Measurement of target spin (in)dependent asymmetries in dimuon production in pion-nucleon collisions at COMPASS

BAKUR PARSAMYAN

CERN, INFN section of Turin

on behalf of the COMPASS Collaboration

"XXIX International Workshop on Deep Inelastic Scattering and Related Subjects"

Santiago de Compostela, Spain

2-6 May 2022

COMPASS collaboration

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

25 institutions from 13 countries
– nearly 200 physicists

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

Wide physics program

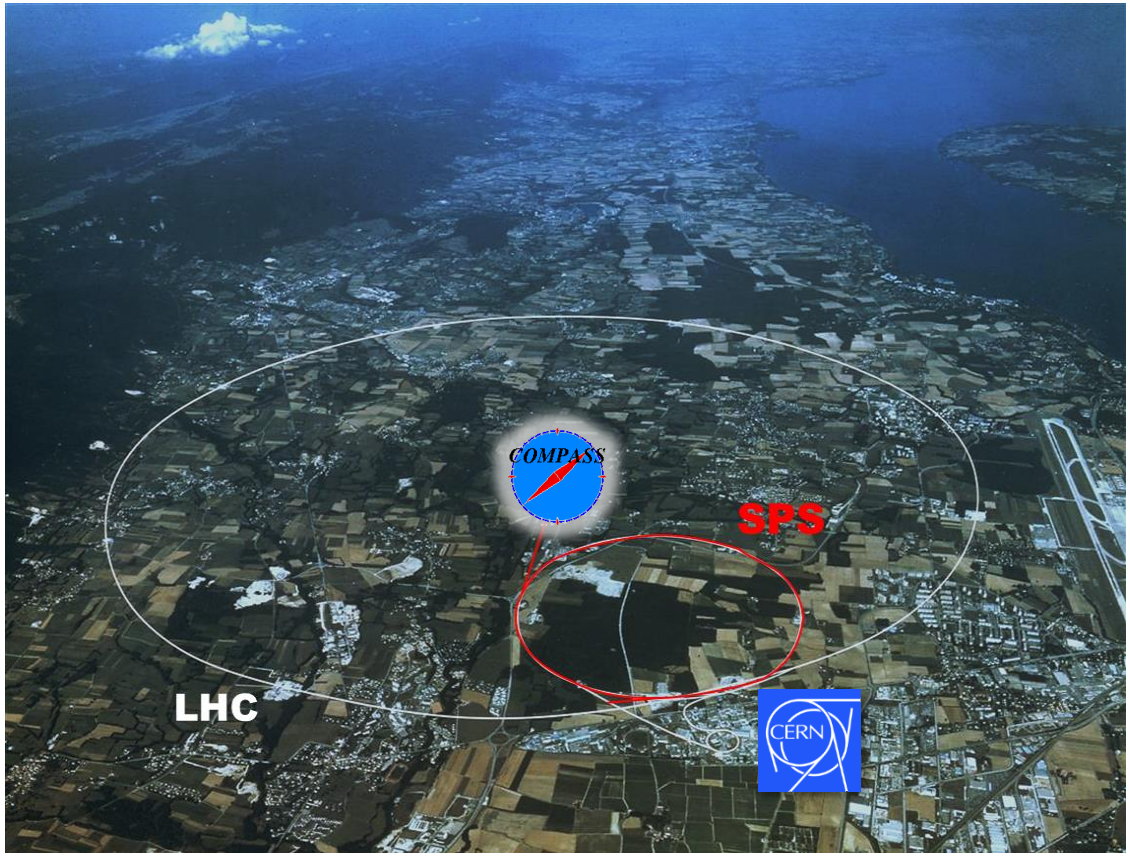
COMPASS-I

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

COMPASS-II

- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS**

See also COMPASS talks by J.Giarra (DVCS) and J.Matousek (SIDIS)



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

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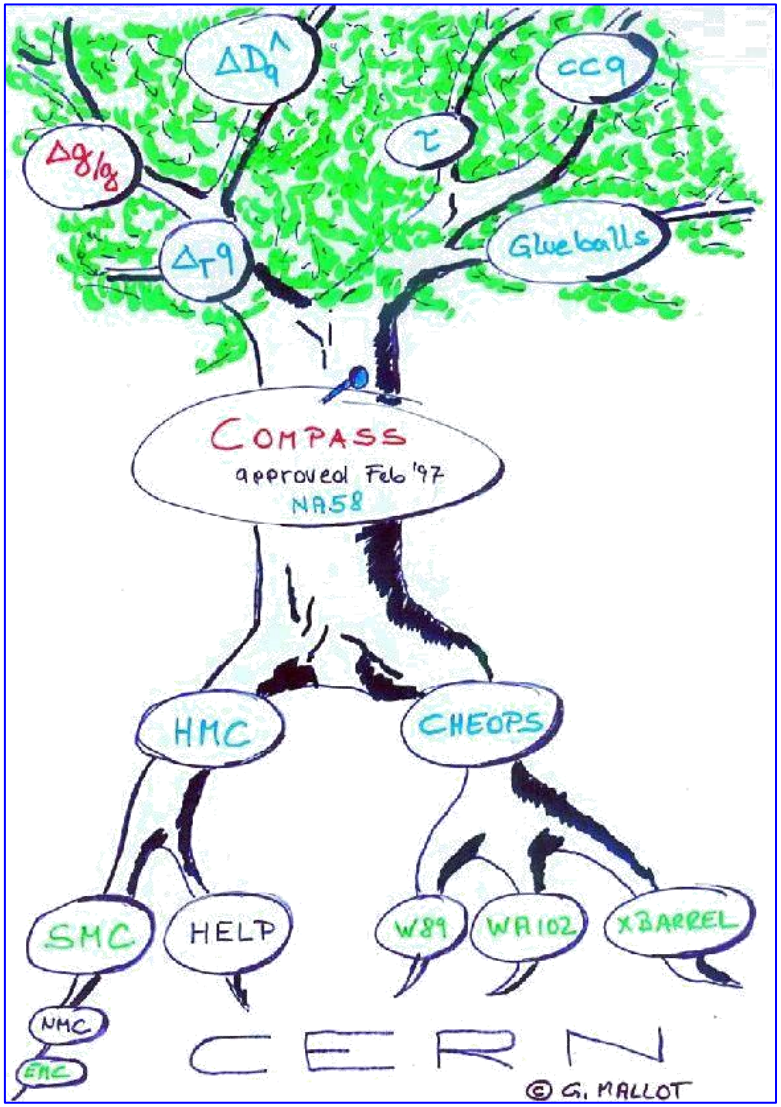
IWHSS-2022 workshop (anniversary edition)

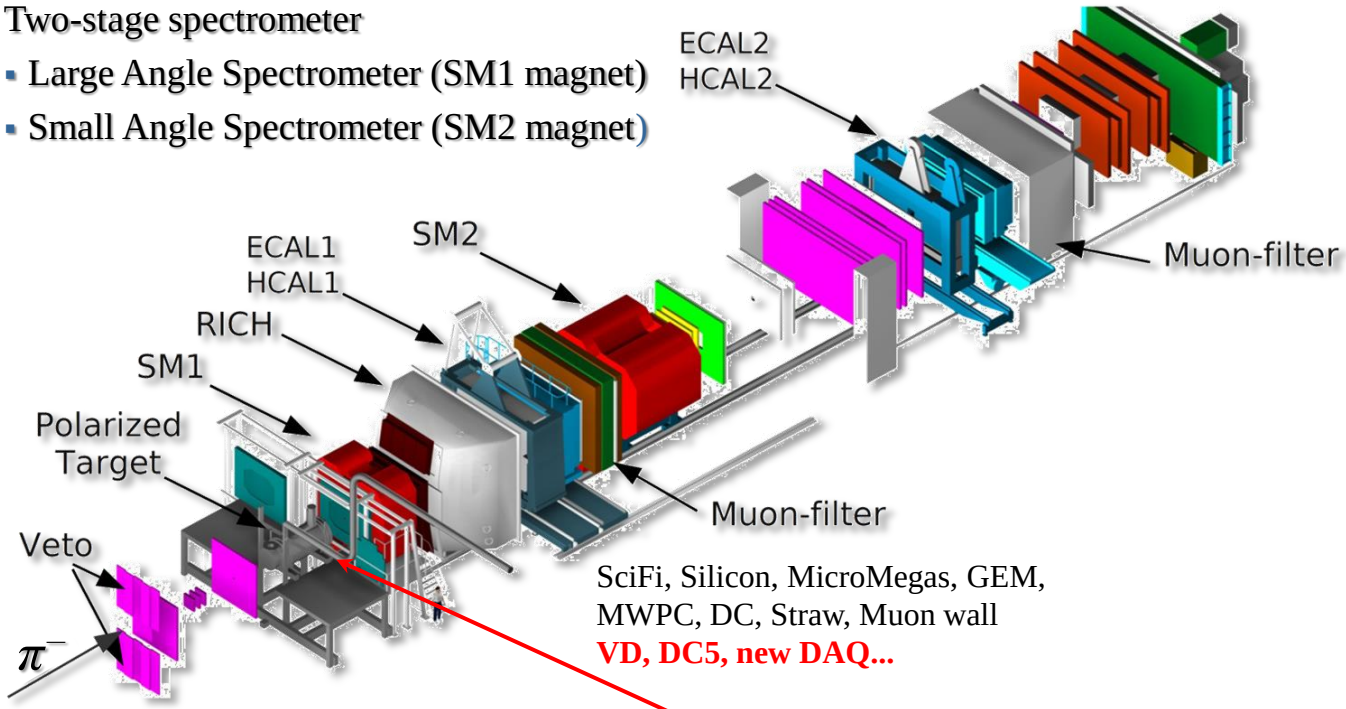
https://indico.cern.ch/e/IWHSS-2022



COMPASS experimental setup: Phase II (DY program)

Two-stage spectrometer

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



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

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

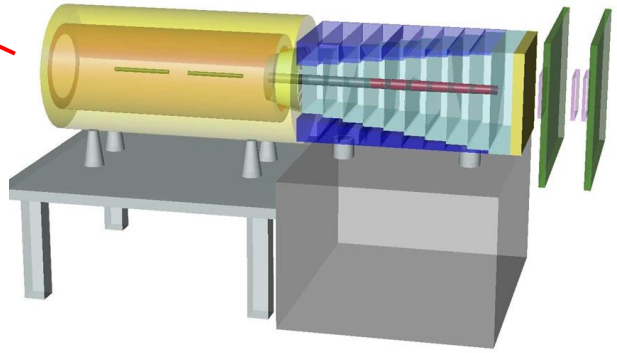
Data-taking years: 2014 (test) 2015 and 2018

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



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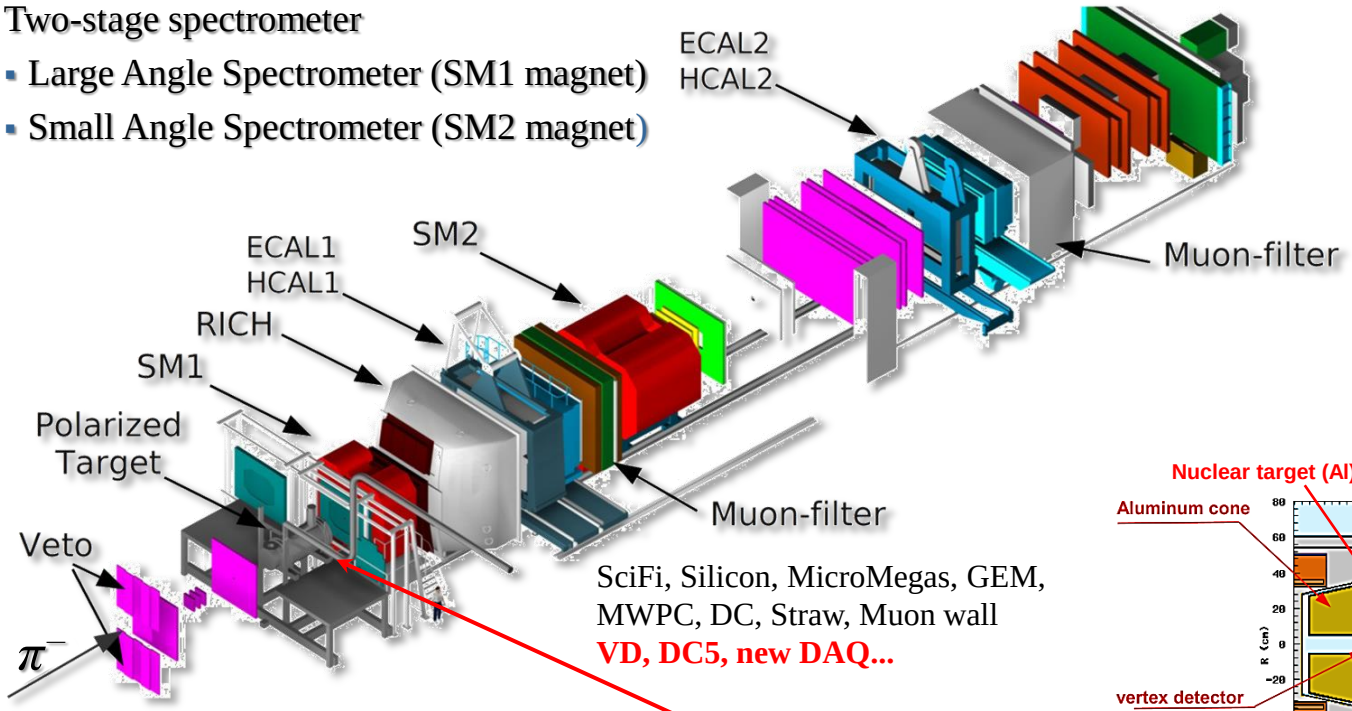

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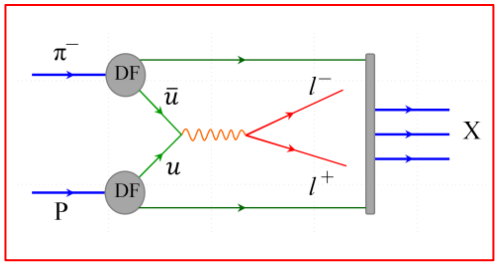
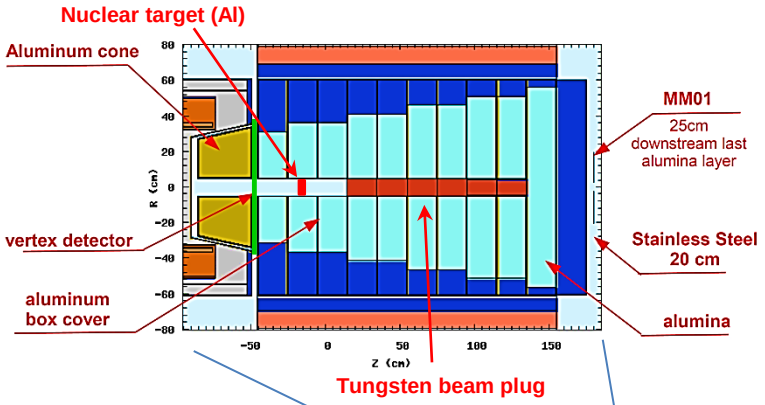
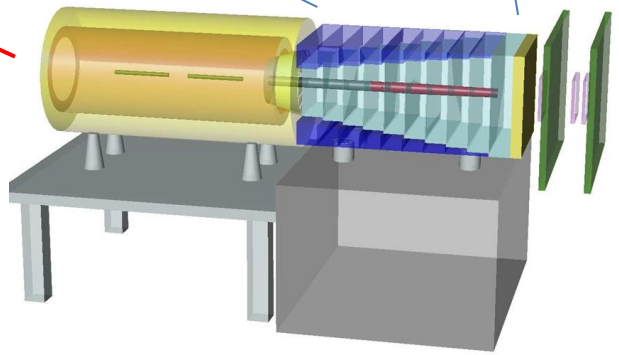


