Holographic Model for Hadrons in Deformed AdS$_5$ Background

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Abstract

Several physical quantities of light hadrons are examined by a new holographic model of QCD, which is the modified version of the one proposed by Erlich et al. defined on AdS$_5$. In our model, AdS$_5$ is deformed by a non-trivial bulk scalar, this is corresponding to adding the mass term of the adjoint fermions to the 4d SYM theory dual to the gravity on AdS$_5$. We find that this deformation should be taken to be rather small, but its important effects are also seen.

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1 Introduction

Recently, the gravity/gauge correspondence has revived the expectation that QCD can be described by a string theory with an appropriate combination of D-branes. Some models are shown in the system of $D_p/D_{p+4}$ branes [1]-[8]. In these, by setting the 10d background with stacked $D_p$ branes, $D_{p+4}$ branes are embedded as a probe to introduce flavor quarks. Then several physical quantities of QCD have been obtained with sufficient values.

When these models are set as 5d theories, we should prepare two kinds of 5d actions, $S_{\text{bulk}}$ and $S_{\text{meson}}$. The former describes the bulk background or closed strings and the latter the hadrons or the system of open strings. They are corresponding to 10d action of gravity and the one of $D_{p+4}$ branes, respectively. The solution of $S_{\text{bulk}}$ gives the gravity-background dual to the Yang-Mills theory. On the other hand, the classical solution of $S_{\text{meson}}$ provides parameters related to quarks, and the meson spectra are obtained from fluctuations around this solution in $S_{\text{meson}}$. However, there is no satisfactory holographic model, which describes QCD, at present. Instead, several authors have proposed phenomenological 5d-models which explain a wide range of hadron properties related to QCD [9, 10, 11, 12]. In these models, the gravity-background is taken as AdS$_5$ and this space is cut off at an appropriate infrared (IR) point in order to realize the quark-confinement of the dual gauge theory. However, true gravity-background dual to QCD should be largely deformed from AdS$_5$ in the infrared region since the AdS$_5$ background is dual to $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) theory. Therefore, even if the infrared region is removed by the IR cutoff mentioned above, we expect that the deformation of the background configuration from AdS$_5$ is observed and it would affect the physical quantities.

Our purpose is to make clear this point in the approaches mentioned above. This would be important to proceed these approaches to the next step.

Here $S_{\text{meson}}$ is set as the form used in [9]. In this action, the mass and the vacuum expectation value (VEV) of bilinear fields of quarks are given through the classical solution of a tachyonic scalar field. As mentioned above, we deform AdS$_5$ by introducing the mass of adjoint fermions into the dual gauge theory. This is realized by adding a non-trivial scalar, whose conformal dimension ($\Delta$) is three, to $S_{\text{bulk}}$. As a result, in the dual gauge theory, the supersymmetry is explicitly broken and the gauge coupling constant is running. So a new parameter is introduced in our model as the mass of the adjoint fermions, through which we examine its dynamical effects on various physical quantities related to light mesons.

In the next section, we give our bulk-background configuration. In section 3, $S_{\text{meson}}$ and the configuration of the scalar of $\Delta = 3$ are given, and physical quantities of light mesons are examined to see effects of our deformation. In the final section, summary is given.

2 Bulk action and deformed SYM

Up to now, many interesting 5d supergravity solutions have been studied as deformed SYM theories. Here we adopt a simple but nontrivial model given in [13], which is
briefly reviewed. Consider the following 5d action with a scalar (φ),

\[ S_{\text{bulk}} = \int d^4x dz \sqrt{-g} \left\{ \frac{1}{2\kappa^2} (R - 2\Lambda) - \frac{1}{2} (\partial \phi)^2 - V(\phi) \right\}, \]  

(1)

\[ V(\phi) = -\frac{9}{2} \frac{\mu^2}{\kappa^2} \sinh^2 \left( \frac{\sqrt{\kappa^2}}{3} \phi \right). \]

(2)

where \( \mu = \sqrt{-\Lambda/6} \). The parameters \( \kappa^2 \) and \( \Lambda \) denote the five-dimensional gravitational constant and the cosmological constant, respectively. From (2), we can see that the mass of \( \phi \) is \( M_\phi^2 = -\frac{3}{2} \mu^2 \), then it corresponds to the conformal dimension three (\( \Delta = 3 \)) operator of \( \mathcal{N} = 4 \) SYM theory [14].

