Probing transverse-spin-dependent nucleon structure in pion-induced dimuon production at COMPASS

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On behalf of the COMPASS Collaboration

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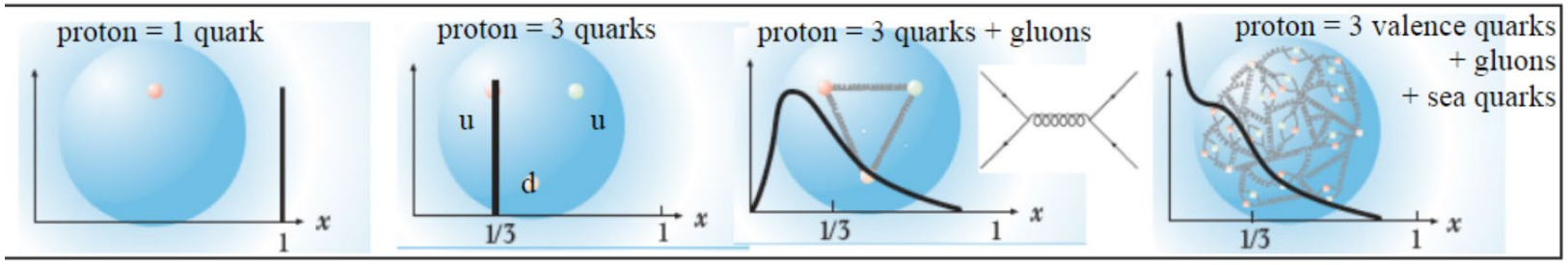
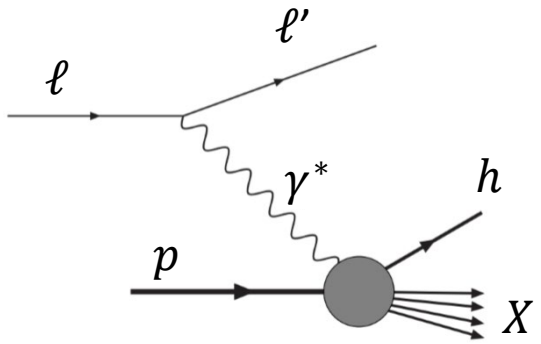
Scattering Experiments Used to Probe Nucleon Substructure

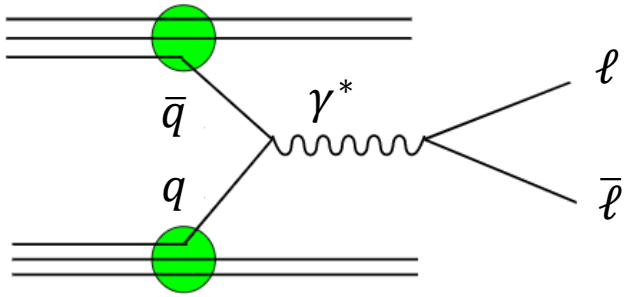
- In the infinite momentum frame of a scattering experiment, nucleon constituents appear to the incoming beam to be free, independent partons
- Each parton carries a fraction of the longitudinal momentum of the nucleon, described by the Bjorken x variable



- Examples of scattering processes must be used to probe transverse-momentum dependence:



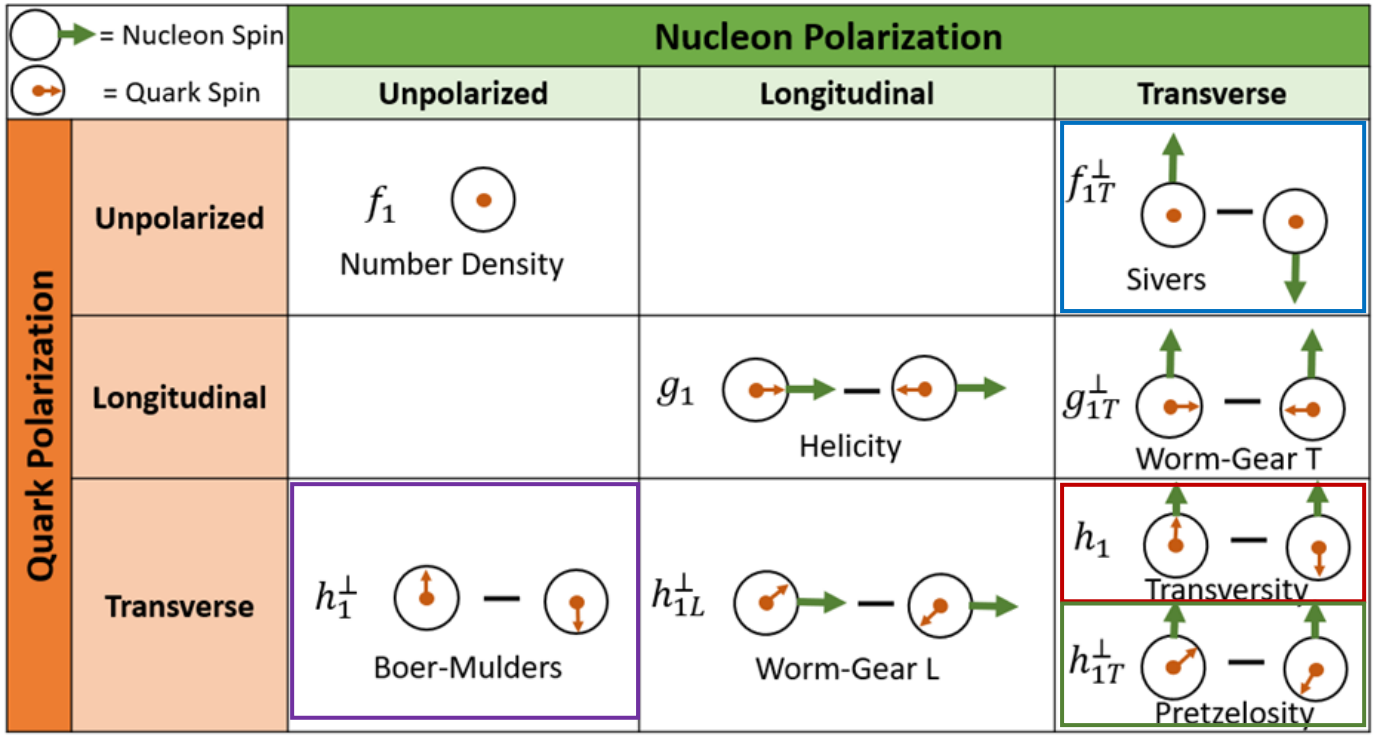
Semi-Inclusive Deep Inelastic Scattering (SIDIS) – Lepton scatters off hadron, one or more outgoing hadrons are measured



Drell-Yan (DY) – quark and antiquark annihilate into a virtual photon, which decays into two leptons

Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs)

Leading twist TMD PDFs describe correlations among the transverse momentum of partons and the polarization of the partons and/or parent nucleon



Quark TMD PDFs that can be extracted from the DY and SIDIS cross-sections:

