Heavy Flavor and Jet Physics with the sPHENIX Detector

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on behalf of the sPHENIX collaboration

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The sPHENIX Physics Program

Jet structure
vary momentum/angular scale of probe

Cold QCD
study proton spin, transverse-momentum, and nuclear effects

Quarkonium spectroscopy
vary size of probe

Parton energy loss
vary mass/momentum of probe

- Υ(3s) 0.78fm
- Υ(2s) 0.56fm
- Υ(1s) 0.28fm

u,d,s
photon
 gluon
c
b
The sPHENIX detector at the Relativistic Heavy Ion Collider is designed to measure high transverse momentum probes of the quark-gluon plasma such as jets and heavy-flavor probes, which can offer insight into the small-scale structure of the QGP.

Tracking:
- MAPS-based Vertex Tracker (MVTX)
- Intermediate Silicon Tracker (INTT)
- Time Projection Chamber (TPC)
- TPC Outer Tracker (TPOT)

Superconducting Magnet
- 1.4T solenoid magnet

Calorimetry:
- Electromagnetic calorimeter
- Inner hadronic calorimeter
- Outer hadronic calorimeter

Event Characterization (Not Pictured):
- Minimum Bias Detector (MBD)
- Event Plane Detector (sEPD)

High rate DAQ and trigger systems
- 15 kHz trigger + streaming readout in pp/pA
Jet Physics

Projected yields, 3 year run proposal

- Jet measurements out to 70 GeV
  - overlap with LHC measurements
- Precision measurements at low $p_T$
- High stats also for
  - photons ($\gamma$-jet measurements)
  - charged hadrons (fragmentation functions, substructure)

### 3 years

<table>
<thead>
<tr>
<th>Signal</th>
<th>Au+Au 0–10% Counts</th>
<th>$p+p$ Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets $p_T &gt; 20$ GeV</td>
<td>22 000 000</td>
<td>11 000 000</td>
</tr>
<tr>
<td>Jets $p_T &gt; 40$ GeV</td>
<td>65 000</td>
<td>31 000</td>
</tr>
<tr>
<td>Direct Photons $p_T &gt; 20$ GeV</td>
<td>47 000</td>
<td>5 800</td>
</tr>
<tr>
<td>Direct Photons $p_T &gt; 30$ GeV</td>
<td>2 400</td>
<td>290</td>
</tr>
<tr>
<td>Charged Hadrons $p_T &gt; 25$ GeV</td>
<td>4 300</td>
<td>4 100</td>
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</tbody>
</table>
What we can learn at sPHENIX: Jet $v_2$

Open question: What is the path-length dependence of energy loss?

- $v_2$ at low $p_T$ $\rightarrow$ flow
- $v_2$ at high $p_T$ (i.e. jet $v_2$) $\rightarrow$ energy loss correlations with initial geometry
  - path-length dependence of energy loss

From the LHC

Cartoon from M. Rybar

**arXiv:2111.06606**

$\sqrt{s_{NN}} = 5.02$ TeV, 2.2 nb$^{-1}$
anti-$k_t$, $R = 0.2$, $|y| < 1.2$
20-40%

$p_T^{\text{jet}}$ or $p_T^{h^+}$ [GeV]

Precision measurements of jet $v_2$ at **high** $p_T$
What we can learn at sPHENIX: Jet $v_2$

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Precision measurements of jet $v_2$ at low $p_T$
- Constrain models of path-length dependence of energy loss for jets near QGP medium scale
What we can learn at sPHENIX: $R$ dependence

Open question: What is the interplay between out of cone energy loss and medium response vs. jet structure dependence?

- Competing effects can lead to larger or smaller suppression for large $R$ jets:
  - Recovery of out of cone energy
  - Inclusion of medium response
  - Jets with wider splittings lose more energy

- Models need input from experiment to balance these effects

- Tension in LHC results at low $p_T$
What we can learn at sPHENIX: $R$ dependence

Open question: What is the interplay between out of cone energy loss and medium response vs. jet structure dependence?

