# Drell-Yan measurements at COMPASS

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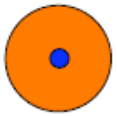
# Outline

- Polarised structure of the nucleon
- Drell-Yan process
- Drell-Yan vs. SIDIS
- Drell-Yan setup at COMPASS
- Polarised double-spin azimuthal asymmetries

# Spin structure of nucleon

- Nucleon structure in momentum phase space described by PDFs
- LO QCD collinear approximation:

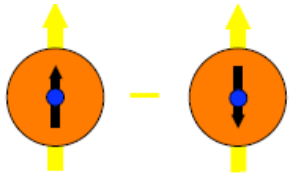
- unpolarised distribution function $f_1(x) = q(x)$

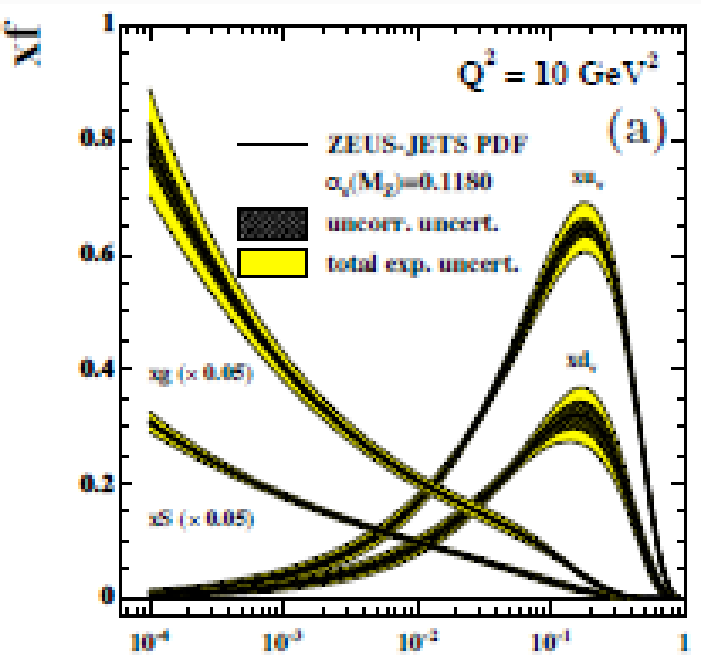


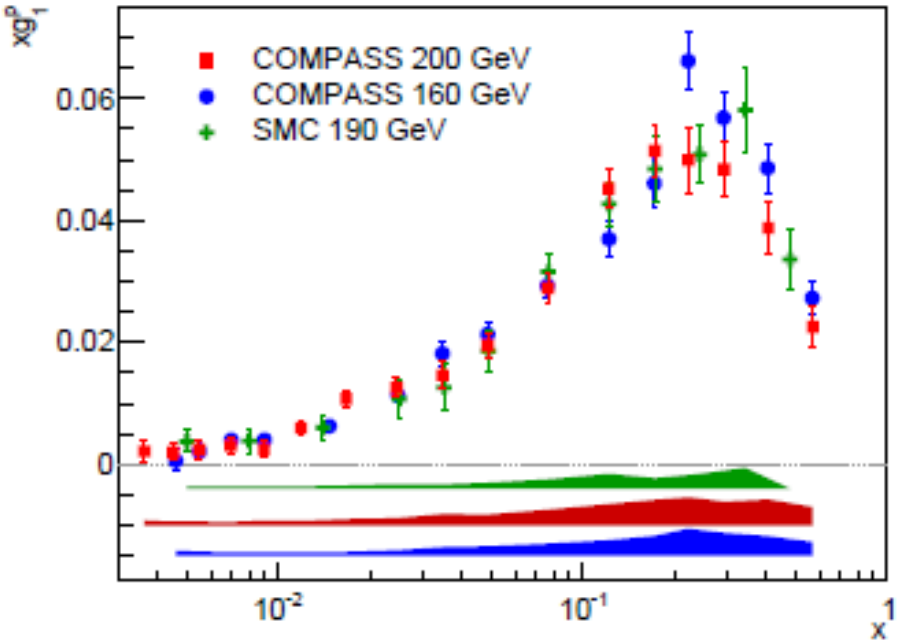
- helicity $g_1^q(x)$

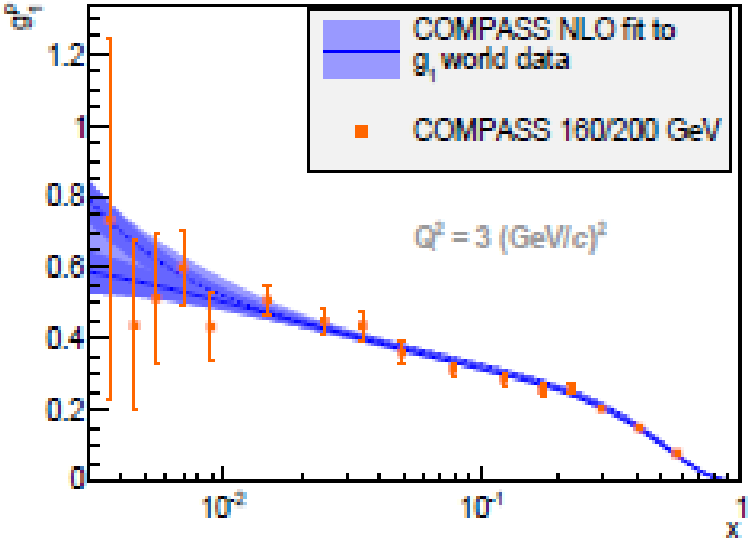
$$g_1^q(x) \equiv \Delta q \equiv q_{1i}\uparrow(x) - q_{1i}\downarrow(x)$$

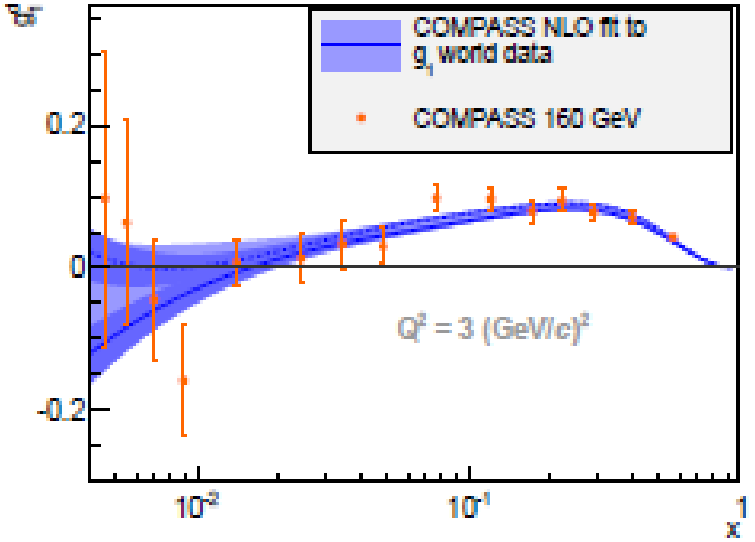
- transverzity $h_1^q(x)$




xf
$Q^2 = 10\ GeV^2$
(a)
ZEUS-JETS PDF
$\alpha_s(M_Z)=0.1180$
uncorr. uncert.
total exp. uncert.
xg (× 0.05)
xS (× 0.05)
$xu_v$
$xd_v$
1
0.8
0.6
0.4
0.2
0
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1