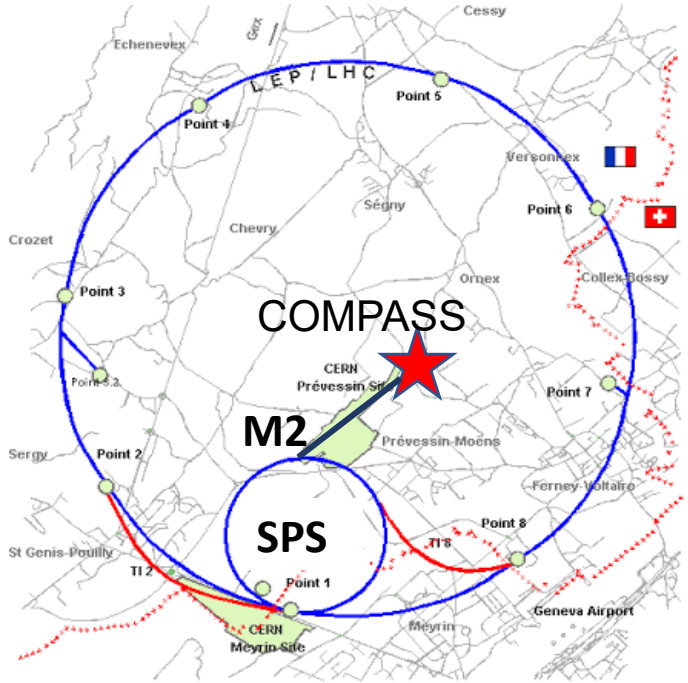
- **Boer-Mulders** – relates spin and transverse momentum of quark in unpolarized nucleon
- **Sivers** – relates transverse momentum of unpolarized quark and transverse polarization of nucleon

-> Predicted to be time-reversal odd and so have opposite sign in SIDIS vs Drell-Yan

- **Transversity** – relates transverse polarization of quark and transverse polarization of nucleon
- **Pretzelosity** – relates transverse momentum of transversely polarized quark and transverse polarization of nucleon

-> Predicted to be time-reversal even and so be process-independent

COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS)



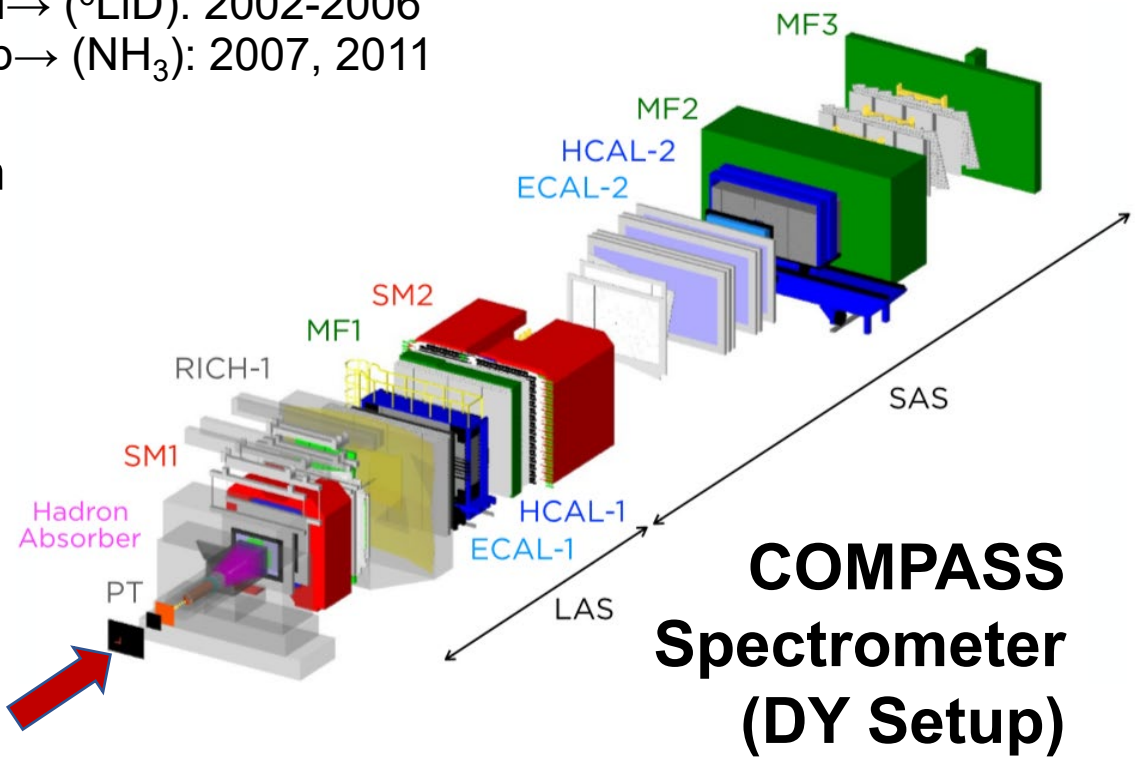
- Fixed target experiment in North Area of CERN
- Beam comes from M2 beam line, originating from the SPS

COMPASS runs with polarized target:

- SIDIS – 160/200 GeV polarized muon beams
  - d↑ (^{6}LiD): 2002-2004, d→ (^{6}LiD): 2002-2006
  - p↑ (NH_3): 2007, 2010, p→ (NH_3): 2007, 2011
  - d↑ (^{6}LiD): 2021-2022
- DY – 190 GeV pion beam
  - p↑ (NH_3): 2015, 2018

During DY runs:

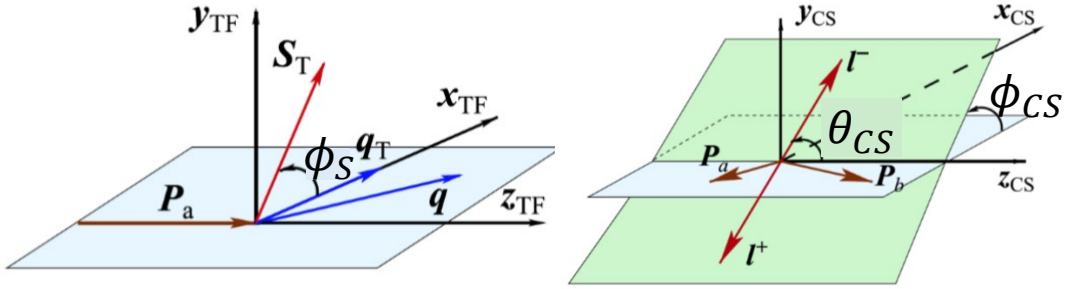
- 2 target cells filled with solid state NH_3
- Protons in each cell polarized in opposite directions
- Polarization flipped periodically to minimize effects of luminosity and acceptance



COMPASS Spectrometer (DY Setup)

Azimuthal asymmetries extracted to probe TMD PDFs

Single-polarized DY Cross-section (at leading twist) in terms of azimuthal asymmetries:



