Exotic $J^{PC} = 0^{--}$ oddballs in AdS/QCD

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- **Glueballs**: bound states of gluons. Elusive hadrons due to the mixing with ordinary $q\bar{q}$ configurations.
- $J^{PC}=0^{--}$ exotic in the quark model ⟶ glueballs with such quantum numbers are promising for identification.
- Odd charge conjugation glueballs must be composed by an odd number of constituent gluons ⟶ ***"oddballs"***
- The $J^{PC}=0^{--}$ glueball is described by the QCD local operator

$$J(x)=g_{YM}^3 d_{abc}\left[\left(\eta_{\alpha\beta}-\frac{\partial_\alpha\partial_\beta}{\partial^2}\right)\tilde{G}^a_{\mu\nu}(x)\right]\left[\partial_\alpha\partial_\beta G^b_{\nu\rho}(x)\right]\left[G^c_{\rho\mu}(x)\right]$$

Symmetric $SU(3)_{\text{color}}$ structure constants — Minkowski metric tensor — Gluon field strength $G^a_{\mu\nu}(x)$, $\tilde{G}^a_{\mu\nu}(x)=\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}G^a_{\rho\sigma}(x)$

Bottom-up AdS/QCD

SUPER-YANG-MILLS (SYM) theory on Minkowski space $\mathcal{M}_4$
- Coupling constant g_{YM}
- N = 4 SUSY generators
- Gauge group $SU(N)_{\text{color}}$

Strong-coupling limit

$N\to\infty,\ \lambda=g_{YM}^2 N\to\infty,\ g_{YM}^2\to 0$

Maldacena ⟷

TYPE IIB STRING theory on $AdS_5(R)\times\mathcal{S}^5(R)$ space
- Coupling constant g_s
- R curvature radius
- $\sqrt{\alpha'}$ length of the string

Supergravity limit

$g_s\to 0$ e $R^2/\alpha'\to\infty$

SYM/SUGRA DICTIONARY *(Gubser, Klebanov, Polyakov, Witten)*

Gauge-invariant scalar with *conformal dimension* Δ ⟷ *Bulk* field with mass M_5 given by $M_5^2R^2=\Delta(\Delta-4)$

Mass scale needed to break conformal invariance (QCD confinement).

Possible production and decay modes of the $J^{PC}=0^{--}$ glueball $\left(m_{0^{--}}=2.8 \text{ GeV}\right)$

RADIATIVE TRANSITIONS

$\chi_{c1}(3510)\to\gamma G(0^{--})$
$X(3872)\to\gamma G(0^{--})$
$\chi_{c2}(3556)\to G(0^{--})$
$\chi_{c2}(3927)\to G(0^{--})$
$\chi_{b1}(9892)\to\gamma G(0^{--})$
$X_{b1}(10255)\to\gamma G(0^{--})$
$\chi_{b2}(9912)\to G(0^{--})$
$\chi_{b2}(10269)\to G(0^{--})$

HADRONIC TRANSITIONS

$X(3872)\to\omega G(0^{--})$
$h_c(3525)\to\pi\pi(I=0)G(0^{--})$
$\chi_{b1}(10255)\to(\omega,\phi,J/\Psi)G(0^{--})$
$\Upsilon(nS)\to(f_1(1270),\chi_{c1},X(3872))G(0^{--})$
$h_b(9899)\to f_0(980)G(0^{--})$
$h_b(10260)\to f_0(980)G(0^{--})$
$h_b(9899)\to G(0^{++})G(0^{--})$
$h_b(10260)\to G(0^{++})G(0^{--})$

DECAY MODES

$G(0^{--})\to\gamma f_1(1285)$
$G(0^{--})\to\omega f_1(1285)$
$G(0^{--})\to\rho a_1(1260)\ (I=0)$
$G(0^{--})\to h_1(1270)f_0(980)$
$G(0^{--})\to\rho\pi\ (I=0)$
$G(0^{--})\to K^{*}K\ (I=0)$
$G(0^{--})\to(\eta,\eta')(\omega,\phi)$

Mass Spectrum in three holographic models

SOFT WALL

Action for the field $O_0(x,z)$ dual to $J(x)$:

$$S_{(SW)}=\frac{1}{k}\int d^5x\sqrt{|g|}e^{-c^2z^2}\left[g^{MN}\partial_M O_0\partial_N O_0-M_5^2O_0^2\right]$$

with g_{MN} the 5D bulk metric and g its determinant; c is the mass scale for the infrared conformal symmetry breaking.

