Energy Loss in Small Quark Gluon Plasmas

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Abstract. The Quark Gluon Plasma (QGP) is a novel state of matter which last occurred naturally only microseconds after the Big Bang. It is well understood that the QGP is formed in heavy-ion collisions at particle colliders such as the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC); however, more recently there have been experimental signatures of QGP formation in small systems including proton heavy-ion and even proton proton collisions. We present a model for energy loss of high momentum particles based on perturbative Quantum Chromodynamics (pQCD), which includes small system size corrections to both the collisional and radiative energy loss. We make quantitative comparisons with suppression measurements of pions produced in central $p + \mathrm{Pb}$ and $\mathrm{Pb} + \mathrm{Pb}$ collisions at the LHC, and $d + \mathrm{Au}$ and $\mathrm{Au} + \mathrm{Au}$ collisions at RHIC. We discuss an uncertainty present in our model in the elastic energy loss sector, which is related to the crossover between Hard Thermal Loop (HTL) and vacuum propagators. Finally, we consider the applicability of the central limit theorem which is typically used to approximate the elastic energy loss distribution as a Gaussian distribution.

1. Introduction

Hard probes, including jets and leading hadrons, are crucial in studying the Quark Gluon Plasma (QGP) formed in heavy-ion collisions at RHIC and the LHC. The nuclear modification factor R_{AB} for the collision system $A + B$ captures the modification of high-p_T hadron spectra due to in-medium energy loss. Measurements of $R_{AB} \sim 0.2$ for leading hadrons in central Au+Au [1, 2] and Pb+Pb [3] collisions, compared to $R_{AB} \simeq 1$ for weakly interacting controls [4, 5, 6], provide strong evidence of medium modifications. This suppression in $A + A$ collisions, contrasted with $R_{AB} \simeq 1$ in minimum bias $d + \mathrm{Au}$ [7, 8] and $p + \mathrm{Pb}$ [9] collisions, suggests significant final state energy loss for partons. Recent observations of collective QGP signatures in high and low multiplicity $p + p$ [10, 11], $p + \mathrm{Pb}$ [12, 13, 14] and $p/d/{}^3\mathrm{He} + A$ [15, 16, 17, 18, 19] collisions, consistent with hydrodynamic model predictions [20, 21], suggest QGP formation even in these small collision systems. However, a consistent picture of nuclear modification across system sizes and $\sqrt{s}$ remains elusive, with qualitatively different R_{AB} results observed at RHIC and LHC for small systems [22, 23, 24].

Applying existing theoretical models to small systems presents challenges. Many assumptions underlying pQCD-based energy loss models may not be applicable in small collision systems [25]. These include dropping terms exponentially suppressed by system size in opacity expansion approaches [26, 27, 28, 29], assuming a large number of collisions for BDMPS-Z based models [29, 30], and modelling elastic energy loss probability distributions as Gaussian [31, 32, 33].

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Here, we focus on uncertainties and approximations in the elastic energy loss sector, including the modelling of the elastic energy loss distribution as Gaussian and the uncertainty in the crossover between HTL and vacuum propagators.

This work utilizes an elastic energy loss kernel [34] derived from Hard Thermal Loop formalism, keeping full kinematics of hard exchanges. We present model results for the nuclear modification R_{AB} of pions in both large $\mathrm{Au}+\mathrm{Au}$ and $\mathrm{Pb}+\mathrm{Pb}$ collisions, as well as small $p+\mathrm{Pb}$ and $d+\mathrm{Au}$ collisions at the LHC and RHIC. Various theoretical predictions are produced by varying elastic and radiative energy loss models to understand the effects of the central limit theorem approximation, and the uncertainty in the elastic energy loss due to the crossover region between HTL and vacuum propagators. Heavy-flavour model results, as well as semi-central and peripheral $\mathrm{Pb}+\mathrm{Pb}$ and $\mathrm{Au}+\mathrm{Au}$ model results are presented in detail in [35].

