International Workshop on Hadron Structure and Spectroscopy 2023

Transverse spin asymmetries in COMPASS Drell-Yan data

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28 VI 2023

COMPASS collaboration

Collaboration:

24 institutes from **13** countries

Fixed target experiment

CERN SPS North-Area
(M2 beam-line)

Drell-Yan with 190 GeV π^- beam and $p^\uparrow \mathrm{NH_3}$, Al, W targets

SIDIS with 160 GeV (200 GeV) μ^+ beam and longitudinally/transversely - polarised proton ($\mathrm{NH_3}$) or deuteron ($^6\mathrm{LiD}$) target

DVCS and hard exclusive processes with 160 GeV $\mu^\pm$ beam and liquid $\mathrm{H_2}$ target.

Hadron spectroscopy with hadron beams and nuclear targets.

Transverse Momentum Dependent PDFs

Nucleon spin structure described 8 twist-2 TMD PDFs.

Quark Polarisation \ Nucleon Polarisation	U	L	T
U	$f_1^q(x, k_T^2)$ Number Density		$f_{1T}^{q\perp}(x, k_T^2)$ Sivers
L		$g_1^q(x, k_T^2)$ Helicity	$g_{1T}^{q\perp}(x, k_T^2)$ Worm-Gear T
T	$h_1^{q\perp}(x, k_T^2)$ Boer-Mulders	$h_{1L}^{q\perp}(x, k_T^2)$ Worm-Gear L	$h_{1T}^q(x, k_T^2)$ Transversity; $h_{1T}^{q\perp}(x, k_T^2)$ Pretzelosity

Nucleon · Nucleon spin · Quark · Quark spin · k_T

This talk

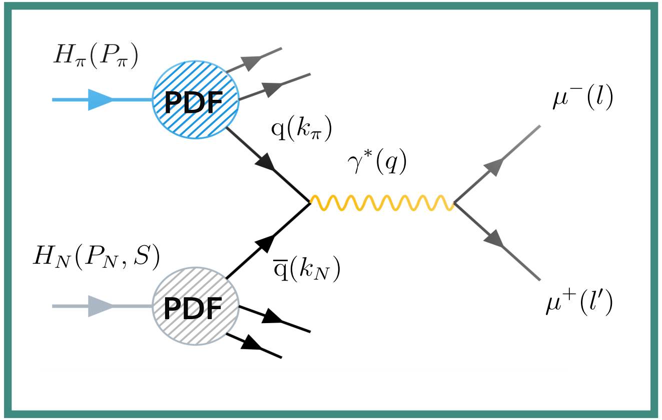
$f_{1T}^{q\perp}(x, k_T^2)$
Sivers

$h_{1T}^q(x, k_T^2)$
Transversity

$h_{1T}^{q\perp}(x, k_T^2)$
Pretzelosity

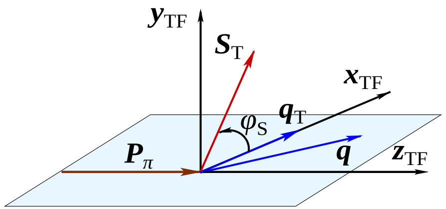
Single polarised Drell-Yan process

Drell-Yan process in LO

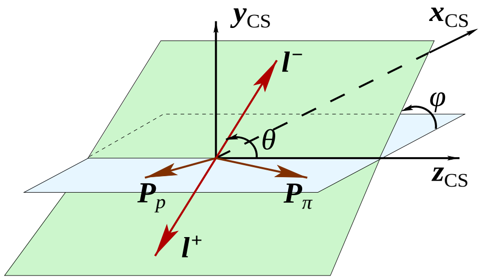


$$\frac{d\sigma^{LO}}{d\Omega\, d^4q} \propto \left\{ \begin{array}{l} 1 + D_{\sin^2\theta} \cos(2\varphi_{CS}) A_U^{\cos(2\varphi_{CS})} \\ + |S_T| \left[\begin{array}{l} \sin(\varphi_S) A_T^{\sin(\varphi_S)} \\ D_{\sin^2\theta} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \end{array} \right\}$$

$$A_{DY} \propto PDF_\pi \otimes PDF_N$$



Target rest frame



Collins-Sopper frame

$$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

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

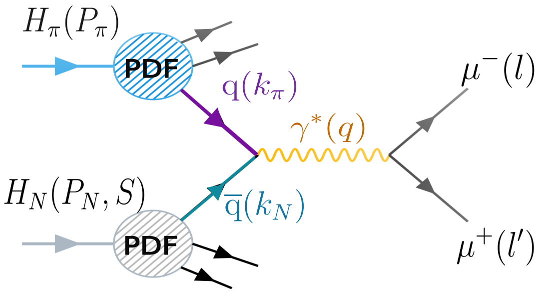
$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

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

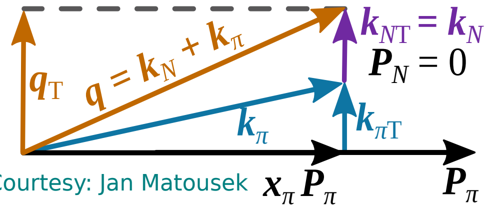
Single polarised Drell-Yan process

The convolution of the TMDs runs over intrinsic transverse momenta

$$\mathcal{C}\left[w\left(\boldsymbol{k_{T,\pi}}, \boldsymbol{k}_{\mathbf{T,N}}, \boldsymbol{q_{\mathbf{T}}}\right) f_\pi f_{\mathrm{N}}\right] = \frac{1}{N_c} \sum_q e_q^2 \int \mathrm{d}^2 \boldsymbol{k_{T,\pi}} \mathrm{d}^2 \boldsymbol{k}_{\mathbf{T,N}} \delta^{(2)} \left(\boldsymbol{q_{\mathbf{T}}} - \boldsymbol{k_{T,\pi}} - \boldsymbol{k}_{\mathbf{T,N}}\right)$$
$$\times w\left(\boldsymbol{k_{T,\pi}}, \boldsymbol{k}_{\mathbf{T,N}}, \boldsymbol{q_{\mathbf{T}}}\right) \left[f_\pi^{\bar{q}}\left(x_\pi, k_{\mathrm{T},\pi}^2\right) f_{\mathrm{N}}^{q}\left(x_{\mathrm{N}}, k_{\mathrm{T,N}}^2\right) + f_\pi^{q}\left(x_\pi, k_{\mathrm{T},\pi}^2\right) f_{\mathrm{N}}^{\bar{q}}\left(x_{\mathrm{N}}, k_{\mathrm{T,N}}^2\right)\right]$$