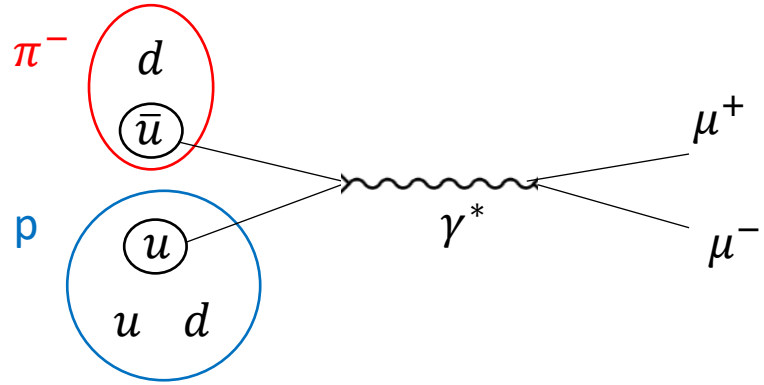
$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \left\{1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos(2\phi_{CS})} \cos(2\phi_{CS}) + S_T \left[A_T^{\sin(\phi_S)} \sin(\phi_S) + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\phi_{CS}+\phi_S)} \sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)} \sin(2\phi_{CS}-\phi_S) \right) \right]\right.$$

- Unpolarized Asymmetry (UA) : $A_U^{\cos(2\phi_{CS})}$ ~ proton Boer-Mulders ⊗ pion Boer-Mulders
- Transverse Spin Asymmetries (TSAs):

$A_T^{\sin(\phi_S)}$ ~ proton Sivers ⊗ pion unpolarized PDF

$A_T^{\sin(2\phi_{CS}+\phi_S)}$ ~ proton Pretzelosity ⊗ pion Boer-Mulders

$A_T^{\sin(2\phi_{CS}-\phi_S)}$ ~ proton Transversity ⊗ pion Boer-Mulders



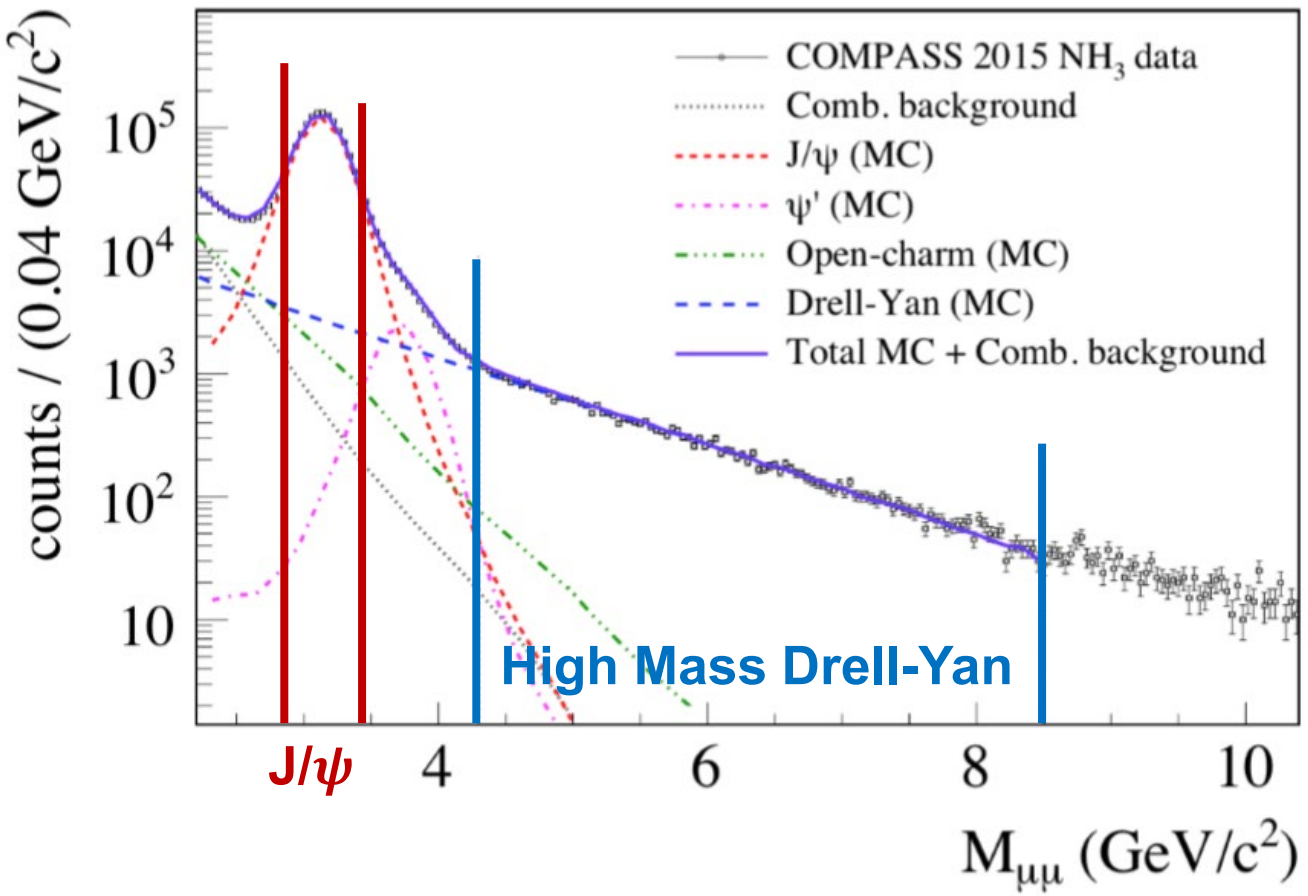
Note: negative pion-induced DY probes valence u-quark PDFs of the proton

