Recent open heavy flavor results from RHIC and LHC

Sooraj Radhakrishnan
Lawrence Berkeley National Laboratory
Relativistic Heavy Ion collisions: An excellent laboratory to study the QGP phase and QCD at extreme temperatures and energy densities.

RHIC: Au+Au, $\sqrt{S_{NN}} = 200$ GeV (Top energy)
LHC: Pb+Pb, $\sqrt{S_{NN}} = 2.76$ TeV, 5.02 TeV
Why study heavy flavor quarks?

- Mass higher than $T_{QGP}, \Lambda_{QCD}$
- Produced predominantly in initial hard-scatterings
- Production cross-sections amenable to pQCD calculations
- Ideal probes to study QGP
Heavy-ion collisions and Heavy Flavor quarks

- Understand parton energy loss mechanism in QGP
- Collisional and radiative energy loss
- Results in suppression of high $p_T$ hadron production
Heavy-ion collisions and Heavy Flavor quarks

Why study heavy flavor quarks?

- Pressure driven collective expansion of QGP medium
- Heavy quarks interact with and gain flow from QGP

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Phi_n))
\]
Heavy-ion collisions and Heavy Flavor quarks

Why study heavy flavor quarks?

- Total HQ conserved - ideal probes to study hadronization
- Hadronization mechanism in the presence of QGP

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Heavy-ion collisions and Heavy Flavor quarks

Why study heavy flavor quarks?

- Large relaxation times - can carry information on initial conditions
- Probes of initial strong magnetic fields?
Heavy-ion collisions and Heavy Flavor quarks

Why study heavy flavor quarks?

- Energy loss in medium
- Anisotropic flow
- Hadronization
- Initial conditions in HIC

• Wealth of new results from RHIC and LHC

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Heavy flavor production in p+p and p+A

- Heavy flavor production in p+p collisions well described by pQCD calculations
- Measured values close to upper edge of FONLL uncertainty bands
- Small system size in p+A collisions
- No suppression seen in p+A within uncertainties

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Suppression in A+A collisions

- Strong suppression of high $p_T$ charm meson production in A+A collisions
- Strong interactions and energy loss of charm quarks in QGP
- Seen for all charm hadrons

\[
R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{AA\text{ binary}} \times dN_{pp}/dp_T}
\]

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Suppression in A+A collisions

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- Strong interactions and energy loss of charm quarks in QGP
- Seen for all charm hadrons
- Suppression decrease towards peripheral collisions

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• Transport models with pQCD cross-sections (BAMPS, PHSD, MC@sHQ, LBT, POWLANG) and lattice QCD inspired interaction potentials (TAMU)

• Radiative energy loss start to dominate at higher $p_T$, interplay of collisional and radiative at lower $p_T$

• Models without radiative energy loss (POWLANG, BAMPS el, TAMU) deviate from data around $p_T \sim 10$ GeV/c
• Energy loss expected to have a mass heirarchy: $\Delta E_b < \Delta E_c < \Delta E_{u,d}$

• Hint of less suppression of $b \rightarrow e$ compared to $c \rightarrow e$ at RHIC

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Mass dependence of suppression

- Energy loss expected to have a mass hierarchy: $\Delta E_b < \Delta E_c < \Delta E_{u,d}$

- R$_{AA}$ of prompt D$^0$ (charm hadrons) and non-prompt D$^0$ and J/Psi (from B hadron decays) at LHC

- Hint of less suppression of b$\rightarrow$e compared to c$\rightarrow$e at RHIC

- Less suppression of B hadrons than D hadrons at LHC

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Mass dependence of suppression

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Phys. Rev. Lett. 123, 022001
Heavy flavor jets at LHC

• **R\_AA of D^0 tagged jets**, consistent with that of D^0

• **Modifications in fragmentation not a large effect for D^0 R\_AA**

• **Does distribution of HQ within jets change in QGP?**

• **Hints of modification of D^0 - jet correlations in QGP**
Elliptic flow of charm mesons

Collective expansion of QGP medium

HQ acquire flow as they transport through and interact with QGP

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Phi_n)) \]
Elliptic flow of charm mesons

Collective expansion of QGP medium

HQ acquire flow as they transport through and interact with QGP

- Large elliptic flow values for D mesons, comparable to that of light hadrons
- Follows NCQ scaling - suggests charm quarks flow along with QGP

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Elliptic flow of charm mesons

- Also can constrain the charm quark diffusion coefficient in QGP
- Small values of $2\pi T D_s$, well constrained by data $\sim T = T_c$
Elliptic flow of charm mesons

- Also can constrain the charm quark diffusion coefficient in QGP
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Simultaneous description of $v_2$ and $R_{AA}$ helps better separate between the models
• Hadronization via coalescence can be important in the presence of QGP
• Enhanced strangess in QGP + coalescence hadronization → $D_s$ enhancement
Hadronization - $D_s$ production

- Hadronization via coalescence can be important in the presence of QGP
- Enhanced strangeness in QGP + coalescence hadronization $\rightarrow D_s$ enhancement

