Jet quenching as a probe of the initial stages in heavy-ion collisions

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In this Letter we prove, for the first time, that a combination of jet quenching observables is sensitive to the initial stages of heavy-ion collisions, where thermalization is expected to happen. Specifically, we find that in order to reproduce at the same time the inclusive particle production suppression, R_{AA}, and the high-p_T azimuthal asymmetries, v_2, the start of the energy loss must be delayed for ~ 0.6 fm. This exploratory analysis shows the potential of jet observables, possibly more sophisticated than the ones studied here, to constrain the dynamics of the initial stages of the evolution.

INTRODUCTION

Heavy-ion collisions are the experimental tools designed to study the properties of the hot and dense Quark Gluon Plasma (QGP). After two decades of experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), jet quenching, the modification of the QCD jet structures due to their interaction with the surrounding matter, has become a fundamental tool for this program. Although the QGP is routinely produced and studied in these colliders, the actual process that so efficiently leads to the production of this locally thermalized state starting from a completely out-of-equilibrium collision system is largely unknown. This process has to happen in a very short time, $\mathcal{O}(1\,\mathrm{fm})$ or a few yoctoseconds. This is why this line of research, that has become one of the most active and interesting topics in QCD, is sometimes nicknamed *Initial Stages*. Up to now, all experimental information on the initial stages of the evolution comes, essentially, from azimuthal asymmetries in correlations between different particles in the soft regime (say, $p_T \lesssim 5$ GeV).

Furthermore, recent experimental results from the LHC, and later from RHIC, in *small system* p-Pb, high-multiplicity p-p and d-Au collisions, show characteristics [1] usually attributed to QGP formation. Indeed, usual key probes of the QGP, such as long-range angular correlations and flow harmonics [2–9], and the strangeness enhancement [10] have been observed in small systems. Interestingly, the only long-established QGP signature missing in these experimental data is jet quenching [11]. Since thermalization and jet quenching are manifestations of basically the same dynamics, the presence of the former and the absence of the latter in these systems is surprising. For this reason, there is an ample consensus that jet quenching is critical to understand small systems and thermalization. We will argue here that jet quenching can be used, in fact, as a complementary and versatile way to probe the dynamics at the early times of the evolution. Actually, jets are extended objects in space and time and different modifications measure different time or energy scales [12]. For instance, it has recently been proposed that the study of the semileptonic decay of $t\bar{t}$ pairs can be used as a yoctosecond chronometer of the time evolution of the QGP [13].

Using azimuthal asymmetries of hard particles as a jet quenching probe was proposed for the first time in [14, 15]. The first data of high-p_T elliptic flow, v_2, was published in 2006 by the PHENIX Collaboration [16] However, even though the nuclear modification factor, R_{AA}, was fairly described by all the energy loss formalisms, the computed high-p_T elliptic flow underestimated the experimental data [17]. It was argued in [18, 19] that soft-hard correlations are essential to properly determine the harmonic coefficients in the hard sector, whose correct definition is given by the scalar product, v_n^{SP} [19], to be defined later.

In this work, we compute the azimuthally averaged R_{AA} for the $20-30\%$ centrality class in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [20]. Our framework consists of a radiative energy loss implemented with the Quenching Weights from Ref. [21], embedded in an EKRT event-by-event (EbyE) hydrodynamic simulation of the medium [22]. Following the approach in [23, 24], we define the jet transport coefficient as $\hat{q} \equiv K \cdot 2\,\epsilon^{3/4}$, driven by the ideal estimate $\hat{q}_{ideal} \sim 2\,\epsilon^{3/4}$ [25]. The local energy density, ϵ, is taken from EKRT hydrodynamic profile, so that there is only one free parameter, the K-factor, which is fitted to the high-p_T R_{AA} experimental data [20] and used for the calculation of the high-p_T harmonic coefficients.

