Probing Nucleon Structure in Drell-Yan Production at COMPASS

April Townsend, on behalf of the COMPASS collaboration

APS GHP Meeting 2021

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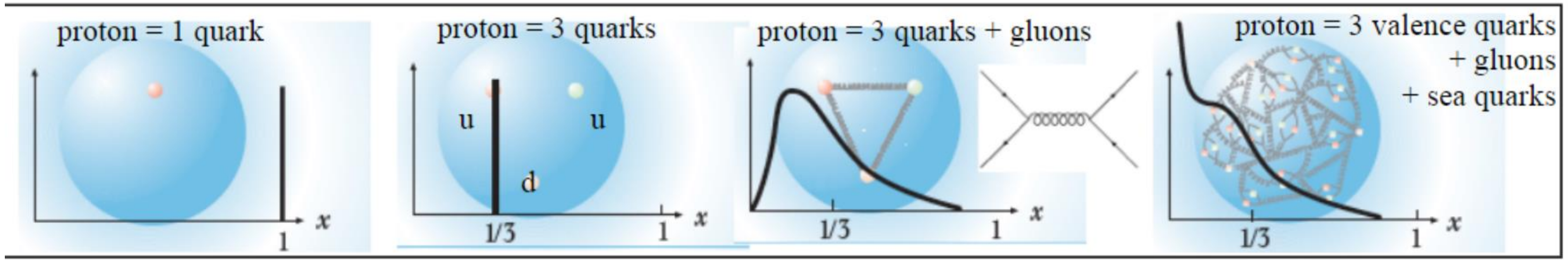
Outline

- Nucleon structure and Transverse-Momentum Dependent (TMD) Parton Distribution Functions (PDFs)
- COMPASS Experiment and Drell-Yan data-taking
- Azimuthal Asymmetries to study TMD PDFs
- Asymmetry Results from COMPASS Drell-Yan data
- Outlook: Asymmetries in J/ψ production in pion-proton collisions

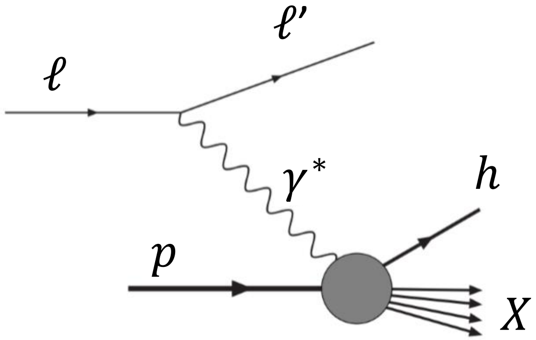
Scattering Experiments Used to Probe Nucleon Substructure

- In the infinite momentum frame of a scattering experiment, nucleon constituents appear to the incoming beam to be free, independent partons

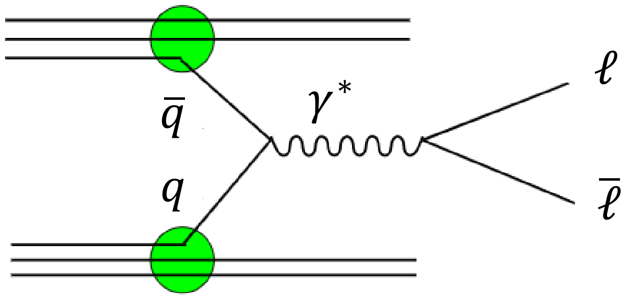
- Each parton carries a fraction of the longitudinal momentum of the nucleon, described by the Bjorken x variable



- Non-inclusive scattering processes must be used to probe transverse-momentum dependence



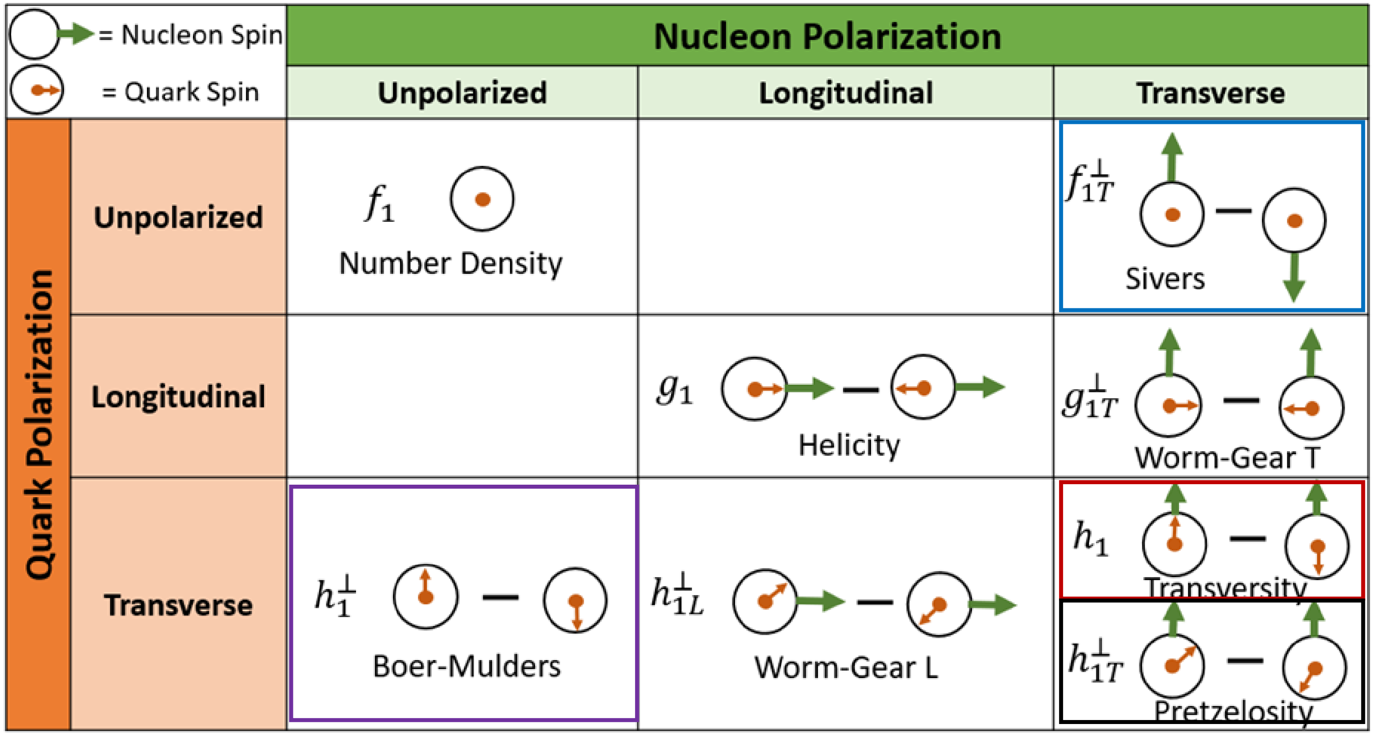
Semi-Inclusive Deep Inelastic Scattering (SIDIS) – Lepton scatters off hadron, one or more outgoing hadrons are measured



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 between the transverse momentum of partons and the polarization of the partons and/or parent nucleon



