DREENA-B framework: first predictions of $R_{AA}$ and $v_2$ within dynamical energy loss formalism in evolving QCD medium

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Our dynamical energy loss formalism, allows generating state-of-the-art suppression predictions in finite size QCD medium. The formalism uses a sophisticated model of high-$p_T$ parton interactions with QGP, but simple medium model with constant temperature was assumed. We here present a newly developed DREENA-B framework, which abolishes the constant temperature assumption, instead using an evolving medium modeled by Bjorken (“B”) expansion. We use this framework to provide joint $R_{AA}$ and $v_2$ predictions, for the first time within the dynamical energy loss formalism in evolving QCD medium. The predictions are generated for both $Pb + Pb$ and $Xe + Xe$ at the LHC, and for both light and heavy flavor probes, at different centrality regions. For $Pb + Pb$, where experimental data are available, DREENA-B framework leads to a good joint agreement with $v_2$ and $R_{AA}$ data. This being significant, as previous energy loss models faced difficulties in jointly explaining these data (even with free parameters), without introduction new phenomena, known as $v_2$ puzzle. For $Xe + Xe$ collisions, we provide predictions to be compared with upcoming experimental data, and also show that introduction of the evolving medium leads to visible difference in predictions, compared to constant temperature framework (DREENA-C). Overall, the results presented here provide confidence that the dynamical energy loss formalism provides a reliable tool for QGP tomography.

INTRODUCTION

It is by now established that Quark-gluon plasma (QGP), being a new state of matter [1,2] consisting of interacting quarks, antiquarks and gluons is created in ultra-relativistic heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC). Energy loss of rare high $p_T$ probes, which are created in such collisions and which transverse QGP, are considered to be excellent probes of this form of matter [3–6]. Such energy loss is reflected through different observables, most importantly angular averaged ($R_{AA}$) [7,13] and angular differential ($v_2$) [14,19] nuclear modification factor, which can be measured and predicted for both light and heavy flavor probes. Therefore, comparing a comprehensive set of predictions, created under the same model and parameter set, with corresponding experimental data allows systematically investigating QCD medium properties, i.e. QGP tomography.

We previously showed that the dynamical energy loss formalism [20,22] provides an excellent tool for such tomography. In particular, we showed that the formalism sows a very good agreement [21,27] with a wide range of $R_{AA}$ data, coming from different experiments, collision energies, probes and centralities. Recently, we also used this formalism to generate first $v_2$ predictions, within DREENA-C framework [23], where DREENA stands for Dynamical Radiative and Elastic ENergy loss Approach, and "C" denotes constant temperature QCD medium. These predictions were compared jointly with $R_{AA}$ and $v_2$ data, showing a very good agreement with $R_{AA}$ data, while visibly overestimating $v_2$ data. This overestimation also clearly differentiates the dynamical energy loss from other models, which systematically underestimated the $v_2$ data, leading to so called $v_2$ puzzle [28,30]. On the other hand, it is also clear that $v_2$ predictions have to be further improved. This is not surprising, as $v_2$ was shown to be quite sensitive to medium evolution [31,32], so that the constant temperature assumption (which is in essence od DREENA-C) does not provide appropriate framework for its calculations. This then motivated us to introduce medium evolution in the dynamical energy loss formalism, which is DREENA-B framework discussed here.

However, introducing temperature evolution in dynamical energy loss formalism is not an easy task. This is mainly due to the fact that the formalism introduces a sophisticated model of high-$p_T$ parton interactions with the medium [24], where we previously showed that all these effects are important for accurately describing experimental data [33]. Therefore, all the ingredients in this model have to be kept, with no additional simplifications used in the numerical procedure. We will start this task of introducing the medium evolution in the dynamical energy loss formalism with DREENA-B framework presented here, where B stands for Bjorken. In DREENA-B framework, QCD medium is modeled by the ideal hydrodynamical $1+1D$ Bjorken expansion [34], which has a simple analytical form of temperature ($T$) dependence on time and does not contain

