Scalar and Tensor Glueballs in Holographic QCD

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[F. Brünner, D. Parganlija and A. Rebhan, Acta Phys.Polon.Supp. 7 (2014) 3, 533 arXiv:1407.6914]

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Special thanks:
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From George Rupp

Subject **Eef70: Planned Workshop on Unquenched Hadron Spectroscopy, 1-5 Sept. 2014, Coimbra, Portugal**

To george

Dear colleagues,

this is an exploratory message announcing our intention to organise a workshop on hadron physics in Coimbra, Portugal, in the week of 1-5 September 2014, thus preceding the XIth "Quark Confinement and theHadron Spectrum" Conference in St. Petersburg, during the week right after. The special occasion for organising such an event is Eef van Beveren's 70th birthday, on September 3rd. Depending on the response we receive to this tentative announcement, we will then decide whether minimum conditions are fulfilled for the workshop to take place as planned.

These developments make a workshop on unquenched hadron spectroscopy very desirable and topical. It could allow to bring together experts from phenomenology, the lattice, and experiment to discuss progress in this hot field and compare results. But also input from related fields, such as chiral quark, Nambu-Jona-Lasinio, and linear sigma models, as well as unitarised perturbation theory and chiral unitary theory should prove very useful. At the same time, it would represent the best way to

Meson Quantum Numbers

- Quantum numbers: J^{PC}

- Scalar mesons: $J^{PC} = 0^{++}$ [σ or $f_0(500)$, $a_0(980)$, $a_0(1450)$…]
- Pseudoscalar mesons: $J^{PC} = 0^{-+}$ [π, η, η'…]
- Vector mesons: $J^{PC} = 1^{--}$ [ρ, ω, $\varphi(1020)$…]
- Axial-Vector mesons: $J^{PC} = 1^{++}$ [$a_1(1260)$, $f_1(1285)$, …]

[For a review see, e.g., M. R. Pennington, AIP Conf. Proc. 1560, 11 (2013) [arXiv:1402.5435]]

Scalar Mesons

- States up to 1.8 GeV (PDG)

State	Mass [MeV]	Width [MeV]
$f_0(500)$	400 - 550	400 - 700
$f_0(980)$	990 ± 20	40 - 100
$f_0(1370)$	1200 - 1500	200 - 500
$f_0(1500)$	1505 ± 6	109 ± 7
$f_0(1710)$	1720 ± 6	135 ± 8
$f_0(1790)$	1790^{+40}_{-30}	270^{+60}_{-30}

Quantum Chromodynamics

- **QCD Lagrangian:**

$$\mathcal{L} = \bar{q}_f\left(i\gamma^\mu D_\mu - m_f\right)q_f - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

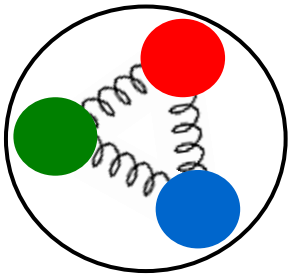
Strong Coupling
Energy-Dependent!

↓

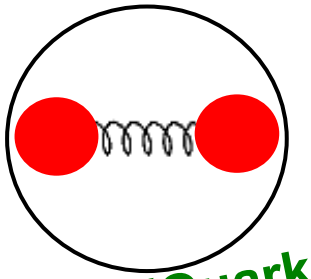
Strongly Nonperturbative

↕

Hadrons Emerge



Half-Integer Spin
Baryons

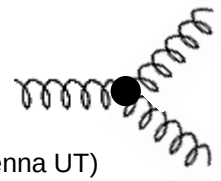


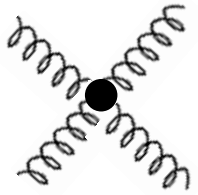
Integer Spin
Mesons

(Quarkonium)

- **Gluons are self-interacting!**

Glueballs!