We can solve equations of motion for metric and \( \phi \) under the ansatz, \( \phi = \phi(z) \) and

\[ ds^2 = g_{MN}dx^M dx^N = A^2(z) \left( \eta_{\mu\nu} dx^\mu dx^\nu + dz^2 \right). \]

(3)

Here \( \{M,N\} \) and \( \{\mu,\nu\} \) denote the 5d and 4d indices, respectively, and our metric convention is \( \eta_{MN} = (-++++) \). Setting as

\[ \lambda = \frac{\kappa^2 \alpha^2}{3}, \]

where \( \alpha \) is a constant, we obtain the following solution

\[ A(z) = \frac{\sqrt{\lambda}}{\mu \sinh \left( \sqrt{\lambda} z \right)}, \quad \phi(z) = \alpha z. \]

(4)

From the second equation of (4), we can see that the parameter \( \alpha \) represents the mass of the adjoint fermions of \( \mathcal{N} = 4 \) SYM theory [14] since \( \phi \) corresponds to the operator of \( \Delta = 3 \) as mentioned above. In this sense, the supersymmetry of the gauge theory is broken for non-zero \( \alpha \), and the gauge coupling would be running.

3 Meson spectra

To discuss the meson properties, we start with the 5d action of the theory with the background (3) and (4). The fields in the bulk we consider here are the gauge fields, \( L_M \) and \( R_M \), and a scalar field \( \Phi \) whose VEV is connected to chiral symmetry breaking. In this letter, we focus on \( N_f = 2 \) flavors. Then \( \Phi \) transforms as a \( (2_L, 2_R) \). The action is

\[ S_{\text{meson}} = \int d^4xdz \sqrt{-g} \text{Tr} \left[ -\frac{1}{4g_5^2} (L_M^N L^{MN} + R_M^N R^{MN}) - |D_M \Phi|^2 - M_\Phi^2 |\Phi|^2 \right], \]

(5)

where the covariant derivative is defined as \( D_M \Phi = \partial_M \Phi + i L_M \Phi - i \Phi R_M \) and \( g \) is the determinant of the metric. \( L_M = L_M^a \tau^a \), where \( \tau^a \) are the Pauli matrices and similarly for other fields. \( g_5 \) is the 5d gauge coupling. We define \( \Phi = S e^{i\pi/\tau^a} \) and \( \frac{1}{2} \nu(z) \equiv \langle S \rangle \), where \( S \) corresponds to a real scalar and \( \pi \) to a real pseudoscalar \( (S \leftrightarrow S \text{ and } \pi \leftrightarrow -\pi \text{ under } L \leftrightarrow R) \). They transform as \( 1 + 3 \) under SU(2)_V.
3.1 Scalar field

**chiral symmetry breaking:** Firstly let us study $v(z)$ in the case of our background. Here and hereafter we take $\mu = 1$. We put $M_\phi^2 = -3$ following [9][10], which corresponds in the CFT side to an operator with the conformal dimension $\Delta = 3$, through the general relation $\Delta = 2 + \sqrt{4 + M_\phi^2}$. Solving the bulk equation of motion for $S$,

$$ (\Box_{5} - M_\phi^2) S = 0 ,$$

where $\Box_{5}$ denotes the five dimensional Laplacian, we obtain [15]

$$ v(z) = \frac{1}{A^3(z)} \left( c + m_q \left[ -\lambda \sinh^{-1}(A(z)/\sqrt{\lambda}) + A(z)\sqrt{A^2(z) + \lambda} \right] \right) .$$

Here $m_q$ and $c$ should be identified with the quark mass (explicit breaking of the chiral symmetry) and the chiral condensate (spontaneous breaking of chiral symmetry), respectively. Actually this is approximated as $v(z) \sim m_q z + c z^3$ near $z = 0$, which reproduces the results of [9][10]. We notice that $v(z)$ includes the parameter $\lambda$ which is specific to our model as well as $m_q$ and $c$. In other words, the gauge theory considered here is characterized by these three parameters.

**$\sigma$-meson:** As for the singlet meson state ($\sigma$), it is obtained as a solution for the fluctuation of $S$, $S = v(z)/2 + \sigma$, with finite four dimensional mass $m^2$ defined as $\partial_\mu \partial^\mu \sigma = m^2 \sigma$. The equation for $\sigma$ is explicitly given in the same form with Eq. (6) as

$$ \frac{1}{A^2} \left[ m^2 + \partial_z^2 + 3 \frac{\partial_z A}{A} \partial_z \right] \sigma = M_\phi^2 \sigma .$$

It should be noticed that this equation is independent of $v(z)$ and depend on $M_\phi^2$ and $\lambda$ through the warp factor $A$.

