The spin program of the COMPASS experiment: recent results and plans

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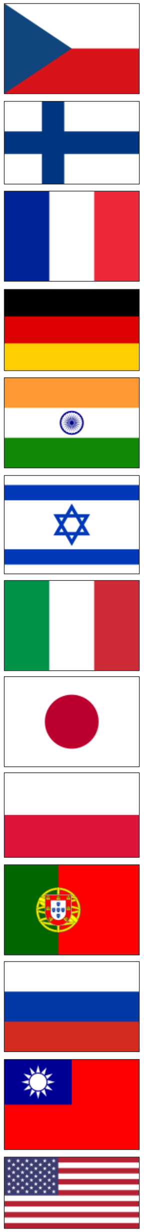
ALMA UNIVERSITAS TAURINENSIS

on behalf of the COMPASS Collaboration

QCD Evolution 2018
International workshop
Santa Fe, NM, US
May 20 – 24, 2018

COMPASS collaboration

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



24 institutions from 13 countries
– nearly 250 physicists

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

Wide physics program

COMPASS-I

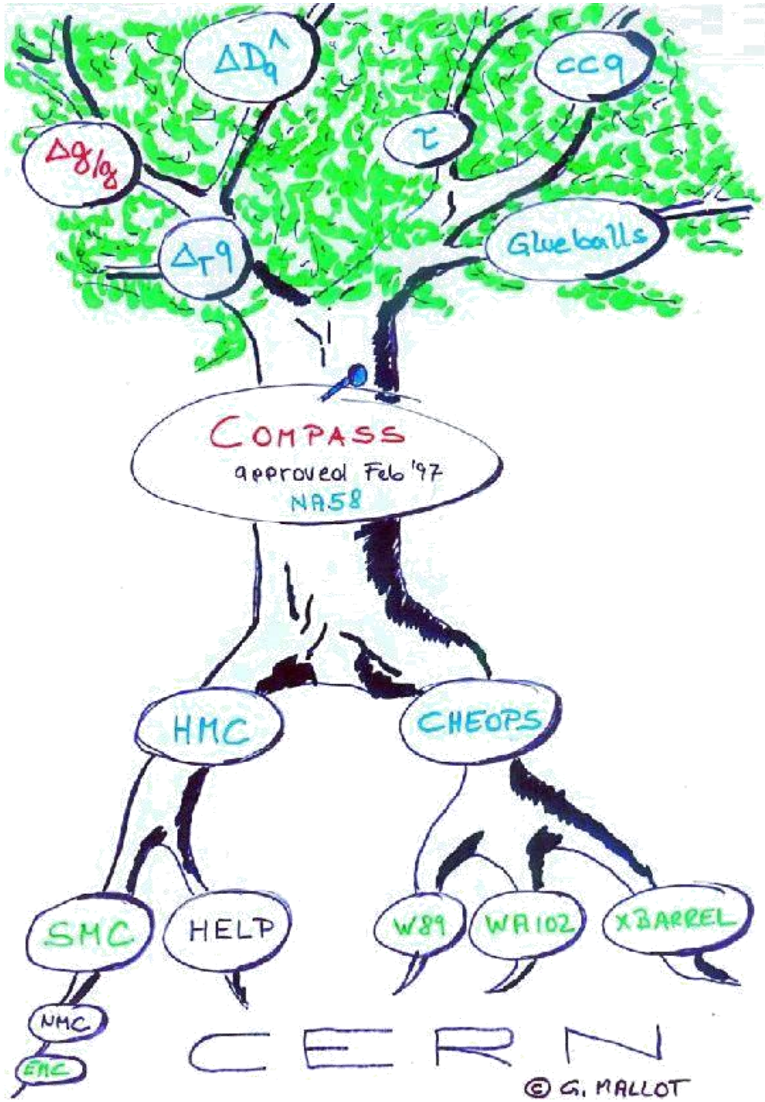
- **Data taking 2002-2011**
- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

COMPASS-II

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

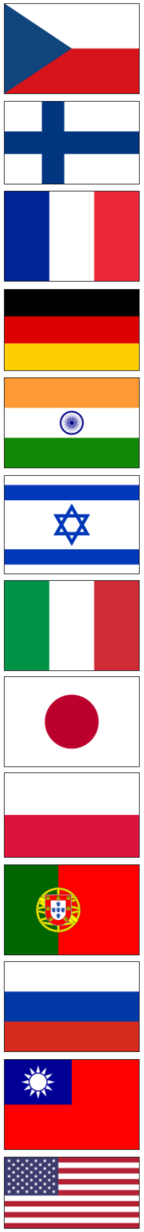
Many "beyond 2021" ideas:

Proton-radius, Drell-Yan, spectroscopy…



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

COMPASS collaboration



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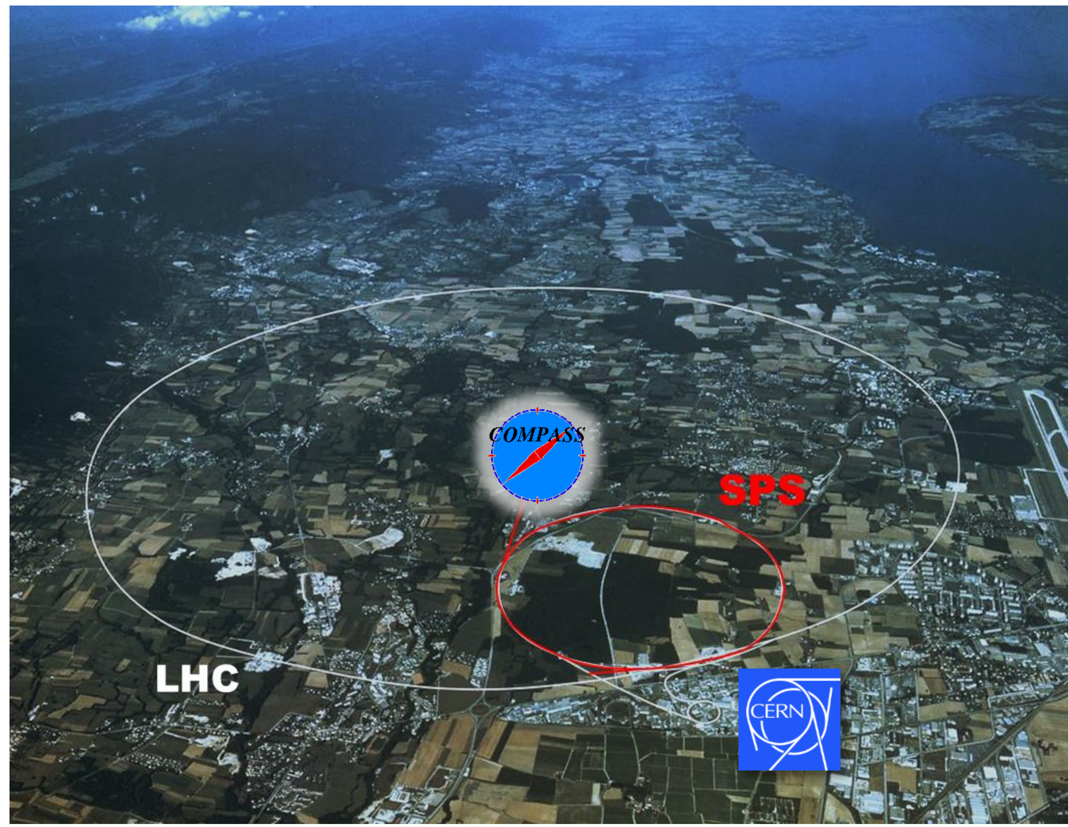

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COMPASS experimental setup: Phase I (muon program)

Two-stage spectrometer

- Large Angle Spectrometer (SM1 magnet)
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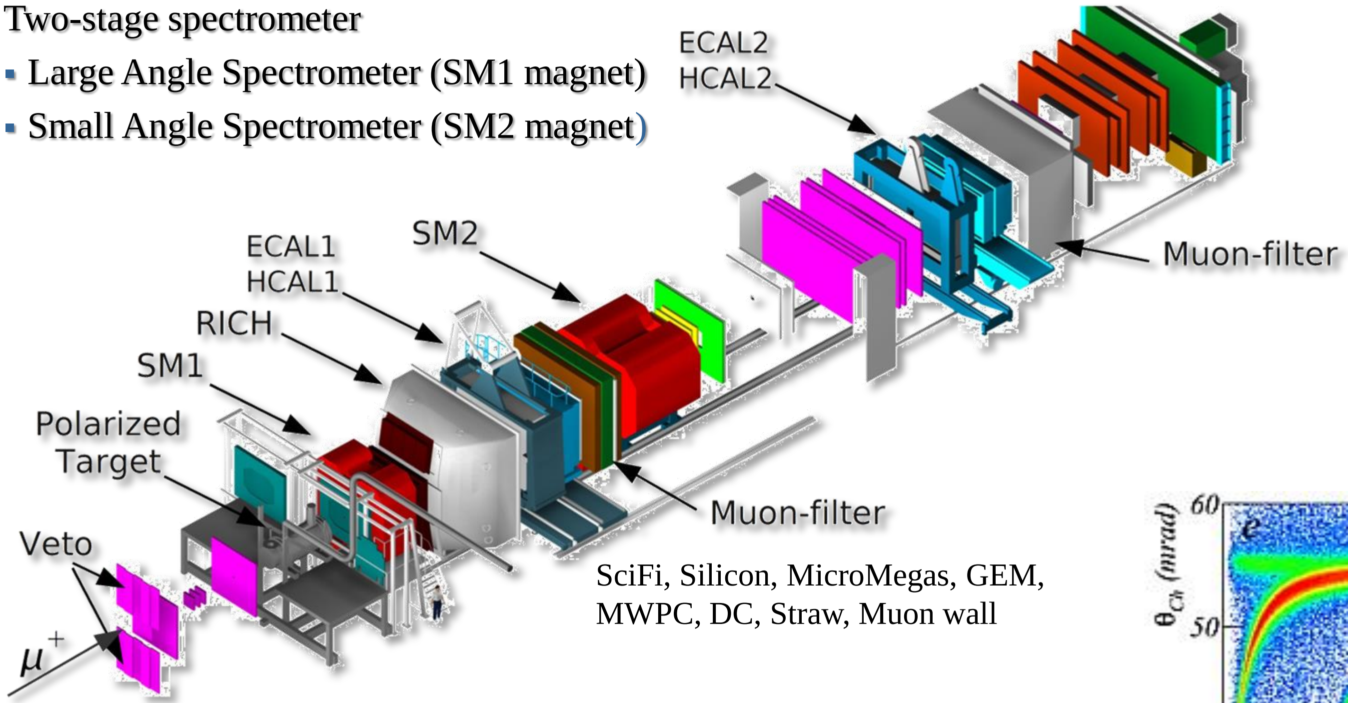
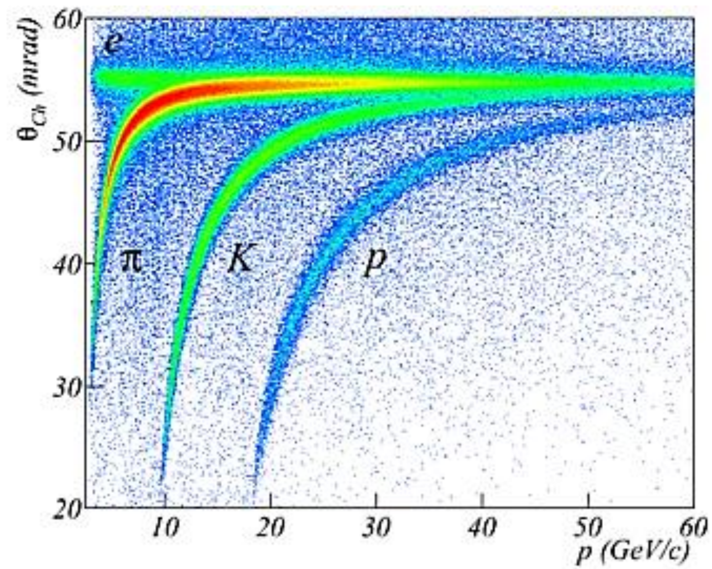


- High energy beam
- Large angular acceptance
- Broad kinematical range
- Momentum, tracking and calorimetric measurements, PID



Data-taking years: 2002-2011

Longitudinally polarized (80%) μ^+ beam:

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

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

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

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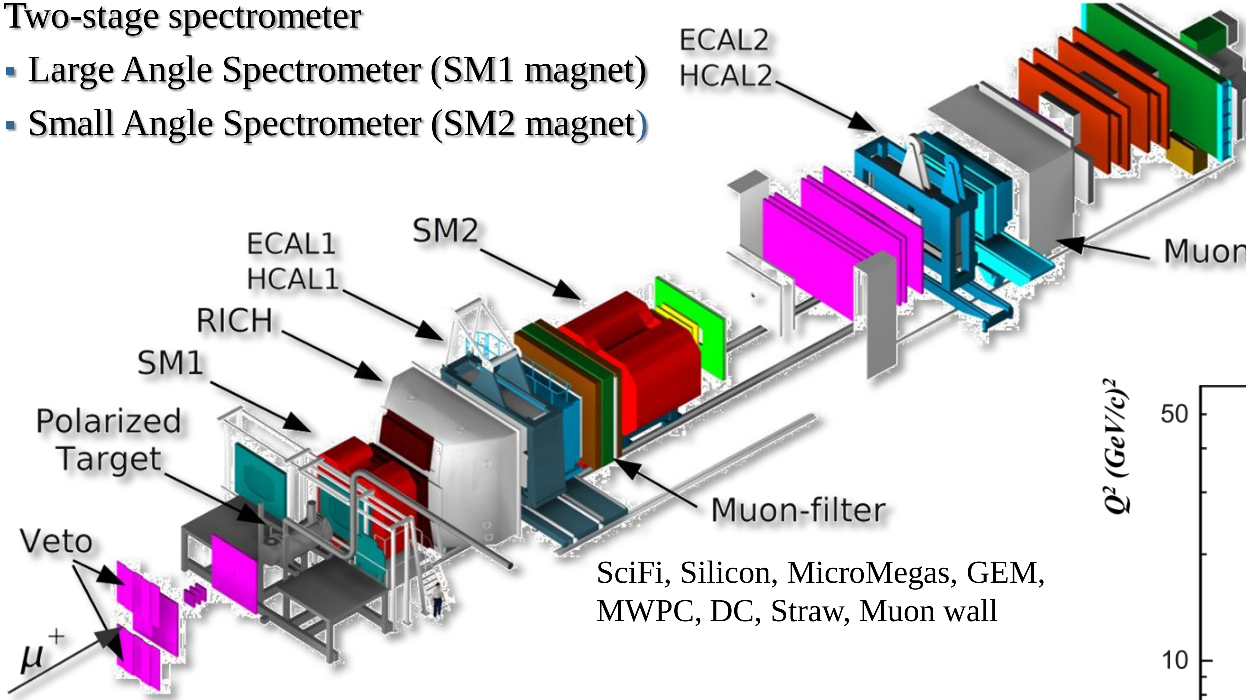

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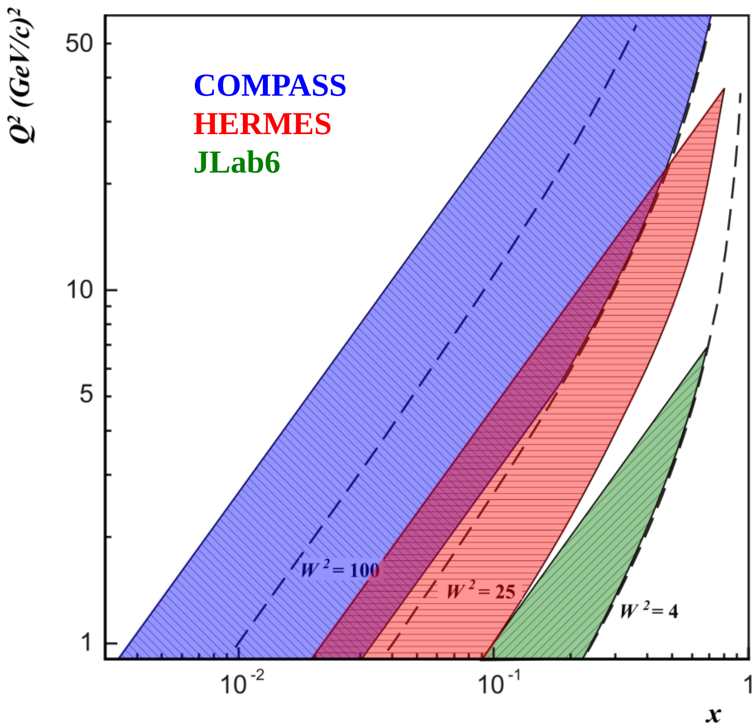

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COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer
- Large Angle Spectrometer (SM1 magnet)
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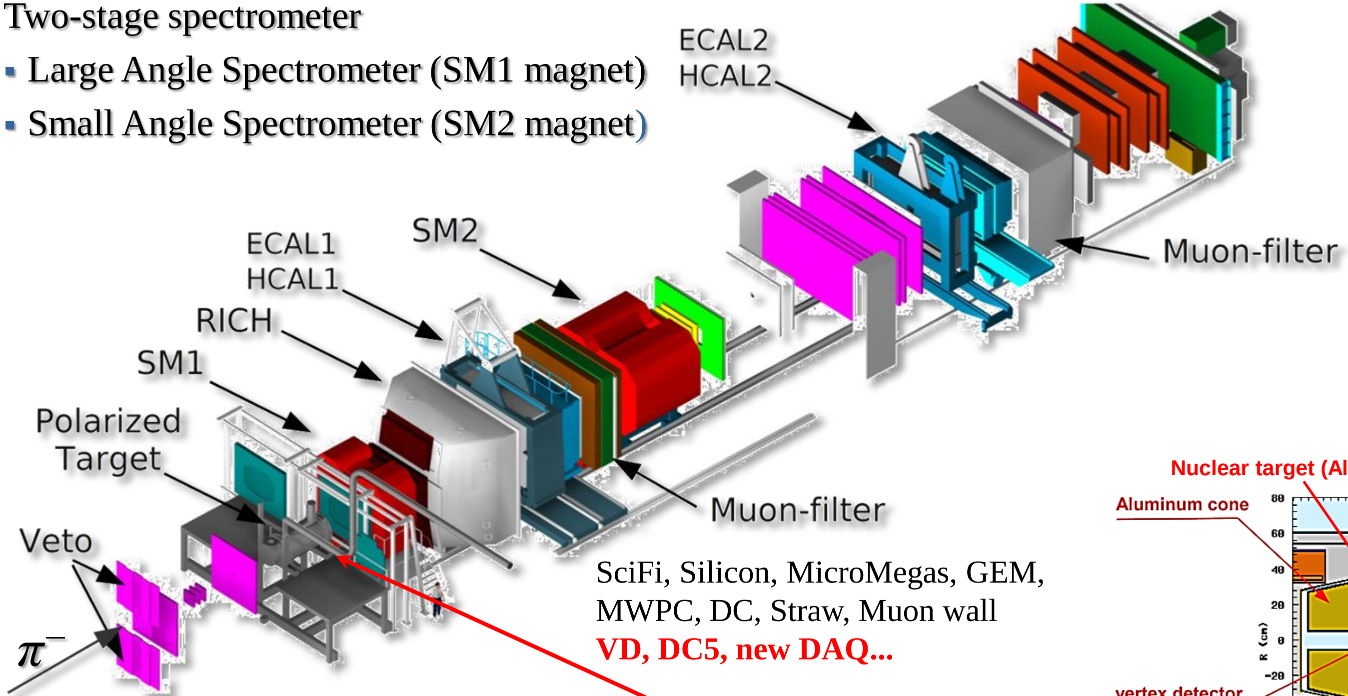
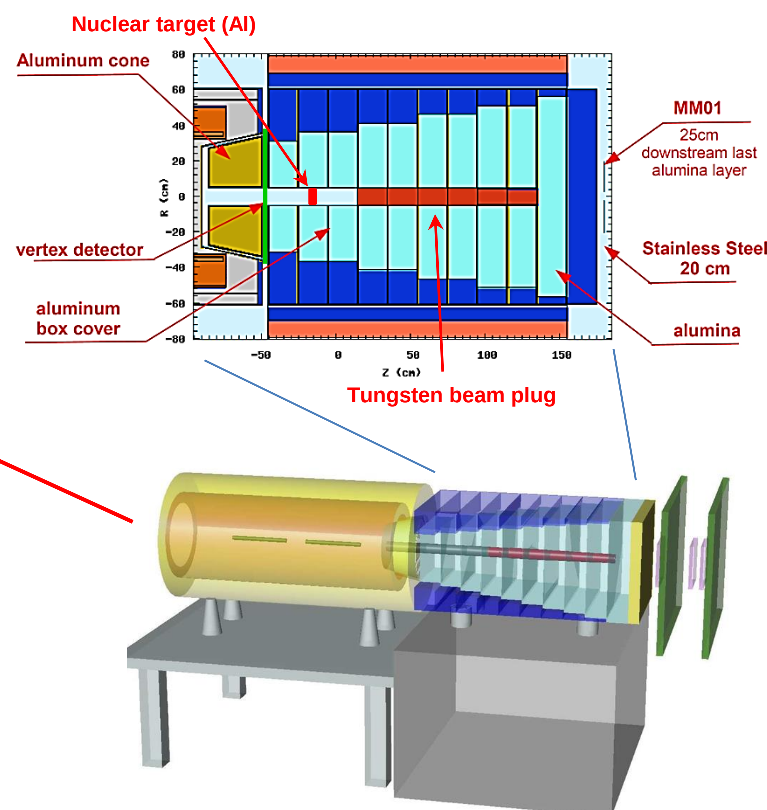


SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
VD, DC5, new DAQ...

Hadron absorber



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

High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

- NH_3 2-cell configuration. Polarization T ~ 73%, f ~ 0.18

COMPASS experimental setup: Phase II (DY program)

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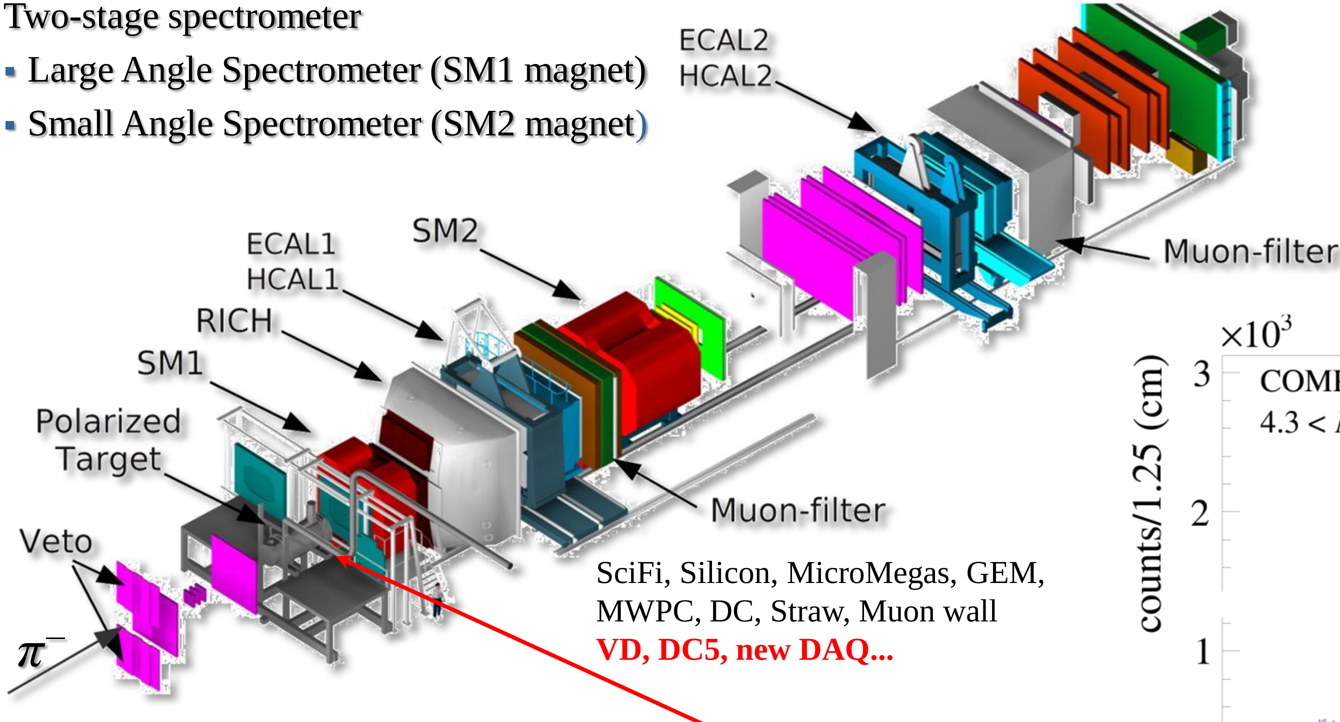

SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon wall
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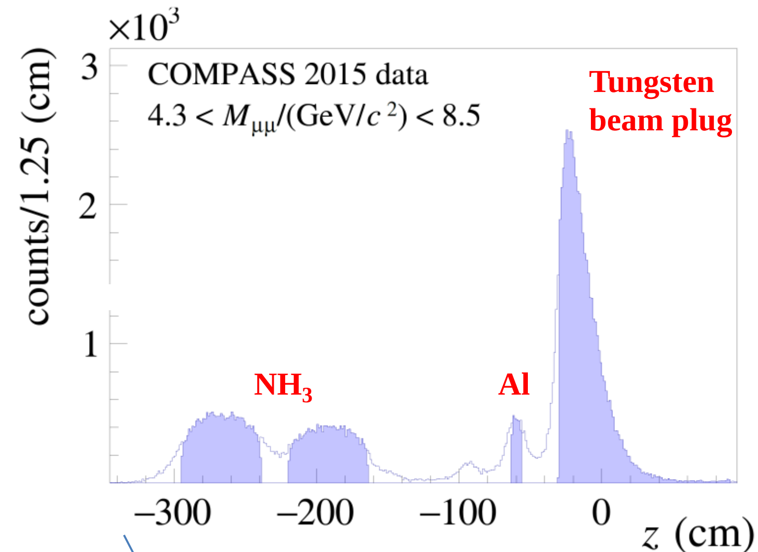

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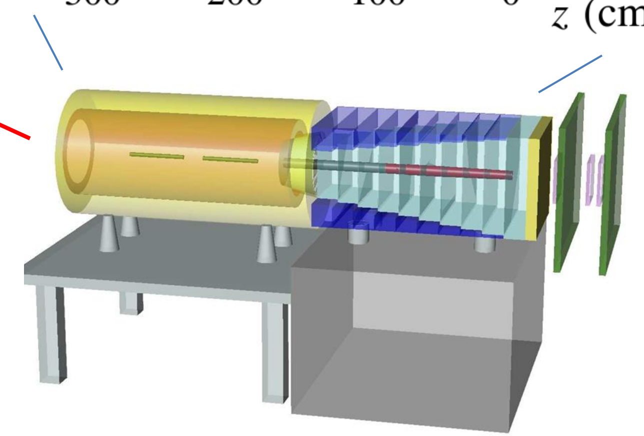

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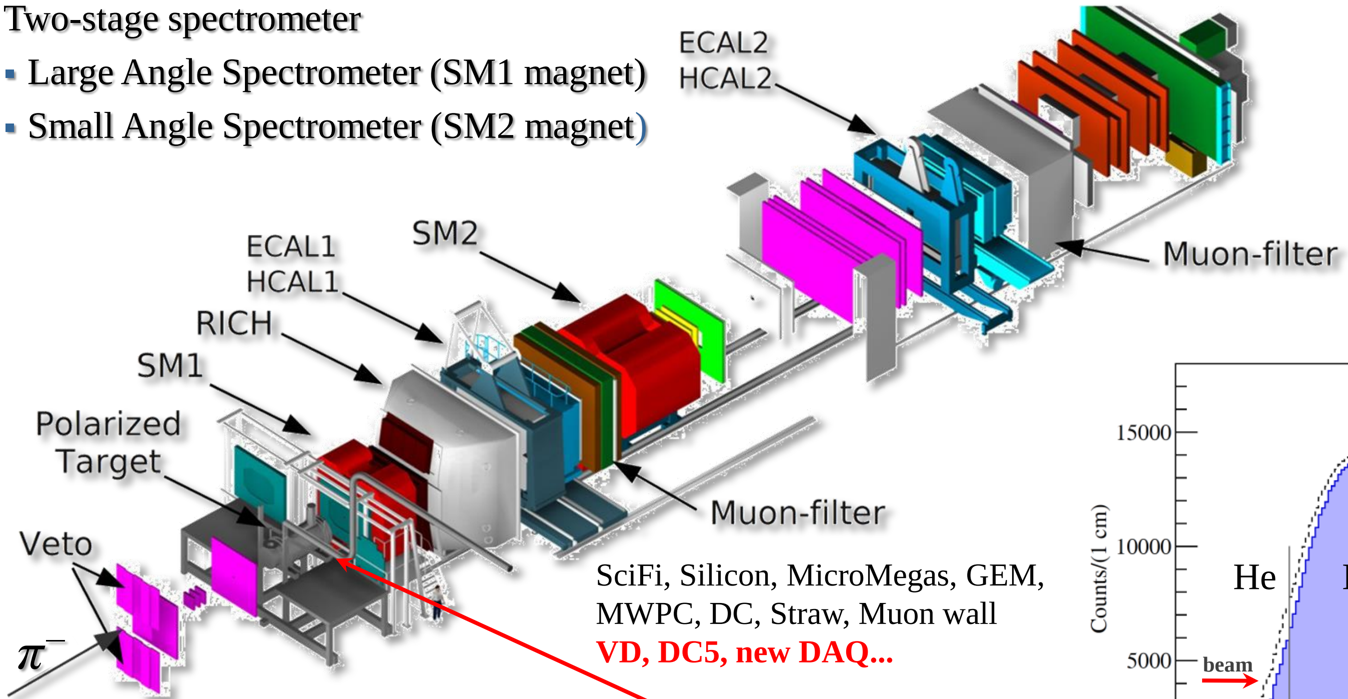

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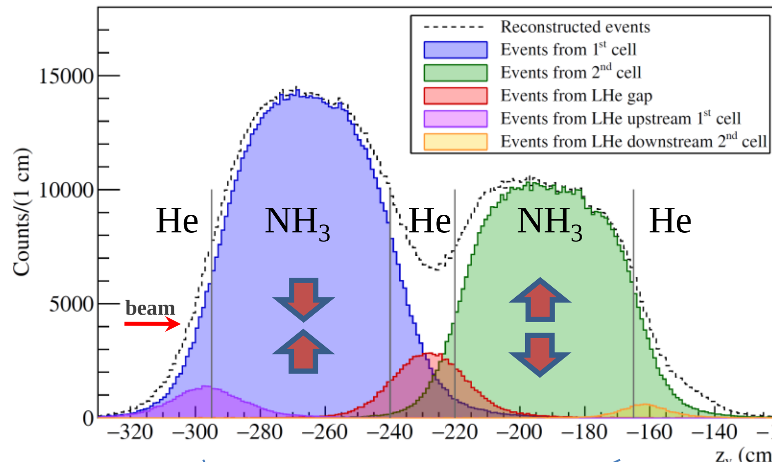
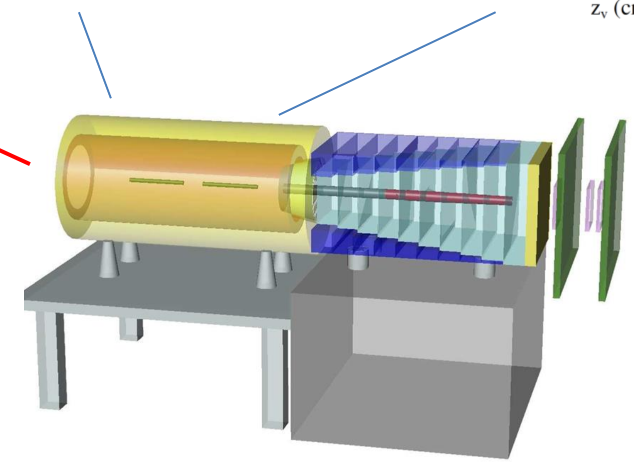




Data-taking years: 2014 (test) 2015 and 2018

High energy π^- beam:

