

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 Muon and Proton Apparatus for Structure and Spectroscopy



24 institutions from 13 countries
– nearly 250 physicists

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (**20 years**)
- Taking data since 2002

Wide physics program

COMPASS-I

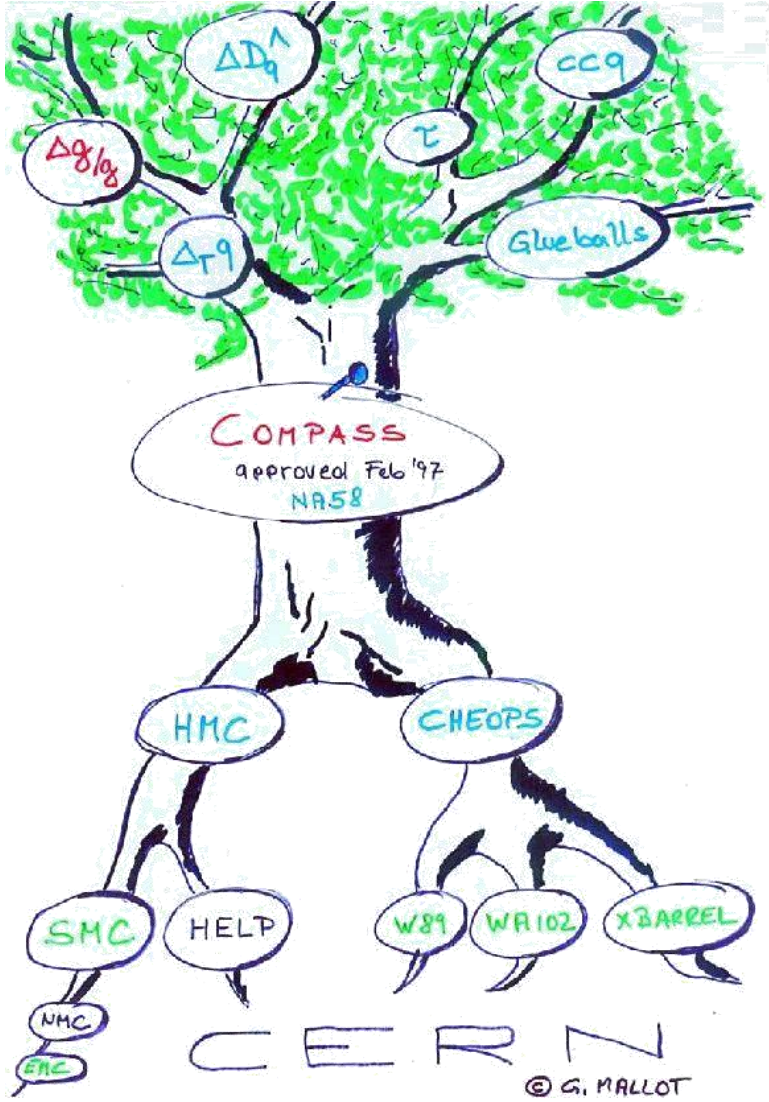
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

COMPASS-II

- Data taking 2012-2018 (**2021?**)
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan
- **Transverse deuteron SIDIS**

Many “beyond 2021” ideas

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



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



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HOME COMMITTEES CONTRIBUTORS BULLETINS PROGRAM REGISTRATION PARTICIPANTS PRACTICAL INFO ACCOMMODATION CONTACTS



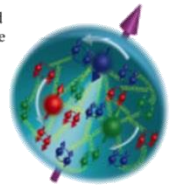
Reminder: cash payments are not accepted on site. - Registration for the social dinner now open -

Modern developments in hadron physics emphasize the role of parton intrinsic motion and spin, and their correlations, which are crucial to our full understanding of the nucleon structure in terms of the quark and gluon degrees of freedom in QCD.

The main aim of the workshop is to provide an environment in which present theoretical and experimental knowledge in the field of transversity, transverse-momentum dependent distribution and fragmentation functions as well as generalized parton distribution functions will be presented and discussed in depth, together with new theoretical ideas and experimental perspectives.

The scientific program will consist of presentations (by invitation only), featuring review talks (30 minutes + 10 minutes for discussion) and research talks (20 minutes + 5 minutes or 15 minutes + 5 minutes for discussion). In addition a round-table will be devoted to the perspectives of the field.

The Workshop follows the successful editions held in : 2005 on Lake Como (Italy), 2008 Ferrara (Italy), 2011 in Losinj (Croatia), 2014 Cagliari (Italy).





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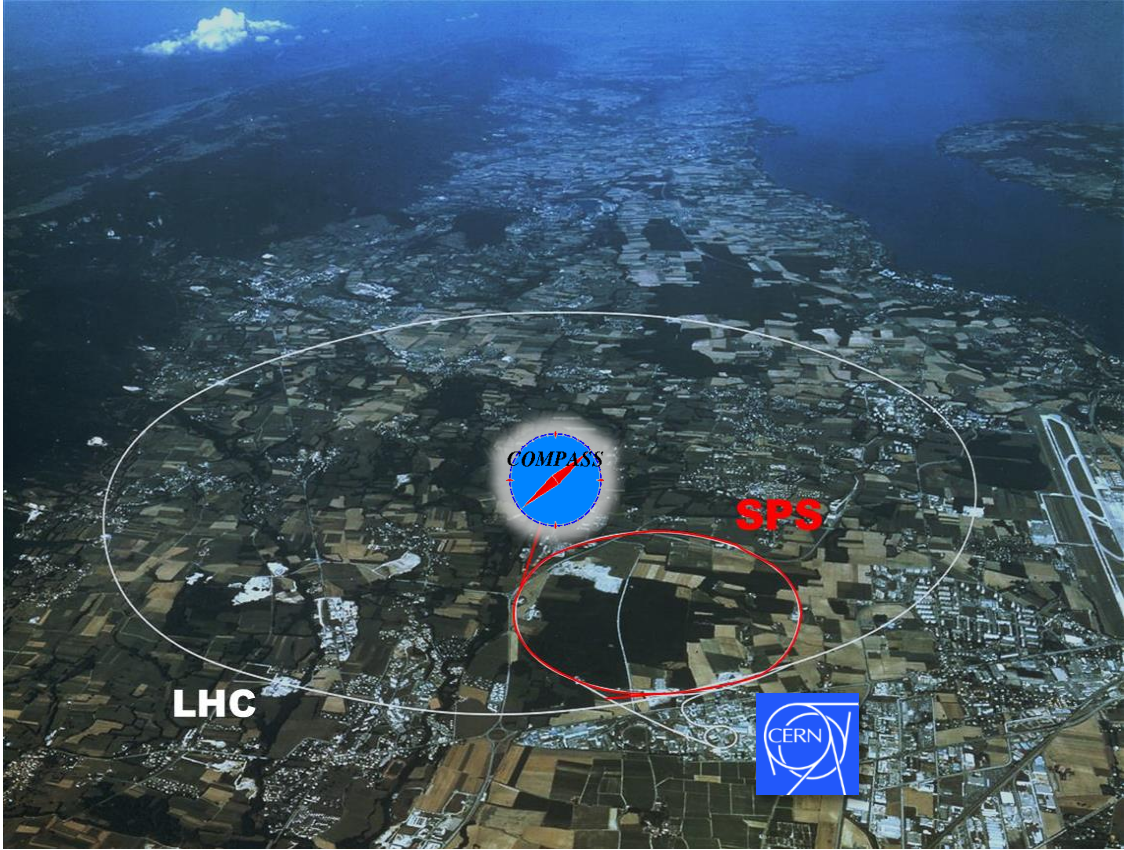
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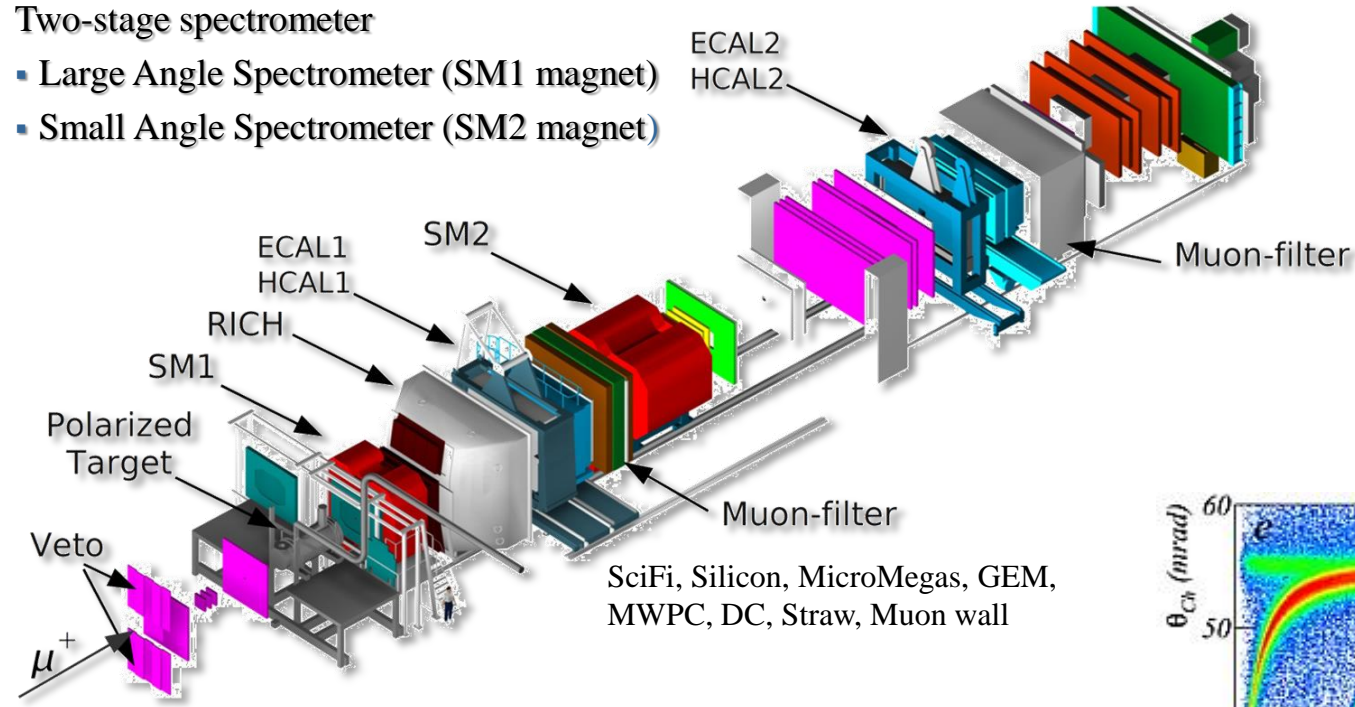
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COMPASS experimental setup: Phase I (muon program)

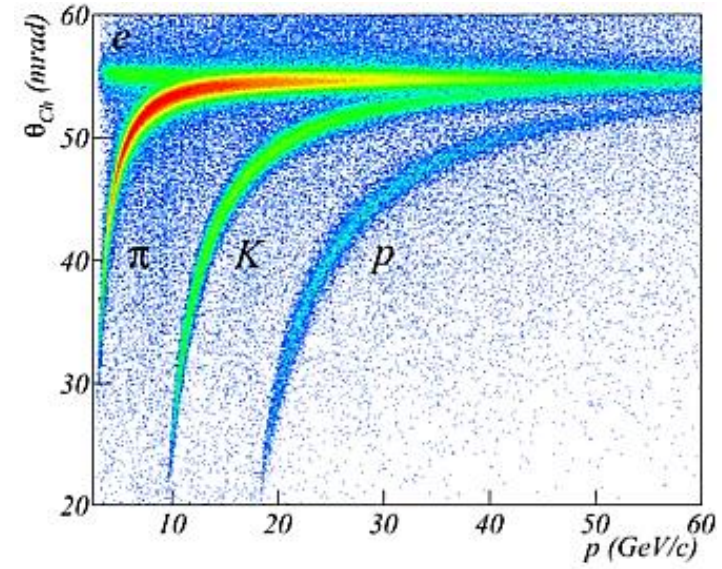
Two-stage spectrometer

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



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

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



Data-taking years: 2002-2011

Longitudinally polarized (80%) μ^+ beam:
 Energy: 160/200 GeV/c, Intensity: $2 \cdot 10^8 \mu^+$ /spill (4.8s).
 Target: Solid state (${}^6\text{LiD}$ or NH_3)

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

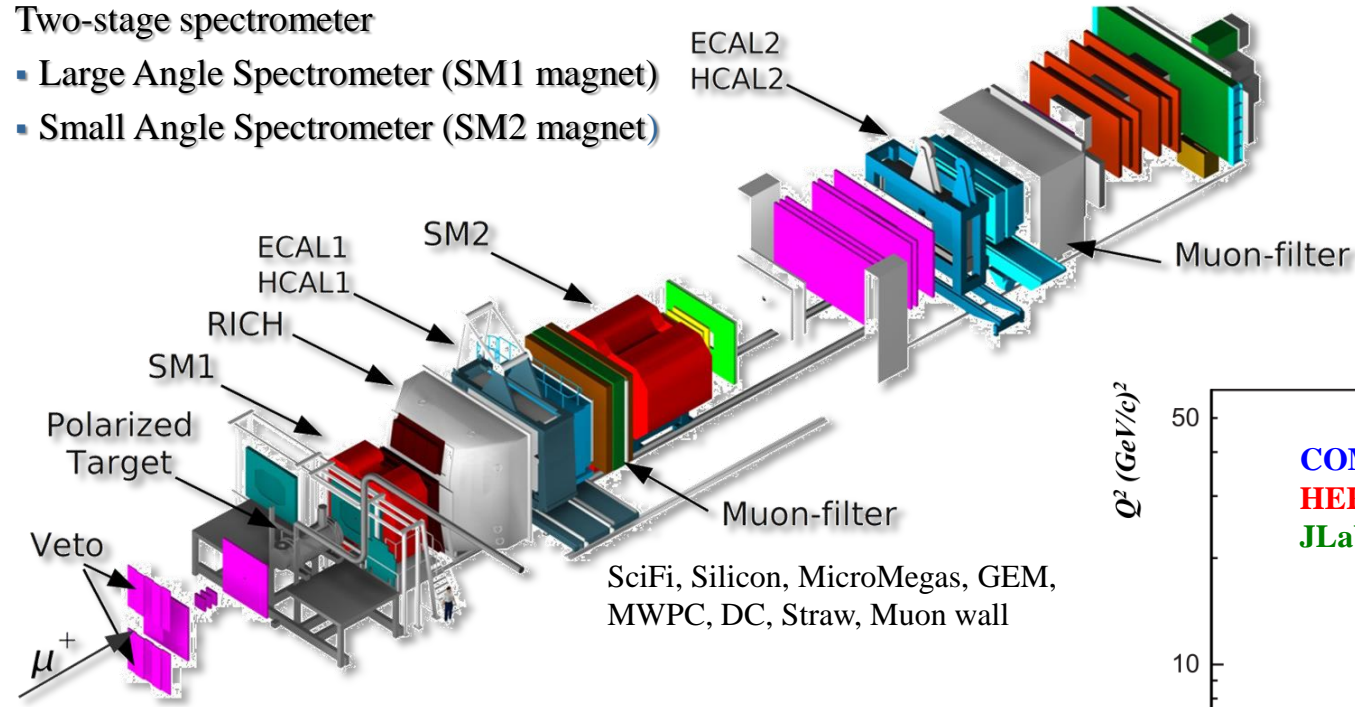
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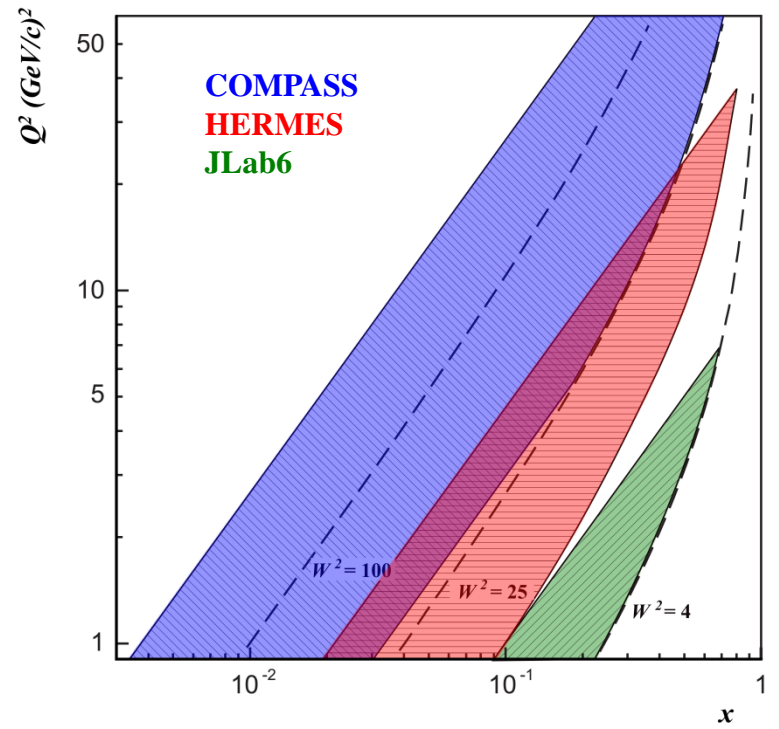


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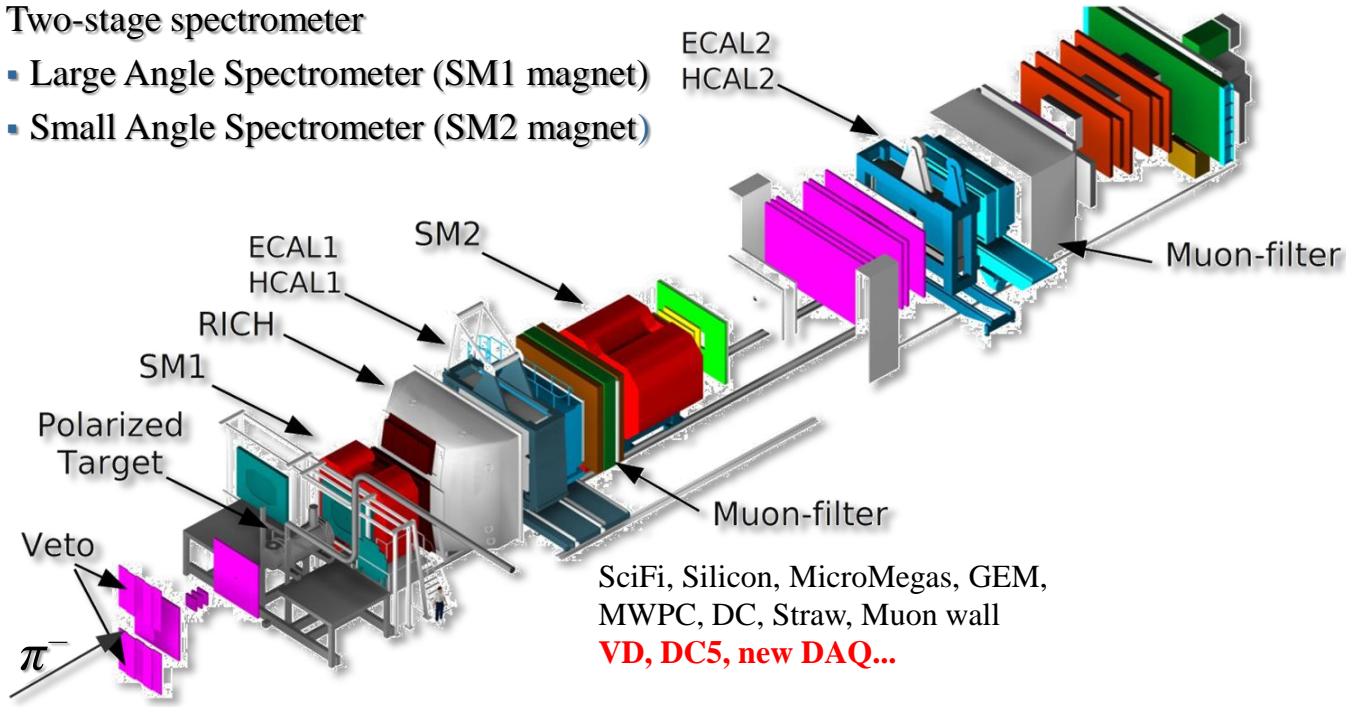




COMPASS experimental setup: Phase II (DY program)

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

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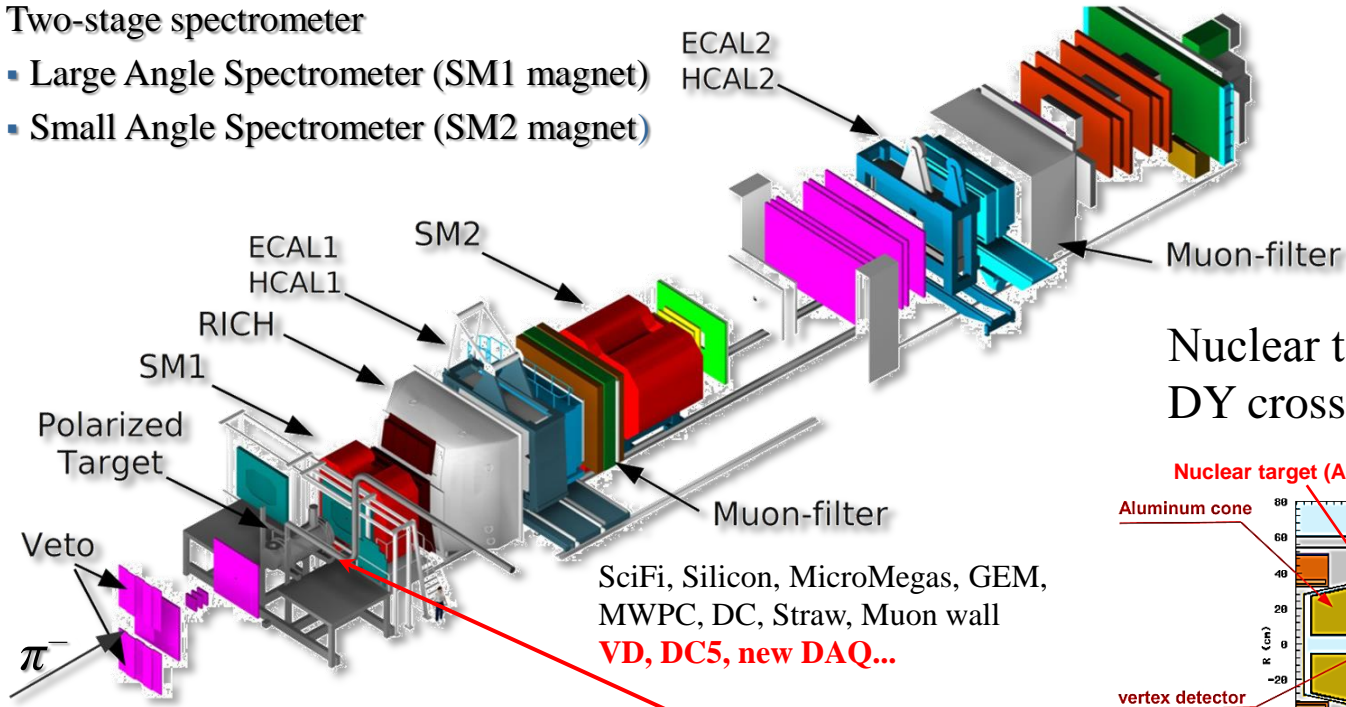
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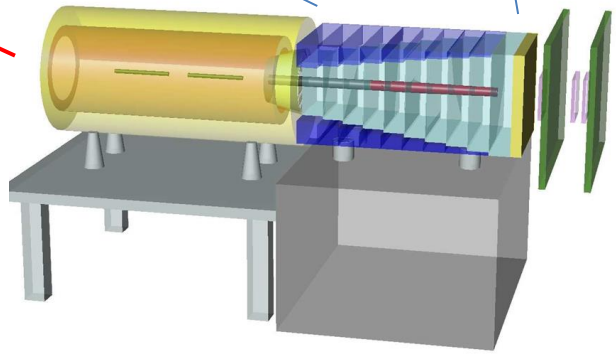
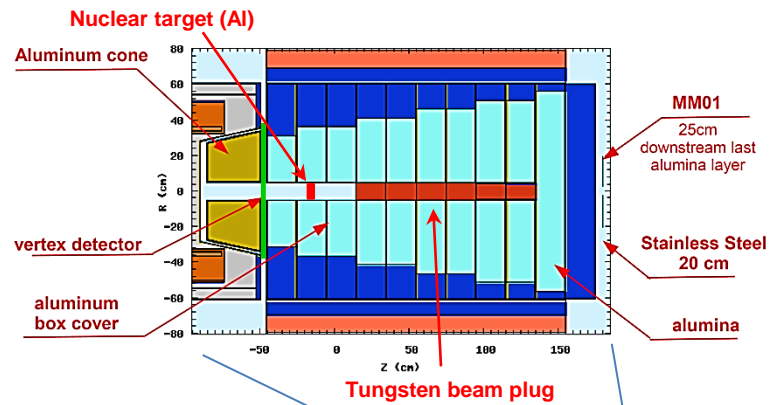
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Nuclear targets → unpolarized DY, DY cross-sections, EMC effect