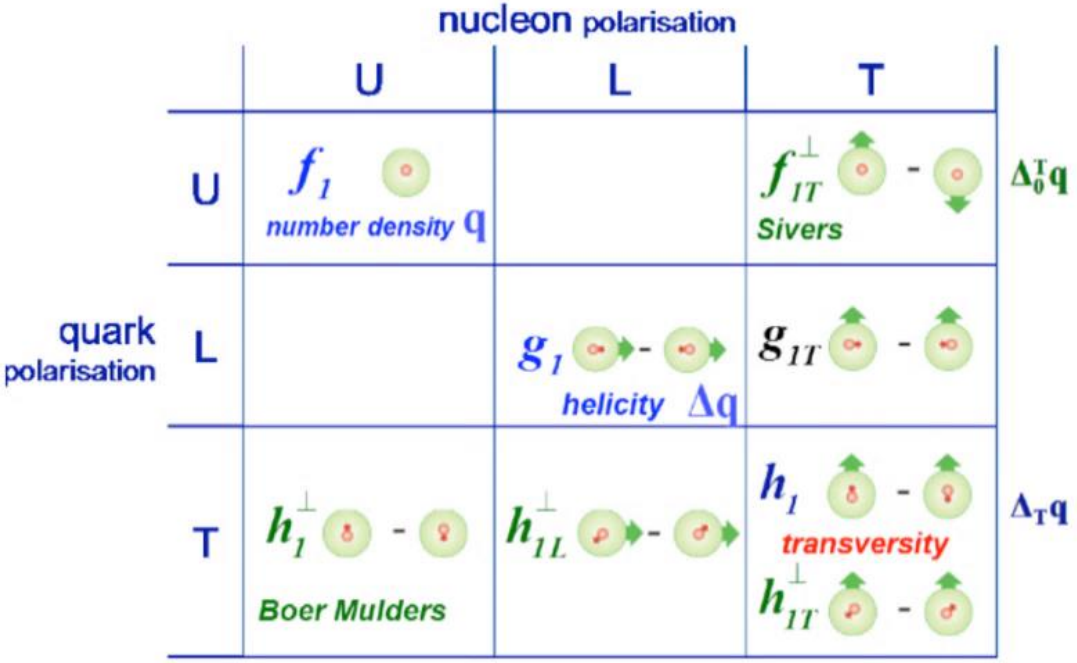

$xg_1^p$
COMPASS 200 GeV
COMPASS 160 GeV
SMC 190 GeV
0.06
0.04
0.02
0
$10^{-2}$
$10^{-1}$
1
x


$g_1^p$
COMPASS NLO fit to $g_1$ world data
COMPASS 160/200 GeV
$Q^2 = 3\ (GeV/c)^2$
1.2
1
0.8
0.6
0.4
0.2
0
$10^{-2}$
$10^{-1}$
1
x


$g_1^p$
COMPASS NLO fit to $g_1$ world data
COMPASS 160 GeV
$Q^2 = 3\ (GeV/c)^2$
0.2
0
-0.2
$10^{-2}$
$10^{-1}$
1
x

# Transverse momentum distributions

- Considering the transverse momentum of partons $k_T$ (only for $k_T << Q^2$)
- 8 leading twist QCD TMD PDFs: 6 T-invariant functions
- 2 *T*-odd TMDs: Boer-Mulders function $h_1^{\perp}$ a Sivers function $f_{1T}^{\perp}$

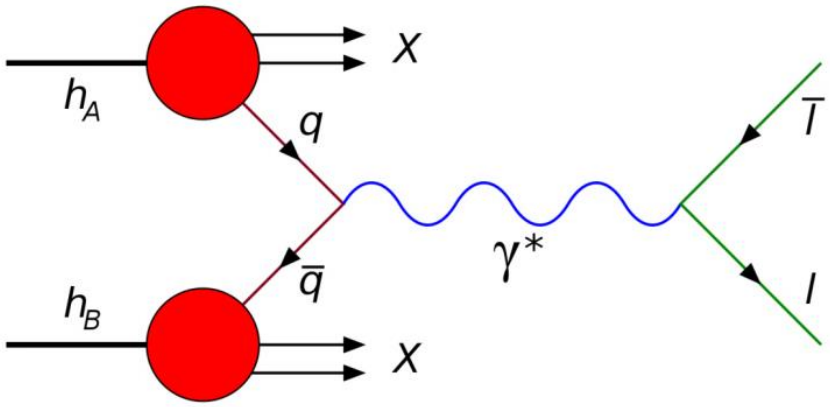


# Drell-Yan process

- Hadron-hadron reaction with production of massive dilepton pair

$$\pi^-(P_\pi) + p(P_p, S_p) \to \gamma^*(q) + X \to \mu^-(l) + \mu^+(l') + X$$

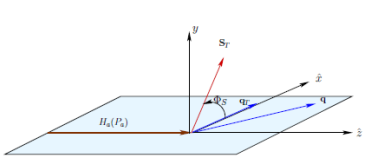
- DY and SIDIS: Excellent tool for accessing transversity $h_1^q$ and T-odd TMDs: Sivers $f_{1T}^\perp$ and Boer-Mulders $h_1^\perp$

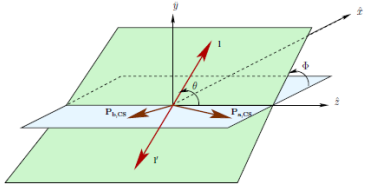


# Drell-Yan

$$\frac{d\sigma}{d^4q d\Omega} \propto \hat{\sigma}_U \left\{ \begin{array}{l} \left(1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}\right) \\ \pm |\overrightarrow{S_T}| \left[ \begin{array}{l} \left(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S}\right)\sin\varphi_S \\ + \sin 2\theta_{CS}\left(A_T^{\sin(\varphi_{CS}+\varphi_S)}\sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)}\sin(\varphi_{CS}-\varphi_S)\right) \\ + \sin^2\theta_{CS}\left(A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)\right) \end{array} \right] \end{array} \right\}$$

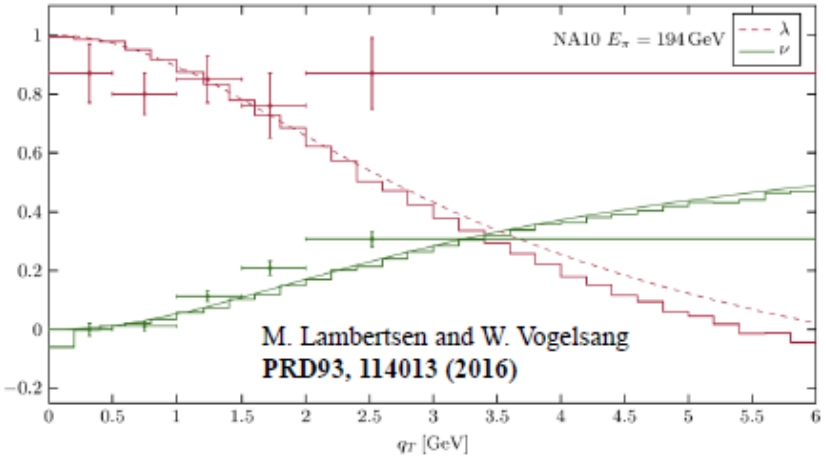
Drell-Yan cross-section in Collins-Soper frame





- unpolarised azimuthal modulations:

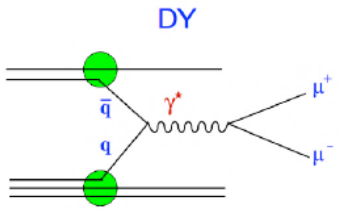
$\lambda = A^1_U, \mu = A_U^{\cos\phi}, \nu = = 2A_U^{\cos 2\phi}$



