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Studying the (pre)equilibrium stage using high-$p_\perp$ partons

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The pre-equilibrium and equilibrium stages of the heavy-ion collisions are studied using the high-$p_\perp$ sector. The high-$p_\perp$ observables are computed using the dynamical energy loss formalism DREENA and compared with the experimental data to put constraints on the early evolution and the bulk medium properties.

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1. Introduction

Quark-Gluon Plasma (QGP), an extreme form of matter consisting of deconfined quarks, antiquarks and gluons, existed just after Big Bang. Today, it is produced in the ultra relativistic heavy-ion collision (HIC) experiments at the Relativistic Heavy Ion Collider (RHIC), BNL and the Large Hadron Collider (LHC), CERN. Traditionally, low-$p_\perp$ particles ($p_\perp \lesssim 5$ GeV) are used to study QGP properties, but the underutilized high-$p_\perp$ sector offers a valuable tool for probing QGP properties. Furthermore, some important bulk properties of the medium are difficult to constrain from the low-$p_\perp$ data/theory [1–4]. Therefore, high-$p_\perp$ theory and experimental data [5–10] can be used as a complimentary tool to explore the bulk properties of QGP. The energy loss of the rare light and heavy flavor high-$p_\perp$ particles [11] while traversing through QGP, provide insights into QGP bulk properties. Moreover, since the QGP properties depend on initial states, high-$p_\perp$ theory can be effectively utilized to infer knowledge about the initial stages before QGP thermalization.

With this goal in mind, the state-of-the-art dynamical jet energy loss formalism is developed that includes various important effects: i) It is based on finite temperature field theory and takes into account dynamical and finite size medium, ii) it includes both radiative [12] and collisional [13] energy loss, iii) applicable for both light and heavy flavors, iv) it has been generalized to the case of finite magnetic mass [14] and running coupling [15], and (v) there is no fitting parameter. This energy loss formalism has been incorporated in the numerical framework 'DREENA' (Dynamical Radiative and Elastic ENergy loss Approach) which includes initial $p_\perp$ distribution of the high energy partons, energy loss with path length and multi gluon fluctuations, and fragmentation functions, to produce the final medium modified distribution of high-$p_\perp$ hadrons. Initially, 'DREENA-C' [16] was developed where 'C' represents constant temperature medium. It was able to present joint theoretical predictions for R_{AA} and v_2 in 2.76 TeV and 5.02 TeV Pb+Pb collisions for both light and heavy flavors, which solved the long standing v_2 puzzle [17]. However, v_2 predictions from DREENA-C slightly overestimated the data. The introduction of 1D Bjorken medium evolution in 'DREENA-B' [18] resolved this discrepancy of v_2 predictions. Furthermore, to include more realistic scenario, the arbitrary temperature evolution has been incorporated in 'DREENA-A' [19]. The event-by-event fluctuation of the initial states has been introduced in 'generalized DREENA-A' [20]. In the following sections, we elaborate on the initial states of HIC and QGP properties as investigated using DREENA.

2. Pre-equilibrium stage of heavy-ion collisions

To constrain the initial stages using DREENA high-$p_\perp$ predictions and the experimental data [21], we consider the four common cases of initial stages before thermalization, which assume the same 1D Bjorken evolution after thermalization at $\tau = \tau_0 = 0.6$ fm: (i) $T = 0$, the free streaming case with no energy loss before τ_0, (ii) the linearly increasing T from $T_C = 160$ MeV at $\tau_C = 0.25$ fm to τ_0, (iii) the constant case with $T = T_0$, and (iv) the divergent case that corresponds to 1D Bjorken expansion from $\tau = 0$. It is clear that the prethermal interactions increase from (i)-(iv) which would result in decreasing R_{AA}. That is indeed the case as can be seen from the Fig. 1. However, the error bars at the LHC did not allow distinguishing these differences. On the other hand, it is found that high-$p_\perp$ v_2 is not sensitive to the initial stages [21]. The results are taken from Ref. [21].

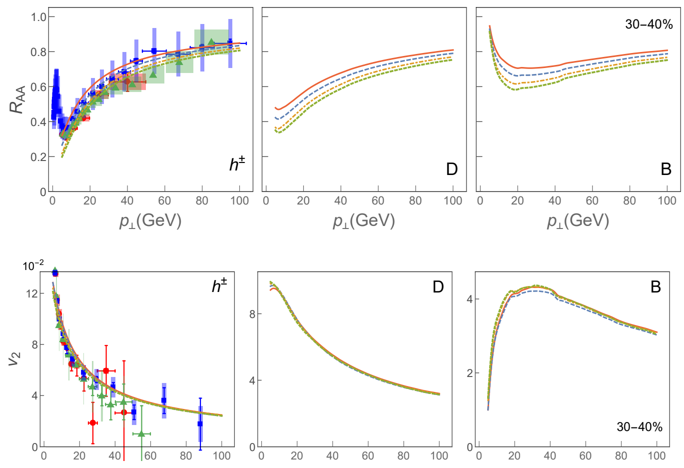

Figure 1: Dependence of R_{AA} (upper panel) and high-$p_\perp$ v_2 (lower panel) on $p_\perp$ for charged hadrons (left), D mesons (central) and B mesons (right panel) at 30-40% centrality bin and $\mu_M/\mu_E = 0.5$ are shown and compared with 5.02 TeV Pb+Pb ALICE [22, 23] (red circles), ATLAS [8, 24] (green triangles), and CMS [5, 9] (blue squares). The red, blue, orange and green curves represent the cases (i)-(iv) respectively. The figure is taken from Ref. [21].

