

Heavy Flavour Energy Loss in Small and Large Systems

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Abstract. We present suppression results for high- p_T D and π mesons produced in $p/d + A$ and $A + A$ collisions at RHIC and LHC. These results are computed using a convolved elastic and radiative energy loss model, which receives small system size corrections to both the elastic and radiative energy loss. We observe that suppression in small systems is almost entirely due to elastic energy loss; furthermore, we find that our model is acutely sensitive to the transition between hard thermal loop and vacuum propagators in the elastic energy loss. Finally, we consider the central limit theorem approximation, which is commonly used to model the elastic energy loss distribution as Gaussian.

1 Introduction

Over the past decade, the observation of quark-gluon plasma (QGP) signatures in small collision systems has created considerable interest within the heavy-ion physics community. Traditional QGP signatures such as quarkonium suppression [1], strangeness enhancement [2], and elliptic flow [3]—typically associated with large heavy-ion collisions—have also been detected in small systems. These findings raise questions about whether QGP forms in even the smallest collision systems.

One of the most robust probes of QGP formation is jet quenching, often measured in terms of the nuclear modification factor R_{AB} for the collision $A + B$. This factor quantifies the degree of energy loss experienced by high- p_T partons as they traverse the medium. A measured $R_{AB} \sim 0.2$ for leading pions in central Au + Au collisions at RHIC [4] has been attributed to significant medium-induced partonic energy loss. By contrast, photons, which do not undergo strong interactions in the medium, exhibit $R_{AB} \sim 1$ [5].

In small systems, determining R_{AB} is more challenging due to centrality bias, leading to an ambiguous measured suppression pattern. Centrality bias refers to a non-trivial correlation between the hard and soft modes of the QGP, potentially leading to an inaccurate normalization for the R_{AB} . This issue is especially pronounced in small systems. LHC data from central $p + \text{Pb}$ collisions finds $R_{AB} \simeq 1\text{--}1.2$ for pions and D mesons [6, 7] at low- to moderate- p_T , suggesting no QGP formation. Conversely, PHENIX observes $R_{AB} \simeq 0.75$ in central $d + \text{Au}$ collisions, qualitatively consistent with QGP formation [8].

The situation on the theoretical front, however, has its own set of challenges. Theoretical energy loss models generally rely on approximations valid only for large systems. For instance, the Djordjevic-Gyulassy-Levai-Vitev (DGLV) framework for radiative energy loss [9] assumes a large pathlength L , neglecting terms proportional to $e^{-\mu L}$, where μ is the Debye

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mass. A *short pathlength correction* (SPL) has been derived that restores these terms [10]. Similar large system size assumptions appear in elastic energy loss models, which often assume a Gaussian energy loss distribution based on the central limit theorem, which is inapplicable in small systems [11]. In this work, we examine a more realistic Poisson distribution for elastic energy loss [11]—which is valid for all system sizes—and compare it to the Gaussian distribution at the level of R_{AB} . Furthermore we interrogate a particular uncertainty in the elastic energy loss, which stems from the transition between hard thermal loop (HTL) and vacuum propagators, by computing results with Braaten and Thoma (BT) elastic energy loss model [12] as well as with HTL-only elastic energy loss [11].

2 Results

We present a model for perturbative QCD energy loss which includes both radiative and elastic contributions. The radiative component is modelled using the DGLV framework, with and without short pathlength corrections (DGLV and DGLV+SPL) [9, 10]. For the elastic component, we compare results using BT [12], Gaussian HTL-only (Gauss. HTL), and Poisson HTL-only (Poiss. HTL) models [11]. Thermodynamic and geometrical quantities are calculated from IP-Glasma initial conditions [13] coupled with subsequent Bjorken expansion. A detailed description of the model may be found in our other works [14, 15].

In Fig. 1, we compare R_{AB} results for pions and D mesons produced in central Pb + Pb, Au + Au, p + Pb, and d + Au collisions at RHIC and LHC. Details are found in the caption of Fig. 1. There are six model results presented which are calculated by varying the radiative energy loss between the DGLV and the DGLV + SPL models, and separately the elastic energy loss between the BT, Poiss. HTL and Gauss. HTL models.

From Fig. 1, we first compare the R_{AB} calculated with the DGLV and DGLV + SPL radiative energy loss models to understand the impact of the SPL correction. Including the SPL correction greatly reduces the π^0 and h^\pm suppression, but only mildly reduces D meson suppression. This flavor-dependence is due to the SPL correction being significantly larger for gluons compared to quarks, over and above the usual $C_A/C_F = 9/4$ colour scaling [10, 14]. We also observe that the magnitude of the SPL correction grows in p_T , which is due to the different asymptotics of DGLV and DGLV + SPL: $\Delta E_{\text{DGLV}} \sim \ln E$ and $\Delta E_{\text{DGLV} + \text{SPL}} \sim E$ respectively [10]. The \sqrt{s} dependence of the SPL correction is due primarily to the larger proportion of gluons which fragment to pions at LHC compared to RHIC [15] and the larger experimentally accessible p_T range. Finally, we observe that the SPL correction is fractionally larger in small systems compared to larger systems due to the $e^{-\mu L}$ scaling of the SPL correction [10, 14].

