# Results from (un)polarised Drell-Yan & J/$\psi$ measurements at COMPASS

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on behalf of the COMPASS Collaboration

University of Illinois at Urbana-Champaign

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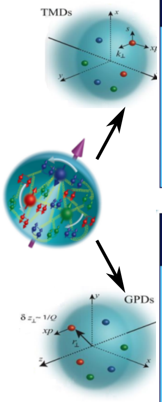
East-Lansing (Michigan)




| Nucleon Polarisation \ Quark Polarisation | Unpolarised (U) | Longitudinally polarised (L) | Tranversely polarised (T) |
|---|---|---|---|
| U | $f_1^q(x, \mathbf{k}_T^2)$ | | $h_1^{q\perp}(x, \mathbf{k}_T^2)$ |
| L | | $g_1^q(x, \mathbf{k}_T^2)$ | $h_{1L}^{q\perp}(x, \mathbf{k}_T^2)$ |
| T | $f_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ | $g_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ | $h_{1T}^q(x, \mathbf{k}_T^2)$ Transversity<br>$h_{1T}^{q\perp}(x, \mathbf{k}_T^2)$ Pretzelosity |

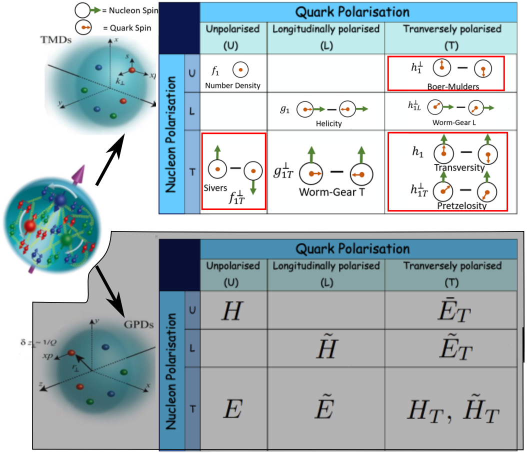
| Nucleon Polarisation \ Quark Polarisation | Unpolarised (U) | Longitudinally polarised (L) | Tranversely polarised (T) |
|---|---|---|---|
| U | $H$ | | $\bar{E}_T$ |
| L | | $\tilde{H}$ | $\tilde{E}_T$ |
| T | $E$ | $\tilde{E}$ | $H_T, \tilde{H}_T$ |

**Nucleon is a complex object**

Most comprehensive description provided by universal non perturbative functions:

- Transverse Momentum Dependent PDFs
- Generalised Parton Distributions

# Motivations




## Nucleon is a complex object

Most comprehensive description provided by universal non perturbative functions:

- Transverse Momentum Dependent PDFs
- Generalised Parton Distributions

**This talk: TMDs**

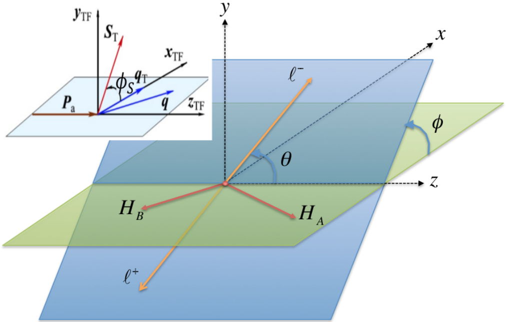
- 4 Chiral-even: $f_1$, $\mathbf{f_{1T}^\perp}$, $g_1$, $g_{1T}^\perp$
- 4 Chiral-odd: $\mathbf{h_1^\perp}$, $\mathbf{h_1}$, $\mathbf{h_{1T}^\perp}$, $h_{1L}^\perp$

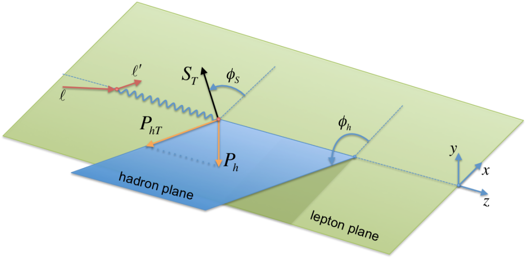
Accessible via:

