Heavy Quark Evolution and Flow in Hot and Dense Medium

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Outline

• Introduction and motivation
• Methodology
  Improved Langevin approach incorporating gluon radiation mechanism
• Results of heavy flavor suppression and flow and comparison with experimental data
• Summary and outlook
Why to Study Heavy Quark

- Mainly produced at early stage: act as a hard probe
- Heavy: supposed to be influenced less by the medium
- Partially thermalized with medium — SC, Bass, *PRC 84, 064902*

- Surprisingly small $R_{AA}$ and large $v_2$ of non-photonic electrons
- Strong coupling between heavy quark and the medium
- How to describe heavy quark energy loss process inside QGP?
Energy Loss Mechanisms

- Two ways for heavy quarks to lose energy:
  - Collisional
  - Radiative

- Unless in the ultra-relativistic limit ($\gamma v \gg 1/g$), gluon radiation is suppressed by the “dead cone effect” → consider collisional energy loss as the dominant factor

- Heavy quark inside QGP medium: Brownian motion

- Description: Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$
From RHIC to LHC

Successful description of RHIC data: **Langevin for HQ + coal. & frag. for hadronization + heavy meson diffusion in hadron gas**

What shall we modify to go from RHIC to LHC?

- Even heavy quark is ultrarelativistic
  - → radiative energy loss may not be ignored
- At high energy, frag. might be sufficient for hadronization

He, Fries, Rapp, *PRC86, 014903*, arXiv:1208.0256, and private communication with He
Improved Langevin Approach
Incorporating Gluon Radiation

Modified Langevin Equation:
\[ \frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \]

Fluctuation-dissipation relation between drag and thermal random force:
\[ \eta_D(p) = \frac{\kappa}{2TE} \langle \xi^i(t)\xi^j(t') \rangle = \kappa \delta^{ij} \delta(t - t') \]

Force from gluon radiation:
\[ \vec{f}_g = -\frac{d\vec{p}_g}{dt} \]

Gluon distribution taken from Higher Twist calculation:
\[ \frac{dN_g}{dxdk^2_{\perp}dt} = \frac{2\alpha_s(k_{\perp})}{\pi} P(x) \frac{\hat{q}}{k^4_{\perp}} \sin^2 \left( \frac{t - t_i}{2T_f} \right) \left( \frac{k^2_{\perp}}{k^2_{\perp} + x^2M^2} \right)^4 \]

Guo and Wang, PRL 85, 3591; Majumder, PRD 85, 014023; Zhang, Wang and Wang, PRL 93, 072301.

Transport Coefficients:
\[ D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa} \]
\[ \hat{q} = 2\kappa C_A/C_F \]
Improved Langevin Approach
Incorporating Gluon Radiation

Numerical Implementation (Ito Discretization)

\[ \vec{p}(t + \Delta t) = \vec{p}(t) - \vec{d}_{Ito}(\vec{p}(t))\Delta t + \vec{\xi}\Delta t - \Delta \vec{p}_{\text{gluon}} \]

Drag force: \[ \vec{d}_{Ito}(\vec{p}) = \eta_D(p)\vec{p} \]

Thermal random force: \[ \langle \xi^i(t)\xi^j(t - n\Delta t) \rangle = \frac{\kappa}{\Delta t} \delta^{ij} \delta^{0n} \]

Momentum of gluon radiated during \( \Delta t \): \[ \Delta \vec{p}_{\text{gluon}} \]
Charm Quark Evolution in Static Medium

$T = 300 \text{ MeV}, D = 7/(2\pi T)$, i.e., $q_{\text{hat}} \sim 1.1 \text{ GeV}^2/\text{fm}$

$E_{\text{init}} = 15 \text{ GeV}$

Evolution of $E$ distribution

- Before 2 fm/c, collisional energy loss dominates; after 2 fm/c, radiative dominates;
- Collisional energy loss leads to Gaussian distribution, while radiative generates long tail.
Heavy Quark Evolution in LHC QGP

• Generation of QGP medium: 2D viscous hydro from OSU group (thanks to Qiu, Shen, Song, and Heinz)

• Initialization of heavy quarks: MC-Glauber for position space and pQCD calculation for momentum space

• Simulation of heavy quark evolution: the improved Langevin algorithm in the local rest frame of the medium

• Fragmentation of HQ into heavy flavor mesons: PYTHIA 6.4

\[ D = \frac{7}{(2\pi T)} \], i.e., q\hat{q} ~ 2.6 \text{ GeV}^2/\text{fm} \text{ at initial temperature (around 400 MeV)}

After freeze-out: free-streaming

Free-streaming outside the medium
Heavy Quark Energy Loss

- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: around 6 GeV.
$R_{AA}$ of D meson

- Collisional dominates low $p_T$, radiative dominates high $p_T$.
- The combination of the two mechanisms provides a good description of experimental data.
Similar trend of competition between the two energy loss mechanisms as revealed by $R_{AA}$

Different geometries and flow behaviors of the QGP medium may have impact heavy flavor $v_2$ while does not significantly influence the overall suppression (SC, Qin and Bass, arXiv:1205.2396)

Influence of coalescence mechanism and hadronic interaction

KLN provides larger eccentricity for the QGP profile than Glauber and therefore larger D meson $v_2$
Prediction for B Meson

- Similar behaviors as D meson – collisional energy loss dominates low $p_T$ region, while radiative dominates high $p_T$.
- The crossing point is significantly higher because of the much larger mass of bottom quark than charm quark.
- B meson has larger $R_{AA}$ and smaller $v_2$ than D meson.
Summary and Outlook

• Study the heavy quark energy loss in hot and dense medium in the framework of the Langevin approach

• Improve the Langevin algorithm to incorporate radiative energy loss by treating gluon radiation as an extra force term

• Reveal the significant effect of radiative energy loss at the LHC energy level and provide description of D meson suppression consistent with LHC data

• Two issues for further improvement:
  Anomalous transport of heavy quark in the pre-equilibrium stage after heavy-ion collisions
  Interaction between heavy mesons and hadron gas
Thank you!
• Collisional energy loss dominates low energy region, while radiative dominates high energy region.
• Crossing point: around 17 GeV, much larger than charm quark because of heavier mass.