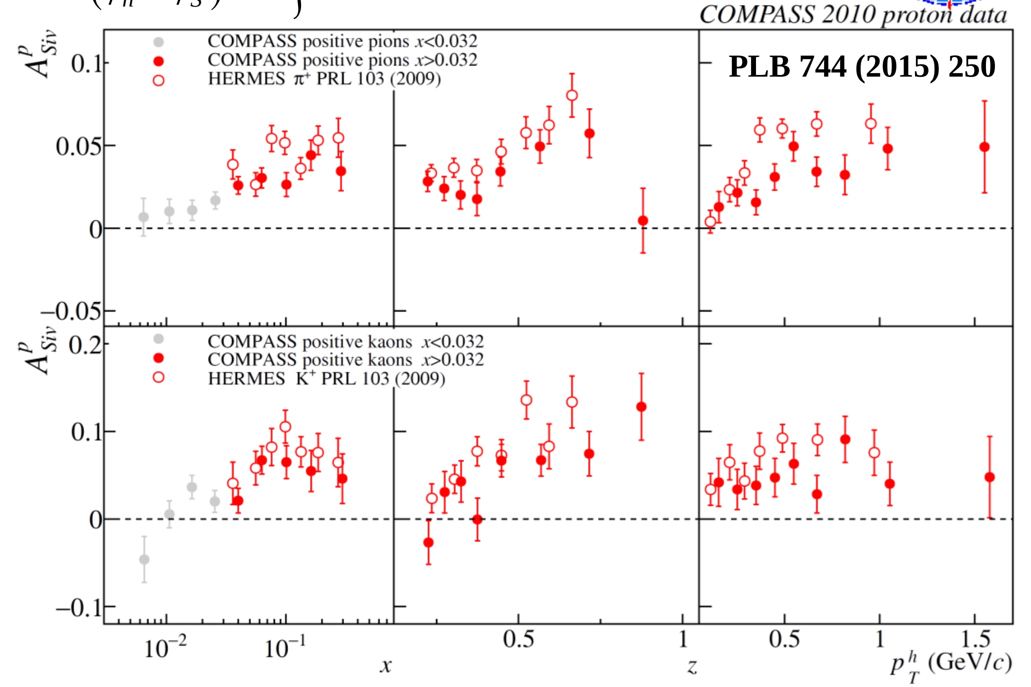

- Measured on proton and deuteron
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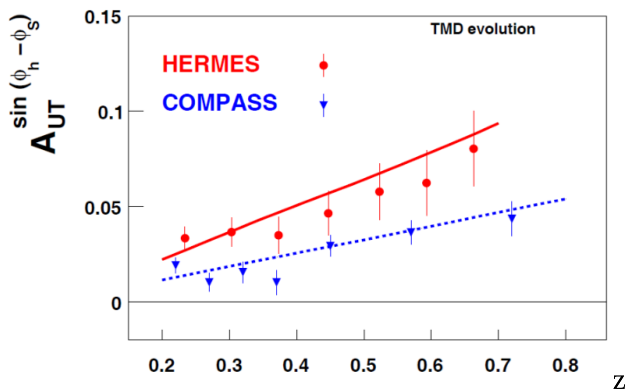
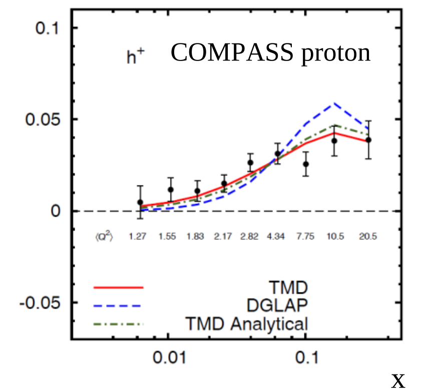
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**





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

SIDIS TSAs (Sivers)

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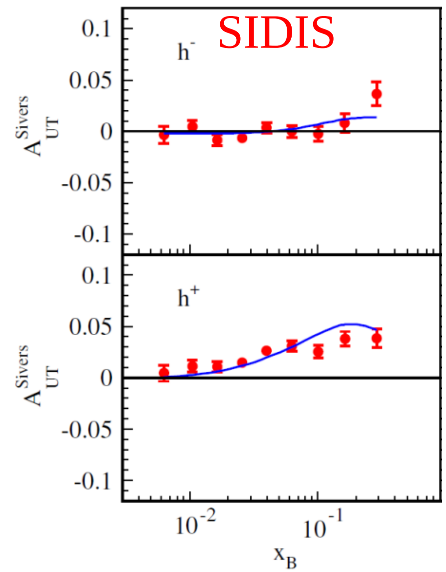
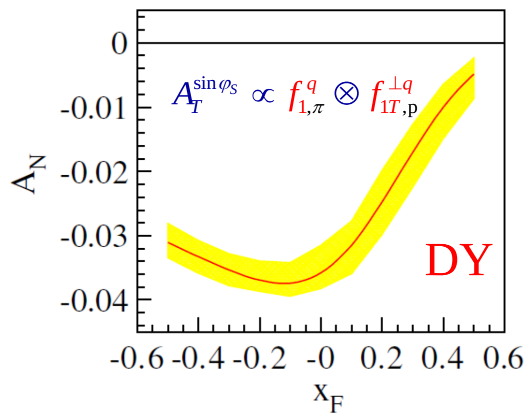
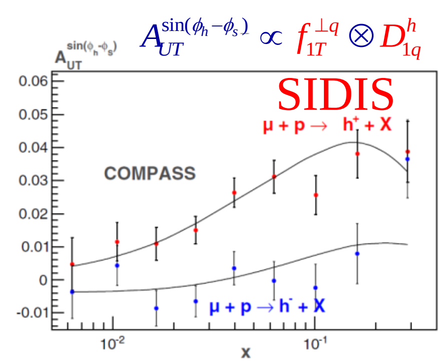
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

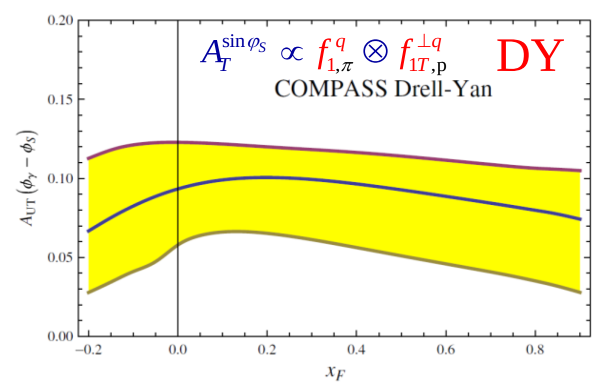
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**





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





SIDIS TSAs (Sivers)

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

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

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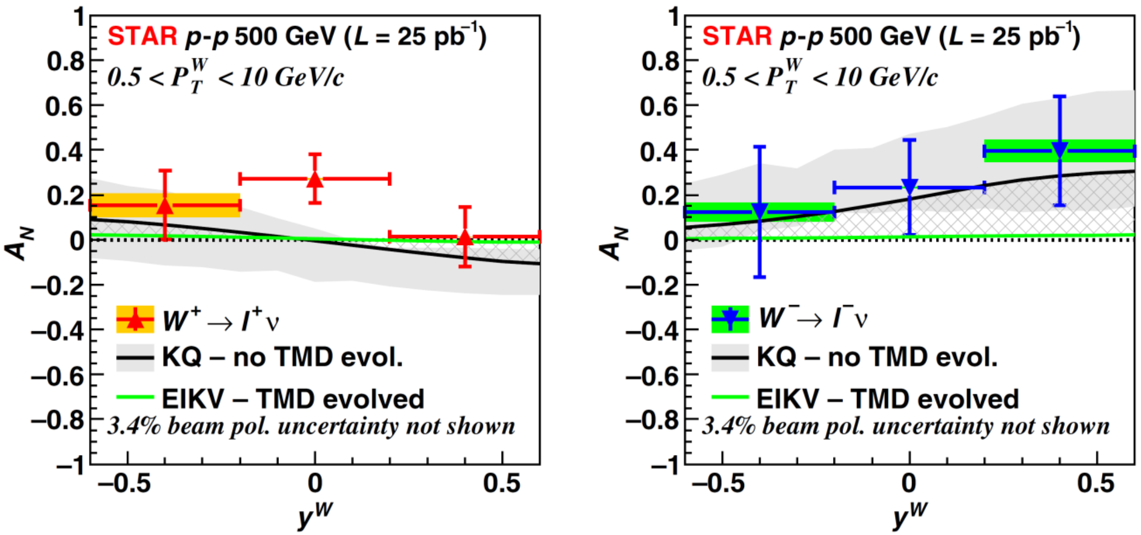
- **Q^2-evolution? Intriguing result!**

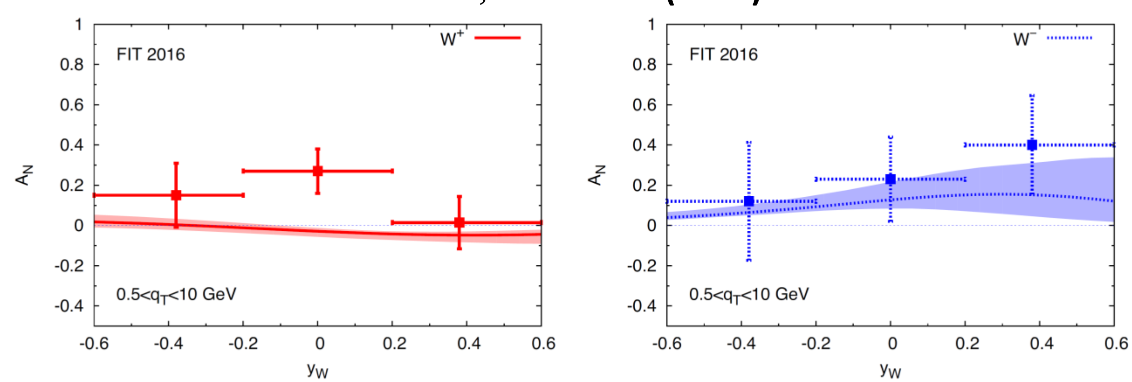
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

- 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)**



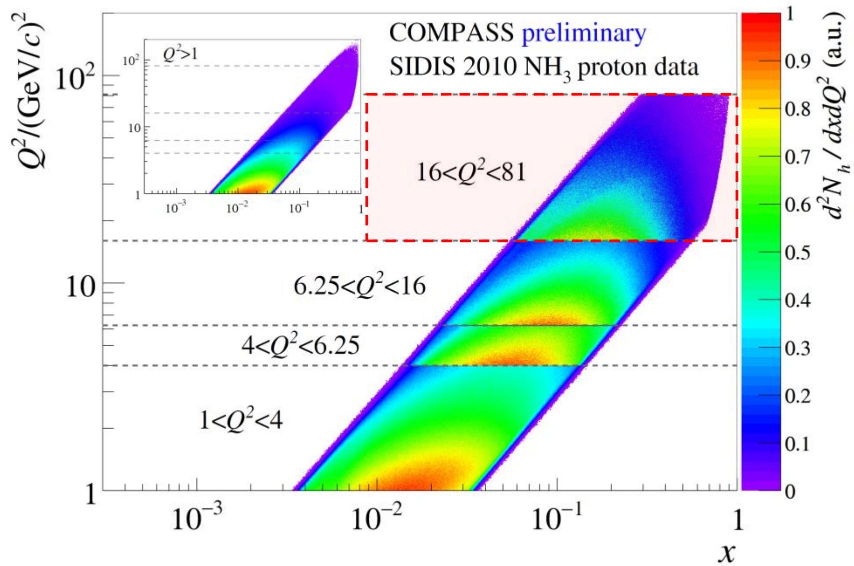
M. Anselmino et al., **JHEP 1704 (2017) 046**

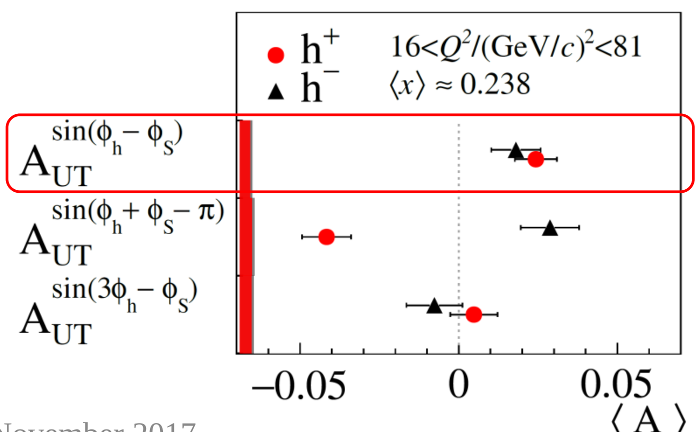


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

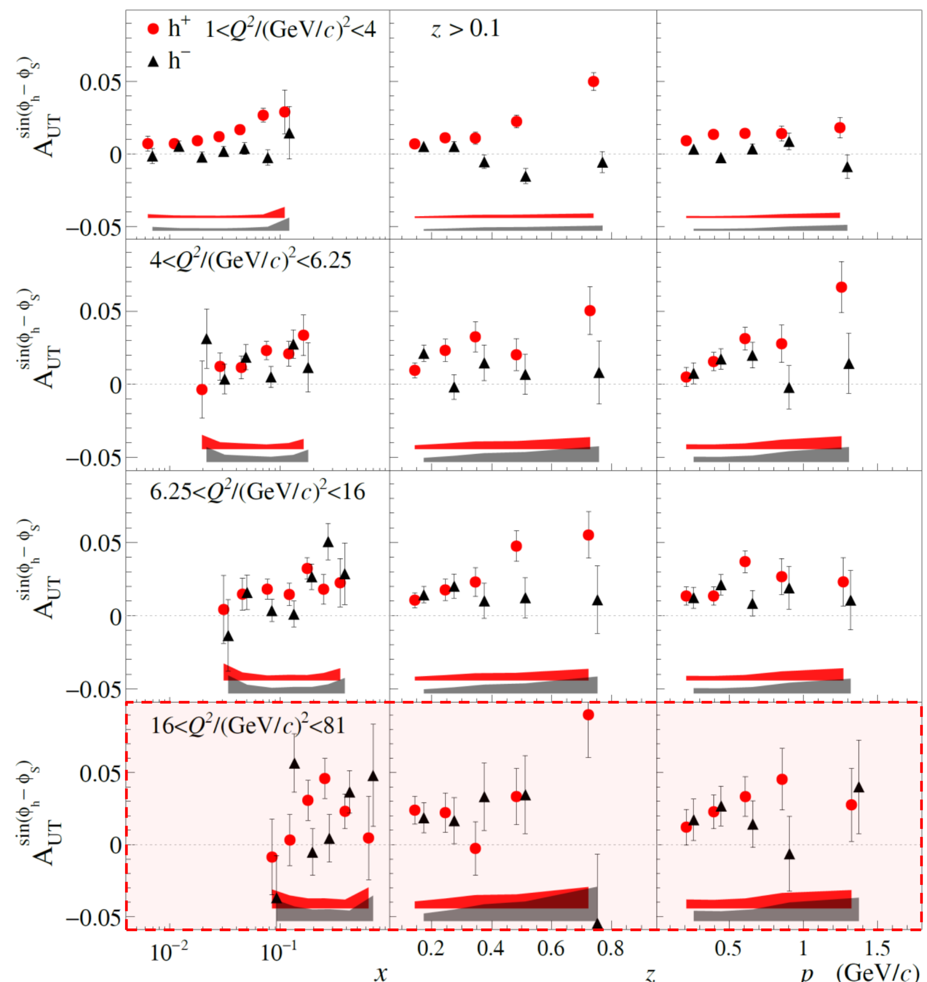
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\, A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