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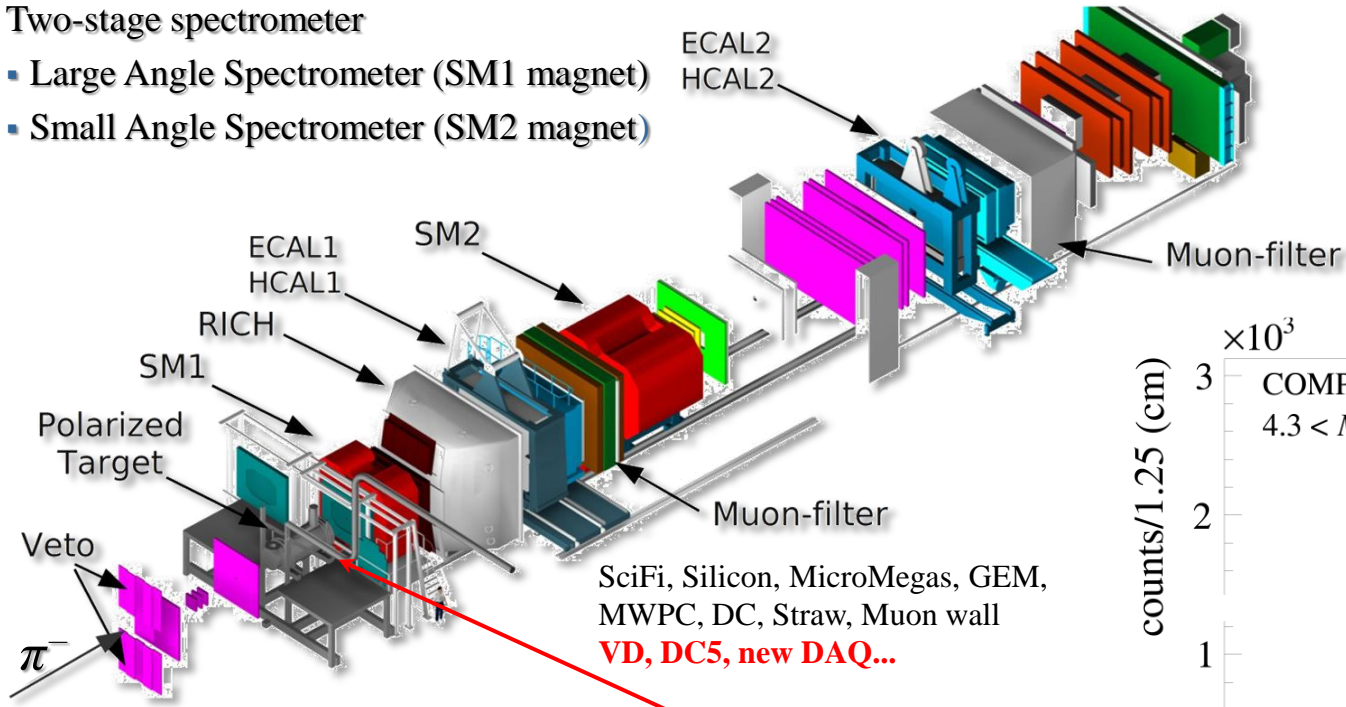
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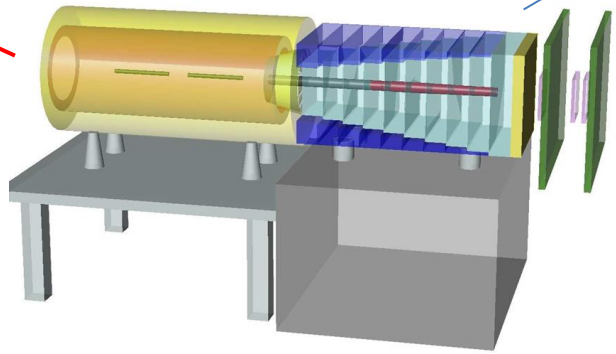
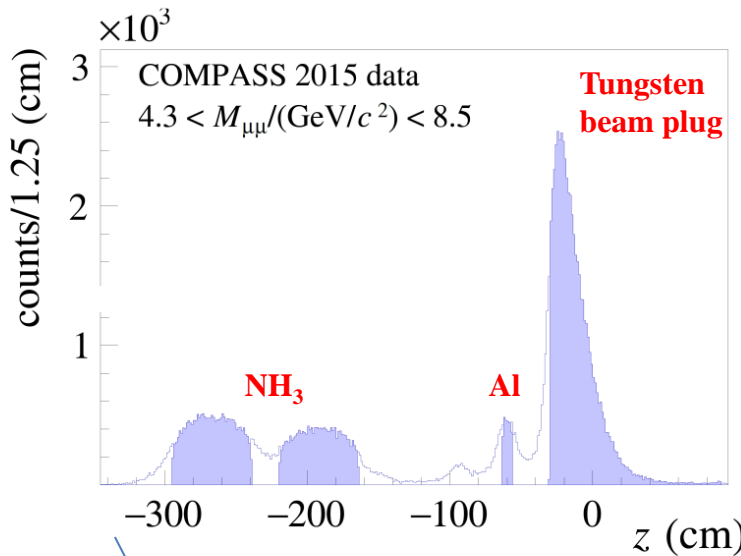
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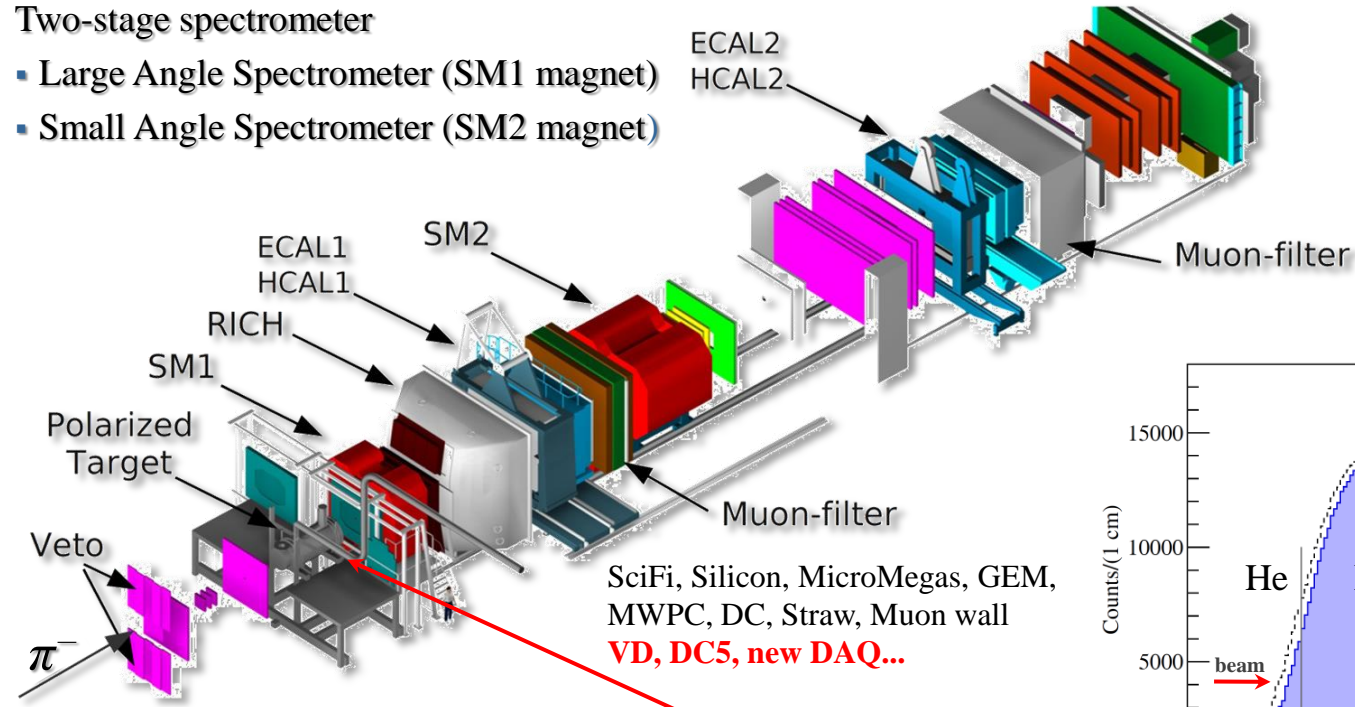
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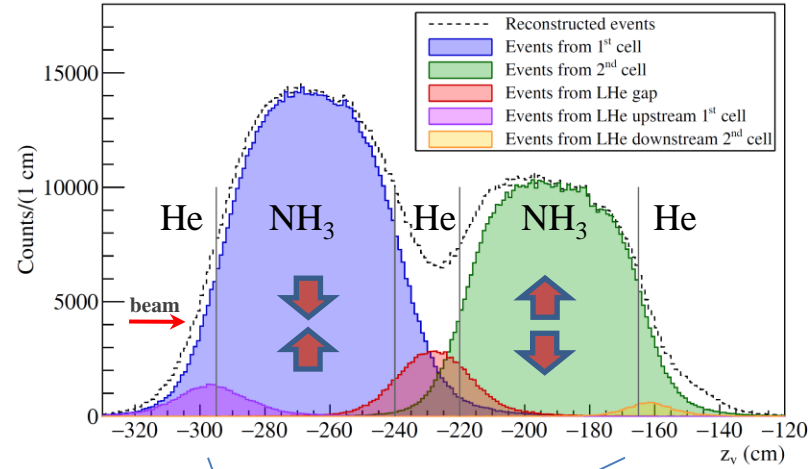
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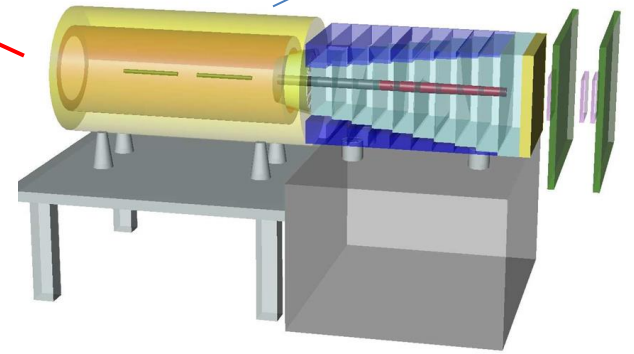
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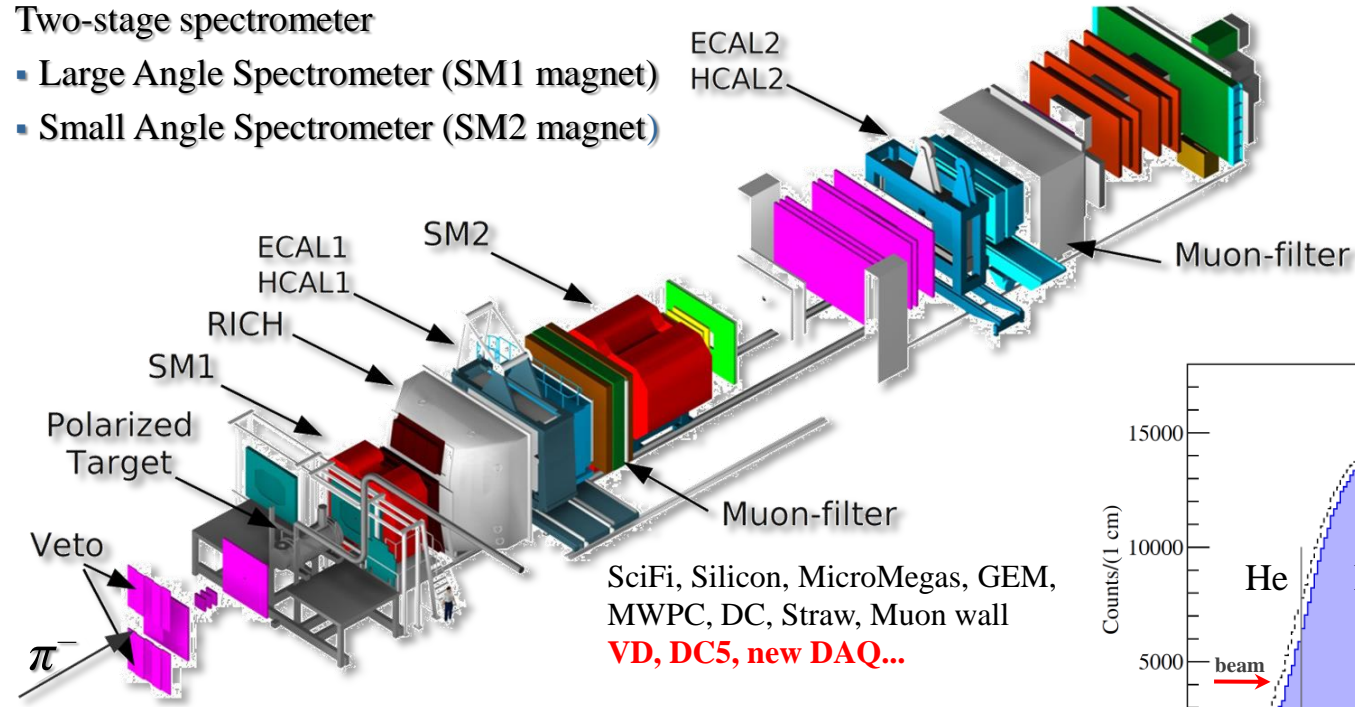




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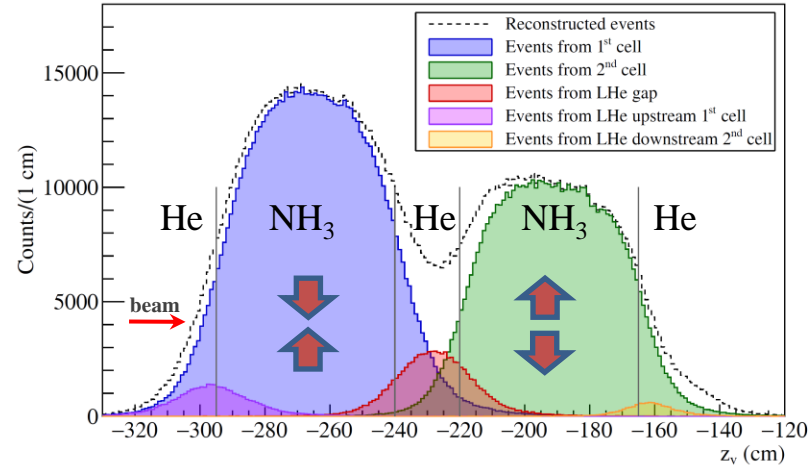
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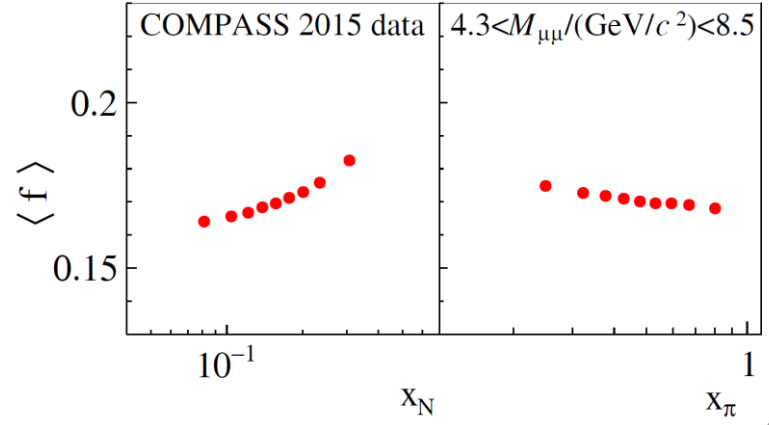
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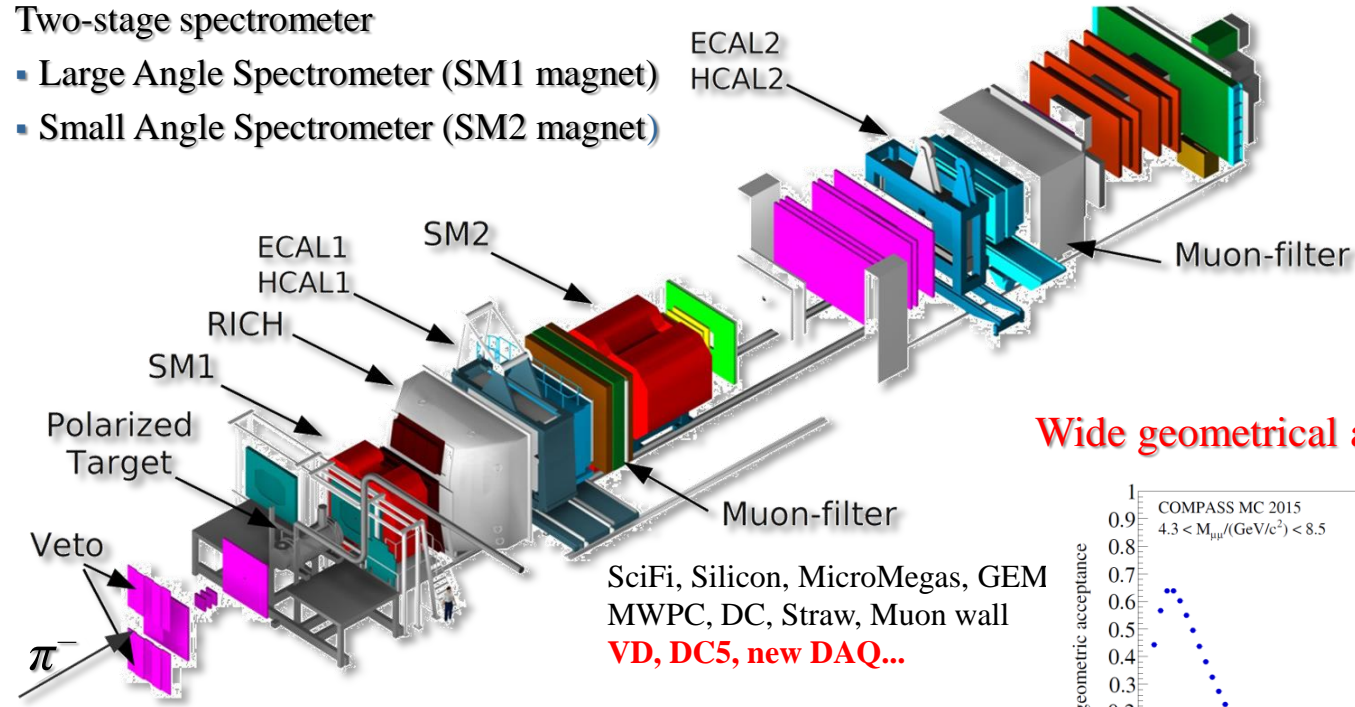




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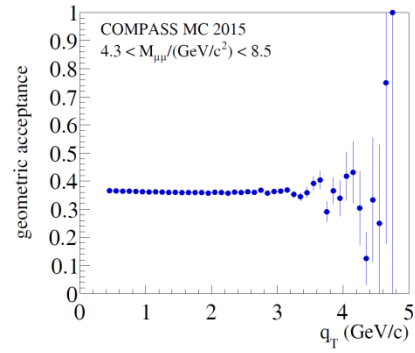
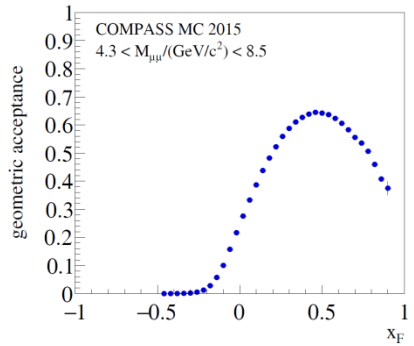
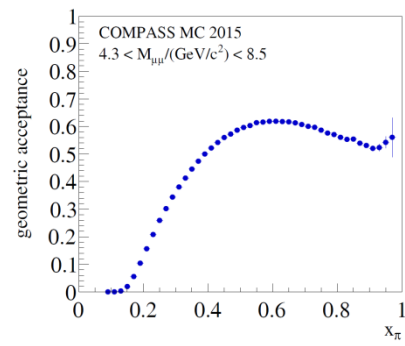
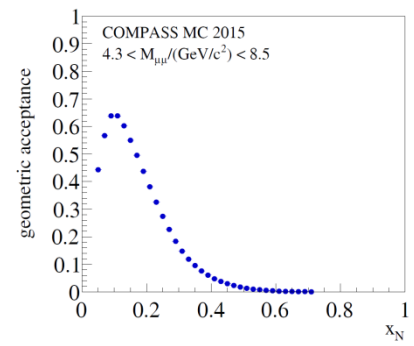
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Wide geometrical acceptance: $8 < \theta_{\mu} < 160$ mrad

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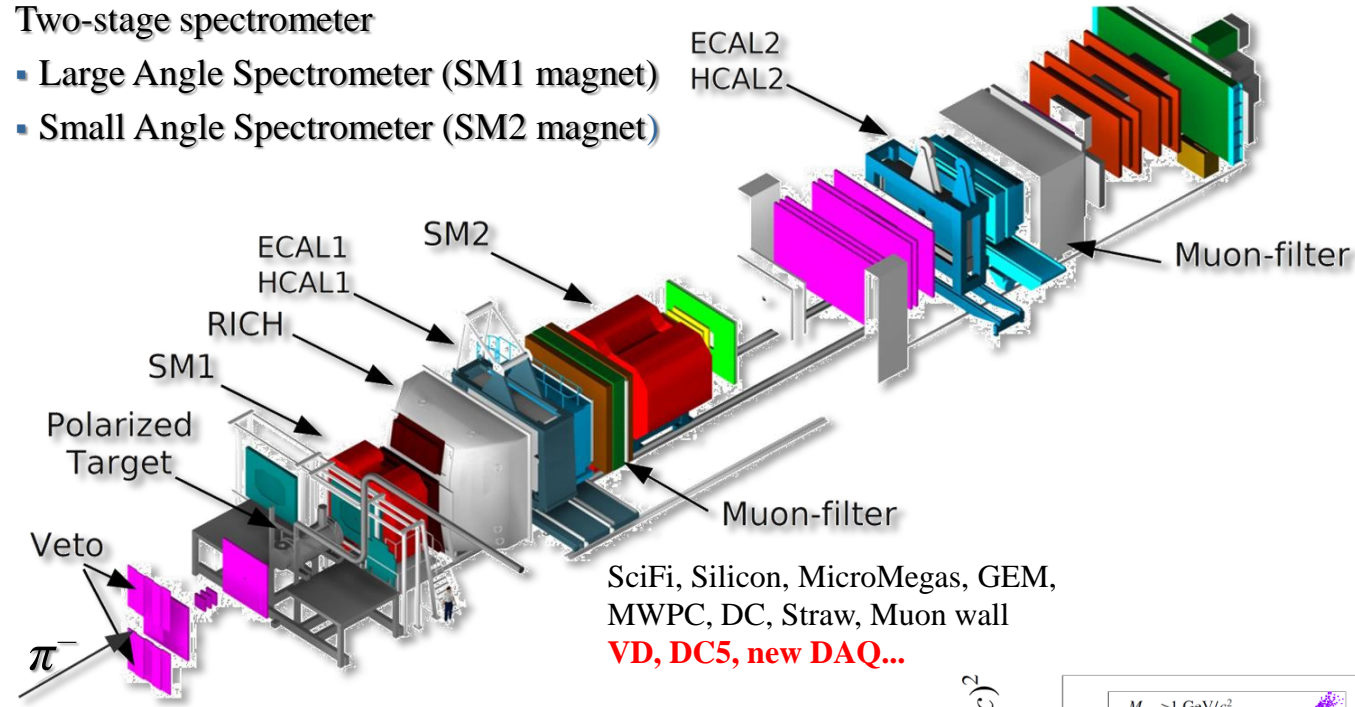
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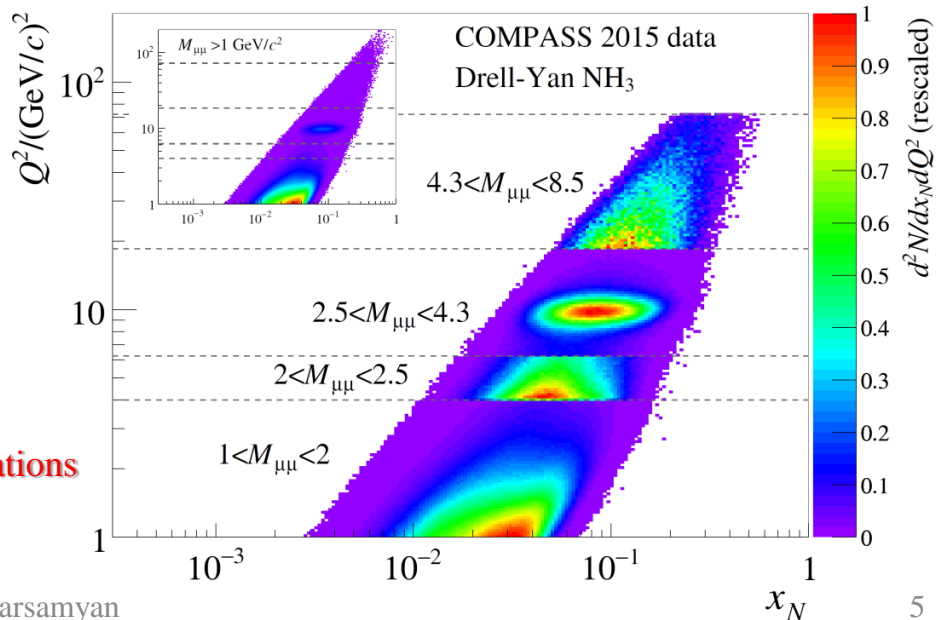
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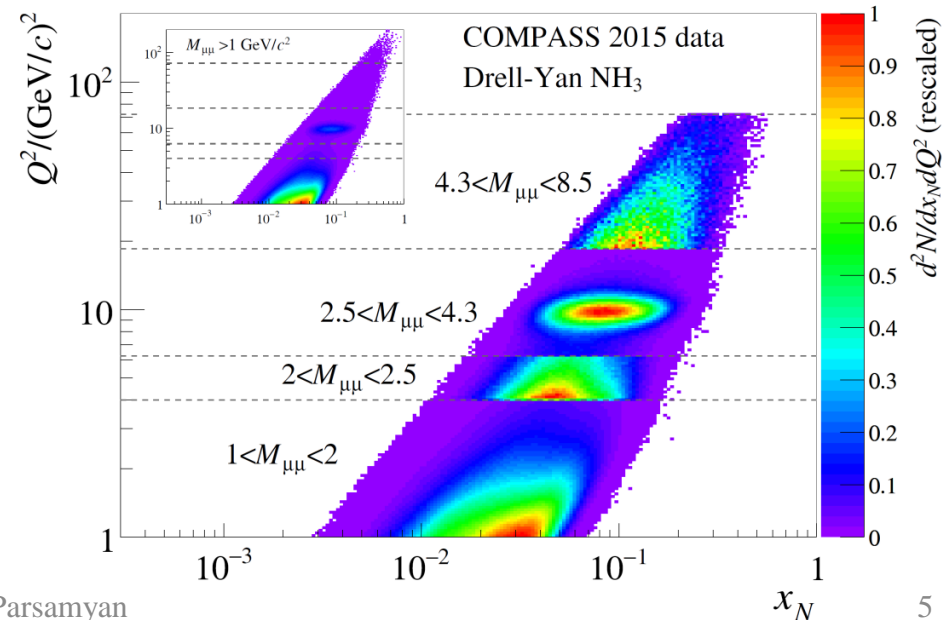
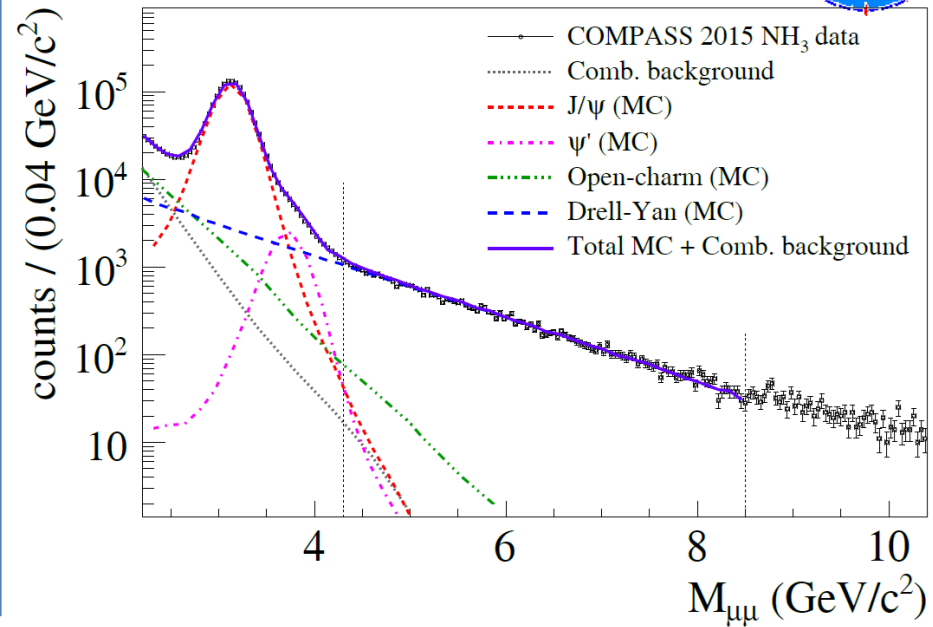
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COMPASS DY mass ranges

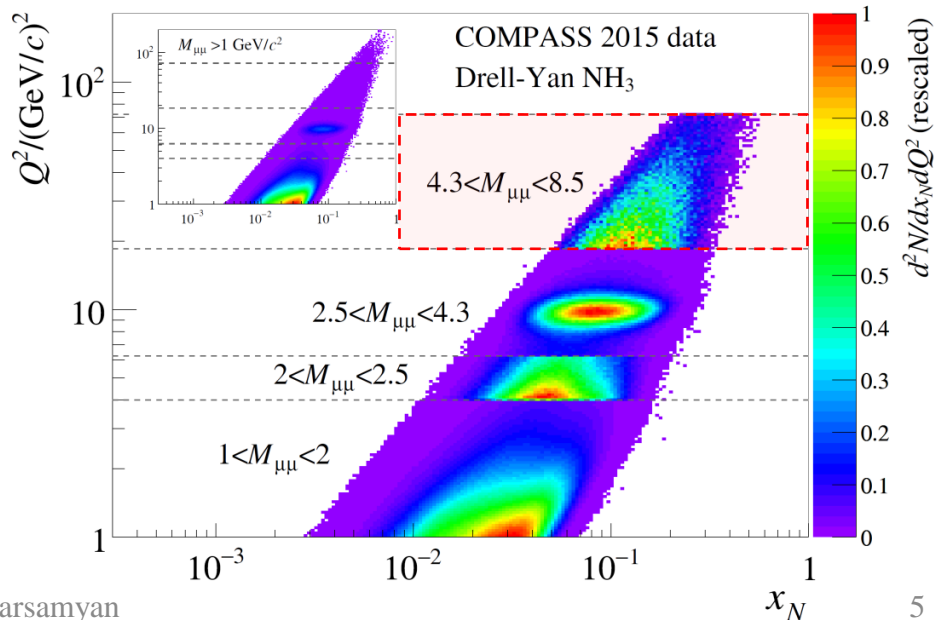
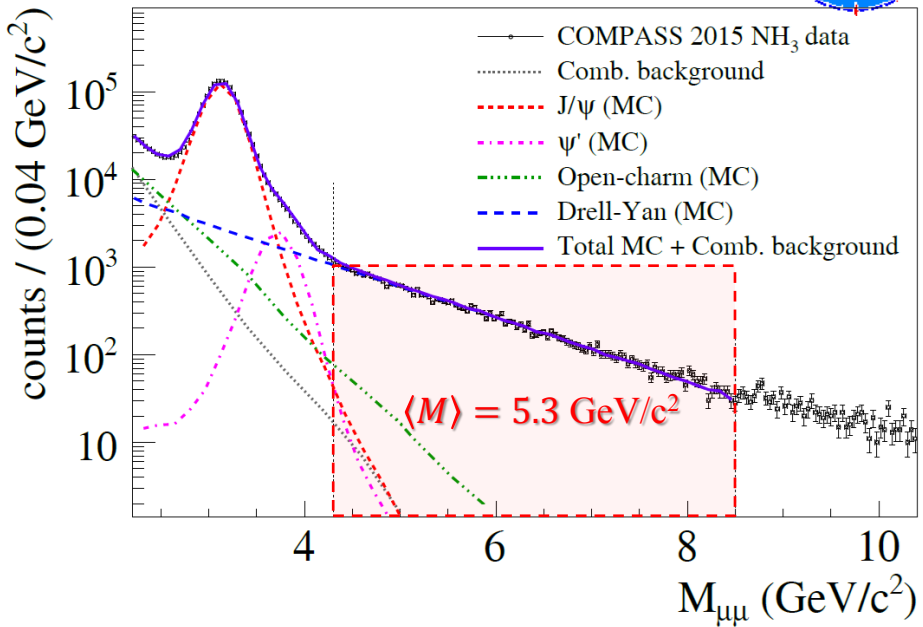
- $1.0 < M/(\text{GeV}/c^2) < 2.0$ “Low mass”
 - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π , K decays
- $2.0 < M/(\text{GeV}/c^2) < 2.5$ “Intermediate mass”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
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 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries



COMPASS DY: high mass range

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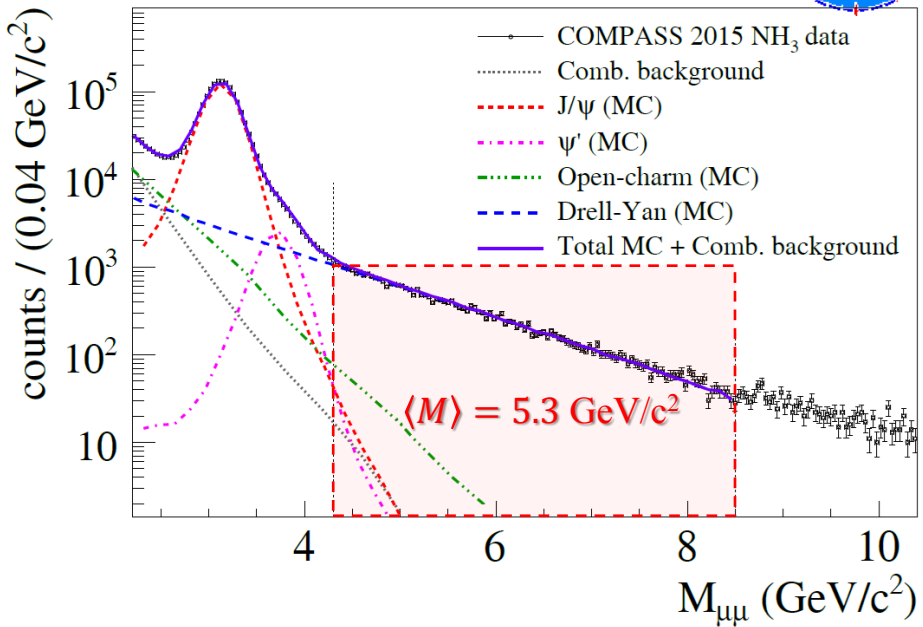
Final sample: 35 000 dimuons in HM



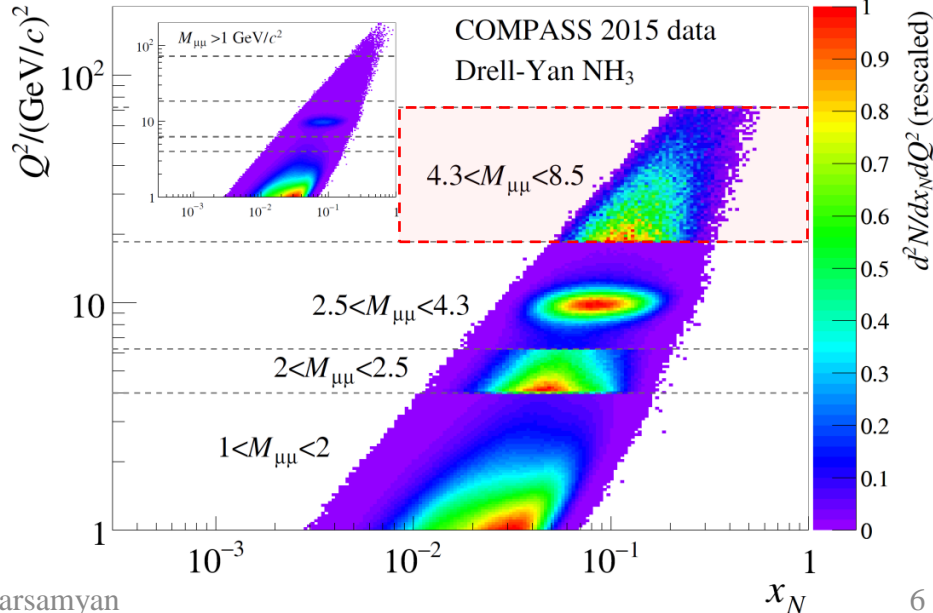
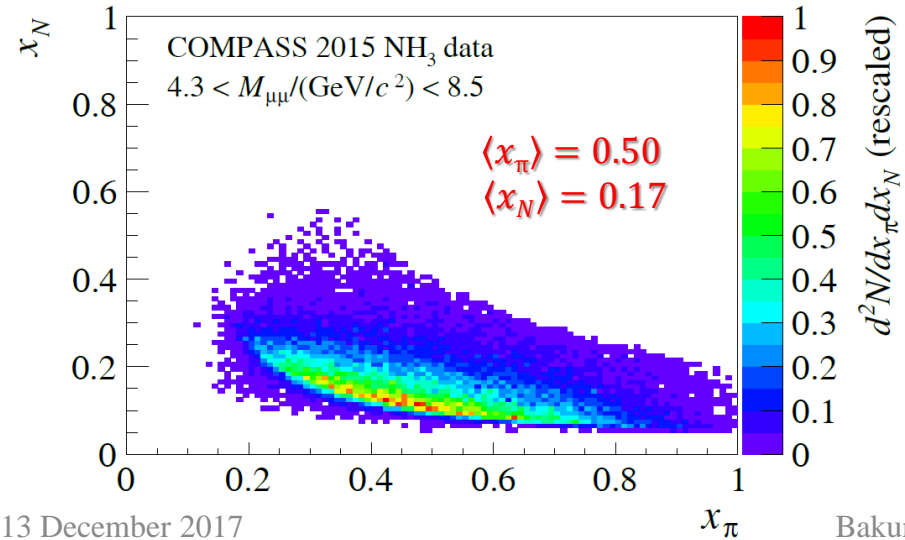
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HM events are in the valence quark range

