Suppression and energy loss in Quark-Gluon Plasma

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Abstract. High momentum suppression of light and heavy flavor observables is considered to be an excellent probe of jet-medium interactions in QCD matter created at RHIC and LHC. Utilizing this tool requires accurate suppression predictions for different experiments, probes and experimental conditions, and their unbiased comparison with experimental data. We developed the dynamical energy loss formalism which takes into account both radiative and collision energy loss computed within the same theoretical framework, dynamical (as opposed to static) scattering centers, finite magnetic mass, running coupling and uses no free parameters in comparison with experimental data. Within this formalism, we provide predictions, and a systematic comparison with the experimental data, for a diverse set of probes, various centrality ranges and various collision energies at RHIC and LHC. We also provide clear qualitative and quantitative predictions for the upcoming LHC experiments. A comprehensive agreement between our predictions and experimental results suggests that our dynamical energy loss formalism can well explain the jet-medium interactions in QGP, which will be further tested by the obtained predictions for the upcoming data.

1. Introduction

Traditionally, light and heavy flavour suppressions are considered to be excellent probes of QCD matter [1–3]. Since suppression for a number of observables has been measured at RHIC and LHC, their comparison with theoretical predictions allows for testing our understanding of QCD matter. Due to this, we will mainly concentrate on theoretical energy loss and suppression predictions, and how well these predictions can explain the experimental data. Note that in these proceedings only the main results will be reviewed; for the full account, the reader should refer to [4–8].

Figure 1 shows a scheme, which represents the main steps in the suppression calculations. These steps involve jet production, energy loss, fragmentation and decay. Therefore, to have reliable calculation of jet suppression, reliable calculations of all the underlying processes are needed. It is generally considered that the critical step in the jet suppression calculations is the jet energy loss [9], so we will first concentrate on this step. We will then go back to discuss the entire numerical procedure, and when discussing the experimental data, we will argue that other steps can be very important as well.

2. Energy loss overview

Initially, most of the energy loss calculations were based on the assumption of static scattering centers [10], and only radiative energy loss was included (see e.g. [11–15]). These calculations, however, lead to obvious disagreements with the experimental data (for overview, see [16]),
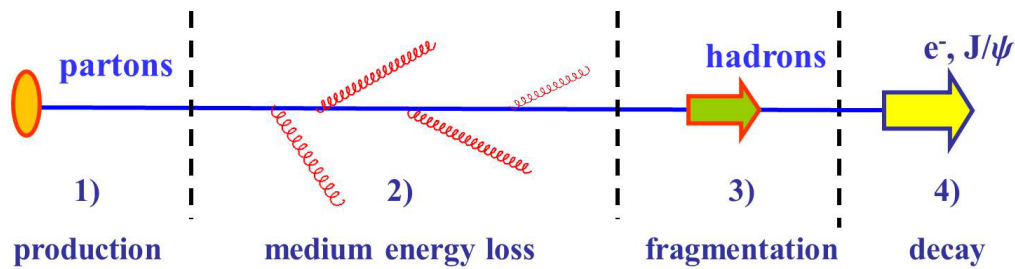
Figure 1. Suppression scheme. The scheme represents important steps in the suppression calculations.

which opened a question whether radiative energy loss really controls the energy loss in QGP, or collision energy loss is also important. Several calculations of the collision energy loss were then performed[17–20], showing that the collision and radiative energy losses are actually comparable, and concluding that collision energy loss is important and should indeed be taken into account in the calculations of jet suppression.

However, the fact that collision energy loss is non-zero opened a fundamental problem with the radiative energy loss formalisms built on the static QCD medium approximation. One consequence of such an approximation is that in a static medium, collision energy loss has to be exactly equal to zero [21]! However, contrary to this expectation, collision energy loss computations[17–20] showed that collision and radiative energy losses are comparable. This leads to the conclusion that collision energy loss results are inconsistent with static approximation, since static medium approximation necessarily leads to zero collision energy loss. So this inconsistency leads to the second conclusion that QCD medium cannot be modeled by static scattering centers, and that dynamical effects have to be included in the radiative energy loss calculations [21].

