New p+p and p+A Physics Opportunities with the Forward sPHENIX Upgrade at RHIC

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(for the PHENIX Collaboration)
Relativistic Heavy Ion Collider at BNL in operation since 2000
RHIC Highlights
Where to go next?

• Discovery of Quark Gluon Plasma (QGP)
  – Strongly interacting QGP
  – Gluon saturation at small-x, CGC etc

• Surprises continue from spin program
  – “small” gluon spin contribution
  – “large” transverse spin asymmetry

• New questions arose:
  – The nature of strongly interacting QGP
    --> super-PHENIX
  – Nucleon 3-D structure, nPDFs and QCD dynamics
    --> Forward sPHENIX -> eRHIC Detector
## Brookhaven Lab Proposed 10 Year Plan

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
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</thead>
<tbody>
<tr>
<td>2014</td>
<td>15 GeV Au+Au, 200 GeV Au+Au</td>
<td>Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies, QCD critical point search</td>
<td>Electron lenses, 56 MHz SRF, STAR HFT, STAR MTD</td>
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<td>2015-16</td>
<td>p+p at 200 GeV, p+Au, d+Au, 3He+Au at 200 GeV, High statistics Au+Au</td>
<td>Extract $\eta/s(T) +$ constrain initial quantum fluctuations, More heavy flavor studies, Sphaleron tests, Transverse spin physics</td>
<td>PHENIX MPC-EX, Coherent e-cooling test</td>
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<td>2017</td>
<td>No Run</td>
<td></td>
<td>Low energy e-cooling upgrade</td>
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<tr>
<td>2018-19</td>
<td>5-20 GeV Au+Au (BES-2)</td>
<td>Search for QCD critical point and onset of deconfinement</td>
<td>STAR ITPC upgrade, Partial commissioning of sPHENIX (in 2019)</td>
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<tr>
<td>2020</td>
<td>No Run</td>
<td></td>
<td>Complete sPHENIX installation, STAR forward upgrades</td>
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<td>2021-22</td>
<td>Long 200 GeV Au+Au with upgraded detectors p+p, p/d+Au at 200 GeV</td>
<td>Jet, di-jet, $\gamma$-jet probes of parton transport and energy loss mechanism, Color screening for different quarkonia</td>
<td>![PHENIX Logo]</td>
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<tr>
<td>2023-24</td>
<td>No Runs</td>
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<td>Transition to eRHIC</td>
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**New Idea: Forward sPHENIX Proposal**
Forward sPHENIX Proposal
(An upgrade path that harvests \textbf{pp, pA and AA} physics and leads to an EIC era)

- Transverse Spin and CNM Physics Centric in the Forward Rapidity
- Significant novel effects observed but not fully understood!
Physics Motivations

Novel Transverse Spin Phenomena
- Origins of large transverse spin asymmetry
- Universality and factorization, p+p v.s. SIDIS
- Nucleon Structure, QCD dynamics and evolution

Cold Nuclear Matter Effects
- Modification of PDFs inside nucleus
- Jet fragmentation and parton energy loss
Possible Origins of Large Transverse SSAs

**Sivers mechanism:**
correlation between proton spin & parton $k_T$

**Collins mechanism:**
Transversity × spin-dep fragmentation

\begin{align*}
A_N \mu & \overline{f}_{1T}^q(x, k_{\perp}^2) \times D_q^h(z) \\
A_N \mu & \delta q(x) \times H_1^\perp(z_2, \vec{k}_{\perp}^2)
\end{align*}

Collinear Twist-3: quark-gluon/gluon-gluon correlation
TMD and Collinear Twist-3

\[ Q \gg Q_T \gtrsim \Lambda_{QCD} \]

Collinear/twist-3

\[ Q, Q_T \gg \Lambda_{QCD} \]
Test the Universality of QCD Descriptions

Are TMD and Twist-3 really consistent?

\[ gT_{q,F}(x, x) = - \int d^2 k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{q}(x, k_\perp^2) \big|_{\text{SIDIS}} \]

Kang, Qiu, Vogelsang, Yuan (2011)

\[ p + p \uparrow \rightarrow \pi(p_T) + X \]

\[ \sin(\theta_h - \phi_s) \]

\[ A_{\text{UT}} \]

\[ x, z, p_T (\text{GeV}) \]
A Surprise: $A_N$ Sign Mismatch?