Momenta in target frame



Courtesy: Jan Matousek

Sivers function
and number density

$$A_T^{\sin(\varphi_S)} = \frac{-\mathcal{C}\left[\frac{\mathbf{q_T} \cdot \mathbf{k_{T,N}}}{q_T \cdot M_N} f_{1,\pi}^q f_{1T,N}^{q\perp}\right]}{\mathcal{C}\left[f_{1,N}^q f_{1,\pi}^q\right]}$$

Pretzelosity and
Boer–Mulders function

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)} = \frac{-\mathcal{C}\left[\frac{2\mathbf{q_T}\cdot\mathbf{k_{T,N}}\left[2\left(\mathbf{q_T}\cdot\mathbf{k}_{\mathbf{T},\pi}\right)\left(\mathbf{q_T}\cdot\mathbf{k_{T,N}}\right)-q_T^2\left(\mathbf{k}_{\mathbf{T},\pi}\cdot\mathbf{k_{T,N}}\right)\right]-q_T^2 k_{T,N}^2\left(\mathbf{q_T}\cdot\mathbf{k}_{\mathbf{T},\pi}\right)}{2q_T^3 M_\pi M_N^2} h_{1,\pi}^{q\perp} h_{1T,N}^{q\perp}\right]}{\mathcal{C}\left[f_{1,N}^q f_{1,\pi}^q\right]}$$

Transversity and
Boer–Mulders function

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} = \frac{\mathcal{C}\left[\frac{\mathbf{q_T}\cdot\mathbf{k}_{\mathbf{T},\pi}}{q_T \cdot M_\pi} h_{1,\pi}^{q\perp} h_{1,N}^{q}\right]}{\mathcal{C}\left[f_{1,N}^q f_{1,\pi}^q\right]}$$

Semi-inclusive Deep Inelastic Scattering

$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,d^2p_T d\phi_h\,d\phi_\psi} \propto \left\{ \begin{array}{c} 1+\cos(2\phi_h)\varepsilon A_{UU}^{\cos(2\phi_h)} \\ +|S_T| \left[\begin{array}{l} \sin(\phi_h+\phi_S)A_T^{\sin(\phi_h+\phi_S)} \\ \sin(\phi_h-\phi_S)A_T^{\sin(\phi_h-\phi_S)} \\ \sin(3\phi_h-\phi_S)A_T^{\sin(3\phi_h+\phi_S)} \end{array} \right] \end{array} \right\}$$

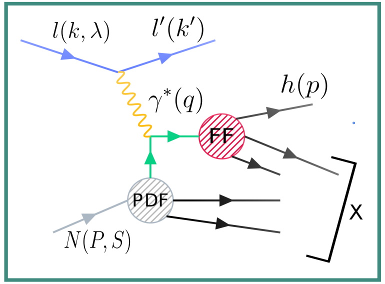
$$A_{SIDIS} \propto PDF_p \otimes FF$$

Drell-Yan process

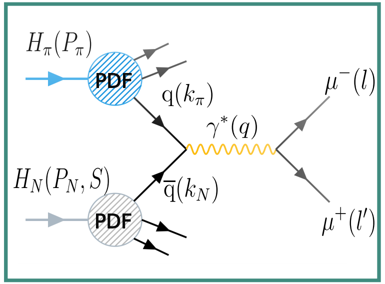
$$\frac{d\sigma^{LO}}{d\Omega\,d^4q} \propto \left\{ \begin{array}{l} 1+D_{\sin^2\theta}\cos(2\varphi_{CS})A_U^{\cos(2\varphi_{CS})} \\ +|S_T| \left[\begin{array}{l} \sin(\varphi_S)A_T^{\sin(\varphi_S)} \\ D_{\sin^2\theta} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right] \end{array} \right\}$$

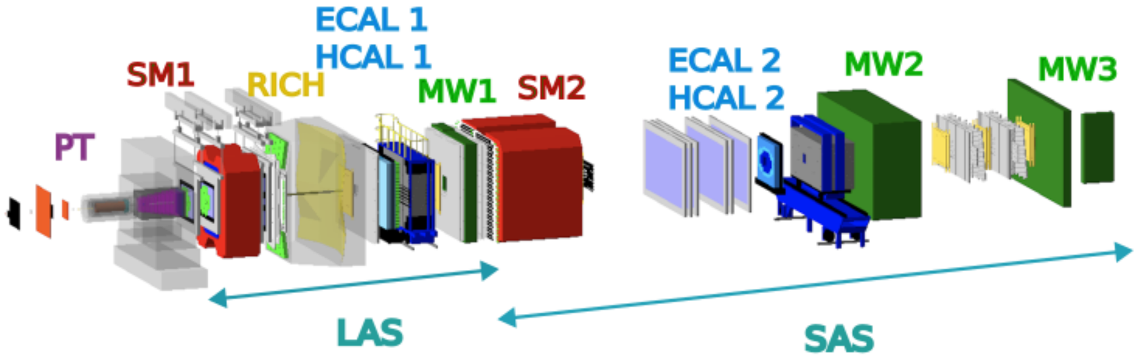
$$A_{DY} \propto PDF_\pi \otimes PDF_N$$

