Dimuon Production with a Transversely Polarized Target in Pion-Induced Collisions at COMPASS

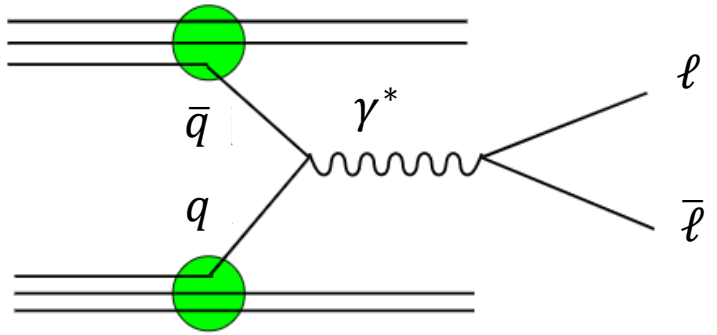
April Townsend, on behalf of the COMPASS Collaboration

PANIC 2021 Conference

September 5, 2021

Drell-Yan Scattering as a Probe of Nucleon Substructure

- **Drell-Yan (DY) Process:** Quark and antiquark annihilate into a virtual photon, which decays into two leptons
- COMPASS: First fixed target experiment to take DY data with a **transversely polarized target**
- Cross-section of pion-nucleon DY lepton-pair production off a transversely polarized nucleon, in terms of **azimuthal asymmetries**:

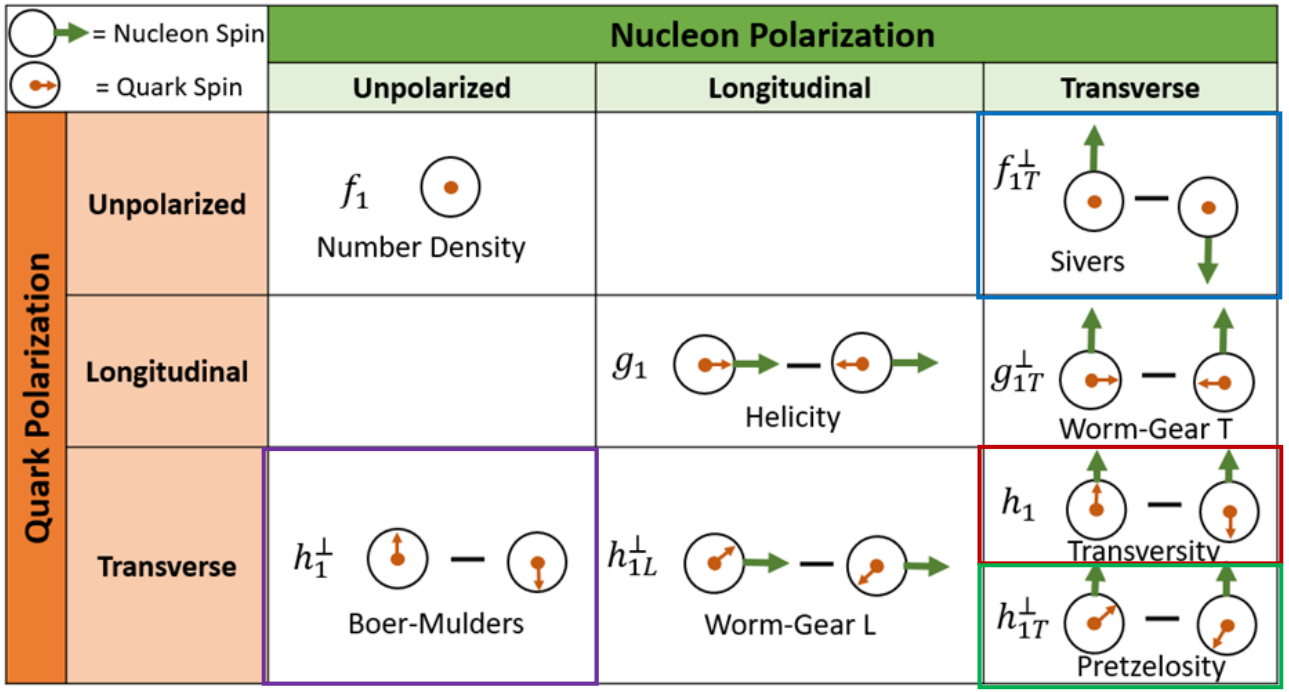


$$\frac{\mathrm{d}\sigma}{\mathrm{d}q^4\mathrm{d}\Omega} \propto \hat{\sigma}_U \Big\{ 1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$
$$+ S_T \Big[(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S}) \sin\varphi_S$$
$$+ \sin 2\theta_{CS} \left(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \right)$$
$$+ \sin^2\theta_{CS} \left(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \Big] \Big\}$$

- Cross-section contains both **spin-averaged asymmetries**, denoted by A_U, and **transverse spin asymmetries** (TSAs), denoted by A_T
- These asymmetries are related to different transverse momentum dependent (TMD) parton distribution functions (PDFs)

Transverse Spin Asymmetries (TSAs) and TMD PDFs

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



Quark TMD PDFs that can be extracted from the leading-order DY cross-section with a transversely polarized target: Sivers, Transversity, Pretzelosity, Boer-Mulders

