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ScienceDirect
Nuclear Physics B 839 (2010) 187–293
NUCLEAR PHYSICS B
www.elsevier.com/locate/nuclphysb

Five easy pieces: The dynamics of quarks in strongly coupled plasmas

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Received 27 August 2009; received in revised form 14 June 2010; accepted 15 June 2010

Available online 18 June 2010

Abstract

We revisit the analysis of the drag a massive quark experiences and the wake it creates at a temperature $\mathcal{T}$ while moving through a plasma using a gravity dual that captures the renormalisation group runnings in the dual gauge theory. Our gravity dual has a black hole and seven branes embedded via Ouyang embedding, but the geometry is a deformation of the usual conifold metric. In particular the gravity dual has squashed two spheres, and a small resolution at the IR. Using this background we show that the drag of a massive quark receives corrections that are proportional to powers of $\log \mathcal{T}$ when compared with the drag computed using AdS/QCD correspondence. The massive quarks map to fundamental strings in the dual gravity theory, and we use this to analyse their behavior at strong 't Hooft coupling. We also study the shear viscosity in the theory with running couplings, analyse the viscosity to entropy ratio and compare the result with the bound derived from AdS backgrounds. In the presence of higher order curvature square corrections from the back-reactions of the embedded D7 branes, we argue the possibility of the entropy to viscosity bound being violated. Finally, we show that our set-up could in-principle allow us to study a family of gauge theories at the boundary by cutting off the dual geometry respectively at various points in the radial direction. All these gauge theories can have well-defined UV completions, and more interestingly, we demonstrate that any thermodynamical quantities derived from these theories would be completely independent of the cut-off scale and only depend on the temperature at which we define these theories. Such a result would justify the holographic renormalisabilities of these theories which we, in turn, also demonstrate. We give physical interpretations of these results and compare them with more realistic scenarios.

Keywords: Gauge/gravity duality; D-branes; F-theory

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0550-3213/$ – see front matter
doi:10.1016/j.nuclphysb.2010.06.014

1. Introduction

There is no question that understanding the behavior of many-body QCD in the strong coupling regime is a hard problem to solve, but this needs to be done. The wealth of intriguing experimental data obtained at the Relativistic Heavy Ion Collider (RHIC) has made this situation abundantly clear. One of the main goals of the RHIC program is the creation and the analysis of the quark gluon plasma, a new phase of matter predicted by lattice QCD. The goal of this paper is to discuss several quantities that can be related to observables measured at RHIC, or to be measured at the LHC. Calculations are done in a regime where the gauge sector is non-perturbative, using techniques borrowed from string theory.

From the early days of the RHIC experiments, the appearance of a strong elliptic hydrodynamic flow was taken as a consequence of early thermalization (before $1\ \mathrm{fm}/c$), and indicative of QGP formation [1]. The elliptic flow, defined as the second harmonic component of the momentum distribution, develops when the system undergoing the hydrodynamic expansion has an elliptical shape with different short and long axes. This difference in the spatial shape causes difference in the pressure-gradient, which in turn causes the particles to accelerate more in the short axis direction. The anisotropy in the acceleration then causes the final momentum distribution to be anisotropic. The efficiency of this process of generating the momentum space anisotropy from the spatial anisotropy, however, depends on the size of the shear viscosity η: a quantity that will be discussed here in some detail. Another experimental observable that has been linked to the formation of a plasma of quarks and gluons is the amount of energy lost by a fast parton travelling through this hot and dense medium. This phenomenon has also been dubbed *jet quenching*. Interestingly, there is a theoretical link between the concept of a small shear viscosity and that of a large jet quenching [2]. The hard partons that travel through the strongly interacting plasma may also leave a wake behind, owing to the medium's response to the source which is the hard jet. Somewhat related, the amount of energy lost by a heavy quark has been of great interest as well: the drag force can be related to the properties of the strongly interacting medium. Interestingly, the kinematics of bound states with a heavy quark can be observed through semileptonic decay channels. We compute the drag force experienced by a quark, as it looses energy to the surrounding medium. A brief introduction to some of these topics follows, before the general organization of the paper is outlined.

1.1. Shear viscosity and the viscosity to entropy bound

The shear viscosity represents the strength of the *collective* interaction between the two laminally flowing layers. Roughly speaking, large shear viscosity means faster mixing of the particles in two neighboring laminas. Somewhat counter-intuitively, the strength of this collective interaction is actually smaller when the microscopic interaction is stronger. This is because the rate of mixing is controlled by the mean free path. When the mean free path is small compared to the typical size of the flow velocity variation, two laminas with different flow velocities cannot easily mix since the exchange of particles is limited to the small volume near the interface of the two laminas: Most particles in the fluid just flows along as if there is no other layers nearby. On the other hand, if the mean free path is comparable to the typical size of the flow velocity variation, then mixing between different layers can proceed relatively quickly.

When the elliptic flow develops, the fluid has anisotropic fluid velocity distribution. Since the shear viscosity controls the mixing, a large shear viscosity can quickly wash out these difference