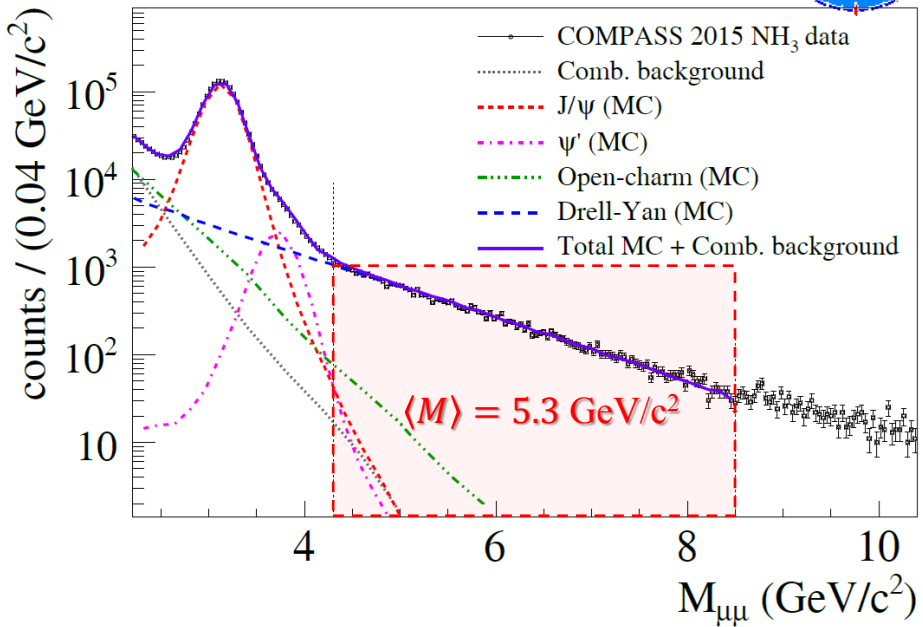




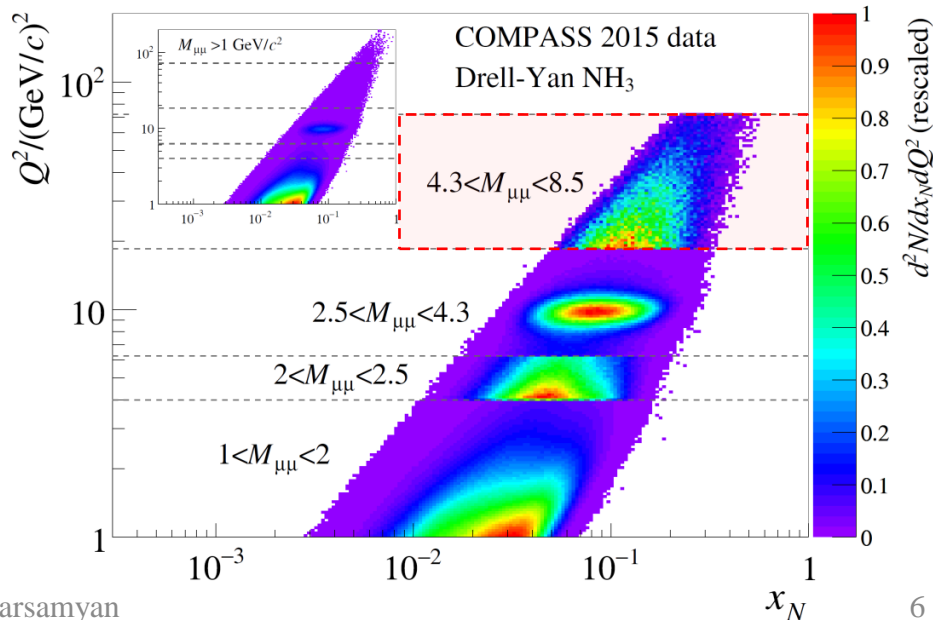
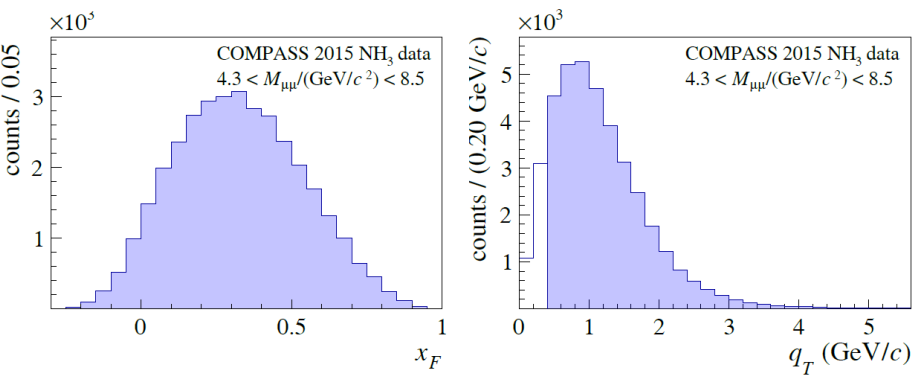
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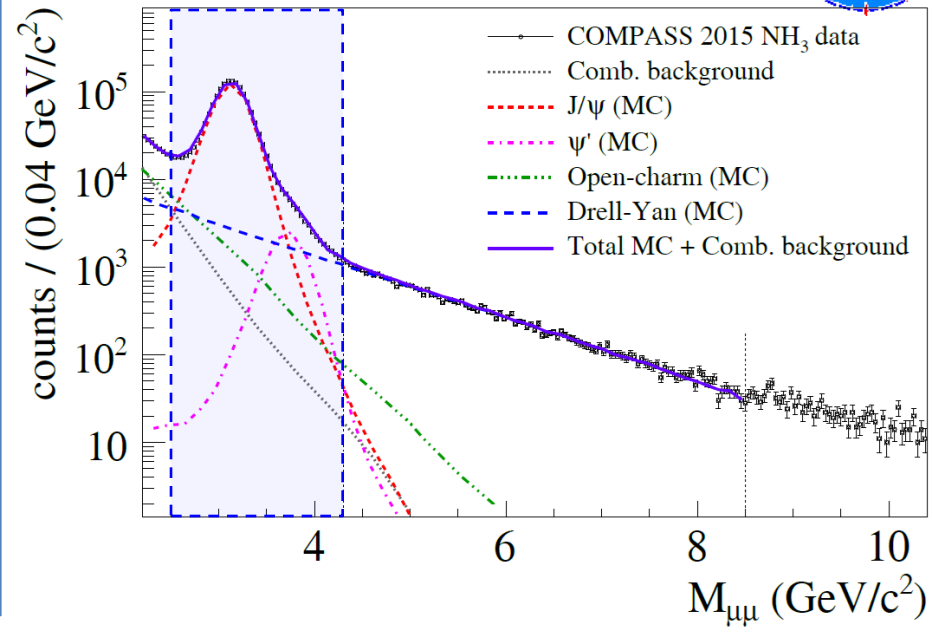
Dimuon transverse momentum $q_T > 0.4 \text{ GeV}/c$
 $\langle x_F \rangle = 0.33$, $\langle q_T \rangle = 1.2 \text{ GeV}/c$



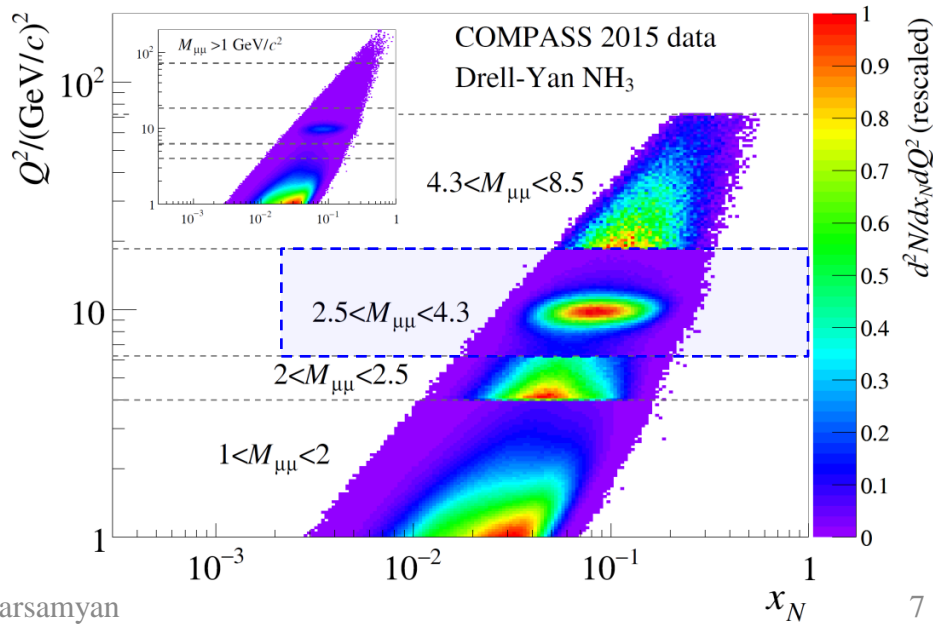
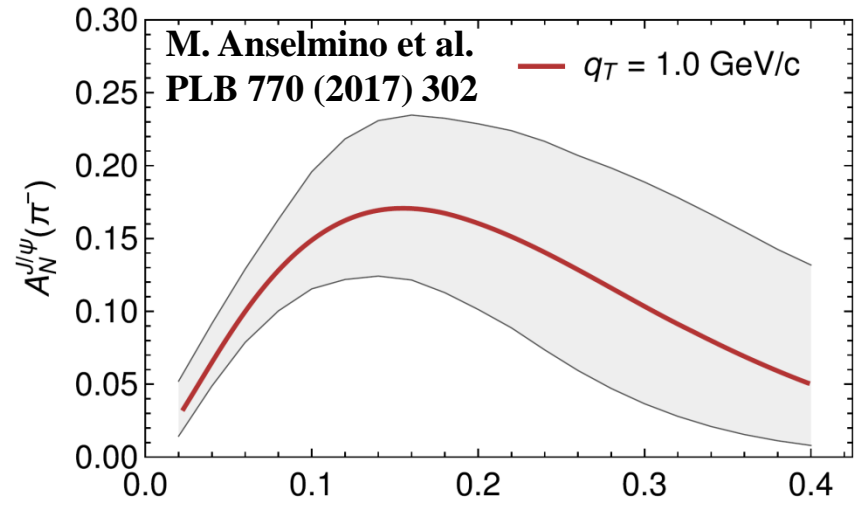
COMPASS DY: Charmonia mass range

ongoing analysis

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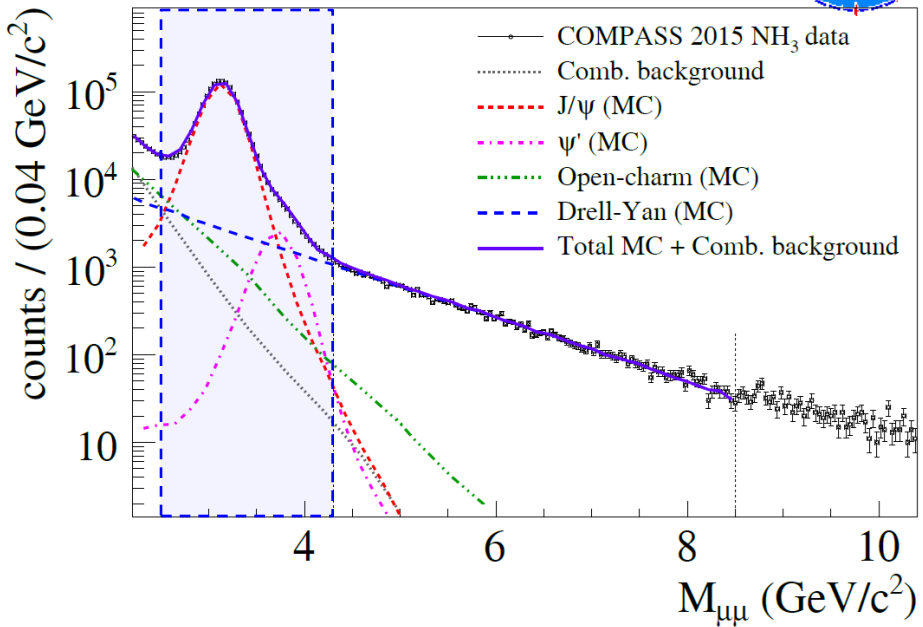
$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1 \text{ GeV}/c$



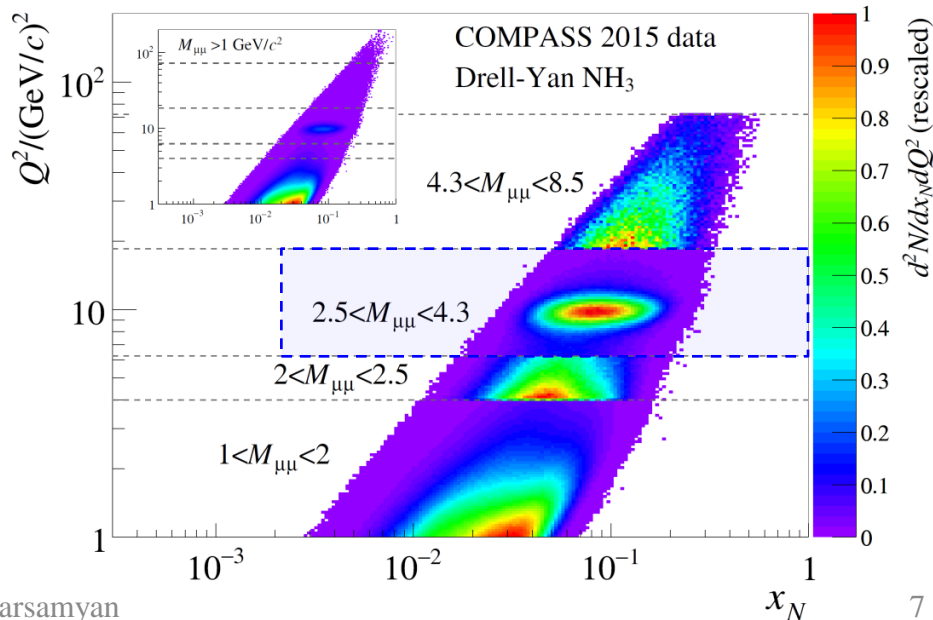
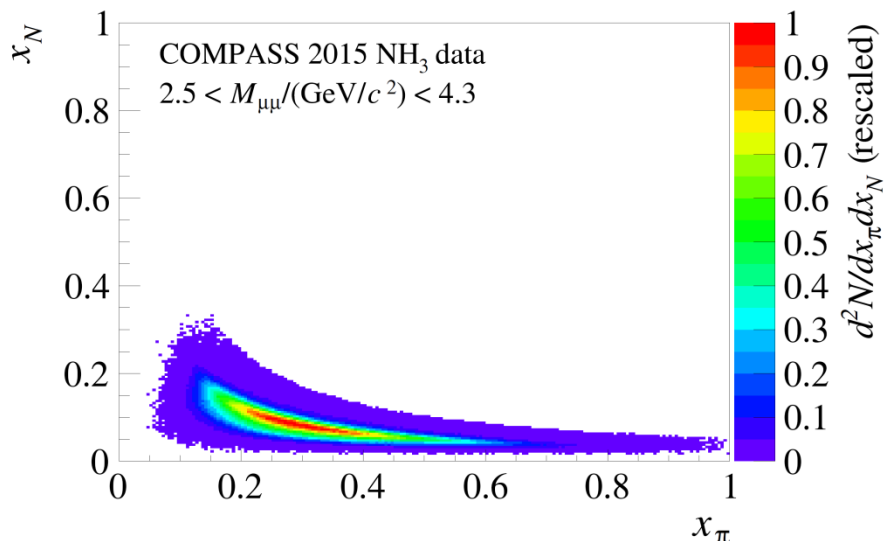
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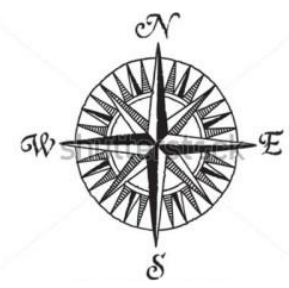
- $1.0 < M / (\text{GeV}/c^2) < 2.0$ “Low mass”
 - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π , K decays
- $2.0 < M / (\text{GeV}/c^2) < 2.5$ “Intermediate mass”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $2.5 < M / (\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M / (\text{GeV}/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries



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



COMPASS bridge



Drell-Pan

SIDS

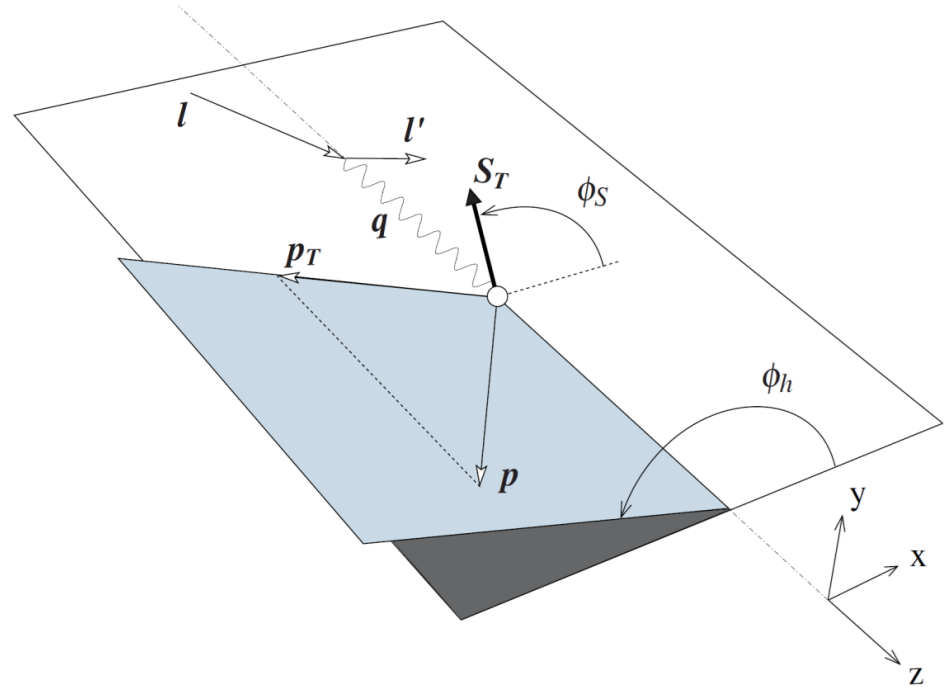
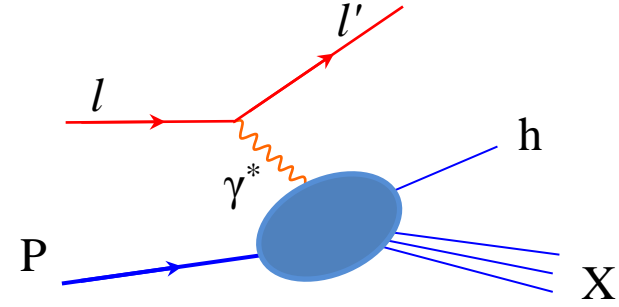


All measured by COMPASS

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

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

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



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

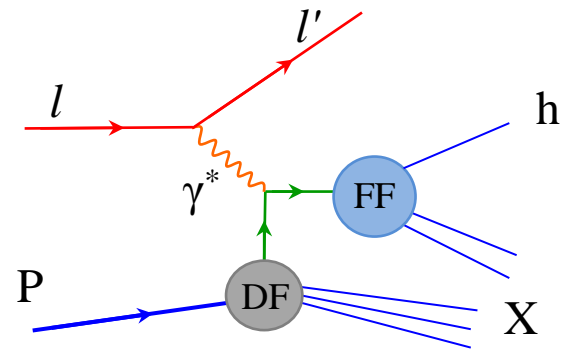


SIDIS x-section and TMDs at twist-2

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

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

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



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

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

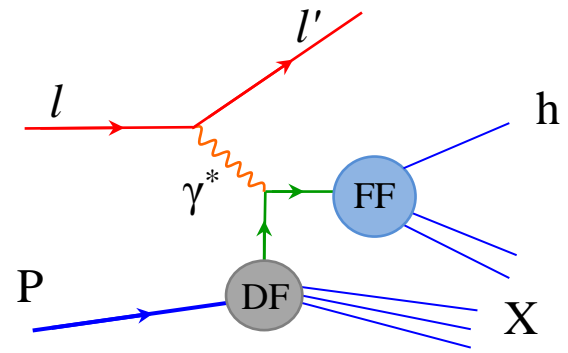


SIDIS x-section and TMDs at twist-2

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

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

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



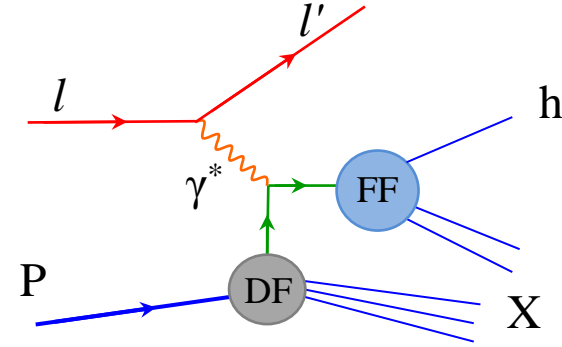
Quark \ Nucleon	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

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



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

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

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

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

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

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

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

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

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

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

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

Twist-2
Twist-3

SIDIS and single-polarized DY x-sections

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

SIDIS

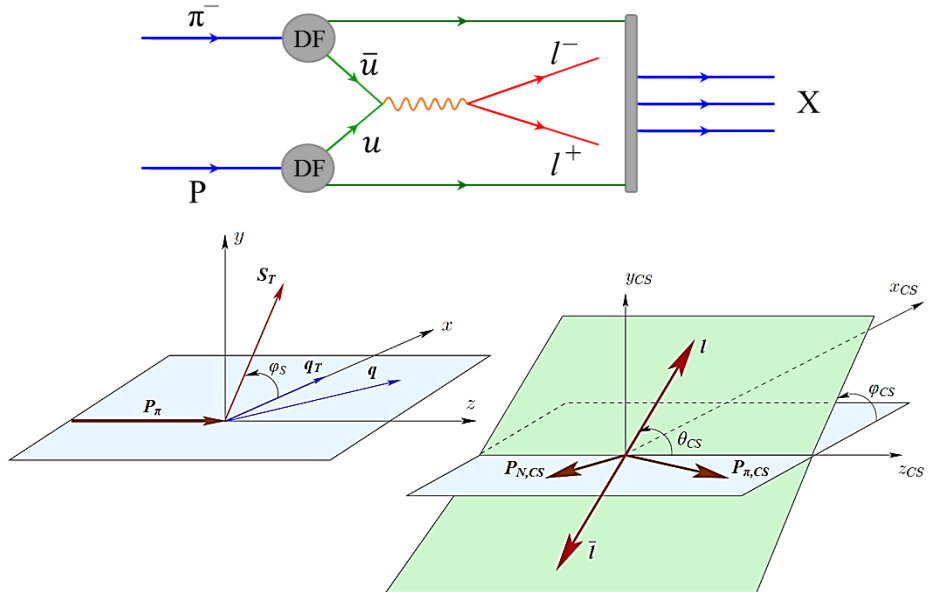
$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

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

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

DY

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





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

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

SIDIS

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

DY

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



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

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



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

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

SIDIS

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

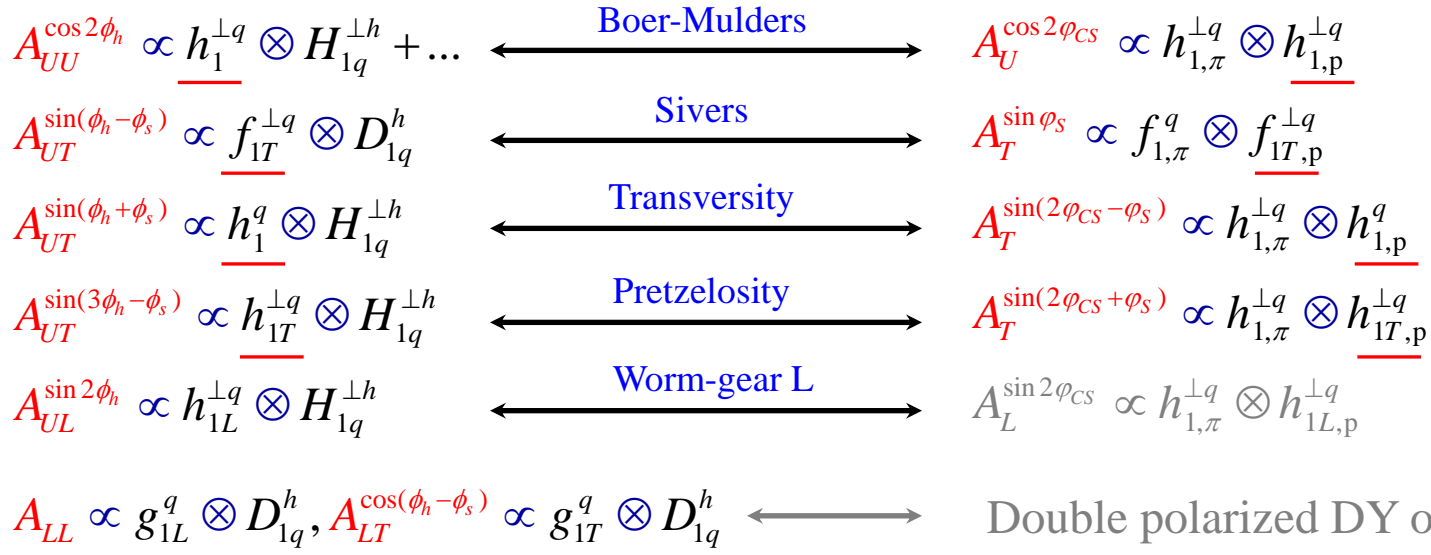
DY

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

SIDIS-DY bridge

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

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

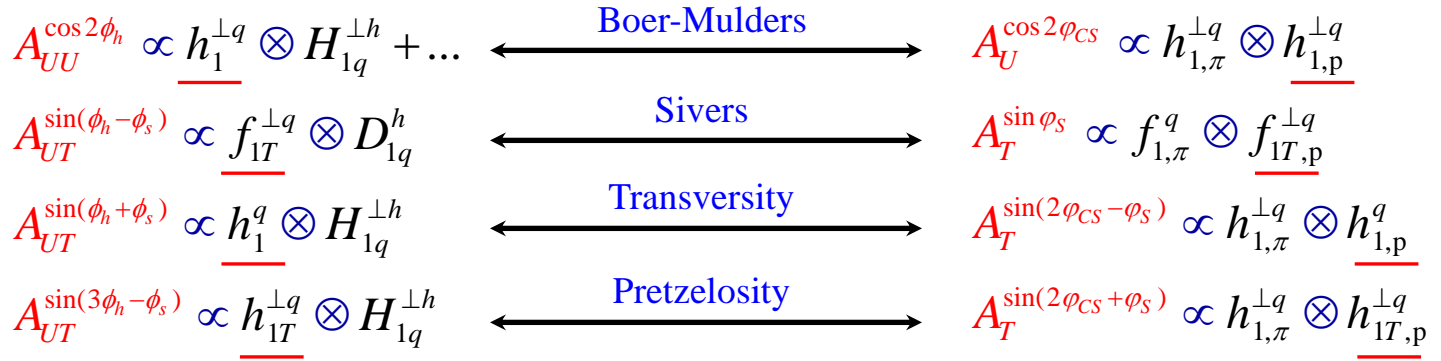


COMPASS accesses all 8 twist-2 nucleon TMD PDFs in SIDIS and 5 nucleon+2 pion TMD PDFs in DY



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

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



within QCD TMD-framework:

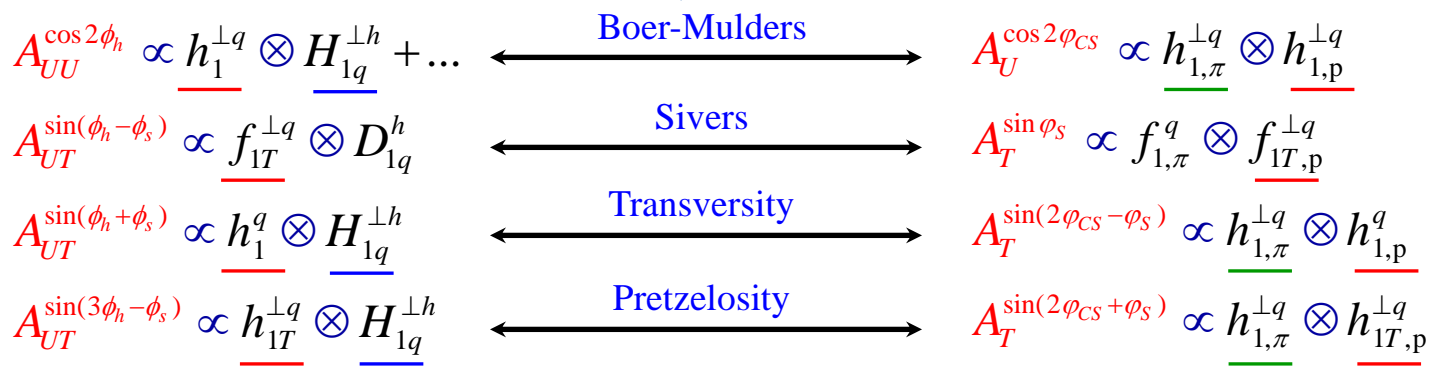
$\underline{h_1^{\perp q}}$ & $\underline{f_{1T}^{\perp q}}$ TMD PDFs are expected to be "conditionally" universal (SIDIS \leftrightarrow DY: **sign change**)

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



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

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



Complementary information from different channels :