Azimuthal asymmetries related to these TMD PDFs:

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

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

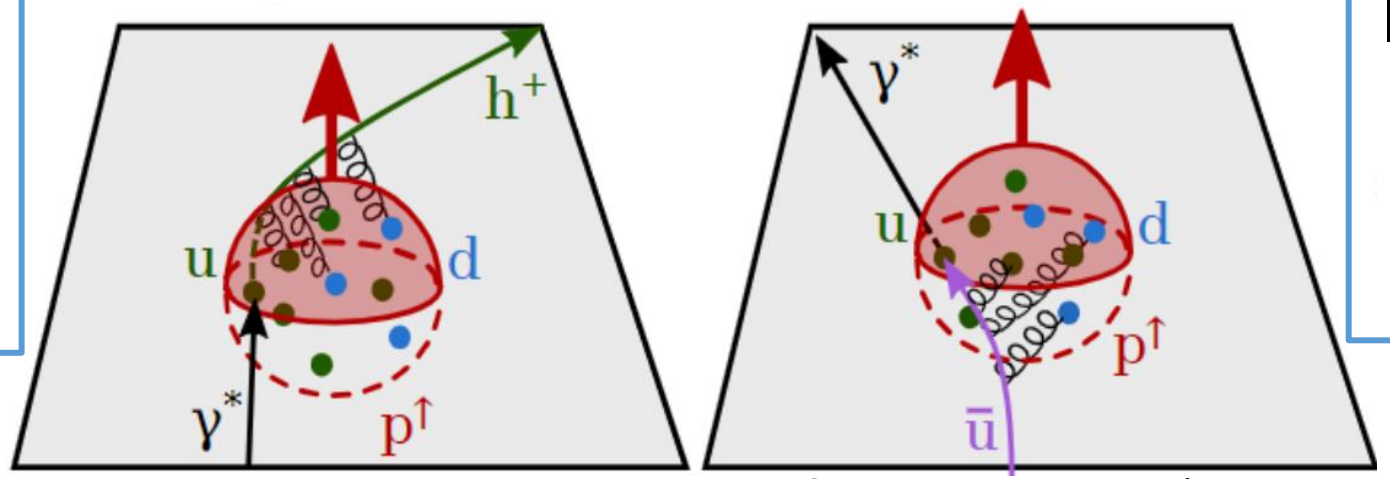
$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$ ~ proton Transversity ⊗ pion Boer-Mulders

$A_U^{\cos(2\varphi_{CS})}$ ~ proton Boer-Mulders ⊗ pion Boer-Mulders

Experimental studies of TMD PDFs important for verifying TMD QCD framework

- Sivers and Boer-Mulders PDFs: time-reversal odd, predicted to have opposite sign in DY compared to Semi-Inclusive Deep Inelastic Scattering (SIDIS)
- Pretzelosity and Transversity: predicted to be process independent
- COMPASS aims to verify these predictions experimentally

In SIDIS, soft gluon exchange is a final state interaction



Courtesy: Jan Matousek

In DY, soft gluon exchange is an initial state interaction

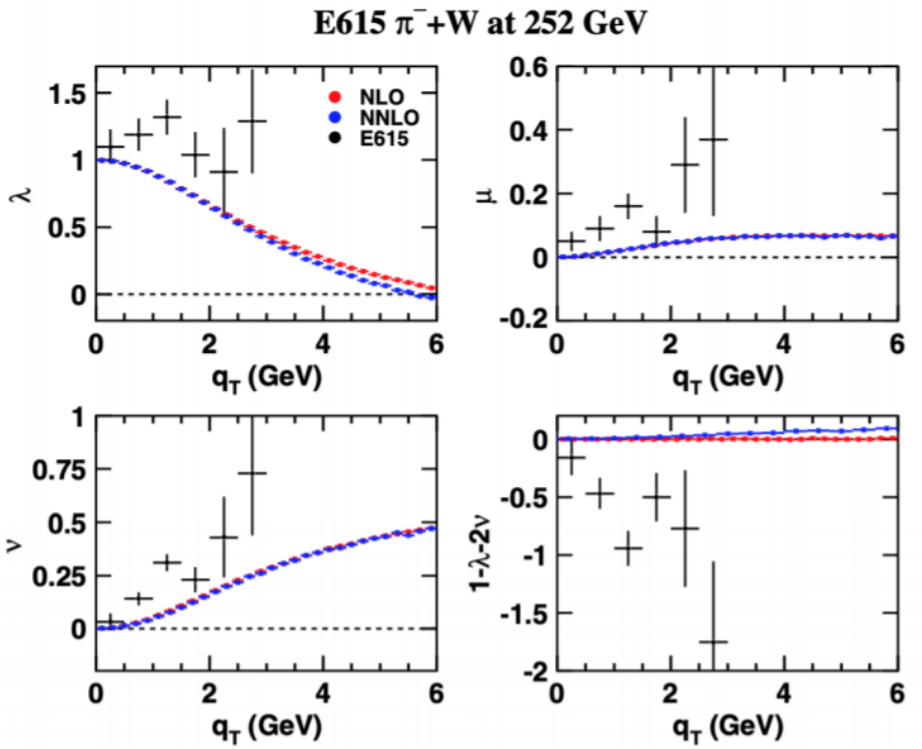
Angular Dependence of the Spin-Averaged DY Cross-Section

