COMPASS results and program on Drell-Yan measurements

BAKUR PARSAMYAN

CERN, University of Turin
and
INFN section of Turin

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

on behalf of the COMPASS Collaboration

"Transversity – 2017"

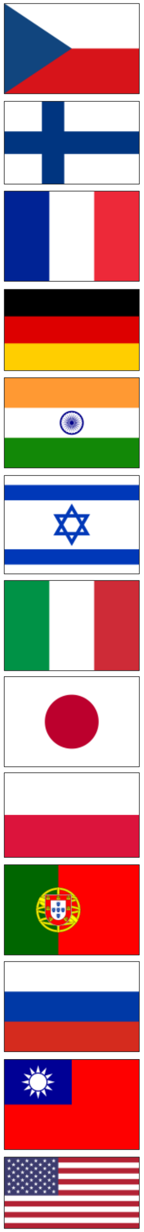
5th International Workshop on Trasverse Polarization Phenomena in Hard Processes

INFN-FNL, Frascati, Italy

December 11 – 15, 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 (20 years)**
- **Taking data since 2002**

Wide physics program

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

COMPASS-II
- **Data taking 2012-2018 (2021?)**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
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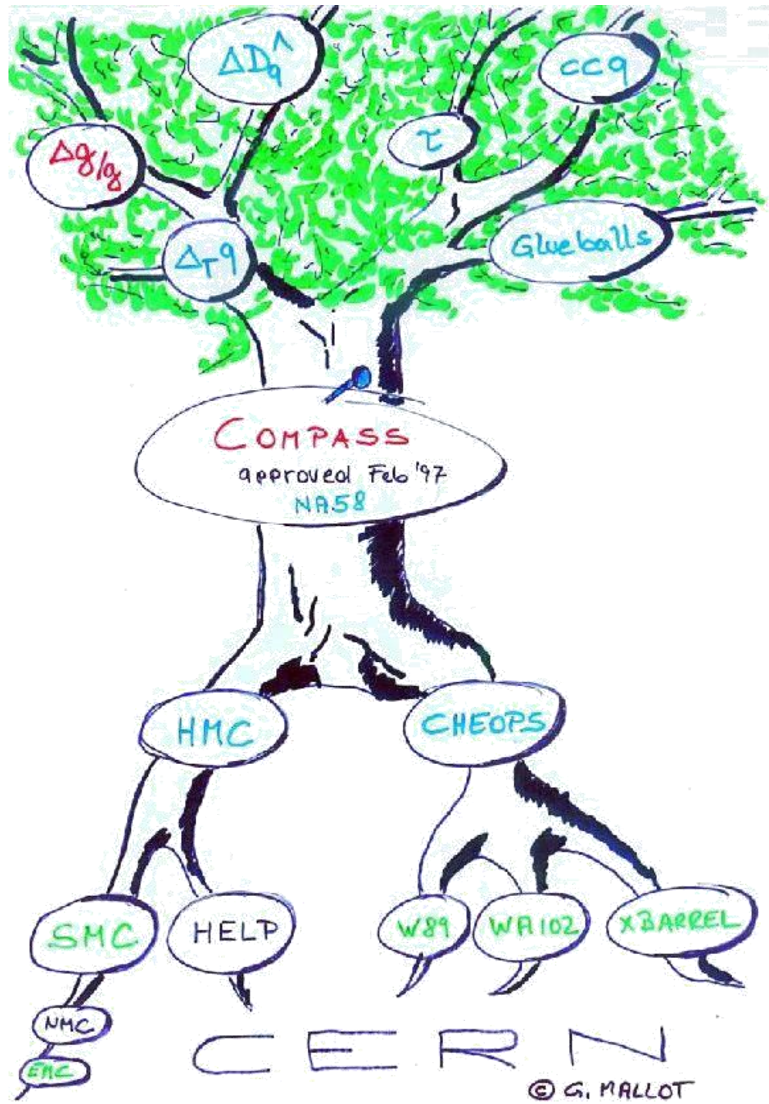
- **Transverse deuteron SIDIS**

Many “beyond 2021” ideas

See COMPASS talks by:
A. Bressan, J. Matoušek, A. Moretti



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

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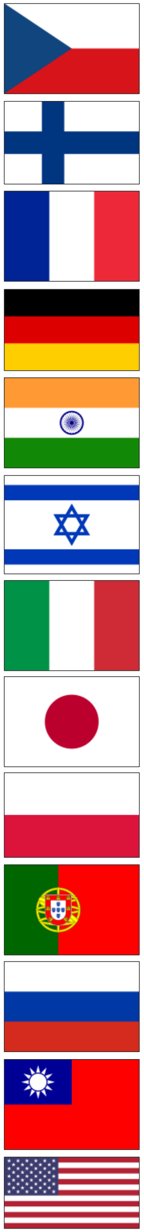

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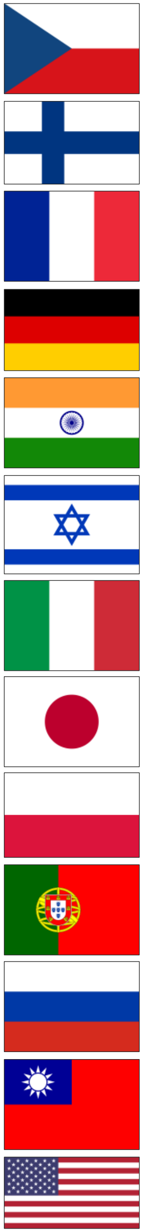

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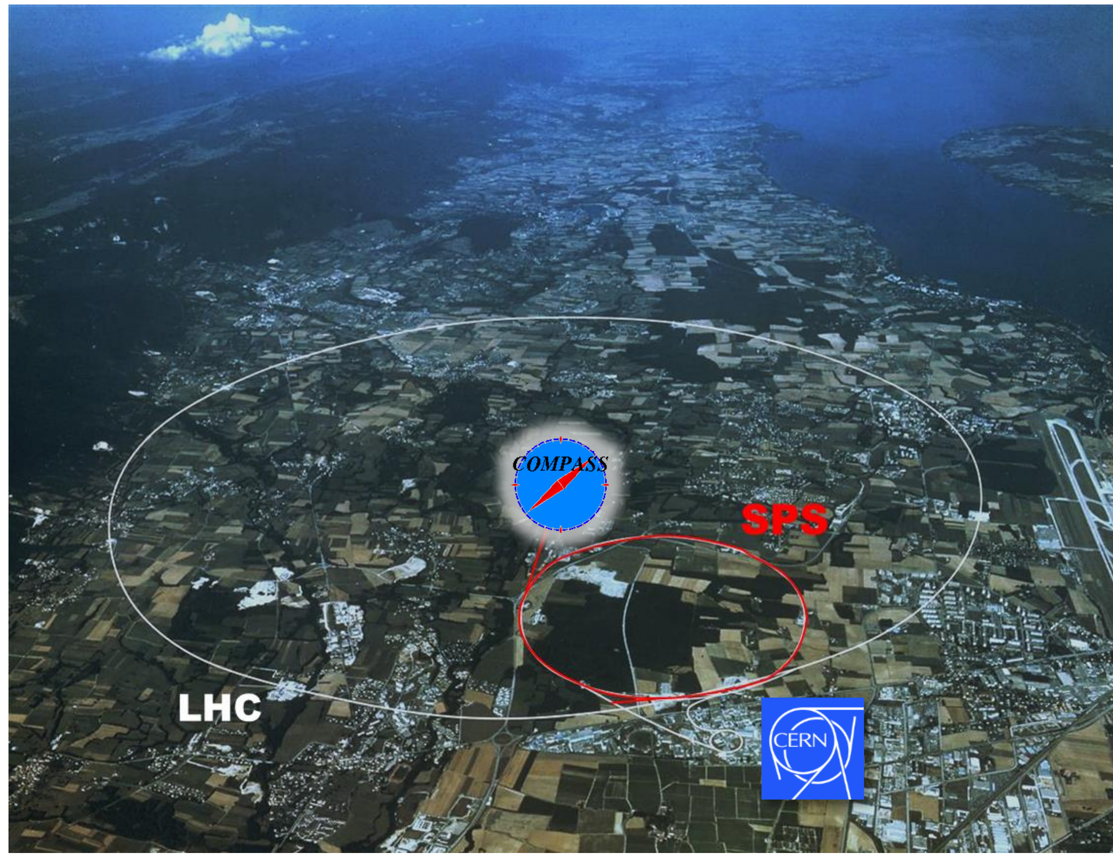

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COMPASS experimental setup: Phase I (muon program)

Two-stage spectrometer

- Large Angle Spectrometer (SM1 magnet)
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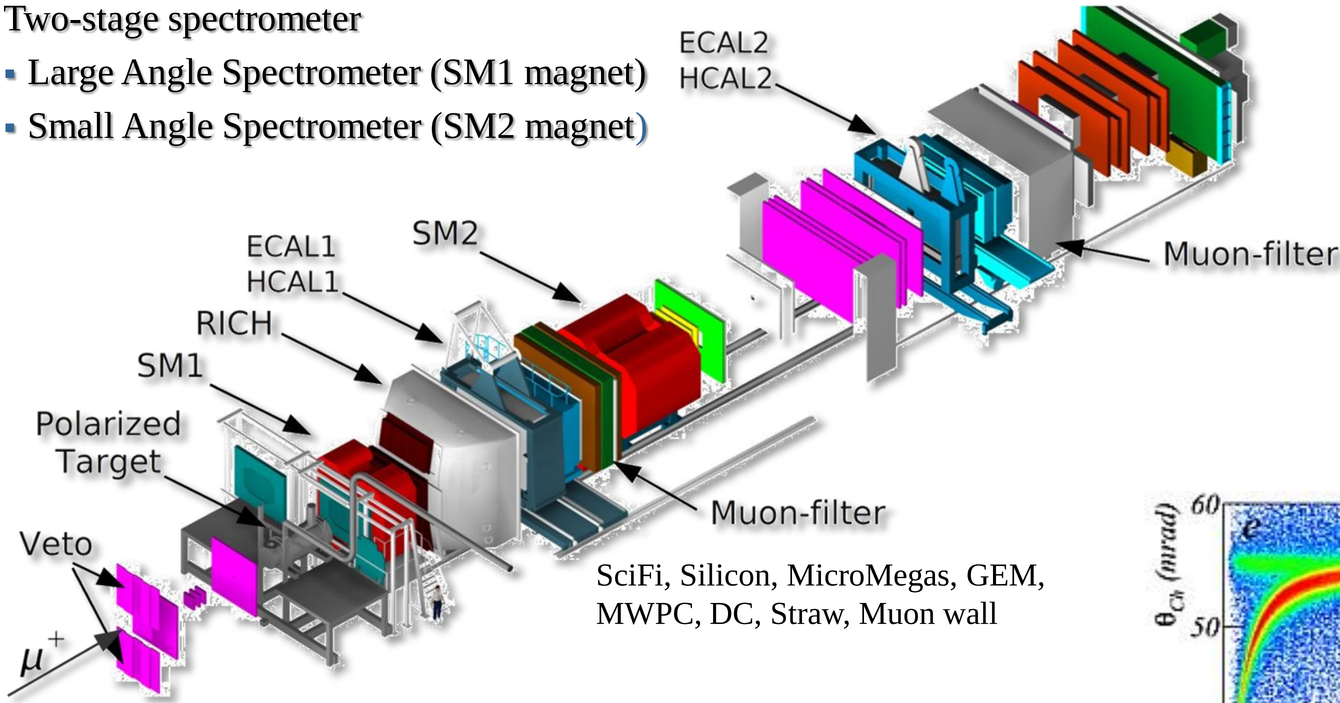
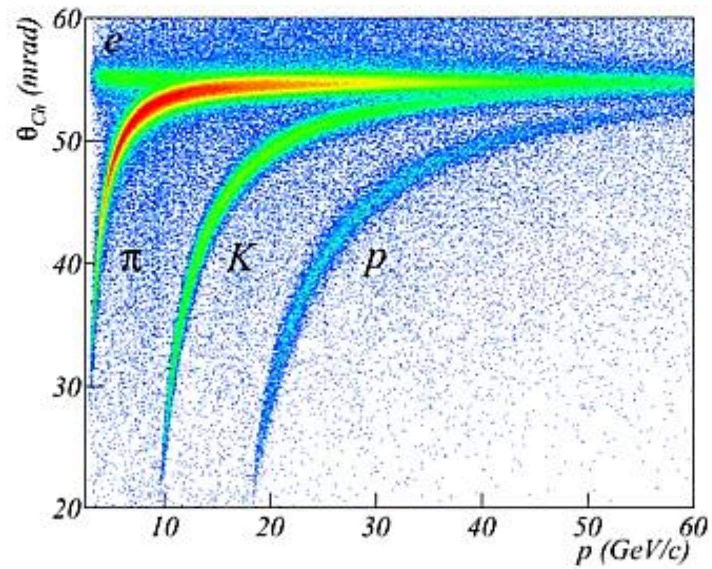


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall

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



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
- NH_3 3-cell configuration. Polarization (L & T) ~ 80%, f ~ 0.14

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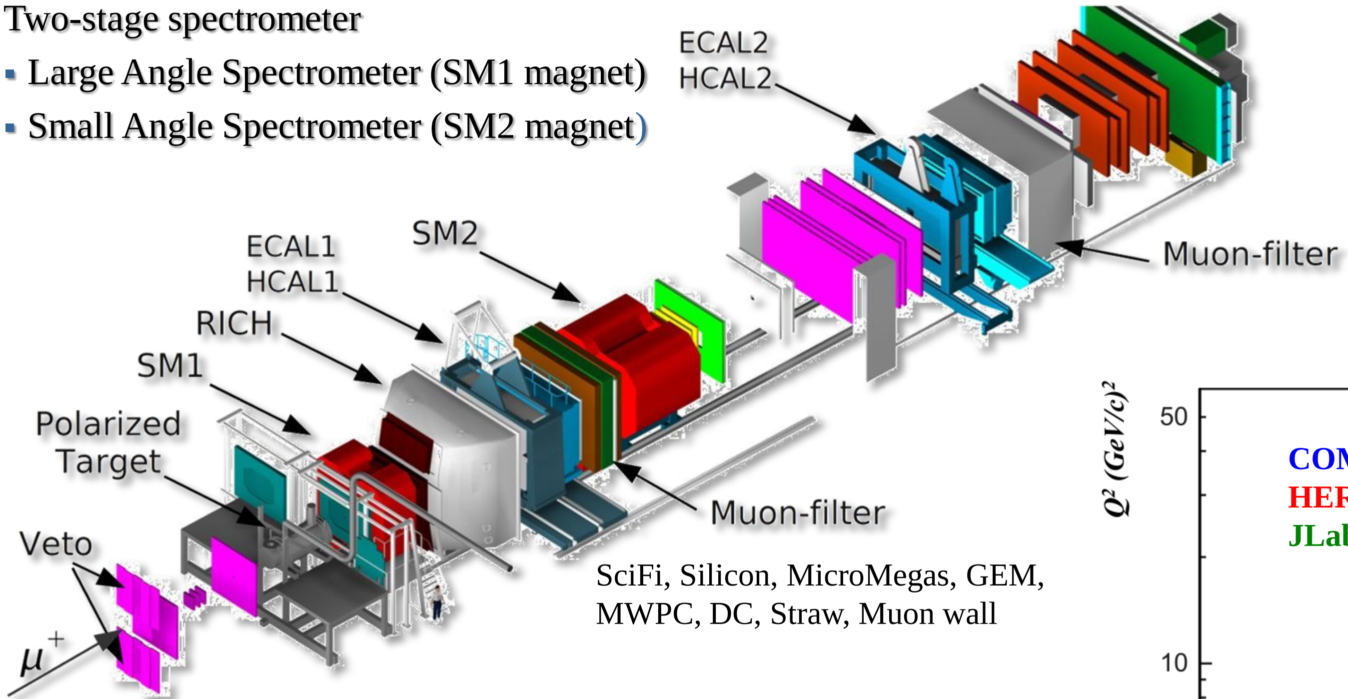

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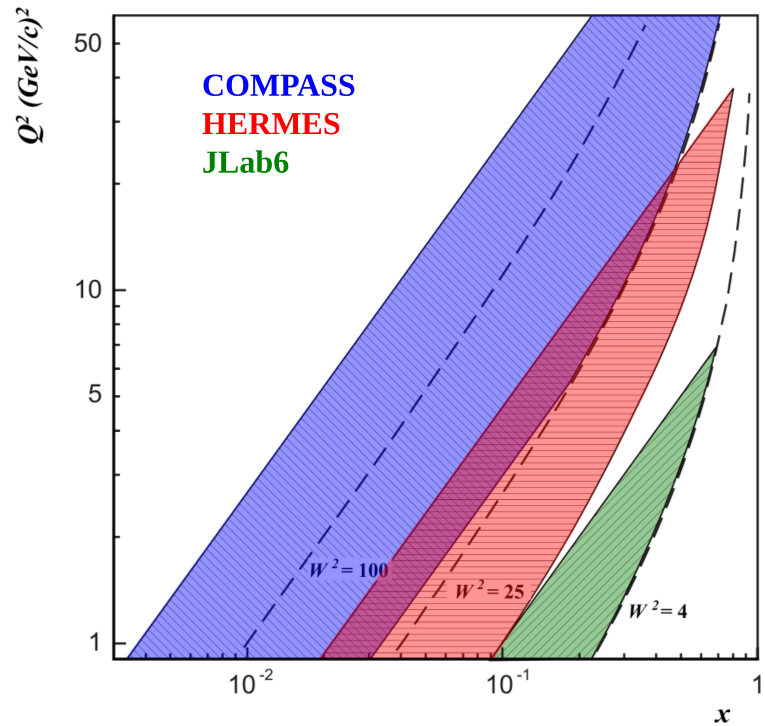

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COMPASS experimental setup: Phase II (DY program)

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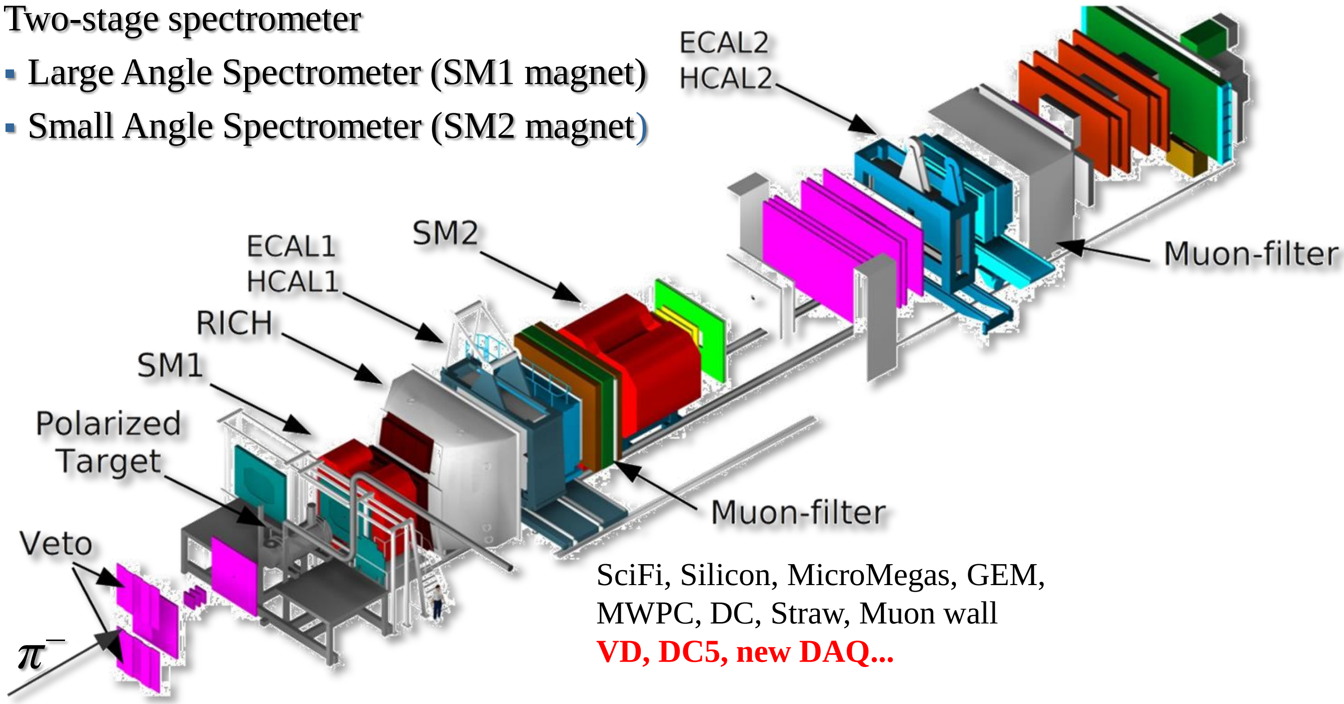

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VD, DC5, new DAQ...

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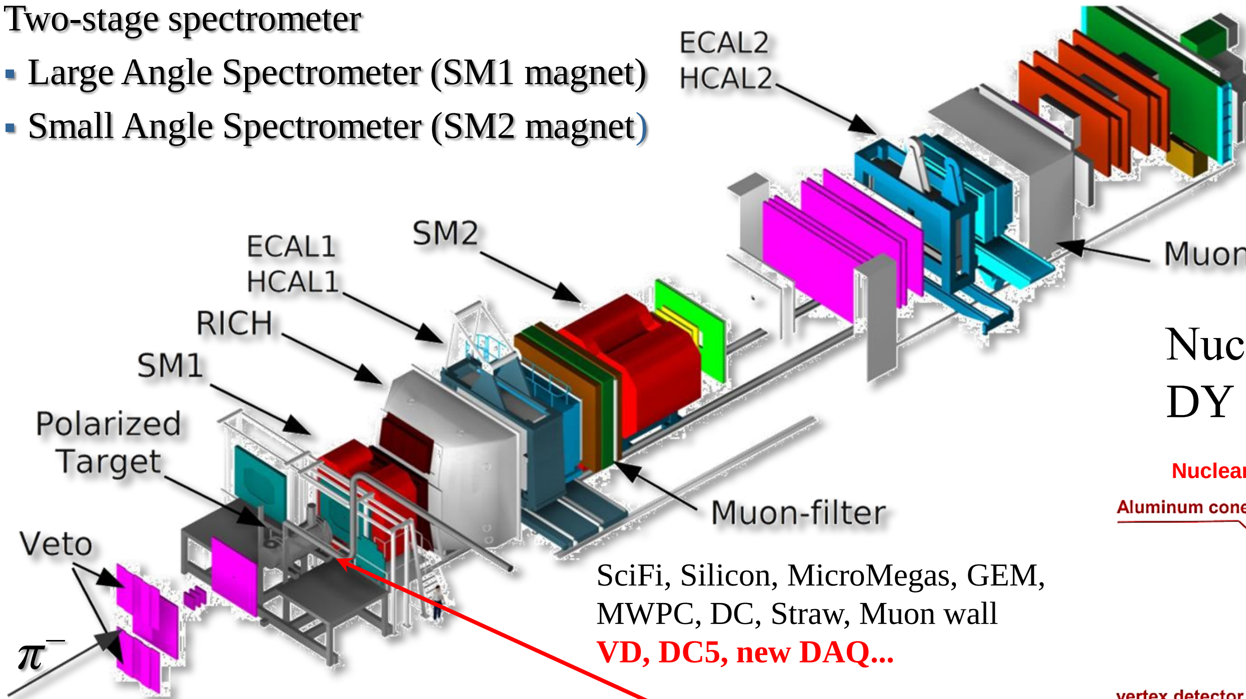

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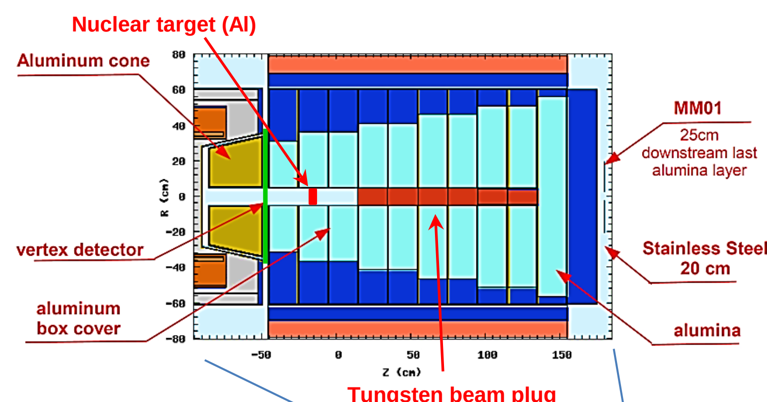
Nuclear targets → unpolarized DY, DY cross-sections, EMC effect



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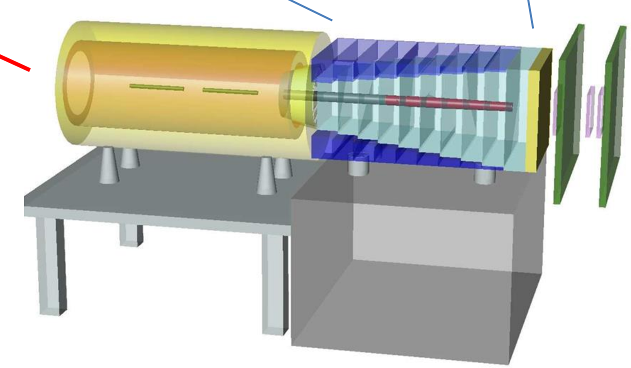

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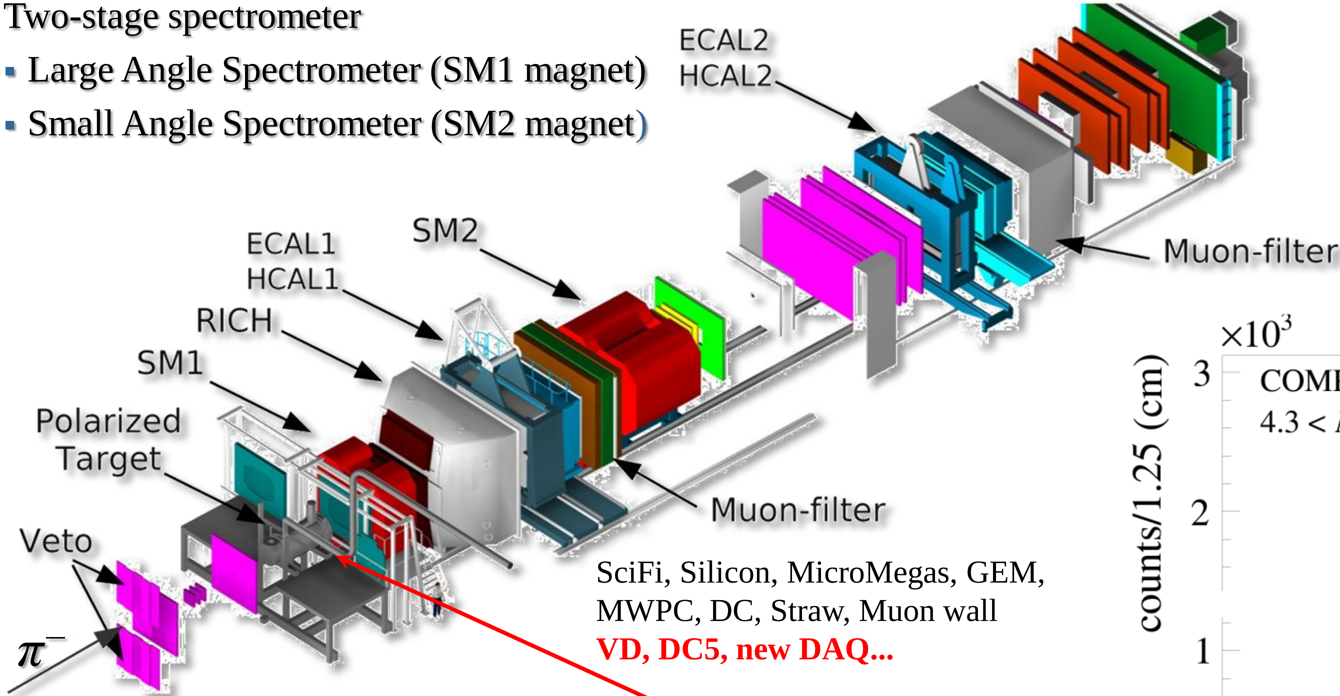

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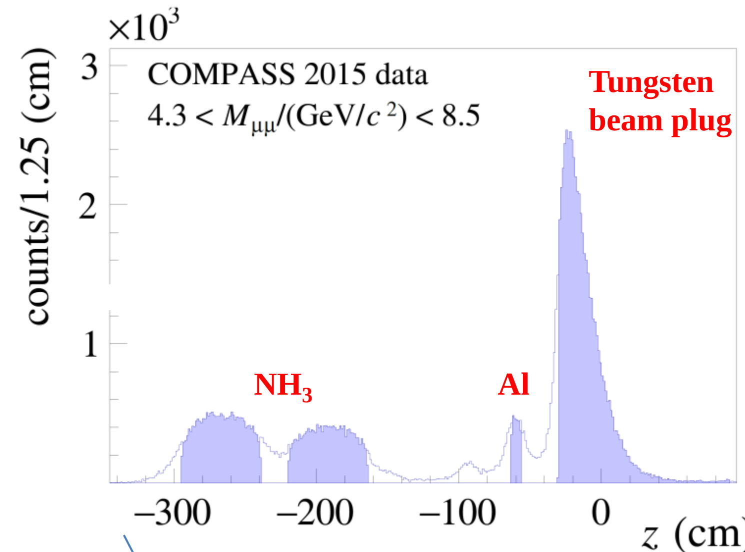

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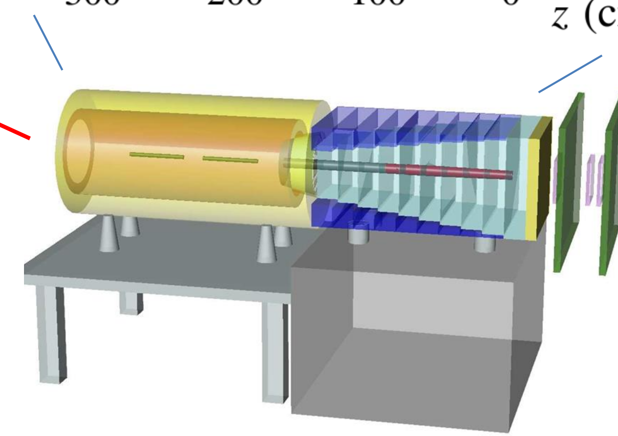

