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

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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 and nonconformal anti–de Sitter (AdS) correspondence. A newly derived Einstein fluctuation-dissipation relation has been used to calculate the heavy flavor diffusion coefficients. Using the drag and diffusion coefficients as inputs, the 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 Large Hadron Collider energy can be reproduced, whereas the nonconformal AdS correspondence fails to reproduce the experimental results. This suggests collisional loss alone within nonconformal AdS correspondence cannot reproduce the experimental results, and inclusion of radiative loss becomes important.

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I. INTRODUCTION

Nuclear collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies are aimed at creating a new state of matter, where the bulk properties of the matter are governed by light quarks and gluons. Such a state of matter is called quark gluon plasma (QGP) [1]. 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 quarks do not constitute the bulk part of the system, and their thermalization time scale is larger than that of the light quarks and gluons; hence heavy quarks can retain the interaction history very effectively. Therefore, the propagation of heavy quarks through QGP can be treated as nonequilibrium heavy quarks executing Brownian motion [2,3] in a thermal bath of QGP, and the Langevin equation can be used to study such a system.

In the recent past several attempts were made to study both heavy flavor suppression [4,5] and elliptic flow [6] within the framework of perturbative QCD [7–23]. However, it was pointed out that the perturbative expansion of the charm-quark diffusion coefficient is not well converged [24] at the temperature range attainable in RHIC and LHC collisions. Hence, nonperturbative [25–27] contributions are important to improve heavy quark diffusion. One possible alternative way to estimate the drag force is the gauge/string duality [28], 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 [29], whereas a few other attempts [30,31] suggest that AdS/CFT underpredicts recent ALICE results [32]. The nonzero value of bulk viscosity obtained from lattice QCD calculations [33] indicates that, at the temperature range relevant to RHIC and LHC collisions, the fluid behavior is nonconformal. 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 constructing AdS/QCD models [34,35]. 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 [12,14,36]:

$$\frac{dp_i}{dt} = -\gamma_D p_i + \xi_i, \quad \langle \xi_i(t)\xi_j(t')\rangle = D_{ij}\delta(t-t'), \qquad (1)$$

where γ_D is the drag coefficient, ξ 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 the dual metric [28]. 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 [37]. The metric of the AdS black hole is

$$ds^2 = \frac{1}{r^2}\left(\frac{dr^2}{f(r)} - f(r)dr^2 + d\vec{x}^{\,2}\right), \quad f(r) = 1 - \left(\frac{r_h}{r}\right)^4, \qquad (2)$$

where $r_h = 1/(\pi T)$ is the horizon of the black hole. According to the standard AdS/CFT prescription, the energy-momentum tensor of dual theory is encoded in the behavior of the metric near the boundary. Using this dictionary we find that metric (2) is dual to a plasma with conformal equation of state $e = 3p$.

By studying the dynamics of the trailing string in this background [38,39], it has been shown that the drag force exerted on a moving quark in a static $N = 4$ SYM plasma is given by

$$F_{\rm conf} = \frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}}{2} T_{\rm SYM}^2 \frac{p}{M} \equiv -\Gamma_{\rm conf}\ p \qquad (3)$$

Also, by investigating the fluctuations around the classical string configuration [40,41], one finds the transverse diffusion coefficient as follows:

$$D = \pi\sqrt{\lambda}\,\gamma^{\frac{1}{2}}\,T_{\rm SYM}^3, \qquad (4)$$

where γ is the Lorentz factor, $\gamma = 1/\sqrt{1-v^2}$.

Using (3) and (4) we find the following "modified Einstein relation" between drag and diffusion coefficient [42,43]

$$D = 2M\,T_{\rm SYM}\sqrt{\gamma}\,\Gamma_{\rm conf}. \qquad (5)$$

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

$$D = 2E\,T_s\,\Gamma_{\rm conf}. \qquad (6)$$

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 [43].

In order to apply $N = 4$ SYM results to QCD, we use an alternative scheme introduced in [44].[1] According to this proposal, one equates the energy density of QCD and SYM, which leads to $T_{\rm SYM} = T_{\rm QCD}/3^{\frac{1}{4}}$. Also, by comparing the string prediction for quark-antiquark potential with lattice gauge theory we find that $3.5 < \lambda < 8$ [44]. Therefore, in terms of QCD temperature and coupling we have

$$\Gamma_{\rm conf} = \alpha\frac{T_{\rm QCD}^2}{M}, \qquad (7)$$

$$D_{\rm conf} = \frac{2\alpha}{3^{\frac{1}{4}}}\gamma^{\frac{1}{2}}T_{\rm QCD}^3, \qquad (8)$$

where $\alpha = \frac{\pi\sqrt{\lambda}}{2\sqrt{3}} = 2.1 \pm 0.5$.

