Importance of different energy loss effects in jet suppression at RHIC

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Jet suppression is considered to be an excellent probe of QCD matter created in ultra-relativistic heavy ion collisions. Our theoretical predictions of jet suppression, which are based on our recently developed dynamical energy loss formalism, show a robust agreement with various experimental data, which spans across different probes, experiments (RHIC and LHC) and experimental conditions (i.e. all available centrality regions). This formalism includes several key ingredients, such as inclusion of dynamical scattering centers, finite size QCD medium, collisional energy loss, finite magnetic mass and running coupling. While these effects have to be included based on theoretical grounds, it is currently unclear what is their individual importance in accurately explaining the experimental data, in particular because other approaches to suppression predictions commonly neglect some - or all - of these effects. To address this question, we here study relative importance of these effects in obtaining accurate suppression predictions for D mesons (a clear energy loss probe) in RHIC experiments. We obtain that several different ingredients are responsible for the accurate predictions, i.e. the robust agreement with the data is a cumulative effect of all ingredients rather than a consequence of one dominant effect.

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INTRODUCTION

Suppression of high transverse momentum light and heavy flavor observables is considered to be an excellent probe of QCD matter created in ultra-relativistic heavy ion collisions at RHIC and LHC. One of the major goals of these experiments is mapping the QGP properties, which requires comparing available suppression data with the theoretical predictions; such comparison tests different theoretical models and provides an insight into the underlying QGP physics. It is generally considered that the crucial ingredient for reliable suppression predictions is accurate energy loss calculation.

We consequently developed the dynamical energy loss formalism which includes the following effects: i) dynamical scattering centers, ii) QCD medium of a finite size, iii) both radiative and collisional energy losses, iv) finite magnetic mass effects and v) running coupling. This energy loss formalism has been incorporated into a numerical procedure that allows generating state-of-the-art suppression predictions. These predictions are able to explain heavy flavor puzzles at both RHIC and LHC and, in general, show a very good agreement with the available suppression data at these experiments, for a diverse set of probes and centrality regions.

Such good agreement of the theoretical predictions with the experimental data however raises a question of which energy loss effects are responsible for accurately explaining the data. In other words, is there a single energy loss effect which is responsible for the good agreement, or this agreement is a cumulative effect of several smaller improvements? This issue is moreover important, given the fact that various approaches to energy loss calculations neglect some (or most) of these effects.

Consequently, we here address the importance of different energy loss ingredients in suppression calculations. For this purpose, it would be optimal to have a probe that is sensitive only to energy loss, i.e. for which fragmentation and decay functions do not play a role. D meson suppression is such a probe, since fragmentation functions do not modify bare charm quark suppression, as previously shown in: To explore different energy loss approximations, which are used in RHIC suppression predictions, we here concentrate on D meson suppression in central 200 GeV Au+Au collisions at RHIC. Our approach is to systematically include different energy loss effects. In particular, we first compare relative importance of radiative and collisional contribution to D meson suppression predictions, to assess the adequacy of historically widely used static approximation. We then investigate the importance of including the dynamical scattering centers, followed by collisional energy loss and finite size (LPM) effects. Finally, we also address the importance of including Ter-Mikayelian effect, finite magnetic mass and the running coupling.

THEORETICAL AND COMPUTATIONAL FRAMEWORKS

We first provide a brief overview of the computational framework and the dynamical energy loss formalism; as mentioned above this formalism leads to a very good agreement with the suppression data. We will also introduce how the energy loss expression is modified, as different ingredients are excluded from the full energy loss formalism. Note that, in the Results and Discussion section, we will for clarity address different energy loss
effects in reverse order; i.e. we will start from the static approximation, and systematically include all the effects, as such (historically-driven) approach is easier to follow.

In order to obtain quenched spectra, we use generic pQCD convolution 8:

\[ \frac{E_f d^3 \sigma}{dp_f^3} = \frac{E_i d^3 \sigma(Q)}{dp_i^3} \otimes P(E_i \rightarrow E_f) \otimes D(Q \rightarrow H_Q) \]  

(1)

In Eq. (1) Q stands for charm quarks and \( \frac{E_i d^3 \sigma(Q)}{dp_i^3} \) denotes the initial charm quark spectrum computed at next to leading order 14. \( P(E_i \rightarrow E_f) \) is the energy loss probability, which includes both radiative and collisional energy losses in a finite size dynamical QCD medium, multi-gluon 15 and path length 16, 17 fluctuations. Path length distributions are extracted from 17. In our calculations we do not use the fragmentation function \( D(Q \rightarrow H_Q) \) of charm quark into D meson, because fragmentation does not alter bare charm quark suppression 10, 11.