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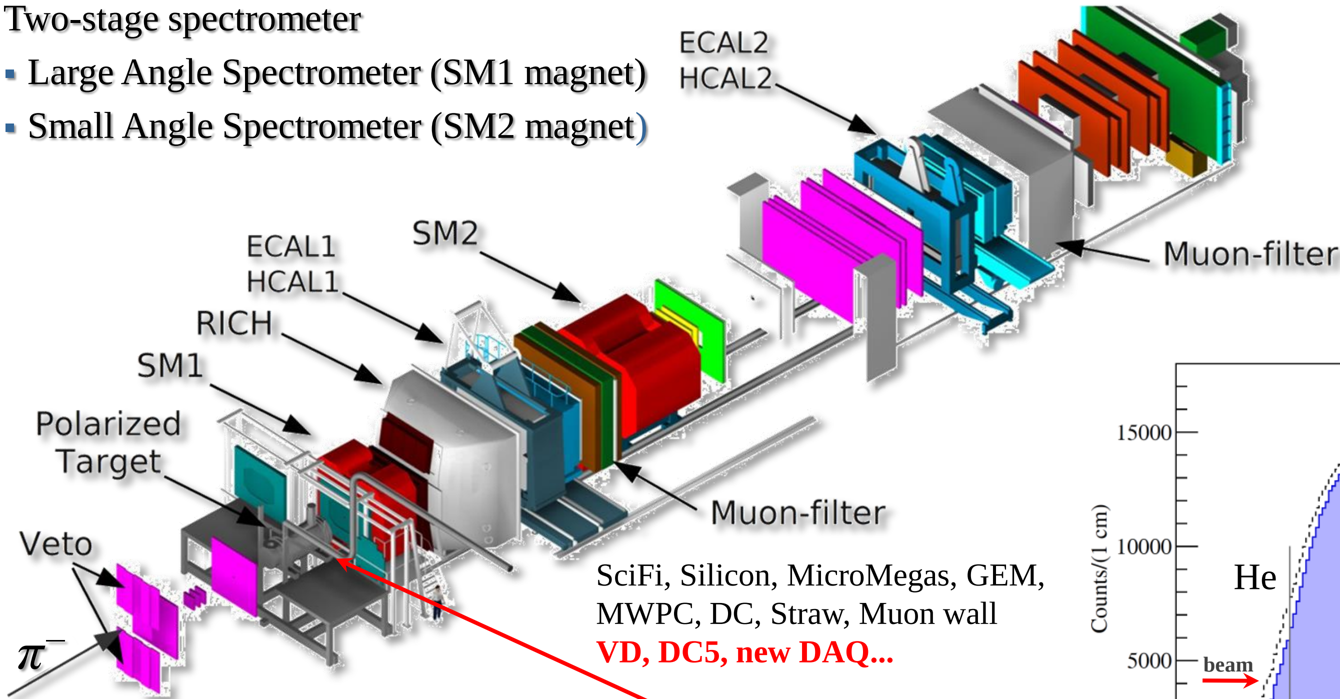

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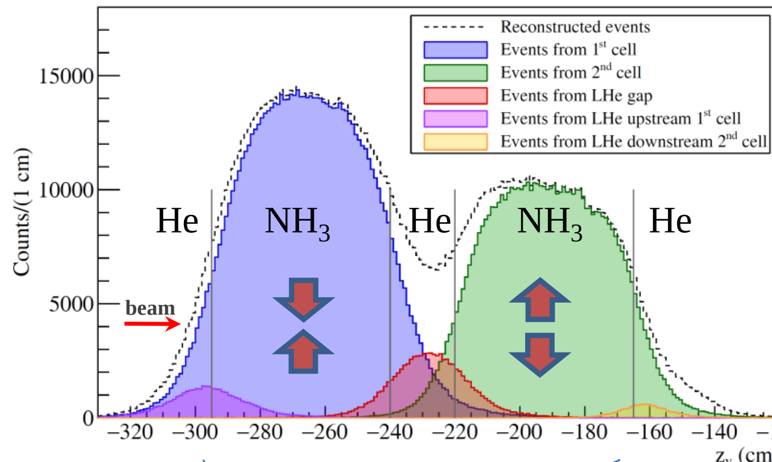

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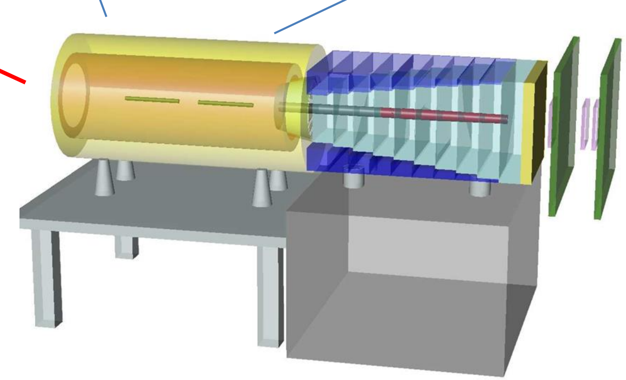

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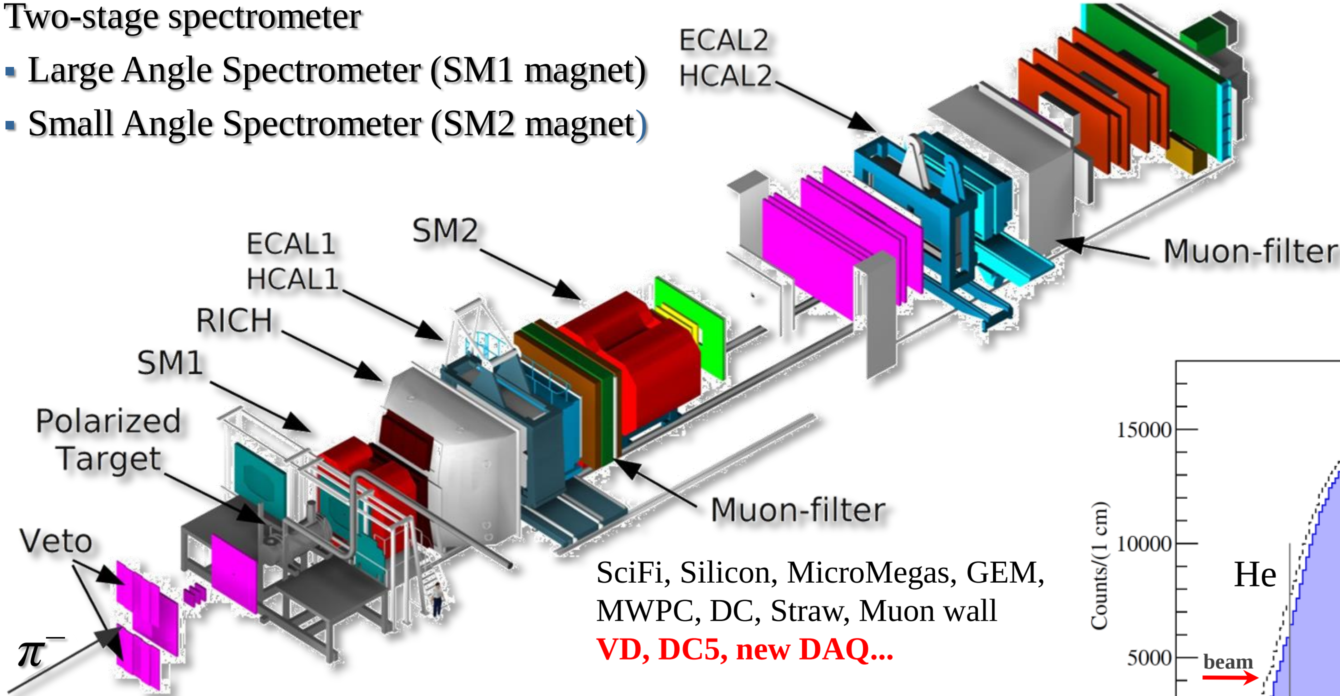

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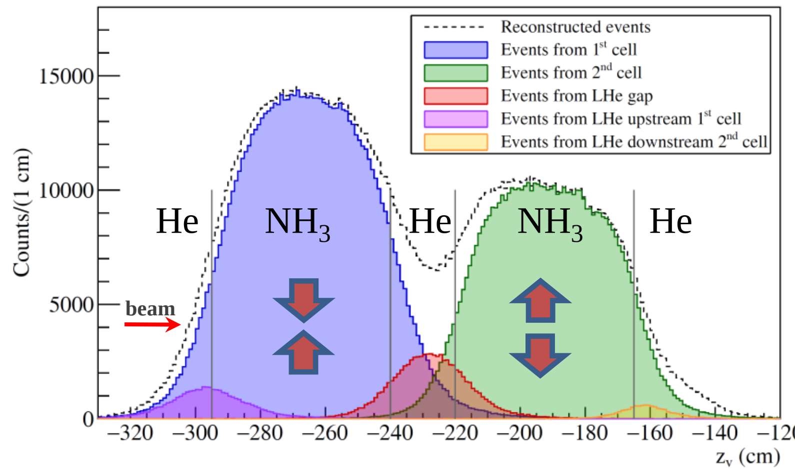

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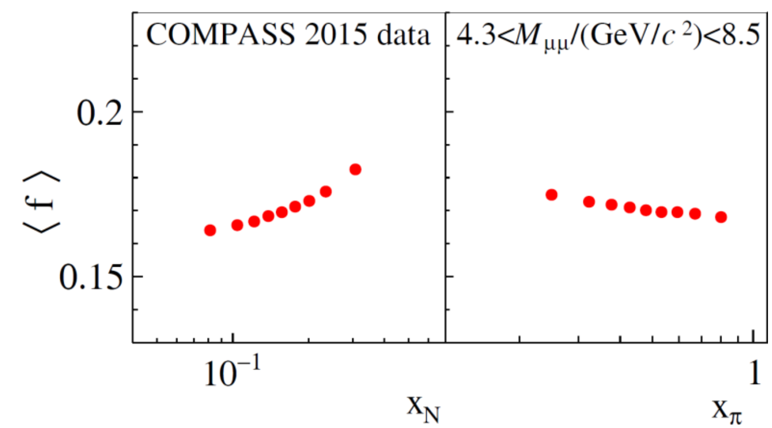

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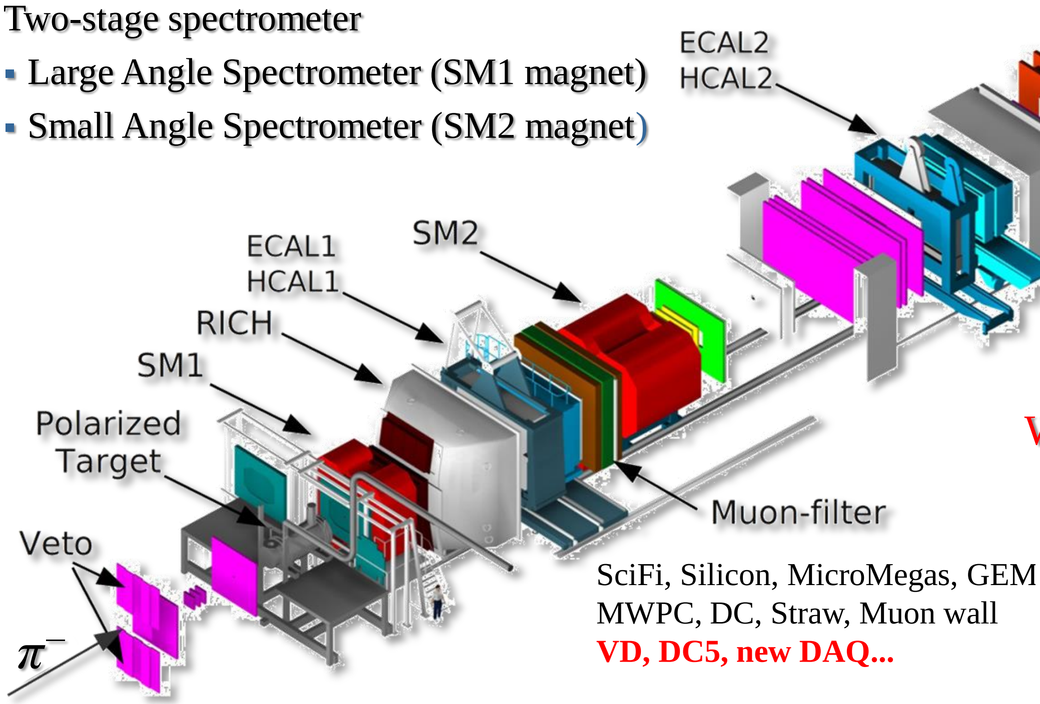

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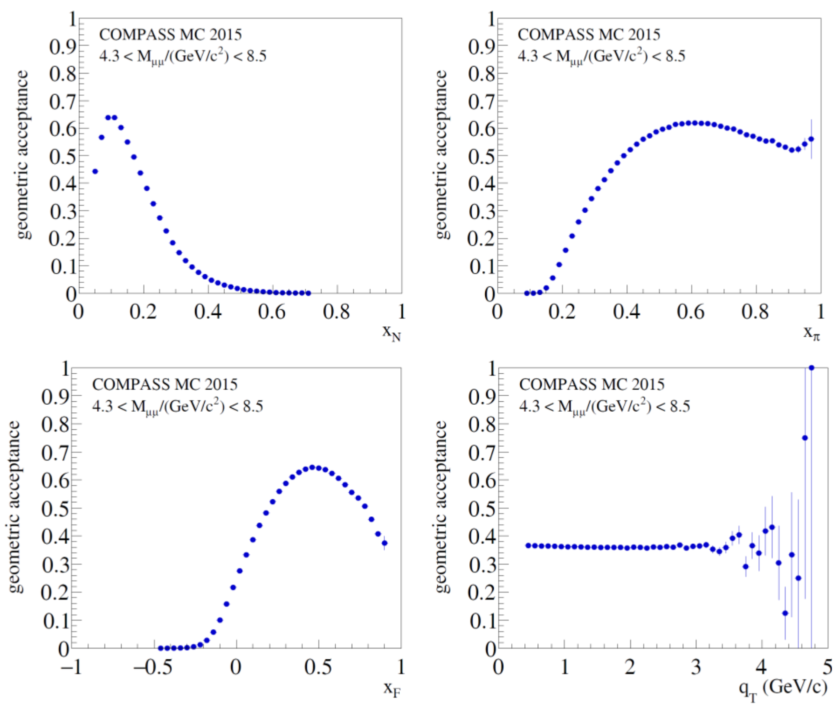
Wide geometrical acceptance: $8 < \theta_\mu < 160$ mrad



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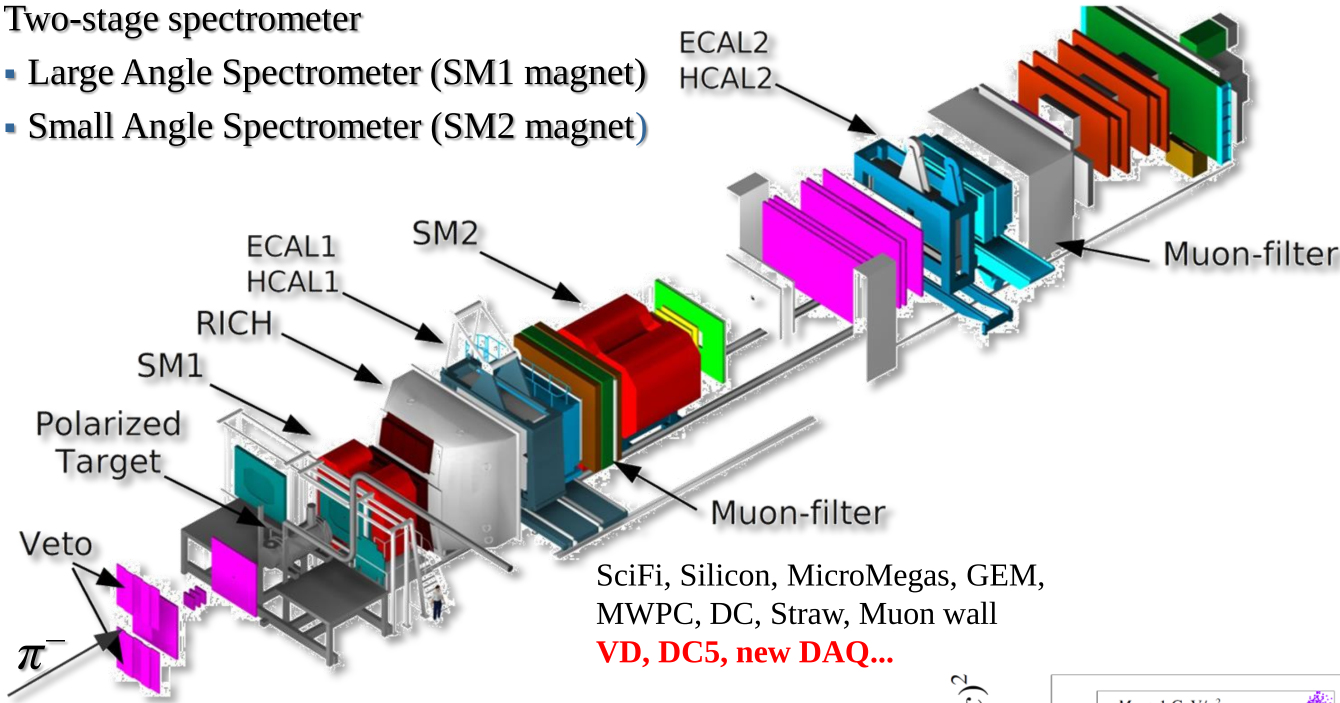

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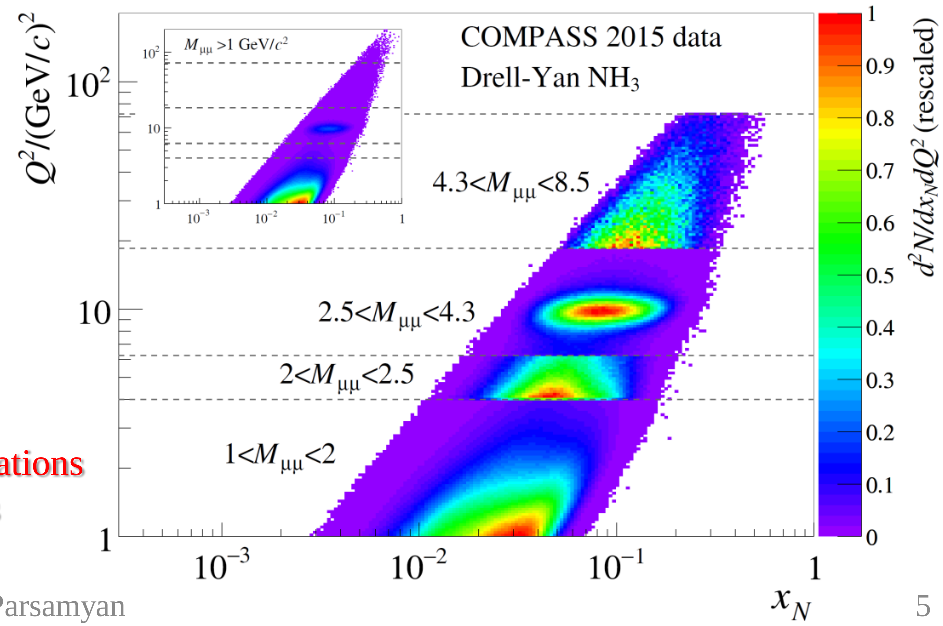

COMPASS DY mass ranges

- $1.0 < M/(GeV/c^2) < 2.0$ "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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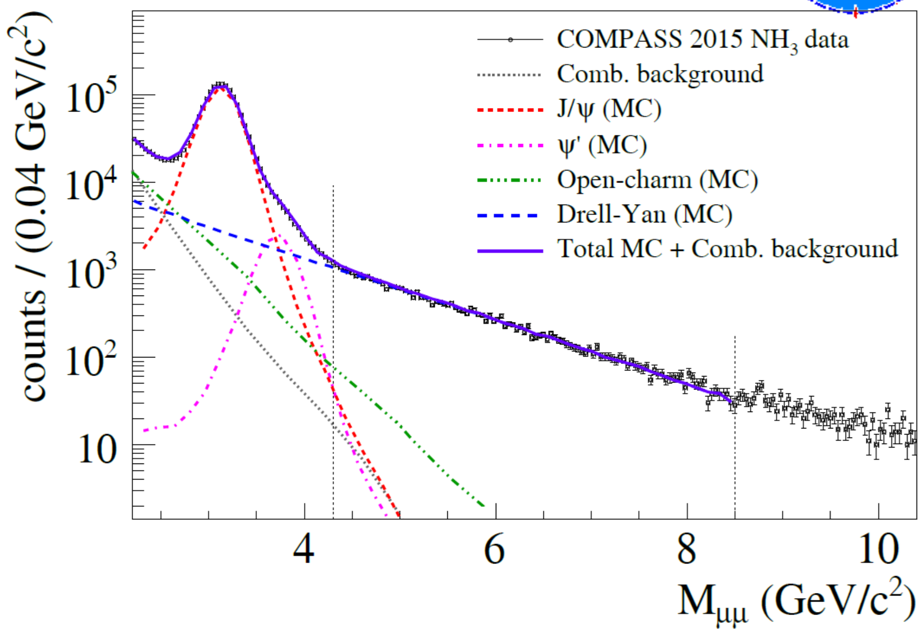
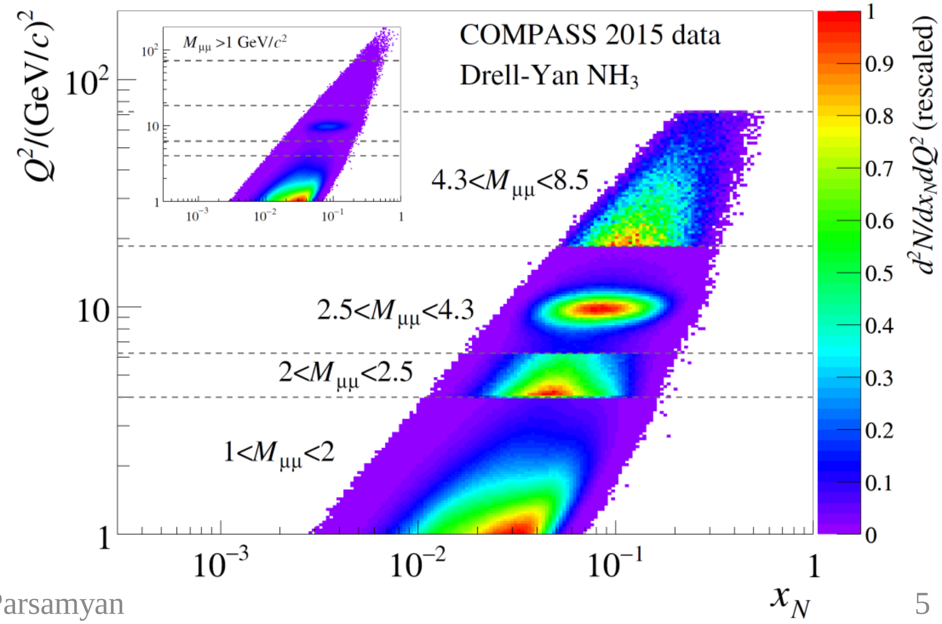
  - Valence region → largest asymmetries





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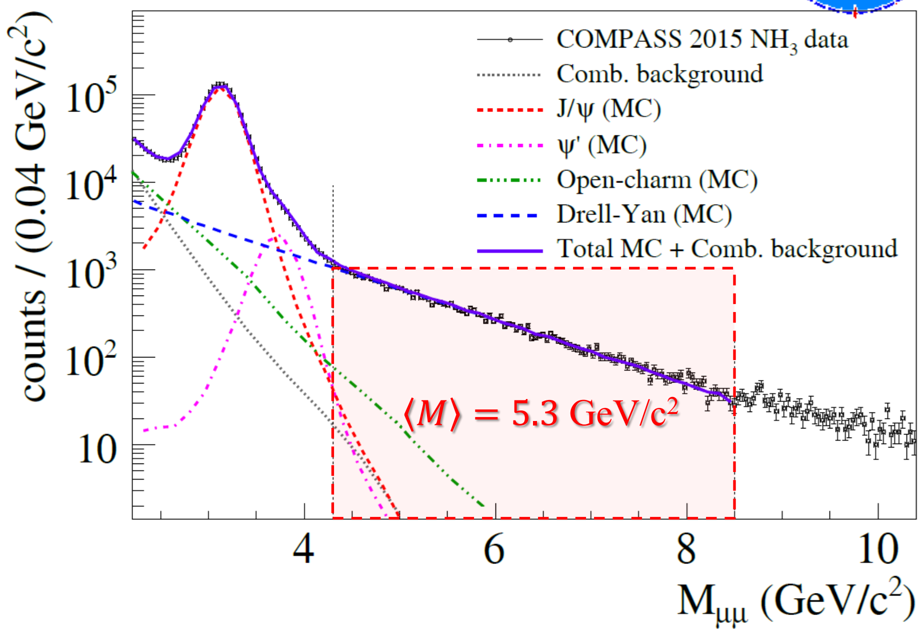
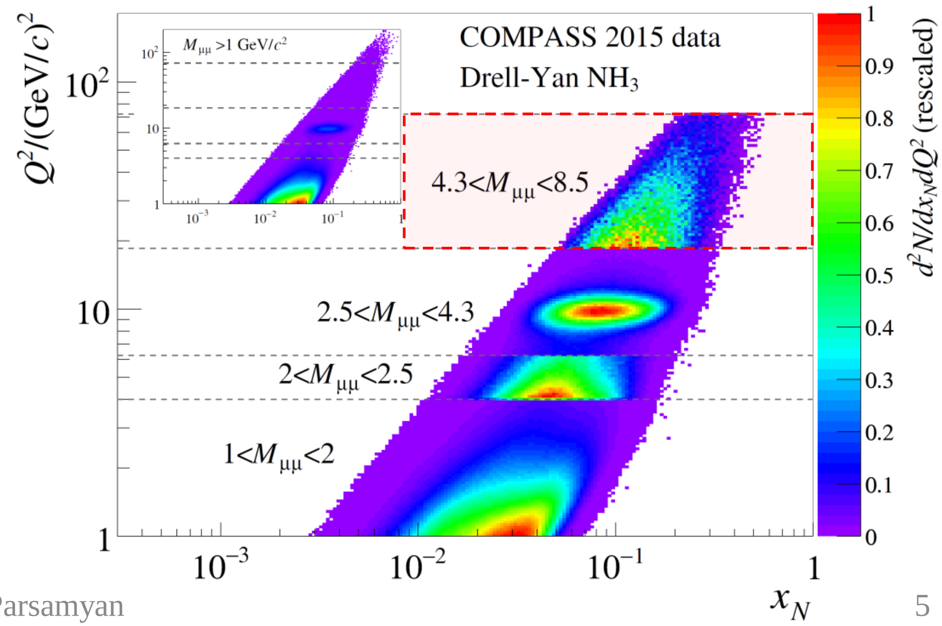
Final sample: 35 000 dimuons in HM





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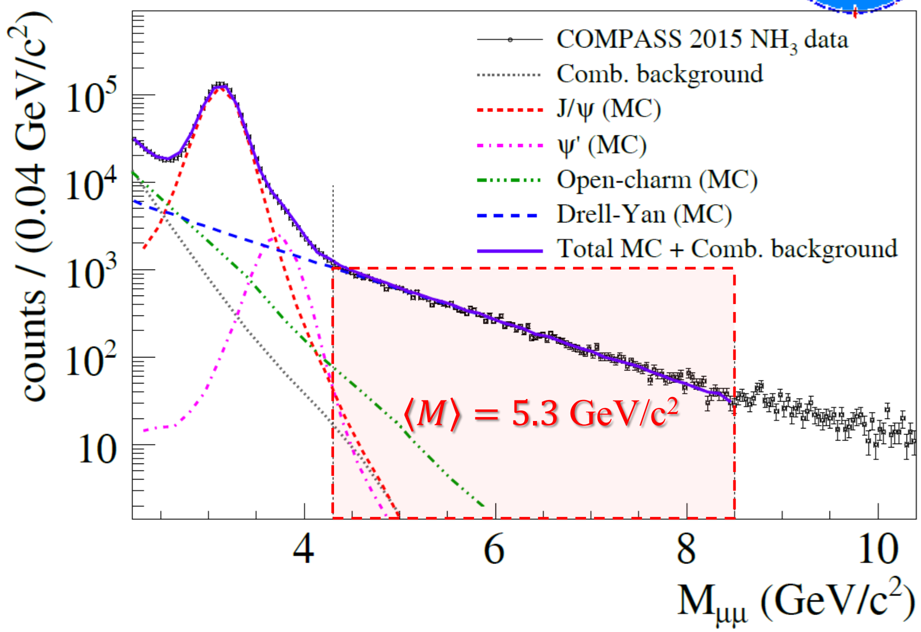
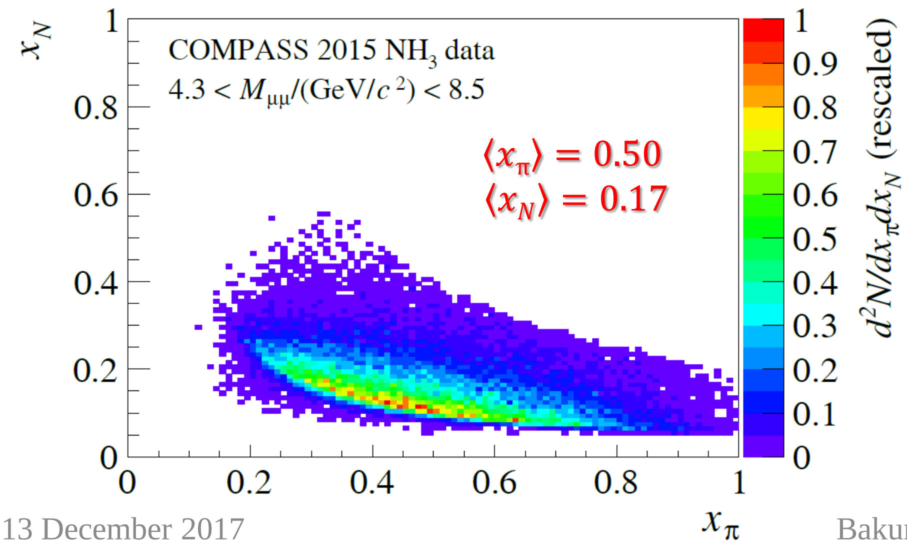
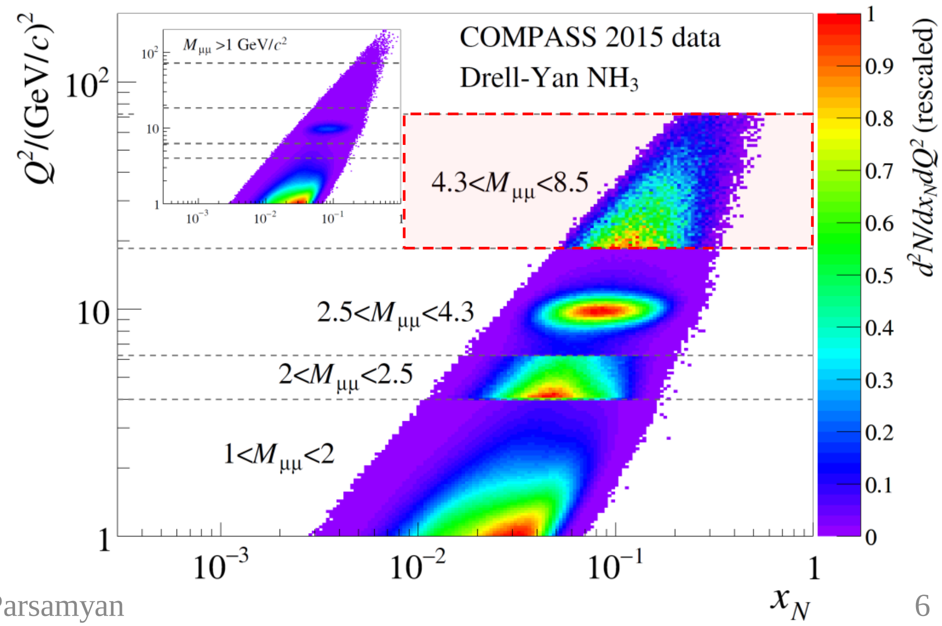


