Der Wissenschaftsfonds.

Holographic Scalar and Tensor Glueballs

Denis Parganlija

[Based on F. Brünner, D. Parganlija and A. Rebhan, arXiv:1501.07906 [hep-ph]]

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F. Brünner and A. Rebhan (Vienna)
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QCD and Its Degrees of Freedom

Quantum Chromodynamics

- **QCD Lagrangian:**

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

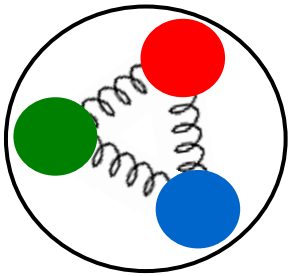
$$\boxed{D_\mu = \partial_\mu - igA^a_\mu t^a}$$

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

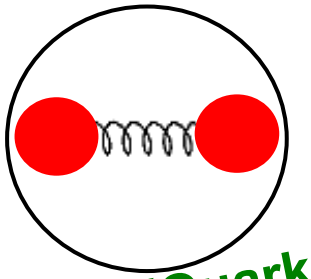
Strong Coupling
Energy-Dependent!

$\updownarrow$

Hadrons Emerge at Small Energies



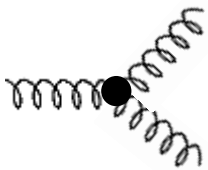
Half-Integer Spin
Baryons

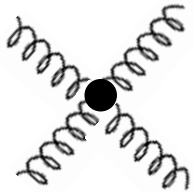


Integer Spin
Mesons

(Quarkonium)

- **Gluons are self-interacting**
- **Gluon bound states: 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

- **Glueballs couple to quarkonia in vacuum → (indirect) influence on chiral restoration**

- **Relevant for PANDA @ FAIR**

Experimental Candidates

Scalar Glueball Candidates

- Five states up to 1.8 GeV (isoscalars)

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
$f_0(1710)$	1722^{+6}_{-5}	135 ± 7

Absent from $\gamma\gamma$:
$f_0(1500)$ [ALEPH; L3]
$f_0(1710)$ [ALEPH]

Can theory help?

Theoretical Input

AdS/CFT Correspondence

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

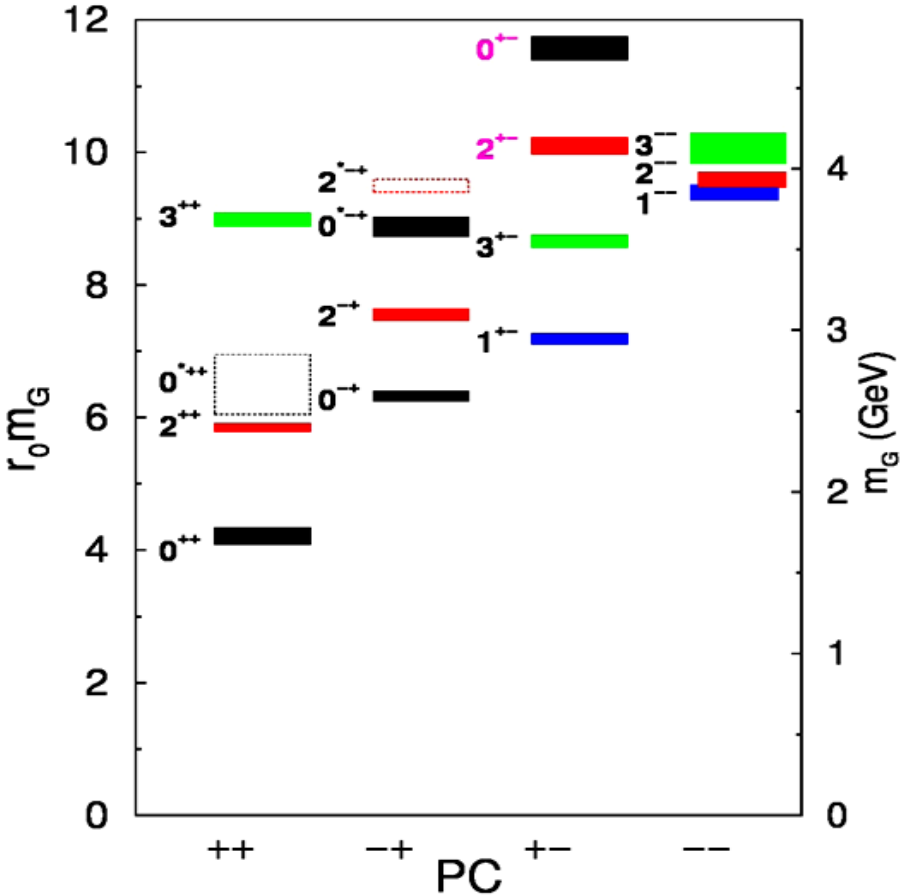
  ↔

  A string theory in a 5-dim. curved (anti-de-Sitter) space (xS^5) [Maldacena 1998] Weakly Coupled

