Jets and heavy flavor with sPHENIX

Outline • Physics Driver • Performance Projection • Detector highlights • Collaboration News

Jin Huang
For the sPHENIX Collaboration
"To understand the workings of the 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."
Evolution of the PHENIX 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 BaBar magnet</td>
<td>Path of PHENIX upgrade leads to a capable EIC detector</td>
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<tr>
<td>Broad spectrum of physics (QGP, Hadron Physics, DM)</td>
<td>Rich jet and HF physics program → nature of QGP</td>
<td>Large coverage of tracking, calorimetry and PID</td>
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<tr>
<td>170+ physics papers with 24k citations</td>
<td>Possible forward tracking, and calorimeter → Spin, CNM</td>
<td>Open for new collaboration/new ideas</td>
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<tr>
<td>Last run in this form 2016</td>
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~2000 2017→2022, CD-0 @ 2016 >2025

RHIC: A+A, spin-polarized p+p, spin-polarized p+A

EIC: e+p, e+A

arXiv:1501.06197 [nucl-ex]
arXiv:1402.1209 [nucl-ex]

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15 kHz MB trigger
10 GB/s data logging

OUTER HCAL
SC MAGNET
INNER HCAL
EMCAL
TPC
INTT
MAPS
ENDCAP
FLUX RETURN

CD-0
CD-1 review
Installation complete
Sept 2016
May 2018
2022
Possible 5-year run plan for sPHENIX baseline

Multi-year run plan scenario for sPHENIX

<table>
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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>
</tr>
<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.
sPHENIX: calorimetry jet at RHIC

- Calorimetric triggering and measurement of jets
- Minimum bias to jet flavor and FF
- Iterative background subtraction [PRC 86 (2012) 024908] demonstrated in sPHENIX full event simulations

![sPHENIX G4 simulation](image)

**p+p**

**Au+Au 0-4fm**
High statistics hard probes

High statistics data represents large extend in hard probes in jets, photon and hadrons
More differential measurement

- High statistics also allows more differential measurements
- For example, path-length dependent studies via γ-jet transverse balance in correlation with event plane
Open heavy flavor observables

- Precision vertex tracker + High rate → Precision bottom observables
- $B$-meson @ Low $p_T$: diffusion of HF quark in QGP
- $b$-jet @ Higher $p_T$: differentiate collision VS radiative energy loss


**b-jet tagging @ sPHENIX**

- Demonstrate b-jet capability: tagging algorithms evaluated using full detector HI simulation
- Reaching a promising working point in central Au+Au collisions

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**Track-counting tagger**

![Track-counting tagger graph]

**Secondary-vertex tagger**

![Secondary-vertex tagger graph]

**Secondary-vertex mass**

![Secondary-vertex mass graph]

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**b-jet projection**

- **Bring inclusive b-jet suppression and \( v_2 \) to RHIC**
  - Covering jet \( p_T = 15-35 \text{ GeV/c} \)
  - Strong constraints of high energy probe in QGP
- **Broader opportunities on more differentiating observables**
  - Di-\( b \)-jet and \( b \)-jet-B-meson correlations
  - \( b \)-jet substructures

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**Inclusive b-jet \( R_{AA} \)**

![sPHENIX Simulation](image)

- Au+Au \( \sqrt{s_{NN}} = 200 \text{ GeV} \)
- PYTHIA8 \( b \)-jet, Anti-\( k_t \), \( R=0.4 \), \( |\eta|<0.7 \), CTEQ6L
- \( p+p \): 200 pb\(^{-1} \), 60% Eff., 40% Pur.

