# Energy loss in jet suppression - what effects matter?

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**Abstract.** 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, based on our recently developed dynamical energy loss formalism, show a robust agreement with various experimental data for different probes, experiments (RHIC and LHC) and centrality regions. Our dynamical energy loss formalism includes the following key ingredients: dynamical scattering centers, collisional energy loss, finite magnetic mass and running coupling. Although all these ingredients are theoretically justified, it is currently unclear how they individually contribute to accurate suppression predictions. Natural question rises: is there one effect which is crucial for the agreement, or is the agreement a joint effect of several smaller improvements. To answer this question, we study how the above mentioned key effects affect the suppression calculations. Our results show that each energy loss effect is important and that a robust agreement between theoretical predictions and experimental data is a cumulative effect of all improvements.

## 1. Introduction

Suppression of high transverse momentum observables [1] is considered to be an excellent probe for mapping the properties of QCD matter created in ultra-relativistic heavy ion collisions at RHIC and LHC. Therefore comparison of available suppression experimental data with the theoretical predictions [2–4] tests different theoretical models and provides the insight into underlying QGP physics. For generating these predictions, we developed dynamical energy loss formalism which includes the following energy loss effects: *i)* dynamical scattering centers, *ii)* QCD medium of a finite size [5, 6], *iii)* both radiative [5, 6] and collisional [7] energy losses, *iv)* finite magnetic mass effects [8] and *v)* running coupling [9]. We further incorporated this energy loss formalism into a numerical procedure [9] in order to obtain suppression predictions. In the numerical procedure, accurate energy loss calculations are considered to be crucial for obtaining reliable suppression predictions.

We have shown that the suppression predictions obtained from this dynamical energy loss formalism are in a very good agreement with the available experimental data for both RHIC and LHC experiments, light and heavy flavor probes and different centrality ranges [9–11].

We here address the importance of different energy loss effects in the suppression calculations for D mesons (as a clear energy loss probe) in central 200 GeV Au+Au collisions at RHIC, because fragmentation function does not modify bare charm quark suppression [10, 12]. Our approach is to systematically include different energy loss effects. In particular, we first investigate the importance of including collisional energy loss and thus necessity of abolishing static in favor of dynamical approximation. Next we address the importance of including finite magnetic mass in the suppression calculations and finally the running coupling.

## 2. Theoretical and computational formalism

In this section, we give a brief description of our dynamical energy loss formalism [9] with regression on how each effect, when added, altered energy loss expression, while in Section 4 we take the reverse approach - the historical approach, starting from a static approximation and moving to systematically include all the effects.

In order to obtain quenched spectra we use generic pQCD convolution given by Eq.(1) from [9]. The initial charm quark spectrum is computed according to [13] and energy loss probability includes both radiative and collisional energy losses in a finite size dynamical QCD medium, multi-gluon [14] and path length [15, 16] fluctuations. In our calculations we do not use the fragmentation function of charm quark into D meson, as explained in Section 1.

The radiative energy loss in a finite size dynamical QCD medium is given by Eq.(2.12) from [5], while the finite magnetic mass and running coupling are introduced according to [8] and [9], respectively. For the finite magnetic mass case we use the following range of magnetic to electric mass ratio: $0.4 < \mu_M/\mu_E < 0.6$, according to non-perturbative approaches [17–21], otherwise, $\mu_M = 0$ is used. Also when the running coupling is not included, in our calculations we use $\alpha_S = \frac{g^2}{4\pi} = 0.3$ and Debye mass $\mu_E = gT$, $(g = 2)$. Collisional energy loss is calculated in accordance with Eq.(14) from [7]. Transition from the static [22] to the dynamical approximation in terms of radiative energy loss is explained in [6].

In our calculations for the charm quark mass we use $M_c = 1.2$ GeV, for 0-5% central 200 GeV Au+Au collisions we assume an average medium temperature of T=225 MeV [10] and for the number of effective light quark flavors we use $n_f = 2.5$.

## 3. Comparison with experimental data

As we mentioned in Section 1, our dynamical energy loss formalism [9] leads to a very good agreement with suppression experimental data for diverse probes at both RHIC [10] and LHC [9] and for different centrality regions [11]. The suppression is expressed by the nuclear modification factor $R_{AA}$ [4], which quantifies the QCD medium effects on the yield of high-$p_T$ particles. Fig. 1, which shows comparison of the D meson $R_{AA}$ predictions with corresponding $R_{AA}$ measured at the LHC and comparison of the single electron $R_{AA}$ predictions with non-photonic single electron $R_{AA}$ measured at RHIC, reflects the above mentioned agreement.

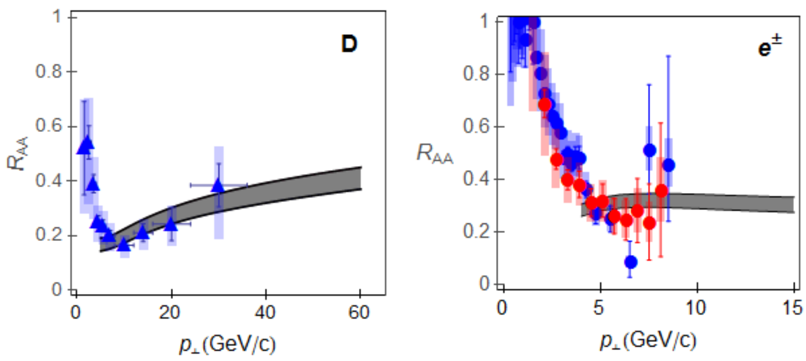


**Figure 1. Theory vs. experimental data for D meson and single electron suppressions as a function of transverse momentum.** Left panel shows comparison of D meson $R_{AA}$ predictions with experimentally measured $R_{AA}$ (triangle) in most central 2.76 TeV Pb+Pb collisions at the LHC. Right panel shows comparison of single electron $R_{AA}$ predictions with non-photonic single electron $R_{AA}$ (circle) measured in most central 200 GeV Au+Au collisions at RHIC. Left (right) panel is adapted from [9] ( [10]).