The Importance of Glueballs

- **Mass of, e.g., nucleons is generated by**
  1. Higgs mechanism (subdominant)
  2. Strong interaction (predominant)

  Glueball mass is generated only by the strong interaction

- **Glueballs must have integer spin → they are mesons**

  Meson spectrum is incomplete without glueballs

- **Relevant for PANDA @ FAIR**
- **Various theoretical approaches**

Two approaches to Low-Energy QCD

QCD

First principles:
Lattice

[Wilson; Fodor, Katz, Dürr, Wagner, Gregory, Irving, Prelovsek, Bali, Lang, Chen, Endrodi…]

scalars very broad, extrapolation problems

Lattice: m_G ~ 1.7 GeV

[Morningstar and Peardon (2004), pure YM]

Bethe-Salpeter Equations

[Roberts, Nicmorus, Eichmann, Williams, Fischer, Oset, …]

have to be non-truncated

Holographic QCD

Effective theories and models:

Linear Sigma Model
Chiral Perturbation Theory

Based on QCD symmetries; may be based on constituent quarks

[Results from Extended Linear Sigma Model (eLSM) → talks by Gy. Wolf and A. Habersetzer (Thursday)]

AdS/CFT Correspondence

- **N=4 SU(∞) supersymmetric and conformal Yang-Mills theory in 4 dim.**

  Strongly Coupled

  ↔

  A string theory in a 5-dim. curved (anti-de-Sitter) space (xS^5)

  [Maldacena 1998]

  Weakly Coupled

  ↓

  Low-energy limit: supersymmetric gravity

- **However: QCD is neither supersymmetric nor conformal**
- **Problem resolution: AdS7 x S^4 with a compactified dimension → unwanted symmetries broken**

  [Witten 1998]

- **Glueballs emerge from graviton modes**

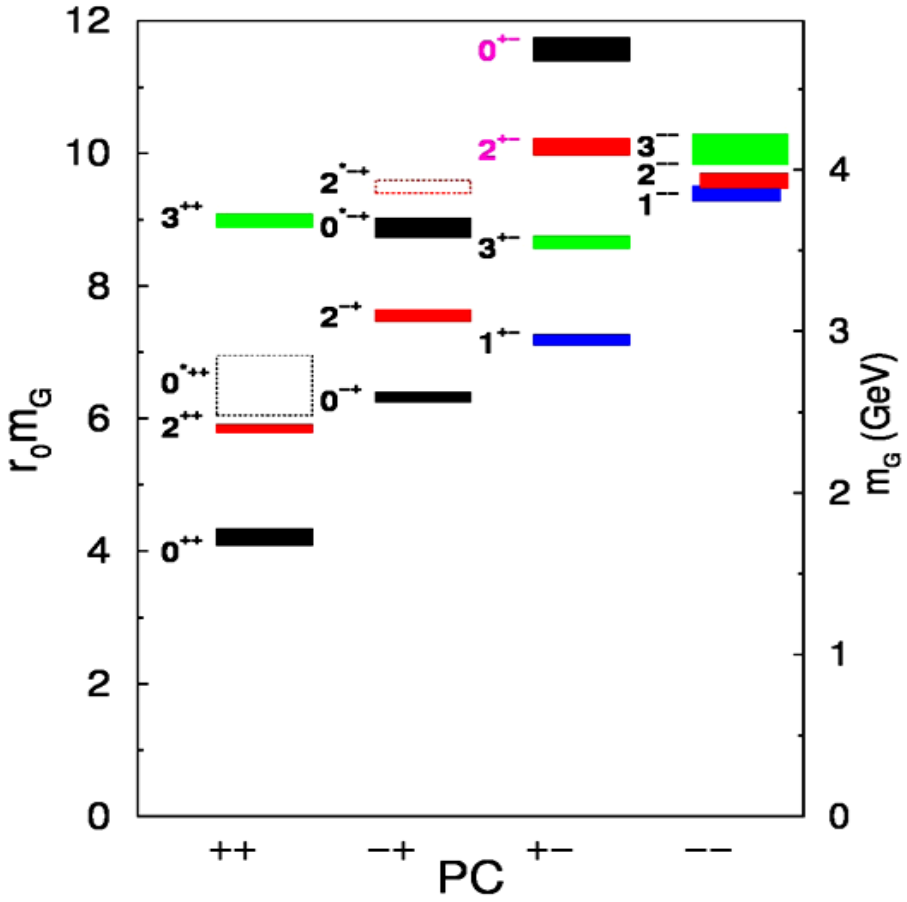
Holographic QCD-Dual

- (Type-IIA) string theory with infinitely many D4-branes ($N_c \to \infty$)
- Compactification of a dimension $x_4 \to x_4 + 2\pi/M_{KK}$