B. Drag and diffusion coefficients in nonconformal 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 high enough temperature, $T \gg T_c$. So it would be interesting to construct a gravitational dual which captures some of the properties of QCD [45–47]. To do so, we have to break the conformal symmetry of AdS space. In [45,46] a five-dimensional nonconformal gravitational model dual to QCD is proposed, where the nontrivial profile of dilation breaks down the conformal symmetry. The action of five-dimensional Einstein dilation is given by

$$S = -\frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R - \frac{4}{3}(\partial\phi)^2 + V(\phi)\right), \quad (9)$$

where G_5 is the five-dimensional Newton constant. By choosing a suitable scalar potential one can mimic the QCD equation of state and other thermal properties. We choose the suggested potential in [48]:

$$V(\lambda) = \frac{12}{l^2}\{1 + V_0\lambda + V_1\lambda^{\frac{4}{3}}[\ln(1 + V_2\lambda^{\frac{4}{3}} + V_3\lambda^2)]^{\frac{1}{2}}\} \quad (10)$$

with

$$F_0 = \frac{8}{9}\beta_0, \quad V_2 = \beta_0^4\left(\frac{23 + 36\frac{\beta_1}{\beta_0^2}}{81V_1}\right)^2,$$
$$\beta_0 = \frac{22}{3(4\pi)^2}, \quad \beta_1 = \frac{51}{121}\beta_0^2. \qquad (11)$$

It has been shown [48] that this potential reproduces the lattice EOS and velocity of sound. Drag force in this model is calculated in [48]:

$$F_{\rm nonconf} = \frac{-v\,e^{2A_s(r_s)}}{2\pi l_s^2} \equiv \Gamma_{\rm nonconf}\ p \qquad (12)$$

where v is the speed of the quark, r_s is the world-sheet horizon, and $A_s(r_s(v))$ is conformal factor of the 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 [48]

$$l_s \simeq 0.15\,l. \qquad (13)$$

Note that, unlike conformal case, the nonconformal drag coefficient is velocity dependent through r_s. It is useful to study the ratio of drag force in nonconformal holography to the conformal case:

$$\frac{F_{\rm nonconf}}{F_{\rm conf}} = \frac{\Gamma_{\rm nonconf}}{\Gamma_{\rm conf}} = \frac{2.1}{\alpha}R\left(v,\frac{T}{T_c}\right), \qquad (14)$$

where R is a function of temperature and velocity of the quark. We reproduced this function in Figs. 1 and 2 for completeness [48].[2] If we take l_s as a free parameter, then this relation takes the following form:

$$\Gamma_{\rm nonconf} = \left(\frac{0.15\,l}{l_s}\right)^2\frac{2.1}{\alpha}R\left(v,\frac{T}{T_c}\right)\Gamma_{\rm conf}$$
$$= \left(\frac{0.15\,l}{l_s}\right)^2 2.1\,R\left(v,\frac{T}{T_c}\right)\frac{T_{\rm QCD}^2}{M}. \qquad (15)$$

[1]Using this scheme, it has been shown [29] that AdS/CFT predictions lead to reasonable results at RHIC energy.

[2]Note that $\frac{T}{T_c}$ is scheme independent. We have checked that our calculations correctly reproduce the results of [48].

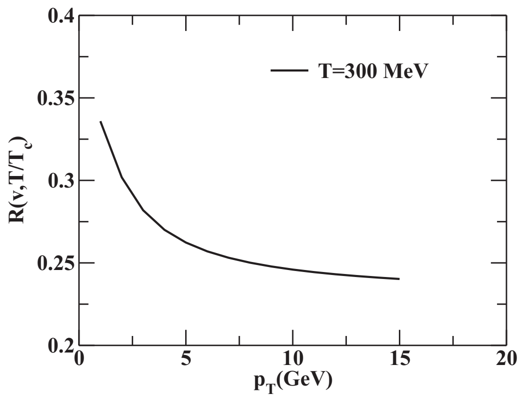

FIG. 1. Variation of $R(v,T/T_c)$ as a function of momentum p_T.