Hadron absorber





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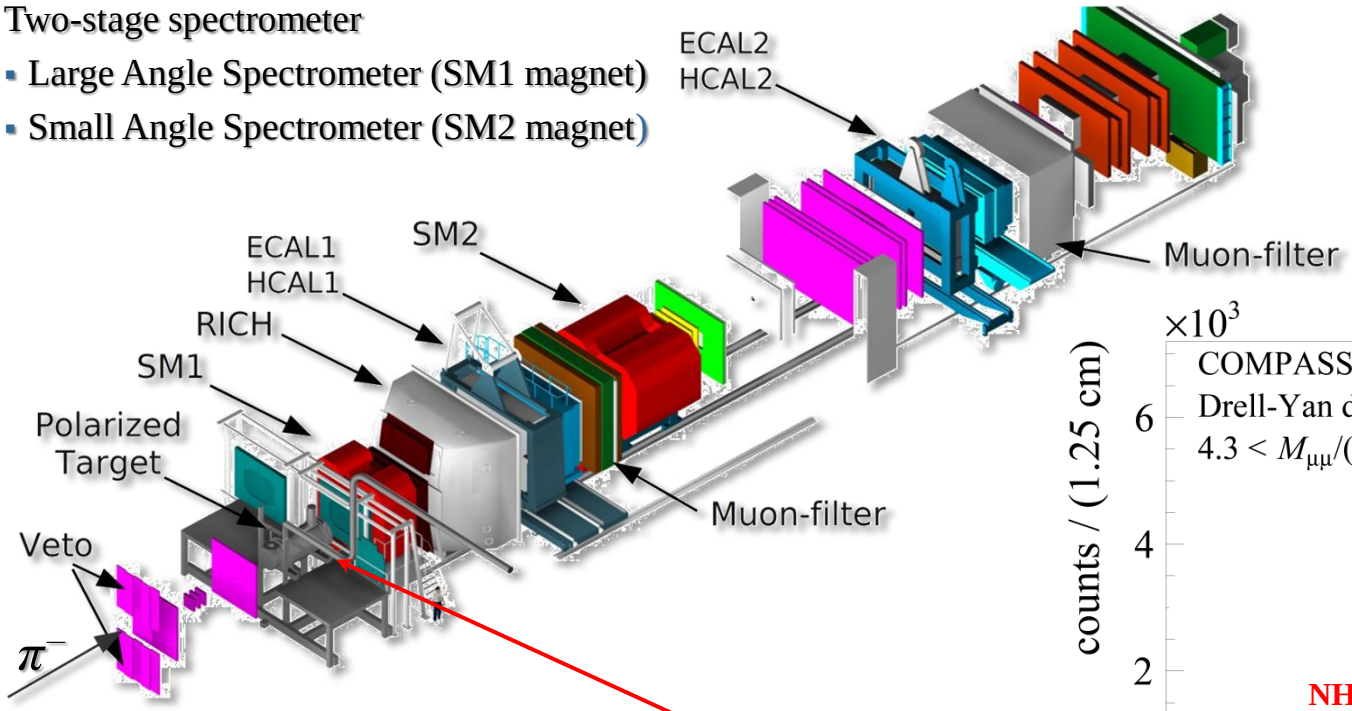

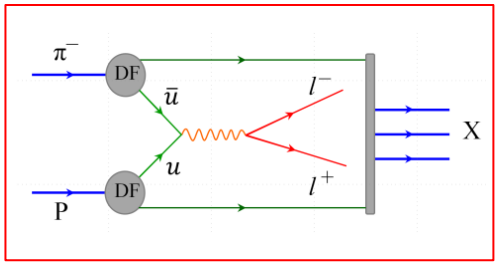

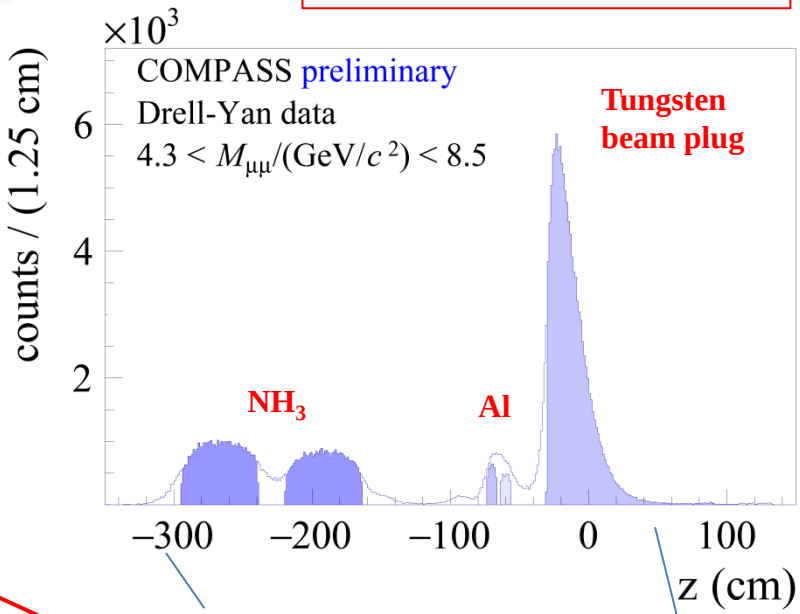

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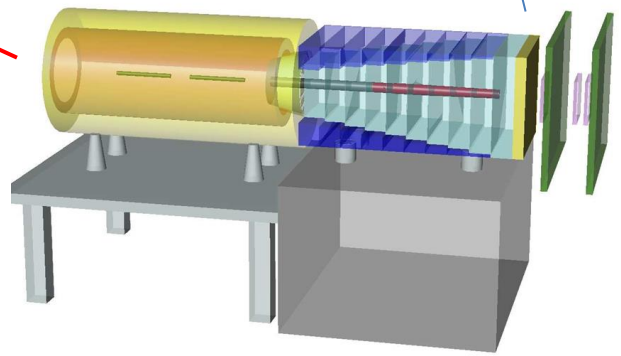

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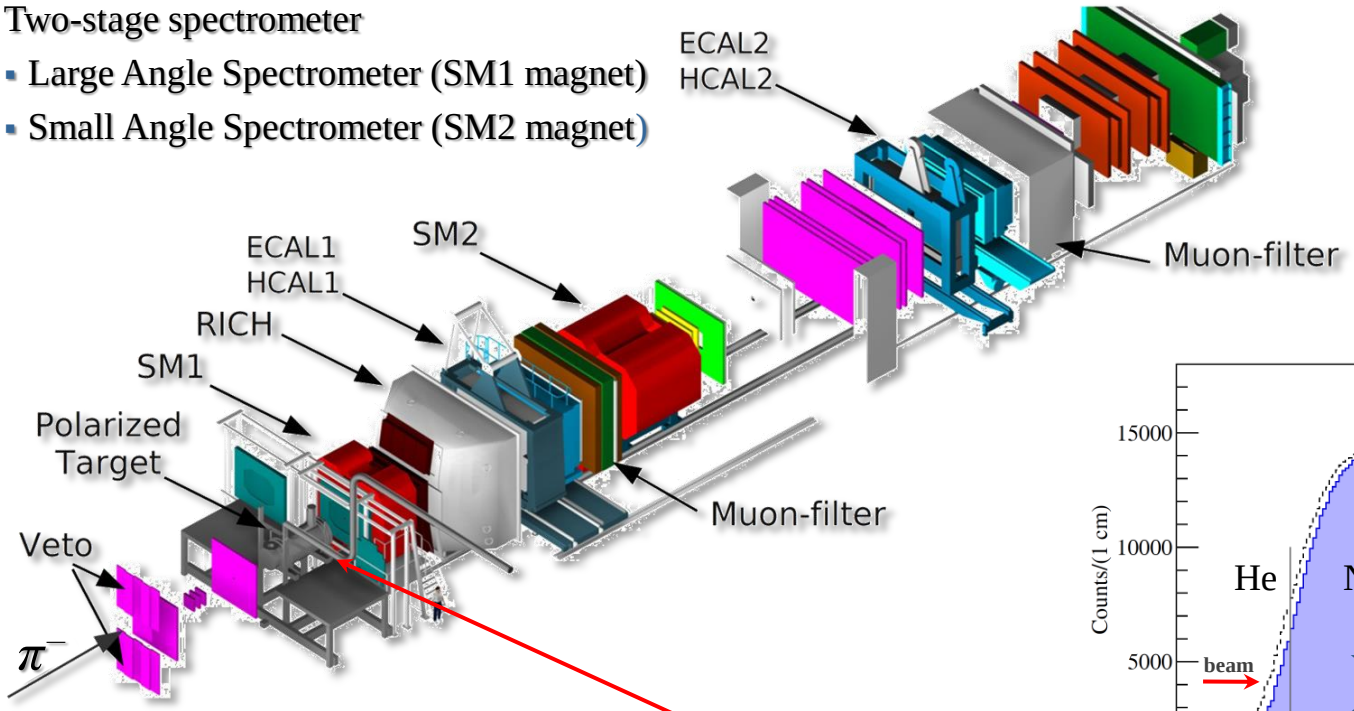

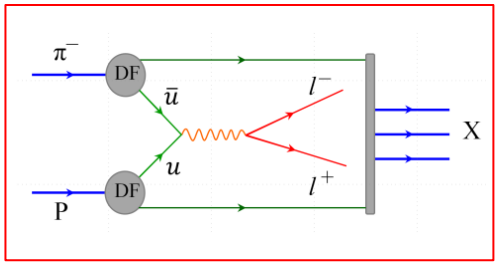

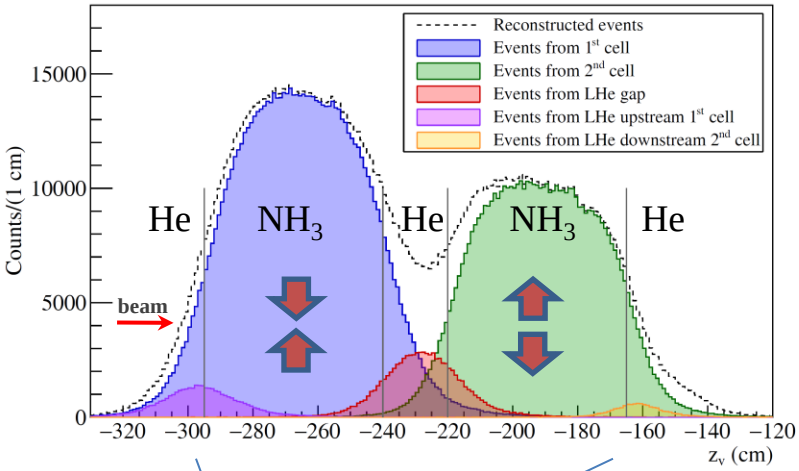

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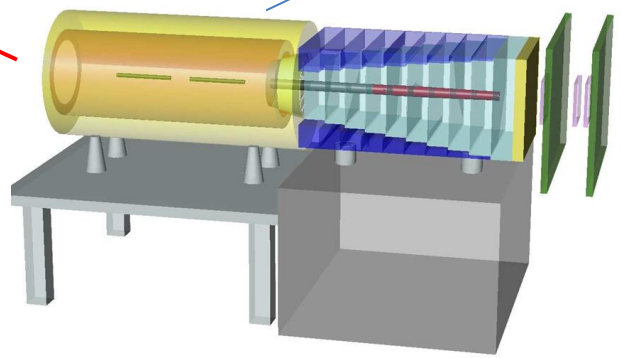

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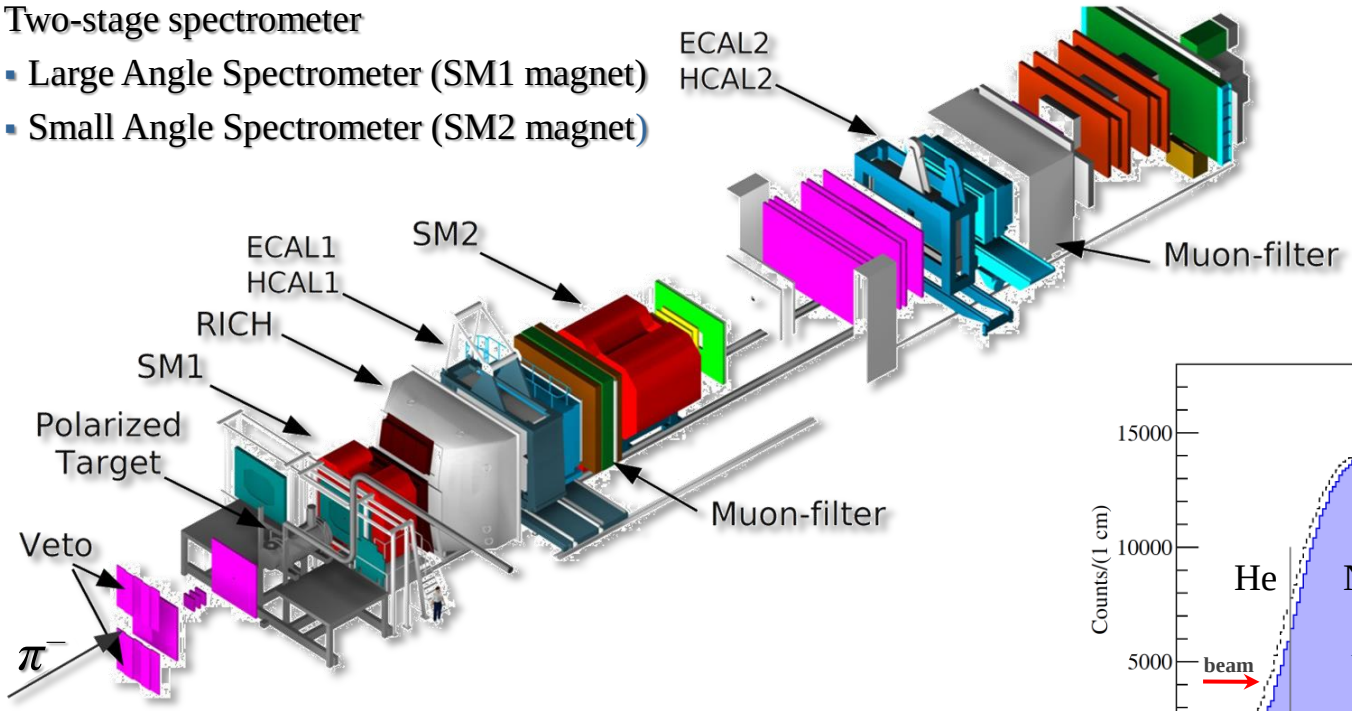

