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

Manu Kurian[1], Mayank Singh[2], Vinod Chandra[3], Santosh Kumar Das[4], Charles Gale[1], Sangyong Jeon[1]

[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

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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 lifetme;

Outline

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

HQ dynamics

B. Svetitsky, PRD 1988,
M.G.Mustafa, D.Pal, D.K.Srivastava, PRC 1998,
S. K. Das, F. Scardina, S. Plumari, V. Greco, PRC 2014
R.Rapp and H.van Hees, 0903.1096

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

$$\frac{\partial f_{HQ}}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(\mathbf{p})\, f_{HQ} + \frac{\partial}{\partial p_j}\left[B_{ij}(\mathbf{p})\, f_{HQ}\right]\right]$$

Drag

Thermal average of the momentum transfer

Diffusion

Square of the momentum transfer

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

- Several attempts to study the dynamics of HQs and interpret related physical observables *PRL 125, 192301 (2008); PRL 98, 172301 (2007); PRC 99, 054907 (2019).*

- 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

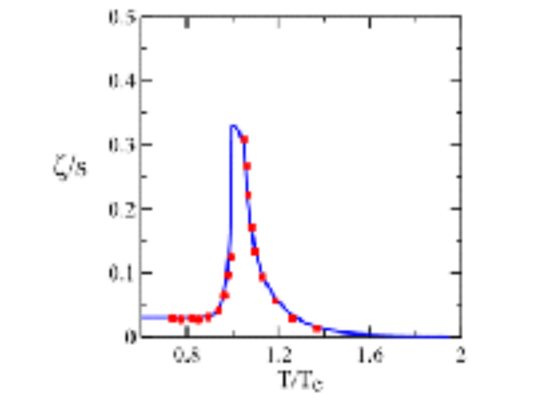
*B. Schenke, S. Jeon, C. Gale, PRC **80**, 054913 (2009)*

Step I: Charm quark drag in an expanding QGP

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

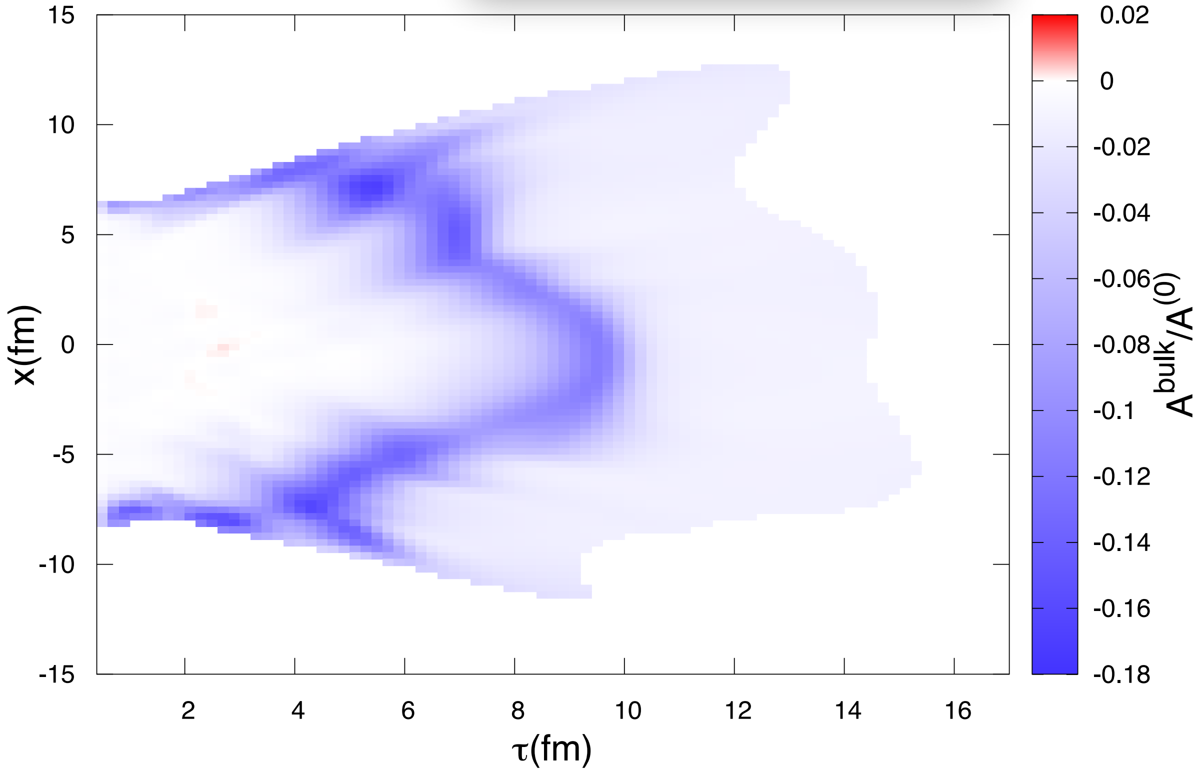
- 3+1-D viscous hydrodynamics approach-**MUSIC**