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



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

SIDIS

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

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

**SIDIS-DY
bridge**

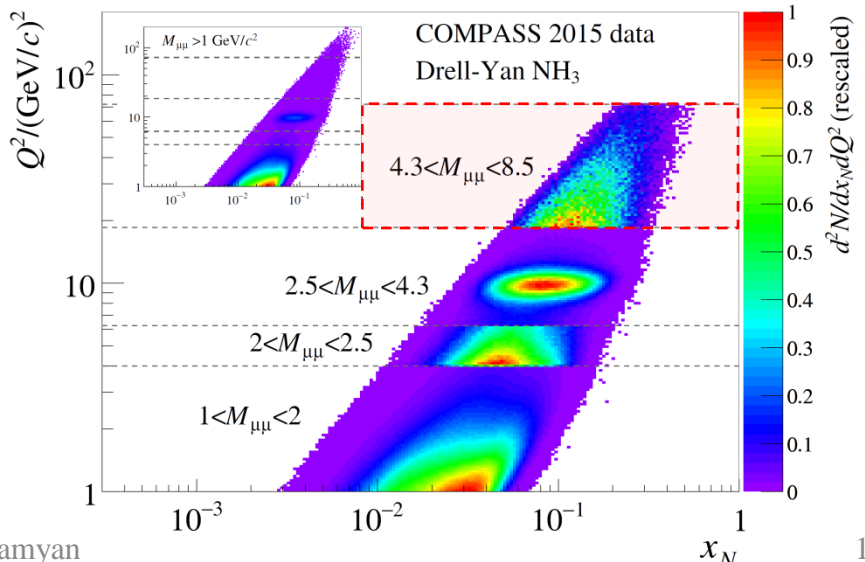
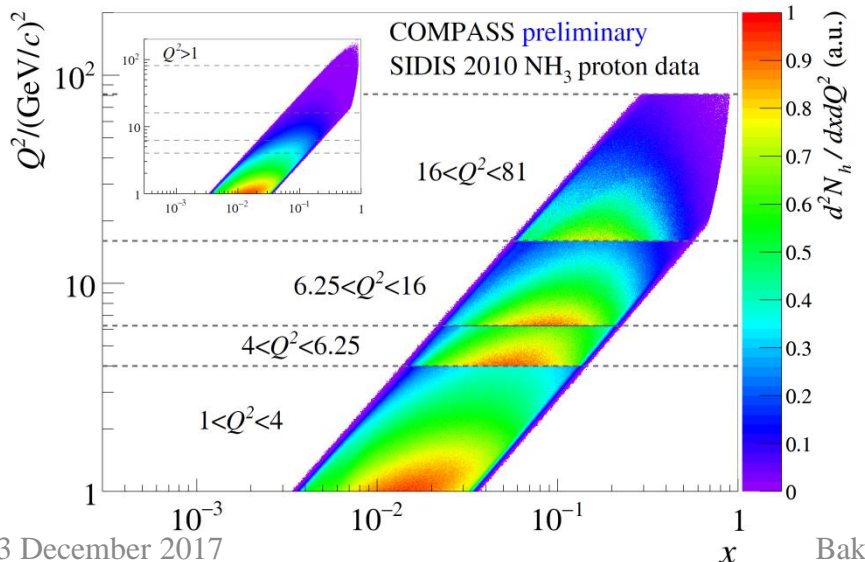
DY

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

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

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

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





- Selected SIDIS results

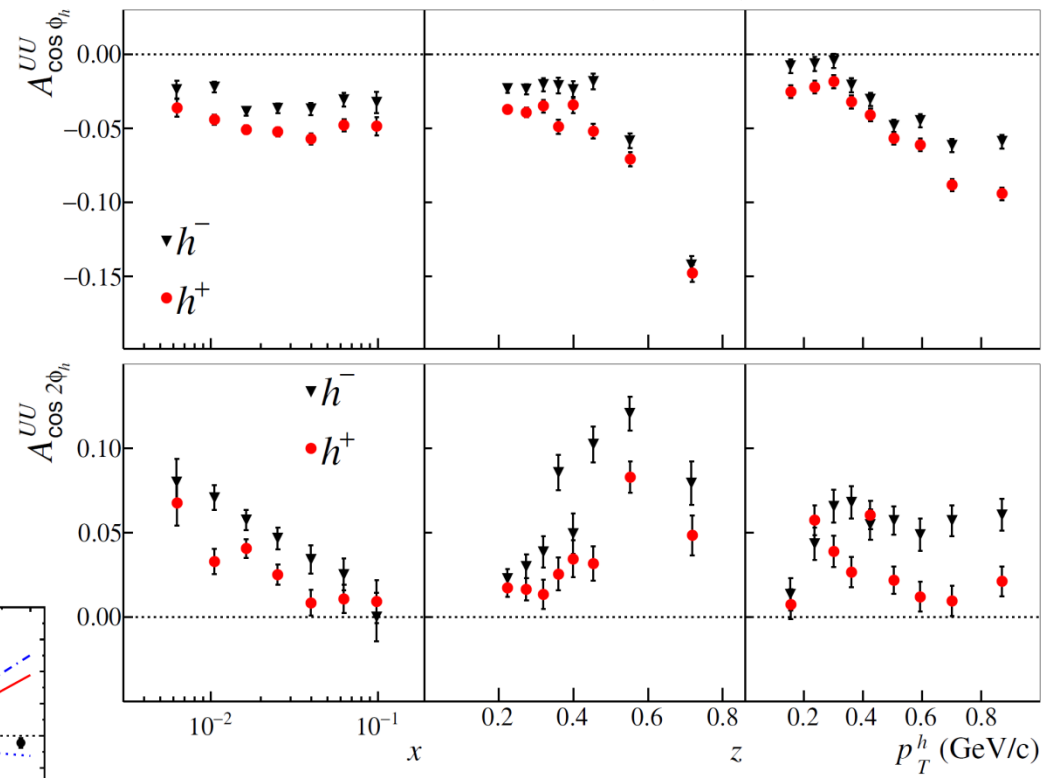


The $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ asymmetries (Cahn+BM)

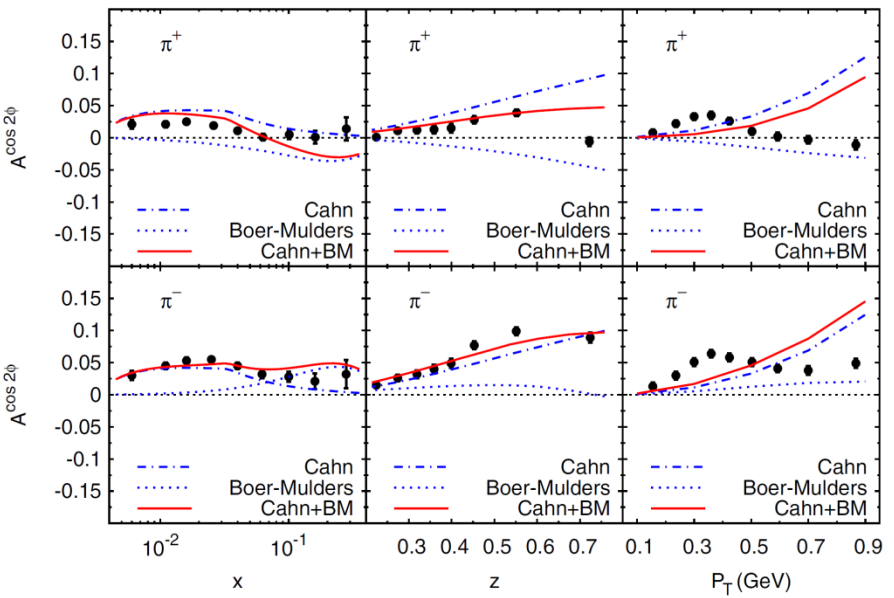
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \times \left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h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

- 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)



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

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

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



SIDIS: target transverse spin dependent asymmetries

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

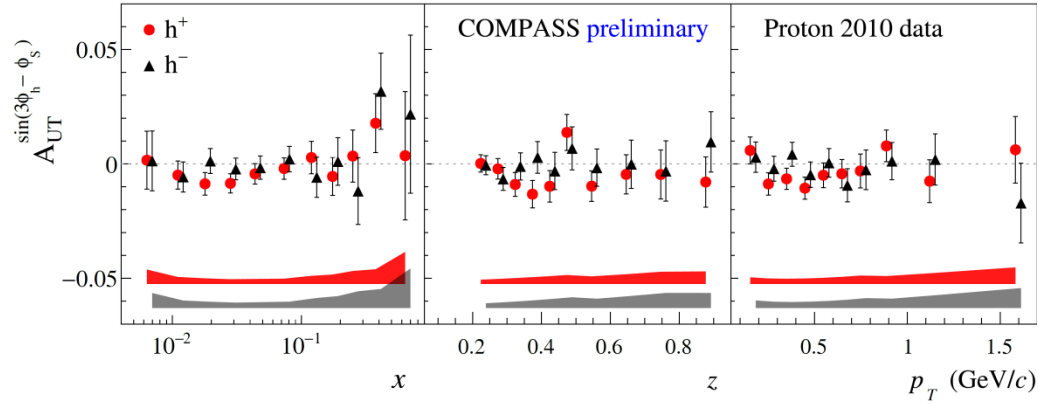


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$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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



COMPASS results

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

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

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

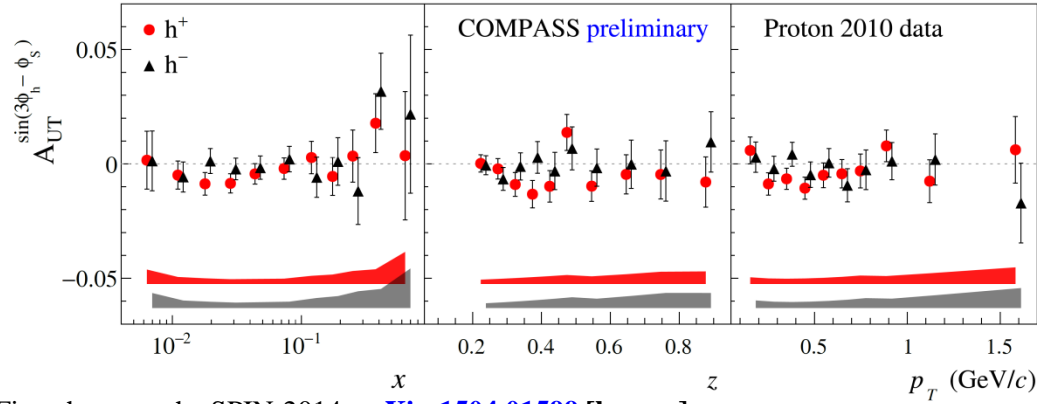


SIDIS: target transverse spin dependent asymmetries

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

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

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

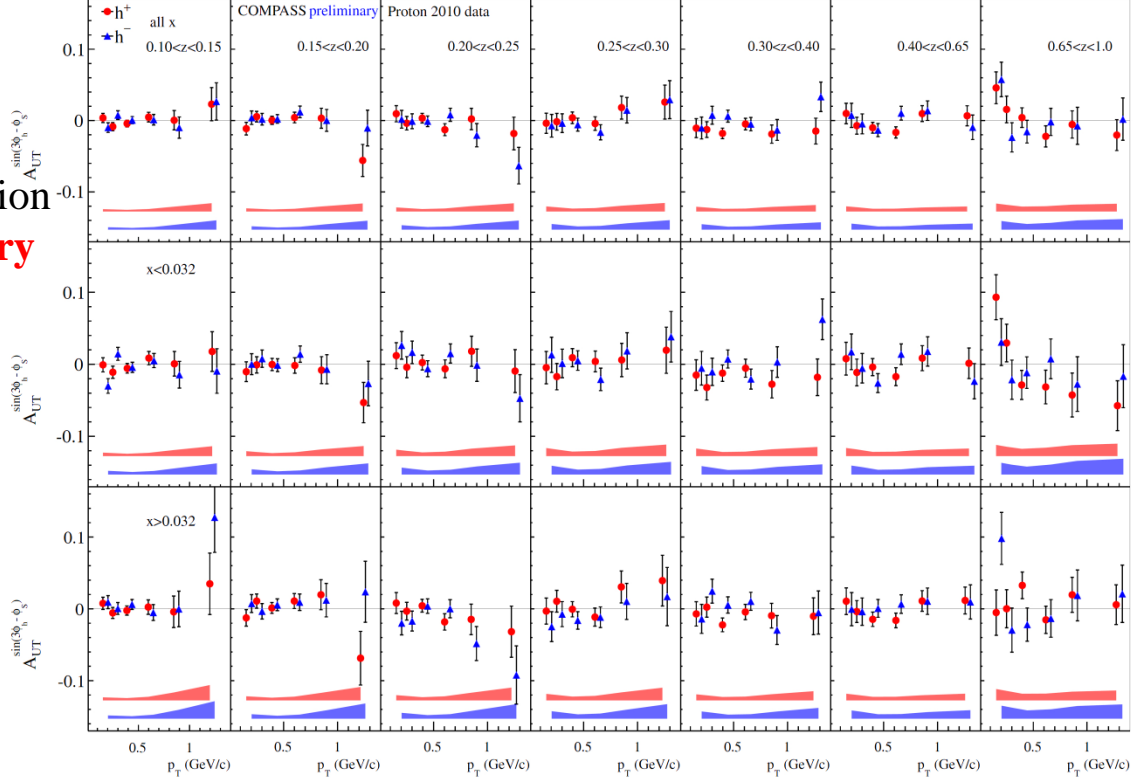


COMPASS results

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

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

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





SIDIS: target transverse spin dependent asymmetries

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

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

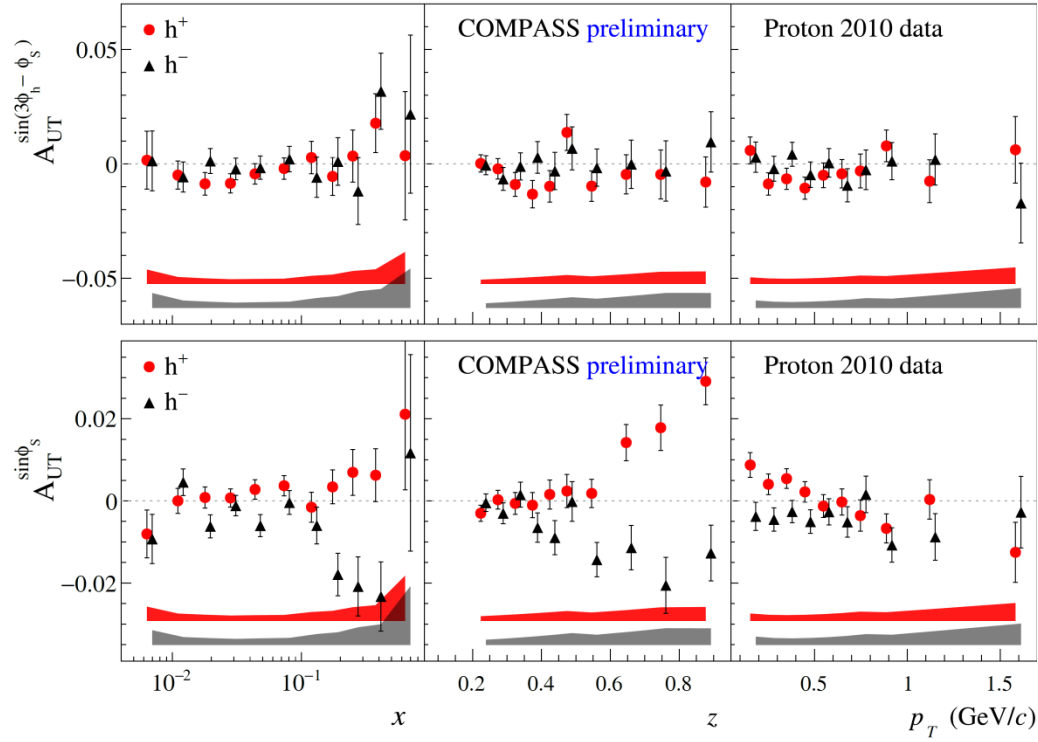
$$+ S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \\ + \dots \end{array} \right]$$

COMPASS results

- 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^+ !**



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



SIDIS: target transverse spin dependent asymmetries

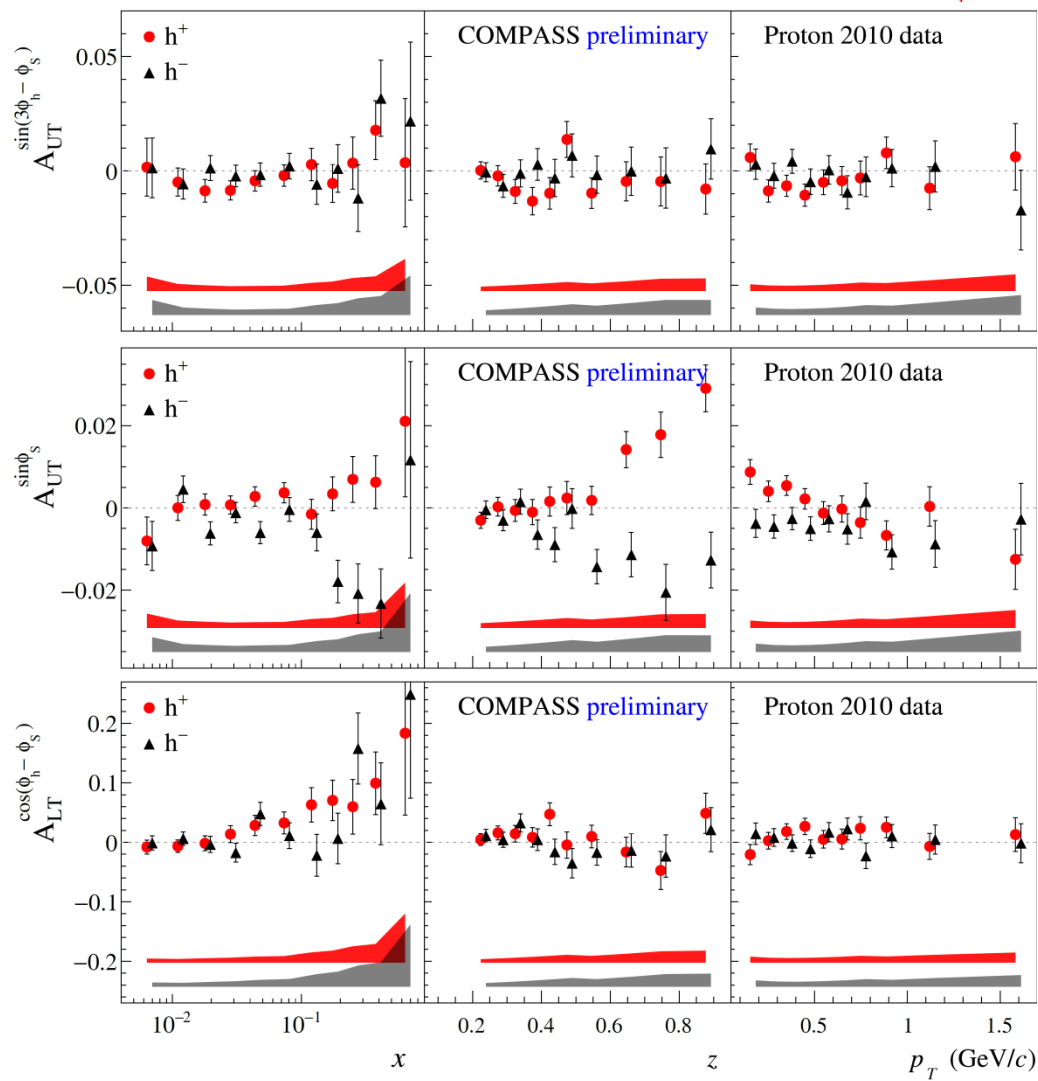
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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- Only “twist-2” ingredients, p_T^2 -suppression
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$$F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[\frac{\hat{h} \cdot \mathbf{k}_T}{M} g_{1T}^q D_{1q}^h \right]$$



SIDIS TSAs (Collins)

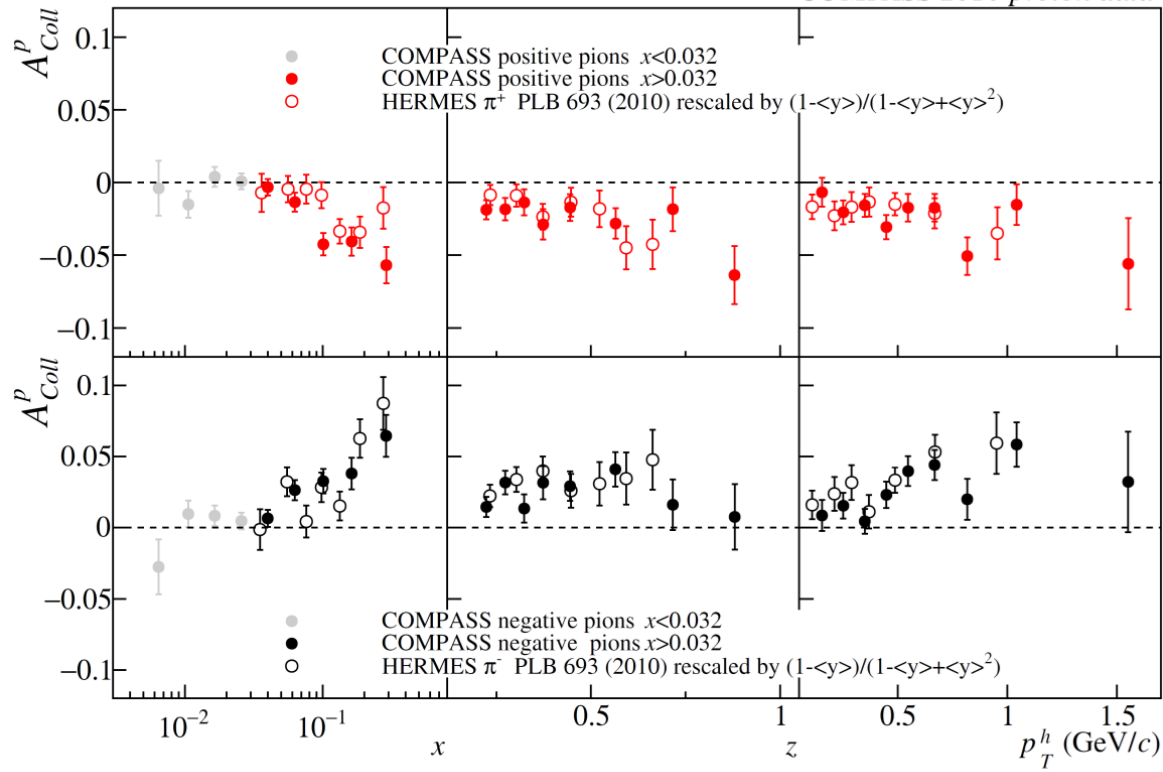
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

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

COMPASS PLB 744 (2015) 250

COMPASS 2010 proton data





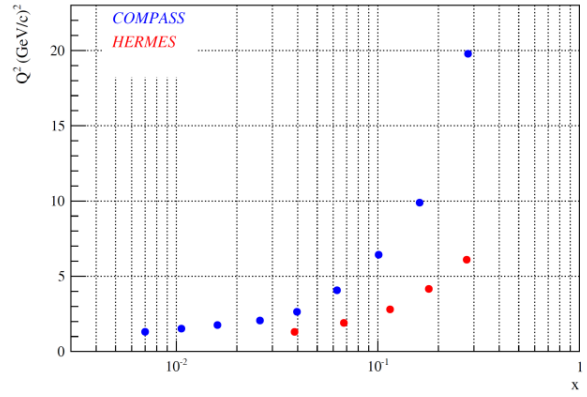
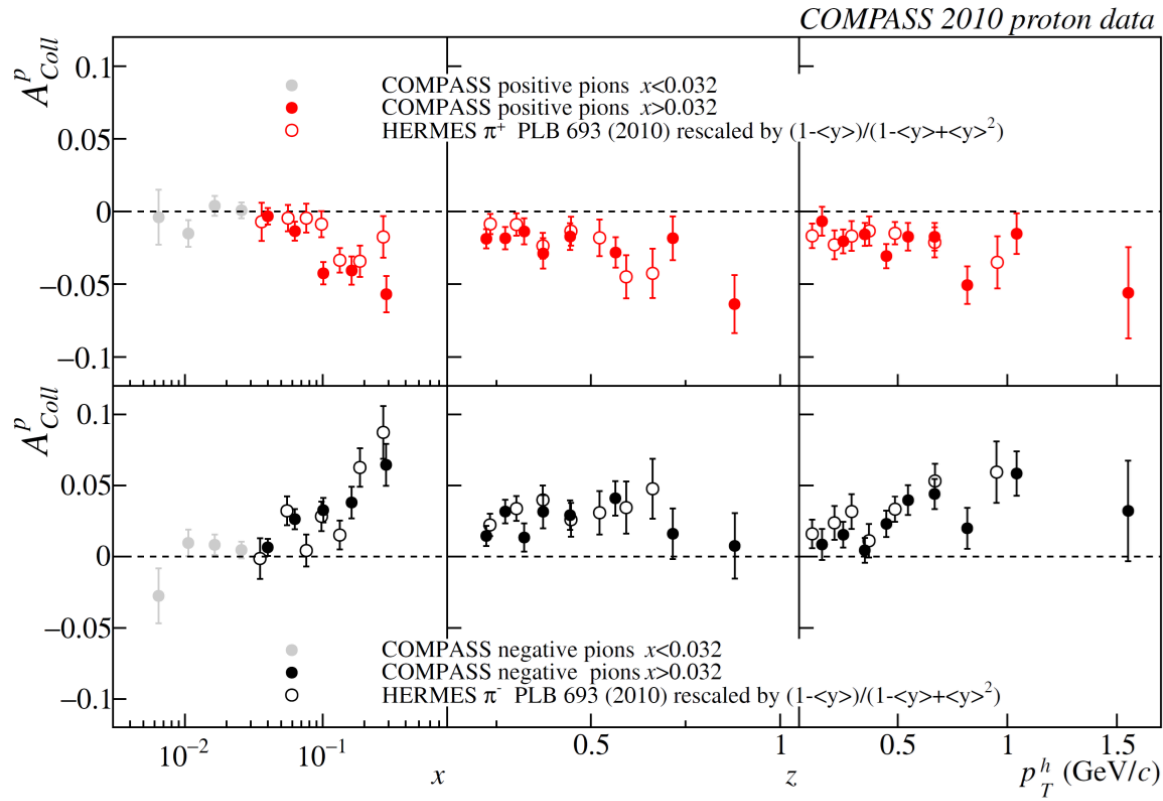
SIDIS TSAs (Collins)

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

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

COMPASS PLB 744 (2015) 250





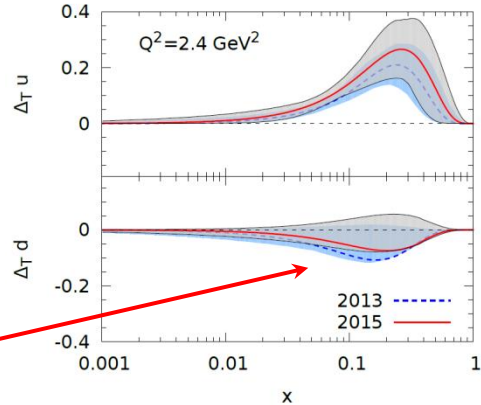
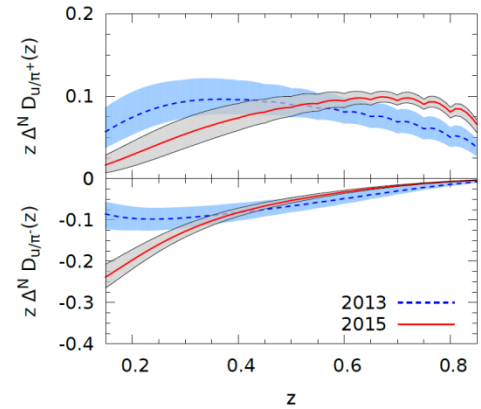
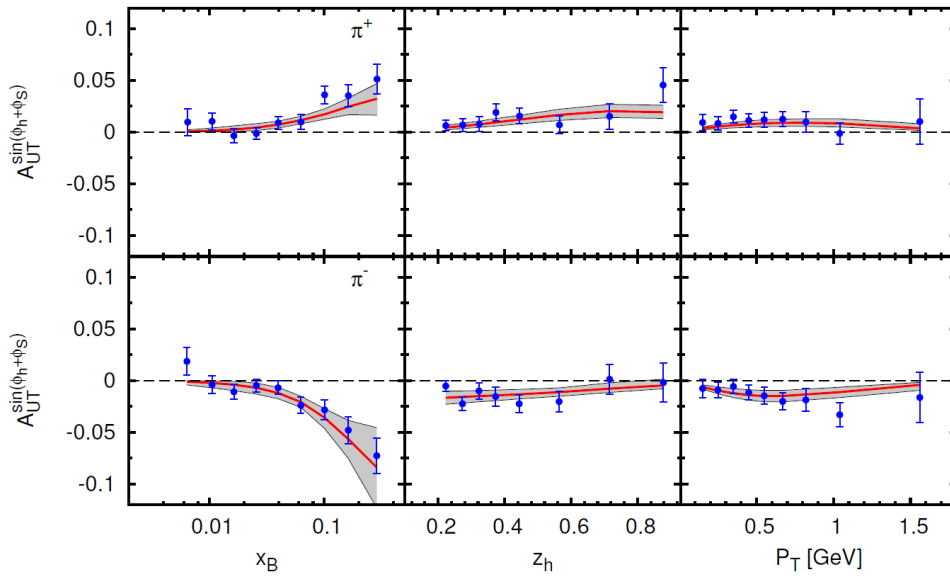
SIDIS TSAs (Collins)

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

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- 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)

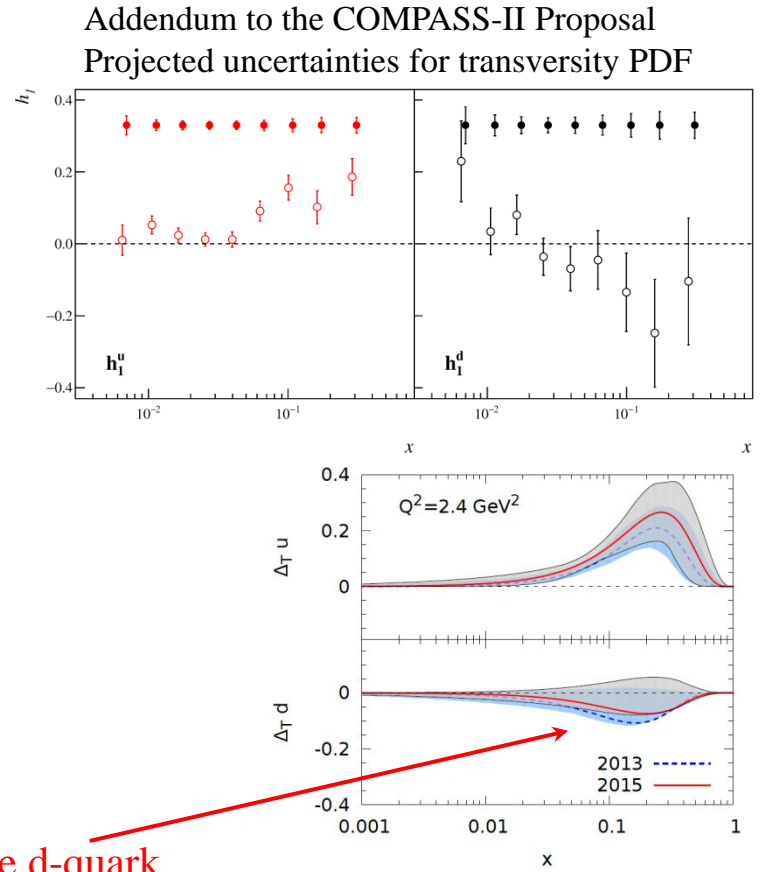
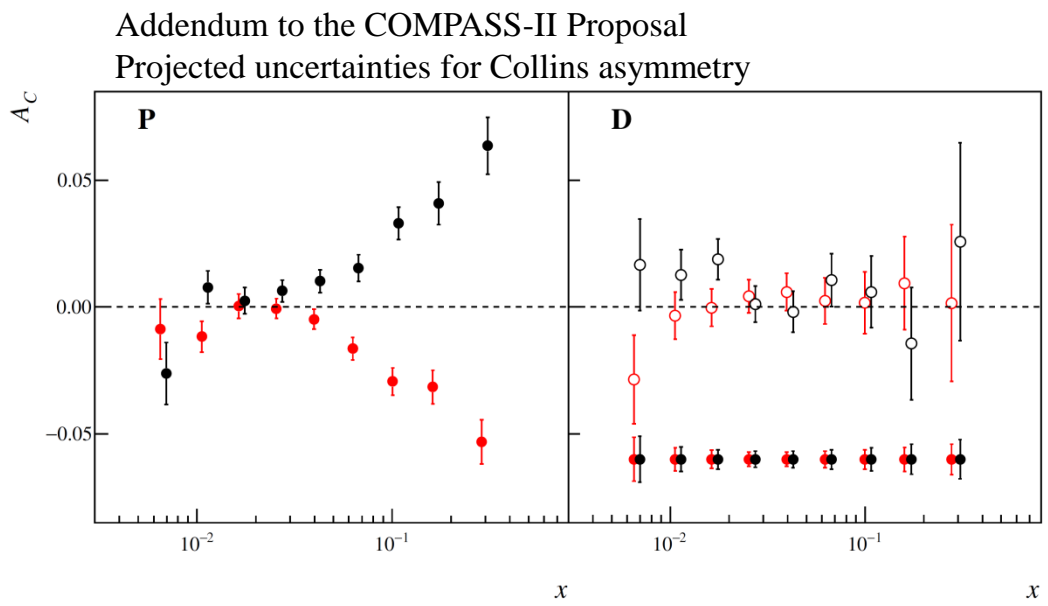
See talk by A. Bressan