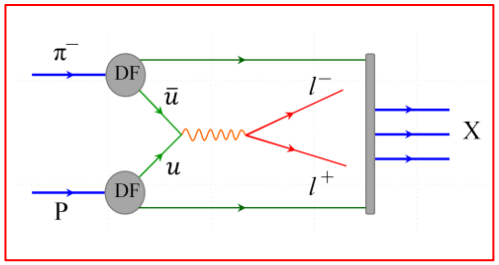

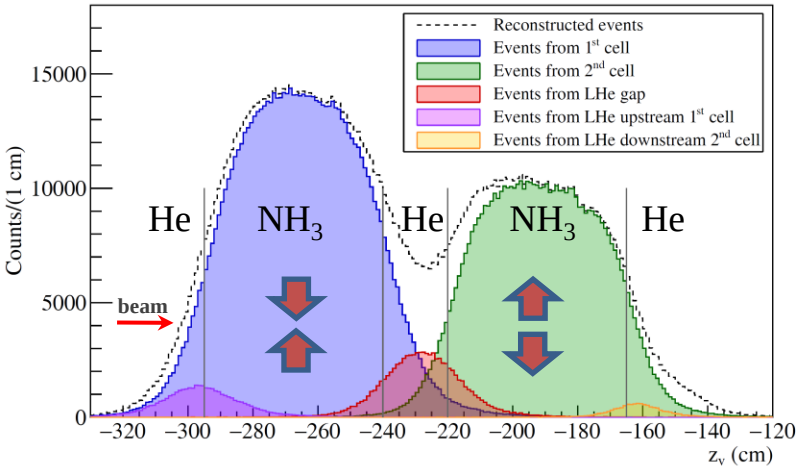

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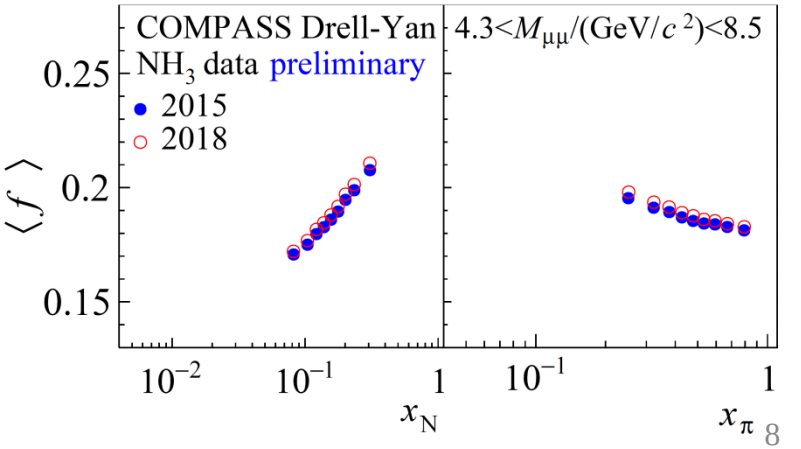
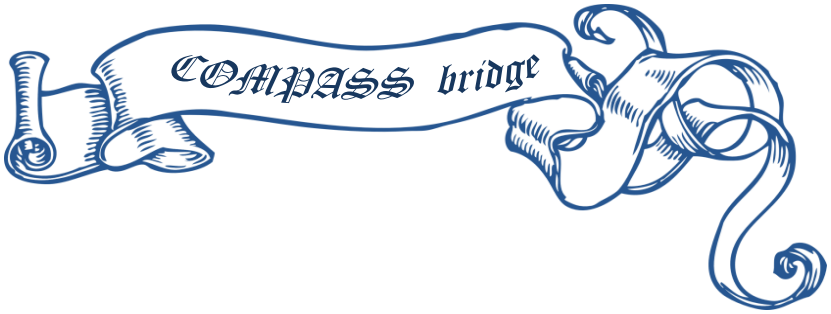
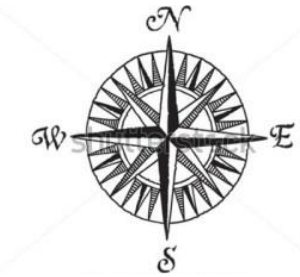






Drell-Yan

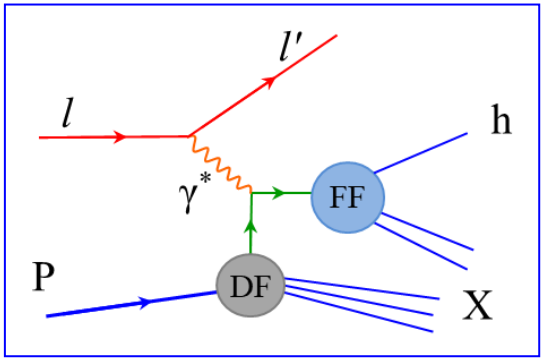
SIDIS

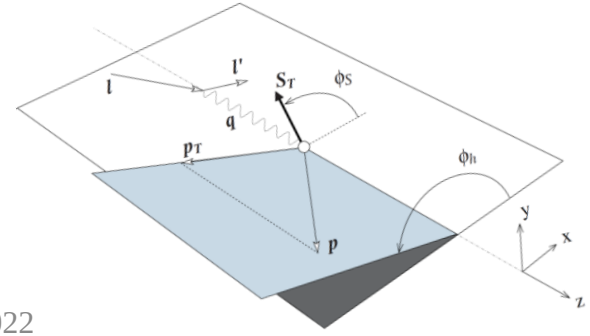
SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

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

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



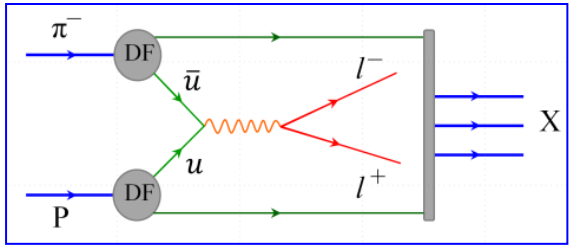


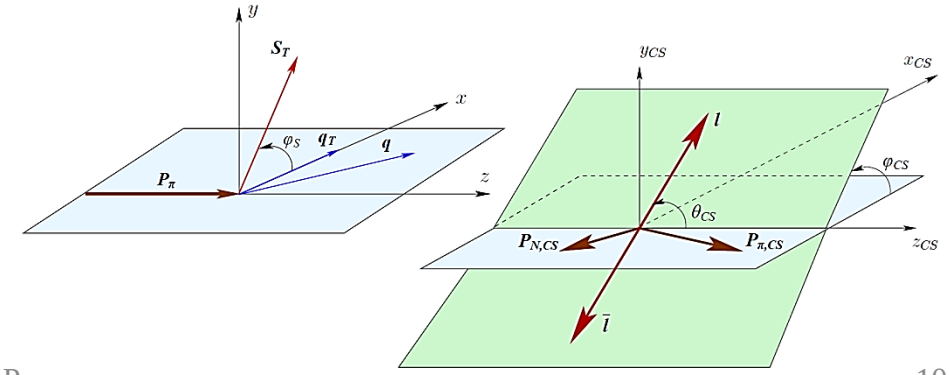
DY

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)$$

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

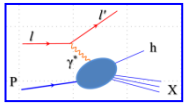
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$





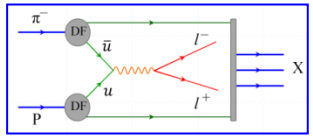
SIDIS and single-polarized DY x-sections at twist-2 (LO)

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



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

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right)$$



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

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

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

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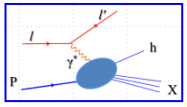

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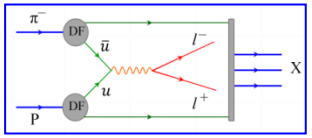

$$\left\{1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL}\right\}$$

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

SIDIS-DY bridge

$$\left\{1+D_{\left[\sin^2\theta_{CS}\right]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} + S_L\sin^2\theta_{CS}A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS}\right\}$$

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

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

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

Complementary information from two different channels :

- SIDIS-DY bridging of nucleon TMD PDFs; Universality studies;
- Sign-change T-odd Sivers and Boer-Mulders TMD PDFs;
- Multiple access to Collins FF $H_{1q}^{\perp h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{\perp q}$

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$$\times \left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \right.$$

$$\left. + S_T \left[A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h-\phi_S\right) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin\left(3\phi_h-\phi_S\right) \right] \right.$$

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

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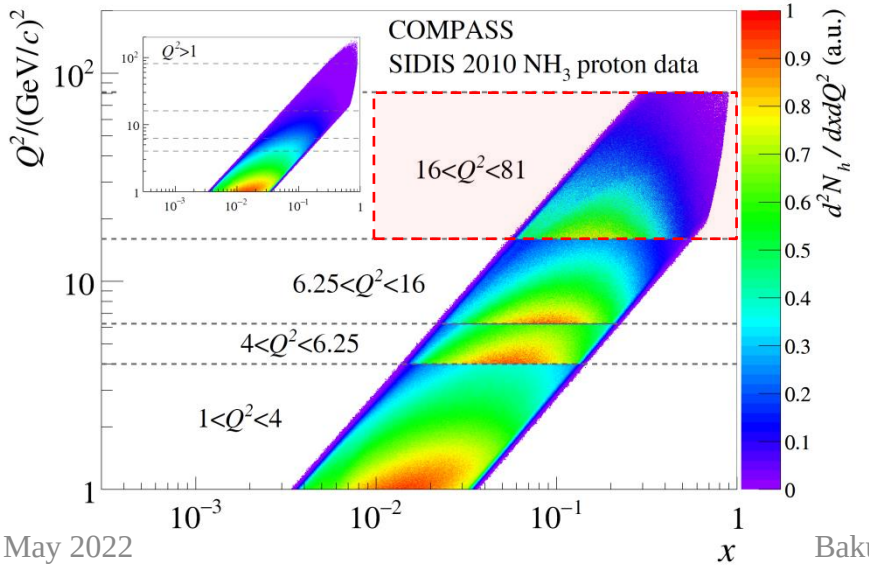
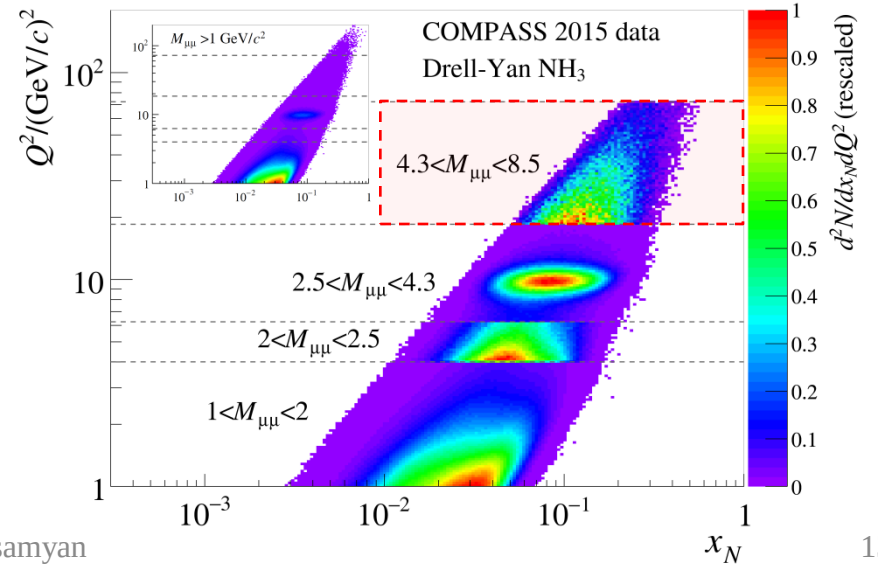
$$\times \left\{ 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right.$$

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

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

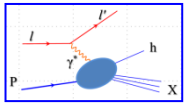
Comparable x:Q^2 coverage – minimization of possible Q^2-evolution effects





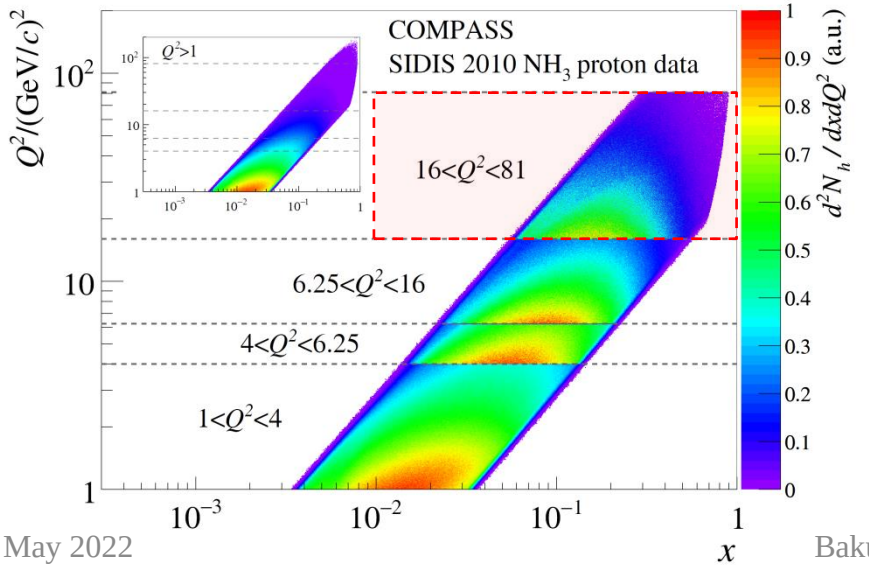
SIDIS counterpart: Sivers TSA – 2D analysis

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



$$\times \left\{ 1 + \boxed{\varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h} + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \right.$$

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



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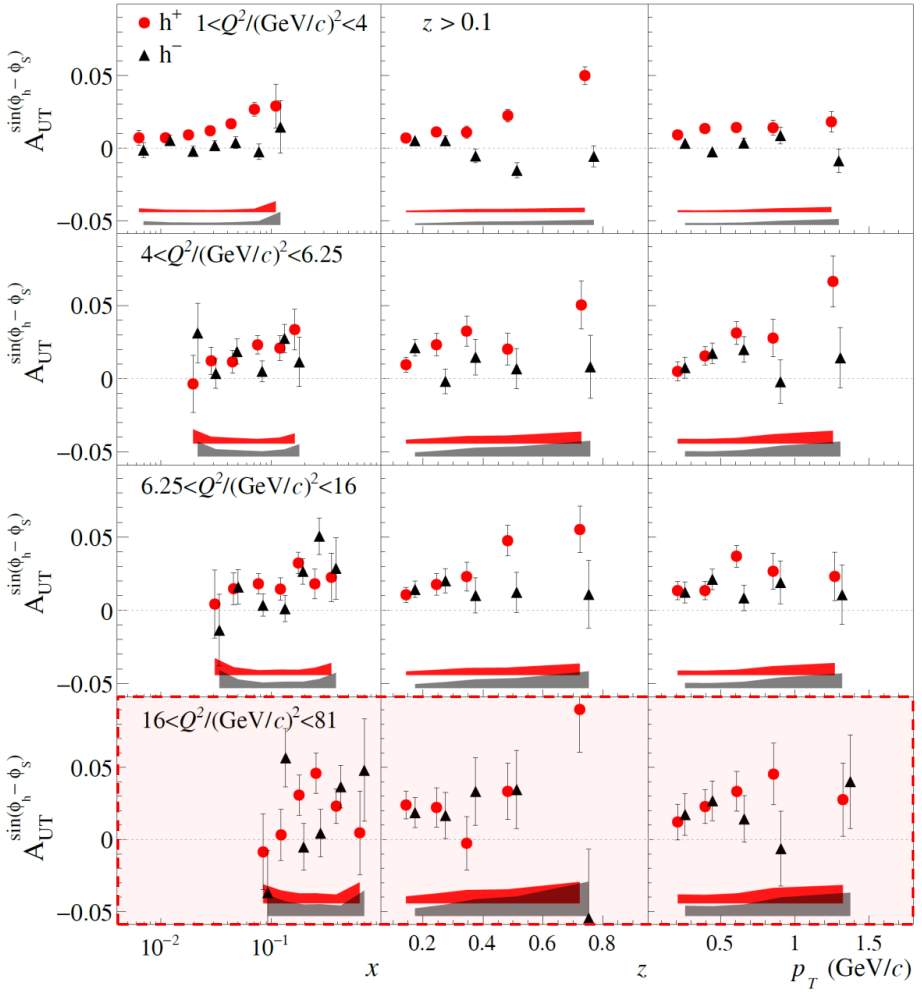
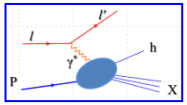
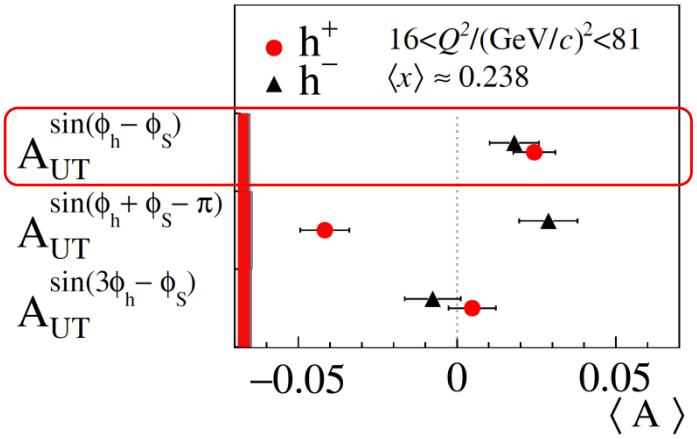


