Nonconformal holographic model for D-meson suppression at energies available at the CERN Large Hadron Collider

Santosh K. Das1,2,3 and Ali Davody4

1 Department of Physics, Yonsei University, Seoul, Korea
2 Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, 1-95125 Catania, Italy
3 Laboratori Nazionali del Sud, INFN-LNS, Via S. Sofia 62, I-95123 Catania, Italy
4 School of Particles and Accelerators, Institute for research in Fundamental Science P. O. Box 11365-9161, Tehran, Iran

The drag force of charm quarks propagating through a thermalized system of Quark Gluon Plasma (QGP) has been considered within the framework of both conformal/non-conformal Anti de Sitter (AdS) correspondence. Newly derived Einstein Fluctuation-Dissipation relation has been used to calculate the heavy flavor diffusion coefficients. Using the drag and diffusion coefficients as inputs Langevin equation has been solved to study the heavy flavor suppression factor. It has been shown that within conformal AdS correspondence the D-meson suppression at LHC energy can be reproduced where as the non-conformal AdS correspondence fail to reproduce the experimental results. It suggests collisional loss alone within non-conformal AdS correspondence can not reproduce the experimental results and inclusion of radiative loss becomes important.

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I. INTRODUCTION

The nuclear collisions at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider(LHC) energies are aimed at creating a new state of matter where the bulk properties of the matter are governed by the light quarks and gluons. Such a state of matter is called Quark Gluon Plasma (QGP). The study of QGP is a field of great contemporary interest and the heavy flavors, mainly, charm and bottom quarks, play a vital role in such studies. This is because heavy quark do not constitute the bulk part of the system and their thermalization time scale is larger than the light quarks and gluons and hence heavy quarks can retain the interaction history very effectively. Therefore, the propagation of heavy quarks through QGP can be treated as the non-equilibrium heavy quark executing Brownian motion within the framework of both conformal/non-conformal Anti de Sitter (AdS) correspondence. Newly derived Einstein Fluctuation-Dissipation relation has been used to study such a system.

In the recent past several attempt has been made to study both heavy flavor suppression and elliptic flow within the framework of perturbative QCD. However it is pointed out that the perturbative expansion of the charm-quark diffusion coefficient is not well convergent at the temperature range attainable at RHIC and LHC collisions. Hence, non-perturbative contributions are important to improve heavy quark diffusion. One possible alternative way to estimate the drag force is the gauge/string duality, namely the conjectured equivalence between conformal N=4 SYM gauge theory and gravitational theory in Anti de Sitter space-time i.e. AdS/CFT. Some attempts have been made in this direction to study heavy flavor suppression. Within this AdS/CFT model RHIC results has been reproduced well whereas a few other attempts suggest that AdS/CFT under predicts recent ALICE results. The non-zero value of bulk viscosity obtained form lattice QCD calculations indicate that at the temperature range relevant of RHIC and LHC collisions the fluid behavior is non-conformal. Therefore, it would be interesting to construct a gravitational dual which captures some of the properties of QCD. This can be done by breaking the conformal symmetry in the AdS space and construct AdS/QCD models. In this paper we have made an attempt to test these AdS/QCD models by studying D-meson suppression at LHC collision energies.

II. LANGEVIN EQUATION AND HOLOGRAPHY

Consider a heavy quark of mass $M$ and energy $E$ passing through QGP at a temperature $T \ll M$. The heavy quark suffers random kicks leading to momentum transfer $q \sim T$ in a single elastic collision with the thermal bath. Hence, it requires many collisions to change the heavy quark momentum significantly. The dynamics of heavy quarks propagating through the QGP can thus be approximated as a succession of uncorrelated momentum kicks which leads to a Fokker-Planck equation that can be realized from the Langevin equation.

\[
\frac{dp_i}{dt} = -\gamma_D p_i + \xi_i, \quad <\xi_i(t)\xi_j(t')> = D_{ij}\delta(t-t') \tag{1}
\]

where $\gamma_D$ is the drag coefficient, $\xi$ is the random force and $D$ is the diffusion coefficient.

