Understanding mass hierarchy in different energy loss mechanisms through heavy flavor data

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Mass hierarchy effect in energy loss mechanisms

- The experimental observations of $R_{AA}$ mass hierarchy (i.e., dead cone) analyzed within radiative models
  
  PLB 519,199; PRD 85, 054012;
  PRD 69, 114003; NPA 733, 265; PRC 77, 024905; PLB 763, 439;
  PRL 93, 072301

- At intermediate-$p_\perp$ range ($p_\perp \lesssim 10$ GeV) charm and bottom collisional – comparable to (or larger) than radiative energy loss
  
  NPA 784, 426; PRC 74, 064907; JPG 42, 075105; PLB 273, 128; PRC 72, 014905; APHA 22, 93

- The mass hierarchy in collisional energy loss is not yet addressed

- The upcoming RHIC and LHC measurements – employ high-$p_T$ heavy flavor data for studying interaction mechanisms in QGP

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Our goals

I. Utilizing complex $R_{AA}$ patterns to differentiate between major energy loss mechanisms

II. Focusing on the region $p_T < 50$ GeV and addressing:

• Which observable could isolate collisional from radiative energy loss

• Analytical derivation of an explicit relation between collisional suppression/energy loss and heavy quark mass

• Analytical and numerical derivation of the mass ordering in collisional energy loss through this observable

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Numerical framework: DREENA-C


• Full-fledged DREENA-C (Dynamical Radiative and Elastic ENergy loss Approach, C stands for constant/average temperature profile) framework:
  • Dynamical energy loss formalism:
    ✓ Complex, unique and realistic features
    ✓ Dominant ingredient for generating high-$p_\perp$ suppression predictions
  • Constant (average) Temperature profile:
    ✓ Excludes complications from details of medium evolution
    ✓ Analytical derivations feasible
    ✓ Insignificant loss of accuracy in $R_{AA}$ predictions (compared to DREENA-B (PLB 791, 236) and DREENA-A), low $R_{AA}$ sensitivity to details of medium evolution

DREENA-C is an optimal framework for these studies (I and II), through $R_{AA}$, as it assumes sophisticated energy loss model.
The dynamical energy loss formalism

✓ Includes:
  • QCD medium of finite size and finite temperature
  • The medium consists of dynamical (i.e., moving) partons
  • Based on finite T field theory and generalized HTL approach
    M. Djordjevic, PRC 74, 064907; PRC 80, 064909; M. Djordjevic, U. Heinz, PRL 101, 022302
  • The same theoretical framework for both radiative and collisional energy loss
  • Applicable to both light and heavy flavor
    M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265
  • Finite magnetic mass effects
    M. Djordjevic and M. Djordjevic, PLB 709, 229
  • Running coupling
    M. Djordjevic and M. Djordjevic, PLB 734, 286
  • Relaxed soft-gluon approximation
    B. Blagojevic, M. Djordjevic, M. Djordjevic, PRC 99, 024901

All ingredients necessary for reliable high-\(p_T\) \(R_{AA}\) predictions!

B. Blagojevic and M. Djordjevic, JPG 42, 075105

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Experimental validation of DREENA-C framework

In generating all predictions we used:

- The same numerical procedure (DREENA-C, D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, JPG 46, no.8, 085101)
- The same parameter set
- No fitting parameter

DREENA-C accurately addresses high-$p_{\perp}$ parton-medium interactions and is adequate for these studies.

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Explains high-$p_{\perp}$ $R_{AA}$ data for different probes, collision systems (experiments), energies and centralities!

Addresses heavy-flavor puzzle and has clear predictive power!
I. Nonintuitive suppression patterns (light or D probes)

With increasing $p_T$, $R_{AA} vs. N_{part}$:
- flatter
- difference between curves smaller

Saturation in $R_{AA} vs. N_{part}$.

Which energy loss mechanism is accountable for these observations?