We will show that the treatment of initial stages is crucial for the simultaneous description of both type of observables, since the jet harmonic coefficients show up to be very sensitive to the starting point of the quenching. In fact, the experimental data on v_2 at high-p_T can only be described by delaying the beginning of the energy loss for ~ 0.6 fm. This is a general conclusion, not limited to our specific implementation, since all the studies that properly determine the jet harmonic coefficients start the energy loss and the hydrodynamical evolution at the same time [19, 26–29], implicitly including this time-delay in their calculations. We do not attempt here to make a full study of all the experimental data on R_{AA} and v_n but rather to show the importance of the initial stages of the evolution for a correct interpretation of the jet quenching data. It would be tempting, on the other hand, to relate our findings on the time-delay for energy loss to the absence of jet quenching in p-Pb collisions. We leave these more extensive studies for future works.

THE FORMALISM

Energy loss . We follow the same formalism as in [24], to which we refer the reader for further details. Here we summarize its most relevant features. The cross section of a hadron h at rapidity y and transverse momentum p_T is given by

$$\frac{d\sigma^{AA\to h}}{dydp_T} = \int dq_T\, dz \frac{d\sigma^{AA\to k}}{dydq_T}\, P(\epsilon) \times\, D_{k\to h}(z, \mu_F \equiv p_T)\, \delta\left(p_T - z(1-\epsilon)q_T\right), \quad (1)$$

where the cross section for producing a parton k, $d\sigma^{AA\to k}/dydq_T$, is computed at next-to leading order (NLO) by using the code in [30]. For the parton distribution functions, we use the CTEQ6.6M [31] together with the EPS09 nuclear modifications [32]. For the fragmentation functions, $D_{k\to h}(z, \mu_F)$, we use either DSS07 [33] or DSS14 [34]. The Quenching Weights, $P(\epsilon)$, are employed in the multiple soft approximation [21]. These probability distributions depend on two variables, ω_c and R, which, for a dynamic expanding medium, are proportional, respectively, to the first and second moment of the jet quenching parameter, $\hat{q}(\xi)$, defined along the trajectory of the radiating parton parametrized by ξ [21, 24]. Therefore, we only need a definition of the jet transport coefficient in terms of the local properties of the medium. We make use of the aforementioned expression:

$$\hat{q}(\xi) \;=\; K \cdot 2\, \epsilon^{3/4}(\xi). \quad (2)$$

The previous equation is valid both for the partonic and for the hadronic phase of the evolution [25]. Nevertheless, most of the phenomenological works that try to extract the value of the quenching parameter assume no energy loss during the hadronic phase [35]. We analyze here two different scenarios: ending the energy loss at the chemical freeze-out, $T_{\rm q} = T_{\rm chem} = 175$ MeV, that is, no energy loss in the hadronic phase, and using Eq. (2) all the way down to the kinetic freeze-out, $T_{\rm q} = T_{\rm dec} =$ 100 MeV, i.e., including jet quenching in both phases[1].

EKRT hydrodynamics The EbyE fluctuating initial energy density profiles for the hydrodynamical evolution are calculated within the EKRT framework [36]. This framework is based on collinearly factorized NLO perturbative QCD computation of minijet transverse energy production and the conjecture of gluon saturation. The saturation momentum $p_{\rm sat}$ controls the computed transverse energy production, and is a function of the given collision energy $\sqrt{s_{\rm NN}}$, the nuclear mass number A, and its dependence on the transverse coordinate $\mathbf{x}_\perp$ comes through the product of the nuclear thickness functions $T_A(\mathbf{x}_\perp)$, computed event-by-event. The essential free parameter $K_{\rm sat}$ in the saturation conjecture is fixed by the charged hardron multiplicity in 0-5% Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. Once $K_{\rm sat}$ is fixed, the initial energy density profiles can be computed for any $\sqrt{s_{\rm NN}}$ and A as long as the saturation momentum remains in the perturbative regime, $p_{\rm sat} = p_{\rm sat}(\sqrt{s_{\rm NN}}, A, T_A T_A(\mathbf{x}_\perp)) > p_{\rm min} =$ 1 GeV. The formation time of the initial condition is then obtained as $\tau_f = 1/p_{\rm min} = 0.197$ fm.

After formation, the subsequent spacetime evolution is computed using a boost-invariant transient Israel-Stewart type of second order relativistic dissipative hydrodynamics, where the essential physical inputs are the QCD matter equation of state and the temperature dependence of shear viscosity $\eta/s(T)$, for details see Ref. [22]. In particular, we obtain the spacetime evolution of the energy density profile $\epsilon(\tau, \mathbf{x}_\perp)$ for each event, which are then used in the computation of the jet quenching parameter in Eq. (2).