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





COMPASS PLB 770 (2017) 138

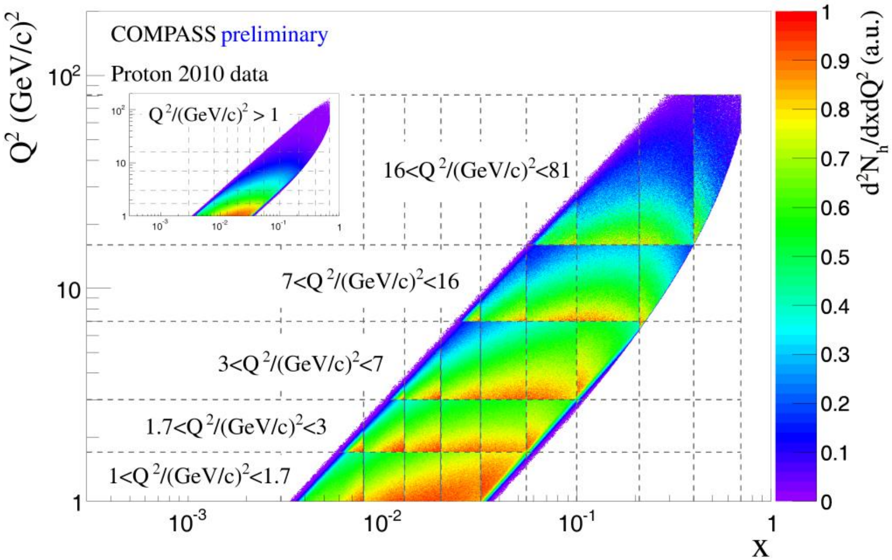


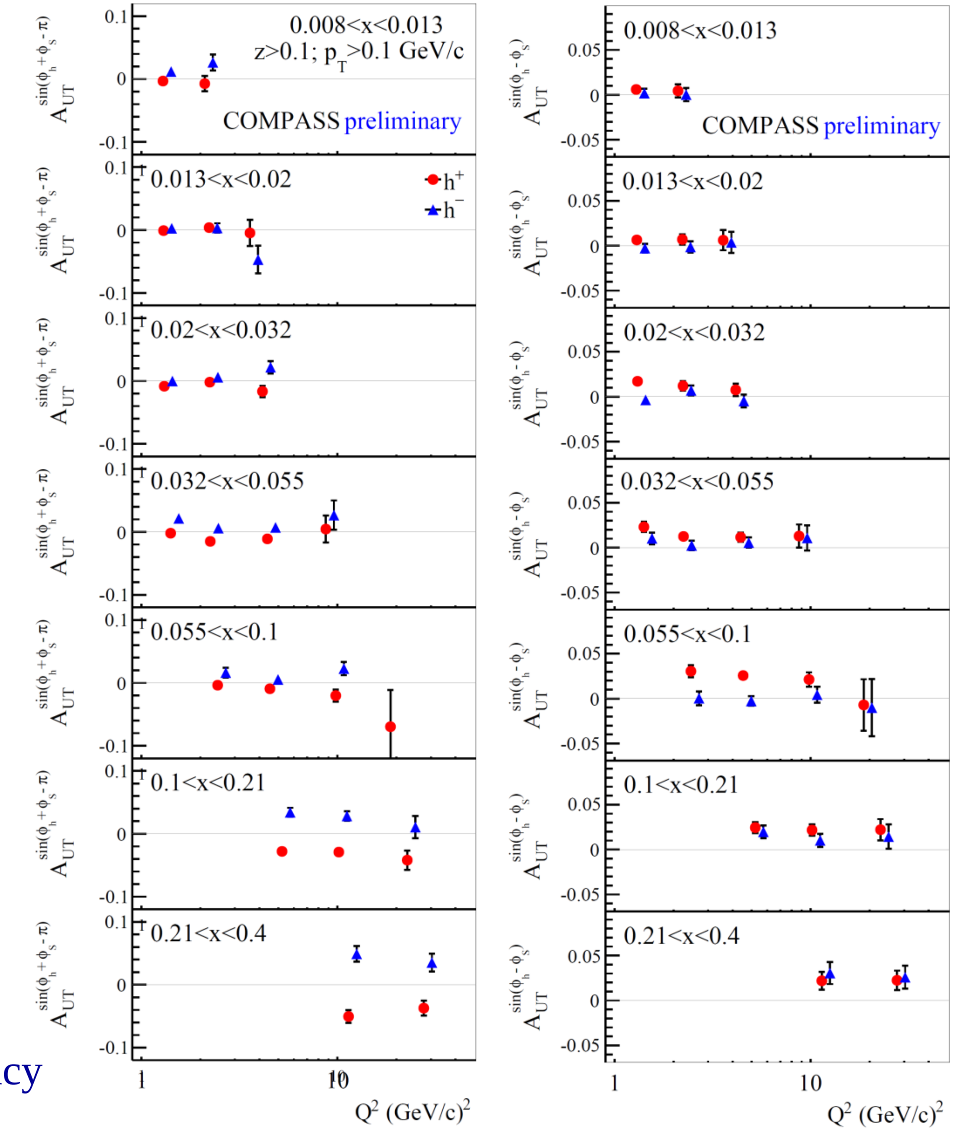
Multi-D TSA analysis

First shown at the SPIN-2014
[arXiv:1504.01599](https://arxiv.org/abs/1504.01599) **[hep-ex]**

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

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





- 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

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

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

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

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

Single-polarized DY x-section: transverse part

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

- **"naive" Drell–Yan model**
  collinear (k_T=0) LO pQCD no rad. processes
  $\lambda=1$, ($F_U^2=0$), $\mu=\nu=0$
- **Intrinsic transverse motion + QCD effects**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$

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

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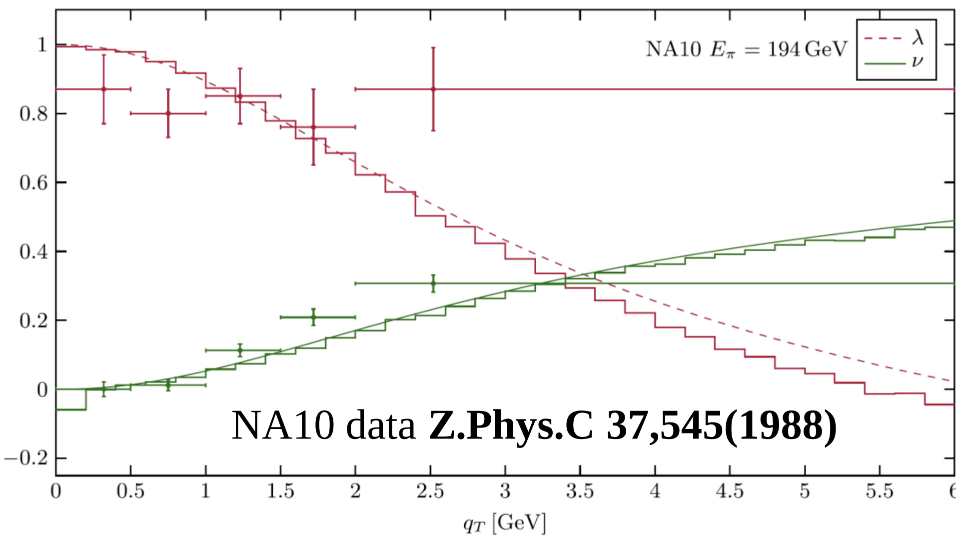
M. Lambertsen, W. Vogelsang **PRD93, 114013 (2016)**



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

See talks by V. Andrieux and C. Quintance

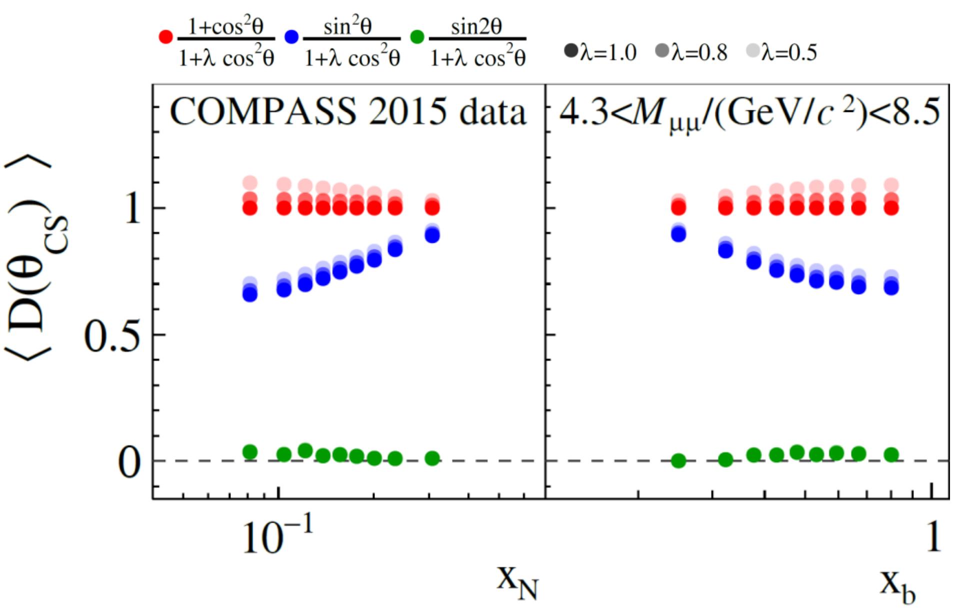
Single-polarized DY x-section: transverse part

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

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

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

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



- 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%.

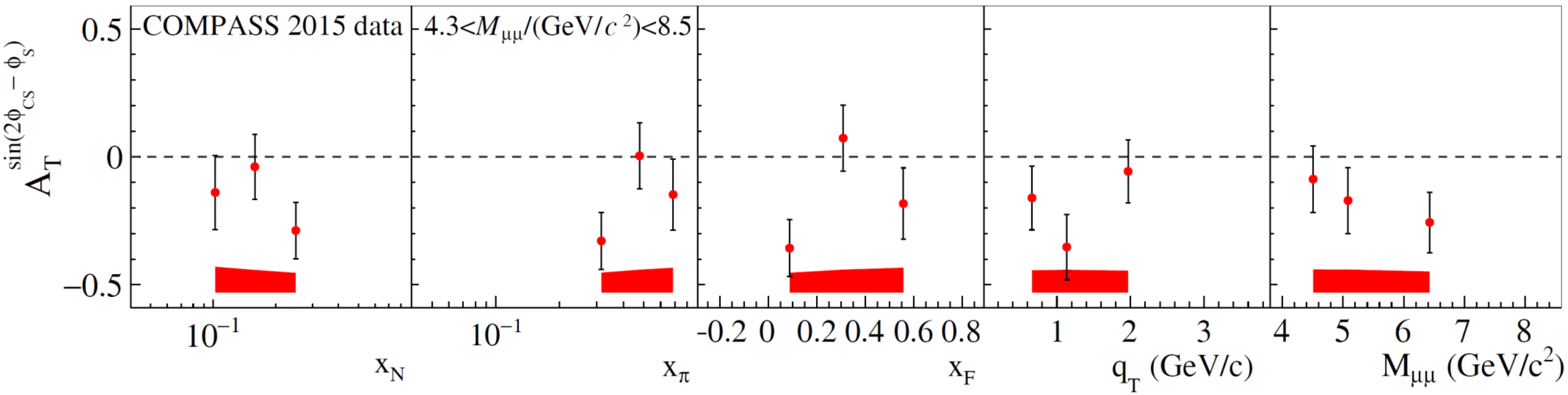
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