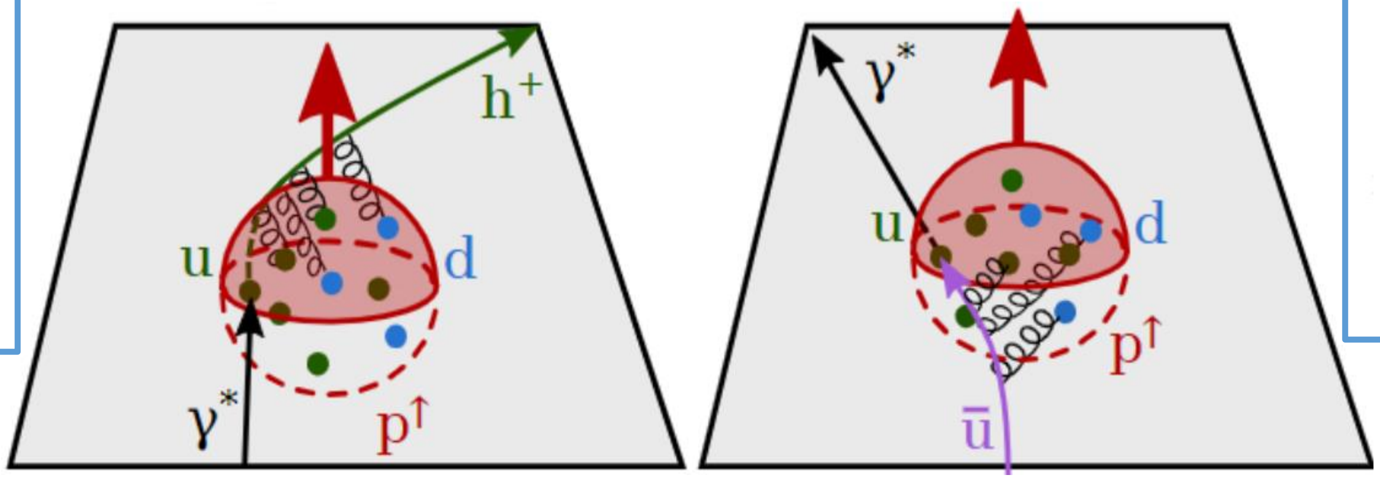
Quark TMD PDFs that can be extracted from the DY and SIDIS cross-sections:

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

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 SIDIS vs DY
- 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

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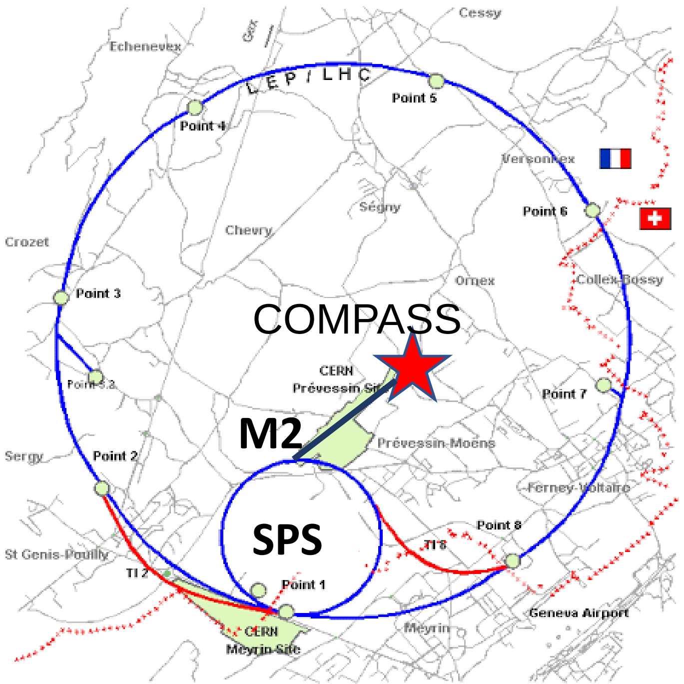
COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS)



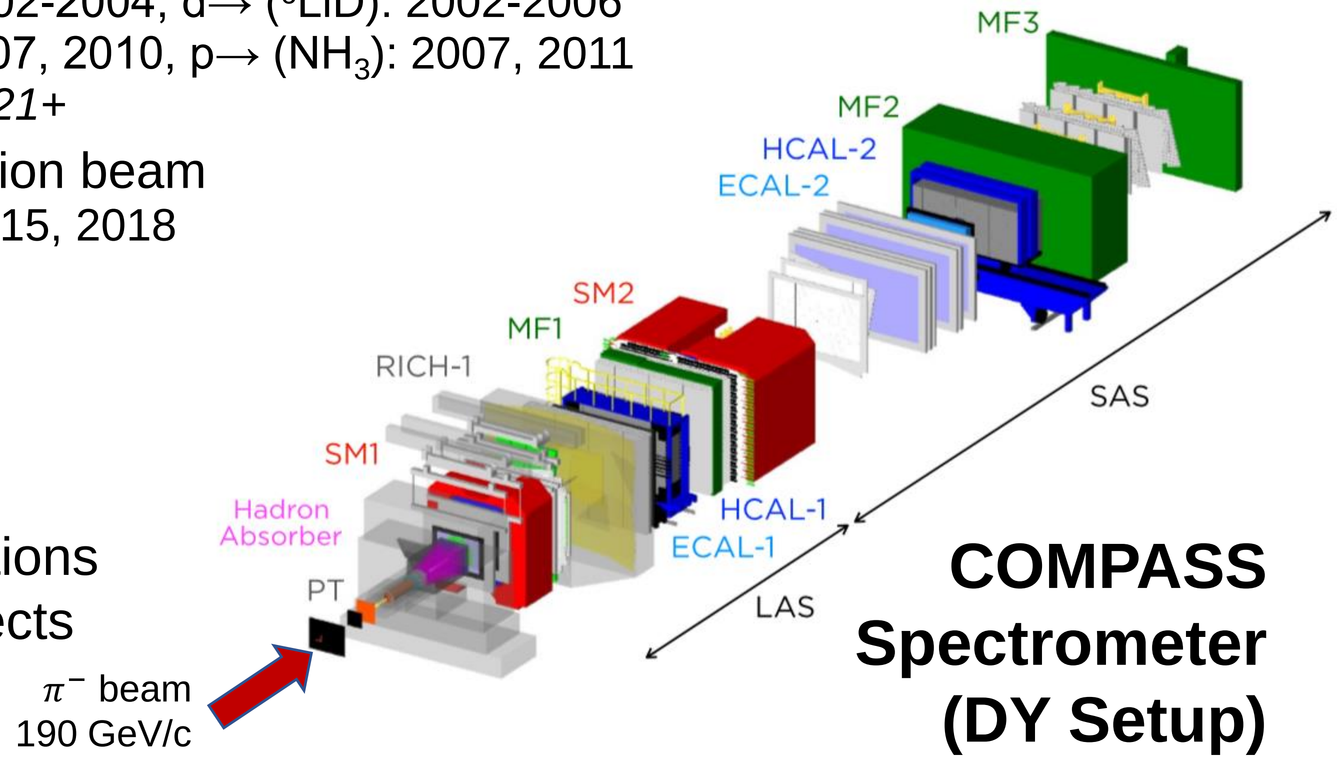
- Fixed polarized target experiment in North Area of CERN
- Beam comes from M2 beam line, originating from the SPS

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 pion beam
  - p↑ (NH_3): 2015, 2018

During DY runs:

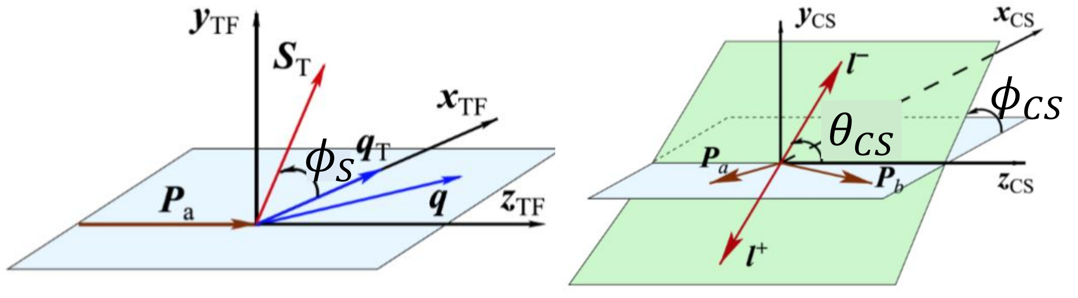
- 2 target cells filled with solid state NH_3
- Protons in each cell polarized in opposite directions
- Polarization flipped periodically to minimize effects of luminosity and acceptance