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NUMERICAL FRAMEWORK

The dynamical energy loss formalism was originally developed for constant temperature QCD medium, as described in detail in [20–22]. We now derived the expression in the medium in which the temperature is changing along the path of the jet, which will be presented elsewhere. In DREENA-B framework, which we present here, the temperature dependence along the jet path is taken according to the ideal hydrodynamical 1+1D Bjorken expansion [34]. The resulting expression is next implemented in the full numerical procedure, which was also employed in the constant temperature case. We here list the main ingredients, while more details can be found with DREENA-C framework [23]: up-to-date initial distributions [35] and fragmentation functions [36–38], dynamical energy loss formalism with collisional [22] and radiative [20] energy loss, running coupling [24] and magnetic mass [39] effects, together with multi-gluon [40] and path-length fluctuations [41]. We also recently abolished the soft-gluon approximation [42], for which we however showed that it does not significantly affect the model results.

Regarding parameters, we implement Bjorken 1+1D expansion [34], with commonly used $T_0 = 0.6$ fm [43] [44], and initial temperatures for different centralities calculated according to $T_0 \sim (dN_{ch}/dy/A_\perp)^{1/3}$ [45], where $dN_{ch}/dy$ is charged multiplicity and $A_\perp$ is overlap area for specific collision system and centrality. We use this equation, starting from $T_0 = 500$ MeV in 5.02 TeV Pb + Pb most central collisions at the LHC, which is estimated based on average medium temperature of 335 MeV in these collisions, and QCD transition temperature of $T_c \approx 150$ MeV [46]. Note that the average medium temperature of 335 MeV in most central 5.02 TeV Pb + Pb collisions comes from [25] the effective temperature ($T_{\text{eff}}$) of 304 MeV for 0-40% centrality 2.76 TeV Pb+Pb collisions at the LHC [17] experiments (as extracted by ALICE). Once $T_0$ for most central Pb + Pb collisions is fixed, $T_0$ for both different centralities and different collision systems ($Xe + Xe$ and Pb + Pb) is obtained from the expression above.

Other parameters used in the calculation remain the same as in DREENA-C [24]. In particular, the path-length distributions for both $Xe + Xe$ and $Pb + Pb$ are calculated following the procedure described in [49], with an additional hard sphere restriction $r < R_A$ in the Woods-Saxon nuclear density distribution to regulate the path lengths in the peripheral collisions. Note that the path-length distributions for Pb + Pb are explicitly provided in [23]. For $Xe + Xe$, it is straightforward to show that $Xe + Xe$ and Pb + Pb distributions are the same up to rescaling factor ($A^{1/3}$ where $A$ is atomic number), as we discussed in [50]. For QGP, we take $\Lambda_{QCD} = 0.2$ GeV and $n_f = 3$. Temperature dependent Debye mass $\mu_E(T)$ is obtained from [51]. For light quarks, we assume $M_\text{QGP} \approx \mu_E/\sqrt{6}$, and for gluon mass $m_g \approx \mu_E/\sqrt{2}$ [52]. The charm and bottom masses are $M = 1.2$ GeV and $M = 4.75$ GeV, respectively. Magnetic to electric mass ratio is extracted from non-perturbative calculations [53–54], leading to $0.4 < \mu_M/\mu_E < 0.6$ - this range of screening masses lead to presented uncertainty in the predictions. We note that no fitting parameters are used in the calculations, that is, all the parameters correspond to standard literature values.

RESULTS AND DISCUSSION

In this section, we will generate joint $R_{AA}$ and $v_2$ predictions for light (charged hadrons) and heavy (D and B mesons) flavor in Pb + Pb and Xe + Xe collisions at the LHC, obtained by DREENA-B framework. Based on path-length distributions from Figure 1 in [23], we will, in Figures 1 to 3, calculate average $R_{AA}$, as well as $v_2$ for light and heavy flavor, in 5.02 TeV Pb + Pb collisions, at different centralities. We start by generating charged hadrons predictions, where data for both $R_{AA}$ and $v_2$ are available. Comparison of our joint predictions with experimental data is shown in Figure 4 where left and right panels correspond, respectively, to $R_{AA}$ and $v_2$. In comparison with DREENA-C model, where we had quantitatively good agreement with the data for $R_{AA}$ and qualitative agreement for $v_2$ (but predictions were still visibly above the data), we here see that inclusion of Bjorken evolution notably improves the quantitative agreement with the data. That is, we see that DREENA-B is able to well explain joint $R_{AA}$ and $v_2$ predictions.