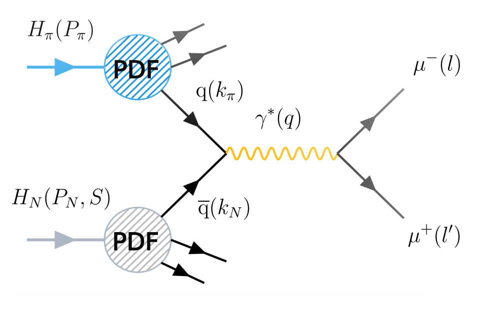
SIDIS		Drell-Yan
$A_{UU}^{\cos(2\phi_h)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$	Boer-Mulders	$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_T^{(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^h$	Sivers	$A_T^{\sin(\varphi_S)} \propto f_{1,\pi}^q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

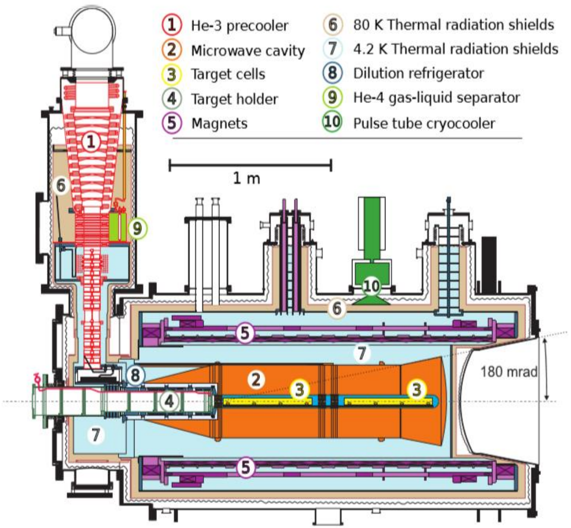


Universality in TMD-QCD parton model approach









Drell-Yan setup

-190 GeV π^- beam

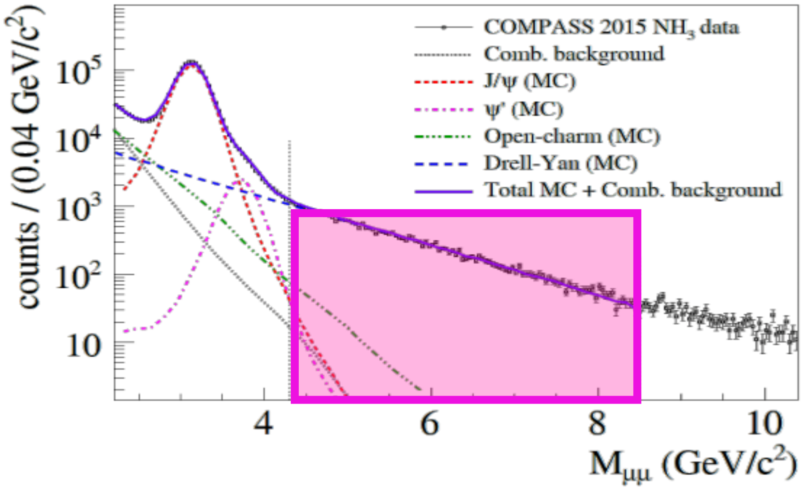
- COMPASS spectrometer
- transversely polarised $\mathrm{NH_3}$ target $p\uparrow$
- Al, W targets
- hadron absorber

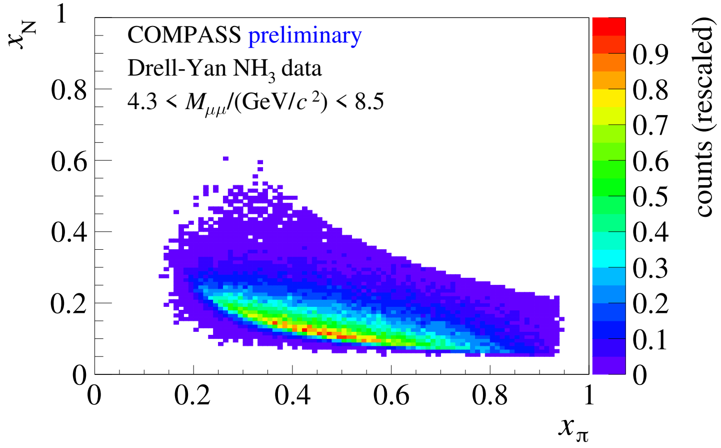
"Low mass" ⟷ $1 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2$
- large background and contatimation

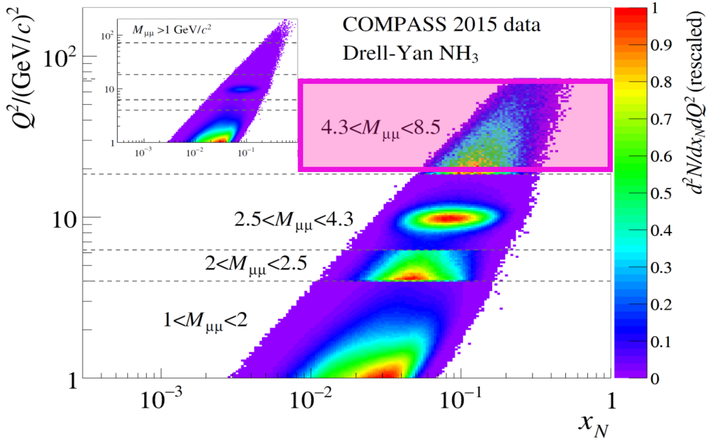
"Intermetiade mass" ⟷ $2 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2.5$
- high DY cross section

"Charmonia mass" ⟷ $2.5 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 4.3$
- strong J/ψ signal
- good signal/background

"High mass" ⟷ $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$
- valence quark region
- low background