HM events are in the valence quark range





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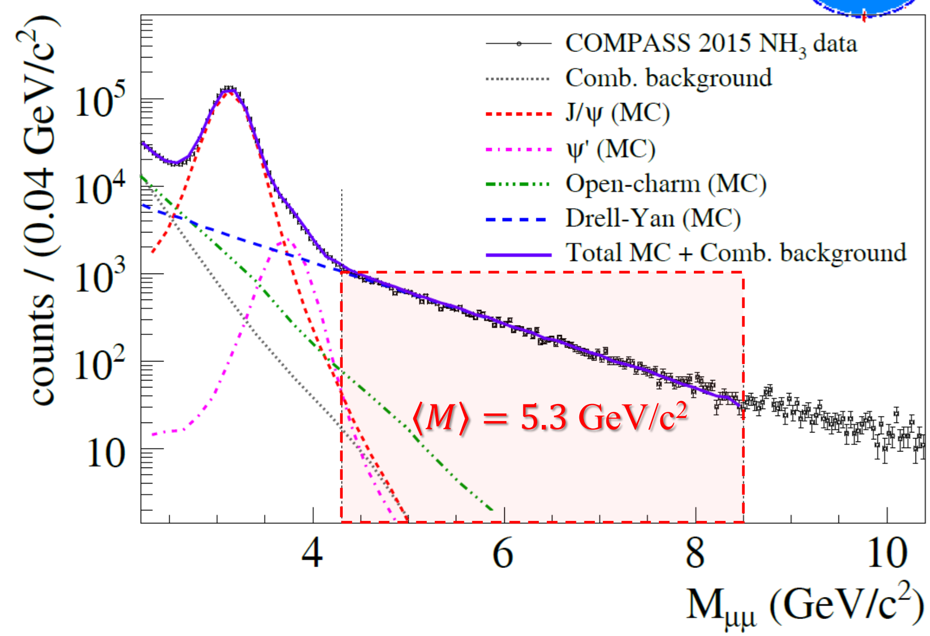
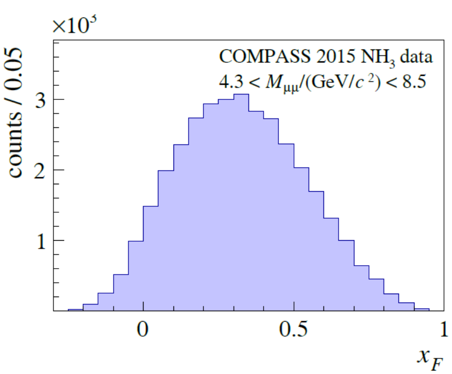
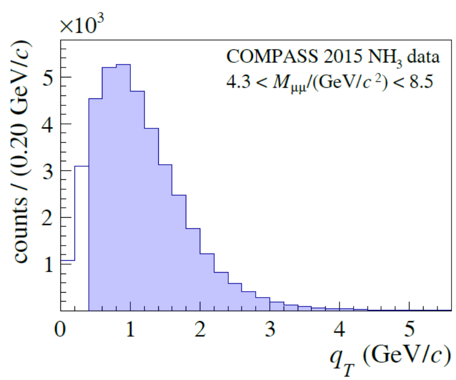
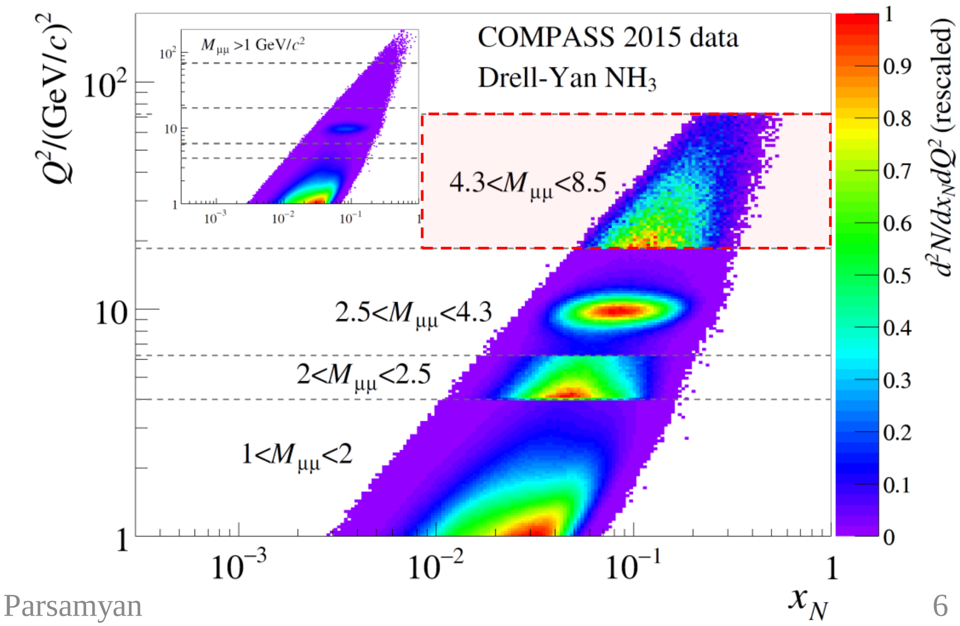


Dimuon transverse momentum $q_T > 0.4$ GeV/c

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







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ongoing analysis

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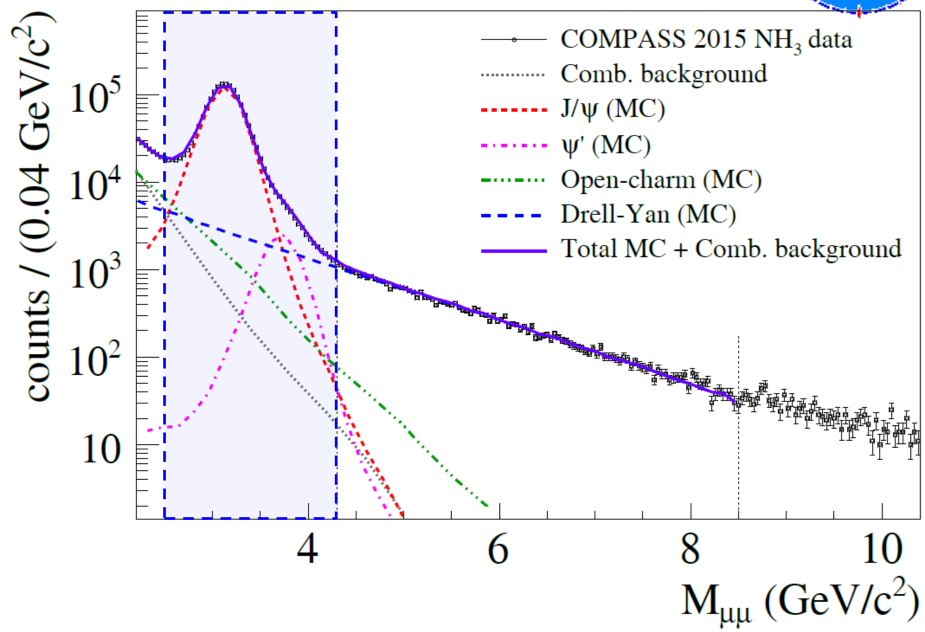
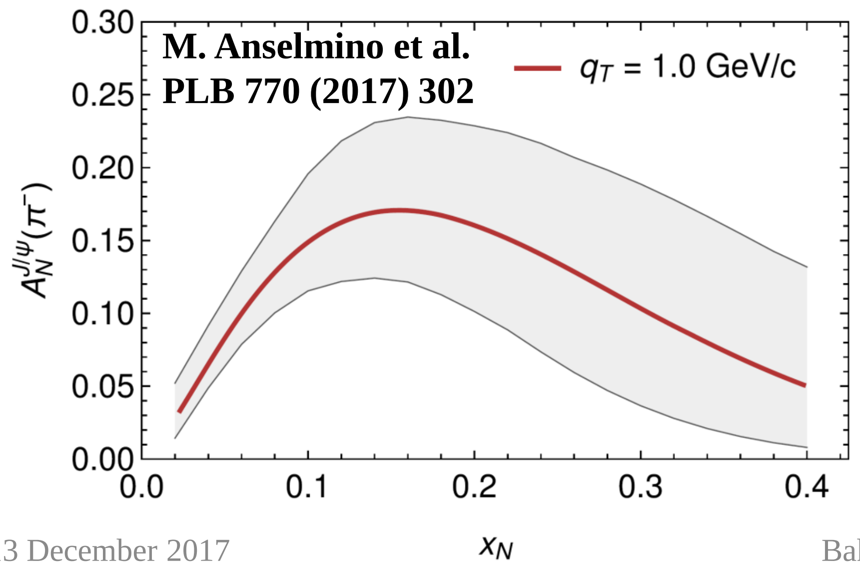
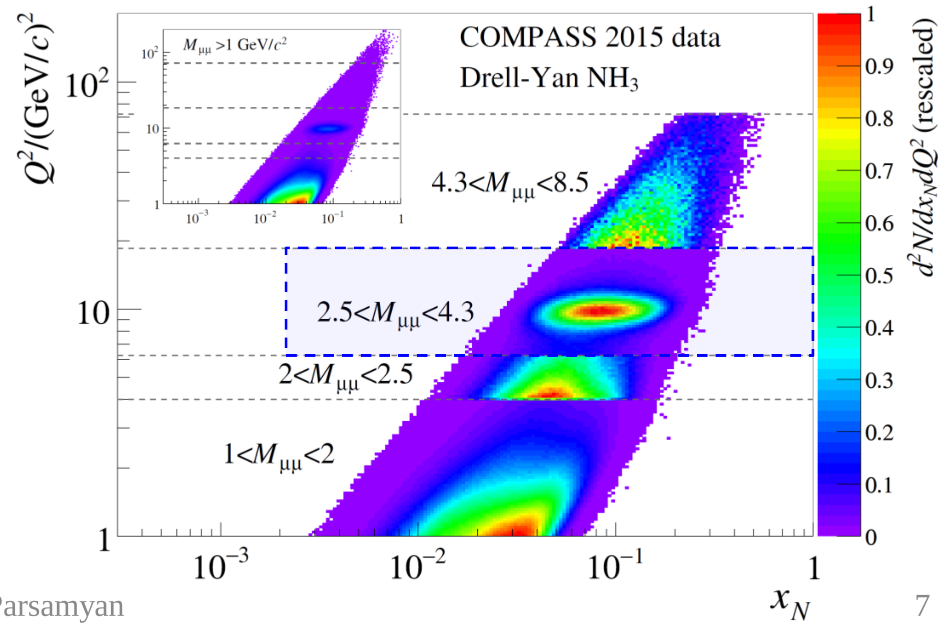


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c

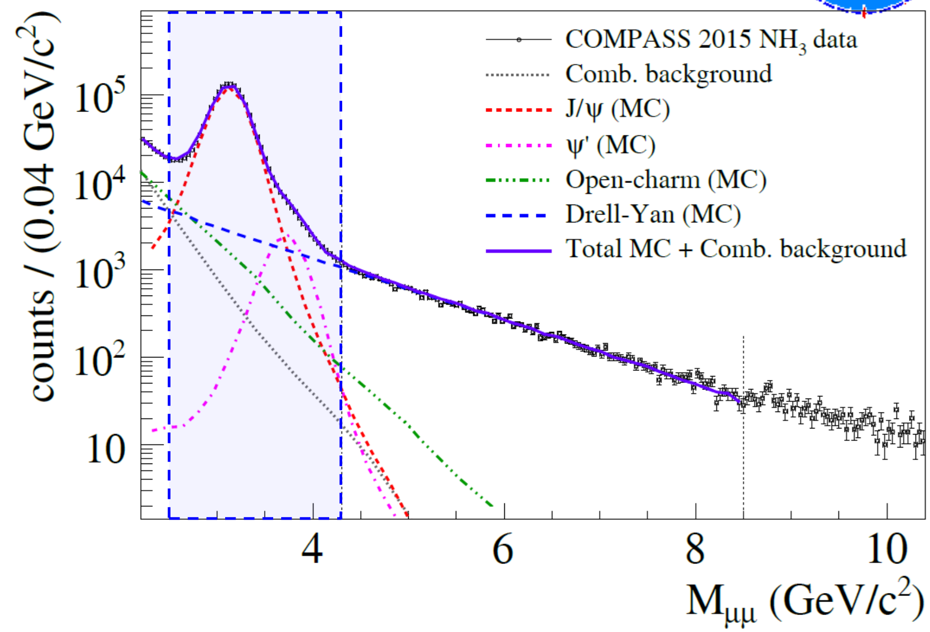




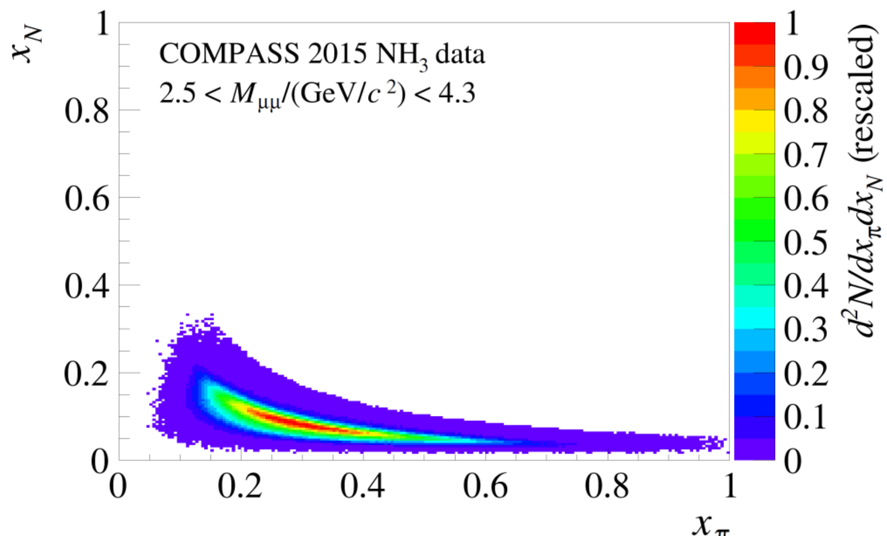
COMPASS DY: Charmonia mass range

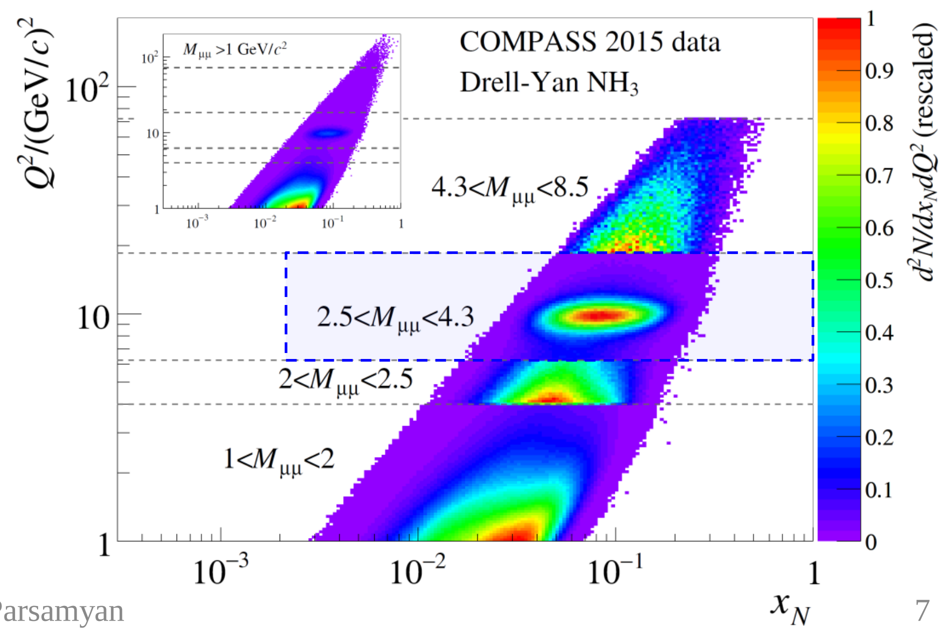
ongoing analysis

- $1.0 < M/(GeV/c^2) < 2.0$ "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
- $2.5 < M/(GeV/c^2) < 4.3$ "Charmonia mass"
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- $4.3 < M/(GeV/c^2) < 8.5$ "High mass"
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

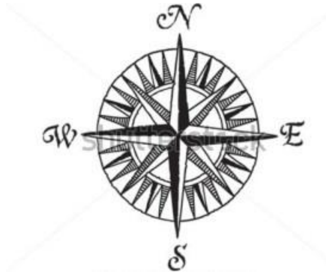


$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c





COMPASS bridge



Drell-Yan

SIDIS

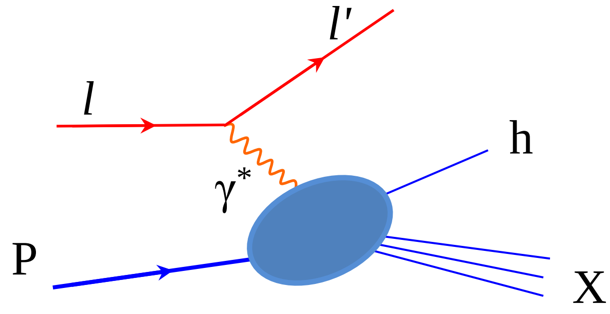
SIDIS x-section

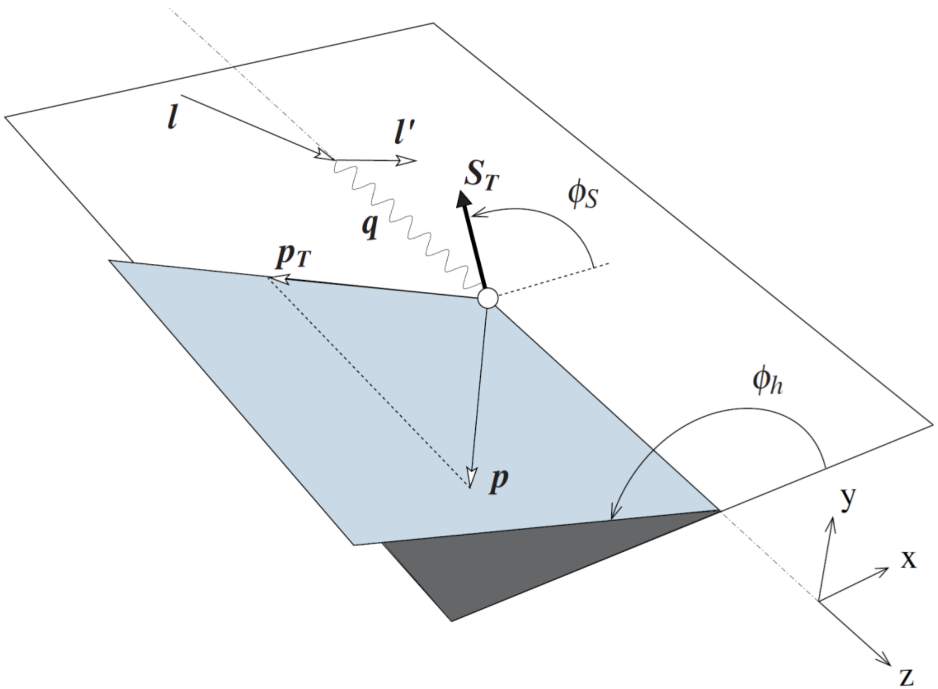
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

All measured by COMPASS

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

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





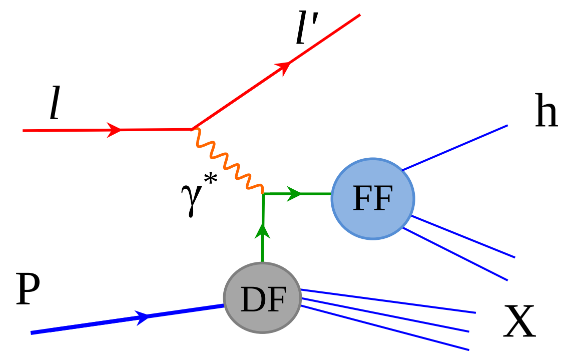
$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}};\quad \varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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**

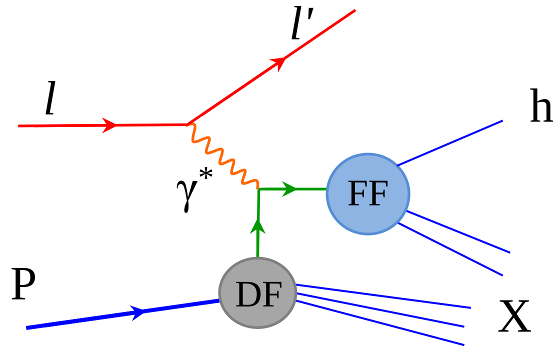
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

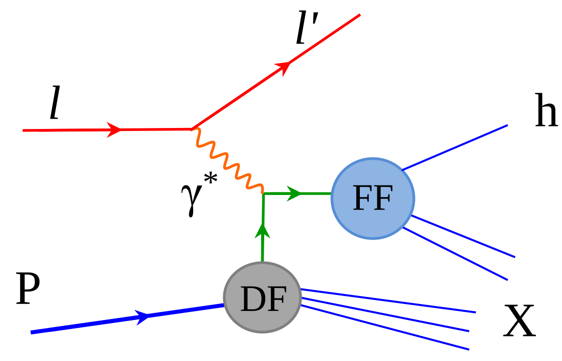
SIDIS x-section and TMDs at twist-2

All measured by COMPASS

See talks by A. Bressan and H. Avakian

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

SIDIS and single-polarized DY x-sections

SIDIS

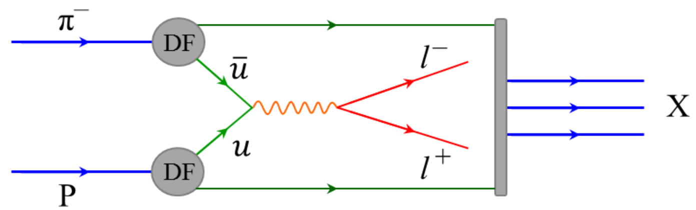
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

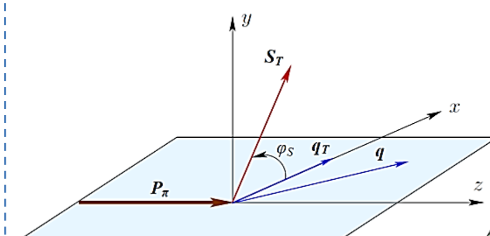
$$\times\left\{\begin{aligned}
&1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\\
&+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h\\
&+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon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

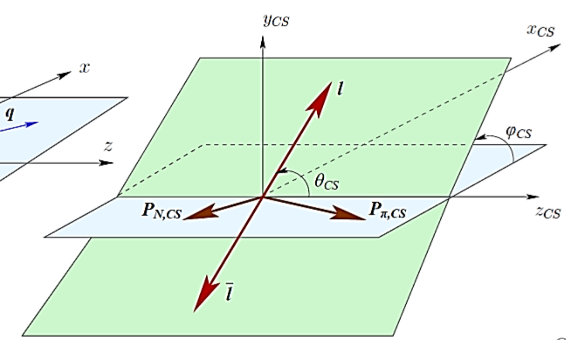
DY

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

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







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

SIDIS

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

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

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

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

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

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

SIDIS-DY bridge

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

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \left\{ \begin{aligned} &1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ &+ S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} \\ &+ S_T\left[\begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ &+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{aligned}\right] \\ &+ S_T\lambda\left[\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right] \end{aligned} \right\}$$

DY

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

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

SIDIS-DY bridge

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

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

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

SIDIS-DY bridge

DY

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

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

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

Complementary information from different channels:

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

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

SIDIS

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \left\{ \begin{aligned} &1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ &+S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} \\ &+S_T\left[\begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ &+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \end{aligned}\right] \\ &+S_T\lambda\left[\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right] \end{aligned}\right\}$$

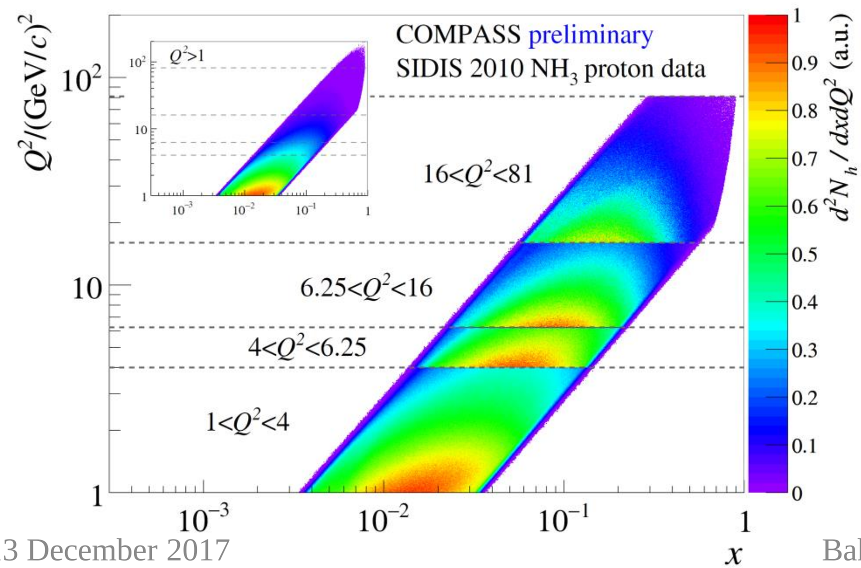
SIDIS-DY bridge

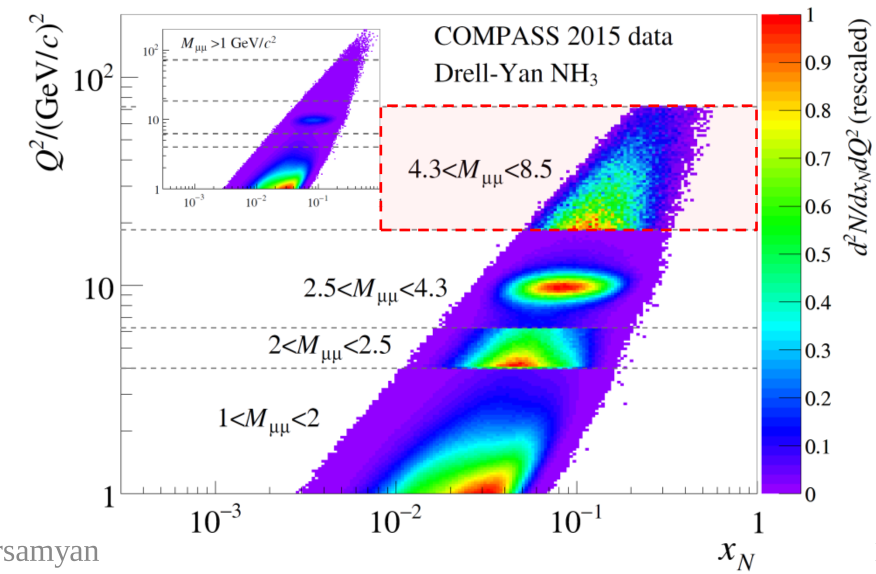
DY

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

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

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





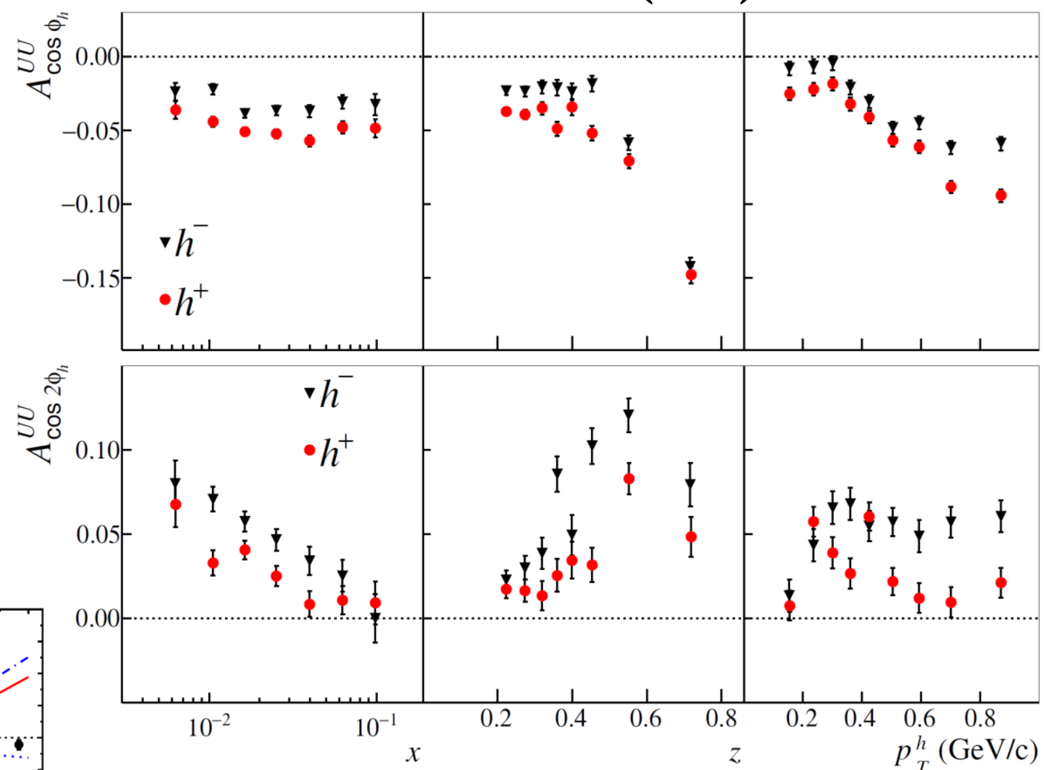
- Selected SIDIS results

The $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ asymmetries (Cahn+BM)

