Medium-induced gluon radiation from massless and massive quarks is treated in the same formalism. The dead cone which regulates gluon radiation from massive quarks in the vacuum at small angles, is filled in the medium but constitutes a small fraction of the available phase space. Our study indicates that the energy loss for charmed hadrons at RHIC should be smaller than for light hadrons, but still sizable.

1 Introduction

Gluon radiation is the dominant process for energy loss of high-energy partons traversing a strongly interacting medium (see [1] for some reviews). It implies the energy degradation of the leading parton, the broadening of its associated parton shower and the increase of the associated hadron multiplicity. Evidences for this mechanism for light partons have been obtained in Au+Au collisions at RHIC (see [2] and references therein). The question we address here is how the medium-induced gluon radiation off a massive quark differs from that off a massless parton; full details can be found in [3].

The conventional formalism describes the medium-modification of the vacuum radiation pattern taking into account all possible rescatterings of the incoming and outgoing partons [1]. In the absence of a medium it reproduces the known results for radiation in the vacuum: for massless quarks it leads to $\omega \frac{dI_{\text{vacuum}}}{d\omega dk_\perp} \propto \frac{1}{k_\perp^2}$, with $\omega$ the energy and $k_\perp$ the transverse momentum of the emitted gluon. On the other hand, it is well known that gluon radiation in the vacuum is modified by a mass of the parent quark: radiation for angles $\theta < m/E$ is suppressed, the so-called dead cone effect [1]. It turns out that the $k_\perp^{-2}$ singularity is changed into

$$
\frac{1}{k_\perp^2} F \left( k_\perp^2, \frac{m\omega}{E} \right),
$$

with $F \left( k_\perp^2, \frac{m\omega}{E} \right)$ the dead cone factor. In a first exploratory study, Dokshitzer and Kharzeev [5] proposed that medium-induced gluon radiation is reduced by the same effect.
It turns out to be convenient to work in the adimensional scaling variables \( \kappa^2 = \frac{k^2}{\hat{q} L^2} \), \( \omega_c = \hat{q} L^2 / 2 \), \( R = \omega_c L \), \( \gamma = \omega_c / \omega \) and \( M^2 = \frac{x^2 \omega^2}{\hat{q} L} \). In Fig. 2 the \( k_\perp \)-differential spectrum of radiated gluons is shown for different gluon energies. For comparison, the massless result and the product of this massless result times the dead cone factor \( F(\kappa^2, \frac{\omega^2}{E}) \) are also shown. It can be seen that the dead cone is filled, but also that it corresponds to a small fraction of the available phase space. On the other hand, at large \( \kappa \) the radiation in the massive case is suppressed. Let us indicate that only the sum of vacuum and medium pieces has to be positive. In the massless case the vacuum contribution for \( \kappa \to 0 \) is positive and divergent, so the medium contribution may become negative;\(^7\) while for the massive case the dead cone effect kills the vacuum radiation for \( \kappa \to 0 \) so the medium contribution cannot be negative.

The \( k_\perp \)-integrated spectrum and the mean energy loss are obtained as

\[
\frac{\omega dI_{\text{medium}}}{d\omega} = \int_{0}^{\omega} d k_\perp \omega dI_{\text{medium}} / d\omega / d k_\perp, \quad \langle \Delta E_{\text{ind}} \rangle = \int_{0}^{E} d\omega \omega dI_{\text{medium}} / d\omega .
\]

Figure 1: Diagram showing the filling of the dead cone due to rescattering of the radiated gluon.
underestimates the emission. Finally, in Fig. 2 right the mean energy loss is shown for parameters taken from [7]. For RHIC, $E \simeq 5 \div 10$ GeV, the energy loss for charmed quarks is a factor $\sim 2$ smaller than that for massless quarks, but should still be observable. At higher energies, the energy loss in both cases tends to the same value. Nevertheless, it can be observed a crossover between the massive and massless cases. While it can be understood from Fig. 3 left considering the moving upper integration limit in Eq. 3, it points out the uncertainties which are present in all computations. Eq. 2 has been derived taking into account only leading terms in $1/E (x \ll 1)$, so the kinematical limits implemented in Eq. 3 are imposed a posteriori and lead to the feature mentioned previously. As a last comment, the results computed with the dead cone factor agree quite closely with those of the full computation, while Eq. 4 underestimates the energy loss.

3 Conclusions

We have computed the medium-induced gluon radiation off massless and massive quarks in the same formalism. Ours in the first $k_\perp$-differential result, consistent with available $k_\perp$-integrated ones [8]. We find that medium-induced gluon radiation fills the dead cone. However, the dead cone (i.e. the low-$k_\perp$ region) does not dominate the energy loss. Our study suggests that energy loss for charmed hadrons at RHIC should be smaller than that for lighter hadrons, but still sizable (for $p_\perp^{\text{hadron}} \simeq 5 \div 10$ GeV/c where hadronization effects inside the medium should be negligible). Finally, the commented uncertainties motivate the computation of $1/E$ corrections. In this way, the study of energy loss of massive quarks (and of more differential observables) offers new possibilities to check the existing formalism and to restrict model parameters.

To conclude let us comment on the experimental situation. As of today, the only experimental information about open charm production in Au+Au collisions at RHIC is the prompt electron spectrum measured by PHENIX [10], which do not indicate a significant parton energy
loss for charmed hadrons but also do not constrain parton energy loss significantly (due to experimental errors, a weak correlation between the transverse momentum of the electron and of the charmed hadron, and the low values of $p_{T,\text{charm}}$ which may be affected by hadronization). The reconstruction of hadronic decays of charmed hadrons will offer new possibilities (see 12).

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