Nonintuitive observations in agreement with our framework!

ATLAS: JHEP 09, 050; PRL 114, 072302

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I. Nonintuitive suppression patterns (B probes)

$R_{AA} \text{ vs. } N_{part}$

pattern qualitatively different (compared to light probes)

Flatter $R_{AA} \text{ vs. } N_{part}$ across the $p_T$ range

Slower $R_{AA} \text{ vs. } p_T$ change (compared to light probes)

Which energy loss mechanism is accountable for these observations?

Nonintuitive observation well reproduced within our framework!

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Qualitative explanation of the observations (light or D probes)

Collisional contribution:
- significant at lower $p_T$ (steep increase)

Radiative contribution:
- important at entire $p_T$ range (slow increase)

$R_{AA}$ vs. $p_T$ pattern result of interplay of collisional and radiative contributions.

The lower $p_T$ arrow spans a much larger $R_{AA}$ range compared to the larger $p_T$ arrows that are similar.

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Qualitative explanation of the observations (B probes)

$R_{AA}$ vs. $p_T$ curves practically equidistant across the $p_T$ range.

At lower $p_T$:
Both collisional and radiative contributions significant (notably smaller than for light/D probes)

At higher $p_T$:
Nearly flat radiative $R_{AA}$ vs. $p_T$ only important.

$R_{AA}$ vs. $p_T$ pattern consequence of mass hierarchy in collisional and radiative energy losses

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II. Mass hierarchy in energy loss mechanisms

The dead-cone effect, i.e., the mass hierarchy in radiative energy loss.

Importantly: Obtained clear mass hierarchy in collisional energy loss also!

Which observable could quantify this effect?

Proposition:
\[ f(1 - R_{AA}) \]
as being particularly sensitive to parton energy loss solely.

Unexpectedly:
For all centralities TOT and COLL ratios nearly overlapping!

Collisional contribution in the origin of heavy flavor $1 - R_{AA}$

$1 - R_{AA}$ ratio might disclose mass hierarchy in collisional energy loss.

Search for an observable

Analytical derivation: Which information does the new observable carry?

Convolution of initial parton $p_T$ distribution and collisional energy loss:

$$\frac{d\sigma_i^f}{dp_T^2} = \int d\varepsilon D(\varepsilon) \frac{d\sigma_i^i(p_T^2 + \varepsilon)}{dp_T^2} = \int d\varepsilon D(\varepsilon) \frac{d\sigma_i^i(p_T^2)}{dp_T^2} + \int d\varepsilon D(\varepsilon) \varepsilon \frac{d}{dp_T} \left( \frac{d\sigma_i^i(p_T^2)}{dp_T^2} \right) + ...$$

$$\approx \frac{d\sigma_i^i}{dp_T^2} + \Delta E_{\text{coll}} \frac{d}{dp_T} \left( \frac{d\sigma_i^i}{dp_T^2} \right)$$

Initial distribution parameterization:

$$\frac{d\sigma_i^i}{dp_T^2} = \frac{C}{(p_T^2 + M^2)^k}$$

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The same $C$ and $k$ for bottom and charm.

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Analytical derivation: Which information does the new observable carry?

Suppression:

\[
R_{AA} = \frac{d\sigma^i}{dp_T^2} / \frac{d\sigma^f}{dp_T^2}
\]

\[
1 - R_{AA} \approx 2k \frac{p_T}{E} \frac{\Delta E_{coll}}{E}
\]

Collisional energy loss:

\[
\frac{\Delta E_{coll}}{E} \sim \frac{1}{E v^2} \left(v + \frac{v^2}{2} - \ln \left(\frac{1+v}{1-v}\right)\right)
\]

\[v = \frac{p_T}{\sqrt{p_T^2 + M^2}}\]

