Heavy vs. light hadron production and medium modification at RHIC and the LHC

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Outline

• Introduction
• A Linear Boltzmann Transport Model (LBT) for parton energy loss in QGP
• Heavy vs. light hadron suppression at RHIC and the LHC (the heavy vs. light flavor puzzle)
• Possible solutions to the $R_{AA}$ vs. $v_2$ puzzle
• Summary and outlook
Motivation

High $p_T$ partons: produced early and probe the full QGP history

“Heavy vs. light flavor puzzle”: is $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ still right?

“$R_{AA}$ vs. $v_2$ puzzle”: can we describe $R_{AA}$ and $v_2$ simultaneously?

Goal: fully understand heavy and light parton dynamics within a unified theoretical/numerical framework
A Linearized Boltzmann Transport Model

Boltzmann equation for parton "1" distribution:

\[ p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1] \]

The collision term:

\[ C[f_1] \equiv \int d^3k \left[ w(p_1 + k, k)f_1(p_1 + k) - w(p_1, k)f_1(p_1) \right] \]

transition rate from \( p_1 \) to \( p_1-k \)

Elastic Scattering (2->2 process)

\[ w(p_1, k) = \sum_{2,3,4} w_{12\rightarrow34}(p_1, k) \]

\[ w_{12\rightarrow34}(p_1, k) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(p_2) \left[ 1 \pm f_3(p_1 - k) \right] \left[ 1 \pm f_4(p_2 + k) \right] \]

\[ \times v_{rel} d\sigma_{12\rightarrow34}(p_1, p_2 \rightarrow p_1 - k, p_2 + k) \]

microscopic cross section of 12->34
A Linearized Boltzmann Transport Model

Scattering rate:

\[
\Gamma_{12\rightarrow34}(\vec{p}_1) = \int d^3k \, w_{12\rightarrow34}(\vec{p}_1, \vec{k}) = \frac{\gamma^2}{2E_1} \int \frac{d^3p_2}{(2\pi)^32E_2} \int \frac{d^3p_3}{(2\pi)^32E_3} \int \frac{d^3p_4}{(2\pi)^32E_4} \times f_2(\vec{p}_2) \left[ 1 \pm f_3(\vec{p}_1 - \vec{k}) \right] \left[ 1 \pm f_4(\vec{p}_2 + \vec{k}) \right] S_2(s, t, u) \\
\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\rightarrow34}|^2
\]

In model calculation:
1. Use total rate \( \Gamma = \sum_i \Gamma_i \) to determine the probability of elastic scattering \( P_{el} = \Gamma \Delta t \)
2. Use branching ratios \( \Gamma_i / \Gamma \) to determine the scattering channel
3. Use the differential rate to sample the \( p \) space of the two outgoing partons

\( \Delta E_{col.} \) from our MC simulation agrees with the semi-analytical result.
Inelastic Scattering (2->2+n process)

Average gluon number in $\Delta t$:

$$\langle N_g \rangle(E, T, t, \Delta t) = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

Spectrum of medium-induced gluon (higher-twist formalism):

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left( \frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4 \sin^2 \left( \frac{t - t_i}{2\tau_f} \right)$$


$\hat{q}$: $dp_\perp^2/dt$ of quark/gluon due to 2->2 scatterings

Splitting time of radiated gluon: $\tau_f = 2Ex(1 - x)/(k_\perp^2 + x^2 M^2)$

Splitting functions:

$$P_{q\to gg} = \frac{(1 - x)(2 - 2x + x^2)}{x},$$

$$P_{g\to gg} = \frac{2(1 - x + x^2)^3}{x(1 - x)}.$$
Number $n$ of radiated gluons during $\Delta t$ – Poisson distribution:

$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

Probability of inelastic scattering during $\Delta t$:

$$P_{\text{inel}} = 1 - e^{-\langle N_g \rangle}$$

**In model calculation:**

1. Calculate $\langle N_g \rangle$ and thus $P_{\text{inel}}$
2. If gluon radiation happens, sample $n$ from $P(n)$
3. Sample $E$ and $p$ of gluons using the differential spectrum
4. Assume 2$\rightarrow$2 first and adjust $E$ and $p$ of the 2+n final partons together to guarantee $E$-$p$ conservation of 2$\rightarrow$2+n process

$\langle E_g \rangle$ from our MC simulation agrees with the semi-analytical result.
Elastic vs. Inelastic Energy Loss

Divide scattering probability of jet parton into two regions:
1. Pure elastic scattering without radiated gluons: \( P_{el}(1 - P_{inel}) \)
2. Inelastic scattering: \( P_{inel} \)
Total probability: \( P_{tot} = P_{el} + P_{inel} - P_{el}P_{inel} \)

In model calculation:
1. Use \( P_{tot} \) to determine whether the jet parton scatter with the thermal medium
2. If so, we then determine whether this scattering is pure elastic or inelastic
3. Simulate the 2->2 or 2->2+n process

HQ energy loss due to elastic and inelastic processes are comparable at early time, but is dominated by the inelastic process at large \( t \).
Hadronization

Heavy Flavor (full $p_T$): Fragmentation + Coalescence

- 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)]

Light flavor (high $p_T$ only): Fragmentation

- Contribution from the bulk matter and jet-thermal recombination will be included in our future effort
Framework Overview

(Parton Evolution inside the QGP)

- Generation of QGP medium: viscous hydro from OSU (2+1 D) or LBL-CCNU (3+1 D) group
- Initialization of hard partons: MC-Glauber for position space and pQCD calculation for momentum space (PDF: CTEQ5+EPS09)
- Simulation of parton evolution: the Boltzmann transport model in the local rest frame of the medium
- Hadronization: fragmentation + coalescence model
Heavy vs. Light Hadron Suppression

