Suppression and Two-Particle Correlation of Open Heavy Flavor in Heavy-Ion Collisions

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Outline

• **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)**

• **Two-particle correlation functions of Heavy Flavor**

• **Summary**
Heavy Flavor Initial Production

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

Significant shadowing effect for heavy quark production at low $p_T$ (especially at the LHC energy) $\Rightarrow$ impact on $R_{AA}$
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:
\[ \eta_D(p) = \frac{\kappa}{2TE} \quad \left\langle \xi^i(t)\xi^j(t') \right\rangle = \kappa \delta^{ij} \delta(t - t') \]

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 Quark Energy Loss

- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: 7 GeV for $c$ and 18 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 Hybrid Coal. + Frag. Model

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

Normalization: $P_{\text{coal.}}(\rho_{\text{HQ}}=0) = 1$ at $T_c = 165$ MeV and $v_{\text{cell}} = 0$

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

UrQMD

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

Consider scatterings with \( \pi \) and \( \rho \) mesons

\( \Lambda \): cutoff parameter in hadron form factors
$R_{AA}$ of LHC $D$ meson

- Collisional dominates low $p_T$, radiative dominates high $p_T$.
- The combination of the two mechanisms provides a good description of experimental data.
$R_{AA}$ and $v_2$ of $D$ mesons

- Shadowing effect reduce $R_{AA}$ significantly at low $p_T$.
- Recombination mechanism raise $R_{AA}$ at medium $p_T$.  
- Coalescence provides larger $v_2$ than fragmentation since it adds the $p$-space anisotropy of light partons to heavy quarks.
$R_{AA}$ of $D$, $B$ mesons and non-prompt $J/\psi$

- Good description of $N_{\text{part}}$ dependence of the $D$ meson $R_{AA}$
- With the same transport coefficient for $c$ and $b$ quarks, reasonable description of the non-prompt $J/\psi$ $R_{AA}$
- Mass hierarchy of heavy quark energy loss: $\Delta E_c > \Delta E_b$
More $R_{AA}$ results for RHIC

Centrality and participant number dependence are also consistent with RHIC observations.
From Single Particle Spectra to Two-Particle Correlations

( arXiv: 1505:01869 )

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

- **Angular correlation function** between heavy flavor pairs
- **Momentum imbalance** between heavy flavor pairs
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.
Near / Away Side Variances

- PYTHIA simulation for heavy quark initial production
- Within each event, loop each D with all Dbar’s

- Away side at medium $p_T$: non-monotonic behavior – longitudinal energy loss vs. transverse momentum broadening.
Momentum Imbalance of $D$ mesons

- Momentum imbalance: $x_T = \frac{p_{T,asso}}{p_{T,\text{trig}}}$
- Energy loss -> less pairs of $D$-$\bar{D}$ within $p_T$ cuts in more central collisions due to energy loss
- Energy loss -> the peak of $x_T$ shifts to the left
Probe Different Regions of QGP

Density distribution of the initial ccbar production points: (a) $x_T \in [0.2, 0.4]$, (b) $x_T \in [0.4, 0.6]$, (c) $x_T \in [0.6, 0.8]$, and (d) $x_T \in [0.8, 1.0]$.

The away side variance of angular correlation functions in different $x_T$ regions: longitudinal energy loss vs. transverse momentum broadening.
Summary

Initial state

Pre-equilibrium

QGP and hydrodynamic expansion

Hadronization

Hadronic phase and freeze-out

Bulk Matter: Glb or KLN (2+1)-d viscous Cooper-Frye

Heavy Flavor: Glauber for x Langevin Hybrid model
             pQCD for p col.+rad. frag.+coal.

Provided descriptions of heavy meson suppression and flow consistent with most of the data at both RHIC and LHC

Discussed two-particle correlation functions of heavy mesons which may provide better insights of heavy flavor dynamics in heavy-ion collisions
Thank you!
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)

\[ D = \frac{5}{(2\pi T)} \text{, i.e., } q_{\text{hat}} \text{ around } 3 \text{ GeV}^2/\text{fm at initial temperature} \](around 350~400 MeV)

hadronize and hadronic scattering (below \( T_c \))

outside the medium
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.
Near / Away Side Variances

- Near side at low $p_T$: asymptotic behavior towards uniform distribution $\pi/\sqrt{12}$.
- Away side at medium $p_T$: non-monotonic behavior – competition between longitudinal energy loss and transverse momentum broadening.