In Figure 2, we provide joint predictions for D meson $R_{AA}$ (left panel) and $v_2$ (right panel) predictions, as well as for in-plane and out-of-plane $R_{AA}$ (middle panel). Predictions are compared with available experimental data. Note that data for both 2.76 TeV and 5.02 TeV are shown, since the data and predictions for these two collision energies overlap [26], and the data for 5.02 TeV are still scarce. We again observe good joint agreement with the available $R_{AA}$, $v_2$ and in- and out-of-plane $R_{AA}$ data.
Figure 3 shows equivalent predictions as Figure 2 only for B mesons. While B meson experimental data are yet to become available, we predict notably large suppression (see also \cite{24,55}), which is consistent with non-prompt $J/\Psi$ $R_{AA}$ measurements \cite{56} (indirect probe od b quark suppression). Additionally, we predict non-zero $v_{2}$ for higher centrality regions. This does not necessarily mean that heavy B meson flows, since we here show predictions for high $p_{\perp}$, and flow is inherently connected with low $p_{\perp} v_{2}$. On the other hand, high $p_{\perp} v_{2}$ is connected with the difference in the B meson suppression for different (in-plane and out-of-plane) directions. From the middle panels of Fig. 3 we see significant difference between in-plane and out-of-plane $R_{AA}$ (coming from the difference in the path-lengths shown in Fig. 1 in \cite{23}), leading to our predictions of non zero $v_{2}$ for high $p_{\perp}$ B mesons.

Overall, we see that comprehensive joint $R_{AA}$ and $v_{2}$ predictions, obtained with our DREENA-B framework, lead to good agreement with all available light and heavy flavor data. This is also the first study to provide such comprehensive predictions for high $p_{\perp}$ observables. In the context of $v_{2}$ puzzle, this study presents a significant development, as to our knowledge, the other models were not able achieve this agreement without introducing new phenomena \cite{57}.

We further continue by providing the equivalent predictions for, yet to come, experimental data for 5.44 TeV $Xe + Xe$ collisions at the LHC. In Figures 4 to 6, we generate equivalent predictions to those presented by Figures 1 to 3. In each figure, predictions obtained with DREENA-B framework are directly compared with predictions obtained with our previously developed DREENA-C framework. Comparison of predictions obtained with DREENA-B and DREENA-C frameworks, allow to directly asses the importance of inclusion of medium evolution on different observables, as the main difference between these two frameworks is that DREENA-B contains Bjorken evolution, while DREENA-C has no evolution (i.e. it assumes constant temperature medium). We see that inclusion of medium evolution has effect on both $R_{AA}$ and $v_{2}$. That is, it systematically somewhat increase $R_{AA}$, while significantly decreasing $v_{2}$; this observation is in agreement with our estimate provided in \cite{23}. Consequently, we see that this effect has large influence on $v_{2}$ predictions, confirming previous observations that $v_{2}$ observable is quite sensitive to medium evolution \cite{31,32}. On the other hand, this effect is rather small on $R_{AA}$, supporting the fact that $R_{AA}$ is not very sensitive to medium evolution. However, our observation from Figures 4 to 6 is that medium evolution effect on $R_{AA}$, though not large, should still not be neglected in precise $R_{AA}$ calculations, especially for high $p_{\perp}$ and higher centralities.
FIG. 2: Joint $R_{AA}$ and $v_2$ predictions for D mesons for $Pb + Pb$ collisions. Left panels: Theoretical predictions for $R_{AA}$ vs. $p_\perp$ are compared with 5.02 TeV $Pb + Pb$ ALICE [9] (red circles) D meson experimental data. Middle panels: Theoretical predictions for in-plane (dashed curves and green triangles for data) and out-of-plane (dot-dashed curves and blue triangles for data) $R_{AA}$ vs. $p_\perp$ are compared with 2.76 TeV $Pb + Pb$ ALICE D meson experimental data [10]. Right panels: Theoretical predictions for $v_2$ vs. $p_\perp$ are compared with ALICE D meson experimental data for 2.76 TeV [10] (green triangles) and 5.02 TeV [17] (red circles) $Pb + Pb$ collisions at the LHC. Rows 1-3 correspond, respectively, to 0–10%, 10–30% and 30–50% centrality regions. On each panel, the upper (lower) boundary of each gray band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