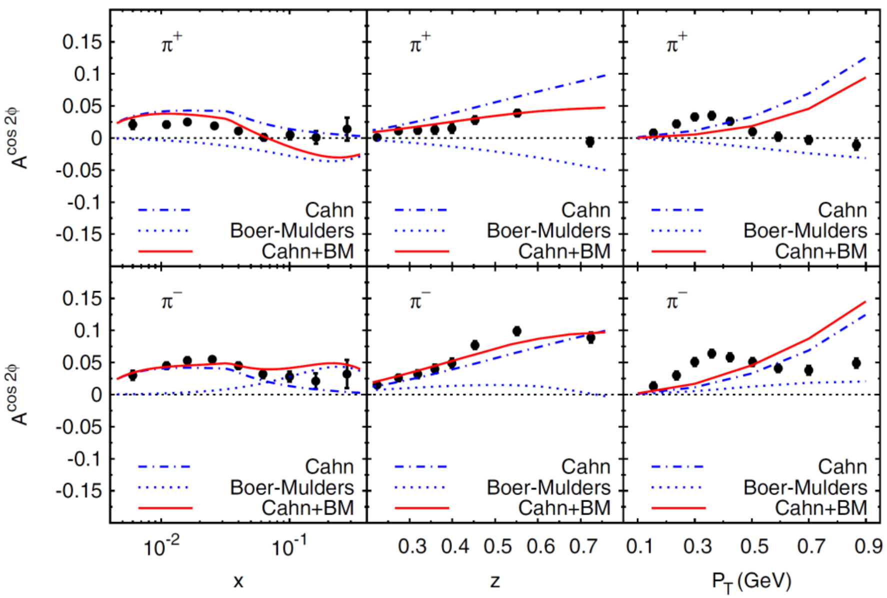
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$
$$\times \left\{ \begin{array}{l} 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + \lambda \sqrt{2\varepsilon(1-\varepsilon)}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

- Complicated mixture Cahn+BM
- Large effects both for h^+ and h^-
- Multi-D results available HERMES P/D COMPASS D and currently also P (DVCS)
- Global Cahn+BM fit attempts see f.i. PRD91,074019 (2015)

COMPASS **NPB 886 (2014) 1046**



V. Barone, S. Melis, A. Prokudin, **PRD 81,** 114026 (2010)



$$A_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}\left\{ -f_1^q \otimes D_{1q}^h - h_1^{\perp q} \otimes H_{1q}^{\perp h} \right\}$$

$$A_{UU}^{\cos 2\phi_h} \propto -h_1^{\perp q} \otimes H_{1q}^{\perp h} + \left(\frac{M}{Q}\right)^2 f_1^q \otimes D_{1q}^h + \ldots$$

See talks by Ch. V. Hulse, A. Bressan and H. Avakian

SIDIS: target transverse spin dependent asymmetries

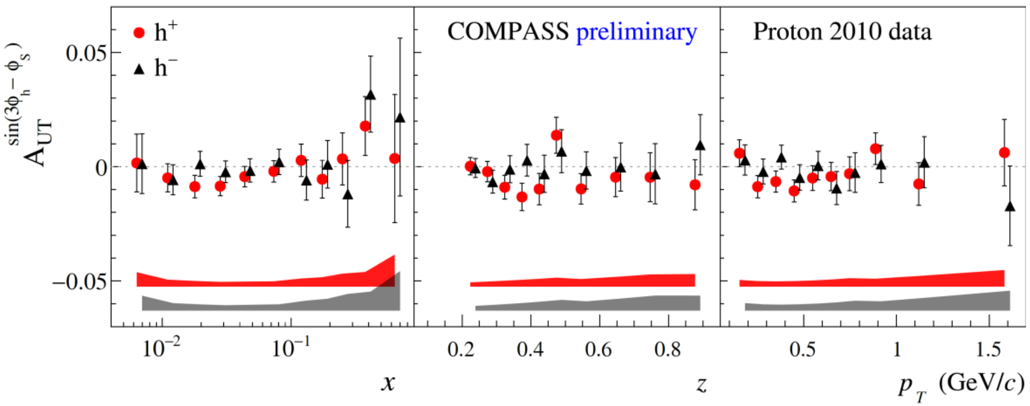
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1+ \dots \right.$$

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

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

SIDIS: target transverse spin dependent asymmetries

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



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

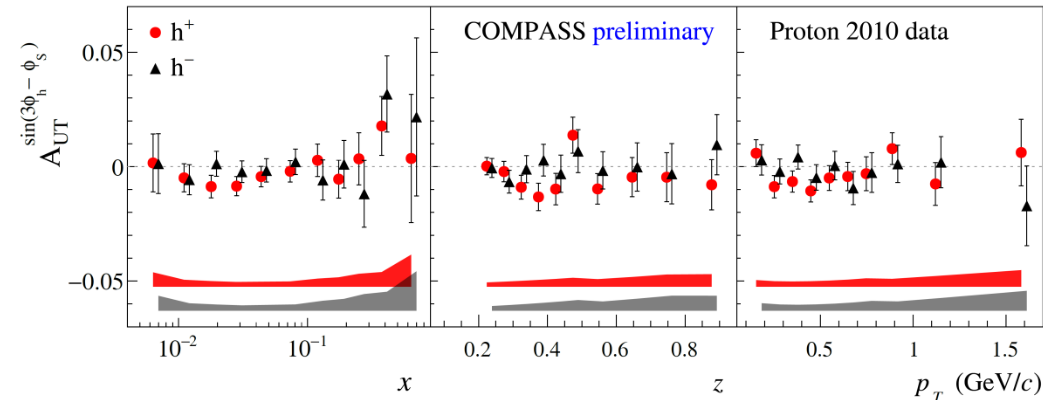
COMPASS results

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

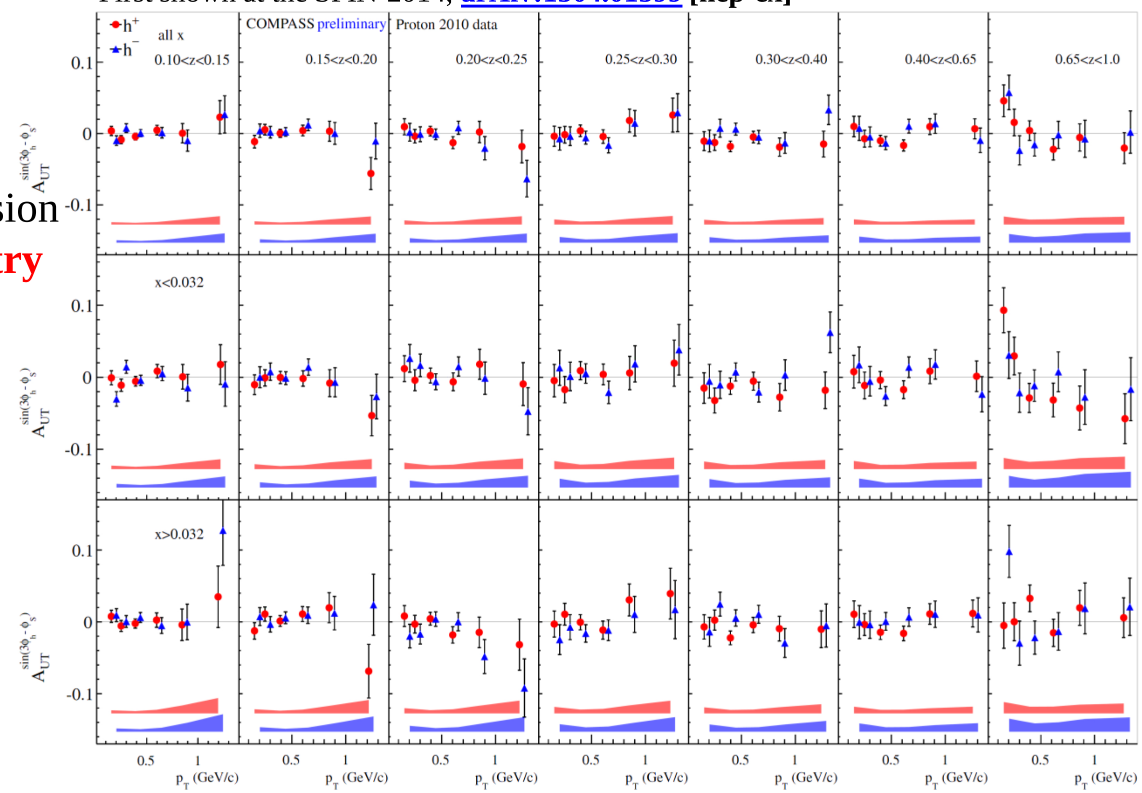
- Only "twist-2" ingredients, p_T^2-suppression
- **Small, compatible with zero asymmetry**

SIDIS: target transverse spin dependent asymmetries

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



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



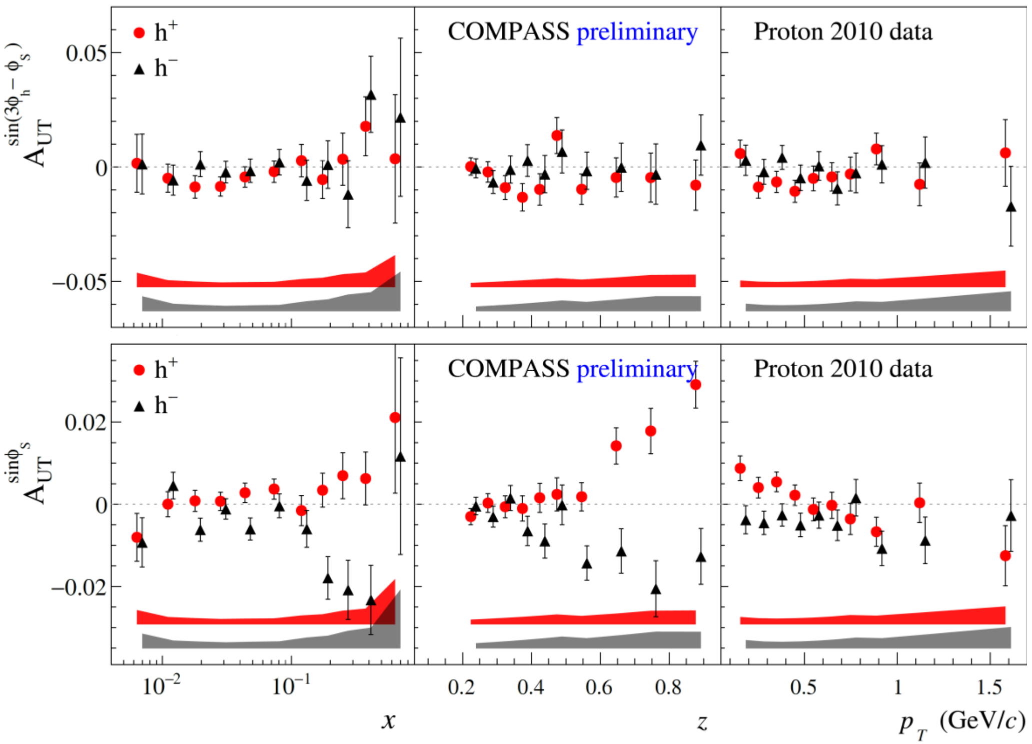
COMPASS results

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

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

SIDIS: target transverse spin dependent asymmetries

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



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

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

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

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

COMPASS results

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

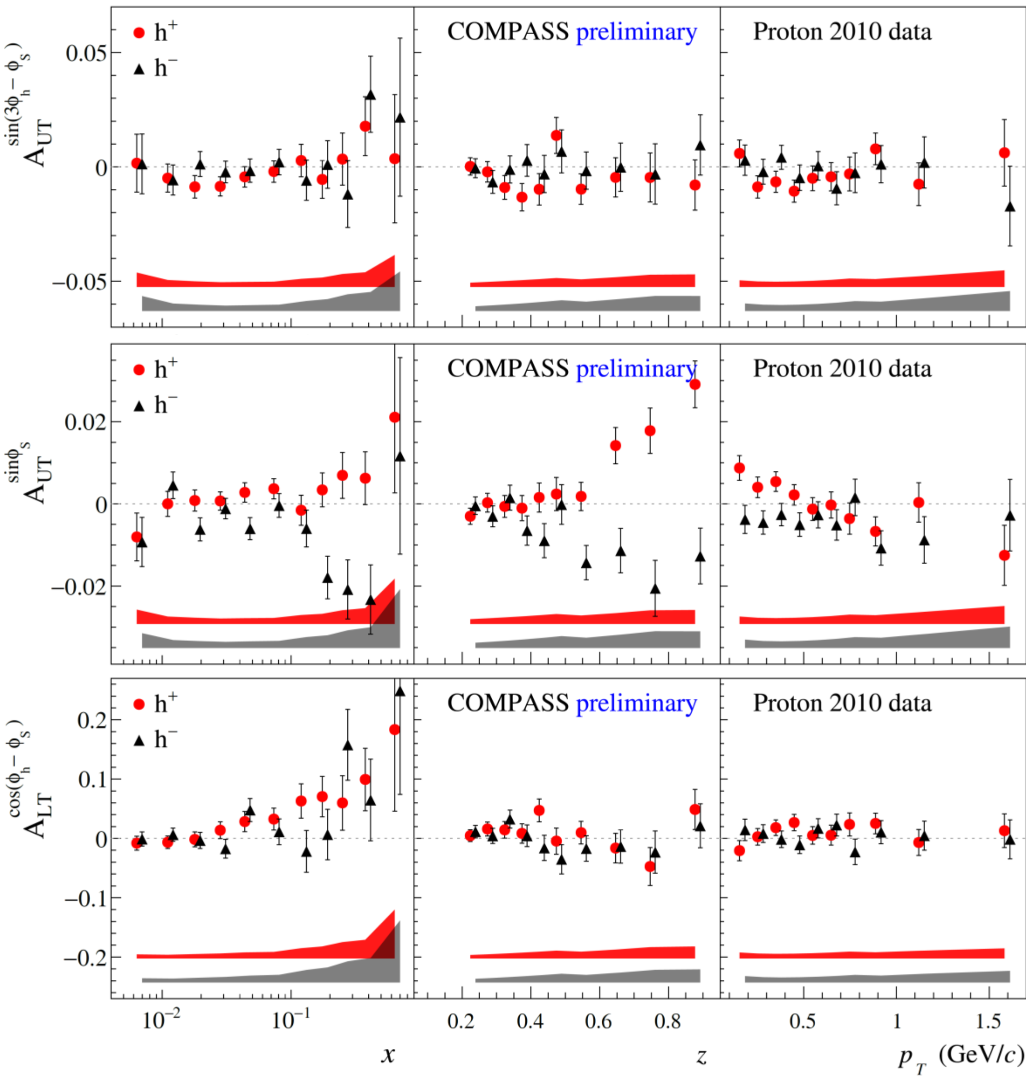
- Only "twist-2" ingredients, p_T^2-suppression
- **Small, compatible with zero asymmetry**

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

- 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^+ !**



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

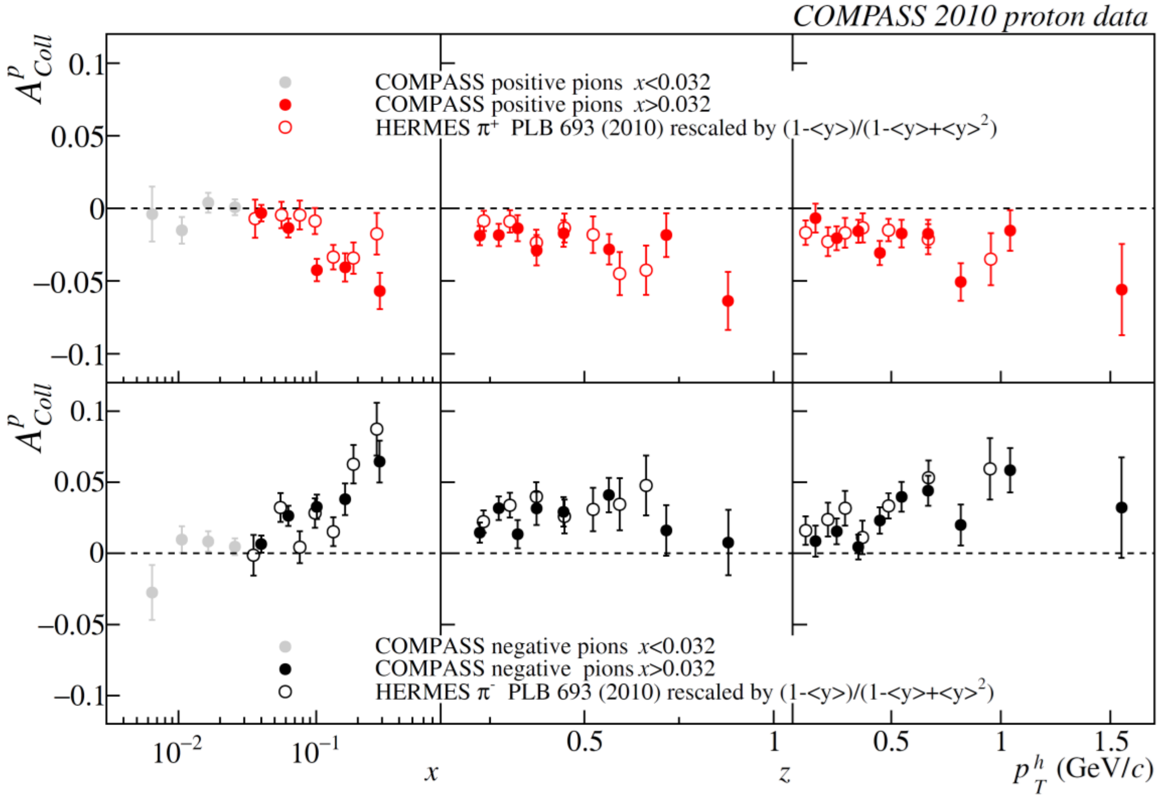
SIDIS TSAs (Collins)

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

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

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

COMPASS PLB 744 (2015) 250



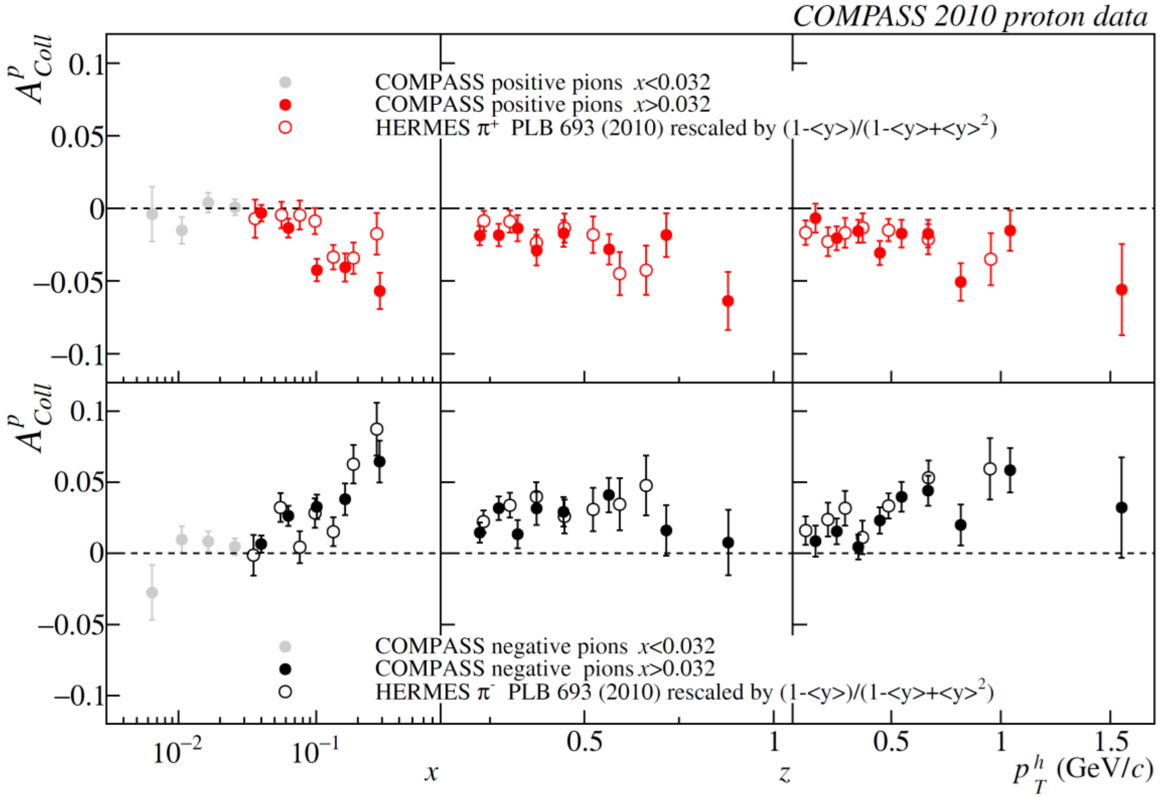
SIDIS TSAs (Collins)

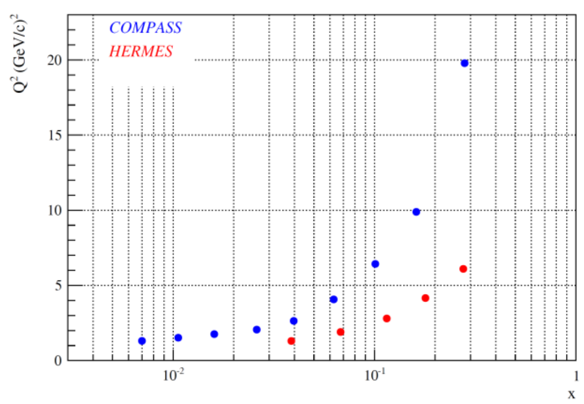
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \ldots\right\}$$

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

- 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 Ch. V. Hulse, A. Bressan and H. Avakian

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

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

- Measured on P/D in SIDIS and in dihadron SIDIS
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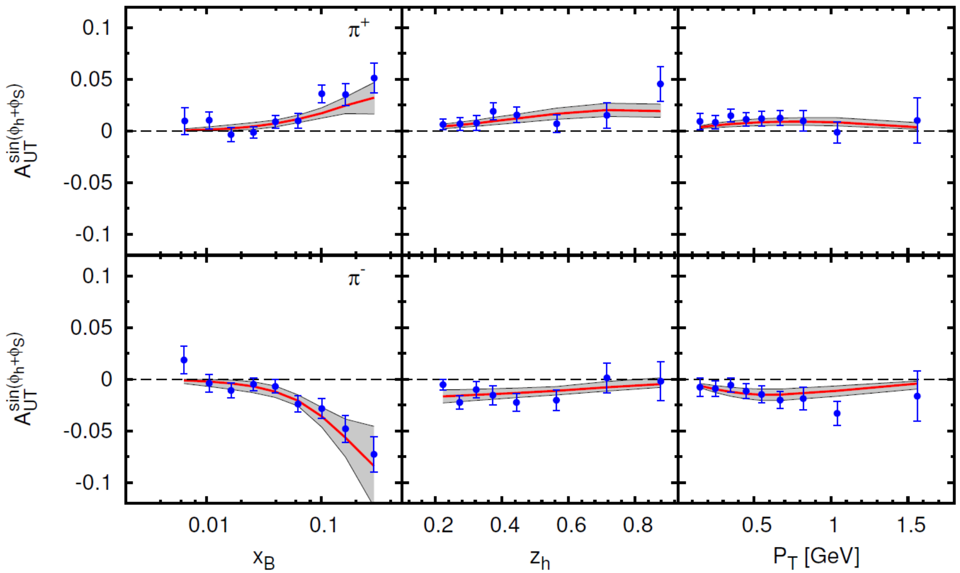
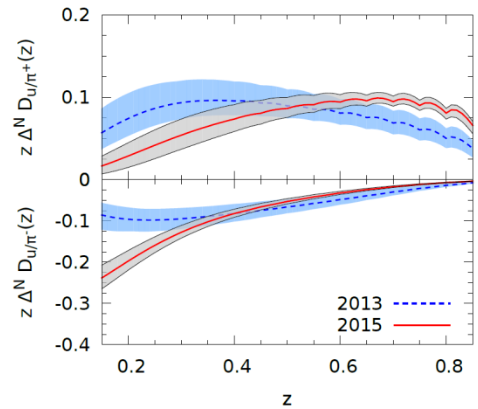
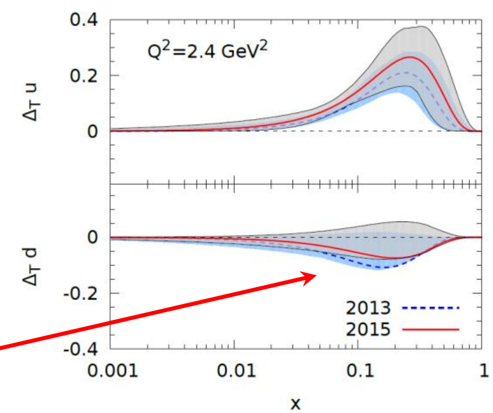
- Extensive phenomenological studies and various global fits by different groups

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







COMPASS-II (2021)

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

SIDIS TSAs (Collins)

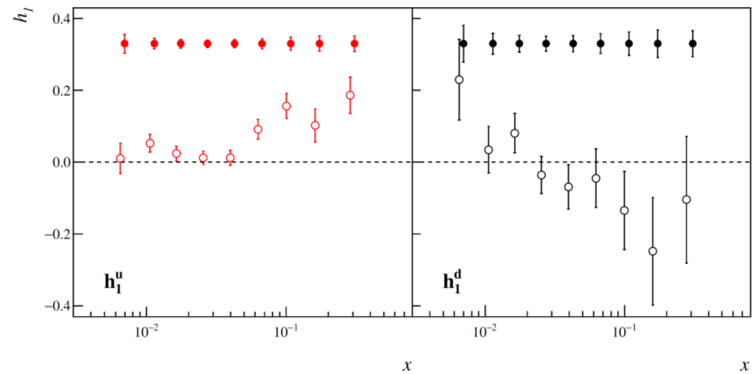
See talk by A. Bressan

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

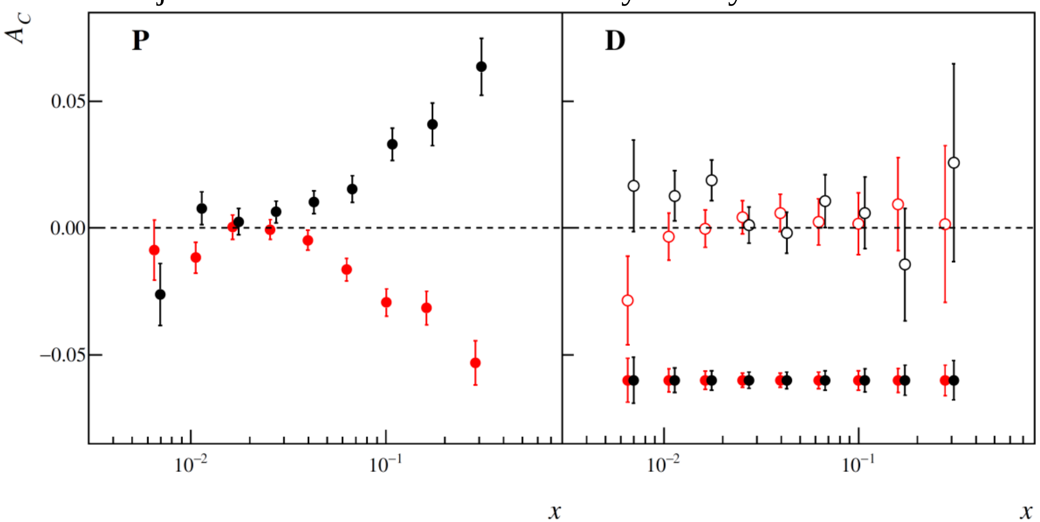
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

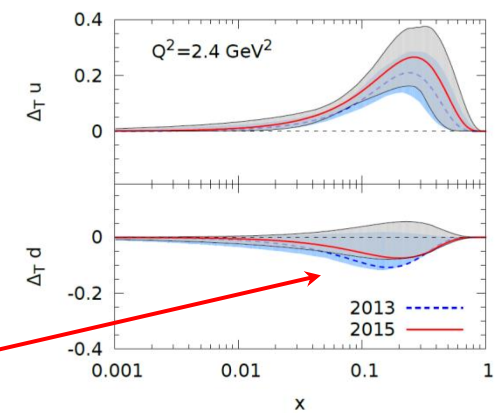
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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



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





COMPASS-II (2021)

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

SIDIS TSAs (Sivers)

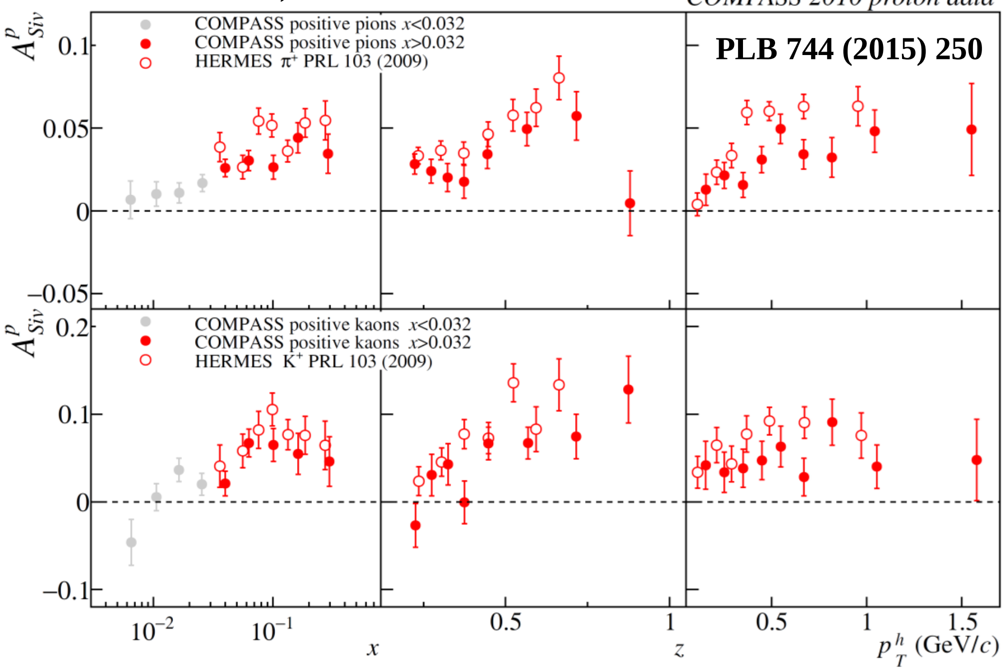
See talks by Ch. V. Hulse, A. Bressan and H. Avakian