Mass dependence of collisional energy loss:

\[
\frac{\Delta E_{coll}}{E} \sim \frac{1}{p_T} \left(1 - \frac{M^2}{p_T^2} \ln(2) + \left(\frac{M}{p_T}\right)^{\frac{M}{p_T}+1} - \frac{M}{p_T}\right)
\]

Mass dependence of \(1 - R_{AA}\) ratio:

\[
1 - R_{AA} \sim \frac{2k}{p_T} \left(1 - \frac{M^2}{p_T^2} \left(\ln 2 + \frac{1}{2}\right) + \left(\frac{M}{p_T}\right)^{\frac{M}{p_T}+1} - \frac{M}{p_T}\right)
\]

Carries information about mass hierarchy in collisional energy loss!

New observable


Dominant terms

Carries information about mass hierarchy in collisional energy loss!
The new observable \( \frac{1 - R_{AA}^b}{1 - R_{AA}^c} \)

Unexpectedly simple relation:

\[
1 - R_{AA}^b \approx \frac{1}{p_T} \left( 1 - \frac{M_b}{p_T} \right)
\]

\[
1 - R_{AA}^c \approx \frac{1}{p_T} \left( 1 - \frac{M_c}{p_T} \right)
\]

It is independent of:

- The collision centrality
- The collision system (size)
- The collision energy

The new observable - applicable to both the RHIC and the LHC experiments.

Testing the adequacy of new observable \( \frac{1-R_{AA}^b}{1-R_{AA}^c} \)

A good agreement between:

Data and our predictions (qualitatively and quantitatively)

DREENA-C predictions and our analytical estimate \( \left(1 - \frac{M_b}{p_T}\right)/\left(1 - \frac{M_c}{p_T}\right) \) (for all centralities).

Data and our analytical mass estimate.

Confirms adequacy of DREENA-C.

Implies validity of our analysis.

Supports adequacy of proposed observable.

Summary

I. Unexpected and significantly different suppression patterns for different flavors - for differentiating between radiative and collisional contributions

II. Focused on $p_T < 50$ GeV region we:
   • Proposed an observable to unravel collisional from radiative energy loss
   • Derived an explicit relation between collisional suppression/energy loss and heavy quark mass
   • Verified the adequacy of the proposed observable against the data
   • Observable robust to collision centrality, system and energy

Outlook: Specific guidelines for future experimental efforts

I. Single particles measurements at higher $p_T$
II. Lower $p_T$, and higher precision measurements → accessible at both RHIC and LHC
II. B meson suppression data would be beneficial
II. B meson (non-prompt J/Ψ, D0) and D meson suppression data should be provided for the same centrality bins
Thank you for your attention!
Backup
DREENA-C: Numerical framework

• Heavy flavor production
  Z.B. Kang, I. Vitev, H. Xing, PLB 718, 482; R. Sharma, I. Vitev, and B. W. Zhang, PRC 80, 054902

• Dynamical energy loss in a finite size QCD medium
  M. Djordjevic and M. Djordjevic, PLB 734, 286

• Multi-gluon fluctuations
  M. Gyulassy, P. Levai, I. Vitev, PLB 538, 282
  S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, NPA 784, 426

• Path-length fluctuations
  A. Dainese, EPJ C33, 495; S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, NPA 784, 426; D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, JPG 46, 085101
For each centrality region.

\( T^3 \sim \frac{dN_g}{dy} \frac{1}{V} \rightarrow T = c \left( \frac{dN_g}{dy} \right)^{1/3} \)

\( V \sim N_{\text{part}} \quad \frac{dN_g}{dy} \frac{1}{N_{\text{part}}} \sim \frac{dN_{ch}}{dy} \frac{1}{N_{\text{part}}/2} \)

M. Gyulassy, P. Levai and I. Vitev, NPB 594 371
M. Djordjevic, M. Djordjevic and B. Blagojevic, PLB 737, 298
D and B mesons (non-prompt J/Ψ....) present genuine charm and bottom probe’s suppression.