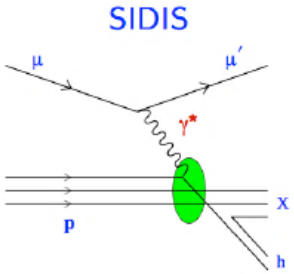
# Polarised Transverse-spin asymmetries

- Amplitudes in the cross-section can be obtained by means of azimuthal asymmetries between two transversely polarised parts of the target oppositely to each other

- $A_U^{\cos 2\phi}$: gives access to Boer-Mulders $h_1^{\perp}(\pi)$ a $h_1^{\perp}(p)$
- $A_T^{\sin\phi_s}$: to unpolarised PDF $f_1(\pi)$ a Sivers $f_{1T}^{\perp}(p)$
- $A_T^{\sin(2\phi+\phi_s)}$: to Boer-Mulders $h_1^{\perp}(\pi)$ and pretzelosity $h_{1T}^{\perp}(p)$
- $A_T^{\sin(2\phi-\phi_s)}$: to Boer-Mulders $h_1^{\perp}(\pi)$ and transverzity $h_1(p)$




# Drell-Yan vs. SIDIS




- *Fundamental QCD prediction based on TMD approach*: Due to their time-reversal odd nature Boer-Mulders and Sivers functions are expected to change sign when measured in SIDIS and Drell-Yan

$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right] \times \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{ 1 + \cos 2\phi_h \left(\varepsilon A_{UU}^{\cos 2\phi_h}\right) \right.$$

$$+ S_T \begin{bmatrix} \sin(\phi_h - \phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right) \\ + \sin(\phi_h + \phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right) \\ + \sin(3\phi_h - \phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right) \end{bmatrix}$$

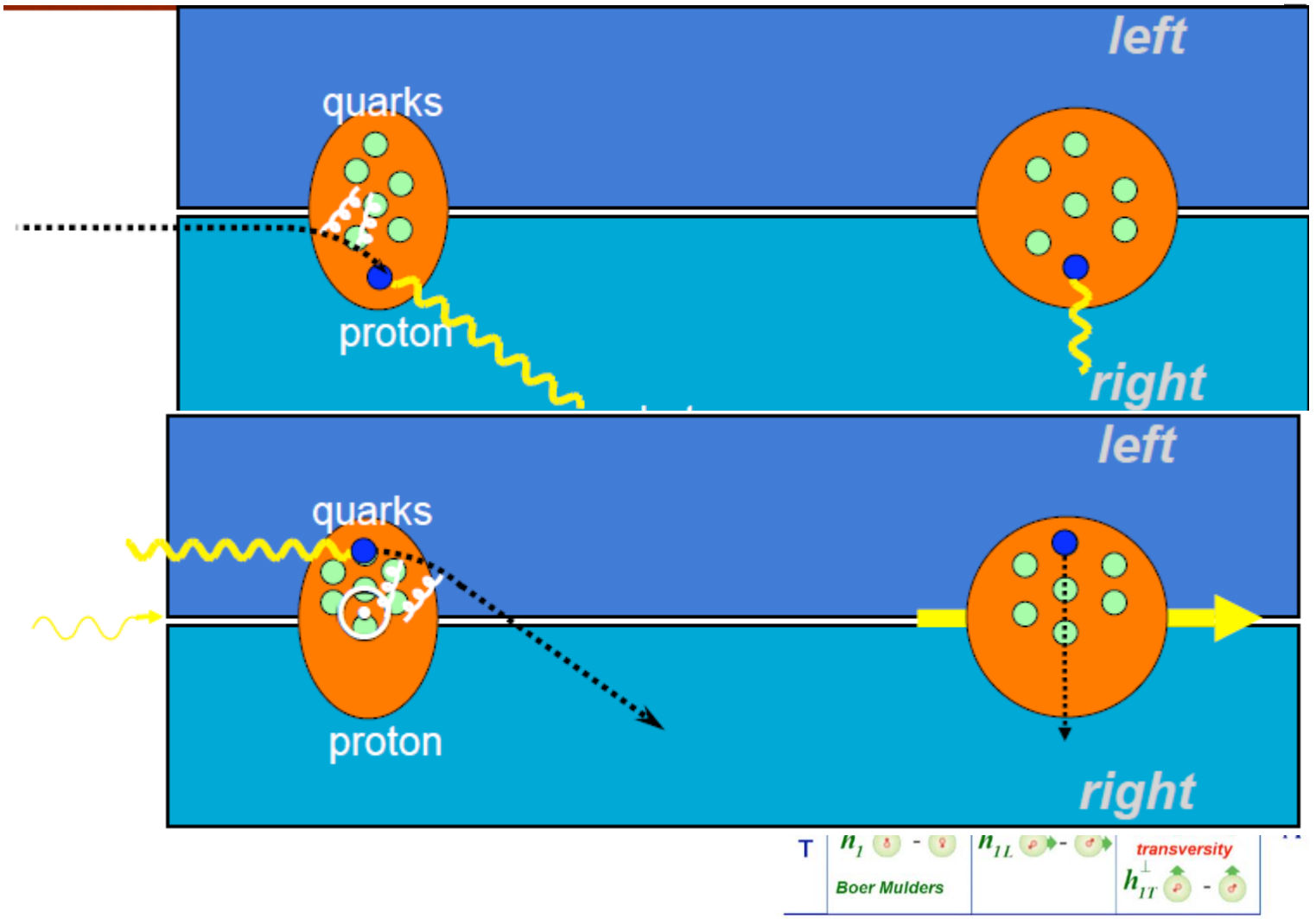
$$\left. + S_T \lambda \left[\cos(\phi_h - \phi_S)\left(\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right] \right\}$$