- \( u/d/s \) are more suppressed than \( c \) quark at low \( p_T \) but they have very similar \( R_{AA} \) at high \( p_T \), \( g \) is significantly more suppressed
- Due to different fragmentation function (harder for \( c \) than for \( u/d/s \)), \( \pi \) from light quark is slightly less suppressed than \( D \)
- \( R_{AA} \) of mixed \( \pi \) is sensitive to fragmentation function of light quark vs. gluon [Chen et. al., J. Phys. 37 (2010) 015004]
Simultaneous Description of $D$ and $\pi R_{AA}$ in 200 GeV Au-Au Collisions
Simultaneous Description of $D$ and $\pi R_{AA}$ in 2.76 TeV Pb-Pb Collisions
Simultaneous Description of $D$ and $\pi R_{AA}$ in 5.02 TeV Pb-Pb Collisions

With a delicate treatment of heavy and light parton in-medium evolution and their hadronization, one may provide reasonable description of heavy and light hadron suppression simultaneously.
The extracted $\hat{q}$ from model to data comparison within our LBT framework is consistent with the value constrained by the earlier work by the JET Collaboration [Phys. Rev. C90, 014909 (2014)].
**Possible Solutions to the $R_{AA}$ vs. $\nu_2$ Puzzle**

1. Near $T_c$ enhancement of transport coefficient (arXiv: 1605.06447)

- While $R_{AA}$ is fixed, the enhancement of transport coefficient near $T_c$ increases $D$ meson $\nu_2$
- Consistent with findings presented in
- The detailed microscopic mechanism is still an open question
Possible Solutions to the $R_{AA}$ vs. $\nu_2$ Puzzle

2. Different bulk evolutions

- Different bulk evolutions that provide same $R_{AA}$ may lead to non-negligible difference in $\nu_2$
- KLN initial condition would give even larger $\nu_2$ due to its larger eccentricity [SC, G.-Y. Qin and S. Bass Phys. Rev. C92 (2015) no.5, 054909]
Possible Solutions to the $R_{AA}$ vs. $v_2$ Puzzle

3. Effect of the initial state fluctuation of the bulk matter

$$v_2^{\text{hard}}(p_T) \sim \langle v_2^{\text{hard}}(p_T) \rangle \left[ 1 + \left( \frac{\delta v_2^{\text{soft}}}{\langle v_2^{\text{soft}} \rangle} \right)^2 \right]$$

Noronha-Hostler et. al. PRL 116 (2016), 252301

- Only around 10% larger $v_2$ (hard) is observed in our calculation after the inclusion of the fluctuation of the bulk matter
- Consistent with $(\delta v_2/\langle v_2 \rangle)^2$ [soft] ~ 10% from our LBL-CCNU hydro + Trento (IP-Glasma), and also the value from MUSIC + IP-Glasma

[ Courtesy of B. Schenke ]
Established a Linear Boltzmann Transport Model that treats heavy and light parton evolution on the same footing and simultaneously incorporates their elastic and inelastic scattering inside QGP

Provided reasonable descriptions of both heavy and light hadron suppression at RHIC and the LHC

Discussed several possible solutions to the “$R_{AA}$ vs. $v_2$ puzzle”, more systematic investigation will be implemented in our upcoming study

Will explore heavy-light hadron correlation in the future, which may provide more constraints on our understanding of the strongly interacting system
Thank you!
Hadronization of Heavy Quarks

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

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

Defined in the rest frame of the produced meson

\( g_M \): color-spin degeneracy of the produced meson

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

Averaging over the position space leads to

\( f^W_M(q^2) = g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2} \quad \sigma = \frac{1}{\sqrt{\mu\omega}} \)

\( \mu \): reduced mass of the 2-particle system

\( \omega \): S.H.O frequency – related meson charge radius (parameter free)

\( \langle r^2_M \rangle_{ch} = \frac{3}{2\omega (m_1 + m_2)(Q_1 + Q_2)} \frac{1}{(Q_1 + Q_2)} \)

Can be generalized to 3-particle recombination (baryon)
Use $f^W$ to calculate $P_{\text{coal.}}(p_{\text{HQ}})$ for all channels $(D/B \Lambda \Sigma \Xi \Omega)$ at $T_c$

Three regions: recombination to $D/B$ mesons, recombination to other hadrons, and fragmentation

In model calculation: in the l.r.f of the freeze-out hypersurface, determine which region each HQ belongs to, and then use either recombination model or Pythia simulation to obtain $D/B$ mesons
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)

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

- Only one parameter $\alpha_s$ in our transport model which determines both the 2->2 rate and $\tilde{q}$ that governs the 2->2+n process
- LO pQCD calculation fails at low $p$ and $T$ near $T_c$, and thus $p$ and $T$ dependent modification of transport coefficient is required in order to describe experimental data:
  \[ \tilde{\alpha}_s = K_T \alpha_s, \quad \tilde{q} = K_p \hat{q} \]
  \[ K_p = 1 + A_p e^{-|\vec{p}|^2/2\sigma_p^2}, \quad K_T = 1 + A_T e^{-(T-T_c)^2/2\sigma_T^2} \]
- At high $p$ and $T$, LO pQCD calculation is respected, at low $p$ and $T$ near $T_c$, non-perturbative modification is introduced
- Only investigate possible phenomenological effects of $K_p$ and $K_T$ in this work; a precise extraction of these non-perturbative effects will be left for a future effort – global fit to experimental data with a Bayesian method [Bernhard et. al., PRC 91 (2015)]