Energy: 190 GeV/c, Intensity: 10^8 π/s

Target: Solid state

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

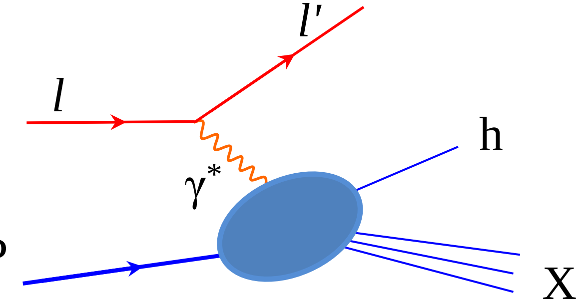
SIDIS x-section

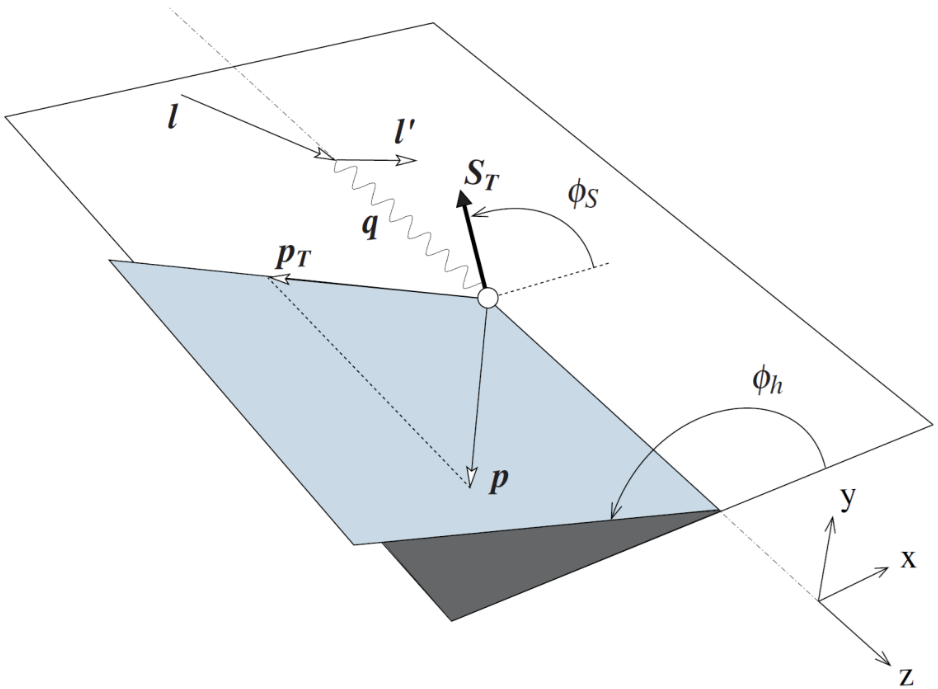
A.Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

All measured by COMPASS

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

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





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

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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+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) \\
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+S_T\lambda\left[\begin{array}{l}
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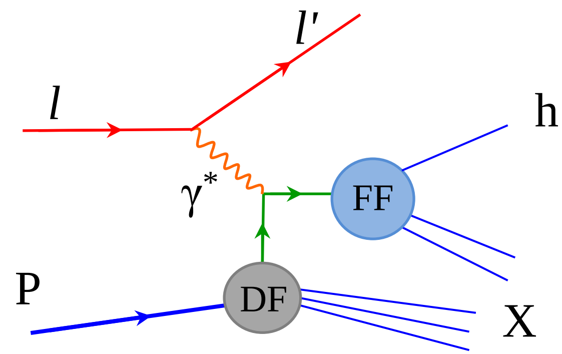

Nucleon \ Quark	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders**
L		$g_1^q(x,\boldsymbol{k}_T^2)$ **helicity**	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ **worm-gear L**
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ **Sivers**	$g_{1T}^q(x,\boldsymbol{k}_T^2)$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

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

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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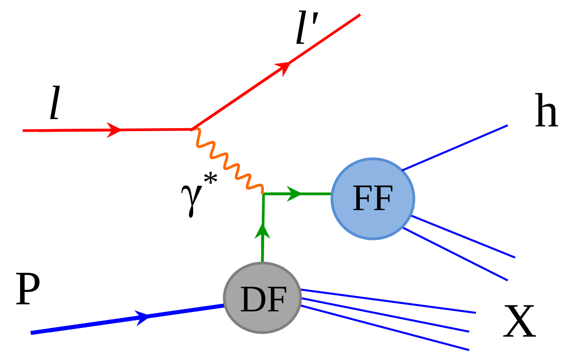

Nucleon \ Quark	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

spin of the nucleon — spin of the quark — k_T

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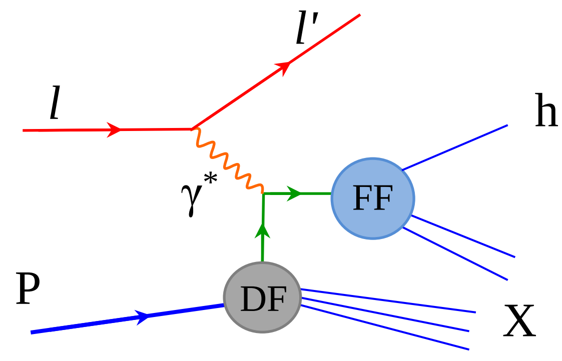

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$$A_{UU}^{\cos\phi_h} \overset{WW}{\propto} Q^{-1}\left(f_1^q\otimes D_{1q}^h+h_1^{\perp q}\otimes H_{1q}^{\perp h}\ldots\right)$$

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

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

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

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

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

Twist-2

Twist-3

WW = Wandzura-Wilczek-type approximation"

See talk by S. Bastami

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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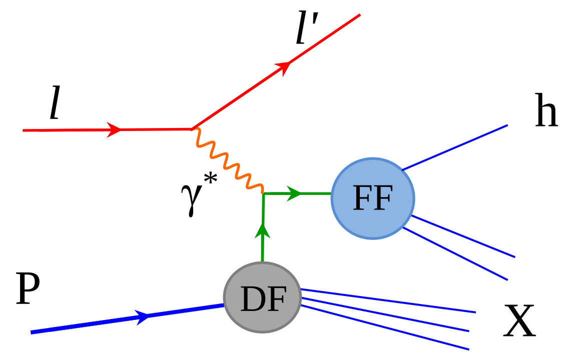


$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^h$$

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

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

Twist-2

Twist-3

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

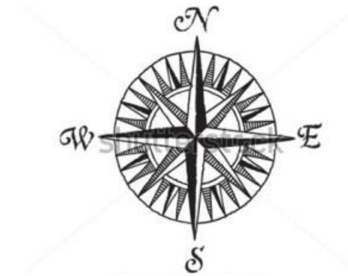
$$A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^h+\ldots\right)$$

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

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

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

COMPASS bridge



SIDIS and single-polarized DY x-sections

SIDIS

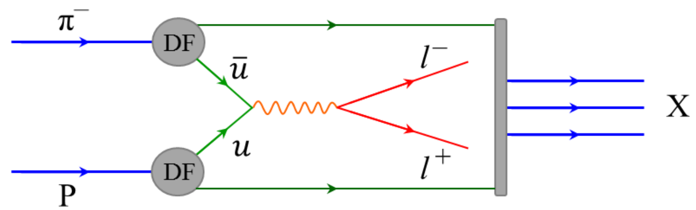
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S}=\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

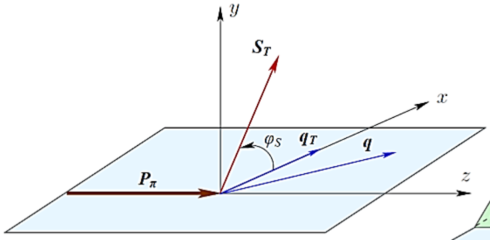
$$\begin{aligned}
\times\Big\{ 1 &+ \sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos2\phi_h}\cos2\phi_h \\
&+ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
&+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin2\phi_h}\sin2\phi_h\right] \\
&+ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
&+ S_T\left[\begin{aligned}
&A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\
&+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\
&+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
&+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\
&+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{aligned}\right] \\
&+ S_T\lambda\left[\begin{aligned}
&\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\
&+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{aligned}\right]\Big\}
\end{aligned}$$

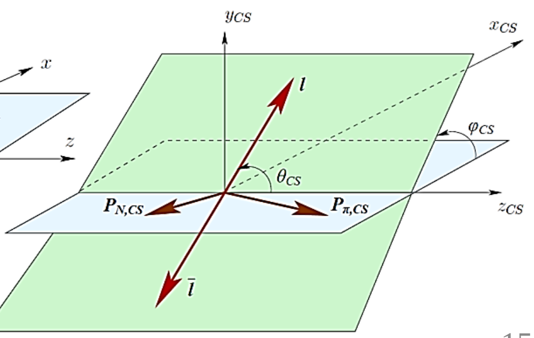
DY

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

$$\begin{aligned}
\times\Big\{ 1 &+ A_U^1\cos^2\theta_{CS} \\
&+ \sin2\theta_{CS}A_U^{\cos\varphi_{CS}}\cos\varphi_{CS}+\sin^2\theta_{CS}A_U^{\cos2\varphi_{CS}}\cos2\varphi_{CS} \\
&+ S_L\left[\sin\theta_{CS}A_L^{\sin\varphi_{CS}}\sin\varphi_{CS}+\sin^2\theta_{CS}A_L^{\sin2\varphi_{CS}}\sin2\varphi_{CS}\right] \\
&+ S_T\left[\begin{aligned}
&\left(A_T^{\sin\varphi_S}+\cos^2\theta_{CS}\tilde{A}_T^{\sin\varphi_S}\right)\sin\varphi_S \\
&+\sin^2\theta_{CS}\left(\begin{aligned}&A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)\\&+A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S)\end{aligned}\right) \\
&+\sin2\theta_{CS}\left(\begin{aligned}&A_T^{\sin(\varphi_{CS}-\varphi_S)}\sin(\varphi_{CS}-\varphi_S)\\&+A_T^{\sin(\varphi_{CS}+\varphi_S)}\sin(\varphi_{CS}+\varphi_S)\end{aligned}\right)
\end{aligned}\right]\Big\}
\end{aligned}$$







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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

SIDIS

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

SIDIS-DY bridge

DY

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

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

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

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

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

SIDIS

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

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

SIDIS-DY bridge

DY

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

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

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

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

within QCD TMD-framework:

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

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

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

SIDIS

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

DY

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

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

SIDIS-DY bridge

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

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

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

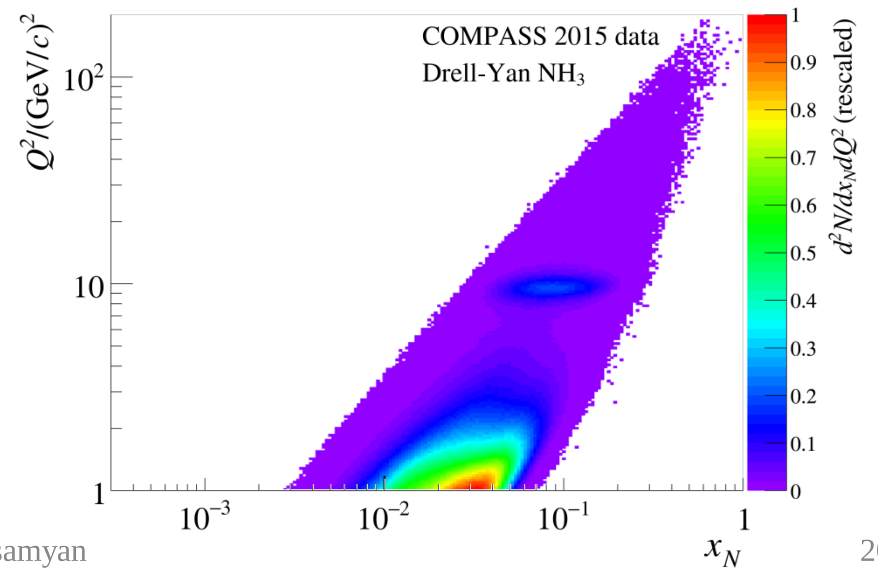
SIDIS-DY bridge

DY

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

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

COMPASS x:Q² phase space (DY 2015 data)



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

SIDIS

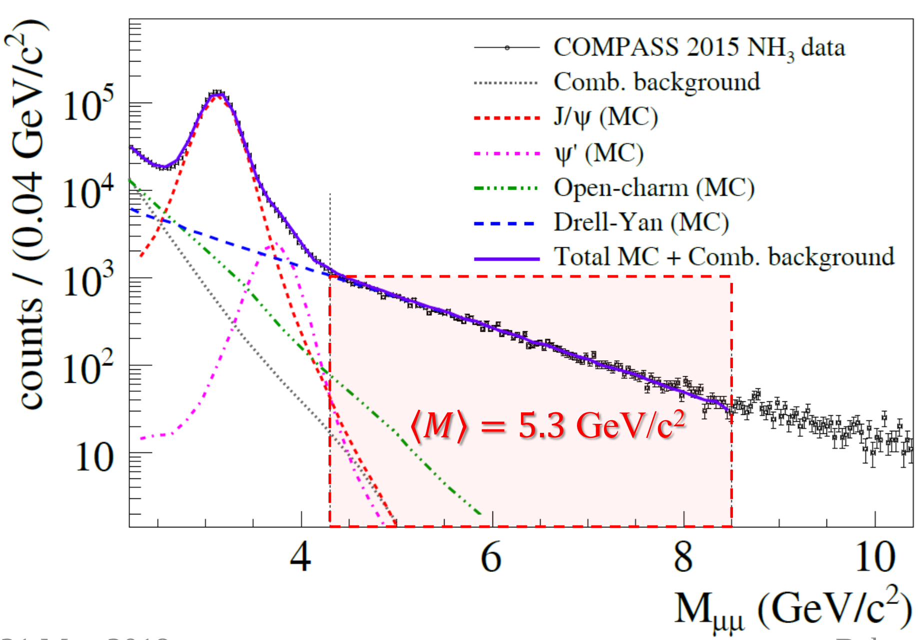
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \Big\{ 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} + S_T\Big[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)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

DY

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

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

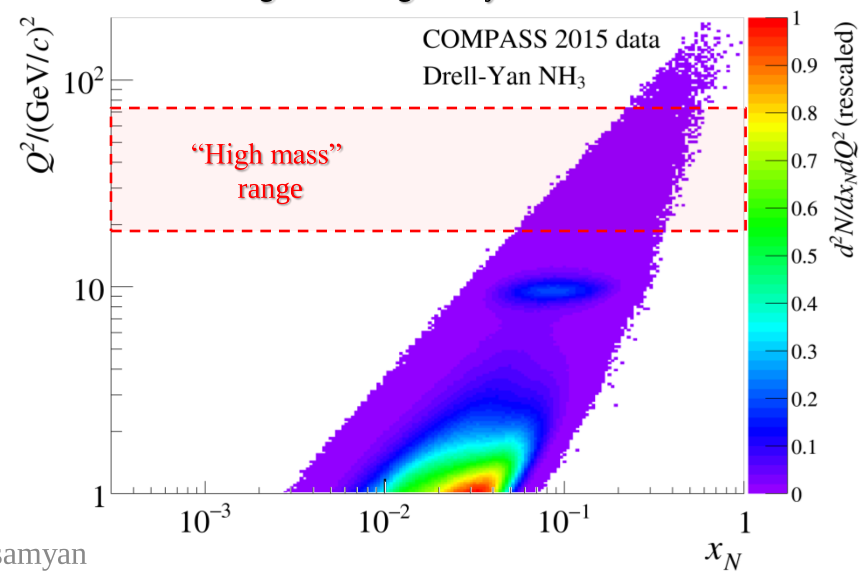
SIDIS-DY bridge



4.3 < M /(GeV/c²) < 8.5 "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries



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

SIDIS

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

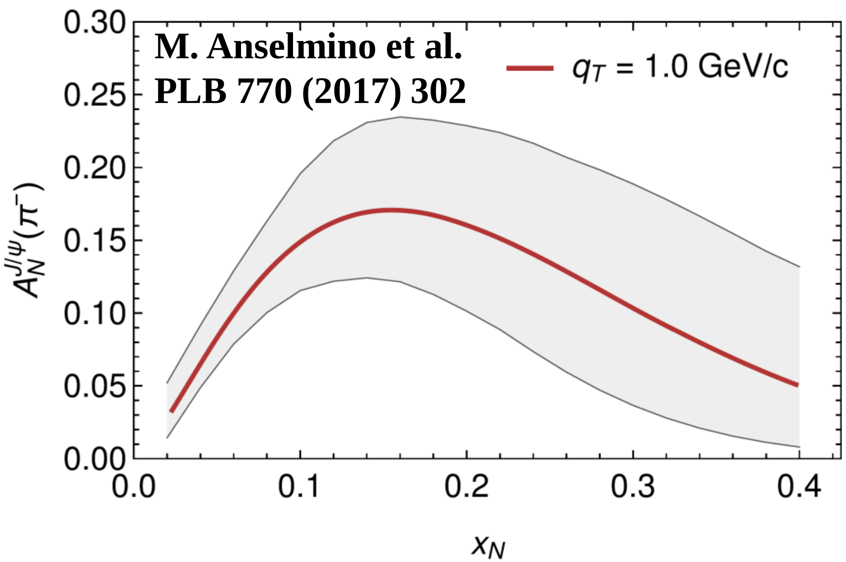
DY

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

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

SIDIS-DY bridge

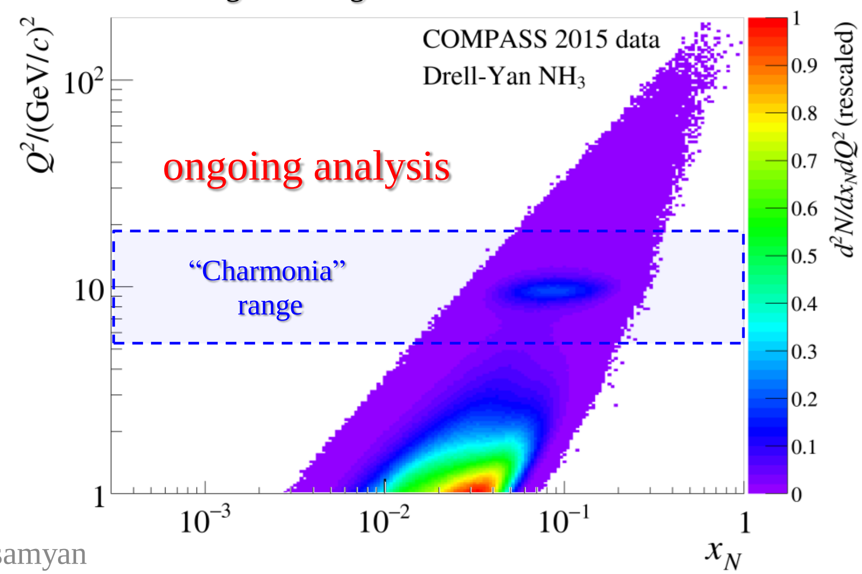
$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c



$2.5 < M/(GeV/c2) < 4.3$ "Charmonia mass"

Strong J/ψ-signal → study of J/ψ physics

Good signal/background



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

SIDIS

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

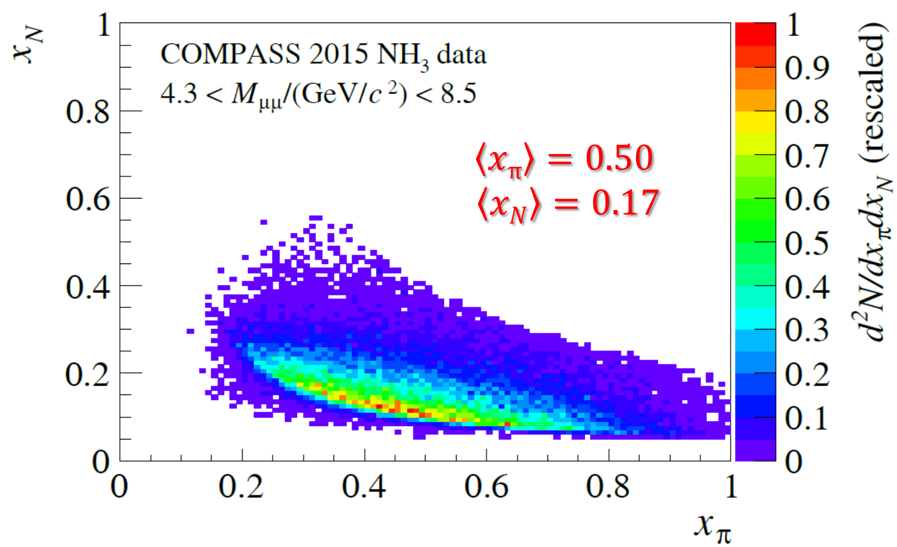
DY

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

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

SIDIS-DY bridge

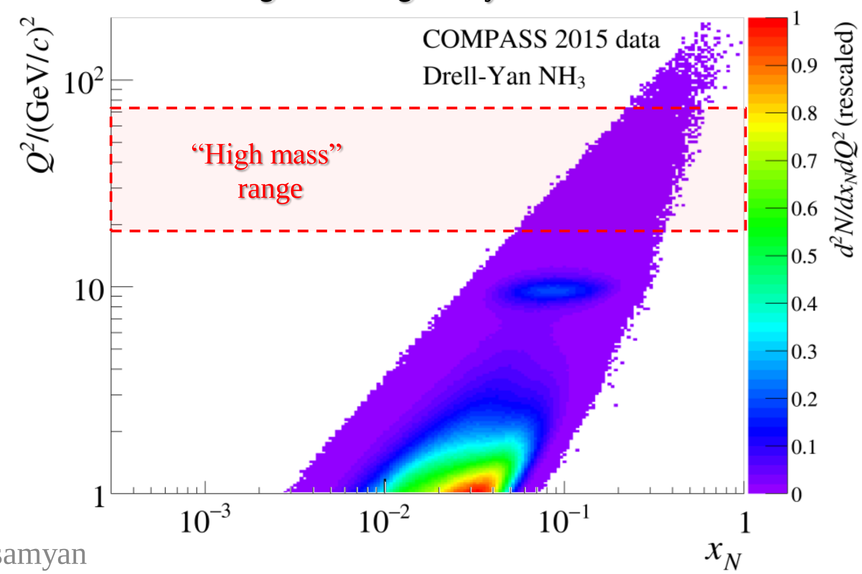
HM events are in the valence quark range



$4.3 < M/(\mathrm{GeV}/c^2) < 8.5$ "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries



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

SIDIS

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

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

DY

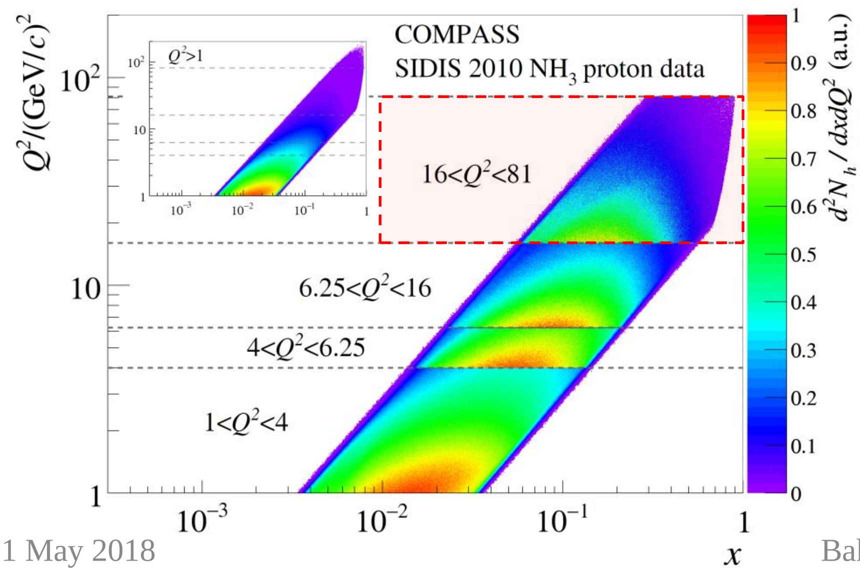
$$\frac{d\sigma^{LO}}{d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

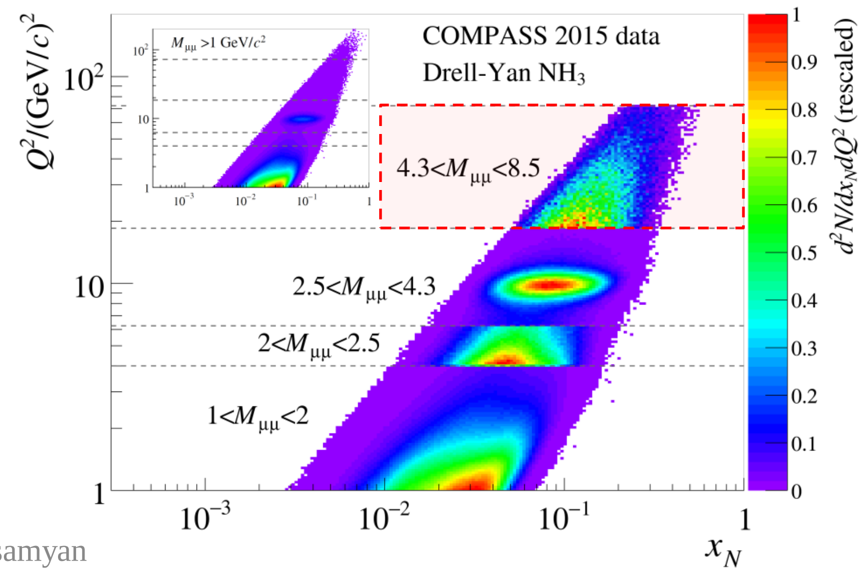
$$\times \left\{ \begin{array}{l} 1 + \boxed{D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ \boxed{+ S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l}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

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

SIDIS-DY bridge

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





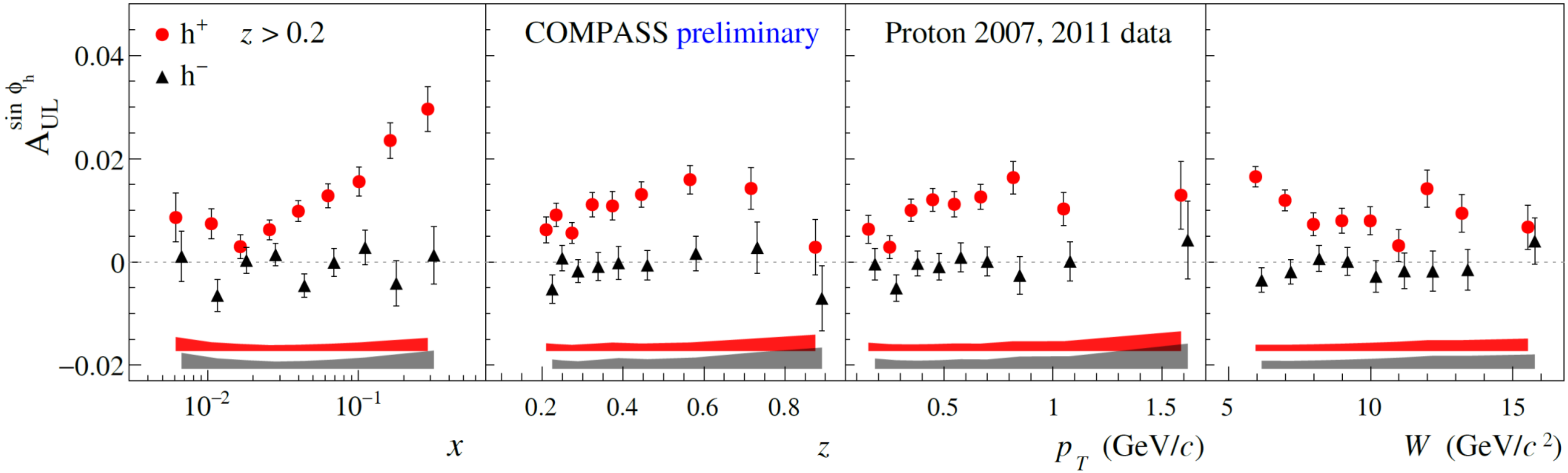
- Longitudinal target spin dependent azimuthal asymmetries

SIDIS: target longitudinal spin dependent asymmetries

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

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

B.Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex] (DIS-2017)



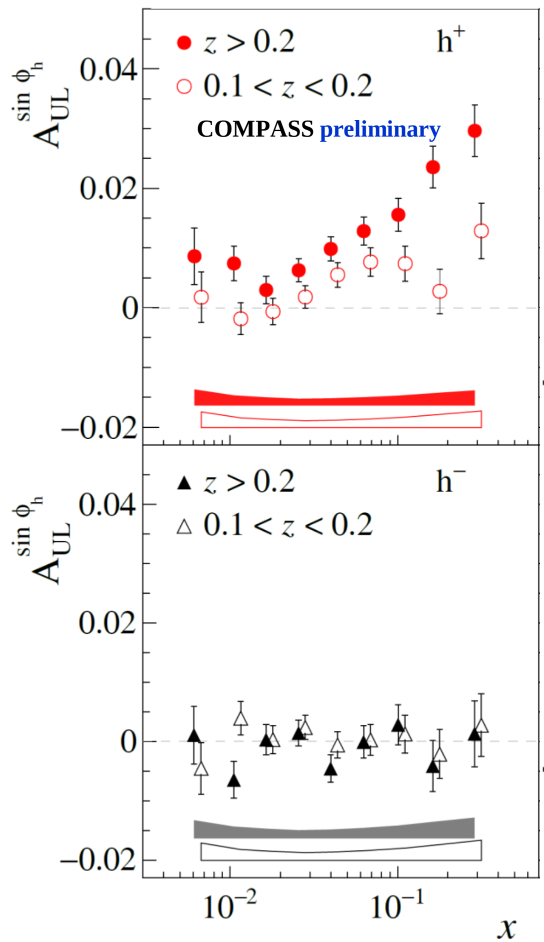
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h^+, h^- compatible with zero**

SIDIS: target longitudinal spin dependent asymmetries

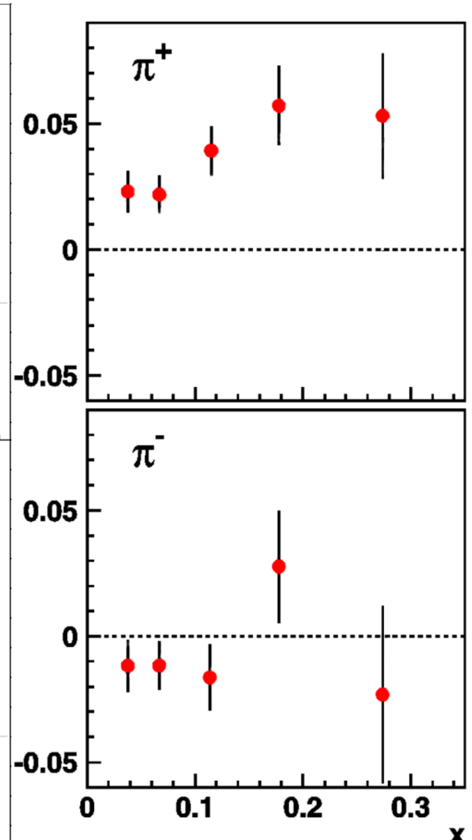
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

Proton 2007+2011 data



HERMES PLB 622 (2005) 14

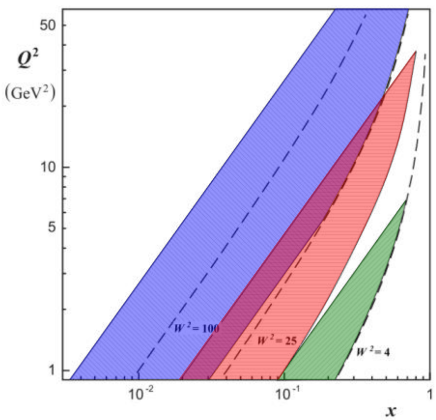


- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h^+, h^- compatible with zero, clear z-dependence**

