Complete Heavy Flavor Program at RHIC with the sPHENIX MAPS Vertex Detector

Outline ● sPHENIX overview ● Detector highlights ● Performance Projection ● Summary

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For the sPHENIX Collaboration
Meeting the grand challenge

To understand the workings of QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid.

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) Prove the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called SPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.
Jet cor. & substructure
Vary momentum/angular size of probe

Parton energy loss
Vary mass/momentum of probe

Upsilon spectroscopy
Vary size of the probe

Next talk:
sPHENIX jet – Songkyo Lee

This talk: HF program

See also: sPHENIX overview – Gunther Roland
2016: Scientific review and DOE mission need Status (CD-0)
2018: Cost/schedule review and DOE approval for production start of long lead-time items (CD-1/3A)
2022: installation in RHIC 1008 Hall; 2023: First data
5-year run scenario

| $\sqrt{s_{NN}} = 200$ GeV | Recorded M.B. Dataset | Sampled Lum. ($|z|<10$ cm) |
|---------------------------|------------------------|-----------------------------|
| Au+Au                     | 35 nb$^{-1}$/239 billion | 80 nb$^{-1}$/550 billion     |
| p+p                        | --                     | 197 pb$^{-1}$/8.3 trillion   |
| p+Au                      | --                     | 0.33 pb$^{-1}$/0.6 trillion  |
sPHENIX tracking detectors

Inner tracker:
- **MVTX**: MAPS pixel sensors (3-layer)
  - Procurement copies of ALICE ITS IB staves integrated into sPHENIX
  - Precision vertexing
- **INTT**: strip silicon sensors (4-layer)
  - Pattern recognition, timing
- **ΔDCA**<sub>π</sub> < 50um for **p**<sub>T</sub> > 1 GeV/c

Outer tracker:
- **TPC**: gateless and continuous readout
  - Provide momentum measurement
- **δp/p < 2% for **p**<sub>T</sub> < 10 GeV/c

See also calorimeters – Songkyo Lee

In Diameter ~ 1.6 m
Highlight of MVTX: production soon

- Stave/RU: starting production soon following ALICE ITS
- Back-end DAQ: sPHENIX production of ATLAS FELIX card

Sensor test with sPHENIX extension

Readout Unit v2

Data Assembly Module (FELIX v2)

In close coordination with R&D and production for ALICE/ATLAS Phase-I upgrade
Highlight of MVTX: 2018 test beam

Feb-July 2018 FermiLab Test beam facility, test of each sPHENIX detector subsystem

4x MVTX sensor in beam

sPHENIX DAQ

MVTX Hit Spatial Resolution: < 5 um
Excellent tracking performance demonstrated in detailed Geant4 simulation and reconstruction chain

- Robust at top projected RHIC collision rate
Precision vertex and open HF observables

- Precision vertex tracker + High rate → Precision bottom observables over wide scales
- Initial observables: $B$-meson @ $2 < p_T < 10$ GeV/c, $b$-jet @ $15 < p_T < 35$ GeV/c
- Goals: Diffusion of HF quark in QGP, differentiate collision VS radiative energy loss, HF hadronization
Precision open bottom meson

\[ B \to \bar{D}^0 + X \]

Prompt and non-prompt D-meson

Exclusive \( B^\pm \)

- 240B MB Au+Au collisions and high precision tracking allow accumulate high significance of HF-meson signals
- Measuring high statistics \( B \) meson via non-prompt D decay channel
- Exclusive \( B \) reconstruction too!
B-meson projections

- Bring high precision non-prompt-$D$ suppression and flow to RHIC
- Determine the bottom quark collectivity → clean access to $D_{HQ}$ at RHIC energy

non-prompt $D$-meson and predictions for sPHENIX
sPHENIX is an excellent calorimetric jet detector. More in Songkyo Lee’s talk

Demonstrate b-jet capability: tagging algorithms evaluated using full detector HI simulation

Reaching an optimal working point in central Au+Au collisions

Track-counting tagger

Secondary-vertex tagger

Secondary-vertex mass


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**b-jet projection**

- Bring inclusive b-jet suppression and $v_2$ to RHIC
- Strong constraints on energy loss model of high energy probe in QGP

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**Inclusive b-jet $R_{AA}$**

- *sPHENIX Simulation*
  - Au+Au $s_{NN}$=200 GeV
  - PYTHIA-8 b-jet, Anti-$k_T$, $R=0.4$, $|\eta|<0.7$, CTEQ6L
  - $p+p$: 200 pb$^{-1}$, 60% Eff., 40% Pur.