- Spin-integrated portion of DY cross-section in common notation:

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin 2\theta_{CS}\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

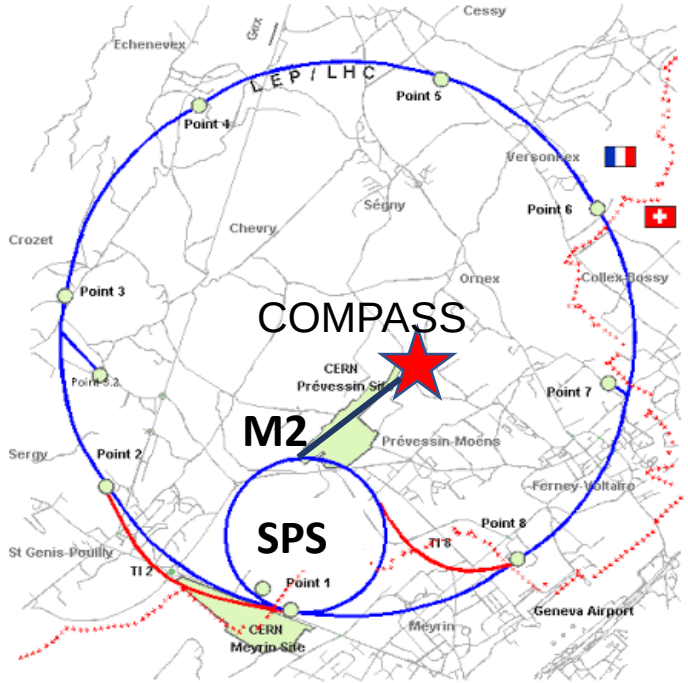
$$\lambda = A_U^1, \quad \mu = A_U^{\cos\varphi_{CS}}, \quad \nu = 2A_U^{\cos 2\varphi_{CS}}$$

- If the DY virtual photon is produced solely by electromagnetic quark-antiquark annihilation, then $\lambda = 1,\ \mu = 0,\ \upsilon = 0$
- Lam-Tung relation $1 - \lambda = 2\upsilon$ predicted when adding QCD corrections, but violated by past pion-induced DY experiments
- Previous DY results for υ disagree with perturbative QCD predictions – this disagreement can be explained by the non-perturbative Boer-Mulders effect



Chang et. al., PRD **99**(2019), 014032

COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS)



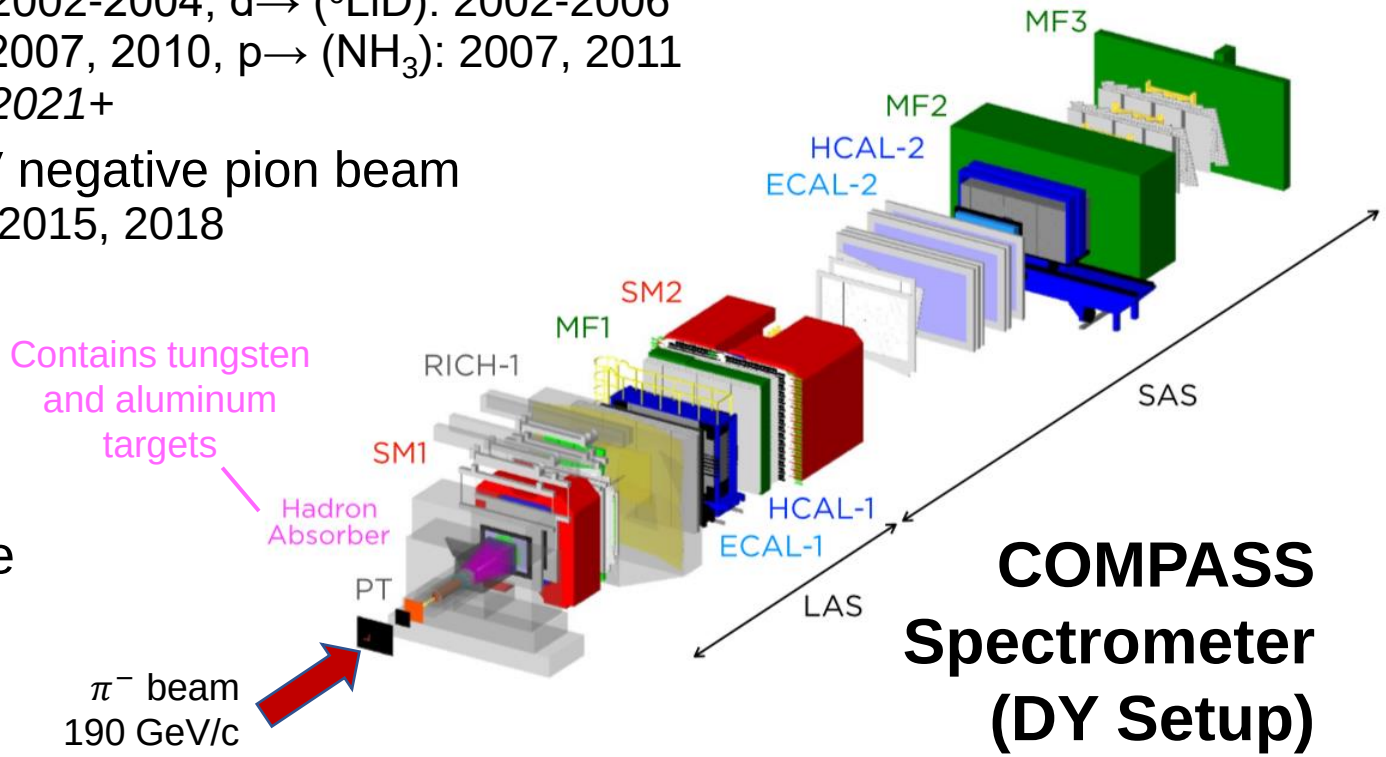
- Fixed polarized target experiment in North Area of CERN
- Beam comes from M2 beam line, originating from the SPS

