Aspects of colliding and radiating charm quark in an expanding quark-gluon plasma

Manu Kurian, Mayank Singh, Vinod Chandra, Santosh Kumar Das, Charles Gale, Sangyong Jeon

1 Department of Physics, McGill University, 3600 University Street, Montreal, QC, H3A 2T8, Canada
2 School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
3 Indian Institute of Technology Gandhinagar, Gujarat, India
4 Indian Institute of Technology Goa, India

Why heavy quarks?
- Heavy quarks (HQs) as effective probes to characterize the QGP properties.
- HQ production: mostly created in the initial moments of the collision
- Thermalization time:
  Charm ~10-15 fm/c;
  Bottom ~25-30 fm/c;
  Greater than QGP lifetime;

Outline
- Introduction to HQ Brownian motion
- Methodology:
  (i) HQ transport in expanding QGP
  (ii) Energy loss in viscous medium
- Impacts on observables
HQ dynamics

- HQs dynamics in the QGP can be studied as a Brownian motion: Fokker-Planck equation

\[
\frac{df_{HQ}}{dt} = \frac{\partial}{\partial p_i} \left[ A_i(p) f_{HQ} \right] + \frac{\partial}{\partial p_j} \left[ B_{ij}(p) f_{HQ} \right]
\]

- Transport coefficients: Drag and Diffusion
- Simplified Boltzmann Equation
- Soft momentum transfer

- Several attempts to study the dynamics of HQs and interpret related physical observables

- However, many calculations supposed the QGP is a static and thermalized medium

**Methodology**

- **Step I:** Hydrodynamic Modelling and HQ transport coefficients in the viscous medium (using MUSIC).
  - B. Schenke, S. Jeon, C. Gale, PRC 82, 014903 (2010)

- **Step II:** Radiative and collisional energy losses of HQs in the viscous medium

- **Step III:** Estimation of HQ observables within Langevin dynamics using MARTINI
  - B. Schenke, S. Jeon, C. Gale, PRC 80, 054913 (2009)
Step I: Charm quark drag in an expanding QGP

*M. Kurian, M. Singh, V. Chandra, S. Jeon, and C. Gale, PRC (2020)*

- 3+1-D viscous hydrodynamics approach-MUSIC

  *B. Schenke, S. Jeon, C. Gale, PRC 2010*
  *B. Schenke, S. Jeon, C. Gale, PRL 2010*

- Pb+Pb collision at 2.76 TeV

- HQ drag: thermal average of the momentum transfer

**Bulk viscous correction to HQ drag**

- Bulk correction to distribution function
- Correction to the thermal average of function in CoM frame
- Bulk correction to HQ drag \[ A_i = A_i^{(0)} + A_i^{\text{bulk}} \]

- Effects of shear and bulk viscous dynamics to the HQ drag and diffusion are non-negligible and the variation ranges from 0% - 30% for different temperature regimes.

- These viscous corrections are essential to maintain consistency in the theoretical description of HQ dynamics in expanding QGP medium.
Step II: Collisional and radiative energy loss

The drag force which accounts for the resistance to the heavy quark motion, leads to its energy loss in the QGP medium.

- The energy loss is sensitive to the initial charm quark momentum.
- The viscous effects are seen to have weaker dependence on the momentum evolution of the charm quark in the initial stages of the collision.
- Collisional energy loss is the dominant mode for heavy quark in the low momenta regime whereas radiative energy loss dominates at higher momentum regime.
- A similar analysis will hold for bottom quarks, and the effects will be less pronounced because of their larger mass.
Step III: Consequences on HQ observables

- Estimation of HQ observables within Langevin dynamics using MARTINI

\[
\begin{align*}
\frac{dx_i}{dt} &= \frac{p_i}{E} dt, \\
\frac{dp_i}{dt} &= -A_i dt + \xi_i(p) dt,
\end{align*}
\]

Drag force \hspace{1cm} Stochastic force

(\textit{collisional+radiative energy loss})

- An up-to-date calculation of HQ experimental signals using the latest developments in the hydrodynamical simulation will shed light on the different observables in the RHIC and LHC data.

- This exploration will be relevant for the interpretation of the recent observations at the RHIC and LHC of the directed flow of the D mesons.

- With the upgrades of the tracking detectors in Run 3 and 4 of the LHC, one expects to obtain higher precision statistics to study QGP properties with heavy-flavor probes (https://cds.cern.ch/record/2661798)
# Back up: Heavy quark drag in bulk viscous medium

For the process \( HQ(P) + g/q(Q) \rightarrow HQ(P') + g/q(Q') \)

\[
A_i = \frac{1}{\gamma_c} \frac{1}{2P^0} \int \frac{d^3 q}{(2\pi)^3 2Q^0} \int \frac{d^3 p'}{(2\pi)^3 2P'^0} \int \frac{d^3 q'}{(2\pi)^3 2Q'^0} \delta^4 (P + Q - P' - Q') \sum |\mathcal{M}_{HQ,g/q}|^2 f_{g/q}(Q) \left( 1 \pm f_{g/q}(Q') \right) (p - p'),
\]

\[\equiv \langle \langle F(p') \rangle \rangle \]

Solve the kinematics in the center-of-momentum frame of the colliding particles

\[
\langle \langle F(p') \rangle \rangle = \frac{1}{512\pi^4 \gamma_c^2} \frac{1}{E^0_p} \int_0^\infty \frac{q^2}{E_q} dq \int_{-1}^1 d\cos \chi f_{g/q}(E_q) \sqrt{(s + m^2 - m^2_{g/q})^2 - 4s m^2} \int_{-1}^1 d\cos \theta_{cm} \sum |\mathcal{M}_{HQ,g/q}|^2 \int_0^{2\pi} d\phi_{cm} e^{iE_p} f_{g/q}(E_q) F(p')
\]

**I: Bulk correction to distribution function**

\[
\delta f_{g/q}(Q, X) = \Pi B_X(X) B_M(Q, T), \quad \quad B_X(X) = \frac{1}{15(\frac{1}{T} - c_s^2)(\epsilon + \mathcal{P})}, \quad \quad B_M(Q, T) = \frac{1}{T} f_{g/q}(Q) \left( 1 \pm f_{g/q}(Q) \right) \left( E_q - \frac{m^2_{g/q}}{E_q} \right).
\]

**II: Correction to the general integral**

\[
\langle \langle F(p') \rangle \rangle_{\text{bulk}} = \frac{\Pi B_X(X)}{512\pi^4 \gamma_c^2} \frac{1}{E_p} \left[ \Lambda_1(p, T) \pm \Lambda_2(p, T) \right],
\]

**III: Bulk correction to HQ drag**

\[
A_i = A_i^{(0)} + A_i^{\text{bulk}}
\]