**Inclusive b-jet $v_2$**

- *sPHENIX Simulation*
  - Au+Au $s_{NN}$=200 GeV, 240B MB
  - PYTHIA-8 b-jet, Anti-$k_T$, $R=0.4$, $|\eta|<0.7$, CTEQ6L
  - $R_{AA, b-jet}=0.6$, 40% Eff., 40% Pur., $\text{Res}(v_2)=0.7$
Broader HF program

- HF-jet-jet, jet-HF-hadron, D-D correlations, HF jet substructure
- Total $b$-cross section for Upsilon program and more decay chan.
- HF baryons, chemistry and hadronization
- Many opportunities. Welcome to join us!

![Di-b-jet $p_T$ balance](image1)

![Exclusive $B^\pm$ in most central Au+Au](image2)

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sPH-HF-2018-001 - MVTX Proposal
See also: sPHENIX jet, Songkyo Lee

**Diagram Description:**

- **R_{AA}**
  - RHIC Today
  - RHIC Tomorrow
  - LHC Today
  - LHC Tomorrow
  - Hadrons
  - Jets
  - D Mesons
  - B Mesons
  - b Jets

- **X+Jet**
  - Ensemble-based measurements
  - x+hadron correlations
  - add low $p_T$ reach
  - Dijets ($P_{T,1}$)
  - $\gamma$+Jets ($p_{T,\gamma}$)
  - $Z^0$+Jets ($p_{T,Z}$)
  - Double b-Tag ($p_{T,1}$)

- **$p_T$ [GeV/c]**
  - 10
  - $10^2$
  - $10^3$
Summary

- Rich heavy flavor physics opportunity at sPHENIX
  - Completing the RHIC mission & good complementarity with the LHC
- sPHENIX production ramping up. First data in 2023
  - MVTX staves / readout following ALICE ITS production
  - DOE official approval of procurement of long lead time items of sPHENIX construction
- Growing collaboration
  - > 70 institutions, Many opportunity to collaborate
- More on sPHENIX
  - Next talk: sPHENIX jet – Songkyo Lee; This PM: sPHENIX – Gunther Roland
Extra Information
Mass of color probe

See also:
- Next² talk, sPHENIX jet, Songkyo Lee
- This PM: sPHENIX experiment, Gunther Roland
Complementarity: RHIC vs. LHC

- Sensitive to different temperature regions

Uniqueness at RHIC (vs. LHC)

- Gluon splitting contribution is much less (~10%)
Full detector simulation + reconstruction

Open source @ GitHub: https://github.com/sPHENIX-Collaboration/
sPHENIX Geant4 display of $p_T=30$ GeV/c $B^+$-hadron

Design to Simulation

Inner tracker (MVTX and INTT)

MVTX Ladders modeled in details

R ~ 4 cm

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Upsilon spectroscopy

Precision tracking → Separated Upsilon states at RHIC → Probe of the QGP at distinct length scales.
B-jet natural abundance and tagger ROC
# Evolution of the RHIC 1008 Interaction region

<table>
<thead>
<tr>
<th>PHENIX experiment</th>
<th>sPHENIX</th>
<th>An EIC detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>16y+ operation</td>
<td>Comprehensive central upgrade base on previous BaBar magnet</td>
<td>Path of PHENIX upgrade leads to a capable EIC detector</td>
</tr>
<tr>
<td>Broad spectrum of physics 180+ physics papers with 25k citations</td>
<td>Rich jet and HF physics program → Microscopic nature of QGP</td>
<td>Large coverage of tracking, calorimetry and PID</td>
</tr>
<tr>
<td>Last run in this form 2016</td>
<td></td>
<td>Open for new collaboration/new ideas</td>
</tr>
</tbody>
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~2000  | 2017→2023, CD-1 Approved | >2025  |

RHIC: A+A, spin-polarized p+p, spin-polarized p+A  |  | EIC: e+p, e+A  |


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MVTX Detector Electronics consists of three parts