2. Energy Loss Framework

The energy loss model presented in this work incorporates elastic and radiative energy loss, realistic collision geometry, and realistic production spectra and fragmentation functions. Our energy loss model is described in detail in our previous works [25, 35], and we summarize the components important for this work briefly here. The radiative energy loss is calculated according to the Djordjevic-Gyulassy-Levai-Vitev (DGLV) model [27], as well as the DGLV model which receives a short pathlength correction (DGLV + SPL) [36]. In our previous work we performed an in-depth investigation of the phenomenological impact of the SPL correction where we found that: it produced a fast rise of the pion R_{AB} in p_T in central $\mathrm{Pb}+\mathrm{Pb}$ collisions, qualitatively consistent with data [24], and an $R_{pA} \simeq 1.2$ at high-p_T consistent with $p_T \gtrsim 50$ GeV $p+\mathrm{Pb}$ data [37]. However, upon a thorough investigation of the self-consistency of various assumptions in the model we found that a particular assumption in the model—the large formation time assumption—was breaking down in small systems and at high momenta. A phenomenological solution to the breakdown in consistency of the large formation time assumption was discussed in [25, 38], which involves restricting the phase space so that no contributions are received from regions where the large formation time assumption is invalid. Future work will explore this in more detail.

The novel subject of this work is the investigation of a fundamental uncertainty in the elastic energy loss, which enters as an ambiguity in the crossover region between vacuum and Hard Thermal Loop (HTL) propagators. The elastic energy loss is calculated in two different ways which allows us to interrogate this uncertainty. The Braaten and Thoma (BT) [39] elastic energy loss model uses vacuum propagators at high momentum transfer and HTL propagators at low momentum transfer, and the Wicks HTL approach (HTL) [34] uses HTL propagators for all momentum transfers. While in the limit of large momentum transfers both the HTL and vacuum propagators are the same, one is sensitive to the precise way in which this crossover occurs. These two results are two extreme cases which capture this uncertainty. In this work we model the elastic energy loss distributions as Gaussian with a width determined according to the fluctuation dissipation theorem [32] and the radiative distributions as Poisson [40]. We additionally model the HTL elastic energy loss distribution as both Poisson and Gaussian, which allows us to assess the validity of the Gaussian approximation.

The elastic and radiative energy loss distributions are convolved together to produce the total energy loss distributions. The total energy loss may then be averaged according to the collision geometry, which is derived from event-by-event varying IP-Glasma initial conditions [21], and evolved according to Bjorken expansion. Finally, we may compute the nuclear modification factor or R_{AB} according to

$$R^h_{AB}(p_T) \equiv \frac{\mathrm{d}N^{AB\to h}/\mathrm{d}p_T}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N^{pp\to h}/\mathrm{d}p_T}, \tag{1}$$

where $N_{\rm coll}$ is the number of binary collisions in the collision geometry, and $\mathrm{d}N^{AB\to h}/\mathrm{d}p_T(\mathrm{d}N^{pp\to h}/\mathrm{d}p_T)$ is the differential number of h hadrons produced in the collisions $A+B(p+p)$. A measured $R_{AB} \ll 1$ indicates significant final state effects.

3. Results

We present original model results for nuclear modification R_{AB} of pions produced in both central large Au + Au and Pb + Pb collisions, as well as central small p + Pb and d + Au collisions at the LHC and RHIC. Six theory curves are generated by varying the elastic energy loss between Poisson HTL, Gaussian HTL [34], and Gaussian BT [39] and the radiative energy loss between DGLV [27] and DGLV + SPL [36]. We note that quantitative agreement with data is not the purpose of this work, and all results are produced with a fixed coupling $\alpha_s = 0.3$. In the future a more quantitative analysis will be performed by globally fitting the value of α_s, which will allow quantitative conclusions to be drawn on the consistency of suppression in small and large systems.