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



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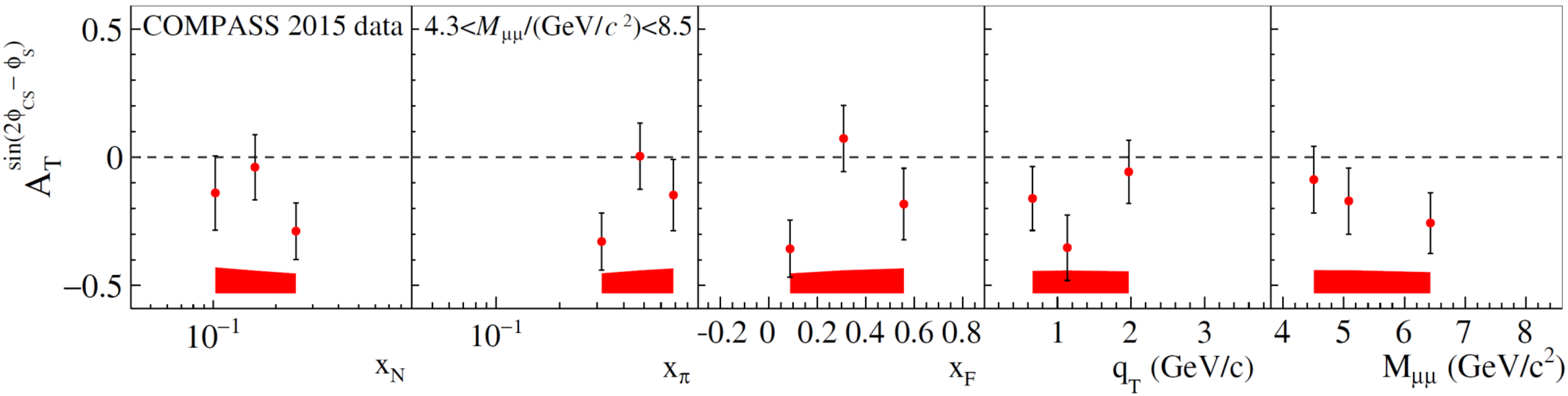
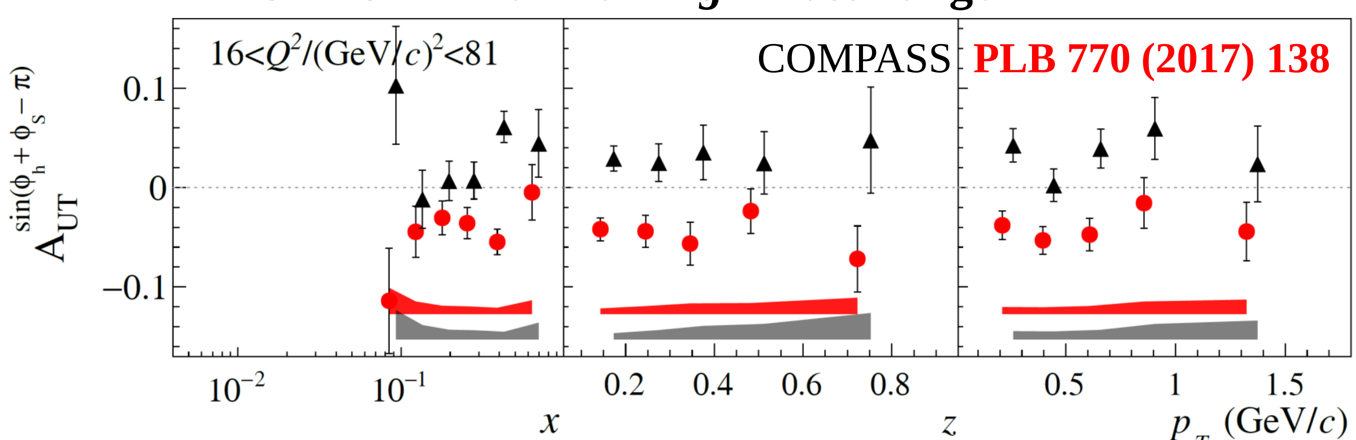
COMPASS **PRL 119, 112002 (2017)**



SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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



Drell-Yan TSAs – Transversity

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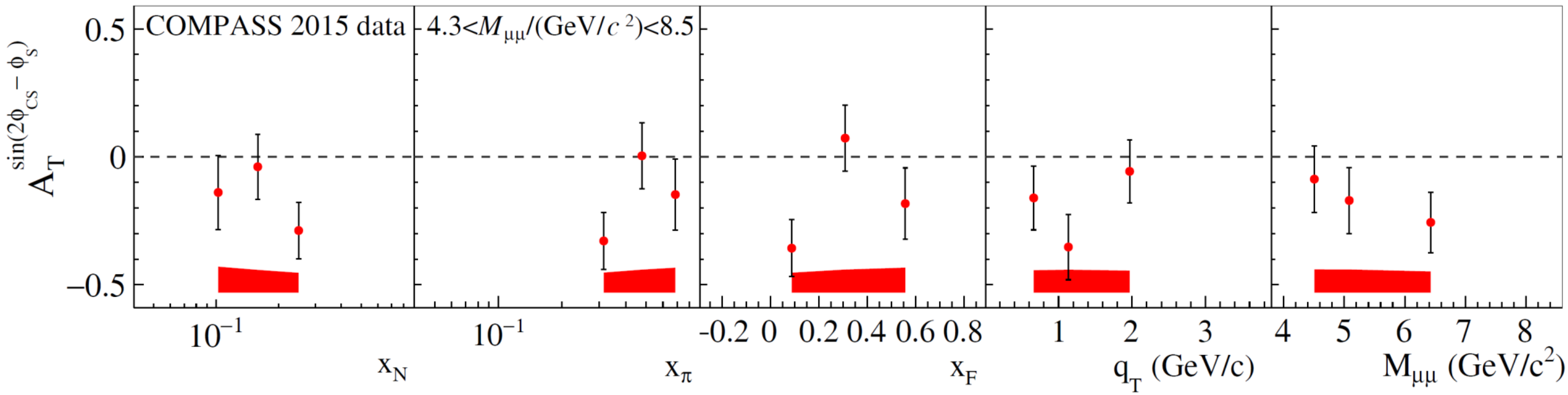
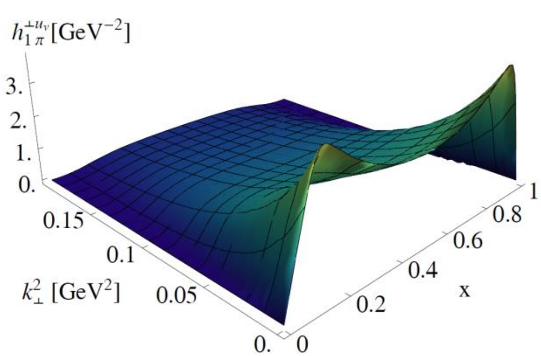
Transversity DY TSA

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

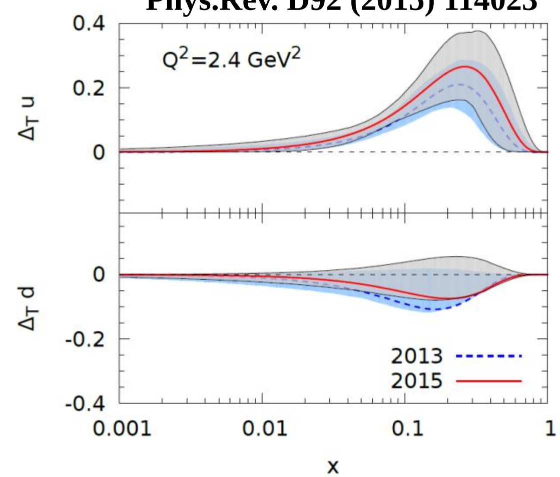
COMPASS PRL 119, 112002 (2017)



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



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



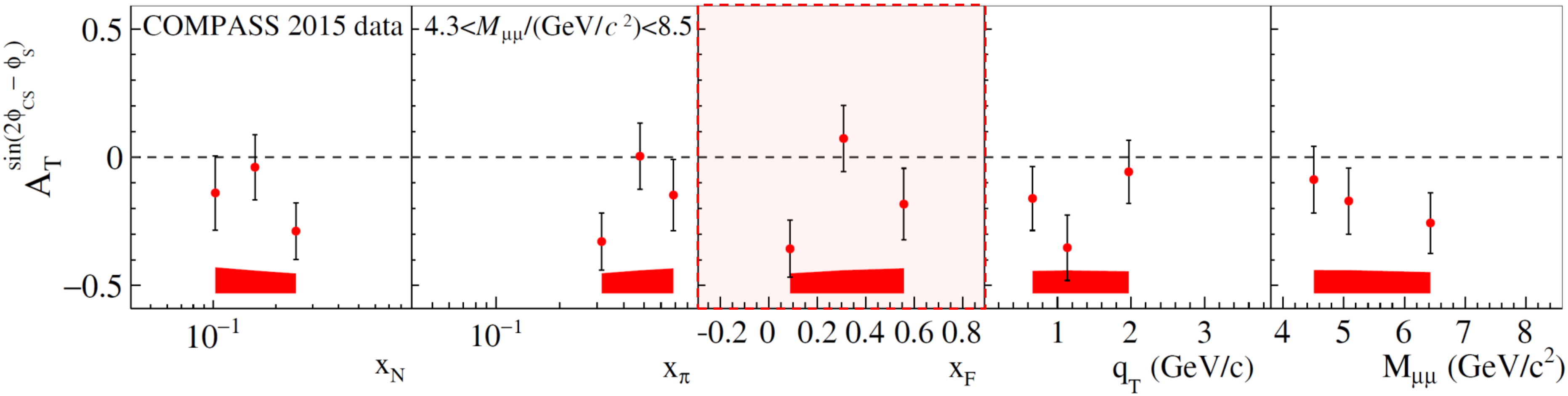
Drell-Yan TSAs – Transversity

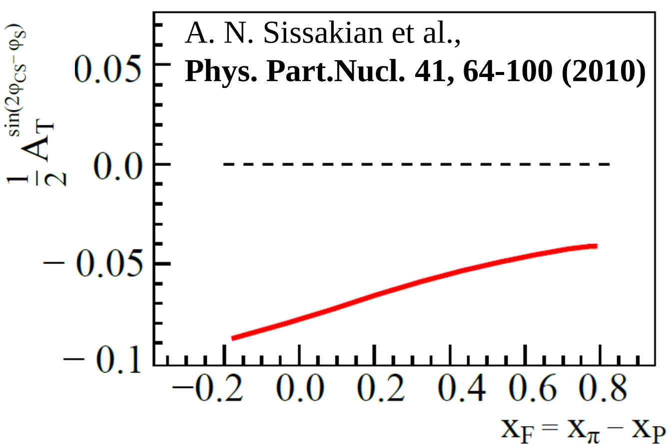
$$\frac{d\sigma}{d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + \ldots \right]$$

Transversity DY TSA

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

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





B. P. Pasquini, P. Schweitzer
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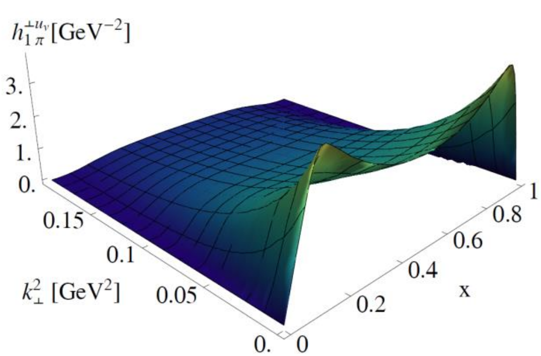
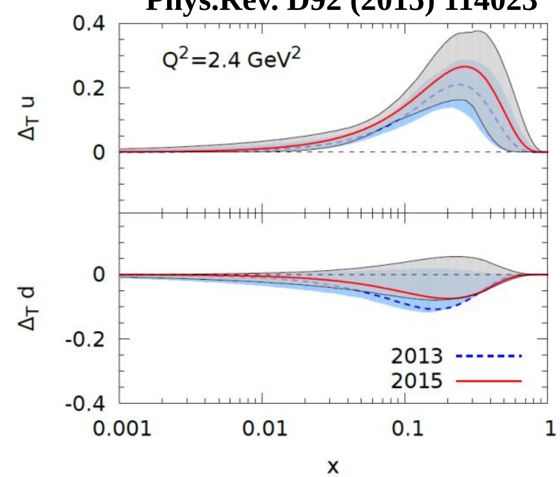


M. Anselmino et al.
Phys.Rev. D92 (2015) 114023



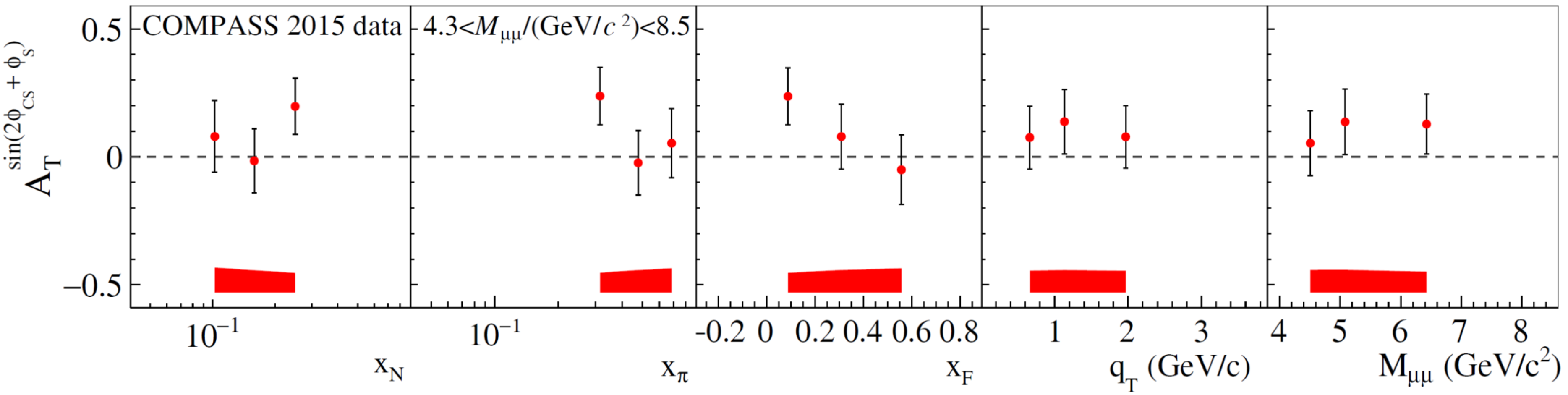
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

COMPASS PRL 119, 112002 (2017)