COMPASS Spectrometer (DY Setup)

Azimuthal asymmetries extracted to probe TMD PDFs

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



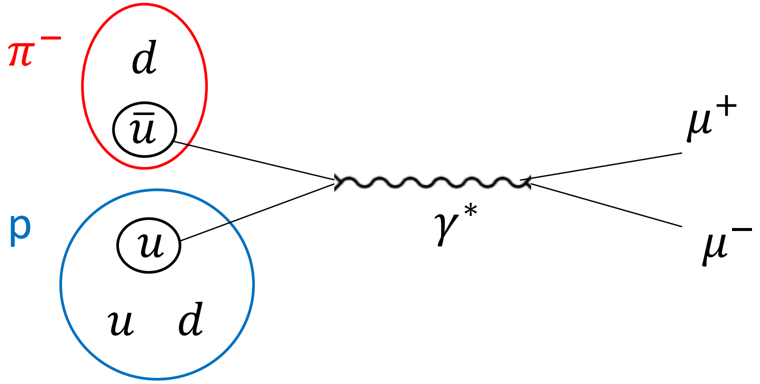
$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{1 + D_{[\sin^2\theta_{CS}]}\boxed{A_U^{\cos(2\phi_{CS})}}\cos(2\phi_{CS})$$
$$+ S_T\Big[\boxed{A_T^{\sin(\phi_S)}}\sin(\phi_S) + D_{[\sin^2\theta_{CS}]}\Big(\boxed{A_T^{\sin(2\phi_{CS}+\phi_S)}}\sin(2\phi_{CS}+\phi_S) + \boxed{A_T^{\sin(2\phi_{CS}-\phi_S)}}\sin(2\phi_{CS}-\phi_S)\Big)\Bi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

- 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

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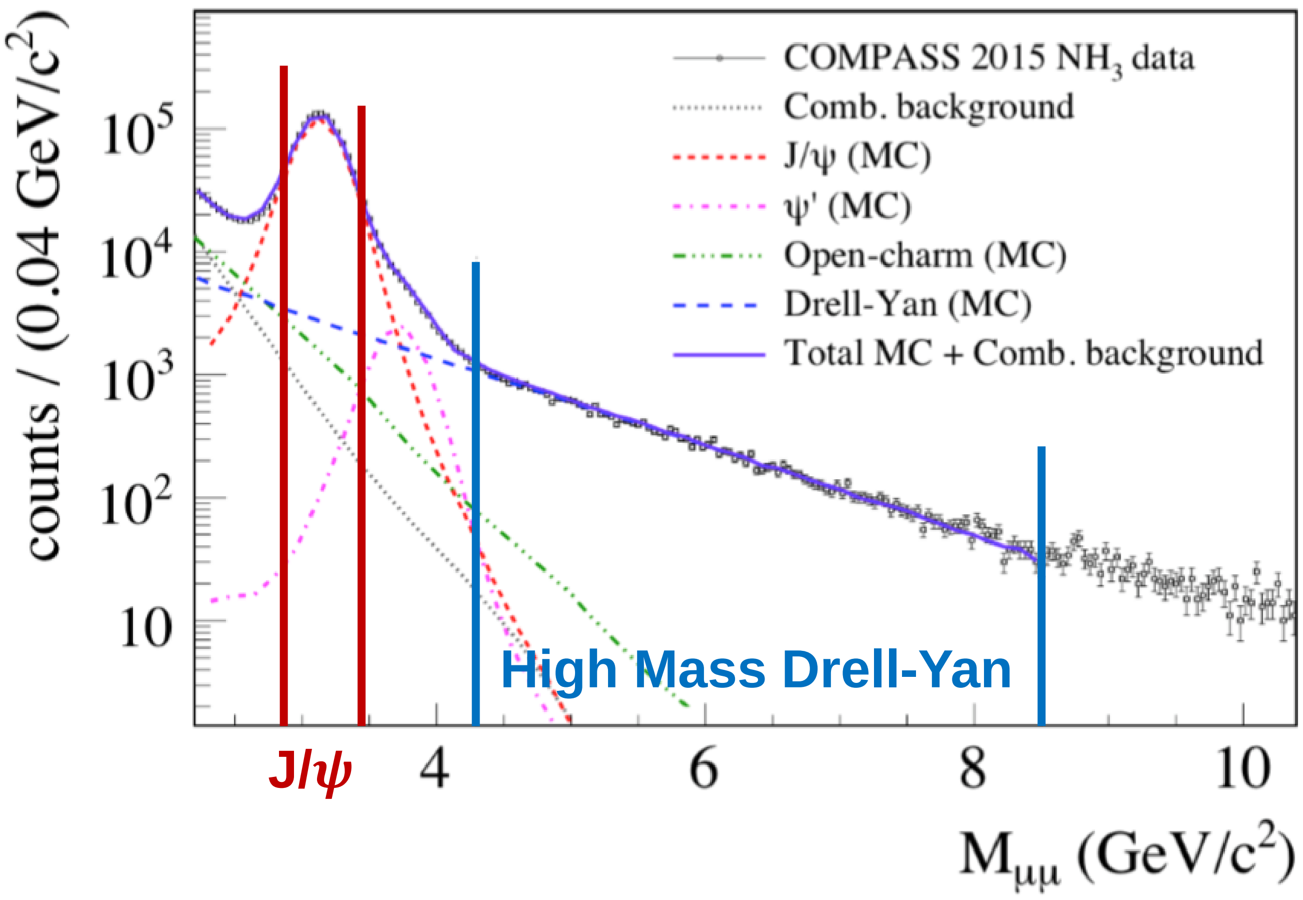
Dimuon Mass Distribution