Fig. 1 shows R_{AB} as a function of p_T for neutral pions produced in 0–10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left) and 0–5% most central Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right). Data from PHENIX [41, 42] (left) and ATLAS [24], CMS [43], and ALICE [44] (right) are shown for comparison. We observe that our results are under suppressed with respect to data, indicating that a larger effective coupling α_s is needed to predict observations.

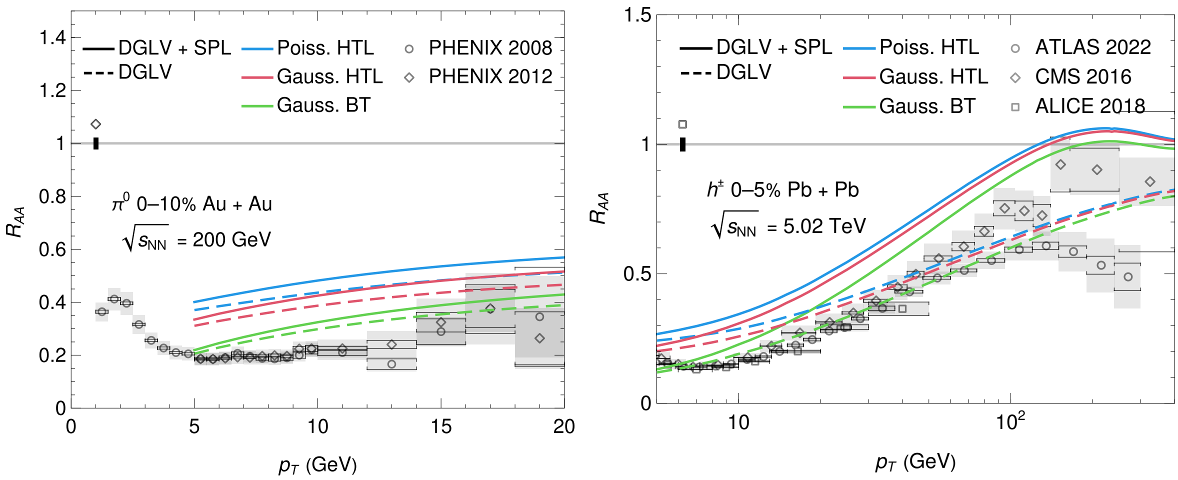

Figure 1. Nuclear modification factor R_{AB} as a function of p_T for neutral pions produced in 0–10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left) and 0–5% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right). Theoretical predictions are produced for pions through our convolved radiative and elastic energy loss model, by varying the elastic model between Gaussian BT [47, 39], Gaussian HTL, and Poisson HTL [34] and the radiative model between DGLV [27] and DGLV + SPL [36, 45]. Data from PHENIX [41, 42] for Au + Au collisions are shown (left) and from CMS [43], ATLAS [24], and ALICE [44] for Pb + Pb collisions (right). Statistical uncertainties are indicated by square brackets, systematic uncertainties by shaded rectangles, and global normalization uncertainties by solid bars around $R_{AB} = 1$.

Comparing predictions made with the Gaussian HTL and Gaussian BT elastic energy loss kernels, we see that we are extremely sensitive to this uncertainty in the elastic energy loss; the ratio of the two curves being $\mathcal{O}$(50–100%) for $p_T \lesssim 20$ GeV. At higher p_T this sensitivity decreases dramatically, which is due to the decreasing fraction of elastic vs. radiative energy loss. Comparing the DGLV and DGLV + SPL results, we observe that the SPL correction is

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much smaller at RHIC compared to the LHC. The SPL correction grows as a function of p_T and is much larger for gluons than for quarks [45, 25]. The small effect of the SPL correction at RHIC compared to the LHC is, therefore, because of the lower maximum momentum and higher fraction of light quarks compared to gluons [46] at RHIC energies compared to LHC energies.