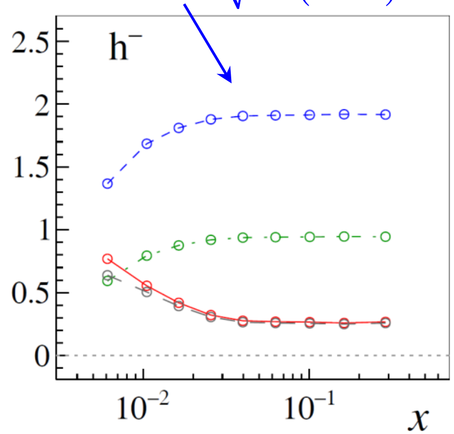
SIDIS: target longitudinal spin dependent asymmetries

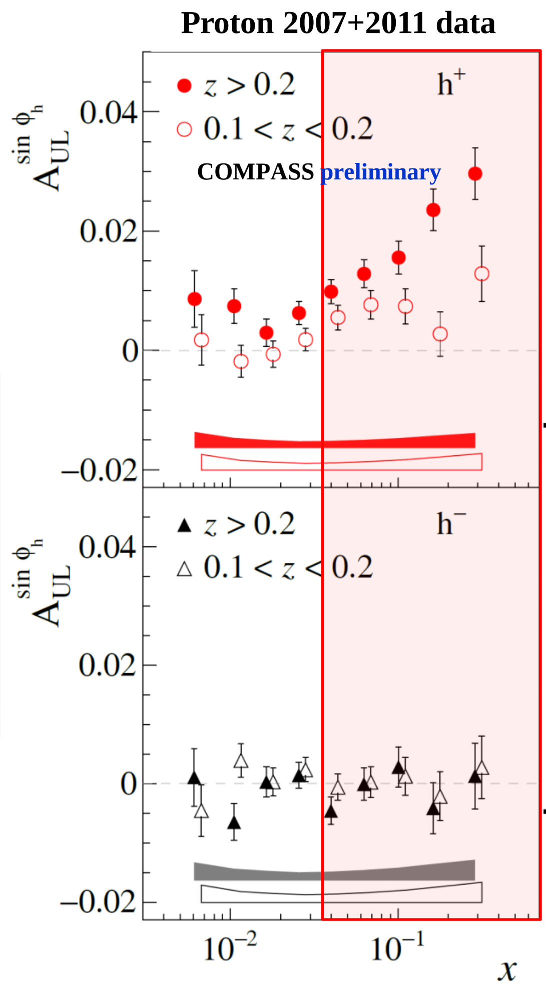
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L \sqrt{2\varepsilon\left(1+\varepsilon\right)} A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\ \right\}$$

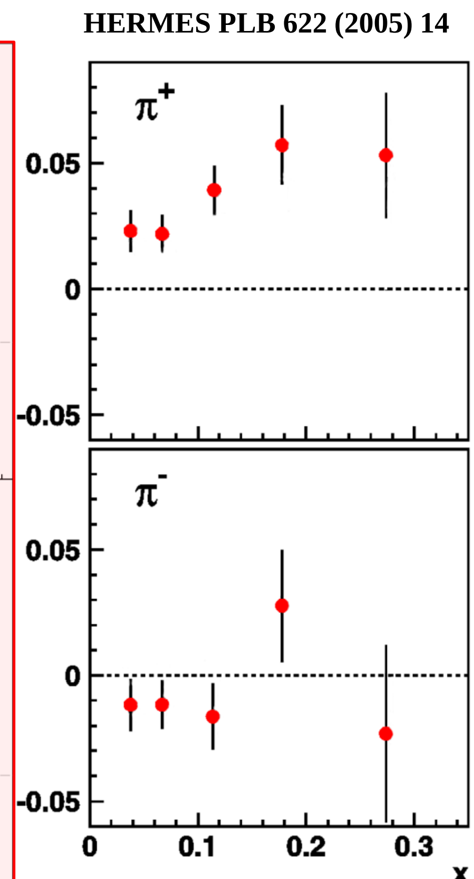
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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



$$D^{\sin(\phi_h)} = \sqrt{2\varepsilon\left(1+\varepsilon\right)}$$







- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- **Non-zero trend for h⁺, h⁻ compatible with zero, clear z-dependence**

SIDIS: target longitudinal spin dependent asymmetries

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

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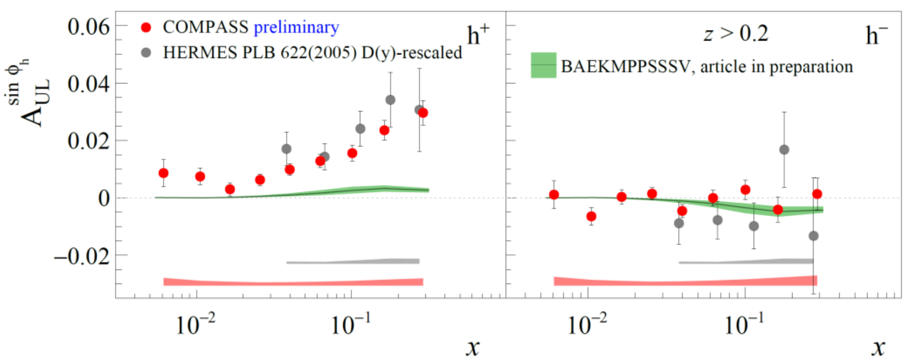
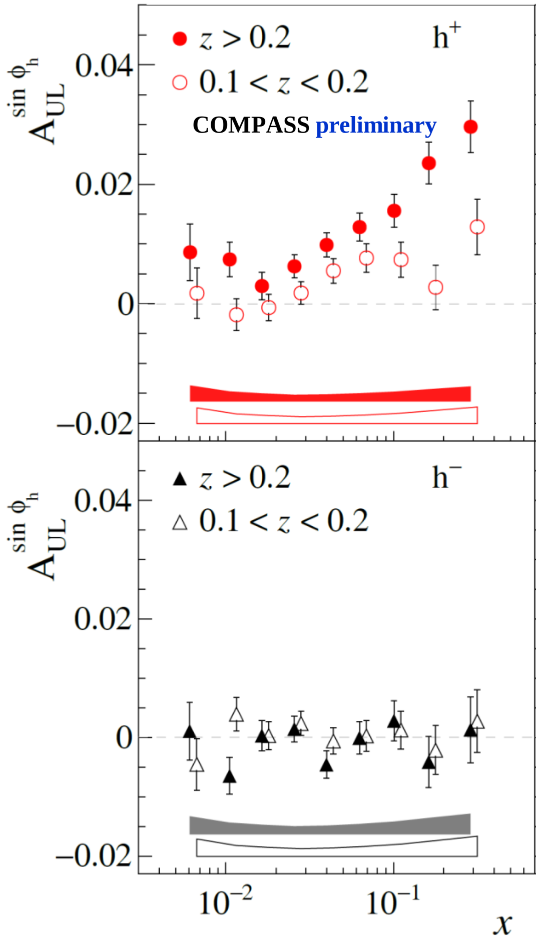
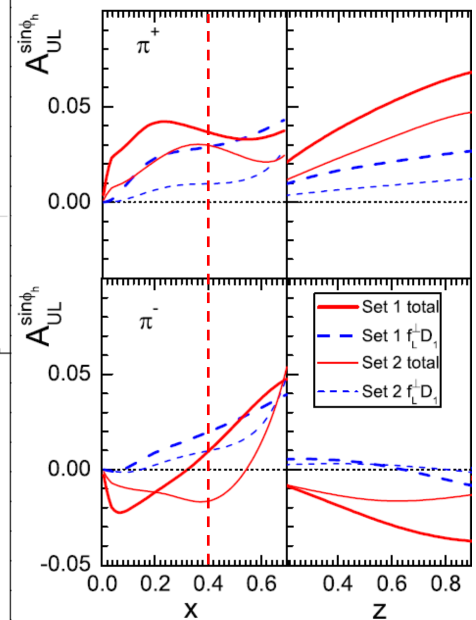
S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang *Article in preparation: "SIDIS in Wandzura-Wilczek-type approximation"* → See talk by S. Bastami



Proton 2007+2011 data



Zhun Lu
Phys. Rev. D 90, 014037(2014)



- Q-suppression, TSA-mixing
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- **Non-zero trend for h^+, h^- compatible with zero, clear z-dependence**

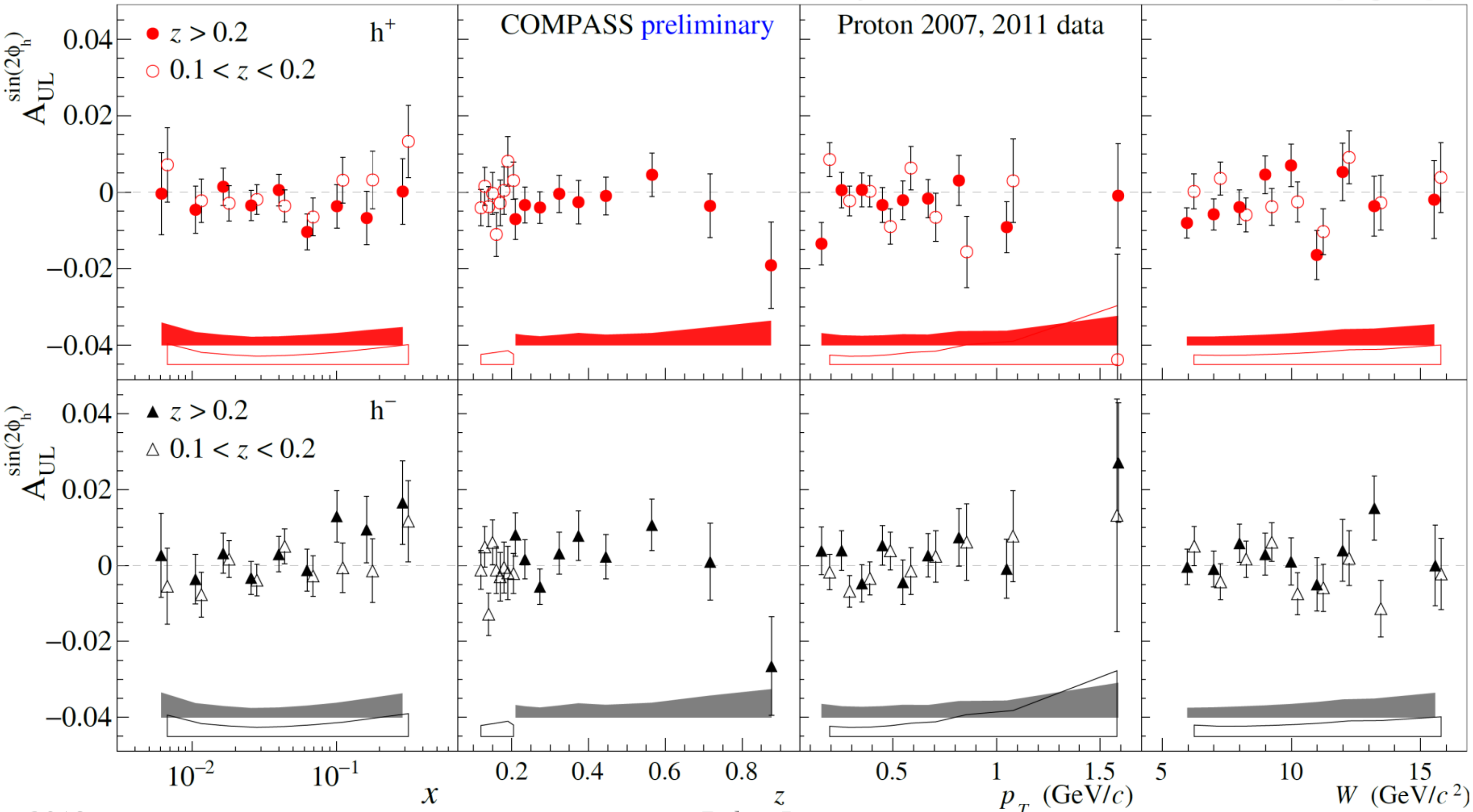
SIDIS: target longitudinal spin dependent asymmetries

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

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

- Only "twist-2" ingredients
- Additional p_T-suppression

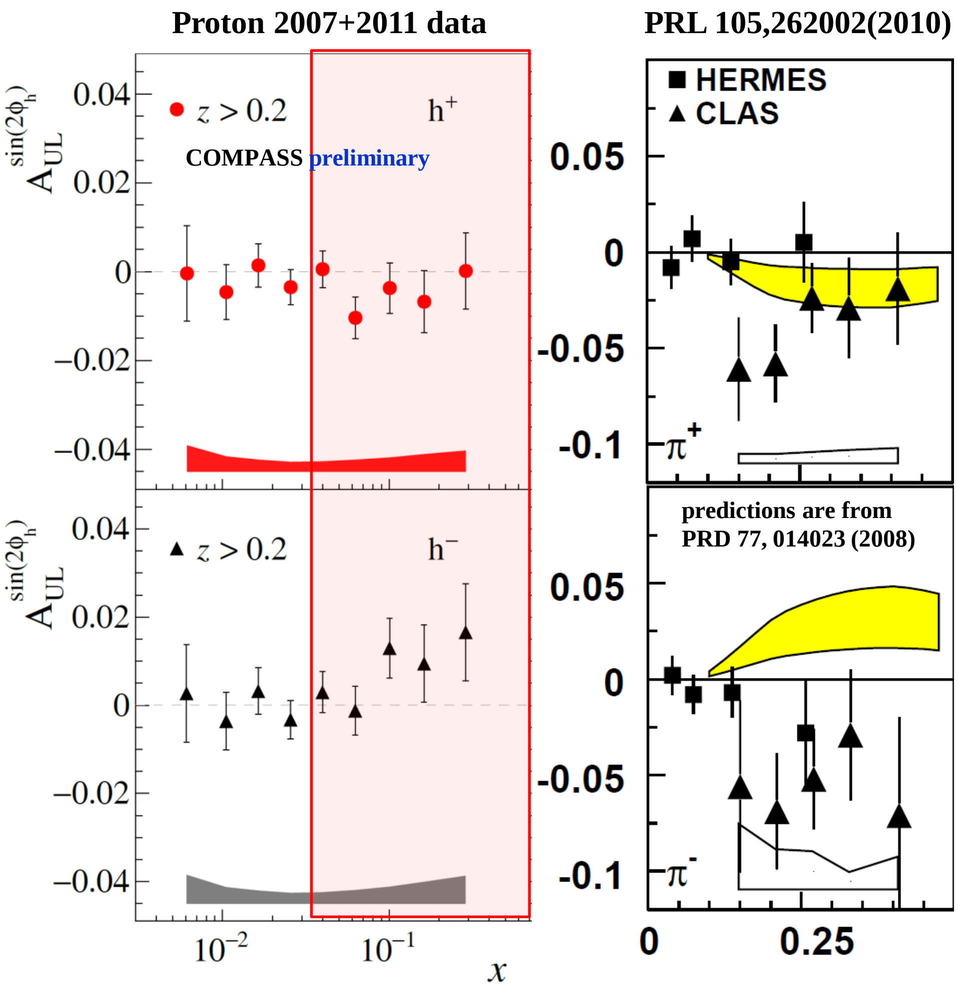
B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex] (DIS-2017)



SIDIS: target longitudinal spin dependent asymmetries

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

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

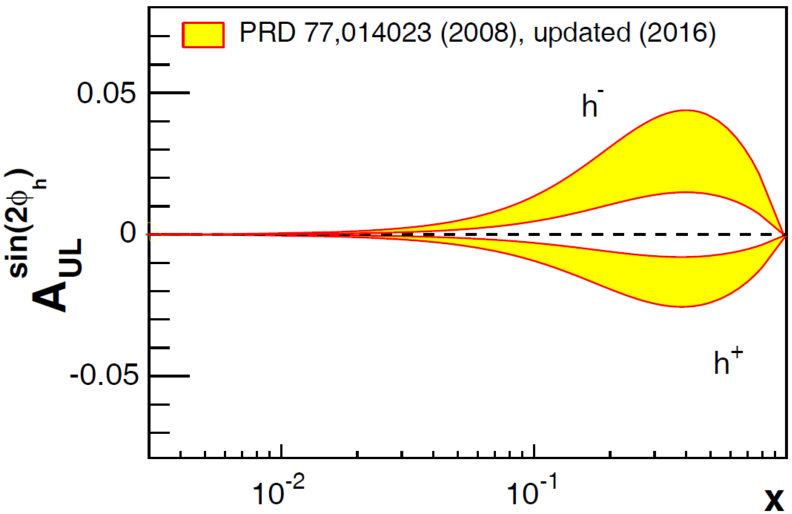


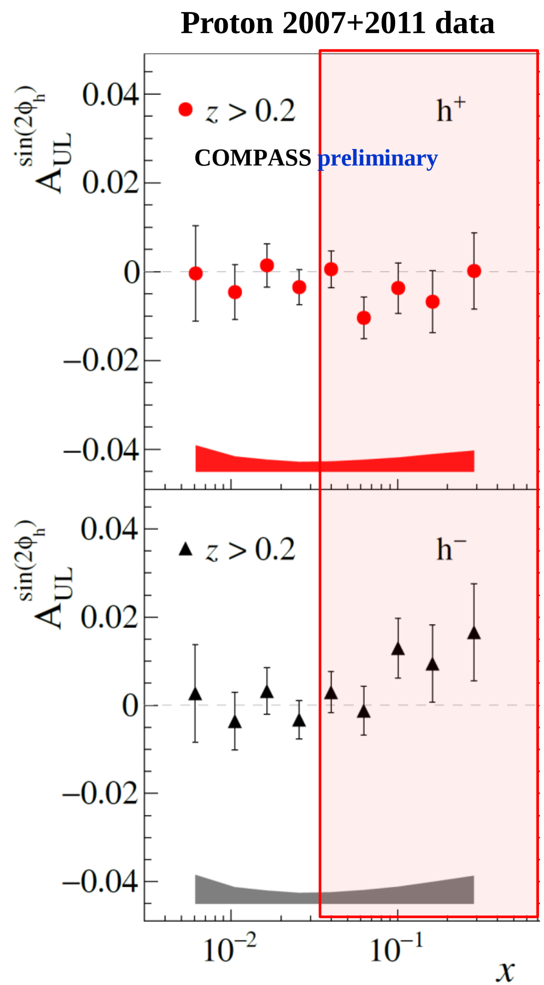
- Only "twist-2" ingredients
- Additional p_T-suppression
- **Collins-like behavior?**
- **In agreement with model predictions**
- **Discrepancy with HERMES and JLab?**

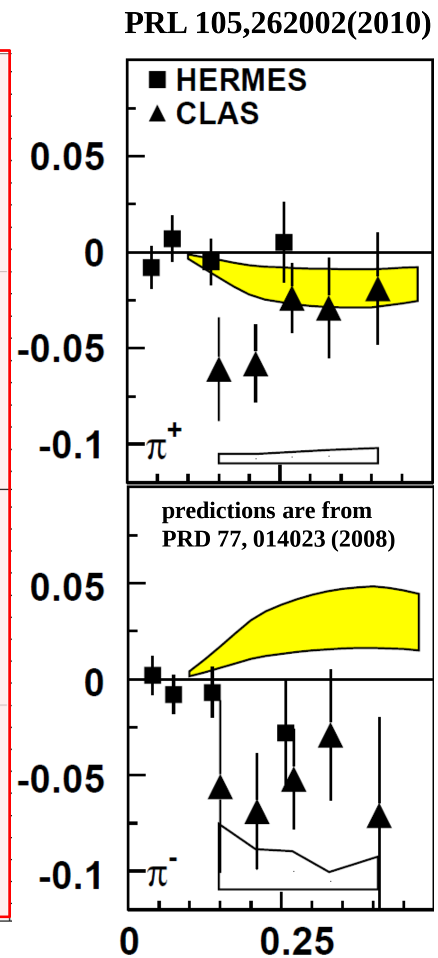
SIDIS: target longitudinal spin dependent asymmetries

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

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







- Only "twist-2" ingredients
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- **Collins-like behavior?**
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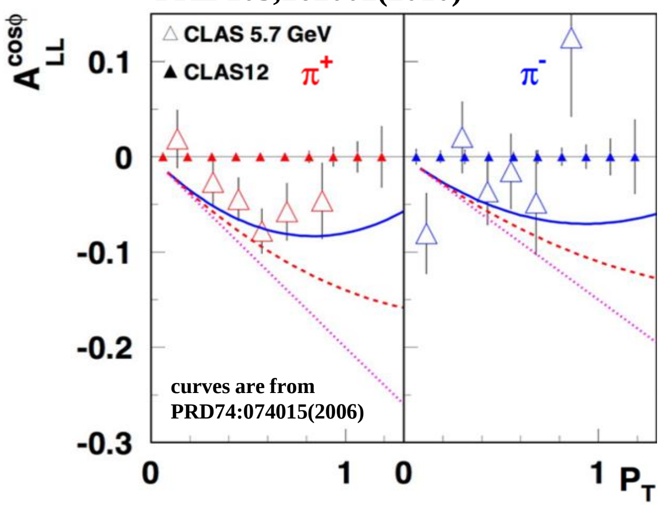
SIDIS: target longitudinal spin dependent asymmetries

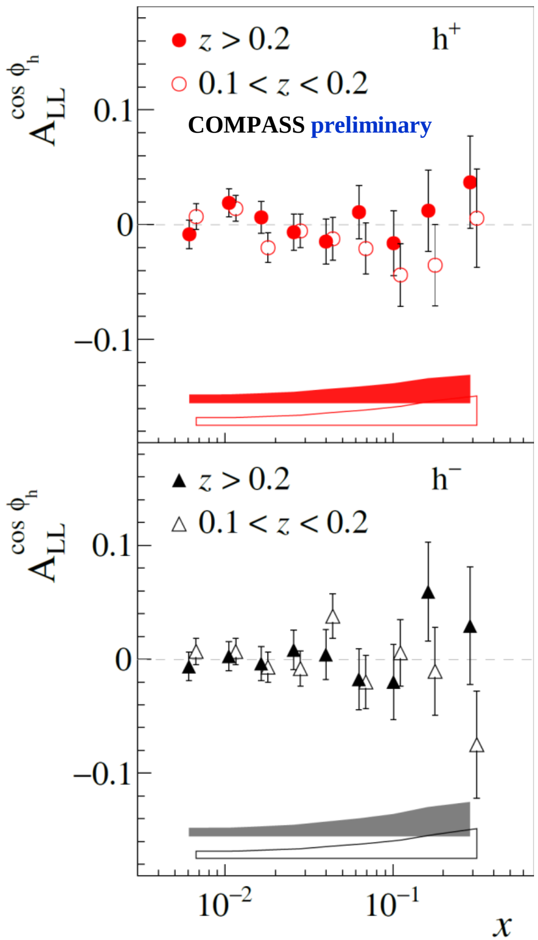
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

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

PRL 105,262002(2010)



Proton 2007+2011 data



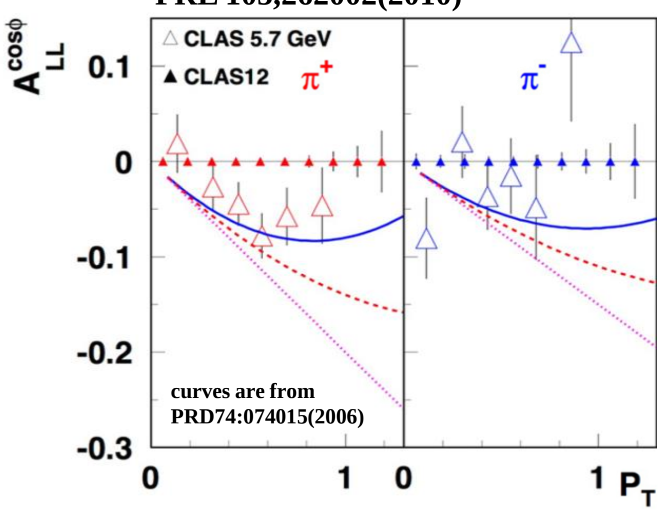
- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab

SIDIS: target longitudinal spin dependent asymmetries

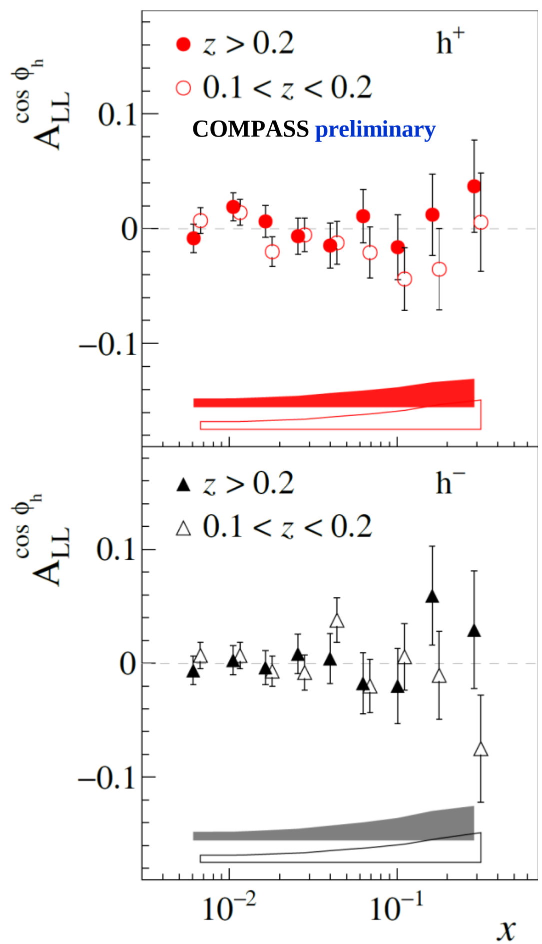
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_L\lambda\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h+\ldots\right\}$$

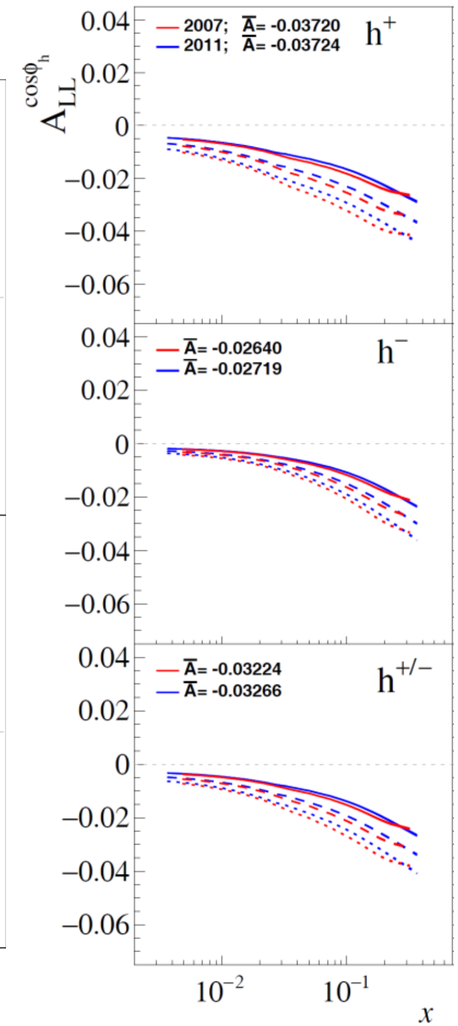
$$F_{LL}^{\cos\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^qH_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp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

PRL 105,262002(2010)



Proton 2007+2011 data





- Various different “twist” ingredients,
- Q-suppression
- Non zero at JLab
- **Small and compatible with zero, in agreement with model predictions**

SIDIS: target longitudinal spin dependent asymmetries

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

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

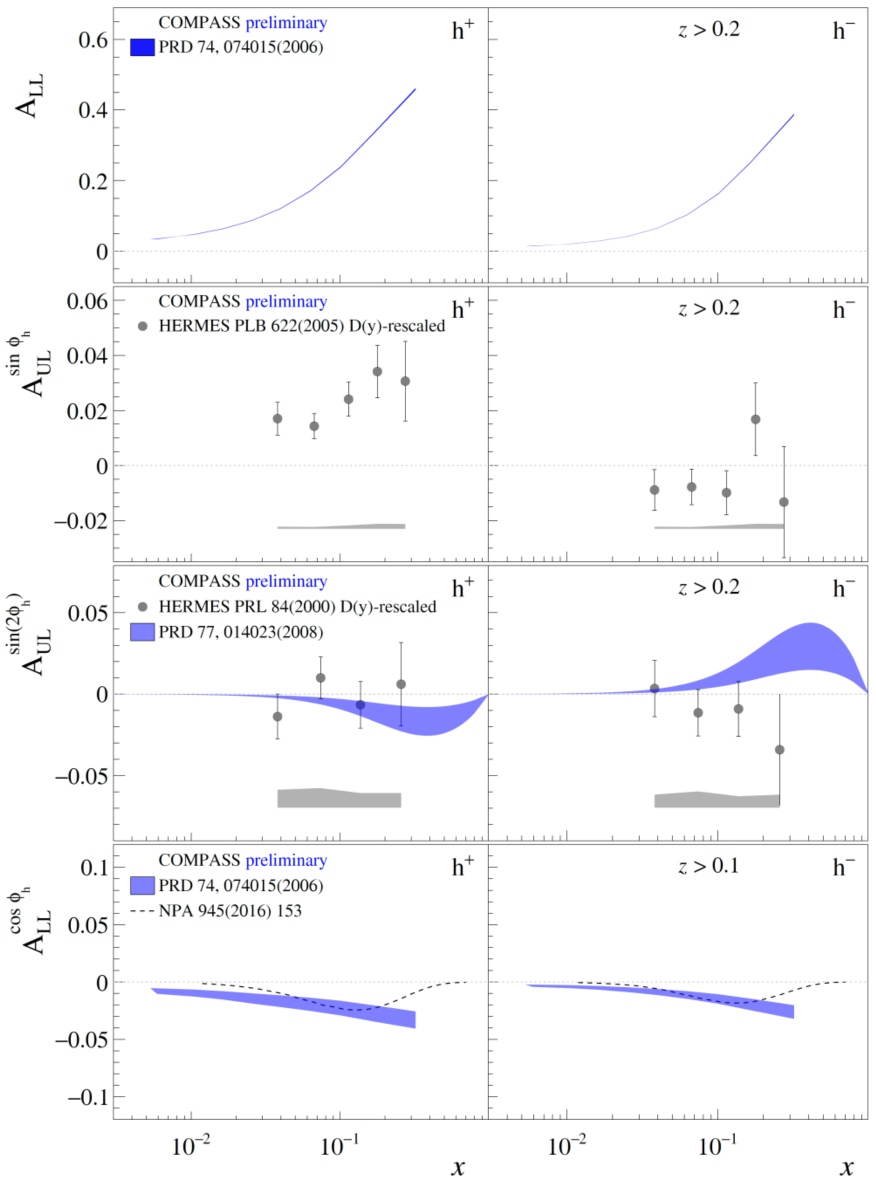
$$\left. + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \right\}$$

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

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

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

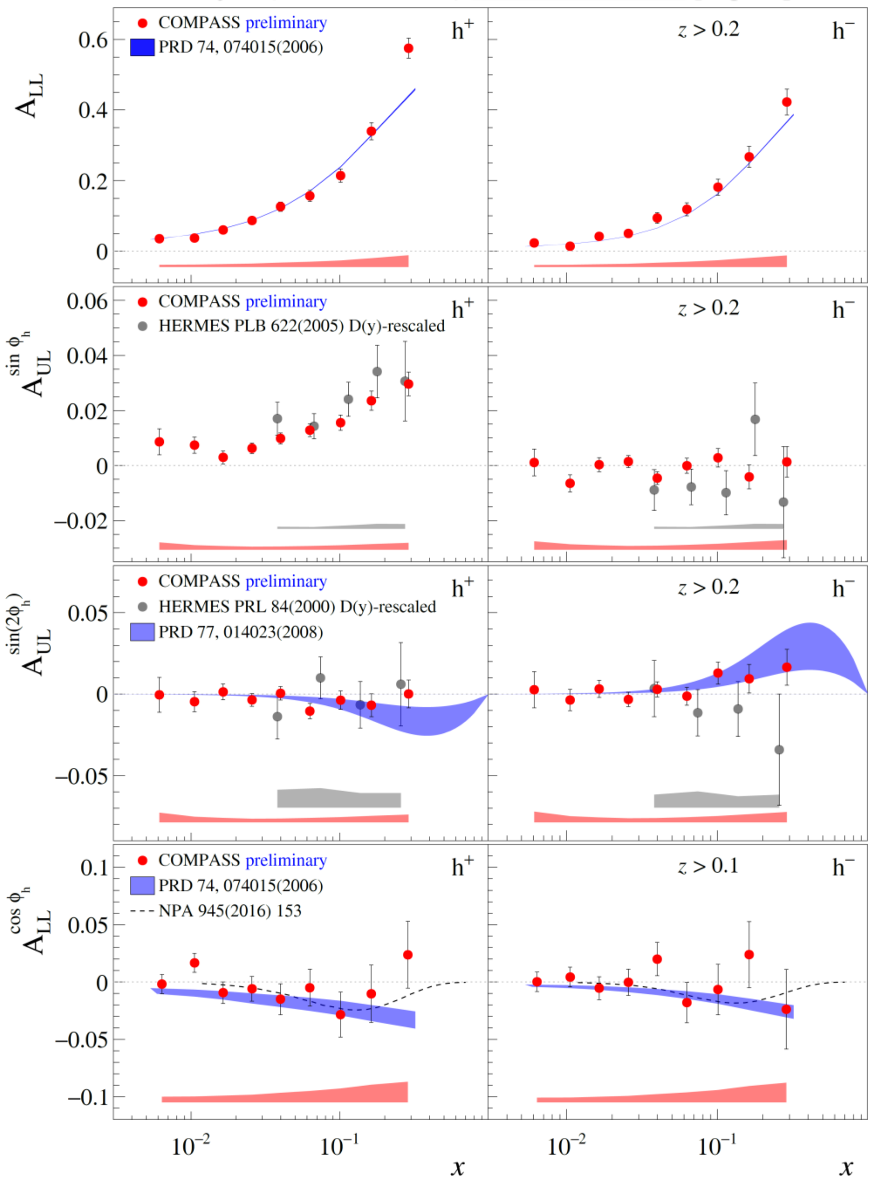
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C}\left\{ -\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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



SIDIS: target longitudinal spin dependent asymmetries

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

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

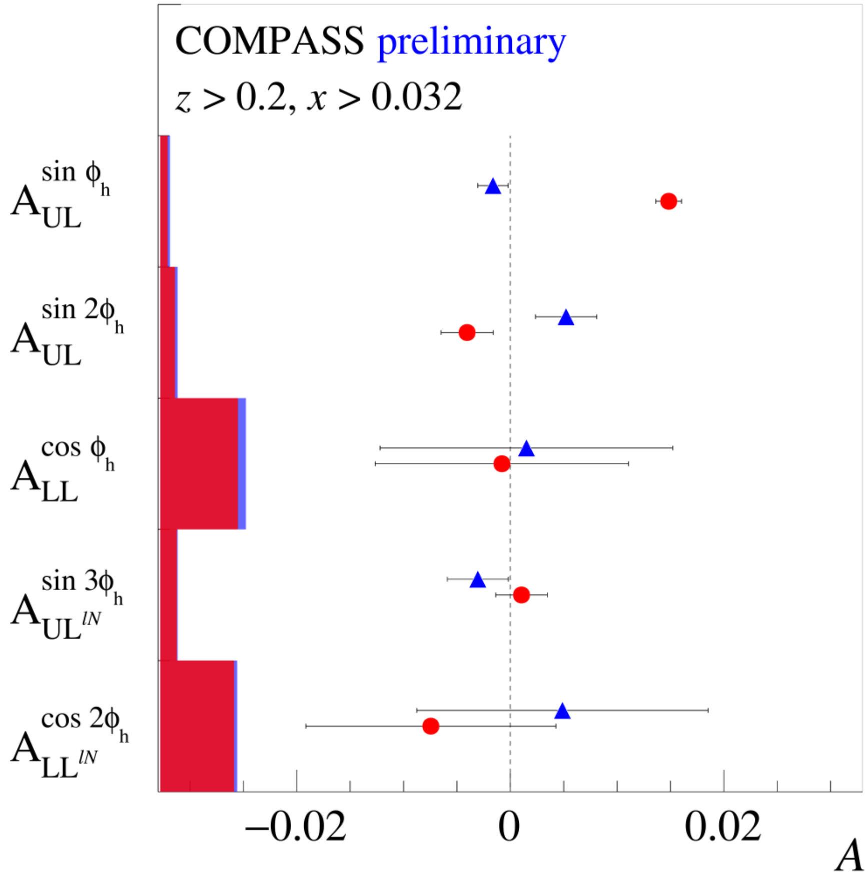
$A_{UL}^{\sin\phi_h}$
- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- **Significant h⁺ asymmetry, clear *z*-dependence**
- **h⁻ compatible with zero**

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

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

SIDIS: target longitudinal spin dependent asymmetries

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision!