A. Drag and diffusion coefficients in conformal holography

AdS/CFT in its original form, relates $N = 4$ SYM gauge theory on four-dimensional space time to the IIB string theory on $AdS_5 \times S^5$ background, where the conformal symmetry of SYM gauge theory is realized in the
conformal isometry of dual metric \[50\]. This correspondence can also be generalized to finite temperature, where the space-time dual to \( N = 4 \) SYM plasma with temperature \( T \) is a black-hole AdS with Hawking temperature \( T \) \[51\]. The metric of AdS black hole is

\[
ds^2 = \frac{1}{r^2}\left(\frac{dr^2}{f(r)} - f(r)dt^2 + d\mathbf{x}^2\right) f(r) = 1 - \left(\frac{r_\text{h}}{r}\right)^4
\]

where \( r_\text{h} = 1/(\pi T) \) is the horizon of the black hole. According to the standard AdS/CFT prescription, the energy-momentum tensor of dual theory is encoded in behavior of metric near the boundary. Using this dictionary we find that metric \[43\] is dual to a plasma with conformal equation of state, \( e = 3p \).

By studying the dynamics of trailing string in this background \[29\] \[40\], it has been shown that the drag force exerted on a moving quark in a static \( \text{N}=4 \) SYM plasma is given by

\[
F_{\text{conf}} = \frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}}{2} T_{\text{SYM}}^3 M \equiv -\Gamma_{\text{conformal}} p
\]

Also by investigating the fluctuations around the classical string configuration \[11\] \[12\], one finds the transverse diffusion coefficient as follows

\[
D = \pi\sqrt{\lambda} \gamma^2 T_{\text{SYM}}^3
\]

where \( \gamma \) is the Lorentz factor, \( \gamma \equiv 1/\sqrt{1-v^2} \).

Using \[43\] and \[44\] we find the following "modified Einstein relation" between drag and diffusion coefficient

\[
D = 2MT_{\text{SYM}}\sqrt{\gamma} \Gamma_{\text{conformal}}
\]

In terms of world-sheet temperature, \( T_s = T/\sqrt{\gamma} \), the above equation takes the following form

\[
D = 2ET_s \Gamma_{\text{conf}}
\]

this is the usual Einstein relation for a relativistic particle moving in a thermal bath with temperature \( T_s \). So the world-sheet temperature, \( T_s = T/\sqrt{\gamma} \), is the effective temperature for a quark moving in a static plasma \[14\].

In order to apply \( N = 4 \) SYM results to QCD, we use alternative scheme introduced in \[45\] \[51\]. According to this proposal, one equates the energy density of QCD and SYM, which leads to \( T_{\text{SYM}} = T_{\text{QCD}}/3^{1/4} \). Also by comparing string prediction for quark-antiquark potential with lattice gauge theory we find that, \( 3.5 < \lambda < 8 \) \[45\]. Therefore in terms of QCD temperature and coupling we have

\[
\Gamma_{\text{conf}} = \frac{T_{\text{QCD}}^3}{M}
\]

\[
D_{\text{conf}} = \frac{2\alpha}{3^{1/4}} T_{\text{QCD}}^3
\]

where \( \alpha = \frac{\sqrt{\lambda}}{2\sqrt{3}} = 2.1 \pm 0.5 \).