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

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

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

COMPASS 2010 proton data



SIDIS TSAs (Sivers)

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

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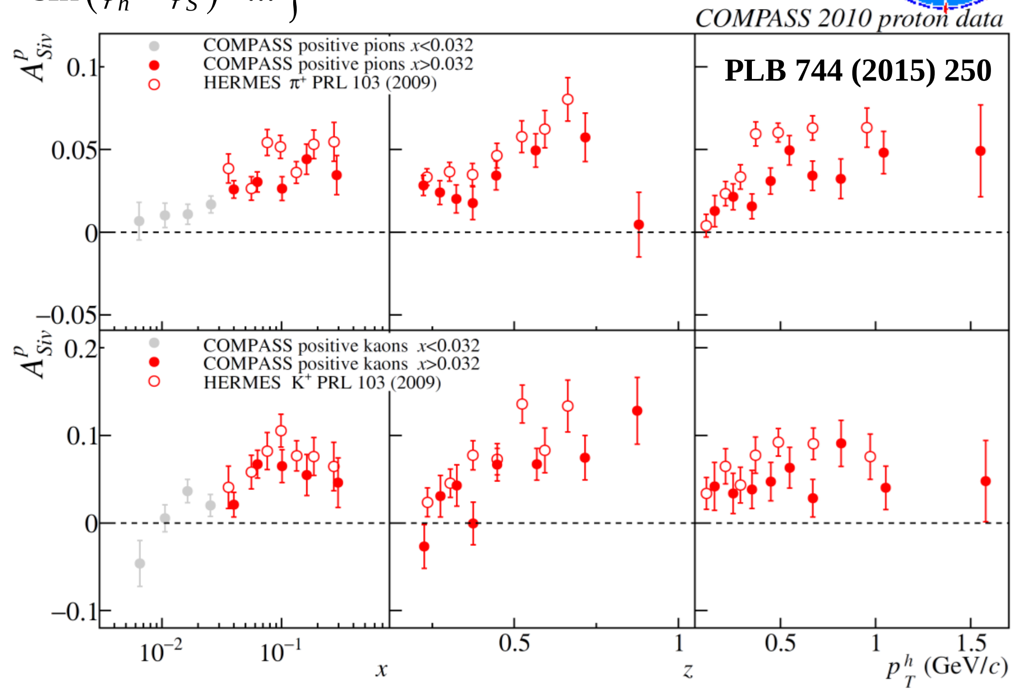
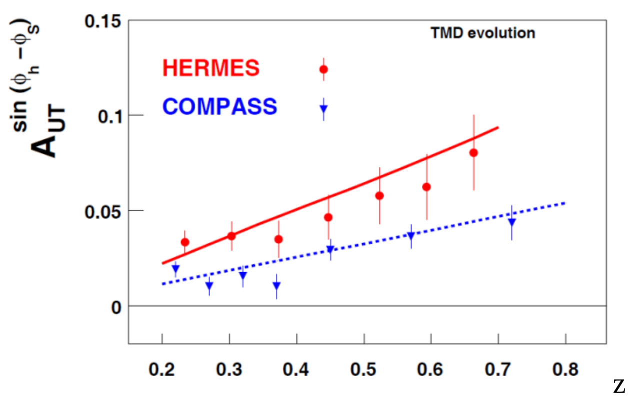
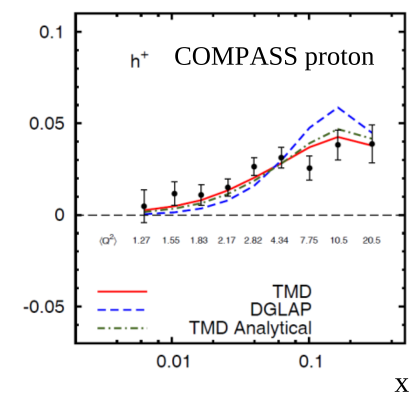


- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854

- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~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)

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

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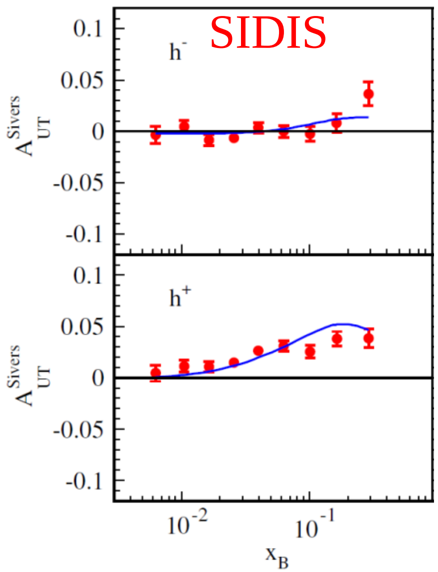
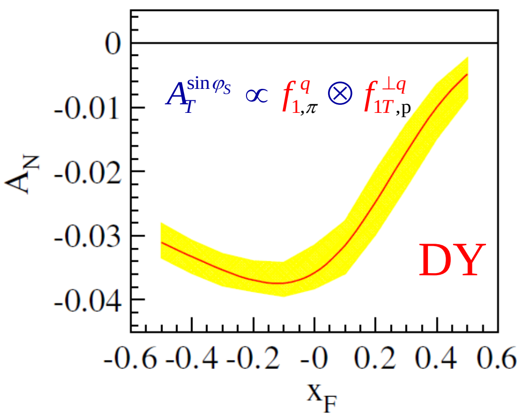
- **Q^2-evolution? Intriguing result!**

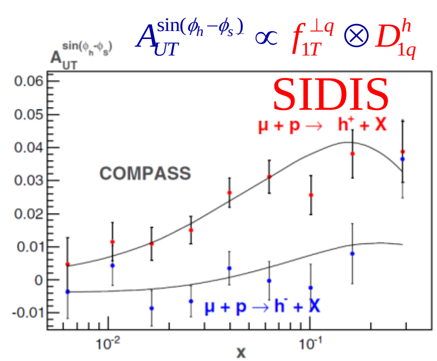
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan

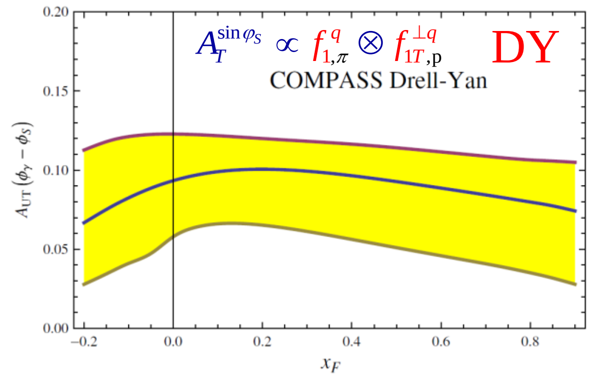
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**





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





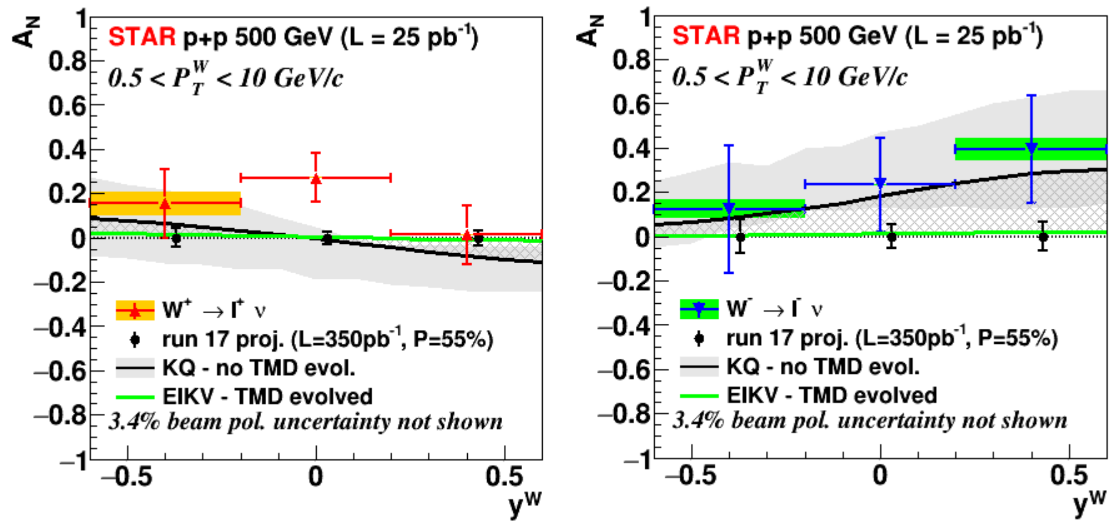
SIDIS TSAs (Sivers)

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

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

See talk by E.C. Aschenauer

STAR collaboration: **PRL 116, 132301 (2016)**



- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854

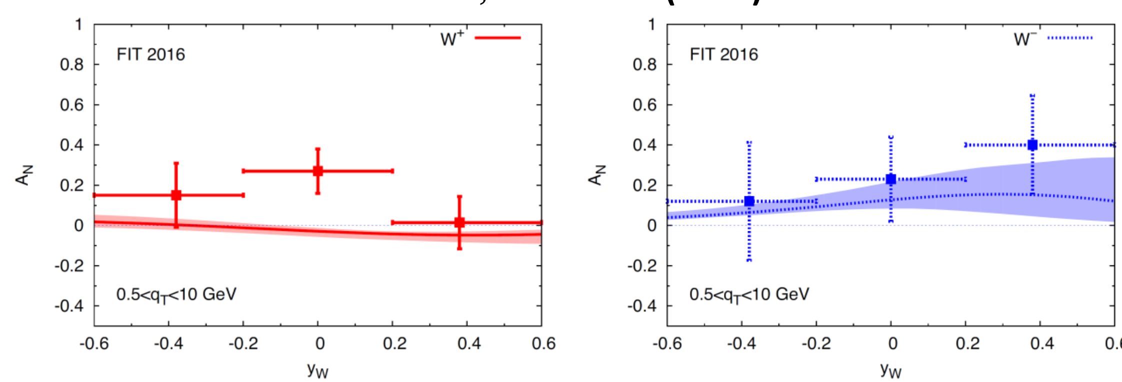
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**

- 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

See talk by M. Boglione

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



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

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

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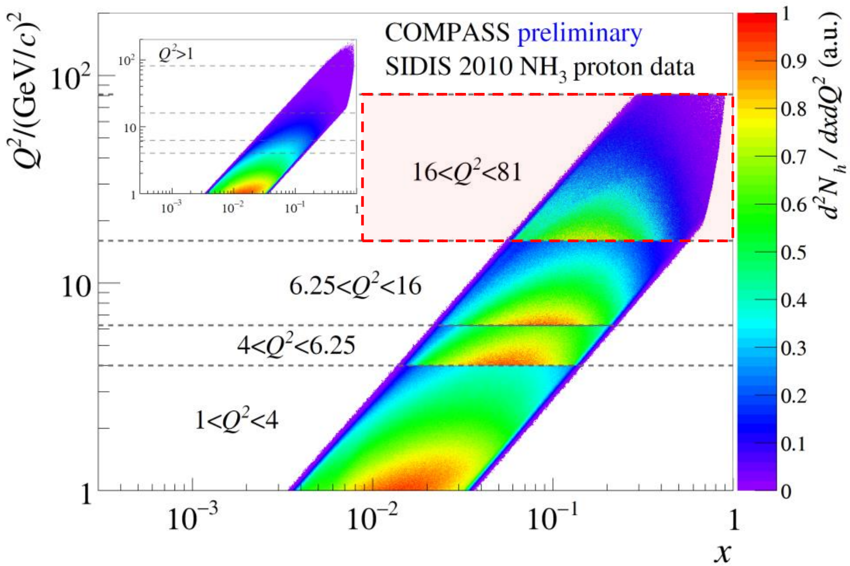
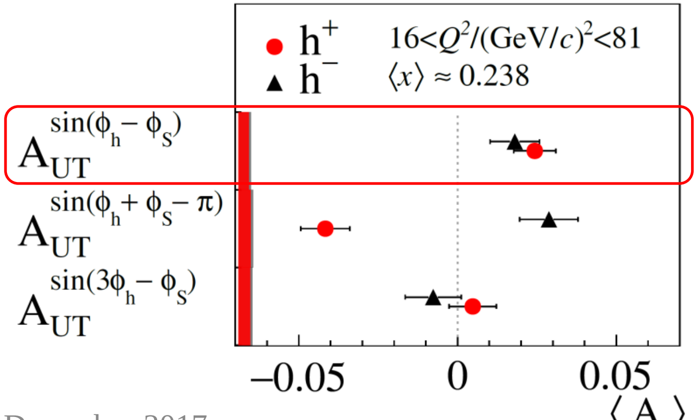
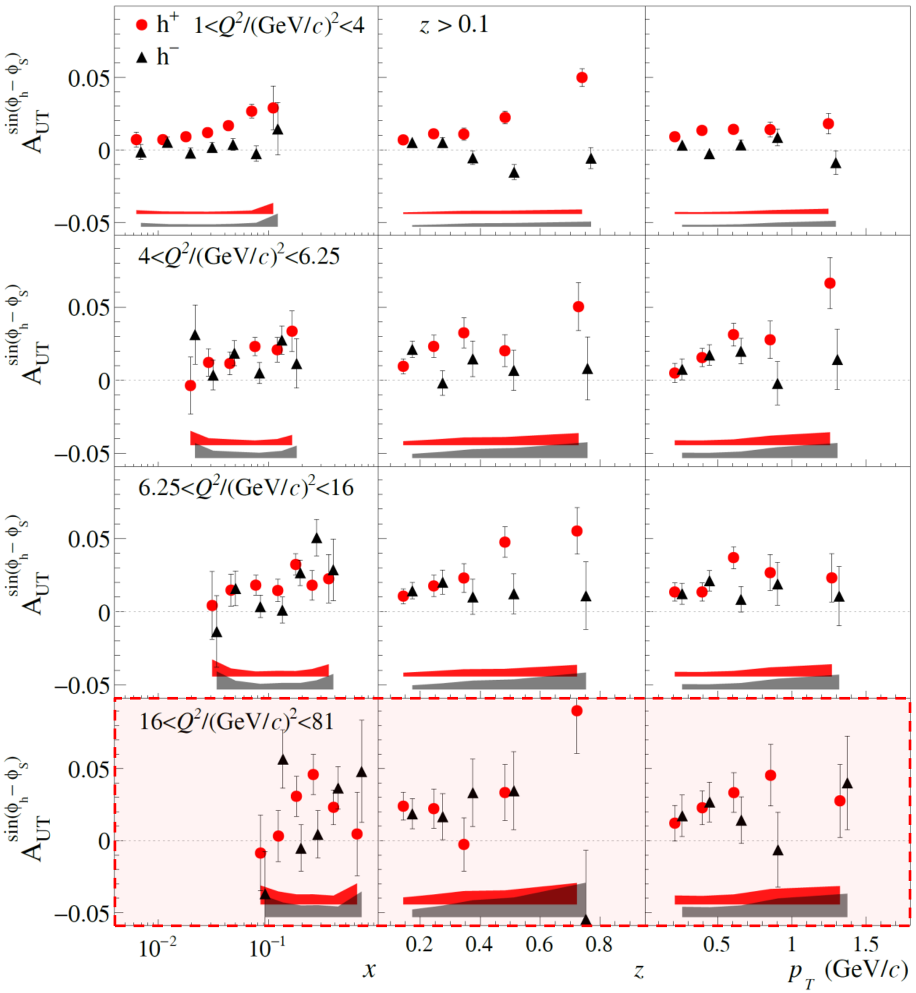
COMPASS PLB 770 (2017) 138







1[st] COMPASS multi-D fit done for all eight TSAs

Multi-D TSA analysis

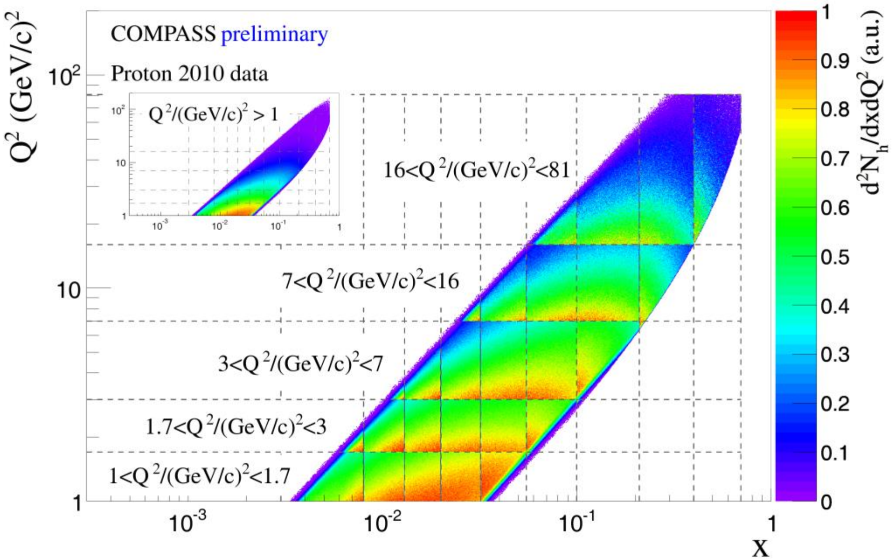
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

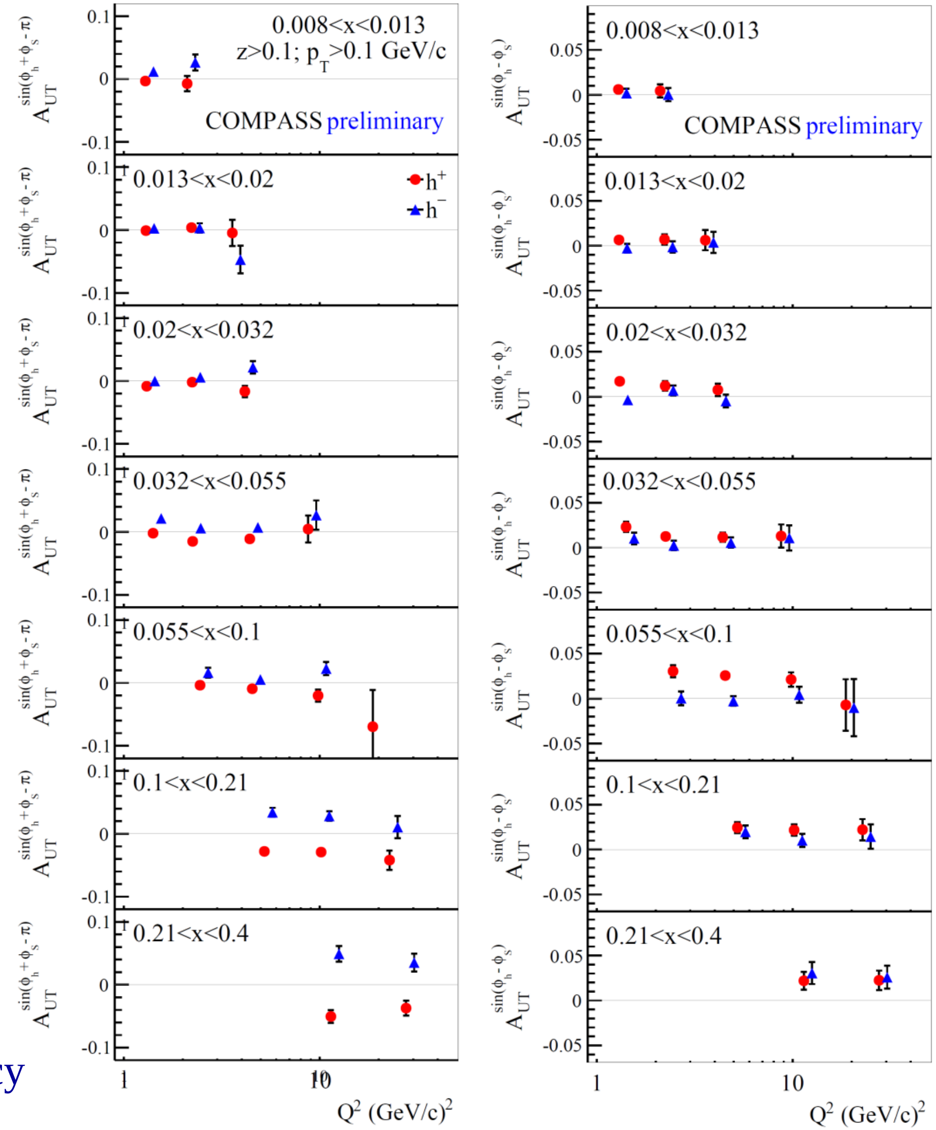
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

COMPASS 4-D fit (x-Q^2; z-p_T; x-Q^2-z-p_T)

All eight TSAs extracted simultaneously

First shown at the SPIN-2014, arXiv:1504.01599 **[hep-ex]**





- 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: unpolarized part

ongoing analysis

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

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

- **“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,**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$

Single-polarized DY x-section: unpolarized part

ongoing analysis

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

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

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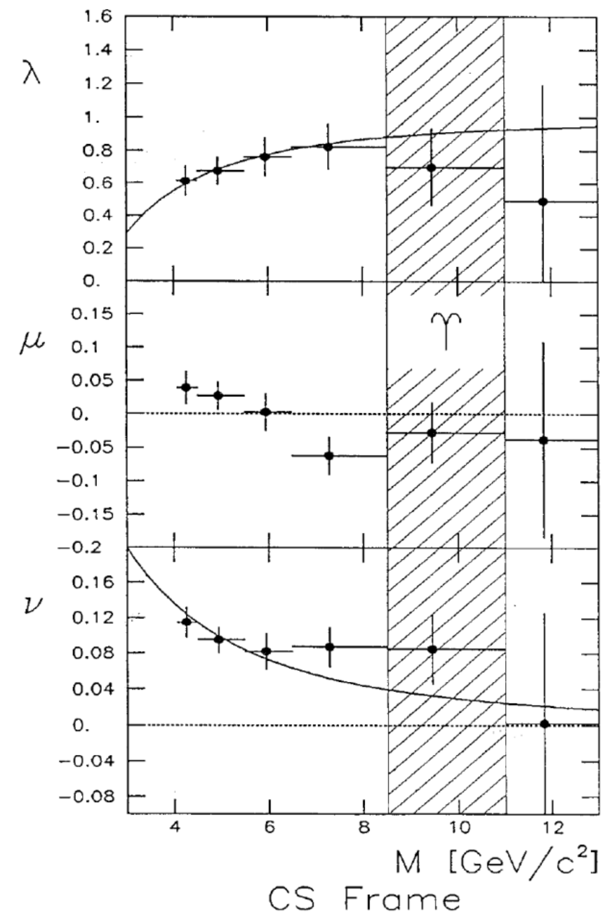
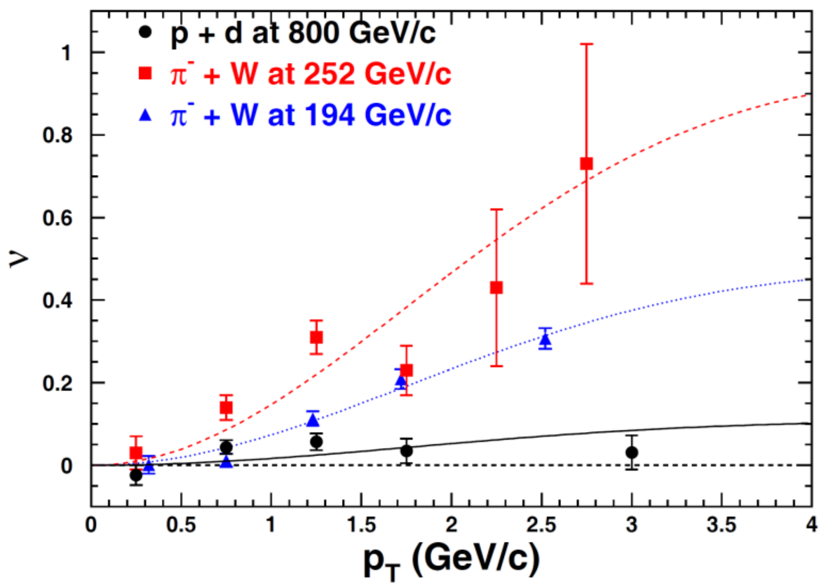
  λ≠1, μ ≠ 0, ν ≠ 0 but 1–λ=2ν (Lam-Tung)
- **Experiment,**
  λ≠1, μ ≠ 0, ν ≠ 0
- ν ≠ 0 - Energy and quark flavour dependence, smaller effect for sea quarks, QCD radiative effects

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





Single-polarized DY x-section: unpolarized part

ongoing analysis

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

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

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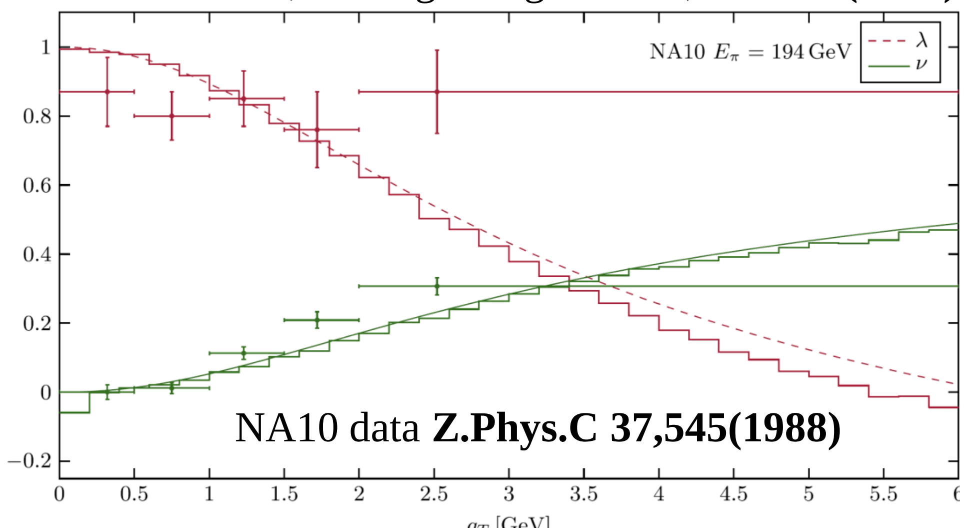
- $\nu \neq 0$ - Energy and quark flavour dependence, smaller effect for sea quarks, QCD radiative effects

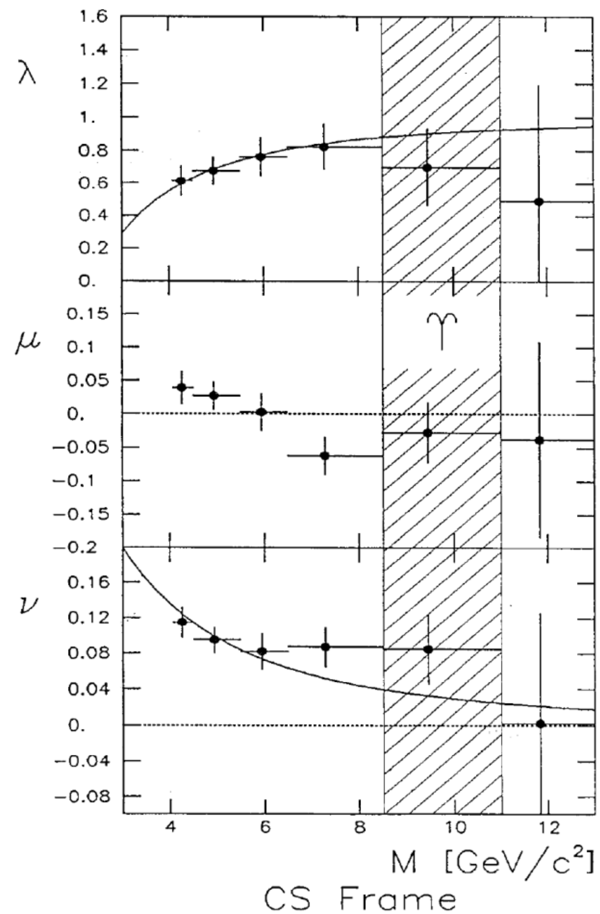
See next talk by W. Vogelsang

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



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

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



Single-polarized DY x-section: transverse part

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

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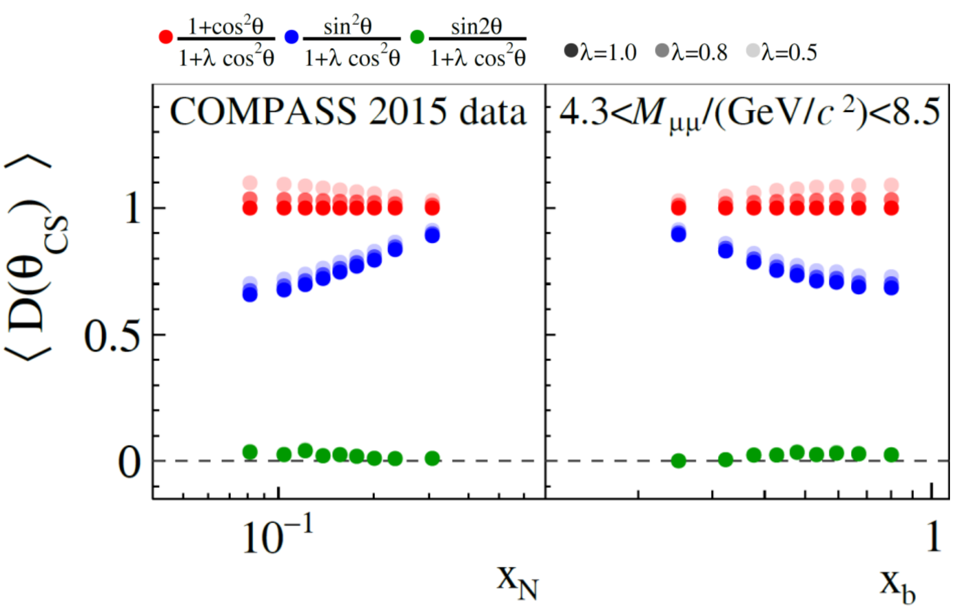
  λ≠1, μ ≠ 0, ν ≠ 0 but 1–λ=2ν (Lam-Tung)
- **Experiment,**
  λ≠1, μ ≠ 0, ν ≠ 0

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

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



- 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≠1 scenarios lead to a normalization uncertainty of at most −5%.