To address this important issue, we developed the radiative jet energy loss formalism in a finite size dynamical QCD medium [19, 22, 23]. The formalism takes into account that the medium constituents are in reality dynamical, i.e. moving particles, and that the medium has finite size. To calculate the energy loss we used the generalized two hard thermal loop approach, which removes assumption of static scattering centers. The calculations are based on the finite temperature field theory, take into account both radiative and collision energy losses, and are applicable to both light and heavy flavor. The formalism has also been recently generalized to the case of finite magnetic mass [24] and running coupling [4]. Regarding the formalism, note that all the dynamical energy loss ingredients are included based on the theoretical grounds that we discussed above. Furthermore, in [25] and the contribution by B. Blagojevic in these proceedings, it is discussed how these model ingredients are important in obtaining accurate numerical predictions.

3. Suppression predictions

3.1. Comparison with the existing experimental data at central collisions

To generate suppression predictions, we incorporated this formalism into a numerical procedure [4], which also includes light and heavy flavor production [26], path-length [27, 28] and multi-gluon [29] fluctuations, fragmentation [30] for light and heavy flavor and, in the case of heavy flavor, decays to single electrons and J/Ψ [31]. As a starting point in our calculations, for LHC we used effective temperature of 304 MeV as extracted by ALICE [32], and for RHIC we used 221 MeV as extracted by PHENIX [33].

We will first concentrate on the existing RHIC and LHC suppression data and our goal is to see how our energy loss formalism can help us in understanding this data. Within this goal, we will first generate a comprehensive set of joint predictions for all the available light and heavy flavor R_{AA} central collision data. Here, we will concentrate on some puzzling data (i.e. data which seems counterintuitive). We will then test how our model works for different centrality regions. All the predictions will be generated by the same formalism, with the same numerical procedure, and with no free parameters used in model testing. Actually, all used parameters correspond to the standard literature values, as stated in [7].
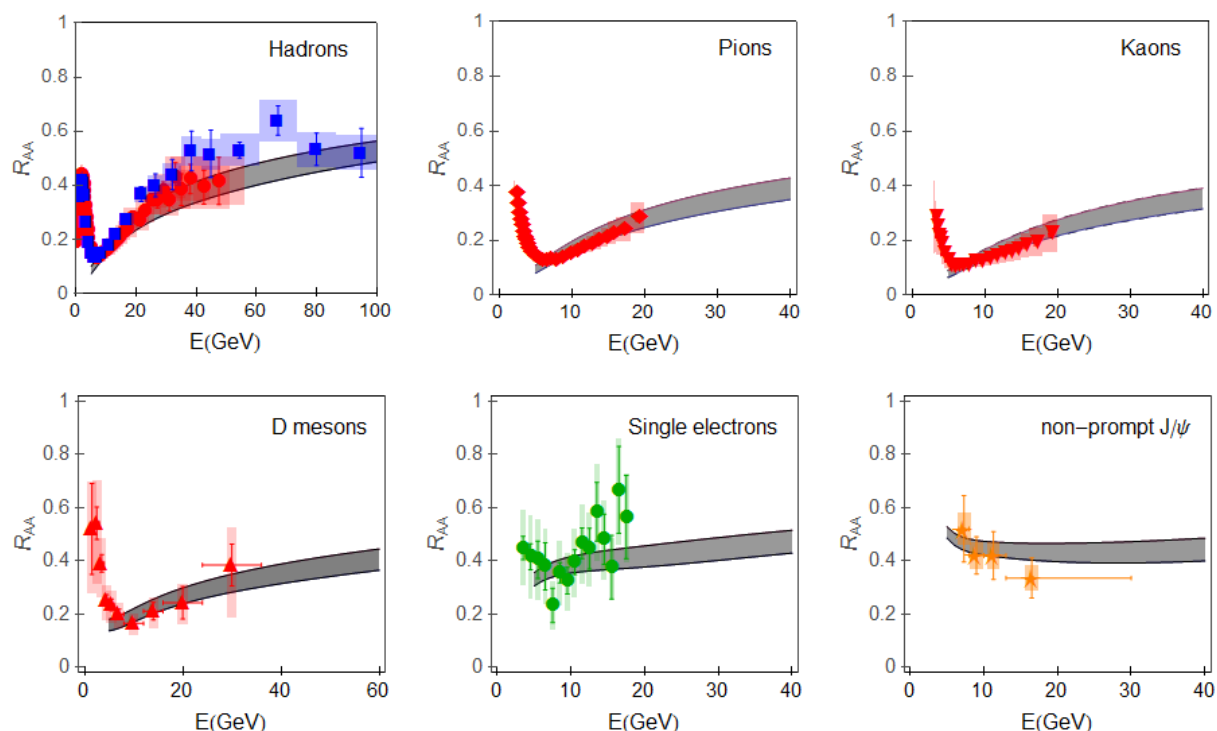