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

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

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SIDIS TSAs (Sivers)

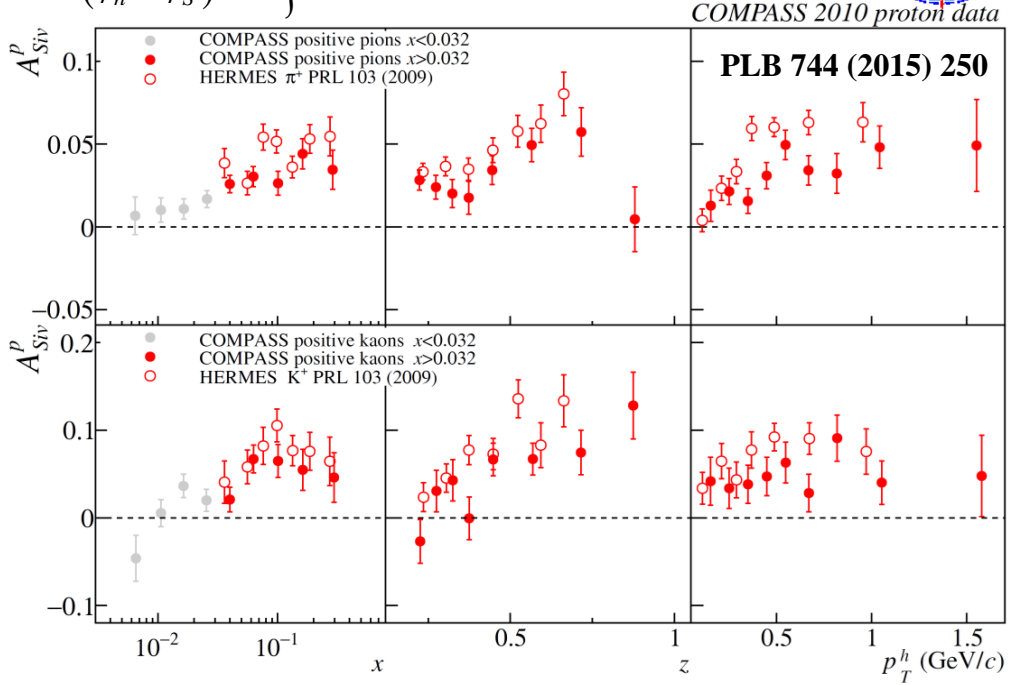
See talks by Ch. V. Hulse, A. Bressan and H. Avakian



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

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

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

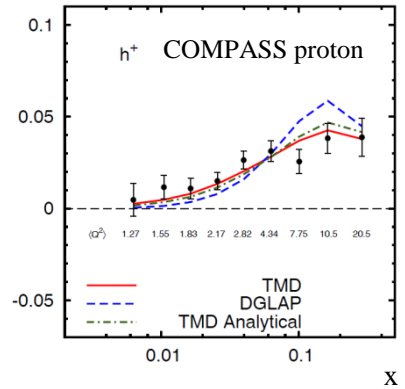
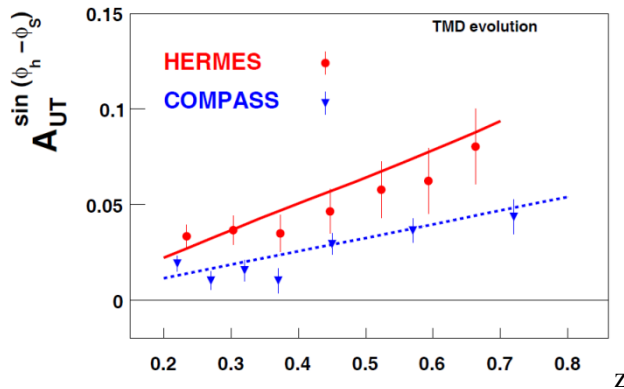
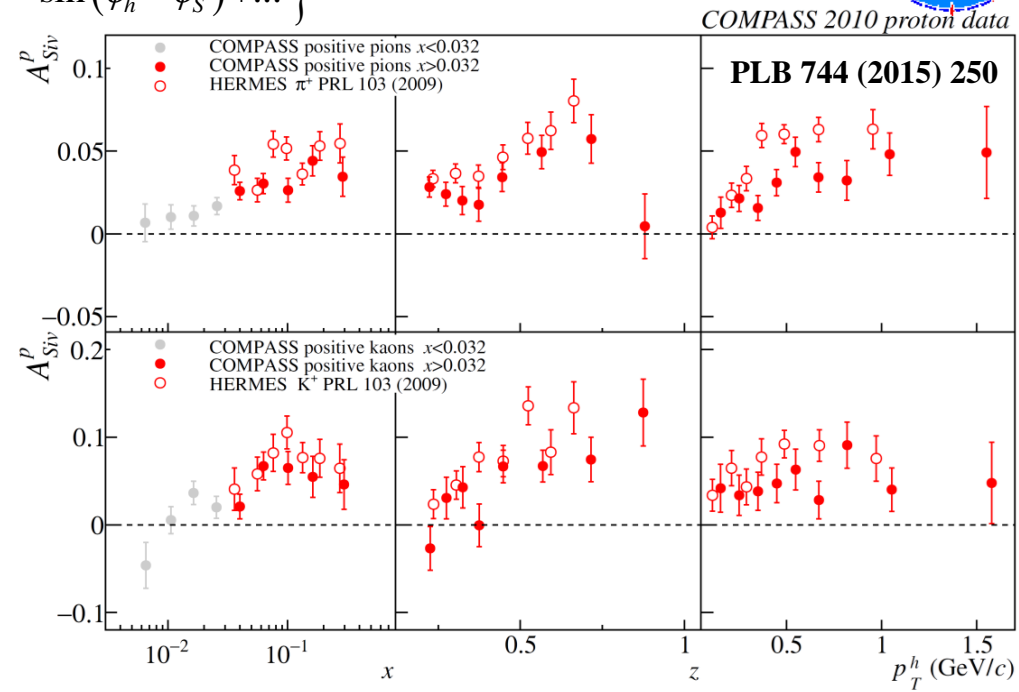


SIDIS TSAs (Sivers)

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

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

- Measured on proton and deuteron
- Recently - gluon Sivers paper
PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q² is different by a factor of ~2-3)
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S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**



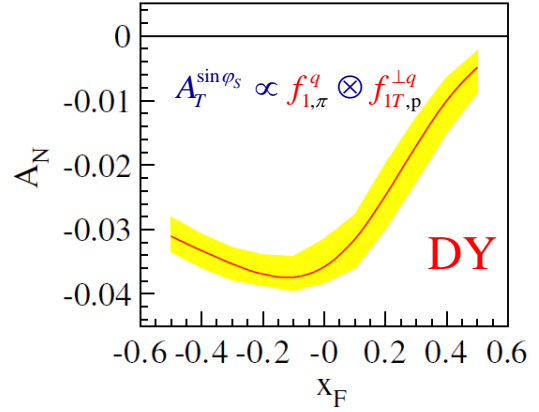
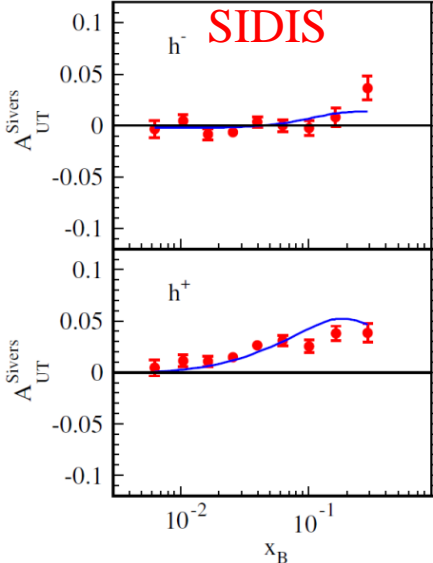
SIDIS TSAs (Sivers)

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

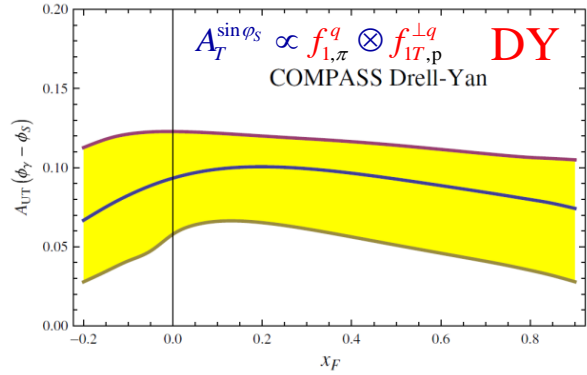
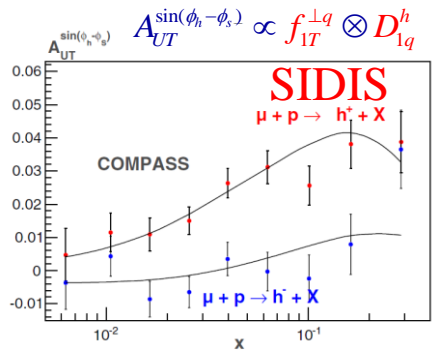
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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- **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)

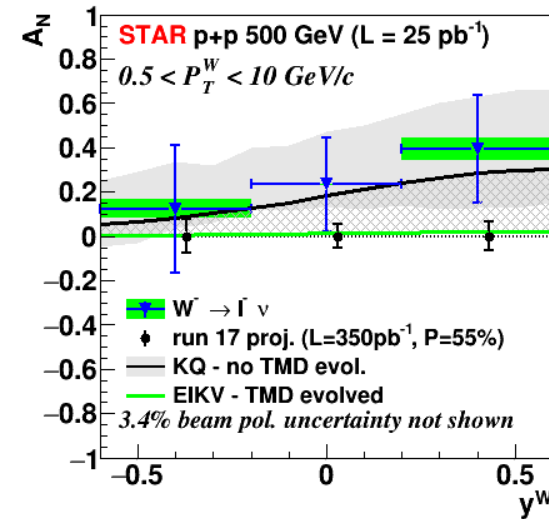
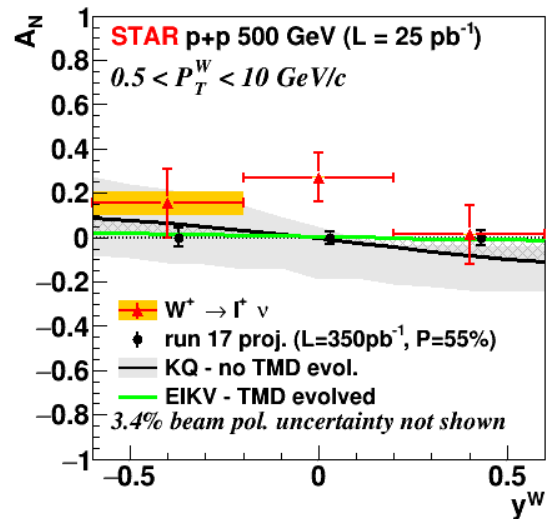
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of $\sim 2-3$)
- **Q^2 -evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- First experimental investigation of Sivers-non-universality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

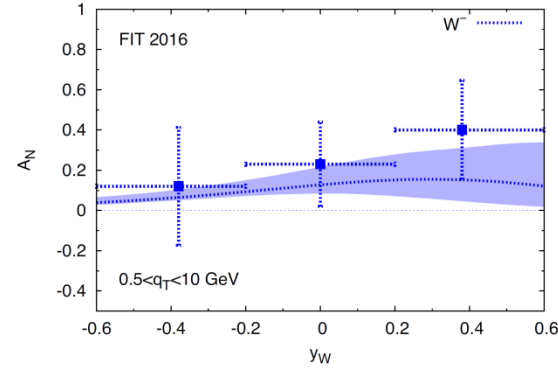
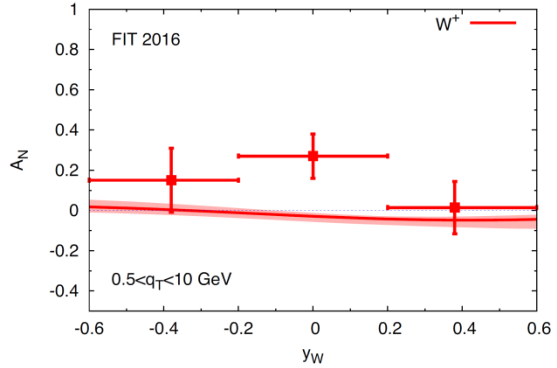
See talk by E.C. Aschenauer

STAR collaboration: PRL 116, 132301 (2016)



See talk by M. Boglione

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

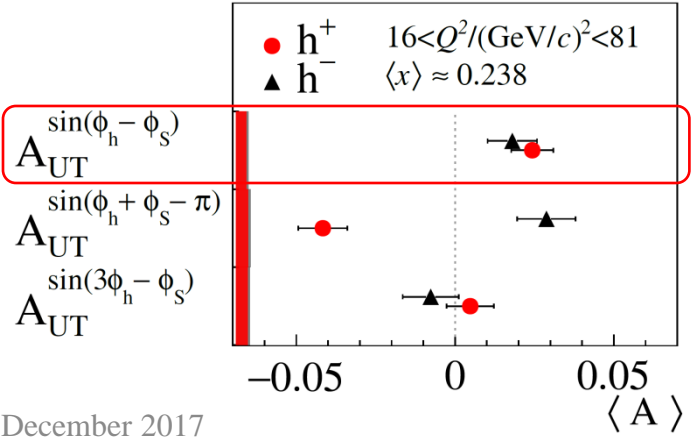
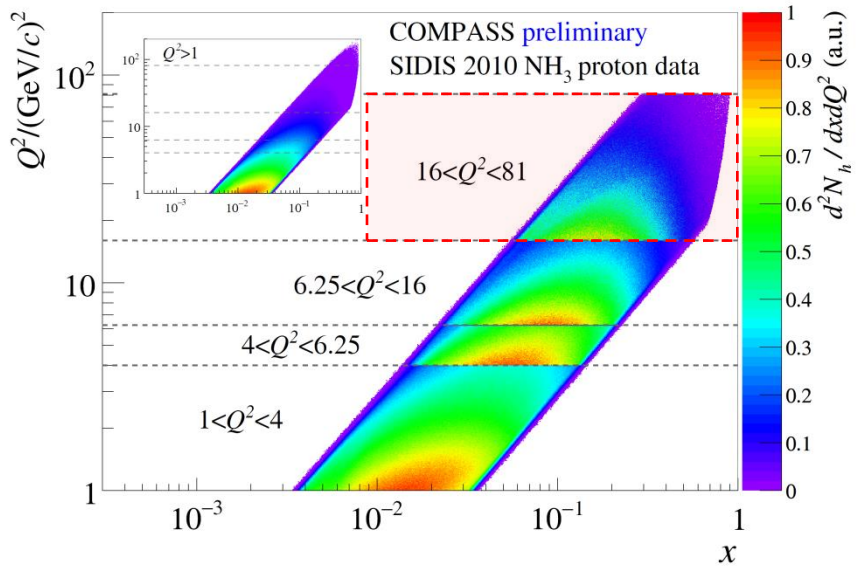




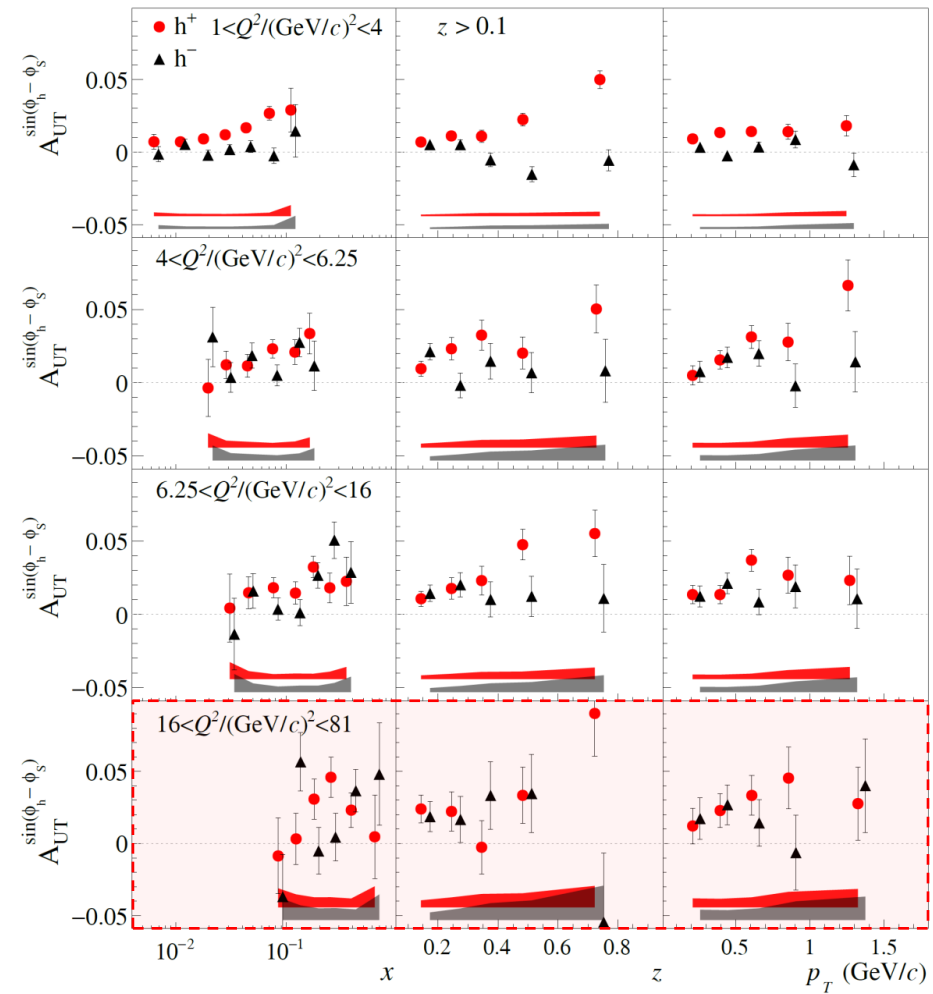
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

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

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



COMPASS PLB 770 (2017) 138



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

Multi-D TSA analysis

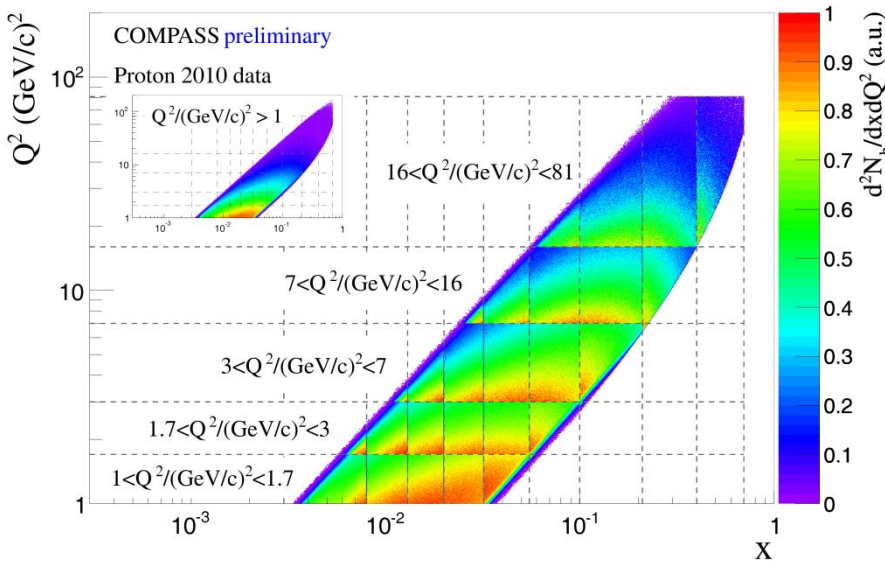
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

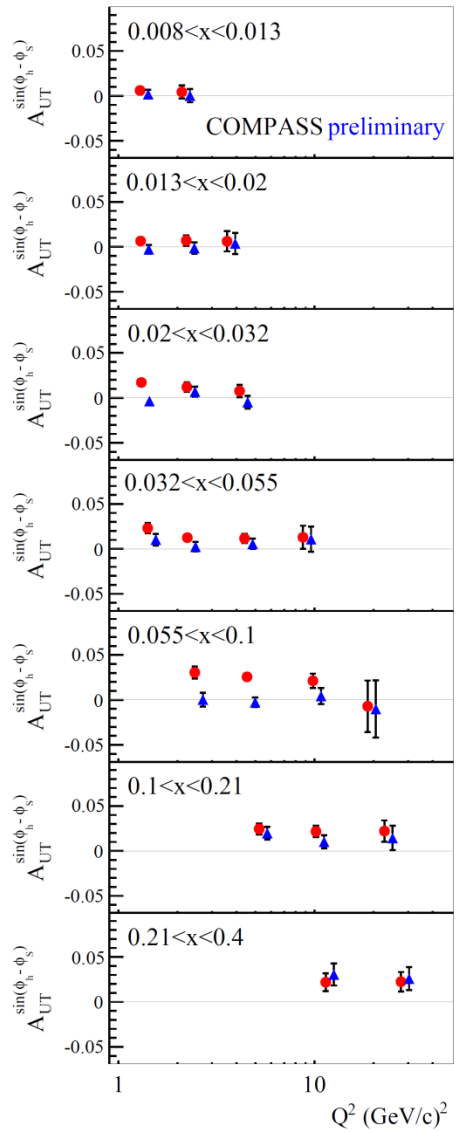
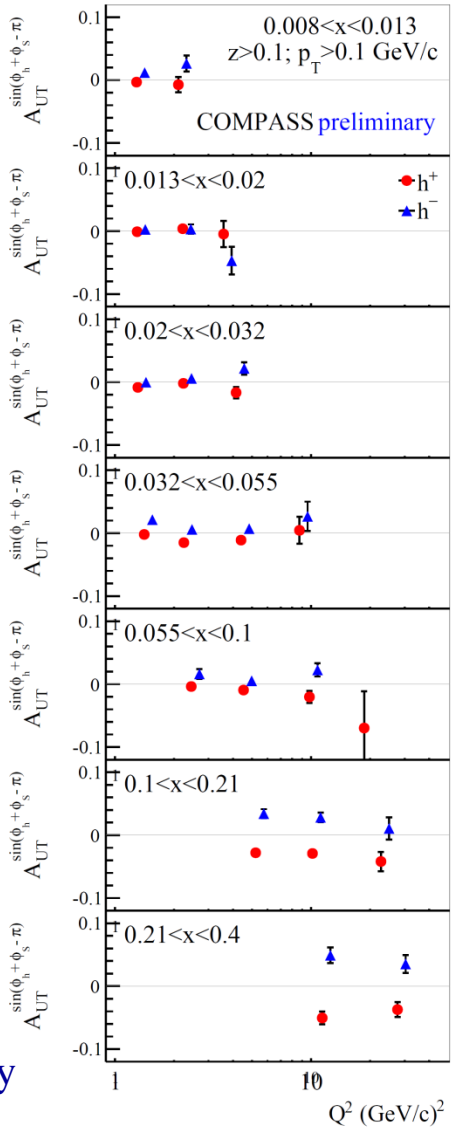
COMPASS 4-D fit (x - Q^2 ; z - p_T ; x - Q^2 - z - p_T)

All eight TSAs extracted simultaneously

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

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

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

ongoing analysis

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

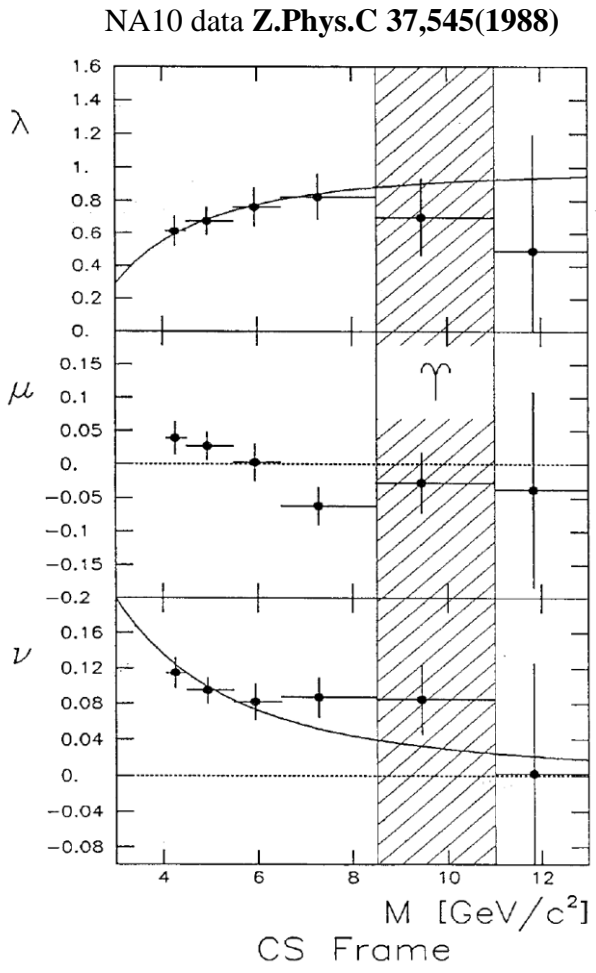
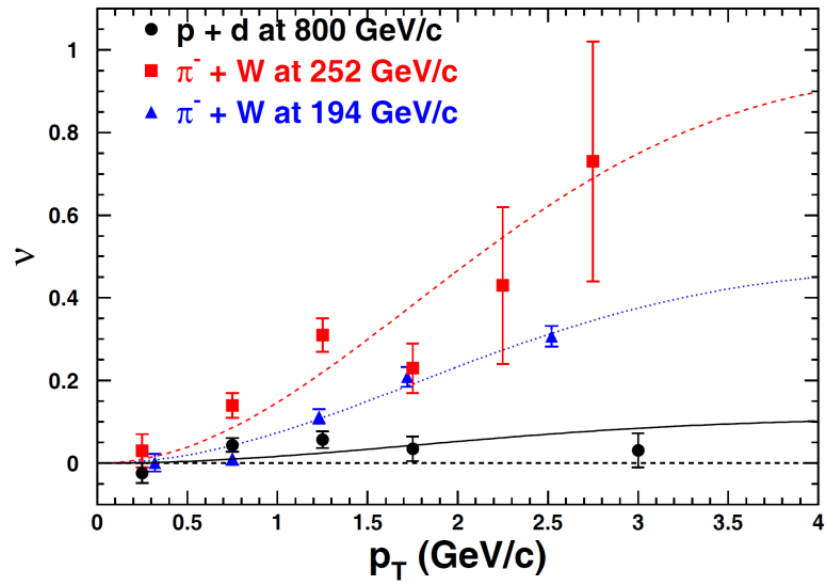
Single-polarized DY x-section: unpolarized part

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

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

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





Single-polarized DY x-section: unpolarized part

ongoing analysis

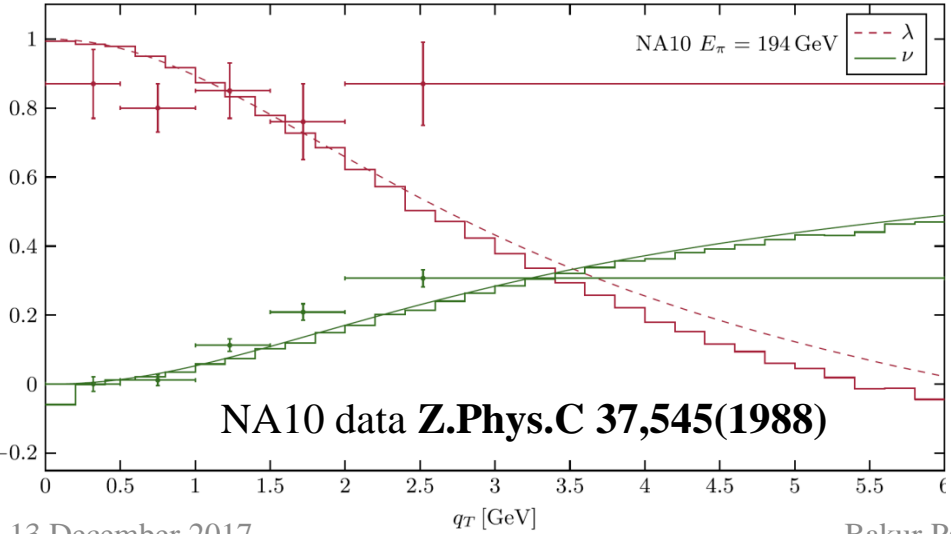
$$\lambda = A_U^1 = \frac{F_U^1 - F_U^2}{F_U^1 + F_U^2}, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2A_U^{\cos 2\varphi_{CS}}$$

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

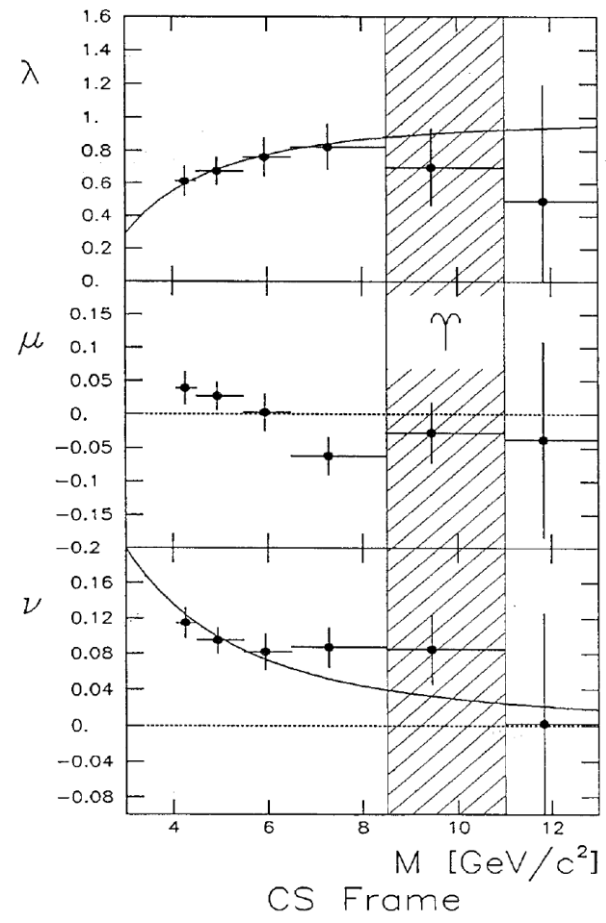
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See next talk by W. Vogelsang