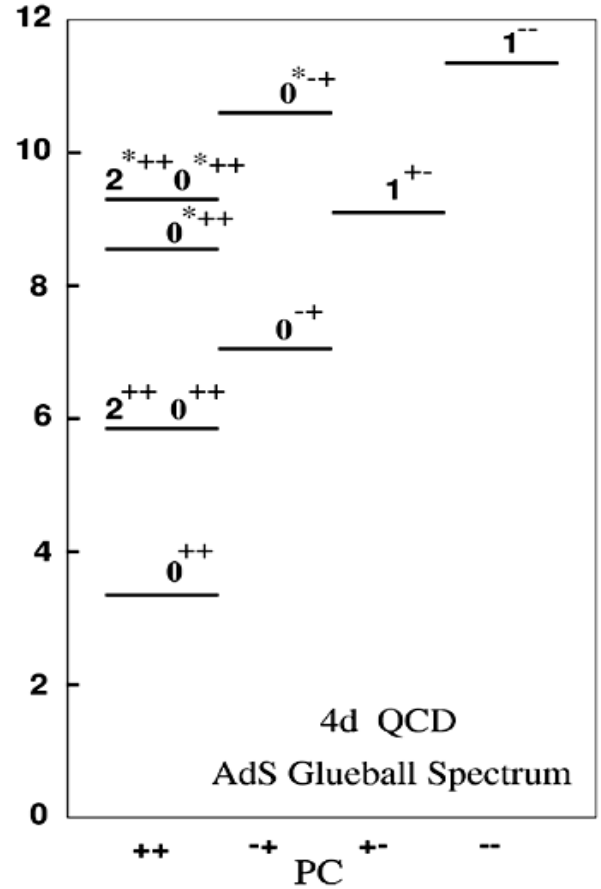
  ↓

  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

Morningstar & Peardon hep-lat/9901004:



Brower, Mathur & Tan 2000:



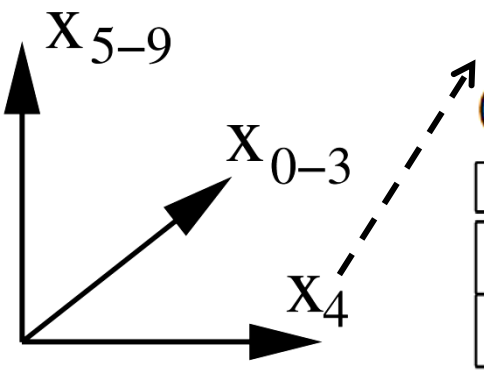
However:

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

Sakai-Sugimoto Model

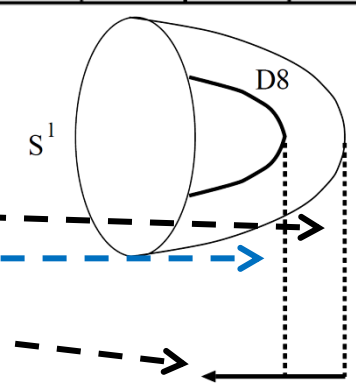
- **A holographic framework first applied for systems with chiral quarks; it can be used for glueballs as well (see later)**



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 $D_8/\bar{D}_8$ $\leftrightarrow$
$\leftrightarrow$ 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 $U(N_f)_L \times U(N_f)_R$ symmetry

[Sakai and Sugimoto 2005]