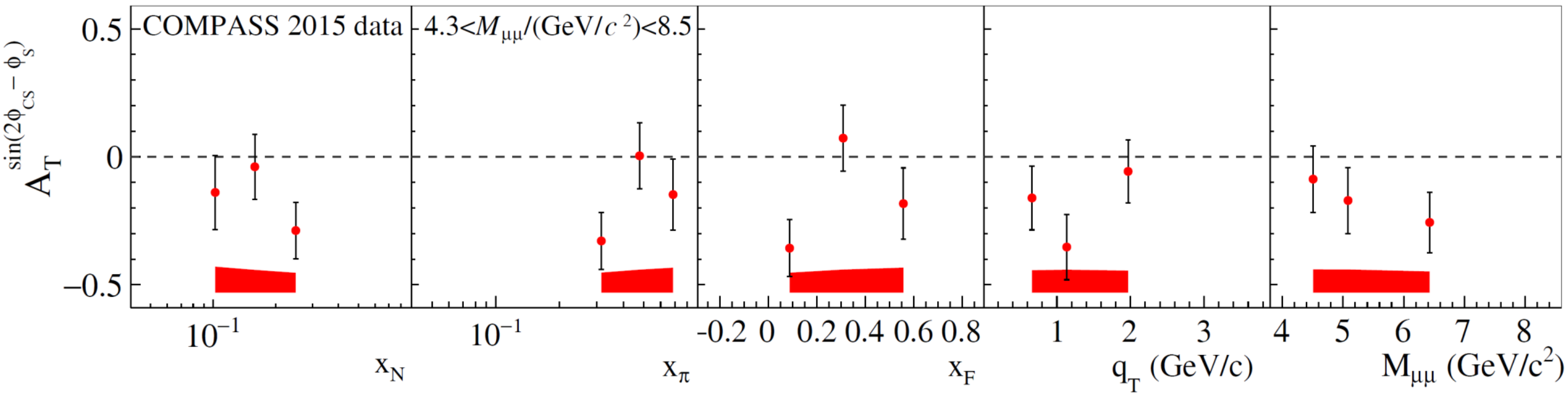
Drell-Yan TSAs – Transversity

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

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)



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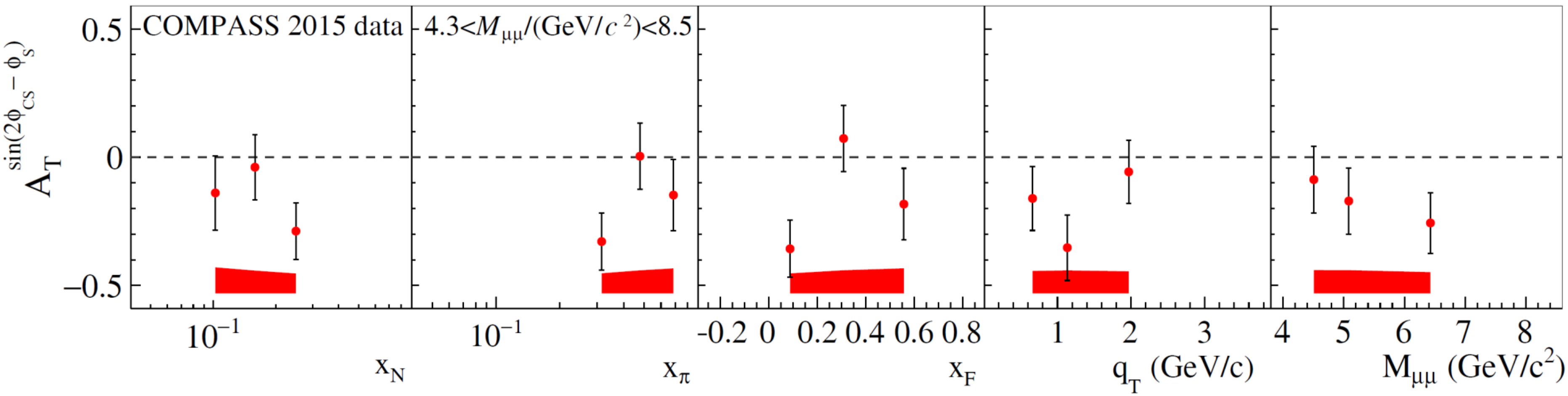
COMPASS PRL 119, 112002 (2017)

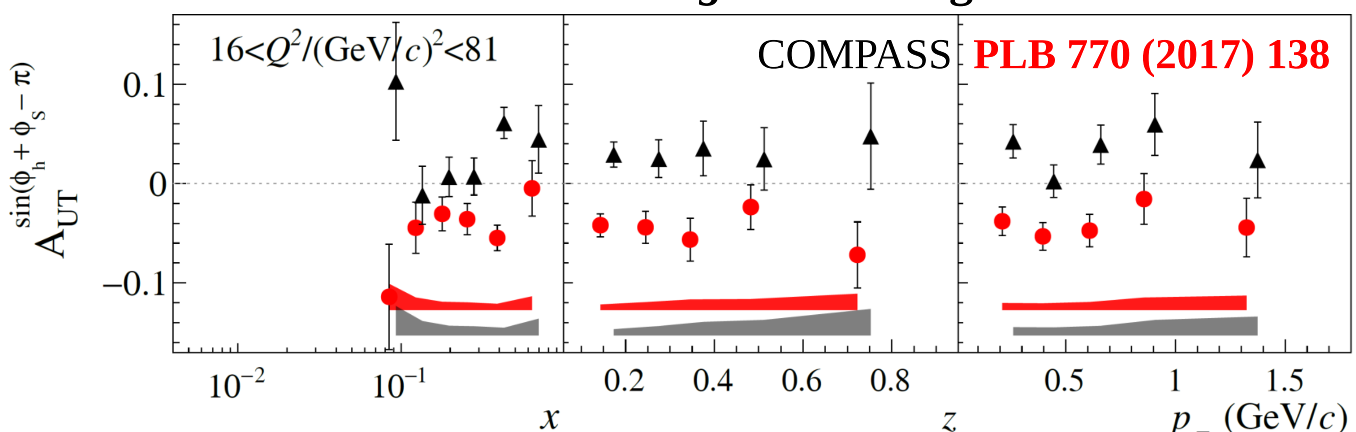


SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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

COMPASS **PLB 770 (2017) 138**



Drell-Yan TSAs – Transversity

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

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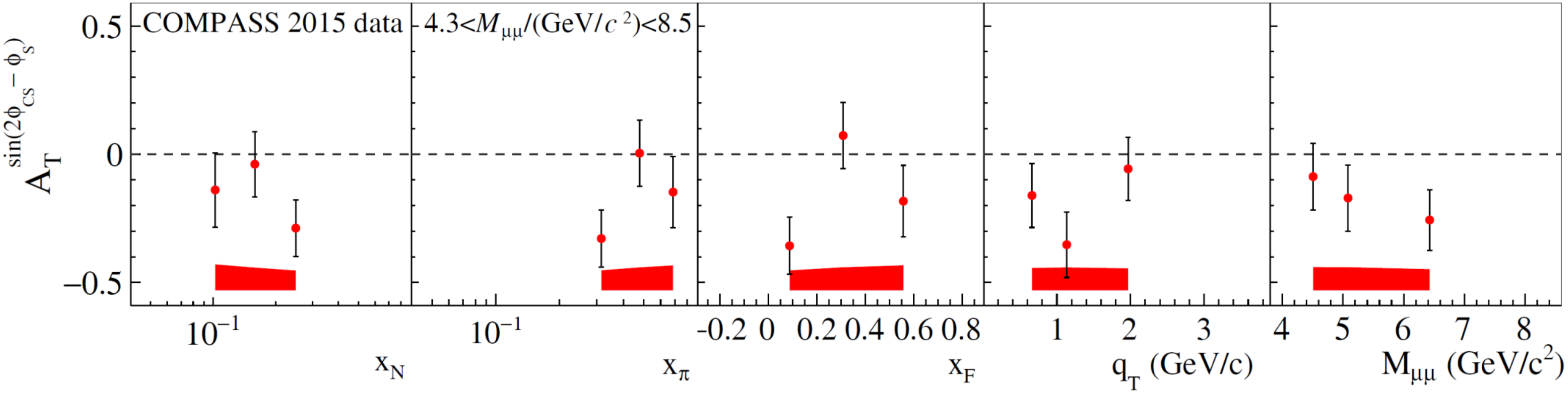
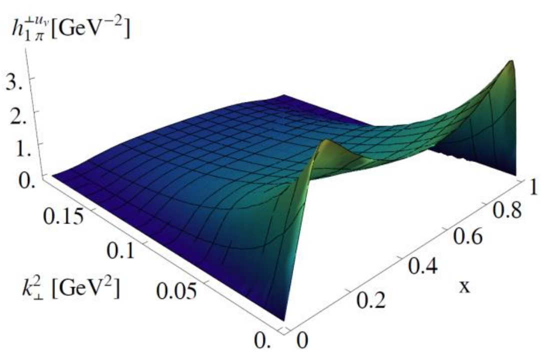
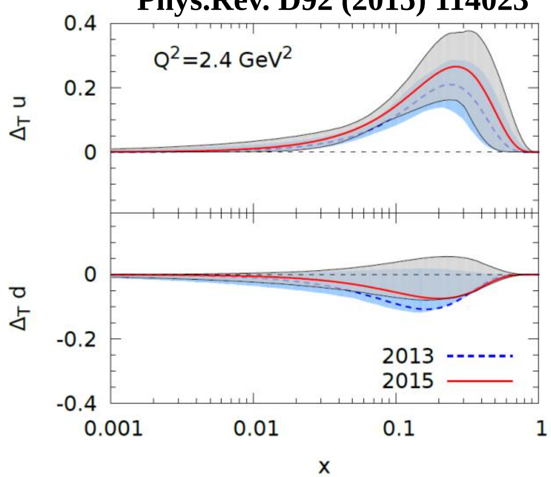
COMPASS PRL 119, 112002 (2017)



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

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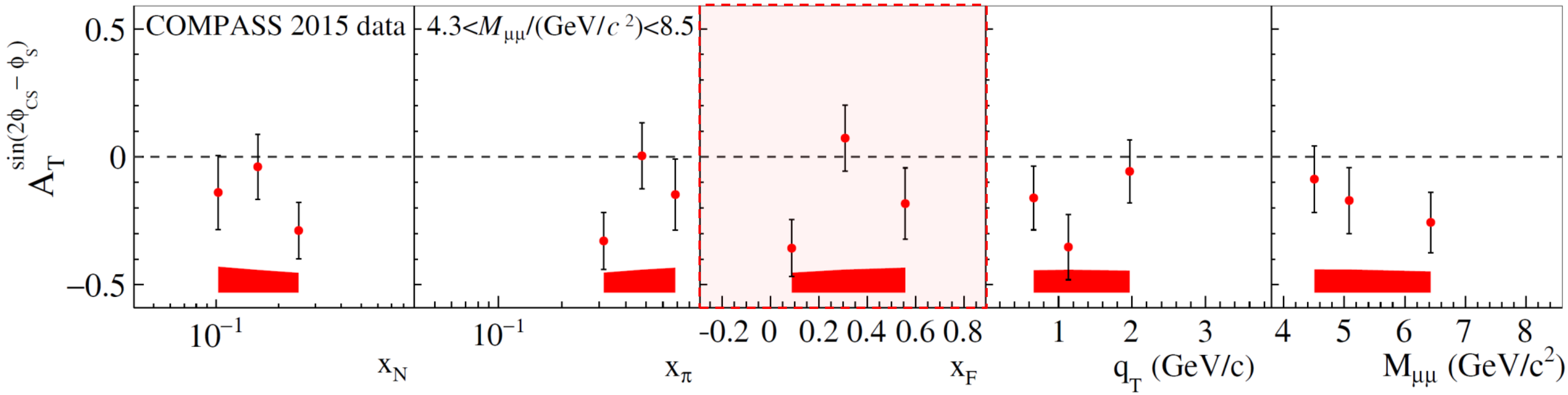
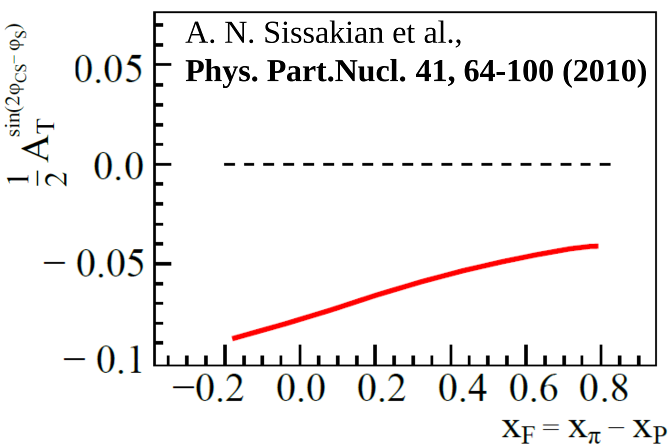
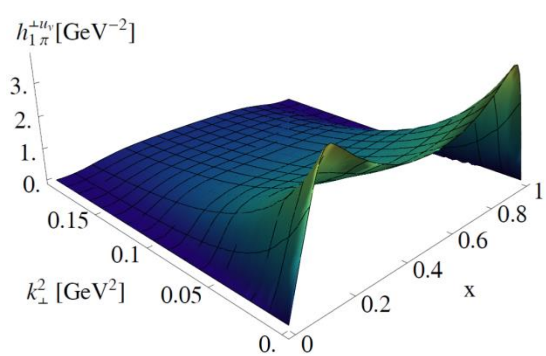
COMPASS PRL 119, 112002 (2017)





A. N. Sissakian et al.,
Phys. Part.Nucl. 41, 64-100 (2010)

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



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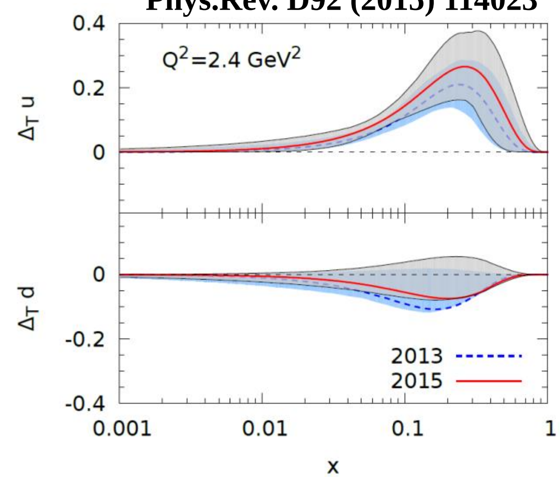
Phys.Rev. D92 (2015) 114023



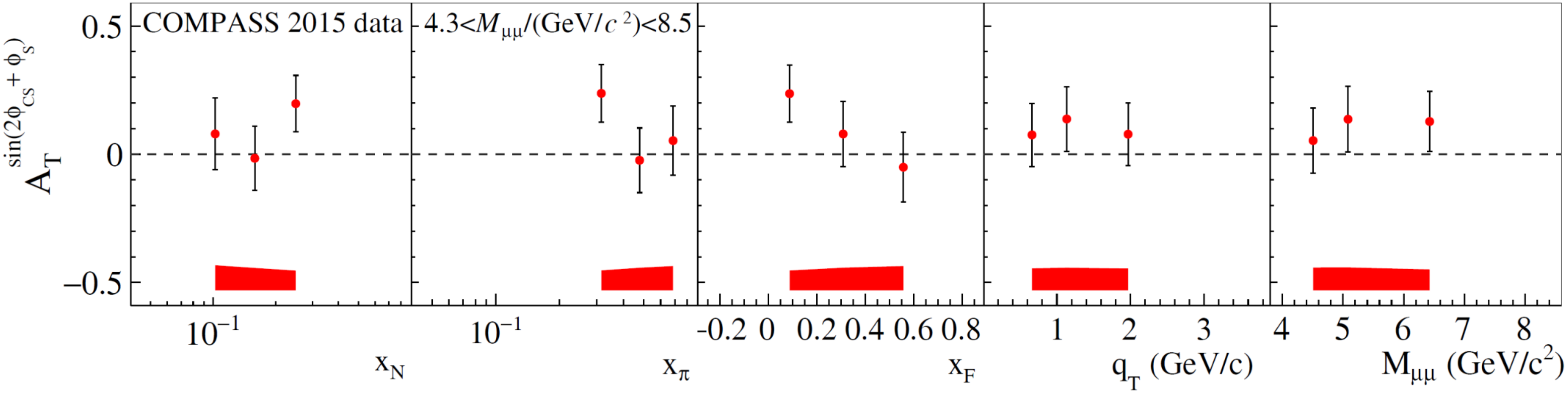
Drell-Yan TSAs – Pretzelosity

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

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)



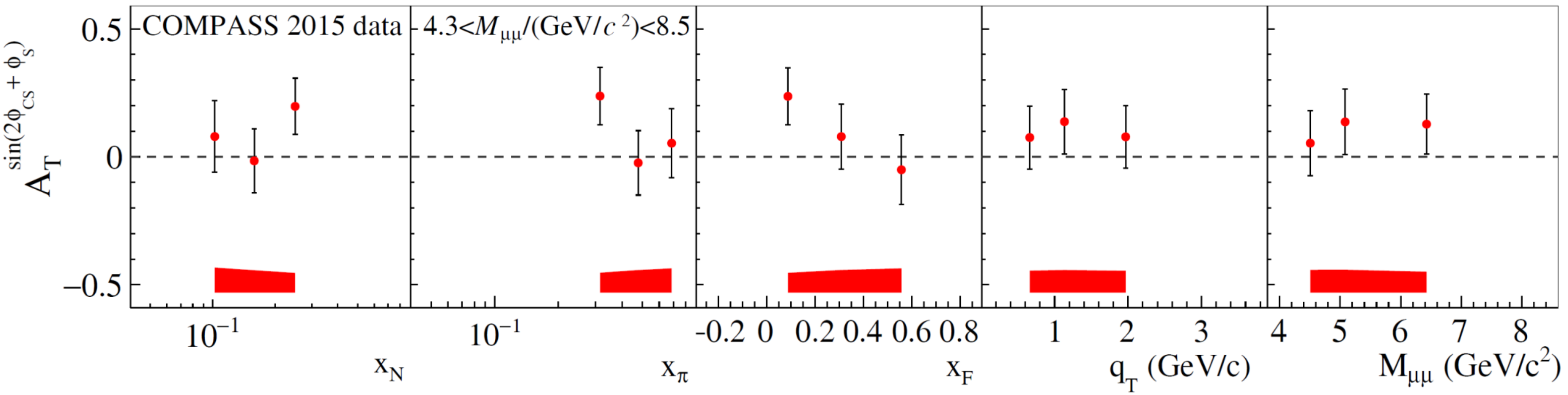
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

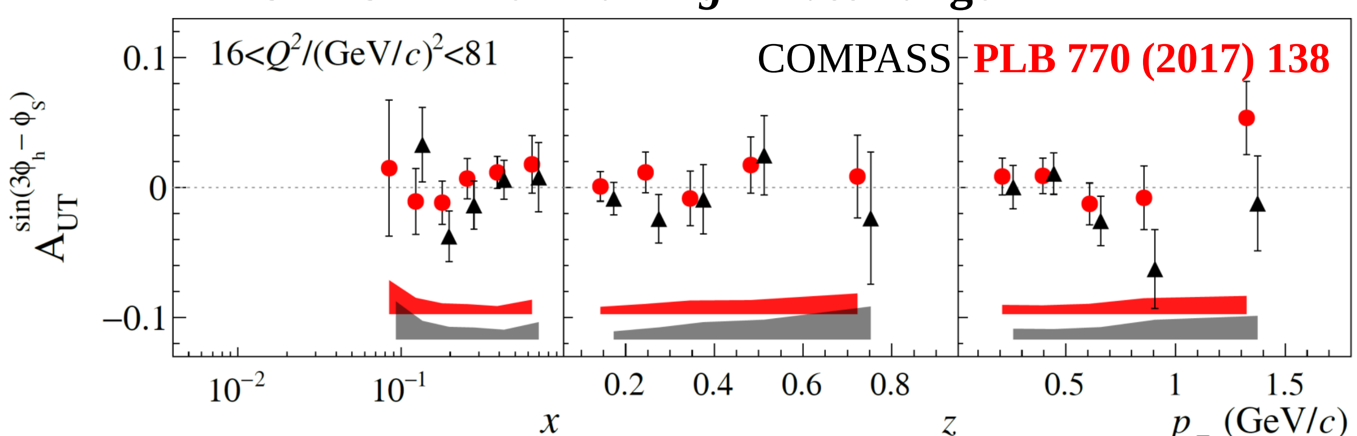
COMPASS PRL 119, 112002 (2017)



SIDIS in Drell-Yan *high-mass* range

Pretzelosity SIDIS TSA

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



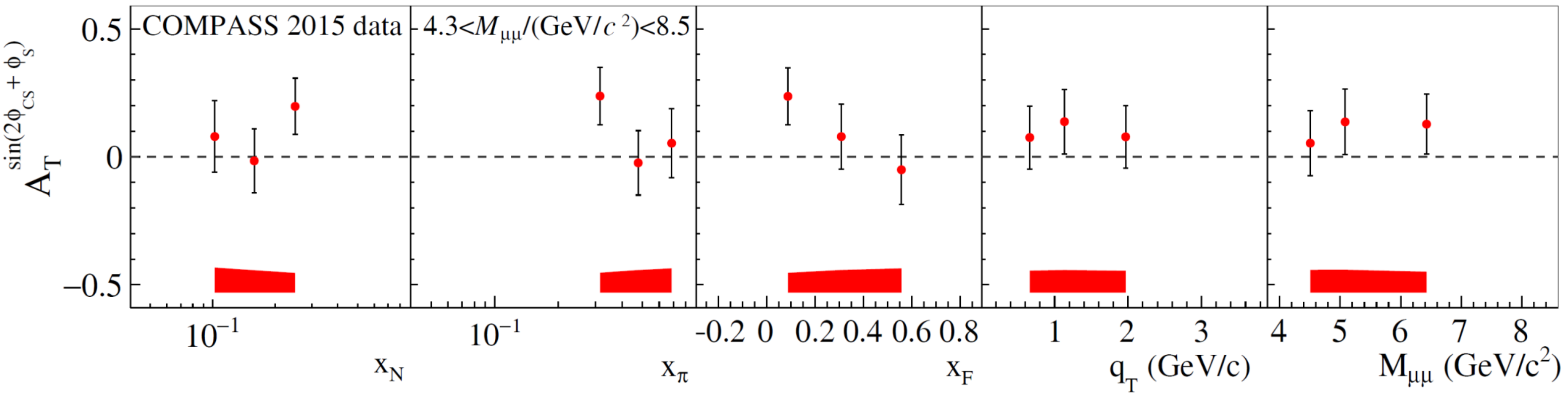
Drell-Yan TSAs – Pretzelosity

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

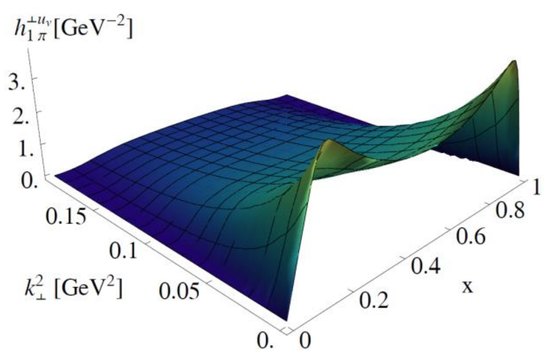
Pretzelosity DY TSA

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

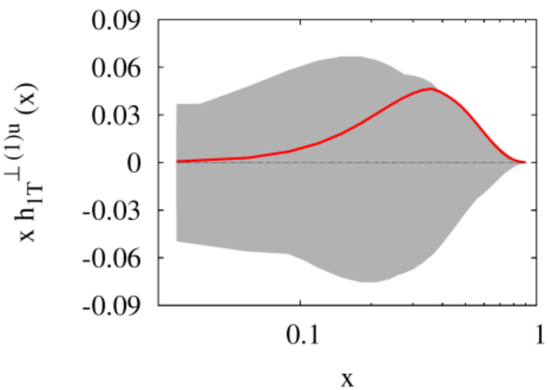
COMPASS **PRL 119, 112002 (2017)**



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



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



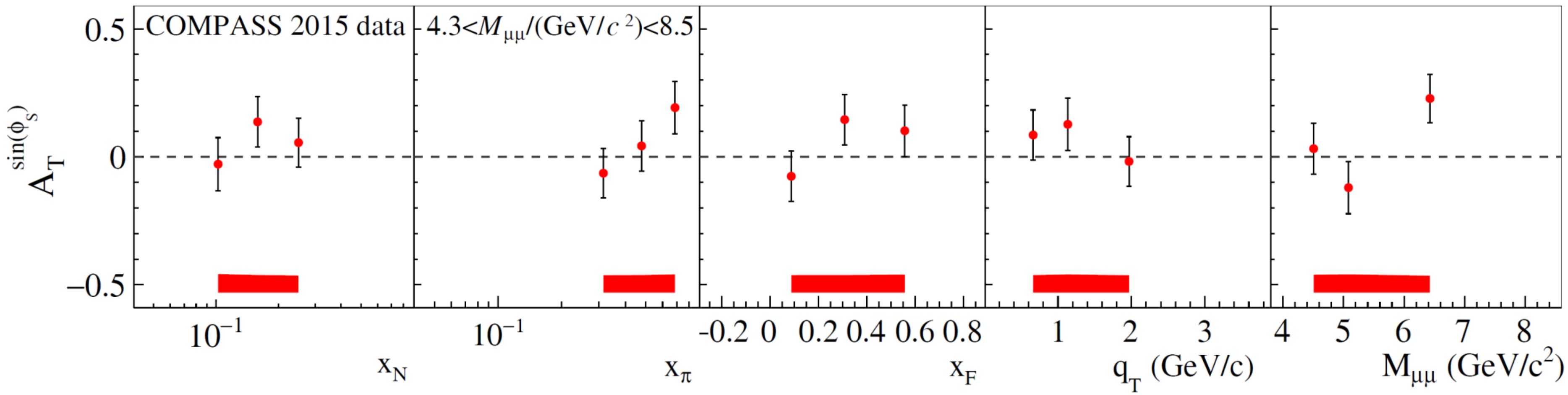
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

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



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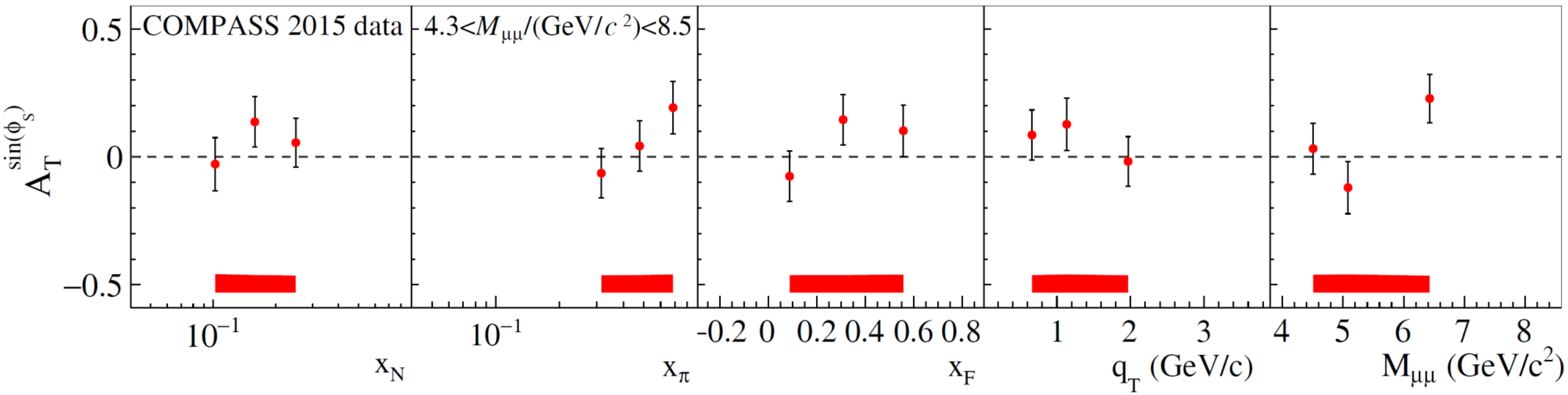
Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)