SIDIS: twist-2 TSAs – 2D analysis

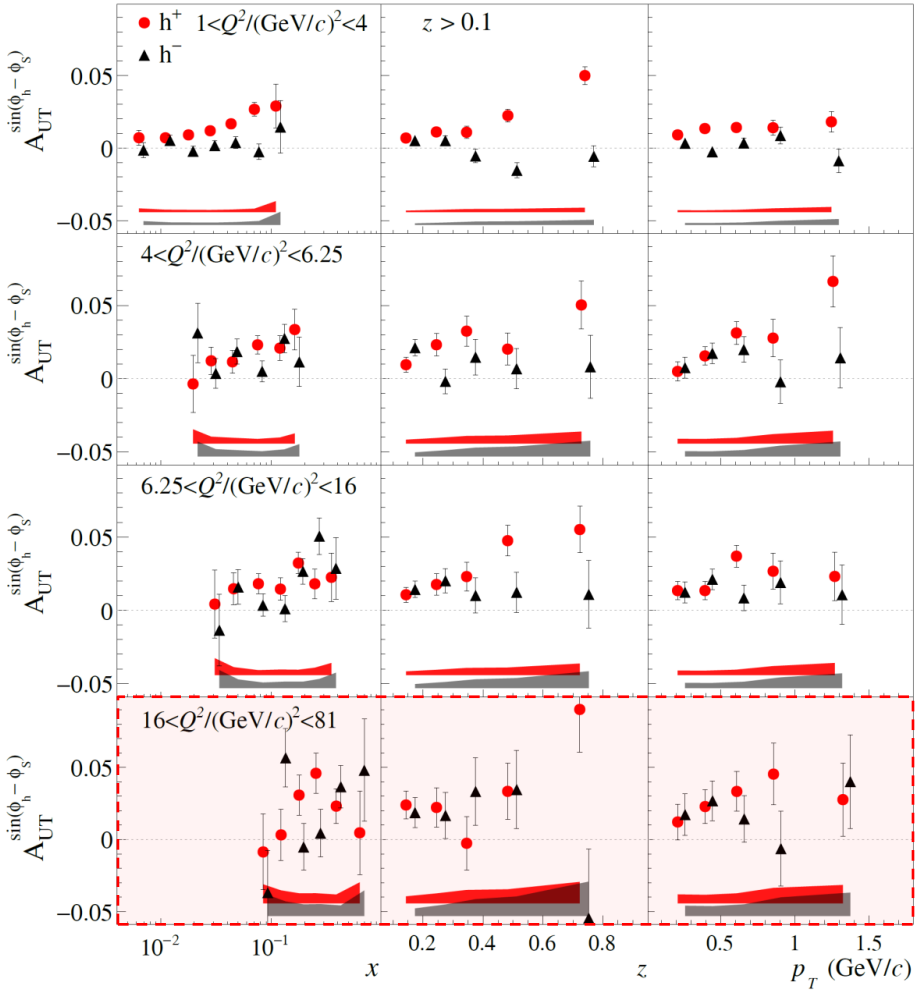
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$



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



COMPASS PLB 770 (2017) 138

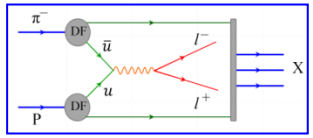


Single-polarized DY measurements at COMPASS

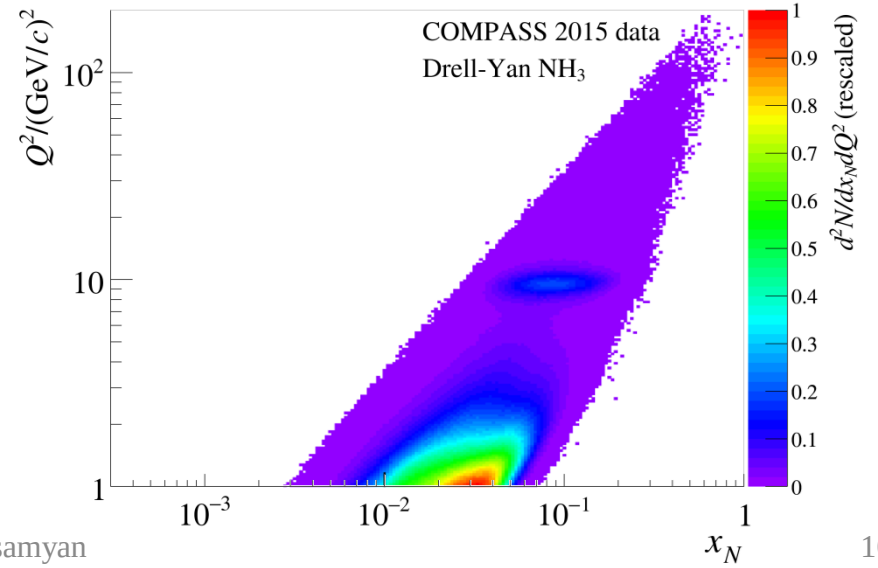
- $1.0 < M/(GeV/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(GeV/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(GeV/c^2) < 4.3$ "Charmonia mass"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

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{\left[\sin^2\theta_{CS}\right]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \right) \right] \right\}$$

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



COMPASS x:Q² phase space



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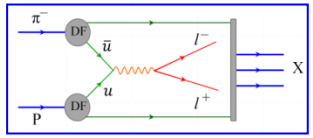
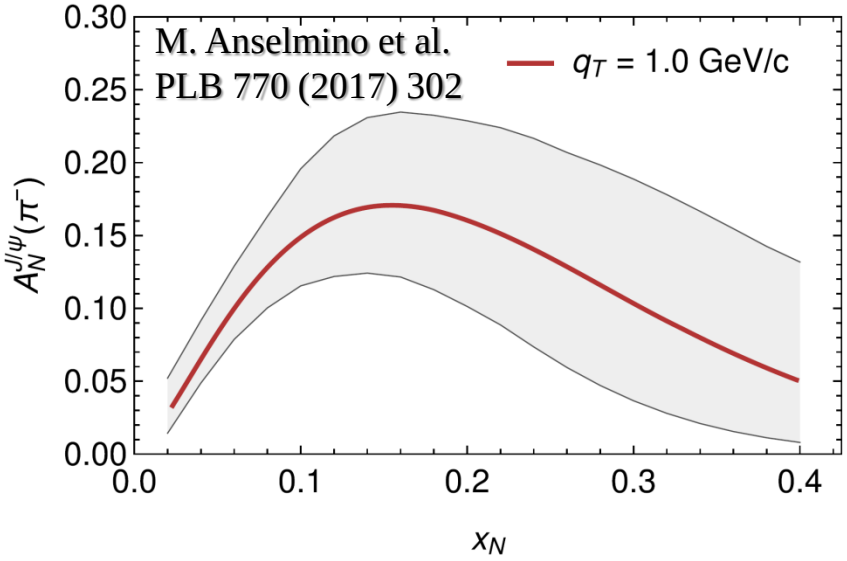
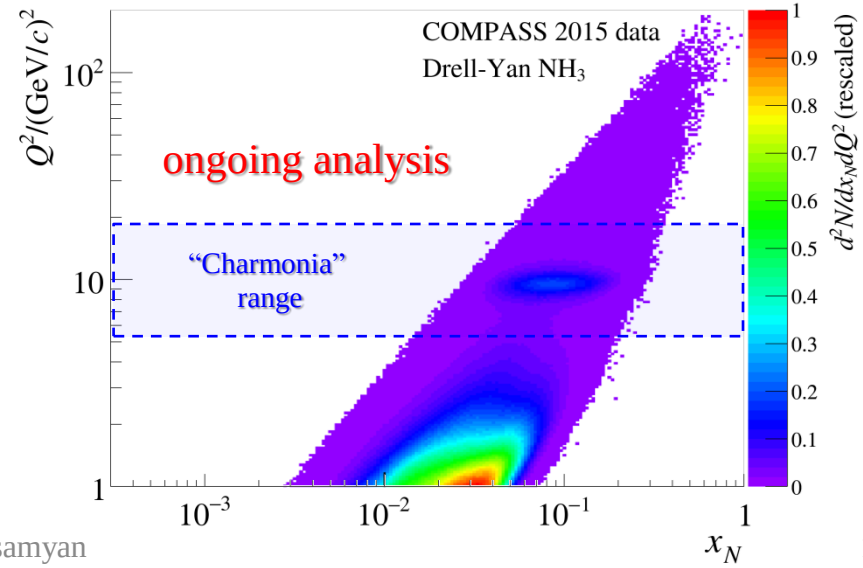
$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$$



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



2.5 < M /(GeV/c2) < 4.3 "Charmonia mass"
Strong J/ψ-signal → study of J/ψ physics
Good signal/background



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  - Good signal/background
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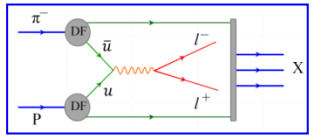
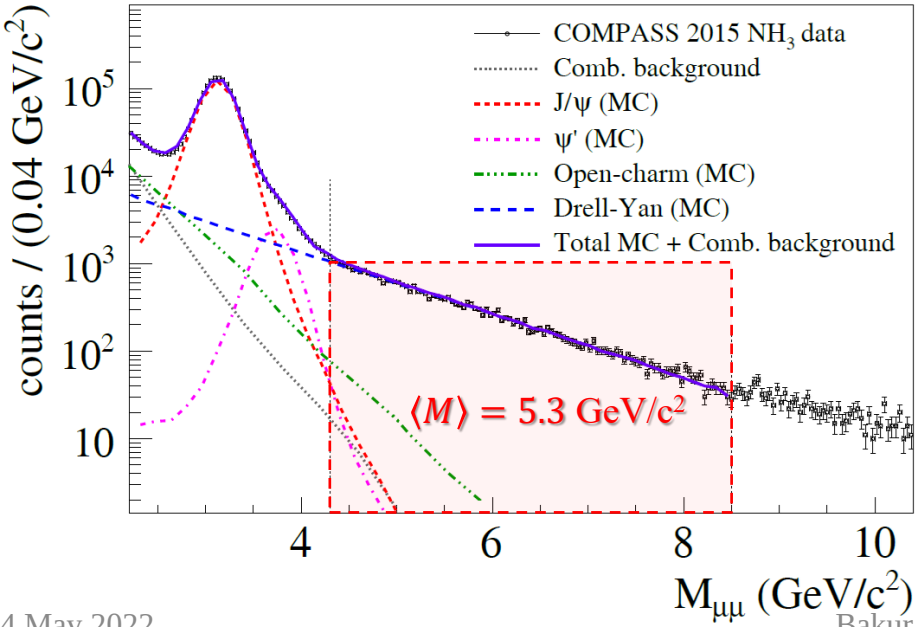
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{\left[\sin^2\theta_{CS}\right]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \right) \right] \right\}$$

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

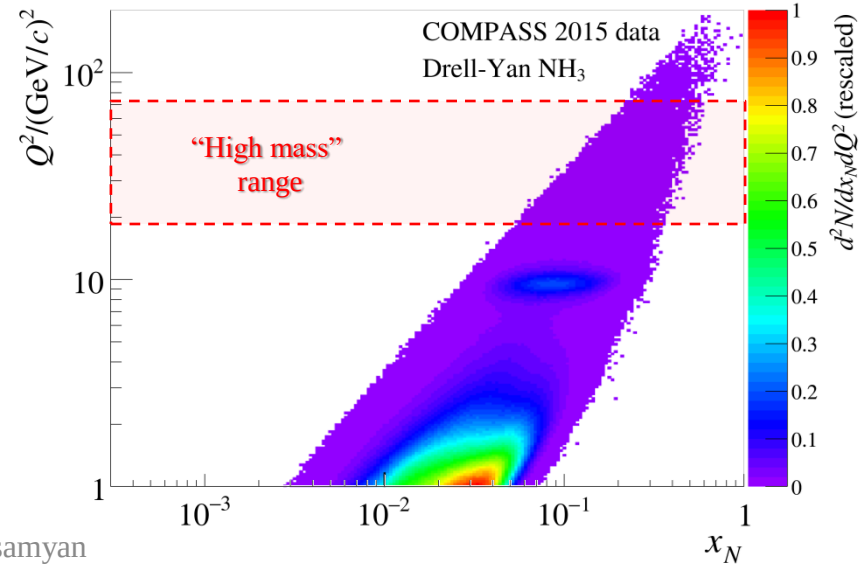




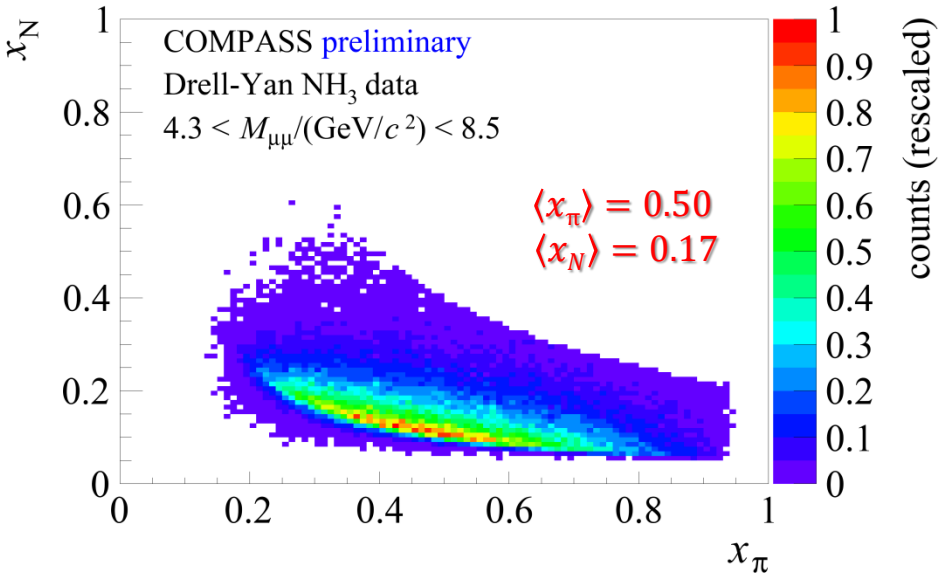
4.3 < M /(GeV/c²) < 8.5 "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries

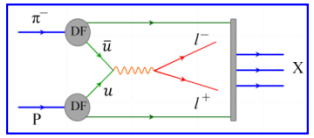


Single-polarized DY measurements at COMPASS

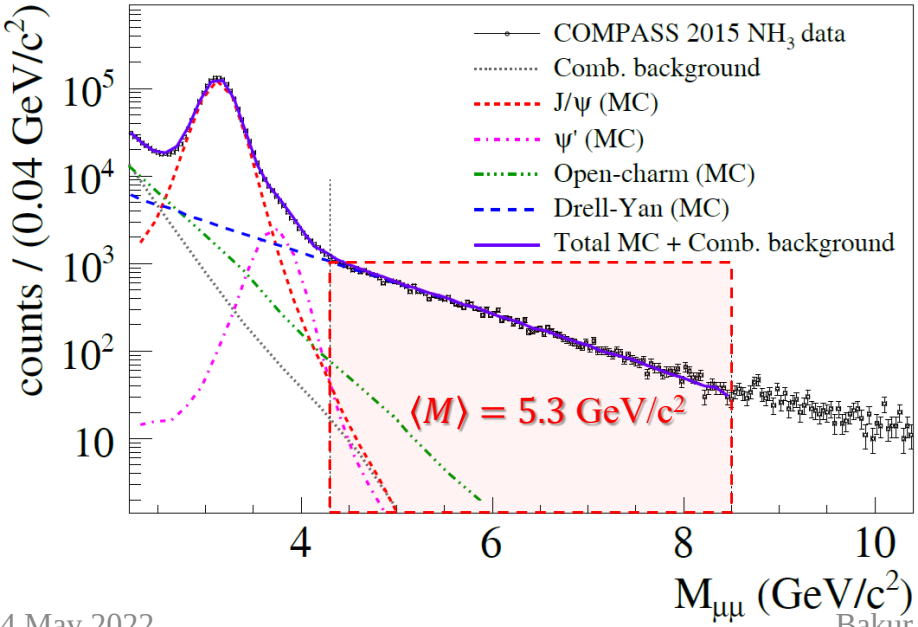


$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right\} \times \left\{ + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \right) \right] \right\}$$

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



HM events are in the valence quark range



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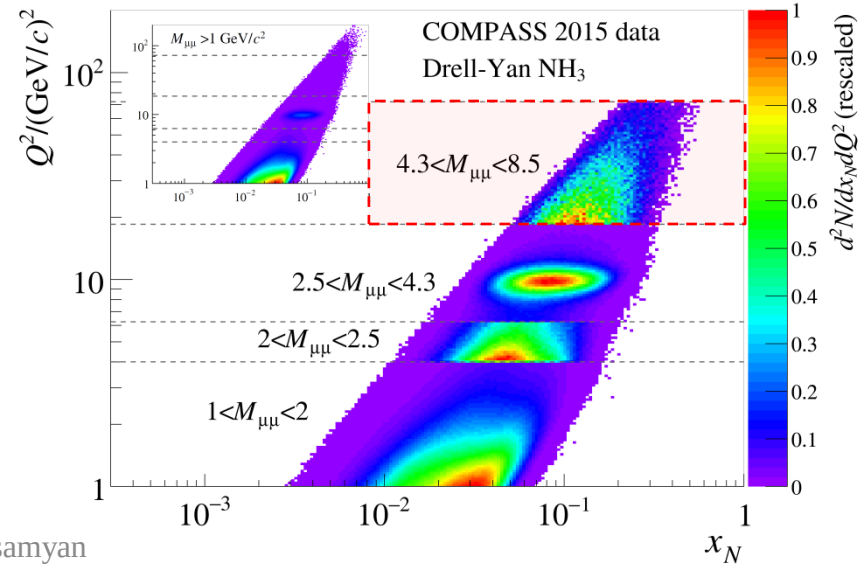
Valence region → largest asymmetries



Single-polarized DY measurements at COMPASS

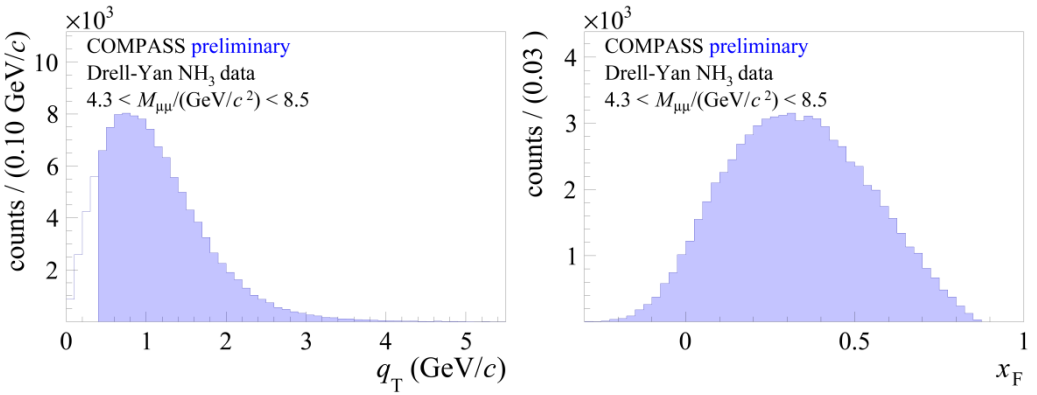
Dimuon transverse momentum $q_T > 0.4$ GeV/c

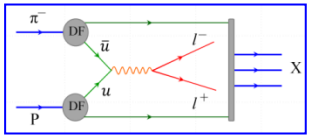
$\langle x_F \rangle = 0.33,\ \langle q_T \rangle = 1.2$ GeV/c

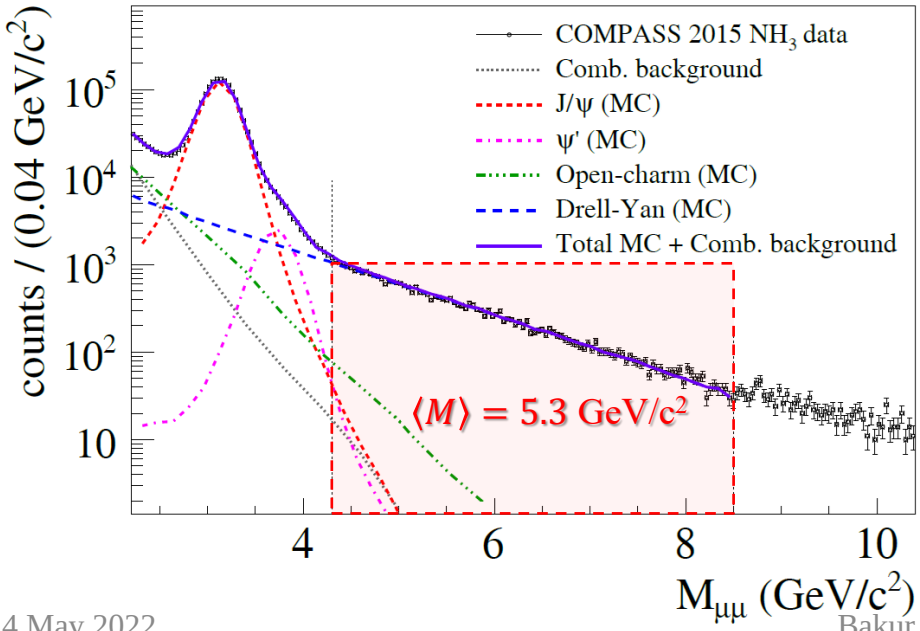
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

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

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







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

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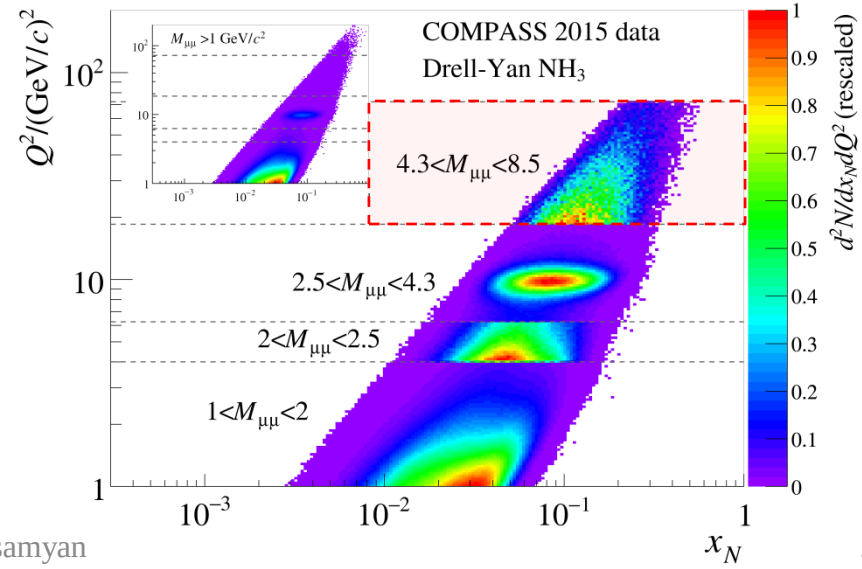
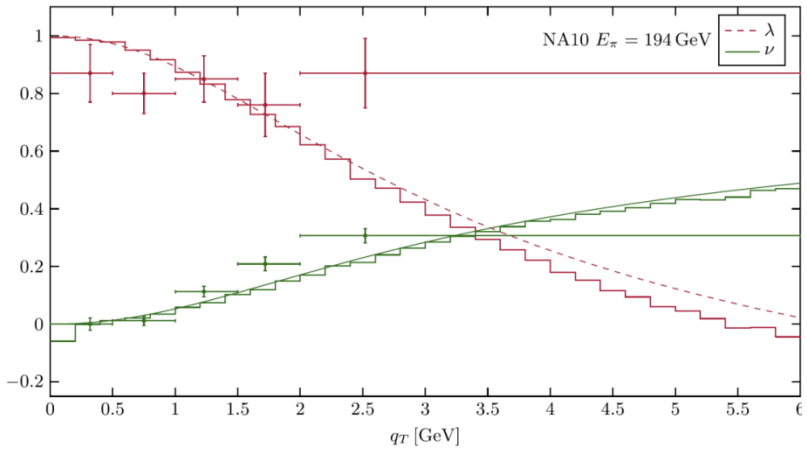


Single-polarized DY x-section: transverse part

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



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

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

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

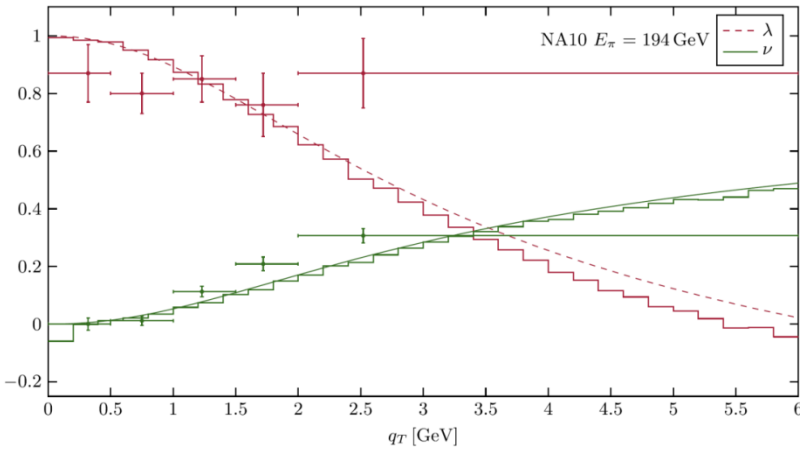
$$D_{[f(\theta_{CS})]} = f\left(\theta_{CS}\right) / \left(1 + A_U^1 \cos^2\theta_{CS}\right)$$

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

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

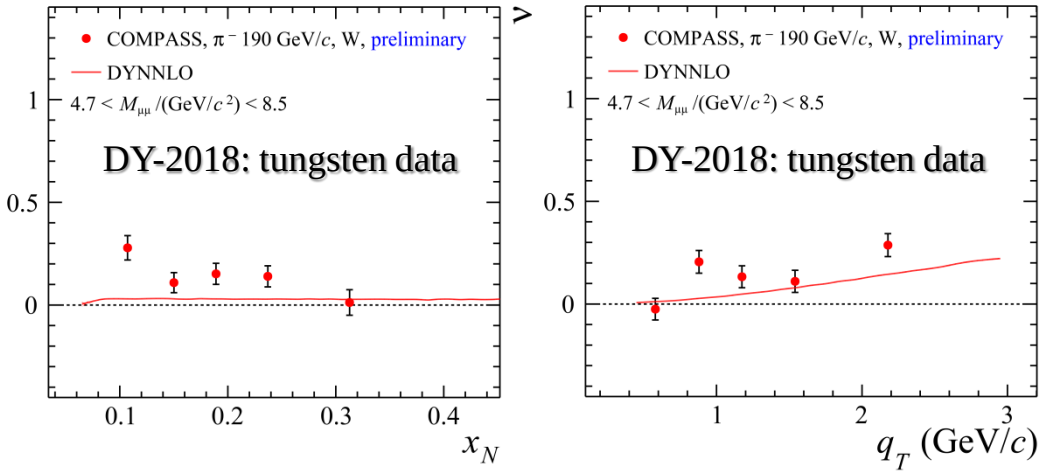
Unpolarized Drell-Yan results (high-mass range)

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



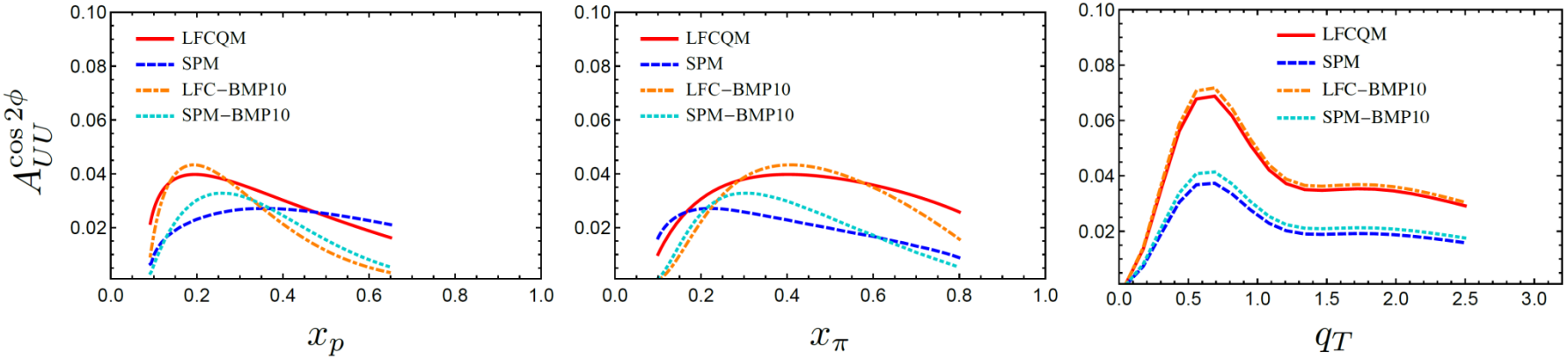
NA10 data **Z.Phys.C 37,545(1988)**

Preliminary results Released for DIS-2021



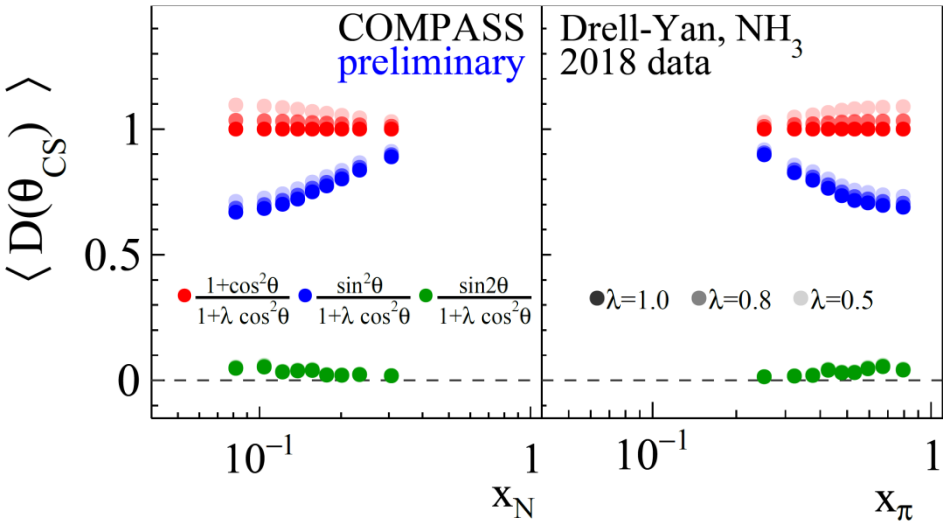
DY-2018 NH_3 data: ongoing analysis

S. Bastami et al. JHEP 02, (2021),166



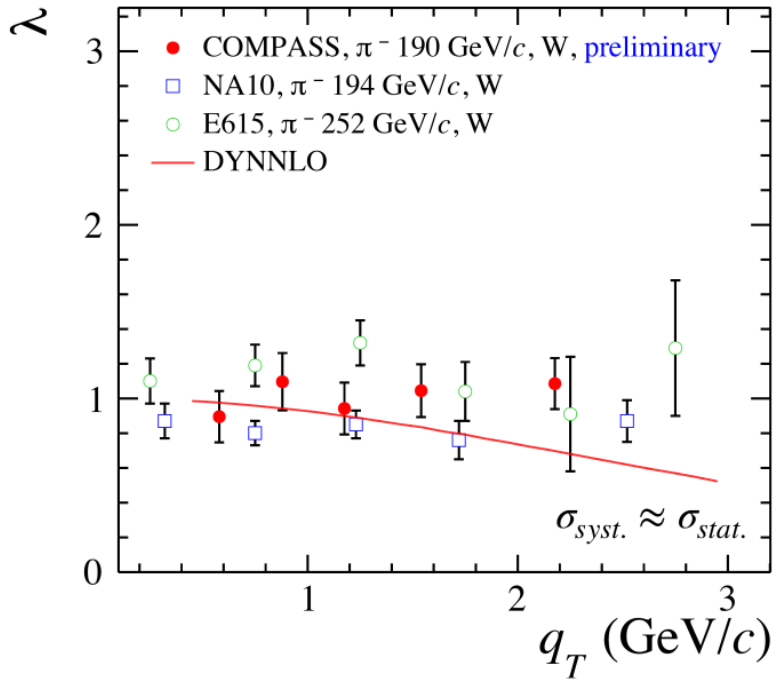
Is there a room for BM at low (COMPASS) q_T?

