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</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>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.</td>
<td>Electron lenses</td>
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<tr>
<td></td>
<td></td>
<td>QCD critical point search</td>
<td>58 MHz SRF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>full STAR HFT</td>
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<td></td>
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<td>STAR MTD</td>
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<tr>
<td>2015-2016</td>
<td>p+p at 200 GeV \ p+Au, d+Au, \ ^3He+Au at 200 GeV</td>
<td>Extract η/s(T) + constrain initial quantum fluctuations \ More heavy flavor studies \ Sphaleron tests</td>
<td>PHENIX MPC-EX</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coherent electron cooling test</td>
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<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</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 weeks p+p @ 200 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 weeks p+Au @ 200 GeV</td>
</tr>
<tr>
<td>2023-24</td>
<td>No Runs</td>
<td></td>
<td>Transition to eRHIC</td>
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</table>

Overlap with planned sPHENIX running.
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) or parton energy loss?
Sources of Transverse SSA’s

“Sivers effect”

**TMD:** Correlation between nucleon spin and parton $k_T$.

\[ d\sigma^\uparrow \propto \bar{f}_{1T}^q(x, k_T^2) \cdot D^q_h(z) \]

*Sivers distribution*

**Twist-3:** Quark-gluon correlations in polarized hadron

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

“Collins effect”

**TMD:** Transversity distributions + Spin dependent fragmentation functions

\[ d\sigma^\uparrow \propto \delta q(x) \cdot H_1^T(z_2, k_\perp^2) \]

*Transversity Collins FF*

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

Sources


Also evolution...
Drell-Yan in Polarized p+p

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

\[ \Delta^N f^{S\text{DIS}}_{q/h_1}(x, k_T) = -\Delta^N f^{\text{DY}}_{q/h_1}(x, k_T) \]

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

- The *fsPHENIX* physics program really depends on what we learn from Run-15/16:
  - 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 \(A_N\) 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.

Jet Measurements in fsPHENIX


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

\[ F_{oM} = \frac{1}{\delta A_T^\text{sin}^2} \]

Shaded regions delinate \( \delta A_T^\text{sin} < 0.1 \)
The Challenge of Drell-Yan

Very basic cuts without concerted effort to reduce backgrounds.

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

Plots reflect MC statistics, not fsPHENIX running.
Drell-Yan Performance (200 GeV, $p_T > 2$GeV)

Plots reflect MC statistics, not fsPHENIX running.
Reducing DY Backgrounds

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

Example: LHCb motivated jet momentum cut.

Possible to get large rejection factors at the expense of some DY pair efficiency. A full characterization of fsPHENIX performance will require detailed simulations.
Conclusion

• 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 may be lost in the transition to the EIC.

• *fsPHENIX* builds on the *sPHENIX* detector and integrates with a future EIC detector.
  – 90% of the estimated cost of *fsPHENIX* is in common with the EIC detector
BACKUP
Reducing Drell-Yan Backgrounds

Cuts on $q_T$ preserve DY and reduce background, but high $q_T$ is difficult theoretically (especially for low mass).

Tighter DCA cuts certainly possible, sacrifice some efficiency for $|z_{VTX}| > 10$cm?
Drell-Yan Performance (200 GeV, no $p_T$ cut)
Drell-Yan Performance (510 GeV, $p_T>2$GeV)

Plots from Cesar
Drell-Yan Statistical Power

\( \sqrt{s} = 510 \text{ GeV} \)

\( 4 < M < 9 \text{ GeV} \)

\( \sqrt{s} = 200 \text{ GeV} \)

\( 4 < M < 9 \text{ GeV} \)
## 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>
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<tr>
<td>FVTX reconfiguration</td>
<td>0.53</td>
<td>0.11</td>
<td>0.31</td>
<td>0.95</td>
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<tr>
<td>Mini-MUID</td>
<td>0.13</td>
<td>0.03</td>
<td>0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>Piston Field Shaper</td>
<td>0.06</td>
<td>0.02</td>
<td>0.04</td>
<td>0.12</td>
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<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>6.7</td>
<td>1.3</td>
<td>3.98</td>
<td>11.98</td>
</tr>
</tbody>
</table>

**$12M overall cost, about 90% common with ePHENIX.**
Jet Physics in Polarized p+p

- Measurements of Jet $A_N$ sensitive to Sivers only (no Collins).

