Why heavy and light quarks radiate energy with similar rates

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The dead cone effect has been expected to reduce the magnitude of energy loss and jet quenching for heavy flavors produced with large $p_T$ in heavy ion collisions. On the contrary, data from RHIC for open charm production demonstrate a flavor independent nuclear suppression. We show that vacuum radiation of a highly virtual quark produced at high $p_T$ with its color field stripped off, develops a much wider dead cone, which screens the one related to the quark mass. Lacking the field, gluons cannot be radiated within this cone until the color field is regenerated and the quark virtuality cools down to the scale of the order of the quark mass. However, this takes time longer than is essential for the observed jet quenching. This is the reason why the light and charm quark jets are quenched equally. Open beauty is expected to be suppressed much less within the $p_T$ range studied so far.

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Energy loss via gluon radiation induced by a dense medium \[Eg\] may be an important source of nuclear suppression, called jet quenching, observed at RHIC \[1, 2\] for hadrons produced with large $p_T$ in heavy ion collisions. Based on the dead cone effect \[3\] in the radiation of heavy quarks, a reduced rate of energy loss induced by a medium was found in \[2\]. This can be easily understood classically, since a current does not radiate if its trajectory is straight. The source of induced radiation is the wiggling of the charge trajectory due to multiple collisions. A heavy particle wiggles in the medium much less than a light one, since its transverse speed is $m_q/m_Q$ times smaller at the same momentum transfer. A very heavy particle always propagates straight.

Correspondingly, it has been expected that jet quenching for heavy flavors, charm and beauty, should be weaker than for light hadrons \[2\]. Surprisingly, measurements at RHIC did not confirm this expectation, since charmed and light hadrons turned out to be similarly suppressed \[3, 4\]. This controversy has not been settled so far \[5, 6\], in spite of the attempts to improve the calculations of energy loss \[7\].

Here we draw the attention of the result \[6\] should be applied to heavy ion collisions with precautions, since the quark which undergoes induced energy loss does not come from infinity, but originates from a hard reaction and its color field is stripped off. Therefore, at the initial state of hadronization the quark has no field to radiate, except the gluons with very large transverse momentum and short coherence time. The initial high virtuality of the quark, $Q \sim p_T$, creates its own dead cone, which is much wider than the one controlled by the quark mass. The quark mass does not play a significant role until the quark virtuality drops down to values of the order of the quark mass. Here we study the interplay of these two phenomena.

High-$p_T$ scattering of partons leads to an intensive gluon radiation in forward-backward directions, which is related to the initial color field of the partons shaken off by the strong acceleration caused by the hard collision. The Weizsäcker-Williams gluons accompanying the parton do not survive the collision and lose coherence up to transverse frequencies $k \lesssim p_T$.

\[\frac{dE_{g}}{dk^2} = \frac{2E}{k^2 + x^2 m_q^2} \tag{1}\]

Here $E = p_T$ is the jet energy; $x$ is the fractional light-cone momentum of the radiated gluon; $M_g^2 = m_q^2/(1-x) + k^2/x(1-x)$ is the invariant mass squared of the quark and radiated gluon.

One can trace how much energy is radiated over the path length $L$ by the gluons which have lost coherence during this time interval,

\[\frac{dE_{g}}{dx ^2} = \frac{2\alpha_s(k^2)}{3 \pi x} \frac{k^2[1+(1-x)^2]}{[k^2 + x^2 m_q^2]^2} \tag{3}\]

where $\alpha_s(k^2)$ is the running QCD coupling, which is regularized at low scale by replacement $k^2 \rightarrow k_0^2 + k^2$ with $k_0^2 = 0.5 \text{GeV}^2$.ovement.
In the case of heavy quark the $k$-distribution Eq. (5) peaks at $k^2 \approx x^2 m_q^2$, corresponding to the polar angle (in the small angle approximation) $\theta = k/xE = m_q/E$. This is the dead cone effect.

The step function in Eq. (2) creates another dead cone: no gluon can be radiated unless its transverse momentum is sufficiently high,

$$ k^2 > \frac{2Ex(1-x)}{L} - x^2 m_q^2. $$

This bound relaxes with the rise of $L$ and reaches the magnitude $k^2 \sim x^2 m_q^2$ characterizing the heavy quark dead cone at

$$ L_q = \frac{E(1-x)}{x m_q^2}. $$

We see that $L_q$ for beauty is an order of magnitude shorter than for charm, but linearly rises with the jet energy.

The characteristic length $L_q$ may be rather long, since gluons are radiated mainly with small $x$. For instance, for a charm quark with $E = p_T = 10$ GeV the sensitivity to the quark mass is restored at $L \gtrsim 1/x$ fm. Only at longer distances, $L \gtrsim L_q$, the dead cone related to the heavy quark mass sets up, and the heavy and light quarks start radiating differently.

The numerical results demonstrating this behavior are depicted in Fig. 1. One can see that a substantial difference between radiation of energy by the charm and light quarks onsets at rather long distances, above 10 fm, while within several fermi the difference is insignificant. The $b$-quark radiation is suppressed already at rather short distances.

Apparently, this concerns not only the vacuum, but also medium induced radiation, which is softer and is even more affected by the vacuum dead cone. As far as the field of the quark is not regenerated yet, it is lacking for induced radiation as well.

Although at sufficiently long distances the field of the quark is restored and a heavy quark starts radiating much less than a light one, this difference does not show up in heavy ion collisions observed at RHIC. Indeed, data show a high-$p_T$ parton inside the produced dense medium is short and allows to neglect the small difference between the rates of energy loss (either vacuum, or induced) of charm and light quarks. Therefore $R_{AA}$ should be also independent of quarks mass.

At the same time, Fig. 1 demonstrates that energy loss of $b$-quarks is significantly reduced already at very short distances, less than fermi, so beauty should be much less suppressed in nuclear collisions. Only at about an order of magnitude larger $p_T$ $b$-quarks will radiate and get suppressed as much as other flavors.

Concluding, a highly virtual quark originated from a hard reaction with its color field stripped off develops a vacuum dead-cone which is controlled by its virtuality. While the virtuality is high, $Q^2(L) \gg m_q^2$, this cone is wider than the one related to the quark mass. There-
fore, either vacuum, or medium-induced energy loss proceed with the rates independent of the quark mass. Only at longer distances, when the quark virtuality decreases down to the scale of the heavy quark mass, its radiation gets reduced compared to the light quark. For a charm quark this regime is reached at a rather long distance of several fermi, outside the dense medium created in heavy ion collisions. This explains the flavor independent suppression observed at large $p_T$ at RHIC. We expect, however, that open beauty should be much less suppressed than other hadrons within the same range of $p_T$, but will reach the universal magnitude of suppression at much larger $p_T$. Notice that the above consideration does not depend on the collisions energy $\sqrt{s}$, but only on $p_T$.

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