$\Rightarrow$ SIDIS talk by C. Riedl for COMPASS results

$\Rightarrow$ **Drell-Yan muon-pair & J/$\psi$ production**

# Experimental access through azimuthal modulations




| DY: | | | | | SIDIS: | | | |
|---|---|---|---|---|---|---|---|---|
| $A_{UU}^{\cos(2\phi)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1,p}^{\perp q}$ | Boer-Mulders | $A_{UU}^{\cos(2\phi_h)}$ | $\propto h_{1,p}^{\perp q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |
| $A_{UT}^{\sin(\phi_S)}$ | $\propto f_{1,h}^{q}$ | $\otimes$ | $f_{1T,p}^{\perp q}$ | Sivers | $A_{UT}^{\sin(\phi_h-\phi_S)}$ | $\propto f_{1T,p}^{\perp q}$ | $\otimes$ | $D_{1q}^{h}$ |
| $A_{UT}^{\sin(2\phi-\phi_S)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1,p}^{q}$ | Transversity | $A_{UT}^{\sin(\phi_h+\phi_S)}$ | $\propto h_{1,p}^{q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |
| $A_{UT}^{\sin(2\phi+\phi_S)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1T,p}^{\perp q}$ | Pretzelosity | $A_{UT}^{\sin(3\phi_h-\phi_S)}$ | $\propto h_{1T,p}^{\perp q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |

# Synergy DY *vs* SIDIS on transversely polarised target

| DY: | | | | | SIDIS: | | | |
|---|---|---|---|---|---|---|---|---|
| $A_{UU}^{\cos(2\phi)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1,p}^{\perp q}$ | Boer-Mulders | $A_{UU}^{\cos(2\phi_h)}$ | $\propto h_{1,p}^{\perp q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |
| $A_{UT}^{\sin(\phi_S)}$ | $\propto f_{1,h}^{q}$ | $\otimes$ | $f_{1T,p}^{\perp q}$ | Sivers | $A_{UT}^{\sin(\phi_h-\phi_S)}$ | $\propto f_{1T,p}^{\perp q}$ | $\otimes$ | $D_{1q}^{h}$ |
| $A_{UT}^{\sin(2\phi-\phi_S)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1,p}^{q}$ | Transversity | $A_{UT}^{\sin(\phi_h+\phi_S)}$ | $\propto h_{1,p}^{q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |
| $A_{UT}^{\sin(2\phi+\phi_S)}$ | $\propto h_{1,h}^{\perp q}$ | $\otimes$ | $h_{1T,p}^{\perp q}$ | Pretzelosity | $A_{UT}^{\sin(3\phi_h-\phi_S)}$ | $\propto h_{1T,p}^{\perp q}$ | $\otimes$ | $H_{1q}^{\perp h}$ |

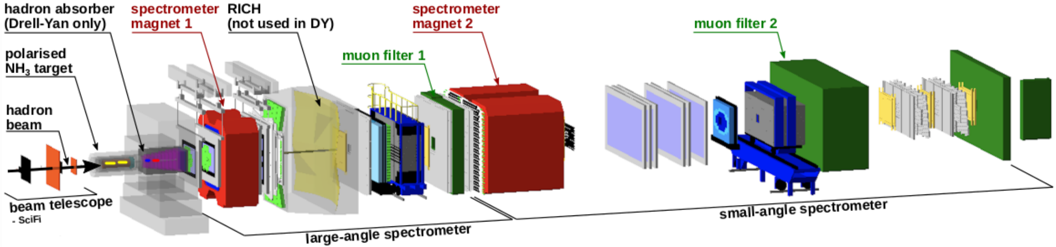
TMD PDFs are **universal** but
final state interaction (SIDIS) *vs.* initial state interaction (DY)
$\rightarrow$ **Sign flip** for naive T-odd TMD PDFs

$$h_{1,p}^{\perp q}|_{DY} = -h_{1,p}^{\perp q}|_{SIDIS} \qquad f_{1T,p}^{\perp q}|_{DY} = -f_{1T,p}^{\perp q}|_{SIDIS}$$

