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# INITIAL TIME $\tau_0$ CONSTRAINED BY HIGH-$p_\perp$ DATA*

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We show that high-$p_\perp$ $R_{AA}$ and $v_2$ are way more sensitive to the initial time of fluid-dynamical expansion $\tau_0$ than the distributions of low-$p_\perp$ particles, and that the high-$p_\perp$ observables prefer relatively late $\tau_0 \sim 1$ fm/$c$. To calculate high-$p_\perp$ $R_{AA}$ and $v_2$, we employ our DREENA-A framework, which combines state-of-the-art dynamical energy loss model with 3+1-dimensional hydrodynamical simulations. Elliptic flow parameter $v_2$ is also more sensitive to $\tau_0$ than $R_{AA}$. This presents an example of applying QGP tomography to constrain a bulk QGP parameter with high-$p_\perp$ observables and related theory.

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## 1. Introduction

Quark–gluon plasma (QGP) is a new form of matter that consists of interacting quarks, antiquarks, and gluons. It is formed in ultrarelativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). In these experiments, the bulk properties of QGP are usually explored by low-$p_\perp$ observables. Rare high-energy probes are, on the other hand, almost exclusively used to understand the interactions of high-$p_\perp$ partons with the surrounding QGP medium. We are advocating high-$p_\perp$ QGP tomography, where bulk QGP parameters are

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*jointly* constrained by low- and high-$p_\perp$ physics. For instance, we have previously demonstrated how the anisotropy of the QGP formed in heavy-ion collisions is reflected in the high-$p_\perp$ observables [1].

In these proceedings, we analyse how high-$p_\perp$ $R_{AA}$ and $v_2$ depend on the initial time $\tau_0$, *i.e.* the time of onset of fluid-dynamical expansion, complementing the more detailed study provided in Ref. [2]. The dynamics before thermalisation, and $\tau_0$, and, therefore, the associated energy loss phenomena, are not established yet. To avoid speculation and to provide a baseline calculation for further studies, we assume free streaming of high-$p_\perp$ particles before $\tau_0$ and neglect the pre-equilibrium evolution of the medium (we explore the effects of pre-equilibrium evolution elsewhere [2]). After $\tau_0$, the QCD medium is described as a relativistic viscous fluid and high-$p_\perp$ probes start to lose energy through interactions with this medium. Consequently, the initial time $\tau_0$ is an important parameter, which affects both the evolution of the system and interactions of the high-$p_\perp$ particles with the medium.

We describe the medium evolution by the 3+1-dimensional viscous hydrodynamical model from Ref. [3] and we use the optical Glauber model for the initial state (see [2] for more details). The model parameters are tuned so that the transverse momentum distributions of charged particles for six different $\tau_0$ values in the range from 0.2 fm/$c$ to 1.2 fm/$c$ agree with experimental data (see Fig. 1 in [2]), which is also true for $p_\perp$-differential elliptic flow parameter $v_2(p_\perp)$ (shown in the low-momentum part ($p_\perp < 2$ GeV) of the lower panels of Fig. 1).

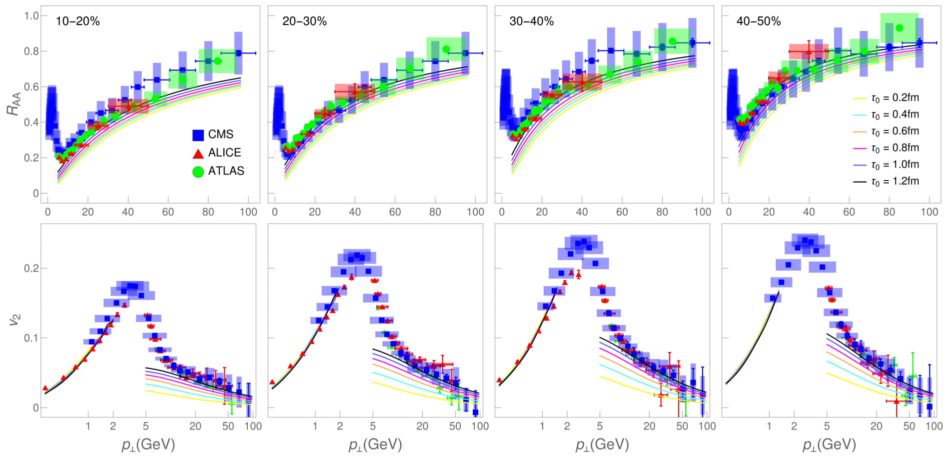


Fig. 1. Charged hadron DREENA-A $R_{AA}$ (upper panels) and $v_2$ (lower panels) predictions, generated for six different $\tau_0$ (indicated on the legend), are compared with ALICE [4, 5], ATLAS [6, 7], and CMS [8, 9] data. Four columns, from left to right, correspond to 10–20%, 20–30%, 30–40%, and 40–50% centralities at $\sqrt{s_{NN}} = 5.02$ Pb+Pb collisions at the LHC.