Comparing predictions made with the Poisson HTL and Gaussian HTL elastic energy loss models, we see that these results are extremely similar–paradoxically so in small systems. If the agreement between these two results was because of the convergence of the Poisson distribution to a Gaussian according to the central limit theorem, then we would expect the opposite system size dependence. We explain this unintuitive result in [35], where we find that the reason the Gaussian and Poisson result are similar is because they are constrained to have identical zeroth and first moments. When there is a small amount of energy loss—as there is in small systems—only the zeroth and first moments are important in calculating the R_{AB}. The results calculated with Gaussian HTL and Poisson HTL converge at high-p_T because the contribution of the elastic energy loss decreases relative to the radiative energy loss [35].

Fig. 2 shows R_{AB} as a function of p_T for charged hadrons produced in 0–10% most central $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV (left) and neutral pions produced in 0–5% most central $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV (right). We observe a similar degree of sensitivity to the choice of elastic energy loss kernel as in the large collision systems, although this is misleading. One may approximate [31, 35] the R_{AB} for small energy loss as $R_{AB} \simeq 1 - n\Delta E/E$, for a constant production spectrum $dN/dp_T \sim p_T^{-n}$. From this we see that the sensitivity at the level of the energy loss $\Delta E \simeq (1 - R_{AB})/n$ is $\mathcal{O}$(80–100%)—much larger than that in large systems. This is because elastic energy loss is the dominant energy loss mechanism in small systems, which stems from the different length L dependencies of elastic vs. radiative energy loss: L and L^2 respectively. As in Fig. 1, we see that the SPL correction is small in collisions at RHIC compared to the LHC. In $p + \text{Pb}$ collisions, we see that the results from the SPL correction are qualitatively compatible with data for $p_T \gtrsim 50$ GeV; however the results for

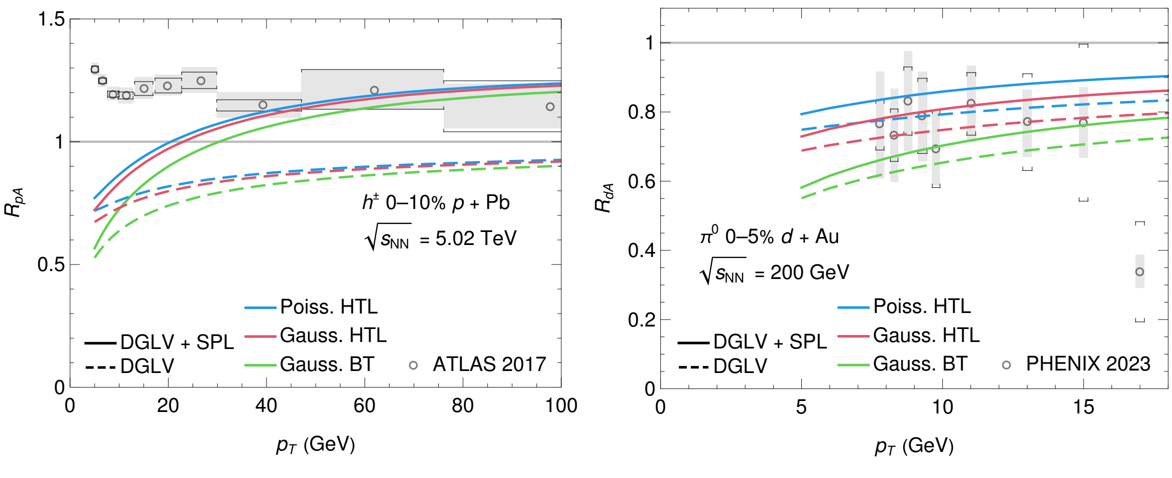

Figure 2. Nuclear modification factor R_{AB} as a function of p_T for charged hadrons produced in 0–10% most central $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV (left) and neutral pions produced in 0–5% most central $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV (right). Theoretical predictions for pions are produced through our convolved radiative and elastic energy loss model, by varying the elastic model between Gaussian BT [47, 39], Gaussian HTL, and Poisson HTL [34] and the radiative model between DGLV [27] and DGLV + SPL [36, 45]. Data from ATLAS [37] for $p + \text{Pb}$ collisions are shown and from PHENIX [23] for $d + \text{Au}$ collisions. Statistical uncertainties are indicated by square brackets, and systematic uncertainties by shaded rectangles.