**B. Drag and diffusion coefficients in non-conformal holography**

In the previous section we have described different ways of evaluating the drag and diffusion coefficients of SYM plasma. However SYM and QCD have different properties: equation of state, phase transition, symmetries, etc. In particular SYM plasma is a conformal fluid with vanishing bulk viscosity. On the other hand, QGP looks like a conformal fluid at very high enough temperature, \( T >> T_c \). So it would be interesting to construct a gravitational dual which captures some of the properties of QCD \[46\] \[48\]. To do so, we have to break the conformal symmetry of AdS space. In \[46\] \[47\] a 5-dimensional non-conformal gravitational model dual to QCD is proposed, where the non-trivial profile of dilation breaks down the conformal symmetry. The action of 5-dimensional Einstein-dilation is given by

\[
S = -\frac{1}{16\pi G_5} \int d^5x \sqrt{-g} (R - \frac{4}{3} (\partial \phi)^2 + V(\phi))
\]

where \( G_5 \) is the five-dimensional Newton constant. By choosing a suitable scalar potential one can mimics the QCD equation of state and other thermal properties. We choose the suggested potential in \[49\]:

\[
V(\lambda) = \frac{12}{l^2} \left(1 + V_0 \lambda + V_1 \lambda^{3/2} \ln(1 + V_2 \lambda^{3/2} + V_3 \lambda^2)\right)^{1/2}
\]

with

\[
V_0 = \frac{8}{9} \beta_0, \quad V_2 = \beta_0^3 \left(\frac{23 + 36 \frac{\beta_0}{\lambda}}{81V_1}\right)^2, \quad \beta_0 = \frac{22}{3(4\pi l_\text{s})^2}, \quad \beta_1 = \frac{51}{121} \beta_0^2.
\]

It has been shown \[49\] that this potential reproduces the lattice EOS and velocity of sound. Drag force in this model is calculated in \[43\]:

\[
F_{\text{non-conf}} = -v e^{2A_s(r_s)} \frac{\sqrt{\frac{\alpha}{2\pi l^2}}}{\Gamma_{\text{non-conf}} p}
\]

where \( v \) is the speed of quark, \( r_s \) is the world-sheet horizon and \( A_s(r_s(v)) \) is conformal factor of metric in string frame evaluated at the world-sheet horizon. Here \( l_s \) is a free parameter which can be fixed by matching the string tension to the string tension derived from the lattice QCD calculations and is given by \[49\]:

\[
l_s \approx 0.15 l
\]
Note that unlike conformal case, non-conformal drag coefficient is velocity dependent through $r_s$. It is useful to study the ratio of drag force in non-conformal holography to the conformal case:

$$\frac{F_{\text{non-conf}}}{F_{\text{conf}}} = \frac{\Gamma_{\text{non-conf}}}{\Gamma_{\text{conf}}} = \frac{2.1}{\alpha} R(v, T/T_c)$$

(14)

where $R$ is a function of temperature and velocity of quark. We reproduced this function in Fig.1 and Fig.2 for completeness [51]. If we take $l_s$ as a free parameter, then this relation takes the following form:

$$\Gamma_{\text{non-conf}} = \left(\frac{0.15}{l_s}\right)^2 \frac{2.1}{\alpha} R(v, T/T_c) \Gamma_{\text{conf}}$$

$$= \left(\frac{0.15}{l_s}\right)^2 \frac{2.1}{\alpha} R(v, T/T_c) \frac{T_{QCD}^2}{M}$$

(15)

The modified Einstein relation (6) for non-conformal becomes

$$D_{\text{non-conf}} = 2E T_{s,\text{non-conf}} \Gamma_{\text{non-conf}}$$

(16)

where $T_{s,\text{non-conf}}$ is the world-sheet temperature in non-conformal case. In terms of the ratio of world-sheet temperature in non-conformal to conformal case, $G(v, T/T_c) = \frac{T_{s,\text{non-conf}}}{T_{s,\text{conf}}}$, the above equation takes the following form [44]

$$D_{\text{non-conf}} = 2E T_{s,\text{conf}} G(v, T/T_c) \Gamma_{\text{non-conf}}$$

$$= \frac{2M}{3} \sqrt{T QCD} G(v, T/T_c) \Gamma_{\text{non-conf}}$$

(17)