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- Precision measurement in region of tension from LHC

- Tension in LHC results at low $p_T$
Other jet measurements in sPHENIX

**Photon + Jets**

- **sPHENIX BUP 2022**
- **JEWEL 2.2.0, T = 260 MeV**
- Years 1-3, $p_T > 30$ GeV
- 62 pb$^{-1}$ samp. $p+p$
- 32 nb$^{-1}$ samp. Au+Au (0-10%)

**Dijets**

- **sPHENIX MIE 2018**
- Dijets, $R=0.2$, $p_T > 50$ GeV
- *generator-level*
- reco-level, $p+p$
- reco-level, Au+Au $b=4.8$fm
- reco-level, Au+Au $b=0.4$fm

**Jet Substructure**

- **sPHENIX BUP 2022, Years 1-3**
- **JEWEL 2.2.0, T = 260 MeV**
- $p_{T_{jet}} > 40$ GeV, $z_{out} = 0.1$, $\beta = 0$
- $p+p$
- Au+Au (0-10%)
Heavy Flavor Jets

Single b-jets

$p+p$: 62 pb$^{-1}$ samp., 60% Eff., 40% Pur.
$Au+Au$: 21 nb$^{-1}$ rec., 40% Eff., 40% Pur.

- $b$-jet Anti-k$_{T}$, $R=0.4$, 0-10% $Au+Au$, Year 1-3

mass dependence of energy loss

- back-to-back $b$-jet measurement reduces contribution from gluon splitting

Di-b-jets

$p+p$: 50 nb$^{-1}$, 60% Eff., 40% Pur.
$Au+Au$: 21 nb$^{-1}$ rec., 40% Eff., 40% Pur.

- $b$-jet tagging using DCA tagger for secondary vertices
  - mass dependence of energy loss
  - back-to-back $b$-jet measurement reduces contribution from gluon splitting
Vary the mass of QGP probes:

- $m_{c,b} \gg \Lambda_{QCD} \rightarrow$ produced primarily in early hard scatterings
- Large mass of $b$-quarks $\rightarrow$ modeled better theoretically
- Study mass dependence of collectivity and energy loss
- Provide constraints on diffusion transport parameter of the QGP
Small Systems

- Heavy flavor flow in p+Au:
  - Collectivity in small systems

- Jet/high $p_T$ hadrons p+Au:
  - Cold nuclear matter effects
  - Potential for energy loss in small systems
  - Cold QCD spin measurements
Detector Status

Carriage installation complete! - Jun. 2021

Magnet installation complete! - Oct. 2021

OHCAL installation complete! - 28th Feb. 2022

IHCAL Barrel assembly complete! - 18th Mar. 2022
sPHENIX detector will provide:
- Full coverage electromagnetic and hadronic calorimetry
- High precision tracking and vertexing
- Fast readout rate

Design allows for:
- High statistics samples of hard probes (jets, photons, high $p_T$ charged hadrons, heavy-flavor)
- Precision reconstruction of secondary vertices for heavy flavor tagging
- Complimentary measurements to LHC

Measurements will improve our understanding of small-scale behavior of the QGP

Data taking to begin in Feb. 2023!
Why Jets in sPHENIX vs. the LHC

- Different QGP:
  - Temperature evolution different between LHC and RHIC

- Different probes:
  - Different quark vs. gluon jet mixture
  - Lower kinematic range—radiation close to the QGP medium scale early in collision

arXiv:1501.06197
Heavy Flavor Toolkit

- Track reconstruction using ACTS

- Heavy flavor reconstruction using KFParticle
  - Developed for CBM experiment and adapted for use in STAR, ALICE, & others

- Tracking, vertexing, & HF reconstruction studied in simulated pp and Au+Au events with pileup

\[ IP \text{ and } IP \chi^2 = \left( \frac{IP}{\sigma_{IP}} \right)^2 \]

Flight Distance \((FD)\chi^2 = \overline{FD}C^{-1}\overline{FD}^T\)

\[ \cos \theta = \frac{\vec{p} \cdot \overline{FD}}{|\vec{p}| |\overline{FD}|} = \text{DIRA} \]

Study effects of medium on hadronization of heavy quarks

Indications of $\Lambda_c/D^0$ enhancement at RHIC

- Study in detail with sPHENIX
- Measure $p+p$ baseline in data

Discerning power between theoretical models