Expression for radiative energy loss in a finite size dynamical QCD medium 9, 10, obtained from HTL approximation, at 1st order in opacity is given by:

\[ \Delta E_{rad}/E = \frac{C_R \alpha_S}{\pi} \int dx \frac{d^2 k d^2 q}{k^2} v(q) \times \left( \frac{1}{\sin \left( \frac{(k+q)^2+\chi}{x E}\right) L} \right) \sqrt{2(k+q)} \left( \frac{(k+q)^2+\chi}{(k+q)^2+\chi} - \frac{k}{k^2+\chi} \right). \]  

(2)

In Eq. (2), \( v(q) \) is effective crosssection defined below, \( L \) is the length of the finite size QCD medium, \( E \) is the jet energy, \( k \) is the transverse momentum of the radiated gluon, while \( q \) is the transverse momentum of the exchanged (virtual) gluon. \( x \) is the longitudinal momentum fraction of the jet carried away by the emitted gluon. Color factor is \( C_R = \frac{4}{3} \). \( \chi = m_T^2 x^2 + m_b^2 \), where \( m_g = \mu_E/\sqrt{2} \) is effective (asymptotic) mass for radiated gluon with hard momenta \( k \geq T \), while \( \mu_E \) is Debye (electric) screening mass. \( \lambda \) is mean free path in QCD medium, and in the dynamical case is given by \( \frac{1}{\lambda_{dyn}} = 3 \alpha_S T \). In the incoherent limit 12, \( \sin \left( \frac{2 q^2 + \chi}{x E} \right) L \rightarrow 0 \).

Effective crosssection, with the included finite magnetic mass effects 13, is given by the equation below, where \( \mu_M \) is the magnetic screening mass:

\[ v(q) = \frac{\mu_E^2 - \mu_M^2}{(q^2 + \mu_E^2)(q^2 + \mu_M^2)} \]  

(3)

Note that, in the case when magnetic mass is equal to zero, the above expression reduces to a well-known HTL effective crosssection 13, 18:

\[ v(q) = \frac{\mu_E^2}{q^2(q^2 + \mu_E^2)} \]  

(4)

Non-perturbative approaches 12, 23 suggest that at RHIC and LHC the range of magnetic to electric mass ratio is \( 0.4 < \mu_M/\mu_E < 0.6 \). We therefore use these values in Eq. (3), when generating suppression predictions in the case of finite magnetic mass. In the case of zero magnetic mass, we use Eq. (4) above.

In the calculations for charm quark mass we use \( M_c = 1.2 \text{ GeV} \), while for most central Au+Au collisions at top RHIC energies we assume an average medium temperature of \( T=225 \text{ MeV} \) 10.

Collisional energy loss is calculated in accordance with 9, i.e. we use Eq. (14) from this reference for finite size QCD medium, and Eq. (16) for incoherent limit.

Running coupling is introduced according to 9 and is defined as in 24:

\[ \alpha_S(Q^2) = \frac{4 \pi}{(11 - 2/3 n_f) \ln(Q^2/\Lambda^2_{QCD})} \]  

(5)

where \( \Lambda_{QCD} \) is perturbative QCD scale (\( \Lambda_{QCD} = 0.2 \text{ GeV} \)), and \( n_f = 2.5 \) is the number of effective light quark flavors. In the case of running coupling, Debye mass \( \mu_E \) 24 is obtained by self-consistently solving the equation

\[ \frac{\mu_E^2}{\Lambda^2_{QCD}} \ln \left( \frac{\mu_E^2}{\Lambda^2_{QCD}} \right) = \frac{1 + n_f/6}{11 - 2/3 n_f} \left( \frac{4 \pi T}{\Lambda_{QCD}} \right)^2 \]  

(6)

Otherwise, when running coupling is not included, constant coupling \( \alpha_S = 0.3 \) and Debye mass \( \mu_E = g T \), \( (g = 2) \) are used.