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



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



Single-polarized DY x-section: transverse part

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

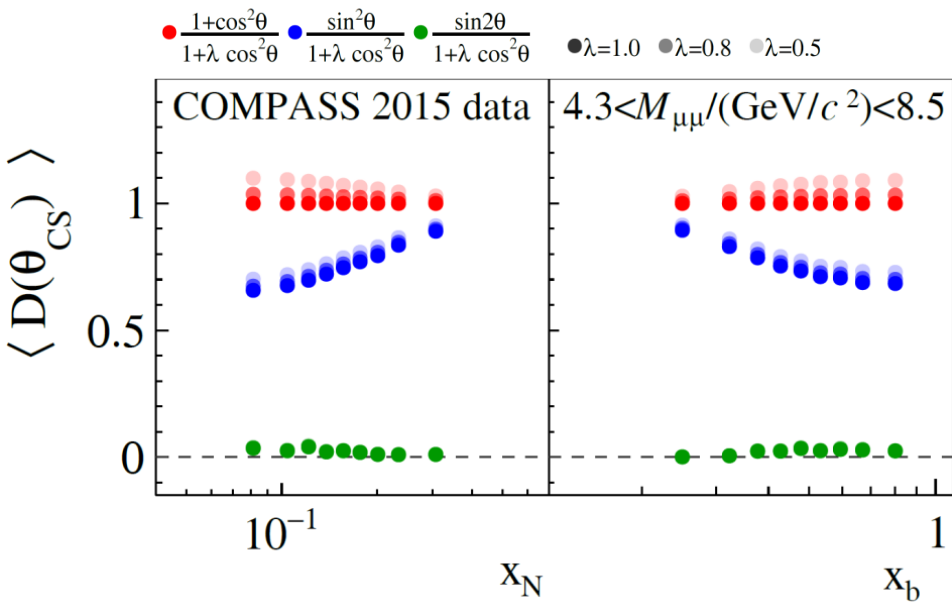
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 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- Experiment,
 $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

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

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

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

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





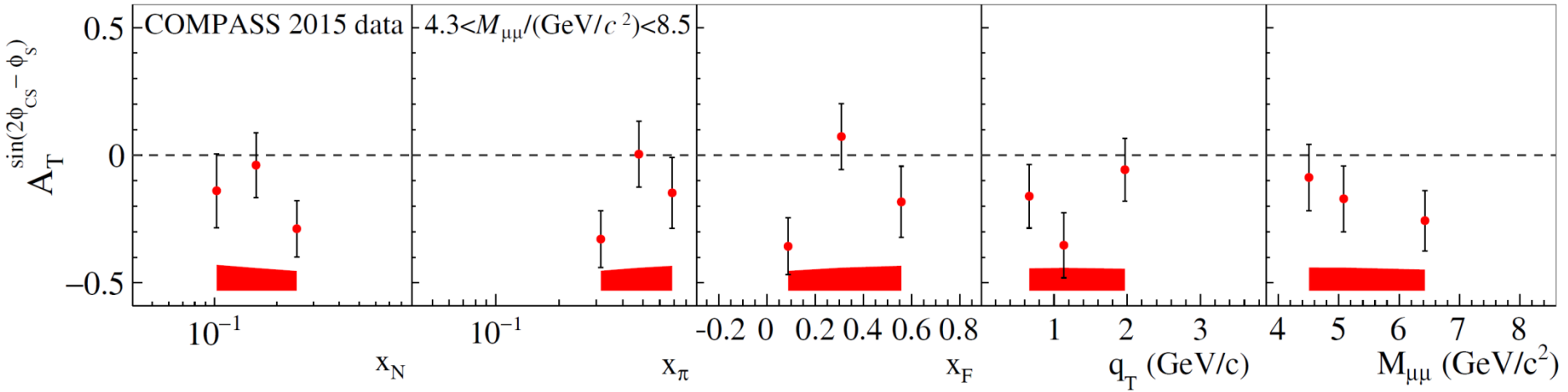
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

COMPASS PRL 119, 112002 (2017)





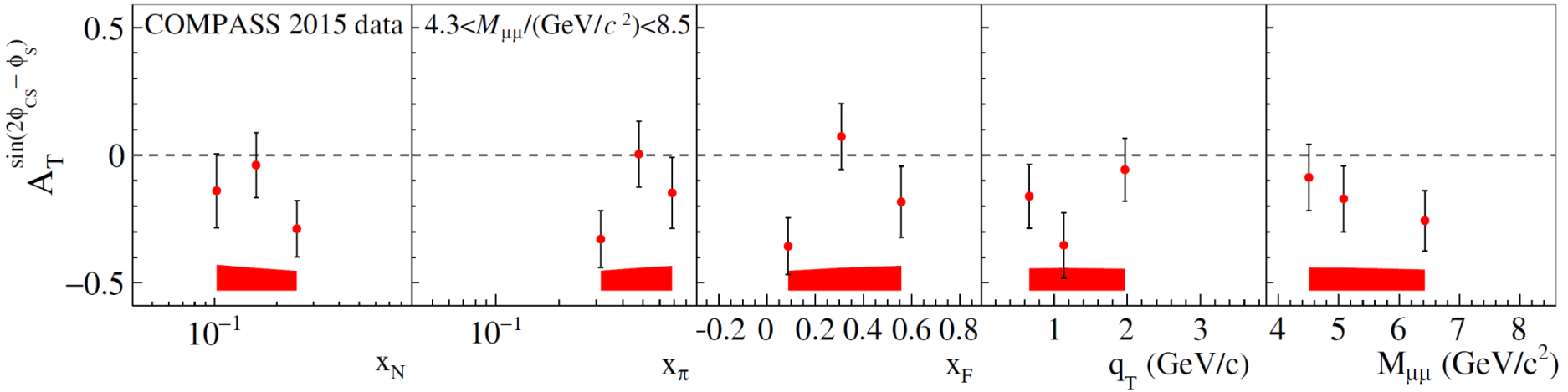
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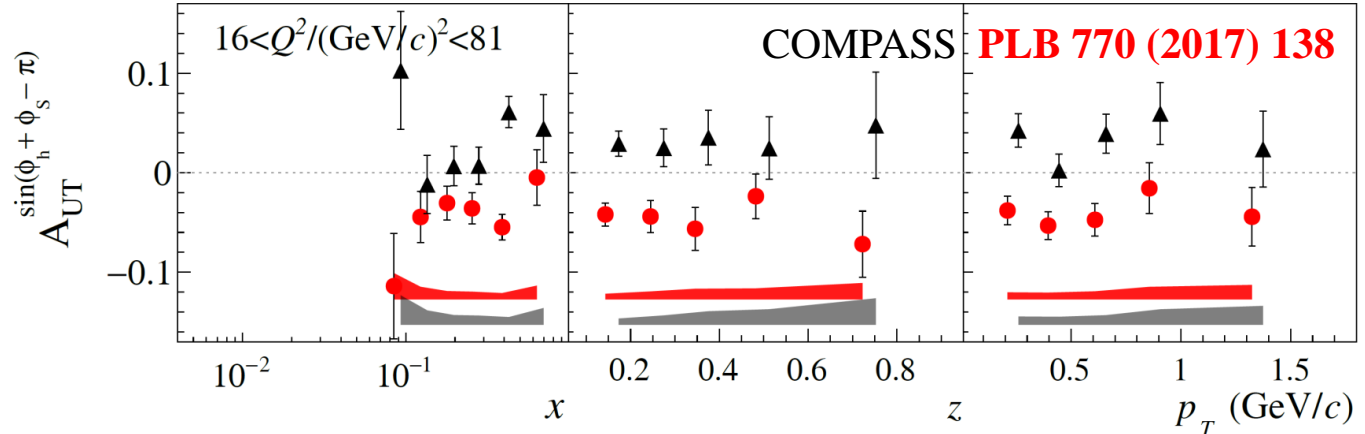
COMPASS PRL 119, 112002 (2017)



SIDIS in Drell-Yan high-mass range

Collins SIDIS TSA

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





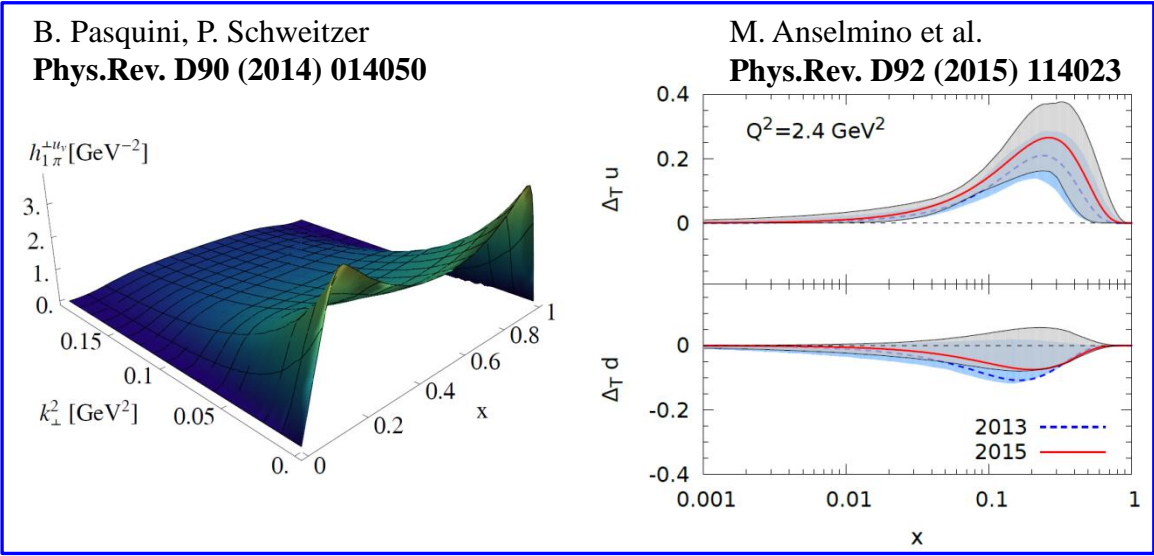
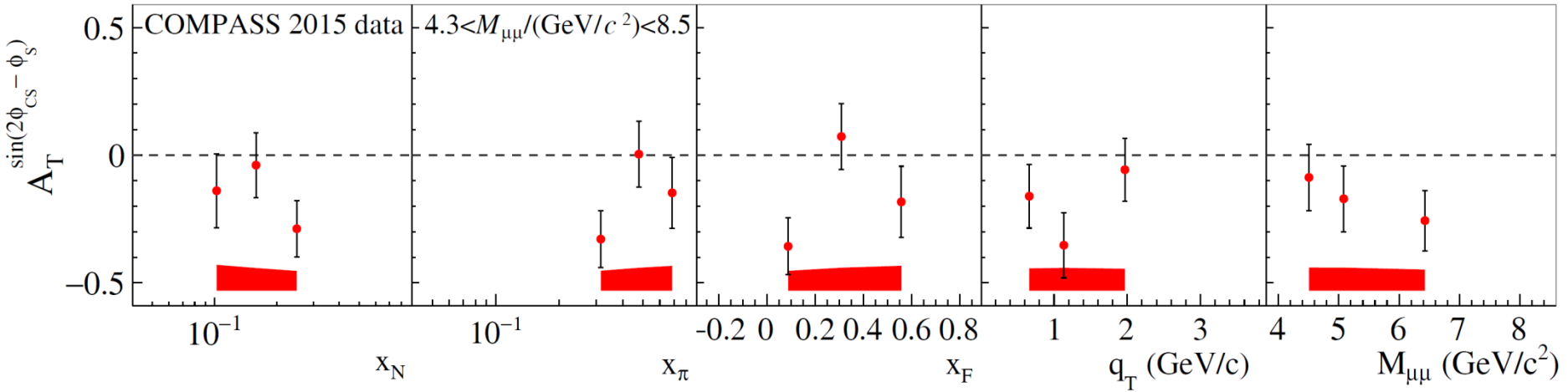
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$$\frac{d\sigma}{d\Omega} \propto 1 + \dots + S_T \left[D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$

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

COMPASS PRL 119, 112002 (2017)





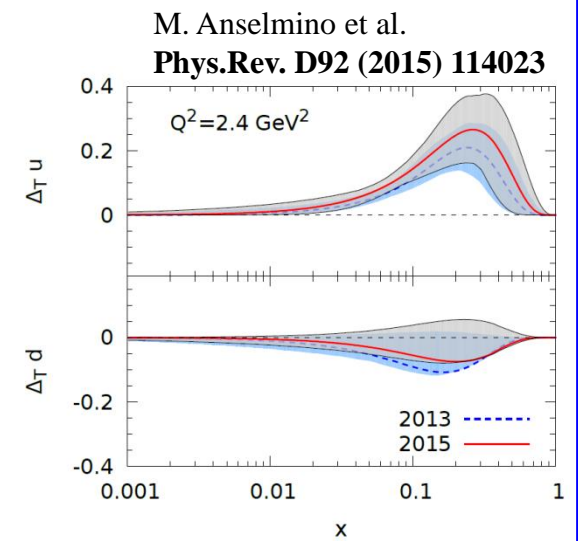
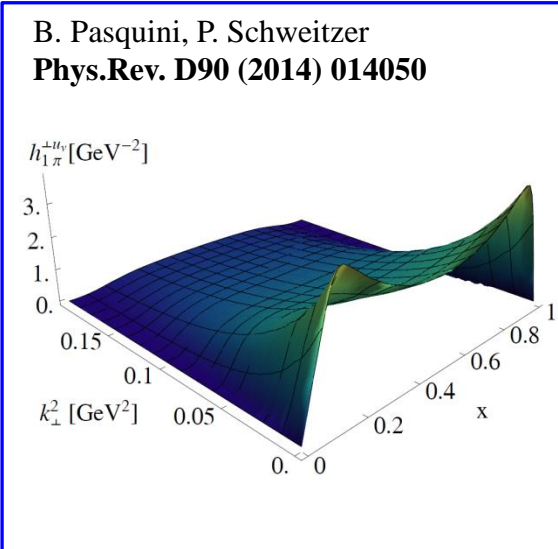
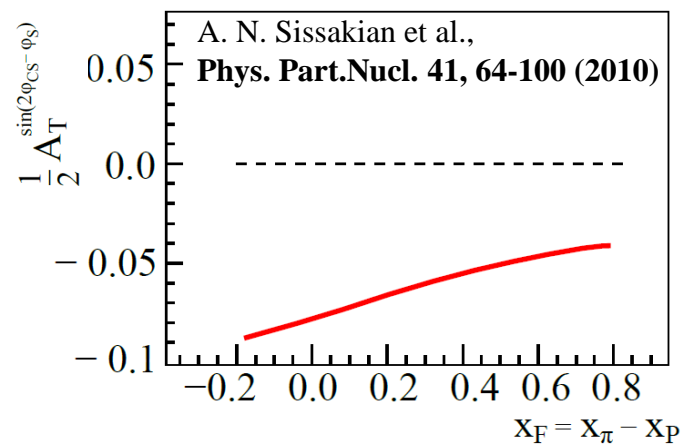
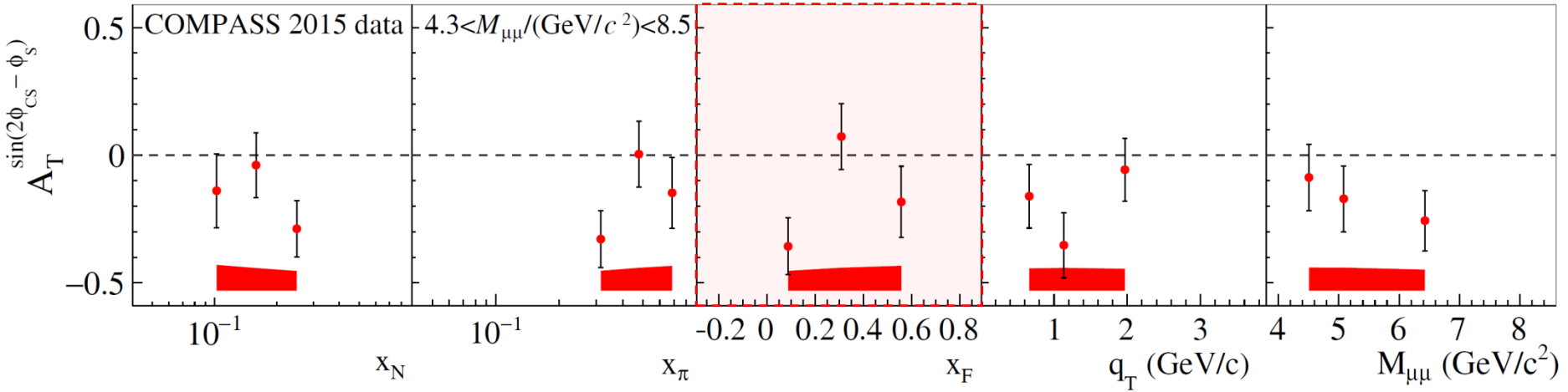
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COMPASS PRL 119, 112002 (2017)





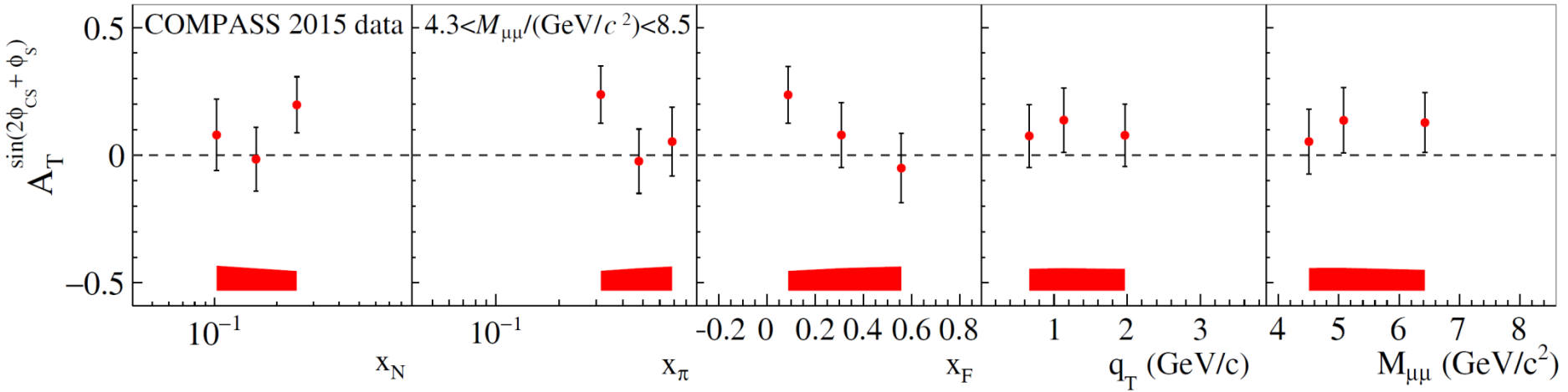
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

COMPASS PRL 119, 112002 (2017)





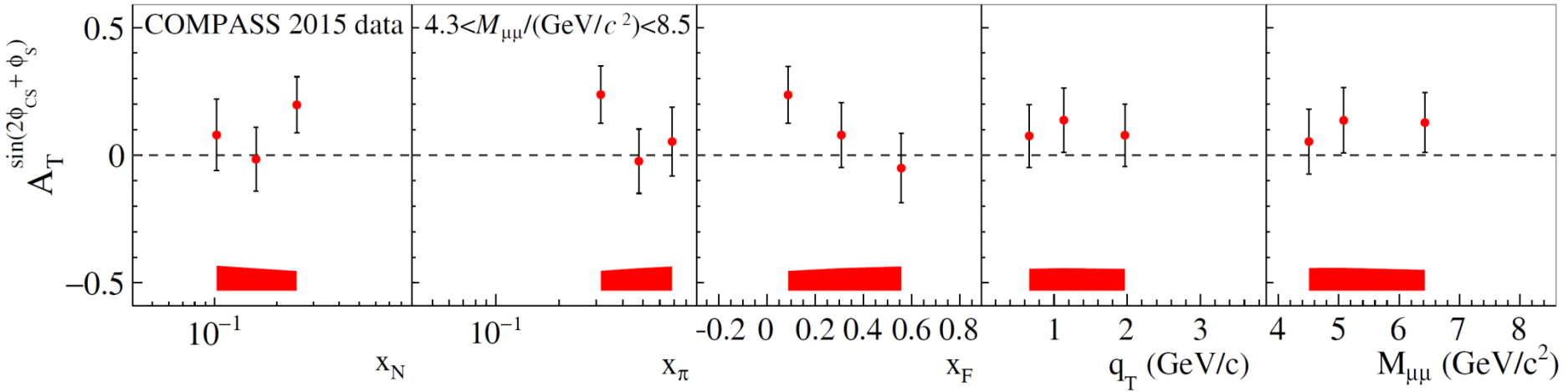
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COMPASS PRL 119, 112002 (2017)

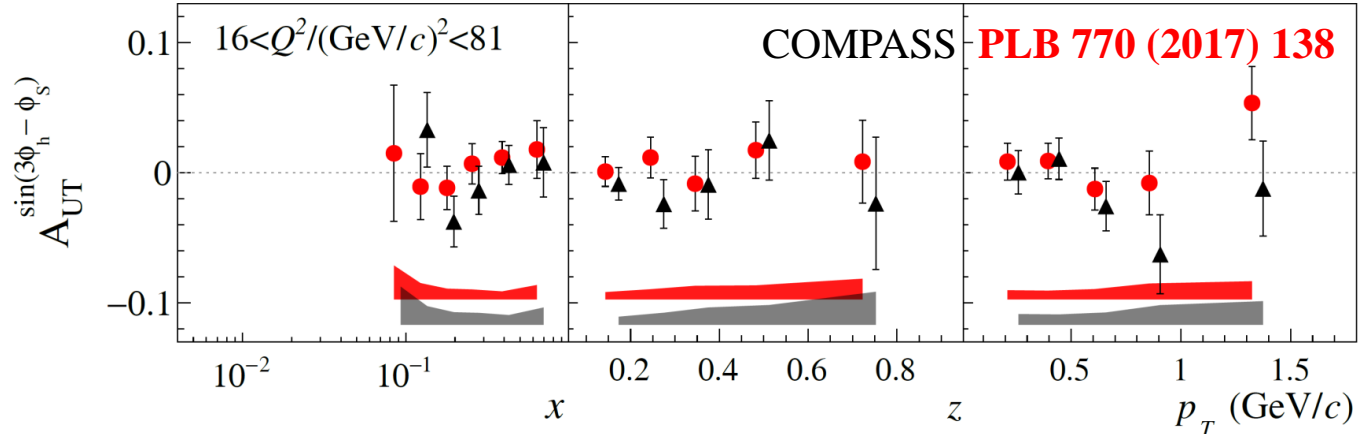


SIDIS in Drell-Yan high-mass range

Pretzelosity SIDIS TSA

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

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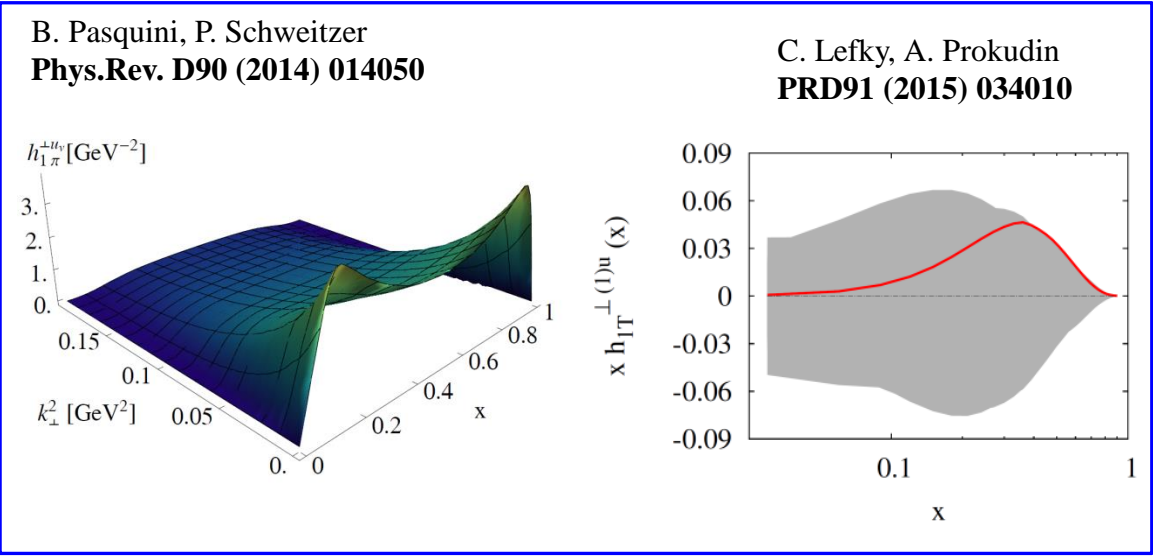
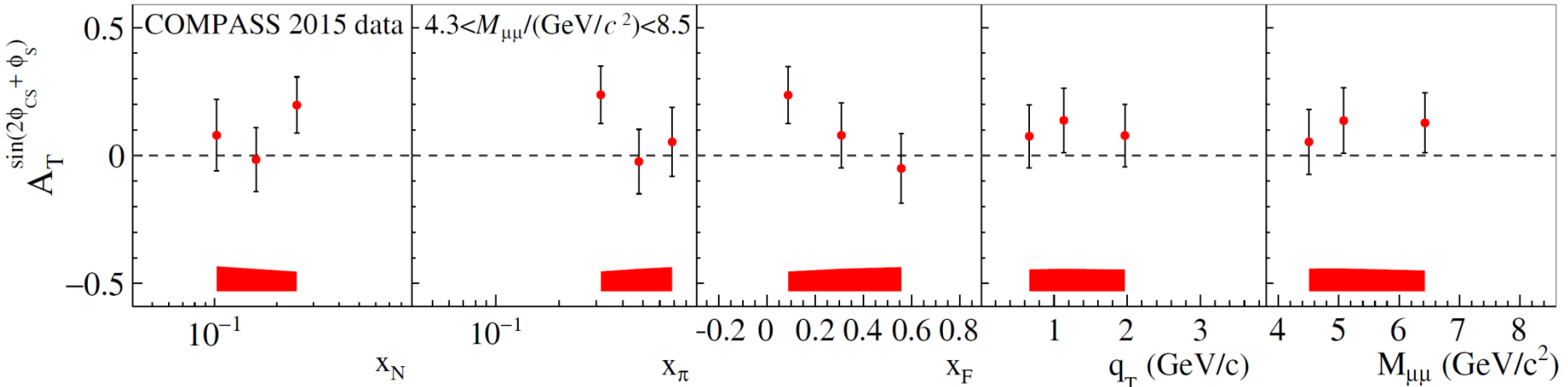
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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COMPASS PRL 119, 112002 (2017)





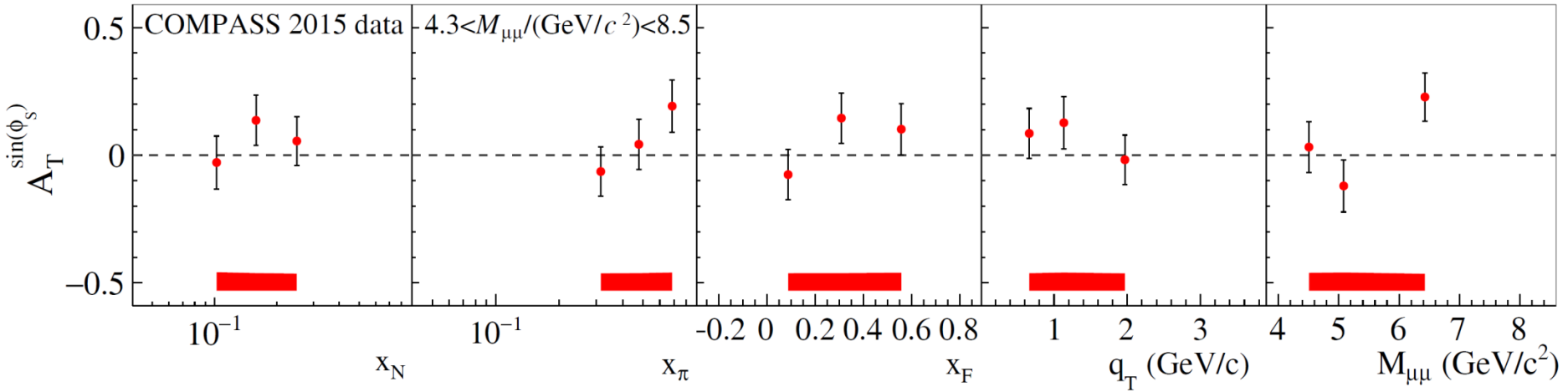
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)





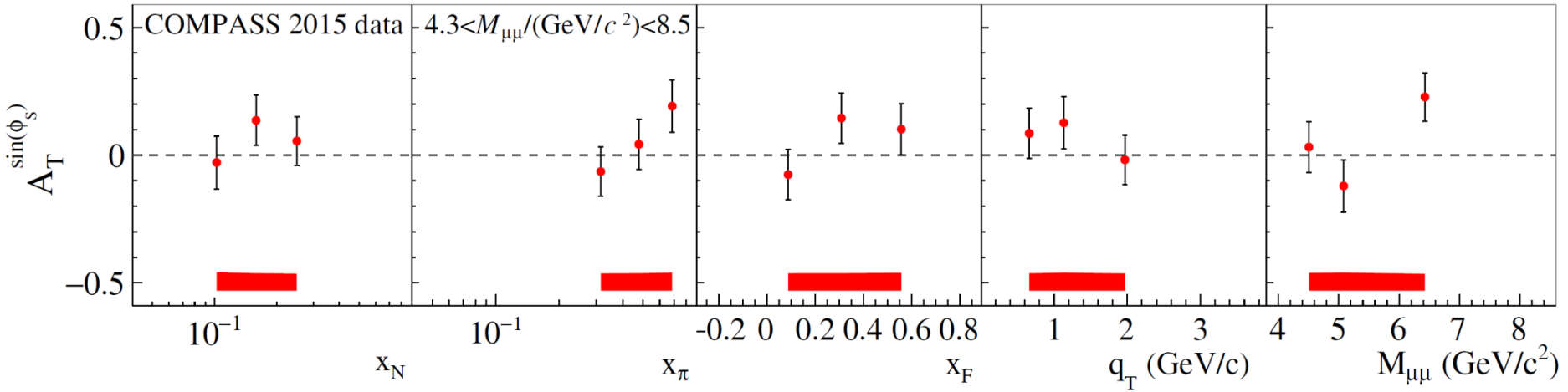
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COMPASS PRL 119, 112002 (2017)

