Energy loss for heavy quarks in relation to light partons; is radiative energy loss for heavy quarks anomalous?

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The scaling properties of jet suppression measurements are compared for non-photonic electrons (e±) and neutral pions (π0) in Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. For a broad range of transverse momenta and collision centralities, the comparison is consistent with jet quenching dominated by radiative energy loss for both heavy and light partons. Less quenching is indicated for heavy quarks because their associated gluon radiation is suppressed by the dead cone effect. In contrast, Zakharov [1] argues that the radiative energy loss for a finite-size QGP could even have an anomalous mass dependence (ie. energy loss for heavy quarks greater than that for light quarks) which stem from quantum final state effects when the gluon formation time is comparable to the “size” of the QGP.

Further insight into properties of the QGP can be gained from the production and propagation of particles carrying heavy quarks (charm or bottom). However, a central issue germane to the development of this probe, is the unsettled question of the quantitative difference between the quenching for light and heavy partons in hot QCD matter. Dokshitzer and Kharzeev [3] have argued that much less quenching is to be expected from heavy quarks because their associated gluon radiation is suppressed by the dead cone effect. In contrast, Zakharov [1, 2] argues that the radiative energy loss for a finite-size QGP could even have an anomalous mass dependence (ie. energy loss for heavy quarks greater than that for light quarks) which stem from quantum final state effects when the gluon formation time is comparable to the “size” of the QGP.

Here, we use the published jet quenching measurements for non-photonic electrons (e±) [13] and neutral pions (π0) [14, 15] at \(\sqrt{s_{NN}} = 200\) GeV to compare, as well as to quantify the difference in the quenching patterns of the transverse momentum spectra for jets produced from scattered light- and heavy quarks. We then use this difference to constrain an estimate of the transport coefficient \(\hat{q}\) and the ratio of viscosity to entropy density \(\eta/s\). We find that the value of these new estimates (of \(\hat{q}\) and \(\eta/s\)) are similar to the ones obtained via jet quenching measurements for light partons via π0’s [10].

The nuclear modification factor \(R_{AA}\) is used to quantify the magnitude of jet suppression in A+A collisions [2].

\[
R_{AA}(p_T) = \frac{1}{N_{evt}} \frac{dN/dydp_T}{dN/dydp_T^{pp}},
\]

where \(dN/dydp_T\) is the particle production cross section in p+p collisions and \(N_{AA}\) is the nuclear thickness function averaged over the impact parameter range associated with a given centrality selection.

\[
(R_{AA}) = \frac{\int T_{AA}(b) db}{\int (1-e^{-\sigma_{pp}^m T_{AA}(b)/b}) db}.
\]

The corresponding average number of nucleon-nucleon collisions, \(N_{coll} = \sigma_{pp}^m T_{AA}\), is obtained with a Monte-Carlo Glauber-based model calculation [16, 17]. To facilitate our comparisons of the quenching patterns of the transverse momentum spectra for jets produced from scattered light (l)- and heavy (h) partons, we exploit the formalism of Dokshitzer and Kharzeev (DK) [3].

\[
R_{AA}^h(p_T, L) \approx \exp \left[ -\frac{2\alpha_s C_F}{\sqrt{\pi}} L \frac{\hat{q} L}{p_T} + \frac{16\alpha_s C_F}{9\sqrt{3}} L \left( \frac{\hat{q} M^2}{M^2 + p_T^2} \right)^{1/3} \right], \tag{1}
\]

where \(\alpha_s\) is the strong interaction coupling strength, \(C_F\) is the color factor, \(L\) is the path length [of the medium] that the parton traverses, \(M\) is the mass of the heavy parton and \(\hat{q}\) is the transport coefficient of the medium.

The first term in the exponent in Eq. 1 represents the quenching of the transverse momentum spectrum which is the same for both light and heavy partons [7],

\[
R_{AA}^l(p_T, L) \approx \exp \left[ -\frac{2\alpha_s C_F}{\sqrt{\pi}} L \frac{\hat{q} L}{p_T} \right],
\]

\[
\hat{L} \approx \frac{d}{d\ln p_T} \ln \left[ \frac{d\sigma_{pp}^m}{dp_T^2}(p_T) \right], \tag{2}
\]

(modulo the difference of the \(\hat{L}\) parameters determined by the \(p_T\) distributions in the vacuum). The second term in the exponent is specific for heavy quarks and is a direct
consequence of the fact that the mass of the heavy quark leads to a suppression of gluon radiation. Hence the prediction that the suppression for the heavy hadron $p_T$ distribution should be smaller than that for light hadrons.