Transition from the static 20 to the dynamical approximation in the case of radiative energy loss is determined through the following two changes, and according to the paper 18. The mean free path is altered as:

\[ \frac{1}{\lambda_{stat}} = \frac{1}{\lambda_q} + \frac{1}{\lambda_{stat}} = 6 \frac{1.2021}{\pi^2} \frac{n_f/4}{1 + n_f/6} \frac{3 \alpha_S T}{c(n_f)} \frac{1}{\lambda_{dyn}} \]  

(7)

where \( c(n_f = 2.5) \approx 0.84 \) is a slowly increasing function of \( n_f \) that varies between \( c(0) \approx 0.73 \) and \( c(\infty) \approx 1.09 \), and the effective crosssection changes to:

\[ v(q)_{stat} = \frac{\mu^2}{(q^2 + \mu_E^2)^2} \]  

(8)

RESULTS AND DISCUSSION

In this section we concentrate on central 200 GeV Au+Au collisions at RHIC, and investigate how different energy loss ingredients affect D meson suppression predictions. We will start the analysis from the static
approach, which has been historically the first approach to the energy loss calculations. After investigating the adequacy of the static approximation, we will address the importance of including the dynamical scattering centers, finite size effect and collisional energy loss. Finally, we will also investigate the importance of Ter-Mikayelian effect, finite magnetic mass and running coupling.

We therefore start from the static approximation, where we use a constant value of strong coupling constant $\alpha_S = 3/\pi = 0.3$ ($g = 2$), and Debye screening mass $\mu_E \approx gT$; note that these values are used in the Figs. 1-6. Also, note that magnetic mass effects are not included ($\mu_M = 0$) in Figs. 1-6 while the finite magnetic mass is considered in Fig. 6. Finite size QCD medium is considered on each figure, whereas Fig. [? ] investigates significance of finite size effects. To test the adequacy of the widely used static approximation (modeled by Yukawa potential) we compare relative importance of radiative and collisional energy loss contributions to the suppression predictions. Namely, in the static approximation, collisional energy loss has to be equal to zero, i.e. the static approximation implies that collisional energy loss can be neglected compared to radiative energy loss. However, in Fig. 1 we see that the suppression due to collisional energy loss is comparable or even larger compared to the radiative energy loss suppression. This then clearly shows that the static approximation is not adequate for the suppression calculations, and that collisional energy loss has to be taken into account in the suppression predictions. Therefore, a number of the approaches which take only radiative energy loss - and some that take only collisional energy loss - are clearly not adequate. Consequently, we will bellow first test the importance of including the dynamical effects in radiative energy loss (Fig. 3), and then also test the importance of collisional energy loss within such dynamical medium.

Therefore, in Fig. 2, we compare D meson suppression from radiative energy loss in the static framework, with the one in dynamical framework. We observe a large difference in two suppressions, with a significant suppression increase in the dynamical framework. This, in turn, indicates that at RHIC there is no jet energy range, where the static approximation becomes adequate, so that the dynamical effects have to be taken into account.

Furthermore, results from Fig. 2 imply a question whether collisional energy loss is still relevant in the dynamical QCD medium, as suppression due to radiative energy loss significantly increases in dynamical QCD medium. To address this question, in Fig. 4 we compare suppressions from collisional and radiative energy loss, both calculated in dynamical QCD medium. We observe that, even when the dynamical effects are accounted, suppressions from both radiative and collisional contributions are important; this further underscores that collisional energy loss has to be included in the suppression predictions. Consistently with this observation, we see that total suppression is significantly larger than either of the two contributions: radiative alone or collisional alone, so that they jointly have to be taken into account for accurate predictions.

Since we showed that collisional and radiative energy losses are important, we will further investigate how they are affected by the finite size (LPM) effect, as this effect is commonly considered not important for heavy flavor

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**FIG. 1:** Static radiative vs. collisional energy loss suppression. D meson suppression predictions, as a function of momentum, are shown for only radiative energy loss in static QCD medium (the dotted curve), and for only collisional energy loss in dynamical QCD medium (the dot-dashed curve). Debye mass is $\mu_E = gT$, coupling constant is $\alpha_S = 0.3$ and no finite magnetic mass effects are included (i.e. $\mu_M = 0$).