Dimuon Mass Distribution

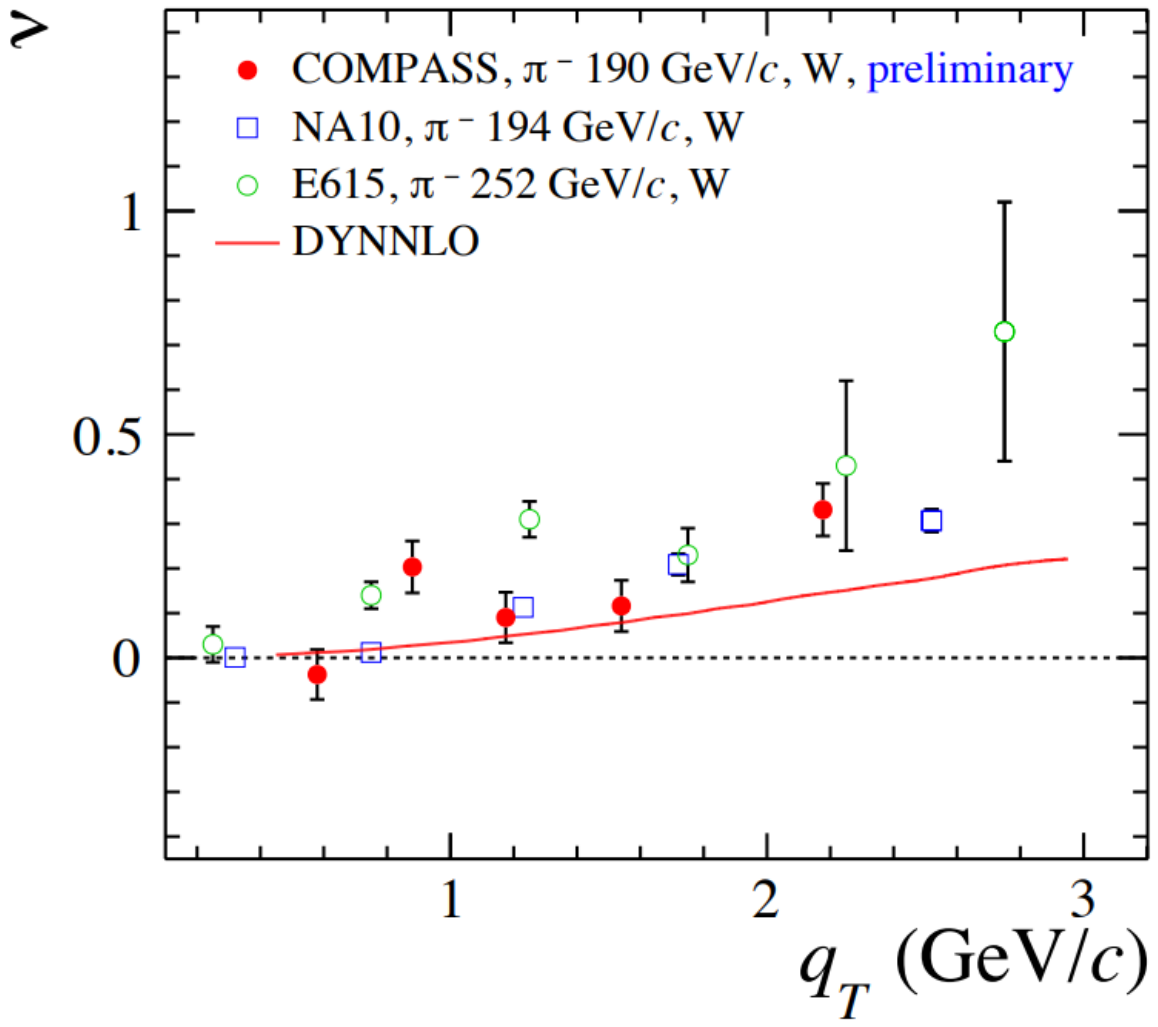
- COMPASS data contains dimuons from DY scattering as well as meson decay and combinatorial background

- **'High mass'** region used in DY analysis:
  - **4.3 GeV/c^2 < $M_{\mu\mu}$ < 8.5 GeV/c^2**
  - ~96% pure

- **J/ψ** mass region (used in ongoing J/ψ analysis):
  - > 90% purity



COMPASS DY Boer-Mulders result

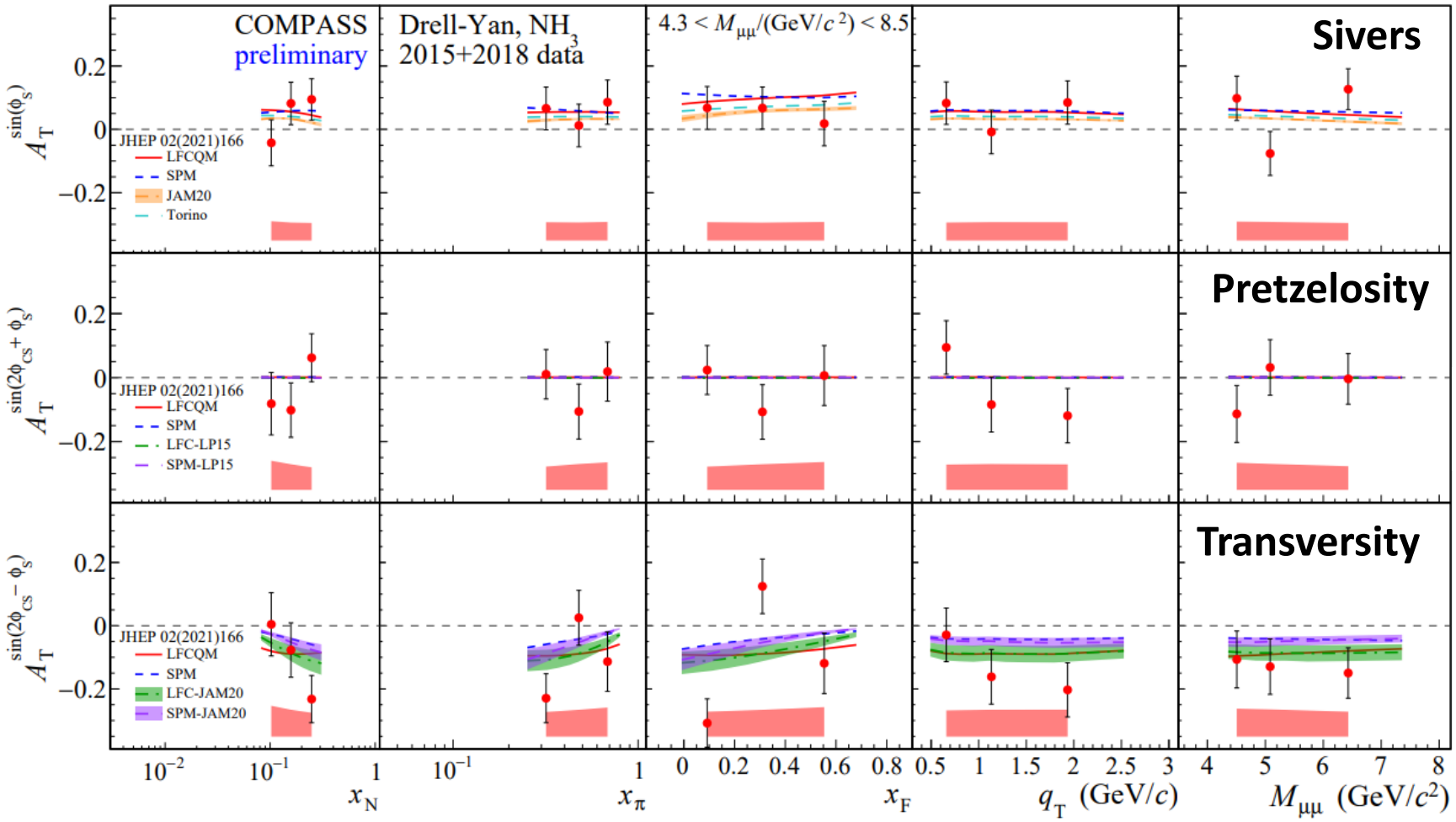


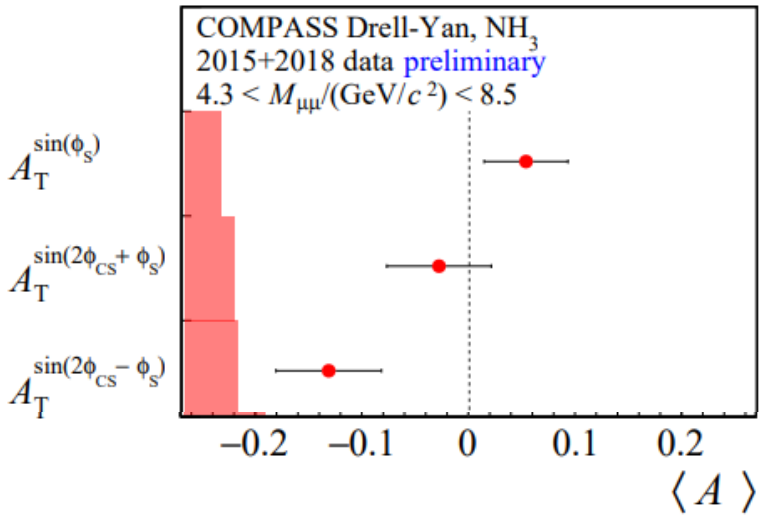
- Unpolarized asymmetry

$$\nu = 2A_U^{\cos(2\phi_{CS})}$$

- Experimental results hint that there may be non-zero Boer-Mulders effects

New COMPASS DY TSA Results (full 2015+2018 data sample)