Sakai-Sugimoto Model

- **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 $\quad \dots$

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

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

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

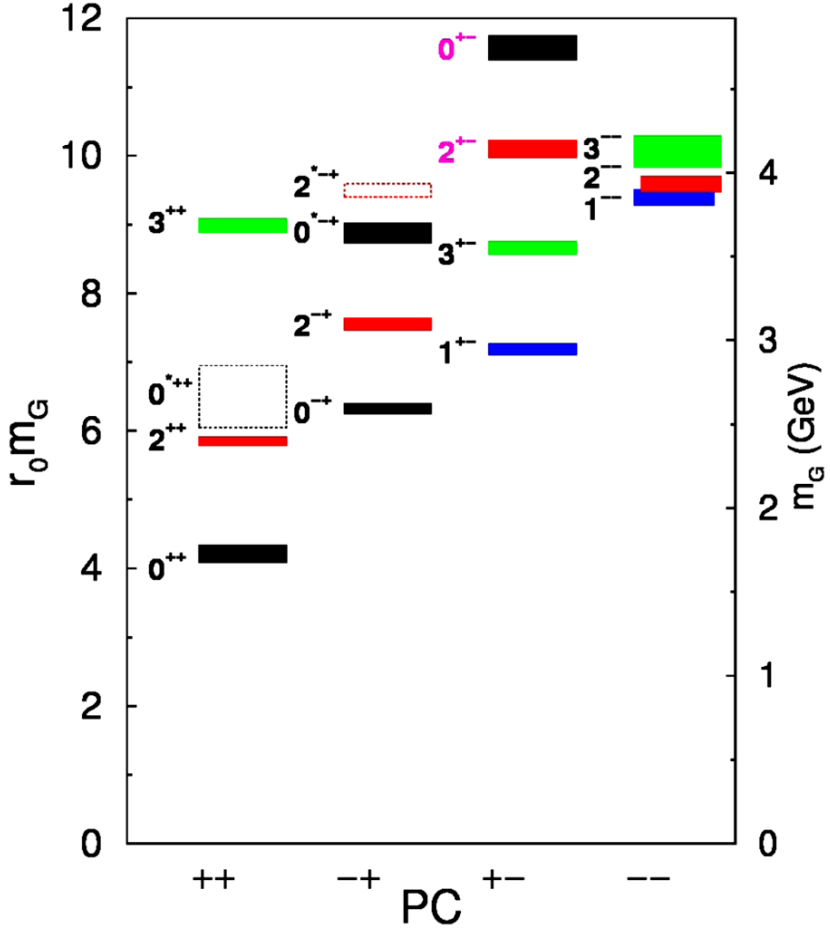
- **This implies e.g.** $m_{a_1}^2/m_\rho^2 \approx 2.4$ $\quad \Gamma_\rho/m_\rho = \frac{g_{\rho\pi\pi}^2}{48\pi} \approx 0.15$

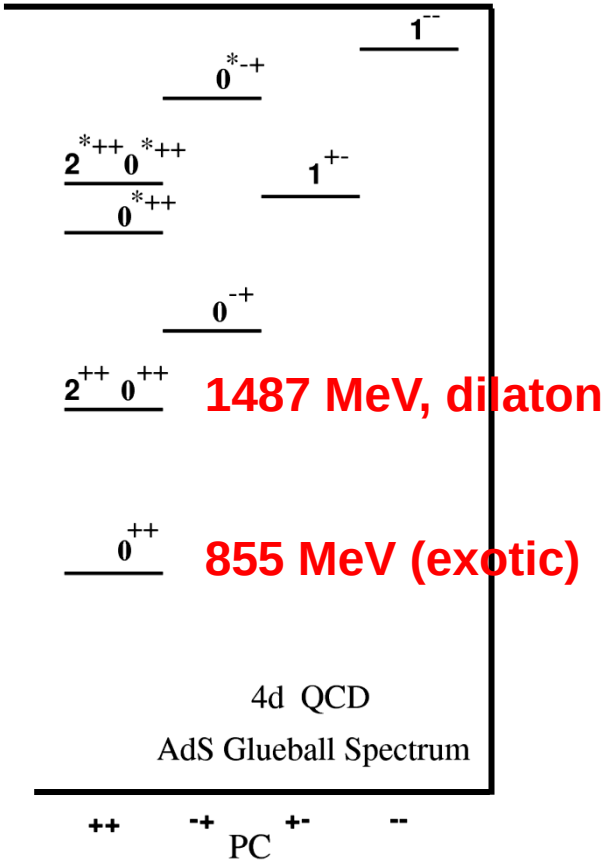
(PDG: 2.5) **(PDG data: 0.19)**

[T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005); 114, 1083 (2006)]

