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Review

Hadron properties in AdS/QCD

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ABSTRACT

We discuss a holographic soft-wall model developed for the description of mesons and baryons with adjustable quantum numbers n, J, L, S. This approach is based on an action which describes hadrons with broken conformal invariance and which incorporates confinement through the presence of a background dilaton field. Results obtained for heavy-light meson masses and decay constants are consistent with predictions of HQET. In the baryon sector, applications to the baryon masses, nucleon electromagnetic form factors and generalized parton distributions are discussed.

1. Introduction

Based on the correspondence of string theory in anti-de Sitter (AdS) space and conformal field theory (CFT) in physical space–time [1], a class of AdS/QCD approaches was recently successfully developed for describing the phenomenology of hadronic properties. In order to break conformal invariance and incorporate confinement in the infrared (IR) region two alternative AdS/QCD backgrounds have been suggested in the literature: the "hard-wall" approach [2], based on the introduction of an IR brane cutoff in the fifth dimension, and the "soft-wall" approach [3], based on using a soft cutoff. This last procedure can be introduced in the following ways: (i) as a background field (dilaton) in the overall exponential of the action, (ii) in the warping factor of the AdS metric and (iii) in the effective potential of the action. These methods are in principle equivalent to each other due to a redefinition of the bulk field involving the dilaton field or by a redefinition of the effective potential. In the literature, there exist detailed discussions of the sign of the dilaton profile in the dilaton exponential $\exp(\pm\varphi)$ [3–7] for the soft-wall model (for a discussion of the sign of the dilaton in the warping factor of the AdS metric, see Ref. [8]). The negative sign was suggested in Ref. [3] and recently discussed in Ref. [7]. It leads to a Regge-like behavior of the meson spectrum, including a straightforward extension to fields of higher spin J. Also, in Ref. [7] it was shown that this choice of the dilaton sign guarantees the absence of a spurious massless scalar mode in the vector channel of the soft-wall model. We stress that alternative versions of this model with a positive sign are also possible. One should just redefine the bulk field $S(x, z)$ as $S(x, z) = e^{\varphi(z)}\,\tilde{S}(x, z)$, where the transformed field corresponds to the dilaton with an opposite profile. It is clear that the underlying action changes, and extra potential terms are generated depending on the dilaton field (see detailed discussion in [9]). Here we present a summary of recent results: meson mass spectrum and decay constants of light and heavy mesons, baryon masses, nucleon electromagnetic form factors and generalized parton distributions [9–11]. Our starting points are the effective $(d + 1)$ dimensional actions formulated in AdS space in terms of boson or fermion bulk fields, which serve as holographic images of mesons and baryons.

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2. Approach

Our starting points are the effective $(d+1)$ dimensional actions formulated in AdS space in terms of boson or fermion bulk fields, which serve as holographic images of mesons and baryons. For illustration, we consider the simplest actions—for scalar fields ($J=0$) [10–12]

$$S_0 = \frac{1}{2}\int d^dxdz\sqrt{g}e^{-\varphi(z)}\left[g^{MN}\partial_M S(x,z)\partial_N S(x,z) - \left(\mu_S^2 + \Delta V_0(z)\right)S^2(x,z)\right] \tag{1}$$

and $J = 1/2$ fermions [13,11]:

$$S_{1/2} = \int d^dxdz\,\sqrt{g}\,e^{-\varphi(z)}\left[\frac{i}{2}\bar{\Psi}(x,z)\epsilon_a^M\Gamma^a\mathcal{D}_M\Psi(x,z)\right.$$
$$\left. - \frac{i}{2}(\mathcal{D}_M\Psi(x,z))^\dagger\Gamma^0\epsilon_a^M\Gamma^a\Psi(x,z) - \bar{\Psi}(x,z)\Big(\mu_\Psi + \varphi(z)/R\Big)\Psi(x,z)\right], \tag{2}$$