Sivers ~1σ above zero

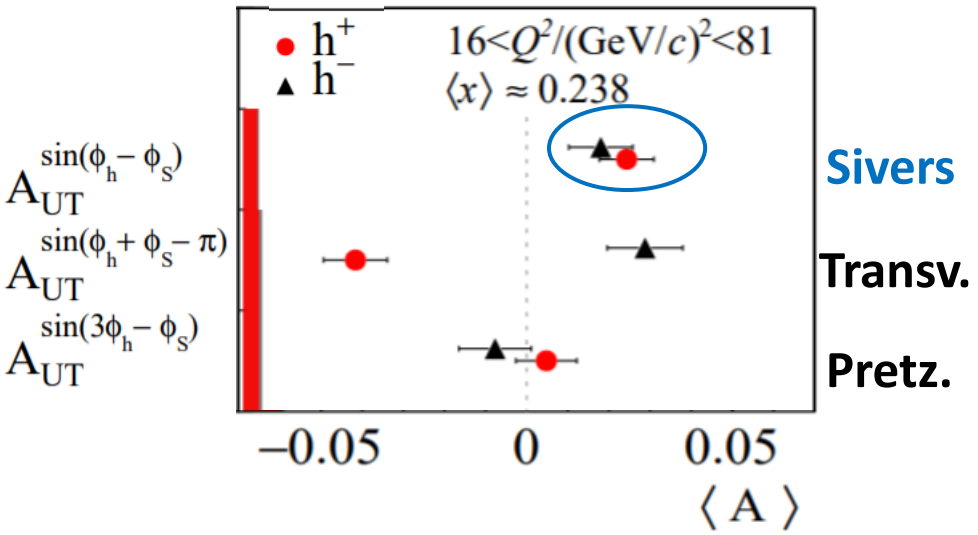
Pretzelosity ~compatible with zero

Transversity ~2σ below zero

COMPASS Sivers TSA measurements favors sign change prediction

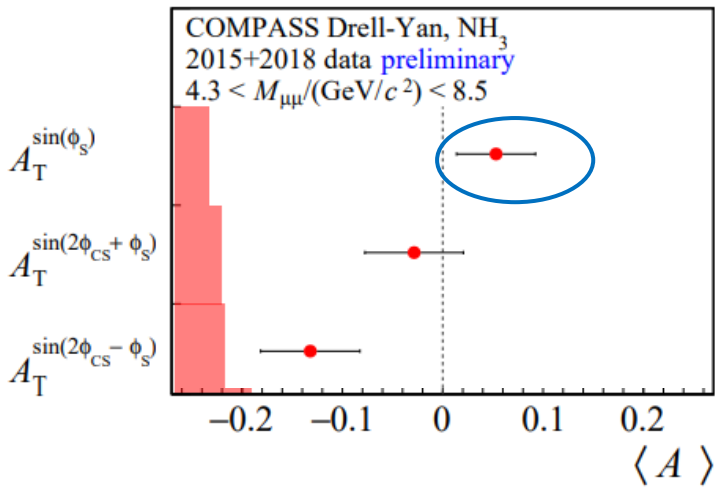
COMPASS collected SIDIS and DY data with the same apparatus, in essentially the same kinematic region

TSAs from SIDIS @ COMPASS

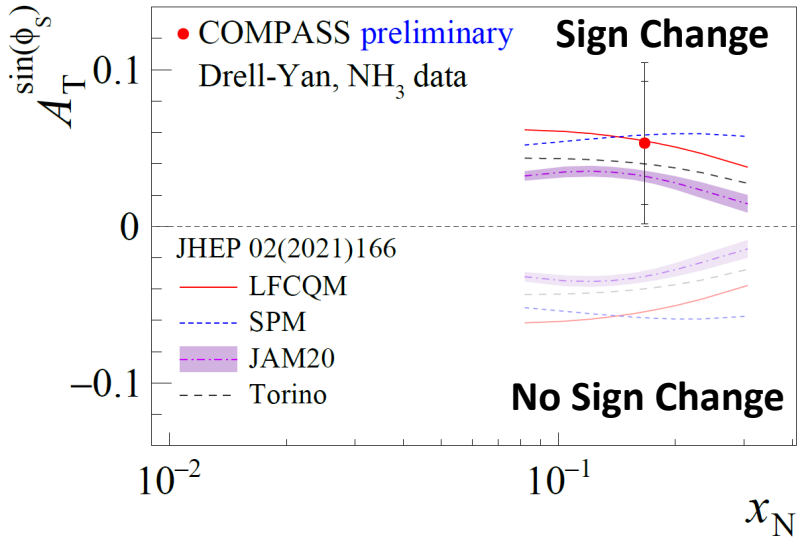


COMPASS, PLB **770**(2017), 138.

TSAs from DY @ COMPASS



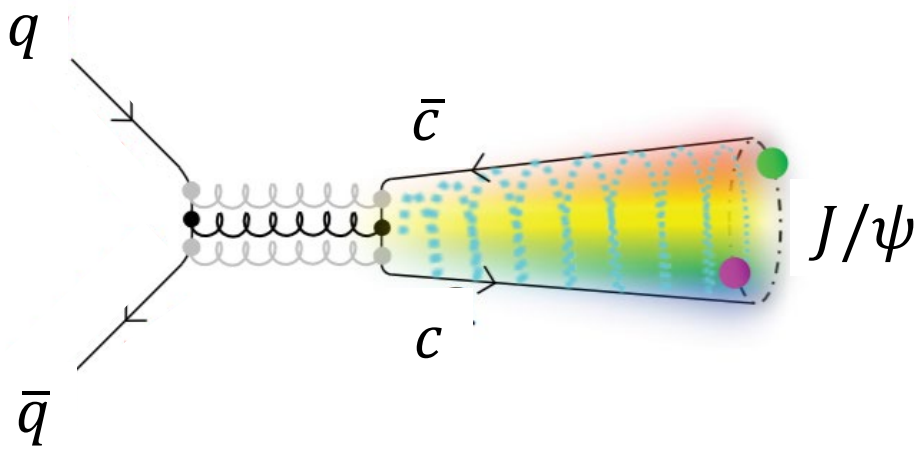
Comparing experimental DY Sivers TSA with theory predictions



Note: Angles defined differently in SIDIS and DY measurements:
same sign Sivers asymmetry -> Sivers PDF of opposite sign