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

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

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

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

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

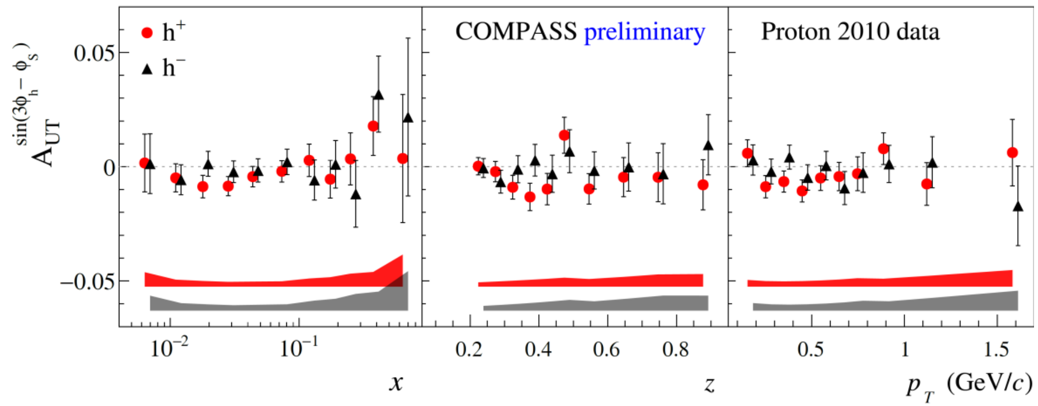
- Q-suppression, Various different "twist" ingredients
- **Compatible with zero, in agreement with models**

- Transverse target spin dependent azimuthal asymmetries

SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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

COMPASS results

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

- Only "twist-2" ingredients, p_T^2-suppression
- $h_{1T}^{\perp q}$ is also small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**

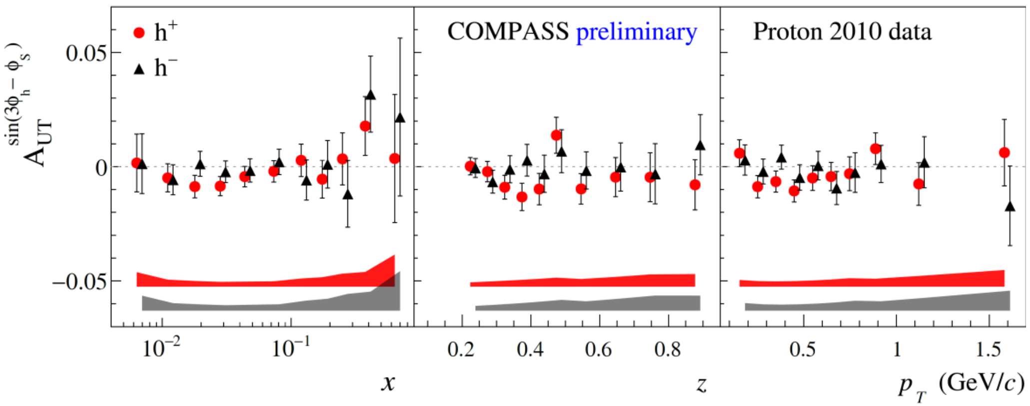
SIDIS: target transverse spin dependent asymmetries

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

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

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



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

COMPASS results

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

- Only "twist-2" ingredients, p_T^2-suppression
- $h_{1T}^{\perp q}$ is also small (see e.g. PLB769 (2017) 84-89)
- **Small, compatible with zero asymmetry**
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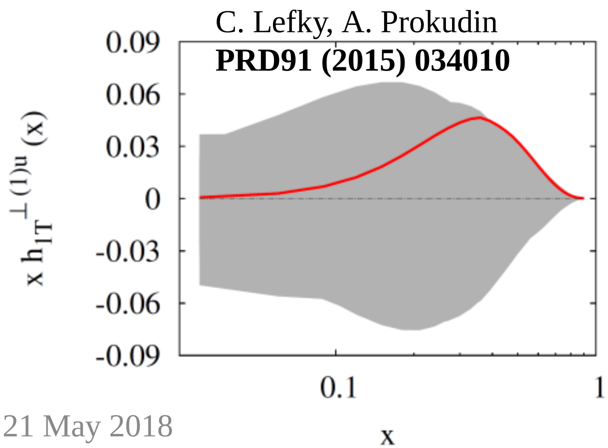
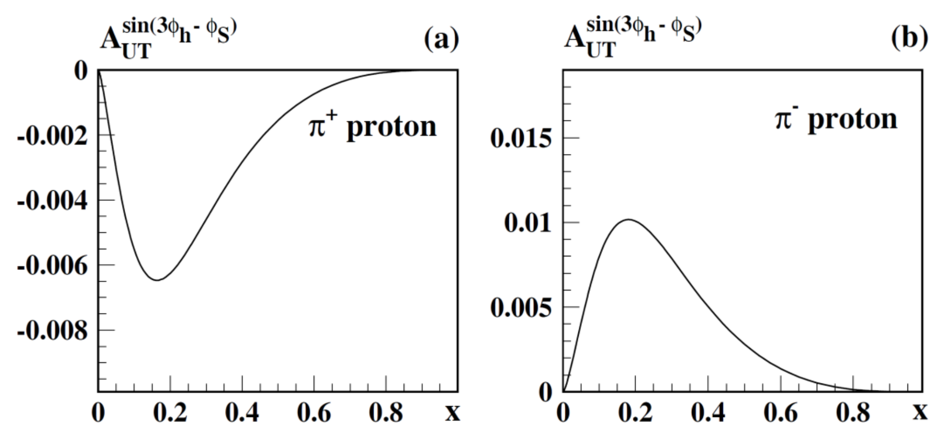


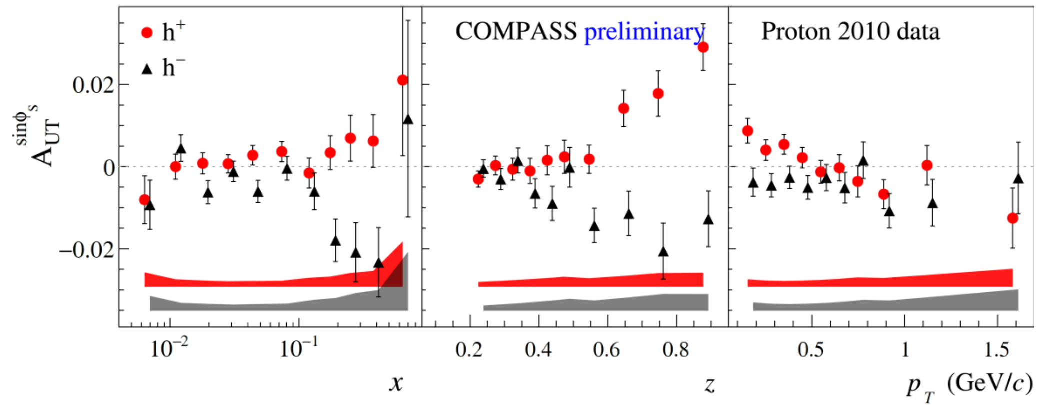
B. Pasquini, S. Boffi, A.V. Efremov, P. Schweitzer
arXiv:0912.1761 [hep-ph]



SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042

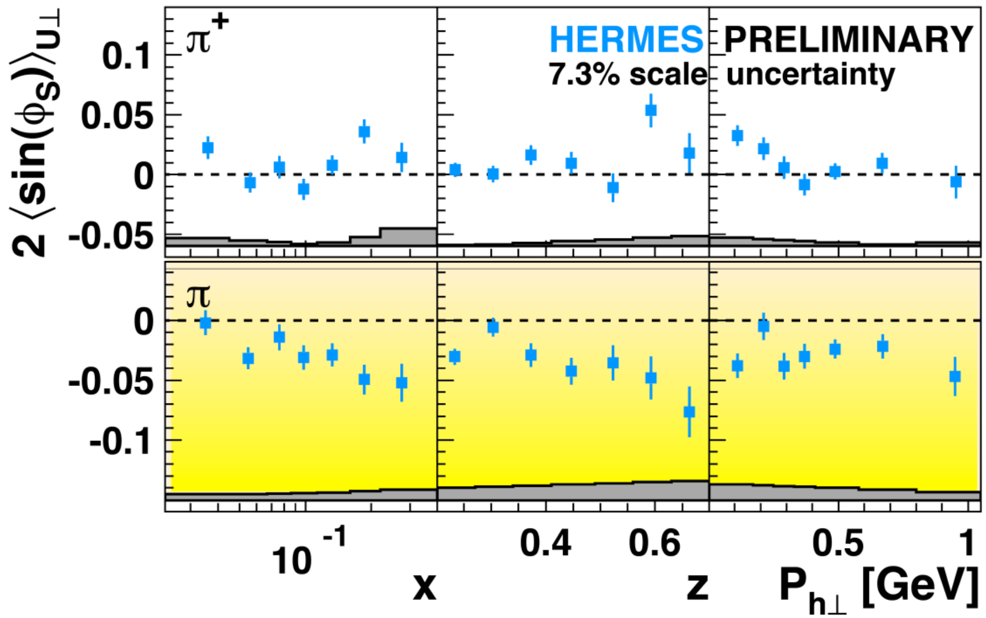


COMPASS results

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

- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻?**

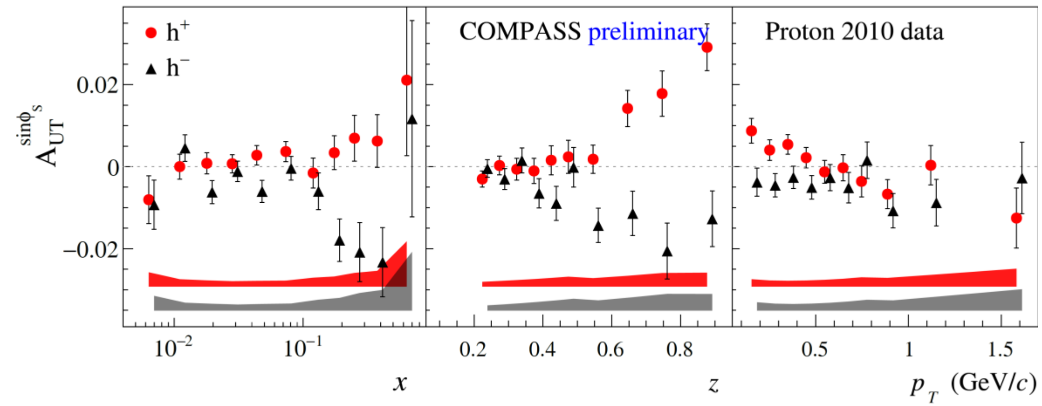
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M}h_1^q\frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1T}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp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



SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

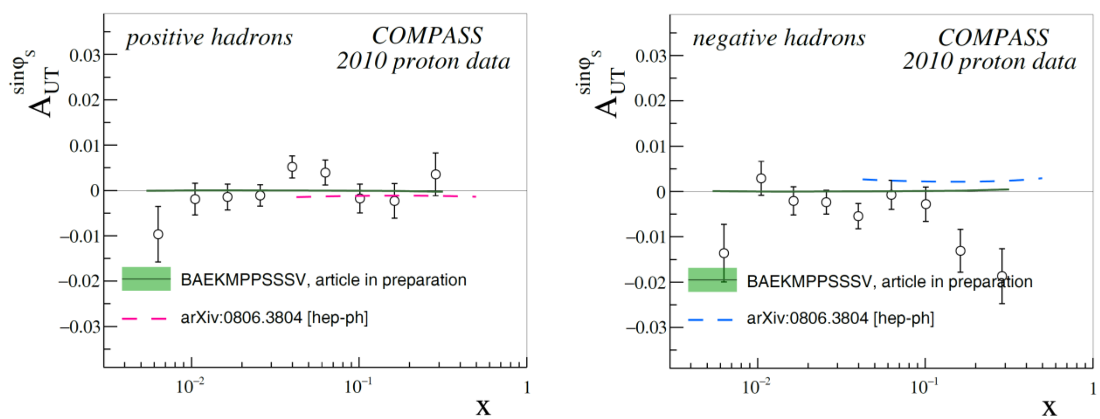
$A_{UT}^{\sin\phi_S}$

- Q-suppression
- Various different “twist” ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻ ?**

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

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang Article in preparation: *“SIDIS in Wandzura-Wilczek-type approximation“* → See talk by S. Bastami

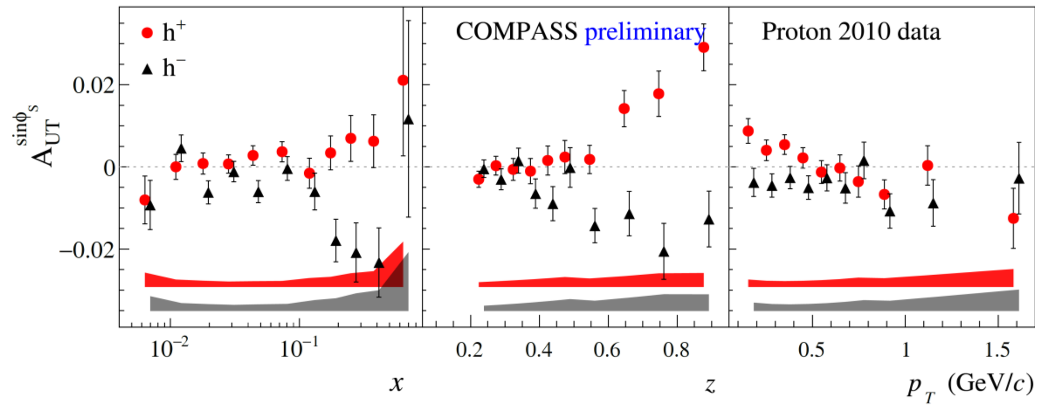
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp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



SIDIS: target transverse spin dependent asymmetries

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

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

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

- Q-suppression
- Various different "twist" ingredients
- Within WW is related to Sivers and Collins
- **Small asymmetry, non-zero signal for h⁻?**

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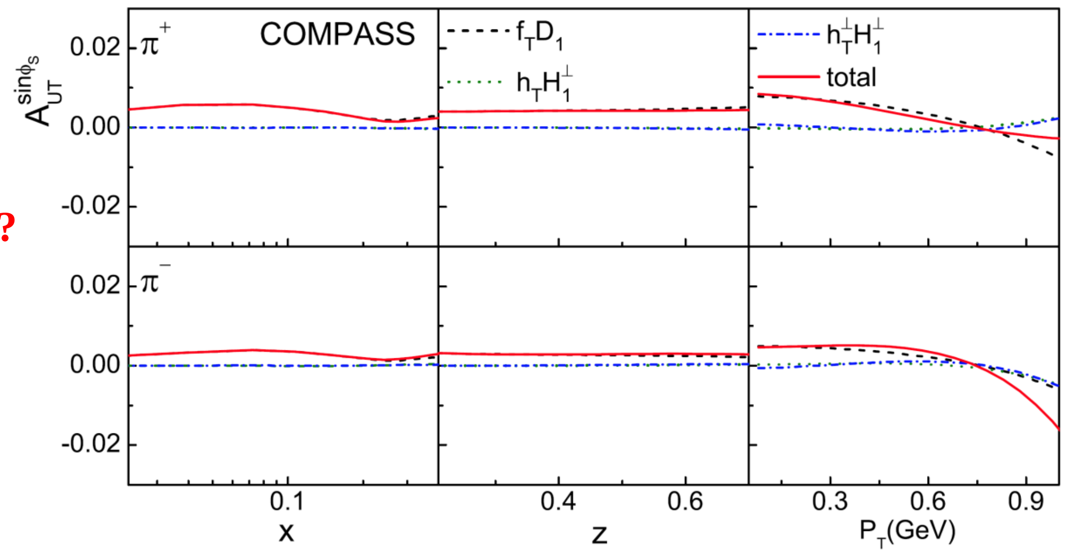
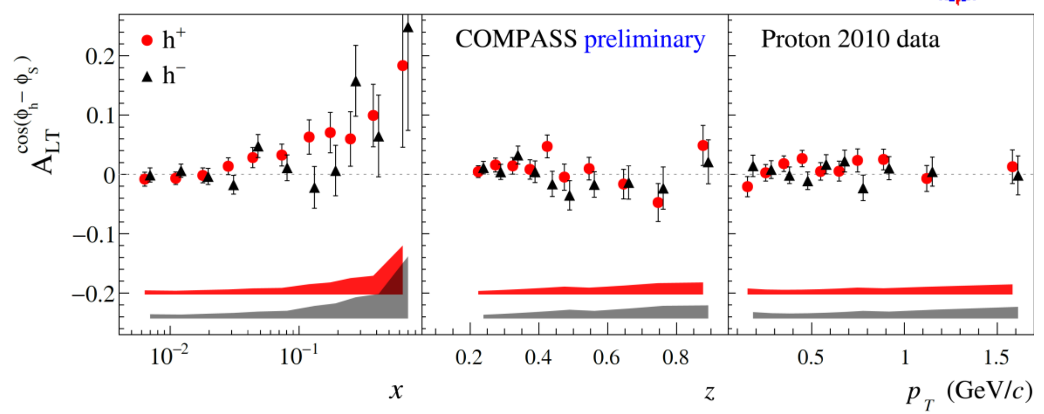
W. Mao, Z. Lu and B.Q. Ma **Phys.Rev. D 90 (2014) 014048**



SIDIS: target transverse spin dependent asymmetries

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

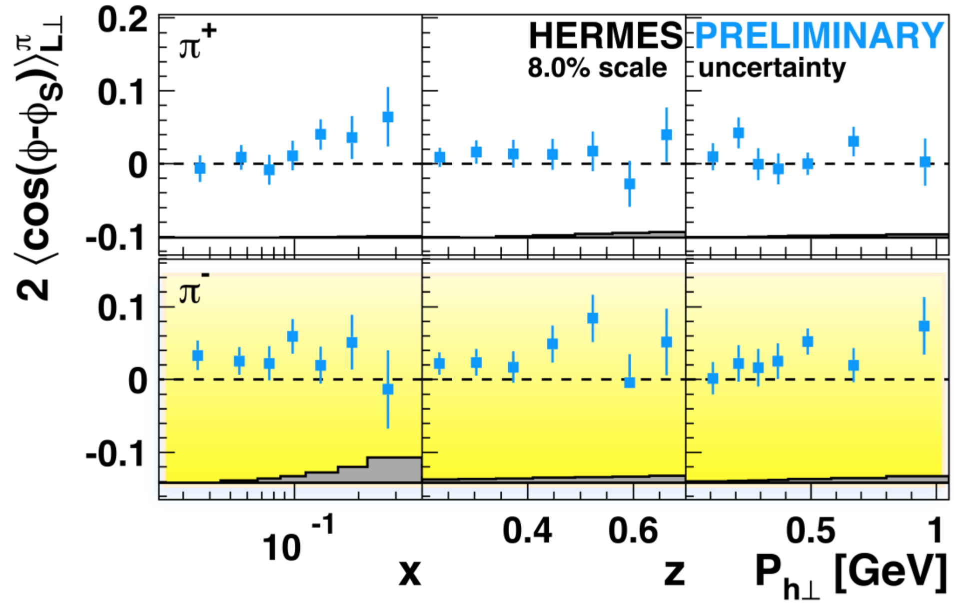
B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



COMPASS results

$A_{LT}^{\cos(\phi_h-\phi_S)}$

- Only “twist-2” ingredients
- **Sizable non-zero effect for h⁺ !**
- **Similar effect at HERMES**



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

SIDIS: target transverse spin dependent asymmetries

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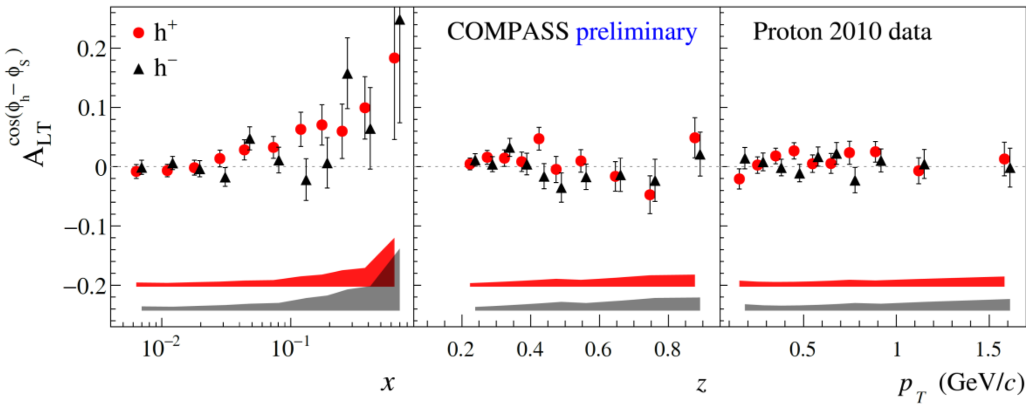
$$\left. + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \ldots \right] \right\}$$

B.Parsamyan (for COMPASS) PoS QCDEV2017 (2018) 042



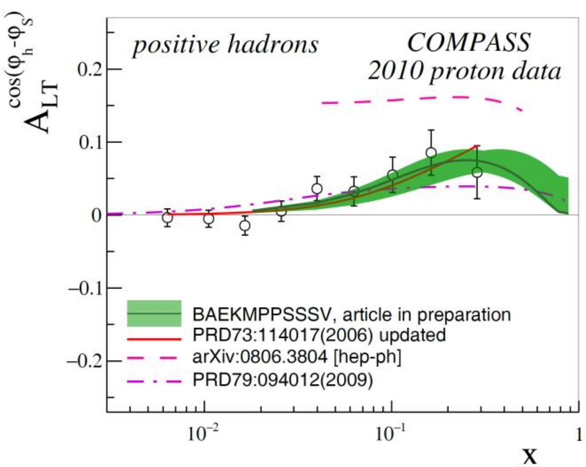
COMPASS results

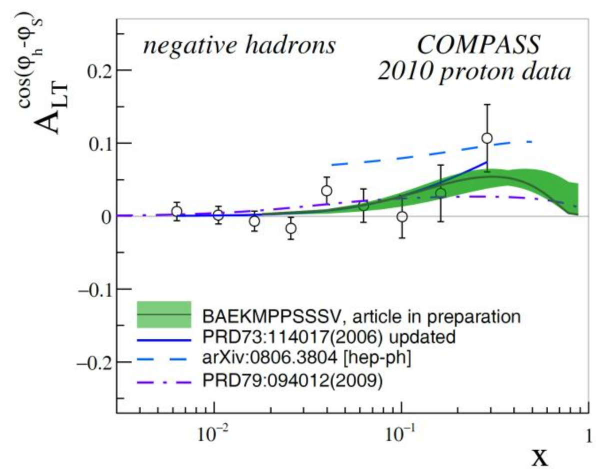
$A_{LT}^{\cos(\phi_h - \phi_S)}$

- Only “twist-2” ingredients
- **Sizable non-zero effect for h$^+$!**
- **Similar effect at HERMES**
- **In agreement with models**

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

S. Bastami, H. Avakian, A. V. Efremov, A. Kotzinian, B. U. Musch, B. Parsamyan, A. Prokudin, M. Schlegel, G. Schnell, P. Schweitzer, W. Vogelsang Article in preparation: *“SIDIS in Wandzura-Wilczek-type approximation“* → See talk by S. Bastami





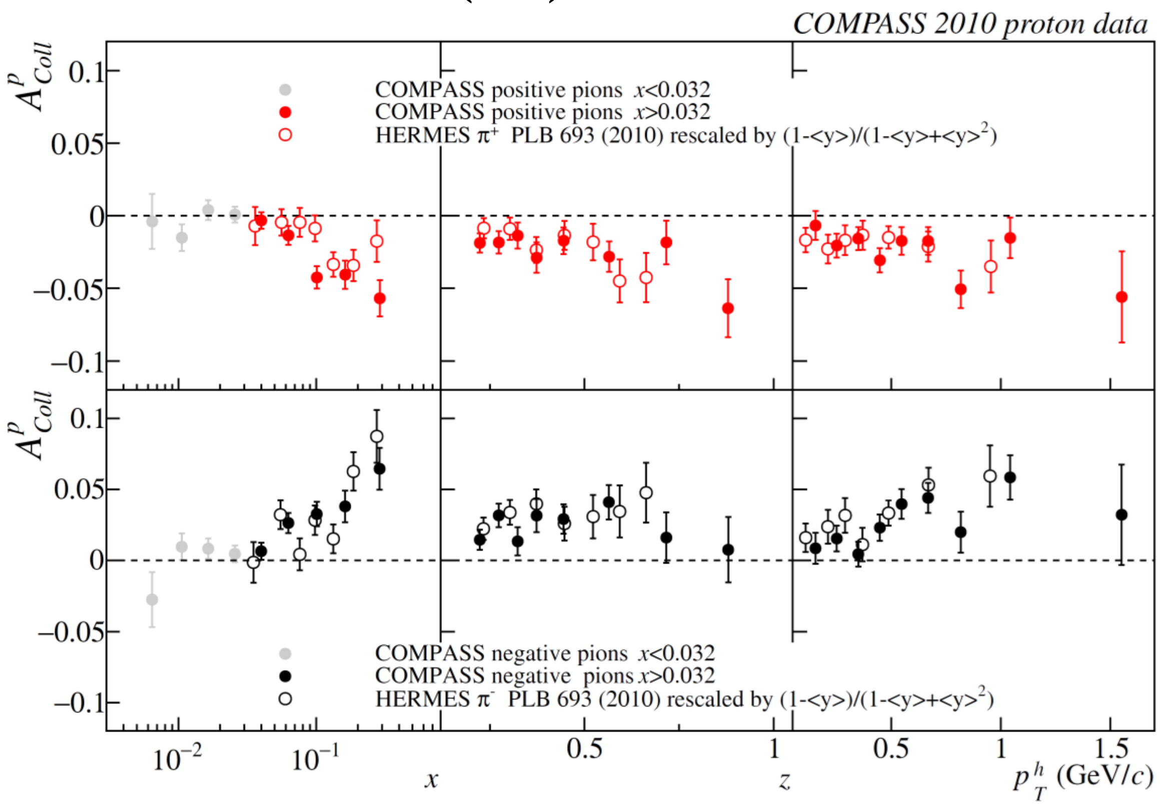
SIDIS TSAs (Collins)