Drell-Yan TSAs – Pretzelosity

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Pretzelosity DY TSA

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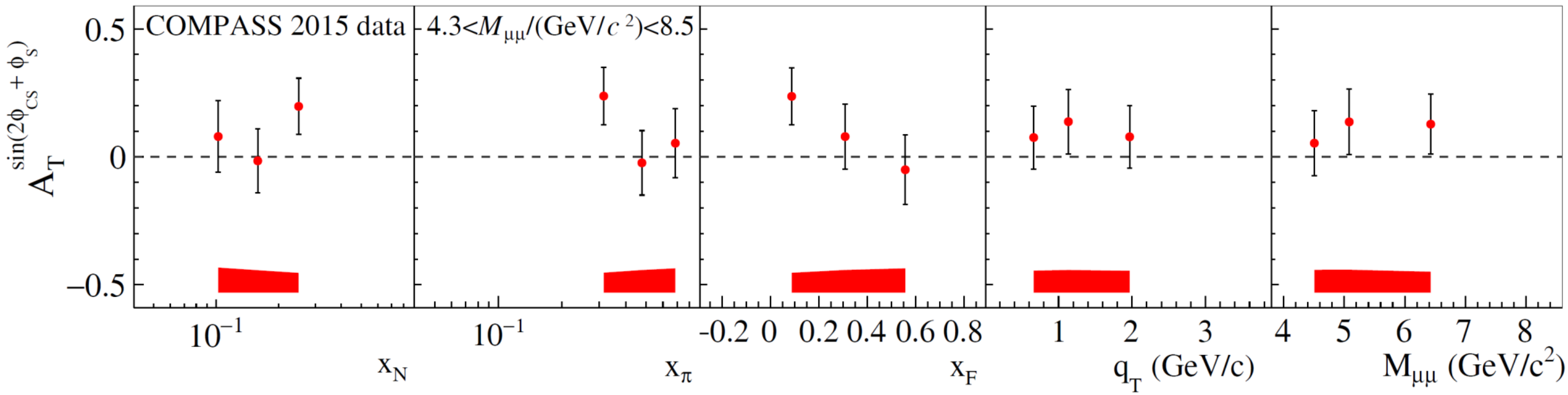
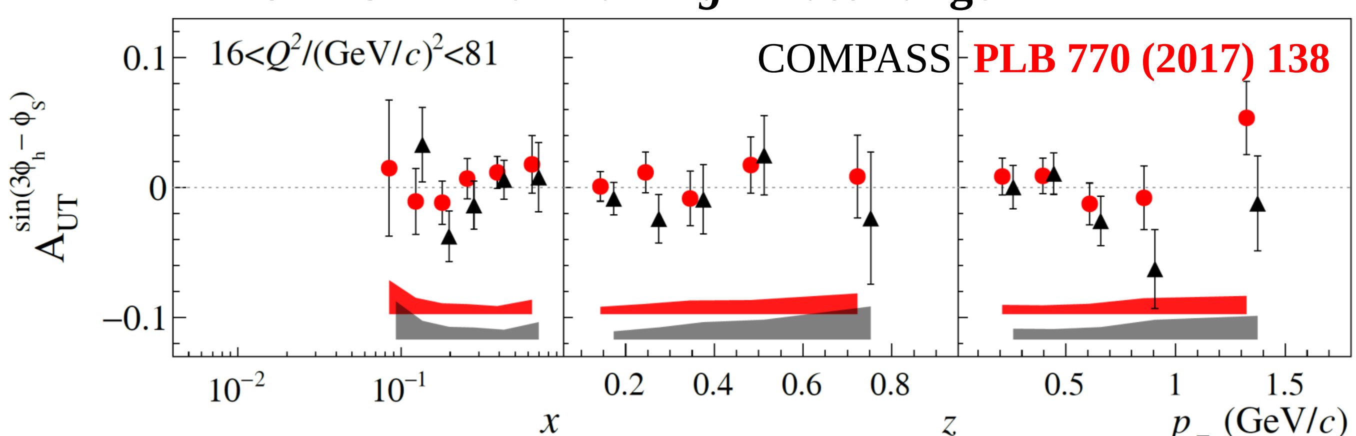
COMPASS **PRL 119, 112002 (2017)**



SIDIS in Drell-Yan *high-mass* range

Pretzelosity SIDIS TSA

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



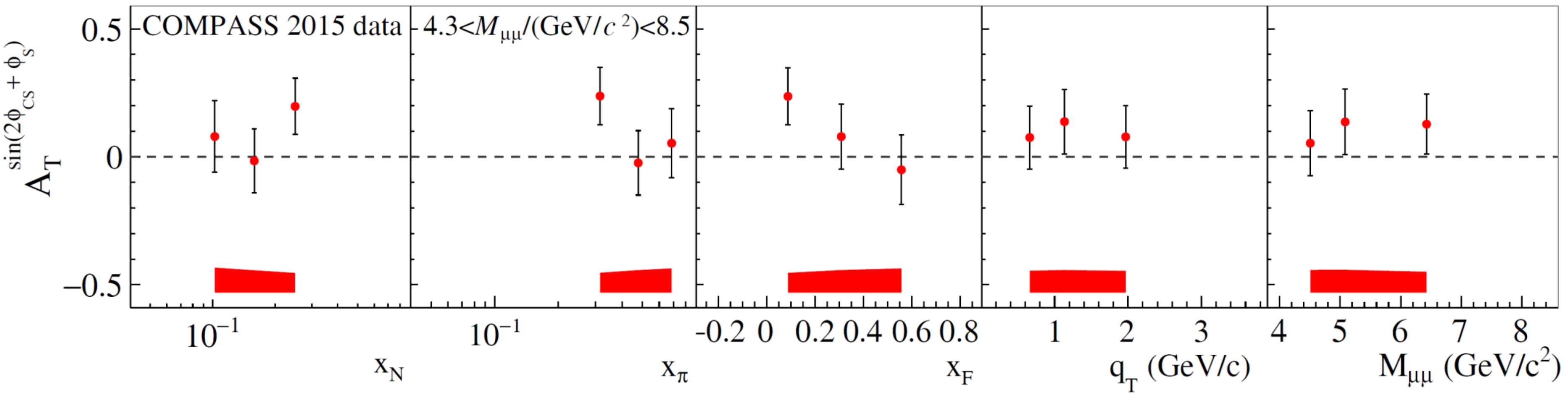
Drell-Yan TSAs – Pretzelosity

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

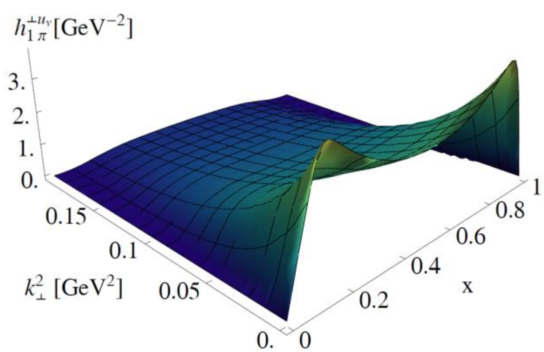
Pretzelosity DY TSA

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

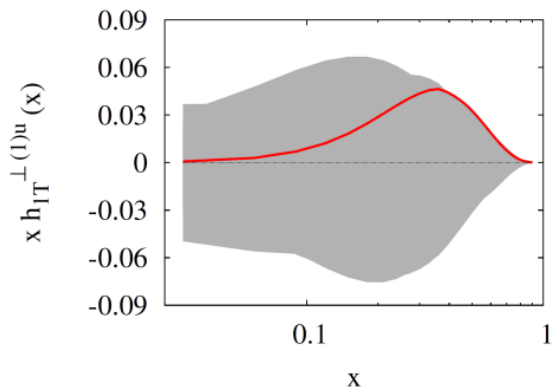
COMPASS PRL 119, 112002 (2017)



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



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



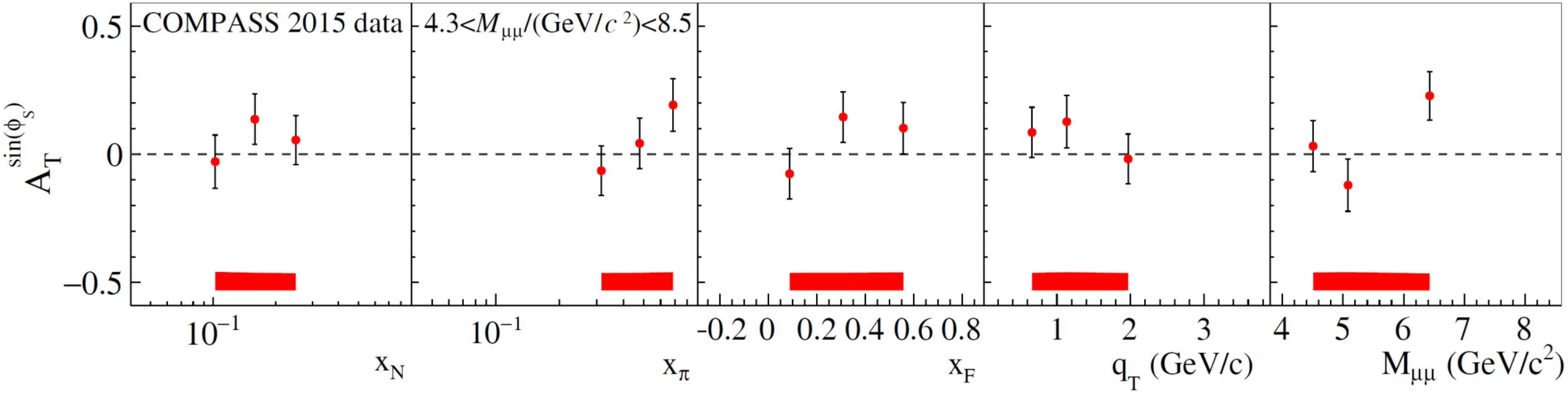
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)



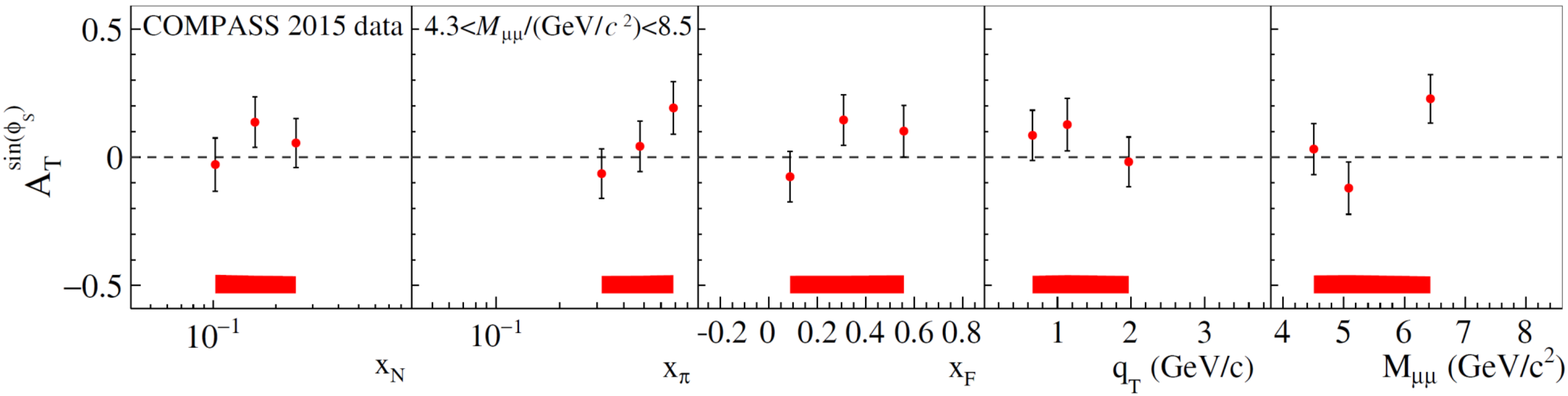
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)

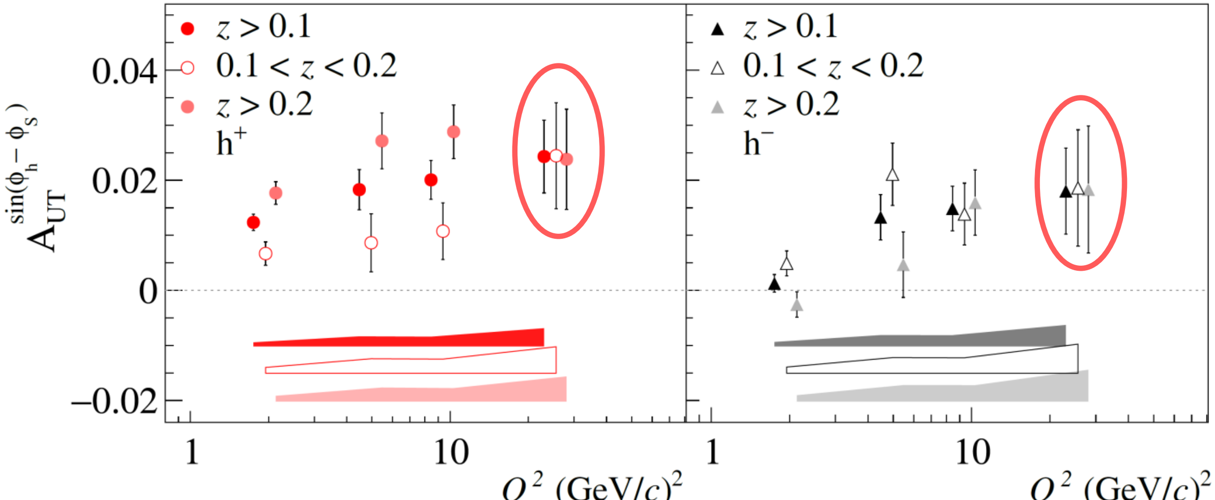


SIDIS in Drell-Yan *high-mass* range

COMPASS **PLB 770 (2017) 138**

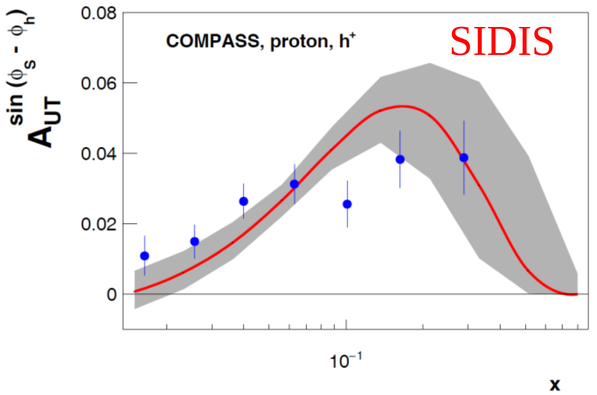
Sivers SIDIS TSA

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

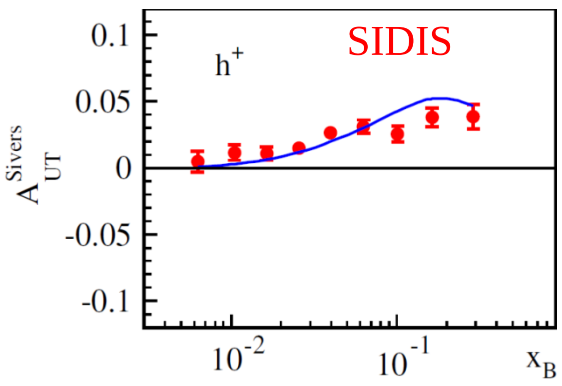


Sivers asymmetry in Drell-Yan: sign change

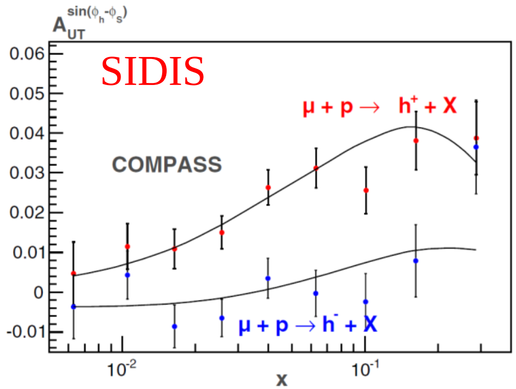
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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



