A Detector for the Study of Nucleon Spin Structure and Cold Nuclear Matter at RHIC

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The RHIC Evolution to the EIC

- STAR/PHENIX charged by the BNL ALD to define a polarized p+p/p+A physics program in 2021-22:

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>510 GeV pol p+p</td>
<td>Sea quark and gluon polarization</td>
<td>upgraded pol’d source, STAR HFT test</td>
</tr>
<tr>
<td>2014</td>
<td>200 GeV Au+Au, 15 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, full STAR HFT, STAR MTD</td>
</tr>
<tr>
<td>2015-2016</td>
<td>p+p at 200 GeV, p+Au, d+Au, 3He+Au at 200 GeV, High statistics Au+Au</td>
<td>Extract η/s(T) + constrain initial quantum fluctuations, More heavy flavor studies, Sphaleron tests</td>
<td>PHENIX MPC-EX, Coherent electron cooling test</td>
</tr>
<tr>
<td>2017</td>
<td>No Run</td>
<td></td>
<td>Electron cooling upgrade</td>
</tr>
<tr>
<td>2018-2019</td>
<td>5-20 GeV Au+Au (BES-2)</td>
<td>Search for QCD critical point and deconfinement onset</td>
<td>STAR ITPC upgrade</td>
</tr>
<tr>
<td>2020</td>
<td>No Run</td>
<td></td>
<td>sPHENIX installation</td>
</tr>
<tr>
<td>2021-2022</td>
<td>Long 200 GeV Au+Au w/ upgraded detectors, p+p/d+Au at 200 GeV</td>
<td>Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism, Color screening for different QQ states</td>
<td>sPHENIX, 10 weeks p+p @ 200 GeV, 10 weeks p+Au @ 200 GeV</td>
</tr>
<tr>
<td>2023-24</td>
<td>No Runs</td>
<td></td>
<td>Transition to eRHIC</td>
</tr>
</tbody>
</table>

Overlap with planned sPHENIX running.

4/30/2014 BNL PAC 2014
Evolve sPHENIX (pp and HI detector) to an EIC Detector (ep and eA detector):

- To utilize e and p (A) beams at eRHIC with e-energy up to 15 GeV and p(A)-energy up to 250 GeV (100 GeV/n)
- $e, \, p, \, He^3$ polarized
- Stage-1 luminosity $\sim 10^{33}$ cm$^{-2}$ s$^{-1}$ (~1fb$^{-1}$/month)
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The Big Picture At RHIC

How do collective, many-body phenomena arise from first-principles QCD?
fsPHENIX Physics

• The fsPHENIX physics program seeks to address key issues in nucleon/nuclear structure:
  – How is transverse spin carried by the partonic constituents of the nucleon?
    • Key tests of theoretical framework – can we relate what we know from SIDIS and polarized p+p?
    • Jet $A_N$, DY modified universality, $Q^2$ evolution,…
  – How are PDF’s modified in the nuclear environment at small-x?
    • Saturation (CGC), parton energy loss…
**Single Transverse Spin Asymmetries**

**Theory Expectation:**
Small asymmetries at high energies  
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

\[ A_N \propto \frac{m_q}{\sqrt{S}} \]

**Experiment:**
(E704, Fermi National Laboratory, 1991)

\[ pp^\uparrow \rightarrow \pi + X \]
\[ \sqrt{S} = 20 \text{ GeV} \]

- \( A_N \propto O(10^{-4}) \) Theory
- \( A_N \propto O(10^{-1}) \) Measured

**E704: Left-right asymmetries**  
\( A_N \) for pions:

- \( \pi^+ \)
- \( \pi^0 \)
- \( \pi^- \)

\[ x_F = \frac{2p_L}{\sqrt{S}} \]
Sources of Transverse SSA's

“Sivers effect”
TMD: Correlation between nucleon spin and parton $k_T$.


$$d\sigma^\uparrow \propto \overline{f}_{1T}^q(x, k_\perp^2) \cdot D_h^q(z)$$

Sivers distribution

Twist-3: Quark-gluon correlations in polarized hadron


$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^q(x, k_\perp^2)$$

“Collins effect”
TMD: Transversity distributions + Spin dependent fragmentation functions


$$d\sigma^\uparrow \propto \delta q(x) \cdot H_{1}^\perp(z_2, k_\perp^2)$$

Transversity Collins FF

Twist-3: Transversity combined with twist-3 quark-gluon fragmentation function

4/30/2014
BNL PAC 2014
Drell-Yan in Polarized p+p

- A **theoretically clean**, fundamental study of the **Sivers effect, modified universality**, and **evolution of TMD’s**:

$$\Delta^N f^{\text{SIDIS}}_{q/h_1}(x, k) = -\Delta^N f^{\text{DY}}_{q/h_1}(x, k)$$

How does evolution change the anticipated asymmetries? Theory predictions vary. Useful to look at **low mass** and **high mass** DY pairs.

