Early evolution constrained by high-$p_{\perp}$ QGP tomography

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We show that high-$p_{\perp}$ $R_{AA}$ and $v_2$ are sensitive to the early expansion dynamics, and that the high-$p_{\perp}$ observables prefer delayed onset of energy loss and transverse expansion. To calculate high-$p_{\perp}$ $R_{AA}$ and $v_2$, we employ our newly developed DREENA-A framework, which combines state-of-the-art dynamical energy loss model with 3+1-dimensional hydrodynamical simulations. The model applies to both light and heavy flavor, and we predict a larger sensitivity of heavy flavor observables to the onset of transverse expansion. This presents the first time when bulk QGP behavior has been constrained by high-$p_{\perp}$ observables and related theory, i.e., by so-called QGP tomography.

Quark-Gluon-Plasma (QGP) [1, 2] is an extreme form of matter that consists of interacting quarks, antiquarks and gluons. This state of matter is formed in ultrarelativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). When analyzing the heavy-ion collision data, the particles formed in these collisions are traditionally separated into high-$p_{\perp}$ (rare hard probes) and low-$p_{\perp}$ particles (bulk, consisting of 99.9% of particles formed in these collisions).

The QGP properties are traditionally explored by low-$p_{\perp}$ observables [3-6], while rare high-$p_{\perp}$ probes are, almost exclusively, used to understand the interactions of high-$p_{\perp}$ partons with the surrounding QGP medium. High-$p_{\perp}$ physics had a decisive role in the QGP discovery [7], but it has been rarely used to understand bulk QGP properties. On the other hand, some important bulk QGP properties are difficult to constrain by low-$p_{\perp}$ observables and corresponding theory/simulations [8-11]. We are therefore advocating QGP tomography, where bulk QGP parameters are jointly constrained by low-$p_{\perp}$ and high-$p_{\perp}$ physics.

During the last few years, our understanding of the very early evolution of QGP has evolved a lot. In particular the discovery of the attractor solutions of the evolution of non-equilibrated systems [12-14], and models based on effective kinetic theory [15, 16] have been significant milestones. However, the exact dynamics of early evolution and hydrodynamization of the medium—i.e. the approach to the state where the system can be described using fluid dynamics—are not settled yet. Furthermore, to our knowledge, there are no reliable methods to calculate jet energy loss in a medium out of equilibrium. Instead of microscopic calculation of the early-time dynamics, we take a complementary approach in this paper. We calculate the high-$p_{\perp}$ $R_{AA}$ and $v_2$ in a few straightforward scenarios, and show what constraints to the early evolution can be obtained from comparison to high-$p_{\perp}$ data.

In the attractor solutions, the final evolution is fluid dynamical even if the initial state is quite far from equilibrium. This allows us to entertain the notion that even if the early state is not in local equilibrium, we could use fluid dynamics to describe its evolution from very early times [17], say from $\tau_0 = 0.2$ fm, where $\tau_0$ is the initial time of fluid dynamical evolution. Correspondingly, we may argue that the temperature entering fluid dynamical evolution controls also jet energy loss, and we may start the jet energy loss at the same time, $\tau_q = 0.2$ fm. On the other hand, we had studied the pre-equilibrium energy loss in various scenarios [18], and seen that even if the data could not properly distinguish these scenarios, Bjorken-type temperature evolution at very early times tended to push $R_{AA}$ too low. This may suggest that applying the equilibrium jet-medium interactions to the pre-equilibrium stage (even if close enough to fluid dynamical) overestimates the energy loss. Due to this, we here, for simplicity, assume an opposite limit, where we start the energy loss later than the fluid dynamical evolution: $\tau_q = 1.0$ fm and $\tau_0 = 0.2$ fm [54].

Frequently used toy model to study the effects of early non-equilibrium evolution is the free streaming approach [19, 20], where (fictional) particles are allowed to stream freely until the initial time of fluid dynamical evolution $\tau_0$. As our third scenario, we allow free streaming until $\tau_0 = 1.0$ fm. Consistently with the assumed absence of interactions in the bulk medium, we assume no jet-medium interactions during the out-of-equilibrium stage, so that $\tau_0 = \tau_q = 1.0$ fm. For comparison’s sake, we also explore the “old-fashioned” scenario where “nothing” happens before the fluid dynamical initial time $\tau_0 = \tau_q = 1.0$ fm, i.e. we start the fluid-dynamical evolution at $\tau = 1.0$ fm with zero transverse flow velocity.