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**Inclusive b-jet \( v_2 \)**

![sPHENIX Simulation](image)

- Au+Au \( \sqrt{s_{NN}} = 200 \text{ GeV} \), 240B MB
- PYTHIA8 \( b \)-jet, Anti-\( k_t \), \( R=0.4 \), \( |\eta|<0.7 \), CTEQ6L
- \( R_{AA,b-jet}=0.6 \), 40% Eff., 40% Pur., Res(\( \Psi' \))=0.7

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**Di-\( b \)-jet \( p_T \) balance**

![sPHENIX Simulation](image)

- \( \sqrt{s_{NN}} = 200 \text{ GeV} \)
- Di \( b \)-jets (Pythia8, CTEQ6L)
- Anti-\( k_t \), \( R=0.4 \), \( |\eta|<0.7 \)
- \( p+p \): 200 pb\(^{-1} \), 60% Eff., 40% Pur.
- Au+Au: 240B Events, 40% Eff., 40% Pur.
Precise open bottom mesons

$$B \rightarrow D^0 + X$$

Prompt and non-prompt D-meson

- Counts / [5 μm]
- sPHENIX Simulation
- Au+Au $$\sqrt{s_{NN}} = 200$$ GeV
- 0-10%, 24B
- 4.0 < $$p_T$$ < 5.0
- After a BDT tagger

$$B^+ \rightarrow D^0 \pi^+$$

Exclusive B

- Counts / [15 MeV]
- sPHENIX Simulation
- Au+Au $$\sqrt{s_{NN}} = 200$$ GeV
- 0-10%, 24B
- 0.0 < $$p_T$$ < 2.0

- 240 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!

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Jets and HF Workshop
**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
- Broader program:
  - Total $b$-cross section for Upsilon program
  - Charm chemistry and HF hadronization
  - $D$ fragmentation function with Jets
Upsilon spectroscopy

$\Upsilon(3s) - 0.78\text{fm}$

$\Upsilon(2s) - 0.56\text{fm}$

$\Upsilon(1s) - 0.28\text{fm}$

Precision tracking $\rightarrow$ Separated Upsilon states at RHIC $\rightarrow$ Probe of the QGP at distinct length scales.

$\Upsilon(1S,2S,3S) \rightarrow e^+e^-$

$p+p$, 197 pb$^{-1}$

signal only

$\alpha_{1S} = 83 \pm 1.2 \text{ MeV}$
Jets in forward upgrades – Portal to EIC

Charge-track tagged jet asymmetry → Access Sivers effect

Charge-track asymmetry in jet → Access Transversity @ large x

sPHENIX simulation
p^+ + p → jet (h^±) + X, √s = 510 GeV

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jets and HF Workshop
**R_{AA}**
- **Hadrons**
- **Jets**
- **D Mesons**
- **B Mesons**
- **b Jets**

**X+Jet**

*Ensemble-based measurements and x+hadron correlations add low p_T reach*

- **Dijets (p_T,1)**
- **γ+Jets (p_Tγ)**
- **Z^0+Jets (p_TZ)**
- **Double b-Tag (p_T,1)**

**p_T [GeV/c]**

- 10
- 100
- 10^3
Detector highlights

| $|\eta|<1.1$ |
| $B_z = 1.4 \text{T}$ |

$outer \ HCAL$

$3.5 \lambda$

$INNER \ HCAL$

$1.0 \lambda$

$18 X_0, 1.0 \lambda$

$EMCAL$

$173$

$140$

$113.5$

$90$

$Radius \ (cm)$

$264.5$

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

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Super conducting magnet

- 1.4 Tesla magnet, \( \Phi = 2.8 \) m, \( L = 3.8 \) m
  - Previously used in BaBar @ SLAC
- Moved to BNL in Feb 2015
- Successful cold low field test in 2016
- On-going full field test as we are speaking.
Tracking detectors

**Inner tracking:**
- **MVTX:** 30-um-pitch MAPS pixel sensors (3-layer)
  - Precision vertexing
- **INTT:** strip silicon sensors (4-layer)
  - Pattern recognition, timing
- $\text{DCA}^{\pi} < 50\text{um for } p_T > 1\text{ GeV/c, } < 10\text{ um for } p_T > 10\text{ GeV/c}$

**Outer tracking:**
- **TPC:** gateless and continuous readout
- Low diffusion, high ion mobility Ne-CF$_4$ gas + Quad GEM + mini pads
- 1 Tbps DAQ, FPGA-based reduction, 100 Gbps data file rate
- $R\delta\Phi < 200\text{ um}$
- $\delta p/p < 2\%$ for $p_T < 10\text{ GeV/c}$