$h_1^{\perp q}$ — $f_{1T}^{\perp q}$ — $h_1^q$ — $h_{1T}^{\perp q}$ — $g_{1T}^q$

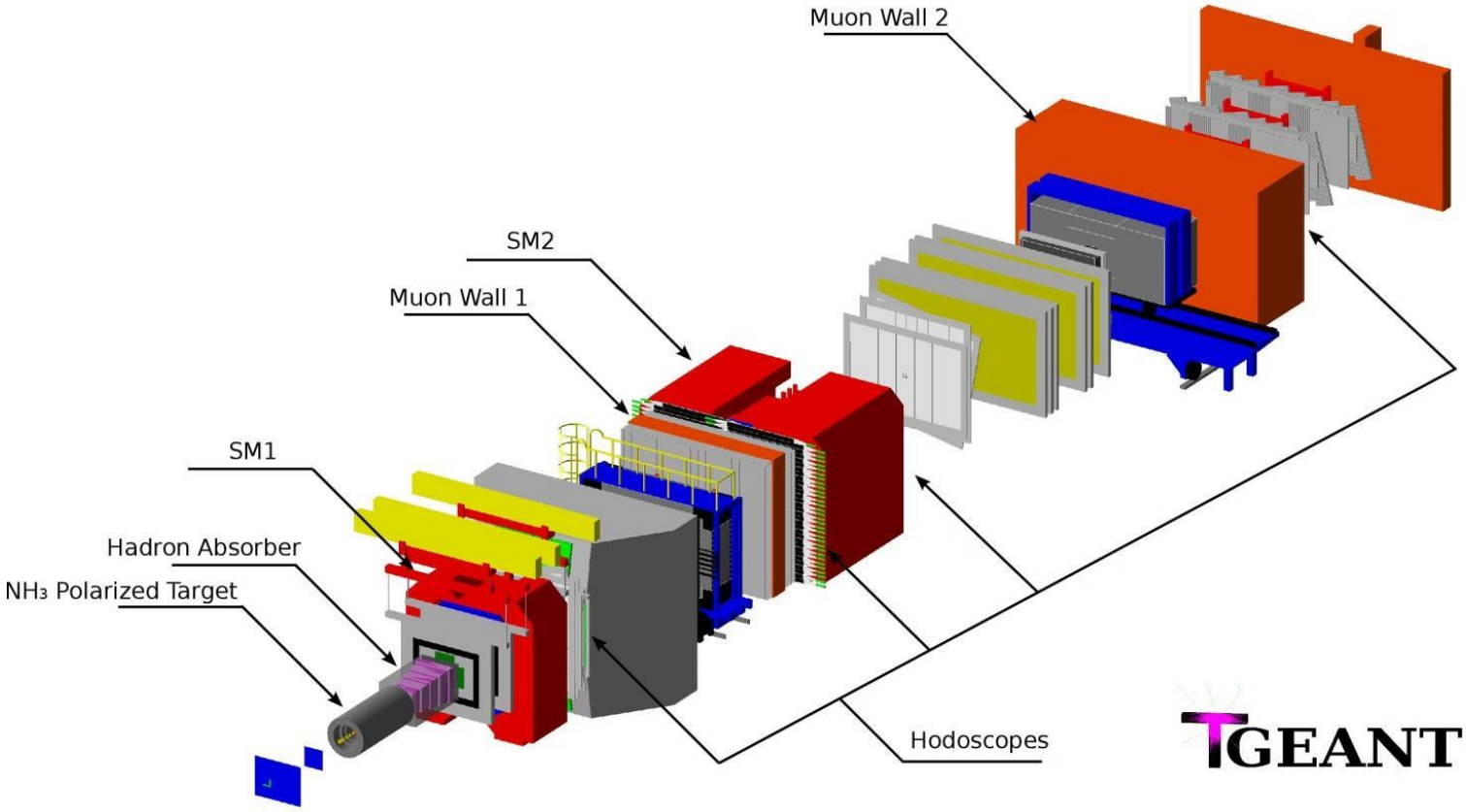
$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left\{ 1 + \cos^2\theta + \sin^2\theta \cos 2\varphi_{CS} A_U^{\cos 2\varphi_{CS}} \right.$$

$$\left. + S_T \begin{bmatrix} \left(1+\cos^2\theta\right)\sin\varphi_S A_T^{\sin\varphi_S} \\ + \sin^2\theta \begin{pmatrix} \sin(2\varphi_{CS}+\varphi_S) A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ + \sin(2\varphi_{CS}-\varphi_S) A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{pmatrix} \end{bmatrix} \right\}$$

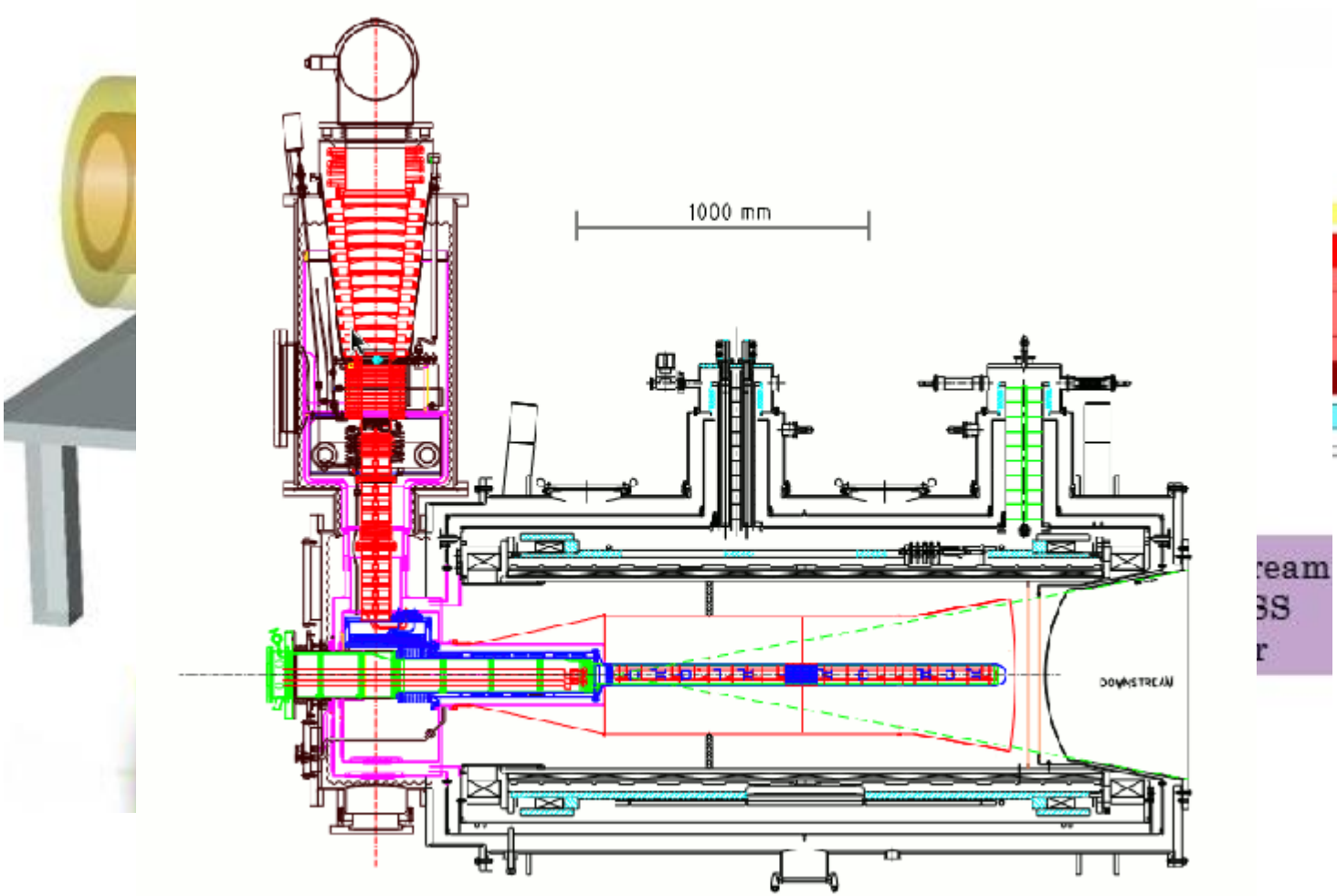
$$f_{1T}^{\perp q}\big|_{DY} = -f_{1T}^{\perp q}\big|_{SIDIS} \qquad h_1^q\big|_{DY} = -h_1^q\big|_{SIDIS}$$


left
quarks
proton
right
left
quarks
proton
right
T
$n_1$
Boer Mulders
$n_{1L}$
transversity
$h_{1T}^{\perp}$

# Experiment COMPASS



# Drell-Yan setup



# History of Drell-Yan measurements at COMPASS

- *2009*: 3-days test run, unpolarised polyethylen ($nCH_2$) target, hadron absorber
- *2014*: 2-months pilot run, unpolarised ammonia ($NH_3$) target, hadron absorber
- *2015* run: 27.4. - 15.11. data taking, polarised ammonia ($NH_3$) target, hadron absorber
  - Beam energy 190 GeV/$c^2$
  - Beam intensity ~$8 \times 10^7$/s
  - ~73% polarisation
  - Data sample after selections: ~35000 muon pairs for analysis