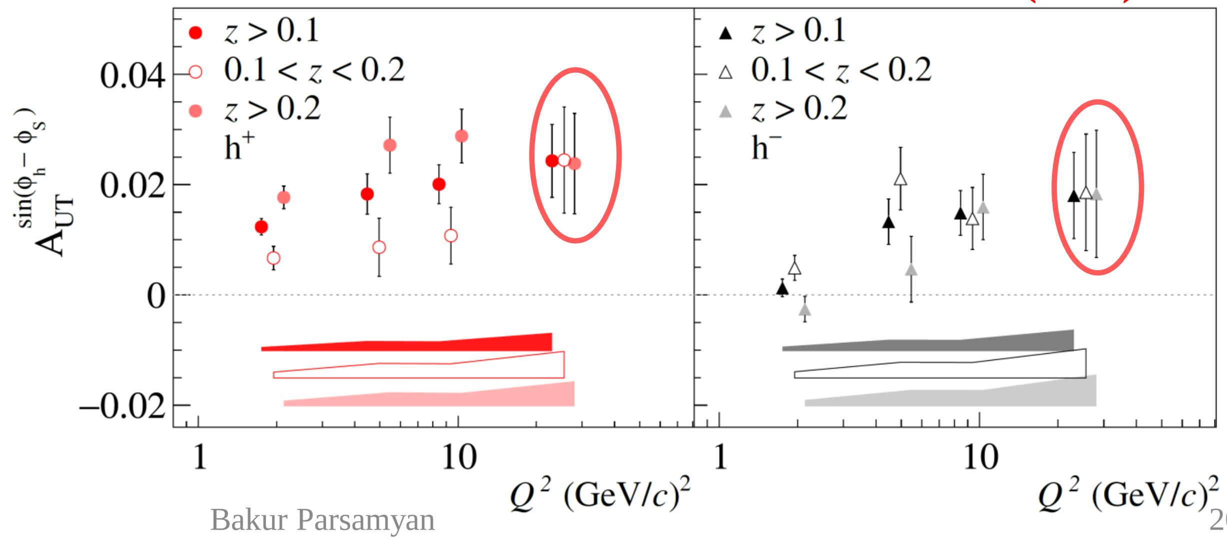


SIDIS in Drell-Yan *high-mass* range

COMPASS **PLB 770 (2017) 138**

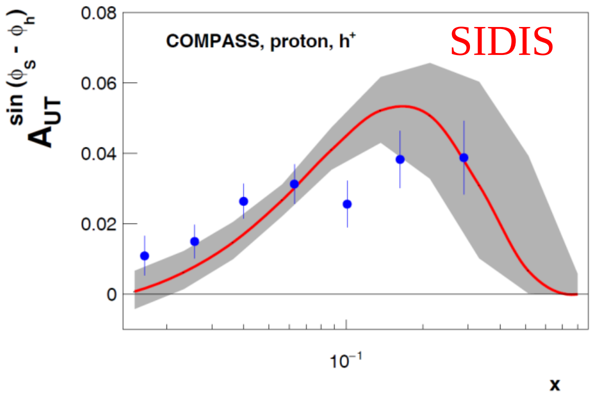
Sivers SIDIS TSA

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

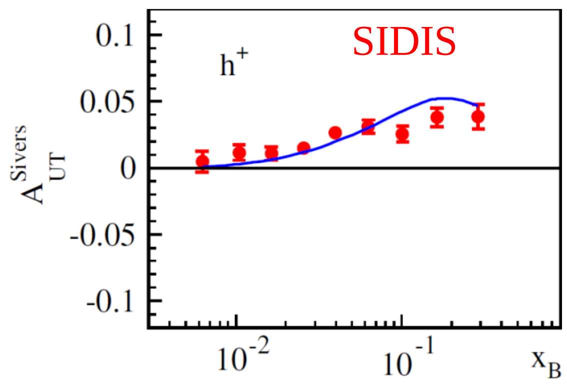


Sivers asymmetry in Drell-Yan: sign change

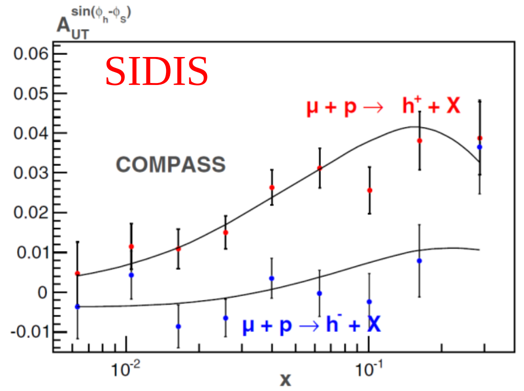
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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



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



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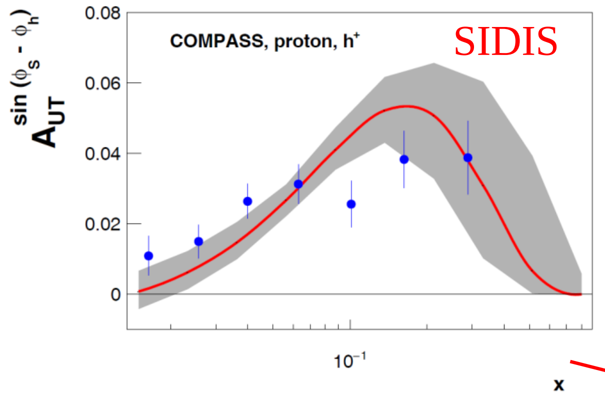

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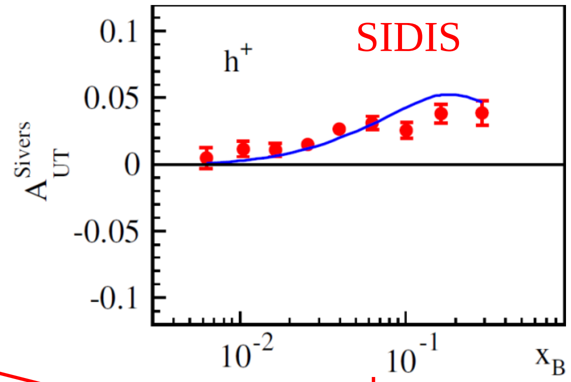

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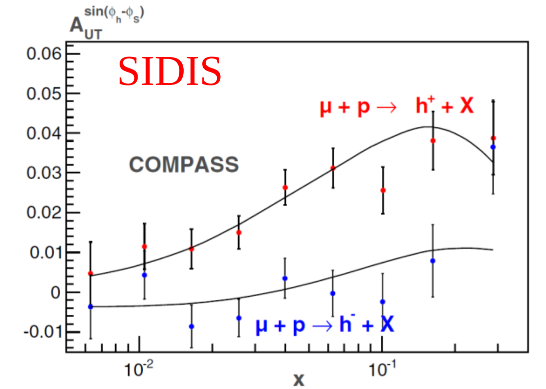

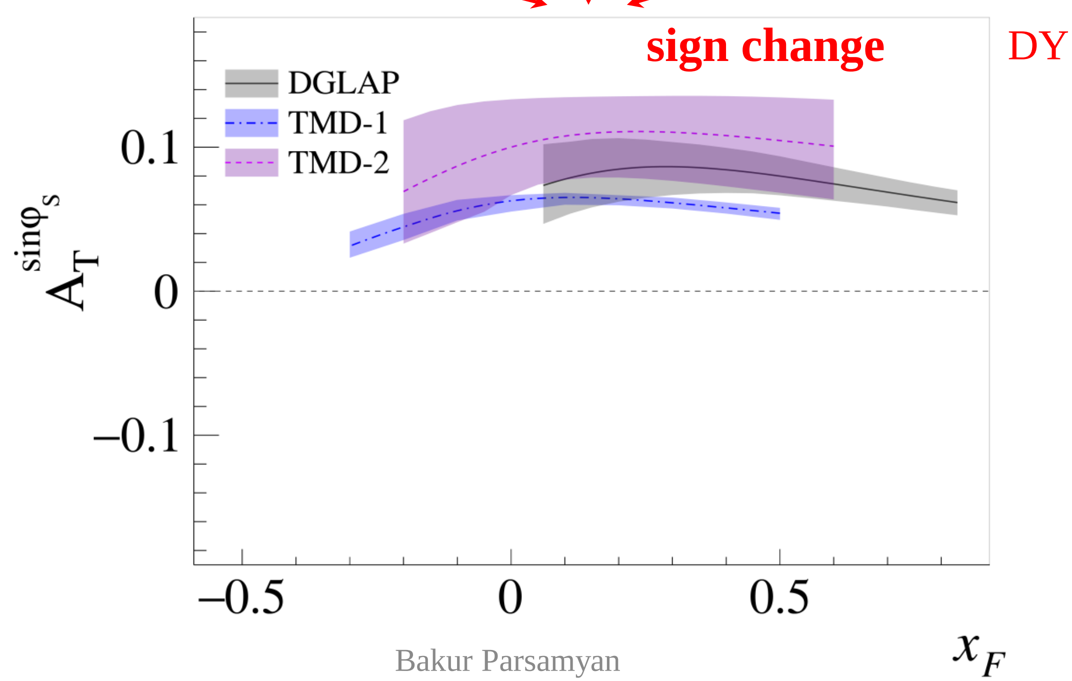

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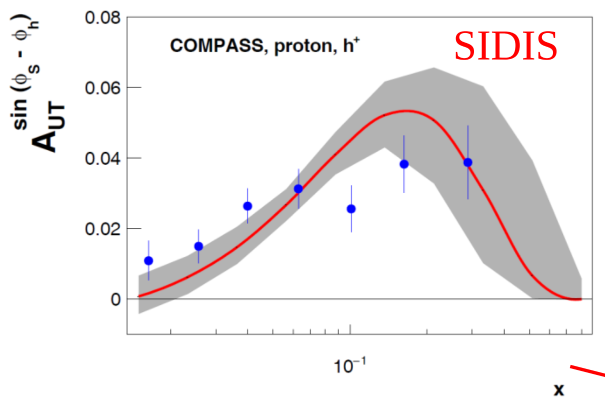

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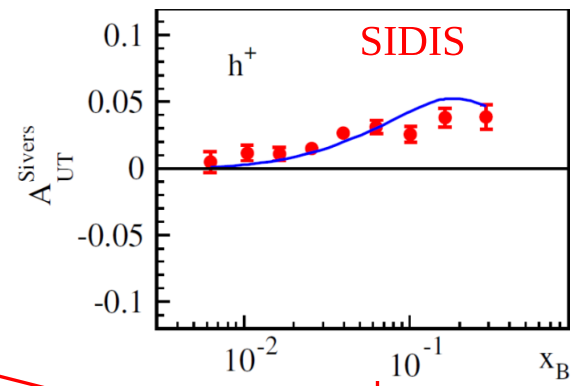

TMD-2 (2013)
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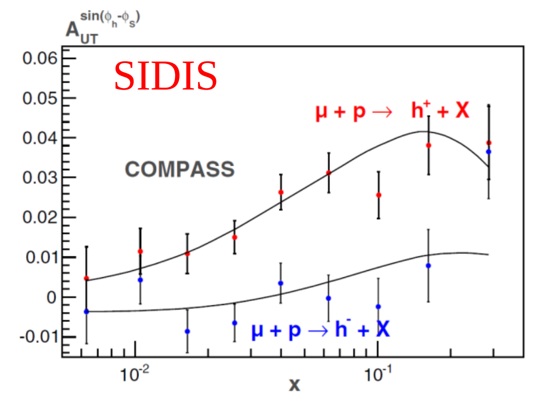

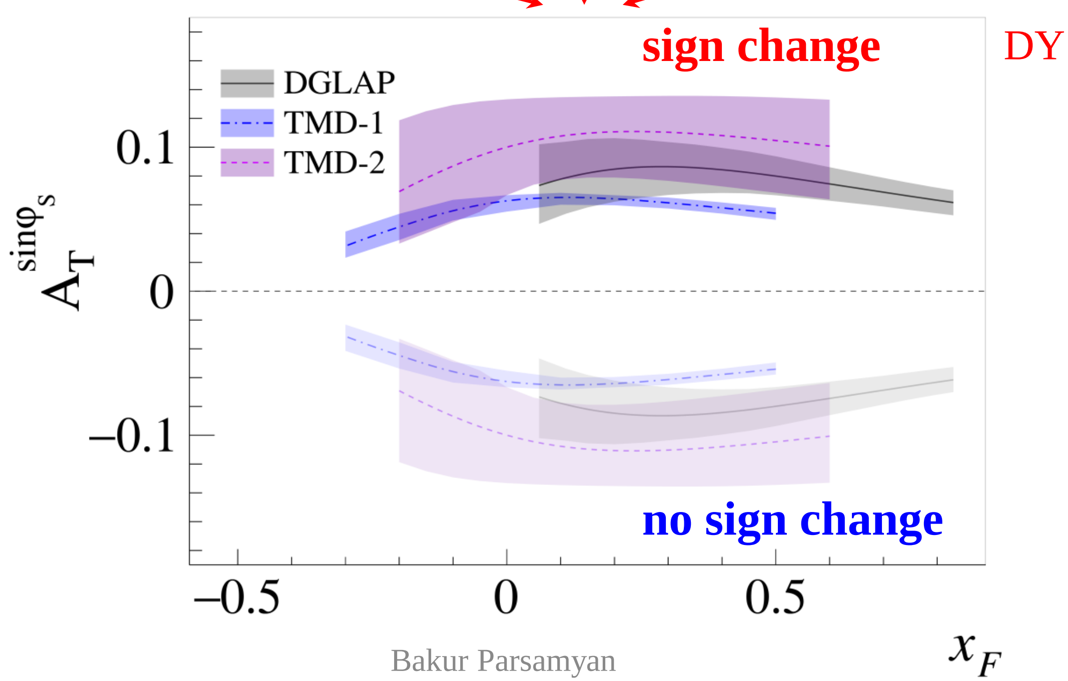

Sivers asymmetry in Drell-Yan: sign change

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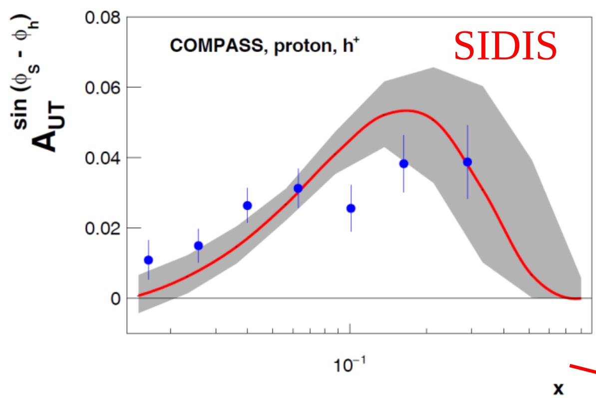

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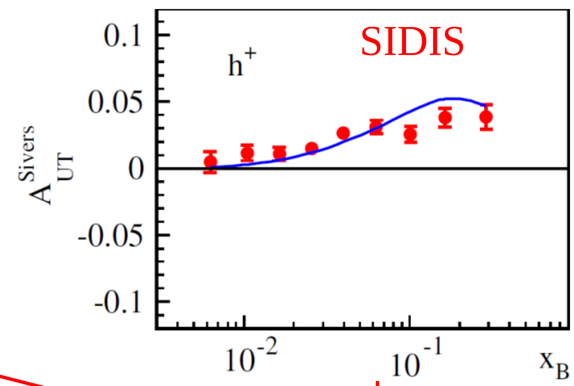

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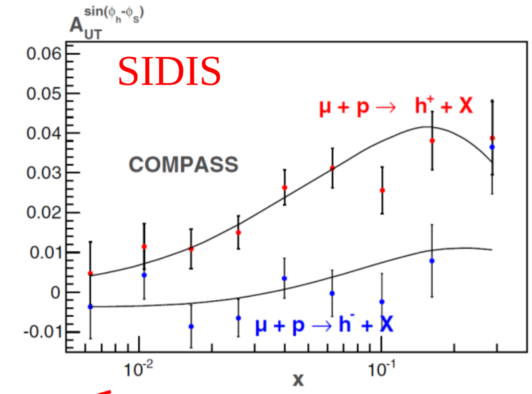
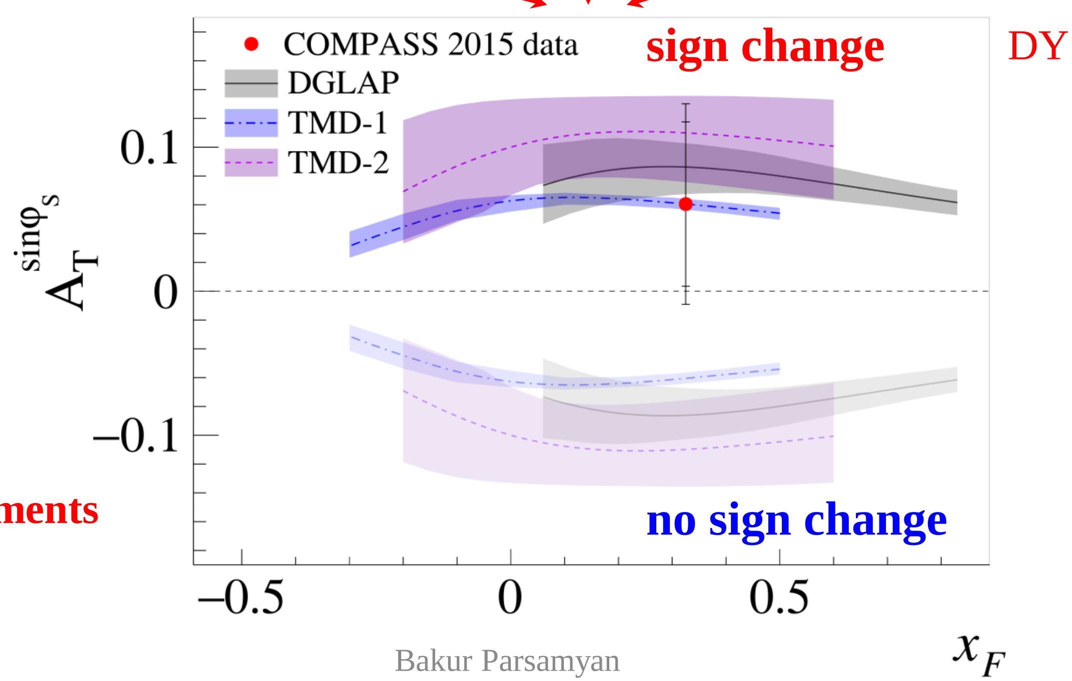


COMPASS
PRL 119, 112002 (2017)

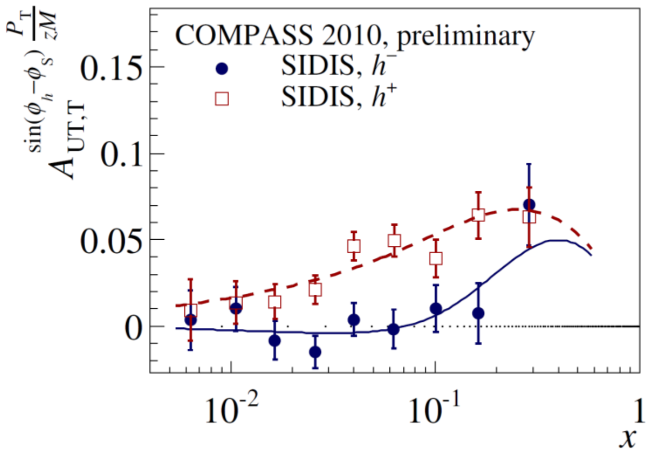


In 2018 – 2nd round of polarized DY measurements at COMPASS

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

See talk by J. Matoušek

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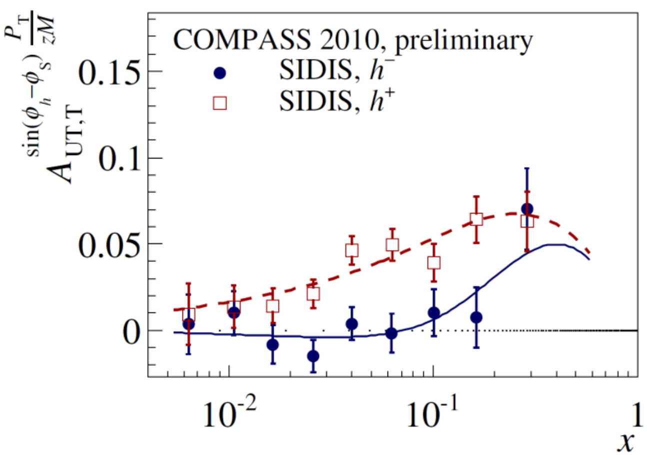

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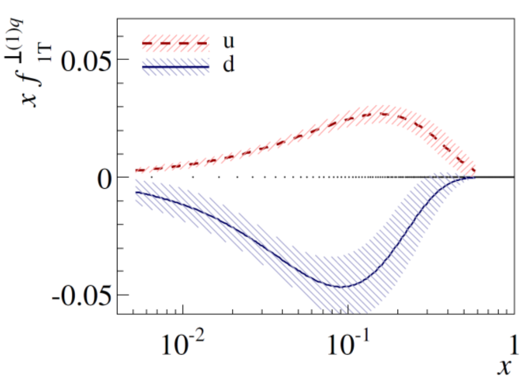
Sivers TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	
Sivers *w*TSA in DY:	$A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$	



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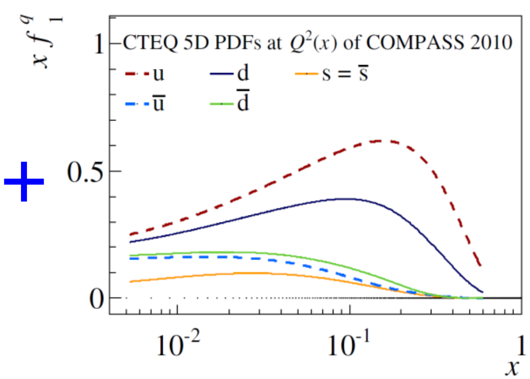

Valence quark dominance
No Q^2-evolution for Sivers PDF

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

See talk by J. Matoušek

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

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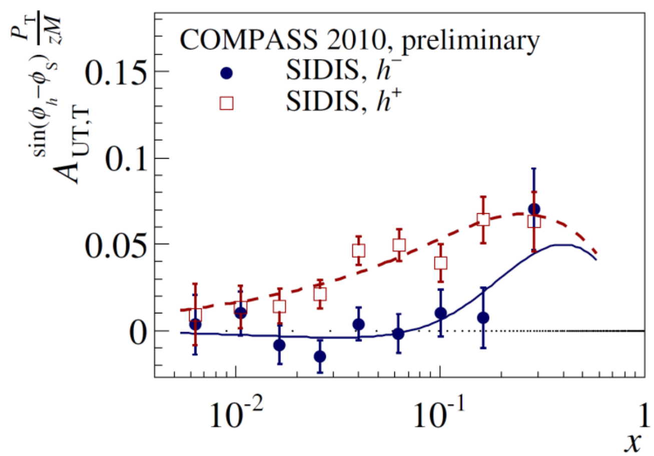

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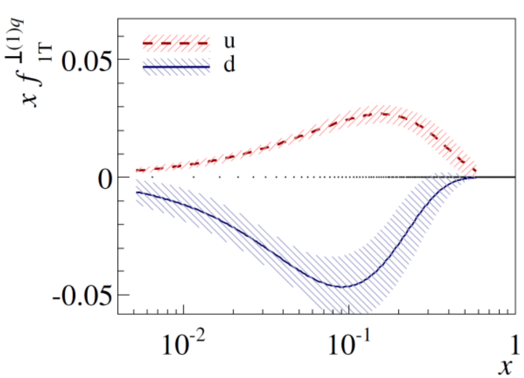

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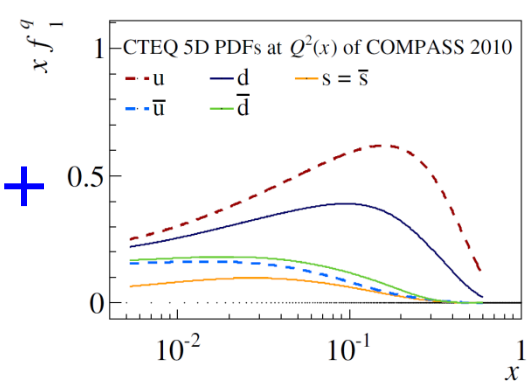
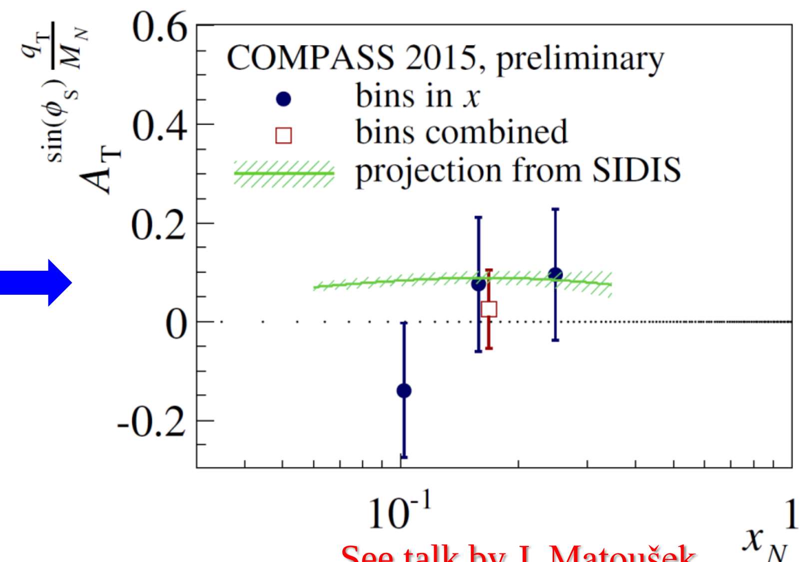


J. Matoušek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]



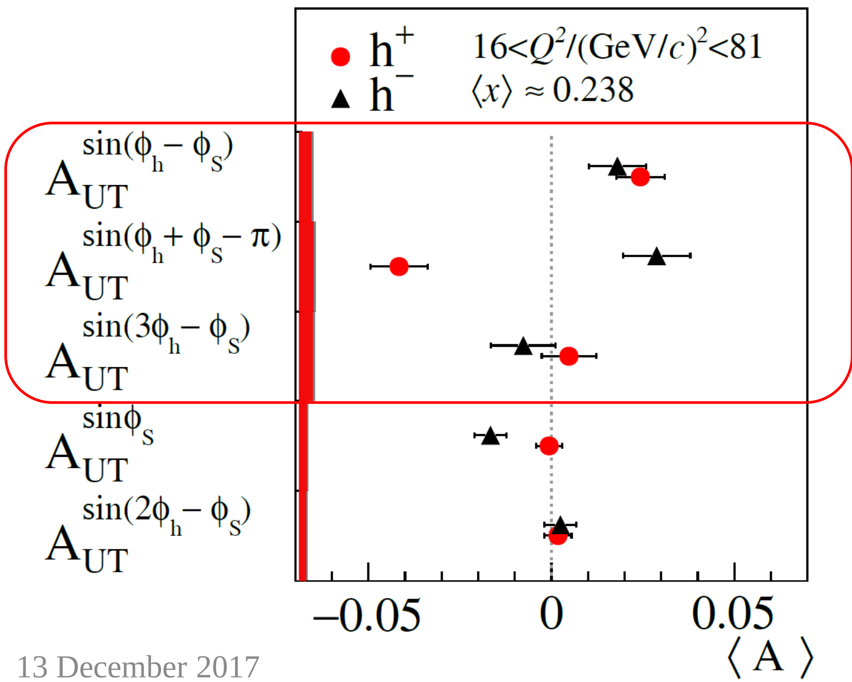
See talk by J. Matoušek

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

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

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

COMPASS PLB 770 (2017) 138



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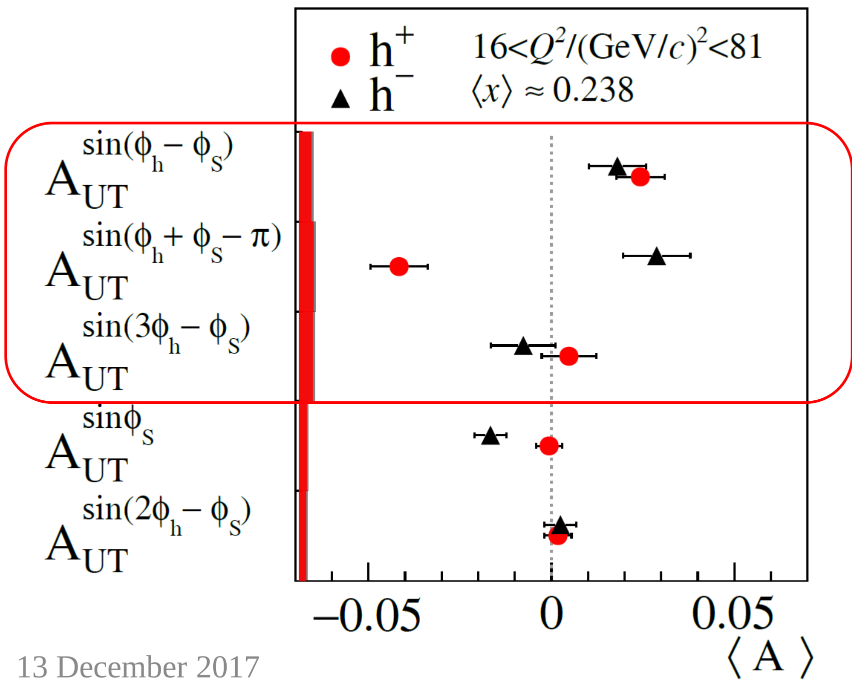
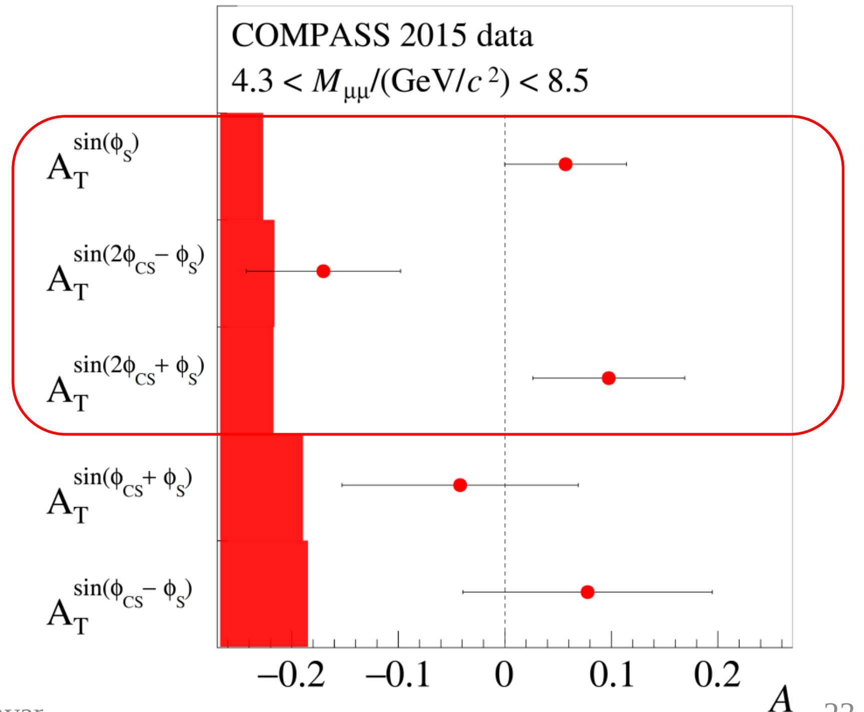
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1\left(1 + \cos^2\theta_{CS}\right)\left\{ 1 + \ldots \right.$$
$$\left. + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\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

