Transverse Single-Spin Asymmetries of Midrapidity π^0 and η mesons in $\sqrt{s_{NN}} = 200$ GeV $p^{\uparrow}$+Au and $p^{\uparrow}$+Al Collisions from PHENIX

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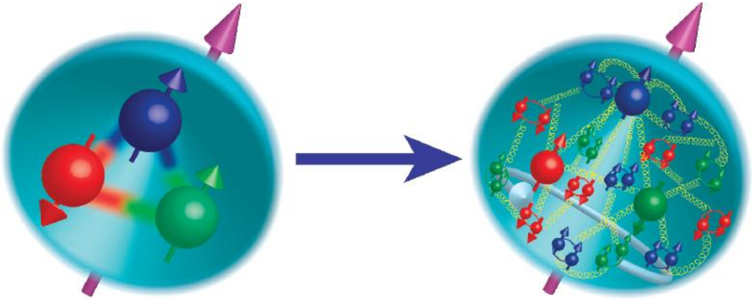
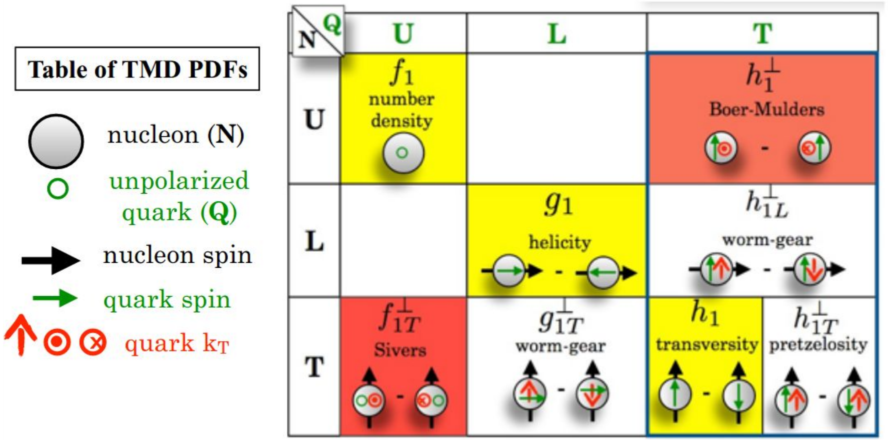
Spin Physics and Proton Structure

Our understanding of proton structure in terms of constituent quarks and gluons has evolved greatly in the past few decades

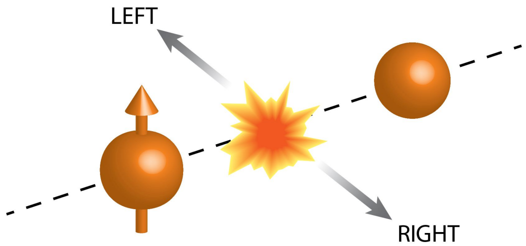


- We know that valence quarks do not carry all of the proton spin…
  - How is the spin of quarks and gluons correlated with proton spin?
  - How is the orbital motion of quarks and gluons correlated with proton spin?

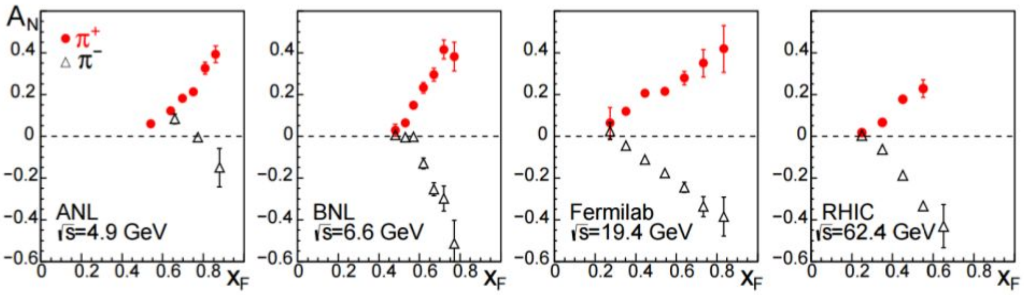


Transverse Single Spin Asymmetries (TSSAs)