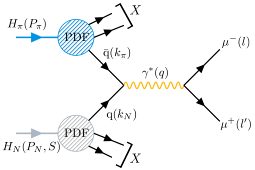
Crucial test of TMD framework in QCD which can be addressed by COMPASS

# COMPASS apparatus for polarised Drell-Yan measurements

NIMA 577 (2007) 455, NIMA 779 (2015) 69, NIMA 1025 (2022) 166069




Reaction:




Beam:

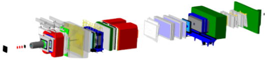
- 190 GeV/c $h^-$ beam, 97%$\pi^-$ and $I$ ~70MHz
- 160 GeV/c $\mu^\pm$

Key elements:

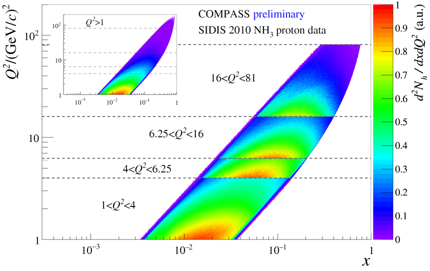
- $2 \times 55$cm $NH_3$ polarised target
- Al and W target (beam plug)
- 2.4m long hadron absorber
- $\sim$ 400 tracking planes
- 2 Muon filters

# Kinematic coverage

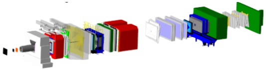
SIDIS on transversely polarised proton
COMPASS 2007, 2010



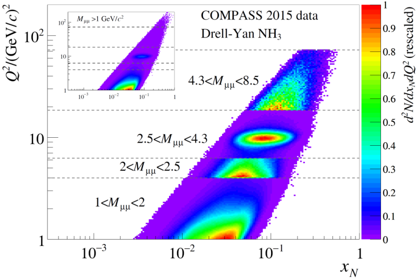
PLB 770 (2017) 138




Pion-induced transversely polarised Drell-Yan
COMPASS 2015, 2018



PRL 119 (2017) 112002




Similar $x$ & $Q^2$ coverage

$\Downarrow$

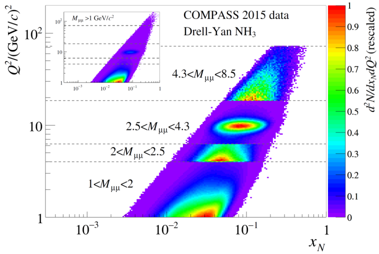
**minimisation** of $Q^2$ **evolution** effects in the comparison of the two processes

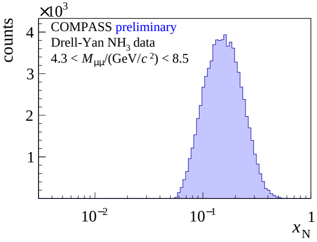
Unique conditions to test TMD universality

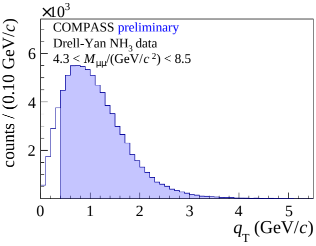
Restrict the analysis to $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

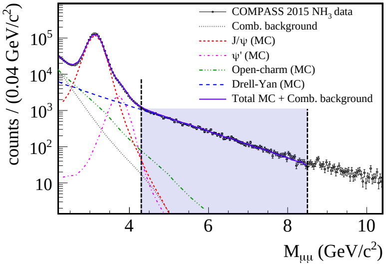
- Drell-Yan purity: 96%
- Probing $\langle x_N \rangle \sim 0.17$: $u$-quark dominance
- $q_T > 0.4$ (GeV/$c$) for angular resolution, $\langle q_T \rangle = 1.17$ (GeV/$c$)
- but low cross-section