The magnitude of the heavy-to-light suppression factor can also be estimated as [3]:

$$
R_{AA}^h(p_T, L) / R_{AA}^l(p_T, L) \approx \exp \left[ 16a_s C_F \frac{\hat{q} M^2}{9v^3 L} \left( \frac{\hat{q} M^2}{M^2 + p_T^2} \right)^{1/3} \right],
$$

(3)

which clearly depends on the size ($L$) of the QGP medium and the properties encoded in the value of its transport coefficient $\hat{q}$.

An essential point reflected in Eqs. 1-3 is that they give specific testable scaling predictions for the $p_T$ and $L$ dependence of $R_{AA}^h(p_T, L)$, and the heavy-to-light suppression ratio [10]. That is, in $R_{AA}^h(p_T, L)$ should scale as $L$ and $1/\sqrt{p_T}$ respectively, and the heavy-to-light suppression ratio should scale as $L$. As discussed below, these scaling properties provide crucial validation tests of our analysis framework, as well as an important constraint for estimating $\hat{q}$ and $\eta/s$.

The result of one such test for Cu+Cu and Au+Au collisions is given in Fig. 1 where we show a plot of $\ln[R_{AA}(p_T, L)]$ vs. $1/\sqrt{p_T}$ for $\pi^0$s. Here, results are shown for $p_T \gtrsim 5$ GeV/c in panel (a) and for $2.75 \lesssim p_T \lesssim 5$ GeV/c in panel (b). Both panels indicate the predicted linear dependence on $1/\sqrt{p_T}$ (cf. Eq. 2), albeit with different slopes for each $p_T$ range. A comparison of the results for the two collision systems also indicate similar quenching magnitudes when the size of the respective collision medium is comparable. Note that better agreement is achieved if the small difference in the length estimate arising from the respective centrality cut is taken into account.

The inset in Fig. 1(b) confirms the predicted linear dependence of $\ln[R_{AA}(p_T, L)]$ on $L$ for Cu+Cu collisions. A similar dependence has been reported earlier for Au+Au collisions [10]. Here, as in Ref. 10, we have used the transverse size of the system $\bar{R}$ as an estimate of the operative path length $L$. To obtain this estimate, the number of participant nucleons $N_{part}$ was estimated for each centrality selection, via a Monte-Carlo Glauber-based model [10, 11]. The corresponding transverse size $\bar{R}$ was then determined from the distribution of these nucleons in the transverse $(x, y)$ plane via the same Monte-Carlo Glauber model: $1/\bar{R} = \sqrt{1/\sigma_x^2 + 1/\sigma_y^2}$, where $\sigma_x$ and $\sigma_y$ are the respective root-mean-square widths of the density distributions. For these evaluations, the initial entropy profile in the transverse plane was assumed to be proportional to a linear combination of the number density of participants and binary collisions [12, 13]. The latter assures that the entropy density weighting is constrained by multiplicity measurements.

Figure 2 shows a comparison of the $R_{AA}$ measurements obtained for neutral pions ($\pi^0$) and non-photonic electrons ($e^\pm$) in minimum-bias Au+Au collisions [13, 14].

As in Fig. 1 results are shown for $p_T \gtrsim 5$ GeV/c in panel (a) and for $2.75 \lesssim p_T \lesssim 5$ GeV/c in panel (b). The latter $p_T$ range for $e^\pm$ is dominated by decay contributions from D-mesons. However, as demonstrated in recent measurements [20, 21], there is an increasing role of the B-meson contributions to the non-photonic electron spectrum for $p_T \gtrsim 5$ GeV/c. Such contributions could serve to complicate the interpretation of the $R_{AA}$ measurements for $e^\pm$ above $p_T \sim 5$ GeV/c.