# DY mass ranges

1. Low mass range 1-2 GeV/$c^2$

-high DY cross-section + high combinational bg (open charm, open bottom)

2. Intermediate mass 2-2.5 GeV/$c^2$

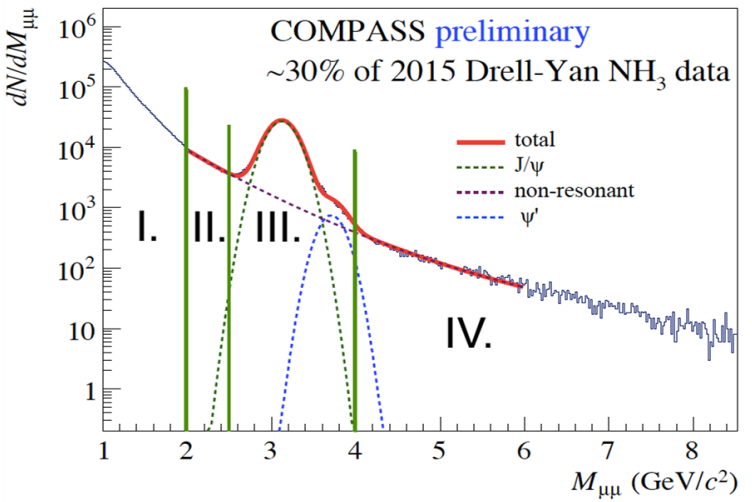
-high contamination of open charm and bg,

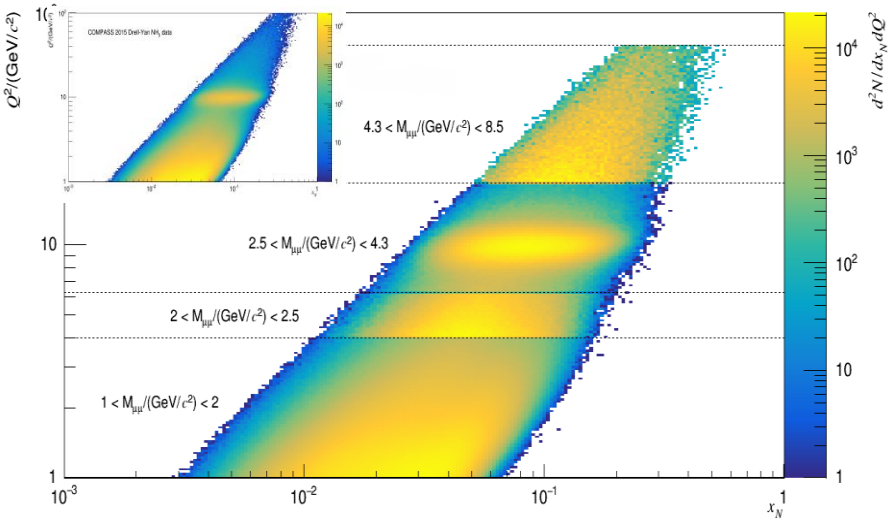
3. J/ψ range 2.5-4.3 GeV/$c^2$

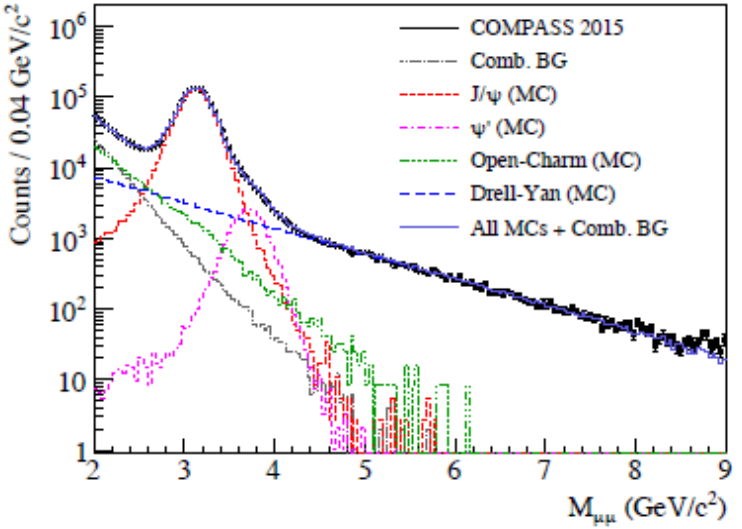
-J/ψ and ψ' peaks

4. High mass 4.3-8.5 GeV/$c^2$

-only 4% contamination of bg. and J/ψ

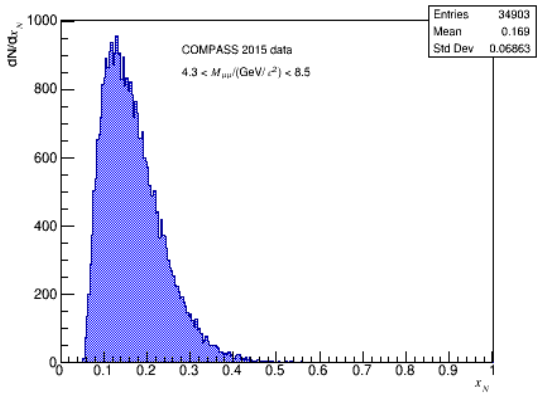


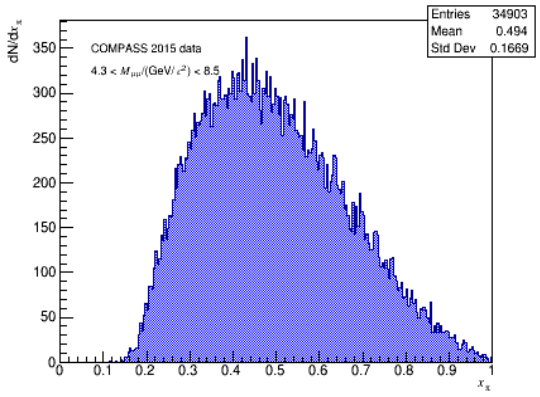



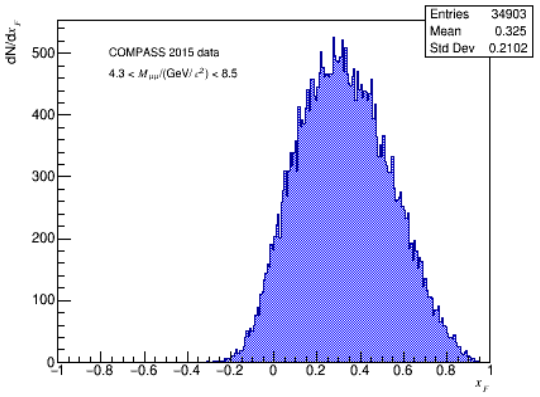



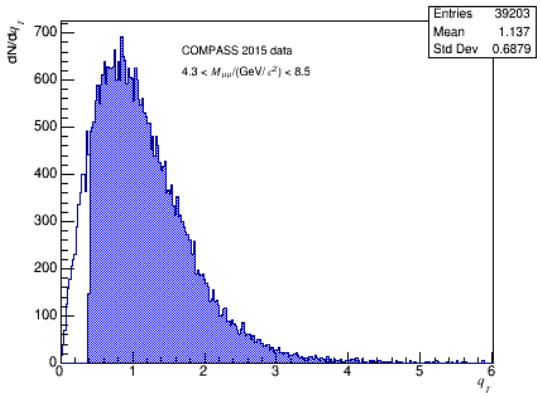
# 2015 kinematic distributions

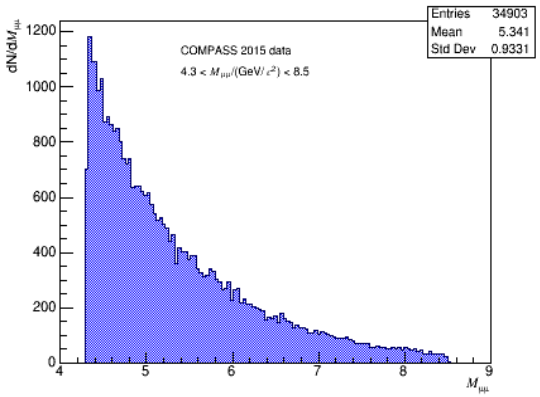
- Kinematic variables: $x_N$, $x_\pi$, $x_F$, $q_T$, $M$