When calculating how the high-$p_{\perp}$ observables depend on our different scenarios we have to ensure that the QGP medium evolution is compatible with the observed distributions of low-$p_{\perp}$ particles. We describe the medium evolution using the 3+1-dimensional viscous hydrodynamical model [24]. For simplicity, we choose a constant shear viscosity to entropy density

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The overall agreement with the data is acceptable. 

The switch from massless non-interacting particles to strongly interacting constituents of QGP causes large positive bulk pressure at \( \tau_0 \). In our calculations bulk viscosity coefficient is always zero, and the initial bulk pressure at \( \tau_0 \) strongly interacting constituents of QGP causes large positive bulk pressure at \( \tau_0 \). Strongly interacting constituents of QGP causes large positive bulk pressure at \( \tau_0 \), and the initial bulk pressure at \( \tau_0 \). The parameters \( C_{\epsilon}, c_1 \) and \( c_2 \) are tuned separately for each scenario, to approximately describe the observed charged particle multiplicities and \( \varepsilon \) in Pb+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV. For the longitudinal profile, we keep the parametrization used for \( \sqrt{s_{NN}} = 2.76 \) Pb+Pb collisions \( ^{22} \). The energy-momentum tensor based on the distribution of both radiative \( ^{25} \) and collisional \( ^{26} \) energy loss in the same theoretical framework. iii) Calculations of both radiative \( ^{25} \) and collisional \( ^{26} \) energy loss framework. iv) Generalization towards running coupling \( ^{33} \), finite magnetic mass \( ^{35} \). All of these features are necessary for accurate predictions \( ^{33} \), but utilizing evolving temperature profiles is highly non-trivial within this complex energy loss framework.

We use the same parameter set to generate high-\( p_T \) predictions as in our earlier studies within DREENA-C \( ^{39} \) and DREENA-B \( ^{37} \) frameworks. The resulting DREENA-A predictions for charged hadron \( R_{AA} \) and \( v_2 \) in four different centrality classes, and four scenarios of early evolution, are shown in Fig. 2 and compared with experimental data. As one can expect, the later the energy loss begins, the higher the \( R_{AA} \) and evaluating the energy loss as in thermalized medium already at \( \tau_0 = 0.2 \) fm is slightly disfavored. Furthermore, early free-streaming evolution leads to larger \( R_{AA} \) than fluid-dynamical evolution. On the other hand, the behavior of \( v_2 \) is different. First, if the early expansion is fluid dynamical, we see that delaying the onset of energy loss hardly changes \( v_2 \) at all. Second, early free-streaming evolution does not lead to better reproduction of the data, but, in peripheral collisions, the fit is even worse. The only case when our \( v_2 \) predictions approach the data, is when both the jet energy loss and the transverse expansion are delayed to \( \tau = 1 \) fm!

As shown in Fig. 3, heavy quarks are even more sensitive to the early evolution. For bottom probes, the data are largely not available, making these true predictions. For charm probes, the available experimental data are much more sparse (and with larger error bars) than the charged hadron data. However, where available, comparison of our predictions with the data sug-
suggests the same preference towards delayed energy loss and transverse expansion as charged hadrons. These results are important, as consistency between light and heavy flavor is crucial (though highly non-trivial, as
e.g. implied by the well known heavy flavor puzzle [38] for studying the QGP properties.

To investigate the origin of the sensitivity of $R_{AA}$ and $v_2$ to the early evolution, we evaluate the temperature along the paths of jets traveling in-plane ($\phi = 0$) and out-of-plane ($\phi = \pi/2$) directions, and average over all sampled jet paths. In Fig. 4 we show the time evolution of the average of temperatures in in- and out-of-plane directions, and their difference in 10–20% and 30–40% central collisions for $\tau_0 = 0.2$ and 1.0 fm, and the free streaming initialization. The behavior of $R_{AA}$ is now easy to understand in terms of average temperature: Larger $\tau_q$, i.e. delay in the onset of energy loss, cuts away the large temperature part of the profile decreasing the average temperature, and thus increasing the $R_{AA}$ [36, 37]. Similarly, for late start of transverse expansion, i.e. $\tau_0 = 1.0$ fm, the temperature is first slightly larger and later lower than for $\tau_0 = 0.2$ fm, and thus the $R_{AA}$ in $\tau_0 = \tau_q = 1.0$ fm and $\tau_0 = 0.2$ with $\tau_q = 1.0$ cases is almost identical. On the other hand, due to the rapid expansion of the edges of the system, free streaming initialization leads to lower average temperature than any other scenario, and thus to the largest $R_{AA}$.

