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Zeroing in on the initial state — tomography using bulk, jets and photons

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Abstract

One of the unsolved problems in the current 'standard model' of heavy ion physics is the apparent rapid thermalization of QCD matter in the pre-equilibrium stage. While it is challenging to probe this mechanism directly, there are now several observables available which allow tomographic imaging of the initial state geometry, which is expected to carry remnant information of the equilibration mechanism. On the fluid dynamics side, scaled fluctuations in the momentum space anisotropy parameters v_n image the initial eccentricity fluctuations ϵ_n almost directly with only a weak dependence on the details of the fluid dynamical evolution. From a different direction, due to the strong non-linear dependence of their emission rates on temperature, thermal photons and their v_n are very sensitive to the initial state graininess. Finally, the v_2 and v_3 of high P_T hadrons coming from hard processes reflect the attenuation pattern of partons propagating through the inhomogeneous matter density after some fluid dynamical evolution. Combining information from all these channels does not yet lead to a fully consistent picture, however intriguing trends pointing towards non-trivial initial state dynamics emerge.

Keywords: Quark gluon plasma; Initial state; Tomography; Jet quenching

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1. Introduction

One of the key concepts in discussing observables in the context of ultrarelativistic heavy-ion (A–A) collisions is tomography, i.e. the ability to image the density distribution of the QCD medium produced in such collisions as well as its time evolution. In particular, accurately imaging the density distribution at early times where a collective state of matter forms would allow to identify the physics processes underlying the equilibration process better.

Several different classes of observables have been demonstrated to have tomographic capabilities. The bulk matter itself evolves like a fluid, and consequently pressure gradients translate the initial spatial eccentricities (usually parameterized in terms of Fourier coefficients ϵ_n) into final state momentum space anisotropies v_n, and it has been argued in [1] that if one scales the event-by-event (EbyE) fluctuations of v_n by the event average, this is almost directly related to the EbyE fluctuations of ϵ_n, thus allowing to image the medium at the very earliest times.

A measurement of thermal photon v_n likewise is a tomographic probe of the early medium evolution. Since the electromagnetic coupling of photons to the medium is small, final state interaction is almost completely absent and thermal photon emission reflects the conditions at the time of photon emission. In particular, photon v_n reflects the pressure-driven collective velocity (flow) field of the medium at the time of photon emission, which in practice predominantly probes the time window between equilibration and 3 fm/c [2].

Finally, high p_T parton production inside the QCD medium leads to a situation in which hard partons undergo a considerable energy degradation due to final state interaction as they propagate through the medium. Since the amount of modification of a parton shower in medium is on average proportional to the length and density of medium traversed, high P_T hadron v_n does not measure a pressure-driven flow but rather an extinction of yield in a given momentum window, i.e. directly images ϵ_n in position space. While it can be shown that the energy degradation of the leading parton peaks between 1–2 fm/c [3], it is also known that high P_T v_2 has sensitivity to late time dynamics which may reach well into the hadronic phase around 5–7 fm/c [4].

Thus, there are various sets of tomographic probes available which all have somewhat different capabilities and probe different timeslices, and the aim of this work is to see whether combining information from these probes forms a coherent picture of initial state physics or not and whether these different probes constitute independent ways of measuring the same physics or are sensitive to rather different physics.

2. Scaling relations

In order to establish what properties of the medium evolution are constrained by current tomographic probes outside the context of a particular model, it is necessary to test a large parameter space of possible evolutions against the data. Until recently, this has been close to impossible due to the substantial numerical efforts needed (note however the recent large scale statistical analysis [5]). However, the discovery of approximate scaling relations has opened a novel avenue to do such an analysis for a subset of observables. In [1], it was realized that $\langle v_n \rangle \approx C_n \epsilon_n$ when averaging over many events with the same spatial eccentricity ϵ_n and that moreover $v_2 \approx C_2 \epsilon_2$ for individual events, i.e. the complications of the fluid dynamics expansion can to good accuracy be absorbed into a series of constants C_n (note however that the relation is not precisely linear across the full centrality range [6]). Thus, constructing observables in which the C_n cancel, like $\delta v_2 = (v_2 - \langle v_2 \rangle)/\langle v_2 \rangle$, allows to compare the EbyE final state probability of finding a v_2 in a centrality class $P(v_2)$ directly to $P(\epsilon_2)$ in the initial state. Similarly, the evolution of C_n with