Progress toward heavy flavor measurements in sPHENIX

Antonio Silva for the sPHENIX Collaboration
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antonio.sphenix@gmail.com
sPHENIX

The conclusion of a 20+ years scientific journey

- sPHENIX is the first new detector at any hadron collider in over a decade!
  - A compact detector with unique, purpose-built capabilities never before deployed at RHIC

- Different initial conditions and evolution for QGP at RHIC and LHC
  - Study of scale and temperature dependence

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.

2015 US NP LRP

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Heavy-flavor physics program

- **Open heavy flavor**
  - Vary momentum/mass of the probe

- **Upsilon spectroscopy**
  - Vary size of the probe
  - \( \Upsilon(3S) \) 0.78 fm
  - \( \Upsilon(2S) \) 0.56 fm
  - \( \Upsilon(1S) \) 0.56 fm

- **Heavy-flavor jets**
  - Vary momentum/angular size of the probe

- **Cold QCD**
  - Vary temperature of QCD matter
  - HF spin asymmetry

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RHIC run plan 2023-2025

| Year | Beam  | $\sqrt{s_{NN}}$ (GeV) | Cryo Weeks | Physics Weeks | $\mathcal{L}_{\text{samp}}$ ($|z|<10\text{cm}$) |
|------|-------|-----------------------|------------|--------------|-----------------------------------------------|
| 2023 | Au+Au | 200                   | 24         | 9            | 4.5 nb$^{-1}$                                 |
| 2024 | p+p   | 200                   | 24         | 12           | 45 pb$^{-1}$                                 |
|      | p+Au  | 200                   | -          | 5            | 0.11 pb$^{-1}$                               |
| 2025 | Au+Au | 200                   | 24         | 20.5         | 21 nb$^{-1}$                                 |

- **Year 1**: Commissioning, calibration and first physics
- **Year 2**: Cold QCD and heavy-ion reference
- **Year 3**: Large Au+Au dataset

- High rate DAQ (15 kHz): trigger capability with streaming readout

“The PAC urges BNL Management and the DOE to do everything possible to ensure sufficient beamtime to accomplish the physics goals in Runs 23, 24, 25 set out for sPHENIX in the 2015 NSAC Long Range Plan.”

PAC Meeting June 2022: [https://indico.bnl.gov/event/15148/](https://indico.bnl.gov/event/15148/)

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The sPHENIX detector

6 meters

sEPD
MVTX
TPC
EMCAL
INTT
iHCAL
MinBIAS
oHCAL
TPO
ZDC

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Upsilon and track resolution

- $p_T$ resolution < 2% for $p_T < 10$ GeV/c
- Meets invariant mass resolution <125 MeV/c$^2$ for $\Upsilon(2S)$ and $\Upsilon(3S)$ direct separation for the first time at RHIC.
Upsilon and track resolution

Time-projection chamber (TPC)
- Ungated continuous readout
- Reconstruction of heavy-flavor electrons and hadron decays
- 150 μm $r\phi$ resolution
- $\Delta p/p \sim 1\%$ at 5 GeV/c charged particles
- TPC outer tracker (TPOT) used for calibrations

TPC event display during commissioning phase
- High voltage and magnet are on
EMCal: Scintillator fiber tungsten sampling calorimeter

- $|\eta| < 1.1$, full azimuthal coverage
- Identification of electrons from HF decays and HF-jets
- Towers with $\sim 0.025 \times 0.025$ in $\eta \times \phi$
- EM $\Delta E/E \sim 5\% + 16\%/\sqrt{E}$

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Quarkonium

- Centrality- and $p_T$-differential $R_{AA}$ measurements
- Clear distinction of three Upsilon states
  - Probing the QGP with color dipoles at three length scales
- Kinematic range allows for comparison between RHIC and LHC measurements

*Considering the $\Upsilon(3S)$ suppression observed at the LHC.