As an equation of state we use the s95p parametrization of the lattice QCD results [37] with chemical freeze-out implemented as in Ref. [38], and the shear viscosity parametrization is $\eta/s(T) = param1$ from Ref. [22]. The corresponding results for soft hadronic observables like multiplicity, average transverse momentum, flow coefficient and flow correlations are in an excellent agreement with the measurements of 200 GeV Au-Au collisions at RHIC, 2.76 TeV Pb-Pb, 5.023 TeV Pb-Pb and 5.44 TeV Xe-Xe collisions at the LHC [22, 39–41].

Early-times treatment The dynamics prior to the applicability of hydrodynamics and, therefore, the associate energy loss phenomena, are not established yet. Thus, there is freedom in the definition of $\hat{q}(\xi)$ from the production time of the hadron to the initialization proper time τ_f of EKRT EbyE hydrodynamics, see Eq. (2). Energy loss in the BDMPS-Z formalism does not require, in principle, neither thermalization nor isotropization, so for times smaller than τ_f can be employed and $\hat{q}(\xi)$ has to be obtained via extrapolations. Up to now, any phenomenological study of this kind – except explicitly indicated – assumes no quenching during the early stages of

[1] We denote as $T_{\rm q}$ the temperature where we stop the energy loss.

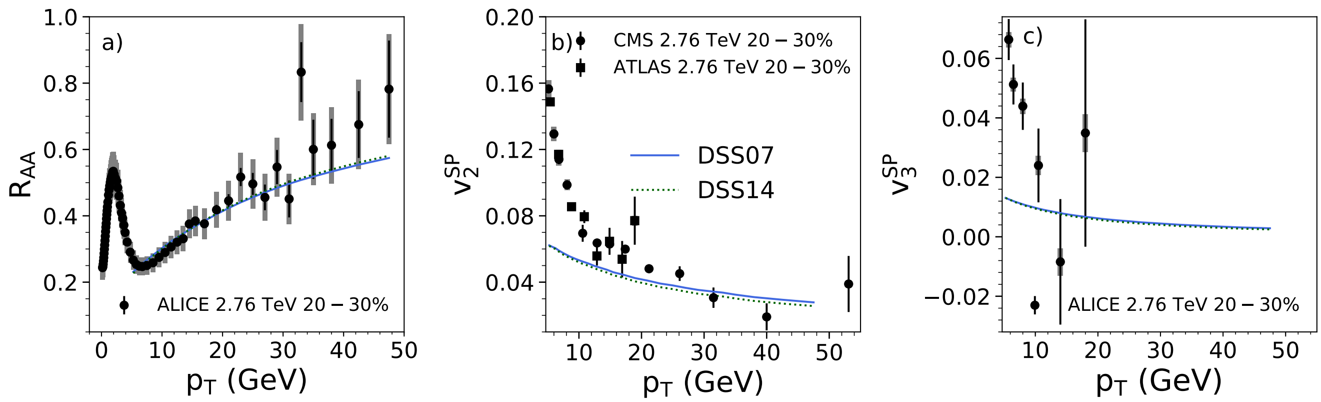

FIG. 1: (Color online) (a) Suppression of inclusive charged particles, (b) high-p_T elliptic flow, (c) high-p_T triangular flow for the 20–30% centrality class of $\sqrt{s_{\rm NN}} = 2.76$ TeV Pb-Pb collisions at the LHC, computed as a function of p_T. Experimental data are from [20, 42–44]. The blue solid and green dotted lines correspond, respectively, to the use of DSS07 [33] and DSS14 [34] fragmentation functions. For the initial and final times of the energy loss – see Section – Case ii) $\tau_q = 0.197$ and $T_{\rm q} = T_{\rm chem} = 175$ MeV are taken.

