Off-mass-shell effects on collisional parton energy loss in a finite QCD media

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Abstract.
We study the collisional energy loss mechanism for particles produced off mass shell in a finite size QCD medium. The off-mass-shell effects introduced consider particles produced in wave packets instead of plane waves and a length scale associated with an in-medium particle lifetime. We show that these effects reduce the energy loss as compared to the case when the particles are described as freely propagating from the source.

INTRODUCTION

The problem of collisional parton energy loss in a QCD medium has been revived by recent RHIC data on nonphotonic single electrons [1] that are not well described within radiative energy loss calculations. At first it was estimated that radiative energy loss in a finite size medium was a more important mechanism to account for energy losses of energetic partons [2, 3, 4]. These last calculations where done for infinite QCD media. The outstanding question was whether collisional energy loss for finite size media was also significant.

In this context there where two results seemingly in contradiction [5, 6]. In Ref. [5] a semiclassical approach based on linear response theory was used to compute the collisional energy loss by means of the work done by the response chromoelectric field on the color-charged heavy parton traversing the medium. However, in Ref. [6] a lowest order perturbative calculation using HTL propagators finds that finite size effects on the collisional energy loss are not significantly suppressed as compared to the infinite medium case. The formulation of the problem is based on the assumption that the scattered particle originates within the medium but otherwise is produced on mass shell.

When particles are emitted by sources lasting a finite amount of time they are not necessarily produced on their mass shell since the source emits over a (wide) range of energies. The particle could lose its identity within the medium.

ENERGY LOSS

We start by describing the interaction of a quark with momentum $P^{\mu} = (p_0, \mathbf{p})$ (not necessarily on its mass-shell), velocity $v = p/E$, mass M and spin s with a massless parton in the non-expanding medium, with momentum $K^{\mu} = (k, \mathbf{k})$ and spin λ. For elastic collisions, these particles retain their identities and after the scattering they have momenta $P'^{\mu} = (E', \mathbf{p}')$ and $K'^{\mu} = (k', \mathbf{k}')$ and spins s' and λ', respectively, and $E' = \sqrt{p'^2 + M^2}$. When the source produces particles off their mass-shell, the matrix element describing the process can be written as

$$\begin{aligned} i\mathscr{M} &= \frac{-g^2}{2M} \int d^4x \, j(t, \mathbf{x}) \int d^4x_1 \int d^4x_2 \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} D_{\alpha\beta}(q) e^{iq\cdot(x_1 - x_2)} \\ &\times \bar{u}(p', s') e^{iP'\cdot x_1} \gamma^{\alpha} S(p) e^{iP\cdot(x - x_1)} u(p, s) \bar{u}(k', \lambda') e^{iK'\cdot x_2} \gamma^{\beta} u(k, \lambda) e^{-iK\cdot x_2} \\ &\times \theta(t_1 - t) \, \theta(L/v - (t_1 - t)), \end{aligned} \tag{1}$$

where $S(p) e^{iP\cdot(x - x_1)} u(p, s)$ represents the amplitude to propagate a quark mode with momentum P from x to x_1. After averaging over the directions of $\mathbf{v}$, the expression for the energy loss can be written as

$$\begin{aligned} \Delta E &= \frac{C_R g^4}{2\pi^4} e^{-\eta L/v} \int_0^{\infty} n_{eq}(k) dk \left(\int_0^k q dq \int_{-q}^{q} \omega d\omega + \int_k^{q_{\max}} q dq \int_{q-2k}^{q} \omega d\omega \right) \\ &\times \left(|\Delta_L(q)|^2 \frac{(2k+\omega)^2 - q^2}{2} \mathscr{J}_0 + |\Delta_T|^2 \frac{[q^2 - \omega^2][(2k+\omega)^2 + q^2]}{4q^4} \right. \\ &\times \left. [(v^2 q^2 - \omega^2) \mathscr{J}_0 + 2\omega \mathscr{J}_1 - \mathscr{J}_2] \right). \end{aligned} \tag{2}$$

NUMERICAL RESULTS

In order to present the quantitative behavior for the energy loss, we take standard values for the parameters involved. The plasma temperature is taken as $T = 0.225$ GeV, the effective number of flavors $N_f = 2.5$, the strength of the coupling constant $\alpha = g^2/4\pi = 0.3$ and the Debye mass $m_D = 0.5$ GeV. The bottom quark mass is taken as 4.5 GeV whereas the charm quark mass is taken as 1.2 GeV. Since we also present results for the energy loss of light quarks, we take their mass to be 0.2 GeV.

Figure 1 shows the fractional energy loss for light, charm and bottom quarks as a function of the medium's length comparing also the cases with and without off mass-shell effects. More details on the behavior of the fractional energy loss as a function of η also for light, charm and bottom quarks are given on ref. [7].

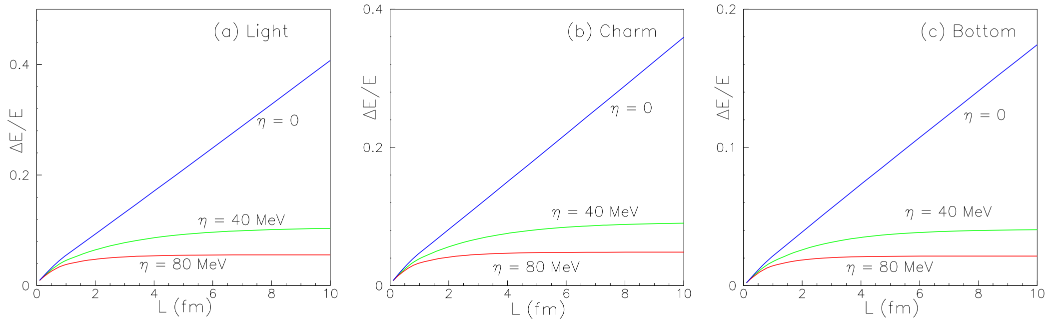

FIGURE 1. Fractional energy loss for light, charm and bottom quarks as a function of the medium's length for a fixed quark momentum $p = 10$. The uppermost curve in each case corresponds to the description without off mass-shell effects. This is compared to the case with off mass-shell effects for two values of $\eta = 40$, 80 MeV. In each case, the fractional energy loss decreases as the value of η increases.

CONCLUSIONS

We have studied the off-mass-shell effects on the collisional energy loss of particles, produced and scattered within a finite size QCD medium, associated with the introduction of a finite width wave packet and therefore a finite particle lifetime. We have shown that this effect decreases the energy loss as compared to the case when these particles are produced on mass shell and therefore these particles live longer than the medium, fragmenting outside it. Recall that the length scales playing a role for the energy loss mechanisms in a finite size, thermal, nonexpanding medium are the medium size L, the average distance between collisions, $d \sim 1/T$, the Debye radius, the mean free path $\delta \sim 1/g^2T$, and the particle formation time $t_f \sim 1/E_p$. When considering the in-medium particle lifetime, one also introduces the length scale $1/\eta$.

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