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Mesons and glueballs in chiral approach and AdS/QCD

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Phenomenology of mesons and glueballs is considered in two frameworks – chiral approach light–front holographic approach proposed by Brodsky and Teramond, which is based on the correspondence of string theory in Anti–de Sitter and conformal field theory in physical space–time.

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1. Introduction

Phenomenology of mesons and glueballs is considered in two frameworks – chiral approach [1, 2] and light–front holographic (LFH) approach proposed by Brodsky and Teramond [3], which is based on the correspondence of string theory in Anti–de Sitter (AdS) and conformal field theory in physical space–time.

First we report our results on strong and electromagnetic decay properties of scalar, pseudoscalar, vector and tensor mesons above 1 GeV within a chiral approach [1, 2]. The isoscalar states are treated as mixed states of quarkonia and glueball configurations. A fit to the experimental mass and decay rates listed by the Particle Data Group is performed to extract phenomenological constraints on the nature of the meson resonances and to the issue of the glueballs decays. A comparison to other experimental and theoretical results and possible hints for exotic mesons and open interpretation–issues are discussed.

Second we present summary of our results for mass spectroscopy and decay constants of light and heavy mesons [4, 5] in the LFH approach [3]. The LFH approach is a covariant and analytic model for hadron structure with confinement at large distances and conformal behavior at short distances. It is analogous to the Schrödinger theory for atomic physics and provides the precise mapping of string modes $\Phi(z)$ in the AdS fifth dimension z to the hadron light–front wave functions in physical space-time in terms of light–front impact variable ζ, which measures the separation of the quark and gluonic constituents inside a hadron.

2. Mesons and glueballs in chiral approach

In this work, starting from an effective chiral Lagrangian [1, 2] derived in Chiral Perturbation Theory (ChPT) [6], we perform a tree-level analysis of the strong and electromagnetic decays of scalar, pseudoscalar and vector mesons settled in the energy range between 1 and 2 GeV. Although chiral approach cannot be rigorously justified at this energy scale, since loop corrections could be large, we intend to use this framework as a phenomenological tool to extract possible glueball-quarkonia mixing scenarios from the observed decays. The scalar glueball is introduced as an extra-flavor singlet composite field with independent couplings to pseudoscalar mesons (and to photons, although suppressed). In particular, we follow the assignment that the bare quarkonia states $N = (\bar{u}u + \bar{d}d)/\sqrt{2}$, $S = \bar{s}s$ and the bare scalar glueball G mix, resulting in the three scalar-isoscalar resonances $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. Such a mixing scheme has been previously investigated by many authors (see e.g. discussion in [2]). The $\eta(1405)$ meson is considered as a strong candidate for the pseudoscalar glueball. Also we take into account it mixture with $\eta(1295) \approx n\bar{n}$ and $\eta(1475) \approx s\bar{s}$ states. Here we present results for the scalar mesons/glueball (Table I) and tensor (Table II) mesons. Further details can be found in Refs. [1, 2].

3. Light and heavy mesons in holographic approach

In series of papers (see e.g. [3]) Brodsky and Teramond developed a semiclassical approximation to QCD - light-front holography (LFH) approach based on correspondence of string theory in Anti-de Sitter (AdS) space and conformal field theory (CFT) in physical space-time [7]. Light-front holography [3] is one of the exciting features of AdS/CFT correspondence. The LFH approach is a covariant and analytic model for hadron structure with confinement at large distances and conformal behavior at short distances. It is analogous to the Schrödinger theory for atomic physics. It provides the precise mapping of string modes $\Phi(z)$ in the AdS fifth dimension z to the hadron light-front wave functions (LFWF) in physical space-time in terms of light-front impact variable ζ which measures the separation of the quark and gluonic constituents inside a hadron. Therefore, different values of the holographic variable z correspond to different scales at which the hadron is examined. The mapping was obtained by matching the matrix elements (e.g. electromagnetic pion form factor, the energy-momentum tensor) in the two approaches - string theory in AdS and light-front theory in Minkowski space-time. In this section we consider application of holographic approach for decay properties of light and heavy mesons.

Table I. Masses and decay properties of scalar mesons and scalar glueball

Quantity	Exp	Theory	χ_i^2
M_{f_1} (MeV)	1350 ±150	1417	0.202
M_{f_2} (MeV)	1507 ± 5	1507	~ 0
M_{f_3} (MeV)	1714 ± 5	1714	0.003
$\Gamma_{f_2\to\pi\pi}$ (MeV)	38.0 ± 4.6	38.52	0.011
$\Gamma_{f_2\to\bar{K}K}$ (MeV)	9.4 ± 1.7	10.36	0.322
$\Gamma_{f_2\to\eta\eta}$ (MeV)	5.6 ± 1.3	1.90	8.109
$\Gamma_{f_3\to\pi\pi}/\Gamma_{f_3\to\bar{K}K}$	0.20 ± 0.06	0.212	0.036
$\Gamma_{f_3\to\eta\eta}/\Gamma_{f_3\to\bar{K}K}$	0.48 ± 0.15	0.249	2.446
$\Gamma_{a_0\to\bar{K}K}/\Gamma_{a_0\to\pi\eta}$	0.88 ± 0.23	0.838	0.032
$\Gamma_{a_0\to\pi\eta'}/\Gamma_{a_0\to\pi\eta}$	0.35 ± 0.16	0.288	0.150
$\Gamma_{K_0^*\to K\pi}$ (MeV)	273 ± 51	59.10	17.590
$(\Gamma_{f_3})_{2P}$ (MeV)	140 ± 10	143.27	0.110
χ^2_{tot}	-	-	29.01