"High mass" ⟷ $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$

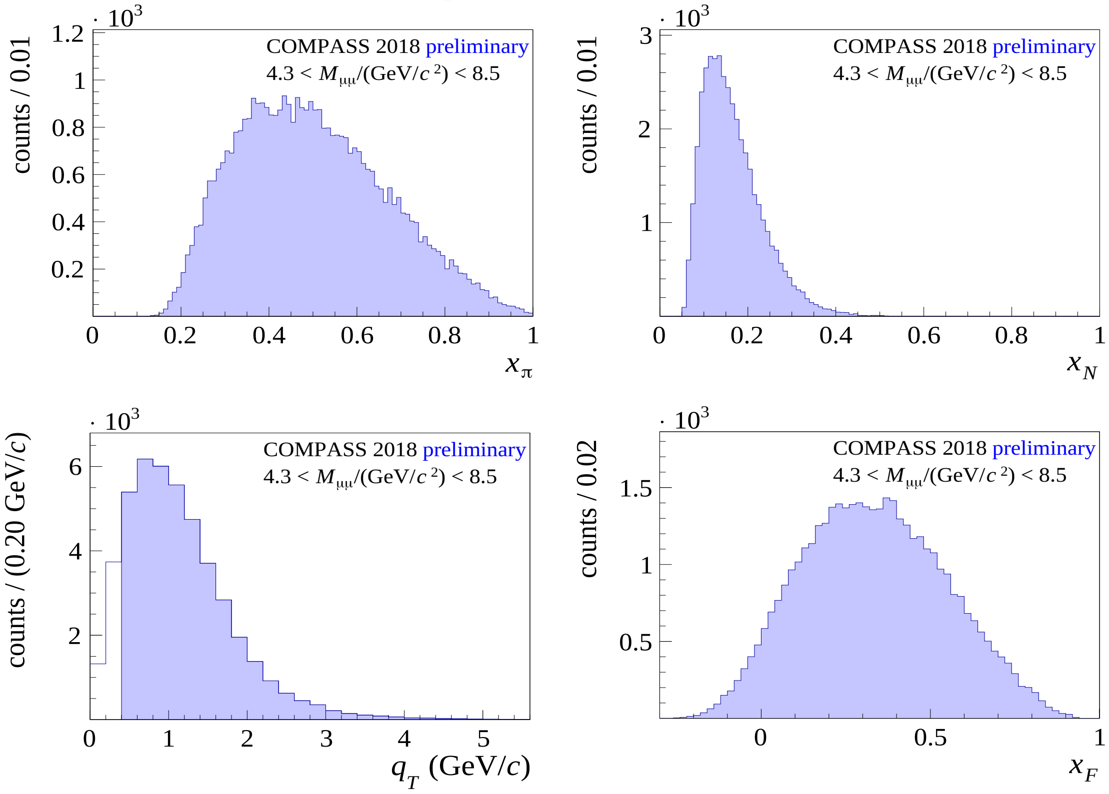
- valence quark region
- low background

$\langle x_\pi \rangle = 0.50$

$\langle x_N \rangle = 0.17$

$\langle q_T \rangle = 1.17\ \mathrm{GeV}/c$

$\langle M_{\mu\mu} \rangle = 5.3\ \mathrm{GeV}/c^2$

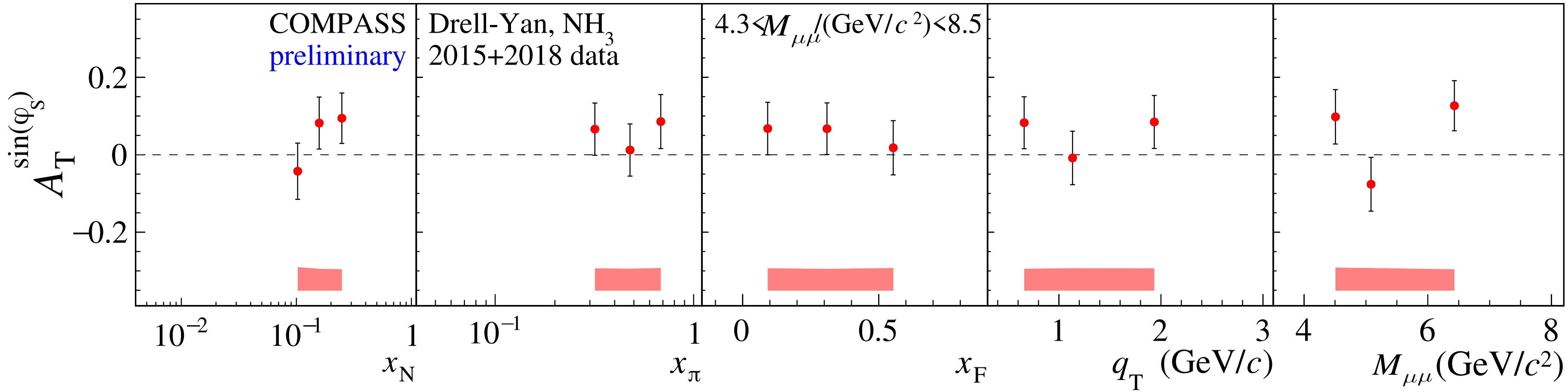


Statistics in 2015 ~ 35 000 events
Statistics in 2018 ~ 37 000 events
Total ~ 71 000 events

Sivers: SIDIS and Drell–Yan TSA results

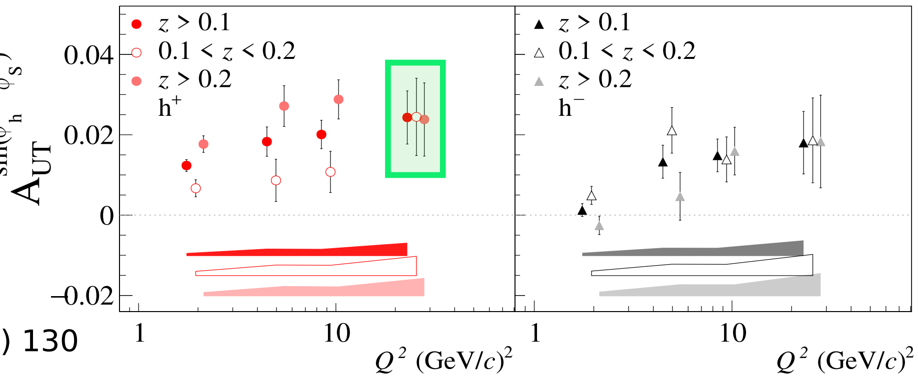
$A_T^{\sin(\varphi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$