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

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

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

COMPASS PLB 744 (2015) 250



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

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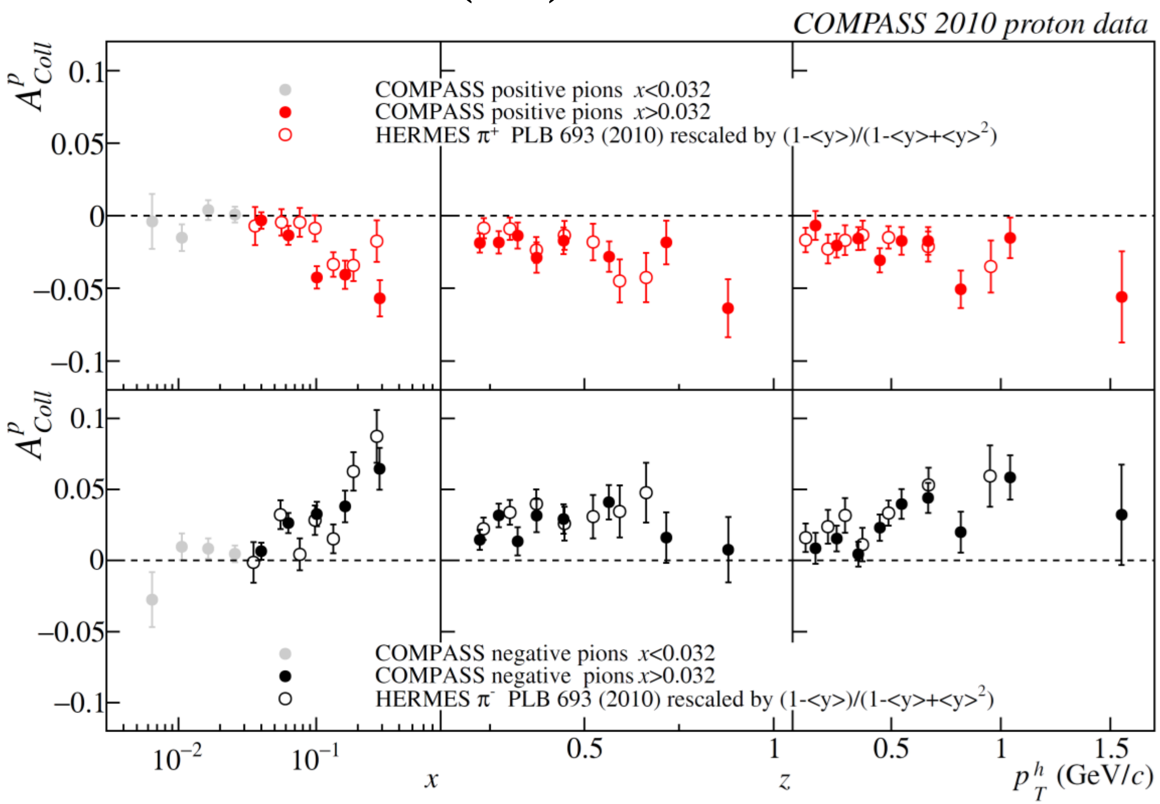
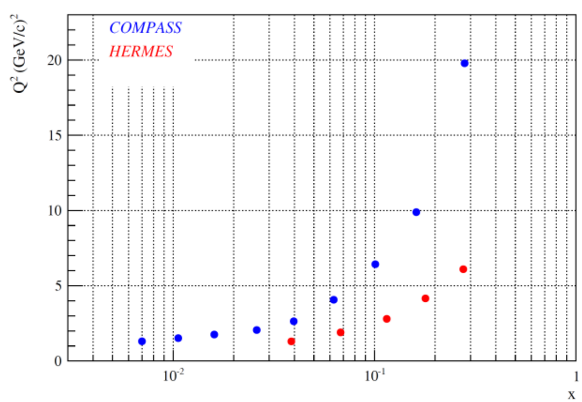
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**

COMPASS PLB 744 (2015) 250





SIDIS TSAs (Collins)

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

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

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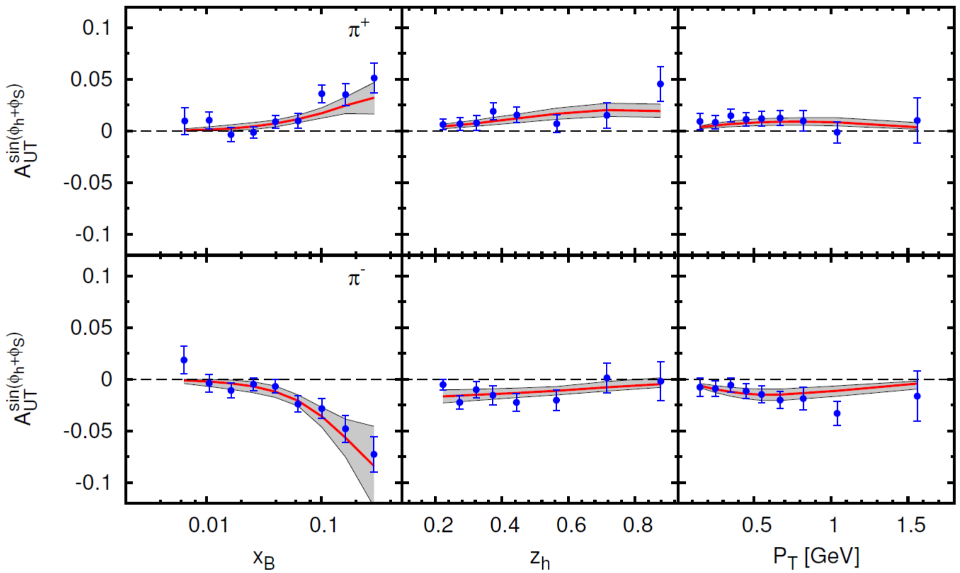
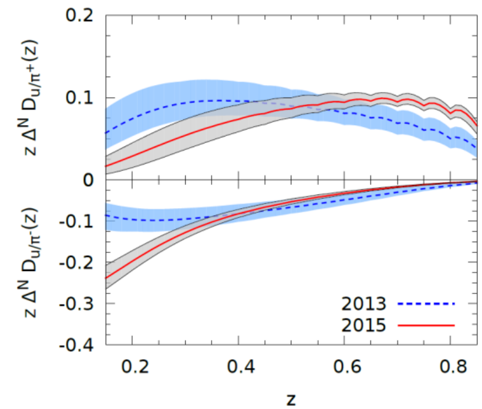
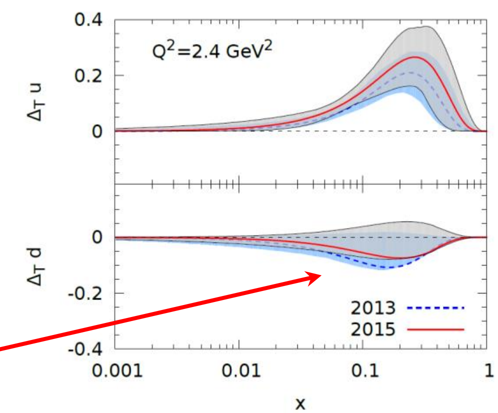
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- **No Q^2-evolution? Intriguing result!**
- Extensive phenomenological studies and various global fits by different groups

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







COMPASS-II (2021)

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

SIDIS TSAs (Collins)

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

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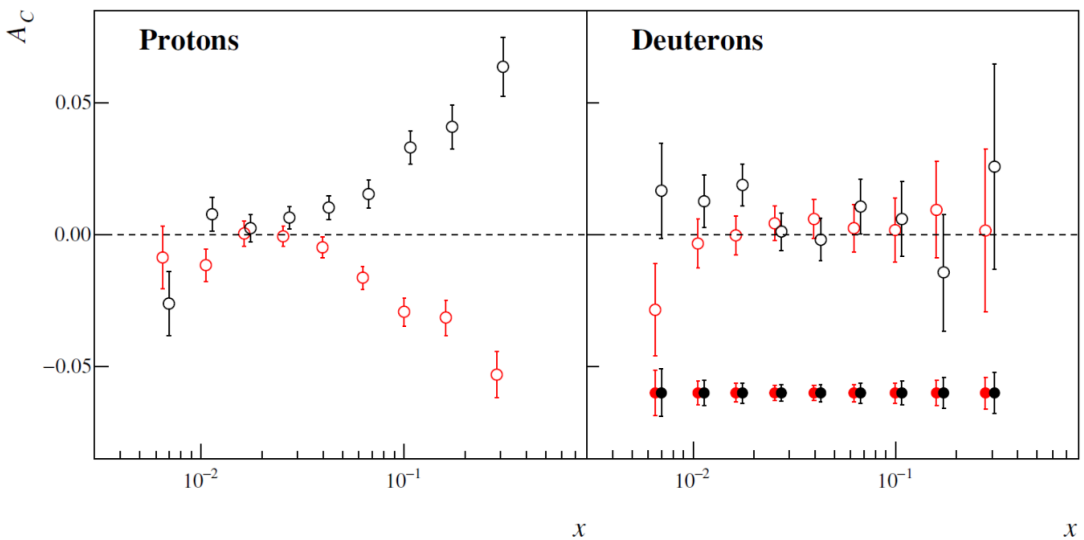
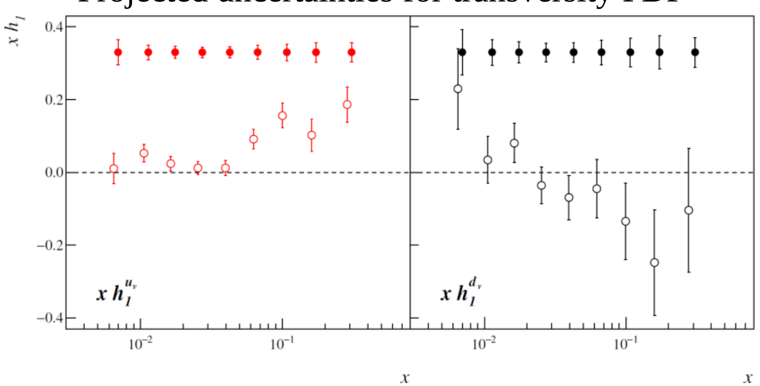
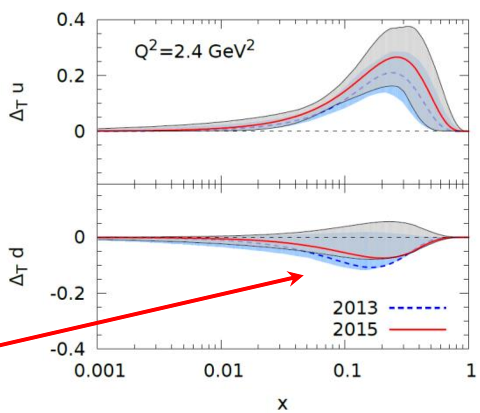
Addendum to the COMPASS-II Proposal
Projected uncertainties for Collins asymmetry



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





COMPASS-II (2021)

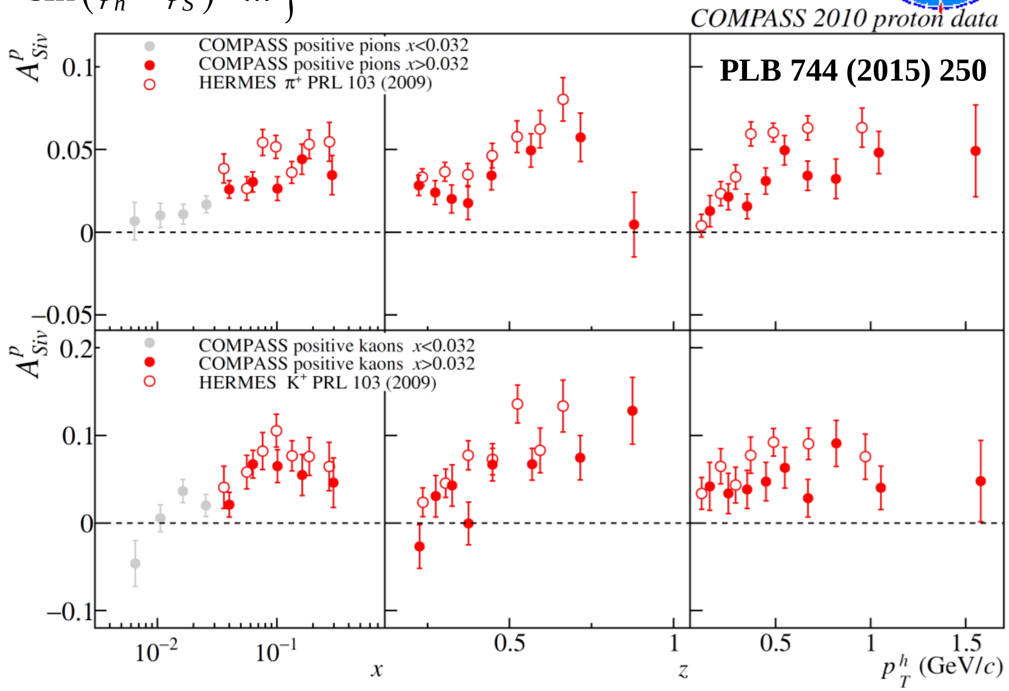
- Deuteron measurement to be repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark

SIDIS TSAs (Sivers)

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

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

- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**



SIDIS TSAs (Sivers)

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

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

- Measured on proton and deuteron
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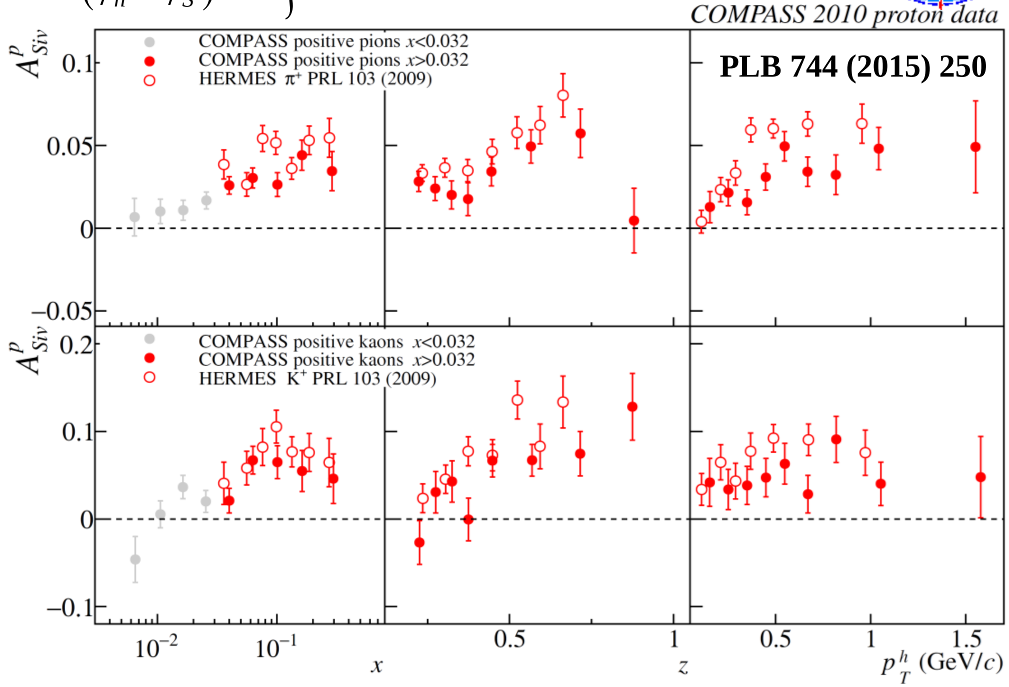
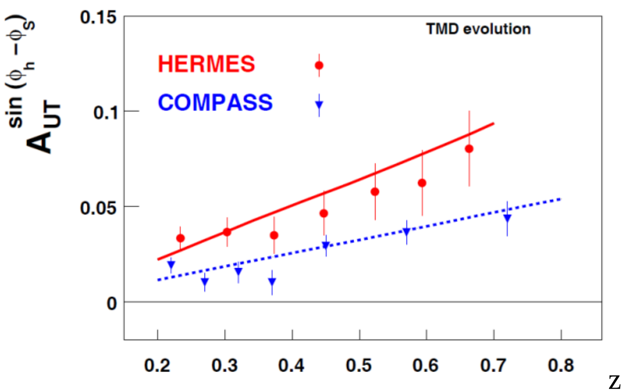
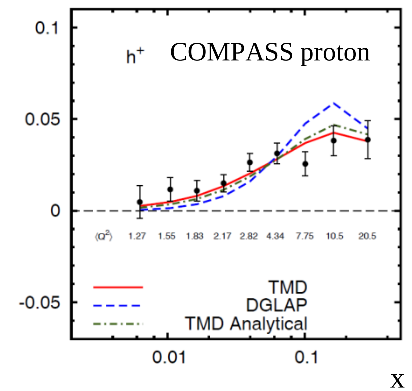
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY







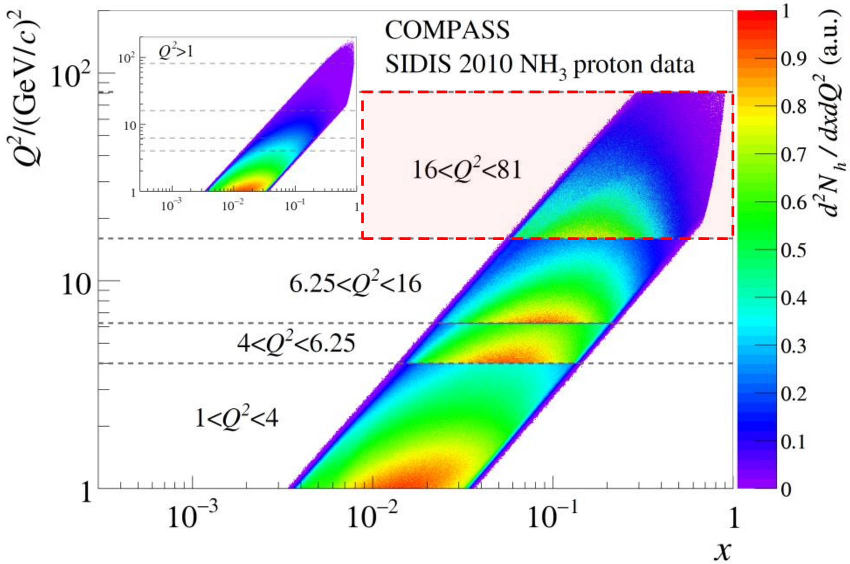
S. M. Aybat, A. Prokudin, T. C. Rogers **PRL 108 (2012) 242003**
M. Anselmino, M. Boglione, S. Melis **PRD 86 (2012) 014028**

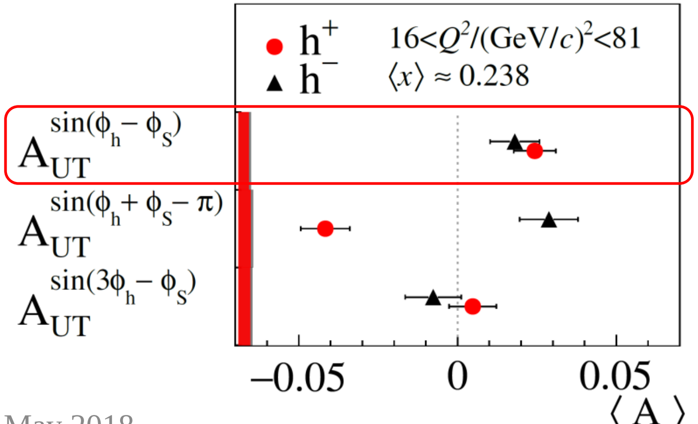
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

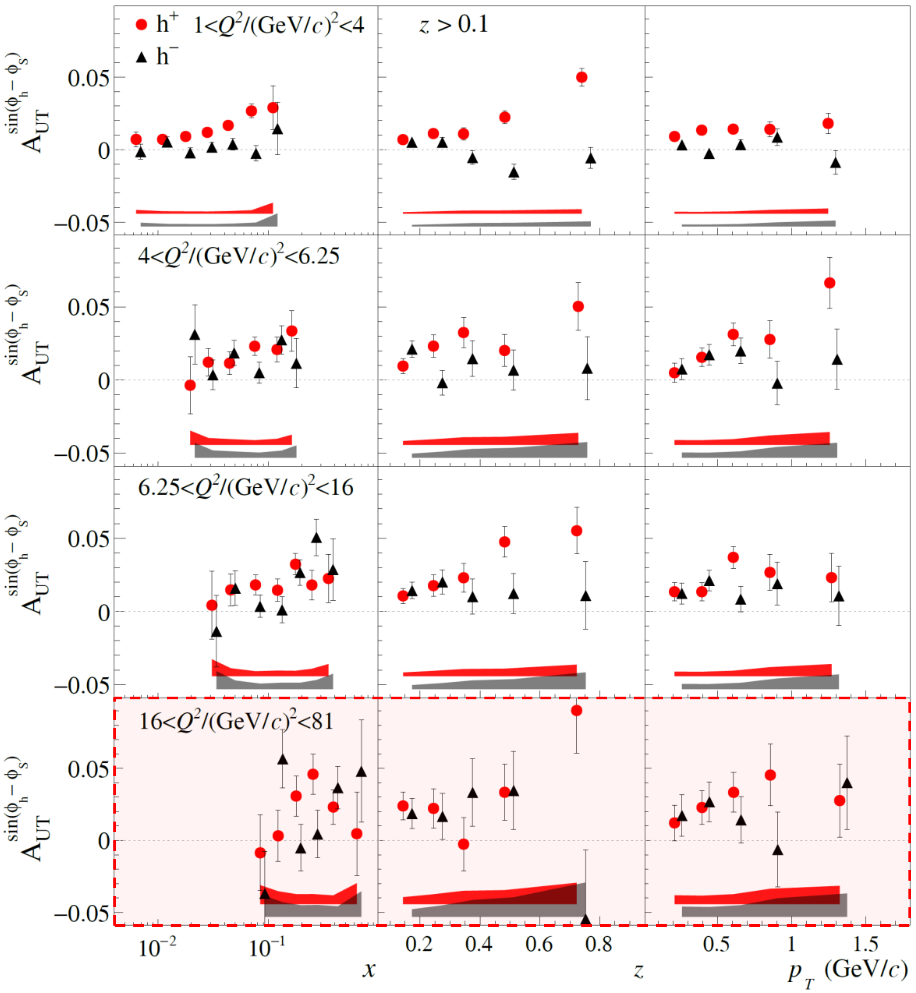
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

COMPASS PLB 770 (2017) 138



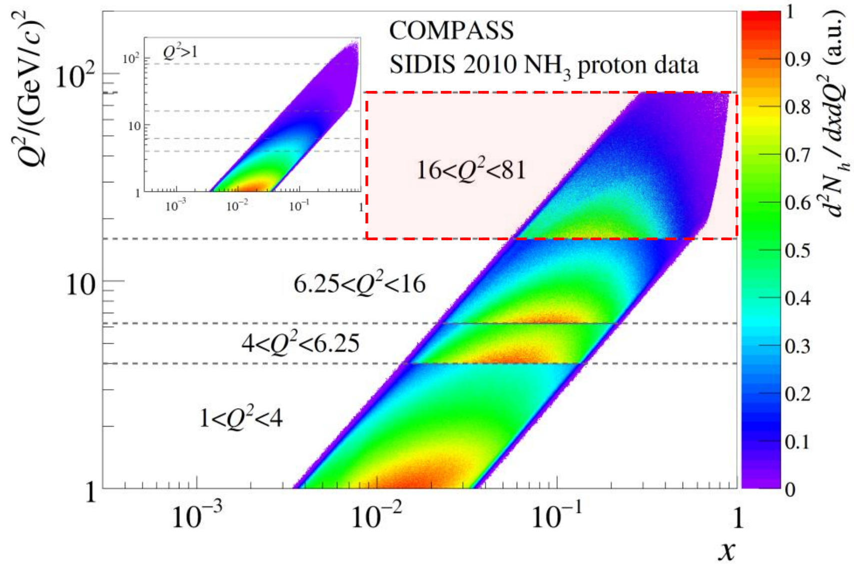


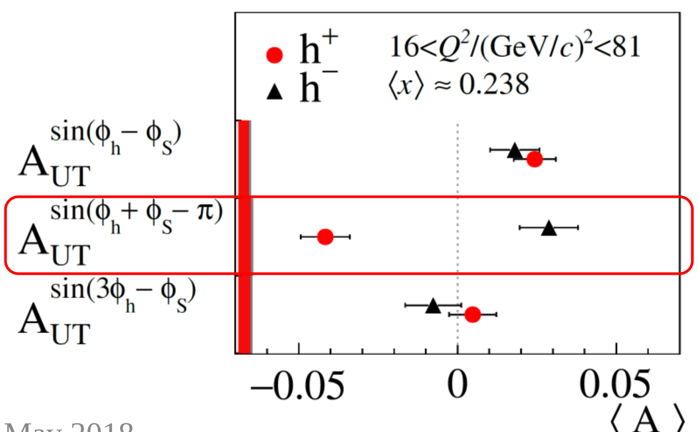


SIDIS Collins TSA in COMPASS Drell-Yan Q^2-ranges

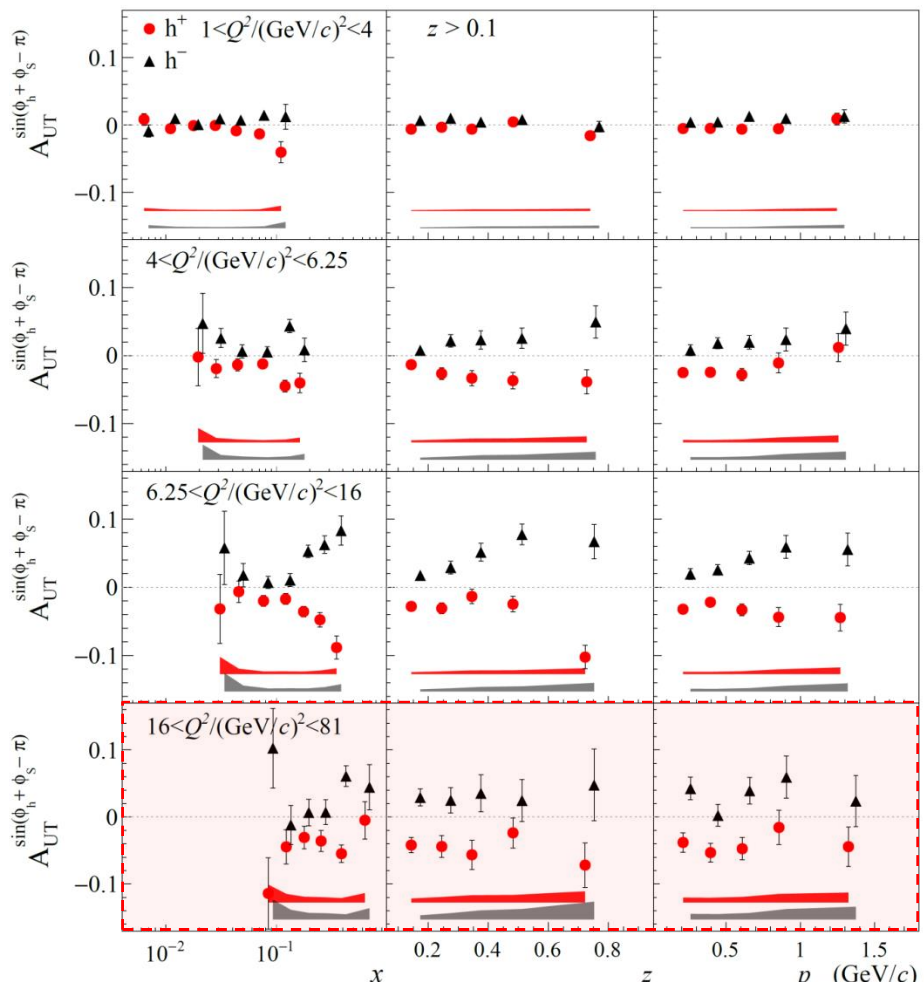
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

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





COMPASS PLB 770 (2017) 138



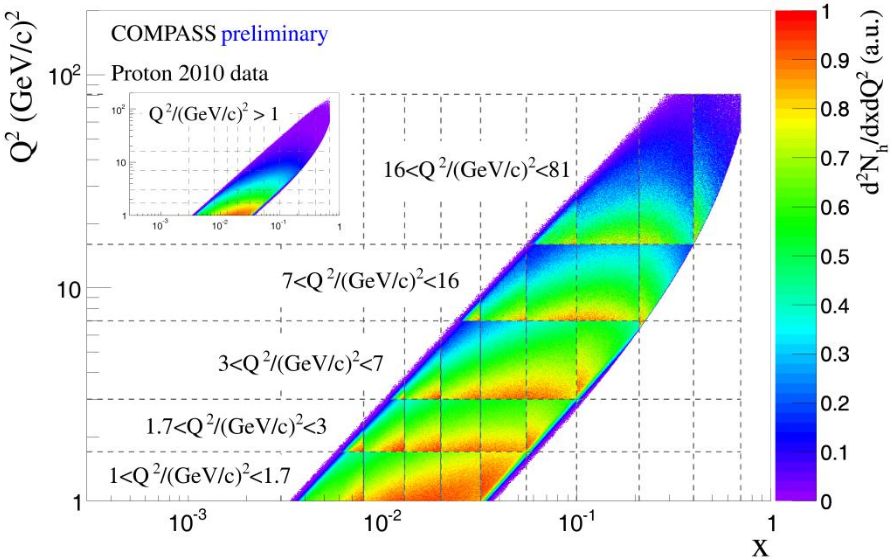
Multi-D TSA analysis

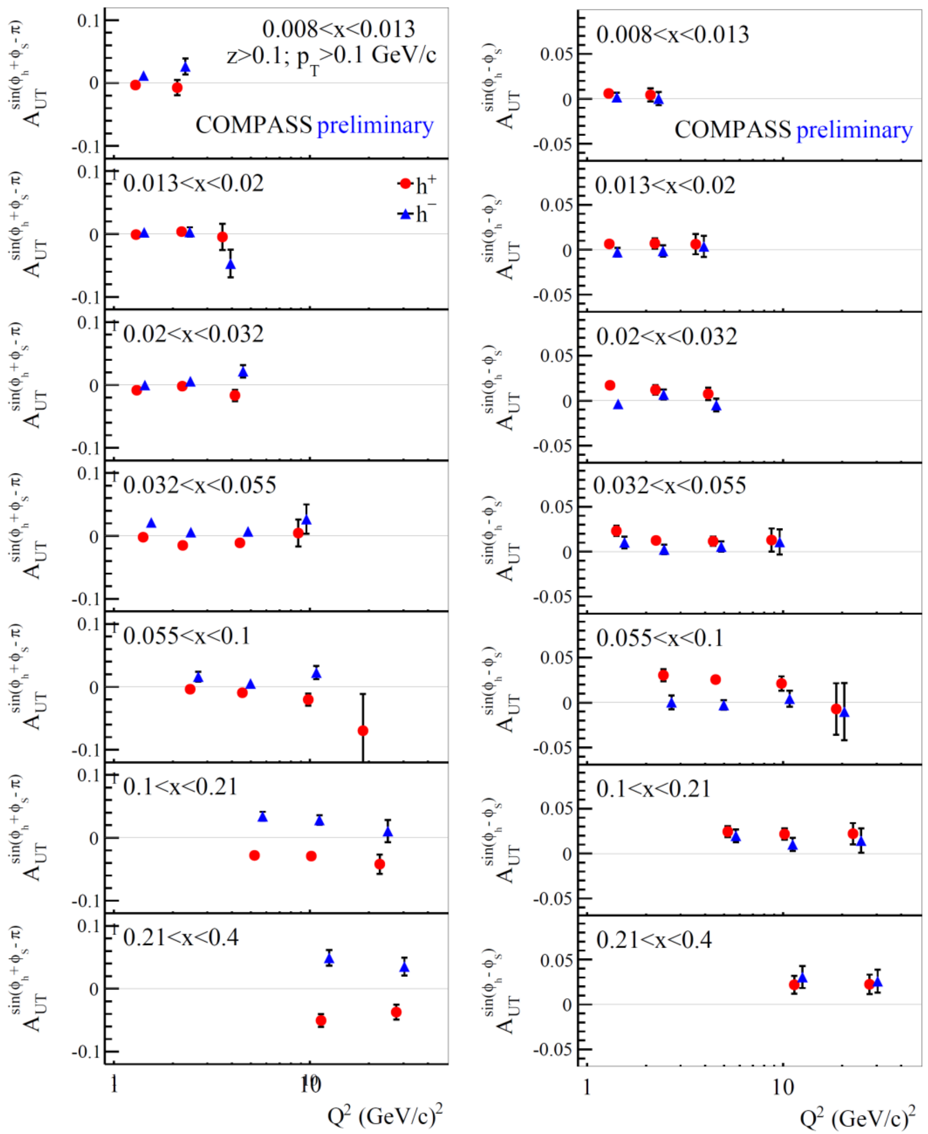
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + S_T \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) \ldots \right\}$$

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

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

B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)