The $\pi^0$ measurements in Fig. 2(a) show the predicted linear dependence on $1/\sqrt{p_T}$. However, the statistical significance of the data for $e^\pm$ does not allow a similarly decisive conclusion in this $p_T$ range. The measurements shown in Fig. 2(b) contrast with those of Fig. 2(a). Here, both data sets confirm the the predicted linear dependence on $1/\sqrt{p_T}$. Even more striking is the observation that the magnitude of the quenching for $\pi^0$s is significantly larger than that for $e^\pm$. This observation is in accord with the prediction of Dokshitzer and Kharzeev (cf. Eq. 4 and Ref. [7]) that the suppression of heavy hadrons should be less than that for light hadrons. As discussed below, it is also congruent with the observation that the magnitude of the azimuthal anisotropy for $e^\pm$ (characterized by the second Fourier coefficient $v_2$) is much less than that for pions (for $p_T \gtrsim 2.5$ GeV/c) [13].

Figure 3 compares and contrasts the $L$ dependence of $\ln[R_{AA}(p_T, L)]$ for $\pi^0$ and $e^\pm$ for the $p_T$ selections indi-
We emphasize here that kinematic studies show that the $p_T$ selection for $e^\pm$ (cf. Fig. 3) leads to a dominant $e^\pm$ decay contribution from D-mesons of higher $p_T$. The dashed and dot-dashed curves in panel (a) are linear fits to the data set for $\pi^0$ and $e^\pm$ respectively (the data point for the most peripheral collision is treated as an outlier). The dashed curve in panel (b) shows the fitted dependence of the ratio $\ln \left[ R_{AA}(p_T, L) \right]$ obtained from the fits in panel (a). These curves validate the predicted linear dependence on $L$ (cf. Eqs. 1-3), as well as the attendant difference in slope for $\pi^0$ and $e^\pm$. We interpret the latter as an independent indication that the mechanism for jet quenching is dominated by radiative energy loss.

The fits to the data in Fig. 3 (a) indicate intercepts of $L = 0.6 \pm 0.1$ fm and $L = 0.9 \pm 0.15$ fm for the light and heavy mesons respectively. This suggests a minimum path length requirement for the initiation of jet suppression for both light and heavy partons, but with the possibility of a larger path length requirement for the heavy quark. The corresponding ratio $\ln \left[ R_{AA}(p_T, L) \right]$, plotted as a function of $L$ in Fig. 3(b), yields a slope value of $0.4 \pm 0.04$ fm$^{-1}$. This value reflects the difference in slope for $\pi^0$ and $e^\pm$ shown in Fig. 3(a). It is noteworthy that the latter is fully compatible with the observed difference of about a factor of two in the measured magnitude of $v_2$ for $\pi^0$ and $e^\pm$ for $p_T > 2.5$ GeV/c [13]. Thus, it provides further confirmation that the azimuthal anisotropy of particle yields (for the meson $p_T$ ranges of interest) stem from the path-length dependence of jet quenching.

This observation further underscores the importance of reporting jet suppression measurements in conjunction with anisotropy ($v_2$) measurements at high $p_T$.

To obtain an “independent” estimate of the magnitude of $\hat{q}$, we assume a negligible $e^\pm$ contribution from B-mesons and use the slope $(0.4 \pm 0.04$ fm$^{-1}$) extracted from Fig. 3(b) in concert with Eq. 3. This gives the value $\hat{q} \approx 0.73 \pm 0.12$ GeV$^2$/fm for the values $\alpha_s = 0.3$ [24], $C_F = 4/3$, $M = 1.5$ GeV and $(p_T) \approx 6$ GeV/c (for D-mesons). This estimate of $\hat{q}$ is comparable to the recent estimate of $\approx 0.75$ GeV$^2$/fm obtained solely from $\pi^0$ suppression measurements with the same definition of $L$ [10]. It is also compatible with the value of 1 - 2 GeV$^2$/fm obtained from fits to hadron suppression data within the framework of the twist expansion [23, 24].