the collision[2]. Indeed, all the proposed solutions to the long-standing problem of describing the high-p_T v_2 delay the interaction of the hard parton with the medium up to the initial time of the hydrodynamic simulation [19, 26, 27], usually $\tau_f = 0.6$ fm, or require a very substantial growth of $\hat{q}$ for temperatures close to the deconfinement temperature, T_c [28, 29]. Since the starting time of EKRT EbyE hydrodynamics is set to $\tau_f = 0.197$ fm, we can study how the R_{AA} and high-p_T jet harmonic coefficients vary when we delay the jet quenching up to a time comparable with that in [19, 26, 27]. Denoting τ_q as the time where the jet quenching begins, we consider the following three cases:

i) $\tau_q = 0$ fm. Before the starting point of our hydrodynamical evolution, τ_f, $\hat{q}(\xi)$ is constant and equal to its value at τ_f. That is, $\hat{q}(\xi) = \hat{q}(\tau_f)$ for $\xi < \tau_f = 0.197$ fm.

ii) $\tau_q = 0.197$ fm. Here, $\hat{q}(\xi) = 0$ for $\xi < \tau_f = 0.197$ fm. In this case, the quenching begins at 0.197 fm.

iii) $\tau_q = 0.572$ fm. Here, $\hat{q}(\xi) = 0$ for $\xi < \tau_q = 0.572$ fm. Hence, the energy loss starts at 0.572 fm.

High-p_T harmonics At this stage, the K-factor in Eq. (2) can be fitted to the experimental R_{AA} data for a given centrality class. Once the K-factor is fixed, the harmonic coefficients associated to the $R_{AA}(p_T, \phi)$ Fourier series, v_n^{hard}, are calculated in the corresponding centrality class, event by event. Then, each v_n^{hard} is *correlated* with the soft flow harmonic in the event and, finally, an average over all the events in the centrality class is performed:

$$v_n^{SP}(p_T) = \frac{\left\langle v_n^{soft} v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right)\right]\right\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}, \tag{3}$$

where ψ_n^{soft} is the event plane angle and $\langle ... \rangle$ denotes the average over the events. This is the so-called scalar product definition of the high-p_T azimuthal asymmetries [18, 19].

RESULTS

We restrict our study of the nuclear modification factor and the high-p_T harmonics to one center of mass energy and one centrality class: LHC Pb-Pb 20 − 30% semi-central collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. We have already analyzed the energy and centrality dependence of the nuclear modification factor for several smooth-averaged hydrodynamics in Ref. [24], showing that, surprisingly, the K-factor for a given center of mass energy seems to be almost independent of the centrality of the collision. More recently, similar results have been found by all the phenomenological works that set the dependence of the medium parameter on the medium properties to be local and monotonous [45, 46]. Finally, in Ref. [47], we have also checked that using an EbyE formalism, the EKRT hydrodynamic simulation employed also here, our conclusions remain the same.

We compute the nuclear modification factor for a set of values of our free parameter, the K-factor, as explained in the previous Sections. Next, we perform a χ^2-fit to determine the value of K that better describes ALICE R_{AA} data [20] for $p_T > 5$ GeV – to stay in the pQCD

[2] See Ref. [23] and Ref. [24] for some early time extrapolations.