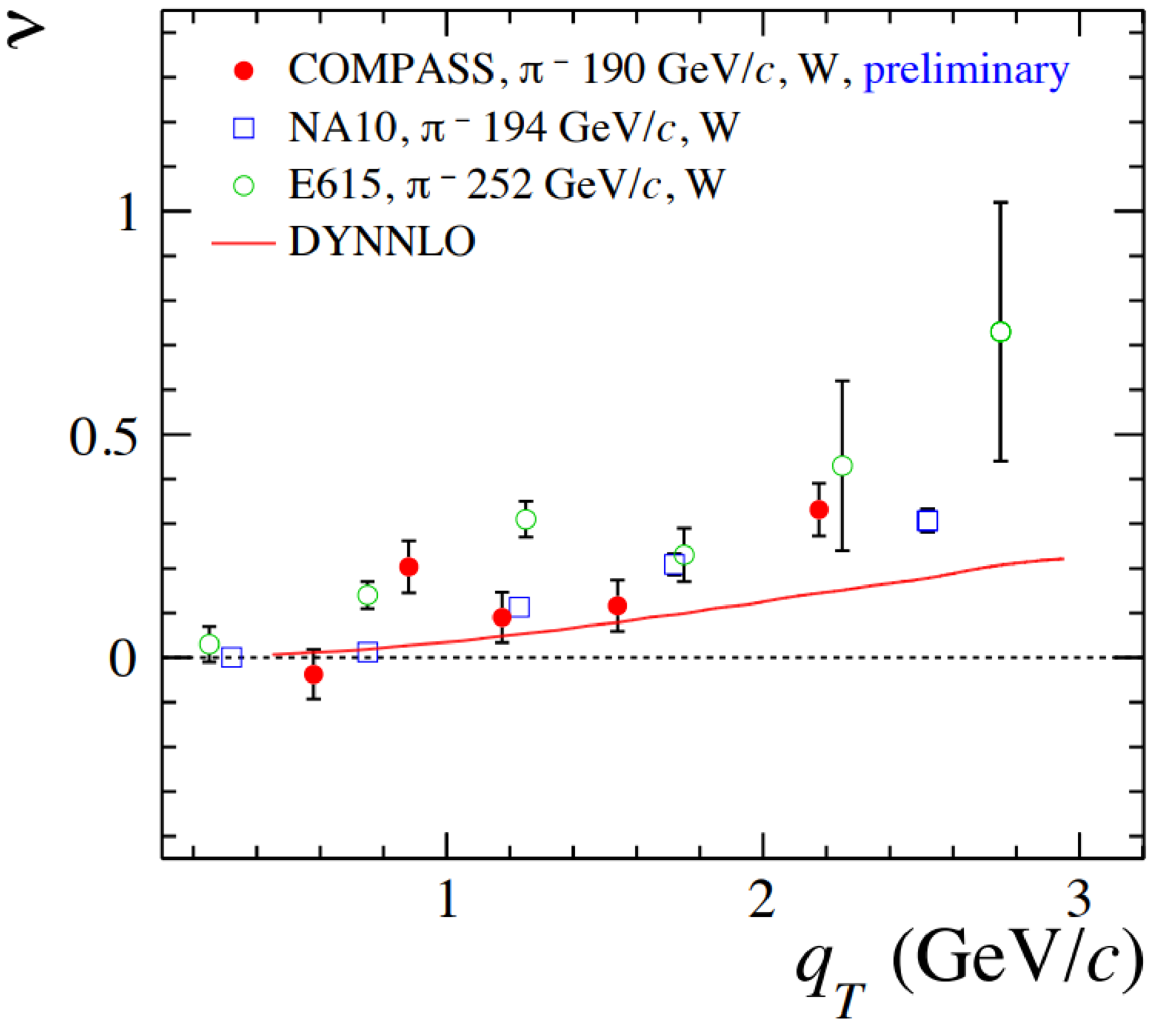
- Data contains dimuons from DY scattering as well as meson decay and combinatorial background

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

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

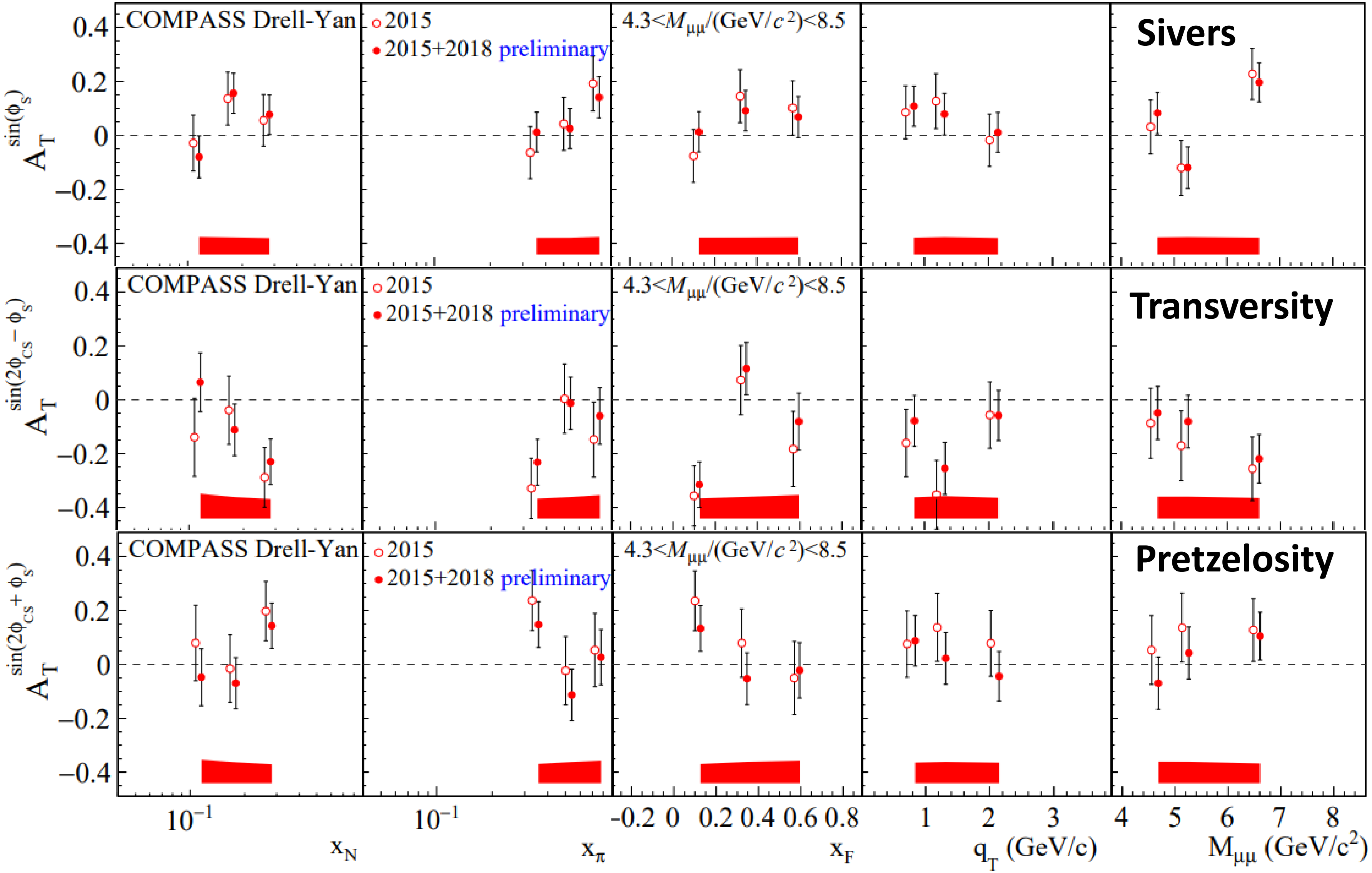


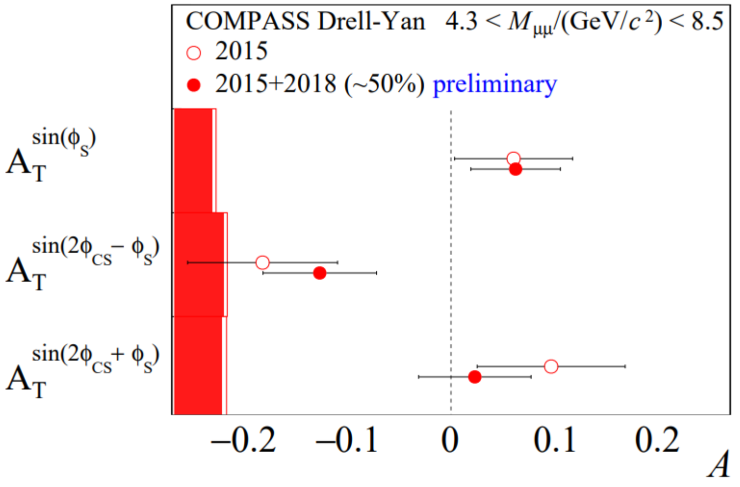
COMPASS DY Boer-Mulders result



- Unpolarized asymmetry $A_U^{\cos(2\phi_{CS})} = \nu/2$
- Experimental results hint that there may be non-zero Boer-Mulders effects