Directly use Sivers function from SIDIS fit (Torino group)

Kang et. al. predict opposite signs for the $u$, $d$ quark asymmetries!
fsPHENIX Luminosity Assumptions

• Guidance from ALD (CAD Delivered):
  – ALD guidance also cautions to assume lower estimates...
  – p+p@510GeV: 200pb\(^{-1}\)/week
    • Increase in bunch intensity by factor of 1.62 over achieved (electron cooling)
    • CAD 2014-2018 Projections (4 June 2013): 216pb\(^{-1}\)/week (max), 40pb\(^{-1}\)/week (min)
      • Max/Min Average = 128pb\(^{-1}\)/week average
  – p+Au@200GeV: 300nb\(^{-1}\)/week
    • Run-14 BUP guidance was 175nb\(^{-1}\)/week
    • Conservative: 225nb\(^{-1}\)/week (75% of maximum)
    • p+p equivalent: 44pb\(^{-1}\)/week
  – p+p@200GeV: no ALD guidance
    • CAD projection 28pb\(^{-1}\) (max), 9.3pb\(^{-1}\)/week (min)
    • Max/Min Average = 18.7pb\(^{-1}\)/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 = \textcolor{red}{69pb^{-1}}
  - p+A@200GeV PHENIX Sampled = \textcolor{red}{831nb^{-1}} p+Au, \textcolor{red}{163pb^{-1}} (pp equiv)
  - p+p@510GeV PHENIX Sampled = \textcolor{red}{714pb^{-1}}

- **Jets:**
  - Assuming PHENIX Efficiency
    - = 0.6 (uptime) x 0.84 (+/-30cm vertex)
  - p+p@200GeV PHENIX Sampled = \textcolor{red}{97pb^{-1}}
  - p+A@200GeV PHENIX Sampled = \textcolor{red}{1165nb^{-1}} p+Au, \textcolor{red}{230pb^{-1}} (pp equiv)
  - p+p@510GeV PHENIX Sampled = \textcolor{red}{1002pb^{-1}}
Drell-Yan Statistics

fsPHENIX DY Statistics assuming all reconstruction efficiencies:

<table>
<thead>
<tr>
<th>System and inv Mass</th>
<th>DY Pairs 1.2&lt;eta&lt;4</th>
<th>DY Pairs 1.2&lt;eta&lt;2</th>
<th>DY Pairs 2&lt;eta&lt;3</th>
<th>DY Pairs 3&lt;eta&lt;4</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p 200 (1.5&lt;M&lt;2.5)</td>
<td>41634</td>
<td>4961</td>
<td>23685</td>
<td>11956</td>
</tr>
<tr>
<td>p+p 200 (2.0&lt;M&lt;2.5)</td>
<td>13469</td>
<td>1871</td>
<td>7997</td>
<td>3317</td>
</tr>
<tr>
<td>p+p 200 (4&lt;M&lt;9)</td>
<td>4153</td>
<td>1188</td>
<td>2743</td>
<td>209</td>
</tr>
<tr>
<td>p+Au 200 (1.5&lt;M&lt;2.5)</td>
<td>98225</td>
<td>11704</td>
<td>55879</td>
<td>28207</td>
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<tr>
<td>p+Au 200 (2.0&lt;M&lt;2.5)</td>
<td>30369</td>
<td>4415</td>
<td>18867</td>
<td>7825</td>
</tr>
<tr>
<td>p+Au 200 (4&lt;M&lt;9)</td>
<td>9798</td>
<td>2803</td>
<td>6472</td>
<td>492</td>
</tr>
<tr>
<td>p+p 510 (1.5&lt;M&lt;2.5)</td>
<td>579788</td>
<td>58575</td>
<td>307025</td>
<td>216419</td>
</tr>
<tr>
<td>p+p 510 (2.0&lt;M&lt;2.5)</td>
<td>207452</td>
<td>23280</td>
<td>113373</td>
<td>72469</td>
</tr>
<tr>
<td>p+p 510 (4&lt;M&lt;9)</td>
<td>116560</td>
<td>20280</td>
<td>75308</td>
<td>26573</td>
</tr>
</tbody>
</table>

200 GeV: Limited program for high-mass pairs, but a solid program for low mass pairs? If DY in p+A is a CNM measurement, do we want to measure another species?

510 GeV: Lots of statistics but HF backgrounds higher, room to cut harder?