Furthermore, DREENA-A, which takes into account the realistic (arbitrary) temperature evolution, has been utilized to constrain QGP anisotropy [25] and the early evolution [26]. Here we consider four initial stage cases: (i) the hydrodynamical evolution starts at $\tau_0 = 0.2$ fm and the energy loss starts at the same time (τ_q), (ii) $\tau_0 = 0.2$ fm, but the energy loss starts later at $\tau_q = 1.0$ fm, (iii) we allow free streaming until $\tau_0 = 1.0$ fm. The jet medium interaction starts at $\tau_0 = \tau_q = 1.0$ fm, and (iv) we consider that 'nothing' happens until the fluid dynamical initial time $\tau_0 = \tau_q = 1.0$ fm. While computing the high-$p_\perp$ observables using DREENA-A, it is ensured that all the cases are compatible with the low-$p_\perp$ observables. After computing the nuclear supression factor R_{AA} and the high-$p_\perp$ v_2, we compare the results with the experimental data. In Fig. 2, we see that R_{AA} increases with the decreasing interactions which is consistent with our previous findings using DREENA-B in Fig. 1. On the other hand, v_2 exhibits an interesting behavior. The first two cases, where the fluid dynamical evolution starts at very early stage, yield nearly identical v_2, deviating significantly from the data. Additionally, the free-streaming case fails to align with the data as early free-streaming washes out the anisotropy of the medium. The only case which approach the data involves delayed energy loss and evolution until $\tau = 1.0$ fm. Therefore, it is evident that the high-$p_\perp$ data does not support the initial free streaming assumption. The results are taken from Ref. [26].

3. Equilibrium properties of the QCD matter

The energy loss of the jets in the QCD matter depends on the temperature of the medium which makes it an excellent probe of the medium properties. The jet transport coefficient ($\hat{q}$) can be computed from the jet medium elastic collision rate. Further, in the weak coupling limit, the specific shear viscosity (η/s) of the medium can be calculated from $\hat{q}$ using the following equation [27, 28]: $\frac{\eta}{s} \approx 1.25\frac{T^3}{\hat{q}}$. The η/s computed from our energy loss formalism is plotted in Fig. 3 where the green band represents the initial jet energy range 3 GeV $< E <$ 10 GeV. As we consider weakly coupled system in our formalism, it is anticipated that our inferred η/s aligns well

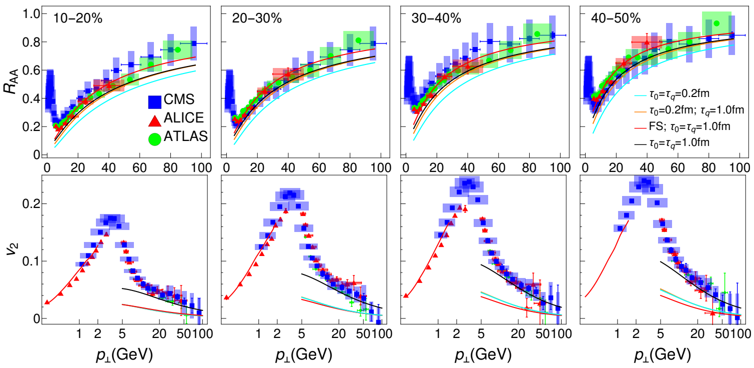

Figure 2: Charged hadron R_{AA} (upper panel) and high-$p_\perp$ v_2 (lower panel) predictions are shown with $p_\perp$ at different centrality bins and compared to the ALICE [22, 23], CMS [5, 9] and ATLAS [8, 24] data. The figure is taken from Ref. [26].

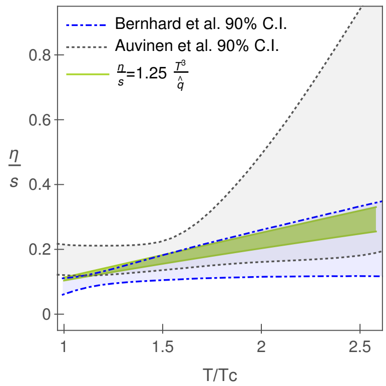

Figure 3: Comparison of our inferred η/s with the 90% credible intervals of the Bayesian analyses of Refs. [4, 29]. The figure is taken from Ref. [30].

with the Bayesian analysis results (depicted by the other bands) at high temperatures. Notably, our results [30] show a narrower band compared to Bayesian analysis, providing more stringent constraints on η/s at high temperatures where Bayesian constraints are the weakest. However, the consistency of our η/s values with those obtained through Bayesian analysis, extending down to the transition temperature, raises the possibility that the quasiparticle picture may remain valid even in the strongly coupled region [30]. Nevertheless, additional investigations are necessary to validate this theoretical interpretation. The results are taken from Ref. [30].

4. Summary

The state-of-the-art dynamical energy loss formalism (DREENA) has been utilized to constrain the early evolution and the bulk medium properties in the heavy-ion collisions. It is found that R_{AA} is sensitive to the initial stages and tends to decrease when the jet medium interaction starts early. It is also observed using DREENA-A, where the early onset of energy loss led to the lowest R_{AA}. Our notable finding indicates that high-$p_\perp$ v_2 does not support the early free-streaming assumption. Instead, it favors scenarios where medium evolution and energy loss are delayed. Additionally, we computed the η/s of the medium from our energy loss formalism which has strong constraint at high temperature compared to the Bayesian analysis results.

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