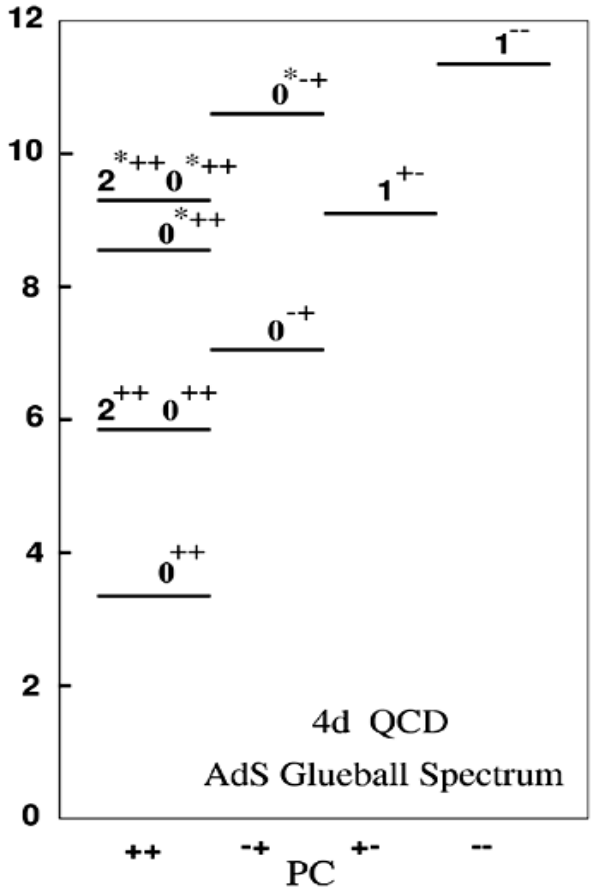
Kaluza-Klein mass

- Supergravity approximation $\leftrightarrow$ weak curvature
- Effectively 5-dim. YM theory for scales below M_{KK} $\leftrightarrow$ conjectured to be dual to QCD

Morningstar & Peardon hep-lat/9901004:



Brower, Mathur & Tan 2000:



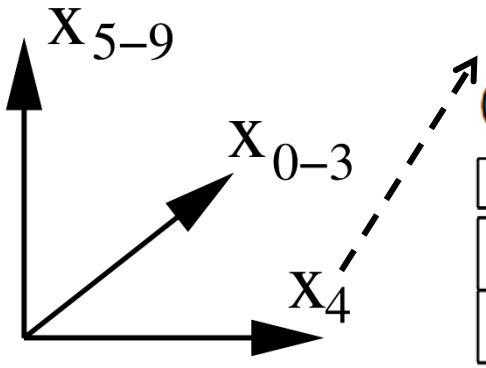
However:

1. No decay widths were calculated

2. Scale matching was perfomed for the 2^{++} state → results differ for another choice of the scale-fixing observable (as we will see in Sakai-Sugimoto Model)

Sakai-Sugimoto Model

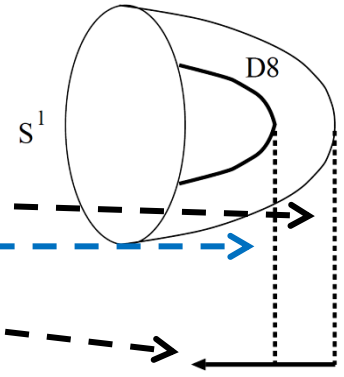
- **A holographic framework first applied for systems with chiral quarks; it can be used for glueballs as well (see later)**



add N_f probe $D_8 -$ and $\bar{D}_8 -$ branes ($N_f \ll N_c$)
(branes are separated in x_4)

	0	1	2	3	4	5	6	7	8	9
D4	x	x	x	x	x					
D8/$\overline{\text{D8}}$	x	x	x	x		x	x	x	x	x

Strings between D_4 and $D_8/\bar{D}_8$ ↔
↔ massless chiral fundamental fermions



The point where D_4 and $\bar{D}_4$ branes end
The point where D_8 and $\bar{D}_8$ branes merge
Radial coordinate transverse to D_4 branes

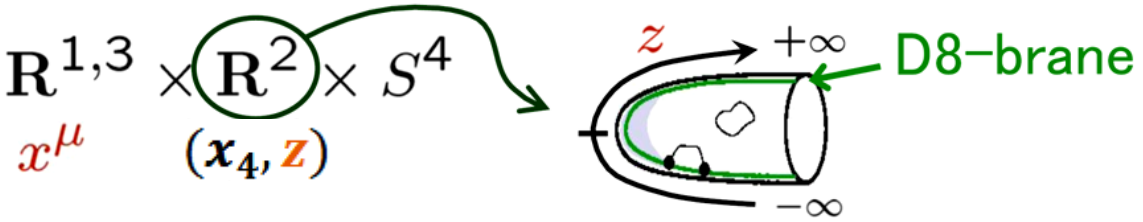
Chiral $U(N_f)_L$ x $U(N_f)_R$ symmetry

[Sakai and Sugimoto 2005]

