Flavor hierarchy of jet quenching in relativistic heavy-ion collisions

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Outline

• Introduction

• A next-to-leading-order (NLO) perturbative QCD framework for heavy and light flavor jet and high $p_T$ hadron production

• A Linear Boltzmann Transport (LBT) model for heavy and light flavor jet evolution in QGP

• The nuclear modification factor of heavy and light hadrons

• Summary
Jet quenching in heavy-ion collisions

- Jet quenching (jet-medium interaction) provides valuable tools to probe QGP properties: parton energy loss.
- Jet-medium interaction depends on QGP properties and jet properties (color, mass and energy).
- Jet suppression — the spectra of high $p_T$ hadrons will be modified, quantified with nuclear modification factor:

$$R_{AA} = \frac{dN^{AA}/d^2p_Tdy}{N_{coll}dN^{pp}/d^2p_Tdy}$$
Flavor hierarchy puzzle of jet quenching

- Color & flavor dependences of parton energy loss: \( \Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b \)

- Expect heavy flavor hadrons exhibit less quenching effects than light charged hadrons.

\[ R_{AA}(D) \approx R_{AA}(h^*) \]

- \( R_{AA} \) at high \( p_T \): No significant flavor dependence observed.
Flavor hierarchy of jet quenching

B mesons & B-decayed D mesons

This provides a unique opportunity to study the flavor hierarchy of jet quenching.
High $p_T$ hadron production in pp collisions

In the next-to-leading-order (NLO) framework

$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b) d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

parton distribution functions (PDFs): CTEQ parameterizations

fragmentation function (FF): include both quark and gluon fragmentations to heavy and light hadron productions


Gluon contribution to heavy quark jet production

- Gluon splitting contribution increases with energy $\sqrt{s}$.
- Gluon splitting contribution increases with heavy quark jet $p_T$.


Light charged hadron and $D$ meson production in pp collisions at 5.02 TeV

- **Charged hadrons**: gluon contribution dominates at low $p_T$ and quark contribution becomes more important with increasing $p_T$.
- **$D$ mesons**: charm and gluon contribute almost equally at low $p_T$, then gluon contribution decreases with increasing $p_T$.
- **Both contributions from quarks and gluons have to be taken into account for high $p_T$ hadron suppression in AA collisions.**
A linear Boltzmann transport (LBT) model

Boltzmann equation for parton “1” evolution:

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

The collision term is:

\[ C[f_1] = \int d^3k \left[ \omega(\vec{p}_1 + \vec{k}, \vec{k}) f_1(\vec{p}_1 + \vec{k}) - \omega(\vec{p}_1, \vec{k}) f_1(\vec{p}_1) \right] \]

For elastic (2->2) process, the transition rate is related to microscopic cross section as:

\[ \omega_{12\rightarrow34}(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2) \left[ 1 \pm f_3(\vec{p}_1 - \vec{k}) \right] \left[ 1 \pm f_4(\vec{p}_1 - \vec{k}) \right] \]

\[ \times \nu_{rel} d\sigma_{12\rightarrow34}(\vec{p}_1, \vec{p}_2 \rightarrow \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k}) \]

The elastic scattering rate for (2->2) process:

\[ \Gamma(\vec{p}_1, \vec{k}) = \int d^3k \omega(\vec{p}_1, \vec{k}) \]

\[ \omega(\vec{p}_1, \vec{k}) = \sum_{2,3,4} \omega_{12\rightarrow34}(\vec{p}_1, \vec{k}) \]

A linear Boltzmann transport (LBT) model

Include the inelastic process:

\[ p_1 \cdot \partial f_1(x_1, p_1) = E_1 \left( C_{el} + C_{inel} \right) \]

The inelastic scattering rate (average gluon number per unit time) is:

\[ \Gamma_{inel} = \left\langle N_g \right\rangle (E, T, t, \Delta t) / \Delta t = \int dx dk_{\perp}^2 \frac{dN_g}{dx dk_{\perp}^2 dt} \]

The medium-induced gluon spectrum is:

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

\[ \tilde{q} : \frac{dp_{\perp}^2}{dt} \text{ is the momentum broadening due to (2->2) elastic process} \]

Nuclear modifications of charged hadrons

- **QGP fireball**: a (3+1)-dimensional viscous hydrodynamics model CLVisc.
  

- Due to color effect, quark-initiated hadrons exhibit less quenching effect than gluon-initiated hadrons.

- Combining both quark and gluon fragmentations to charged hadrons, we obtain a nice description of charged hadron $R_{AA}$ over a wide range of $p_T$. 
Nuclear modifications of $D$ mesons

$Pb$-$Pb$ @5.02 TeV

0 - 10%

- Combining both charm quark and gluon contributions, we obtain successful description of $D$ meson $R_{AA}$.

- Collisional energy loss gives non-negligible contributions to $R_{AA}$ at not-very high $p_T$ regime and diminishes with increasing $p_T$.

- A natural solution to the flavor hierarchy puzzle of jet quenching.
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV
0 - 80%

Graph showing the variation of $R_{AA}$ with $p_T$ (GeV) for different jet quenching flavors.
Flavor hierarchy of jet quenching

Pb-Pb @ 5.02 TeV 0 - 80%
Flavor hierarchy of jet quenching

Pb-Pb @5.02 TeV 0 - 80%
• Above 30-40 GeV, our model predicts similar suppression effects for $B$ mesons to charged hadrons and $D$ mesons, which can be tested by future measurements.
Flavor hierarchy of jet quenching

**Pb-Pb @5.02 TeV 0 - 80%**

- Above 30-40 GeV, our model predicts similar suppression effects for $B$ mesons to charged hadrons and $D$ mesons, which can be tested by future measurements.

- Our model can simultaneously describe the nuclear modifications of charged hadrons, prompt $D$ mesons, $B$ mesons and $B$-decayed $D$ mesons.
Summary

• By incorporating all important ingredients in our pQCD-based jet quenching model, we obtain the first satisfactory description of $R_{AA}$ for charged hadrons, prompt $D$ mesons, $B$ mesons and $B$-decayed $D$ mesons for $p_T=8-300$ GeV).

• A natural solution to the flavor hierarchy puzzle of jet quenching.

• At $p_T > 30$-40 GeV, $B$ mesons will exhibit similar suppression effects to charged hadrons and $D$ mesons, which can be tested by future measurements.

• With a solid understanding on how jet-medium interaction depends on jet properties (color, mass and energy), we can now use jets to quantitatively probe the QGP properties.
Thank You!