Figure 2. **Comparison of suppression predictions with R_{AA} experimental data in central 2.76 TeV Pb+Pb collisions at the LHC.** Our suppression predictions (shown as gray bands) are compared with the available experimental R_{AA} data for charged hadrons, pions, kaons, D mesons, non-photonic single electrons and J/ψ. The figure is adapted from [4]. The bands comes from the uncertainty in the magnetic mass value, see Ref. [4].

In Fig. 2 we show the predictions for central collisions at LHC, which are, as we said, generated for a diverse set of probes, for which LHC measurements are available. Specifically, we compare predictions with experimental data [34–39] for charged hadrons, pions, kaons, D mesons, single electrons and non-prompt J/Ψ. We see that we obtain excellent agreement for light flavor and D mesons. We see that the single electron data is quite noisy, but we still obtain good agreement with the predictions. There is also good agreement for non-prompt J/ψ, except for the last data point, which comes with large error bars. Now, if we look at the D mesons and charged hadrons, we can see that they reveal a puzzle, which we call the heavy flavor puzzle at LHC, and which we will briefly overview below (for more details, please refer to [6]).

3.2. Heavy flavor puzzles at RHIC and LHC

While D meson suppression is a clear charm probe, charged hadrons are composed of both light quarks and gluons. Moreover, the gluons have significant (even dominant in the lower momentum region) contribution to charged hadron production [6]. Also, from the left panel in Fig. 3 we see that charm and light quarks have about the same suppression, while the suppression of gluons is much higher. Based on this and on the common expectation that energy loss is the most important step in the jet suppression, we clearly expect that $R_{AA}(D) > R_{AA}(h)$.
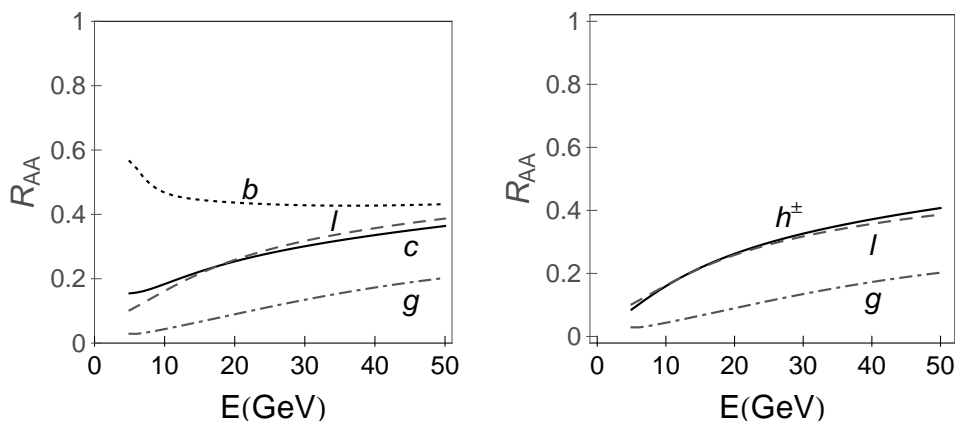

Figure 3. Comparison of the light and heavy flavor suppression predictions. The left panel shows the momentum dependence of the jet suppression for bottom quarks (the dotted curve), charm quarks (the full curve), light quarks (the dashed curve) and gluons (the dot-dashed curve). The right panel shows the comparison of charged hadron suppression predictions (the full curve) with light quark (the dashed curve) and gluon (the dot-dashed curve) suppression predictions, as a function of momentum. The figure is adapted from [6].