FIG. 3: Joint $R_{AA}$ and $v_2$ predictions for B mesons for $Pb + Pb$ collisions. Left panels: Theoretical predictions for $R_{AA}$ vs. $p_\perp$ are shown. Middle panels: Theoretical predictions for in-plane and out-of-plane $R_{AA}$ vs. $p_\perp$ are shown as dashed and dot-dashed curves, respectively. Right panels: Theoretical predictions for $v_2$ vs. $p_\perp$ are shown. Rows 1-3 correspond, respectively, to 0–10%, 10–30% and 30–50% centrality regions. On each panel, the upper (lower) boundary of each gray band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).
FIG. 4: Joint $R_{AA}$ and $v_2$ predictions for charged hadrons for 5.44 TeV Xe + Xe collisions. Theoretical predictions for $R_{AA}$ and $v_2$ vs. $p_{T}$ are shown on the left and the right panels, respectively. Rows 1-7 correspond, respectively, to 0 – 5%, 5 – 10%, 10 – 20%, ..., 50 – 60% centrality regions. Full and dashed curves correspond, respectively, to the predictions obtained with DREENA-B and DREENA-C frameworks. In each panel, the upper (lower) boundary of each gray band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

FIG. 5: Joint $R_{AA}$ and $v_2$ predictions for D mesons for 5.44 TeV Xe + Xe collisions. Theoretical predictions for $R_{AA}$ and $v_2$ vs. $p_{T}$ are shown on the left and the right panels, respectively. Full and dashed curves correspond, respectively, to the predictions obtained with DREENA-B and DREENA-C frameworks. Rows 1-3 correspond, respectively, to 0 – 10%, 10 – 30% and 30 – 50% centrality regions. On each panel, the upper (lower) boundary of each gray band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

FIG. 6: Joint $R_{AA}$ and $v_2$ predictions for B mesons for 5.44 TeV Xe + Xe collisions. The figure caption is the same as in the previous figure.
CONCLUSION

We here developed DREENA-B framework, which introduces medium evolution through 1+1D Bjorken expansion in computational suppression procedure based on our dynamical energy loss formalism. This presents a first step towards introducing more complex medium evolution in our model, in particular those corresponding to profiles coming from hydrodynamic and parton-transport calculations. Therefore, while our model previously contained a sophisticated description of high $p_T$ parton interactions with the QCD medium, it did not include the medium evolution at all. Therefore, DREENA-B framework is the first step towards developing a framework which will include both realistic descriptions of high $p_T$ parton medium interactions and of QCD medium evolution.

In the context of the goal stated above, the results presented here are encouraging. In particular, for both $Pb + Pb$ and $Xe + Xe$ collisions, we found that introducing the Bjorken evolution visibly impacts the predictions. Moreover, for $Pb + Pb$, where experimental data are already available, DREENA-B is able to well explain joint $R_{AA}$ and $v_2$ predictions. Since the other models, to our knowledge cannot achieve this without introducing new phenomena [57], this is a significant development in the context of $v_2$ puzzle. For $Xe + Xe$, we provide an extensive set of predictions for both $R_{AA}$ and $v_2$, for different flavors and centralities, to be compared with the upcoming experimental data. Reasonable agreement with these data would provide a strong argument that the dynamical energy loss formalism can provide a reliable tool for precision QGP tomography, which presents our major future goal.

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