## 4. Results and discussion

We start from the static approximation [22, 23] and use a constant value of the strong coupling constant and of Debye mass (as mentioned above), and no finite magnetic mass effects ($\mu_M$=0); note that these values are used in Figs. 2 and 3, while the importance of finite magnetic mass is considered in Fig. 3. Previously, the static approximation was widely used, which assumed that collisional energy loss can be neglected compared to radiative. Left panel of Fig. 2 shows that static approximation has to be abolished, because collisional energy loss suppression is comparable or even larger than static radiative one. Therefore, central panel of Fig. 2 addresses the significance of including dynamical effects by comparing static with dynamical radiative energy loss $R_{AA}$. We observe a significant suppression increase in the dynamical approximation, so we conclude that dynamical effects are important. Right panel of Fig. 2 investigates whether collisional energy loss is still relevant in dynamical approximation, by comparing radiative with collisional contribution to $R_{AA}$ in the dynamical QCD medium. We conclude that even in dynamical approximation, both radiative and collisional contributions are important, so we further include both radiative and collisional (total) energy losses in dynamical QCD medium.

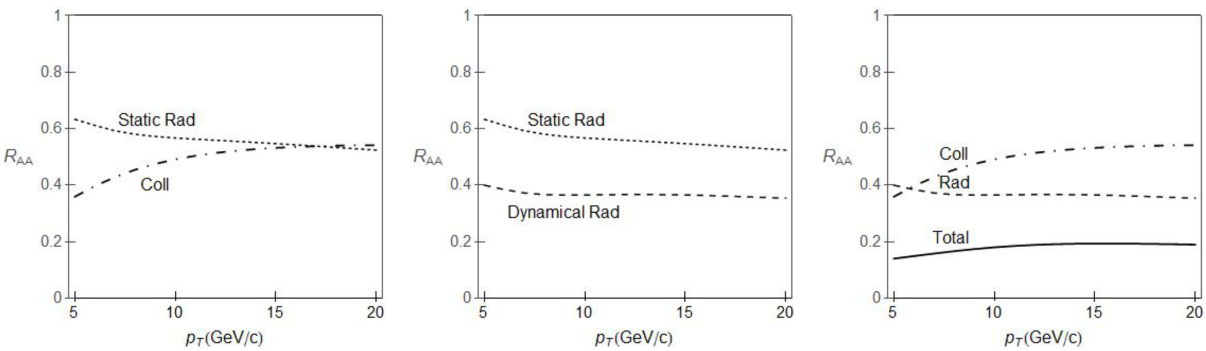


**Figure 2. Static vs. dynamical approximation.** D meson suppression predictions are shown as a function of transverse momentum. Left panel shows comparison of static radiative (dotted curve) with dynamical collisional (dot-dashed curve) contribution to $R_{AA}$. Central panel shows comparison of static radiative (dotted curve) with dynamical radiative (dashed curve) contribution to $R_{AA}$. Right panel shows radiative (dashed curve), collisional (dot-dashed curve) and radiative + collisional (solid curve) contribution to $R_{AA}$ 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 ($\mu_M = 0$). Adapted from [24].

Next we consider how inclusion of finite magnetic mass in radiative energy loss calculations [8] affects the $R_{AA}$ predictions, as indicated in Section 2. By comparing $R_{AA}$ with and without finite magnetic mass (Fig. 3), we observe significant suppression decrease due to finite magnetic mass effects. Hence, we conclude that finite magnetic mass effects are important.

Also, the importance of taking into account running coupling [9] is considered in Fig.7 from [24], where we observe suppression increase due to running coupling only at lower jet energies. Consequently running coupling is also important.

## 5. Conclusions

Since dynamical energy loss formalism led to a robust agreement with the suppression data for different experiments, probes and centrality ranges [9–11], we wanted to determine whether the agreement was a consequence of one dominant effect or a joint effect of several smaller

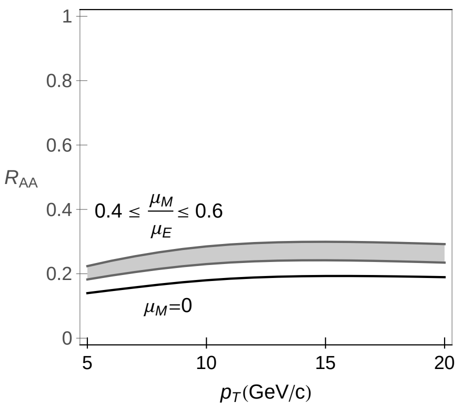


**Figure 3. Magnetic mass effects on $R_{AA}$.** D meson suppression predictions are shown, as a function of transverse momentum, for radiative and collisional energy loss in dynamical QCD medium, with (band) and without (solid curve) magnetic mass. Debye mass is $\mu_E = gT$ and coupling constant is $\alpha_S = 0.3$. The upper (lower) boundary of the band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$). Adapted from [24].

improvements introduced to energy loss calculations. In order to examine the importance of each effect we followed first a historical approach starting from the static approximation and gradually introduced different energy loss effects in D meson suppression calculations (as a clear energy loss probe) until reaching dynamical energy loss formalism [9]. The conclusion is that each energy loss effect is important and that a robust agreement is a cumulative effect of all these improvements. Therefore, in order to obtain reliable suppression predictions we need to accurately account for all the relevant energy loss ingredients.


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