However, contrary to this expectation, LHC experimental results actually show the same R_{AA} for charged hadrons and D mesons [34, 37]. Having in mind the above, a naive conclusion would be that quarks and gluons lose the same amount of energy, which is however not in accordance with pQCD. Even more surprisingly, as shown in Fig. 2 (see also [6]), we see that our theoretical predictions, which are based on pQCD, are actually in excellent agreement with the data. We therefore ask why both the experimental data and the theoretical predictions are not in agreement with the qualitative expectations that we summarized in the previous slide.

Therefore, for explaining the puzzling data, steps in the jet suppression shown in Fig. 1, other than the energy loss, must also be important. In the case of the heavy flavor puzzle, we expect that the other important step is jet fragmentation, since it defines a transfer from the parton to hadron level. With regard to the D mesons, it is well known that fragmentation does not modify bare charm quark suppression (see e.g. [6]). Consequently, the D meson suppression is indeed a genuine probe of the charm quark suppression in QCD medium. However, things are much more complicated for charged hadrons, that is, fragmentation functions significantly modify the suppression patterns of light quarks and gluons, as demonstrated in the right panel of Fig. 3 (see also [6]). In particular, due to fragmentation functions, charged hadron/pion suppression unexpectedly becomes almost the same as bare light quark suppression.

Therefore, as a summary of the puzzle, the main result that we obtained is that charged hadron suppression is almost identical to the light quark suppression which is despite the dominant gluon contribution in the charged hadron production. Since we also have that D

meson R_{AA} is the same as the charm R_{AA} and that the light and charm quarks have almost the same R_{AA}s, we obtain the solution of the puzzle, i.e. that the charged hadrons and D mesons indeed should have the same suppression, as observed in the experiment and confirmed by our theoretical predictions. Consequently, it is not only the energy loss, but an unexpected interplay between the energy loss and the fragmentation functions, which is responsible for explaining the heavy flavor puzzle at the LHC.
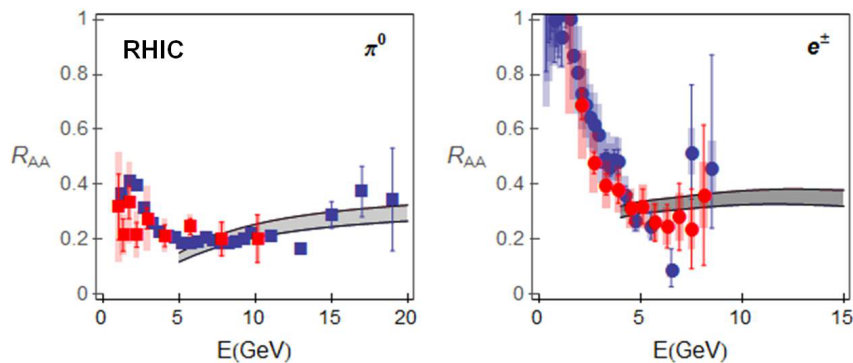

Figure 4. Comparison of suppression predictions with R_{AA} experimental data in central 200 MeV Au+Au collisions at RHIC. Our suppression predictions (shown as gray bands) are compared with the available experimental R_{AA} data for neutral pions and non-photonic single electrons. The figure is adapted from [5]. The bands comes from the uncertainty in the magnetic mass value, see Ref. [5].

We now test how our model works for RHIC central-collision data, since we know that the suppression data shown here leads to a well-known heavy flavor puzzle at RHIC; that is, the previous static energy loss models were not able to explain this data. However, from Fig. 4 we see that the dynamical energy loss formalism outlined in the previous slides can well explain the data (see also [5]). Note that no free parameters are used in model testing.