Also in this case, the bound state spectrum is obtained by introducing an IR cutoff, $z_m$, into the fifth dimension [9][10], which corresponds to $\Lambda_{\text{QCD}}$. In this case, the boundary conditions are adopted such that $\sigma(z)|_{z_0 = \partial_z \sigma(z)|_{z_m} = 0}$, where $z_0$ is the UV cutoff which is taken to zero after all. Then the mass of $\sigma$ depends on the parameters, $\lambda$ and $z_m$ since $M_\phi^2$ is fixed. The numerical results are shown in the Fig.1(B), where the spectrum of vector fields are also shown in (A). In order to reproduce the experimental value $m_\sigma = (400 - 1200)$ MeV, $\lambda$ should be smaller than 0.35. The upper-bound for $m_\sigma$ is shown by the dotted line in the Fig.1(B).

3.2 Vector meson

As for the gauge bosons, they are separated to the vector and the axial vector bosons $V_M$ and $A_M$, and are defined as $L_M \equiv V_M + A_M$ and $R_M \equiv V_M - A_M$, respectively.

First of all, we discuss some properties of the vector mesons. The linearized equation of motion for $V_\mu$ is (employing $V_z = 0$ gauge)

$$ [(m_n^V)^2 + A^{-1} \partial_z A \partial_z] f_n^V = 0 ,$$

where $m_n^V$ is defined as
where the mode expansion \( V_\mu(x, z) = \sum_n V_\mu^{(n)}(x) f_n^V(z) \) is applied and \( m_n^V \) is the four dimensional mass of the \( n \)-th excited vector meson. The boundary condition for vector mesons is given by \( f_n^V(z_0) = \partial_z f_n^V(z_m) = 0 \), similarly for the case of the sigma meson. Note that Eq. (9) is independent of \( v(z) \). Then the masses of vector mesons are given as the function of \( \lambda \) and \( z_m \) as in the case of the \( \sigma \) meson.

It is convenient to solve (9) numerically with the above boundary conditions. The first excited vector meson mass, \( m_\rho \), is obtained as the function of \( \lambda \) and \( z_m \). By using the experimental value of \( m_\rho \), the IR cutoff \( z_m \) is expressed as the function of \( \lambda \). As the result, the second and all highly excited vector meson masses depend on \( \lambda \). We find that the lowest and the next excited \( m_\rho \)-meson are fitted by the parameters \( z_m = 4 \) and \( \lambda = 0.8 \).

The vector meson decay constant is computed through the second derivative of its own wave function according to [9]

\[
F_{V_n}^2 = \frac{1}{g_5^2} \left[ \frac{d^2 f_n^V}{dz^2} \right]_{z_0}^2, \quad g_5^2 = \frac{12 \pi^2}{N_c}.
\]

Here \( N_c = 3 \). However, its numerical value given for \( z_m = 4 \) and \( \lambda = 0.8 \) deviates from the experimental value. So we must change the value of \( \lambda \) to the smaller side in order to obtain more reliable result.

![Fig. 1: (A) \( \lambda \) dependence of the second excited vector meson \( m_{V_2} \) (a) and the \( \rho \) meson decay constant \( F_{1/2}^{\rho} \) (b) divided by their experimental values [18], which are used hereafter. (B) The curve and the dotted line denote \( m_\sigma \) (MeV) and its experimental upper bound, respectively.](image)

Our results are shown in Fig. 1 where we find that a good fit would be obtained near \( \lambda \sim 0.8 \) if we consider only the vector meson sector. Note here that in this sector, \( v(z) \) (or equivalently, the quark mass \( m_q \) and/or the chiral condensate \( c \)) does not appear. This is contrasted with the results from, for instance, the QCD sum rules [16, 17], where the vector meson masses depend on the chiral condensate. This is due to the fact that the spontaneous chiral symmetry breaking is introduced by hand in this model, which was done by the choice of the profile of the scalar field \( S \). In this sense, the analysis can not be complete at this stage.