The value for $\hat{q}$ can be used to estimate the ratio of the shear viscosity ($\eta$) to the entropy density ($s$) as [25]:

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

where $T$ is the temperature. This gives the estimate $4\pi \frac{\alpha_s}{\hat{q}} \approx 1.4 \pm 0.4$ for $T \sim 220$ MeV [26], which is comparable to the value estimated via $\pi^0$ suppression measurements [10] and flow measurements [13, 27]. We conclude therefore, that the relatively short mean free path in the QGP [13] leads to hydrodynamic-like flow with small shear viscosity, as well as significant quenching of both light and heavy partons.
In summary, we have compared the scaling properties of jet quenching for both light- and heavy partons, via suppression measurements for $\pi^0$ and $e^\pm$. Our comparisons confirm the predicted $p_T$ and $L$ dependence for medium-induced gluon radiation in a hot and dense QGP. The difference in the magnitude of the quenching for light- and heavy partons, do not give a strong indication for anomalous heavy quark energy loss in the $p_T$ range studied. Instead, it is compatible with the prediction that gluon radiation from heavy quarks is suppressed by the dead cone effect. This difference also gives an estimate $\hat{q} \sim 1$ GeV$^2$/fm, which is essentially the same as that obtained via $\pi^0$ suppression measurements. Future detailed measurements of D- and B-mesons at high $p_T$, as well as model calculations which take full account of the reaction dynamics, will undoubtedly provide more detailed mechanistic insights for heavy quark energy loss and improved constraints for the transport properties of the QGP.

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[1] M. Gyulassy and X.-n. Wang, Nucl. Phys. B420, 583 (1994), nucl-th/9306003.
[2] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. 91, 072301 (2003), nucl-ex/0304022.
[3] J. Adams et al. (STAR), Phys. Rev. Lett. 91, 172302 (2003), nucl-ex/0305015.
[4] R. Baier, D. Schiff, and B. G. Zakharov, Ann. Rev. Nucl. Part. Sci. 50, 37 (2000), hep-ph/0002198.
[5] A. Kovner and U. A. Wiedemann (2003), hep-ph/0304151.
[6] M. Gyulassy, P. Levai, and I. Vitev, Nucl. Phys. B594, 371 (2001), nucl-th/0006010.
[7] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B519, 199 (2001), hep-ph/0106202.
[8] X.-N. Wang and X.-f. Guo, Nucl. Phys. A696, 788 (2001), hep-ph/0102230.
[9] A. Majumder and B. Muller, Phys. Rev. C77, 054903 (2008), 0705.1147.
[10] R. A. Lacey et al. (2009), 0907.0168.
[11] B. G. Zakharov, JETP Lett. 86, 444 (2007), 0708.0816.
[12] P. Aurenche and B. G. Zakharov (2009), 0907.1918.
[13] A. Adare et al. (PHENIX), Phys. Rev. Lett. 101, 232301 (2008), 0801.4020.
[14] A. Adare et al. (PHENIX), Phys. Rev. Lett. 98, 172301 (2007), nucl-ex/0611018.
[15] A. Adare et al. (PHENIX), Phys. Rev. Lett. 101, 162301 (2008), 0801.4555.
[16] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205 (2007), nucl-ex/0701025.
[17] B. Alver et al., Phys. Rev. Lett. 98, 242302 (2007).
[18] T. Hirano and Y. Nara, Phys. Rev. C79, 064904 (2009), 0904.4080.
[19] R. A. Lacey, A. Taranenko, and R. Wei (2009), 0905.4368.
[20] A. Adare et al. (PHENIX), Phys. Rev. Lett. 103, 082002 (2009), 0903.4851.
[21] Y.-f. Zhang (2008), 0805.2202.
[22] S. A. Bass et al., Phys. Rev. C79, 024901 (2009), 0808.0908.
[23] H. Zhang, J. F. Owens, E. Wang, and X.-N. Wang, Phys. Rev. Lett. 98, 212301 (2007), nucl-th/0701045.
[24] A. Majumder, C. Nonaka, and S. A. Bass, Phys. Rev. C76, 041902 (2007), nucl-th/0703019.
[25] A. Majumder, B. Muller, and X.-N. Wang, Phys. Rev. Lett. 99, 192301 (2007), hep-ph/0703082.
[26] A. Adare et al. (PHENIX) (2008), 0804.4168.
[27] R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007), nucl-ex/0609025.