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+*
- DY – 190 GeV negative pion beam
  - p↑ (NH_3): 2015, 2018

During DY runs:

- 2 target cells filled with solid state NH_3
- Protons in each NH_3 cell polarized in opposite directions
- W and Al targets part of hadron absorber



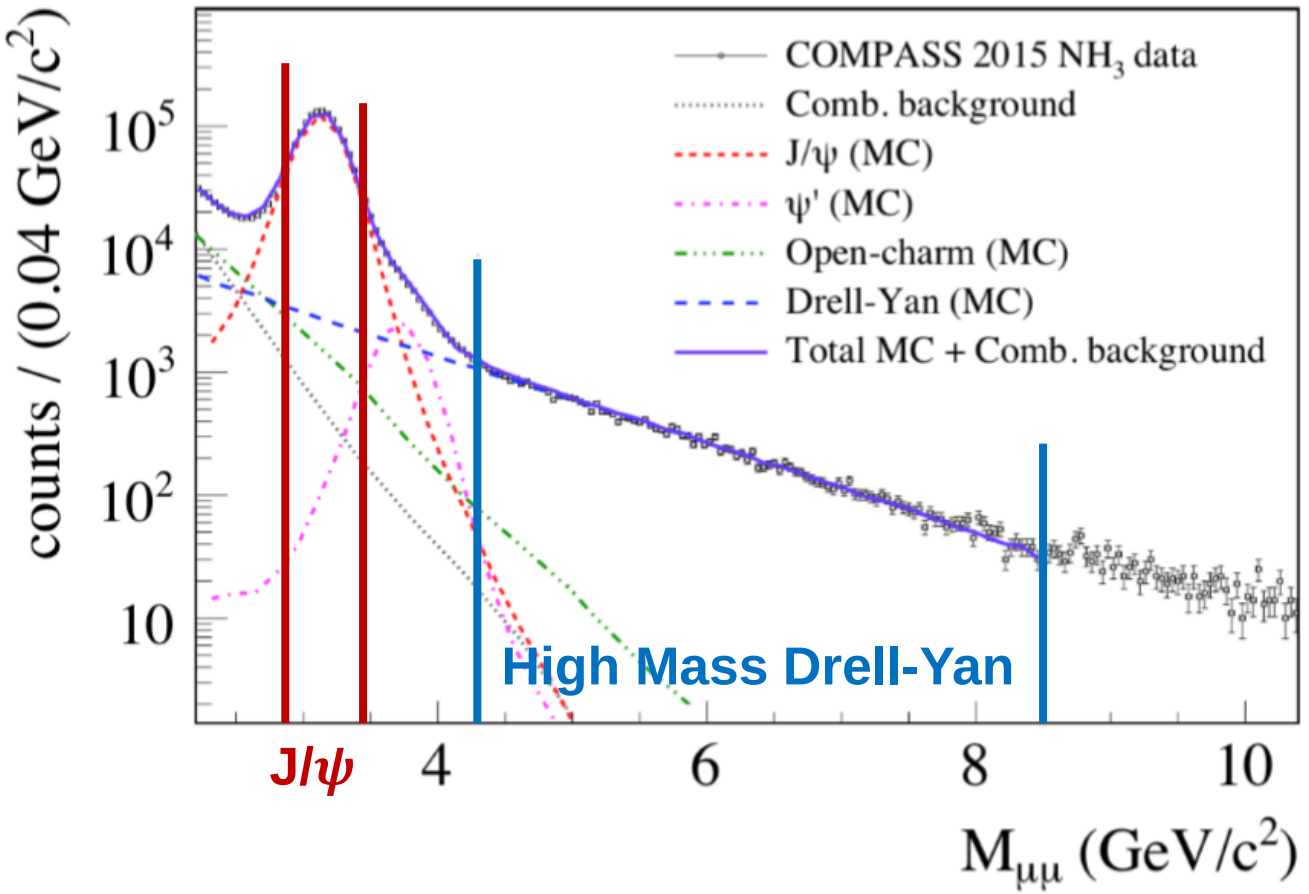
COMPASS Spectrometer (DY Setup)