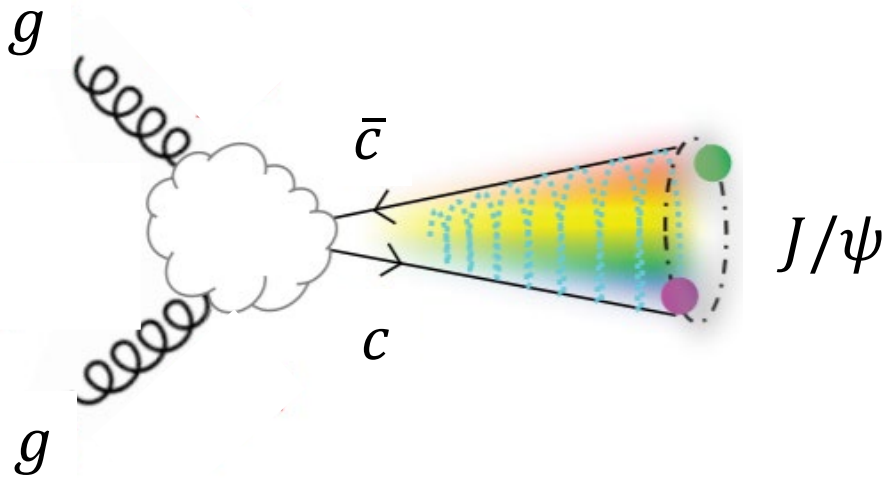
J/ψ production in pion-proton collisions

Two leading order J/ψ production processes



Quark-antiquark ($q\bar{q}$) annihilation

- Sensitive to quark TMDs
- Can complement DY results



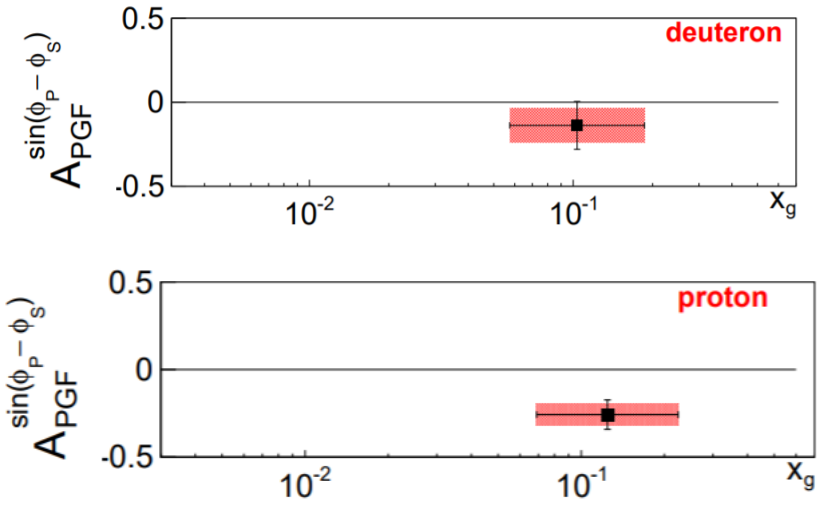
Gluon-gluon (gg) fusion

- Sensitive to gluon TMDs

Diagrams courtesy of Pietro Faccioli

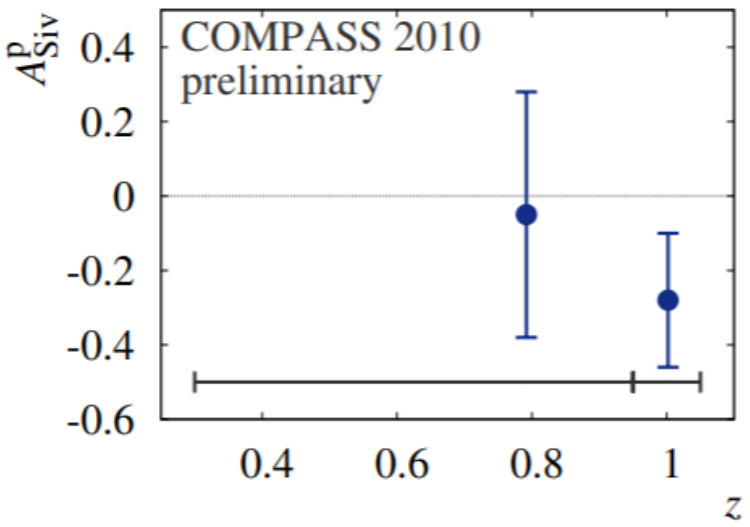
Further gluon Sivers studies would be valuable

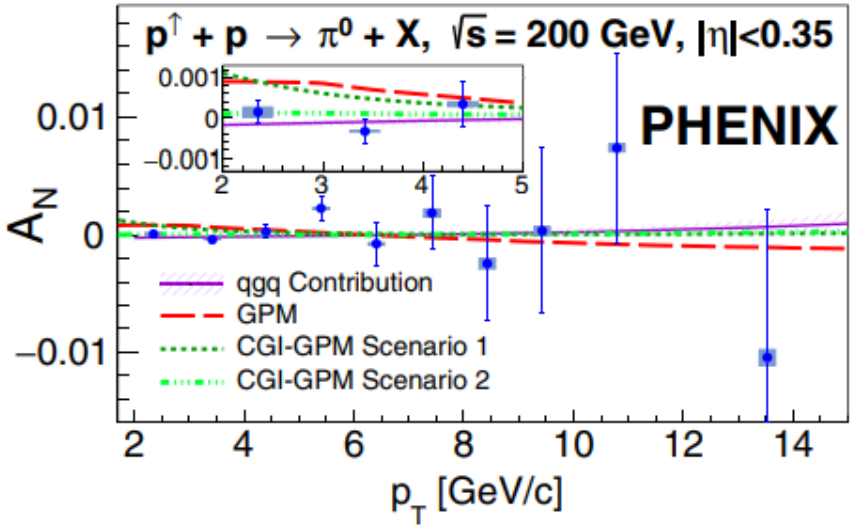
- COMPASS measured a gluon Sivers effect two sigma below zero in photon-gluon fusion
- COMPASS measured a similar size effect in exclusive J/ψ leptoproduction, but the result at lower z is compatible with zero
- PHENIX found a gluon Sivers effect compatible with zero in π^0 production in pp collisions
- The two experiments cover different kinematic regions, and the extraction of the gluon Sivers function is challenging



COMPASS, PLB **772**(2017), 854.