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



Sivers asymmetry in Drell-Yan: sign change

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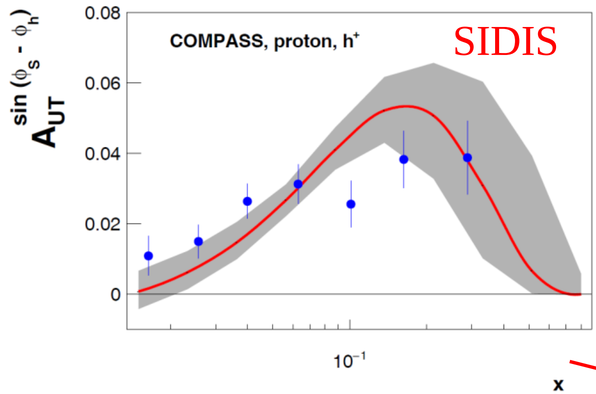

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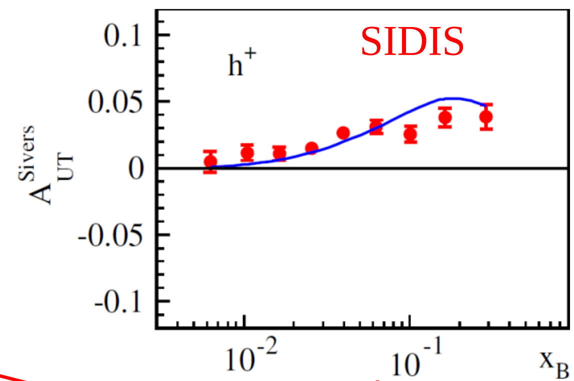
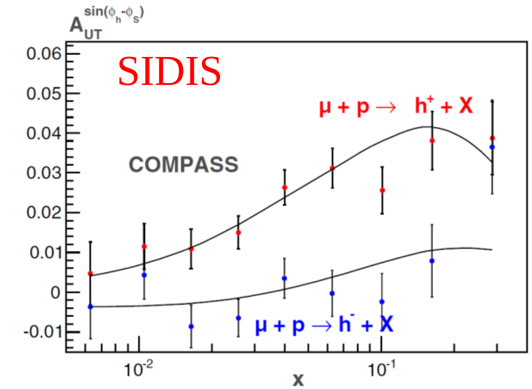
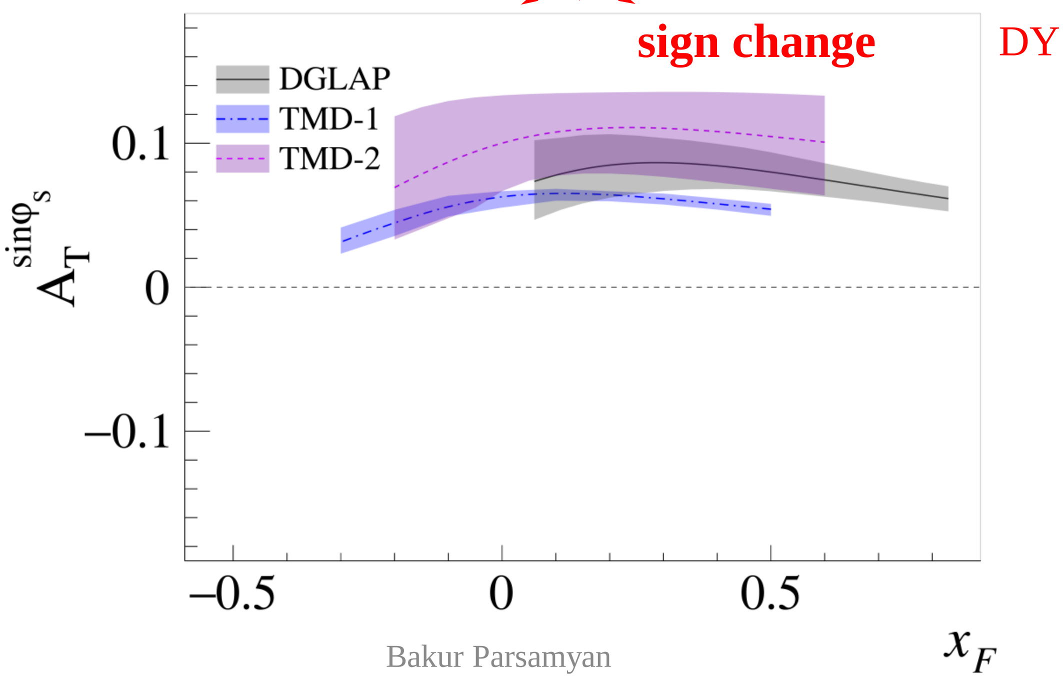


TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**





Sivers asymmetry in Drell-Yan: sign change

DGLAP (2016)
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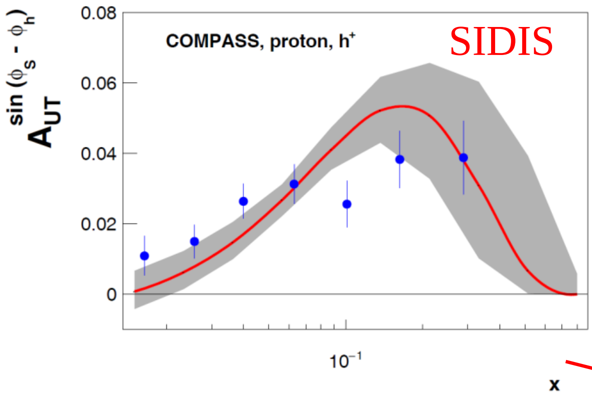
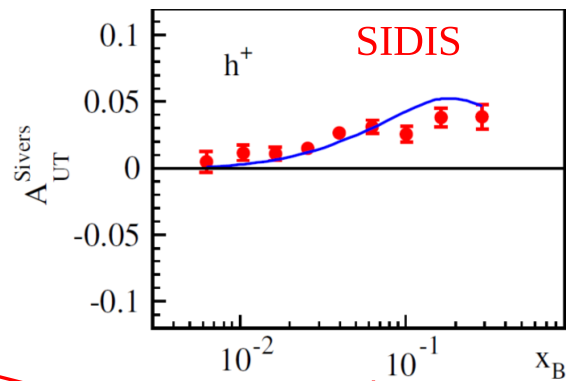
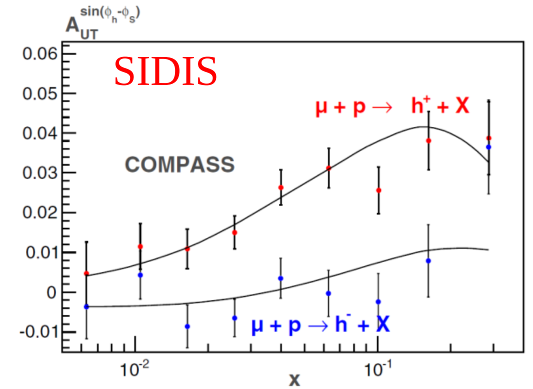
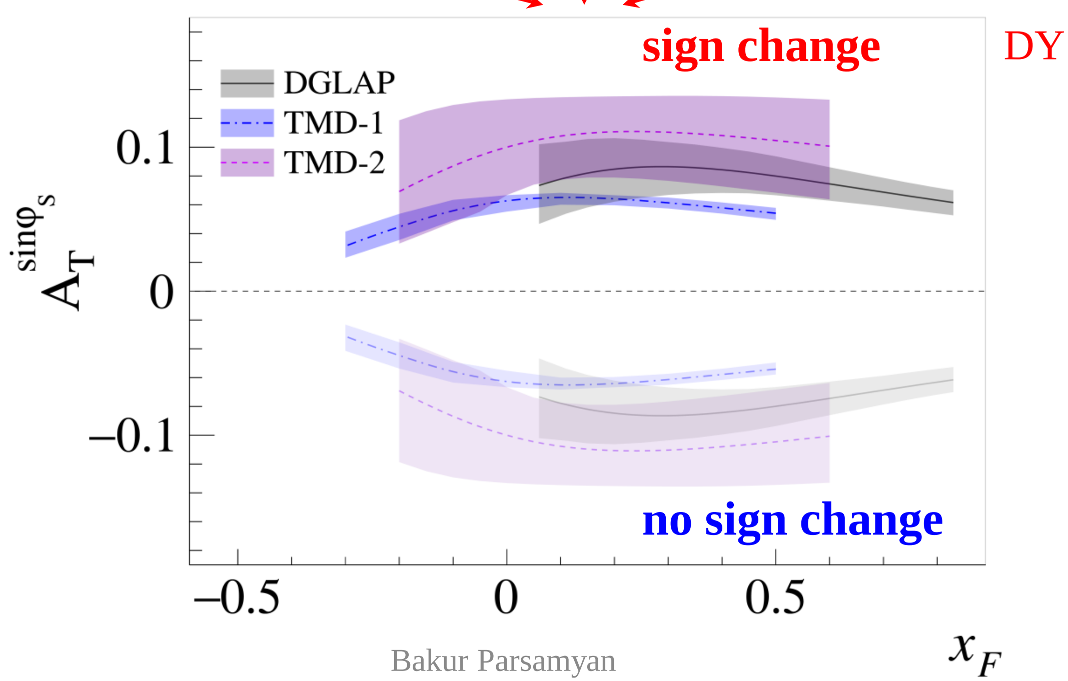


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



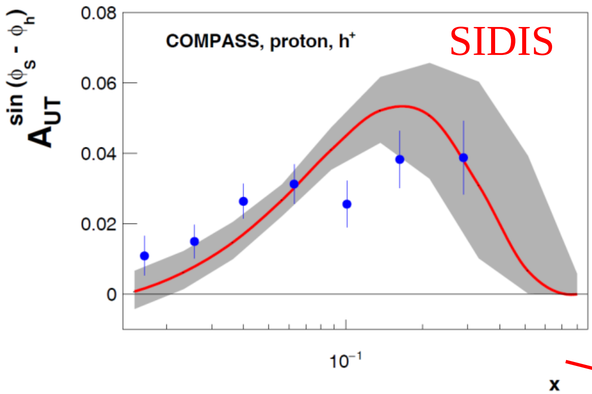
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



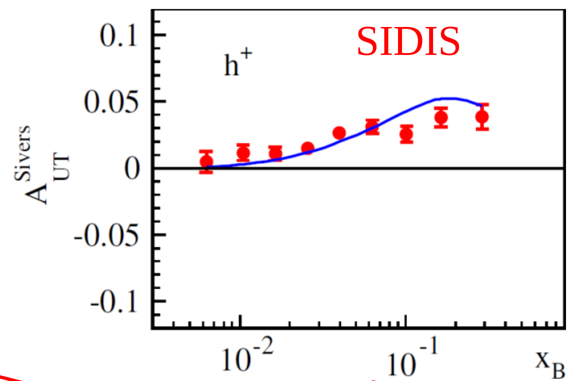


Sivers asymmetry in Drell-Yan: sign change

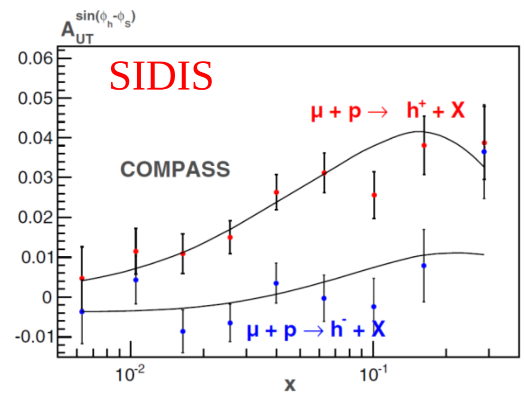
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



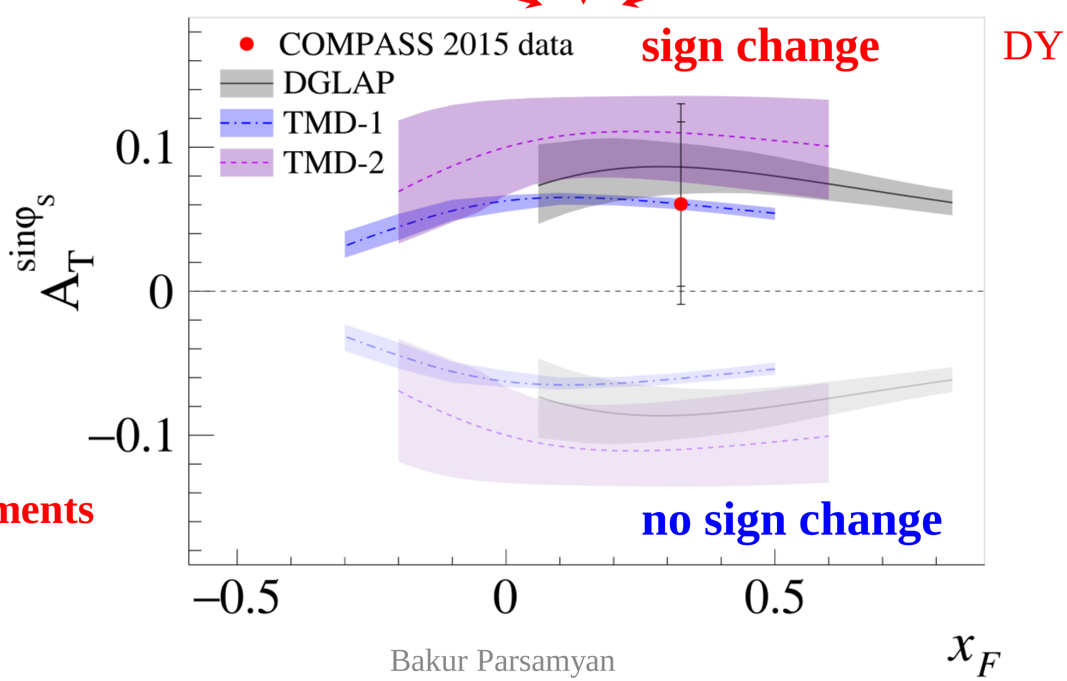
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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