  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

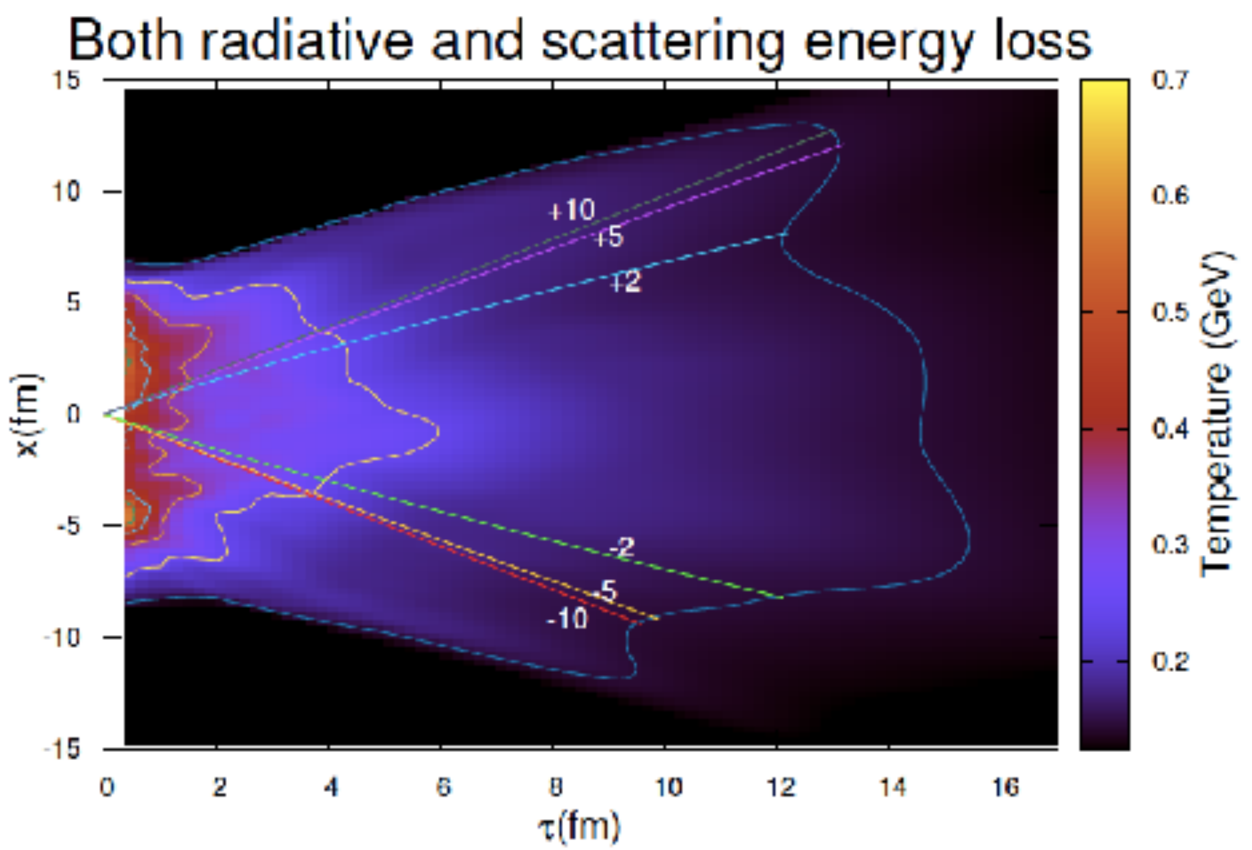
- ☑ Bulk correction to distribution function
- ☑ Correction to the thermal average of function in CoM frame
- ☑ Bulk correction to HQ drag $A_i \simeq A_i^{(0)} + A_i^{bulk}$