Sivers TSA in Drell-Yan, 2015+2018 DATA



Sivers TSA in SIDIS

$$A_T^{(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$$



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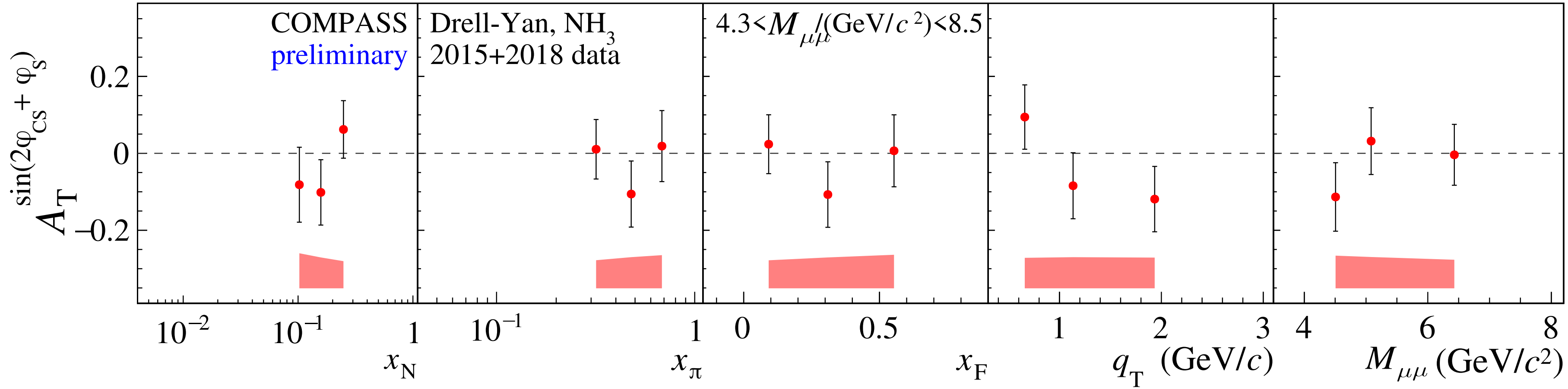
Pretzelosity: Drell–Yan and SIDIS TSA results

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

Pretzelosity TSA in Drell-Yan, 2015+2018 DATA



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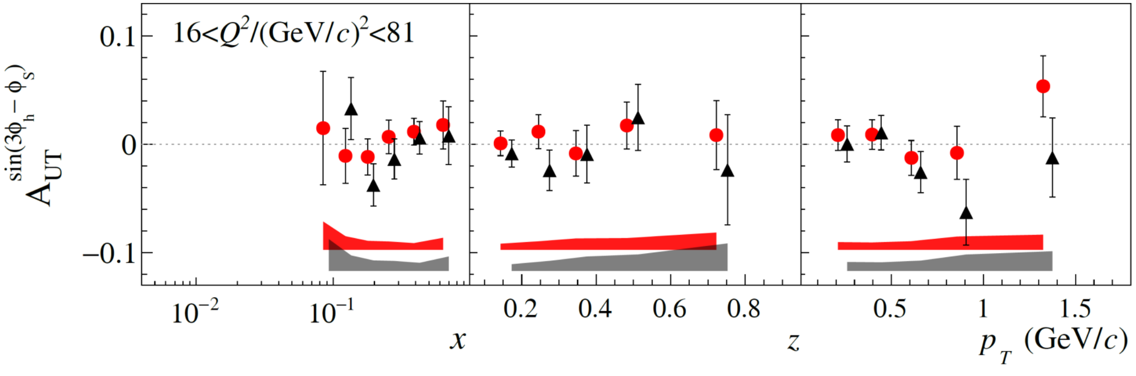
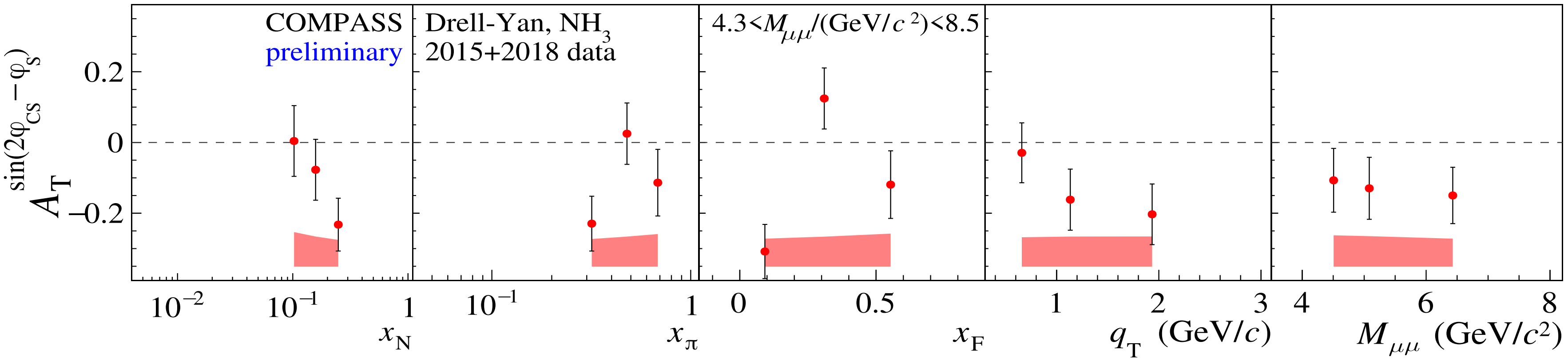
Pretzelosity TSA in SIDIS