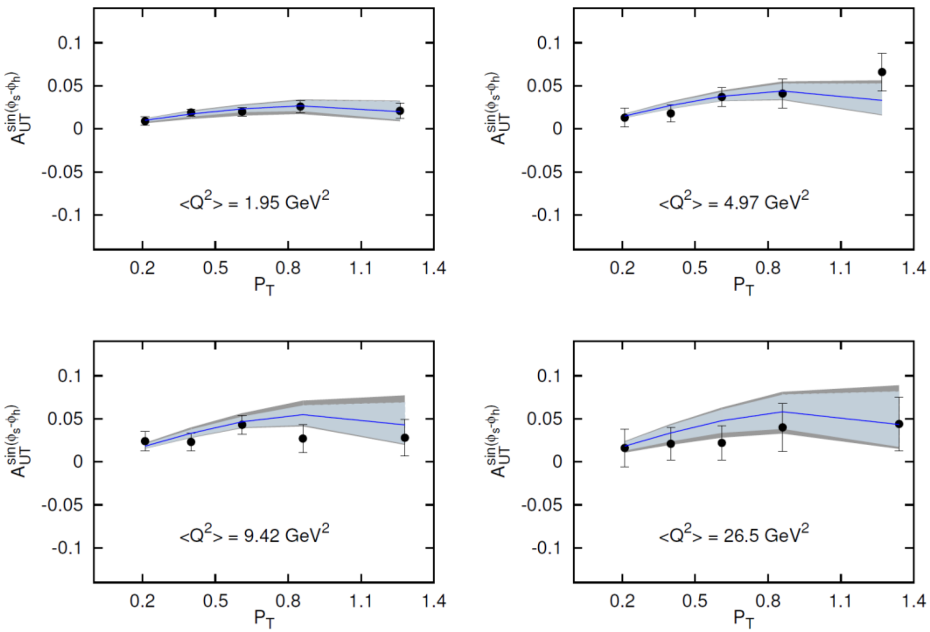


- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

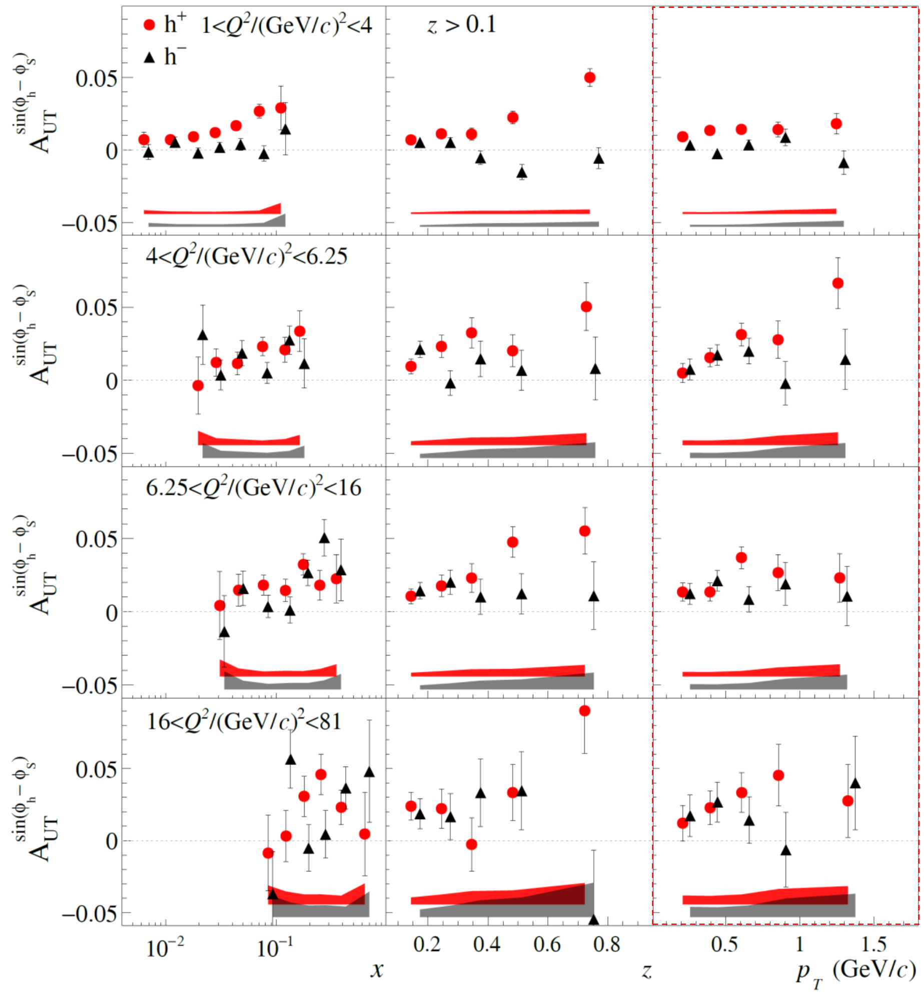
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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



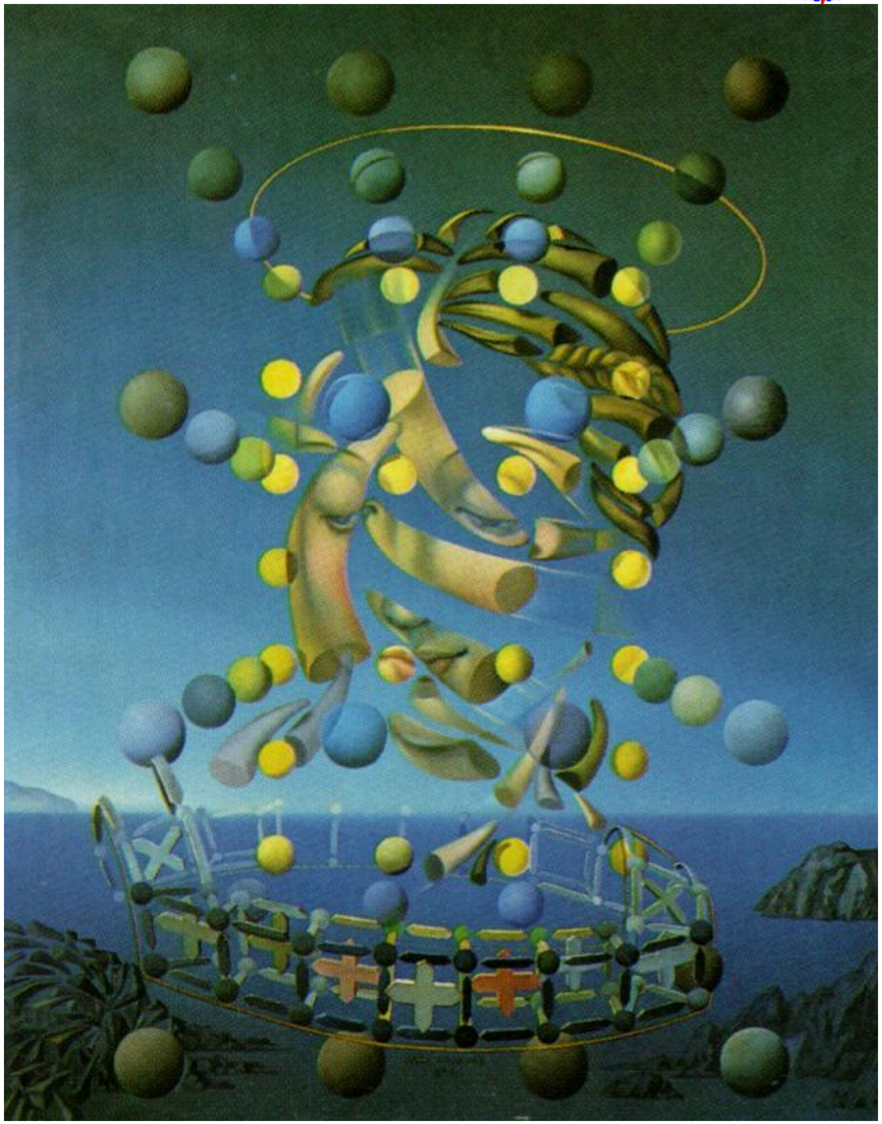
COMPASS PLB 770 (2017) 138



Courtesy of M. Boglione, J.O. Gonzalez-Hernandez (ongoing study)

"Nature" *"1D"*

Raphael *"Madonna del Prato"*



Salvador Dali *"Maximum Speed of Raphael's Madonna"*

Original idea by H. Avakian

“Nature”

Raphael *“Madonna del Prato”*

“multi-D” with available statistics

Raphael *“Madonna del Prato” (poor resolution)*

- 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**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$ but $1-\lambda=2\nu$ (Lam-Tung)
- **Experiment,**
  $\lambda\neq1$, $\mu \neq 0$, $\nu \neq 0$

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

COMPASS ongoing analysis

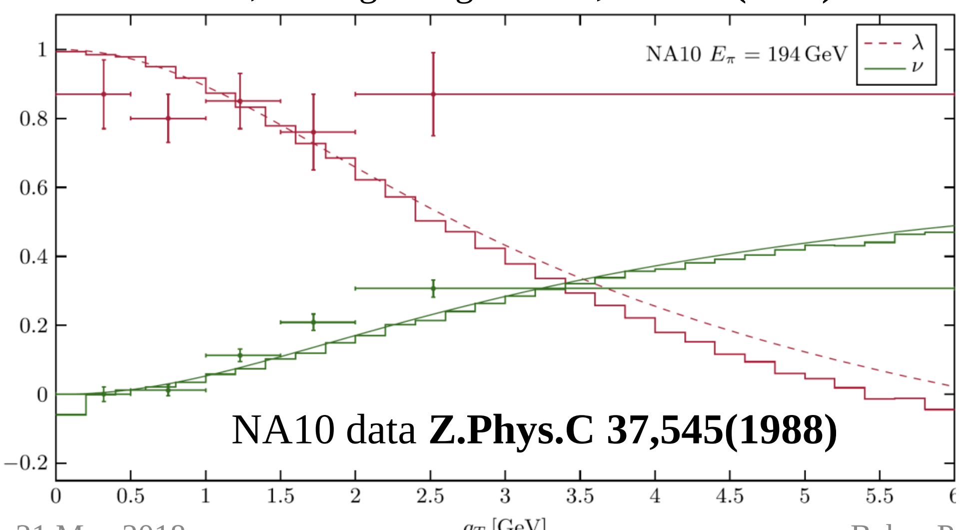
Single-polarized DY x-section: unpolarized part

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

- **“naive” Drell–Yan model**
  collinear (k_T=0) LO pQCD no rad. processes
  λ=1, (F_U^2=0), μ=ν=0
- **Intrinsic transverse motion + QCD effects**
  λ≠1, μ ≠ 0, ν ≠ 0 but 1–λ=2ν (Lam-Tung)
- **Experiment,**
  λ≠1, μ ≠ 0, ν ≠ 0
- ν ≠ 0 - Energy and quark flavour dependence, QCD radiative effects, non-coplanarity
  (PRD93, 114013 (2016), PLB 758 (2016) 384)

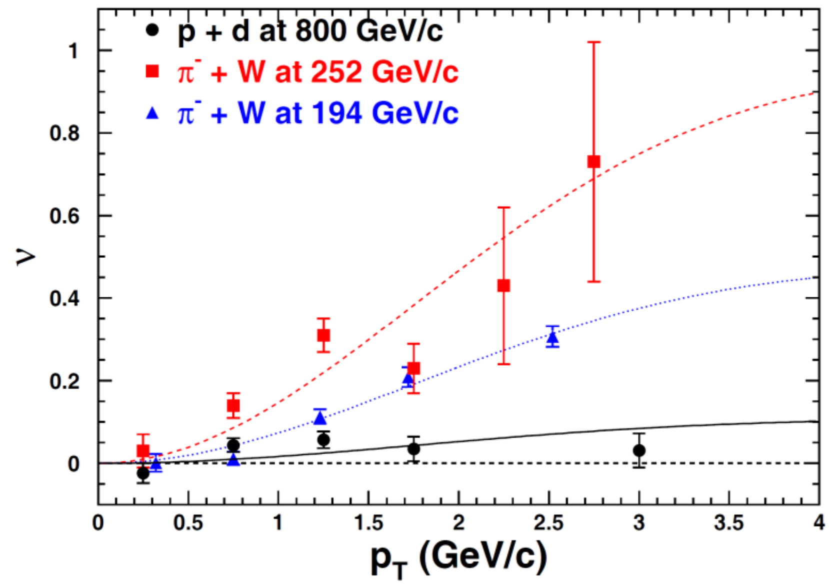
See talk by J.-C. Peng

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



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

COMPASS ongoing analysis



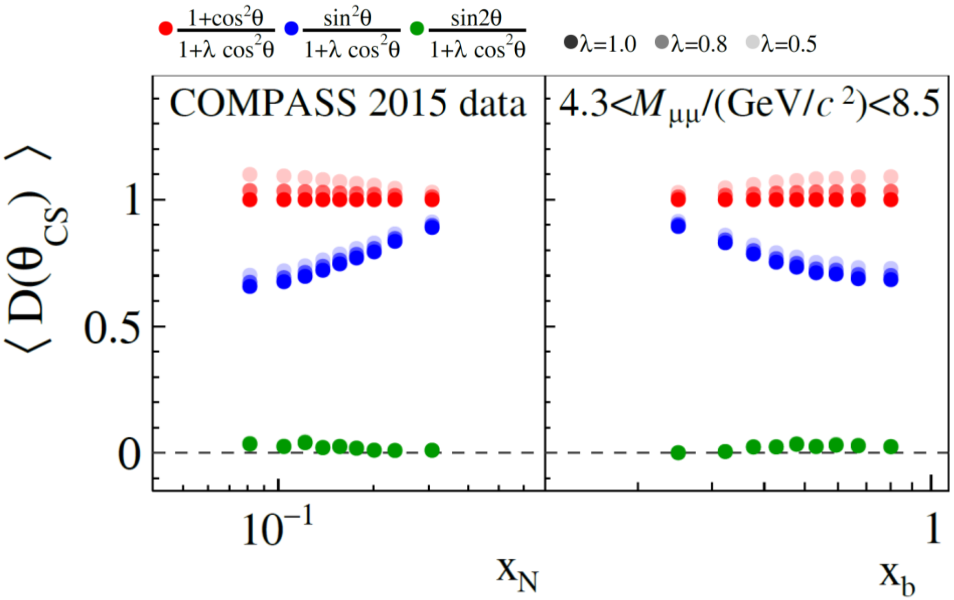
Single-polarized DY x-section: transverse part

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

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

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

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



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

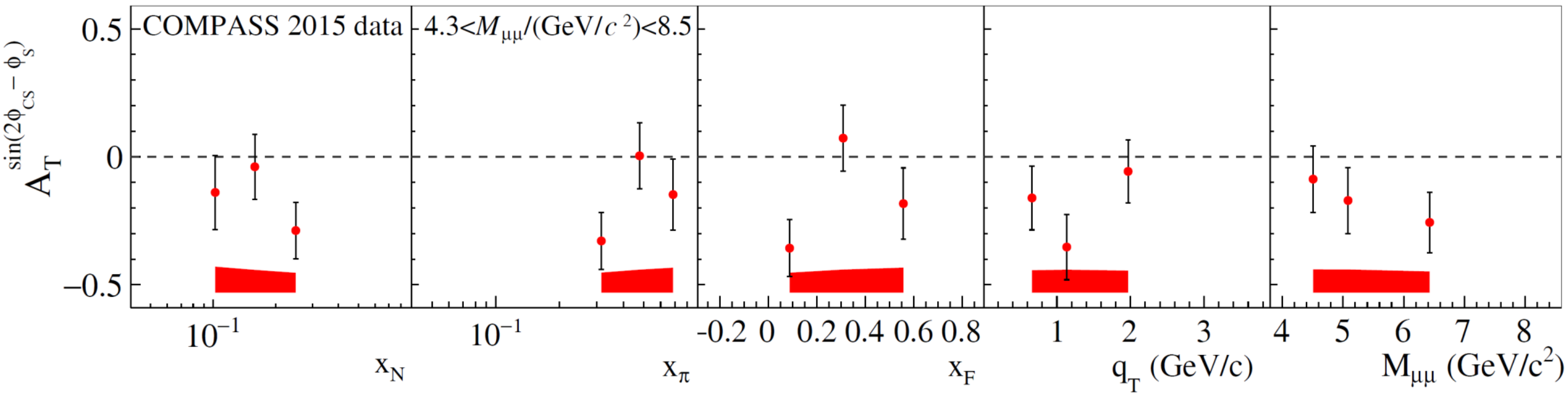
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

COMPASS PRL 119, 112002 (2017)



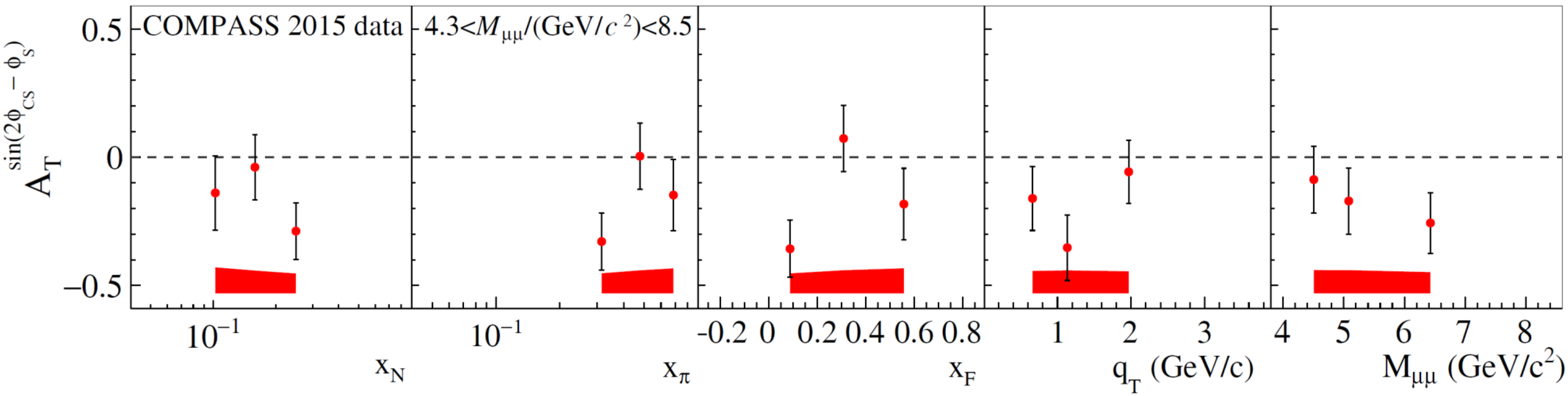
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

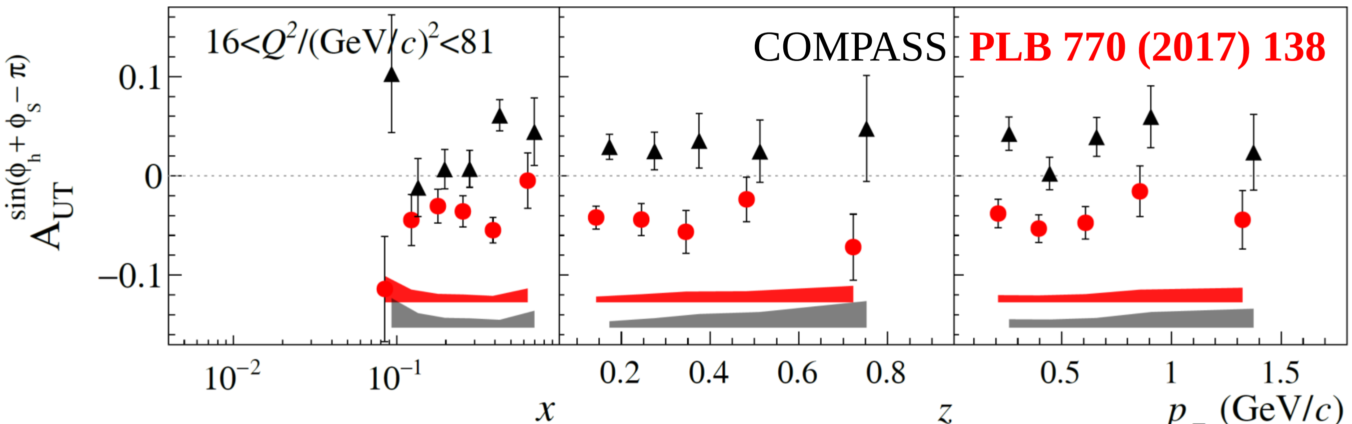
COMPASS **PRL 119, 112002 (2017)**



SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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



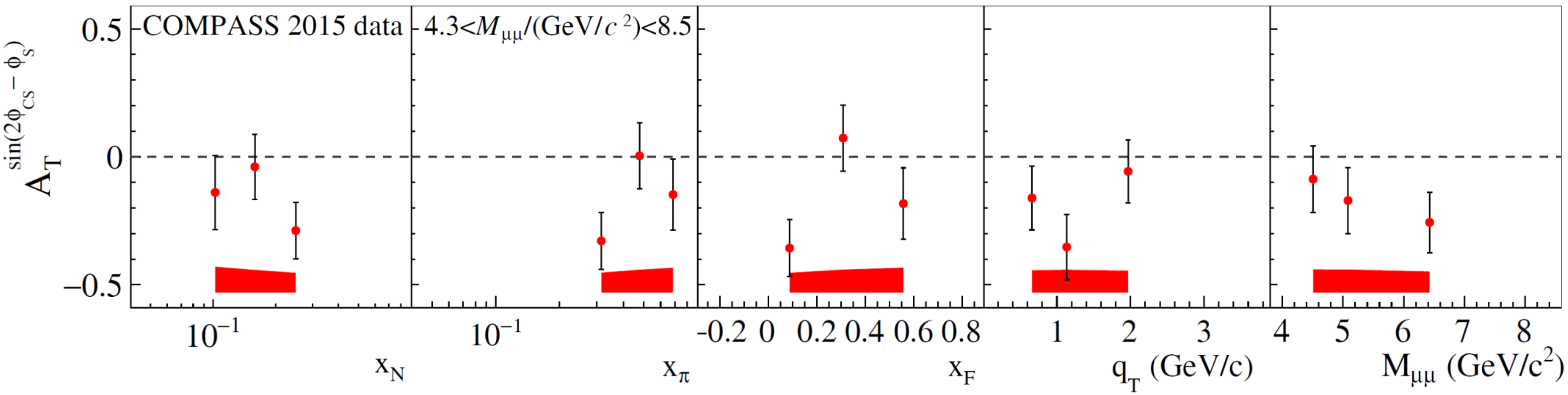
Drell-Yan TSAs – Transversity

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

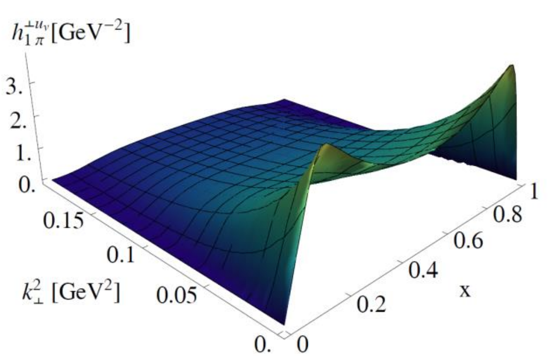
Transversity DY TSA

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

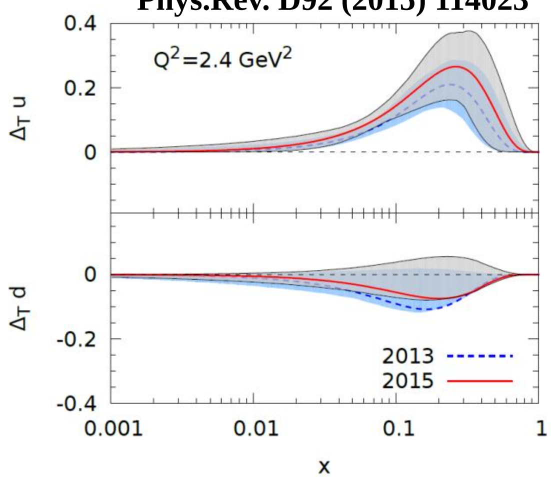
COMPASS PRL 119, 112002 (2017)



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



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



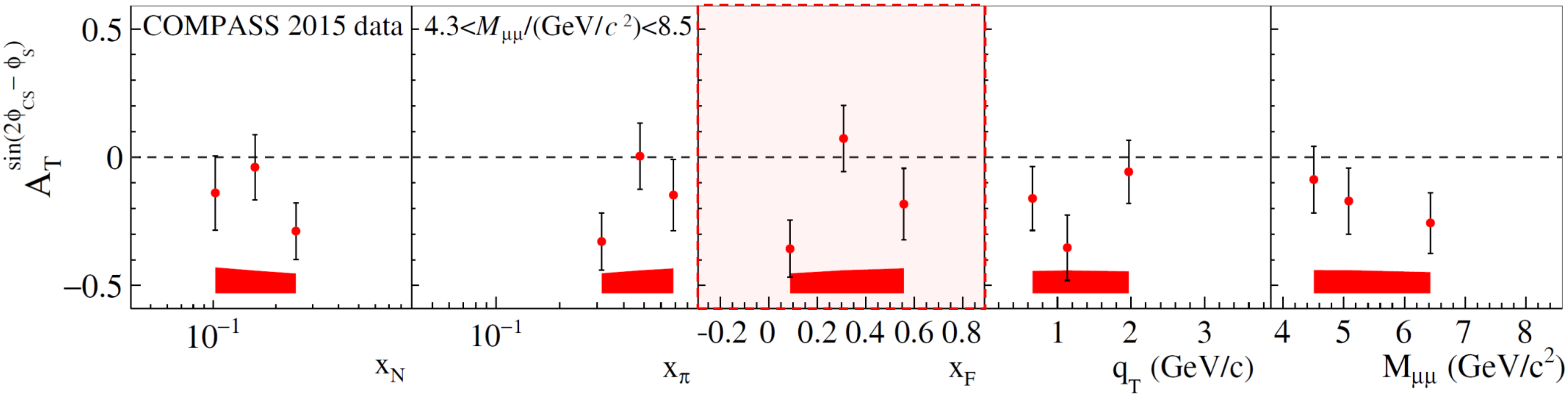
Drell-Yan TSAs – Transversity

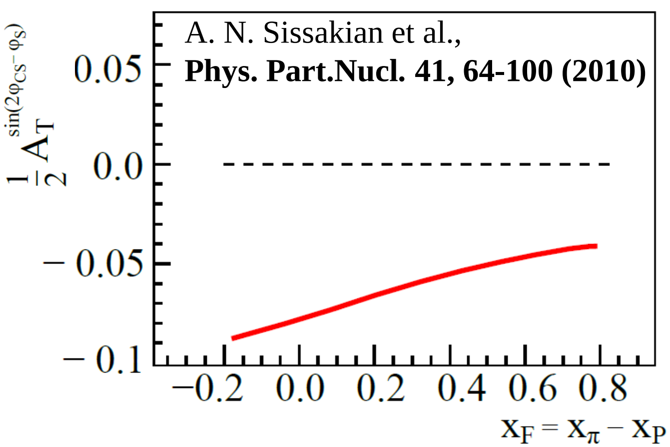
$$\frac{d\sigma}{d\Omega} \propto 1+\ldots+ S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S)+\ldots \right]$$

Transversity DY TSA

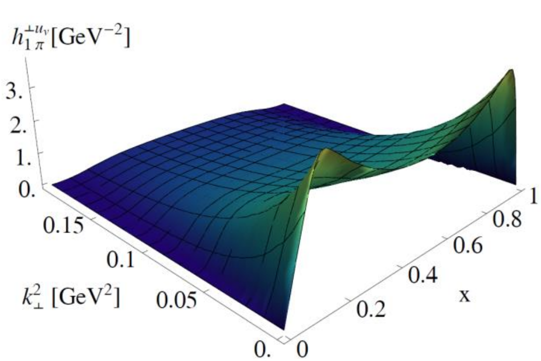
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

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

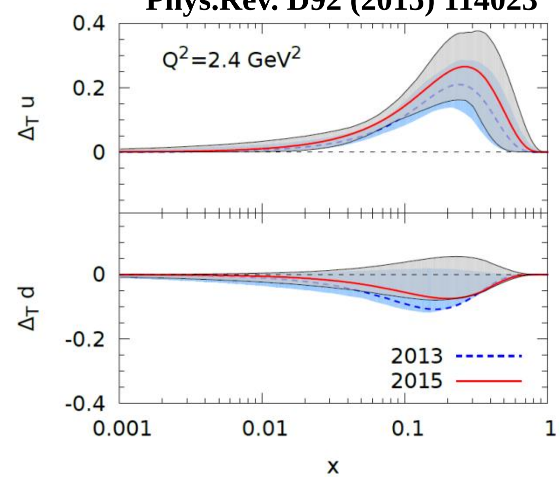




B. P. Pasquini, P. Schweitzer
Phys.Rev. D90 (2014) 014050



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



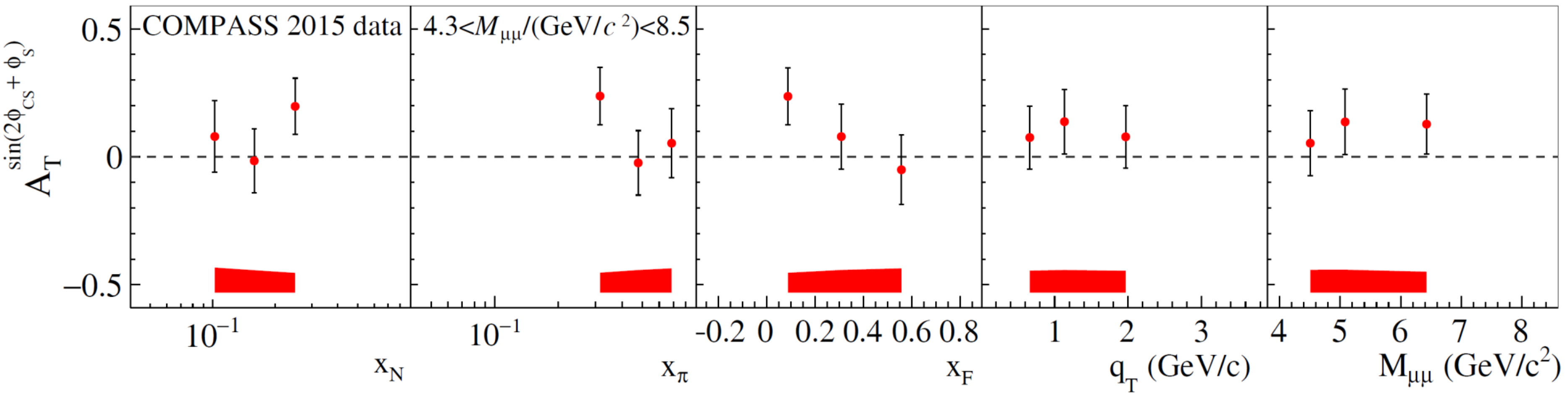
Drell-Yan TSAs – Pretzelosity

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

Pretzelosity DY TSA

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

COMPASS PRL 119, 112002 (2017)



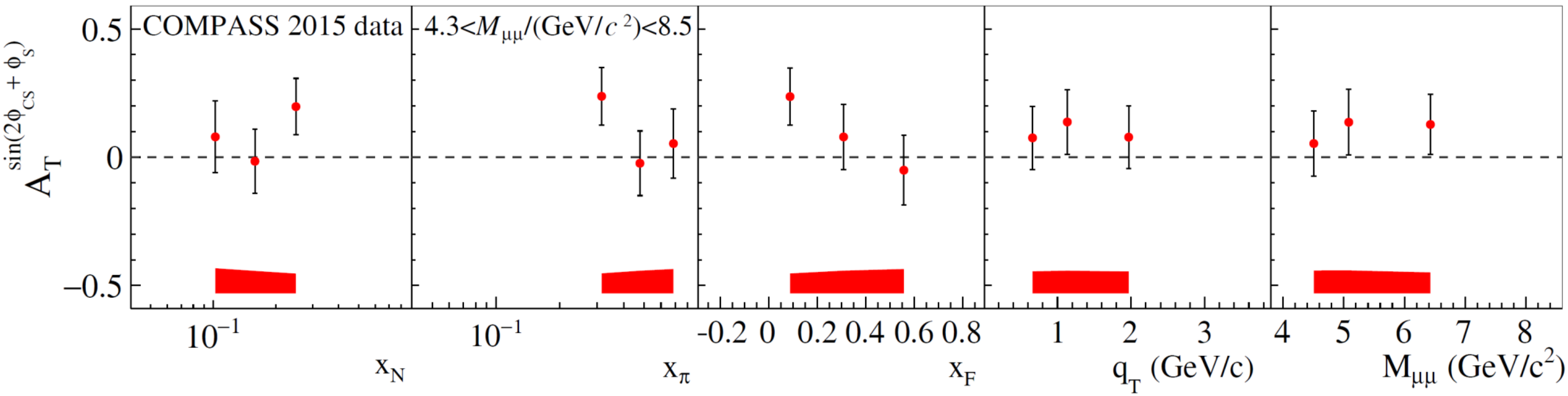
Drell-Yan TSAs – Pretzelosity

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

COMPASS PRL 119, 112002 (2017)