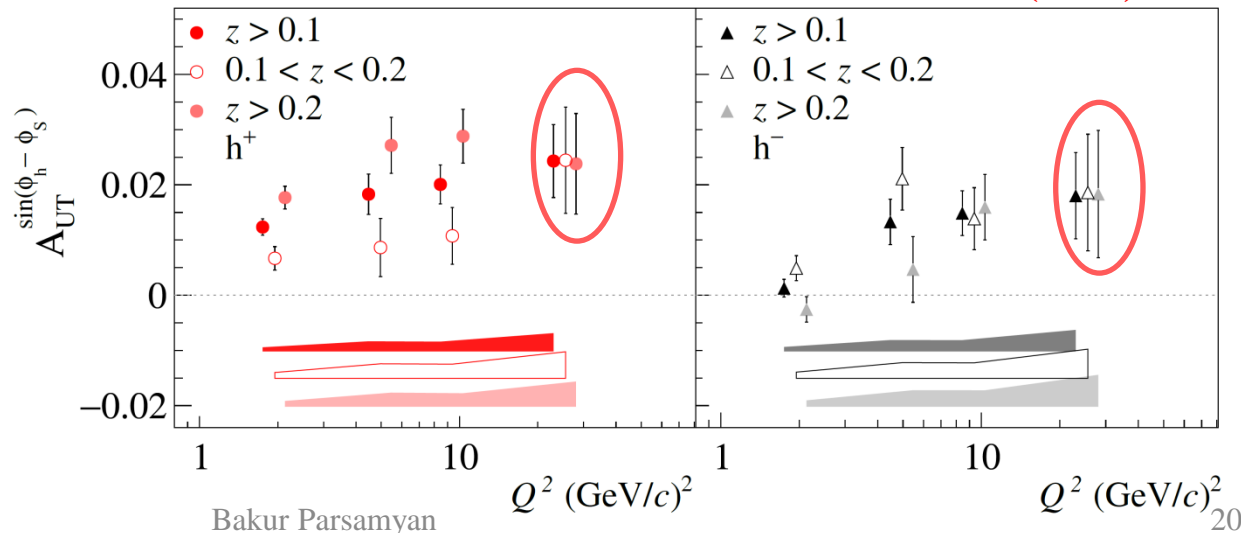


SIDIS in Drell-Yan high-mass range

COMPASS PLB 770 (2017) 138

Sivers SIDIS TSA

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

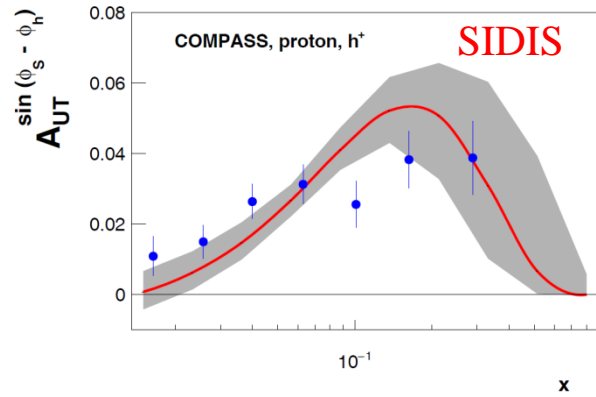




Sivers asymmetry in Drell-Yan: sign change

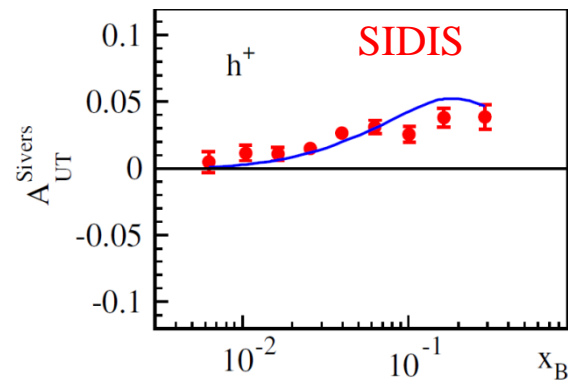
DGLAP (2016)

M. Anselmino et al., arXiv:1612.06413



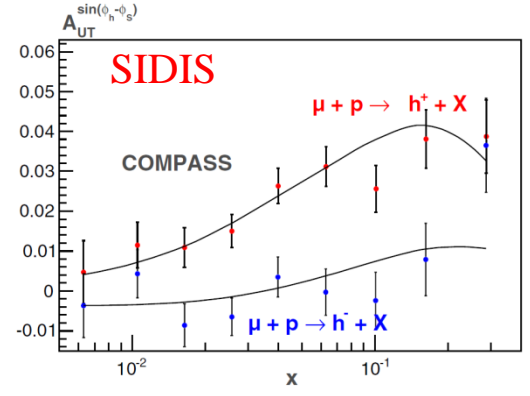
TMD-1 (2014)

M. G. Echevarria et al. PRD89,074013



TMD-2 (2013)

P. Sun, F. Yuan, PRD88, 114012

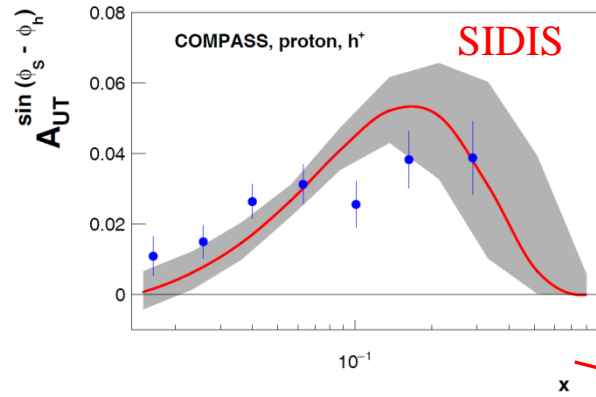




Sivers asymmetry in Drell-Yan: sign change

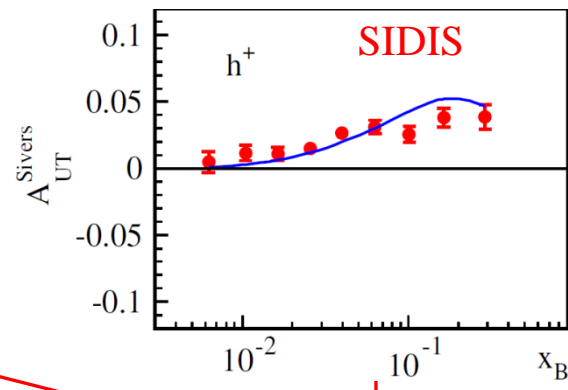
DGLAP (2016)

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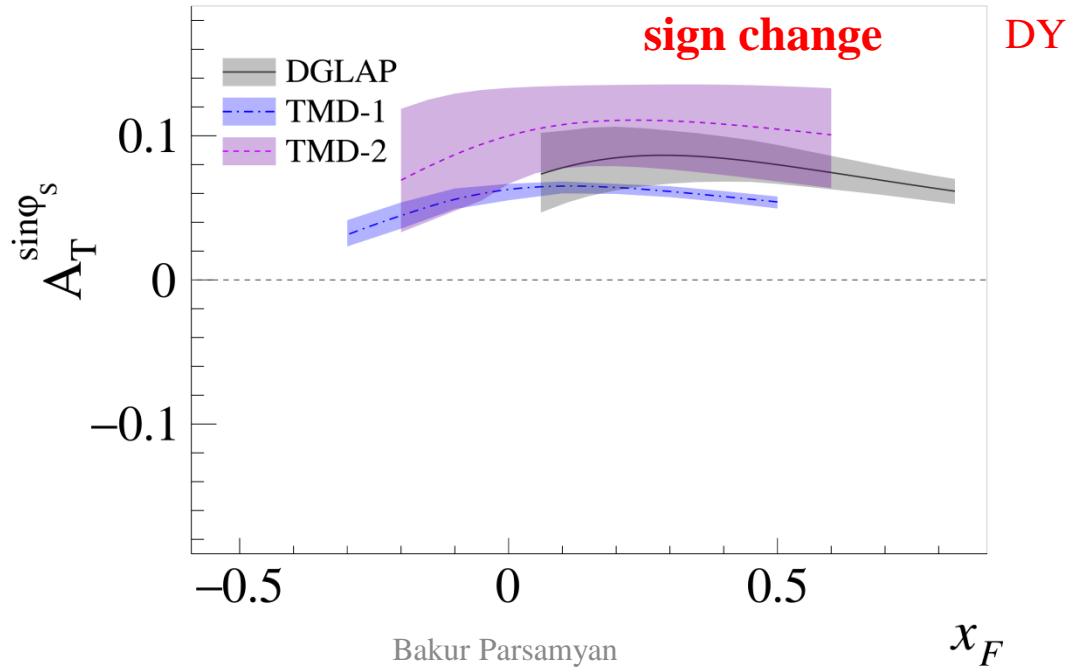
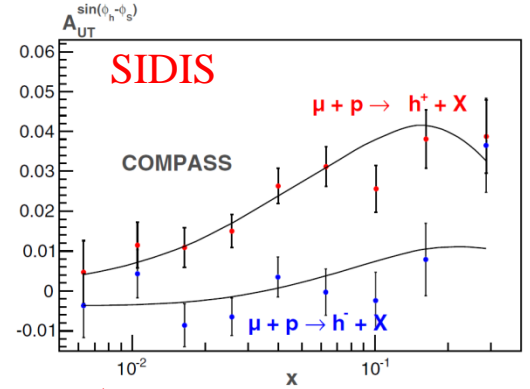
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Sivers asymmetry in Drell-Yan: sign change

DGLAP (2016)

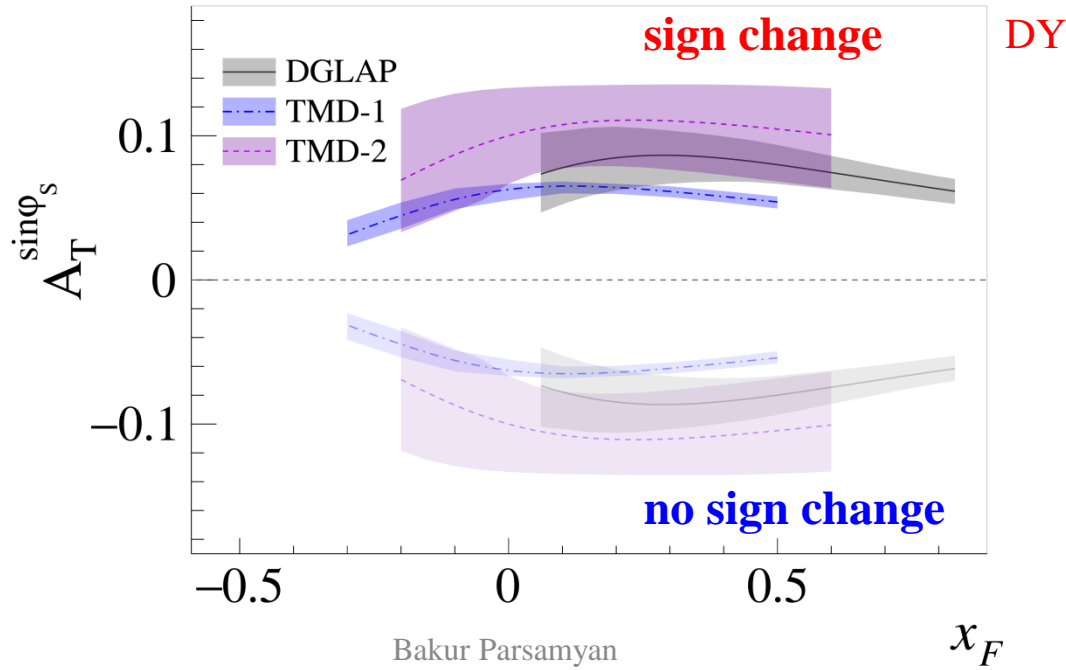
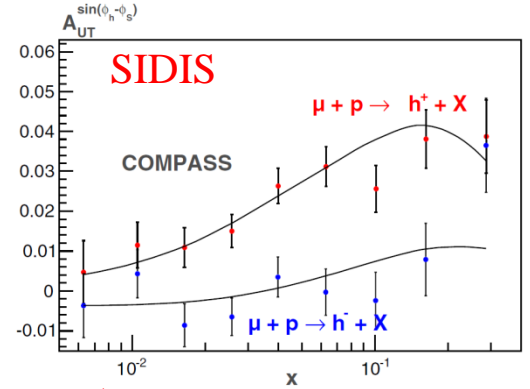
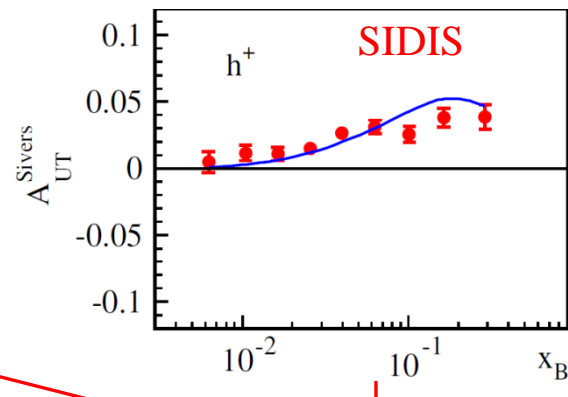
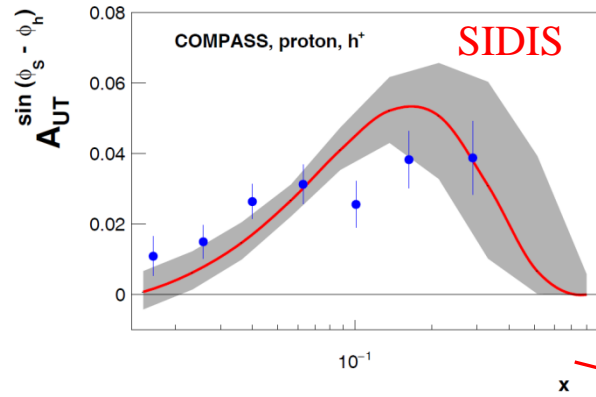
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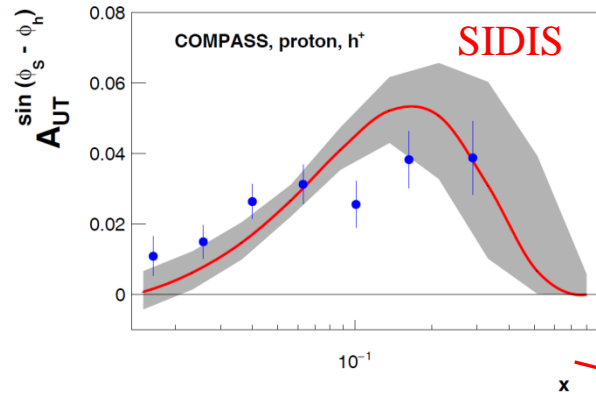
P. Sun, F. Yuan, PRD88, 114012



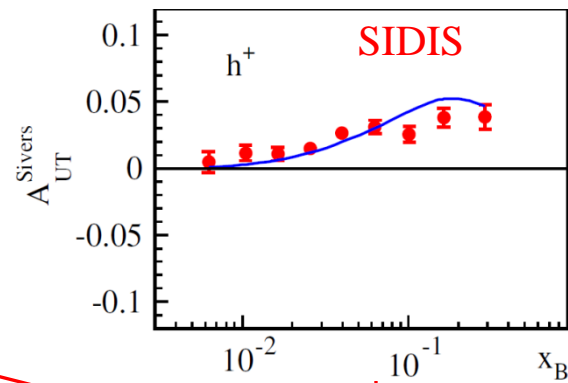


Sivers asymmetry in Drell-Yan: sign change

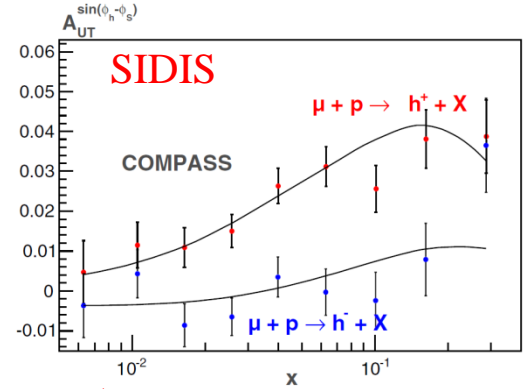
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TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**

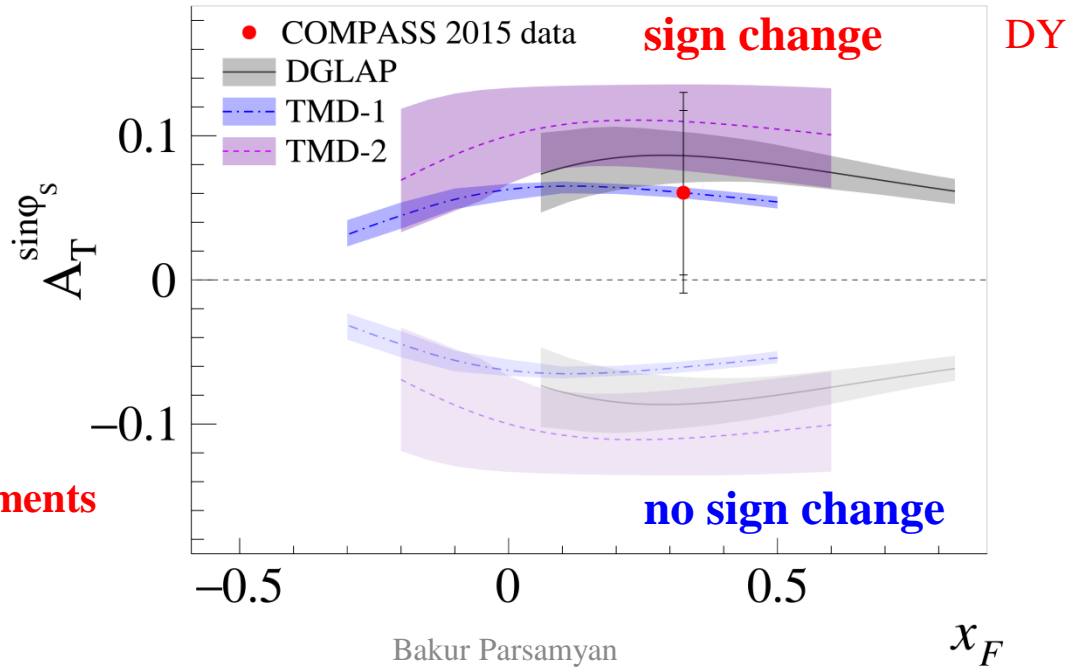


TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



COMPASS
PRL 119, 112002 (2017)

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

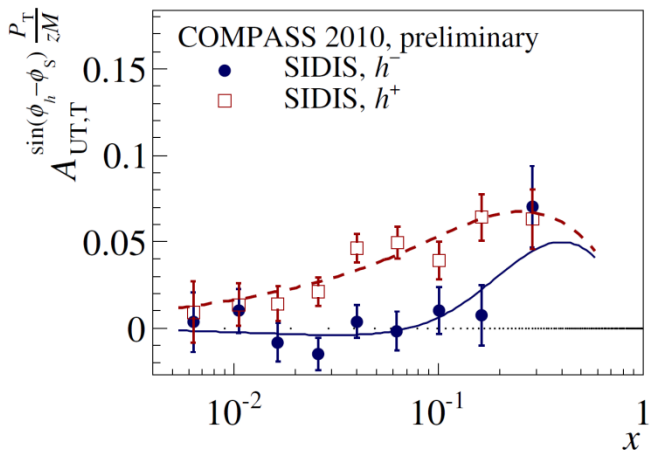




The p_T (q_T) – weighted SIDIS(DY) Sivvers asymmetry

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

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



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

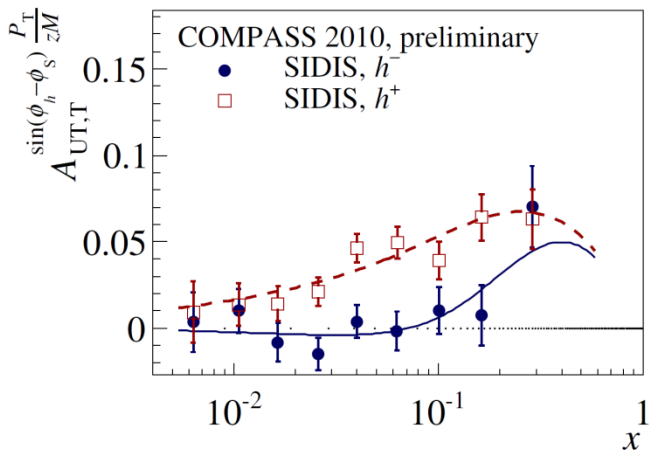
Sivvers wTSA in SIDIS: $A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q (1)} \times D_{1q}^h$



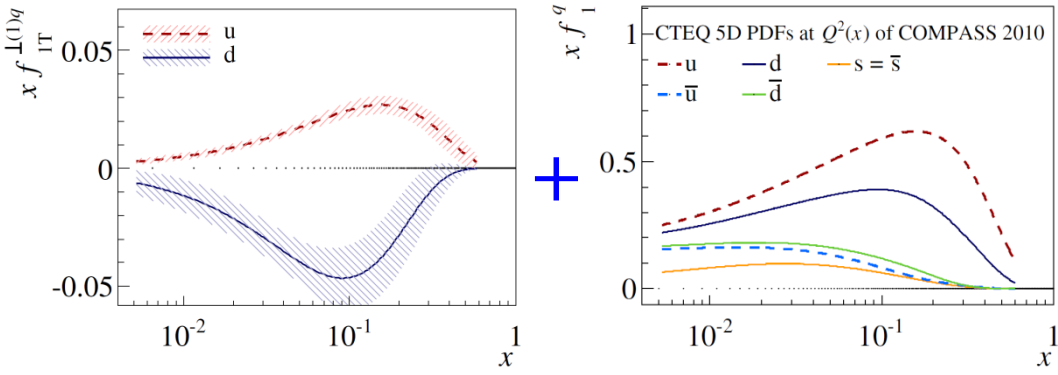
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Sivers TSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
Sivers wTSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q (1)}$



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

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

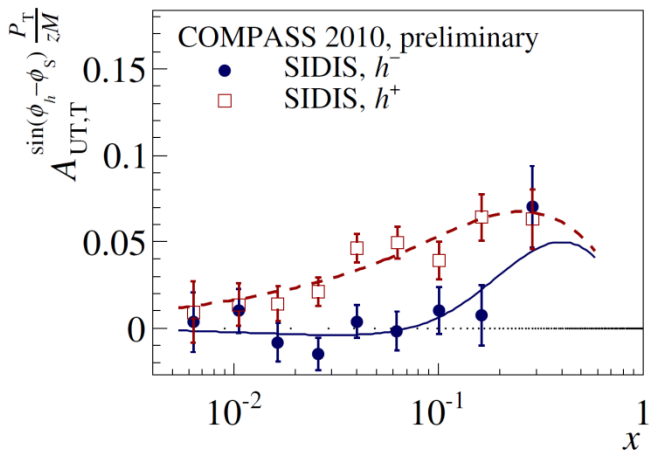




The p_T (q_T) – weighted SIDIS(DY) Siverts asymmetry

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

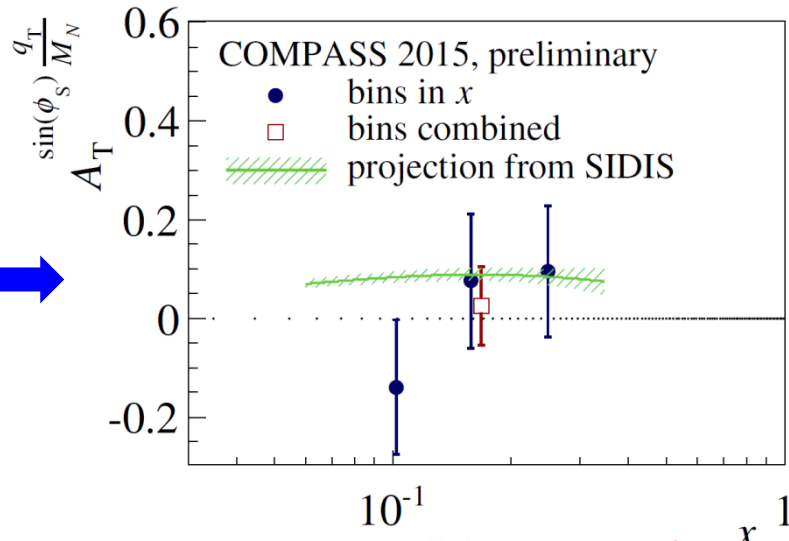
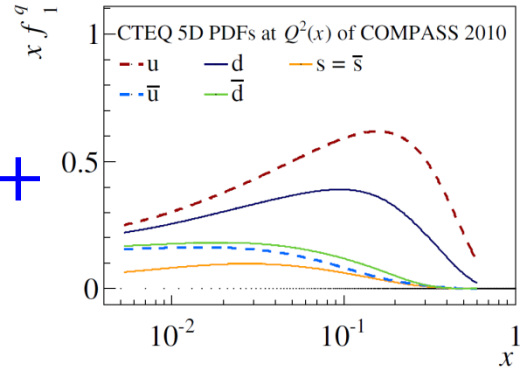
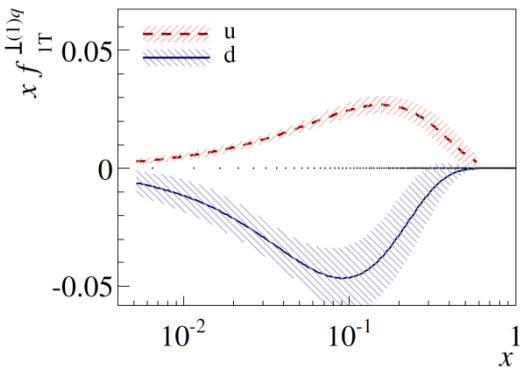
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 Siverts TSA in DY: $A_T^{\sin \phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
 Siverts wTSA in DY: $A_T^{\sin \phi_S} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q (1)}$



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





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

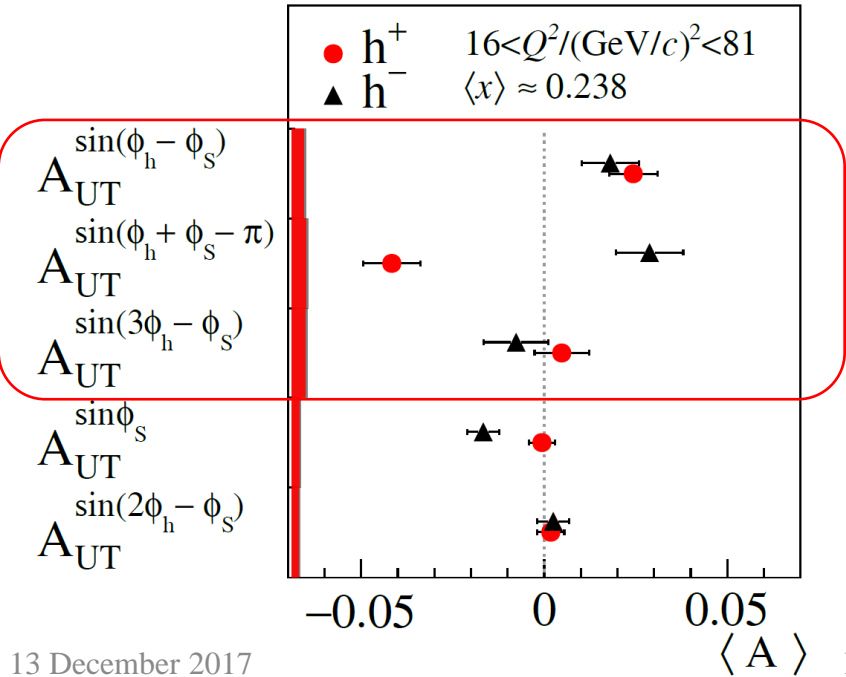
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

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

COMPASS PLB 770 (2017) 138





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

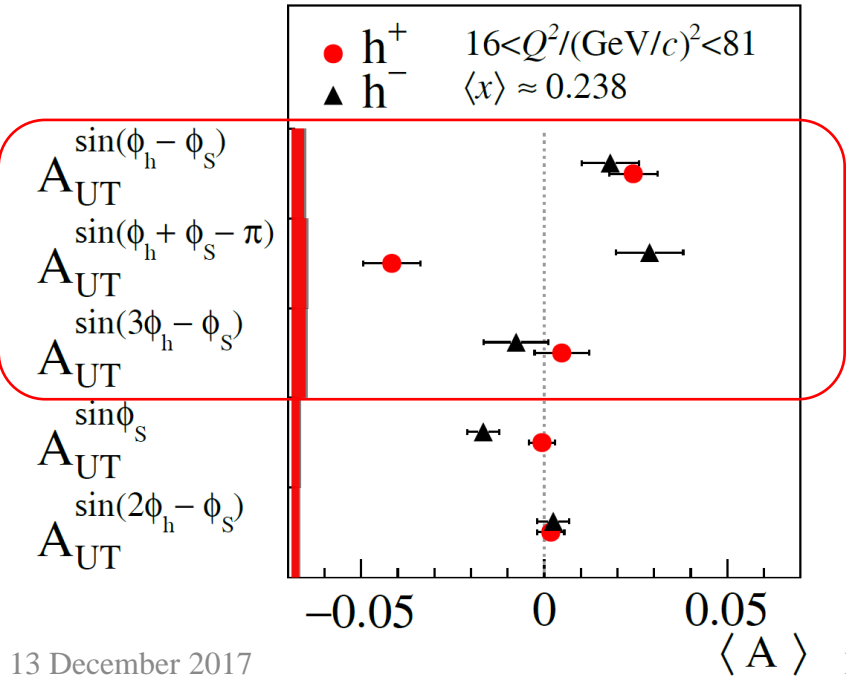
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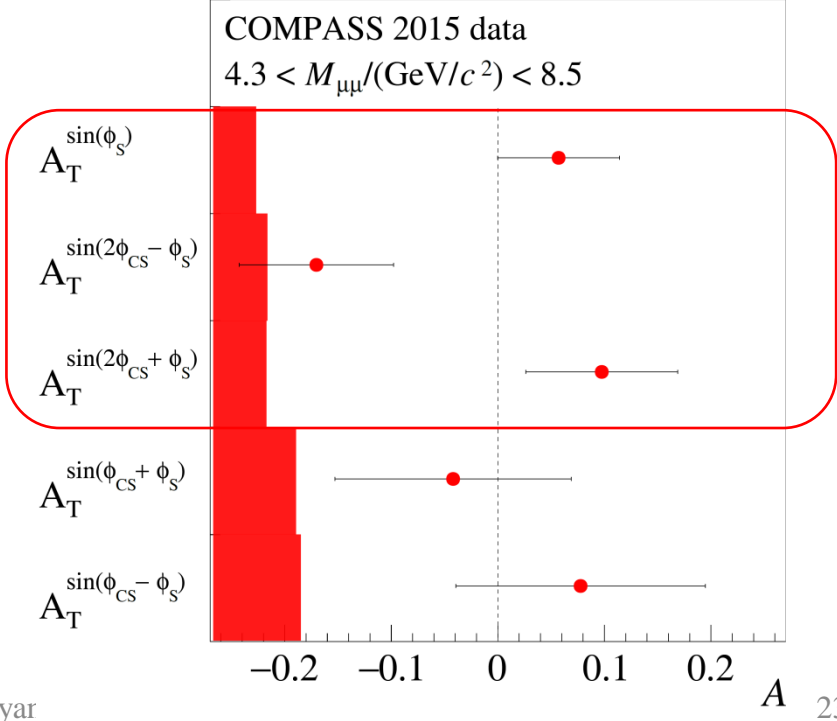
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS}) \left\{ 1 + \dots \right.$$

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

COMPASS PLB 770 (2017) 138



COMPASS PRL 119, 112002 (2017)





“COMPASS-like” future long-term experiment

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

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

XIV International Workshop on Hadron Structure and Spectroscopy

Longitudinal and Transverse Spin Structure of the Nucleon
 Fragmentation Functions
 Search for Glueballs, Hybrid Mesons and Multi-quark States
 Meson Spectroscopy
 TMDs, GPDs and GTMDs
 New opportunities for physics beyond colliders
 Cosmic rays and accelerator physics

Local Organizing Committee

Maxim Alexeev
 Antonino Anselmino
 Michela Chiosso
 Riccardo Longo
 Daniele Panfili (Chair)
 Bakur Parsamyan

@iwhss17@to.infn.it
 #iwhss17.to.infn.it
 @iwhss17

IWHSS17 April 2-5, 2017
 Cortona, Italy

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INFN COMPASS UPO CAEN

ECT* ECT* ECT*

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

ILLINOIS

Castello di Trento ("Tria"), watercolor 19.8 x 27.7, painted by A. Direr on his way back from Venice (1495). British Museum.

Dilepton Production with Meson and Antiproton Beams
 Trento, November 6-10, 2017

Main Topics
 Theoretical and experimental aspects of high-mass dilepton production with meson and antiproton beams.
 Physics of partonic structures of pion and kaon.
 Exclusive Drell-Yan process.
 Opportunities to carry out new measurements on high-mass lepton pairs productions using meson and antiproton beams.