Open heavy flavour: DCA resolution

- DCA resolution in $r\phi < 40 \, \mu m$ for $p_T > 0.5 \, GeV/c$
- Crucial for the open heavy flavor and heavy-flavor jets program
- Separation of prompt and non-prompt $D^0$
  - Proxy for B mesons

INTT+MVTX
- Reconstruction of heavy-flavor decay topology
Open heavy flavor: MVTX

MVTX: MAPS based vertex tracker
- ALPIDE chip - near copy of the ITS2 inner layer from ALICE
- ~5 μm position resolution

Critical for reconstruction of the open heavy-flavor decay topology

- Correlation between layer 1 and 2 of the MVTX

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Open heavy flavor: INTT

INTT: silicon strip tracker
- 78 μm pitch
- Single beam-crossing timing

Critical for reconstruction of the open heavy-flavor decay topology

- Correlation between INTT and TPOT clusters

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Open heavy flavour measurements

- Study of heavy-flavor energy loss ($R_{AA}$)
  - Interplay between collisional and radiative energy loss

- Study of collective effects ($v_2$)
  - Access to the bottom quark collectivity

- High precision measurements → deeper understanding of the interaction mechanisms between heavy-quarks and the QPG

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HF flow, baryons, and spin asymmetry

- Heavy-flavor flow: $D^0 \nu_1$
  - Separated for $D^0$ and $\bar{D}^0$

- Charmed baryon $\Lambda_c$
  - $\Lambda_c/D$ ratio for central Au+Au and p+p

- $D^0$ transverse single spin asymmetry in p+p at $\sqrt{s} = 200$ GeV
Heavy-flavor jets: D-tagged jets

- Jets reconstructed with a D meson as one of the constituents
  - Full jet reconstruction → tracking + calorimeters
  - Strong rejection of combinatorial jets at low momentum
- Wide range of jet structure measurements
- Interesting comparison to b-jets and inclusive jets

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Heavy-flavor jets: b-jets

- First b-jet tagging at RHIC
  - Track DCA based tagger
  - Secondary vertices tagger
- Full jet reconstruction → tracking + calorimeters

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Heavy-flavor jets: HCal

- Heavy-flavor jet reconstruction
  - Combination of tracking and calorimeters
  - Implementation of particle flow

- Inner and Outer HCal commissioning
  - Inner (left) and Outer (right) HCal total energy as a function of MBD charge

Outer and Inner HCal
- First hadronic calorimeter at midrapidity at RHIC
- $|\eta| < 1.1$, full azimuthal coverage $\rightarrow$ HF-jets

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Summary

- All sPHENIX subsystems are progressing well during the commissioning phase
- The conclusion of a scientific mission to probe the inner workings of the QGP and resolving its properties
  - Heavy flavor is an important part of this mission
- Unique capabilities to probe the QGP at distinct length and mass scales at RHIC
  - $\Upsilon(2S)$ and $\Upsilon(3S)$ measurements at RHIC
- Open heavy flavor and heavy-flavor jet physics programs
  - Precision tracking
    - Including hadrons originating from $b$ quarks
  - Full jet reconstruction
    - $b$-jets and HF-hadron tagged jets

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Backup slides
## Potential 2 more years run 2026-2027

| Year | Beam      | $\sqrt{s_{NN}}$ (GeV) | Cryo Weeks | Physics Weeks | $\mathcal{L}_{samp}$ ($|z|<10\text{cm}$) |
|------|-----------|-----------------------|------------|---------------|--------------------------------------|
| 2026 | p+p       | 200                   | 28         | 15.5          | 80 pb$^{-1}$                        |
|      | O+O       | 200                   | -          | 2             | 37 nb$^{-1}$                        |
|      | Ar+Ar     | 200                   | -          | 2             | 12 nb$^{-1}$                        |
| 2027 | Au+Au     | 200                   | 28         | 24.5          | 30 nb$^{-1}$                        |

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Quarkonium measurements

- CMS measurement
- CMS-HIN-21-007, CERN-EP-2023-011
Quarkonium measurements

Y(1S), Y(2S) and Y(3S) $R_{AA}$ as a function of centrality

- Comparison to LHC measurements

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