PRL 119 (2017) 112002



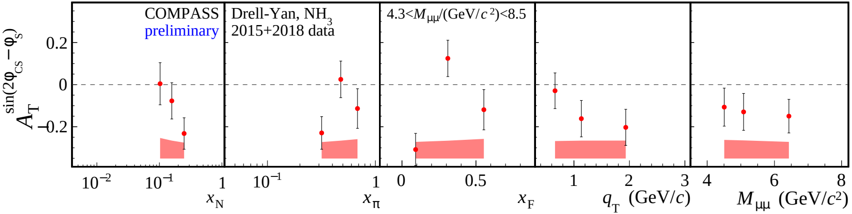



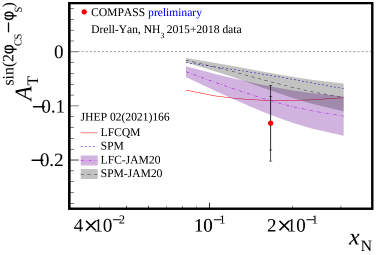



# High mass Drell-Yan region: Transversity

$A^{\sin(2\phi_{CS}-\phi_S)} \propto h_{1,\pi}^{\perp} \otimes h_{1,p}$ Boer-Mulders⊗Transversity



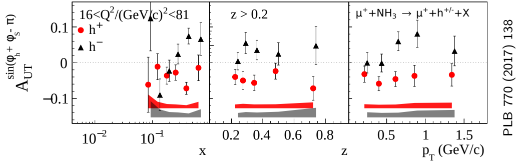

No significant kinematic dependence

Overall negative with $\sim 1.5\sigma$ significance

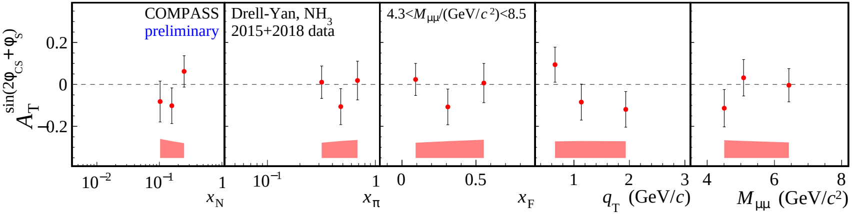
In agreement with model predictions

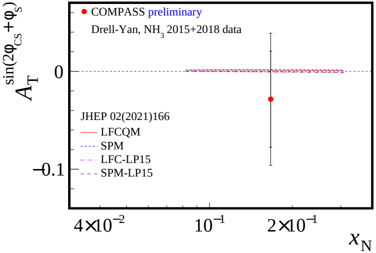
Additional scale uncertainty $\sim$ 10% not shown due to dilution factor, $A_U^1 = 1$ & polarisation

$A^{\sin(\phi_h+\phi_S-\pi)} \propto h_{1,p} \otimes H_1^{\perp,h}$ Transversity⊗ Collins FF



$A^{\sin(2\phi_{CS}+\phi_S)} \propto h_{1,\pi}^{\perp} \otimes h_{1T,p}^{\perp}$ Boer-Mulders⊗Pretzelosity



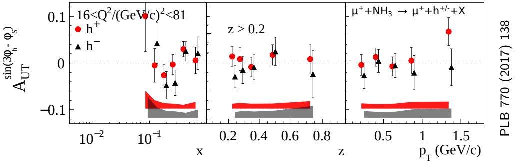

No visible kinematic dependence

Compatible with zero

In agreement with model prediction for very small signal

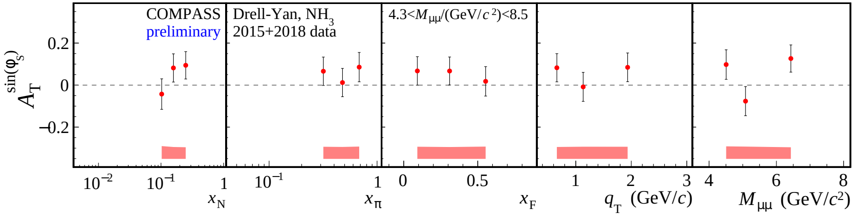
Additional scale uncertainty ∼ 10% not shown due to dilution factor, $A_U^1 = 1$ & polarisation