where S and Ψ are the scalar and fermion bulk fields, $\mathcal{D}_M$ is the covariant derivative acting on the fermion field, $\Gamma^a = (\gamma^\mu, -i\gamma^5)$ are the Dirac matrices, $\varphi(z) = \kappa^2 z^2$ is the dilaton field, R is the AdS radius, $\Delta V_0(z)$ is the dilaton potential. μ_S and μ_Ψ are the masses of scalar and fermion bulk fields defined as $\mu_S^2R^2 = \Delta_M(\Delta_M - d)$ and $\mu_\Psi R = \Delta_B - d/2$. Here $\Delta_M = \tau_M = 2 + L$ and $\Delta_B = \tau_B + 1/2 = 7/2 + L$ are the dimensions of scalar and fermion fields, which due to the QCD/gravity correspondence are related to the scaling dimensions (twists τ_M, τ_B) of the corresponding interpolating operators, where $L = \max|L_z|$ [4] is the maximal value of the z-component of the quark orbital angular momentum in the LF wavefunction or the minimum of the orbital angular momentum of the corresponding hadron. These actions give information about the propagation of bulk fields inside AdS space (bulk-to-bulk propagators), from inside to the boundary of the AdS space (bulk-to-boundary propagators) and bound state solutions-profiles of the Kaluza–Klein (KK) modes in extra-dimension, which correspond to the hadronic wave functions in impact space. We suppose a free propagation of the bulk field along the d Poincaré coordinates with four-momentum p, and a constrained propagation along the $(d+1)$-th coordinate z (due to confinement imposed by the dilaton field). In particular, it was shown [4] that the extra-dimensional coordinate z corresponds to the light-front impact variable. It was also shown [7] that in case of the scattering problem the sign of the dilaton profile is important to fulfill certain model-independent constraints. But we recently showed [9] that in case of the bound state problem the sign of the dilaton profile is irrelevant, if the action is properly set up. Moreover, in solving the bound-state problem, it is more convenient to move the dilaton field from the exponential prefactor to the effective potential [4,9]. Then we use a KK expansion for the bulk fields factorizing the dependence on d Poincaré coordinates x and the holographic variable z. e.g. in case of scalar field it is given by $S(x,z) = \sum_n S_n(x)\,\Phi_n(z)$, where n is the radial quantum number, $S_n(x)$ is the tower of the KK modes dual to scalar mesons and Φ_n are their extra-dimensional profiles (wave-functions) satisfying the Schrödinger-type equation with the potential depending on the dilaton field. Then using the obtained wave functions Φ_n, we calculate matrix elements describing hadronic processes.

3. Results

We present the results of our calculations for mesonic decay constants (Table 1), the meson spectrum (Tables 2 and 3) [10] and the baryon spectrum (Tables 4 and 5). A detailed analysis of nucleon helicity-independent generalized parton distributions (GPDs) H_v^q and E_v^q [11] is discussed. Note, by construction we reproduce the power scaling of nucleon electromagnetic (EM) form factors at large Q^2 [13,11]:

$$\begin{aligned}
F_1^p(Q^2) &= C_1(Q^2) + \eta_p C_2(Q^2),\\
F_2^p(Q^2) &= \eta_p C_3(Q^2),\\
F_1^n(Q^2) &= \eta_n C_2(Q^2),\\
F_2^n(Q^2) &= \eta_n C_3(Q^2),
\end{aligned} \tag{3}$$

where $Q^2 = -t$. The C_i functions, defining the Dirac and Pauli factors, are given by:

$$\begin{aligned}
C_1(Q^2) &= \frac{a+6}{(a+1)(a+2)(a+3)},\\
C_2(Q^2) &= \frac{2a(2a-1)}{(a+1)(a+2)(a+3)(a+4)},\\
C_3(Q^2) &= \frac{12m_N\sqrt{2}}{\kappa}\,\frac{1}{(a+1)(a+2)(a+3)},
\end{aligned} \tag{4}$$