There are several limits on AdS/CFT results discussed here. In [30] the effects of hydrodynamic expansion of QGP on drag force exerted on a moving quark have been studied. It was shown that there is an upper bound for velocity of quark ($v_{\text{bound}} \approx 0.98$) such that below this bound, drag force acting on the quark is just the localized version of static plasma (replacing the temperature in drag formula of static plasma by instantaneous temperature of QGP). On the other hand, for a fast quark with a velocity bigger than the above bound (for charm quark this bound in velocity corresponds to around $10 GeV$ in energy) drag force is not a local function of the medium variables. Thus, for $p_T \gg 10 GeV$ the local approximation is not valid due to hydrodynamic expansion.

Also it has been shown in [16] that for $p_T > 10 GeV$ the white noise approximation in Langevin equation breaks down. Above this bound, one needs the full frequency-dependent correlators to study the diffusion process [51].

### III. INITIAL CONDITION AND SPACE TIME EVOLUTION

After obtaining the drag and diffusion coefficients from the conformal and non-conformal holography, we need the initial heavy quark momentum distributions for solving the Langevin equation. In the present work, the $p_T$ distribution of charm quarks in pp collisions have been generated using the POWHEG [52] code, implementing pQCD at NLO. It should be mentioned here that the $p_T$ distribution of charm quarks in pp collisions generated using POWHEG can reproduce the experimental results [16, 53]. With this initial heavy quarks momentum distribution, the Langevin equation has been solved. We convolute the solution with the fragmentation functions of the heavy quarks to obtain the $p_T$ distribution of D mesons. For heavy quark fragmentation, we use the Peterson function [54]. Experimental data (pp collisions) on the electron spectra originated from the decays of the heavy mesons can be described if Peterson fragmentation is applied to the POWHEG output. This has been studied in Ref. [16].

The experimental interest is the nuclear suppression factor ($R_{AA}$), defined as

$$R_{AA}(p_T) = \frac{d N_{AA}}{d^3 p_{T} d y} \frac{N_{\text{coll}}}{d^3 p_{T} d y}$$

(18)

a ratio that summarizes the deviation from what would be obtained if the nucleus-nucleus collision is an incoherent superposition of nucleon-nucleon collisions. In Eq. 18 $N_{\text{coll}}$ stands for the number of nucleon-nucleon interactions in a nucleus-nucleus collision. In the present scenario the variation of temperature with time is governed by the the equation of state (EOS) or velocity of sound of the thermalized system undergoing hydrodynamic expansion. Hence, ($R_{AA}$) is sensitive to velocity of sound.

![FIG. 1: Variation of $R(v, T/T_c)$ as a function of momentum $p_T$.](image)

The system formed in nuclear collisions at relativistic energies evolves dynamically from the initial QGP state at temperature, $T_i$ to the quark-hadron transition temperature, $T_c$. Boost invariance Bjorken [55] model has been used for the space time description of the QGP. It
is expected that the system formed in nuclear collisions at RHIC and LHC energy in the central rapidity region is almost free from net baryon density. Therefore, the equation governing the conservation of net baryon number need not be considered in the present case.

The total amount of energy dissipated in the system by the charm quarks depends on the number of interaction it undergoes i.e. on the path length \( L \) it traverses within the medium. The value of \( L \) in turn depends on the spatial co-ordinates, \((r, \phi)\) of the point of creation of the charm quark. The probability, \( P(r, \phi) \) that a charm quark is created at \((r, \phi)\) depends on the number of binary collisions at that point. \( P(r, \phi) \) is given by:

\[
P(r, \phi) = \frac{2}{\pi R^2} \left(1 - \frac{r^2}{R^2}\right) \theta(R - r) \tag{19}
\]

where \( R \) is the nuclear radius. It should be mentioned here that the expression in Eq. (19) is an approximation for the collisions with zero impact parameter. In obtaining the above expression for \( P(r, \phi) \) spherical geometry has been assumed, therefore, it is better applicable for central collisions. The charm quark created at \((r, \phi)\) in the transverse plane of the medium will propagate a path length, \( L \) given by:

\[
L = \sqrt{R^2 - r^2 \sin^2 \phi - r \cos \phi}.
\]