\( f_n^V(z) \) is the wave-functions for vector mesons with the normalization condition \( 1 = \int_{z_0}^{z_m} dz A(z)(f_n^V(z))^2 \).
3.3 Axial-vector meson and $\pi$-meson

The linearized equations of motion for the axial vector meson $A_\mu$ and the pion $\pi$ are obtained from the following quadratic action

$$S_{\text{axial}} = \int dx^4 dz \left[ -\frac{A}{4g_5^2} (F_A^a)^2 - \frac{v^2 A^3}{2} (\partial \pi^a + A^a)^2 \right] ,$$

where $v(z)$ is given by (7). Decomposing $A_\mu$ into the transverse and the longitudinal part, $A_\mu = A_{\mu\perp} + \partial_\mu \varphi$, one can obtain equations for these fields,

$$[m_A^2 + A^{-1} \partial_z A \partial_z - g_5^2 A^2 v^2] A_{\mu\perp} = 0 ,$$

$$\partial_z (A \partial_z \varphi) - g_5^2 A^3 v^2 (\pi + \varphi) = 0 ,$$

$$m_\pi^2 \partial_z \varphi + g_5^2 A^2 v^2 \partial_z \pi = 0 .$$

These equations are solved numerically under the boundary conditions, $A_{\mu\perp}(z_0) = \partial_z A_{\mu\perp}(z_m) = 0$, $\varphi(z_0) = \partial_z \varphi(z_m) = \pi(z_0) = 0$. The decay constants of the axial mesons and the pion are calculated from the wave functions as [9]

$$F_{A_n}^2 = \frac{1}{g_5^2} \left[ \frac{d^2 f_n^A}{dz^2} \right]^2 (n \neq 0) , \quad F_\pi^2 = -\frac{1}{g_5^2} \frac{\partial_z f}{z} \bigg|_{z_0} ,$$

where $A_{\mu\perp}(x, z) = \sum_n A_\mu(x) f_n^A(z)$ and $f_n^A(z)$ is normalized as $1 = \int_{z_0}^{z_m} dz A(z) (f_n^A(z))^2$, and $f$ is the solution to Eq. (12) with $m_A^2 = 0$, satisfying $f = 0$ at $z = z_0$ and $df/dz = 0$ at $z = z_m$.

The masses and the decay constants of axial-vector mesons and pion depend on four parameters $m_q$, $c$, $z_m$ and $\lambda$ through $v(z)$ and $A(z)$ in Eqs. (12)-(14), while those of vector mesons do only on $z_m$ and $\lambda$. For the consistency between the vector and axial-vector meson sectors, here we take the same $z_m$ as that determined in the vector meson sector. The $z_m$ depends on $\lambda$ as $1/z_m = 0.323 - 0.09125 \lambda$ [GeV] for $\lambda < 0.8$.

![Fig. 2: The $m_q$ dependence of $m_\pi^2$ and $m_{A_1}^2$. The solid line represents $m_\pi^2$, and the dotted line corresponds to $m_{A_1}^2/100$. The GOR relation is shown by closed circles.](image)

First, we show that the present model reproduces the Gell-Mann-Oakes-Renner (GOR) relation, $m_\pi^2 F_\pi^2 = 2m_q c$, well satisfied in real QCD. Figure 2 shows the $m_q$ dependence of $m_\pi^2$, where other parameters are fixed at $\lambda = 0.1$, $c = (0.3256 \text{ GeV})^3$. 


and $1/z_m = 0.315$ GeV. The solid line is a result of direct calculations of $m_{\pi}^2$, and the closed circles are a result obtained from calculated $F_{\pi}$ through the GOR relation $m_{\pi}^2 = 2m_q c/F_{\pi}^2$. The two results agree with each other. Thus, the GOR relation is satisfied for the case of $\lambda = 0.1$. This is also true for other $\lambda$, as shown later. In this figure, when $m_q = 2.41$ MeV, calculated $m_{\pi}$ and $F_{\pi}$ reproduce the corresponding experimental values simultaneously. For comparison, we also plot the $m_q$ dependence of $m_{\pi}^2$ by the dotted line. The $m_q$ dependence is quite weak. This means that the value of $m_{\pi}$ is determined not by $m_q$ but by the chiral condensate $c$.

Figure 3 shows the $c$ dependence of $m_{A_1}$ and $F_{A_1}^{1/2}$, in which other parameters are fixed at $\lambda = 0.1$, $m_q = 2.41$ MeV and $1/z_m = 0.315$ GeV. The two quantities in the axial-vector sector have a similar $c$ dependence. They monotonously increase as $c$ increases, and they almost reproduce the corresponding experimental values at $c \sim 0.025$ GeV$^3$. Mass $m_{A_1}$ is reduced to about 60% of the experimental value in the limit of no chiral condensate. Thus, 40% of the observed mass is generated by the finite chiral condensate.