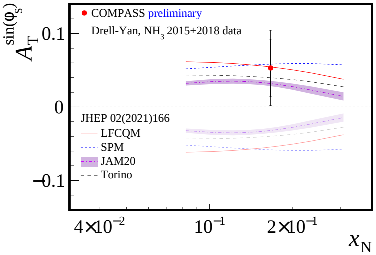
$A^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp} \otimes H_1^{\perp,h}$ Pretzelosity⊗ Collins FF



# High mass Drell-Yan region: Sivers

$A^{\sin(\phi_S)} \propto f_{1,\pi} \otimes f_{1T,p}^{\perp}$   Number density$\otimes$Sivers



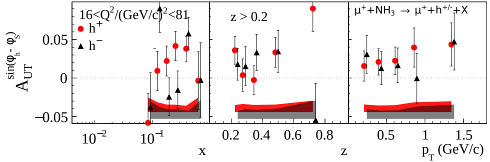

No significant kinematic dependence

Overall positive with $\sim 1\sigma$ significance

**Favours sign change scenario**

Additional scale uncertainty $\sim$ 10% not shown due to dilution factor, $A_U^1 = 1$ & polarisation

$A^{\sin(\phi_h - \phi_S)} \propto f_{1T,p}^{\perp} \otimes D_1^h$ Sivers$\otimes$ unpolarised FF




PLB 770 (2017) 138

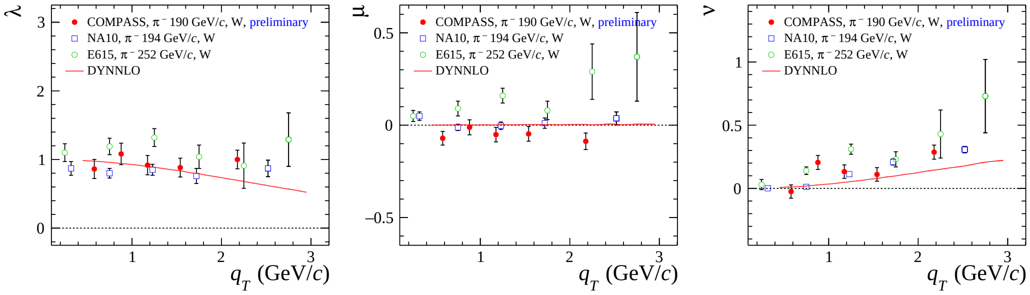
General expression for spin independent cross-section:

$$\frac{dN}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2(\theta_{CS})+\mu\sin(2\theta_{CS})\cos(\phi_{CS})+\frac{\nu}{2}\sin^2(\theta_{CS})\cos(2\phi_{CS})\right)$$

where $\lambda = A_U^1$, $\mu = A_U^{cos(\phi_{CS})}$ and $\nu = 2A_U^{cos(2\phi_{CS})} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$

In naive Drell-Yan: LO (pure electromagnetic) and no $k_T$: $\lambda = 1, \mu = \nu = 0$

Preliminary 2018 data results, systematic uncertainty (not shown) similar to the statistical ones




- Large effect from higher order corrections
- Hint for non-zero Boer-Mulders effect

# Lam-Tung relation

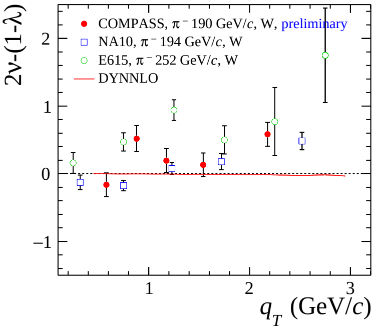
C.S. Lam and W.K. Tung, PRD18 (1978) 2447