Kang and Qiu, PRD 84 054020
Echevarria et. al., arXiv 1401.5078
The nucleus is an amplifier of high gluon densities.

\[
\left( Q_s^A \right)^2 \approx c Q_s^0 \left( \frac{A}{x} \right)^{1/3}
\]
Polarized p+A Collisions

- The *fsPHENIX* physics program really depends on what we learn from Run-15:
  - Are the single spin asymmetries suppressed in polarized p+A?
  - Does DY offer any advantages as a small-x probe?
  - Jet-Jet vs. Hadron-Hadron correlations
    - Take full advantage of *fsPHENIX+sPHENIX* jet coverage

Polarized p+A a unique capability of RHIC!
fsPHENIX –"forward" sPHENIX!

A detector for a comprehensive program of spin structure and cold nuclear matter investigations.

fsPHENIX HCAL, GEM trackers derived from EIC detector

- FVTX covering two regions
  - 3 planes covering $1.1 < \eta < 3$
  - 3 planes covering $3 < \eta < 4$
- field shaper piston made of 50% Co + 50%Fe
- 3 GEM tracker stations
- forward HCAL
- current MuID
fsPHENIX Jets @ 200GeV

fsPHENIX Jet acceptance $1.7 < \eta < 3.3$ with anti-$k_T$ $R=0.7$

Is the small $A_N^\text{DY}$ asymmetry a cancellation between $u$ and $d$ quarks?
Jet Sources

Jets from standard PYTHIA Tune A, beam remnants from Tune A with $k_T=0.36$.

A cut on the charge of the leading hadron changes the composition of the jet sample.
Jet Measurements in fsPHENIX


Projected fsPHENIX data points (97pb⁻¹) compared to theoretical model.
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Projected fsPHENIX data points (97pb⁻¹) compared to theoretical model.
Collins in Jets

Lots of statistics for Collins in jets using charged hadrons. Issue is $z$-resolution as a function of jet energy.

With addition of PID kaon measurements also have excellent statistics (not part of baseline).
Drell-Yan: fsPHENIX and COMPASS-II
The Challenge of Drell-Yan

200 GeV

200 GeV offers better S/B (lower HF cross section), but reduced luminosity makes it difficult to get high statistics. 510 GeV offers much higher luminosity (higher statistics) but higher backgrounds as well.

Dramatically improve S/B at higher $p_T$, Drell-Yan at $p_T>Q$ similar to direct photon. Berger et. al., PRD 65 034006

510 GeV

Very basic cuts without concerted effort to reduce backgrounds.

Plots reflect MC statistics, not fsPHENIX running.
Improving Drell-Yan Background

Make use of the fact that most of the background is jet-associated, and DY is not (fsPHENIX is a jet detector!)

New results (post-whitepaper)

- HCal jet-cone isolation cut
- Back-to-back jet-veto cut
## Improving Drell-Yan Background

New results (post-whitepaper)

Drell-Yan S/B with event shape cuts added.

<table>
<thead>
<tr>
<th>Kinematics (200 GeV)</th>
<th>Low mass (2.0 &lt; M &lt; 2.5 GeV)</th>
<th>High mass (4.0 &lt; M &lt; 8.0 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2&lt;y&lt;4</td>
<td>No Cut</td>
<td>0.07</td>
</tr>
<tr>
<td>3&lt;y&lt;4</td>
<td>No Cut</td>
<td>0.28</td>
</tr>
<tr>
<td>1.2&lt;y&lt;4</td>
<td>p_\perp&gt;2 GeV</td>
<td>0.20</td>
</tr>
<tr>
<td>3&lt;y&lt;4</td>
<td>p_\perp&gt;2 GeV</td>
<td>1.8</td>
</tr>
</tbody>
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<th>Kinematics (510 GeV)</th>
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</tr>
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<tbody>
<tr>
<td>1.2&lt;y&lt;4</td>
<td>No Cut</td>
<td>0.01</td>
</tr>
<tr>
<td>3&lt;y&lt;4</td>
<td>No Cut</td>
<td>0.03</td>
</tr>
<tr>
<td>1.2&lt;y&lt;4</td>
<td>p_\perp&gt;2 GeV</td>
<td>0.02</td>
</tr>
<tr>
<td>3&lt;y&lt;4</td>
<td>p_\perp&gt;2 GeV</td>
<td>0.07</td>
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Improving Drell-Yan Background

New results (post-whitepaper)  Drell-Yan S/B with event shape cuts added.