First attempt to check the “Universality of QCD description of TSSA”

- Twist-3 ($p+p$) v.s. TMD Sivers (SIDIS)

Very active investigations:
- Collins
- Node in Sivers TMD functions
- Twist-3 …
- etc.

Many recent papers and presentations

Kanazawa, Koike, Metz and Pitonyak (2014)

Need new experimental data to test models
Access “Sivers” and “Collins” Asymmetries with Jets

\[
\frac{E_j d\sigma^{A(S_A)B\rightarrow jet+\pi+X}}{d^3 p_j dz d^2 k_{\perp \pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2 k_{\perp a} \\
\times d^2 k_{\perp b} \rho_{\lambda_a \lambda_a'}^{A/A_S} \hat{f}_{a/A_S} (x_a, k_{\perp a}) \rho_{\lambda_b \lambda_b'}^{B/B} \hat{f}_{b/B} (x_b, k_{\perp b}) \\
\times \hat{M}_{\lambda_c, \lambda_c'}^{\lambda_d, \lambda_d'} \hat{M}^*_{\lambda_c', \lambda_d', \lambda_a, \lambda_b} \delta(\hat{s} + \hat{i} + \hat{u}) \hat{D}_{\lambda_c, \lambda_c'} (z, k_{\perp \pi}).
\]

Experimental variables:
- Jet $P_j, x_F$
- Hadrons, Charge and PID
- Beam polarization

Feng Yuan, PRL 100, 032003 (2008)
Umberto D’Alesio et al PRD 83 034021 (2011)
Forward sPHENIX
-1 < eta < 4

- Clearly isolate “Sivers” and “Collins”
- CNM physics, nPDFs and dE/dX
Jet Production Rates @NLO
200GeV p+p: Lumi = 50pb⁻¹

\[ X_1 \sim \frac{E_{\text{jet}}}{100} \]
Access high \(-x\)

\[ Q \sim pT \]
Jet Quark-Flavor Tagging with Charged Hadrons

Jet $+ h^+(z>0.5)$ favors u-quark

Jet $+ h^-(z>0.5)$ favors d-quark
Jet TSSA: Test Process Dependence

- Change of sign in flavor-tagged Jet TSSA

Naïve DIS Fit Sivers

Included 1) process dependence and 2) $Q^2$ evolution
Drell-Yan TSSA: Test Sign Change

- Fundamental test of pQCD factorization and gauge-link formalism
  - Theoretically clean
  - Experimentally challenging
  - TMD (pp) vs TMD (SIDID)

\[ \Delta^N f_{q/h^\uparrow}^{\text{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\text{DY}}(x, k_\perp) \]

Kang and Qiu, PRD 84 054020
Exchevarria et. al., arXiv 1401.5078
Hadron Collins Asymmetry in Jets

- Test universality of Collins FF
- SIDIS vs pp
  - TMD
  - Twist-3

Jet + h^{+/−} Collins Asymmetry: A_N vs Z

10 GeV < Jet E < 100 GeV

Collins asymmetry on proton

charged hadrons - published 2007 & 2010 data results

very good agreement between the two independent data sets
combined 2007 – 2010 results

• precise measurements
• clear signal at x > 0.3, with opposite sign for h+ and h−
p+A Physics: from Nucleon to Nucleus

Are parton distributions modified significantly inside nucleus?

- **(Anti)Shadowing**
  - Gluon saturation/CGC
  - EMC etc.
- **Hadronization**
- **Energy loss $dE/dx$**
Forward J/Psi and Drell-Yan: Small-x Saturation

DY challenges:
- DY background rejection
- Study in progress

Other channels:
- Hadron, jet, J/Psi etc.

\[ R = \frac{\sigma(p+A)}{A \times \sigma(p+p)} \]
Polarized p+A

Forward pi0 TSSA to probe saturation scale

Run 2015: first transverse p+A @RHIC!