Pretzelosity DY TSA

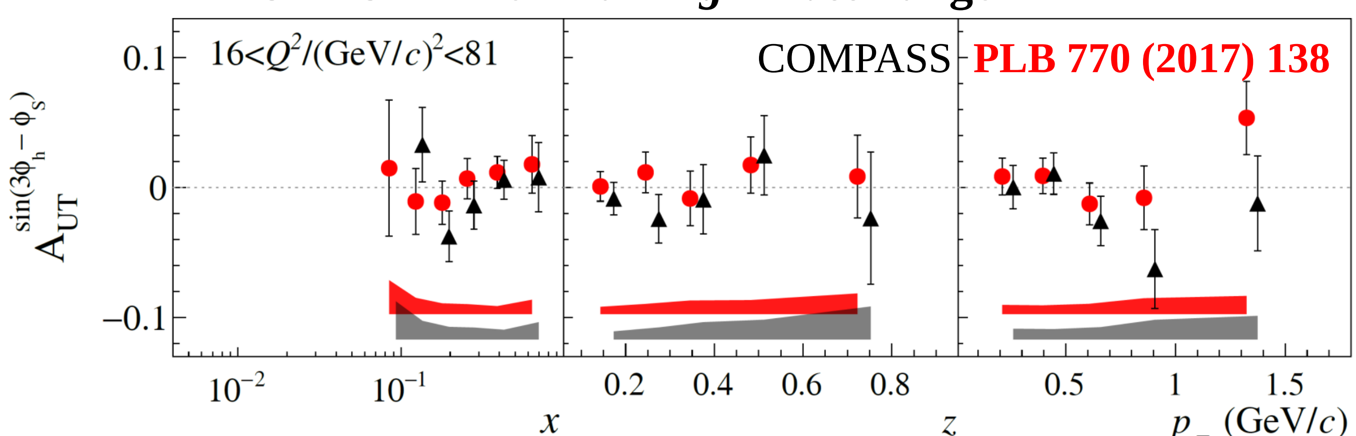
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$



SIDIS in Drell-Yan *high-mass* range

Pretzelosity SIDIS TSA

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



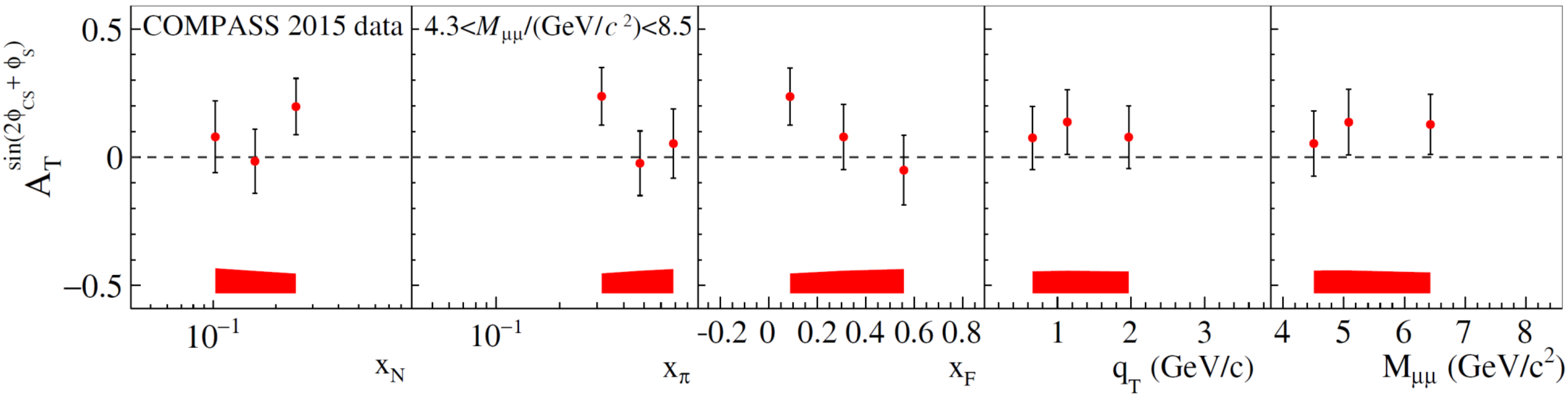
Drell-Yan TSAs – Pretzelosity

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

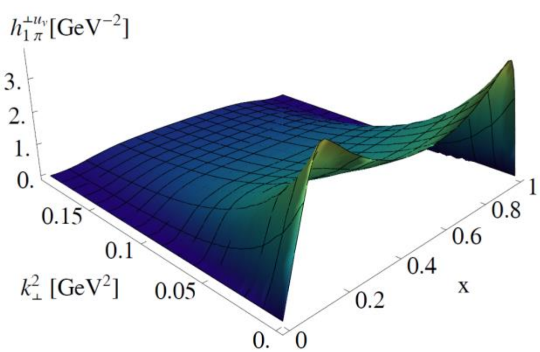
Pretzelosity DY TSA

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

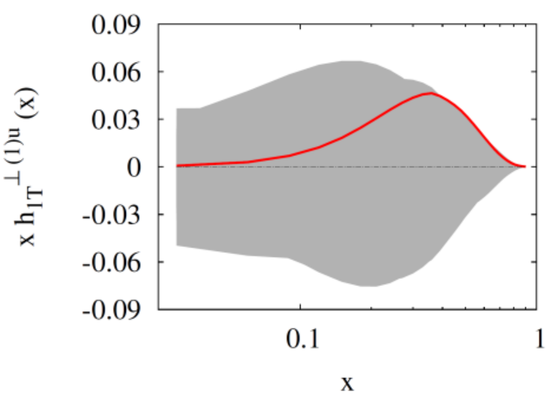
COMPASS PRL 119, 112002 (2017)



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



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



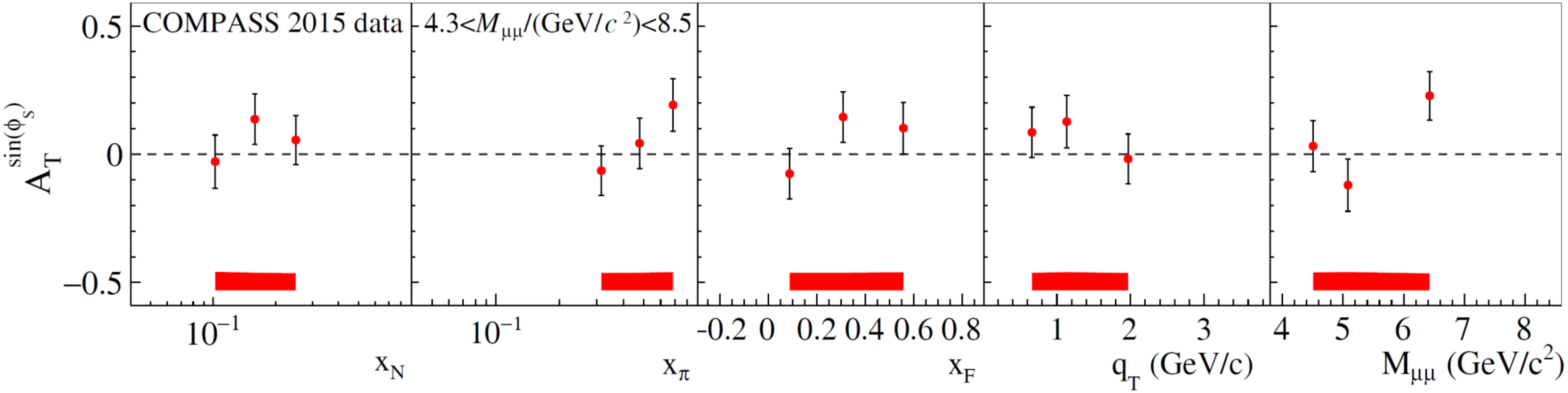
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)



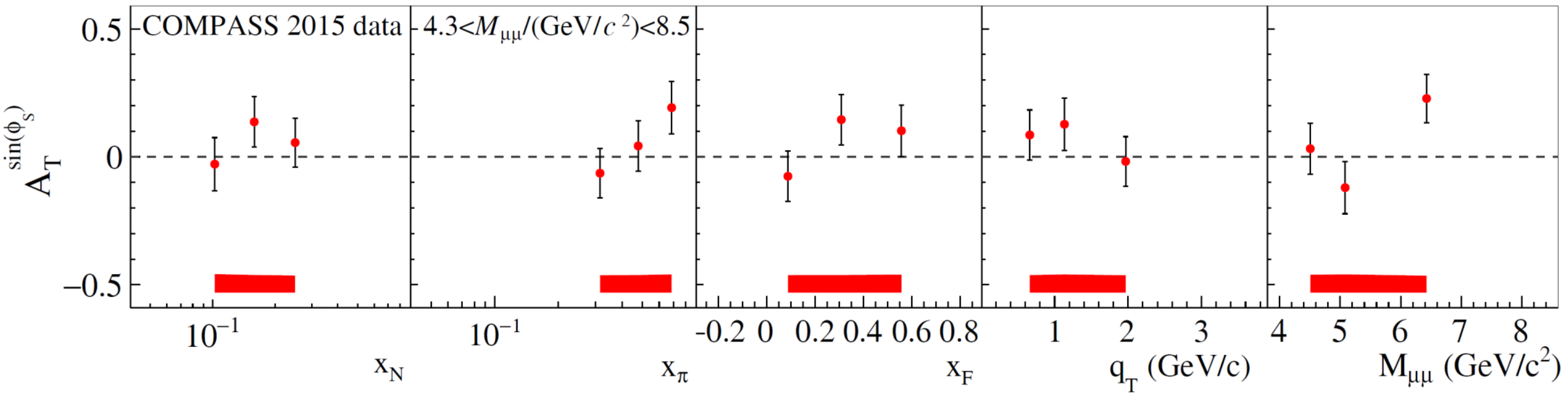
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS PRL 119, 112002 (2017)

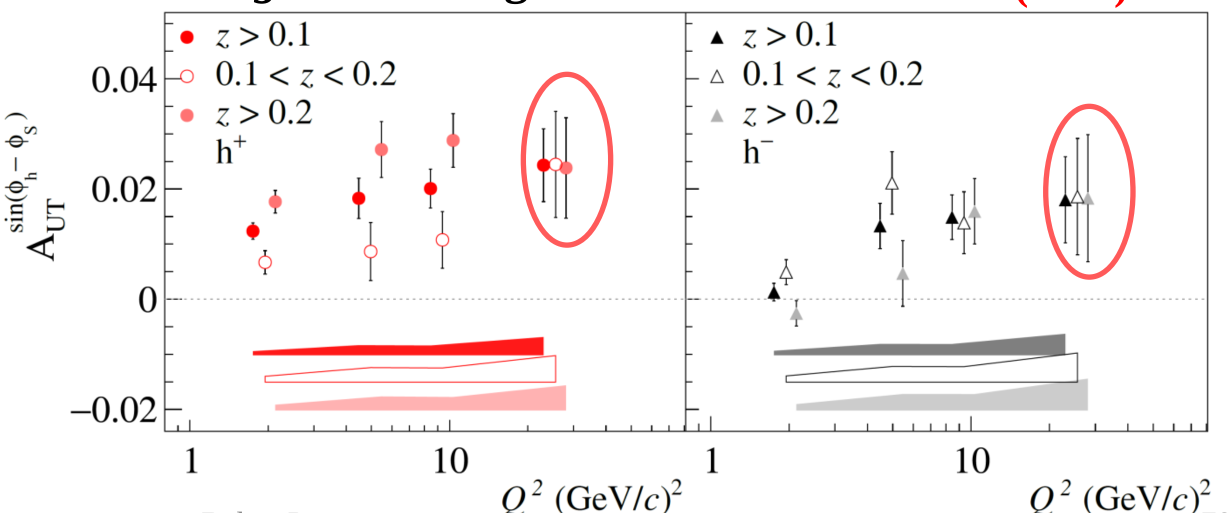


SIDIS in Drell-Yan *high-mass* range

COMPASS **PLB 770 (2017) 138**

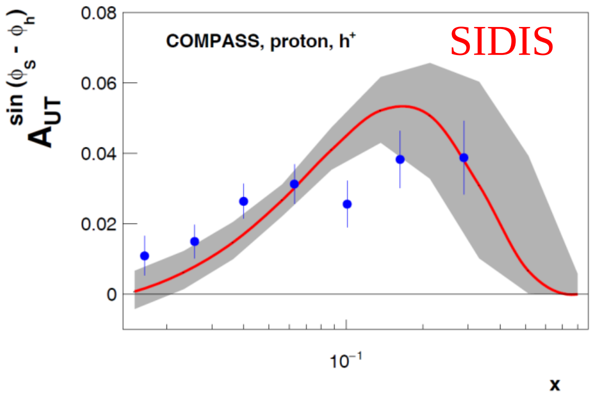
Sivers SIDIS TSA

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

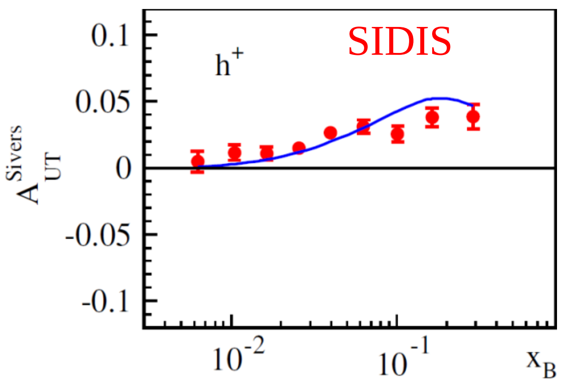


Sivers asymmetry in Drell-Yan: sign change

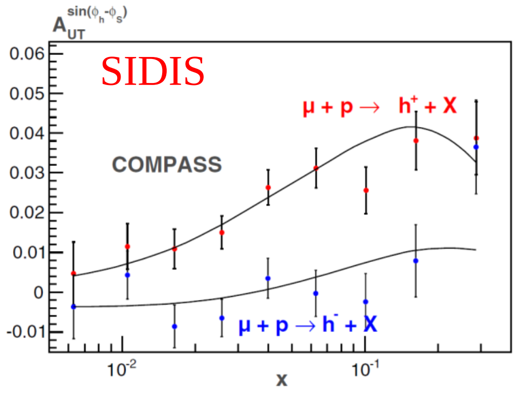
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



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

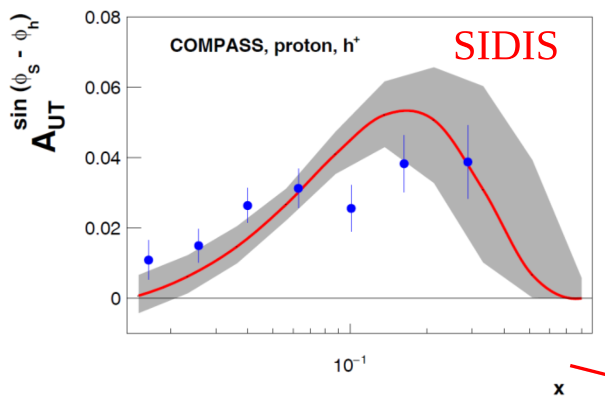


TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**

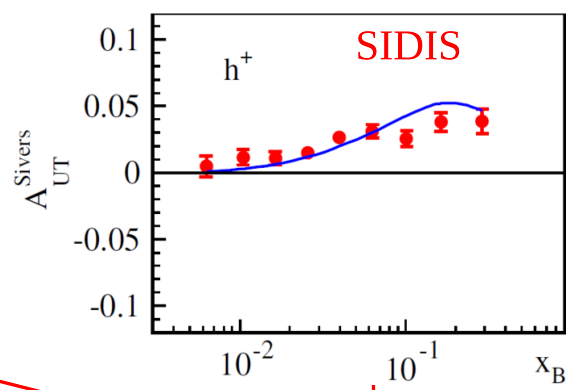


Sivers asymmetry in Drell-Yan: sign change

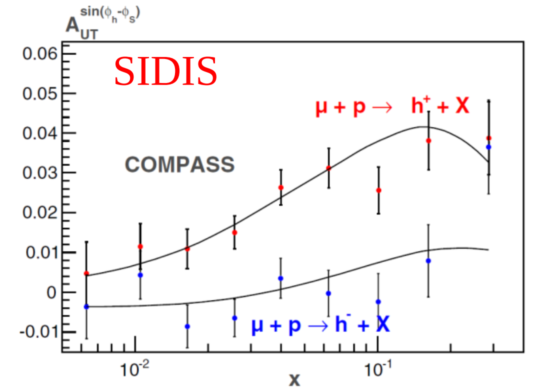
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.0641**3

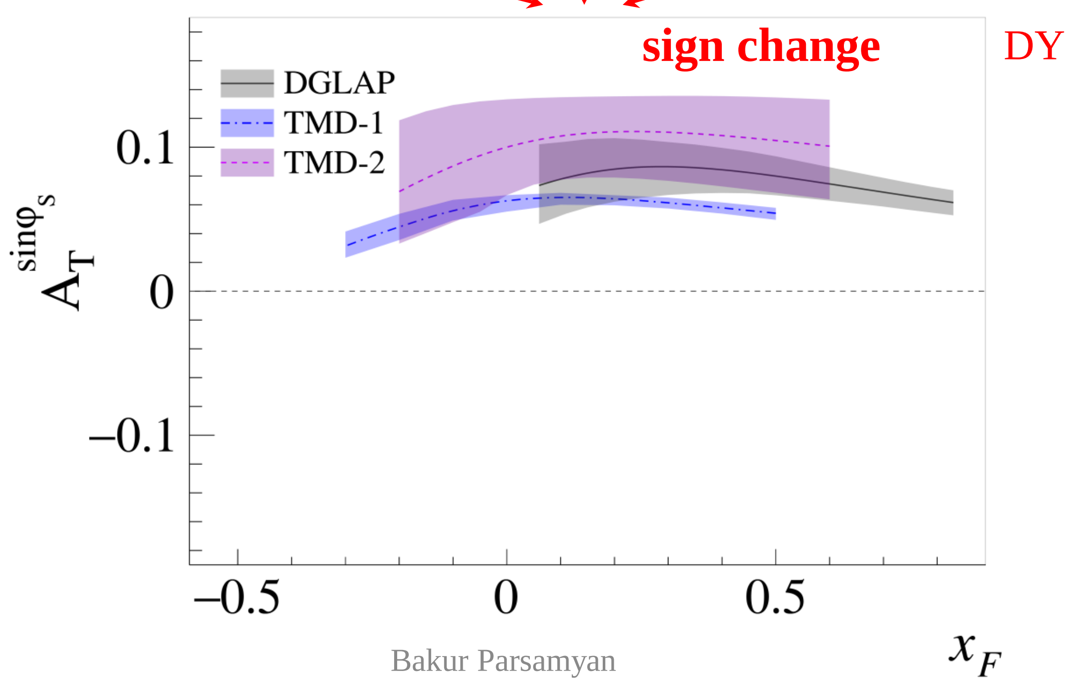


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



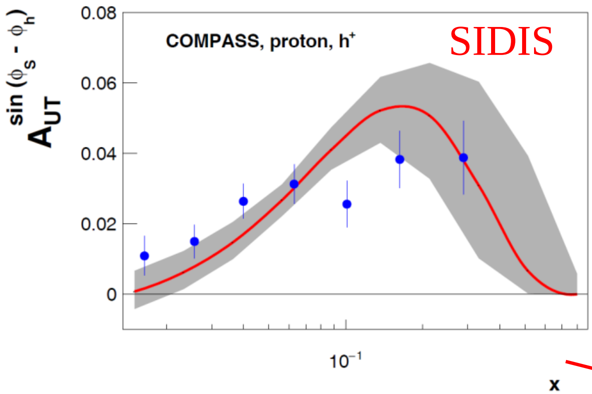
TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



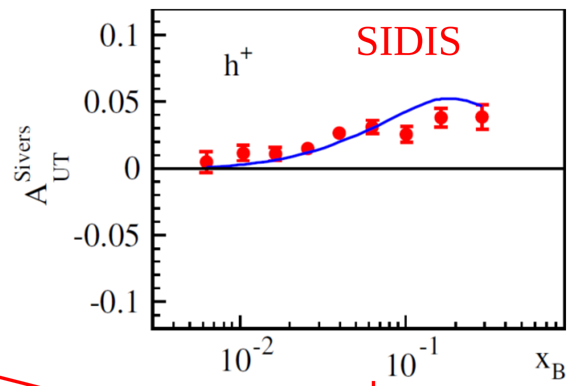


Sivers asymmetry in Drell-Yan: sign change

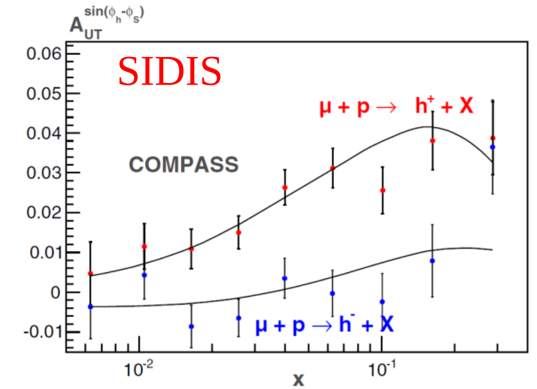
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**

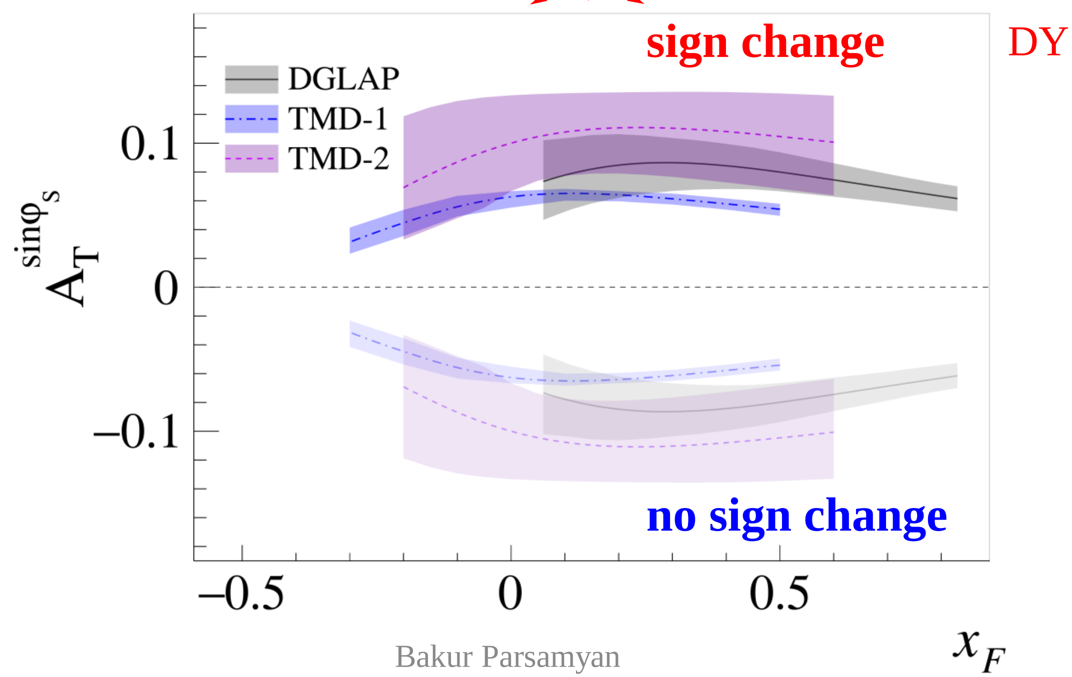


TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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





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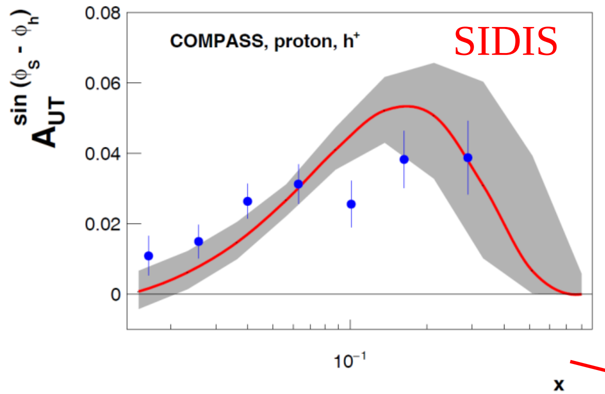

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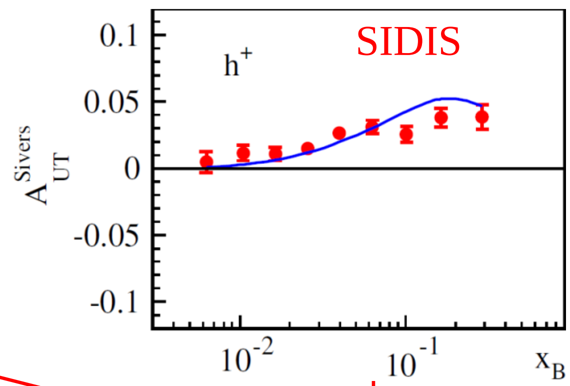

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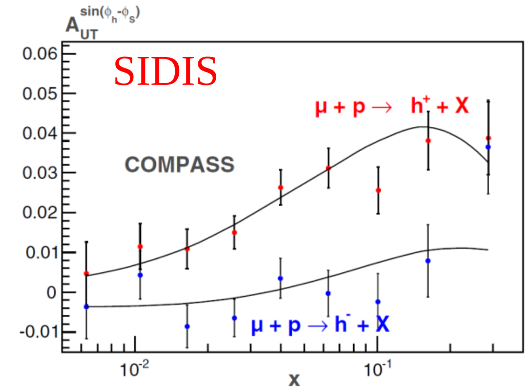
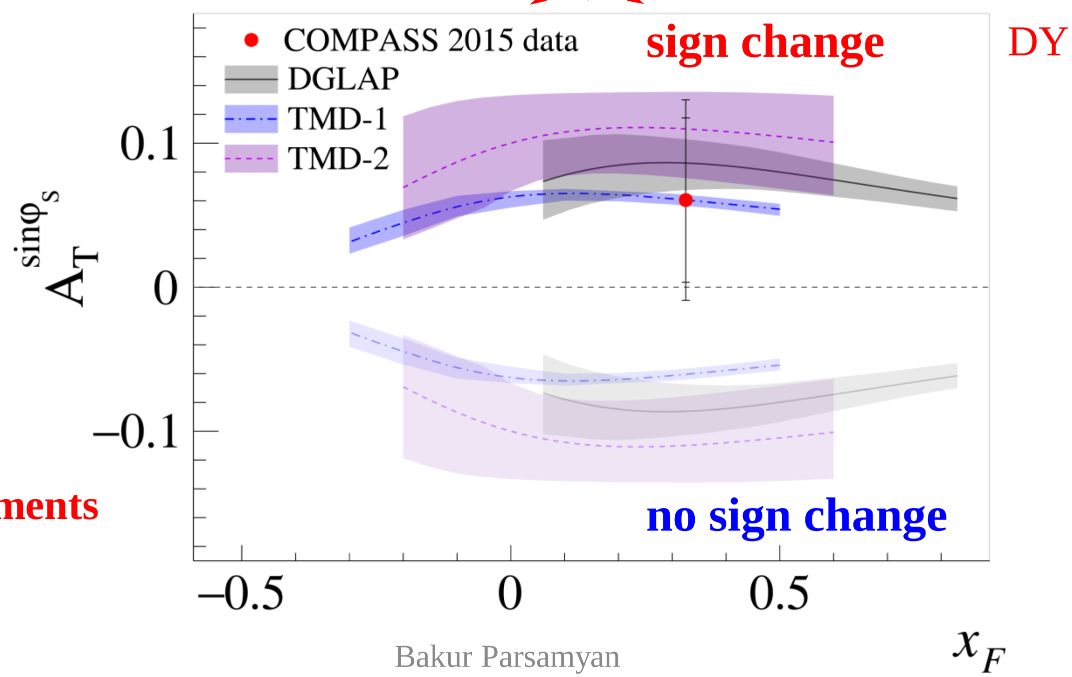


COMPASS
PRL 119, 112002 (2017)

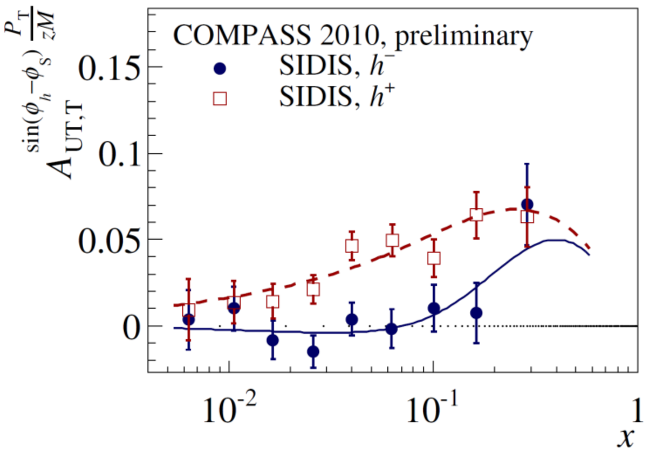


In 2018 – 2nd round of polarized DY measurements at COMPASS

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

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

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



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

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

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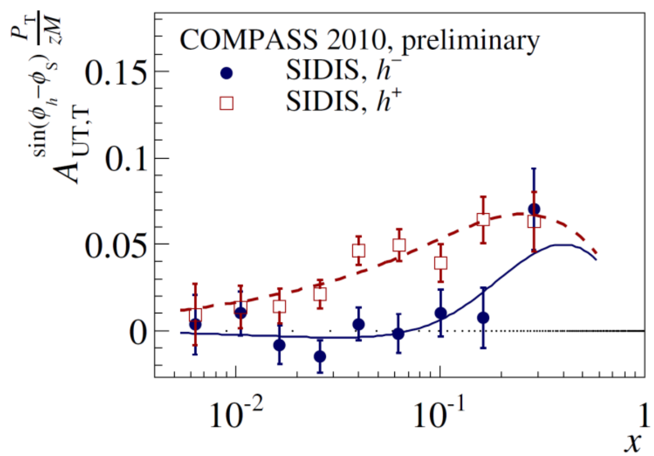

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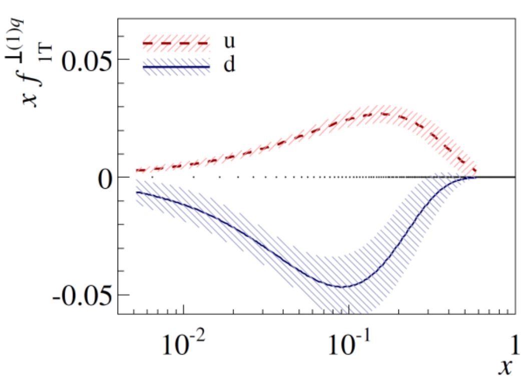
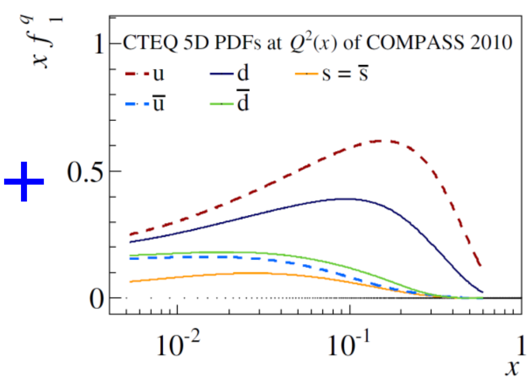
Sivers TSA in DY:	$A_T^{\sin\varphi_S}$	$\propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
Sivers *w*TSA in DY:	$A_T^{\sin\varphi_S}$	$\propto f_{1,\pi}^{q} \times f_{1T,p}^{\perp q\,(1)}$



+



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

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

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

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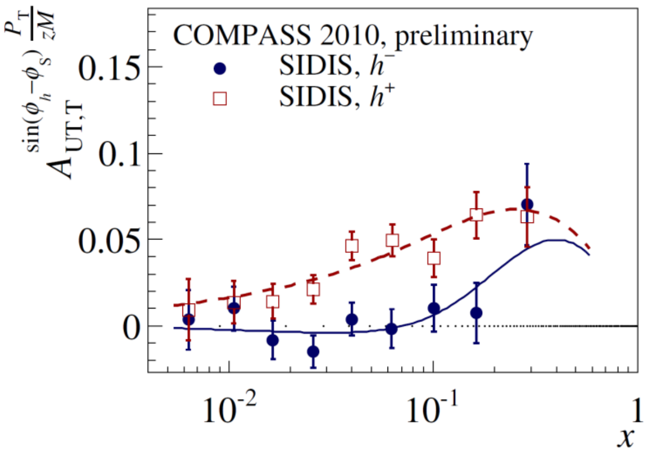