COMPASS PLB 770 (2017) 138



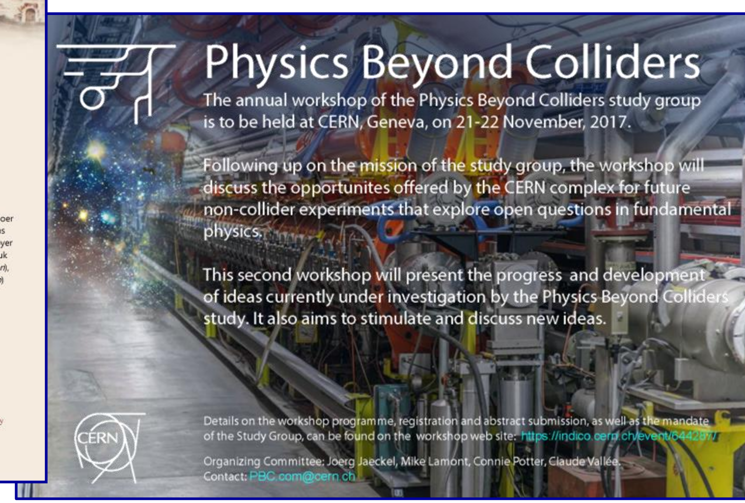
COMPASS PRL 119, 112002 (2017)



“COMPASS-like” future long-term experiment

COMPASS beyond 2020 workshop, CERN, March 21-22, 2016
Physics Beyond Colliders kick-off workshop CERN, September 6-7, 2016
IWHSS17 COMPASS workshop, Cortona, April 2-5, 2017
Dilepton Productions with Meson and Antiproton Beams workshop, ECT*, Trento, November 2017
Physics Beyond Colliders annual workshop, CERN, November 21-22, 2017

IWHSS18 – COMPASS workshop, Bonn, March 19-21, 2018



“COMPASS-like” future long-term experiment

LoI is open for new ideas/proponents

A.) RF separated kaon and anti-proton beam:
- 1. Hadron spectroscopy ✔
- 2. Drell-Yan physics ✔
- 3. Primakoff with kaon beam
- 4. Direct Photons with kaon ✔
- 5. RF separated beam

B.) Standard muon beam:
- 1. DVCS with trans. polarised proton target
- 2. Elastic muon proton scattering ✔

C.) Standard hadron beam:
- 1. Polarised/Unpolarised DY with various targets ✔
- 2. Absolute cross-section measurements p + He -> pbar X ✔
- 3. Hadron spectroscopy with antiprotons

D.) Spectrometer upgrades – hardware

For the moment it is ~50 pages long document

12/12/2017 Oleg Denisov 9

Unique new DY-measurements with a RF separated beam

- Kaon structure including valence sea separation
- Test of Lam Tung relation
- Model free TSA in DY with antiproton beam
- Requirement for RF separated, ongoing
- Evaluation apparatus design, ongoing

New collaborators are welcome

Vincent Andrieux (UIUC) ECT* 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
- A "COMPASS-like" future experiment is being discussed to take place after 2021
  - Particular attention is given to possible Drell-Yan measurements

Spare slides

D. Kikoła et al. arXiv:1702.01546 [hep-ex]

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\rm eff}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	p+^{3}He$^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	190	19	$0.1 \div 0.3$	$2 \cdot 10^{33}$	18%	$6.5 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

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

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

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

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

COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

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

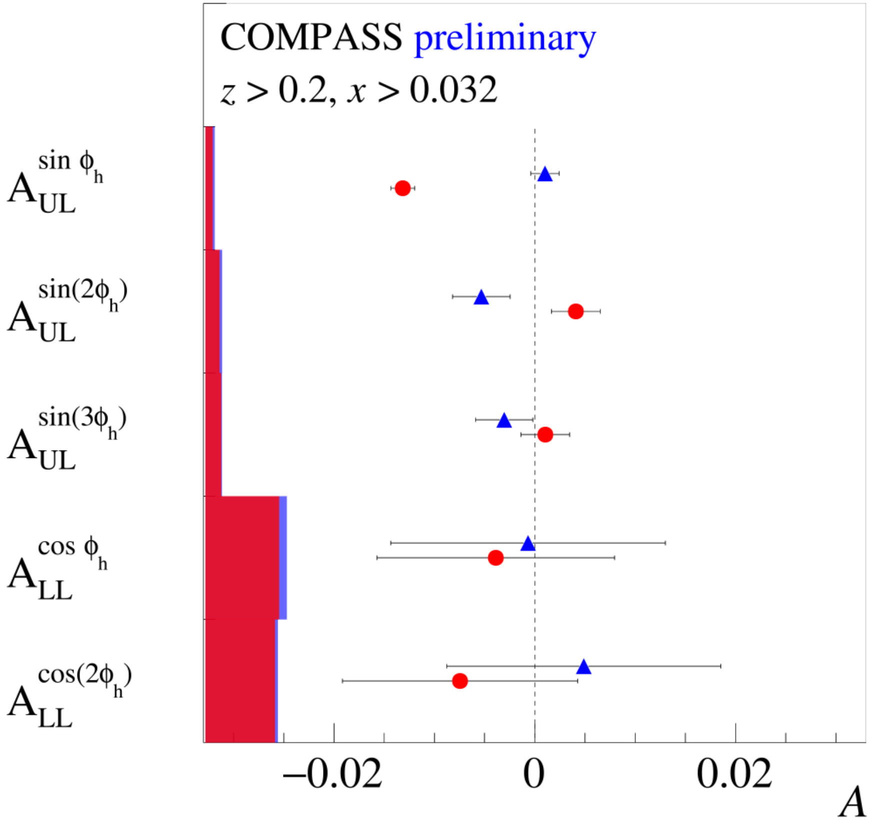
- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- **Significant h^+ asymmetry, clear *z*-dependence,**
- **h^- compatible with zero**

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

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

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

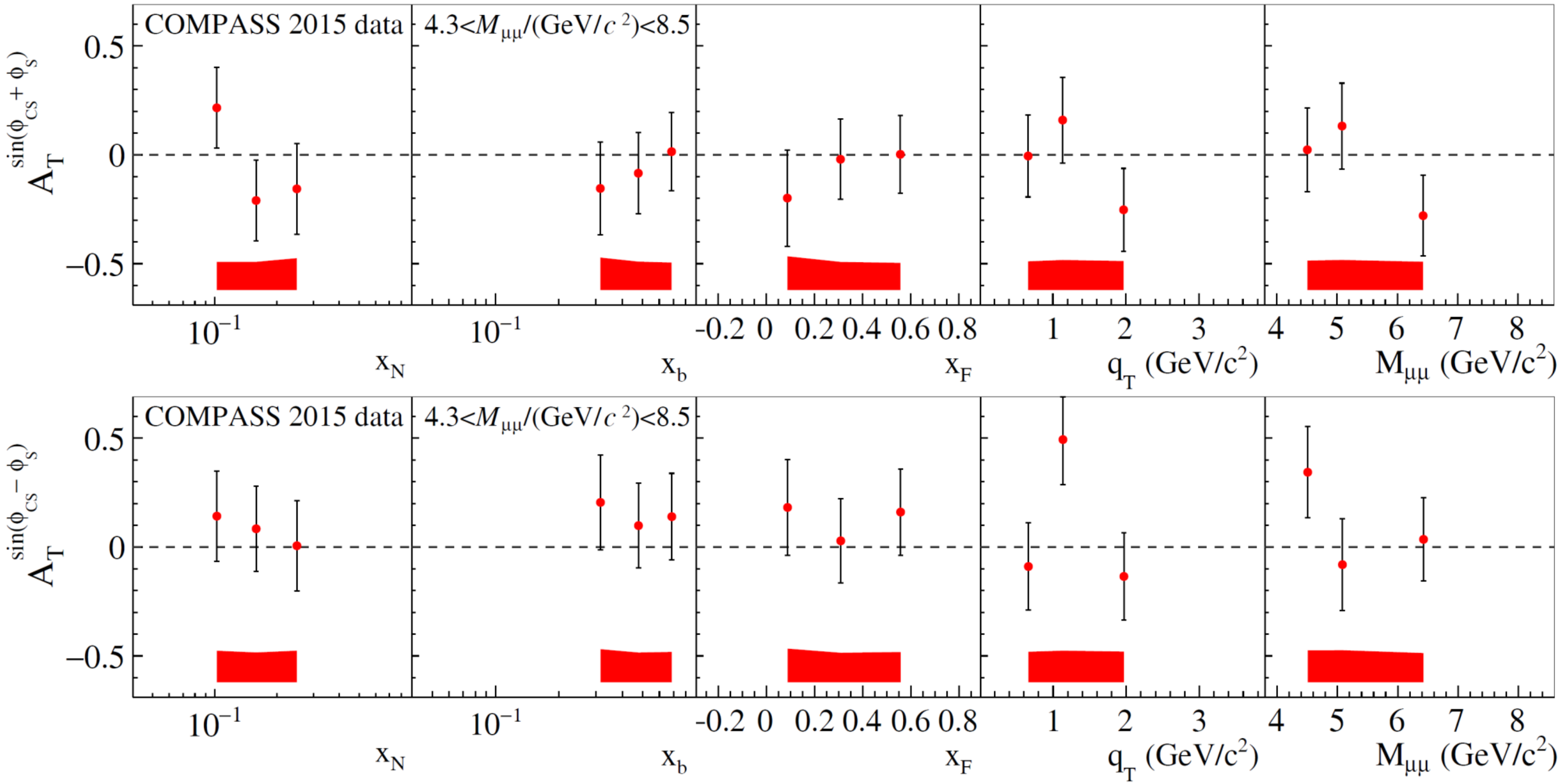
- Q-suppression, Various different "twist" ingredients
- **Compatible with zero, in agreement with models**



Drell-Yan TSAs – “higher twists”

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

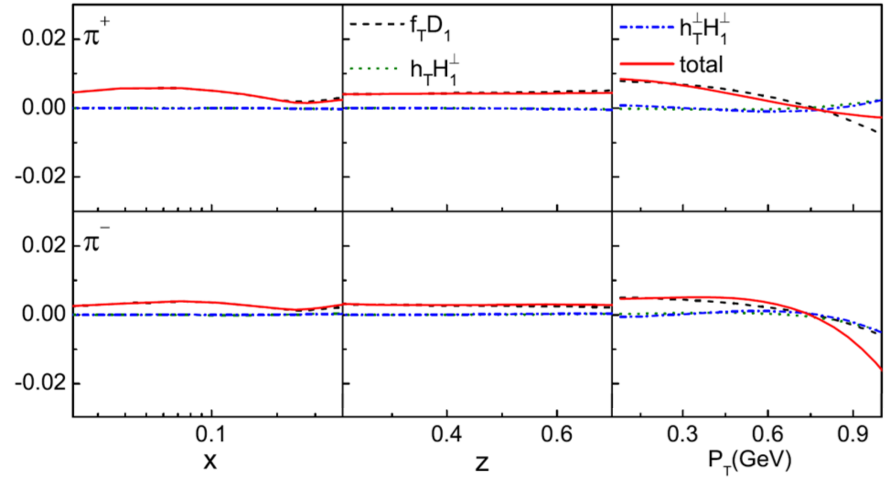
New! COMPASS arXiv:1704.00488[hep-ex]



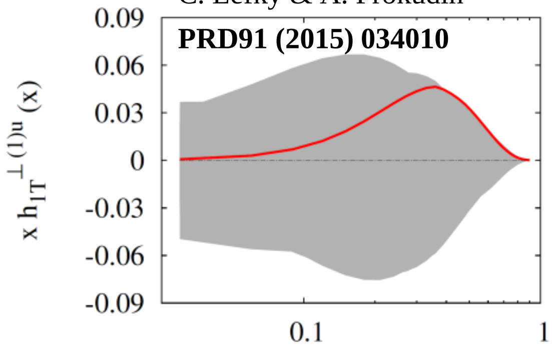
SIDIS: target transverse spin dependent asymmetries

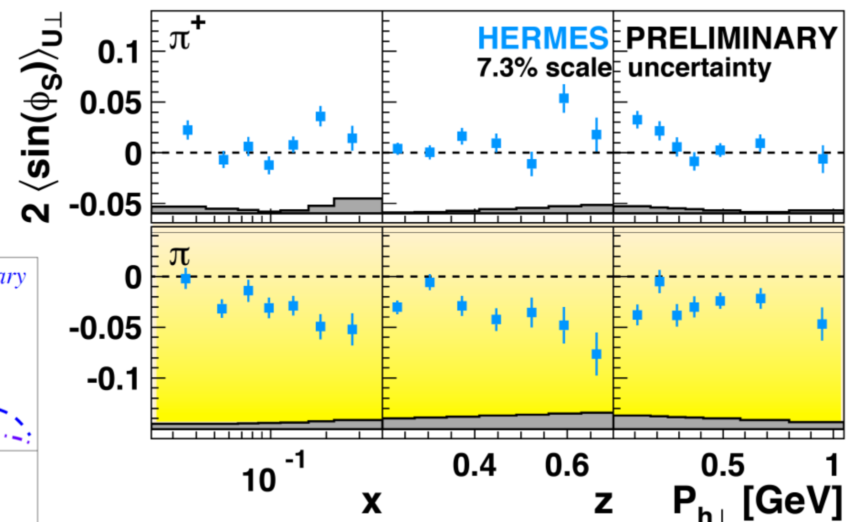
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\dots + S_T\left[+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S + \dots \right] + S_T\lambda\left[\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_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

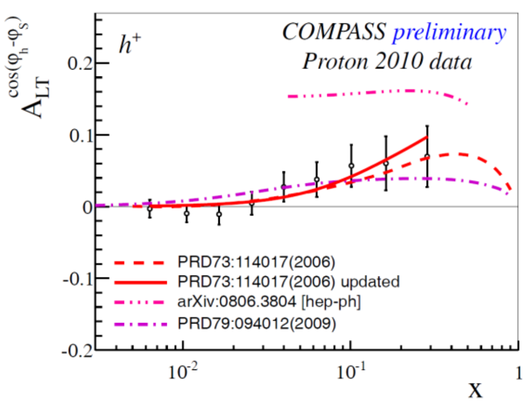
W. Mao, Z. Lu and B.Q. Ma **Phys.Rev. D 90 (2014) 014048**

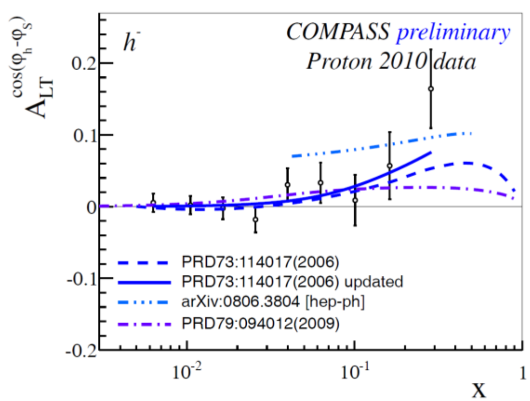


C. Lefky & A. Prokudin







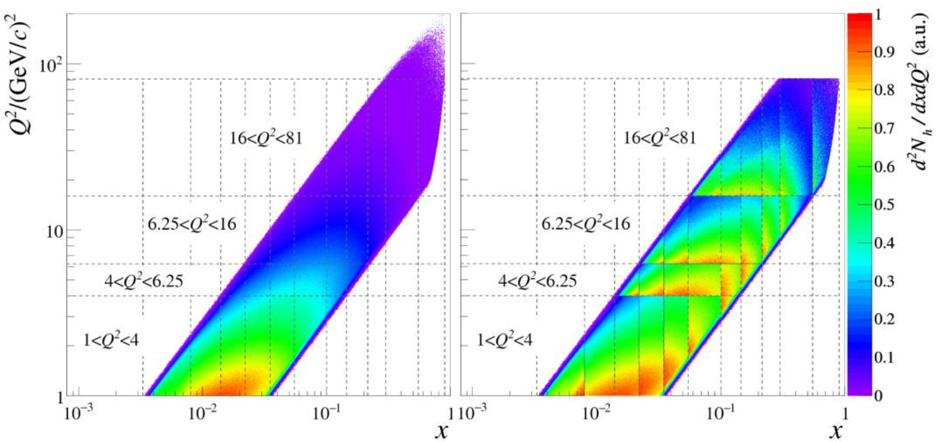


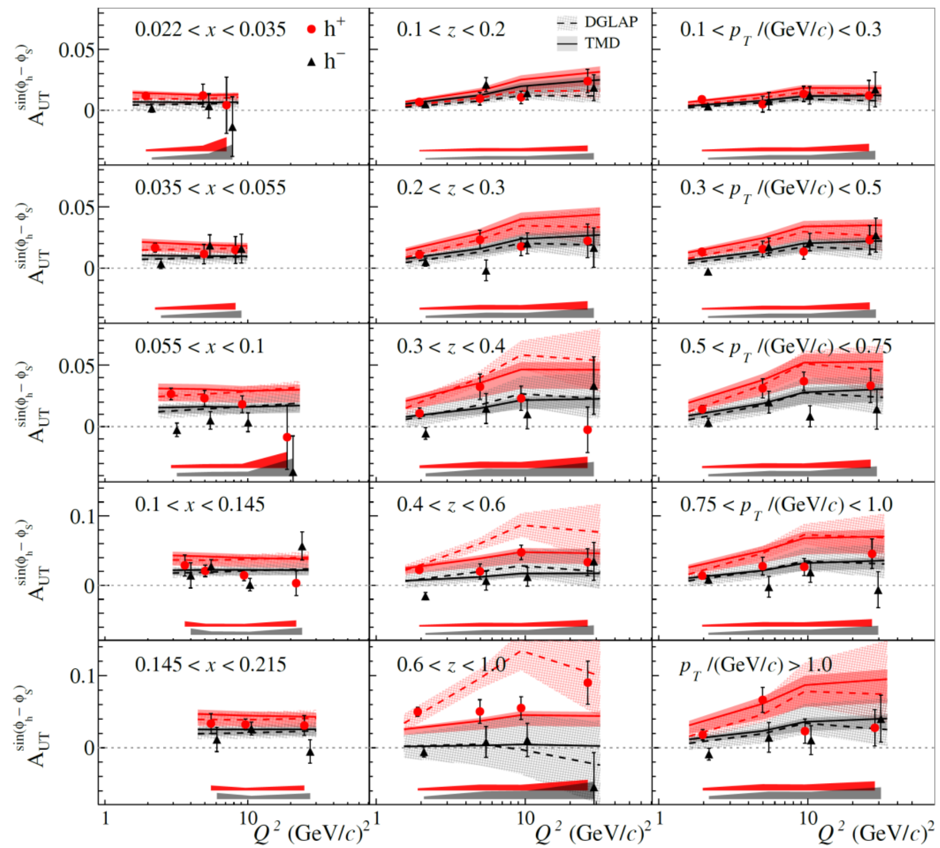
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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

PLB 770 (2017) 138



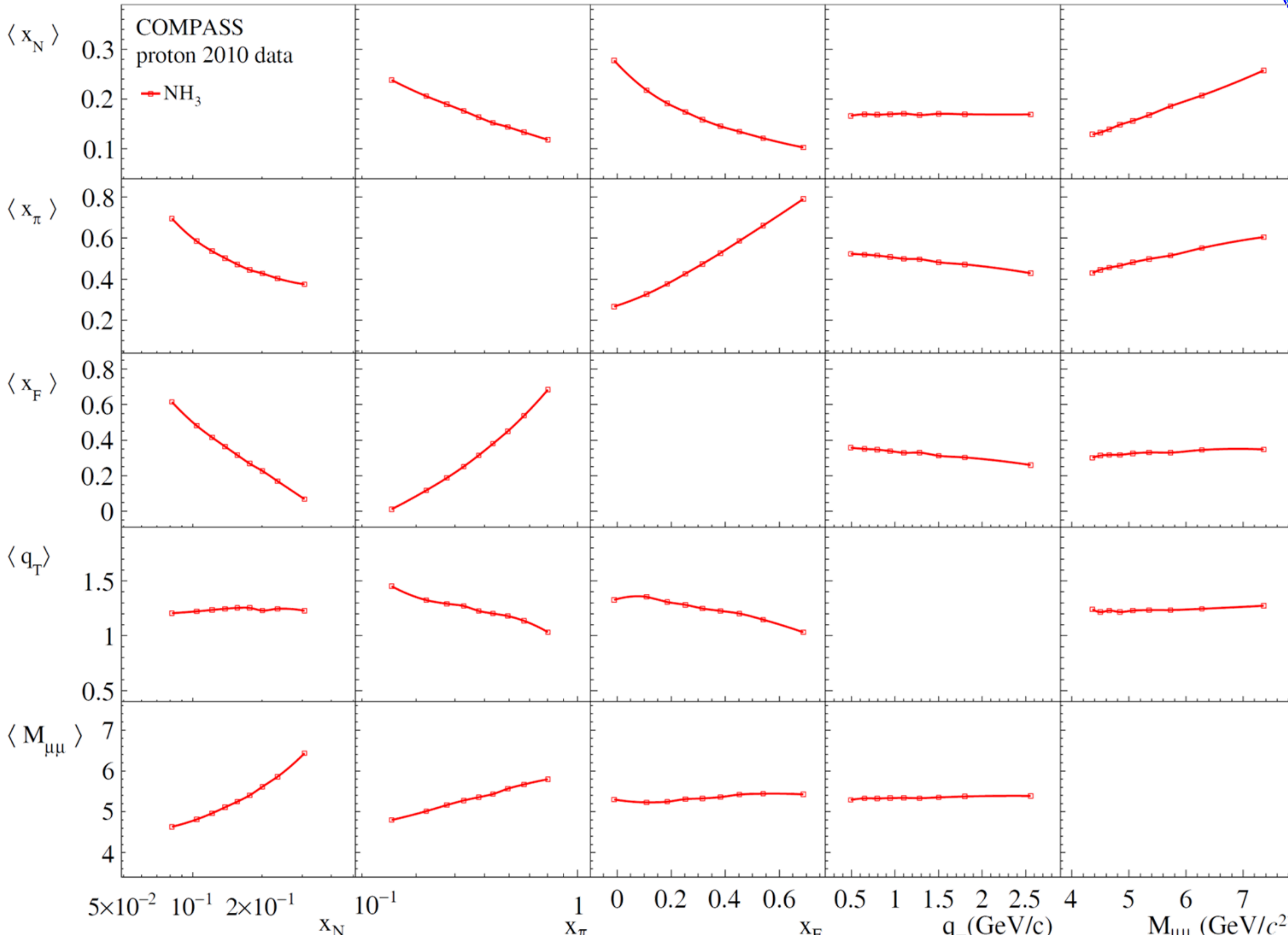


Multi-dimensional input for TMD evolution studies

- 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



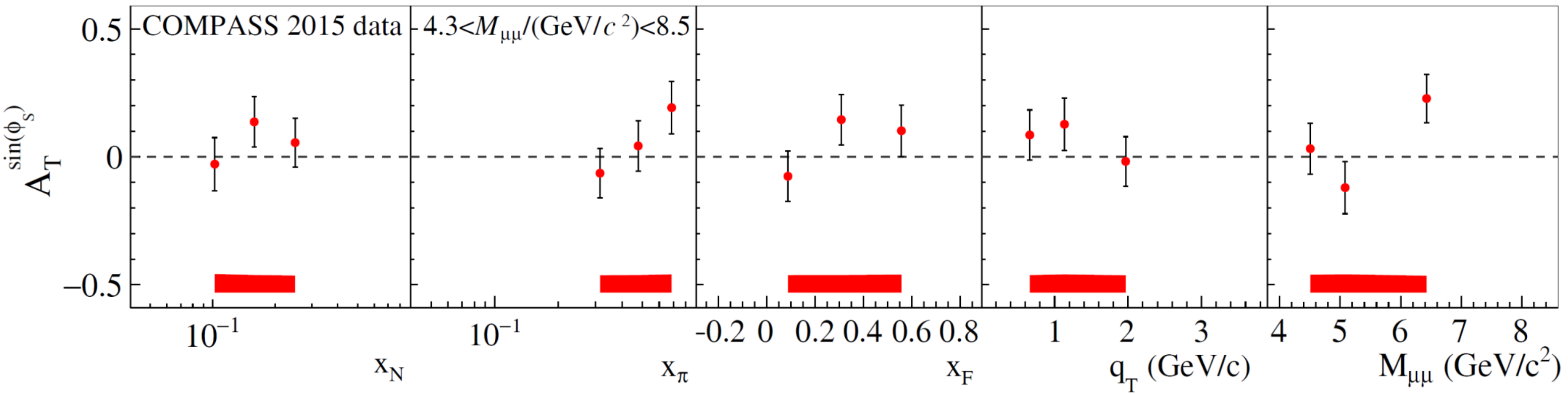
Drell-Yan TSAs – Sivers

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

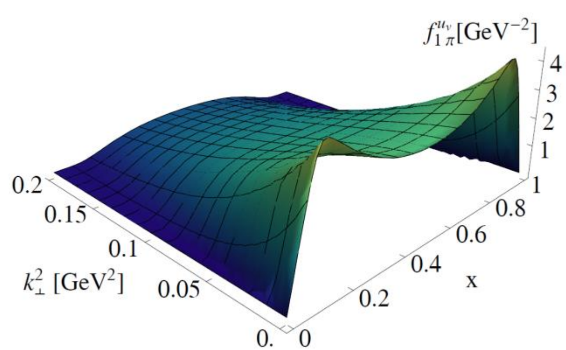
Sivers DY TSA

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

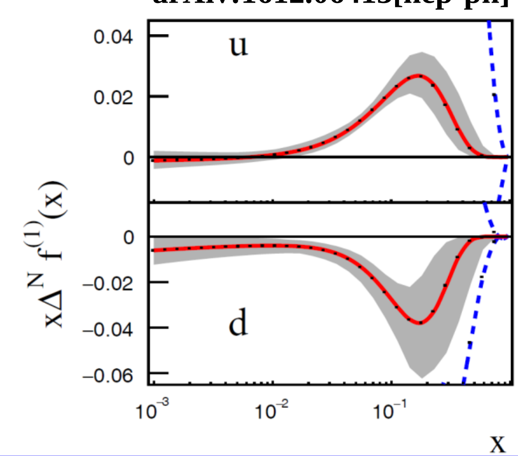
New! COMPASS arXiv:1704.00488[hep-ex]



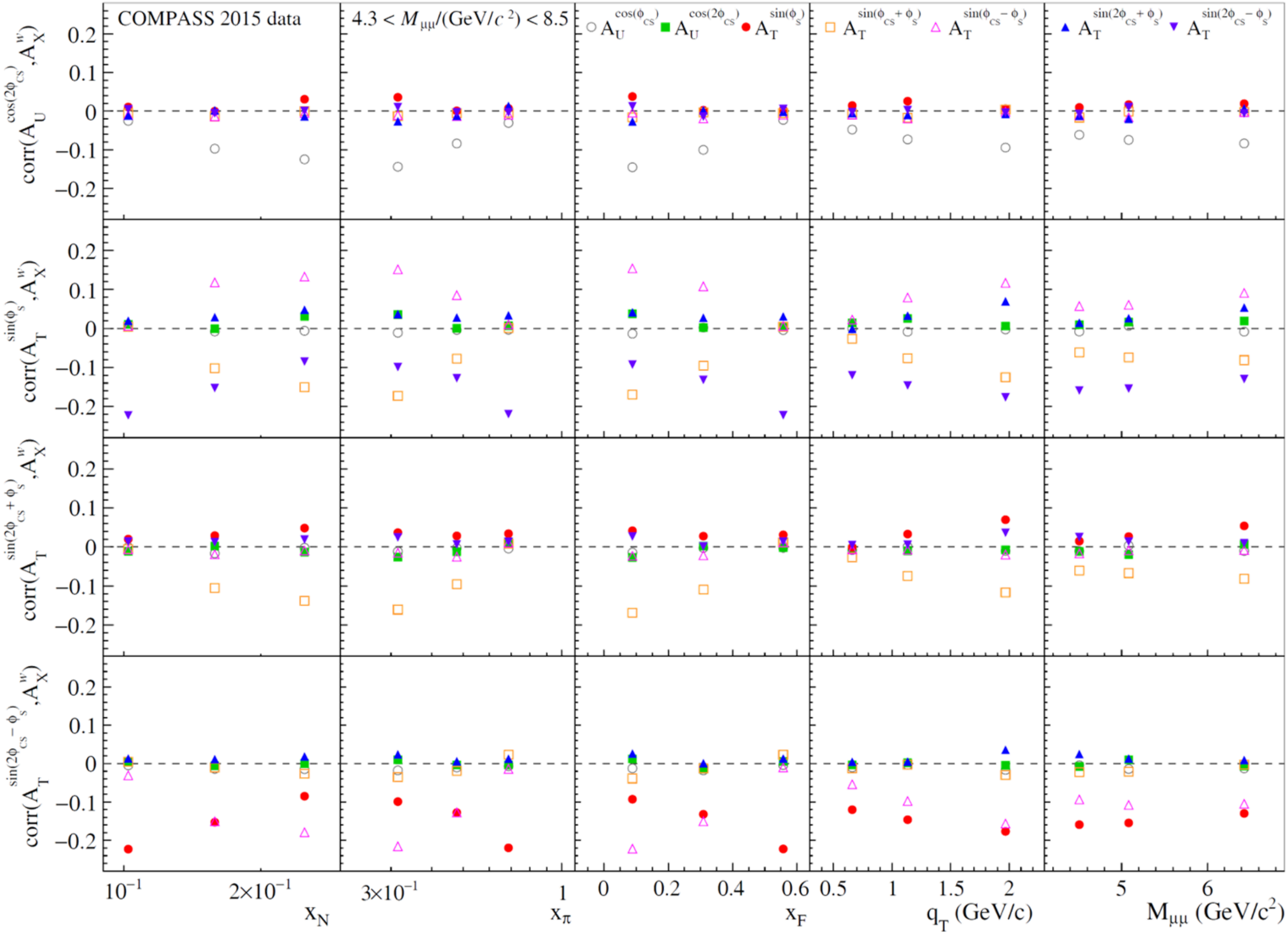
B. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



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**)

$$\int d^2 \boldsymbol{q}_T \frac{q_T}{M_p} F_T^{\sin\phi_S} = -\int d^2 \boldsymbol{q}_T \frac{q_T}{M_p} \mathcal{C}\left[\frac{\boldsymbol{q}_T \cdot \boldsymbol{k}_{pT}}{q_T M_p} f_{1,\pi} f_{1T,p}^{\perp}\right]$$

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

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

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:	$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q\,(1)} \times D_{1q}^h$
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:	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q\,(1)}$

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

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

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

$$A_T^{\sin\phi_S \frac{q_T}{M_p}}(x_N, Q^2) \approx 2\frac{f_{1T,p}^{\perp(1)u}(x_N, Q^2)}{f_{1,p}^{u}(x_N, Q^2)}$$