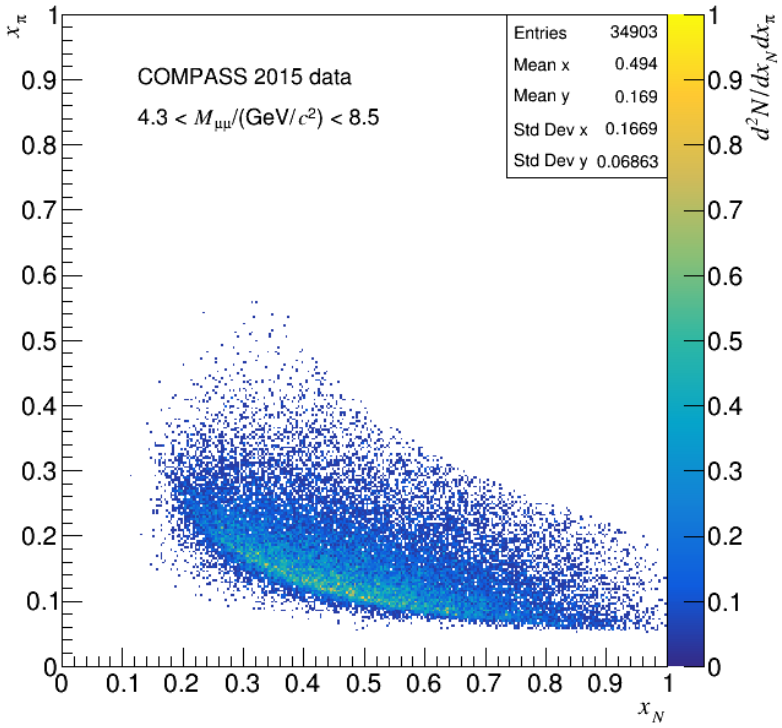



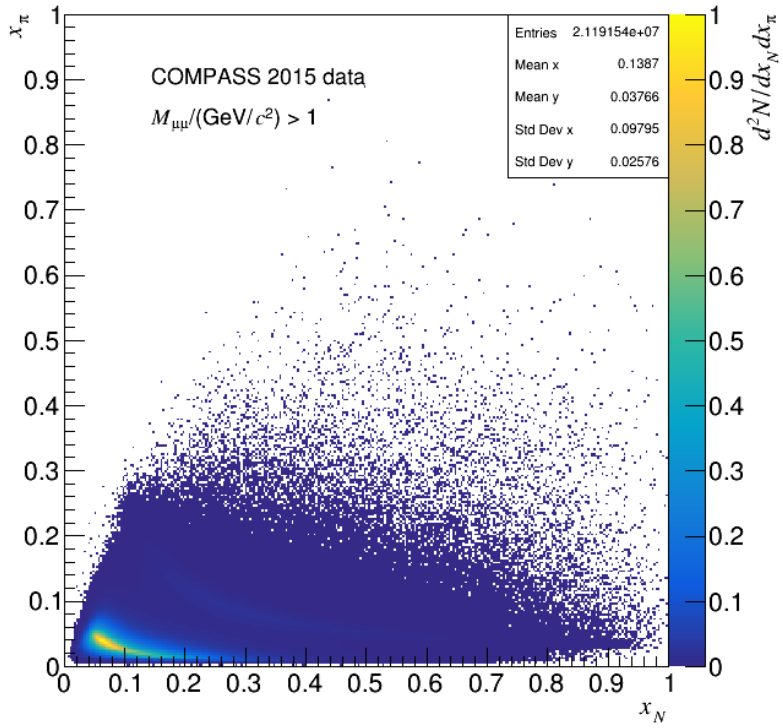



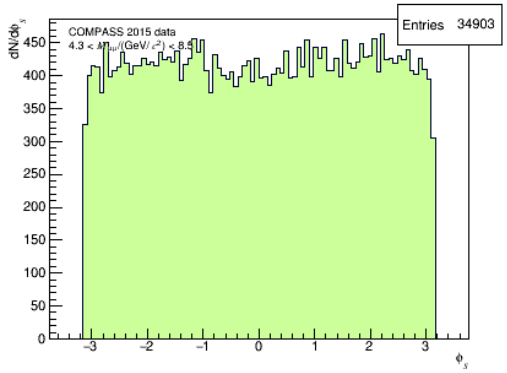



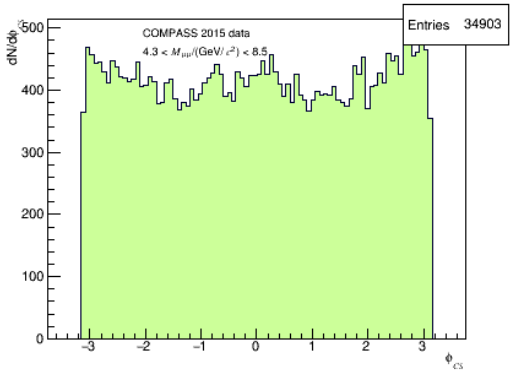
# DY HM phase-space

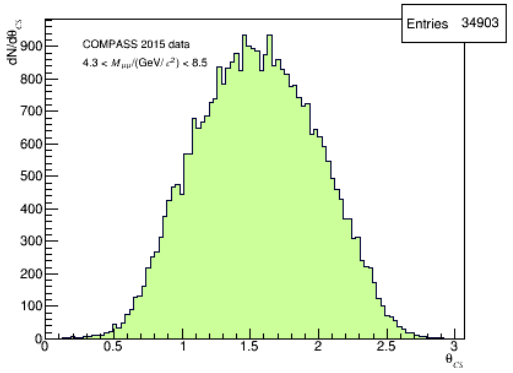


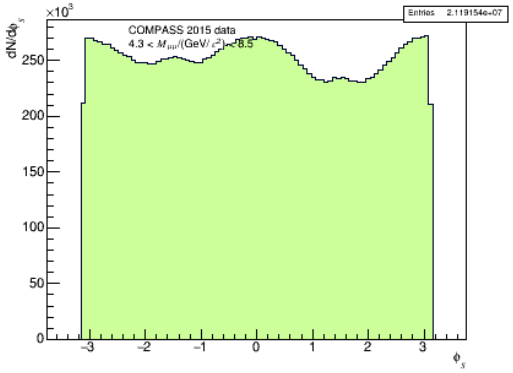



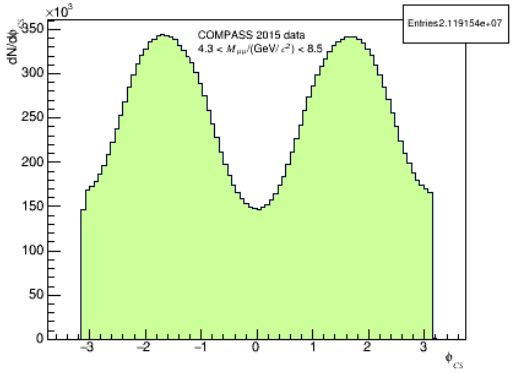
# Distribution of CS angles in HM

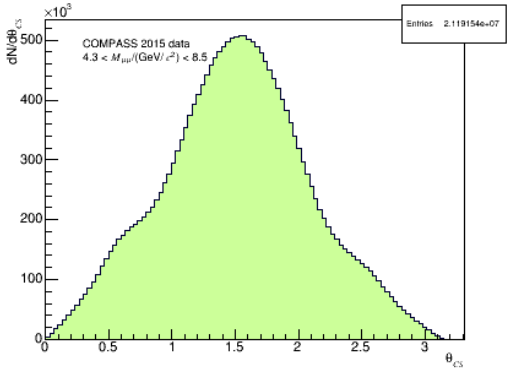