- $p^{\uparrow} + p$ or $p^{\uparrow} + A$ initial state
- Measure particle production on either side of the polarized proton-going direction (measure azimuthal asymmetry)
- Perturbative QCD predicted to contribute negligibly to TSSAs in the past (<1%)*
    - Recent calculations suggest possible contributions at 2 loops (PRD100, 094027)
- Large TSSA measurements imply nonperturbative spin-momentum and spin-spin correlations within proton



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



**

$x_F = 2p_Z/\sqrt{s}$

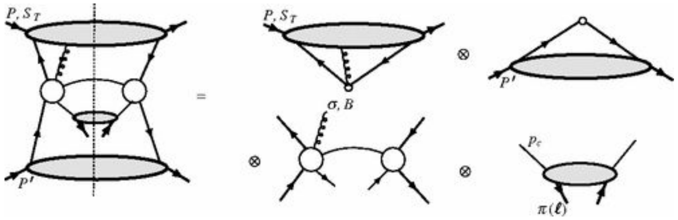
*G. L. Kane, J. Pumplin, and W. Repko PRL 41, 1689 (1978).
C.A. Aidala, S.D. Bass, D. Hasch, and G.K. Mallot, Rev. Mod. Phys. **85 655 (2013).

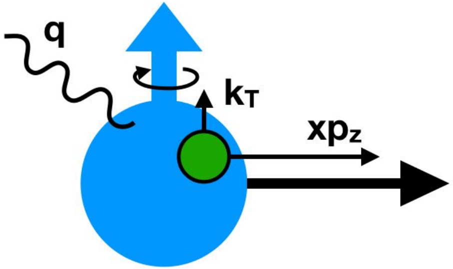
Transverse Single Spin Asymmetries (TSSAs)

Theoretical frameworks for describing measured TSSAs

- **Higher Twist Effects**
  - Collinear, so only need one hard scale (Q)
    - Access via p_T of measured particle
  - Need higher twist (i.e. twist 3) to describe observed TSSAs
    - **Higher Twist:** Power suppressed terms in factorization expansion by $(1/Q)^{n-2}$
      - Twist 3 suppressed by 1/Q
- **Transverse Momentum Dependent Functions (TMDs)**
  - Explicit dependence on transverse momentum of partons within the proton
  - Need access to both a hard and soft scale with sufficient scale separation (i.e. Q and k_T with Q >> k_T)

Quantum interference between 2 → 2 process and itself with extra gluon with similar x





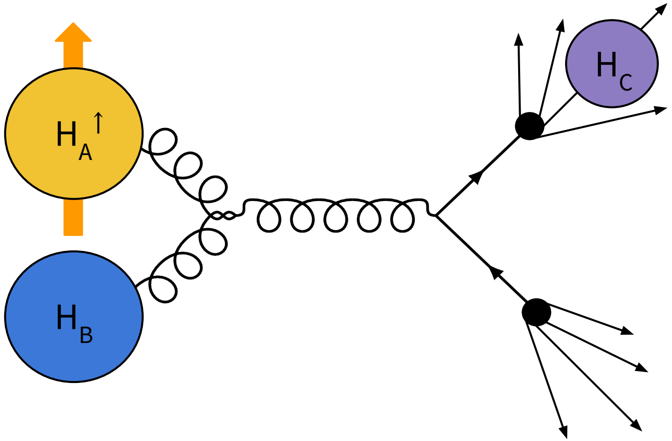
Unification of two frameworks has been demonstrated

$$T_{q,F}(x,x) = \frac{1}{M_p} \int d^2\vec{k}_\perp \vec{k}_\perp^2 q_T(x, k_\perp)^*$$

Twist 3 correlator (qgq) **Sivers TMD PDF**

*Kang, Qiu, Vogelsang, Yuan, PRD78, 114013

Twist 3 Correlators



$$A_N \propto \sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to C}(z) + \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}' \otimes D_{c\to C}(z) + \sum_{abc} \delta q_{a/A}(x, \vec{s}_\perp) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}'' \otimes D^{(3)}_{c\to C}(z_1, z_2).$$ *

- Terms with A, B in subscript → initial state effects
- Terms with C in subscript → final state effects
- Terms with (3) in superscript → twist 3 correlators

Measuring A_N for different final state particles gives access to specific terms in the sum

