The future Cold QCD program with the sPHENIX detector

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- Data collection expected to begin 2023
- Cold QCD Physics Program
  - Parton Dynamics (TMD PDFs)
  - Proton/Nuclear Structure (PDFs)
  - Hadronization + Jet Substructure (FFs, $\hat{q}$, etc.)
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| Year   | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $|z| < 10$ cm | Samp. Lum. $|z| < 10$ cm |
|--------|---------|------------------------|------------|---------------|------------------------|------------------------|
| 2023   | Au+Au   | 200                    | 24 (28)    | 9 (13)        | 3.7 (5.7) nb$^{-1}$     | 4.5 (6.9) nb$^{-1}$     |
| 2024   | $p^+p^-$| 200                    | 24 (28)    | 12 (16)       | 0.3 (0.4) pb$^{-1}$ [5 kHz] | 4.5 (6.2) pb$^{-1}$ [10%-str] |
| 2024   | $p^+Au$ | 200                    | -          | 5             | 0.003 pb$^{-1}$ [5 kHz] | 0.01 pb$^{-1}$ [10%-str] |
| 2025   | Au+Au   | 200                    | 24 (28)    | 20.5 (24.5)   | 13 (15) nb$^{-1}$       | 21 (25) nb$^{-1}$       |
Full azimuthal detector (Central Barrel)

Data collection expected to begin 2023

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Tamamushi, S. (2017)

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sPHENIX Detector
Transverse Spin Measurements in $p^\uparrow + p^{(\uparrow)}$ and $p^\uparrow + \text{Au}$
Sivers Transverse Momentum Dependent PDF

- $f_{1T}^{±}$ = distribution of parton transverse momentum in a transversely polarized proton
  - Can be measured in p+p(Au) systems via jet and photon channels
  - Choice of channel determines sensitivity to particular parton species

- Connected to twist-3 framework
  - Twist-2 $\rightarrow$ traditional PDF/FFs (one incident parton – one fragmenting parton)
  - Twist-3 $\rightarrow$ introduce gluon interaction with incident or fragmenting parton (one incident parton + g – one fragmenting parton | one incident parton – one fragmenting parton + g)
  - E.g. trigluon correlations


Phys. Rev. D 78, 114013
Gluon Dynamics via Transverse Single Spin Asymmetry $A_N$

Direct Photon Asymmetry

- Will be used to constrain twist-3 trigluon correlator in transversely polarized protons
  - Related to $f_{1T}^\perp$ of gluons in the proton
- Insensitive to hadronization effects at LO

\[ A_N(\phi_q) = \frac{1}{P} \frac{Y^\uparrow - R \cdot Y^\downarrow}{Y^\uparrow + R \cdot Y^\downarrow} = \frac{1}{P} \frac{L(\sigma^\uparrow(\phi_q) - R \cdot \sigma^\downarrow(\phi_q))}{L(\sigma^\uparrow(\phi_q) + R \cdot \sigma^\downarrow(\phi_q))} \]

\[\text{Phys. Rev. C 92, 014907}\]
Heavy Flavor Asymmetry

- Will be used to constrain twist-3 trigluon correlator in transversely polarized protons
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- Insensitive to hadronization effects at LO
- $A_N(\phi_q) = \frac{1}{P} \frac{Y^\uparrow - R \cdot Y^\downarrow}{Y^\uparrow + R \cdot Y^\downarrow} = \frac{1}{P} \frac{L(\sigma^\uparrow(\phi_q) - R \cdot \sigma^\downarrow(\phi_q))}{L(\sigma^\uparrow(\phi_q) + R \cdot \sigma^\downarrow(\phi_q))}$
- Possible due to sPHENIX streaming DAQ
  - 10% of collisions will be recorded in this triggerless configuration
Gluon Dynamics via Transverse Single Spin Asymmetry $A_N$

Gamma-jet Asymmetry

- Gluon-induced Compton scattering
  - Constrain gluon $p_T$ distribution in polarized proton
  - sPHENIX is designed to be a jet detector due to the relevance of this and similar channels to heavy-ion physics

![Graph showing $A_N$ vs. $y_{jet}$ with different $M_{jet}$ ranges and colored markers representing different energy thresholds.](image-url)
Parton Dynamics via $A_N$

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Dijet Asymmetry

- Sensitive to gluon and light quark Sivers TMD PDFs
- Charge-tagging for flavor-dependent Sivers asymmetry measurement
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Both channels constrain LO parton kinematics

Nuclear Effects in $A_N$

Charged hadron Asymmetry

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- $s$PHENIX to improve statistics in this region of $x_F$
  - Specifically for $p^{↑}+p^{↑}$ and $p^{↑}+Au$ data points
  - Finer binning is expected
Unpolarized Measurements in $p+p$ and $p+Au$
Nuclear Effects in Hadronization

- Due to sPHENIX Central Barrel and Vertex Detector
  - Direct photons and charged hadrons up to ~45 GeV
  - Jets up to ~70 GeV
- Nuclear modification of hadron-in-jet distributions planned

sPH-TRG-2020-001
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  - w.r.t. z, $j_T$, r, etc.

\[
z = \frac{p_j \cdot p_h}{|p_j|^2} \quad j_T = \frac{|p_j \times p_h|}{|p_j|} \quad r = \sqrt{(\phi_h - \phi_j)^2 + (y_h - y_j)^2}
\]
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- Similarly, can measure transport coefficient for gamma-jet systems
  - \( \langle \hat{q}L \rangle / 2 \equiv \langle p_{\text{out}}^2 \rangle_{pA} - \langle p_{\text{out}}^2 \rangle_{pp} \)


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Constraining nPDFs

- nPDFs unconstrained at low $Q^2$

Phys. Rev. D 100, 014004
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- Measurement of nuclear modifications can be used to constrain existing nPDFs
- Channels expected for simultaneous analysis
  - Drell-Yan
  - Dijet
  - Photon-jet

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- Expecting improved uncertainties in gluon and antiquark nPDFs with this method
  - Particularly in shadowing region

*Uncertainties from constraining EPPS16 nPDFs with sPHENIX Central Barrel ("CB") measurements*
Further Prospects

- Sivers via inclusive jet $A_N$
  - Uncertainty expected on the order of $10^{-4}$
  - Complementary study to be done at EIC

- Collins Fragmentation Function
  - $H_1^\perp$ = distribution of in-jet hadron transverse momentum produced by a polarized quark
  - Provides us much needed access to transversity in protons
  - $h_1$ = parton transverse spin polarization in a transversely polarized proton

- Interference Fragmentation Function
  - Coupling between transversity and dihadron hadronization
  - Measured via dihadron angular distributions
Summary

- sPHENIX is actively constructing a cold QCD program that will provide much needed constraints and measurements for parton dynamics and cold nuclear effects during our 2024 $p^\uparrow + p(\uparrow)$ and $p^\uparrow + Au$ runs

- Transverse spin dependent observables grant us access to
  - Gluon dynamics via photon, photon-jet (new), heavy flavor, and dijet asymmetries
  - Quark dynamics via charge-tagging in dijet channel
  - $A_N$ nuclear and pseudorapidity dependencies via inclusive hadron measurements

- Spin-independent measurements at sPHENIX will contribute to understanding of transport coefficients as well as the nuclear modification of
  - Direct photons, charged hadrons, and inclusive jet production
  - Heavy flavor distributions in jets
  - Gluon and antiquark PDFs via Drell-Yan, dijet, and photon-jet channels in p+Au

*Additional Collaborators Welcome!*
Backup
$p_{out}$ Distribution
Compton Scattering Dominance