AdS$_5$ metric $ds^2=\frac{1}{z^2}\left(dx_0^2-d\vec{x}^2-dz^2\right),\quad z>0\quad(R=1)$

The normalizable solutions of the Euler-Lagrange equation for $\tilde{O}_0(p,z)$ and the poles of the two point correlation function of $J(x)$ correspond to the Regge-like mass spectrum

$$m_n^2=4c^2(n+4)$$

with n the radial (in the extra-dimension) quantum number. Setting $c=m_\rho/2=388$ MeV from the ρ meson mass, we get

$$m_0=1.55 \text{ GeV},\quad m_1=1.74 \text{ GeV}$$

HARD WALL

5D action $S=\frac{1}{k}\int d^5x\sqrt{|g|}\left[g^{MN}\partial_M O_0\partial_N O_0-M_5^2O_0^2\right]$

AdS$_5$ metric with a sharp cutoff $z\le z_m$ (mass scale)

Mass spectrum $m_n^2\sim n^2$. Setting $1/z_m=346$ MeV, we get

$$m_0=2.80 \text{ GeV},\quad m_1=4.14 \text{ GeV}$$

EINSTEIN-DILATON

The 5D bulk geometry

$$ds^2_{(ED)}=\frac{e^{2\delta^2z^2-\frac{4}{3}\Phi(z)}}{z^2}\left(dx_0^2-d\vec{x}^2-dz^2\right)$$

involves a scalar dilaton field $\Phi(z)$ whose profile is obtained solving the Einstein equations for the metric-dilaton system. The Euler-Lagrange equation for the oddball field $\tilde{O}_0(p,z)$ and the choice $\delta=0.43$ GeV give

$$m_0=2.82 \text{ GeV},\quad m_1=4.07 \text{ GeV}$$

Mass of the lightest $J^{PC}=0^{--}$ glueball in other models

	FLUX TUBE	Lattice QCD	QCD sum rules
$m_{0^{--}}$	2.79 GeV	(5.166 ± 1.000) GeV	(3.81 ± 0.12) GeV (4.33 ± 0.13) GeV

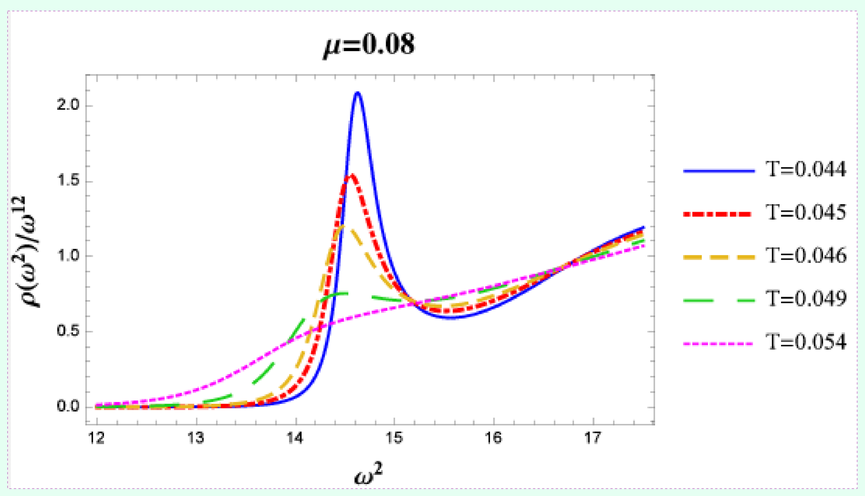
EFFECTS OF FINITE TEMPERATURE T AND CHEMICAL POTENTIAL μ (SOFT WALL MODEL)