Single-polarized DY x-section: transverse part



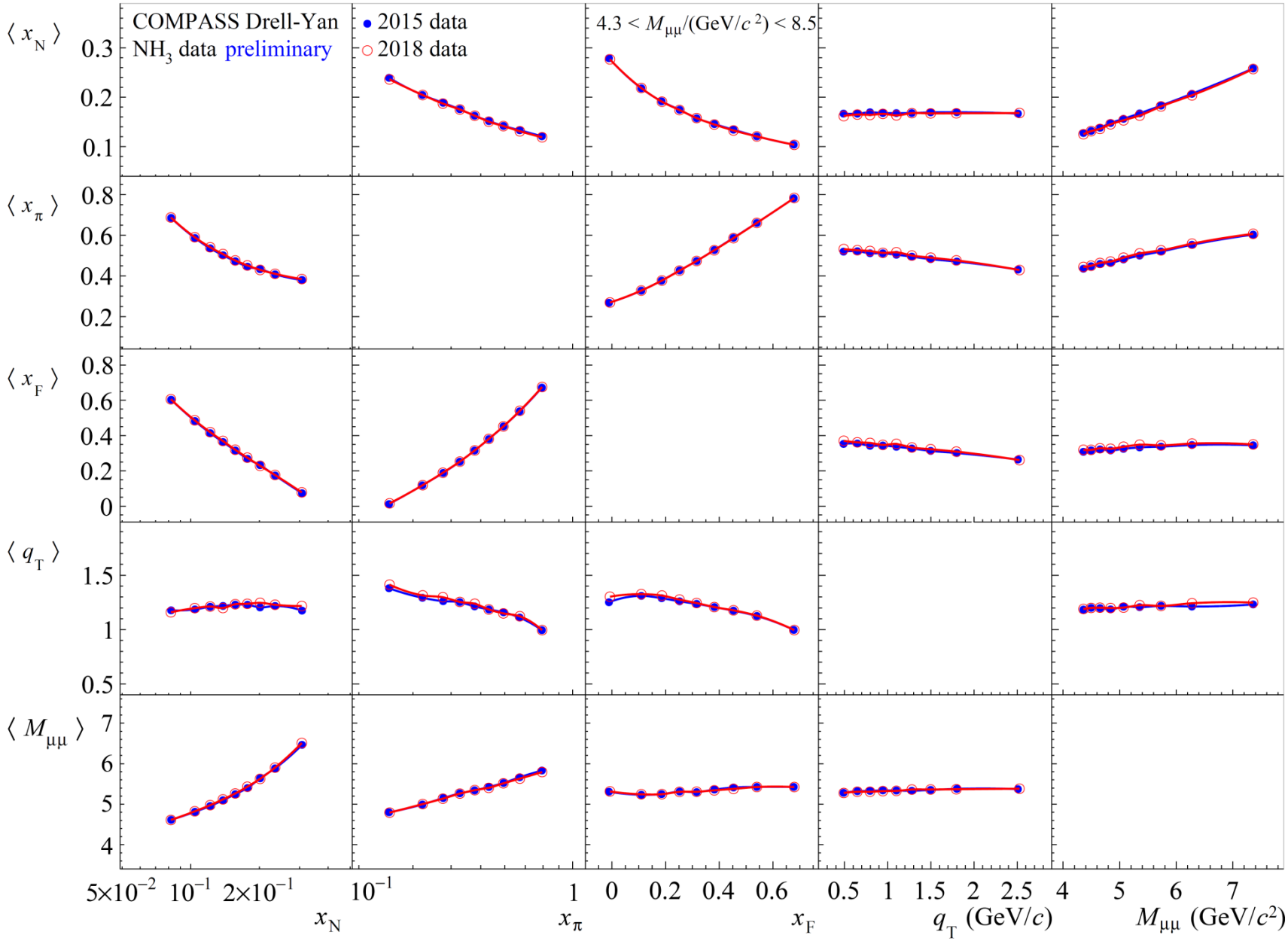
$$\frac{d\sigma}{d\Omega} \propto \left(F_U^1 + F_U^2\right)\left(1 + A_U^1 \cos^2\theta_{CS}\right) \times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + D_{[\sin 2\theta_{CS}]} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S +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

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



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

Kinematic map: high mass range 2015 and 2018 data



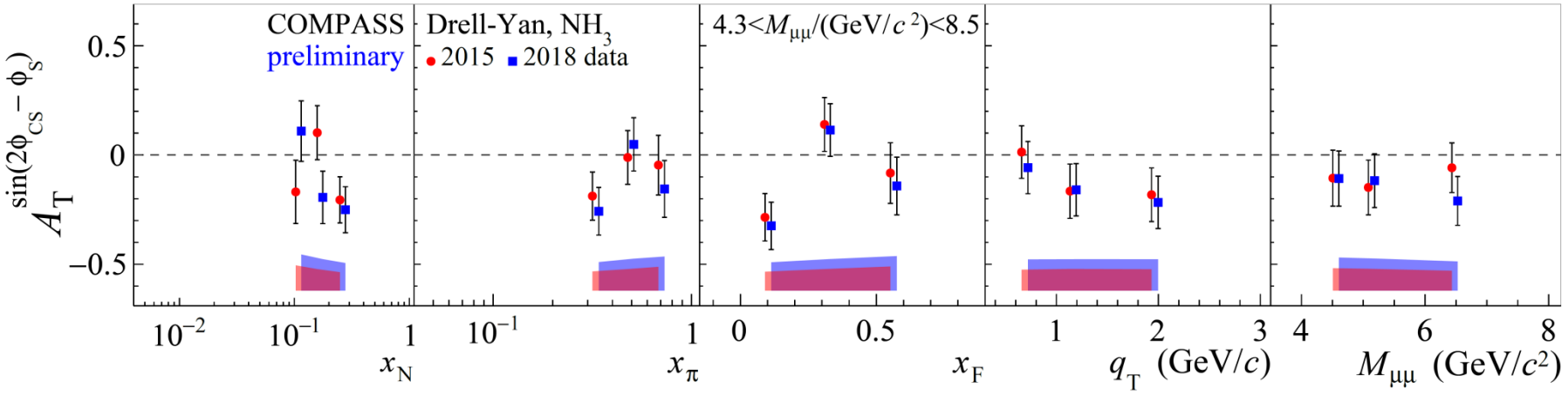
Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + \ldots \right]$$

Transversity DY TSA

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

COMPASS 2015 + 2018 data **NEW!**



- Full re-processing and re-analysis of both 2015 and 2018 samples
- Results from 2015 and 2018 samples are in agreement
  - Somewhat larger systematics for 2018 sample
- Combined TSAs from 2015 and 2018 are presented – **NEW!**

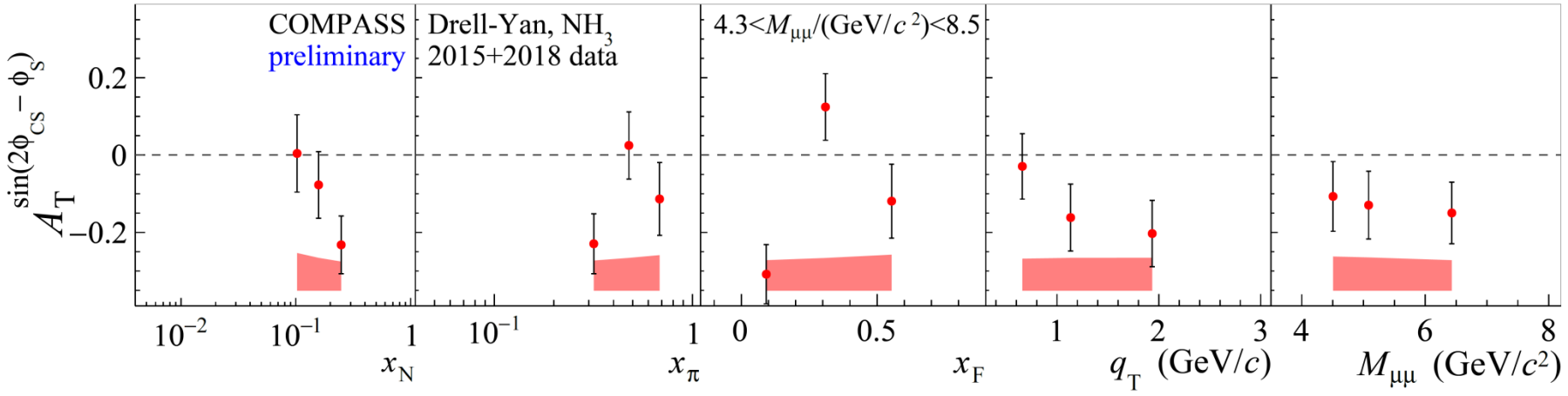
Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + \ldots \right]$$

Transversity DY TSA

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

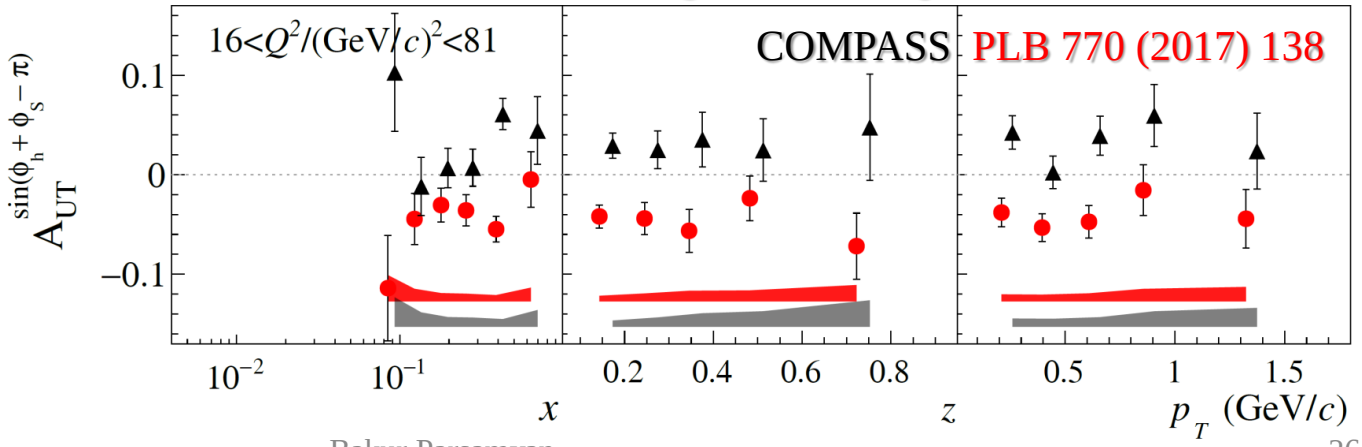
COMPASS 2015 + 2018 data **NEW!**



Collins SIDIS TSA

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

SIDIS in Drell-Yan *high-mass* range



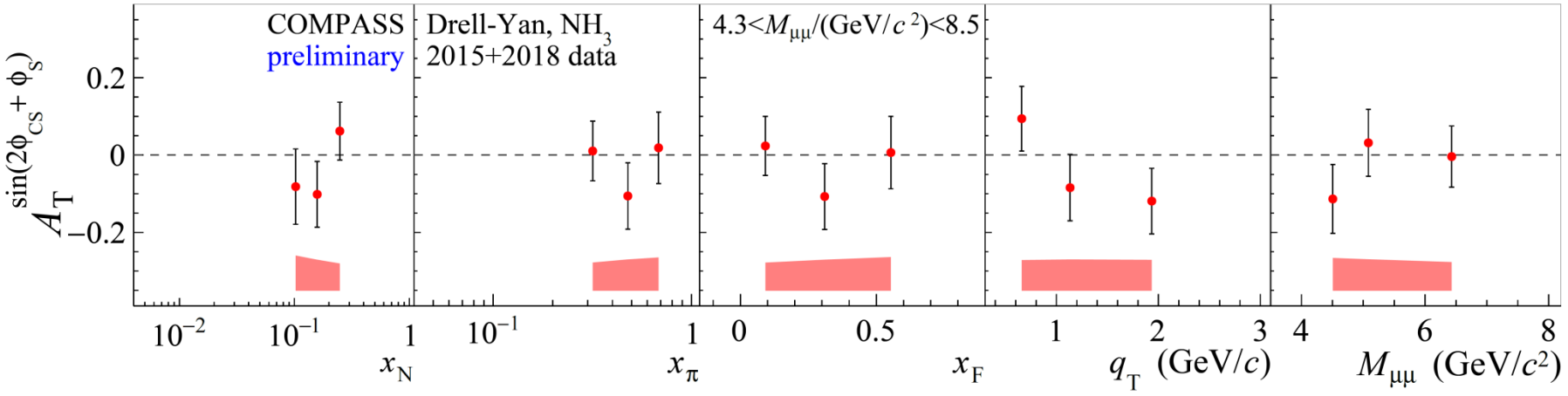
Drell-Yan TSAs – Pretzelosity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS} - \varphi_S\right) + \ldots \right]$$