**FIG. 2:** Radiative energy loss suppressions in static vs. dynamical QCD medium. D meson suppression predictions are shown as a function of momentum, assuming only radiative energy loss in static (the dotted curve) and in dynamical (the dashed curve) QCD medium. Debye mass is $\mu_E = gT$, coupling constant is $\alpha_S = 0.3$ and no finite magnetic mass effects are included (i.e. $\mu_M = 0$).
at RHIC. In Fig. 4 we separately investigate finite size effect for radiative (the left panel), collisional (the central panel) and radiative plus collisional (the right panel) energy loss. We see that, while finite size effect is indeed negligible for collisional energy loss suppression, it is, on the other hand, significant for both radiative and total energy loss suppressions. Consequently, contrary to common expectation, LPM effect has to be taken into account in heavy flavor suppression predictions at RHIC.

We next include both radiative and collisional energy loss in a dynamical (finite size) QCD medium, and address the importance of including the effective gluon mass (Ter-Mikayelian effect \cite{13}) in the suppression calculations. To that end, in Fig. 5 we compare D meson suppression with and without the effective gluon mass. We see that including the gluon mass leads to a significant decrease in the suppression for a lower momentum range, i.e. Ter-Mikayelian effect is also important.

We next investigate the significance of taking into account finite magnetic mass in the suppression calculations. Namely, all previous energy loss calculations assumed zero magnetic mass, in accordance with perturbative QCD. However, different non-perturbative approaches \cite{19–23} reported a non-zero magnetic mass at RHIC and LHC, which indicated that finite magnetic mass has to be included in radiative energy loss calculations \cite{8}. Hence in Fig. 6 we compare D meson suppression predictions with and without finite magnetic mass included in the suppression calculations. Figure 6 shows that including finite magnetic mass effects leads to a significant decrease in the suppression; consequently, finite magnetic mass effects are also important.
FIG. 4: Finite size effects on $R_{AA}$. D meson suppression predictions are shown as a function of momentum, with (the dashed curve) and without (the dotted curve) finite size effects. Left, central and right panel show, respectively, the finite size effects on radiative, collisional and total (radiative + collisional) energy loss in dynamical QCD medium. Debye mass is $\mu_E = gT$, coupling constant is $\alpha_S = 0.3$, and no finite magnetic mass effects are included (i.e. $\mu_M = 0$).

CONCLUSIONS

Since dynamical energy loss formalism led to a robust agreement with suppression data for different experiments, probes and experimental conditions (i.e. centrality ranges) [9, 10, 11], we investigated how different energy loss ingredients contribute to such good agreement. In particular, we aimed determining whether such good agreement is a consequence of a single dominant effect, or it is a consequence of several smaller improvements. We here investigated this issue for the case of D mesons, which have the advantage that their suppression patterns are not modified by the fragmentation functions, i.e. they present a clear energy loss probe. We used an approach where we started from the simplest (reasonable) energy loss model - including only radiative energy loss - and then gradually adding different model improvements. This approach both allows investigating importance of different energy loss ingredients, and obtaining the historical perspective on improving the energy loss model. In particular, we studied the importance of the transition from static to dynamic framework and of including collisional energy loss (in both static and dynamical QCD medium), finite size effects, Ter-Mikayelian effect, finite magnetic mass and running coupling. As the overall conclusion, we found that each energy loss effect is important, and that a robust agreement between theoretical predictions and experimental data is a cumulative effect of all these improvements. Therefore, for obtaining reliable suppression predictions we need to accurately account for all the relevant energy loss ingredients. As an outlook, the presented results suggest that further improvements in the energy loss model may be crucial for accurately explaining data outside of the energy ranges and observables that we tested so-far.

We finally consider how running coupling [9] affects $R_{AA}$. Consequently, in Fig. 7 we compare D meson suppression predictions with fixed coupling, and when running coupling is accounted, as a function of momentum. From Fig. 7 we observe that running coupling leads to an increase in suppression at lower jet energies, while it makes no difference at higher jet energies. Note that such unequal difference notably changes the shape of the suppression pattern, so that accounting for the running coupling is also important.
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