The modified Einstein relation (6) for the nonconformal case becomes

$$D_{\rm nonconf} = 2E\, T_{s,\rm nonconf}\, \Gamma_{\rm nonconf}, \tag{16}$$

where $T_{s,\rm nonconf}$ is the world-sheet temperature in the nonconformal case. In terms of the ratio of world-sheet temperature in nonconformal to conformal case, $G(v,\frac{T}{T_c}) = \frac{T_{s,\rm nonconf}}{T_{s,\rm conf}}$, the above equation takes the following form [43]:

$$\begin{aligned} D_{\rm nonconf} &= 2E\, T_{s,\rm conf}\, G\left(v,\frac{T}{T_c}\right)\Gamma_{\rm nonconf} \\ &= \frac{2M}{3^{\frac{1}{4}}}\sqrt{\gamma}\, T_{\rm QCD}\, G\left(v,\frac{T}{T_c}\right)\Gamma_{\rm nonconf}. \end{aligned} \tag{17}$$

There are several limits on AdS/CFT results discussed here. In [49] 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 the quark ($v_{\rm bound} \approx 0.98$) such that below this bound drag force acting on the quark is just the localized version of static plasma (replacing the temperature in the drag formula of the static plasma with instantaneous temperature of the QGP). On the other hand, for a fast quark with a velocity bigger than the above bound (for a 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.

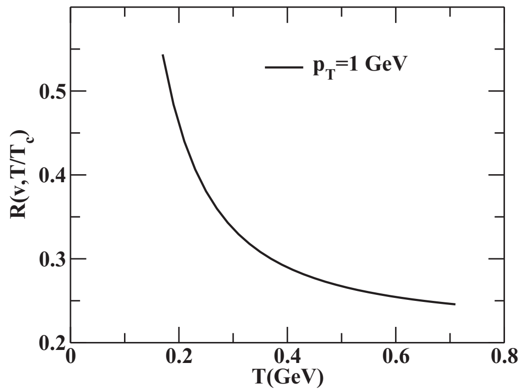

FIG. 2. Variation of $R(v,T/T_c)$ as a function of temperature T.

Also, it has been shown in [43] that, for $p_T > 10$ GeV the white noise approximation in the Langevin equation breaks down. Above this bound, one needs the full frequency-dependent correlators to study the diffusion process [50].

III. INITIAL CONDITION AND SPACE-TIME EVOLUTION

After obtaining the drag and diffusion coefficients from the conformal and nonconformal holography, we need the initial heavy quark momentum distributions to solve the Langevin equation. In the present work, the p_T distribution of charm quarks in pp collisions have been generated using the POWHEG [51] code, implementing pQCD at next-to-leading order (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 [16,52]. With this initial heavy quark momentum distribution, the Langevin equation has been solved. We convolve 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 [53]. Experimental data (pp collisions) on the electron spectra originating 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 ($R_{\rm AA}$), defined as

$$R_{\rm AA}(p_T) = \frac{\frac{dN}{d^2p_T dy}^{\rm Au+Au}}{N_{\rm coll} \times \frac{dN}{d^2p_T dy}^{p+p}}, \tag{18}$$

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) $N_{\rm coll}$ 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, ($R_{\rm AA}$) is sensitive to the velocity of sound.

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. The boost invariance Bjorken [54] 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 energies 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 coordinates (r,ϕ) of the point of creation of the charm quark. The probability $P(r,\phi)$ that a charm quark is created at (r,ϕ) 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 more applicable for central collisions. The charm quark created at (r,ϕ) 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 (τ_i) of the background QGP are constrained by the following equation:

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

where (dN/dy) is the measured all-hadronic multiplicity, $\zeta(3)$ is the Riemann zeta function, and $a_{\text{eff}} = \pi^2 g_{\text{eff}}/90$ 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. Equation (20) works in the absence of viscous loss where the time reversal symmetry of the system is valid. Initial conditions for the LHC and RHIC energies have been taken from Refs. [55] and [16] respectively.

IV. RESULTS

The ratio of interaction obtained from nonconformal to conformal case is displayed in Fig. 1 with respect to p_T. It is observed that the nonconformal drag force is reduced by a factor of 3–4 compared to the the conformal case. The momentum dependence is also weak, as shown in Fig. 1. Similarly in Fig. 2, the variation of the ratio from nonconformal to conformal is plotted with respect to T for fixed p_T. It is found that the nonconformal drag force is reduced by a factor 2–4 compared to the conformal. We use $T_c = 170$ MeV.