Pretzelosity DY TSA

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

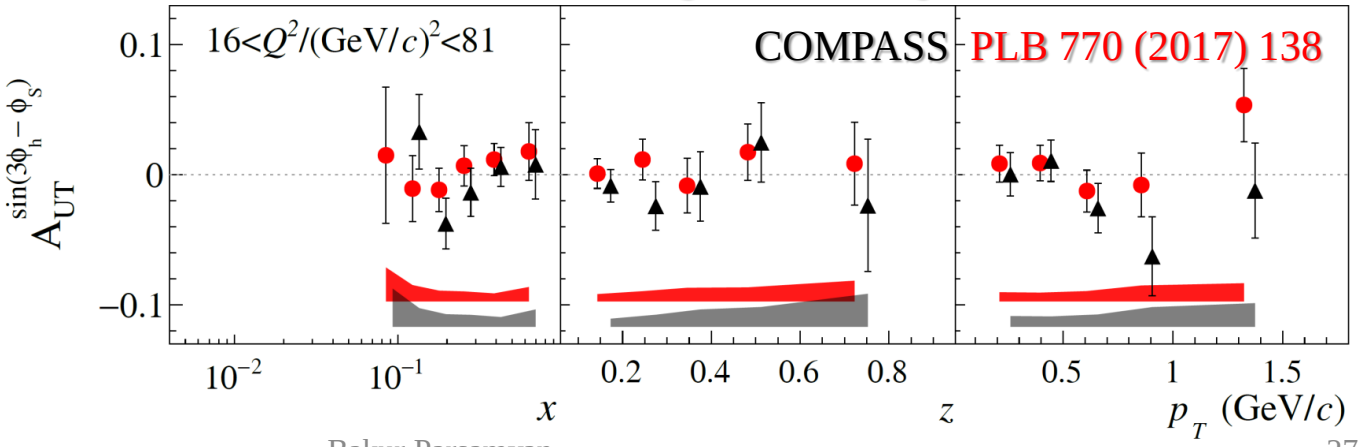
COMPASS 2015 + 2018 data **NEW!**



Pretzelosity SIDIS TSA

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

SIDIS in Drell-Yan *high-mass* range



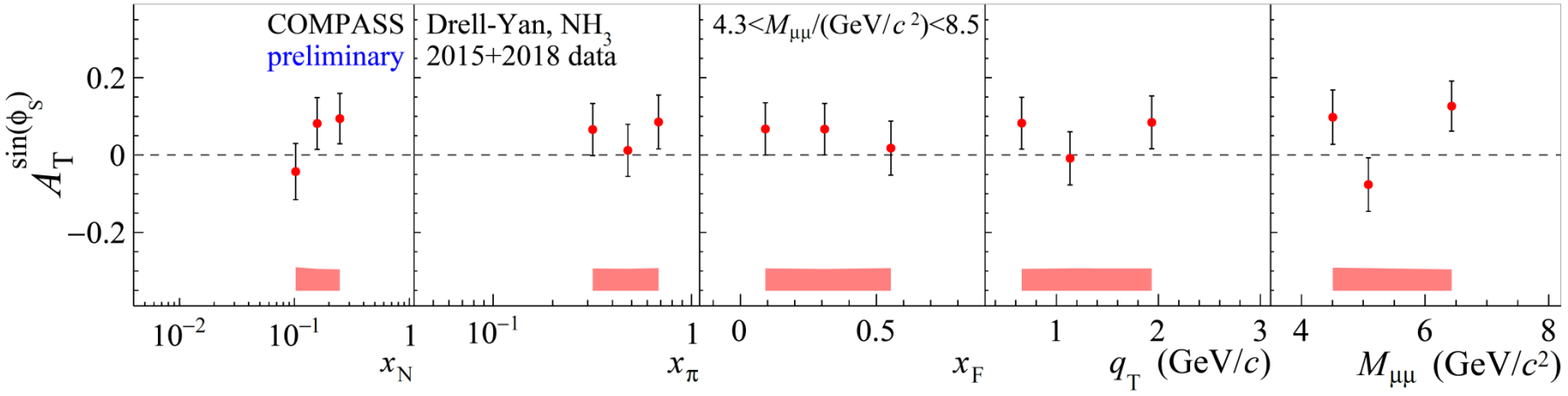
Drell-Yan TSAs – Sivers

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

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

COMPASS 2015 + 2018 data **NEW!**



Sivers SIDIS TSA

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

SIDIS in Drell-Yan *high-mass* range

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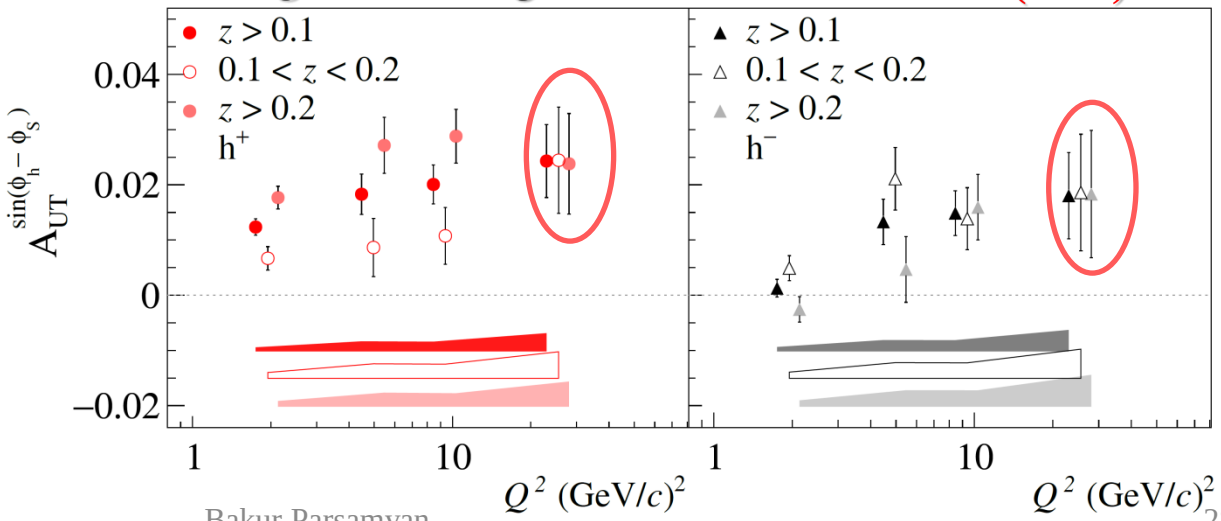
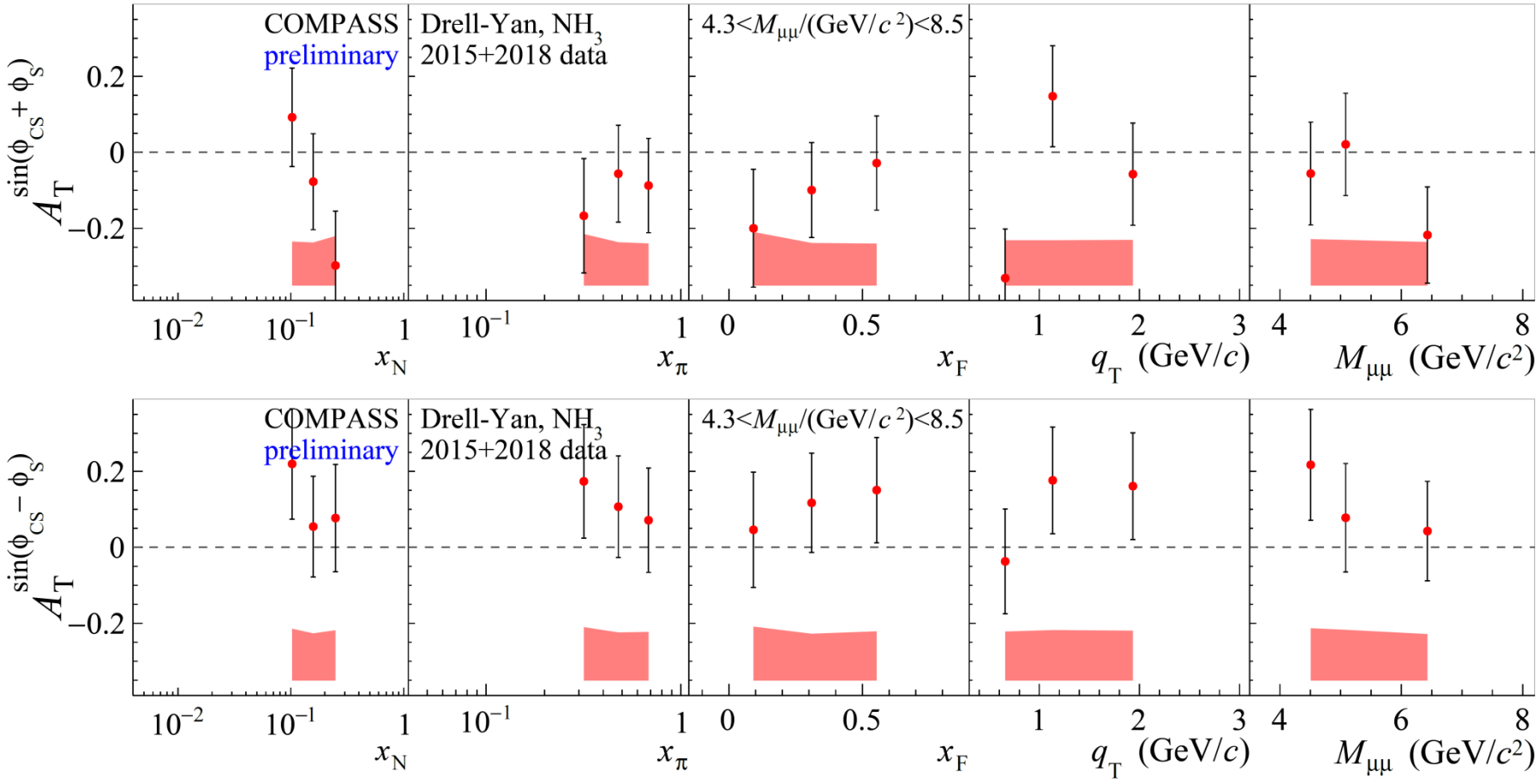


Drell-Yan TSAs – "higher twists"

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

COMPASS 2015 + 2018 data **NEW!**



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

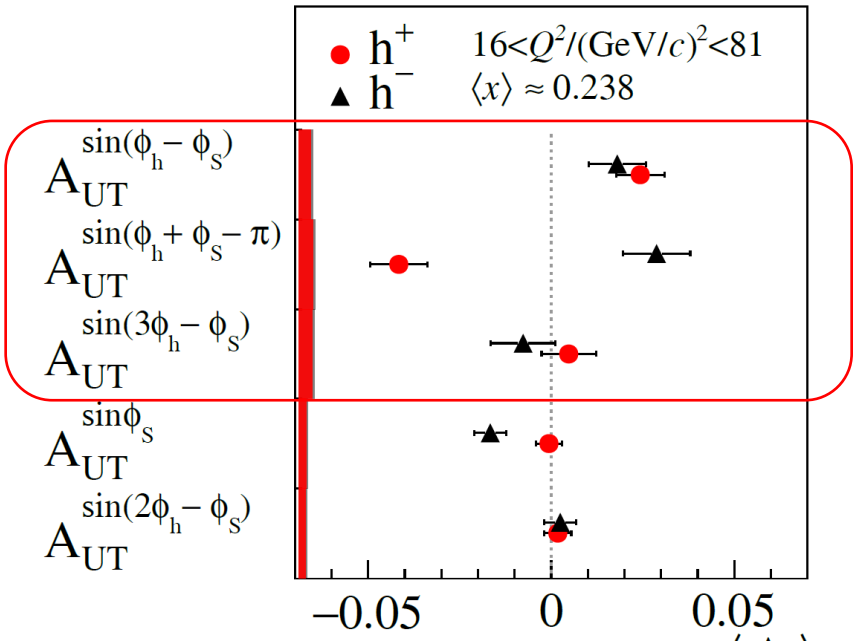
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ \quad 1+\ldots \right.$$

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

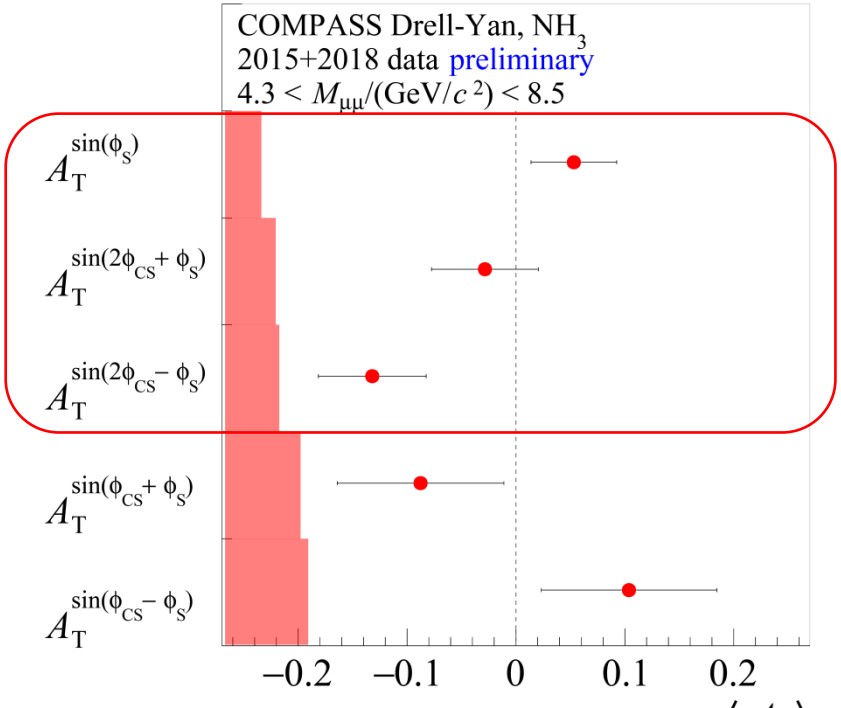
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)\left\{ \quad 1+\ldots \right.$$

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

COMPASS PLB 770 (2017) 138

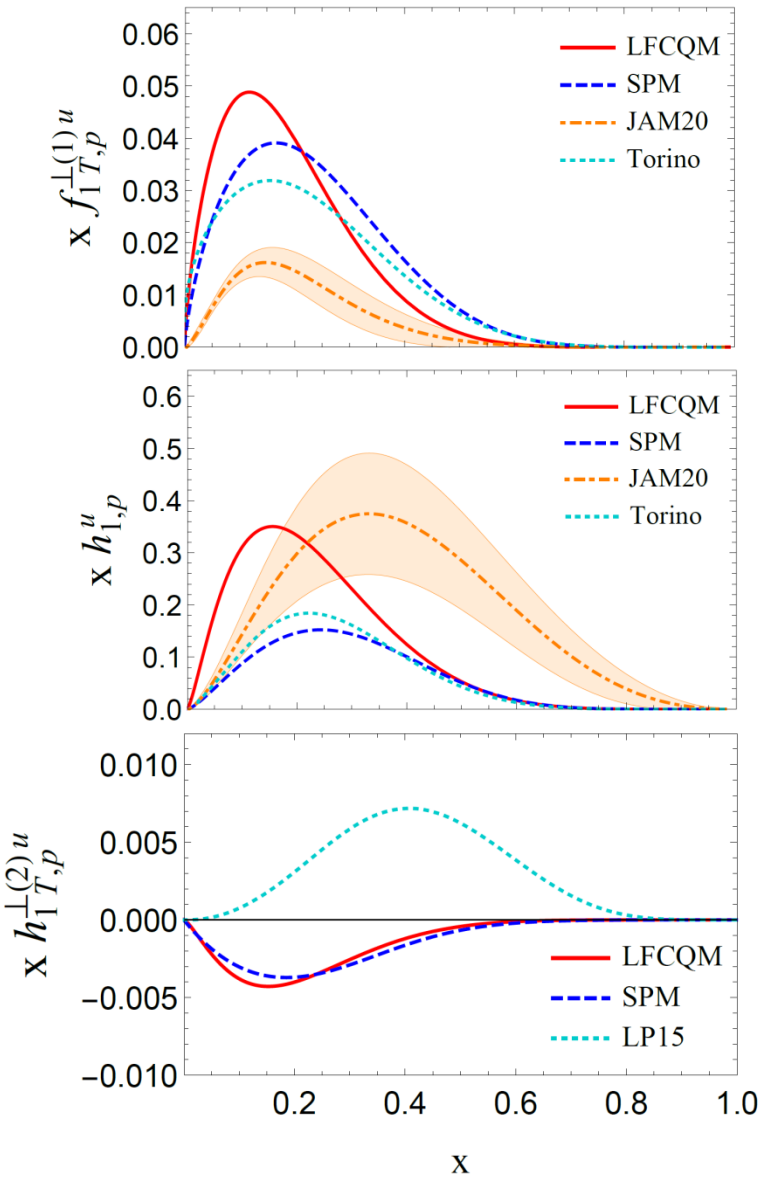


COMPASS 2015 + 2018 NEW!