The geometric averaging has been performed for the the drag and diffusion coefficients along the path length. The initial temperature \( (T_i) \) and thermalization time \( (\tau_i) \) of the background QGP are constrained by the following equation:

\[
T_i^3 \tau_i \approx \frac{2\pi^4}{45\zeta(3)} \frac{1}{4a_{eff}} \frac{1}{\pi R^2} \frac{dN}{dy} \tag{20}
\]

where \( (dN/dy) \) is the measured all hadronic multiplicity, \( \zeta(3) \) is the Riemann zeta function and \( a_{eff} = \pi^2 g_{eff}/90 \) where \( g_{eff} = (2 \times 8 + 7 \times 2 \times 2 \times 3 \times N_F)/8 \) is the degeneracy of quarks and gluons in QGP, \( N_F = \) number of flavors. We use the measured total hadronic multiplicity at central rapidity, \( dN/dy \approx 1100 \) for RHIC and \( dN/dy \approx 2400 \) for LHC energies. Eq. (20) works in absence of viscous loss where the time reversal symmetry of the system is valid. Initial conditions for the LHC and RHIC energies has been taken from Ref [56] and Ref [16] respectively.

### IV. RESULTS

![FIG. 3: Variation of \( R_{AA} \) as a function of momentum \( p_T \) for D meson at ALICE within conformal model. Experimental data taken from [34]. Although we have present the results here upto \( p_T \sim 15 \) GeV, it should be mentioned here that the white noise approximation in the Langevin equation is not valid beyond \( p_T = 10 \) GeV. In this backdrop the theoretical results should be taken.](image3.png)

The ratio of interaction obtained from non-conformal to conformal is displayed in Fig 1 with respect to \( p_T \). It is
observed that the non-conformal drag force reduced by a factor 3-4 time than the conformal case. The momentum dependent is also weak as shown in Fig 1. Similarly in Fig 2 the variation of the ratio from non-conformal to conformal is plotted with respect to $T$ for fixed $p_T$. It is found that non-conformal drag force reduced by a factor 2-4 than the conformal. We use $T_c=170$ MeV.

With the formalism discussed above the result for $(R_{AA})$ are shown in Fig 3 for the conformal holography. It is found that the ALICE data can be explained reasonably well for $\alpha = 2$. For $\alpha = 3$ we under predicts the experimental data. Here it may be mentioned that within the conformal holographic model the RHIC results was explained reasonable well for $\alpha = 2-3$ in Langevin dynamics. However the conformal holography model based on HQ energy loss under predict the recent ALICE data [34] presented in ref [32, 33]. As the conformal results are away from reality, in a very first attempt we are implemented the con-conformal results with the Langvine equation to study the D-meson suppression at LHC energy.

In Fig 4 the variation of $(R_{AA})$ has been shown as a function of $p_T$ for various value of $l_s$ within the non-conformal holography. It is found that non-conformal drag force over predicts the data for a realistic value of $l_s = 0.15$. It is quite expected as the non-conformal drag forces suppressed by a factor 2-4 as compare to conformal case (in Fig 1 and Fig 2) depending on temperature and momentum. Apart from the drag force, the conformal and non-conformal AdS follow different Einstein relation to have the diffusion coefficients as well as they have different EOS [57] which indeed affect the RAA [12, 21]. Considering only the collisional loss within the non-conformal holographic fail to reproduced the experimental data. The results will improve if the radiative loss from the non-conformal holography will be taken into account. We may mention, the calculation of radiative energy loss in holography can be found in Ref. [58] for conformal case and in Ref. [60] for non-conformal holography. In Fig 5 the time evolution of the temperature at the RHIC energy has been shown for both the conformal and non conformal scenarios. It is found that the time evolution is bit slow in the non conformal case in comparison with the conformal case and hence the life time of the QGP is larger for the non conformal case.