Analog of DIS Callan-Gross relation for Drell-Yan:

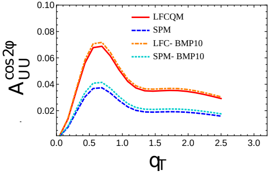
$$2\nu = 1 - \lambda$$

- Reflect the spin 1/2 of the quarks
- Less affected by first order QCD corrections

Preliminary systematic uncertainty (not shown) similar to the statistical ones




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

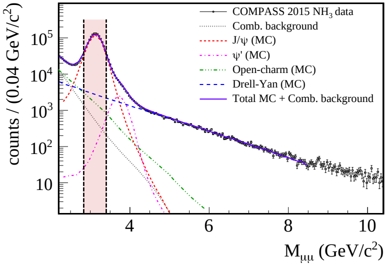


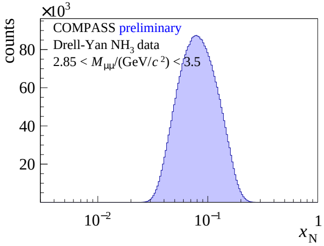

- Consistent with results obtained by past pion-induced Drell-Yan experiments
- Preliminary results indicate a possible violation of Lam-Tung relation
- This leaves some room for Boer-Mulders effects: $2\nu - (1-\lambda) \approx 4A_U^{cos(2\phi_{CS})}$

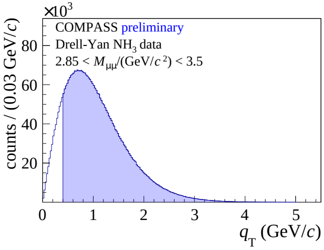
# J/$\psi$ region

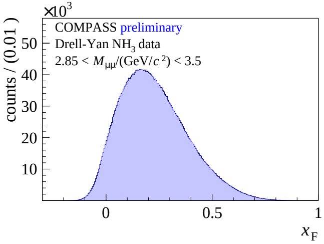
Restrict the analysis to $2.85 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 3.4$

- Larger cross-section $\rightarrow \sim 30\times$ more data compared to high-mass Drell-Yan region
- J/$\psi$ purity: 92%
- Probing $\langle x_N \rangle \sim 0.09$: $\approx$valence domain
- $q_T > 0.4$ (GeV/$c$) for angular resolution, $\langle q_T \rangle = 1.05$ (GeV/$c$)



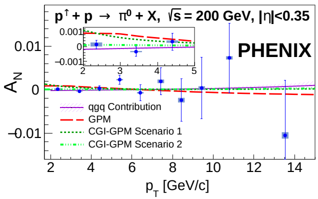



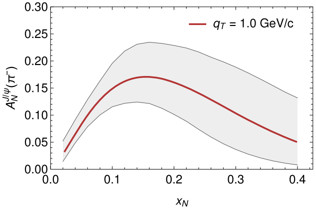
- TSA of $\pi^0$ production at PHENIX leaves small room for gluon Sivers effects
- Assuming $q\bar{q}$ dominance
  neglecting feed-down $J/\psi$ contribution

  $\Rightarrow$ **Large signal expected**

PHENIX, PRD 103 (2021) 052009




Anselmino, *et al.* PLB 770 (2017) 302

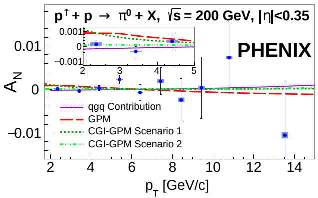


# Expectations for Sivers effects in J/$\psi$

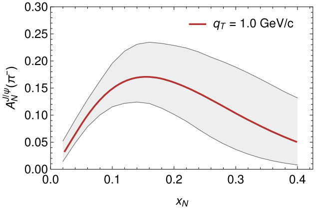
- TSA of $\pi^0$ production at PHENIX leaves small room for gluon Sivers effects
- Assuming $q\bar{q}$ dominance
  neglecting feed-down J/$\psi$ contribution