Invited speakers
 Vincent Andrieux (U. Illinois), Mauro Anselmino (U. Turin), Francois Arleo (Ecole Polytechnique), Johannes Bernhard (CERN), Daniel Boer (U. Groningen), Stan Brodsky (SLAC), Jan-Ping Chen (Lab), Alex Deyo (Heinrich Heine), Oleg Denisov (INFN, Torino), Matthias Grosse-Perdekamp (U. Illinois), Boris Gruber (Tech U. Munich), Aleksey Gusakov (JINR, Dubna), Cynthia Hadjilakas (EPN, Orsay), Paul Hoyer (Helsinki U.), Xiangdong Ji (U. Maryland/Shanghai Jiaotong U.), Peter Kroll (U. Wuppertal), Shunzo Kumano (KEK), Wally Melnitchouk (Ulab), Hiroyuki Nouni (Osaka U.), Bakur Parsamyan (U. Turin), Bogdan Povh (U. Heidelberg), Catarina Marques Quintans (LIP, Lisbon), Paul Reimer (ANU), Craig Roberts (ANU), Takahiro Sawada (U. Michigan), Ingo Schienbein (LPG, Grenoble), Rikutarō Yoshida (Ulab)

Organisers
 Jen-Chieh Peng (Department of Physics, University of Illinois at Urbana-Champaign) jcpeng@illinois.edu
 Wen-Chen Chang (Institute of Physics, Academia Sinica) changwc@phys.sinica.edu.tw
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 Oleg Teruyaev (Bogolubov Laboratory of Theoretical Physics, JINR) teruyaev@theor.jinr.ru

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

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.
 For local organization please contact: Ines Campo - ECT* Secretariat - Villa Tamburini - Strada delle Tabarelle 286 - 38122 Villazono (Trento) - Italy
 Tel.: +39-0461 314721 Fax: +39-0461 314750, E-mail: ect@ect.tn.it or visit <http://www.ect.tn.it>

Physics Beyond Colliders

The annual workshop of the Physics Beyond Colliders study group is to be held at CERN, Geneva, on 21-22 November, 2017.

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

This second workshop will present the progress and development of ideas currently under investigation by the Physics Beyond Colliders study. It also aims to stimulate and discuss new ideas.

Details on the workshop programme, registration and abstract submission, as well as the mandate of the Study Group, can be found on the workshop web site: <https://indico.cern.ch/event/304423/>

Organizing Committee: Joerg Jaeckel, Mike Lamont, Connie Potter, Claude Vallée
 Contact: PRC.oom@cern.ch



“COMPASS-like” future long-term experiment



Lol is open for new ideas/proponents



Unique new DY-measurements with a RF separated beam

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 $p + He \rightarrow pbar X$ ✓
- 3. Hadron spectroscopy with antiprotons

D.) Spectrometer upgrades – hardware

- 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

For the moment it is ~50 pages long document



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](https://arxiv.org/abs/1702.01546) [hep-ex]

Experiment	particles	beam energy (GeV)	\sqrt{s} (GeV)	x^\uparrow	\mathcal{L} (cm ⁻² s ⁻¹)	\mathcal{P}_{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	$p + ^3\text{He}^\uparrow$	7000	115	0.05 \div 0.95	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE _{μ}	$p + p^\uparrow$	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

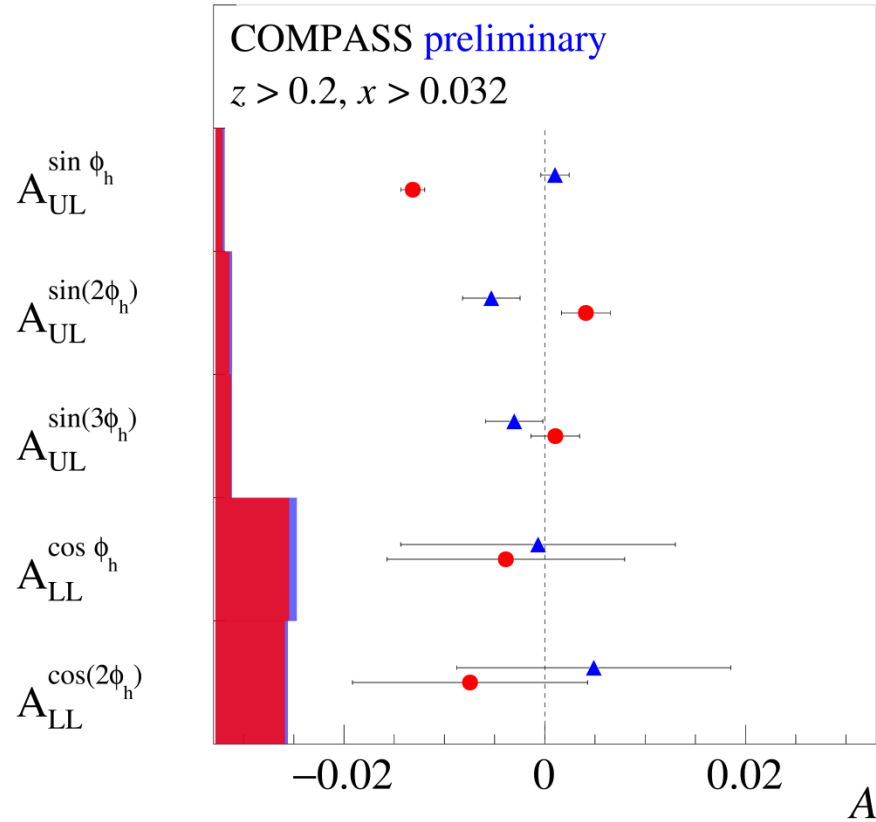
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots \right.$$

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

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

COMPASS collected large amount of L-SIDIS data
Unprecedented precision!

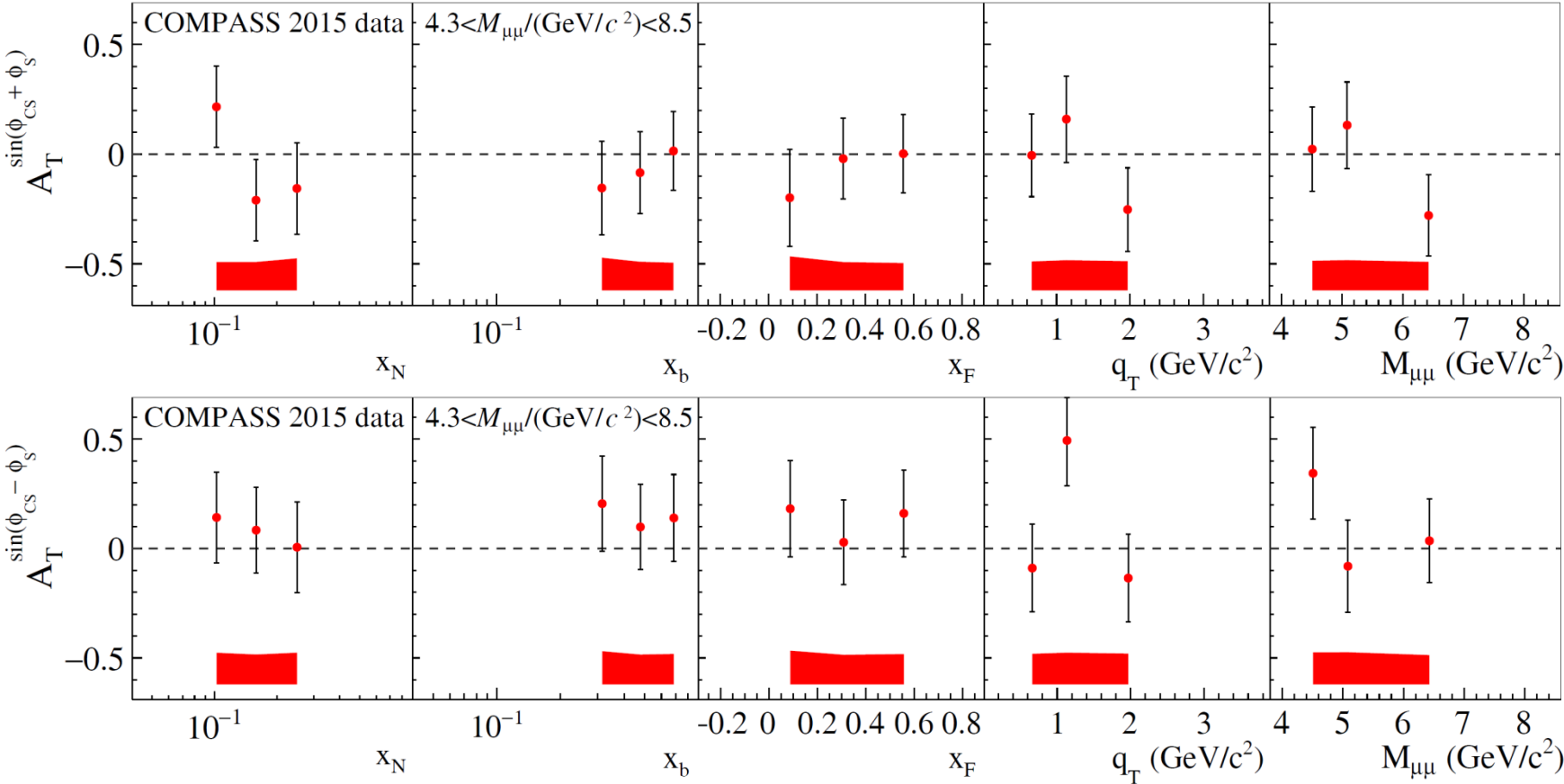
- $A_{UL}^{\sin\phi_h}$
- Q-suppression, Various different “twist” ingredients
- Sizable TSA-mixing
- **Significant h^+ asymmetry, clear z -dependence,**
- **h^- compatible with zero**
- $A_{UL}^{\sin 2\phi_h}$
- Only “twist-2” ingredients
- Additional p_T -suppression
- **Compatible with zero, in agreement with models**
- **Collins-like behavior?**
- $A_{LL}^{\cos\phi_h}$
- Q-suppression, Various different “twist” ingredients
- **Compatible with zero, in agreement with models**



Drell-Yan TSAs – “higher twists”

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

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





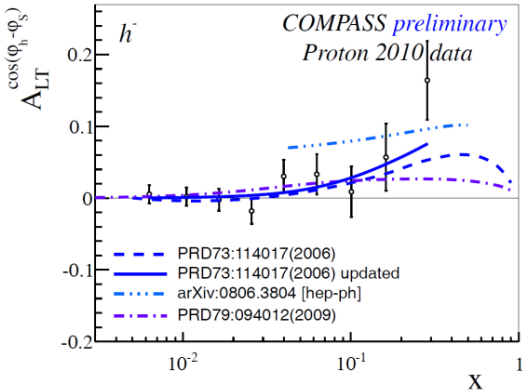
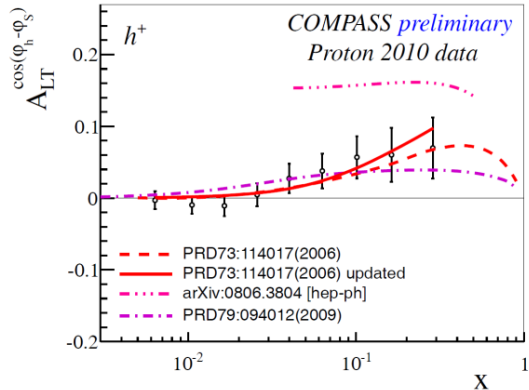
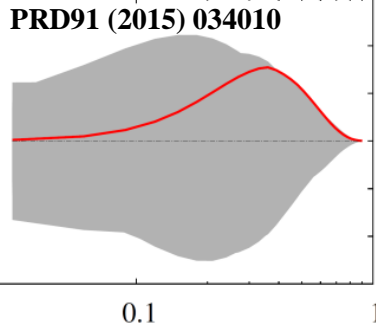
SIDIS: target transverse spin dependent asymmetries

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

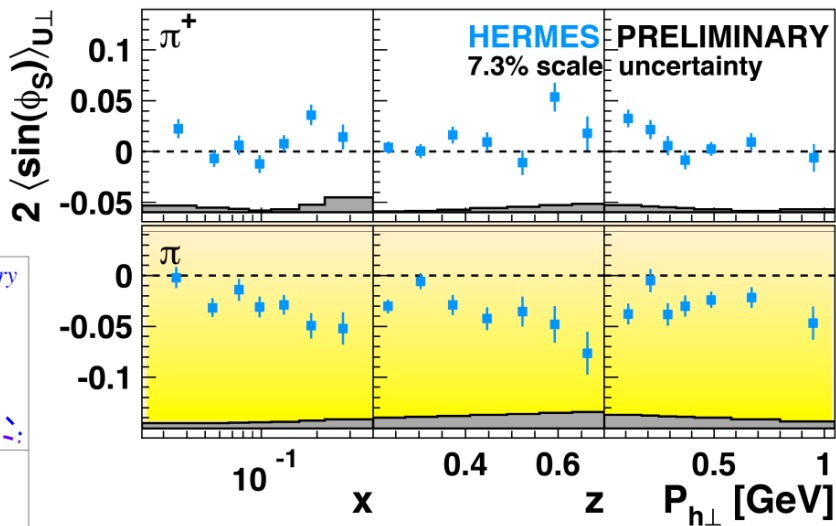
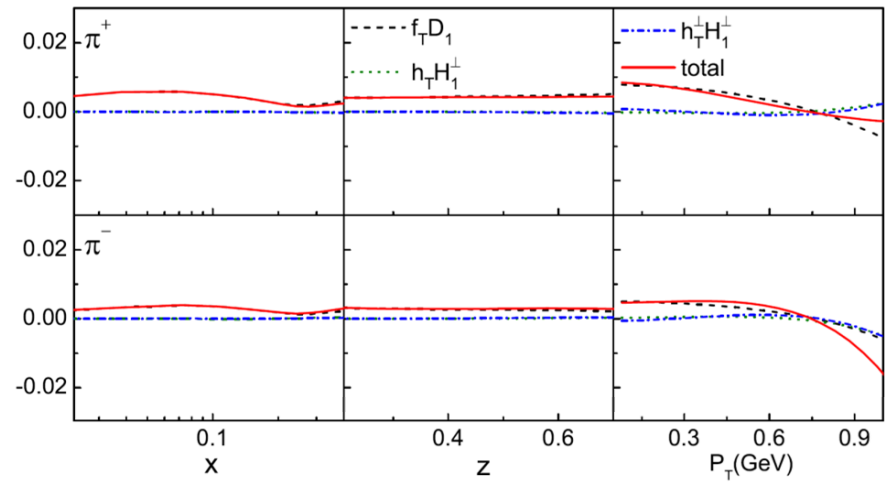
$$+ S_T \left[\begin{aligned} &+ \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \\ &+ \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ &+ \dots \end{aligned} \right]$$

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

C. Lefky & A. Prokudin



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



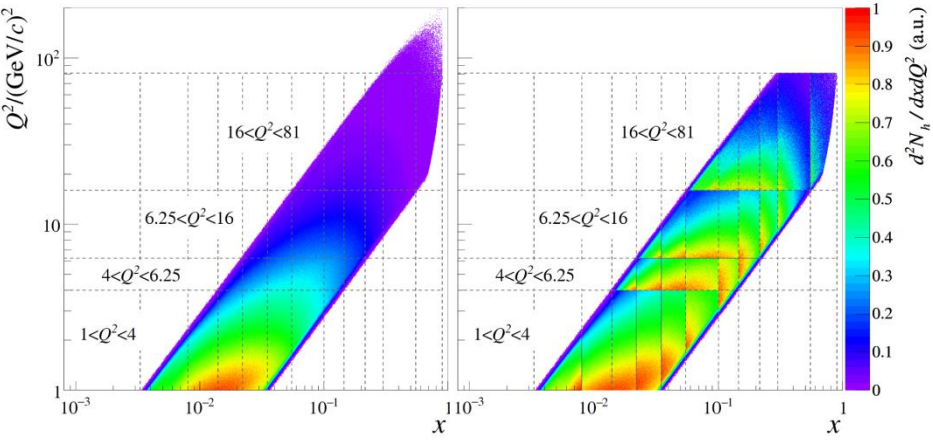


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2 -ranges

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

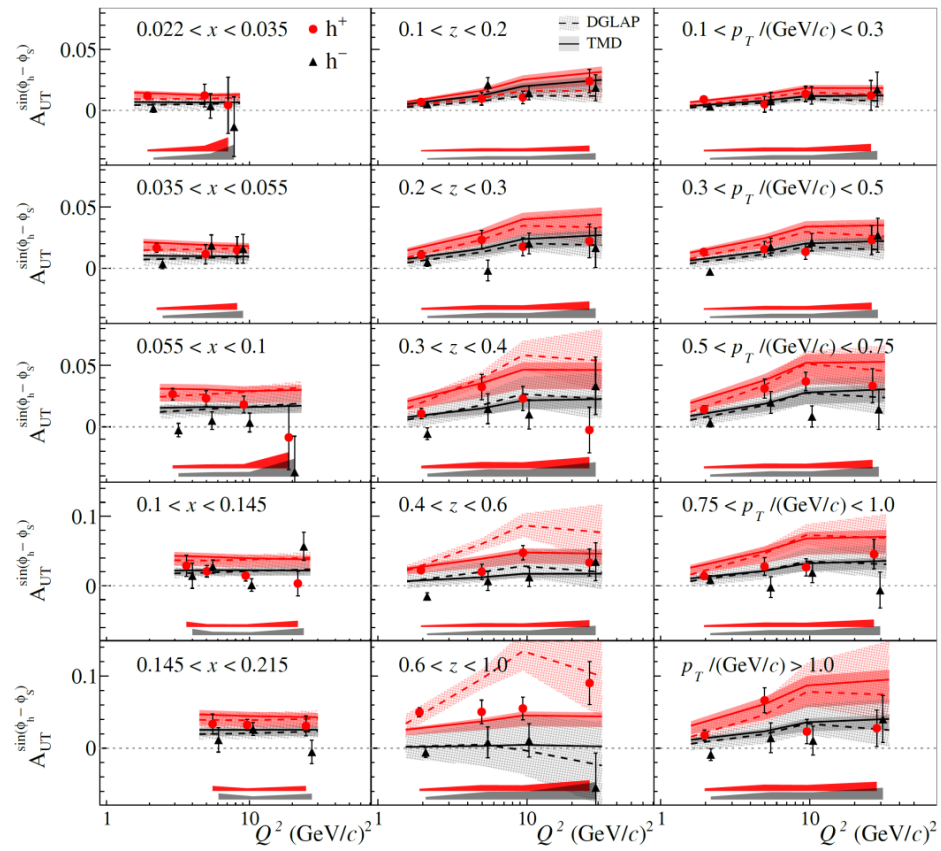
$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

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Multi-dimensional input for TMD evolution studies

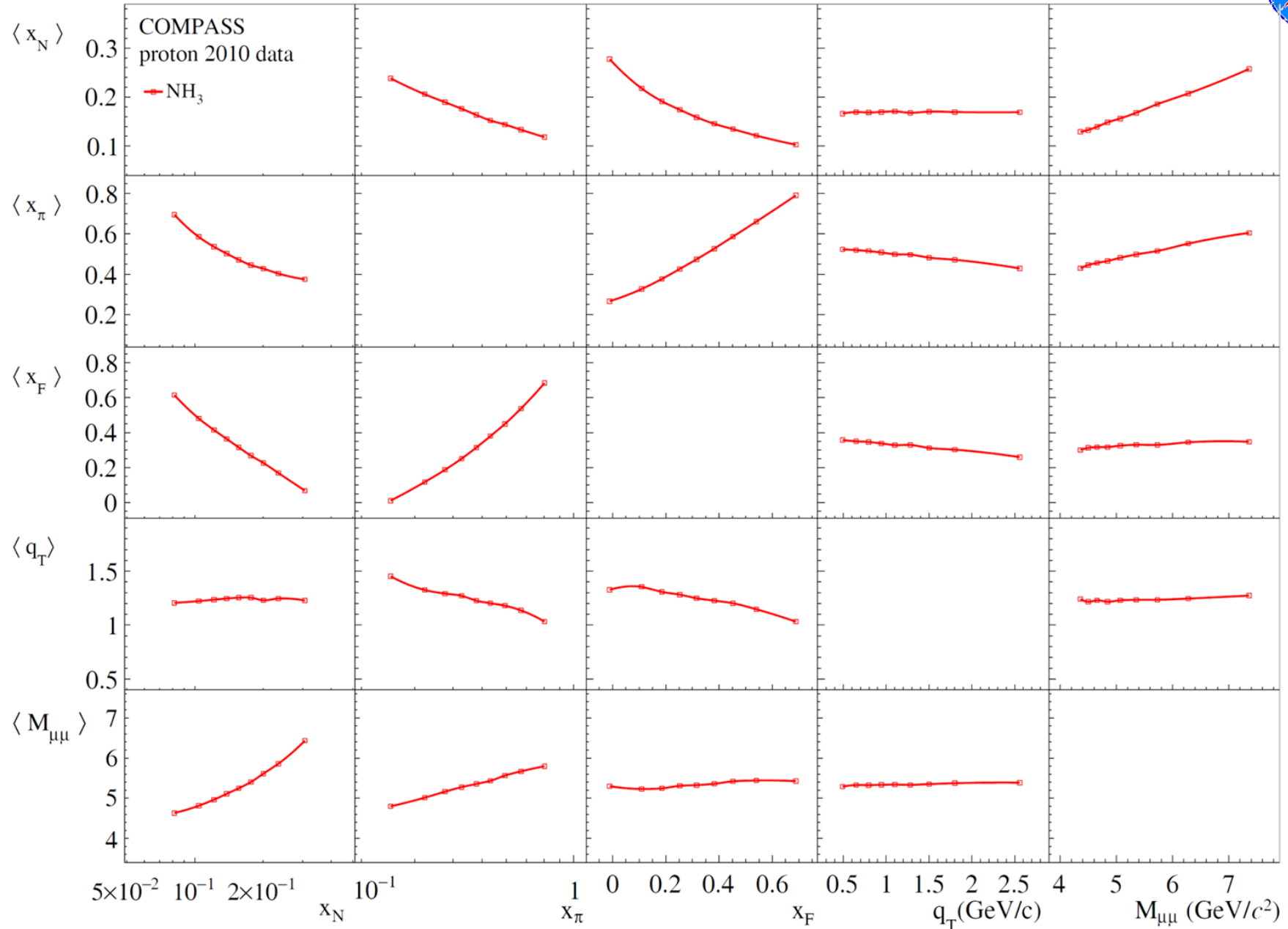
- No clear Q^2 -dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?



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



Kinematic map: high mass range





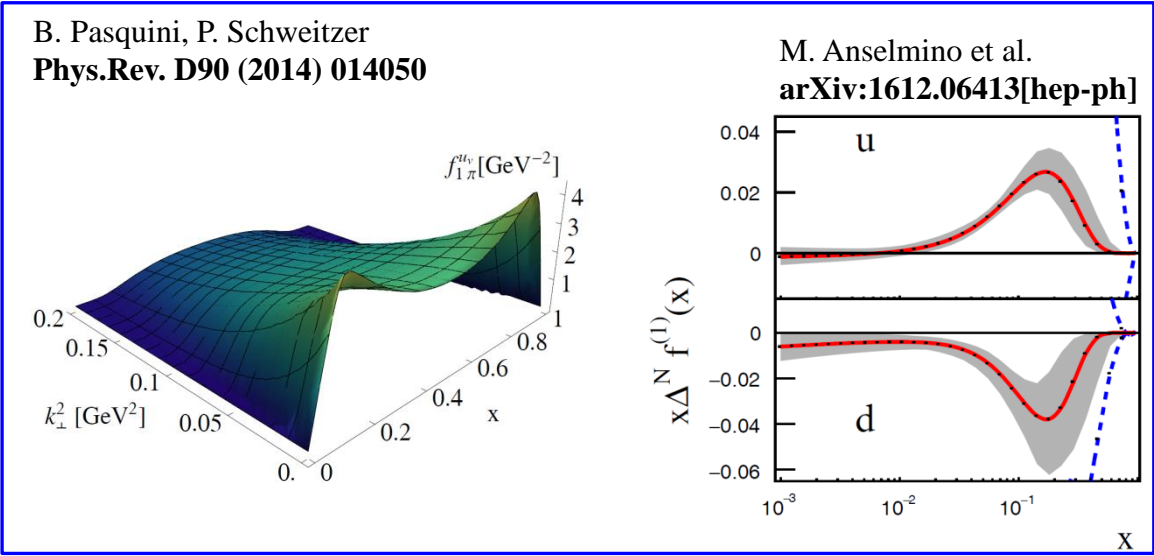
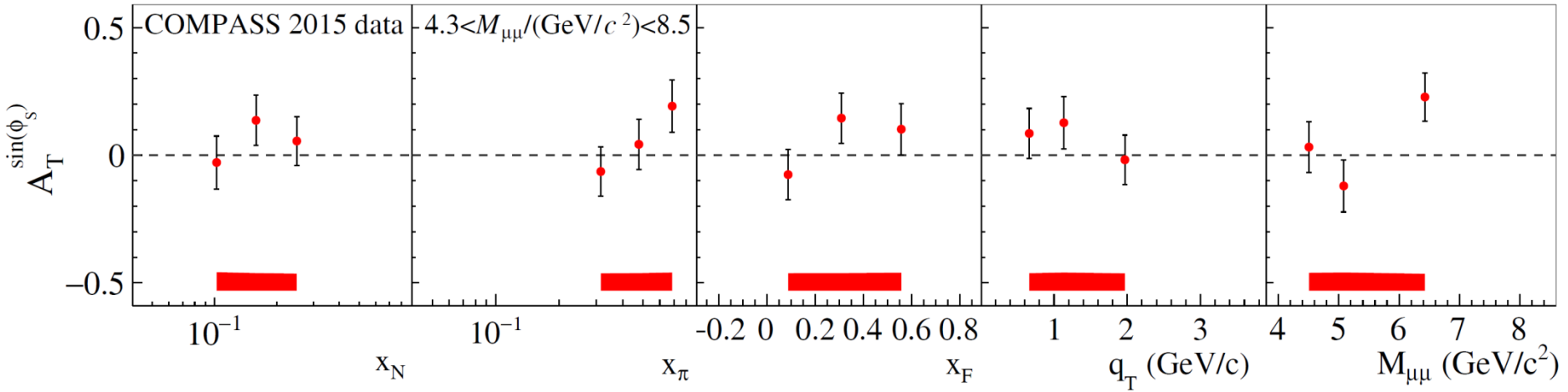
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

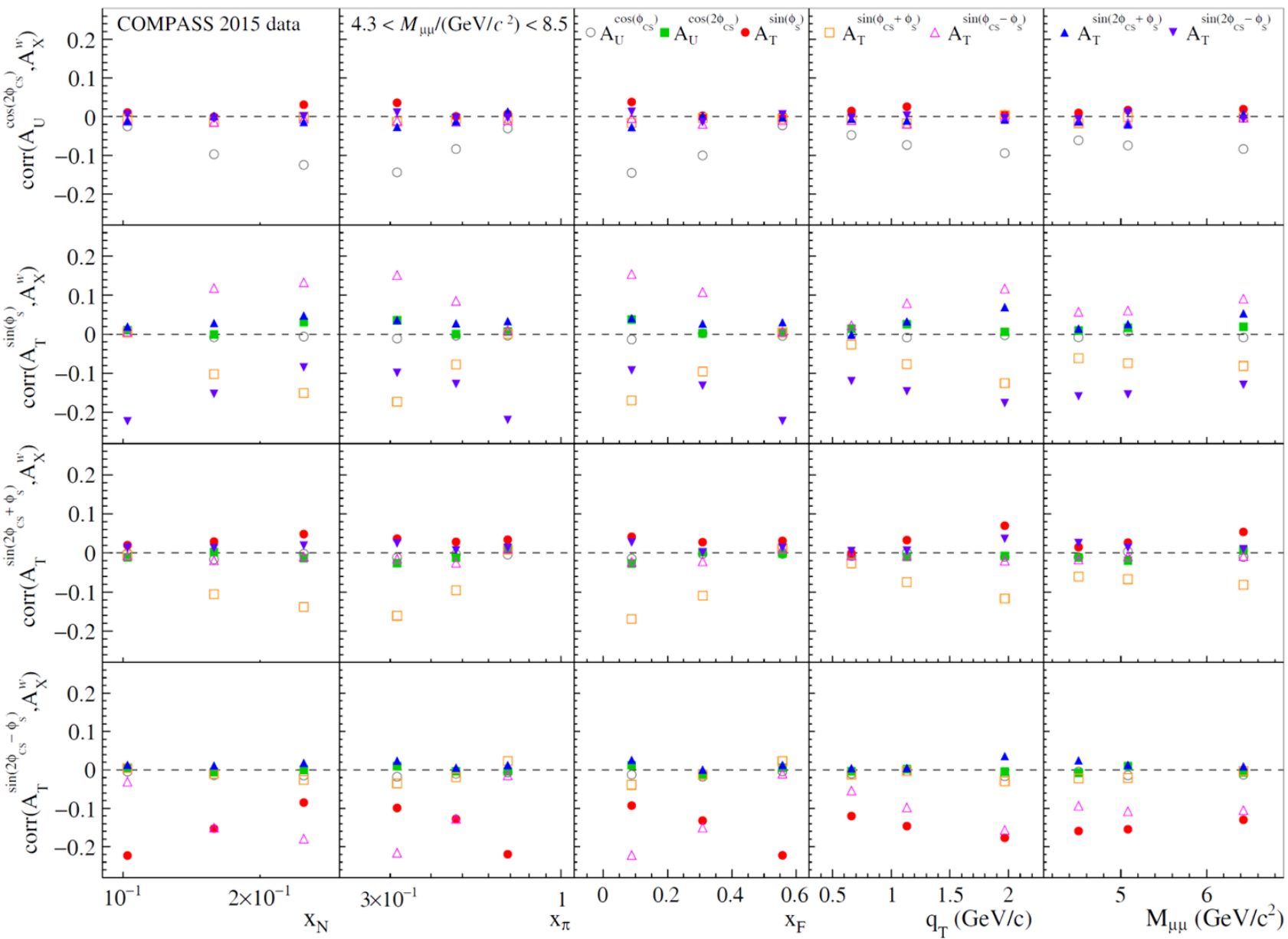
$$A_T^{\sin\phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

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





Correlation coefficients



Maximum correlations are about ~0.2



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

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

$$\begin{aligned} \int d^2 \mathbf{q}_T \frac{q_T}{M_p} F_T^{\sin \phi_S} &= - \int d^2 \mathbf{q}_T \frac{q_T}{M_p} \mathcal{C} \left[\frac{\mathbf{q}_T \cdot \mathbf{k}_{pT}}{q_T M_p} f_{1,\pi} f_{1T,p}^\perp \right] \\ &= - \frac{2}{N_c} \sum_q e_q^2 [f_{1,\pi}^{\bar{q}}(x_\pi) f_{1T,p}^{\perp(1)q}(x_p) + (q \leftrightarrow \bar{q})] \\ &\approx \frac{2e_u^2}{N_c} f_{1,\pi}^{\bar{u}}(x_\pi) f_{1T}^{\perp(1)u}(x_N) \end{aligned}$$

Sivvers TSA in SIDIS:	$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$
Sivvers wTSA in SIDIS:	$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q(1)} \times D_{1q}^h$
Sivvers TSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
Sivvers wTSA in DY:	$A_T^{\sin \phi_S} \propto f_{1,\pi}^q \times f_{1T,p}^{\perp q(1)}$

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

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

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

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