$$A_T^{(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$$



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

Transversity TSA in Drell-Yan, 2015+2018 DATA



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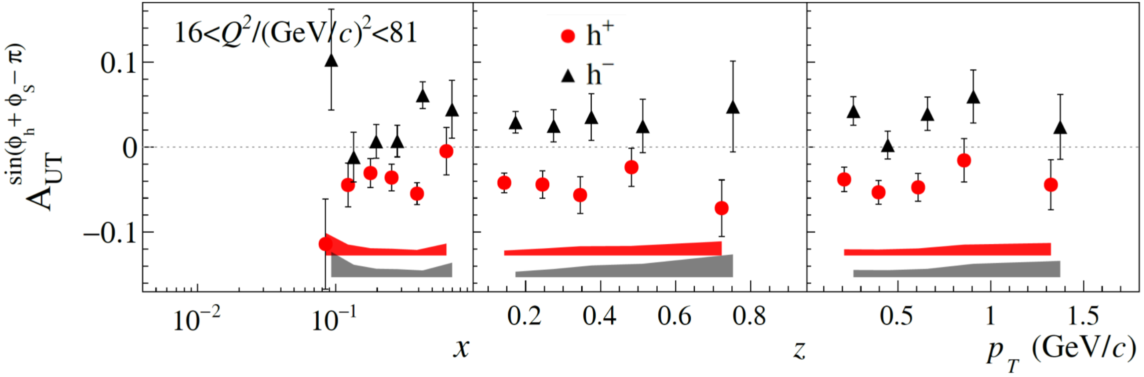
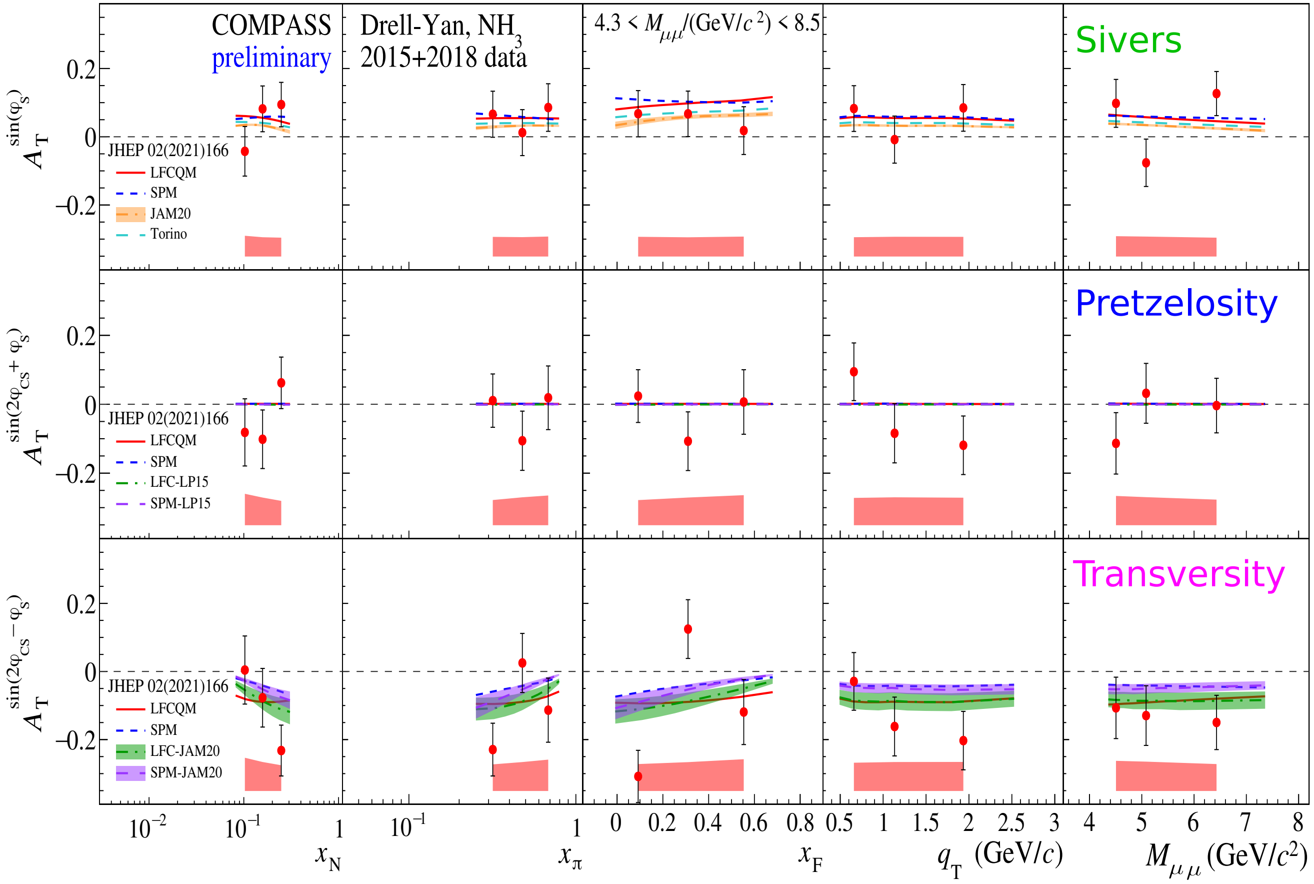
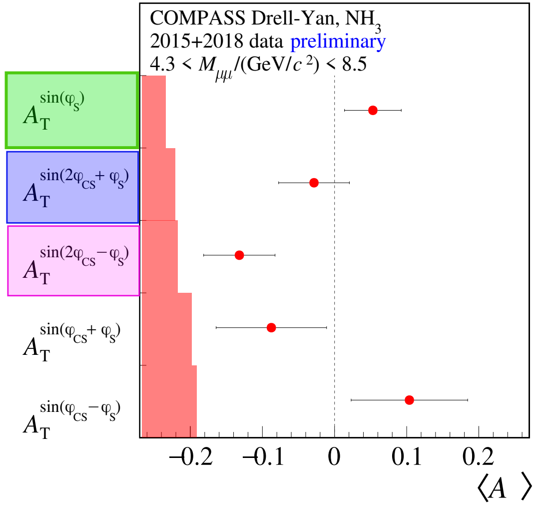
Collins TSA in SIDIS