J/ψ leptoproduction





PHENIX, PRD **103**(2021) 052009

TSAs in J/ψ production may be used to determine which production mechanism is dominant

- Anselmino et.al. predict a large Sivers asymmetry in COMPASS J/ψ production

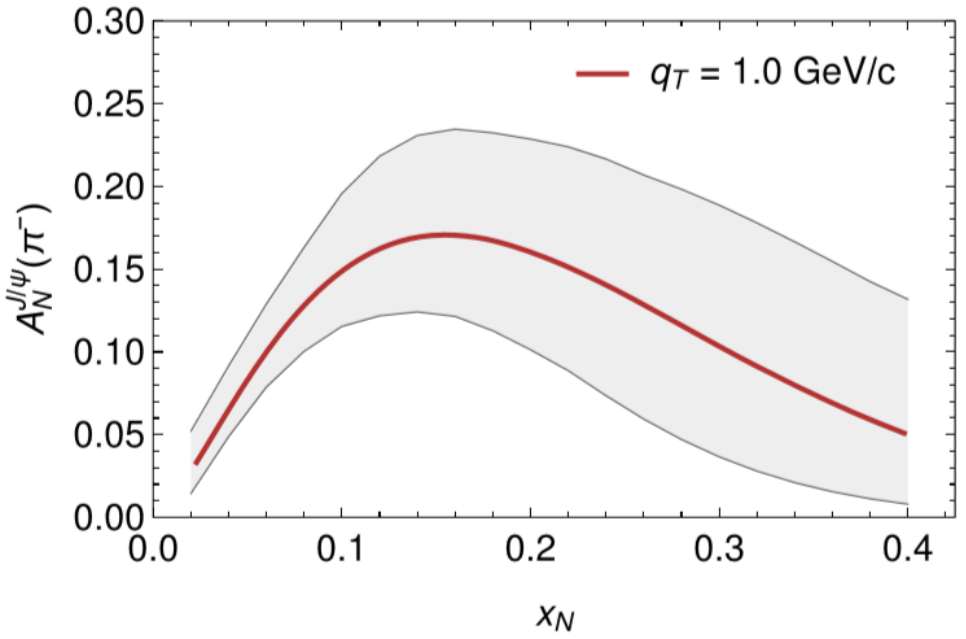
  M. Anselmino, V. Barone, M. Boglione. *Phys. Lett. B*, **770**(2017), 302-306.

- Calculation assumed only $q\bar{q}$ annihilation and no feed-down J/ψ
- Recent studies by Chang et.al. suggest that gg fusion dominates at COMPASS

  W. Chang, J. Peng, S. Platchkov, T. Sawada, *Phys. Rev. D,* **102**(2020), 054024

- Comparison of experiment and theory can illuminate further which production mechanism dominates at COMPASS kinematics

M. Anselmino, et. al. PLB **770**(2017), 302-306.

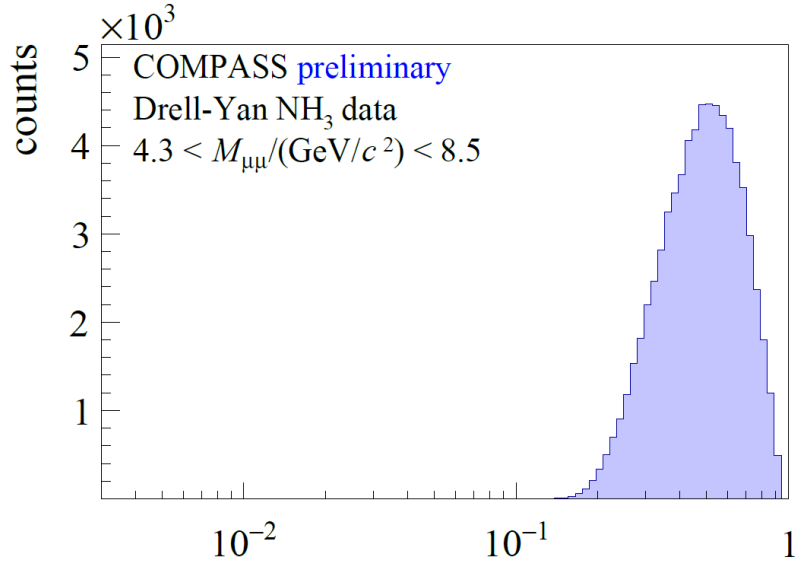


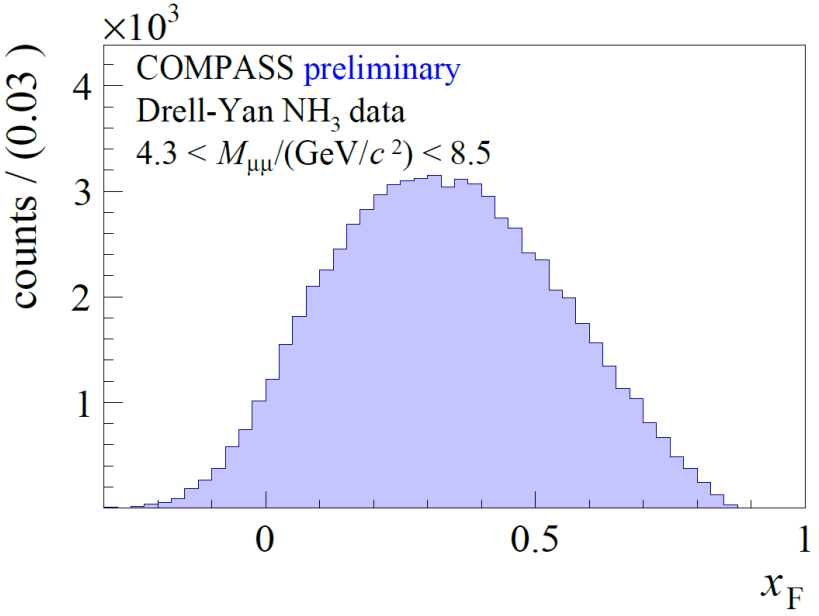
Summary

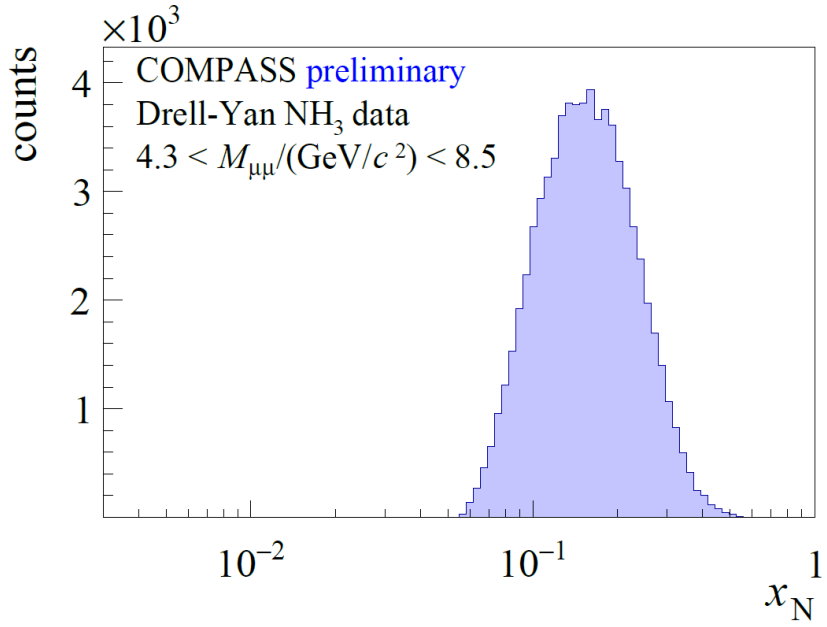
- TMD PDFs describe transverse-momentum dependent behavior of partons inside a nucleon
- Azimuthal asymmetries in COMPASS Drell-Yan data give access to quark Sivers, Pretzelosity, Transversity, and Boer-Mulders TMD PDFs
- Newest COMPASS TSA results (full 2015+2018 data sample)
  - Sivers TSA results favor sign change prediction
  - Pretzelosity and Transversity compatible with theoretical predictions
  - Hint of a non-zero Boer-Mulders effect
- Ongoing TSA extraction from J/ψ production in pion-proton collisions should offer insight about the J/ψ production mechanism and information about the gluon Sivers function