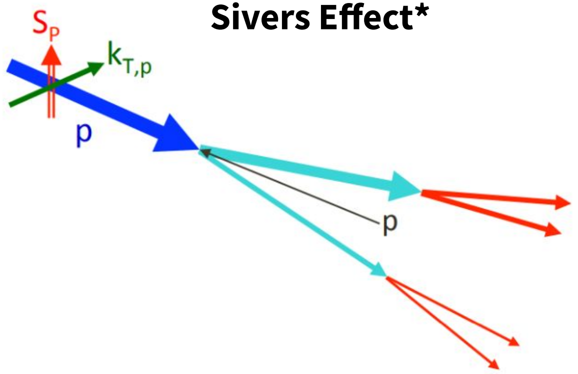
π^0 and η production is sensitive to initial and final state spin-momentum correlations, related to the Sivers (initial state) and Collins (final state) effects

*PRD 74 114013 (2006)

Transverse Momentum Dependent Functions

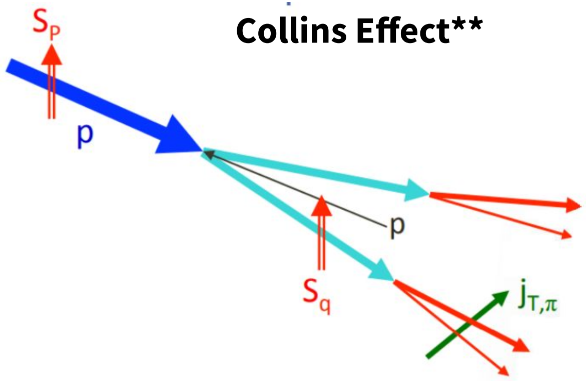
The following mechanisms are expected to contribute to TSSAs for π^0 and η production in hadronic collisions

Sivers Effect*



Initial state correlation between proton spin (S_p) and parton transverse momentum (k_T) → polarized proton generates asymmetric PDF

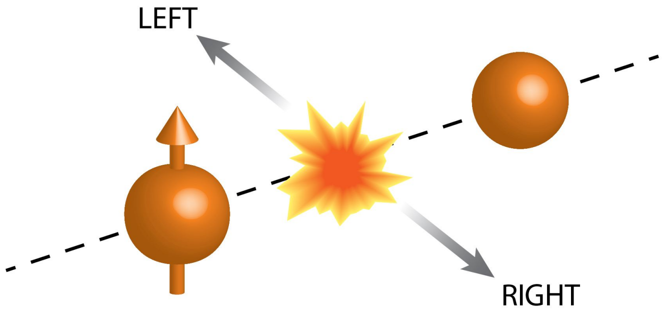
Collins Effect**

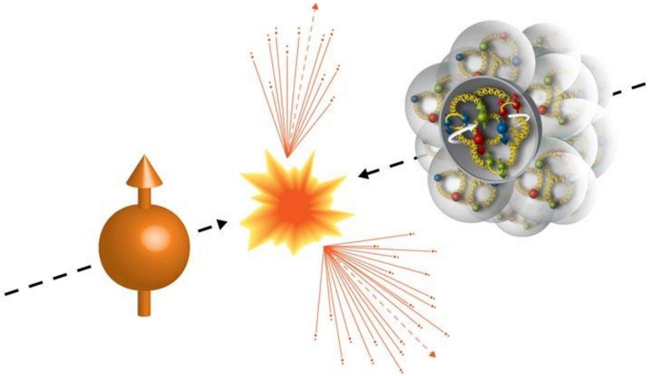


Convolution of Collins fragmentation function [final state correlation of quark spin (S_q) and hadron transverse momentum w.r.t. quark momentum (j_T)] and transversity [initial state correlation of proton spin (S_P) and quark spin (S_q)] → polarized quark undergoes asymmetric fragmentation

*Phys.Rev.D 41 (1990) 83; **Nucl.Phys.B 396 (1993) 161-182
Figures from L. Nogach 2006 RHIC AGS Users Meeting

TSSAs in p+A Collisions





The 2015 RHIC dataset is the only collider dataset with polarized proton on heavy nuclei collisions --- what can we learn from this?