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Sivers TSA in DY: $A_{T}^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$

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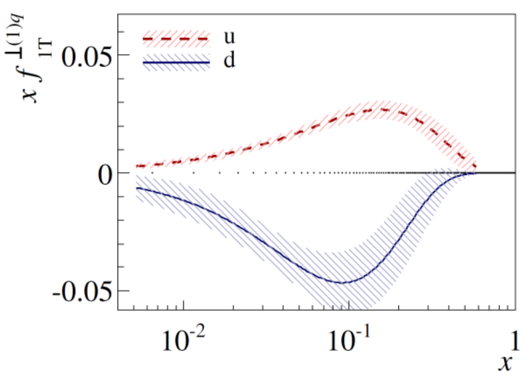
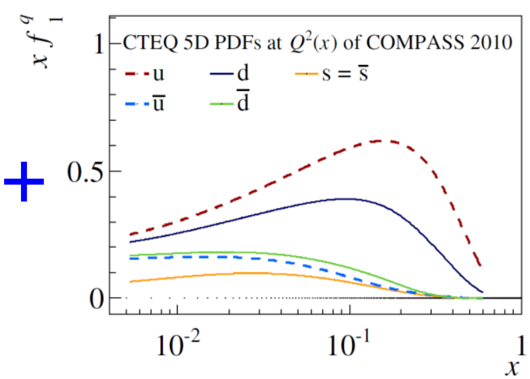
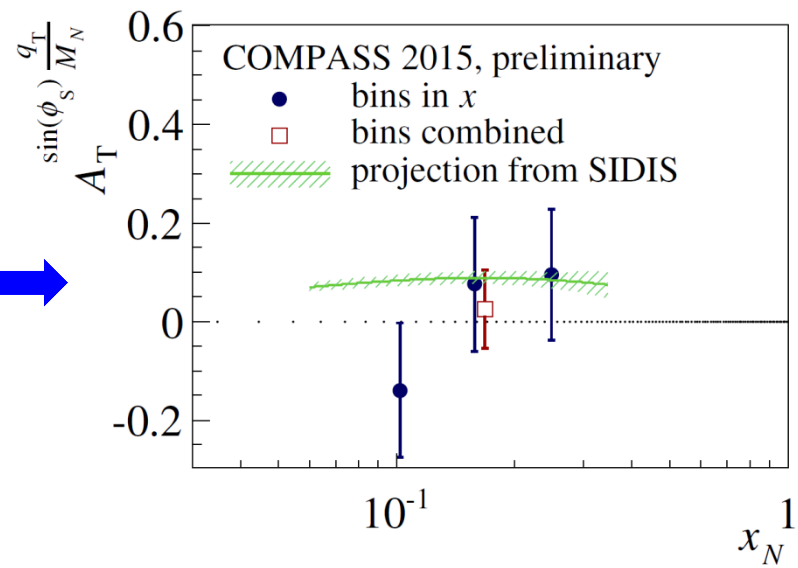




J. Matoušek (COMPASS at DSPIN-2017)
arXiv:1710.06497 [hep-ex]

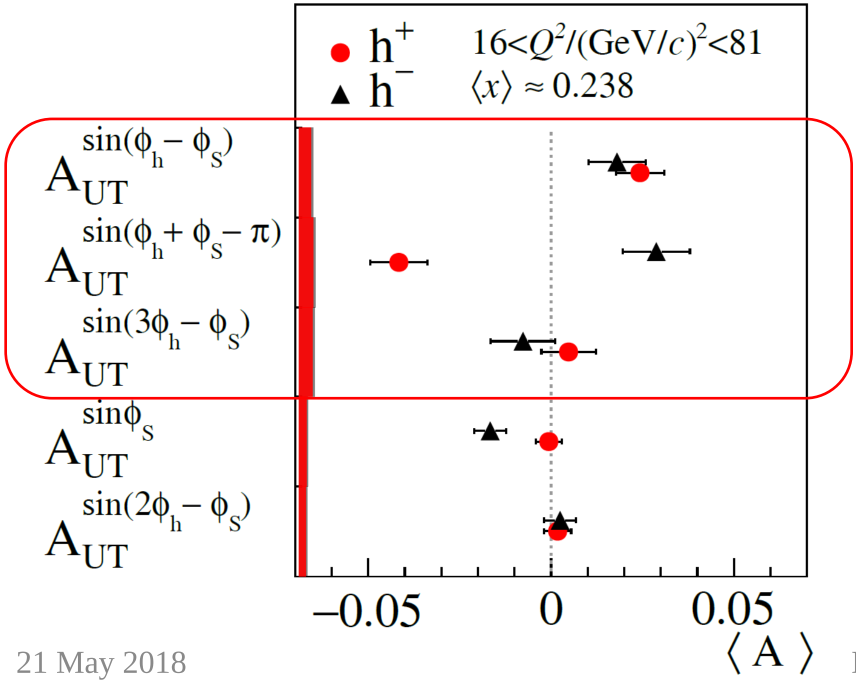


SIDIS and DY TSAs at COMPASS (high-mass range)

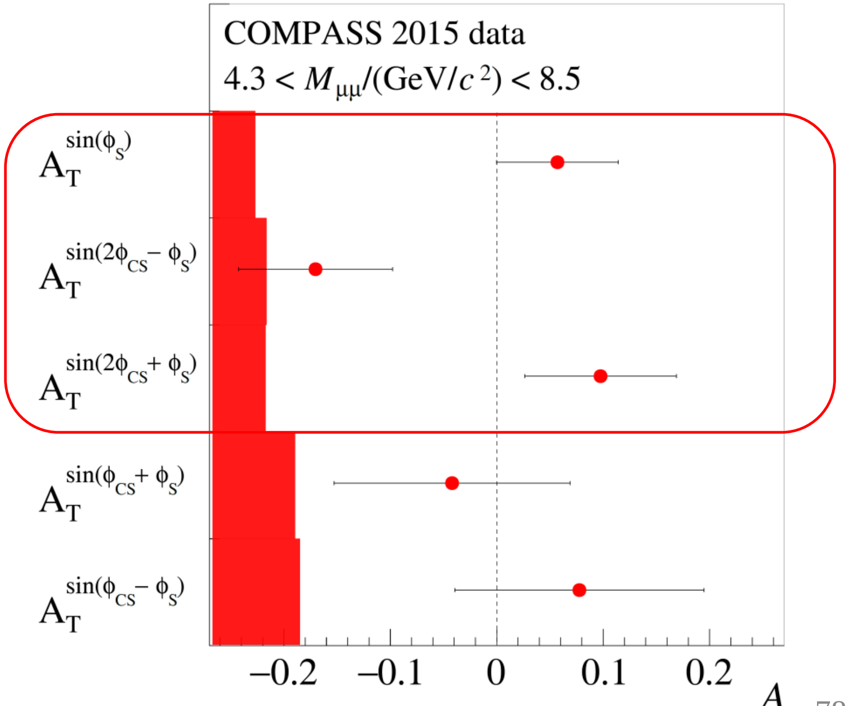
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots + S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)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

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

COMPASS PLB 770 (2017) 138

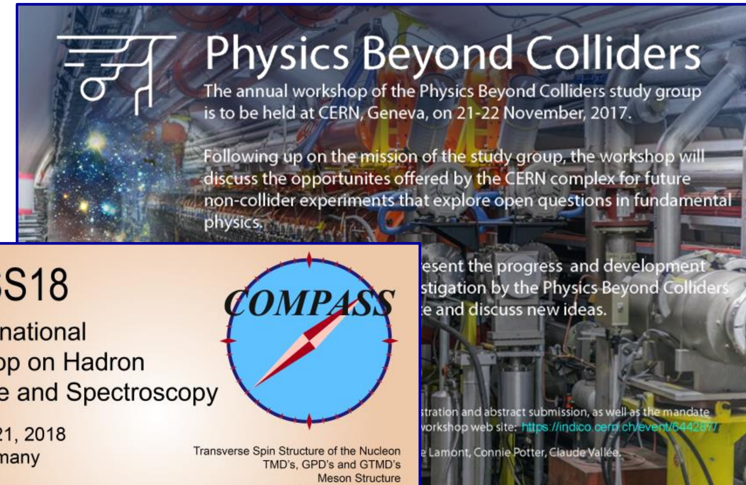


COMPASS PRL 119, 112002 (2017)



“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



Conclusions

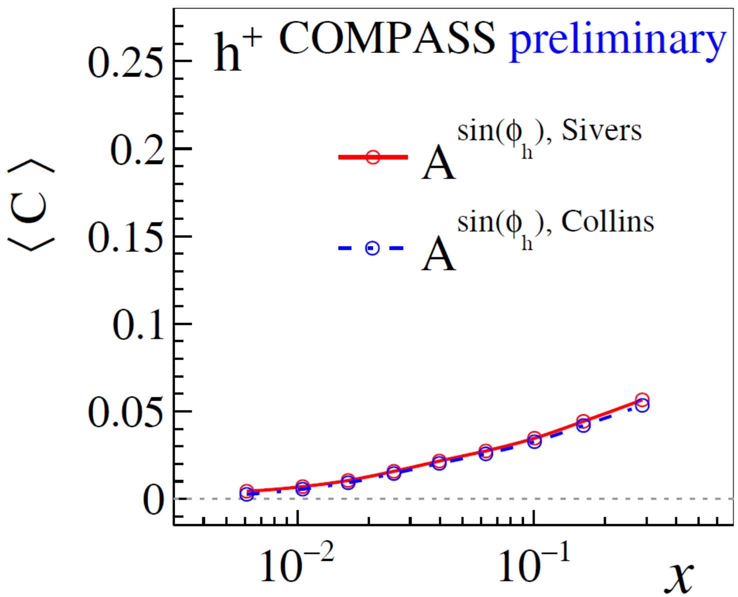
- During phase I COMPASS has measured all possible SIDIS azimuthal LSAs and TSAs
  - Recently COMPASS has performed first multidimensional analysis of SIDIS proton TSAs: PLB 770 (2017) 138
    - No hints for significant Q^2-dependences of Sivers and Collins TSAs
    - Apart from Sivers and Collins effects non-zero signal was observed for *twist-2* $A_{LT}^{\cos(\phi_h-\phi_S)}$ and *subleading-twist* $A_{UT}^{\sin\phi_S}$ TSAs
  - COMPASS has measured SIDIS proton LSAs with unprecedented precision
    - *twist-2* $A_{UL}^{\sin 2\phi_h}$ asymmetry seem to exhibit a Collins-like behavior
    - Significant effect was observed for *subleading-twist* $A_{UL}^{\sin\phi_h}$ LSA
- In 2015 COMPASS has successfully collected first ever polarized DY data PRL 119, 112002 (2017)
  - A second year of polarized DY data-taking will take place in 2018
- The future of COMPASS collaboration is being currently actively discussed
  - SIDIS measurements with transversely polarized deuteron target in 2021
  - New experiment beyond 2021, the LOI will become public soon
    - Particular attention is given to possible Drell-Yan measurements

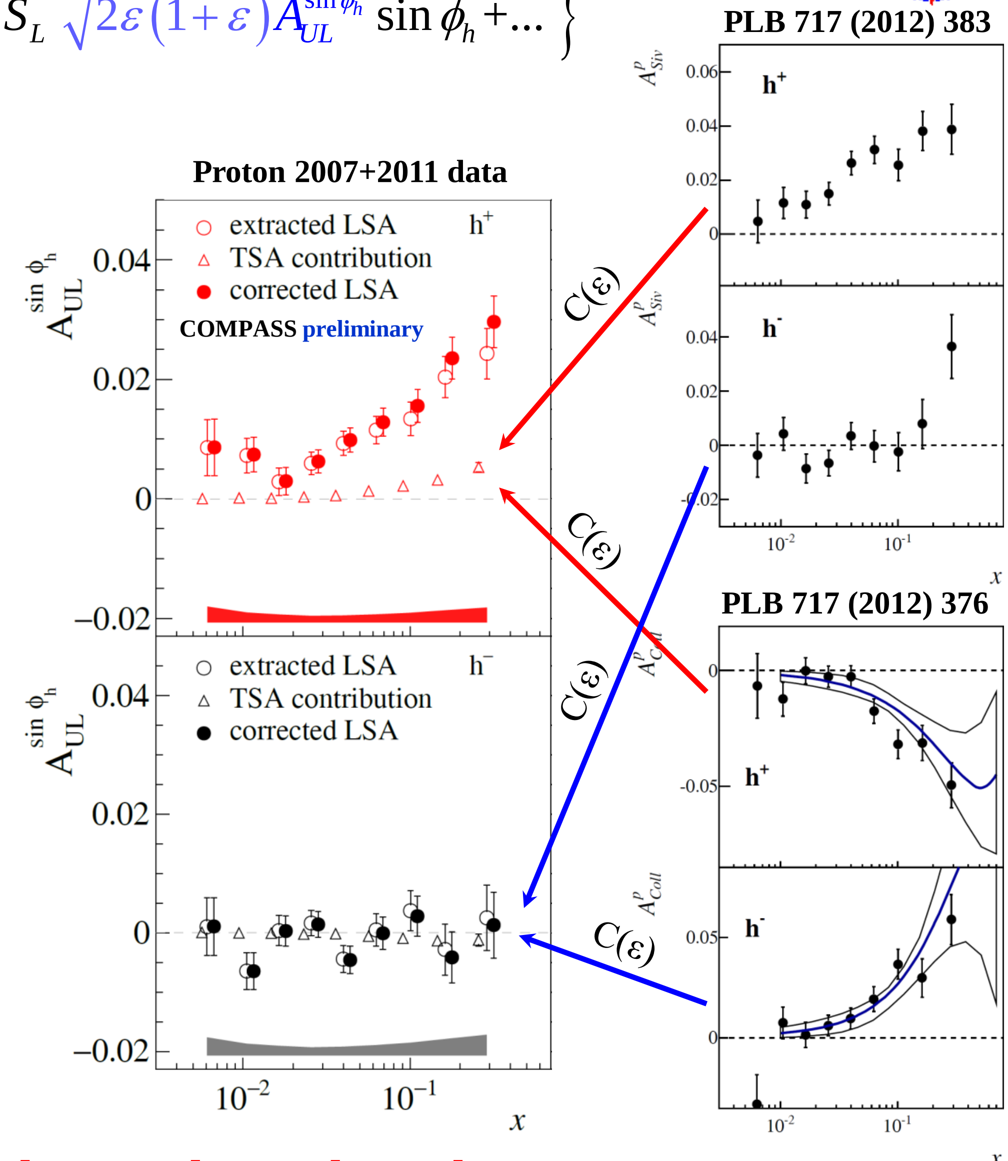
Spare slides

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

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

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



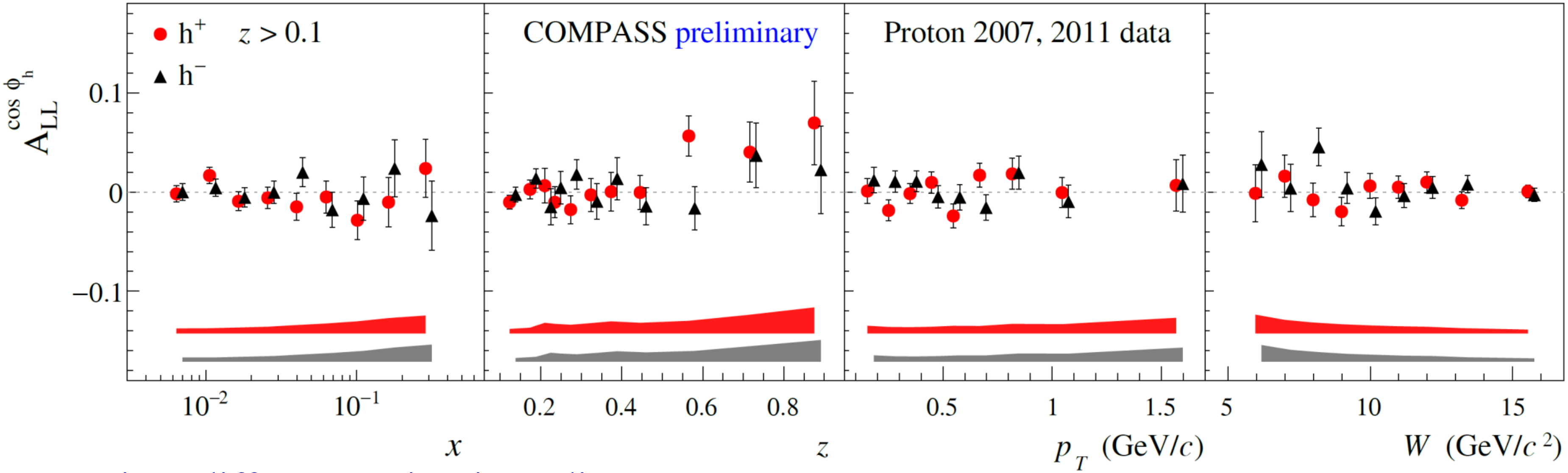


- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Non-zero trend for h^+, h^- compatible with zero, clear z-dependence**

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

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

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



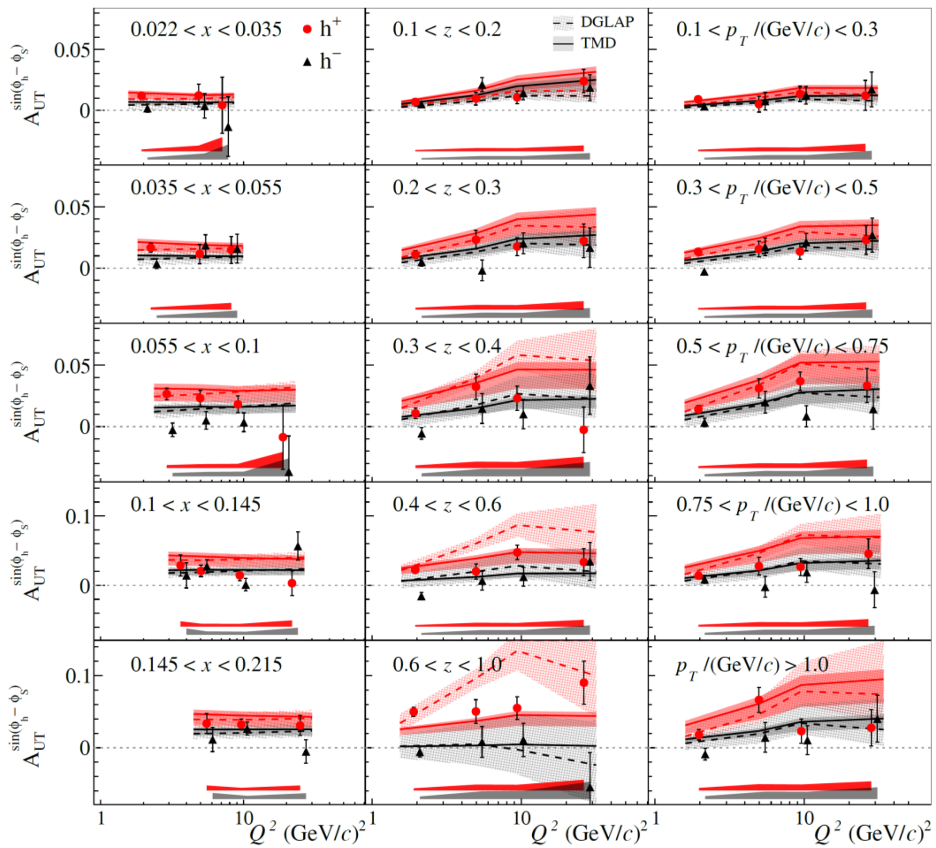
- Various different “twist” ingredients,
- Q-suppression

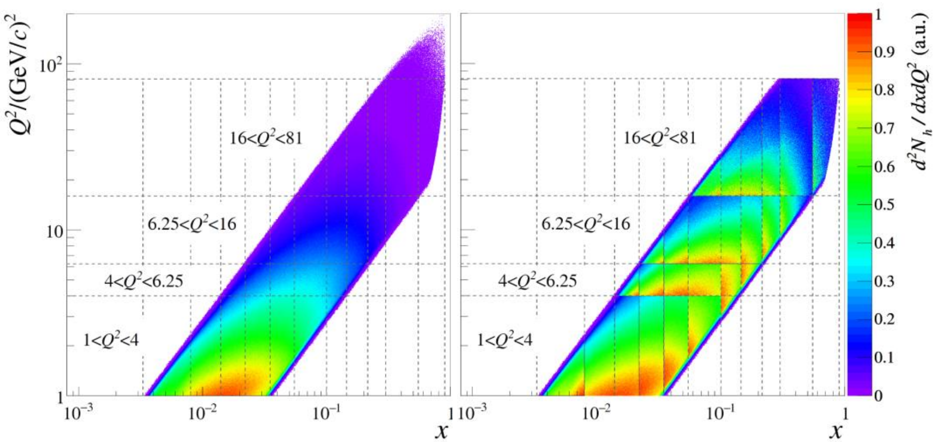
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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

COMPASS PLB 770 (2017) 138





Multi-dimensional input for TMD evolution studies

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

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

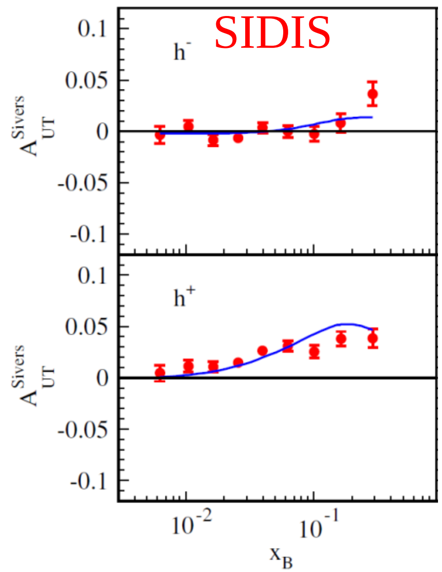
SIDIS TSAs (Sivers)

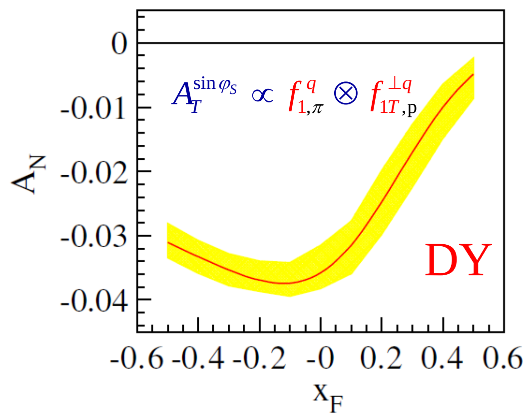
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

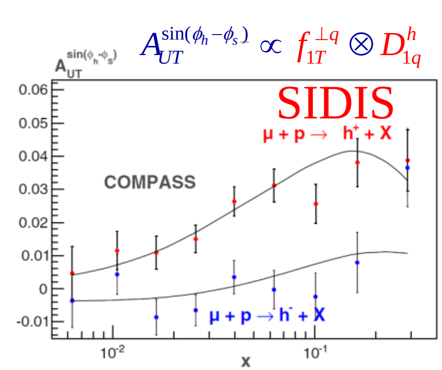
- Measured on proton and deuteron
- Recently - gluon Sivers paper PLB 772 (2017) 854
- Sivers effect at COMPASS is slightly smaller w.r.t HERMES results (Q^2 is different by a factor of ~2-3)
- **Q^2-evolution? Intriguing result!**
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY

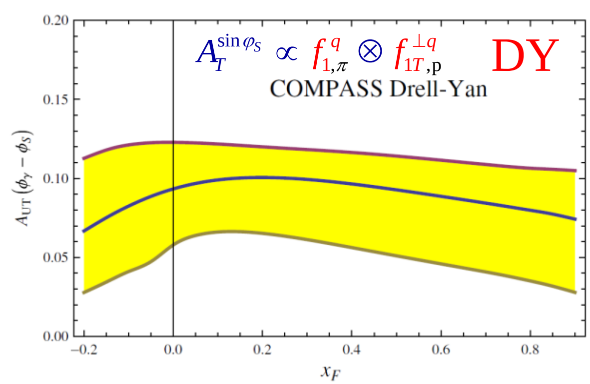
M.G. Echevarria, A.Idilbi, Z.B. Kang and I. Vitev, **PRD 89 074013 (2014)**





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

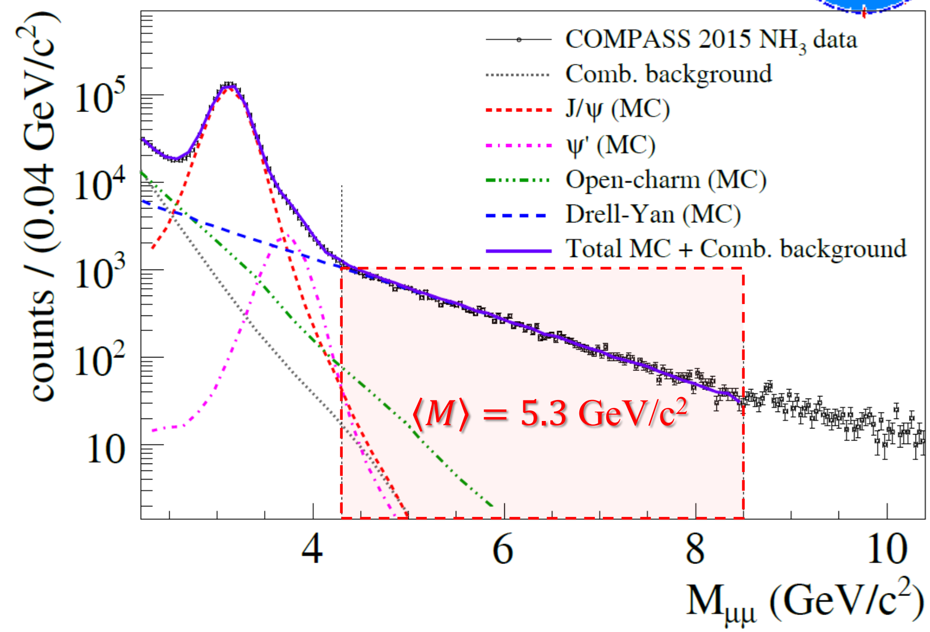




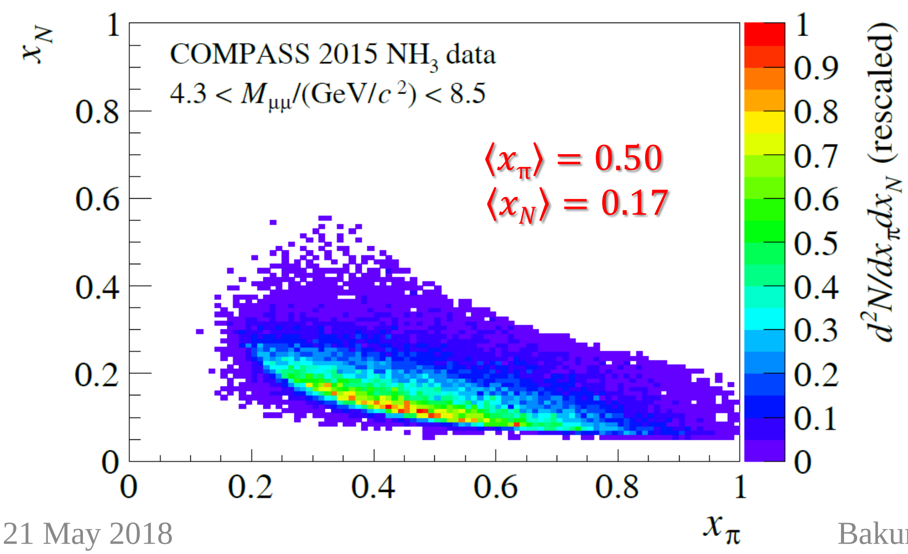
COMPASS DY: high mass range

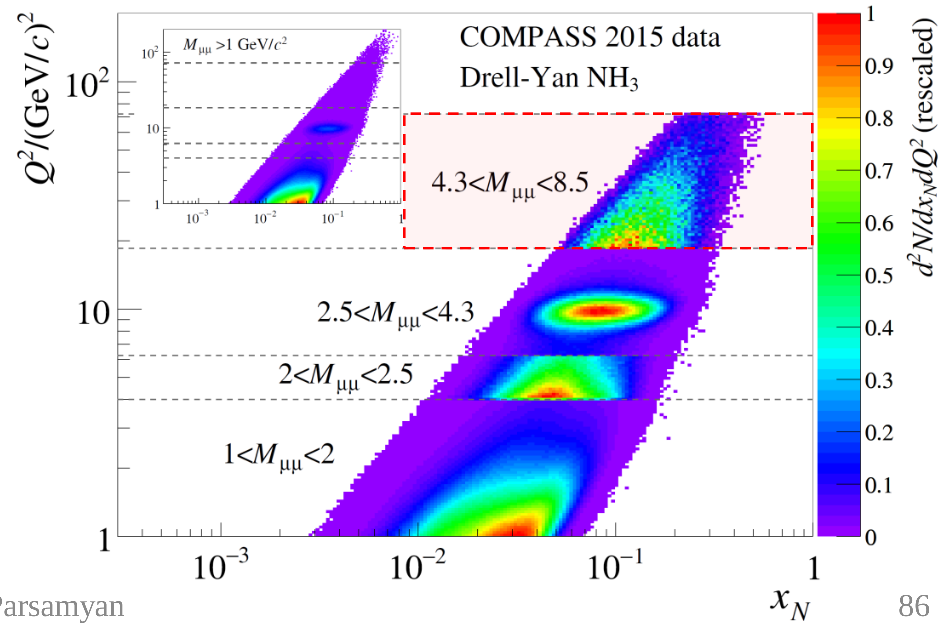
- $1.0 < M/(\mathrm{GeV}/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(\mathrm{GeV}/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(\mathrm{GeV}/c^2)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

Final sample: 35 000 dimuons in HM



HM events are in the valence quark range





SIDIS TSAs (Sivers)

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

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

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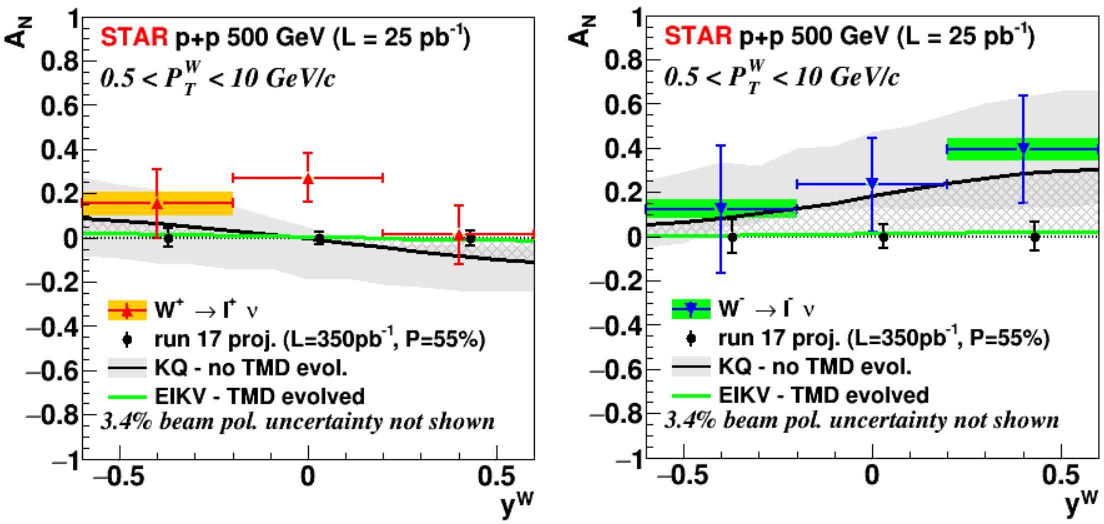
- Global fits of available 1-D SIDIS data
- Different TMD-evolution schemes
- Different predictions for Drell-Yan
- Sivers TMD PDF is predicted to change the sign between SIDIS and DY

- First experimental investigation of Sivers-non-universality by STAR
- Different hard scale compared to FT
- Evolution effects may play a substantial role

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



M. Anselmino et al., **JHEP 1704 (2017) 046** (no TMD evolution)