  $\Rightarrow$ **Large signal expected**

PHENIX, PRD 103 (2021) 052009

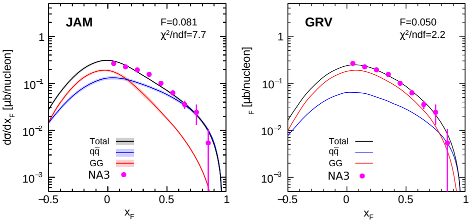



Anselmino, *et al.* PLB 770 (2017) 302

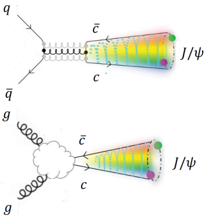



W.-C. Chang *et al.*, PRD 102 (2020) 054024
J. Badier *et al.* (NA3), Z. Phys. C 20 (1983) 101

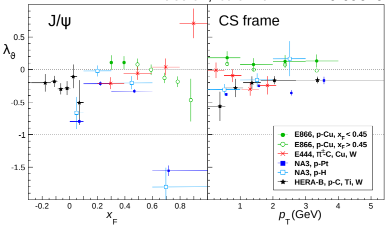
$\pi^-$+p at 200 GeV/c, NLO CEM




GG:$q\bar{q}$ $\sim$30:70 at $x_F \sim 0.3$ GG:$q\bar{q}$ $\sim$70:30 at $x_F \sim 0.3$




Faccioli, *et al.* arXiv:2210.09845



# TSA for $J/\psi$

No significant kinematic dependence

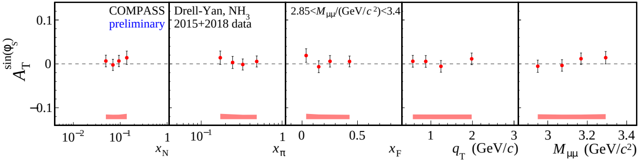
All TSA are compatible with zero

Additional scale uncertainty $\sim$ 10% not shown due to dilution factor, $A_U^1 = 0$ & polarisation

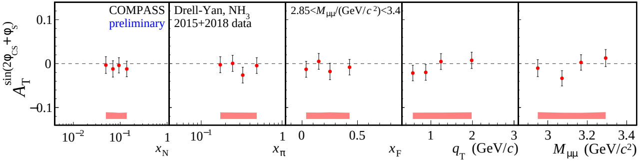
In favour of large gluon dilution

Parallel analyses ongoing on unpolarised angular distribution and absolute cross-section to provide further insights

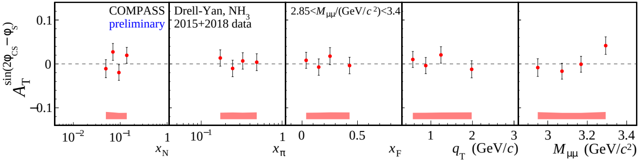
Number density⊗Sivers




Boer-Mulders⊗Pretzelosity




Boer-Mulders⊗Transversity



# Cold nuclear effects

- Two nuclear targets: Al & W
- Two complementary processes: DY and $J/\psi$

$\Downarrow$

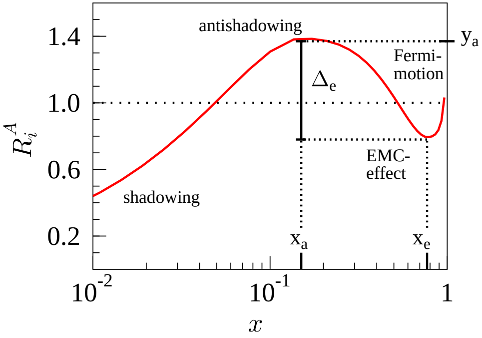
- Constrain nPDF ($x_{target}$)
- Cronin effects ($p_T$)
- Parton energy loss ($x_{beam}$)