**Sensor**-Stave (9 ALPIDE chips) | **Front End**-Readout Unit | **Back End**-FELIX
Recent Achievements on Bottom

**LHC 2.76 TeV**

\[ R_{AA}(J/\psi_B) > R_{AA}(D) \]

\[ R_{AA}(e_B) > R_{AA}(e_{D+B}) \]

**RHIC 200 GeV**

\[ R_{AA}(e_B) > R_{AA}(e_D) \]
### Possible 5-year run plan for sPHENIX baseline

#### Multi-year run plan scenario for sPHENIX

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</thead>
<tbody>
<tr>
<td>2022</td>
<td>Au+Au</td>
<td>200</td>
<td>16.0</td>
<td>7 nb⁻¹</td>
<td>8.7 nb⁻¹</td>
<td>34 nb⁻¹</td>
</tr>
<tr>
<td>2023</td>
<td>p+p</td>
<td>200</td>
<td>11.5</td>
<td>—</td>
<td>48 pb⁻¹</td>
<td>267 pb⁻¹</td>
</tr>
<tr>
<td>2023</td>
<td>p+Au</td>
<td>200</td>
<td>11.5</td>
<td>—</td>
<td>0.33 pb⁻¹</td>
<td>1.46 pb⁻¹</td>
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<tr>
<td>2024</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>26 nb⁻¹</td>
<td>88 nb⁻¹</td>
</tr>
<tr>
<td>2025</td>
<td>p+p</td>
<td>200</td>
<td>23.5</td>
<td>—</td>
<td>149 pb⁻¹</td>
<td>783 pb⁻¹</td>
</tr>
<tr>
<td>2026</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>48 nb⁻¹</td>
<td>92 nb⁻¹</td>
</tr>
</tbody>
</table>

- Guidance from ALD to think in terms of a multi-year run plan
- Consistent with language in DOE CD-0 “mission need” document
- Incorporates updated C-AD guidance now officially documented
- Run plan relates to capabilities of full barrel detector
- Incorporates commissioning time in first year

Minimum bias Au+Au at 15 kHz for |z| < 10 cm:
47 billion (2022) + 96 billion (2024) + 96 billion (2026) = Total **239 billion events**

For topics with Level-1 selective trigger (e.g. high p_T photons), one can sample within |z| < 10 cm a total of 550 billion events. One could consider sampling events over a wider z-vertex for calorimeter only measurements, 1.5 trillion events.
Detector highlights

$|\eta| < 1.1$

$B_z = 1.4 \, T$

Radius (cm)

OUTER HCAL

3.5 $\lambda$

1.4 $X_0$

INNER HCAL

1.0 $\lambda$

18 $X_0$, 1.0 $\lambda$

EMCal SPACAL prototype
Calorimeters beam tests

February 2014  
Proof of principle

February 2016  
η~0 prototype

February 2017  
η~0.9 prototype

Next Month!  
Final η~0.9 prototype

Electron, Energy resolution

Pion, Energy resolution and linearity

sPHENIX Preliminary
4x4 cm region within one SPACAL block

- 10° Incident Angle, Hadoscope Corrected
- Fit, ΔE/E = 2%(Δp/p) + 1.6% + 13%/√E
- 10° Incident Angle, Position Corrected
- Fit, ΔE/E = 2%(Δp/p) + 1.3% + 13.6%/√E
- GEANT4 Simulation
ΔE/E = 2%(Δp/p) + 2.5% + 12.7%/√E

sPHENIX Preliminary
EMCAL+HCALIN+HCALOUT
ΔE/E = 2%(Δp/p) + 13.1% + 73.6%/√E
HCALIN+HCALOUT (EMCAL MIP)
ΔE/E = 2%(Δp/p) + 11.3% + 86.3%/√E
HCALOUT (EMCAL+HCALIN MIP)
ΔE/E = 2%(Δp/p) + 15.2% + 82.1%/√E

sPHENIX Preliminary
EMCAL+HCALIN+HCALOUT
E_{\text{true}} = 1.000 E_{\text{true}}
HCALIN+HCALOUT (EMCAL MIP)
E_{\text{true}} = 1.007 E_{\text{true}}
HCALOUT (EMCAL+HCALIN MIP)
E_{\text{true}} = 1.006 E_{\text{true}}
 PHENIX are designed to handle large background environment of central AuAu collisions

Such background is simulated with HIJING → full detector in Geant4 → full analysis chain

Folded into electron ID and jet projections via embedding

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