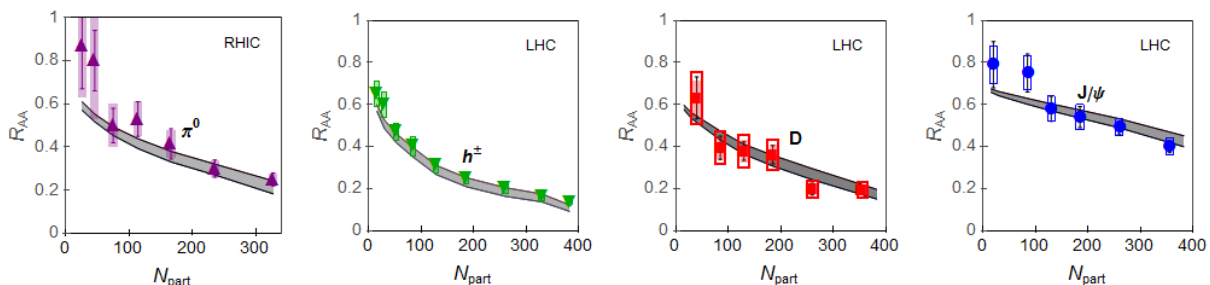*3.3. Comparison with the data for non-central collisions*

Figure 5. Comparison of suppression predictions with R_{AA} experimental data in non-central collisions at RHIC and the LHC. Our suppression predictions (shown as gray bands), as a function of a number of participants, are compared with the available experimental R_{AA} data for neutral pions at RHIC and charged hadrons, D mesons and non-prompt J/Ψ at LHC. The figure is adapted from [7].

We next generate predictions for non-central collisions and compare them with available LHC [41–43] and RHIC [40] data. In these proceedings, we concentrate on the case when the suppression is measured for fixed momentum range and the changing centrality (for additional comparisons, see [7]), for different probes at RHIC and LHC. We see RHIC data for neutral pions, and LHC data for charged hadrons, D mesons, and non-photonic J/Ψ. We also obtain a very good agreement with the experiments. Therefore, our model is able to explain the non-central measurements at the RHIC and LHC very well.

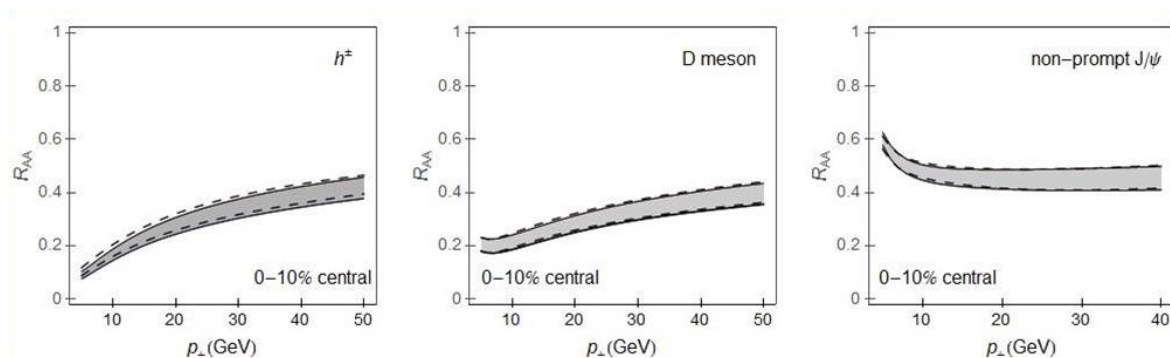*3.4. Predictions for the upcoming 5.1 TeV Pb+Pb at LHC*

Figure 6. Suppression predictions for central 5.1 TeV Pb+Pb collisions the LHC. Charged hadron, D meson and non-prompt J/ψ suppression predictions, as a function of transverse momentum, are shown on the left, central and the right panel, respectively. Full (dashed) curves correspond to R_{AA} predictions at 5.1 TeV (2.76 TeV) Pb+Pb collisions at the LHC. The figure is adapted from [8]. The bands comes from the uncertainty in the magnetic mass value, see Ref. [8].

We will now concentrate on suppression predictions for the upcoming 5.1 TeV Pb+Pb collision energies at the LHC. Within this, we will concentrate on most central collisions and provide suppression predictions for charged hadrons, D mesons and J/Psi, as a function of momentum, which we also compare with analogous predictions for 2.76 TeV beam energy, see Fig. 6. We see that we obtain the same suppressions predictions between these two collision energies, for all types of probes. Moreover, this agreement is in line with BES energy scan, which show similar suppressions between RHIC and LHC. Furthermore, we predict that this similar suppression behavior will continue to higher beam energies as well.