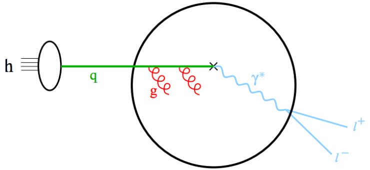
We measure the nuclear modification factor:

$$R^{J/\psi}_{\pi^- A}(W/Al) = \frac{A_{Al}}{A_W}\frac{\sigma^{J/\psi}_{\pi^- W}}{\sigma^{J/\psi}_{\pi^- Al}}$$

Al: ~80 k $J/\psi$ & W: ~600 k $J/\psi$

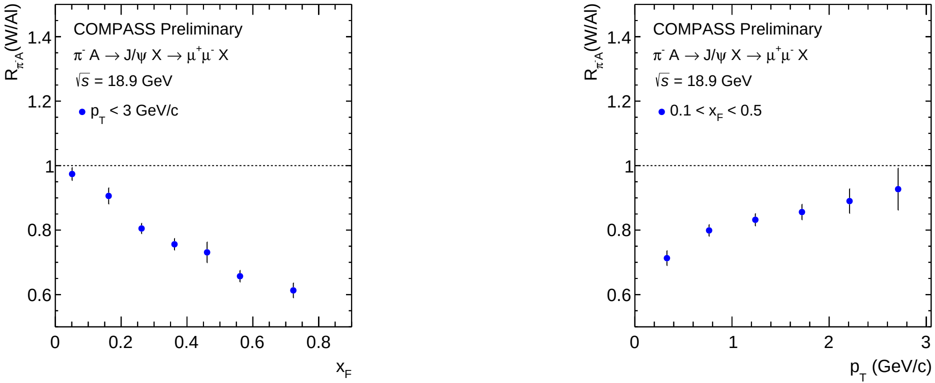
Kari J. *et al.* JHEP 07 (2008) 102



# Results of nuclear modification factor

Ongoing analysis, preliminary systematic uncertainties $\leq 10\%$ (not shown)

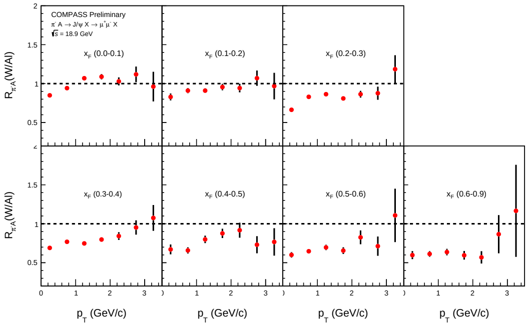



- Similar effects as observed by past experiments, *e.g* NA03 Z.Phys.C20 (1983) 101
- Strong suppression towards large $x_F$ (*i.e* low $x_{target}$ and large $x_{beam}$)
- Increase with $p_T$ due Cronin effect

# Nuclear modification factor in 2 dimensions

To better desentangle the various nuclear effects, the analysis is performed as a function of $x_F$ and $p_T$

Systematics uncertainty not shown: $\lesssim 10\%$




Potentially more prominent suppression towards high $x_F$ at low $pT$

Additional insights compared to past experiments

# Conclusion and Outlook

- ⇒ Final TSA results from Drell-Yan process were shown
  Sivers asymmetry is measured 1-sigma positive, in favour of a sign change
  Results to be published this year
- ⇒ Preliminary TSA results from J/$\psi$ production are all compatible with zero
- ⇒ Preliminary unpolarised azimuthal asymmetries in Drell-Yan from W target leave some room for Boer-Mulders effects
- ⇒ Preliminary results of $R_{\pi A}(Al/W)$ for J/$\psi$ production in $(x_F, p_T)$ were shown and can serve to constrain nuclear effects

Many ongoing analyses with new results expected soon: DY cross-section, DY cross-section ratio, J/$\psi$ cross section and angular dependence ...

Stay tuned

# BACKUP