$$A_T^{(\phi_h+\phi_S)} \propto h_{1,p}^{q} \bigotimes H_{1q}^{\perp h}$$

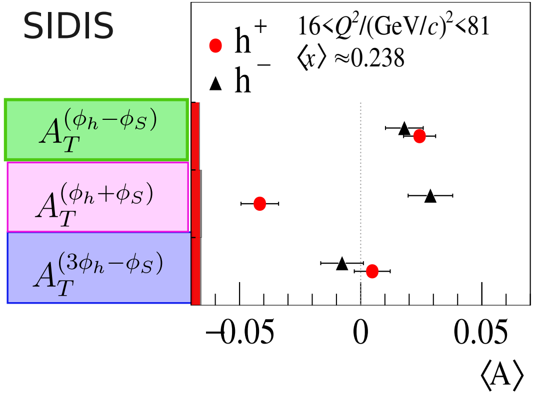


Drell–Yan TSA results





SIDIS



Weighted TSAs in Drell–Yan: Introduction

Possible alternative: **weighting with powers of the transverse momentum**

Example: integration over $\mathrm{d}^2\mathbf{q_T}$ with weight = q_T/M_N

$$A_{\mathrm{T}}^{\sin\phi_S \frac{q_{\mathrm{T}}}{M_N}} = \frac{2}{|\boldsymbol{S}_{\mathbf{T}}|} \frac{\int \mathrm{d}\phi_S \; \mathrm{d}q_{\mathrm{T}}^2 \; \mathrm{d}\phi \sin\phi_S \frac{q_{\mathrm{T}}}{M_N} \mathrm{d}\sigma_{\mathrm{DY}}}{\int \mathrm{d}\phi_S \; \mathrm{d}q_{\mathrm{T}}^2 \; \mathrm{d}\phi \mathrm{d}\sigma_{\mathrm{DY}}} = \frac{\int \mathrm{d}^2 \boldsymbol{q}_{\mathbf{T}} \frac{q_{\mathrm{T}}}{M_N} F_{\mathrm{T}}^{\sin\phi_S}}{\int \mathrm{d}^2 \boldsymbol{q}_{\mathrm{T}} F_{\mathrm{U}}^1}$$

The n-th moment of TMD PDF

$$f^{(n)}(x) = \int \mathrm{d}^2 \boldsymbol{k}_{\mathbf{T}} \left(\frac{k_{\mathrm{T}}^2}{2M_h^2}\right)^n f\left(x, k_{\mathrm{T}}^2\right)$$

TMD framework

Weighted Sivers asymmetry

$$A_{\mathrm{T}}^{\sin\varphi_S \frac{q_{\mathrm{T}}}{M_{\mathrm{N}}}} = -2\frac{\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi)\, f_{1T,N}^{q(1)\perp}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi)\, f_{1,\mathrm{N}}^{q}(x_N) + (q \leftrightarrow \bar{q})\right]}$$

Weighted asymmetry induced by proton pretzelosity and pion Boer–Mulders function

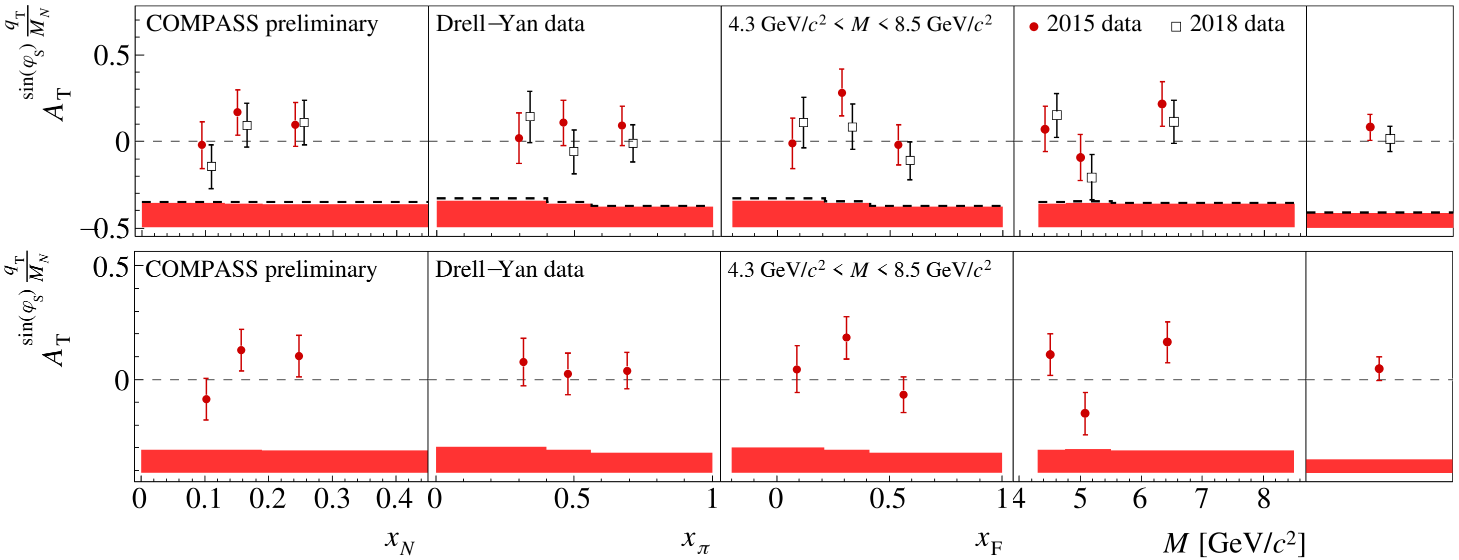
$$A_{\mathrm{T}}^{\sin(2\varphi+\varphi_S)\frac{q_{\mathrm{T}}^3}{2M_\pi M_{\mathrm{N}}^2}} = -6\frac{\sum_q e_q^2 \left[h_{1,\pi}^{\bar{q}(1)\perp}(x_\pi)\, h_{1\mathrm{T},\mathrm{N}}^{q(2)\perp}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi) f_{1,\mathrm{N}}^{q}(x_N) + (q \leftrightarrow \bar{q})\right]}$$