The PHENIX and STAR collaborations [4, 5] have measured the $R_{AA}(p_T)$ of non-photonic single electrons originating from the decays of mesons containing both open charm and bottom quarks at RHIC energy. It will be interesting to study the the RHIC data within the ambit of the present model described above. The $p_T$ spectra of non-photonic electrons originating from the heavy ion collisions can be obtained as follows (for details we refer to [12, 14]): (i) First we obtain the $p_T$ spectra of D and B mesons by convoluting the solution of the Langevin equation for the charm and bottom quarks with their respective fragmentation functions as discussed earlier. (ii) Then we calculate the $p_T$ spectra of the single electrons resulting from the decays of $D$ and $B$ mesons: $D \rightarrow Xe\nu$ and $B \rightarrow Xe\nu$ respectively. In the same way, the electron spectrum from the pp collisions can be obtained from the charm and bottom quark distributions, which represent the initial conditions for the solution of the Langevin equation. Theoretical results obtained within the conformal model contrasted with the experimental data from RHIC experiments in Fig. 6. It is found that the RHIC data can be explained reasonably well within the conformal model for $\alpha = 3$. It can be mentioned that the suppression we are getting for $\alpha = 2$ is less than the suppression obtained in [31]. This is may be due to the different initial condition as well as the uncertainty associated with the addition of electron coming from the decay of D and B mesons [21]. In Fig. 7 we compare the RHIC data with our results obtained within the non-conformal holography.
conformal model. The results reveal that non-conformal model over predicts the data for the realistic value of $l_s = 0.15$ like the LHC case.

It may be mentioned here that in the present study we are using the Gaussian white noise approximation to include the collision. According to the recent study [44] for the conformal case white noise approximation will be valid if

$$T_s \gg \eta_D$$ (21)

where $T_s$ is the world-sheet horizon and $\eta_D$ is the drag force coefficient. Using $T_s = T/\sqrt{\gamma}$ and the value of the drag coefficient used in the present calculation leads to the bound on charm quark momentum at $T \sim T_c$ is $p_{max} \sim 10$ GeV and at $T \sim 2T_c$ is $p_{max} \sim 4.5$ GeV. In this backdrop the theoretical results should be taken. The corresponding bound on the bottom quark is about 100 GeV and 50 GeV at $T \sim T_c$ and $T \sim 2T_c$ respectively. For non conformal case the momentum bound is much less restrictive than the conformal case as the non conformal drag coefficient is much smaller than the conformal case. Moreover the white noise approximation is a good approximation for the non conformal background than the conformal case.

V. SUMMARY AND CONCLUSIONS

In an attempt, we have studied the D-meson suppression at LHC energy within both the conformal and the non-conformal holographic model. It is observed that the non-conformal holographic model over predicts the ALICE data where as the data can explained reasonably well for $\alpha = 2$ within the conformal holography. This is because the non-conformal drag force suppressed by a factor of 2-4 compared to the conformal case. The same formalism has been applied to study the experimental data on nonphotonic single-electron spectra measured by STAR and PHENIX collaborations at the highest RHIC energy. The data is well reproduced within the conformal model for $\alpha = 3$ where as the non-conformal holographic model over predicts the data for the realistic value of $l_s$. We found that, within the conformal holographic model, RHIC and LHC data can not be reproduced simultaneously with the same value of $\alpha$. It is expected that inclusion of the radiative loss from the non-conformal side will improve the results. Therefore, more systematic studies are needed from the non-conformal side like inclusion of radiative loss, etc to improve the description of the experimental results.

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[60] Using this scheme it has been shown [31] that AdS/CFT predictions lead to reasonable results at RHIC energy
[61] Note that $T$ is scheme independent
[62] we have checked that our calculations correctly reproduce the results of [49]