- How are transverse spin observables affected by the extended nuclear environment?
  - In a factorized picture, one would expect only modification to final state spin-momentum correlations in the process of hadronization as scattered partons pass through nuclear matter, while initial state spin-momentum correlations are unmodified
  - Allowing for factorization breaking effects, the larger nuclear remnant in p+A collisions could potentially modify the observed TSSAs (PRD 81 094006 (2010), PRD 88 014002 (2013))

- Potential to probe gluon saturation effects in the nucleus (Phys.Rev.D 84 (2011) 034019)

Below the saturation scale $\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}}$

Above the saturation scale $\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \gg Q_s^2} \approx 1$

Existing Collider p+A TSSA Measurements

- Charged hadron TSSA at intermediate rapidity ($1.4 < |\eta| < 2.4$) [PHENIX] -- See Jeongsu Bok's talk Tuesday @ 16:30
  - https://inspirehep.net/literature/1725616 (A dependence)
  - https://inspirehep.net/literature/2641474 (p_T and x_F dependence)
  - These measurements show strong nuclear suppression of A_N for charged hadrons at intermediate rapidity
- J/ψ TSSA at intermediate rapidity ($1.2 < |\eta| < 2.2$) [PHENIX]
  - https://inspirehep.net/literature/1671782
  - p+p and p+A are mostly consistent, further investigation is needed for low p_T p+Au asymmetries
- π^0 TSSA at forward rapidity ($2.7 < \eta < 3.8$) [STAR]
  - https://inspirehep.net/literature/1836342
  - These measurements show moderate nuclear suppression of A_N for π^0 at forward rapidity
- neutron TSSA at far forward rapidity ($\eta > 6.8$) [PHENIX]
  - https://inspirehep.net/literature/1520869 (A dependence)
  - https://inspirehep.net/literature/1944868 (p_T and x_F dependence)
  - These measurements show strong nuclear dependence of A_N for neutrons at far forward rapidity, understood to be due to the interplay of electromagnetic and hadronic interactions in ultra peripheral collisions
- π^0 and η TSSA at midrapidity ($|\eta| < 0.35$) -- **Presented in this talk**
  - https://inspirehep.net/literature/2641468

In summary: p+A TSSA data have yielded surprises and more investigation is needed to understand and interpret what has been measured

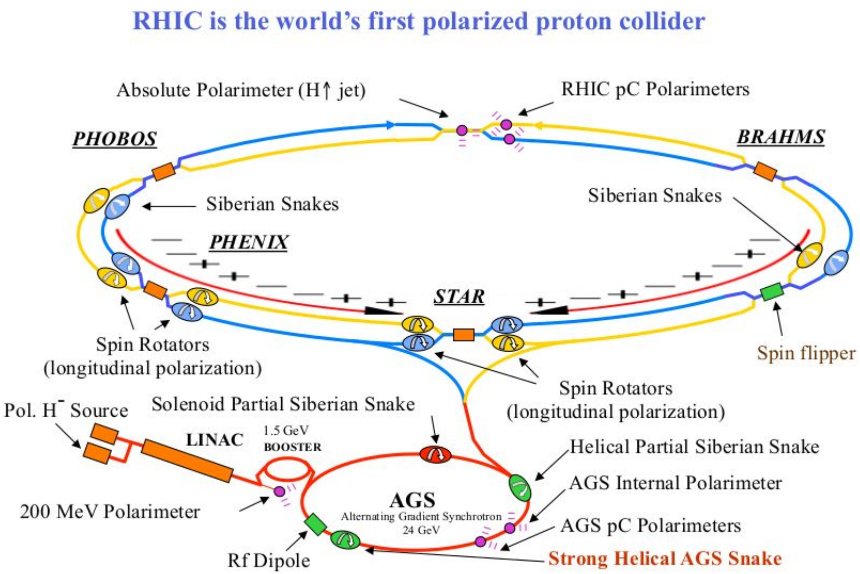
Spin Physics at RHIC

Extremely versatile collider!