Glueballs in Sakai-Sugimoto Model

- **Scale fixed by the rho mass**



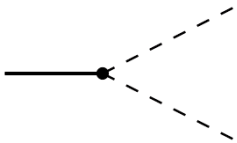


[F. Brünner, D. Parganlija and A. Rebhan, arXiv:1501.07906 [hep-ph]]

Scalar Glueball

Non-Extrapolated Results

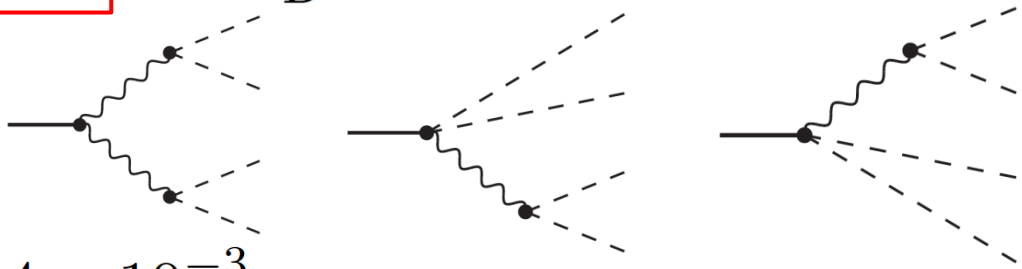
- **Two-Pion Decay**



$$\Gamma_{G_D\to\pi\pi}/M_D = \frac{1.359}{\lambda N_c^2} = 0.009$$

$$\boxed{\Gamma_{G_D\to\pi\pi} = 13\ \mathrm{MeV}};\ m_{G_D} = 1487\ \mathrm{MeV}$$

- **Four-Pion Decay**



$$\Gamma_{G_D\to 4\pi}/M_D \approx 2.44\times 10^{-3}$$

$$\Gamma_{G_D\to 4\pi} \approx 4\ \mathrm{MeV}$$

Quite narrow!

- **Data:**

$$\Gamma_{f_0(1500)\to\pi\pi} = (38\pm5)\ \mathrm{MeV};\ \Gamma_{f_0(1500)\to 4\pi} = (54\pm5)\ \mathrm{MeV}$$

$$\Gamma_{f_0(1710)\to\pi\pi} = (29\pm7)\ \mathrm{MeV}\ \ \boxed{\Gamma_{f_0(1710)\to\pi\pi} = (16\pm4)\ \mathrm{MeV}}$$

[D. Parganlija, arXiv:1208.0204
BES Collaboration (2006), arXiv: hep-ex/0603048]

[D. Parganlija, arXiv:1208.0204
WA102 Collaboration (1999),
arXiv: hep-ex/9907055]

Extrapolated Results

decay	M^{exp}	Γ/M (exp.)	$\Gamma/M[G_D(M^{\text{exp}})]$
$f_0(1500)$ (total)	1505	0.072(5)	0.027...0.037
$f_0(1500) \to 4\pi$	1505	0.036(3)	0.003...0.005
$f_0(1500) \to 2\pi$	1505	0.025(2)	0.009...0.012
$f_0(1500) \to 2K$	1505	0.006(1)	0.012...0.016
$f_0(1500) \to 2\eta$	1505	0.004(1)	0.003...0.004
$f_0(1710)$ (total)	1722	0.078(4)	*0.059...0.076*
$f_0(1710) \to 2K$	1722	$* \begin{cases} 0.041(20) \\ 0.047(17) \end{cases}$	0.012...0.016
$f_0(1710) \to 2\eta$	1722	$* \begin{cases} 0.020(10) \\ 0.022(11) \end{cases}$	0.003...0.004
$f_0(1710) \to 2\pi$	1722	$* \begin{cases} 0.017(4) \\ 0.009(2) \end{cases}$	0.009...0.012
$f_0(1710) \to 4\pi$	1722	?	*0.024...0.030*
$f_0(1710) \to 2\omega \to 6\pi$	1722	seen	*0.011...0.014*

[F. Brünner, D. Parganlija and A. Rebhan, 1501.07906]

Scalar Ambiguities

- **How many scalar states exist between 1.7 GeV and 1.8 GeV?**

$f_0(1710)$ and $f_0(1790)$ known from J/ψ decays:

- $J/\psi \to \omega K^+K^-$ $\quad J/\psi \to \omega\pi^+\pi^-$

  $J/\psi \to \varphi K^+K^-$ $\quad J/\psi \to \varphi\pi^+\pi^-$

[M. Ablikim *et al.* (BES II Collaboration), Phys. Lett. B 603, 138 (2004) and Phys. Lett. B 607, 243 (2005)]

According to BES Collaboration:

$f_0(1710)$:

$m_{\mathrm{PDG}} = (1720 + 6 - 5)\ \mathrm{MeV}$,

$\Gamma_{\mathrm{PDG}} = (135 \pm 7)\ \mathrm{MeV}$

$f_0(1790)$:

$m = 1790^{+40}_{-30}\ \mathrm{MeV}$,

$\Gamma = 270^{+60}_{-30}\ \mathrm{MeV}$

Can they represent the same resonance?

Scalar Ambiguities

- **Assume that they are the same resonance $\tilde{f}_0$**

$$\frac{\Gamma_{\tilde{f}_0\to\pi\pi}}{\Gamma_{\tilde{f}_0\to KK}} < 0.11$$

$$J/\psi \to \omega K^+K^- \qquad J/\psi \to \omega\pi^+\pi^-$$

$$J/\psi \to \varphi K^+K^- \qquad J/\psi \to \varphi\pi^+\pi^-$$

$$\frac{\Gamma_{\tilde{f}_0\to\pi\pi}}{\Gamma_{\tilde{f}_0\to KK}} = 1.82 \pm 0.33$$

[M. Ablikim *et al.* (BES II Collaboration), Phys. Lett. B 603, 138 (2004) and Phys. Lett. B 607, 243 (2005)]

$f_0(1710)$ and $f_0(1790)$ are two distinct resonances

…according to BES Collaboration

Tensor Glueball

Tensor Decays

decay	M	$\Gamma/M[T(M)]$
$T \to 2\pi$	1487	$0.013\ldots0.018$
$T \to 2K$	1487	$0.004\ldots0.006$
$T \to 2\eta$	1487	$0.0005\ldots0.0007$
T (total)	1487	$\approx 0.02\ldots0.03$
$T \to 2\rho \to 4\pi$	2000	$0.135\ldots0.178$
$T \to 2\omega \to 6\pi$	2000	$0.045\ldots0.059$
$T \to 2\pi$	2000	$0.014\ldots0.018$
$T \to 2K$	2000	$0.010\ldots0.013$
$T \to 2\eta$	2000	$0.0018\ldots0.0024$
T (total)	2000	$\approx 0.16\ldots0.21$
$T \to 2\rho \to 4\pi$	2400	$0.159\ldots0.211$
$T \to 2\omega \to 6\pi$	2400	$0.053\ldots0.070$
$T \to 2\phi$	2400	$0.053\ldots0.070$
$T \to 2\pi$	2400	$0.014\ldots0.019$
$T \to 2K$	2400	$0.012\ldots0.016$
$T \to 2\eta$	2400	$0.0025\ldots0.0034$
T (total)	2400	$\approx 0.29\ldots0.39$

Heavy tensor glueball is quite broad:

Γ_{total} ~ 370 MeV

Γ_{total} ~ 820 MeV

Note #1: there may be quarkonium admixtures

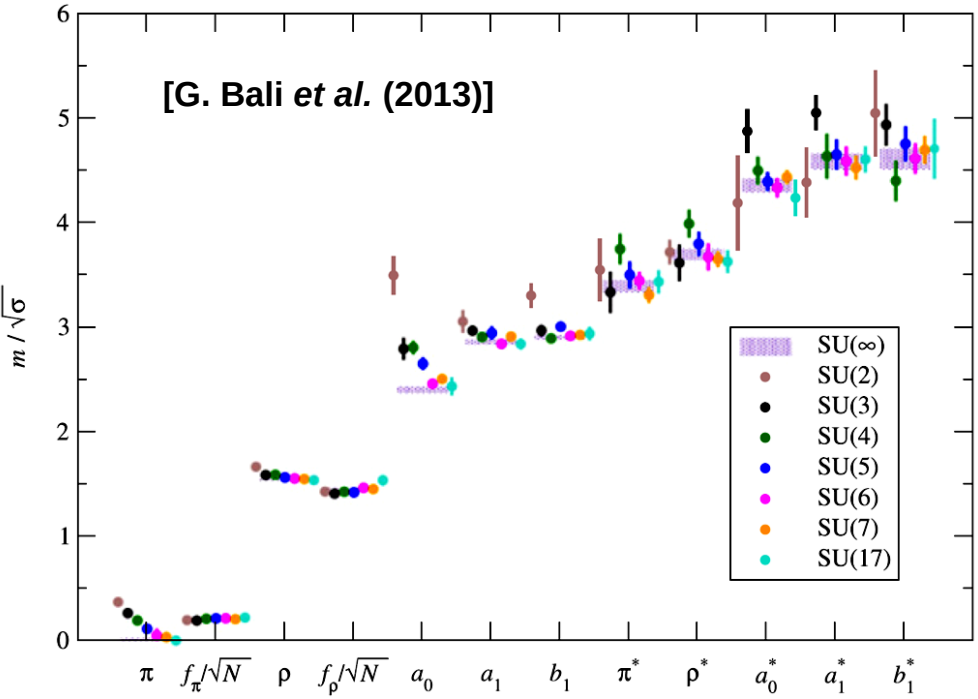
Note #2: 4π the strongest channel for the tensor