COMPASS
PRL 119, 112002 (2017)

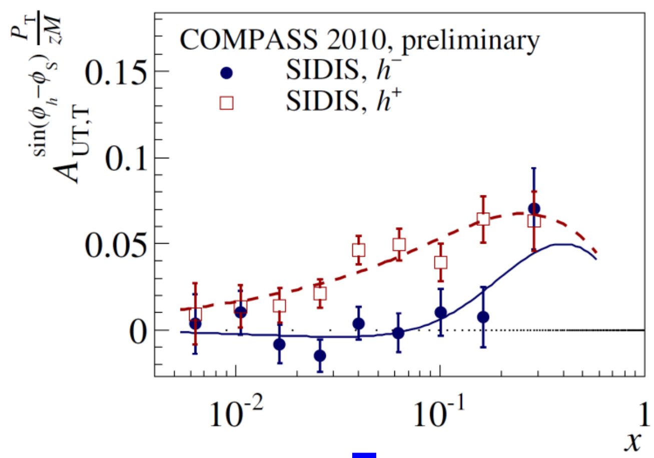


In 2018 – 2nd round of polarized DY measurements at COMPASS

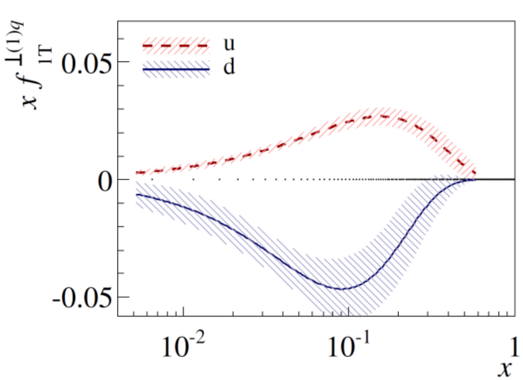
The p_T (q_T) – weighted SIDIS(DY) Sivers asymmetry

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

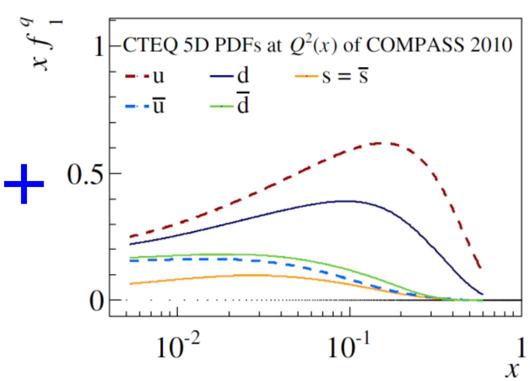
F. Bradamante (COMPASS at SPIN-2016)
arXiv:1702.00621 [hep-ex]



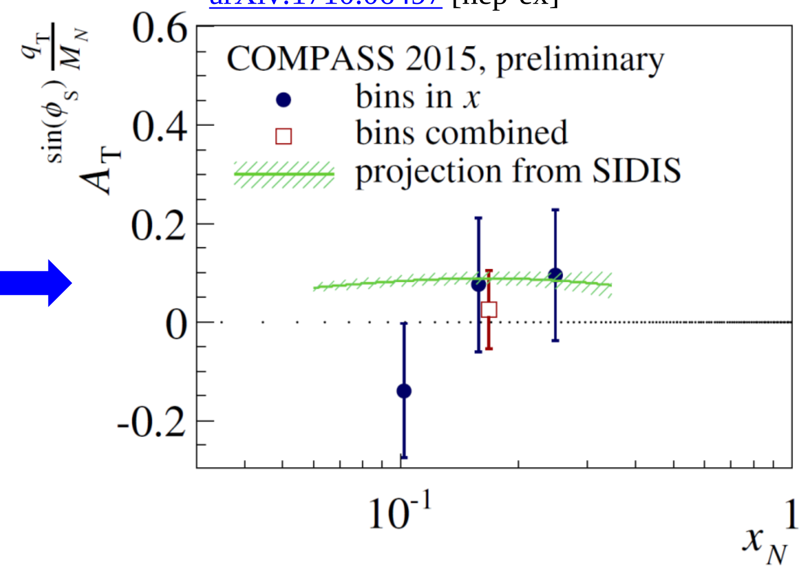
Sivers TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	
Sivers *w*TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q\,(1)} \times D_{1q}^{h\,(1)}$	
Sivers TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	
Sivers *w*TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q\,(1)} \times f_{1T,p}^{\perp q\,(1)}$	



+



J. Matoušek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]



See talk by F. Bradamante

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

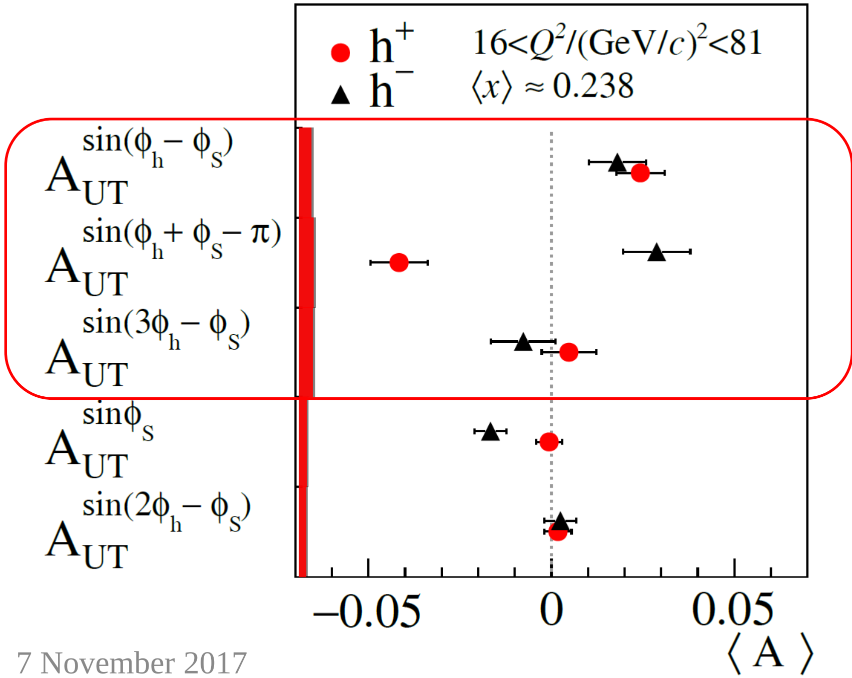
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Bigg\{ 1 + \ldots$$

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

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

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

COMPASS PLB 770 (2017) 138

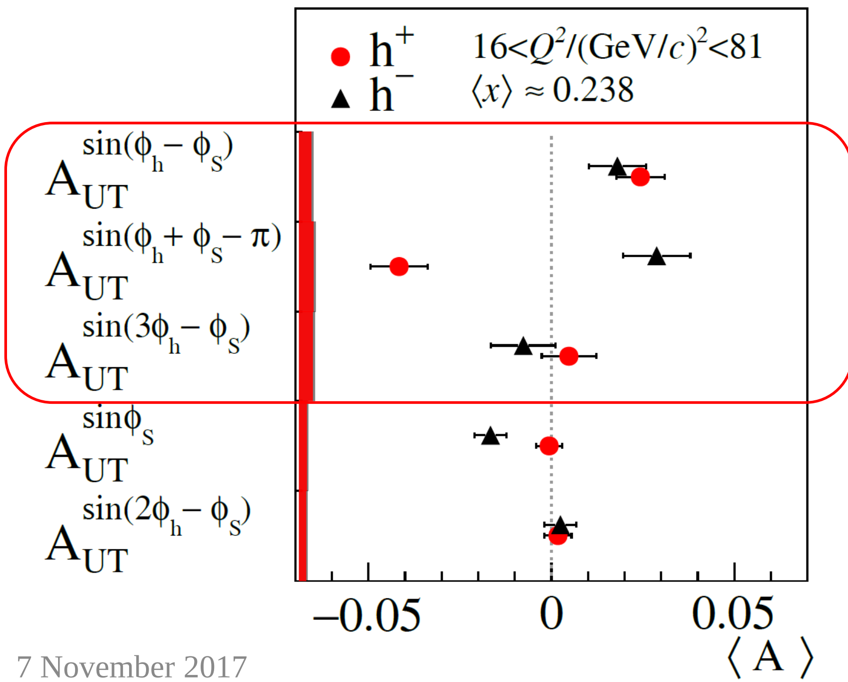


SIDIS and DY TSAs at COMPASS (high-mass range)

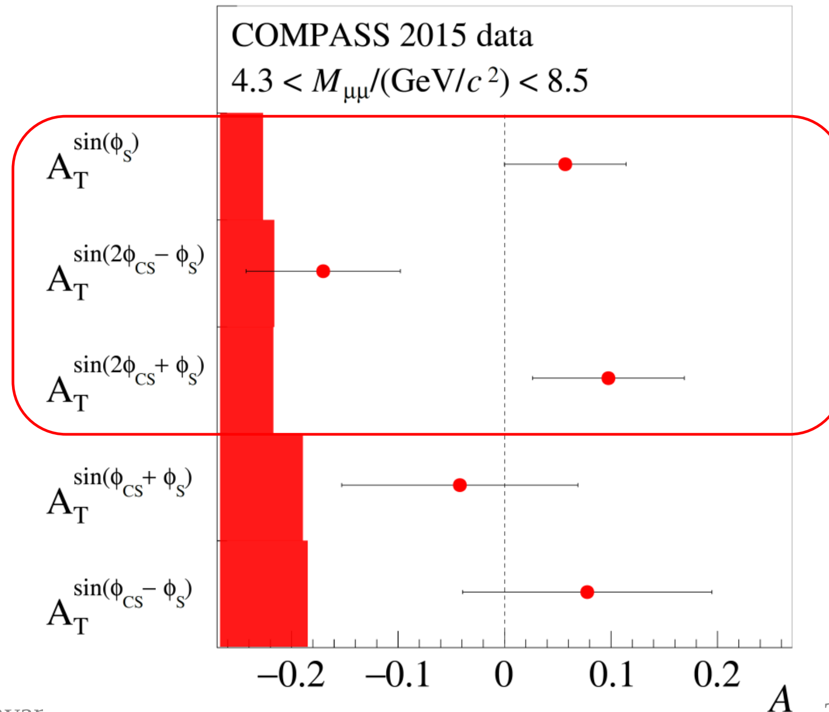
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\ldots + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S} \sin\phi_S \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{array} \right] \right\}$$

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

COMPASS PLB 770 (2017) 138



COMPASS PRL 119, 112002 (2017)



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 PRL 119, 112002 (2017)
  - 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 future is being discussed to take place after 2020
  - SIDIS measurements with transversely polarized deuteron target in 2021
  - Particular attention is given to possible Drell-Yan measurements (See talks by V. Andrieux, F. Bradamante, B. Grube, O. Denisov, C. Quintance)

Eagerly waiting for 2018 Drell-Yan COMPASS data…

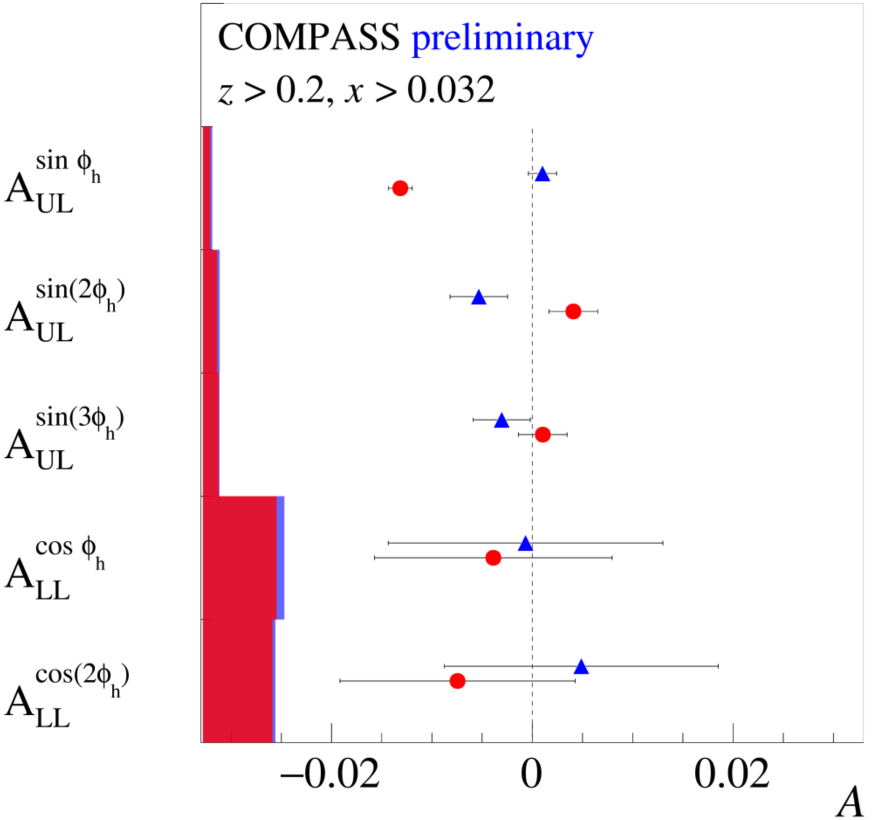
Eagerly waiting for 2018 Drell-Yan COMPASS data…

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, $h_{1T}^{\perp}$	

SIDIS: target longitudinal spin dependent asymmetries

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

$A_{UL}^{\sin\phi_h}$
- Q-suppression, Various different “twist” ingredients
- Sizable TSA-mixing
- **Significant h^+ asymmetry, clear *z*-dependence,**
- **h^- compatible with zero**