We next ask why we observe the same suppressions between 2.76 and 5.1 TeV, which is addressed in Fig. 7. We see that the reason for the same suppression is an interplay between initial distribution and energy loss effects. That is, the initial distributions become flatter with an increase in the beam energy, which has a tendency to lower the suppression from 2.76 to 5.1 TeV, as seen in the left panel of Fig. 7. On the other hand, the energy loss increases with an increase in beam energy, which has a tendency to increase the suppression from 2.76 to 5.1 TeV, as shown in the right panel of Fig. 7. These two effects approximately cancel, leading to the same suppression patterns between the two collision energies. Therefore, contrary to the heavy flavor puzzle, where the interplay between energy loss and fragmentation functions was crucial for explaining the puzzle, this case provides a clear example on the importance of initial distributions; that is, similarly predicted (and measured) suppressions for different collision energies is a consequence of an interplay between initial production and energy loss.
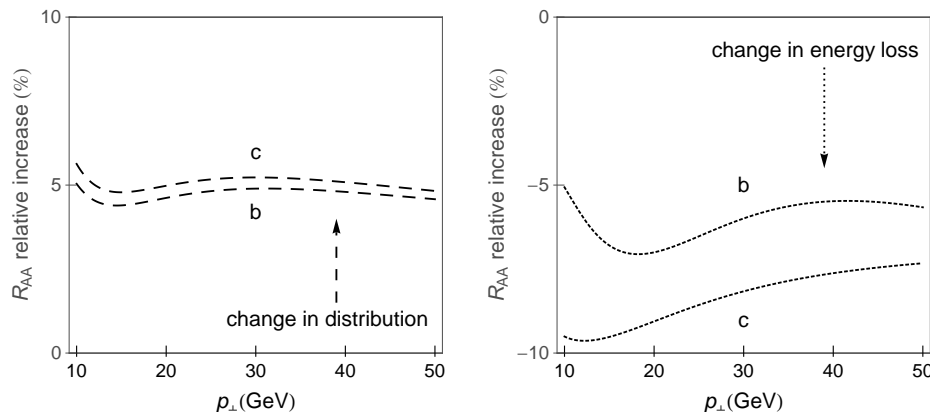
Figure 7. Relative increase in R_{AA} between 2.76 and 5.1 TeV. The left panel shows momentum dependence of the relative increase in R_{AA} between 2.76 and 5.1 TeV Pb+Pb collisions at the LHC due to differences in the initial momentum distributions; to calculate the relative increase in R_{AA} due to different initial momentum distributions, the energy loss is kept fixed and calculated for 2.76 TeV case, while the distributions are varied between 2.76 and 5.1 TeV. The right panel shows momentum dependence of the relative increase in R_{AA} between 2.76 and 5.1 TeV collisions at the LHC due to differences in the energy loss; to calculate the relative increase in R_{AA} due to different energy losses, the initial momentum distribution is kept fixed and calculated for 2.76 TeV case, while the energy loss is varied between 2.76 and 5.1 TeV. The figure is adapted from [8].

4. Summary

We developed the dynamical energy loss formalism, which includes different important effects. The predictions of the model were then comprehensively tested against angular averaged R_{AA} data, which is considered to be largely insensitive to the medium evolution [44,45]. We obtained robust agreement for wide range of probes, centralities and beam energies. We have seen that the model can also obtain an understanding of the intuitively puzzling data. Finally, we obtained clear predictions for future experiments. Therefore, these results provide us with a good level of confidence that our dynamical energy loss formalism can explain the jet-medium interactions in QGP well.

As an outlook, since we have the jet-medium interactions under control, and since the model can explain the wide range of data without free parameters, we can combine this model with the sophisticated simulations of the bulk medium evolution [46]. We can than generate predictions of high p_t angular differential suppression variables, which are, in distinction to the angular average suppression variables, considered to be highly sensitive to the medium evolution.

Acknowledgments

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