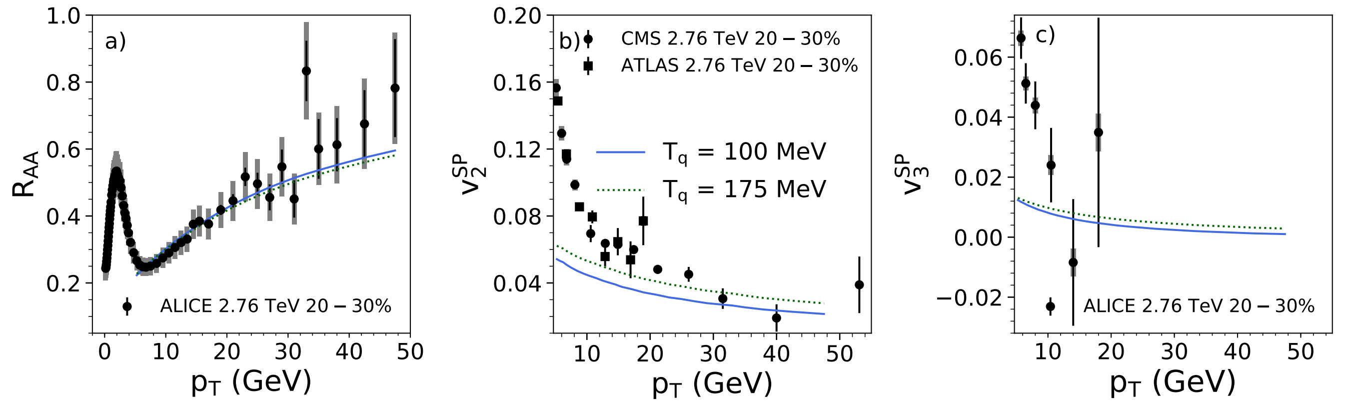

FIG. 2: (Color online) (a) $R_{AA}(p_T)$, (b) $v_2^{SP}(p_T)$, (c) $v_3^{SP}(p_T)$ for the 20–30% centrality class of $\sqrt{s_{\rm NN}} = 2.76$ TeV Pb-Pb collisions at the LHC compared to their respective experimental data [20, 42–44]. The blue solid line corresponds to stop the energy loss at the kinetic freeze-out, $T_{\rm q} = T_{\rm dec} = 100$ MeV. For the green dotted line the quenching finishes at $T_{\rm q} = T_{\rm chem} =$ 175 MeV. DSS07 [33] fragmentation functions and Case ii) $\tau_q = 0.197$ fm are employed, see Section .

region. Then, the fitted value of K is used to determine the high-p_T asymmetries by means of the scalar product given by Eq. (3). In Fig. 1 we show the dependence of these observables on the fragmentation functions employed, i.e. DSS07 or DSS14. In this figure, there is neither energy loss before the initial proper time of the hydrodynamic profile, $\tau_f = 0.197$ fm, nor after the chemical freeze-out, $T_{\rm chem} = 175$ MeV. It can be seen that, independently of the fragmentation functions used, our model fairly describes the R_{AA} but underestimates the azimuthal asymmetries in the hard sector. Moreover, our calculations of both the nuclear modification factor and the high-p_T harmonics are hardly sensitive to the fragmentation functions. Consequently, any of them can be implemented in our computations, without altering our conclusions. All the following results in this Letter were obtained by using DSS07 fragmentation functions.

In Fig. 2 we analyze how the R_{AA} and the jet harmonic coefficients vary with the end-point of the energy loss. As in the previous figure, we assume here no energy loss before the starting time of EKRT hydrodynamic profile, that is, Case ii) $\tau_q = 0.197$, according to the notation in Section . While the nuclear modification factor can be well described both with and without energy loss in the hadronic phase, the high-p_T asymmetries are sensitive, especially the $v_2^{SP}(p_T)$, to the end-point of the quenching, pointing out to a better description of the data when there is only energy loss in the partonic phase. Nevertheless, no matter when we stop our simulation, yet the jet harmonic coefficients remain underestimated.

The dependence of the $R_{AA}(p_T)$, $v_2^{SP}(p_T)$, and $v_3^{SP}(p_T)$ on the starting time on the energy loss is presented in Fig. 3. This is done for the case where there is no quenching in the hadronic phase, $T_{\rm q} = T_{\rm chem}$. As it can be seen on the left panel of this figure, the dependence of the nuclear modification factor on τ_q is mild, however, the corresponding K-fitted values for the three curves of this panel, shown in Table I, are quite different. Regarding the asymmetries in the hard sector, Fig. 3 shows that they are very sensitive to the starting point of the quenching. Actually, the $v_2^{SP}(p_T)$ is well described within our formalism if and only if the starting point of the energy loss is delayed up to ~ 0.6 fm. This corresponds to the set-up employed in any approach that aims to describe the jet harmonics coefficients using a smooth dependence of the medium parameter on the medium properties [19, 26, 27].

Early time extrapolation	K-factor
Case i) $\tau_q = 0$ fm	$2.120^{+0.091}_{-0.074}$
Case ii) $\tau_q = 0.197$ fm	$2.90^{+0.13}_{-0.11}$
Case iii) $\tau_q = 0.572$ fm	4.56 ± 0.20

TABLE I: K-factor obtained from fits to the ALICE R_{AA} data [20] for the three different early time extrapolations. DSS07 fragmentation functions and $T_{\rm q} = T_{\rm chem} = 175$ MeV are employed, see Section .