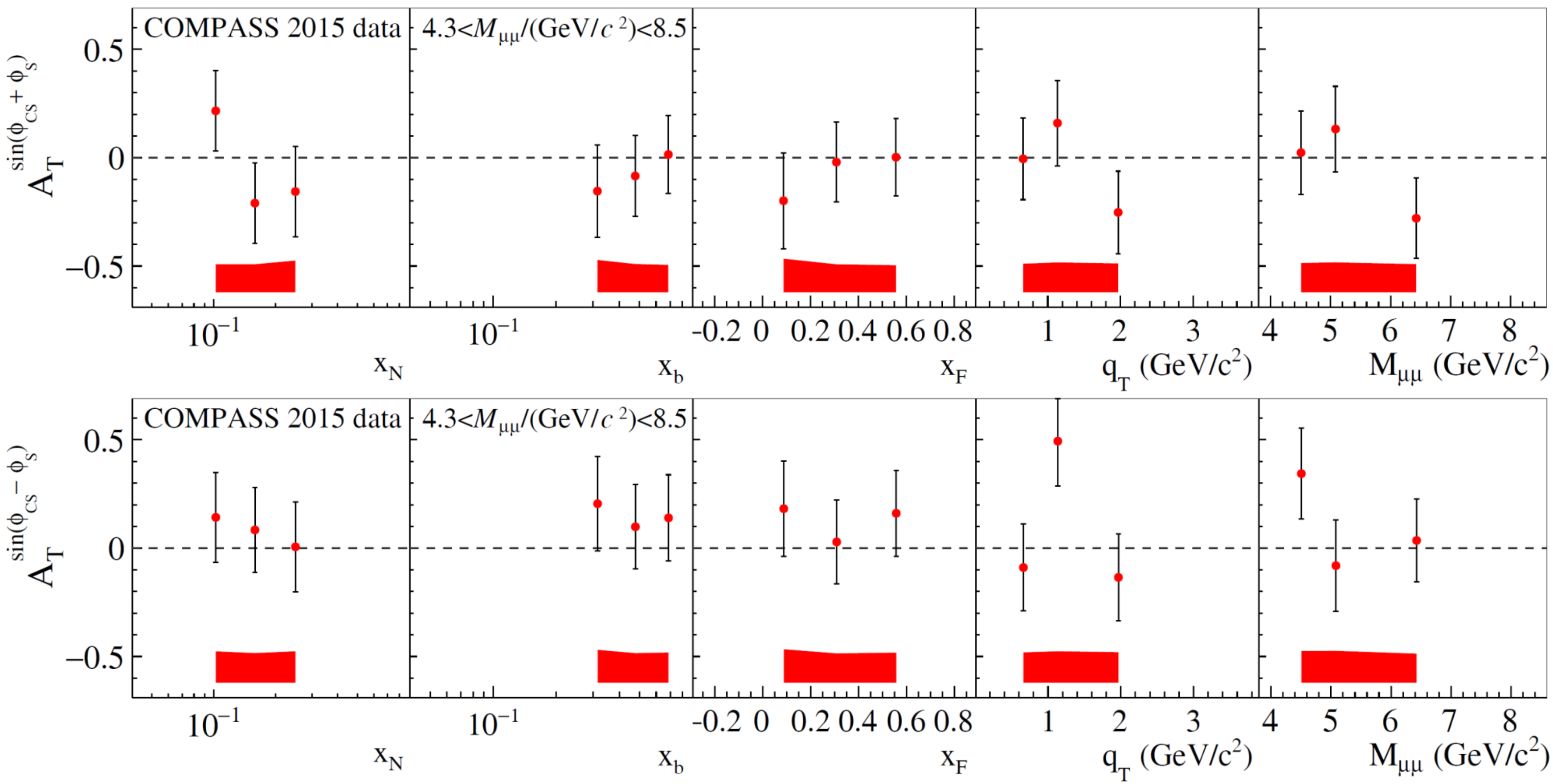
$A_{UL}^{\sin 2\phi_h}$
- Only “twist-2” ingredients
- Additional p_T-suppression
- **Compatible with zero, in agreement with models**
- **Collins-like behavior?**

$A_{LL}^{\cos\phi_h}$
- Q-suppression, Various different “twist” ingredients
- **Compatible with zero, in agreement with models**

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! COMPASS arXiv:1704.00488[hep-ex]



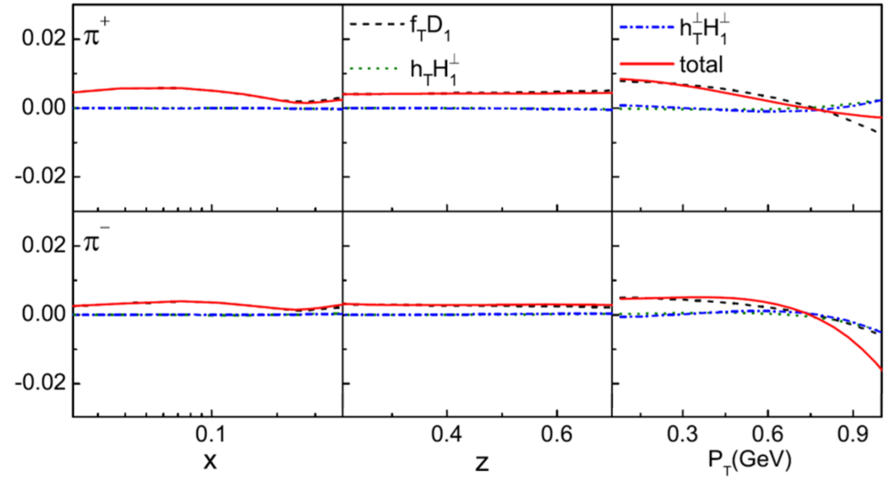
SIDIS: target transverse spin dependent asymmetries

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

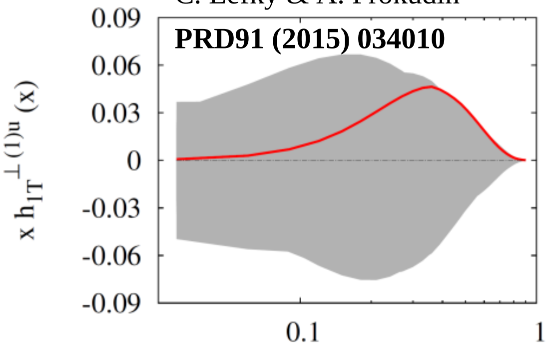
$$+\ S_T \left[\begin{array}{l} +\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin\left(3\phi_h-\phi_S\right) \\ +\ \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S} \sin\phi_S \\ +\ \ldots \end{array} \right]$$

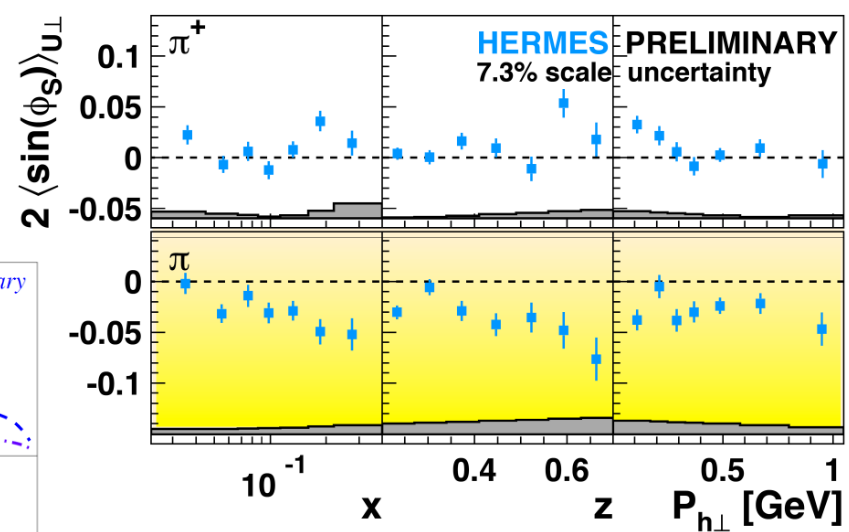
$$\left. +\ S_T\lambda \left[\begin{array}{l} \sqrt{\left(1-\varepsilon^2\right)}\,A_{LT}^{\cos(\phi_h-\phi_S)} \cos\left(\phi_h-\phi_S\right) \\ +\ \ldots \end{array} \right] \right\}$$

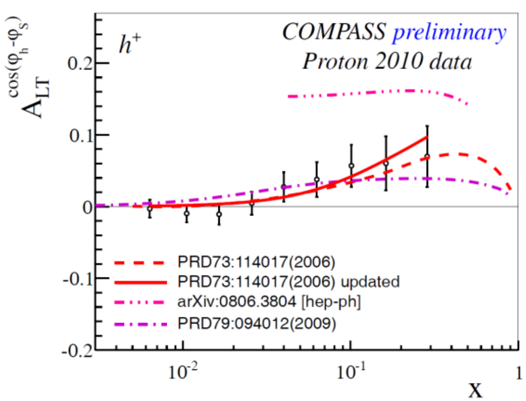
W. Mao, Z. Lu and B.Q. Ma **Phys.Rev. D 90 (2014) 014048**

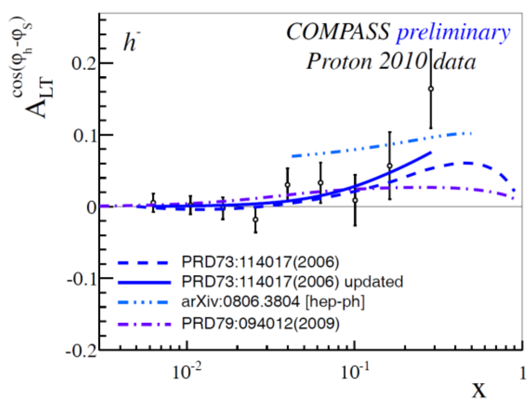


C. Lefky & A. Prokudin







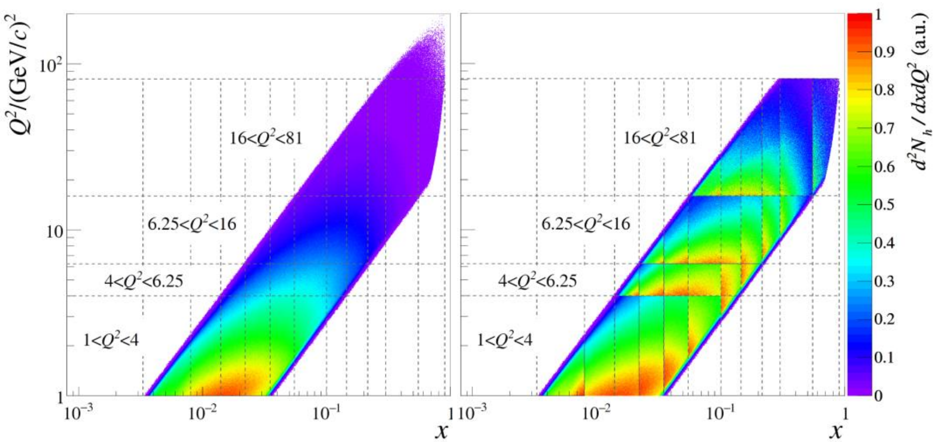


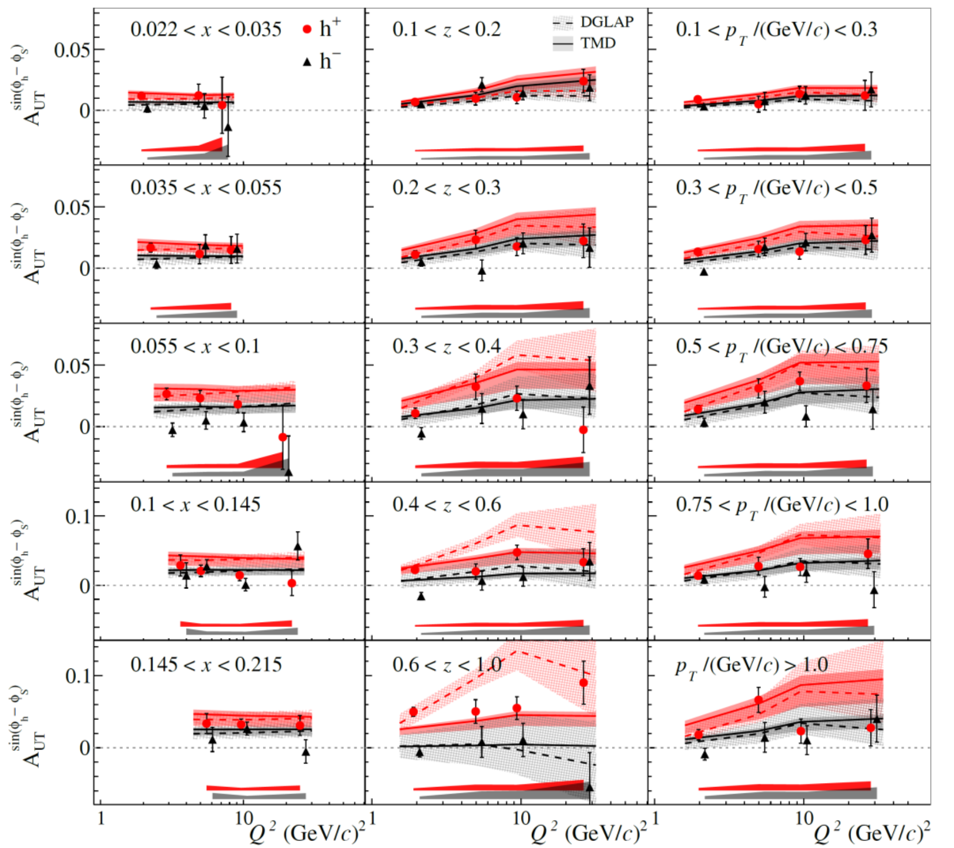
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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