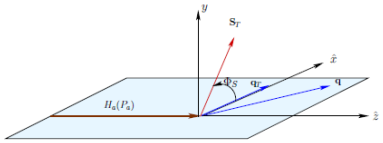



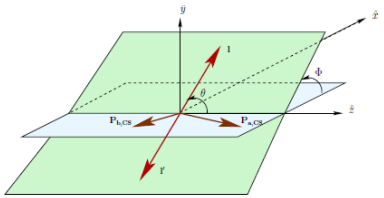





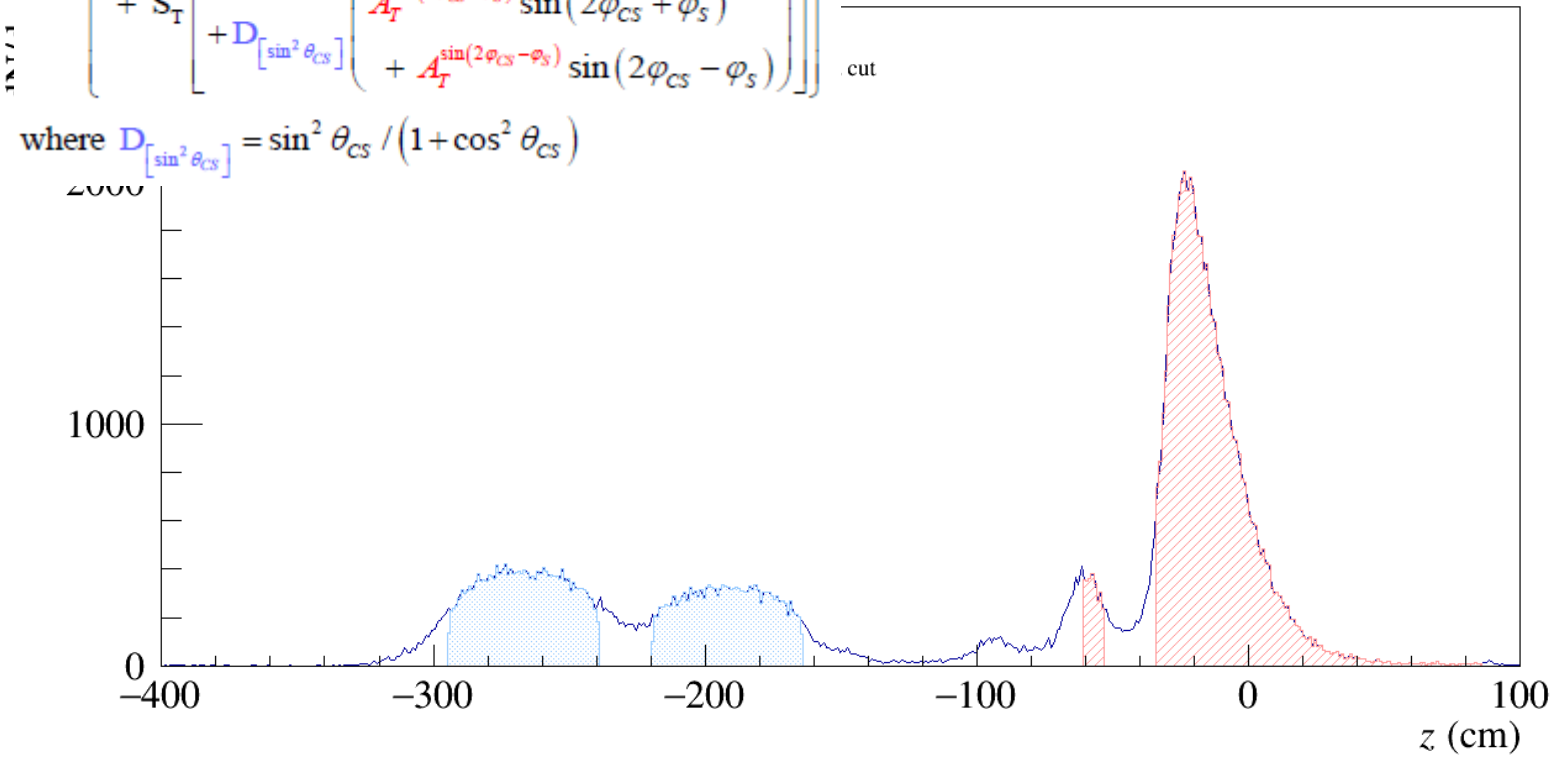
# Extraction of transverse-spin asymmetries

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

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

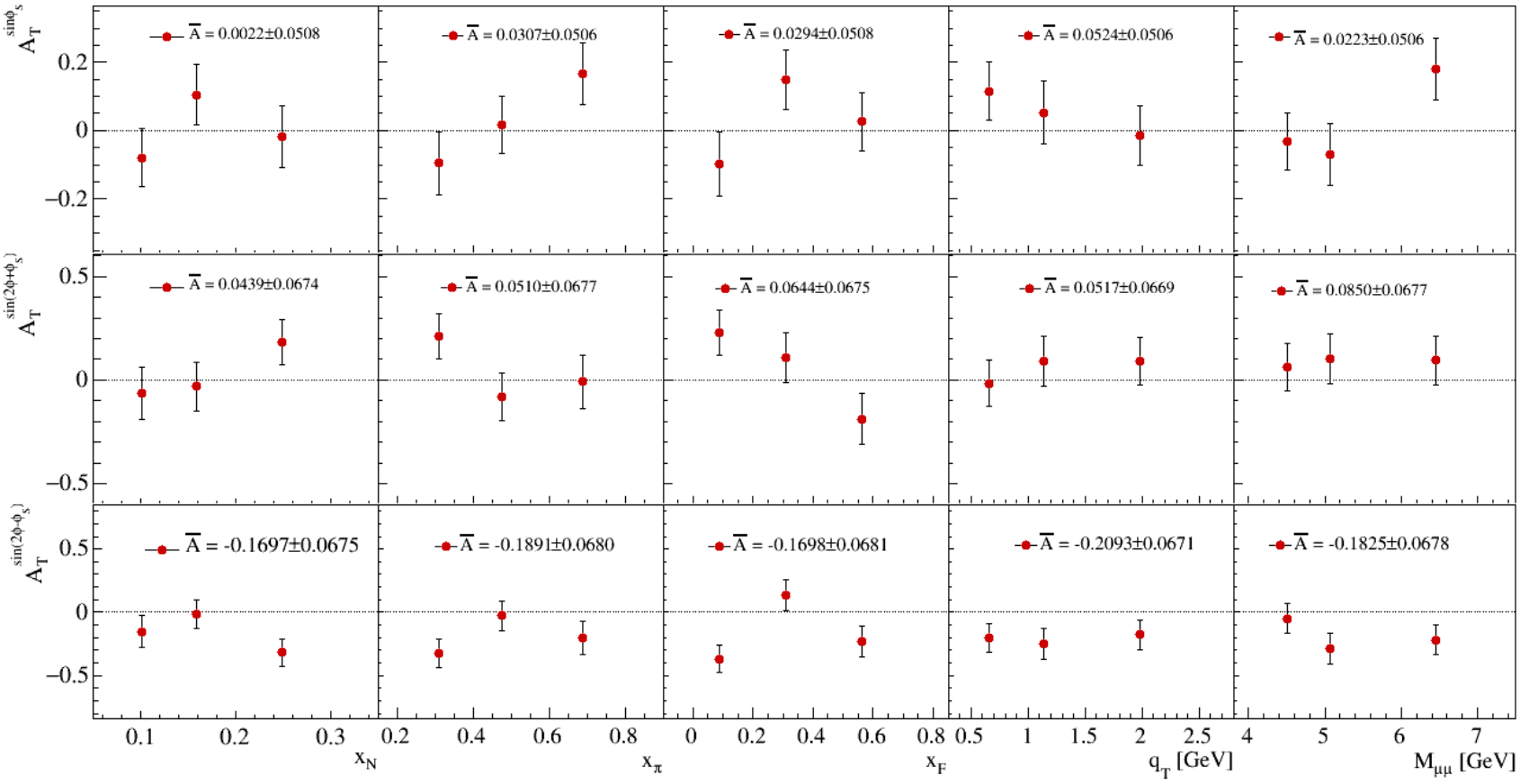
$$DR = \frac{N^{1\uparrow} N^{2\uparrow}}{N^{1\downarrow} N^{2\downarrow}}$$