With the formalism discussed above the results 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 underpredict the experimental data. Here it may be mentioned that within the conformal holographic model the RHIC results were explained reasonably well for $\alpha = 2$–3 [29] in Langevin dynamics. However, the conformal holography model based on heavy quark (HQ) energy loss underpredicts the recent ALICE data [32] presented in Refs. [30,31]. As the conformal results are always from reality, in a very first attempt we implemented the conconformal 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 values of l_s within the nonconformal holography. It is found that the nonconformal drag force overpredicts the data for a realistic value of $l_s = 0.15$. This is quite expected, as the nonconformal drag force is suppressed by a factor 2–4 compared to the conformal case (in Figs. 1 and 2) depending on temperature and momentum. Apart from the drag force, the conformal and nonconformal AdS models follow different Einstein relations in order to have different diffusion coefficients as well as different EOS [56], which indeed affect the RAA [12,57,58]. Considering only the collisional loss within the nonconformal holographic model fails to reproduce the experimental data. The results will improve if the radiative loss from the nonconformal holography will be taken into account. Note that the calculation of radiative energy loss in holography can be found in Ref. [59] for the conformal case and in Ref. [60] for nonconformal holography. In Fig. 5 the time evolution of the temperature at the RHIC energy has been shown for both the conformal and nonconformal scenarios. It is found that the time evolution is a bit slow in the nonconformal case in comparison with the

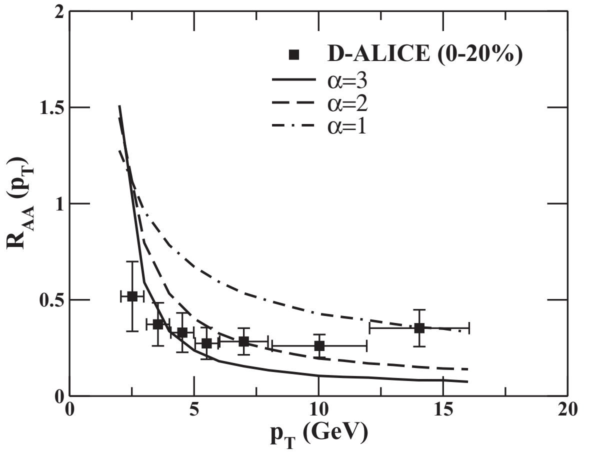

FIG. 3. Variation of R_{AA} as a function of momentum p_T for D mesons at ALICE within conformal model. Experimental data are taken from [32]. Although we have presented the results here up to $p_T \sim 15$ GeV, it should be mentioned here that the white noise approximation in the Langevin equation is not valid beyond $p_T = 10$ GeV. In this backdrop the theoretical results should be taken.

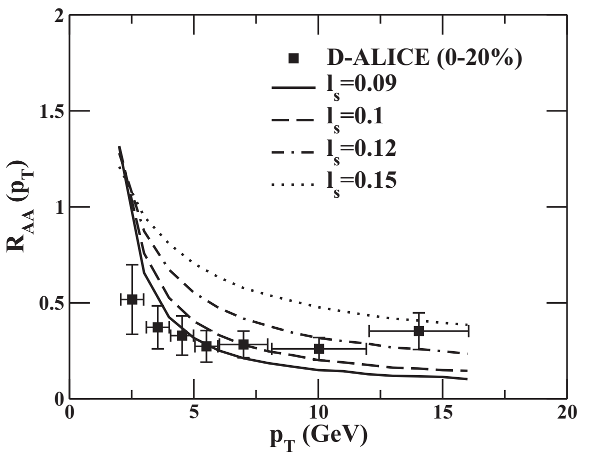

FIG. 4. Variation of R_{AA} as a function of momentum p_T for D mesons at ALICE within the nonconformal model. Experimental data are taken from [32].

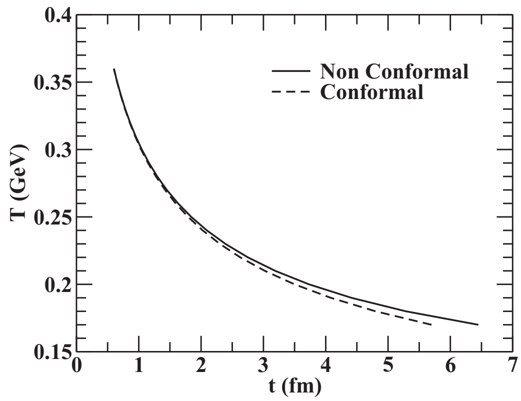

FIG. 5. Time evolution of the temperature for both the conformal and nonconformal scenarios.