DY TSAs at COMPASS (high-mass range)

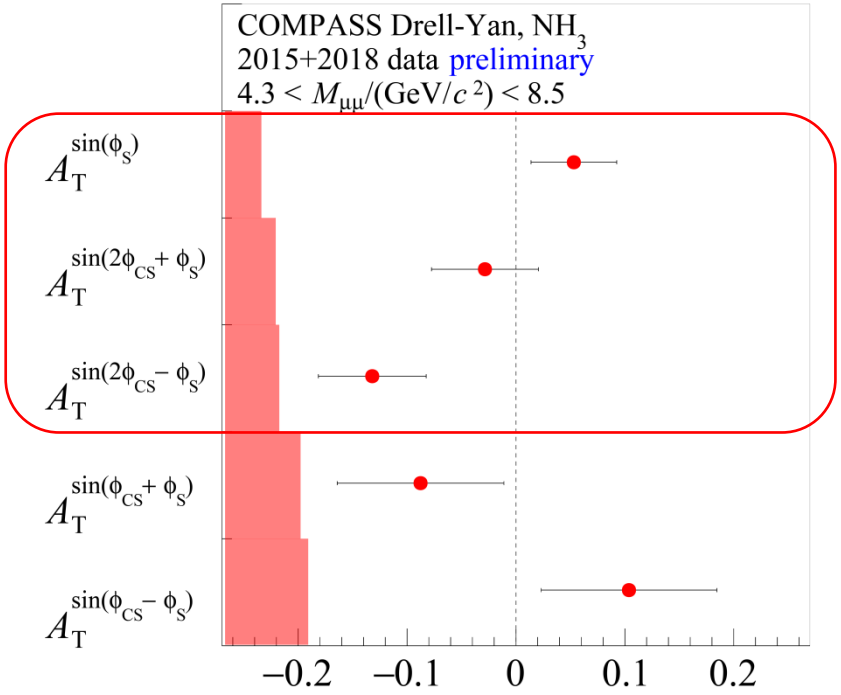
S. Bastami et al. JHEP 02, (2021),166



$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)\Big\{ \quad 1+\ldots$$

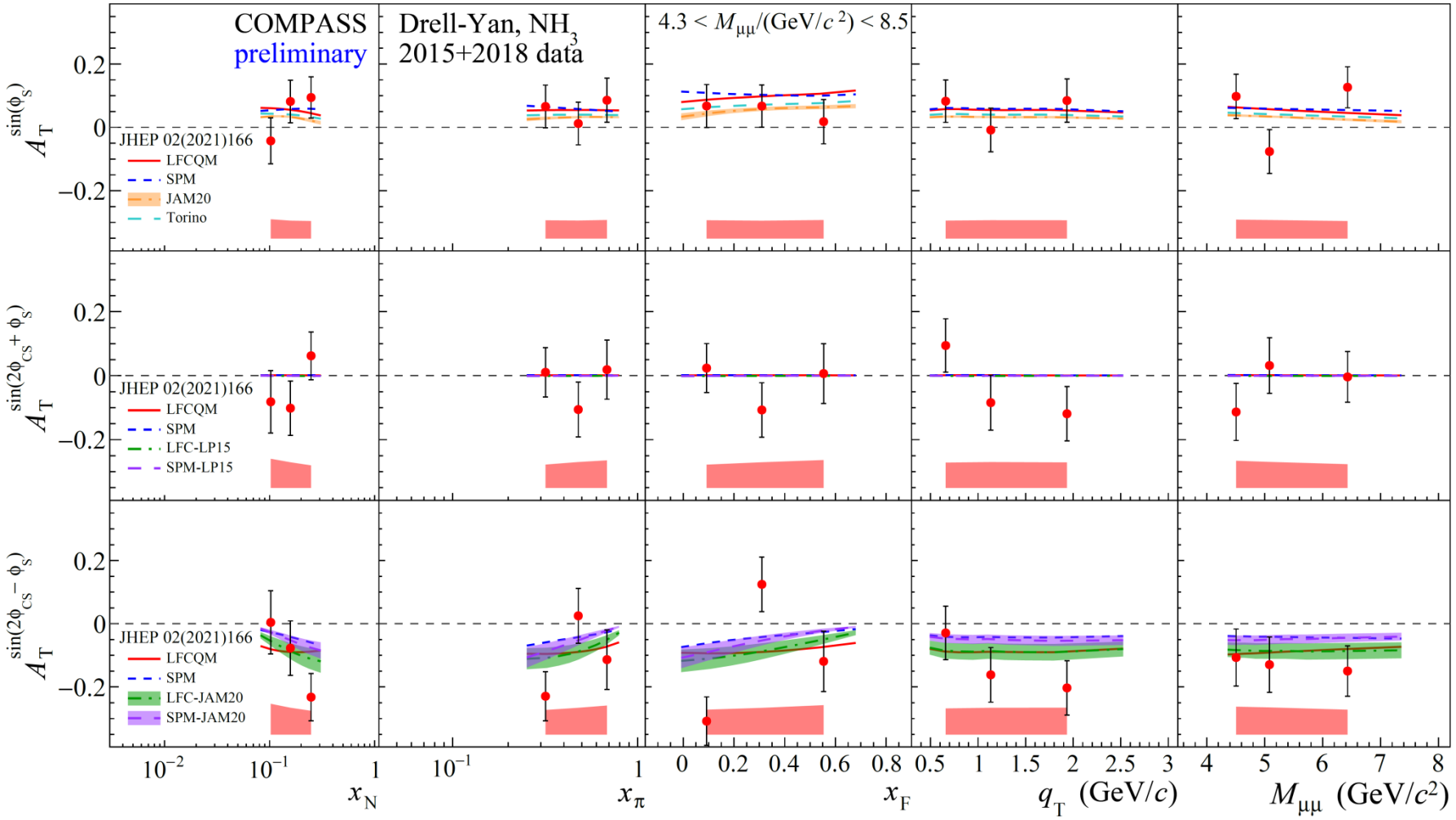
$$+ S_T \Bigg[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \right) + D_{[\sin 2\theta_{CS}]} \left(A_T^{\sin(\varphi_{CS}-\varphi_S)}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

COMPASS 2015 + 2018 NEW!



DY TSAs at COMPASS (high-mass range)

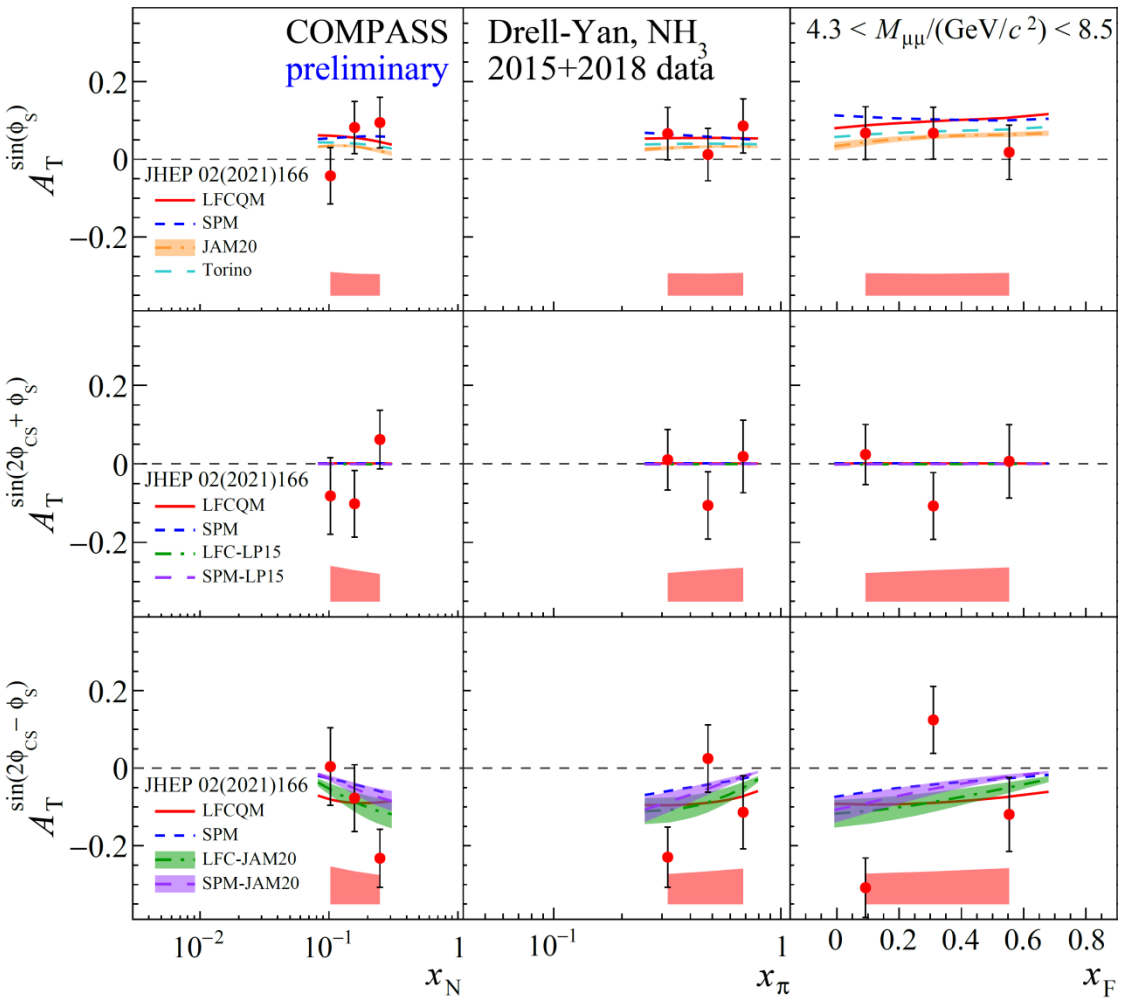
Theory curves based on S. Bastami et al. JHEP 02, (2021),166

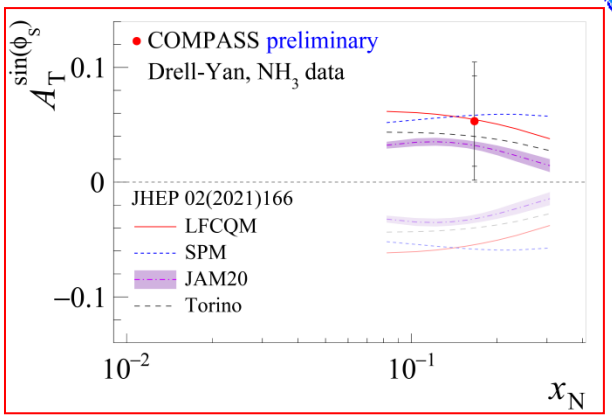


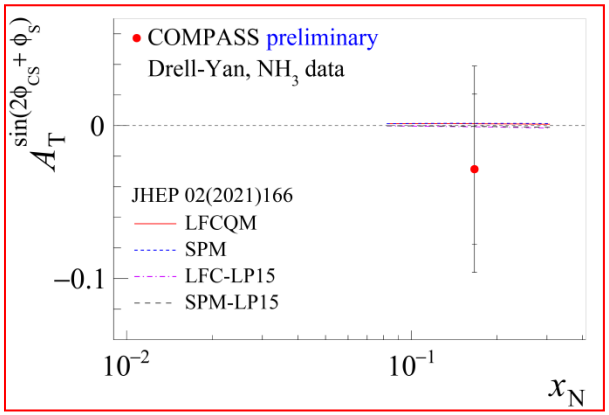
- General agreement with available theory predictions

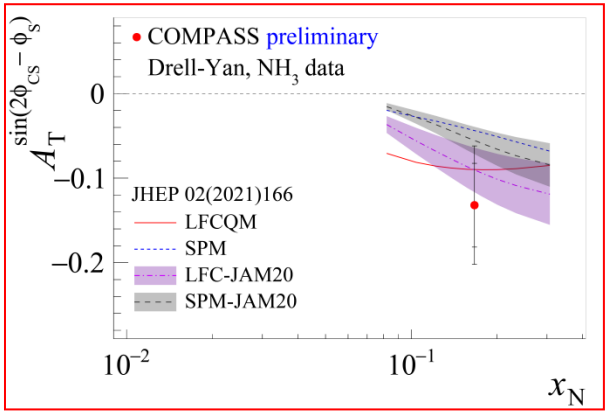
DY TSAs at COMPASS (high-mass range)

Theory curves based on S. Bastami et al. JHEP 02, (2021),166





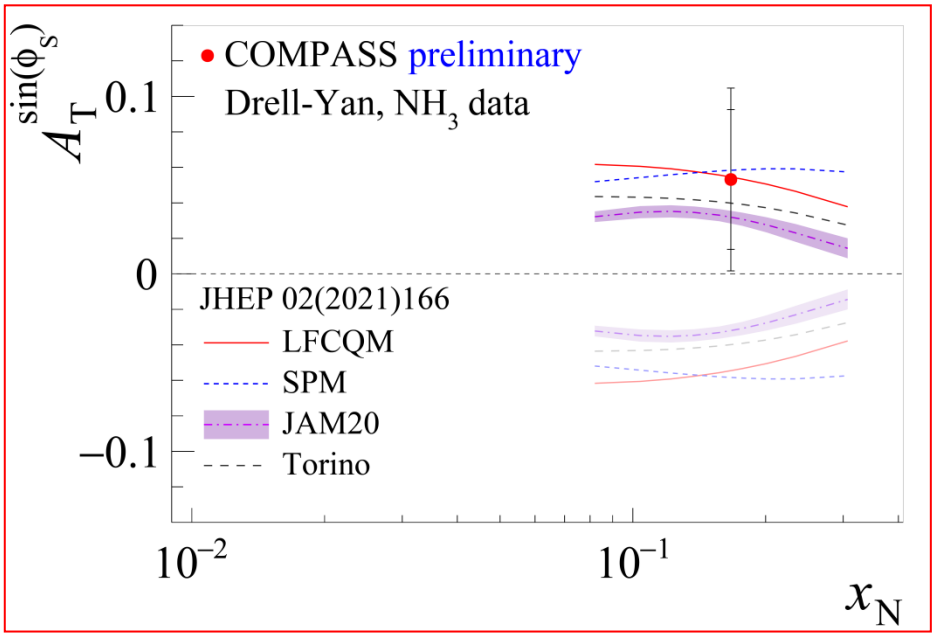




- General agreement with available theory predictions

Conclusions

- During phase I COMPASS has measured all possible SIDIS TSAs.
  - Non-zero Sivers and Collins SIDIS-TSAs in the Drell-Yan “high-mass range”: PLB 770 (2017) 138
- In 2017 COMPASS has published the results for the first polarized DY measurements: PRL 119, 112002 (2017)
- The second year of polarized DY data-taking was performed in 2018
- Re-production and re-analysis of both 2015 2018 data is over
- Final results have been presented today: the paper is in preparation
- COMPASS data favors the sign-change of Sivers TMD PDF

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