COMPASS DY TSA Results





Sivers ~1σ above zero

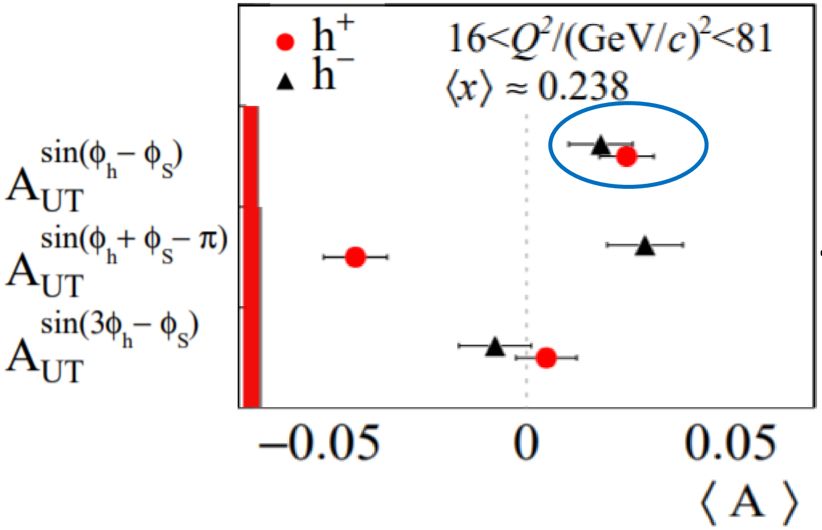
Transversity ~2σ below zero

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



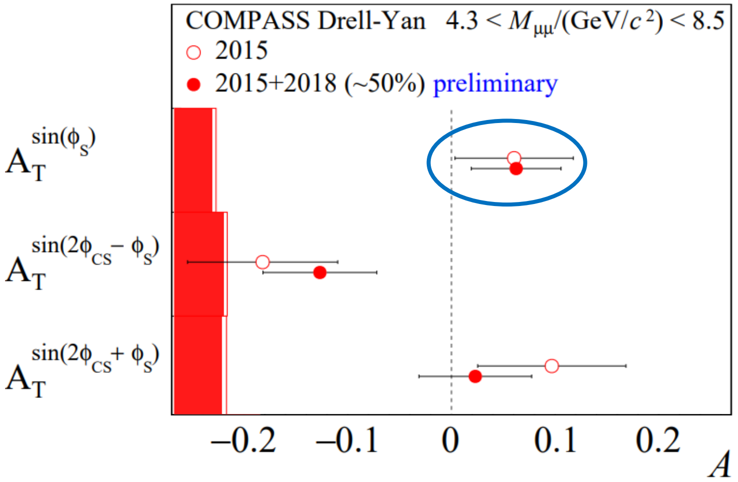
COMPASS, PLB **770**(2017), 138.

Sivers

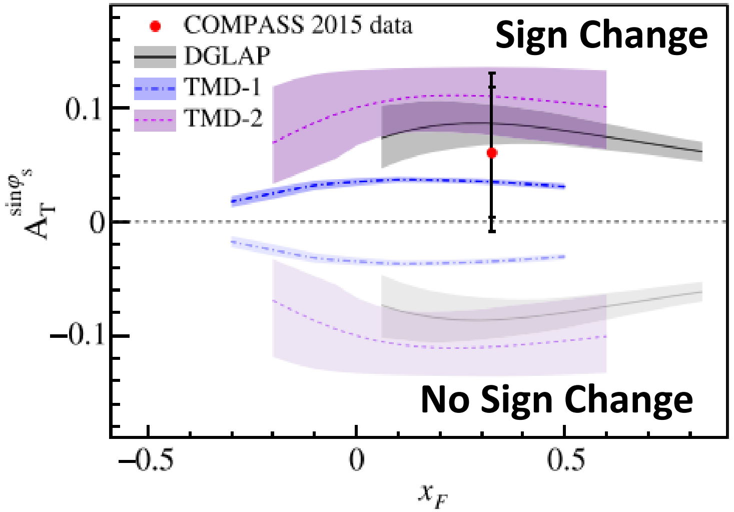
Transv.

Pretz.

TSAs from DY @ COMPASS



Comparing experimental DY Sivers TSA with theory predictions



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

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

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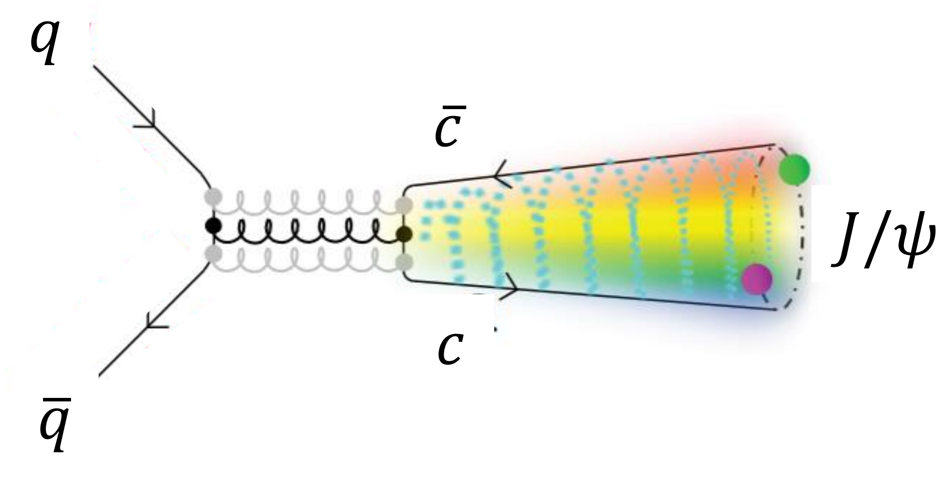
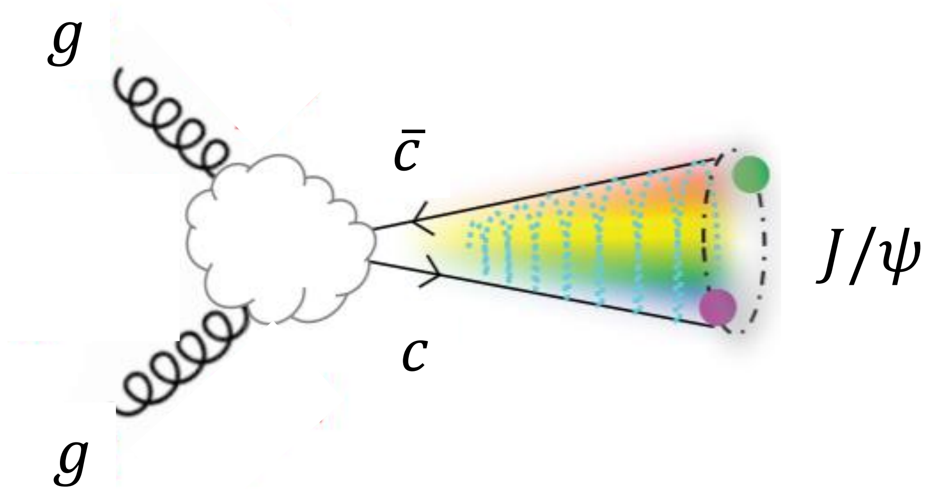
J/ψ production in pion-proton collisions