Dimuon Mass Distribution

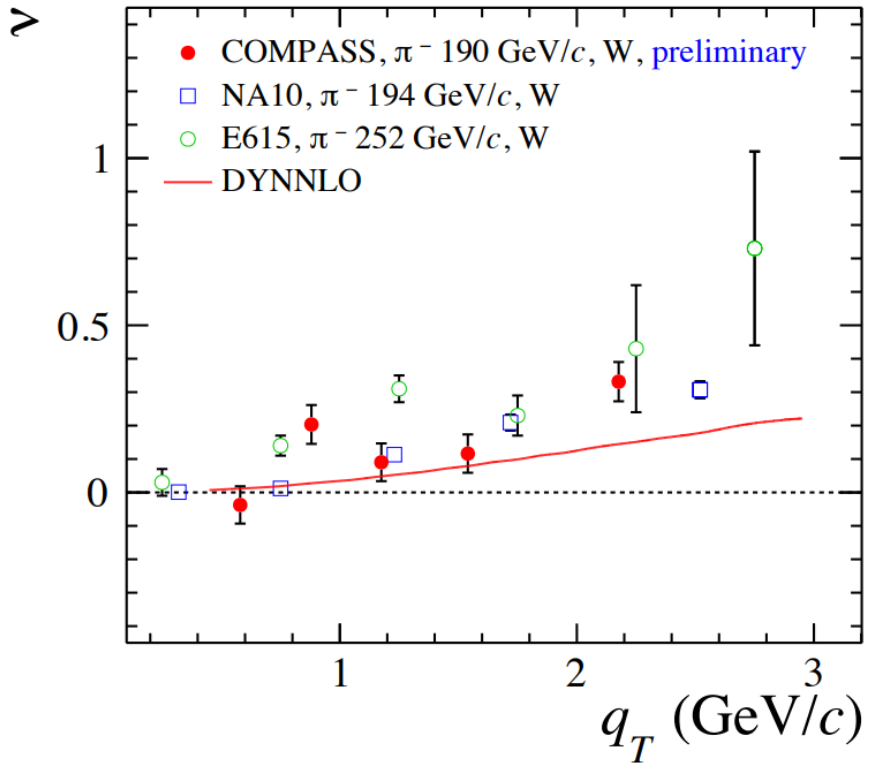
- Data contains dimuons from DY scattering as well as meson decay and combinatorial background

- **'High mass'** region used for DY analysis:
  - **4.3 GeV/c^2 < $M_{\mu\mu}$ < 8.5 GeV/c^2**
  - ~95% pure

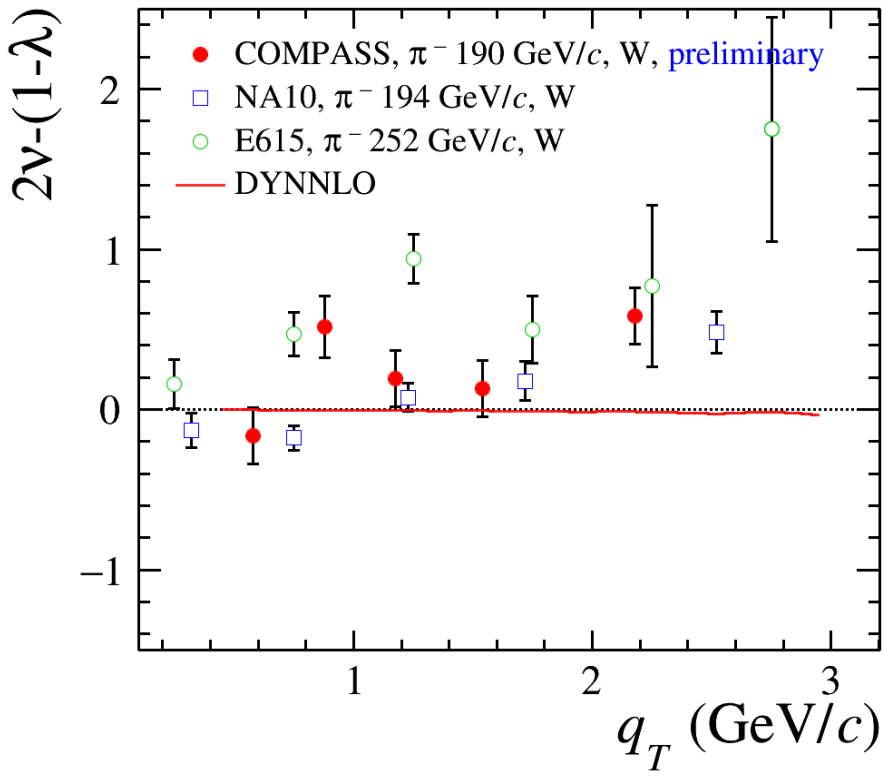
- **J/ψ** mass region (used in ongoing J/ψ analysis):
  - > 90% purity