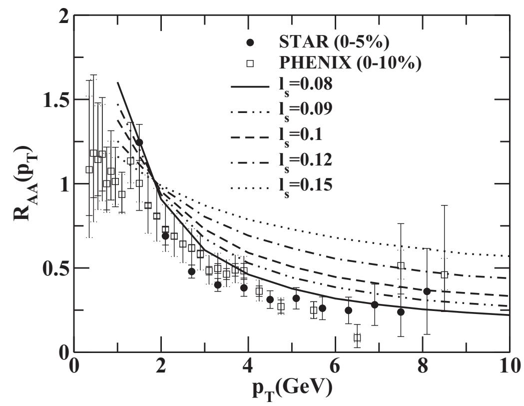

FIG. 7. Comparison of R_{AA} obtained within the nonconformal model with the experimental data obtained by STAR and PHENIX Collaboration. Experimental data are taken from [5,6].

conformal case, and hence the lifetime of the QGP is larger for the nonconformal case.

The PHENIX and STAR Collaborations [4,5] have measured the $R_{\mathrm{AA}}(p_T)$ of nonphotonic 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 scope of the present model described above. The p_T spectra of nonphotonic 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: $D \to Xe\nu$ and $B \to Xe\nu$ 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 are 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 $\alpha = 3$. Note

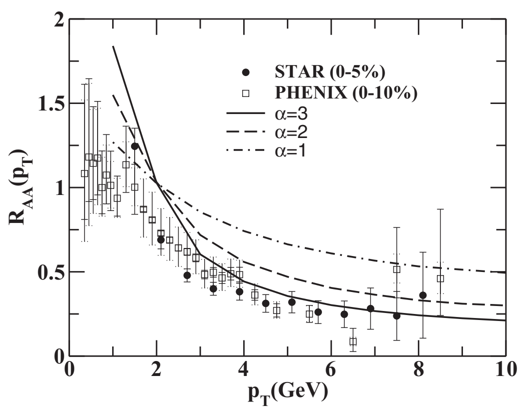

FIG. 6. Comparison of R_{AA} obtained within the conformal model with the experimental data obtained by STAR and PHENIX Collaborations. Experimental data are taken from [5,6].

that the suppression we are getting for $\alpha = 2$ is less than the suppression obtained in [29]. This may be due to the different initial condition as well as the uncertainty associated with the addition of electrons coming from the decay of D and B mesons [21]. In Fig. 7, we compare the RHIC data with our results obtained within the nonconformal model. The results reveal that the nonconformal model overpredicts the data for the realistic value of $l_s = 0.15$, like the LHC case.

In the present study we are using the Gaussian white noise approximation to include the collision. According to a recent study [43], for the conformal case the white noise approximation will be valid if

$$T_s \gg \eta_D, \tag{21}$$

where T_s is the world-sheet horizon and η_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 a bound on charm quark momentum at $T \sim T_c$ of $p_{\max} \sim 10$ GeV, and at $T \sim 2T_c$ of $p_{\max} \sim 4.5$ GeV. In this backdrop the theoretical results should be taken. The corresponding bound on the bottom quark is about 100 and 50 GeV at $T \sim T_c$ and $T \sim 2T_c$ respectively. For the nonconformal case the momentum bound is much less restrictive than in the conformal case, as the nonconformal drag coefficient is much smaller than in the conformal case. Moreover the white noise approximation is a better approximation for the nonconformal background than in the conformal case.

V. SUMMARY AND CONCLUSIONS

We have studied D-meson suppression at LHC energy within both the conformal and the nonconformal holographic models. We observed that the nonconformal holographic model overpredicts the ALICE data, whereas the data can explained reasonably well for $\alpha = 2$ within the conformal holography. This is because the nonconformal 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 the STAR and PHENIX Collaborations at the highest RHIC energy. The data are well reproduced within the conformal model for $\alpha = 3$, whereas the nonconformal holographic model overpredicts 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 α. It is expected that inclusion of the radiative loss from the nonconformal side will improve the results. Therefore, more systematic studies are needed from the nonconformal side, including radiative loss, etc., to improve the description of the experimental results.

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