Sakai-Sugimoto Model

- **In other words:**

  The topology of the D4 background is



  D8−branes are extended along $(x^\mu, z) \times \mathbf{X}^4$

Note: only SO(5)-invariant states are considered

↓

Gauge theory is 5-dimensional

- **Calculations are performed using DBI (Dirac-Born-Infeld) action for D8 branes:**

radial coordinate

$$S_{\rm D8} = \frac{g_{\rm YM}^2 N_c^2}{216\pi^3} \int d^4x\, dz\, {\rm Tr}\left[\frac{1}{2}(1+z^2)^{-1/3} F_{\mu\nu}^2 + (1+z^2) F_{\mu z}^2\right] + \dots$$

field strength for $A_\mu(x^\mu, z) = \sum_{n\geq 1} B_\mu^{(n)}(x^\mu)\psi_n(z)$

field strength for $A_z(x^\mu, z) = \sum_{n\geq 0} \varphi^{(n)}(x^\mu)\phi_n(z)$

with the interpretations:

$\varphi^{(0)} \sim$ pion

$B_\mu^{(1)} \sim \rho$ meson $\quad B_\mu^{(2)} \sim a_1$ meson $\quad \cdots$

Quarkonia in Sakai-Sugimoto Model

- **Determining the scale and one free parameter:**

$$m_\rho \simeq 776\,\text{MeV} \rightarrow M_{KK} = 949\,\text{MeV}$$

$$f_\pi = \frac{\lambda N_c}{54\pi^4} M_{KK}^2 \rightarrow \lambda = g_{\text{YM}}^2 N_c \cong 16.6$$

since eigenvalue of ψ_1 leads to $m_\rho = \sqrt{0.669} M_{KK}$

$$-(1+z^2)^{1/3}\partial_z\left[(1+z^2)\partial_z\psi_1\right] = \lambda_1\psi_1$$

- **This implies e.g.**

$$m_{a_1}^2/m_\rho^2 \approx 2.4 \quad \textbf{(PDG data: 2.5)}$$

$$\Gamma_\rho/m_\rho = \frac{g_{\rho\pi\pi}^2}{48\pi} \approx 0.15 \quad \textbf{(PDG data: 0.19)}$$

For further results see

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)]

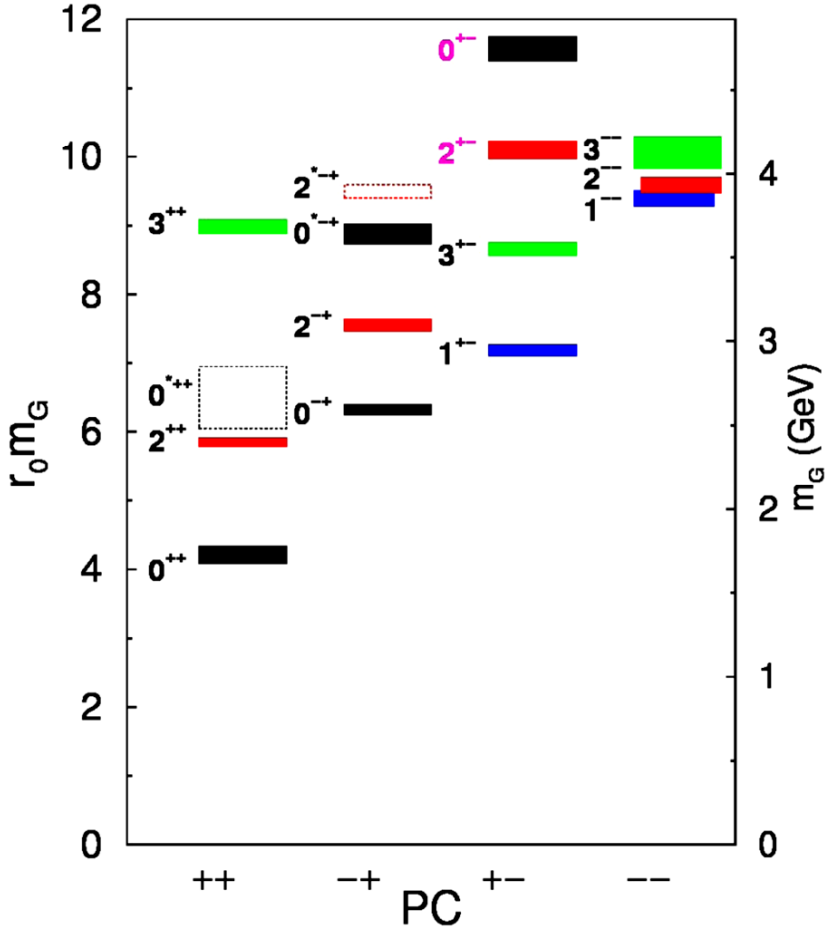
[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 114, 1083 (2006)]