To evaluate the high-$p_\perp$ parton energy loss, we use our recently developed DREENA-A framework, the details of which are outlined in [10]. The resulting predictions for charged hadron $R_{AA}$ in four different centrality classes, and for $\tau_0$ in the range of 0.2–1.2 fm, are shown in the upper panel of Fig. 1, and compared with experimental data. In the lower panel of Fig. 1, we show a similar comparison of predicted high-$p_\perp$ $v_2$ to data. In distinction to the low-$p_\perp$ distributions, we see that high-$p_\perp$ predictions can be resolved against experimental data, and that the later onset of fluid dynamics is clearly preferred by both $R_{AA}$ and $v_2$. This resolution is particularly clear for $v_2$ predictions, which approach the high-$p_\perp$ tail of the data, as $\tau_0$ is increased. It also increases for higher centralities, as analysed below.

What is the reason behind such sensitivity? One proposal [11] was that jet quenching may start later than the fluid dynamical evolution. We test this scenario by introducing a separate quenching start time $\tau_q \geq \tau_0$. In Fig. 2 (A) we show the high-$p_\perp$ $R_{AA}$ and $v_2$ in 20–30% centrality for $\tau_0 =$ 0.2 fm, and $\tau_q$ values in the range of 0.2–1.2 fm. The sensitivity to $\tau_q$ is similar in other centralities, for larger $\tau_0$ and for heavy flavour. $R_{AA}$ shows similar sensitivity to $\tau_q$ as to $\tau_0$; compare Figs. 2 (A) and 1. The $v_2$ is surprisingly insensitive to $\tau_q$, and way below the data, not supporting this scenario.

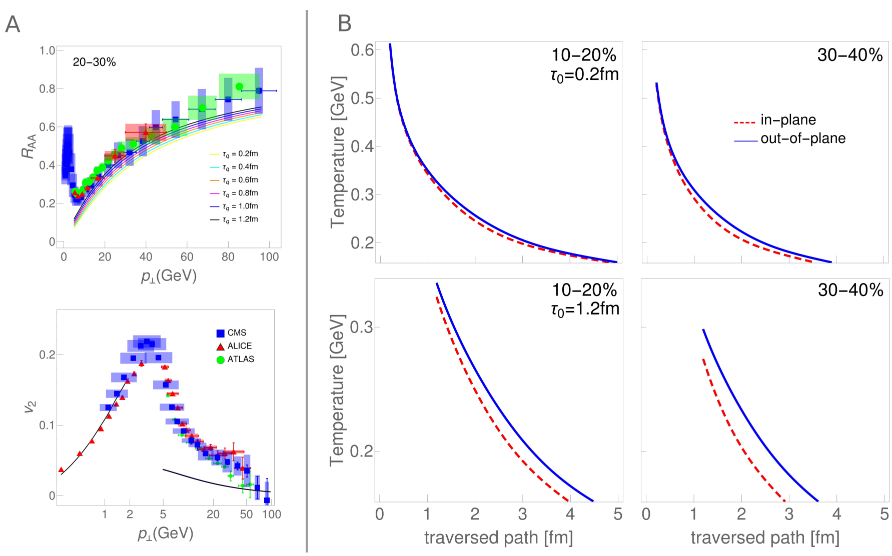


Fig. 2. (A) DREENA-A predictions for charged hadron $R_{AA}$ (left) and $v_2$ (right) in 20–30% centrality class of $\sqrt{s_{NN}}$ = 5.02 TeV Pb+Pb collisions at the LHC, generated for $\tau_0 = 0.2$ fm and six different $\tau_q$. The predictions are compared with ALICE [4, 5], ATLAS [6, 7], and CMS [8, 9] data. (B) The average temperature along the jet path traversing the system in out-of-plane and in-plane directions.

We next investigate if the origin of the sensitivity is due to the difference in the temperature profiles. For this, we evaluate the average temperature along the paths of jets travelling in-plane and out-of-plane directions. In Fig. 2 (B), we show the resulting temperature evolution in 10–20% and 30–40% centrality for $\tau_0 = 0.2$ and 1.2 fm. As $\tau_0$ is increased, the differences between in-plane and out-of-plane temperature profiles also increase. Since $v_2$ is proportional to the difference in suppression along in-plane and out-of-plane directions, a larger difference along these directions leads to larger $v_2$, and causes the observed dependency on $\tau_0$. As well, for fixed $\tau_0$, increasing $\tau_q$ hardly changes $v_2$ since at early times, the average temperature in- and out-of-plane directions is almost identical, and no $v_2$ is built up at that time in any case. Furthermore, the more peripheral the collision, the larger the difference in average temperatures, which leads to higher sensitivity of $v_2$ to $\tau_0$ as seen in the lower panels of Fig. 1. Consequently, the temperature profile differences are a major contributor to such sensitivity.

We here presented how high-$p_\perp$ theory and data can be used to constrain a parameter weakly sensitive to bulk QGP evolution. We used high-$p_\perp$ $R_{AA}$ and $v_2$ to infer that experimental data prefer late onset of fluid dynamical behaviour. $v_2$ shows a higher sensitivity to $\tau_0$ than $R_{AA}$, and we showed that $v_2$ is affected by $\tau_0$ due to differences in the in- and out-of-plane temperature profiles. This demonstrates inherent interconnections between low- and high-$p_\perp$ physics, supporting our proposed QGP tomography approach.

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