Future Heavy Flavor and Quarkonia

Measurements from sPHENIX

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sPHENIX science mission

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) **Probe 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.**
Core sPHENIX physics program

**Jet cor. & substructure**
Vary momentum/angular size of probe

**Parton energy loss**
Vary mass/momentum of probe
- $g$
- $u,d,s$
- $c$
- $b$

**Upsilon spectroscopy**
Vary size of the probe
- $\Upsilon(2s)$ – 0.56 fm
- $\Upsilon(3s)$ – 0.78 fm
- $\Upsilon(1s)$ – 0.28 fm

This talk: Heavy flavor and quarkonia physics
sPHENIX detector

High luminosity
High rate

15 kHz trigger
>10 GB/s data

Full $\phi$ coverage

For $|z|<10$ cm: $|\eta|<1.1$
sPHENIX tracking system

Outer tracker:
- **TPC** (20 cm < r < 78 cm):
  - gateless and continuous readout
  - Provide momentum measurement

Inner tracker:
- **INTT** (6 cm < r < 12 cm):
  - strip silicon sensors (2-layer)
  - Pattern recognition, timing
- **MVTX** (2.3 cm < r < 3.9 cm):
  - MAPS pixel sensors (3-layer)
  - Procurement copies of ALICE ITS IB staves integrated into sPHENIX
  - Precision vertexing
Au+Au @ 200 GeV at 15 kHz for |z| < 10 cm: Total 239 billion events

p + p @ 200 GeV at 15 kHz for |z| < 10 cm: Total 8300 billion sampling events

High statistics!
Precision Upsilon spectroscopy

**Why $\Upsilon$ @ RHIC?**
Regeneration is smaller compared to $J/\psi$;
Less effect from bottom coalescence;
Temperature dependence of Debye screening length.

**Quarkonium:**
Color screening $\rightarrow$ dissociation

Different binding energy and radii of different states
$\rightarrow$ “Sequential melting”

QGP “Thermometer”
A. Mocsy, EPJ C61, 705 (2009)

Illustration: A. Rothkopf
Precision Upsilon

Challenge:
Small production cross section
\( \sim \bar{b}b \) pair 0.05/event

Goal:
Separate \( \Upsilon(1s)/\Upsilon(2s)/\Upsilon(3s) \)

Requirement:
\( \delta M / M < 125 \text{ MeV} \)

Tracking efficiency
> 90% efficiency

Momentum resolution
\( \delta p/p < 2\% \) for \( p_{T} < 10 \text{ GeV/c} \)

Central Au+Au
\( sPHENIX \) simulation

\( p + p \)
\( sPHENIX \) simulation
Electron identification

- $\gamma(ns) \rightarrow ee$
- Use $E_{CEMC}/p$ for eID
  - $E_{CEMC}$ is the energy deposit in central EMC
- Hadron rejection factor is considered
  - $K/\pi/p/\bar{p}$
- 90% eID efficiency

Hadron rejection factor
= electron efficiency / hadron efficiency

Inverse pion rejection factor
Upsilon signal projections

- sPHENIX provides excellent mass resolution.

\[ \Upsilon(ns) \rightarrow ee \]
Upsilon $R_{AA}$ projections

- Precise $\Upsilon(1s)$ and $\Upsilon(2s)$ $R_{AA}$ measurement is expected at $0 < p_T < 8$ GeV.

MVTX: enable HF physics!

In close coordination with ALICE / ATLAS Phase-I upgrade

-Sensors:
ALICE ALPIDE sensors identical ITS/IB design

-Readout:
ALICE frontend Readout Unit(RU)
ATLAS upgrade backend FELIX boards

-Mechanics:
Modified mechanical frame design for sPHENIX

MVTX: 3-layer MAPS pixel sensors
Active length 27 cm
~8 cm

Hit spatial resolution: < 5 μm

MVTX spatial resolution full chain test beam at FNAL @2018
Heavy flavor observables

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

`sPHENIX` simulation

`sPH-HF-2018-001 - MVTX Proposal`
Precise $B \rightarrow D$ measurement

- Explore $B \rightarrow D$ (non-prompt D meson) through $D^0$ DCA distribution

![Graph showing prompt and non-prompt D-meson distributions](image)

$B \rightarrow D^0 + X$
Non-prompt D projections

- Explore $B \rightarrow D$ (non-prompt D meson) through $D^0$ DCA distribution
- High statistics and significance $B$ meson via non-prompt D decay

After a BDT tagger

Prompt and non-prompt D-meson
Non-prompt D projections

- High precision non-prompt-$D$ suppression @ RHIC
  - Collisional and radiative energy loss
- Determine the bottom quark collectivity
  - clean access to $D_{HQ}$ at RHIC energy
  non-prompt $D$-meson and predictions for sPHENIX
Precise $B^+$ measurement

- Reconstruct $B^+$ through $B^+ \rightarrow D^0 \pi^+$
- Beautiful signal event at $p_T < 2$ GeV

![sPHENIX Simulation](image)
Precise $B^+$ measurement

- Reconstruct $B^+$ through $B^+ \rightarrow D^0 \pi^+$
- Beautiful signal event at $p_T < 2$ GeV
- Precise $B^+$ spectra measurement is expected.
b-jet tagging @ sPHENIX

- sPHENIX is an excellent jet detector
- b-jet: very small cross section
- B-hadron decay topology:
  - decay length ~ few mm
  - decay to multi-particles.