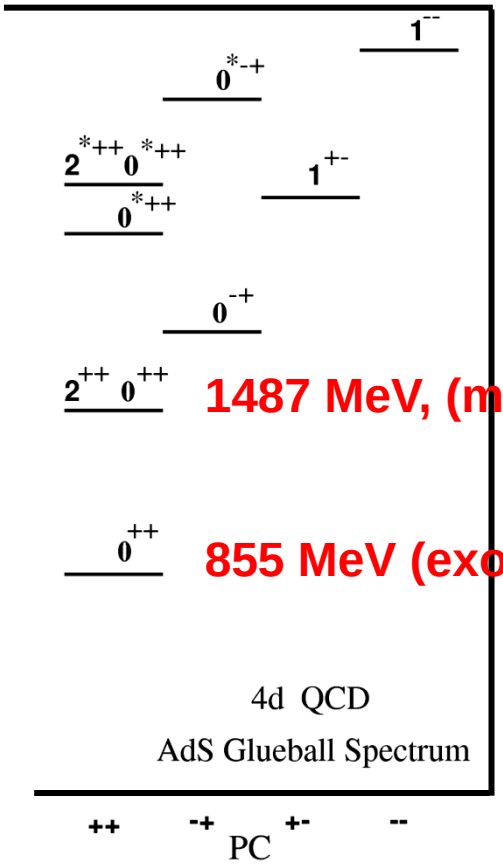
[F. Brünner, D. Parganlija and A. Rebhan, Acta Phys.Polon. Supp. 7 (2014) 3, 533 arXiv:1407.6914]

- **What about glueballs?**

Glueballs in Sakai-Sugimoto Model

- **Scale fixed by the rho mass**





1487 MeV, (mostly) dilaton

855 MeV (exotic)

Scalar and Tensor Glueballs

- **We have looked into: (1) 2π decays, (2) 4π decays, (3) hypothesis of universal narrowness of glueballs**

$$\Gamma_{\text{Dilaton}\to 2\pi}/M_{\text{Dilaton}} = 0.009$$

$$\Gamma_{\text{Tensor}\to 2\pi}/M_{\text{Tensor}} = 0.014$$

… at tensor mass = 1487 MeV

Experiment: $\Gamma_{f_0(1500)\to 2\pi}/M_{f_0(1500)} = 0.025$

[K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C38, 090001 (2014)]

PDG lists several f_2 states but only $f_J(2200)$ has accordant $\Gamma / m \sim 0.010$

$$\Gamma_{f_0(1710)\to 2\pi}/M_{f_0(1710)} = 0.017$$

[M. Ablikim et al., Phys. Lett. B 642, 441 (2006) [arXiv:hep-ex/0603048] + PDG data on eta and kaon decays]

$$\Gamma_{f_0(1710)\to 2\pi}/M_{f_0(1710)} = 0.009$$

[D. Barberis et al. [WA102 Collaboration], Phys. Lett. B 462, 462 (1999) [arXiv:hep ex/9907055] + PDG data on eta and kaon decays]

[See also: S. Janowski, F. Giacosa and D. H. Rischke, arXiv:1408.4921 [hep-ph]]

4π decays of scalar glueball strongly suppressed

Holographic glueball is narrow

Summary and Outlook

- **Glueball identification is an unsettled issue, relevant for PANDA@FAIR**
- **Our approach: non-perturbative QCD via AdS/CFT – Sakai-Sugimoto Model**
- **Chiral fundamental holographic quarks implemented; glueballs emerge from graviton modes**
- **Glueballs are narrow**
- **Preliminary puzzle: decay of the scalar glueball points to $f_0(1710)$, though the mass is more compatible with $f_0(1500)$**
- **Probable puzzle resolution: no mixing with antiquark-quark states – to be implemented in the future**