See X. Jiang's PHENIX MPC-EX talk (Tue)
**Outlook:** PHENIX -> *Forward/sPHENIX-*->eRHIC


<table>
<thead>
<tr>
<th>Current PHENIX</th>
<th>Forward sPHENIX</th>
<th>An EIC detector</th>
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<tbody>
<tr>
<td>• Current PHENIX as discussed in many previous talks</td>
<td>• <strong>sPHENIX:</strong> comprehensive central upgrade based on BaBar magnet</td>
<td>• Path of PHENIX upgrade leads to a capable EIC detector</td>
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<tr>
<td>• 14y+ work</td>
<td>• <strong>fsPHENIX:</strong> forward tracking, HCal and muon ID</td>
<td>• Large coverage of tracking, calorimetry and PID</td>
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<tr>
<td>• 100+M$ investment</td>
<td>• Key tests of theoretical frameworks for transverse spin and CNM</td>
<td>• New collaboration/new ideas</td>
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<td>• 130+ published papers to date</td>
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<tr>
<td>• Last run in this form 2016</td>
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~2000 2017→2020 ~2025

**RHIC:** A+A, polarized p+p, polarized p+A  
**eRHIC:** e+p, e+A

10/22/14 Ming Liu @SPIN2014
backup
Flavor Tagged Jet Asymmetry

- Jet and leading $h^+$ and $h^-$
  - Forward jets: $\eta = [1.7, 3.3]$

Why Jet $A_N$ from AnDY is so small?
Cancellation of u and d quarks' Sivers asymmetry?

Directly use Sivers function from SIDIS fit
Tag Quark Flavor with Leading Charged Hadrons

• @Z = 0.5

\[
\frac{\sigma_q}{\sigma_{all}} = e_f^2 q_f \cdot D_f^n / \sum e_i^2 q_i \cdot D_i^n
\]

DSS FF

\[
D_{\pi^+} = D_{\pi^+} = N \cdot D_{\pi^+}
\]

\[
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\]

\[
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\]

Proton π+

Proton π−

Proton K+

Proton K−

\(Q^2 = 4.0 \text{ GeV}^2\)

\(Z_h = 0.5\)

\(u \quad d \quad s \quad \bar{u} \quad \bar{d} \quad \bar{s}\)

Ming Liu @SPIN2014
Possible Resolutions?

“Collins”? Node in “Sivers”? Etc.

$A_N$ from twist-3 fragmentation functions
(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

Sarah Sivers and Collins in p+p! fsPHENIX!

Need new direct measurements of
Sivers and Collins in p+p! fsPHENIX!

SIDIS/TMD

Node in Sivers Func.

pp/Twist-3

Kang, Prokudin PRD (2012)
Collins Asymmetry inside Jets

- Significant non-zero spin asymmetry observed @RHIC
Energy Loss and Hadronization in p+A


\[ R = \frac{\sigma(p+A)}{A \times \sigma(p+p)} \]

Gluon shadowing

\[ \rho(A) \rightarrow J/\psi + X \]

\[ dE/dx \]

Need to isolate \( dE/dx \) from other effects => E906 @Fermilab!
Could “A” affect Collins Fragmentation Function?

- Unpolarized quark fragmentation “is modified” in SIDIS
  - hadronization

- How about Collins polarized fragmentation functions in p+A?
  - Hadronization in CGC?

Key observables:
- Collins A_N asymmetry inside a Jet in p+A
- Centrality dependence, (pT, z, PID...)
- NO polarized e+“A”, unique @RHIC
Conceptual f/s/ePHENIX Design
eRHIC Physics

- **Gluon spin structure**
  - Process: Inclusive DIS
  - Observable: scattered electron measurements
  - Detector: EMCal + tracking
- **Strange spin, TMD, Propagation of hadron in nucleon**
  - Process: semi-inclusive DIS
  - Observable: DIS + hadron with ID
  - Detector: DIS + h-PID for -1<eta<4
- **3D tomography of proton**
  - Process: exclusive production
  - Observable: Electron, photon, proton, exclusiveness
  - Detector: tracking, EMCal, Roman pots
- **Saturation physics**
  - Process: diffractive production
  - Observable: rapidity gap
  - Detector: Hcal in -1<eta<5
- **Not included in stage-I**
  - Heavy flavor production
  - Electro-weak physics