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Fluid dynamical response to initial state fluctuations

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Abstract

We investigate a fluid dynamical response to the fluctuations and geometry of the initial state density profiles in ultrarelativistic heavy ion collisions.

Keywords: Initial state fluctuations; Relativistic fluid dynamics

1. Introduction

The aim of the experiments in ultrarelativistic heavy ion collisions is to understand the properties of nearly thermalized strongly interacting matter. In extracting these properties a good understanding of the dynamics of the formed system is essential, as almost none of the characteristics of the matter can be understood directly from the data, but some degree of theoretical interpretation is necessary. Relativistic fluid dynamics has become a standard tool in describing the spacetime evolution of the formed matter. For example finding constraints for the shear viscosity of the matter is largely based on the systematics of the azimuthal asymmetries of the hadron transverse momentum spectra, generated by the secondary interactions in the created system [1]. A magnitude of the asymmetries depend on the transport properties of the matter, and

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the evolution of the matter with non-zero viscosity is relatively straightforward to describe with fluid dynamics.

In the fluid dynamical picture the azimuthal asymmetries of the spectra are generated by initially asymmetric density or pressure gradients. The asymmetries of the final spectra then depend not only on the properties of the matter like equation of state and transport coefficients, but also on the asymmetries in the initial state. The initial state remains one of the largest uncertainties in extracting e.g. the shear viscosity of the strongly interacting matter.

In the recent years it has become evident that the initial density profiles fluctuate from collision to collision, even with a fixed impact parameter. Understanding these fluctuations does not only provide more information on the collisions, but it has become clear that even in describing the average properties of the system it is necessary to take into account the event-by-event nature of the collisions. Therefore it is essential to understand how the fluctuations in the initial state are reflected into the final observable hadron spectra.

2. Fluid dynamics and hadron spectra

A basic quantity in fluid dynamics is the energy–momentum tensor $T^{\mu\nu}$ that can be decomposed as

$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}. \tag{1}$$

In the fluid dynamical limit the evolution of the system can be described in terms of $T^{\mu\nu}$ alone, and a starting point for describing the evolution are the conservation laws

$$\partial_{\mu} T^{\mu\nu} = 0. \tag{2}$$

The conservation laws are completely general, but not sufficient to close the system. The fluid dynamical approximation comes into play when one writes the evolution equations for the viscous parts of the energy–momentum tensor. For example in the Israel–Stewart type of theories [2] the shear-stress tensor satisfies the equations of motion of the form

$$\tau_{\pi} \frac{\mathrm{d}}{\mathrm{d}\tau} \pi^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta \nabla^{\langle\mu} u^{\nu\rangle} + (\text{non-linear terms}), \tag{3}$$

where η is the shear viscosity coefficient and τ_{π} is the corresponding relaxation time, for further details see Ref. [3]. If one further specifies an equation of state, the spacetime evolution of $T^{\mu\nu}$ can be solved from the above equations provided that the initial values of $T^{\mu\nu}$ are given.

Once the full spacetime evolution is known, it can be converted to the hadron spectra e.g. via the Cooper–Frye procedure [4]. The resulting transverse momentum (p_T) spectra are then usually characterized in terms of its Fourier components v_n with respect to the azimuthal angle ϕ,

$$\frac{\mathrm{d}N}{\mathrm{d}y\,\mathrm{d}p_T^2\,\mathrm{d}\phi} = \frac{\mathrm{d}N}{\mathrm{d}y\,\mathrm{d}p_T^2}\left[1 + 2v_1(p_T)\cos(\phi - \psi_1) + 2v_2(p_T)\cos\left[2(\phi - \psi_2)\right] + \cdots\right], \tag{4}$$

where the event-plane angle ψ_n can be defined as

$$\psi_n = (1/n)\arctan\bigl(\langle p_T \sin n\phi\rangle / \langle p_T \cos n\phi\rangle\bigr). \tag{5}$$

A characterization of an ensemble of collisions requires also probabilities for observing $\mathrm{d}N/\mathrm{d}y$, v_n, ψ_n, ..., not only their averages. In addition, the full characterization requires in principle all the possible correlations as well. Here we consider the probability distributions of the Fourier coefficients $\mathcal{P}(v_n)$ and correlations between them $c(v_i, v_j)$.