COMPASS DY Results for the Angular Dependence of the Unpolarized Cross-Section



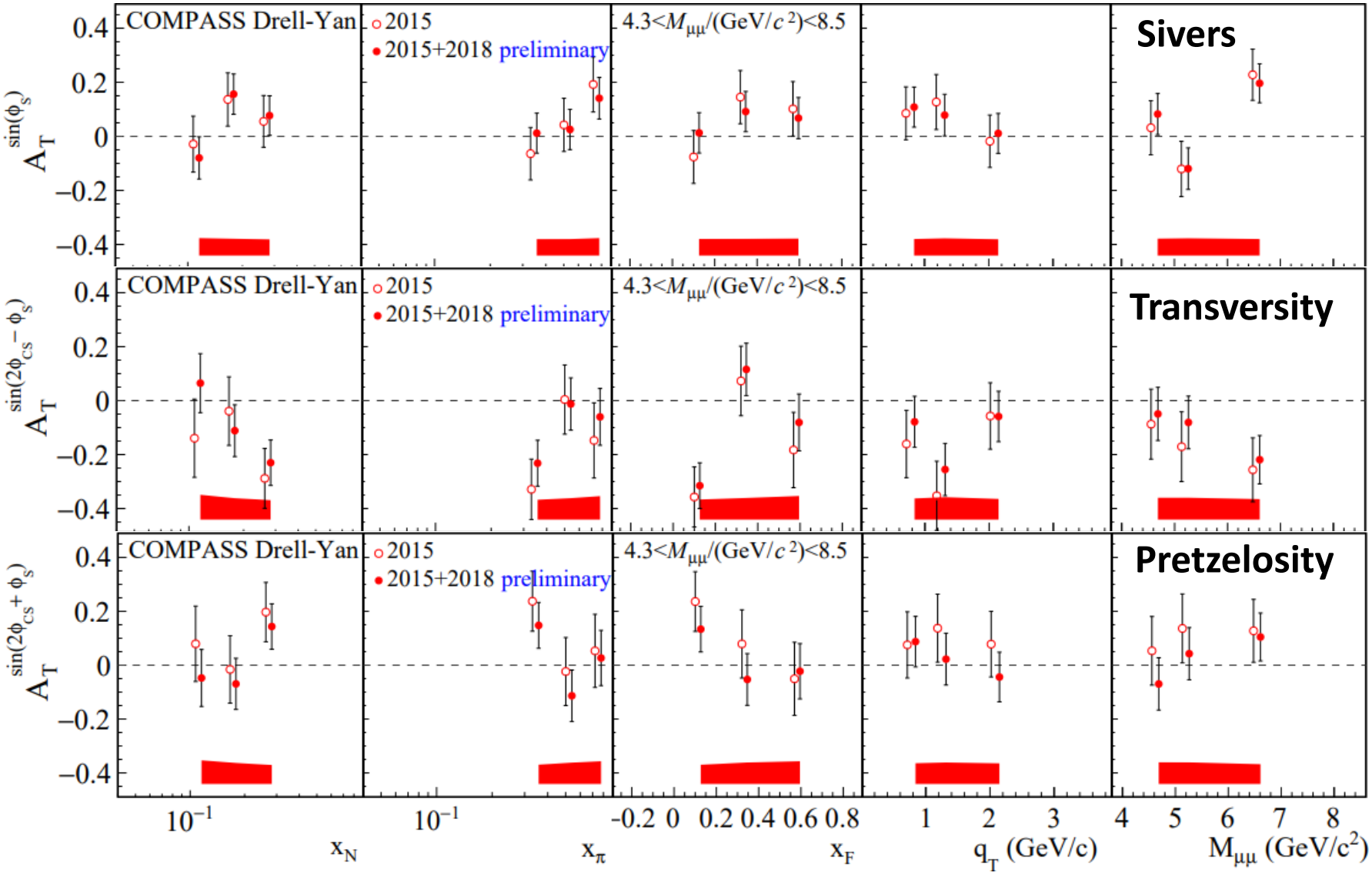
Hint of a non-zero Boer-Mulders effect

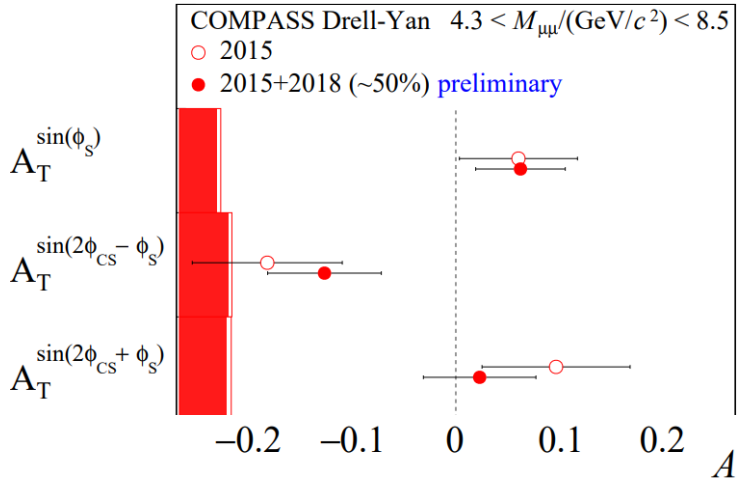


Lam-Tung relation appears to be violated

Analysis with data from the polarized NH_3 target is in progress

COMPASS DY TSA Results





Sivers ~1σ above zero

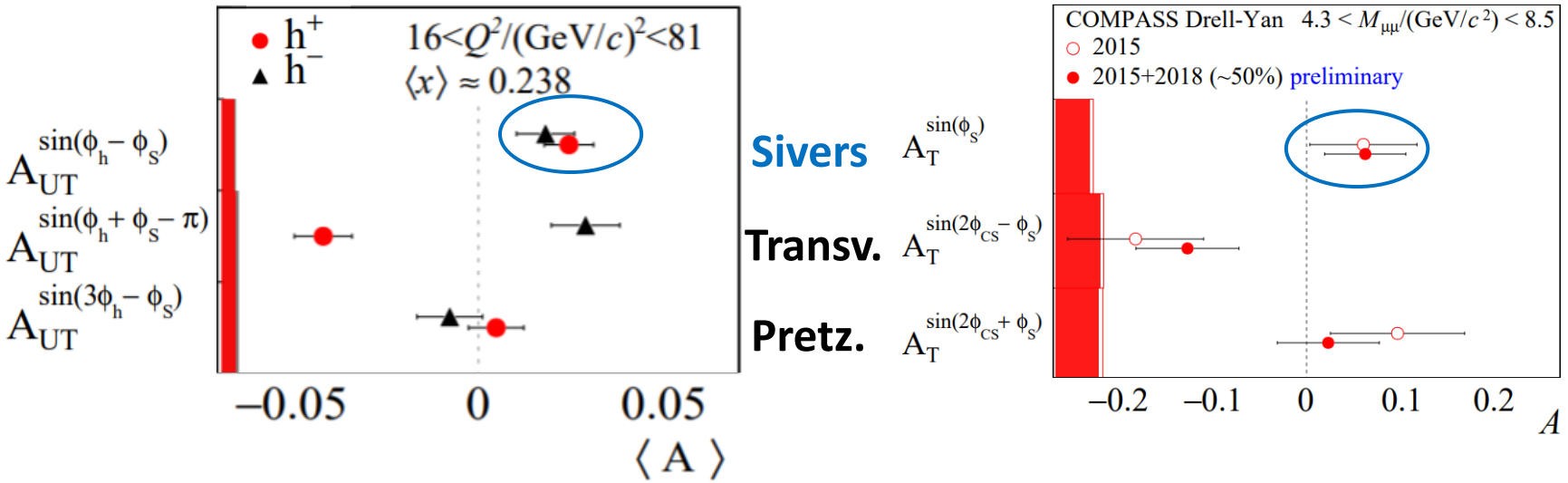
