Heavy Flavor Dynamics in Relativistic Heavy-ion Collisions

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Outline

• Introduction

• Heavy flavor dynamics in QGP and Hadron Gas
  
  *Initial production*: Glauber + pQCD;
  *In-medium evolution*: an improved Langevin approach (col. + rad.)
  *Hadronization*: a hybrid frag. + coal. model
  *Hadronic interaction*: the UrQMD model

• Heavy flavor suppression and flow (comparison with LHC/RHIC data)

• Angular correlation function of Heavy Flavor

• Summary
Why to Study Heavy Quarks?

- Heavy $\rightarrow$ produced at early stage: probe the full QGP history
- Heavy $\rightarrow$ thermal modification to mass is negligible: stable probe
- Heavy $\rightarrow$ supposed to be influenced less by the medium

“Heavy flavor puzzle”: is $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ still right?
Challenge: fully understand heavy flavor dynamics – whole evolution
Heavy Flavor Initial Production

- Initial production: MC-Glauber for the position space and LO pQCD calculation (Combridge, 1979) for the momentum space
- Parton distribution functions: CTEQ5 (Lai, 2000)
- Nuclear shadowing effect: EPS09 (Eskola, 2009)

(Taken from Eskola 2009)

Significant shadowing effect for heavy quark production at low $p_T$ (especially at the LHC energy) $\rightarrow$ impact on $R_{AA}$
Energy Loss Mechanisms

Two ways for heavy quarks to lose energy:

Abir et al. PLB 715 183

“Dead cone effect”: Unless in an ultrarelativistic limit, gluon radiation is suppressed by the large mass of heavy quark → 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**

He, Fries, Rapp, *PRC*86, 014903, arXiv:1208.0256, and private communication with He

**Going from RHIC to LHC?**

- Even heavy quark is ultrarelativistic
  - radiative energy loss can not be ignored
Heavy Flavor Evolution inside QGP (Improved Langevin Approach)

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:
$$\eta_D(p) = \frac{k}{2TE} \langle \xi^i(t)\xi^j(t') \rangle = \kappa \delta^{ij} \delta(t - t')$$

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

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


Transport Coefficients:
$$D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa} \quad \hat{q} \sim 2\kappa C_A/C_F$$
Heavy Flavor Evolution inside QGP (Improved Langevin Approach)

Numerical Implementation (Ito Discretization)

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

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

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 \( \Delta t \): \( \Delta \vec{p}_{\text{gluon}} \)

**Lower cut for gluon radiation:** \( \pi T \)

- Balance between gluon radiation and absorption
- Guarantee equilibrium after sufficiently long evolution
Charm Quark Evolution in Static Medium

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

$T = 300 \text{ MeV}, D=6/(2\pi T)$, i.e., $q_{\text{hat}} \sim 1.3 \text{ GeV}^2/\text{fm}$

**Evolution of $E$ distribution**

- Before $2 \text{ fm/c}$, collisional energy loss dominates; after $2 \text{ fm/c}$, radiative dominates;
- Collisional energy loss leads to Gaussian distribution, while radiative generates long tail.
Charm Quark Evolution inside the 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
- Hadronization and hadronic scattering (discuss later)

\[ D = \frac{6}{(2\pi T)} \], i.e., qhat around 2~3 GeV\(^2\)/fm at initial temperature (around 350~400 MeV)

outside the medium (below \( T_c \)) hadronize and hadronic scattering
Heavy Quark Energy Loss

- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: 6 GeV for $c$ and 16 GeV for $b$ quark.
- Collisional energy loss alone may work well to describe previous RHIC data but is insufficient for LHC.
Hadronization

QGP: Cooper-Frye Freeze-out (OSU iSS)

\[ E \frac{dN}{d^3p} = \int_{\sigma} f(x, p) p^\mu d\sigma_\mu \]

- \( f(x, p) \): thermal distribution of soft hadrons
- \( \sigma \): hypersurface of freeze-out

HQ: Fragmentation + Recombination

- Most high momentum heavy quarks fragment into heavy mesons: use PYTHIA 6.4
- Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism: use the instantaneous coalescence model (Oh, 2009)
The Instantaneous Coalescence Model

Two-particle recombination:

\[
\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1} \frac{dN_2}{d^3p_2} f^W_M(\vec{p}_1, \vec{p}_2) \delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)
\]

\[\frac{dN_i}{d^3p_i}\] Distribution of the \(i\)th kind of particle

Light quark: thermal in the l.r.f of the hydro cell

Heavy quark: the distribution at \(T_c\) after Langevin evolution

\[f^W_M(\vec{p}_1, \vec{p}_2)\] Probability for two particles to combine

\[f^W_M(\vec{r}, \vec{q}) = Ng_M \int d^3r' e^{-i\vec{q} \cdot \vec{r}'} \phi_M(\vec{r} + \frac{\vec{r}'}{2}) \phi^*_M(\vec{r} - \frac{\vec{r}'}{2})\]

\[\vec{r} = \vec{r}_1 - \vec{r}_2\]

\[\vec{q} = \frac{1}{E'_1 + E'_2}(E'_2\vec{p}_1 - E'_1\vec{p}_2)\]

Variables on the R.H.S. are defined in the c.m. frame of the two-particle system.
The Instantaneous Coalescence Model

\[ f^W_M(\vec{r}, \vec{q}) \equiv N g_M \int d^3r' e^{-i\vec{q} \cdot \vec{r}'} \phi_M(\vec{r} + \frac{\vec{r}'}{2})\phi^*_M(\vec{r} - \frac{\vec{r}'}{2}) \]

- \( N \): normalization factor
- \( g_M \): statistics factor

E.g. D ground state: \( 1/(2 \times 3 \times 2 \times 3) = 1/36 \) – spin and color

- D*: \( 3/(2 \times 3 \times 2 \times 3) = 1/12 \) – spin of D* is 1

- \( \Phi_M \): meson wave function – approximated by S.H.O.