- $D_s/D^0$ ratio higher in A+A compared to p+p and e+e,e+p
- Enhancement predicted by coalescence model calculations, but underpredicts data at RHIC

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Hadronization - $D_s$ and $B_s$ production

- Hadronization via coalescence can be important in the presence of QGP
- Enhanced strangeness in QGP + coalescence hadronization $\rightarrow D_s$ enhancement
- Hint of enhancement also for $B_s$ production at LHC

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arXiv:1810.03022
Baryon production - $\Lambda_c$

- Baryon/meson ratio at low $p_T$ valuable tool to study hadronization

- Strong enhancement of $\Lambda_c$ production in $p+p$ and $p+Pb$ collisions compared to fragmentation ratios measured at high $p_T$

- PYTHIA with CR also underpredict $\Lambda_c$ production

- How does charm baryon production evolve in heavy-ion collisions?
Baryon production - $\Lambda_c$

- Coalescence hadronization can produce further enhancement in A+A collisions

- Strong enhancement in A+A collisions compared to vacuum fragmentation values
- Coalescence model calculations are closer to data
- Enhancement higher than in p+p collisions

- Enhancement seen at RHIC larger than at LHC
Total charm cross section at RHIC

- Hadron yield ratios change, how about the total charm cross-section?

  - $D^0$ yields are measured down to zero $p_T$

  - For $D^{+/−}$, and $D_s$, Levy (power law) fits to measured spectra are used for extrapolation (systematics)

  - For $Λ_c$, three model fits to data are used and differences are included in systematics

<table>
<thead>
<tr>
<th>Charm Hadron</th>
<th>Cross Section $dσ/dy$ (μb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$41 ± 1 ± 5$</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$18 ± 1 ± 3$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$15 ± 1 ± 5$</td>
</tr>
<tr>
<td>$Λ_c^+$</td>
<td>$78 ± 13 ± 28^*$</td>
</tr>
<tr>
<td>Total</td>
<td>$152 ± 13 ± 29$</td>
</tr>
</tbody>
</table>

  * derived using $Λ_c^+/D^0$ ratio in 10-80%

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<th>Charm Hadron</th>
<th>Cross Section $dσ/dy$ (μb)</th>
</tr>
</thead>
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<tr>
<td>Total</td>
<td>$130 ± 30 ± 26$</td>
</tr>
</tbody>
</table>

- Suppression of $D^0$, enhancement of $D_s$ and $Λ_c$

- Total charm cross-section consistent with $p_T$ within uncertainties

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HQ as probes of initial conditions

- Very strong EM fields at initial stages in HIC

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HQ as probes of initial conditions

- HQ produced predominantly in initial hard scatterings
- Larger relaxation times
- Can carry information on initial conditions

- Charge dependent splitting of directed flow, $v_1 \langle p_x/p_T \rangle$ relative to RP

- Very strong EM fields at initial stages in HIC

- Model calculations predict a few percent difference in $v_1$ of $D^0$ and $\bar{D}^0$ after transport through QGP
HQ as probes of initial conditions

- Difference between charges consistent with zero at RHIC
- Non-zero difference seen at LHC
- Dominant charge independent contribution from initial geometry
- Need more precision measurements
Summary and Outlook

• Strong suppression and energy loss of high \( p_T \) HF hadrons in HIC
  • Disentangling energy loss mechanisms

• Large elliptic flow values
  • Together with \( R_{AA} \) provides better constrains on HQ interactions in QGP

• Hadronization mechanism
  • Modification of hadrochemistry in A+A
  • Importance of coalescence hadronization in heavy-ion collisions

• HF meson \( v_1 \) a potential tool to study the strong initial EM fields

• High precision HF measurements major focus at upcoming sPHENIX and LHC Run3
  • Dedicated high resolution HF tracking systems - ALICE ITS and sPHENIX MVTX
  • Expected integrated luminosity of \( 10^{-1} \) nb (13\(^{-1} \) \( \mu \)b existing) at ALICE and 240 Billion MB events (2B existing) at sPHENIX

THANK YOU!!
Back up
Bottom flow?

- Early attempts at bottom $v_2$ measurements
- Suggests smaller values, but limited statistics at present

$v_2$ of $c \rightarrow e$ (left) and $b \rightarrow e$ (right), and of non-prompt J/Psi (bottom)
• Small systems at high multiplicity show features of collective expansion!
• Large $v_2$ also for HF hadrons

- Seen at RHIC and LHC

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HF $v_2$ in small systems at high multiplicity

- Small systems at high multiplicity show features of collective expansion!
- Large $v_2$ also for HF hadrons
- Smaller $v_2$ values after NCQ scaling for charm compared to light hadrons in p+Pb

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$\Lambda_c/D^0$ model comparisons

- Peak is shifted to lower $p_T$ at RHIC energies in model calculations
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$D^0 v_1$ from initial geometry

- QGP bulk is tilted in Reaction Plane as a function of rapidity
- HQ production profile is symmetric in rapidity
- Causes enhanced initial first order asymmetry in density distributions
- Viscous drag from the expanding bulk medium produces large $v_1$ for heavy flavor quarks