Transversity ~2σ below zero

Pretzelosity ~1σ above 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

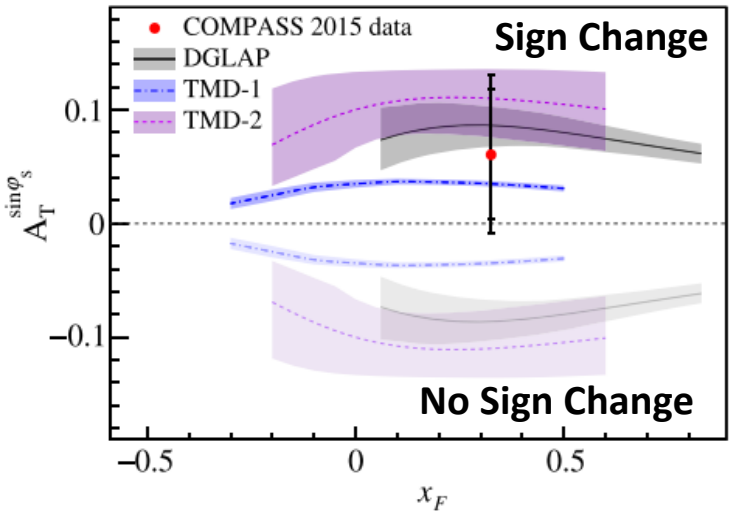
TSAs from SIDIS @ COMPASS



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

TSAs from DY @ COMPASS

Comparing experimental DY Sivers TSA with phenomenological predictions



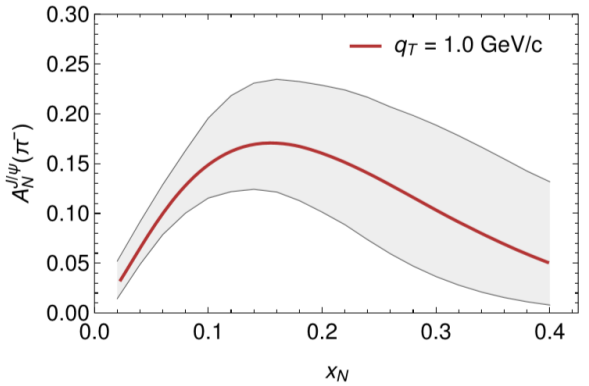
COMPASS, PRL **119**(2017), 112002.