Integrating over the position space leads to

\[ f^W_M(q^2) = N g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2} \]

- \( \mu \): reduced mass of the 2-particle system
- \( \omega \): S.H.O frequency – calculated by meson radius
  - 0.106 GeV for c, and 0.059 GeV for b

Can be generalized to 3-particle recombination (baryon)
The Hybrid Coal. + Frag. Model

Use $f^W$ to calculate $P_{\text{coal.}}(p_{\text{HQ}})$ for all channels: $D/B \Lambda \Sigma \Xi \Omega$

Normalization: $P_{\text{coal.}}(p_{\text{HQ}}=0) = 1$

Use Monte-Carlo to determine the hadronization channel of each HQ: frag. or recomb.? recomb. to $D/B$ or a baryon?

Fragmentation dominates $D$ meson production at high $p_T$.

Recombination significantly enhances the $D$ meson spectrum at intermediate $p_T$. 
Hadronic Interactions

Soft hadrons from QGP
Heavy mesons from heavy quarks

Charm Meson Scattering Cross Sections:
(Lin and Ko, 2001)

Consider scatterings with $\pi$ and $\rho$ mesons

$\Lambda$: cutoff parameter in hadron form factors
Interim Summary of HF Dynamics

Bulk Matter: Glb/KLN initial condition
(2+1)-d viscous hydro (OSU)
Cooper-Frye (OSU iSS)

Heavy Flavor: Glauber for $x$
LOpQCD+CTEQ
+EPS09 for $p$
Improved Langevin col.+rad.
Hybrid model of frag.+coal.

UrQMD
• Collisional dominates low $p_T$, radiative dominates high $p_T$.
• The combination of the two mechanisms provides a good description of experimental data.
$R_{AA}$ of LHC $D$ meson

- Shadowing effect reduce $R_{AA}$ significantly at low $p_T$.
- Recombination mechanism raise $R_{AA}$ at medium $p_T$. 
frag. only: force fragmentation, i.e., $f^W(q)=0$ for any $q$.
recomb. only: force combination, i.e., $f^W(q)=1$ for any $q$.
Recombination mechanism provides larger $v_2$ than fragmentation.
However, due to the momentum dependence of the Wigner function, our combined mechanism only slightly raises the $Dv_2$ at medium $p_T$. 
Hadronic interaction further suppresses $R_{AA}$ at large $p_T$ but slightly enhances it at low $p_T$. Good description of the experimental data.
Hadronic interaction enhances $D$ meson $v_2$ by over 30%
Difference between the Glb to KLN initial condition for hydro leads to another 30% uncertainties in $D$ meson $v_2$
Still under-estimate $D$ meson $v_2$ as measured by ALICE
Hadronic interaction suppresses $R_{AA}$ at large $p_T$ and enhances $v_2$

Our calculations are consistent with the RHIC data
More $R_{AA}$ results for RHIC

Centrality and participant number dependence are also consistent with RHIC observations.
From Single to Double Particle Spectra
(Angular Correlation of Heavy Flavor)

At LO: Back-to-back production of initial QQbar with the same magnitude of momentum
Angular De-correlation of CCbar

- Though each energy loss mechanism alone can fit $R_{AA}$ to certain accuracy, they display very different behaviors of angular de-correlation.
- Pure radiative energy loss does not influence the angular correlation significantly; pure collisional leads to peak at collinear distribution because of the QGP flow.
More Realistic Analysis

- MCNLO + Herwig radiation for HQ initial production
- Angular correlation function of final state ccbar pairs

Experimental observations will help distinguish the energy loss mechanisms of heavy quark inside QGP.

- Within each event, loop each D with all Dbar’s
- Similar shape as ccbar pairs, but on top of a large background

![Graphs showing angular correlation and D-Dbar correlation](image)
Current Experiments (HF-Hadron Correlation)

(e from c, b) - h correlation
(talk by Pereira at HP2013)

Calculation of D-hadron correlation

Peaks around 0 and π
Complication introduced by the medium flow to the correlation function
Differences between various energy loss mechanisms depend on y and $p_T$ cut (should be investigated later)
Summary

• Established a comprehensive framework of heavy flavor dynamics in relativistic heavy-ion collisions, including initial production, energy loss inside QGP, hadronization process and hadronic interaction in hadron gas.

• Revealed the significant effect of gluon radiation at high energies and recombination at medium $p_T$, The hadronic interaction further suppresses $D$ meson $R_{AA}$ at large $p_T$ and enhances its $v_2$.

• Provided descriptions of $D$ meson suppression and flow consistent with most of the data at both RHIC and LHC.

• Discussed about the heavy-flavor tagged correlation functions – may help distinguish between different energy loss mechanisms of heavy quarks inside QGP.
Thank you!
Check of Detail Balance

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

\(\vec{f}_g\) Gluon radiation only, may break the detail balance

\[
\eta_D(p) = \frac{\kappa}{2TE} \quad \langle \xi^i(t)\xi^j(t') \rangle = \kappa \delta^{ij} \delta(t-t')
\]

Cut off gluon radiation at low energies where collisional energy loss dominates and detail balance is preserved.

Large enough cut reproduces charm quark thermalization behavior.

More rigorous solution: include gluon absorption term into the higher-twist formalism directly and recalculate \(\vec{f}_g\) term.
The shadowing effect for $b$-quark is not as significant as $c$-quark, but still non-negligible. “Anti-shadowing” at RHIC energy.