In Fig. 1, we additionally compare the R_{AB} calculated with the BT and Gauss. HTL elastic energy loss models, which is sensitive to the uncertainty in the transition between HTL and vacuum propagators. We observe that this uncertainty leads to an $O(30\text{--}80)\%$ effect in large systems and an $O(20\text{--}40)\%$ effect in small systems. Finally, we compare the Poiss. HTL and Gauss. HTL results to understand the effect of the commonly used central limit theorem approximation. We observe that this effect is $O(5\text{--}10)\%$ in large systems and $< 2\%$ in small systems. This agreement between Poisson and Gaussian results cannot be attributed to convergence under the central limit theorem, as one would expect the results to align more closely in larger systems than in smaller ones. In actuality, the agreement is because the R_{AB} in small systems depends mostly on the zeroth and first moments of the elastic energy loss distributions—which are constrained to be the same for Gaussian and Poisson distributions—while in large systems the radiative energy loss dominates over the elastic [15]. The Poisson and Gaussian results are more similar at LHC energies because the steeper production spectrum at RHIC makes higher-order moments more important than at LHC.

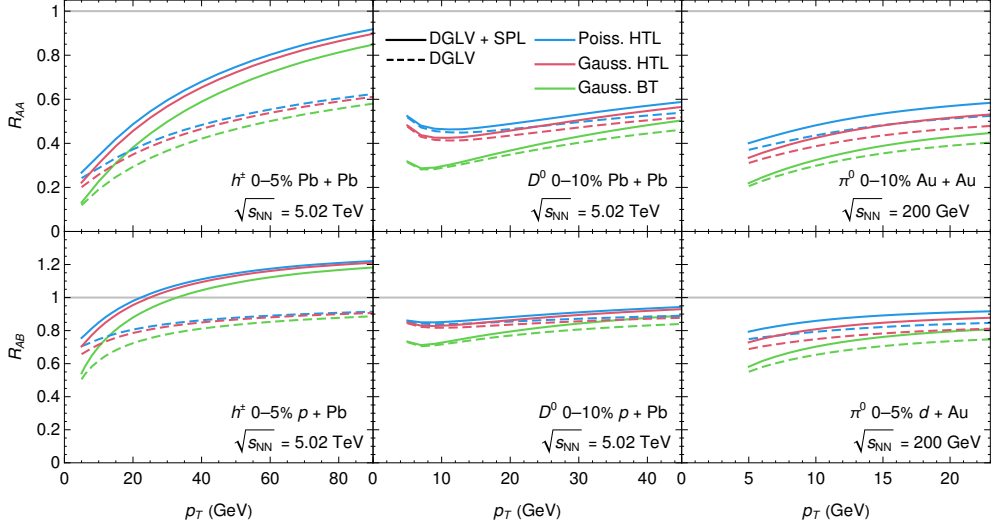


Figure 1. The top row displays R_{AA} results from our model for charged hadrons produced in 0–5% centrality Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV; D^0 mesons produced in 0–10% centrality Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV; and neutral pions produced in 0–5% centrality Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The bottom row shows R_{AB} for charged hadrons produced in 0–5% centrality $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV; D mesons produced in 0–10% centrality $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV; and neutral pions produced in 0–5% $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Model results are produced by varying the radiative energy loss between the DGLV [9] and DGLV + SPL models [10], and separately the elastic energy loss between the BT [12], Gauss. HTL, and Poiss. HTL models [11].

3 Conclusions

We have presented suppression results for high- p_T D and π mesons produced in $p/d + A$ and $A + A$ collisions at RHIC and LHC, from a model which receives small system size corrections to both the radiative and elastic energy loss. We found that an uncertainty in the transition between HTL and vacuum propagators in the elastic energy loss imparts a $O(40\text{--}80)\%$ uncertainty on the R_{AB} for all systems and final states at low- to moderate- p_T . Furthermore, we found that the application of the central limit theorem to model the elastic distribution as Gaussian produced a negligible effect at the level of the R_{AB} , particularly so in small systems. We attributed this to the fact that for small suppression the R_{AB} depends mostly on the zeroth and first moments of the elastic energy loss, which are constrained to be identical for Gaussian and Poisson distributions, while for larger momenta radiative energy loss dominates.

Future work may involve fitting the strong coupling α_s to data to determine whether observed small and large system suppression can be simultaneously described by a single model. Additionally, one may further analyse the sensitivity to various uncertainties in elastic and radiative energy loss, including the large formation time assumption, which we previously found was not satisfied self-consistently in the DGLV model [14, 16]. Moreover, placing energy loss models on a more rigorous theoretical foundation could involve carefully treating the kinematics [17], computing the scales at which the coupling runs at finite temperature and system size, and understanding the validity of various approximations in the calculations [18]. Lastly, investigating QGP formation in small systems may also include examining the impact

of small system size on the coupling [19], thermodynamics [20], the equation of state [21], and jet substructure observables [22].

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