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

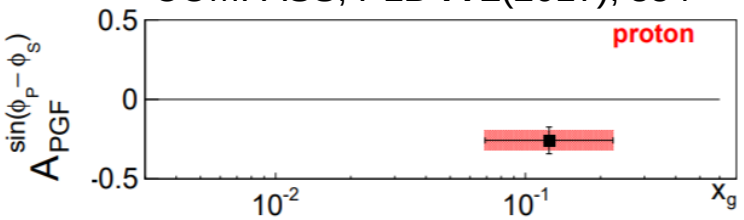
Extracting TSAs from J/ψ production can provide valuable information

- Two leading order J/ψ production processes:
  - Quark-antiquark annihilation – sensitive to quark TMDs, complements DY results
  - Gluon-gluon fusion – sensitive to gluon TMDs
- Extracting the Sivers asymmetry from J/ψ production may give insight into which production mechanism dominates at COMPASS
  - Anselmino et.al. predict a large Sivers asymmetry in COMPASS J/ψ production assuming only $q\bar{q}$ annihilation
  - Recent studies by Chang et.al. suggest that gg fusion dominates at COMPASS (PRD **102**(2020), 054024)
- Gluon Sivers function is poorly understood
  - COMPASS measured a gluon Sivers effect two sigma below zero in photon-gluon fusion
  - PHENIX found a zero A_N in π^0 production in pp collisions at mid-rapidity and low p_T
  - These experiments cover different kinematic regimes

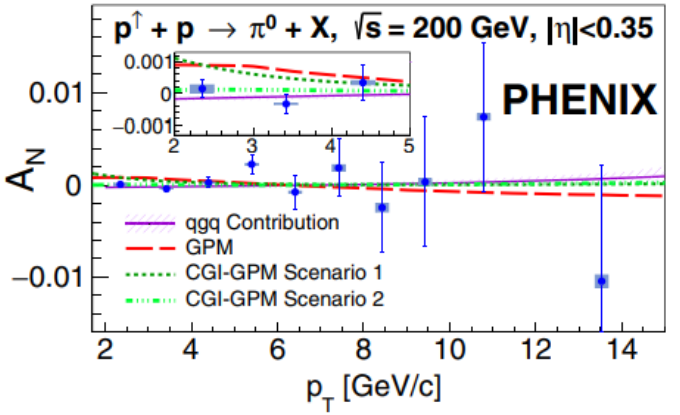
Anselmino, et. al. PLB **770**(2017), 302-306



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



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

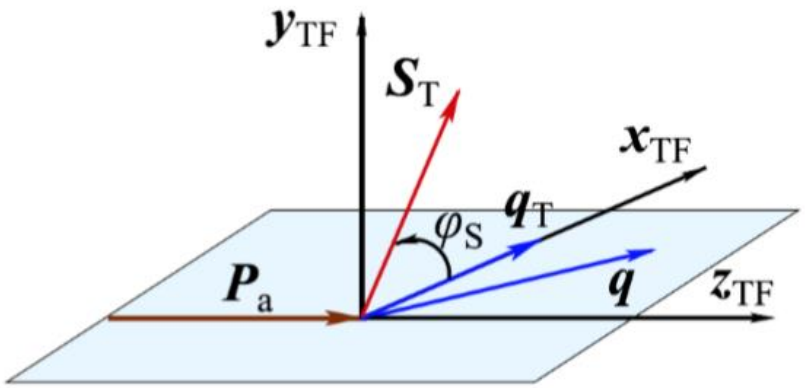


Conclusions

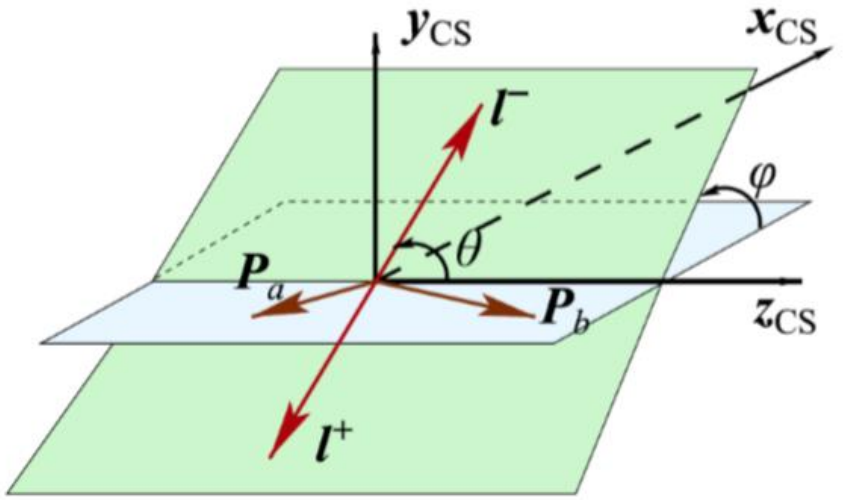
- Azimuthal asymmetries in COMPASS DY data give access to TMD PDFs and spin-orbit correlations in the proton
- COMPASS DY spin-independent asymmetries hint at a non-zero Boer-Mulders effect and violation of the Lam-Tung relation
- COMPASS DY Sivers result (with ~70% of the total data sample) favors the sign change prediction between DY and SIDIS
- Ongoing analyses with larger data samples will improve the statistical precision of results
- 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

COMPASS Reference Frames



Target Rest Frame



Collins-Soper Frame

COMPASS Polarized Target and Hadron Absorber during DY Runs