PLB 770 (2017) 138



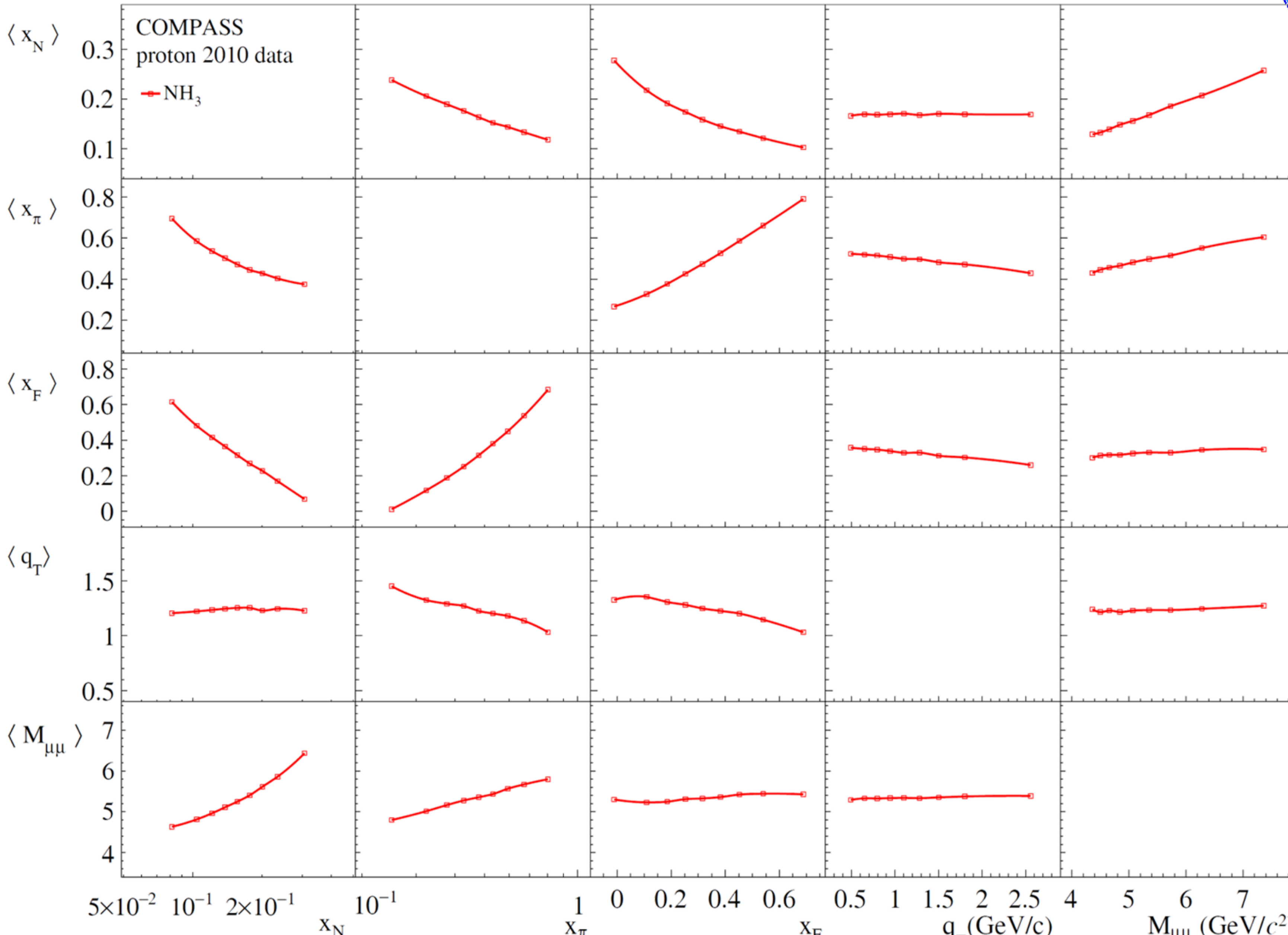


Multi-dimensional input for TMD evolution studies

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

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

Kinematic map: high mass range



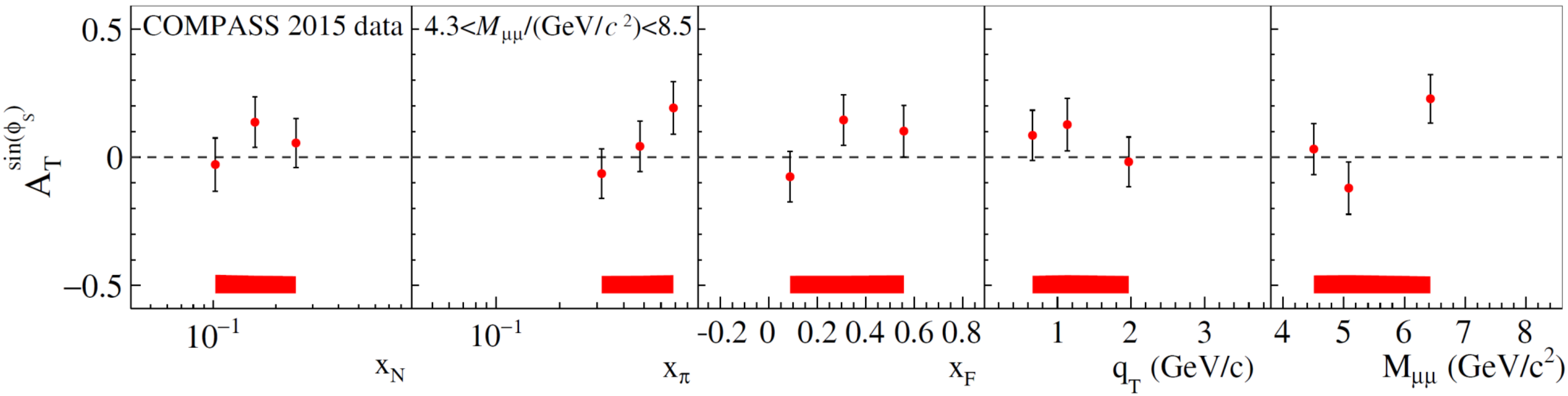
Drell-Yan TSAs – Sivers

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

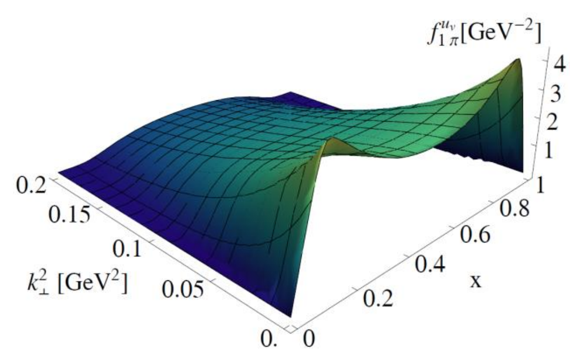
Sivers DY TSA

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

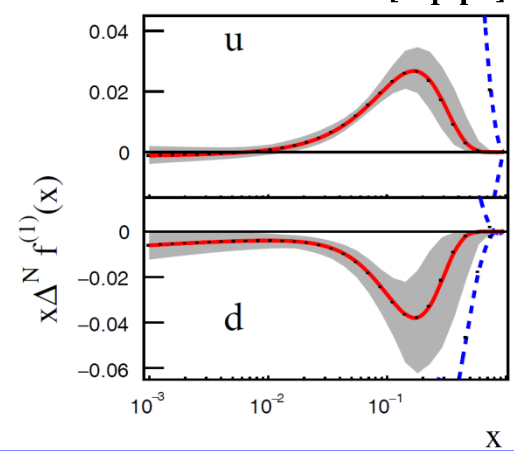
New! COMPASS arXiv:1704.00488[hep-ex]



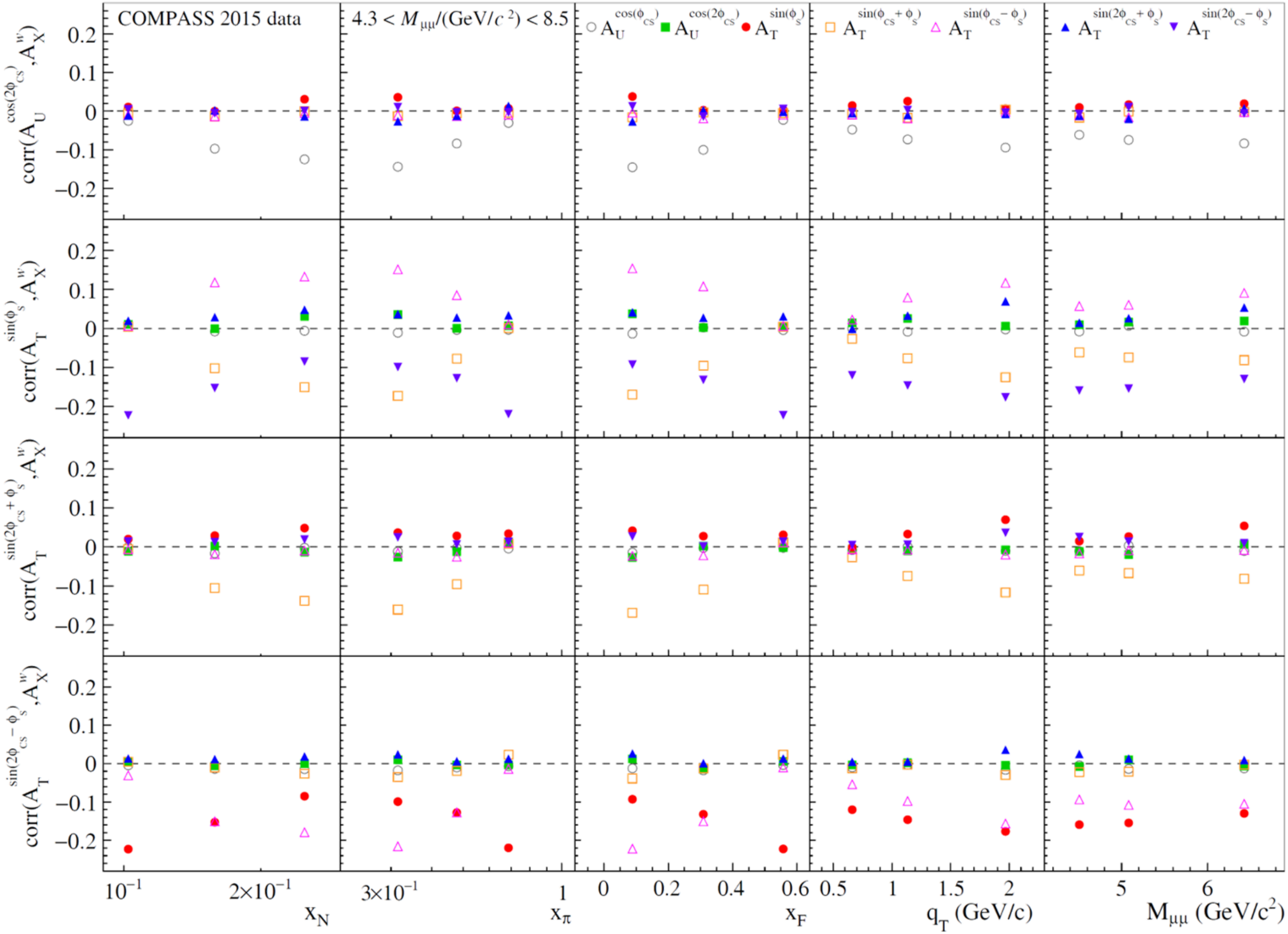
B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



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



Correlation coefficients



Maximum correlations are about ~0.2

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

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

$$\int d^2\boldsymbol{q}_\mathrm{T}\,\frac{q_\mathrm{T}}{M_\mathrm{p}}F_\mathrm{T}^{\sin\phi_\mathrm{S}} = -\int d^2\boldsymbol{q}_\mathrm{T}\,\frac{q_\mathrm{T}}{M_\mathrm{p}}\,\mathcal{C}\left[\frac{\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{k}_\mathrm{pT}}{q_\mathrm{T}M_\mathrm{p}}f_{1,\pi}f_{1\mathrm{T,p}}^{\perp}\right]$$

$$= -\frac{2}{N_c}\sum_q e_q^2\left[f_{1,\pi}^{\bar{q}}(x_\pi)\,f_{1\mathrm{T,p}}^{\perp(1)q}(x_\mathrm{p}) + (q\leftrightarrow\bar{q})\right]$$

$$\approx \frac{2e_\mathrm{u}^2}{N_c}f_{1,\pi}^{\bar{\mathrm{u}}}(x_\pi)\,f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N)$$

Sivers TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^{h}$
Sivers *w*TSA in SIDIS:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q\,(1)}\times D_{1q}^{h\,(1)}$
Sivers TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q}\otimes f_{1T,\mathrm{p}}^{\perp q}$
Sivers *w*TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q\,(1)}\times f_{1T,\mathrm{p}}^{\perp q\,(1)}$

$$f_{1\mathrm{T}}^{\perp(1)q}(x) = \int d^2\boldsymbol{k}_\mathrm{T}\,\frac{k_\mathrm{T}^2}{2M^2}\,f_{1\mathrm{T}}^{\perp q}(x,k_\mathrm{T}^2)$$

$$A_{\mathrm{UT,T},h^\pm}^{\sin(\phi_\mathrm{h}-\phi_\mathrm{S})\frac{P_\mathrm{T}}{zM}}(x,Q^2) = 2\,\frac{\frac{4}{9}f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x,Q^2)\,\tilde{D}_{1,\mathrm{u}}^{h^\pm}(Q^2) + \frac{1}{9}f_{1\mathrm{T}}^{\perp(1)\mathrm{d}}(x,Q^2)\,\tilde{D}_{1,\mathrm{u}}^{h^\pm}(Q^2)}{\sum_q e_q^2\,f_1^q(x,Q^2)\,\tilde{D}_{1,\mathrm{u}}^{h^\pm}(Q^2)}$$

$$\tilde{D}_{1,q}^{h^\pm}(Q^2) = \int_{0.2}^{1}dz\,D_{1,q}^{h^\pm}(z,Q^2) \qquad x f_{1\mathrm{T}}^{\perp(1)q}(x) = a_q\,x^{b_q}\,(1-x)^{c_q}$$

$$A_\mathrm{T}^{\sin\phi_\mathrm{S}\frac{q_\mathrm{T}}{M_\mathrm{p}}}(x_N,Q^2) \approx 2\,\frac{f_{1\mathrm{T,p}}^{\perp(1)\mathrm{u}}(x_N,Q^2)}{f_{1,\mathrm{p}}^{\mathrm{u}}(x_N,Q^2)}$$