- World's first polarized p+p collider
  - As well as $p^{\uparrow}$+Al, $p^{\uparrow}$+Au
- Capable of running with various collision energies and collision species
- Home to general purpose detectors (s)PHENIX and STAR

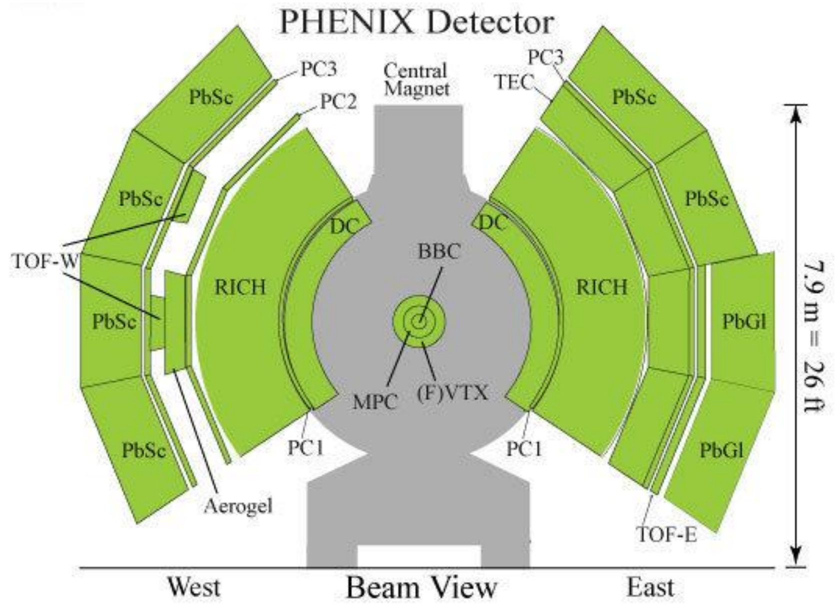
Collisions with polarized proton beams allow for a vast spin physics program

- A richer substructure of the nucleon can be studied when polarization is taken into account



Midrapidity π^0 and η Detection at PHENIX

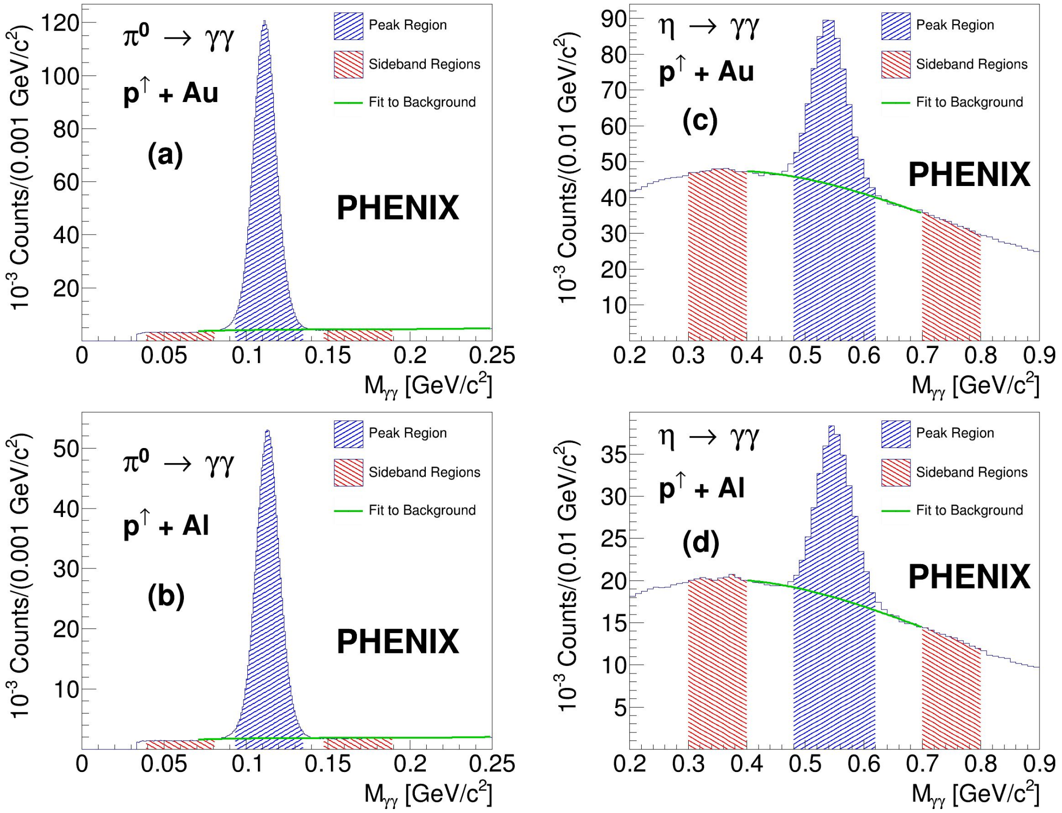
- **Acceptance:** $\Delta\phi = 0.5\pi$ per arm, $|\eta| < 0.35$
- Electromagnetic Calorimeter (EMCal) measures energy deposits
  - Primary detector for photons
- EMCal trigger
  - Used in coincidence with a minimum bias trigger to select high p_T photons
- Drift chamber (DC) and pad chambers (PCs) measure charged particle momenta
  - Used to veto charged tracks