High-$p_T$ $v_2$, on the other hand, is proportional to the difference in temperature along in-plane and out-of-plane directions, and to lesser extent to the average temperature. Delaying the onset of transverse expansion to $\tau_0 = 1.0$ fm leads to larger difference than either early fluid-dynamical or free streaming expansion, and thus $v_2$ is largest in that case. As well, delaying the onset of energy loss by increasing $\tau_q$ hardly changes $v_2$, since at early times the temperature seen by jets in in- and out-of-plane directions is almost identical, and no $v_2$ is built up at that time. Early free streaming and early fluid-dynamical expansion lead to similar differences in temperatures. The slightly larger difference in the 10–20% centrality class is counteracted by slightly lower temperature, and thus final $v_2$ is practically identical in both cases. In the more peripheral 30–40% class the differences in temperature are almost identical, but the lower average temperature leads to lower $v_2$ for free streaming.

The delay in transverse expansion affects the average temperature along the jet in two ways. First, smaller $\tau_0$ means larger initial gradients, faster build-up of flow, and faster dilution of the initial spatial anisotropy. Similarly, free-streaming leads to even faster build-up of flow and dilution of spatial anisotropies than early fluid-dynamical expansion. Second, since the initial jet production is azimuthally symmetric, and jets travel along eikonal trajectories, at early times both in- and out-of-plane jets probe the temperature of the medium almost the same way. Only with course of time will the spatial distribution of in- and out-of-plane jets differ, and the average temperature along their paths begins to reflect the anisotropies of the fluid temperature. This qualitative understanding indicates that the obtained conclusions are largely model independent.

We note that the idea of comparing different bulk-evolution scenarios to see how they affect jet energy loss is not new, see e.g. Refs. [49, 50]. However, these approaches used simplified energy loss, which cannot adequately describe the jet-medium interactions, and are therefore not suitable for jet tomography purposes. In contrast, our approach is unique as it combines both state-of-the-art energy loss and bulk medium evolution. Consequently, we do not need to fix any energy loss parameters by fitting the heavy-ion data and can even use $R_{AA}$ to make conclusions about the bulk properties of the system. Since the energy loss during most of the system lifetime is under control, our $R_{AA}$ results imply that the energy loss during the first fm (or so) is weaker than energy loss in a fully thermal system.

Furthermore, our study shows that not only is early energy loss suppressed [50, 52], but the early build-up of transverse expansion must be delayed as well. It is not sufficient to delay cooling as suggested in Ref. [50], but the initial anisotropy must be diluted at much slower rate than given by either free streaming or by fluid dynamics. We do not expect current more sophisticated approaches to pre-equilibrium dynamics, like KoMPoST based on effective kinetic theory [15, 16], to resolve this issue. As seen in Ref. [53], except in most peripheral collisions, both KoMPoSTing and free streaming lead to very similar final distributions. Thus we may expect that at the time of switching to fluid dynamics, they both have lead to very similar flow and temperature profiles (and thus anisotropies).

Alternatively, the initial spatial anisotropies could be way larger than considered here. It is known that both IP-Glasma and EKRT approaches lead to larger eccentricities than Glauber, but we have tested that they both lead to too low high-$p_T$ $v_2$, if the fluid dynamical evolution begins as usually assumed in calculations utilizing IP-Glasma or EKRT initializations. Event-by-event fluctuations may enhance spatial anisotropies as well, and by generating shorter scale structures, they may enhance the sensitivity of high-$p_T$ $v_2$ to spatial anisotropies. However, for these additional structures to enhance the high-$p_T$ $v_2$, they should be correlated with the event plane, which is not necessarily the case. While we have postponed a study of event-by-event fluctuations to a further work, our preliminary results do not indicate substantial influence on high-$p_T$ predictions.

In summary, we presented (to our knowledge) the first example of using high-$p_T$ theory and data to provide constraints to bulk QGP evolution. Specifically, we inferred that experimental data require that at early times ($\tau \lesssim 1$ fm) both the energy loss and transverse expansion of the system should be significantly weaker than in conventional models. Heavy flavor show large sensitivity to the details of early evolution, so our conclusion will be further tested by the upcoming high luminosity measurements. Our results demonstrate
inherent interconnections between low- and high-$p_{\perp}$ physics, strongly supporting the utility of our QGP tomography approach, where bulk QGP properties are jointly constrained by low- and high-$p_{\perp}$ data.

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