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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

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Evolving upgrade concepts

arXiv:1501.06197
CDR in preparation

Letter of Intent for Forward Instrumentation at sPHENIX

To RHIC PAC 2017

LOI/arXiv:1402.1209
Evolving sPHENIX collaboration

- Established in Dec 2015
- ~70 institutions and growing
- Most recent: 7 Chinese institution joined in Dec 2017 as consortium with interesting of construction and analysis

Dec 2017 sPHENIX collaboration meeting, in this courtyard
Summary

- **Rich physics cases**
  - Precision jet and HF @ RHIC, probes inner working of QGP when combined with LHC
  - Predictions on sPHENIX observables welcomed!
  - Completing scientific RHIC mission and connect to EIC

- **Advanced design** and many progress in detector R&D
  - CD-0 approved, in preparation for CD-1.
  - Planned data taking start 2023

- **Growing collaboration**
  - ~70 institutions with 9 new in the past year
  - Abundant opportunities to contribute
Extra Information
Welcome to join the collaboration

Welcoming more collaborators!

Many opportunities to contribute: in physics program and in detector R&D/construction
Inclusive $b$-jet $R_{AA}$ Performance

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

- $b$-jet $R_{AA}$, Au+Au 0-10% C, $\sqrt{s_{NN}}=200$ GeV

### Mass dependence of parton energy loss
- Cleaner access to partonic kinematics

### Uniqueness at RHIC (vs. LHC)
- Gluon splitting contribution is much less ($\sim$10%)
EMCal: EM-shower energy resolution

Request:
- Update with EMCal tower-by-tower calibration
- Apply sPHENIX style

Joe Osborn (UMich), June 13 Sim meeting
Updated and more detailed simulation show good safety margin on electron-ID performance on top of the baseline design (as required to reach Upsilon program physics goal)

Baseline performance, design goals
- Sum all scintillator energy
- 1D SPACAL material with hits grouped into 2D SPACAL towers

2D projective SPACAL
- Updated studies (Preliminary)
- Sum all hadron taking account of hadron ratio
- Full digitization (w/ Birk corrections)
- Full tracking with silicon opt.
- Fully implemented 2D SPACAL (tower/support structure)

1D projective SPACAL
- Updated studies (Preliminary)
- Sum all hadron taking account of hadron ratio
- Full digitization (w/ Birk corrections)
- Full tracking with silicon opt.
- Ideally towering (no-tower boarder, no enclosure structure)
EMCal: Hadron rejection

Hadron rejection @ 90% electron eff. for embedded particle in 0-4.4 fm Au+Au collision
Work by Sasha Lebedev (ISU), quoted from Quarkonium-TG wiki, June-2017 Col. meeting

Requests in priorities:
1. Update to sPHENIX plotting style
2. Produce Upsilon spectrum update with updated background
3. Use 2017 EMCal design and tracking simulations. Help on running?
4. Finalizing Upsilon R_AA projection?

More in Sasha’s talk today.
Performance: Single Hadron showers

- Single pion shower studied with clusters of digitized towers (3x3 and 5x5 clusters), which is compared with ideal sum of Geant4 hit in scintillator (label G4Hits).
- Energy resolution satisfied design goal. Tails <= 10%.
- Refinement underway: time cut-off and light collection variations.

- Energy resolution
  - Fit (p>16GeV):
    - G4Hits: \(\frac{46\%}{\sqrt{E}}\) \(+7.4\%\)
    - 3x3 SP: \(\frac{64\%}{\sqrt{E}}\) \(+10.4\%\)
    - 5x5 SP: \(\frac{46\%}{\sqrt{E}}\) \(+8.6\%\)
  - Requirement: 100%/\(\sqrt{E}\) \(+10\%\)

- Single-side tail
  - 10% stat. in each tail
  - 2.5% stat. in tails as expected from Gauss shape

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sPHENIX 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