π^0 and η identification at PHENIX

[arXiv:2303.07190] **(Submitted to PRD)**

- Time-of-flight: |TOF| < 5 ns
- Photon energy: $E_\gamma > 0.5$ GeV
- Charged track veto
- Trigger photon is paired with another measured in the same spectrometer arm
- Energy asymmetry: $\alpha = |E_1 - E_2|/(E_1 + E_2) < 0.8$
- Signal regions (blue regions)
  - π^0: ± 25 MeV/c^2 from mass peak
  - η: ± 70 MeV/c^2 from mass peak
- Background regions (red regions)
  - π^0: 47-97 ∪ 177-227 MeV/c^2
  - η: 300-400 ∪ 700-800 MeV/c^2
- Background fit (green lines)
  - 3^{rd} order polynomial, used to quantify the background fraction
- **All Panels:** 4 < p_T [GeV/c] < 5 ; West Spectrometer Arm



Analysis Procedure

TSSA Observable

A_N is calculated using the Relative Luminosity formula, integrating over the ϕ ranges of the east and west arms

$$A_N = \frac{1}{P\langle cos(\phi)\rangle}\frac{N^{\uparrow} - \mathcal{R}N^{\downarrow}}{N^{\uparrow} + \mathcal{R}N^{\downarrow}}$$

$\mathcal{R} = \mathcal{L}^{\uparrow}/\mathcal{L}^{\downarrow}$
(relative luminosity)

Background Correction

Once A_N is calculated, it must be corrected for background as follows

$$A_N^{\text{sig}} = \frac{A_N - r \cdot A_N^{\text{BG}}}{1 - r}$$

A_N : calculated in (blue) signal regions in the $M_{\gamma\gamma}$ spectrum

A_N^{BG} : calculated in (red) side-band regions in the $M_{\gamma\gamma}$ spectrum

r : calculated from (green lines) third order polynomial fit to $M_{\gamma\gamma}$ spectrum

Cross checks and systematic studies

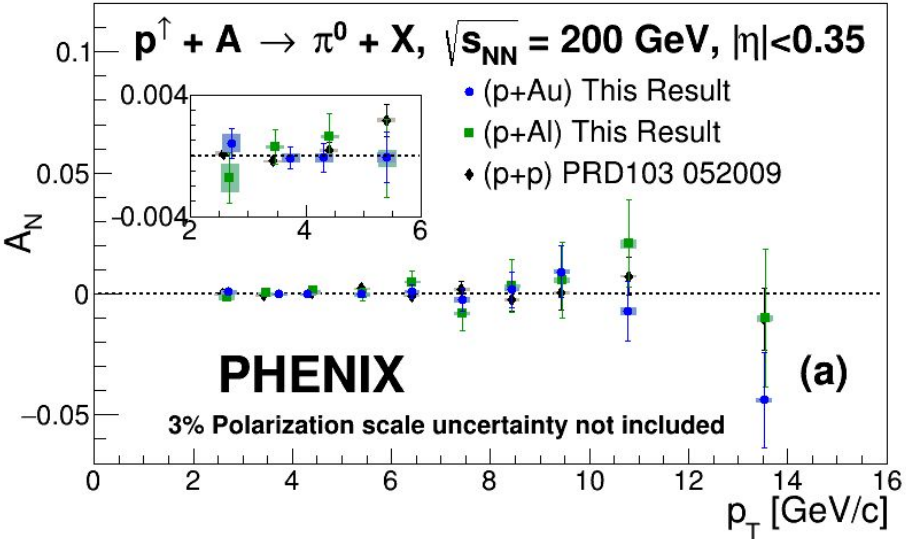
- Geometric mean formula (Square Root formula)
  - $|A_N^{sqrt} - A_N^{Lumi}|$ taken as systematic
- cosϕ modulation fit $A_N \cdot \cos\phi_s = \frac{1}{P}\frac{N^{\uparrow}(\phi_s) - R \cdot N^{\downarrow}(\phi_s)}{N^{\uparrow}(\phi_s) + R \cdot N^{\downarrow}(\phi_s)}$
  - 3 ϕ bins per arm
- Bunch shuffling
  - Randomize polarization direction, measure A_N/σ_{AN} to determine if deviations of A_N from 0 are consistent with statistical uncertainty
- Propagation of systematics on background fractions through background correction formula
  - Adjust fit range of third order polynomial to obtain uncertainty on r