Summary

- A holographic top-down approach to QCD (Sakai-Sugimoto Model)
- Glueball phenomenology considered
- Indication is that $f_0(1710)$ is more likely than $f_0(1500)$ to have a noticeable glueball component
- Pure tensor glueball very broad: ~ (400-800) MeV
- More data is needed to identify glueballs!

Spare Slides

How close is $N_c = 3$ to $N_c = \infty$?



continuum limit			
	$m_{0^{++}}/\sqrt{\sigma}$	$m_{0^{++\star}}/\sqrt{\sigma}$	$m_{2^{++}}/\sqrt{\sigma}$
SU(2)	3.844(61)	6.06(16)	5.59(15)
SU(3)	3.607(87)	6.07(30)	5.13(22)
SU(4)	3.49(14)	6.80(45)	5.21(21)
SU(5)	3.38(16)	6.16(55)	4.88(38)
SU(∞)	3.37(15)	6.43(50)	4.93(30)

Table 5: The continuum limit of the lightest scalar and tensor glueball masses, and the first excited scalar mass, all in units of the string tension σ. The extrapolation of these to $N = \infty$ is also shown.

[B. Lucini and M. Teper (2001)]

Two approaches to Low-Energy QCD

QCD

First principles:

Lattice

[Wilson; Dürr, Fodor, Gregory, Irving, Katz, Lang, Mohler, Morningstar, Peardon Prelovsek, …]

scalars very broad, extrapolation problems

Bethe-Salpeter Equations

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

have to be non-truncated

Effective theories and models:

Linear Sigma Model

Chiral Perturbation Theory*

Based on QCD symmetries; may be based on constituent quarks

[Extended Linear Sigma Model (eLSM) → talk by P. Kovacs (next)]

Holographic QCD (Witten-Sakai-Sugimoto Model)

A Problem for PANDA

The Problem of Numbers

- **Glueball ground state is scalar**
- **Scalar glueball will correspond to an f_0 state (or contribute to several to them)**
- **How many f_0 states are there?**
- **In particular: how many between 1.7 GeV and 1.8 GeV?**

Scalar Mesons

- $I = 0$ 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
$f_0(1710)$	1722^{+6}_{-5}	135 ± 7

Scalar Ambiguities

- States up to 1.8 GeV (PDG)

State	Mass [MeV]	Width [MeV]
$f_0(500)$	400 - 550	400 - 700
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$f_0(1500)$	1505 ± 6	109 ± 7
$f_0(1710)$	1722^{+6}_{-5}	135 ± 7
$f_0(1790)$	1790^{+40}_{-30}	270^{+60}_{-30}

PANDA can confirm or disprove this!

What I Propose To Be Done:

- Look into $\pi\pi$ final states starting at ~ 1.65 GeV; this should be possible via formation if not production (lighter scalars well known from other data)
- Look into KK final states starting at ~ 1.65 GeV to discriminate between $f_0(1710)/f_0(1790)$
- Look into 4π final states starting at ~ 1.65 GeV: glueball coupling may be strong

Summary

- There can be no complete glueball spectrum without the scalar glueball
- There will be no pure scalar glueball, but a predominantly glueball scalar state
- A clear identification of this predominantly glueball state is only possible all f_0 states are known
- These will couple to 2π, $2K$, 4π final states
- PANDA can resolve glueball uncertainties!