Elliptic Flow at Finite Shear Viscosity in a Kinetic Approach at RHIC
V. Greco\textsuperscript{a}\textsuperscript{b}, M. Colonna\textsuperscript{b}, M. Di Toro\textsuperscript{a}\textsuperscript{b} and G. Ferini\textsuperscript{a}

\textsuperscript{a}Dipartimento di Fisica e Astronomia, Universit\`{a} di Catania, Via S. Sofia 64, 95125 Catania, Italy

\textsuperscript{b}INFN-LNS, Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy

Within a covariant parton cascade, we discuss the impact of both finite shear viscosity $\eta$ and freeze-out dynamics on the elliptic flow generated at RHIC. We find that the enhancement of $\eta/s$ in the cross-over region of the QGP phase transition cannot be neglected in order to extract the information from the QGP phase. We also point out that the elliptic flow $v_2(p_T)$ for a fluid at $\eta/s \sim 0.1 - 0.2$ is consistent with the one needed by quark number scaling drawing a nice consistency between the nearly perfect fluid property of QGP and the coalescence process.

1. Introduction

The measure of the elliptic flow, $v_2(p_T)$, in the ultra-relativistic heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) has revealed that the so-called quark-gluon plasma (QGP) is an almost perfect fluid. However several approaches indicate that even a small finite value of the shear viscosity to entropy density ratio $\eta/s \sim 0.1 - 0.2$ affect significantly the strength of $v_2(p_t)$ \cite{1, 2}. Hence viscous corrections to ideal hydrodynamics are indeed large and causality and stability problems present in first order relativistic Navier Stokes hydrodynamics cannot be avoided \cite{3, 4}. Second-order Israel-Stewart approach has been developed to simulate the RHIC collision providing a first estimate of the $\eta/s$ \cite{3}. Such an approach, apart from the limitation to 2+1D simulations, has the more fundamental problem that it is based on a gradient expansion at second order that is not complete and that anyway cannot be sufficient to describe correctly the dynamics of a fluid with large $\eta/s$ as the one in the hadronic phase \cite{3, 4}.

We have developed a covariant kinetic approach that is able to simulate a fluid at finite $\eta/s$ by mean of a local renormalization of the cross section, $\sigma \cdot \eta/s = (p)/15\rho$, similarly to \cite{4}, see Ref.\cite{5, 6} for more details. This has the advantage to be a 3+1D approach not based on a gradient expansion that is valid also for large viscosity and for out of equilibrium momentum distribution allowing a reliable description also of the intermediate $p_T$ range where the important properties of quark number scaling (QNS) of $v_2(p_t)$ have been observed \cite{7}.
2. Impact of $\eta/s$ increase in the cross-over region

We focus on the $Au + Au$ collisions at $\sqrt{s} = 200$ AGeV employing standard Glauber initial conditions in r-space, a Boltzmann equilibrium distribution in momentum space for partons at $p_T < 2$ GeV and a minijet distribution at higher $p_T$.

A first objective is to evaluate the importance of the increase of the $\eta/s$ of the matter in the cross-over transition and in the hadronic phase [8]. This is of particular relevance because most of the work done till now to evaluate $\eta/s$ has been done in the viscous hydrodynamics framework keeping the $\eta/s$ constant during the entire evolution of the hadronic phase [11][2]. As also mentioned in Ref.[3], it is desirable to take into account the evolution of the $\eta/s$ inside and below the QCD phase transition. We have realized this imposing an increase of the $\eta/s$ as a function of the local energy density, as shown in Fig.1. While in hydrodynamics the $\eta/s$ is kept constant during the entire evolution of the system (dashed lines) in our calculation it increases when the cross-over region starts. The impact of such increase on the $v_2(p_T)$ is shown on the right side of Fig.1. We see that even if most of the $v_2(p_T)$ is built up during the pure QGP phase, the cross-over region can still produce a damping of the elliptic flow. Such a finding is similar to Ref.[9], but here it is entwined in the context of QGP finite $\eta/s$ showing the relevance for its evaluation. From Fig.1 we can deduce that neglecting the expected increase of $\eta/s$ across the transition can introduce a systematic error of the order of $40-50\%$.

3. Scalings of $v_2$

An energy density dependent $\eta/s$ represents also a way to realize a smooth kinetic freeze-out (f.o.) of the system. In Ref.[6], Fig.2 (left) here, we have shown that it is indeed the f.o. mainly responsible for the observed breaking of the scaling of $v_2(p_T)$ with the initial space eccentricity $\epsilon_x$ [10][11], at variance with ideal hydrodynamics prediction.
Figure 2. Left: $v_2(p_T)$ over eccentricity for different impact parameters. Right: Elliptic flow vs. $p_T$ for three different value of $\eta/s_{QGP}$ at $b=5$fm. Circles are data for the corresponding centrality [10] rescaled according to the $n_q$-scaling.

We notice the effect of viscosity increases with $p_T$ and is larger in the intermediate-$p_T$ region see Fig.[2]. Moreover when both a suitable f.o. condition and a finite $\eta/s$ are taken into account for the description of the fireball evolution, not only the breaking of the $v_2/\epsilon_x$ scaling is reproduced along with the persistent $v_2(p_T)/<v_2>$ one [11], but also the shape of $v_2(p_T)$ is consistent with the one expected from QNS [7]. In Fig.(2) (right) $v_2(p_T)$ at partonic level for different $\eta/s$ is shown together with the data from PHENIX, rescaled by the number of quarks that in the QNS scenario should correspond to quark one. We can see that a $\eta/s \sim 0.15 - 0.2$ is consistent with $n_q$ scaling. Quantitatively a comparison with experiments needs the inclusion of an equation of state with phase transition that in the context of hydrodynamics has been shown to reduce significantly the $v_2$ [2] and therefore it can be envisaged to shift the agreement with the data down to $\eta/s \sim 0.1$. The inclusion of a mean field dynamics with phase transition is under investigation [12].

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