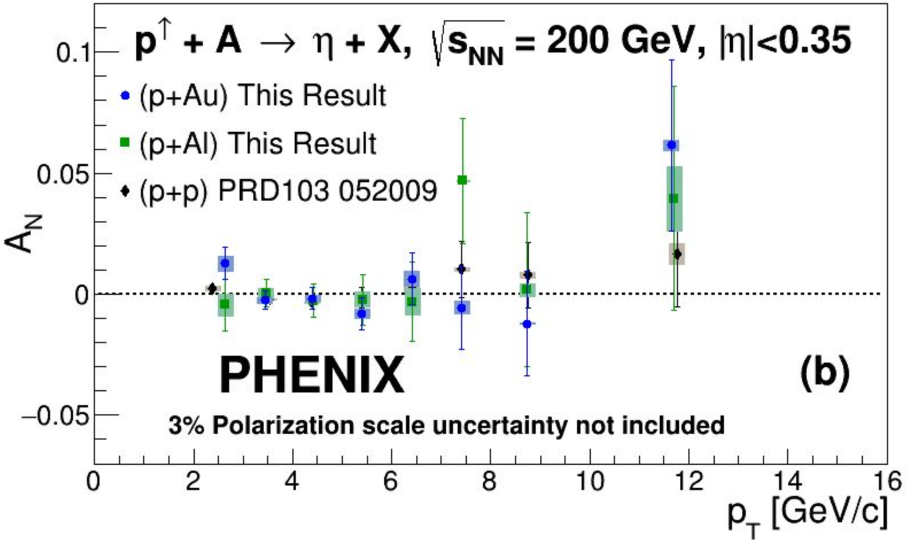
Midrapidity π^0 and η Transverse Single-Spin Asymmetry

[arXiv:2303.07190](Submitted to PRD)

Consistent with p+p measurement (PRD103 052009 (2021)) and zero across the entire p_T range for both meson species and collision systems

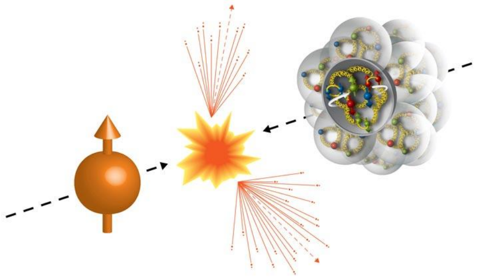
- No nuclear modification of the TSSAs is observed





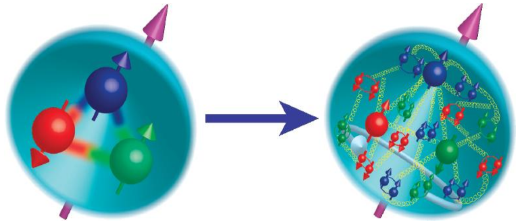
Summary

- Transverse single spin asymmetries of π^0 and η mesons provide access to nonperturbative parton-hadron spin-momentum correlations within the proton and hadronization process



- TSSA measurements in p+A collisions provide an interesting opportunity to study transverse spin effects in the presence of a more complex nuclear environment

- First measurement of midrapidity π^0 and η meson A_N in p+A collisions [arXiv:2303.07190] **(Submitted to PRD)**
    - $p^{\uparrow}$+ Au and $p^{\uparrow}$+ Al, $\sqrt{s_{NN}} = 200$ GeV, $|\eta| < 0.35$
    - Consistent with 2015 $p^{\uparrow}$ + p measurements and zero
        - No evidence of modification from the more complex nuclear environment in p+A collisions



- Other results in preparation
    - Forward heavy flavor muon A_N ($p^{\uparrow}$ + p)