$p_T \lesssim 30$ GeV is dramatically inconsistent with data. We conclude that neither the inclusion of the SPL correction to radiative energy loss nor the uncertainty in the elastic energy loss can explain the lack of suppression in $p+\text{Pb}$ collisions at the LHC. In the right panel of Fig. 2 we see that all model curves are compatible with suppression data from $d+\text{Au}$ collisions at RHIC. We note that a crucial difference between the PHENIX [23] and ATLAS [37] data is the method of normalization. The ATLAS data use the Glauber model, as is standard in heavy-ion collisions, while the PHENIX data use the high-p_T photon spectrum to generate a self-normalized R_{AB}. In small systems it is likely that nontrivial correlations between the high and low momentum parts particles in the collision lead to an incorrect normalization of the R_{AB} ratio. The ATLAS result is sensitive to such a bias while the PHENIX result is significantly less sensitive.

4. Conclusions

We have presented novel results for the nuclear modification factor R_{AB} for pions produced central $p + \text{Pb}$ and $\text{Pb} + \text{Pb}$ collisions at the LHC and $d + \text{Au}$ and $\text{Au} + \text{Au}$ collisions at RHIC. These results were produced with our energy loss model [25, 35] which includes small system size corrections [36] to the radiative energy loss, and includes realistic production spectra, fragmentation functions, and collision geometry [21]. We have expanded our model to include two elastic energy loss kernels—Braaten and Thoma [39] and Wicks HTL [34]—which allowed us to assess the degree of uncertainty present in the elastic sector of the model.

We saw that the uncertainty in the elastic energy loss is $\mathcal{O}(50\text{–}100\%)$ for $p_T \lesssim 20$ GeV for $A + A$ collisions, and $\mathcal{O}(80\text{–}100\%)$ in $p/d + A$ collisions. We found that the SPL correction to radiative energy loss is significantly smaller in collisions at RHIC compared to the LHC, owing to the smaller maximum momenta and the higher proportion of quarks vs. gluons at RHIC compared to the LHC. We saw that the SPL correction describes qualitatively well the fast growth of the pion R_{AB} in p_T in central $\text{Pb} + \text{Pb}$ collisions, as well as the $R_{pA} \simeq 1.2$ of pions in $p + A$ collisions. However, the $R_{pA} \simeq 0.5\text{–}0.8$ for $p_T \lesssim 20$ GeV predicted with our model is incompatible with the measured $R_{pA} \simeq 1.2$ for the same p_T range.

We found that while RHIC $\text{Au} + \text{Au}$ and $d + \text{Au}$ data could be simultaneously qualitatively described by all theoretical variations of our model, the lack of measured suppression at the LHC in $p + \text{Pb}$ collisions could not be reconciled with the measured suppression in $\text{Pb} + \text{Pb}$ collisions.

Future work should make this qualitative analysis more quantitative by tuning the strong coupling α_s to measured suppression in large system, and from there infer whether small and large system suppression data is compatible under the hypothesis that QGP forms in these small systems. Work is needed to remove or reduce the uncertainty in the crossover between HTL and vacuum propagators in the elastic energy loss, and the uncertainty from the large formation time assumption. Additionally, a more careful treatment of the geometry of the collisions, especially in how this effects small systems, will be crucial. Other important work in understanding suppression in small systems may include derivations of finite size effects from first principles [48, 49], studying of substructure observables in small systems [50], and studying minimum bias collisions to avoid centrality bias [51].

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