Table II. Decay properties of tensor mesons

Mode	Exp (MeV)	Theory (MeV)	χ_i^2
$\Gamma_{f_2\to\pi\pi}$	157.0 ± 7.6	153.51	0.210
$\Gamma_{f_2\to\bar{K}K}$	8.5 ± 0.9	9.15	0.526
$\Gamma_{f_2\to\eta\eta}$	0.83 ± 0.20	0.80	0.023
$\Gamma_{f_2'\to\pi\pi}$	0.60 ± 0.16	0.55	0.102
$\Gamma_{f_2'\to\bar{K}K}$	64.8 ± 7.6	41.64	9.288
$\Gamma_{f_2'\to\eta\eta}$	7.5 ± 2.9	6.49	0.196
$\Gamma_{a_2\to\bar{K}K}$	5.2 ± 1.1	6.64	1.716
$\Gamma_{a_2\to\eta\pi}$	15.5 ± 2.0	18.42	2.134
$\Gamma_{a_2\to\eta'\pi}$	0.57 ± 0.12	0.80	3.652
$\Gamma_{K*_2\to\bar{K}K}$	49.1 ± 2.5	40.08	~ 0
χ^2_{tot}	-	-	18.496

Our starting point is the equation of motion (EOM) for the AdS mode in the fifth dimension z (holographic coordinate). The soft-wall model developed in Ref. [3] is based on the following one-dimensional Schrödinger EOM:

$$\Big[-\frac{d^2}{dz^2}-\frac{1-4L^2}{4z^2}+U(z)\Big]\Phi(z)=M^2\Phi_1(z) \tag{3.1}$$

where $U(z)$ is the effective confinement potential:

$$U(z)=\kappa^4z^2+2\kappa^2(L+S-1)\,. \tag{3.2}$$

n,L,S are the radial, orbital and spin quantum numbers, respectively; κ is the scale parameter related to the dilaton field.

The string mode is given by normalizable solution

$$\Phi(z)=\sqrt{\frac{2n!}{(n+L)!}}\,\kappa^{1+L}z^{\frac{1}{2}+L}e^{-\frac{1}{2}\kappa^2z^2}L_n^L(\kappa^2z^2) \tag{3.3}$$

with $\int_0^\infty dz\Phi^2(z)=1$. Here $L_n^L(x)$ is the generalized Laguerre polynomials. From Eqs. (3.1) we get the hadron spectrum at zero quark masses

$$M^2=4\kappa^2\Big(n+L+\frac{S}{2}\Big)\,. \tag{3.4}$$

$\Phi(z)$ can be directly mapped to the LFWF due to correspondence of AdS and light–front amplitudes. In particular, considering the case with two partons q_1 and $\bar{q}_2$ and making correspondence of the holographic coordinate z to the impact variable ζ in the LF formalism

$$z\to\zeta,\qquad \zeta^2=\mathbf{b}_\perp^2x(1-x) \tag{3.5}$$

where $\mathbf{b}_\perp$ is the impact separation and Fourier conjugate to the transverse momentum $\mathbf{k}_\perp$, we obtain the relation between the AdS mode and meson LFWF $\widetilde{\psi}_{q_1\bar{q}_2}(x,\zeta)$ in massless case:

$$|\widetilde{\psi}_{q_1\bar{q}_2}(x,\zeta)|^2=x(1-x)f^2(x)\frac{|\Phi(\zeta)|^2}{2\pi\zeta}\,, \tag{3.6}$$

where $f(x)=1$. Extension to massive quarks has been suggested by Brodsky and Teramond [3] and later was considered in [5]:

$$-\frac{d^2}{d\zeta^2}\to-\frac{d^2}{d\zeta^2}+\mu_{12}^2\,,\quad \mu_{12}^2=\frac{m_1^2}{x}+\frac{m_2^2}{1-x}$$
$$f(x)\to f(x,m_1,m_2)\equiv N\,f(x)\,e^{-\dfrac{\mu_{12}^2}{2\lambda^2}}\,, \tag{3.7}$$

where N is normalization constant, λ is additional scale parameter.