CONCLUSIONS

In this Letter we have computed the nuclear modification factor and the high-p_T harmonics v_2, v_3 for charged particle production in the 20 − 30% centrality class of $\sqrt{s_{\rm NN}} = 2.76$ TeV Pb-Pb collisions at the LHC. The computations are done by using the formalism of Quenching Weights embedded in state-of-the art EbyE EKRT hydrodynamic model of the medium. We have analyzed the dependence of these observables on the fragmentation functions, on the lack - or not - of energy loss in the

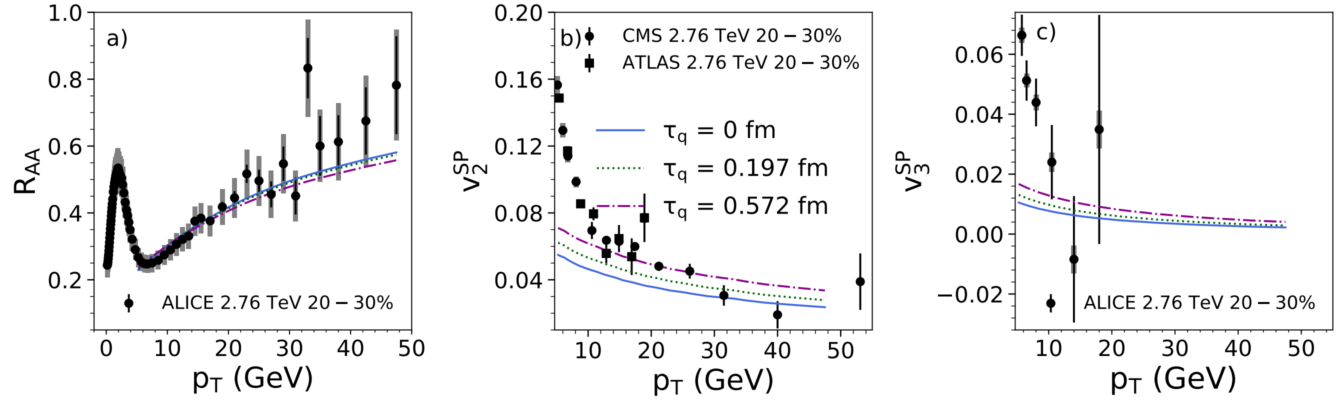

FIG. 3: (Color online) (a) $R_{AA}(p_T)$, (b) $v_2^{SP}(p_T)$, (c) $v_3^{SP}(p_T)$ for the 20–30% centrality class of $\sqrt{s_{\rm NN}} = 2.76$ TeV Pb-Pb collisions at the LHC compared to their respective experimental data [20, 42–44]. The blue solid, $\tau_q = 0$ fm, dotted green, $\tau_q = 0.197$ fm, and dashed purple, $\tau_q = 0.572$ fm, lines correspond, respectively, to Cases i), ii) and iii) of the early times treatment, see Section . DSS07 [33] fragmentation functions and $T_{\rm q} = T_{\rm chem} = 175$ MeV are used.

hadronic phase of the evolution, and on the starting time of the quenching. Any work that correctly determines the harmonic coefficients in the hard sector starts the energy loss at the starting time of the hydrodynamic simulation employed, which usually is $\tau_f = 0.6$ fm (or later). Therefore, they implicitly assume no quenching during the first 0.6 fm after the collision. Since the starting time of the EKRT hydrodynamic evolution is $\tau_f = 0.197$ fm, it provides a framework that, first ever, enables to vary the quenching in the early stages of the evolution and thus to establish when the quenching begins. We find that the simultaneous and proper description of these three observables demands no energy loss for the first ~ 0.6 fm after the collision, in agreement with the set-up that other studies were implicitly adopting.

We conclude that this is not a particular feature of our approach but a general outcome. Hence, high-p_T asymmetries are introduced here, for the first time, as a direct signature of the less known initial stages of the collision, showing the incompatibility of the simultaneous description of the experimental measurements on the charged hadron suppression and the azimuthal asymmetries with the presence of energy loss during the first ~ 0.6 fm after the collision. This work sets the foundations for future jet quenching analysis that may be crucial for improving our understanding of these initial stages, and extendable from large to small systems.

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