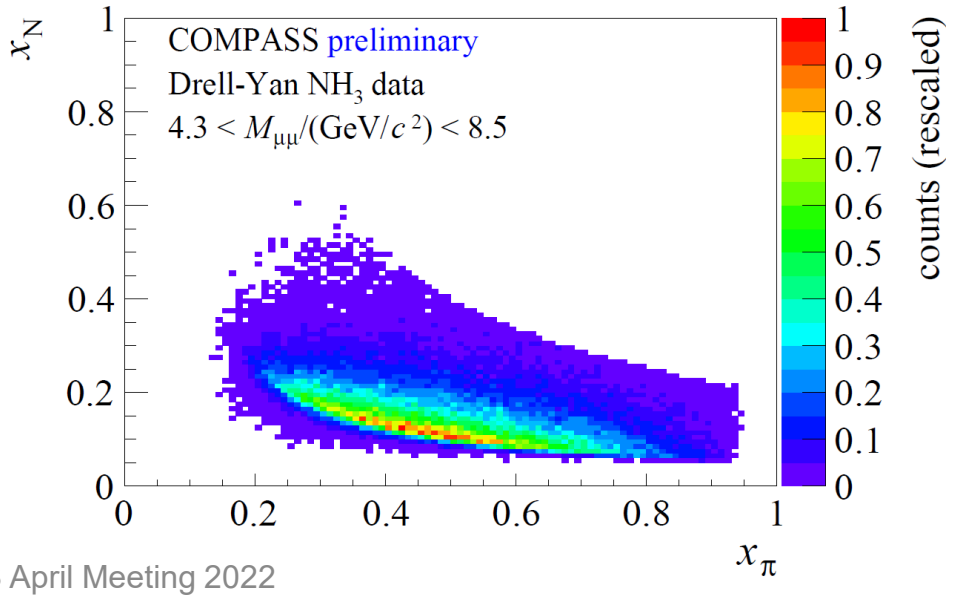
Backup Slides

Kinematic Distributions – Total DY Data Sample

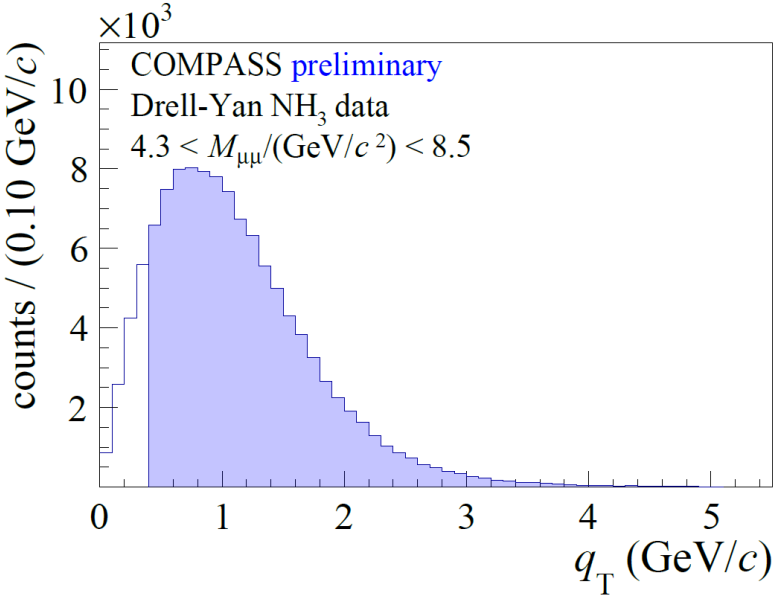


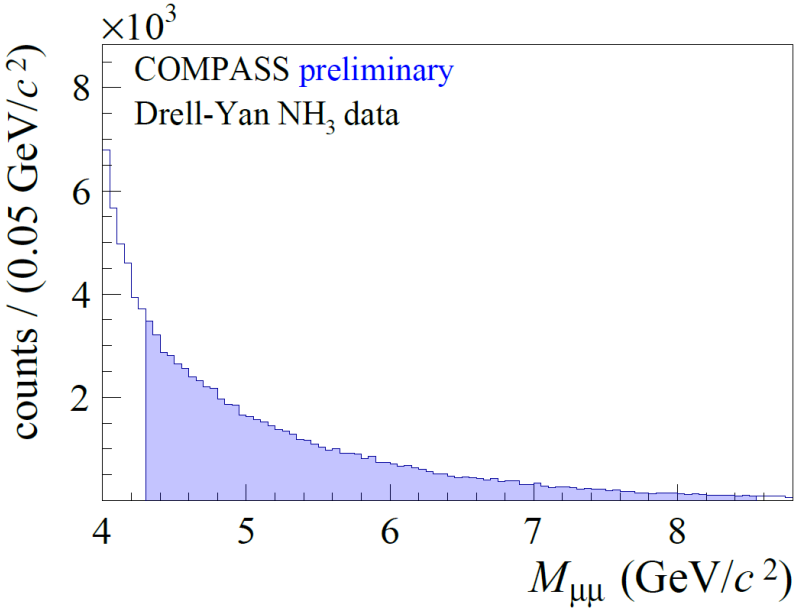


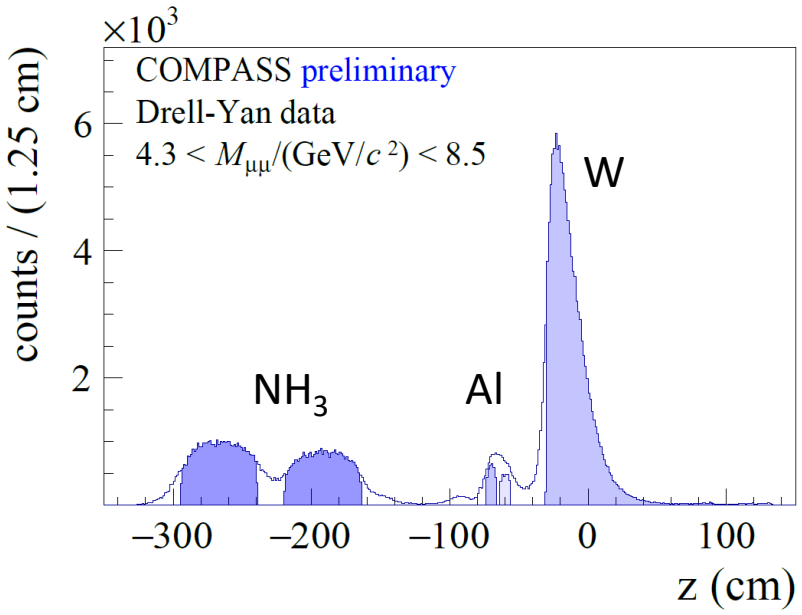




Kinematic Distributions – Total DY Data Sample







Kinematic Correlations