cut



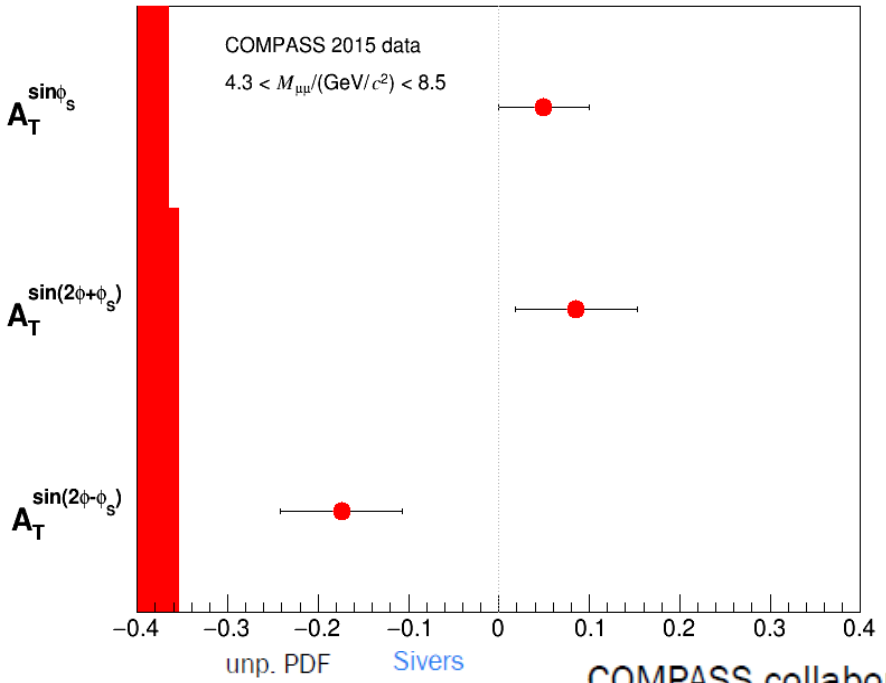
# Results for transverse-spin asymmetries

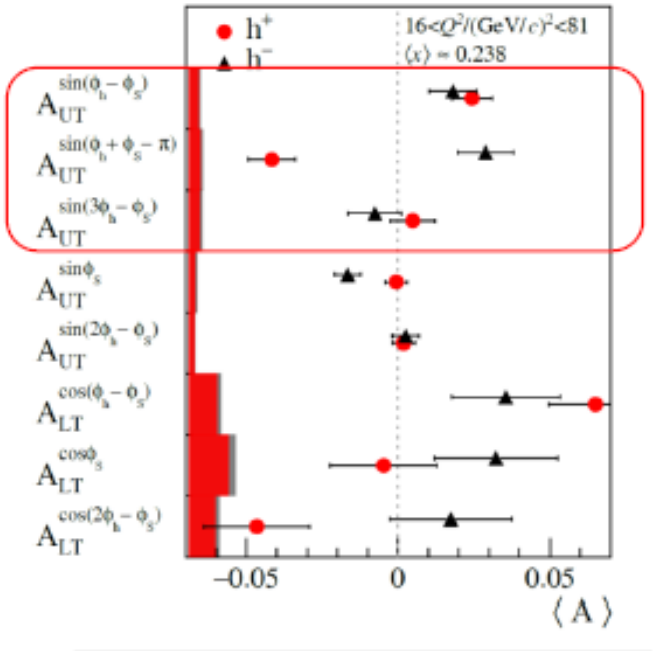
- Systematical error: $0.7 \cdot \sigma_{stat}$



# Integrated TSAs

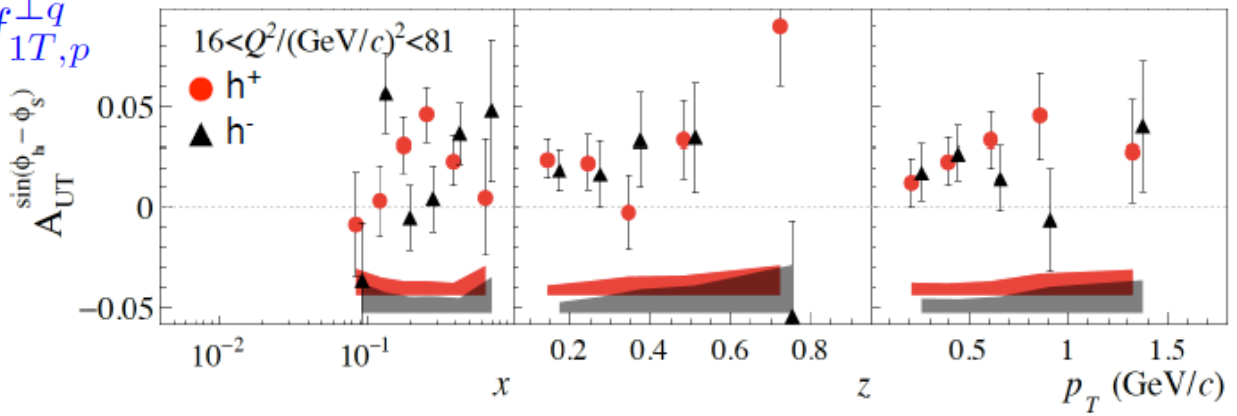
$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$




$$A_{UT}^{\sin(\phi s)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

COMPASS collaboration arXiv:1609.07374



# Conclusion

- In 2015 COMPASS collected the first sample of polarised Drell-Yan data
- Additional polarised DY measurement is planned for 2018
- Hint for sign change!

… Stay tuned ☺


# Thank you for your attention

- www.facebook.com/compasscern