Two leading order J/ψ production processes





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

- Sensitive to quark TMDs
- Can complement DY results

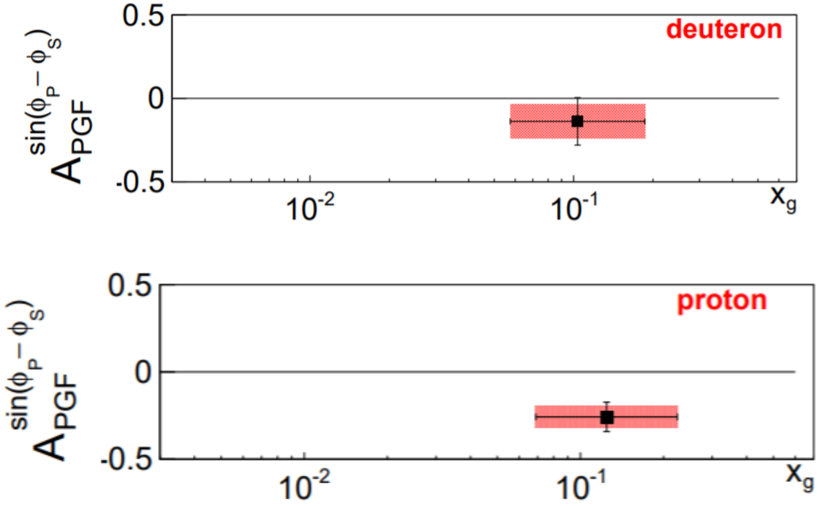
Gluon-gluon (gg) fusion

- Sensitive to gluon TMDs

Diagrams courtesy of Pietro Faccioli

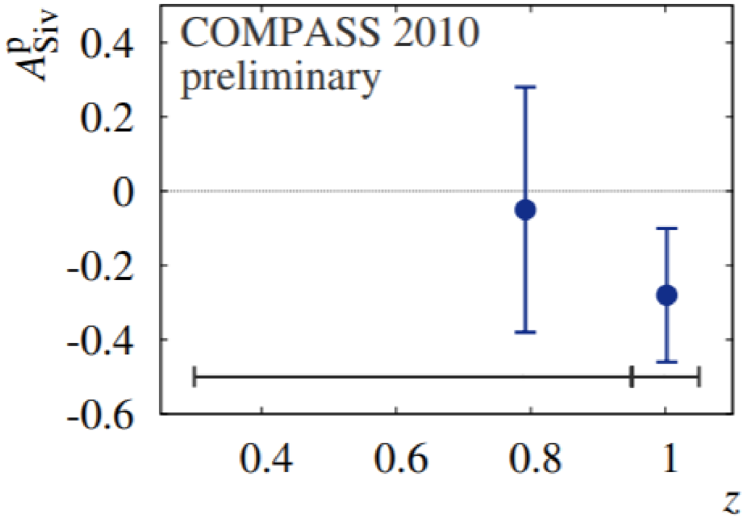
Further gluon Sivers studies would be valuable

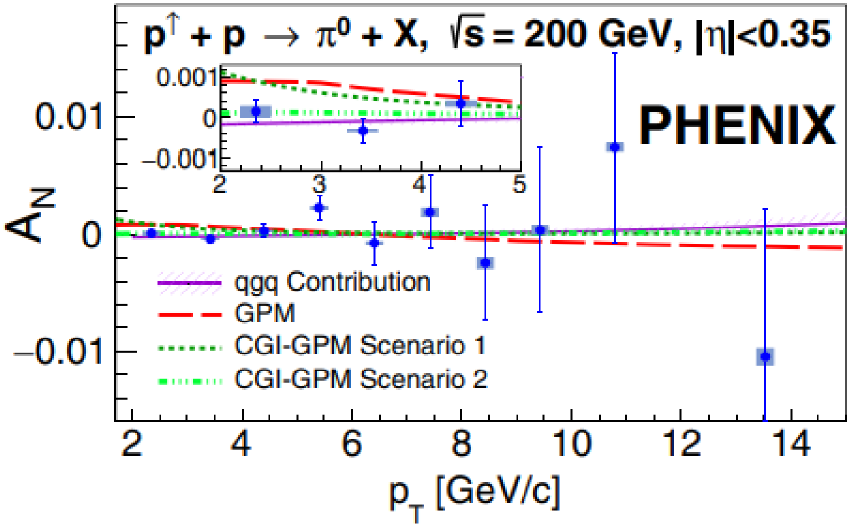
- COMPASS measured a gluon Sivers effect two sigma below zero in photon-gluon fusion
- COMPASS measured a similar size effect in exclusive J/ψ leptoproduction, but the result at lower z is compatible with zero
- PHENIX found a gluon Sivers effect compatible with zero in π^0 production in pp collisions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



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.

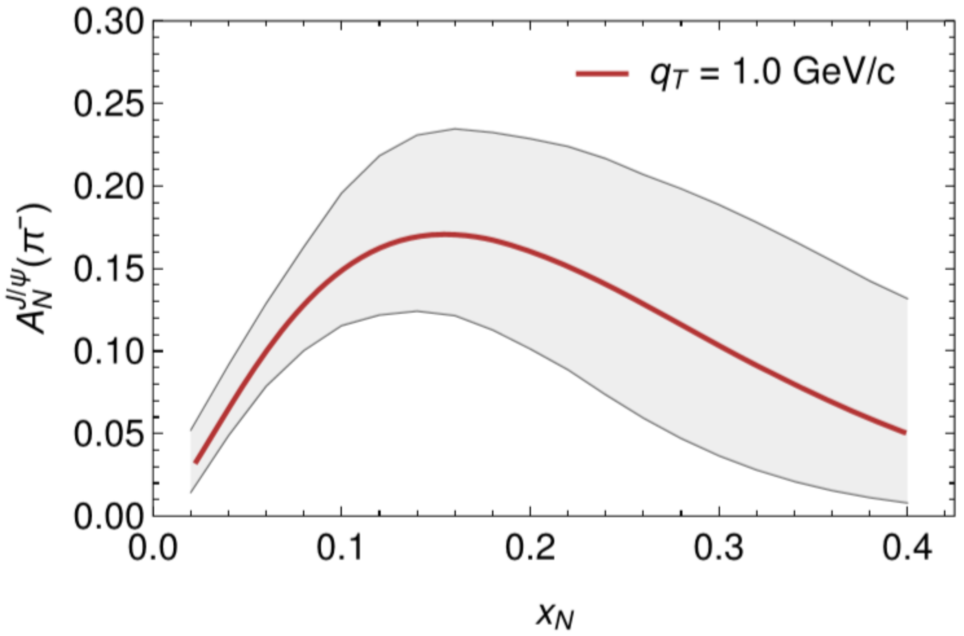
- Calculation assumed only $q\bar{q}$ annihilation and no feed-down J/ψ