The modified hadronic wave function and mass spectrum are written as:

$$\psi_{q_1\bar{q}_2}(x,\zeta,m_1,m_2)=\frac{\Phi(\zeta)}{\sqrt{2\pi\zeta}}\;f(x,m_1,m_2)\,\sqrt{x(1-x)}\,,$$
$$M^2=\int\limits_0^\infty d\zeta\Phi(\zeta)\Big(-\frac{d^2}{d\zeta^2}-\frac{1-4L^2}{4\zeta^2}+U(\zeta)\Big)\Phi(\zeta)+\int\limits_0^1 dx\Big(\frac{m_1^2}{x}+\frac{m_2^2}{1-x}\Big)f^2(x,m_1,m_2) \tag{3.8}$$

One should stress that this approach correctly reproduces mass spectrum of heavy–light mesons in the heavy quark limit

$$M_{Qq}^2 = 4\kappa^2\Big(n+L+\frac{S}{2}\Big) + \int\limits_0^1 dx\Big(\frac{m_q^2}{x}+\frac{m_Q^2}{1-x}\Big) f^2(x,m_q,m_Q) + \cdots$$
$$= \Big(m_Q + \bar\Lambda + \mathcal{O}(1/m_Q)\Big)^2 \qquad (3.9)$$

where dimensional parameters are scaled as $\kappa = \mathcal{O}(m_Q^0)$ and $\lambda = \mathcal{O}(\sqrt{m_Q})$. It is seen that Eq. (3.9) is in agreement with prediction of heavy quark effective theory (HQET):

$$M_V - M_P = \frac{2\kappa^2}{M_V+M_P} \sim \frac{1}{m_Q} \qquad (3.10)$$

It is also interesting to consider the limit of heavy quark masses for heavy quarkonia $(Q_1\bar{Q}_2)$. For this we express the longitudinal momentum fractions through the z-component of the internal momentum $\mathbf{k} = (\mathbf{k}_\perp, k_z)$ as (see also [8]):

$$x = \frac{e_1+k_z}{e_1+e_2}\,, \quad 1-x = \frac{e_2-k_z}{e_1+e_2}\,, \qquad (3.11)$$

where $e_i = \sqrt{m_{Q_i}^2+\mathbf{k}^2}$ and $\mathbf{k}^2 = \mathbf{k}_\perp^2 + k_z^2$. Then considering heavy quark limit $m_{Q_1}, m_{Q_2} \gg \mathbf{k}_\perp, k_z$ we get

$$x = \frac{m_{Q_1}+k_z}{m_{Q_1}+m_{Q_2}} + \mathcal{O}(1/m_Q^2)\,, \quad 1-x = \frac{m_{Q_2}-k_z}{m_{Q_1}+m_{Q_2}} + \mathcal{O}(1/m_Q^2)\,. \qquad (3.12)$$

Hence,

$$\frac{m_{Q_1}^2}{x} + \frac{m_{Q_2}^2}{1-x} = (m_{Q_1}+m_{Q_2})^2 + \mathcal{O}(1) \qquad (3.13)$$

Therefore the leading term of the integral containing the longitudinal mode is simply given by $(m_{Q_1}+m_{Q_2})^2$, which is the leading contribution to the mass squared of the heavy quarkonia. It means that we correctly reproduce an expansion of heavy quarkonia mass in heavy quark limit:

$$M_{Q_1\bar{Q}_2} = m_{Q_1} + m_{Q_2} + E + \mathcal{O}(1/m_{Q_{1,2}})\,, \qquad (3.14)$$

where E is binding energy.

As application we present results for decay constants of pseudoscalar and vector mesons including light and heavy quarks (see Tables III-V).

Table III. Decay constants f_P of pseudoscalar mesons

Meson	Data [MeV]	f_P [MeV]	$R = f_P/f_P^{\rm exp}$	κ [GeV]
π^-	$130.4 \pm 0.04 \pm 0.2$	130.4	1	0.425
K^-	$155.5 \pm 0.2 \pm 0.8$	155.5	1	0.507
D^+	205.8 ± 8.9	182.1	0.88	0.6
D_s^+	273 ± 10	183	0.67	0.6
B^-	216 ± 22	165.7	0.77	0.6
B_s^0	$253 \pm 8 \pm 7$	166.2	0.66	0.6
B_c	$489 \pm 5 \pm 3$	399	0.82	1.33

Table IV. Decay constants f_V of vector mesons with open flavor

Meson	Data [MeV]	f_V [MeV]	$R = f_V/f_V^{\rm exp}$	κ [GeV]
D^*	$245 \pm 20^{+3}_{-2}$	182.1	0.74	0.6
D_s^*	$272 \pm 16^{+3}_{-20}$	183	0.67	0.6
B^*	$196 \pm 24^{+39}_{-2}$	165.7	0.85	0.6
B_s^*	$229 \pm 20^{+41}_{-16}$	166.2	0.73	0.6

Table V. Decay constants f_V of vector mesons with hidden flavor

Meson	Data [MeV]	f_V [MeV]	$R = f_V/f_V^{\rm exp}$	κ [GeV]
ρ^0	154.7	130	0.84	0.6
ω	45.8	43.3	0.95	0.6
ϕ	76	63.2	0.83	0.6
J/ψ	277.6	201.1	0.72	1
$\Upsilon(1s)$	238.4	142.2	0.60	1.37

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