Algorithms for b-jet tagging:
- Tracking counting tagging:
  - Count No. of tracks > DCA cut
- Secondary vertex tagging:
  - multiple tracks coming from the same secondary vertex.
$b$-jet tagging @ sPHENIX

- Demonstrate $b$-jet capability: tagging algorithms evaluated using full detector HIJING simulation
- Reaching an optimal working point in central Au+Au collisions

**Track-counting tagger**

**Secondary-vertex tagger**

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$b$-jet projection

- High precision inclusive $b$-jet suppression and $v_2$ measurement @ RHIC
- Strong constraints on energy loss model of high energy probe in QGP.

Working point: 
- p+p 60% purity 40% efficiency
- Au+Au 40% purity 40% efficiency
Broader topic: Bottom observables

Opportunities for new ideas and new measurements!

- HF-jet-jet
- jet-HF-hadron
- D-\bar{D} correlations
- HF jet substructure
- Total $b$-cross section
- other B decay channels
  - $B \to J/\psi$ and more?

$\frac{p_{T,2}}{p_{T,1}}$ Di-b-jet $p_T$ asymmetry
$\Lambda_c$ production @ RHIC

- Heavy quark hadronization mechanism
- Strong enhancement of $\Lambda_c/D^0$ ratio compared to PYTHIA calculations.
  - Coalescence hadronization;
  - $\Lambda_c$ contributes sizably to the total charm cross section.

\[ \Lambda_c^+ = udc \]
\[ ct = 59.9 \mu m \]
\[ \Lambda_c^+ \rightarrow K^-\pi^+ (6.23\%) \]

Explore capability of $\Lambda_c$ measurement at future sPHENIX experiment!
**Particle identification scenarios**

1. **No PID**
   - currently default in the simulation.

2. **clean PID**
   - at low pT enabled by TOF, no PID at high pT.
     - K/π separation up to 1.6 GeV/c, protons up to 3 GeV/c;
     - TOF matching efficiency (~58%) taken from STAR.

3. **Hybrid PID**
   - TOF PID if matched to TOF;
     - otherwise no PID.

4. **Ideal TOF PID**
   - similar as 2, but assuming 100% TOF matching efficiency.
• Precise measurement of $\Lambda_c$ is expected at sPHENIX at 0-80%;
• PID detector helps suppress the background significantly.
Projected $\Lambda_c$ significance

Most central collision

- Very nice performance at $p_T > 3$ GeV in 0-10%;
- Low $p_T$ (< 2 GeV) measurement might need the help from PID detector in 0-10%;
- Enable more precise centrality dependence study.

Most peripheral collision
Summary

• Rich heavy flavor physics opportunity at sPHENIX
  • Upsilon: Color screening length
  • b-jets, B mesons: HF energy loss in QGP, HF diffusion coefficient
  • HF baryons: HF hadronization mechanism

• sPHENIX construction ramping up. First data in 2023
  • Successful PD 2/3 review
  • MVTX electronics and sensor staves production starting soon at CERN
sPHENIX collaboration

Currently 77 institutions
sPHENIX collaboration

Currently 77 institutions

Thank you!
• Back up slides
MVTX beam test @ FNAL 2019
$\Lambda_c$ simulation @ sPHENIX

**Signal:**
Decay $\Lambda_c$ by EventGen;
$\Lambda_c$ $p_T$ weight: $\Lambda_c/D^0 \times D^0$ spectra fitted to STAR data.

**Combinatorial background**
Particles from primary vertex:
Sample the $p_T$, $\eta$, $\varphi$ of particles
Particles from secondary vertex:
Charm decay $K/\pi/p$
Generated by PYTHIA 8
Tracking

$p + p, \sqrt{s} = 200 \text{ GeV}$
di-$b$-jet production at $p_T \approx 40 \text{ GeV/c}$
Science mission: Complementarity of RHIC and LHC

High $p_T$ @LHC:
Extend kinematic reach vs RHIC
Add new probes

Overlap in kinematic reach:
Study the same probe for different QGP evolution

High $p_T$ @LHC:
Extend kinematic reach vs RHIC
Add new probes
5-years run plan

Table 1: Five-year run plan scenario for sPHENIX. The recorded luminosity (Rec. Lum.) and first sampled luminosity (Samp. Lum.) values are for collisions with z-vertex $|z| < 10$ cm. The final column shows the sampled luminosity for all z-vertex values, relevant for calorimeter only measurements.

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<tbody>
<tr>
<td>Year-1</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>Year-2</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>Year-2</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>Year-3</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>Year-4</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>Year-5</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>
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Table 2: Summary of integrated samples summed for the entire five-year scenario.

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<tbody>
<tr>
<td>Au+Au</td>
<td>200</td>
<td>35 nb$^{-1}$ (239 billion)</td>
<td>80 nb$^{-1}$ (550 billion)</td>
<td>214 nb$^{-1}$ (1.5 trillion)</td>
</tr>
<tr>
<td>p+p</td>
<td>200</td>
<td>—</td>
<td>197 pb$^{-1}$ (8.3 trillion)</td>
<td>1.0 fb$^{-1}$ (44 trillion)</td>
</tr>
<tr>
<td>p+Au</td>
<td>200</td>
<td>—</td>
<td>0.33 pb$^{-1}$ (0.6 trillion)</td>
<td>1.46 pb$^{-1}$ (2.6 trillion)</td>
</tr>
</tbody>
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Upsilon measurement by STAR

STAR Preliminary

STAR Au+Au @ 200 GeV (0-60%)
Γ(1S) → μ⁺μ⁻, |y|<0.5

CMS Pb+Pb @ 2.76 TeV (0-100%)
Γ(1S), |y|<2.4