- 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 and Outlook

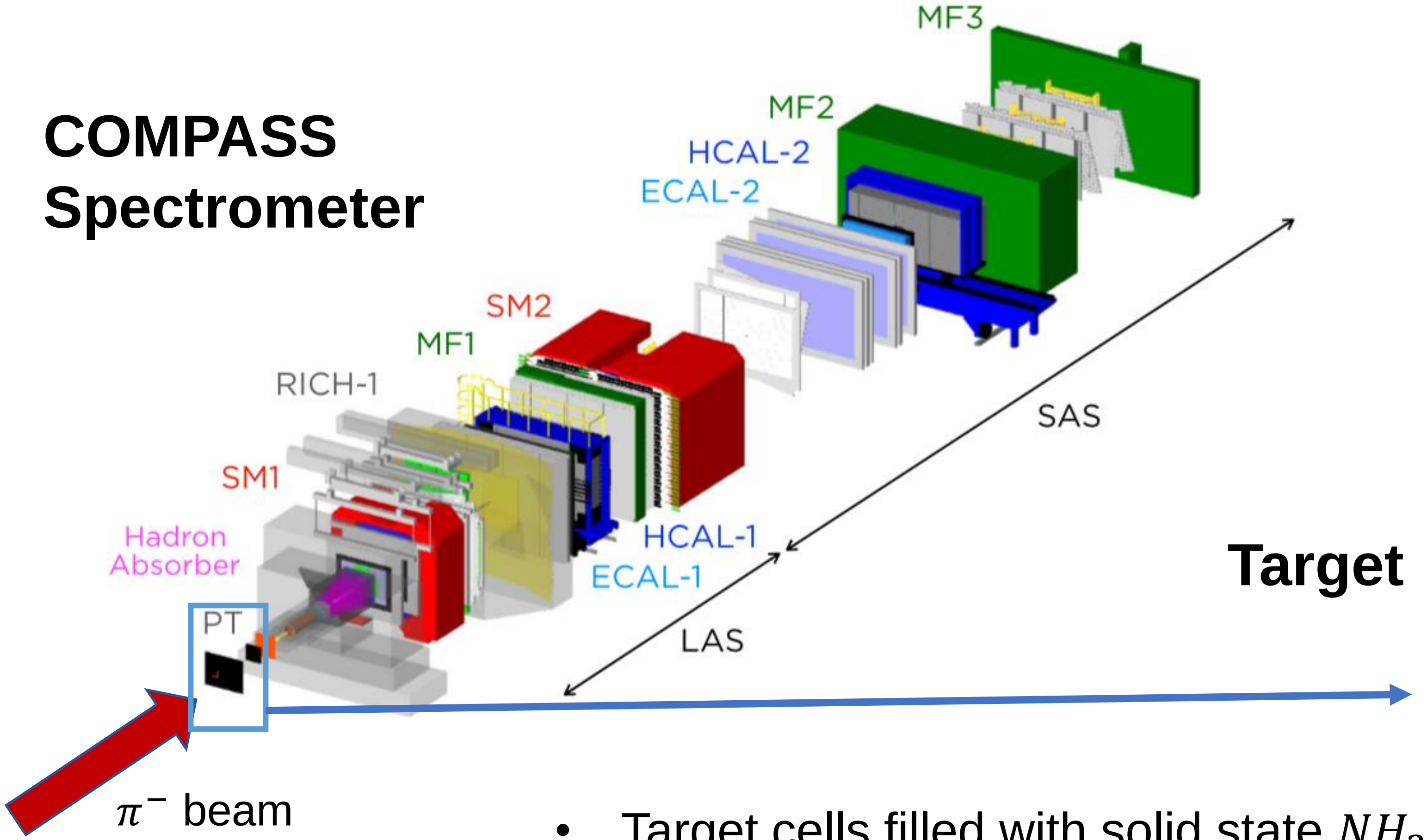
- TMD PDFs describe transverse-momentum dependent behavior of partons inside a nucleon
- Azimuthal asymmetries in COMPASS Drell-Yan data give access to quark Sivers, Pretzelosity, Transversity, and Boer-Mulders TMD PDFs
- From ~70% of total DY data sample:
  - Hint of a non-zero Boer-Mulders effect
  - Sivers TSA results favor sign change prediction
- Ongoing analysis with full data sample should 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

= Nucleon Spin = Quark Spin	Nucleon Polarization		
Quark Polarization	**Unpolarized**	**Longitudinal**	**Transverse**
Unpolarized	f_1 Number Density		$f_{1T}^{\perp}$ — Sivers
Longitudinal		g_1 — Helicity	$g_{1T}^{\perp}$ — Worm-Gear T
Transverse	$h_1^{\perp}$ — Boer-Mulders	$h_{1L}^{\perp}$ — Worm-Gear L	h_1 — Transversity $h_{1T}^{\perp}$ — Pretzelosity

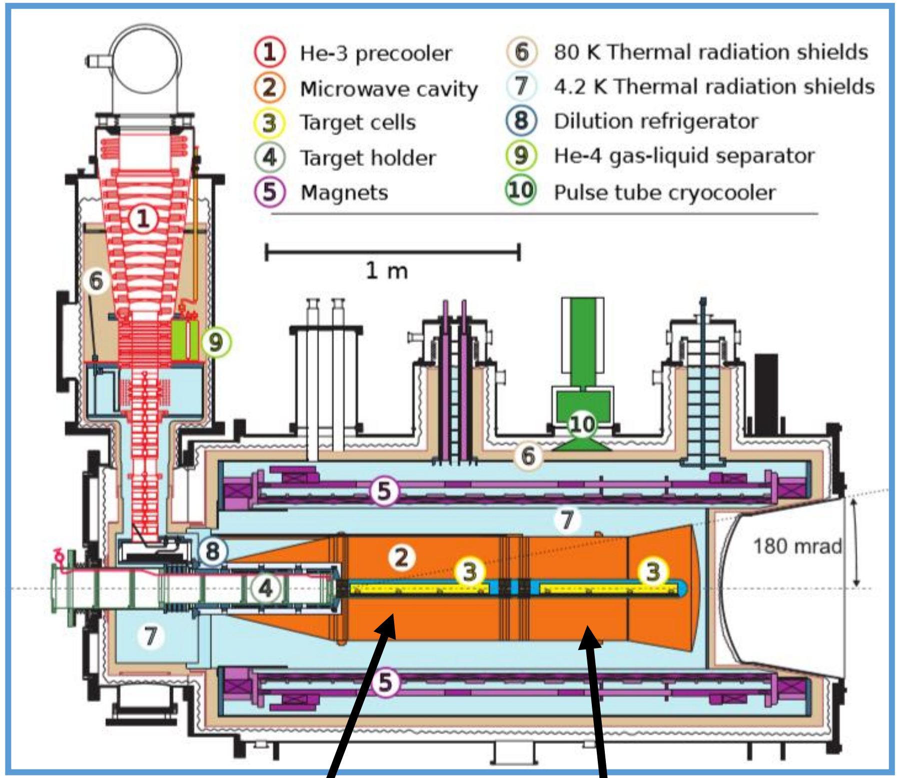
COMPASS setup during DY runs (2015, 2018)

