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Viscous corrections to anisotropic flow and transverse momentum spectra from transport theory

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Abstract

Viscous hydrodynamics is commonly used to model the evolution of the matter created in an ultra-relativistic heavy-ion collision. It provides a good description of transverse momentum spectra and anisotropic flow. These observables, however, cannot be consistently derived using viscous hydrodynamics alone, because they depend on the microscopic interactions at freeze-out. We derive the ideal hydrodynamic limit and the first-order viscous correction to anisotropic flow (v_2, v_3 and v_4) and momentum spectrum using a transport calculation. The linear response coefficient to the initial anisotropy, $v_n(p_T)/\varepsilon_n$, depends little on n in the ideal hydrodynamic limit. The viscous correction to the spectrum depends not only on the differential cross section, but also on the initial momentum distribution. This dependence is not captured by standard second-order viscous hydrodynamics. The viscous correction to anisotropic flow increases with p_T, but this increase is slower than usually assumed in viscous hydrodynamic calculations. In particular, it is too slow to explain the observed maximum of v_n at $p_T \sim 3$ GeV/c.

Keywords: Quark–gluon plasma; Collective flows; Kinetic theory

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1. Introduction

Relativistic viscous hydrodynamics [1,2] is the state of the art for describing the evolution of the strongly-coupled system formed in an ultrarelativistic heavy-ion collision at RHIC or LHC. It has long been realized [3] that ideal hydrodynamics naturally explains the large magnitude of elliptic flow [4,5]. However, the system formed in such a collision is so small that deviations from local thermal equilibrium are sizable, resulting in the inclusion of viscosity [6] in hydrodynamic calculations. Viscosity typically reduces the magnitude of elliptic flow by 20% [7]. Viscous effects on higher harmonics of anisotropic flow [8,9], such as triangular flow [10], are even larger [11].

Even though there is a consensus that viscosity matters, the calculation of viscous corrections to observables is not yet under control. The reason is that viscosity affects not only the space–time history of the fluid [12], but also the momentum distribution of particles at "freeze-out", which has an off-equilibrium part proportional to viscosity [13,14]. Viscous hydrodynamics itself does not fully specify this off-equilibrium part. The only requirement is that the system of particles should generate the same energy–momentum tensor as the fluid just before freeze out [15]. This requirement, however, does not constrain the dependence of the relative deviation to equilibrium on the momentum p in the rest frame of the fluid, which is essentially a free function $\chi(p)$. This function is not universal, and involves the differential cross sections between constituents [16]. It is typically put by hand in hydrodynamic calculations.

The common lore is that effects of viscosity are more important for particles with larger transverse momenta [2]. This is due to the fact that most hydrodynamic calculations use the "quadratic" ansatz [13] $\chi(p) \propto p^2$. While this choice generally results in an improved description of experimental data [2] (see however [15]), it is not supported by any theoretical argument [16]. We evaluate viscous corrections to observables (specifically, transverse momentum spectra and anisotropic flow) by solving numerically a relativistic Boltzmann equation. We simulate relativistic particles undergoing $2 \to 2$ elastic collisions with a total cross section $\sigma_{\rm tot}$. In the limit $\sigma_{\rm tot} \to +\infty$, a generic observable $f(\sigma)$ can be expanded in powers of $1/\sigma_{\rm tot}$:

$$f(\sigma_{\rm tot}) \underset{\sigma_{\rm tot}\to\infty}{\approx} f^{(0)} + \frac{1}{\sigma_{\rm tot}}\delta f + \mathcal{O}\left(\frac{1}{\sigma_{\rm tot}^2}\right). \tag{1}$$

The leading term $f^{(0)}$ is the limit of infinite cross section, which corresponds to ideal hydrodynamics in the limit of a vanishing freeze-out temperature [17,18]. The next-to-leading term δf is a viscous correction: since the shear viscosity η scales like $1/\sigma_{\rm tot}$ [19], this correction is proportional to η.[1]

We evaluate $f^{(0)}$ and δf by solving numerically the relativistic Boltzmann equation for several large values of the cross section $\sigma_{\rm tot}$. Our primary goal is to illustrate by an explicit calculation how the viscous correction to anisotropic flow depends on transverse momentum p_T, and to what extent this dependence is sensitive to the structure of the differential cross section. We do not mean here to carry out a full realistic simulation of a heavy-ion collision. In particular, for sake of simplicity, our transport calculation uses massless particles which supply the possibility of having only shear viscosity with no bulk viscosity [20–22]. The resulting equation of state is harder [23] than that of QCD near the deconfinement crossover [24]. This results in larger v_n and harder p_T spectra.

[1] Note that in hydrodynamic calculations, δf often denotes the viscous correction at freeze-out. Here, δf is the full viscous correction, which also contains a contribution from the hydrodynamic evolution.