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

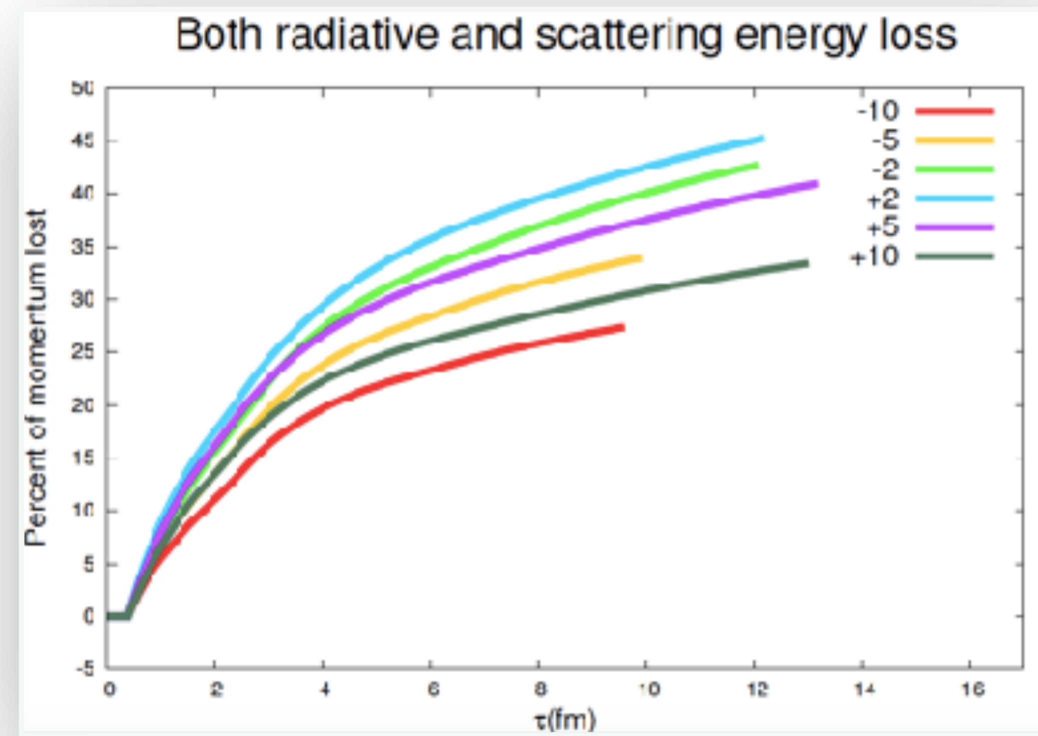
- These viscous corrections are essential to maintain consistency in the theoretical description of HQ dynamics in expanding QGP medium.

<u>Step II:</u> 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.



Trajectory of charm quark motion in the space-time with different initial momentum.



The charm quark percentage of momentum lost with proper time in the viscous medium at LHC for the trajectory.

- 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

$$
\begin{aligned}
dx_i &= \frac{p_i}{E} dt, \\
dp_i &= -A_i\, dt + \xi_i(\mathbf{p}) dt,
\end{aligned}
$$

Drag force Stochastic force

(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 $HQ(P)+g/q(Q)\to HQ(P^{'})+g/q(Q^{'})$

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

$$\equiv<<\left(\mathbf{p}-\mathbf{p}'\right)_i>>$$

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

$$\langle\langle F(p^{'})\rangle\rangle=\frac{1}{512\pi^4\gamma_c}\frac{1}{E_p}\int_0^\infty\frac{q^2}{E_q}dq\int_{-1}^{1}d\cos\chi f_{g/q}(E_q)\frac{\sqrt{(s+m_c^2-m_{g/q}^2)^2-4sm_c^2}}{s}\int_{-1}^{1}d\cos\theta_{cm}\sum|\mathcal{M}_{HQ,g/q}|^2\int_0^{2\pi}d\phi_{cm}e^{\beta E_{q^{'}}}f_{g/q}(E_{q^{'}})F(p^{'})$$

I: Bulk correction to distribution function

$$\delta f_{g/q}(Q,X)=\Pi B_X(X)B_M(Q,T),\qquad B_X(X)=\frac{1}{15\left(\frac{1}{3}-c_s^2\right)\left(\epsilon+\mathscr{P}\right)},\qquad B_M(Q,T)=\frac{1}{T}f^0_{g/q}(Q)\left(1\pm f^0_{g/q}(Q)\right)\left(E_q-\frac{m_{g/q}^2}{E_q}\right).$$

II: Correction to the general integral

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

III: Bulk correction to HQ drag $\quad A_i\simeq A_i^{(0)}+A_i^{bulk}$