Weighted asymmetry induced by proton transversity and pion Boer–Mulders function

$$A_{\mathrm{T}}^{\sin(2\varphi-\varphi_S)\frac{q_{\mathrm{T}}}{M_\pi}} = -2\frac{\sum_q e_q^2 \left[h_{1,\pi}^{\bar{q}(1)\perp}(x_\pi)\, h_{1,\mathrm{N}}^{q}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi) f_{1,\mathrm{N}}^{q}(x_N) + (q \leftrightarrow \bar{q})\right]}$$

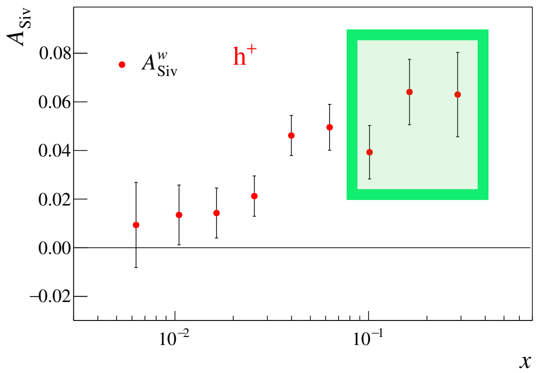
Sivers: Drell–Yan and SIDIS weighted TSA results

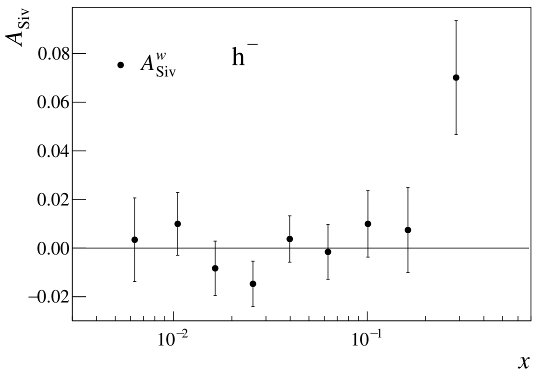
Sivers weighted TSA in Drell-Yan, 2015 + 2018 DATA



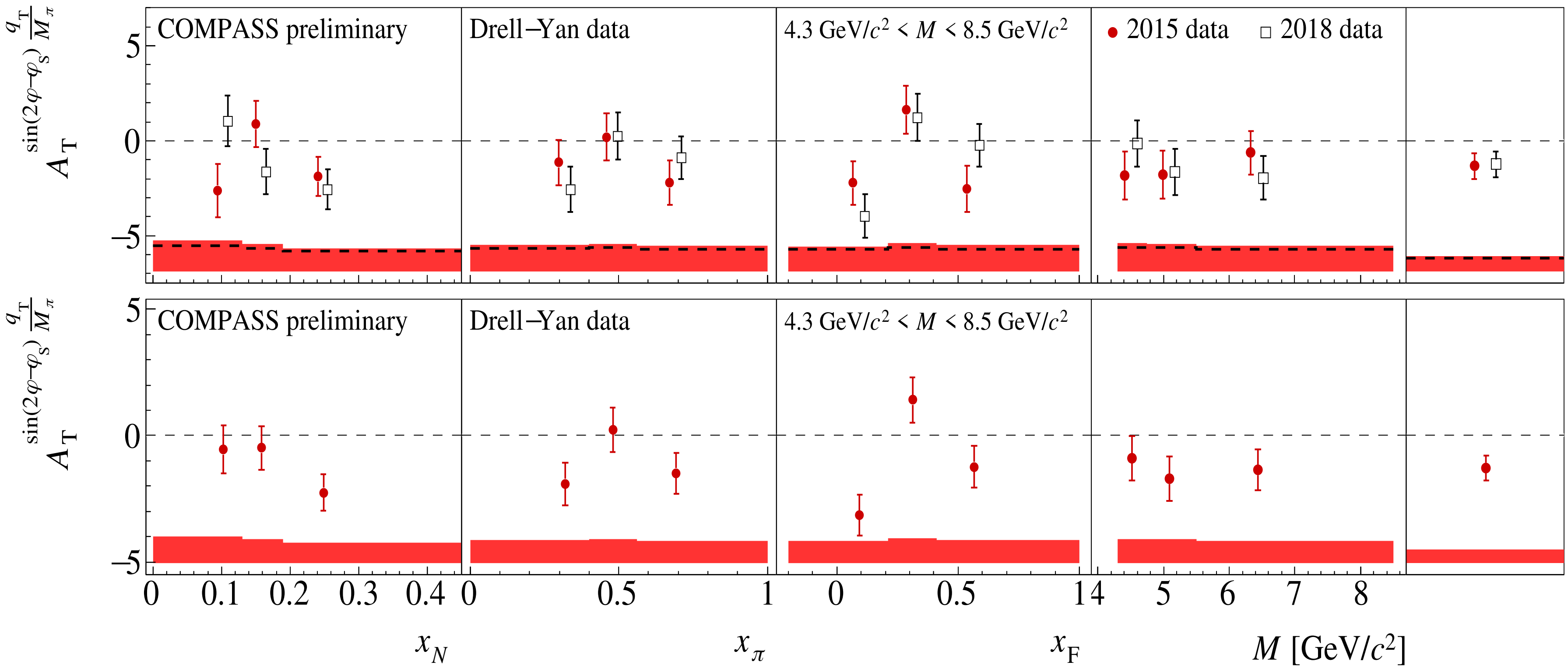
Sivers weighted TSA in SIDIS

[COMPASS, Nucl.Phys. B940 (2019) 34]





Transversity weighted TSA in Drell-Yan, 2015+2018 DATA



Conclusions

Combined conventional Drell-Yan TSA

Sivers found to be positive, ~1 σ away from zero
Transversity found to be negative, ~2 σ away from zero
Pretzelosity found to be small and compatible with zero

Transverse momentum weighted asymmetries

A way to overcome the convolution over intrinsic k_T
A direct access to the k_T^2 moments of TMD PDFs

Combined Drell-Yan weighted TSA

Result consistent with conventional TSAs

Prospects

Paper in preparation
Extranction of first k_T^2 -moment of TMD PDFs

Thank you for attention!