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<tr>
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<td></td>
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Very encouraging at this level of simulation. Full, detailed simulations required to evolve *fsPHENIX* design and verify physics capabilities.
Drell-Yan vs. $p_T$

$p_T << Q$
- Dominant process is quark-antiquark annihilation
- TMD factorization valid
- Direct comparison of modified universality with SIDIS

$p_T >> Q$
- Dominant process is gluon-Compton scattering to virtual photon
- Same information as direct photon
- TMD factorization NOT valid
- Can be interpreted in Twist-3 approach

Berger, Qiu and Zhang, Phys. Rev. D 65, 034006
Kang, Qiu and Vogelsang, Phys. Rev. D 79, 054007
Conclusions

• The *fsPHENIX* physics program covers a broad range of key scientific questions:
  – The spin structure of the nucleon
  – The structure of nuclear matter at small-x

• The ability to pursue these questions in p+p and p+A collisions will be lost in the transition to the EIC without the *fsPHENIX* program.

• *fsPHENIX* builds on the *sPHENIX* detector and integrates with a future EIC detector.
  – Extends jet acceptance of sPHENIX
  – 90% of the estimated cost of *fsPHENIX* is in common with the EIC detector
BACKUP
## fsPHENIX Cost

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Overhead</th>
<th>Contingency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCal</td>
<td>3.90</td>
<td>0.68</td>
<td>2.29</td>
<td>6.87</td>
</tr>
<tr>
<td>GEM Tracker</td>
<td>0.67</td>
<td>0.17</td>
<td>0.41</td>
<td>1.25</td>
</tr>
<tr>
<td>FVTX reconfiguration</td>
<td>0.53</td>
<td>0.11</td>
<td>0.31</td>
<td>0.95</td>
</tr>
<tr>
<td>Mini-MUID</td>
<td>0.13</td>
<td>0.03</td>
<td>0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>Fiston Field Shaper</td>
<td>0.06</td>
<td>0.02</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>HCal electronics/sensors</td>
<td>0.38</td>
<td>0.05</td>
<td>0.22</td>
<td>0.65</td>
</tr>
<tr>
<td>GEM electronics/sensors</td>
<td>0.63</td>
<td>0.16</td>
<td>0.39</td>
<td>1.18</td>
</tr>
<tr>
<td>Mini-MUID electronics/sensors</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>MUID trigger electronics</td>
<td>0.35</td>
<td>0.07</td>
<td>0.21</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.7</strong></td>
<td><strong>1.3</strong></td>
<td><strong>3.98</strong></td>
<td><strong>11.98</strong></td>
</tr>
</tbody>
</table>

$12M overall cost, about 90% common with the EIC Detector.
fsPHENIX Luminosity Assumptions

- **Guidance from ALD (CAD Delivered):**
  - ALD guidance also cautions to assume lower estimates...
  - \( p+p@510\text{GeV} \): \( 200\text{pb}^{-1}/\text{week} \)
    - Increase in bunch intensity by factor of 1.62 over achieved (electron cooling)
    - CAD 2014-2018 Projections (4 June 2013): \( 216\text{pb}^{-1}/\text{week} \) (max), \( 40\text{pb}^{-1}/\text{week} \) (min)
    - Max/Min Average = \( 128\text{pb}^{-1}/\text{week} \) average
  - \( p+\text{Au@200GeV} \): \( 300\text{nb}^{-1}/\text{week} \)
    - Run-14 BUP guidance was \( 175\text{nb}^{-1}/\text{week} \)
    - Conservative: \( 225\text{nb}^{-1}/\text{week} \) (75% of maximum)
    - \( p+p \) equivalent: \( 44\text{pb}^{-1}/\text{week} \)
  - \( p+p@200\text{GeV} \): no ALD guidance
    - CAD projection \( 28\text{pb}^{-1} \) (max), \( 9.3\text{pb}^{-1}/\text{week} \) (min)
    - Max/Min Average = \( 18.7\text{pb}^{-1}/\text{week} \)

Use these #'s for fsPHENIX
fsPHENIX Run Length

- **PHENIX Guidance:**
  - Assume 10 weeks running for p+p@200GeV
  - Assume 10 weeks running for p+Au@200GeV
- **What do we assume for Drell Yan p+p@510GeV?**
  - Make table assuming one 15-week run
- **Additional running time for different p+A species?**
- **Dell-Yan:**
  - Assuming PHENIX Efficiency
    = 0.6 (uptime) x 0.62 (-30<z_v<10cm vertex)
  - p+p@200GeV PHENIX Sampled = 69pb⁻¹
  - p+Au@200GeV PHENIX Sampled = 831nb⁻¹ p+Au, 163pb⁻¹ (pp equiv)
  - p+p@510GeV PHENIX Sampled = 714pb⁻¹
- **Jets:**
  - Assuming PHENIX Efficiency
    = 0.6 (uptime) x 0.84 (+/-30cm vertex)
  - p+p@200GeV PHENIX Sampled = 97pb⁻¹
  - p+Au@200GeV PHENIX Sampled = 1165nb⁻¹ p+Au, 230pb⁻¹ (pp equiv)
  - p+p@510GeV PHENIX Sampled = 1002pb⁻¹