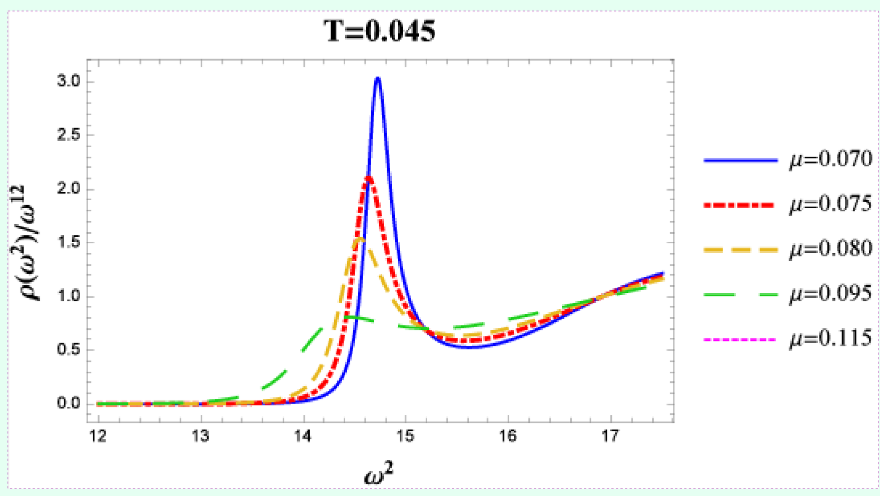
The in-medium properties of this gluonium can be investigated introducing a deformation $f(z)$ in the AdS geometry: $ds^2=\frac{1}{z^2}\left(f(z)dx_0^2-d\vec{x}^2-\frac{dz^2}{f(z)}\right)$

- Deconfined phase ⟶ **AdS/RN metric** $f(z)=1-\left(\frac{1}{z_h^4}+q^2z_h^2\right)z^4+q^2z^6$ ⟶ Black hole with outer horizon $z=z_h$ and charge q

$$T=\frac{1}{4\pi}\left|\frac{df}{dz}\right|_{z=z_h}=\frac{1}{\pi z_h}\left(1-\frac{Q^2}{2}\right),\quad \mu=\kappa\frac{Q}{z_h},\ \text{with } Q=qz_h^3 \text{ and } 0\le Q\le\sqrt{2}.$$

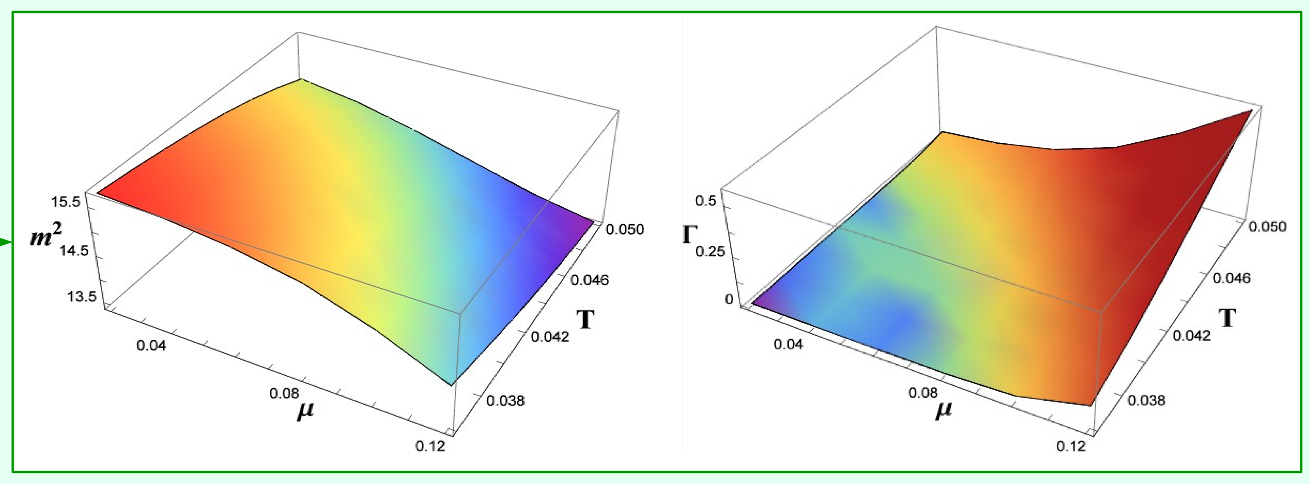
At (T,μ) below the deconfinement (*Hawking-Page*) transition AdS/RN represents a metastable state. Information on the stability against thermal and density fluctuations can be inferred from the **spectral function** $\rho(\omega^2)=\text{Im}\,\Pi^R(\omega^2)$, with $p^\mu=(\omega,\vec{0})$ and Π^R the retarded Green's function of $J(x)$.





Effects of temperature and density: mass reduction, broadening and melting of the bound states.

(T,μ) - dependence of the lightest oddball's mass m and width Γ



The state turns out to be more unstable than all the other hadrons investigated by the same technique.

- Confined phase ⟶ **thermal-charged AdS metric** $f(z)=1+q^2z^6$

T is implemented using a periodic Euclidean time $\tau=it$, with period $\beta=1/T$ and $\mu\propto q$.