COMPASS Spectrometer



π^- beam
190 GeV/c

Target

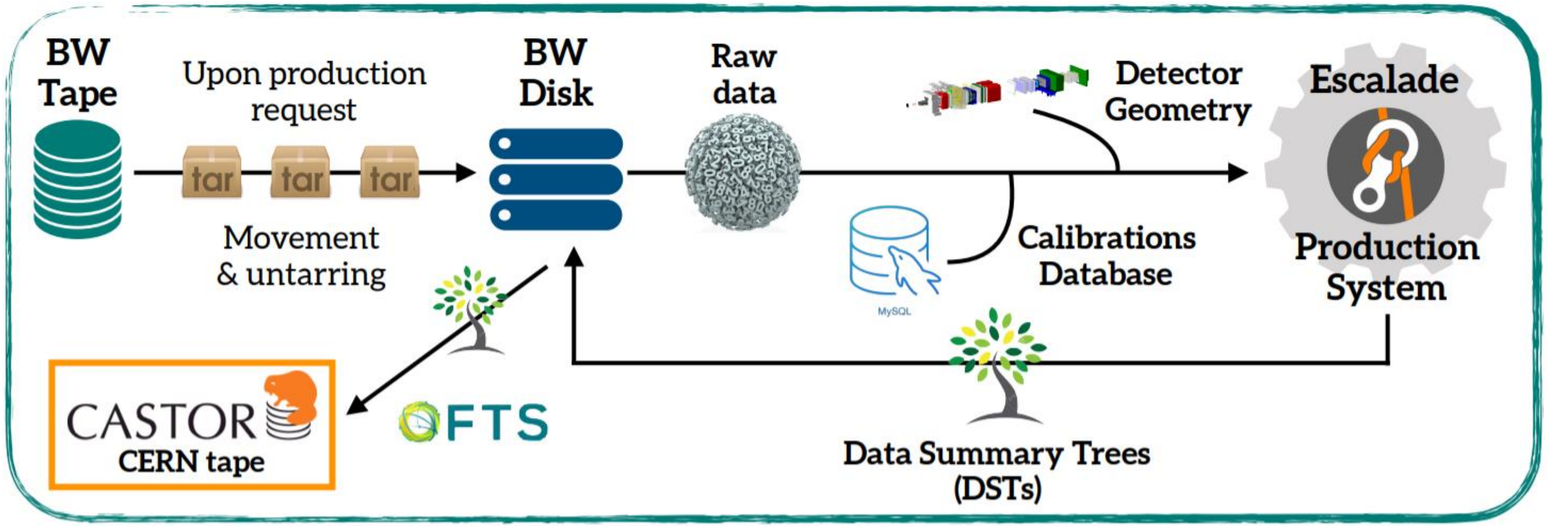


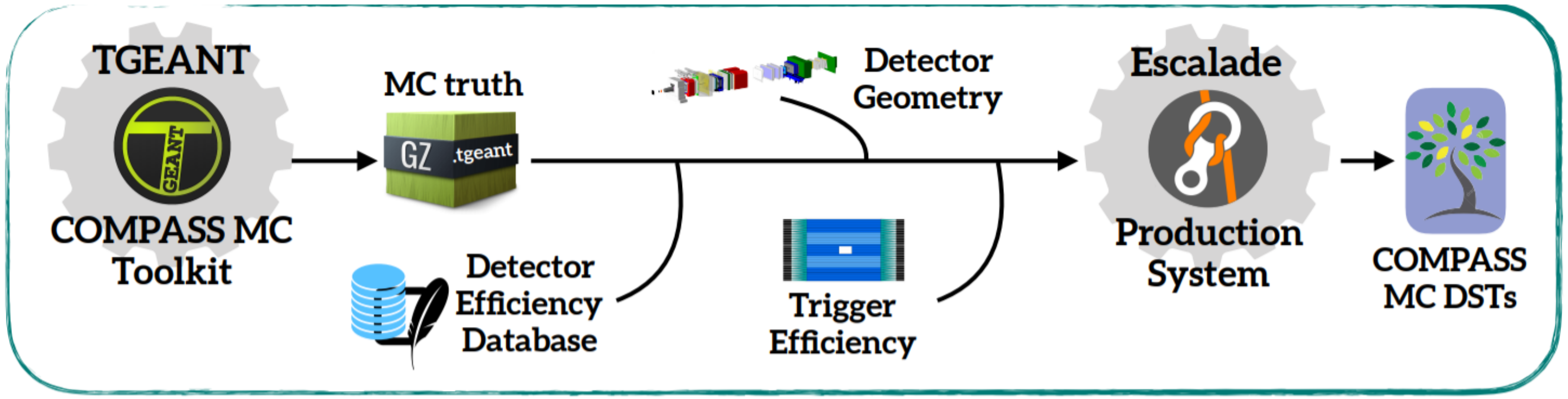
Upstream Cell **Downstream Cell**

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

COMPASS Real and Monte-Carlo (MC) Data Production on Supercomputers

- Digital raw data reconstructed into physics quantities using COMPASS Reconstruction and Analysis Libraries (CORAL)
  - 2 PB of raw data from 2015/2018 DY runs
- MC simulation 'raw data' also reconstructed with CORAL and used to study detector performance
- High performance parallel computing resources needed for real and MC data production
- Utilize allocations on NSF-funded Blue Waters and now Frontera





Unbinned Maximum Likelihood Method of TSA Extraction

Maximize likelihood function → Minimize negative log likelihood function

$$\mathcal{L}(x, \vec{A}) = \prod_{i=1}^{N} f(x_i, \vec{A}) \longrightarrow -\ln \mathcal{L}(x, \vec{A}) = -\sum_{i=1}^{N} \ln f(x_i, \vec{A})$$

Probability distribution function (pdf) for target cell i with polarization $\pm$:

$$\begin{aligned} f_{i\pm}(\phi_S, \phi, \theta, \vec{A}) = 1 &+ D_{[\sin(2\theta)]} \boxed{A_U^{\cos(\phi)}} \cos(\phi) + D_{[\sin^2(\theta)]} \boxed{A_U^{\cos(2\phi)}} \cos(2\phi) \\ &\pm |S_T| \Big[\boxed{A_T^{\sin(\phi_S)}} \sin(\phi_S) \\ &+ D_{[\sin^2(\theta)]} \left(\boxed{A_T^{\sin(2\phi+\phi_S)}} \sin(2\phi + \phi_S) + \boxed{A_T^{\sin(2\phi-\phi_S)}} \sin(2\phi - \phi_S) \right) \\ &+ D_{[\sin(2\theta)]} \left(\boxed{A_T^{\sin(\phi+\phi_S)}} \sin(\phi + \phi_S) + \boxed{A_T^{\sin(\phi-\phi_S)}} \sin(\phi - \phi_S) \right) \Big] \end{aligned}$$

11 unknowns: 2 unpolarized asymmetries, 5 TSAs, 4 normalization factors (1 per pdf)

Unbinned Maximum Likelihood Method of TSA Extraction

Extended UBML: add a Poissonian term to the likelihood function:

$$-\ln \mathcal{L}(\vec{A}) = \sum_{(i=1,2)} \sum_{(\text{sign}=+,-)} \left[I_{i,\text{sign}} - \sum_{n=1}^{N_{i,\text{sign}}} \ln\Big(C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta, \vec{A}) \Big) \right]$$

$$I_{i,\text{sign}} = \int C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta)\, \mathrm{d}\phi_S\, \mathrm{d}\phi\, \mathrm{d}\theta = 8\pi^2 C_{i,\text{sign}}$$

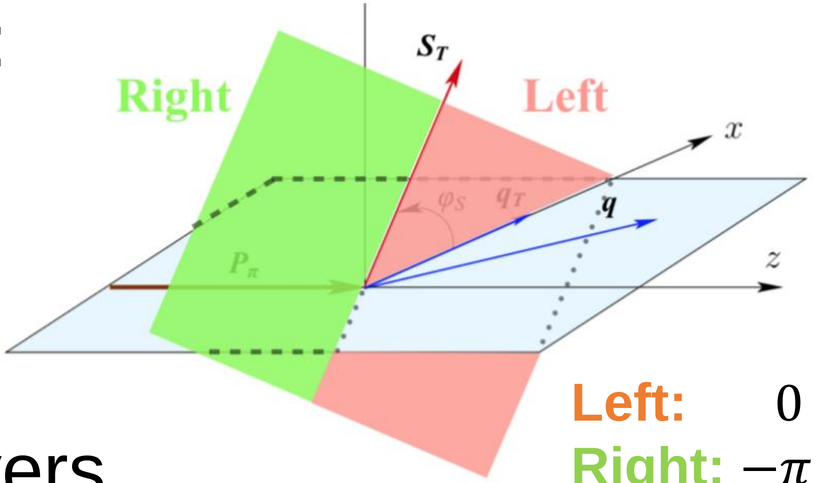
Reweight each term to account for finite statistics

$$\boxed{-\ln \mathcal{L}(\vec{A}) = \sum_{(i=1,2)} \sum_{(\text{sign}=+,-)} \left[\frac{\bar{N}}{N_{i,\text{sign}}} \left(8\pi^2 C_{i,\text{sign}} - \sum_{n=1}^{N_{i,\text{sign}}} \ln\Big(C_{i,\text{sign}} f_{i,\text{sign}}(\phi_S, \phi, \theta, \vec{A}) \Big) \right) \right]}$$

Left-right asymmetry A_N also related to Sivers function

- Another SSA is the left-right asymmetry:

$$A_{lr} = \frac{1}{|S_T|} \frac{\sigma_l - \sigma_r}{\sigma_l + \sigma_r}$$



Left: $0 < \phi_S < \pi$
Right: $-\pi < \phi_S < 0$

- Analyzing power A_N is related to the Sivers function in a similar way to $A_T^{\sin(\phi_S)}$:

$$A_N = \frac{\pi}{2} A_{lr}$$