![Fig. 3: The $c$ dependence of $F_{A_1}^{1/2}$ and $m_{A_1}$. These quantities are divided by the corresponding experimental values.](image)

We focus our analysis on the $\lambda$ dependence of $F_{A_1}, m_{A_1}, F_{\pi}$. Parameters $m_q$ and $c$ are fixed as follows. First, $c$ is assumed to be determined from $m_q$ through GOR relation, $\bar{m}_{\pi}^2 F_{\pi}^2 = 2m_q c$, where $\bar{m}_{\pi}$ and $F_{\pi}$ denote experimental values of $m_{\pi}$ and $F_{\pi}$. Second, $m_q$ is fixed so as to reproduce the observed pion mass. The resultant $m_q$ depends on $\lambda$ as $m_q = 2.26 + 1.25\lambda$ [MeV] for $\lambda < 0.4$.

Figure 4(A) shows $\lambda$ dependence of predicted values of $F_{A_1}^{1/2}, m_{A_1}, F_{\pi}$. As for all $\lambda$ up to 0.4, calculated $F_{\pi}$ agrees with the experimental value with $\sim 1\%$ error. In the present analysis, we assumed the calculated $F_{\pi}$ to reproduce the experimental value when we used the GOR relation as a relation between $c$ and $m_q$. The good agreement shows that our assumption is consistent and then the GOR relation is well satisfied for all $\lambda$ at least up to 0.4. As for $F_{A_1}^{1/2}$ and $m_{A_1}$, the agreement of the theoretical results with the observed ones becomes better as $\lambda$ decreases. One then see that the $\lambda = 0$ case, namely the AdS$_5$ case, yields a best fit if we consider only the axial-vector meson sector.

Figure 4(B) summarizes all predictions of our model in both the vector and axial-vector meson sectors. As for three of five quantities, $F_{A_1}^{1/2}, m_{A_1}, F_{\rho}^{1/2}$, the agreement of
Fig. 4: Predictions of the model in the axial-vector sector (A) and in both the vector and axial-vector meson sectors (B). As for (A), the solid lines, a, b, c, denote $F_{A_1}^{1/2}$, $m_{A_1}$, $F_\pi$, respectively. As for (B), the solid lines, d, e, g, h, represent $F_{A_1}^{1/2}$, $m_{A_1}$, $F_\pi$, $F_{\rho}^{1/2}$, respectively, and the dotted line, f, corresponds to $m_{V_2}$. All quantities are divided by the corresponding experimental values.

the predictions with the corresponding observations is best at $\lambda = 0$, but as for one of the five, i.e. for $m_{V_2}$ the best fit is obtained at $\lambda \sim 0.8$. Hence, we can conclude that totally the best fit is realized at small $\lambda$. This result is welcomed to obtain a realistic mass of $\sigma$ meson shown in Fig 4.

4 Summary

We present a new holographic model of QCD in which the gravity-background is deformed from pure $AdS_5$ and the extra dimension is cut off at an appropriate infrared point. This is a natural extension of the holographic models of Refs. [9, 10, 11, 12] in which the $AdS_5$ background is taken and the extra dimension is cut off in the same manner. These holographic models based on $AdS_5$ well reproduced observed quantities on light mesons. Nevertheless, there is no strong reason why $AdS_5$ is taken as a background of the gravity dual to QCD, since QCD has a running coupling constant and then the gravity-background should be modified from $AdS_5$. Our new model is proposed to answer this question.

In our model, parameter $\lambda$ represents the magnitude of the deformation of $AdS_5$ background. For any $\lambda$, our model reproduces the GOR relation which is well satisfied in real QCD. As for light mesons except the excited $\rho$ meson, a best fit of our predictions to the corresponding observed quantities is obtained at $\lambda = 0$, that is, in the $AdS_5$ limit. Meanwhile, the excited $\rho$ meson mass is reproduced at $\lambda = 0.8$. Hence, a best fit to all of them is realized at small $\lambda$. The parameter $\lambda$ is related to the five-dimensional Planck mass $M_5$ and the scale of the supersymmetry breaking $\Lambda_{SUSY}$ as $\lambda = \Lambda_{SUSY}^5/(3M_5^3)$. The smallness of $\lambda$ would imply $M_5 \gg \Lambda_{SUSY}$ in the gravity dual to QCD.

It is well known that the chiral condensate $c$ plays an important role on all quantities of light mesons. In this sense, the quantities should depend on $c$. Our model has the property for the axial-vector meson sector, but not for the vector meson sector. Thus, the present model is insufficient for the vector meson sector. The holographic models
of Refs. [9, 10, 11, 12] have essentially the same problem. This is an important problem to be solved in future.

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