CEP of glueballs and their decay

Predictions from holographic QCD

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Ever elusive: Glueballs

Spectrum of *bare* glueballs
(prior to mixing with $q\bar{q}$ states)
more or less known from lattice:

$m_{0^{++}} \sim 1.7$ GeV
$m_{2^{++}} \sim 2.4$ GeV
$m_{0^{-+}} \sim 2.6$ GeV
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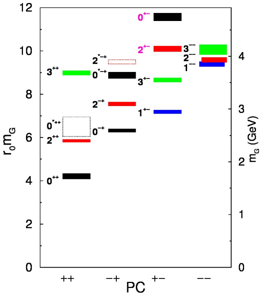
Morningstar & Peardon hep-lat/9901004



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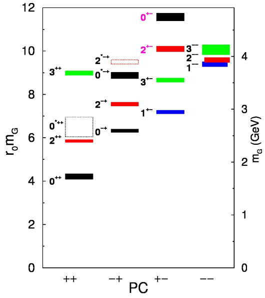

Interactions of glueballs still unclear:

- Are glueballs broad or narrow?
- Do they mix with $q\bar{q}$ strongly or weakly?

$\rightarrow$ no conclusive identification of any glueball in meson spectrum

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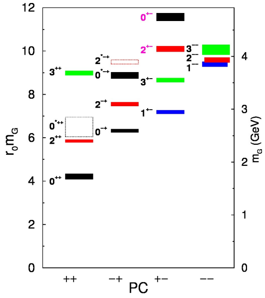

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most discussed lowest 0^{++} candidates:

narrow $f_0(1500)$ or $f_0(1710)$ vs. very broad background ("red dragon")

various phenomenological models describe $f_0(1500)$ or $f_0(1710)$
alternatingly as $\sim$50-70% or $\sim$75-90% glue

[G and two isoscalar $q\bar{q}$ states $u\bar{u} + d\bar{d}$ and $s\bar{s}$ can be shared by $f_0(1370)$, $f_0(1500)$, $f_0(1710)$]

Even more elusive: Pseudoscalar glueball

Pseudoscalar glueball ($\tilde{G}$):

- closely related to η' and the $U(1)_A$ problem
- in 1980: first glueball candidate the isoscalar pseudoscalar $\iota(1440)$, now listed as two states $\eta(1405)$ and $\eta(1475)$ in PDG
- together with $\eta(1295)$ $\Rightarrow$ a supernumerary state beyond the first radial excitations of the η and η' mesons, with $\eta(1405)$ singled out as glueball candidate
- BUT: lattice predicts $m(\tilde{G}) \sim 2.6$ GeV ! $\Rightarrow$ Still to be discovered

  indeed: evidence for three η states between 1.2 and 1.5 GeV under dispute

  ($\eta(1405)$ and $\eta(1475)$ could after all be one state $\eta(1440)$; also $\eta(1295)$ sometimes questioned)

Strategy

Seeking help from closest (top-down) holographic model of (large-N_c) low-energy QCD:

the **Witten-Sakai-Sugimoto model**

for guessing (qualitatively, semi-quantitatively) glueball production and decay pattern:

$\to$ estimates (educated guesses) of glueball vertices:

- K. Hashimoto, C.-I. Tan, S. Terashima, PRD77 (2008) 086001
- Scalar and Tensor Glueballs: F. Brünner, D. Parganlija, AR, PRD91 (2015) 106002
- F. Brünner, AR, PRL115 (2015) 131601; PRD92 (2015) 121902
- (Pure) Pseudoscalar Glueball: F. Brünner, AR, PLB770 (2017) 124
- Pseudovector Glueball: F. Brünner, J. Leutgeb, AR, PLB788 (2019) 431
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High-energy scattering outside of regime of supergravity approximation in holographic QCD (higher spin states require quantum strings in curved background — prohibitively difficult)

Possible strategy for CEP:

hybrid approach with vertices taken from WSS model,
but propagators of tensor glueballs Reggeized

Anderson, Domokos, Harvey, Mann 2014; Iatrakis, Ramamurti, Shuryak 2016

Large-N_c QCD

Lattice: glueball spectrum at $N_c = 3$ rather similar to large N_c

't Hooft limit (1974): $N_c \to \infty$ with $\lambda = g^2 N_c$ (and N_f) fixed
- If confining, $N \to \infty$ QCD free theory of (infinite no. of) stable mesons and glueballs

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Finite, large N:
— mixing of mesons and glueballs at most $\sim N^{-1/2}$
— meson decay rates $\sim N^{-1}$
— glueball decay rates $\sim N^{-2}$

If large-N limit appropriate starting point for approximations:

glueballs should be weakly mixed and relatively stable

(though in Veneziano limit $N_c \sim N_f \gg 1$ strong mixing!)

$1/N_c$ expansion may, occasionally, be numerically good expansion even at $N_c = 3$

Large-N_c QCD $\rightarrow$ Holographic QCD

Celebrated AdS/CFT duality relates strongly coupled large-N_c supersymmetric Yang-Mills theories to supergravity on anti-de Sitter space in 5 dimensions (AdS$_5 \times S^5$)

Holographic QCD: generalization to nonconformal nonsupersymmetric case
Options:

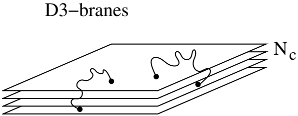
- **Bottom-up**: breaking of conformal invariance (necessary for confinement) by hand and matching to QCD with holographic dictionary, e.g.
  hard-wall model (Erlich-Katz-Son-Stephanov 2005)
  soft-wall model (Karch-Katz-Son-Stephanov 2006)
- **Top-down**: first-principles constructions from superstring theory with nonconformal D-branes
  - here: **Witten**[1998]-**Sakai-Sugimoto**[2004] **model**

Both approaches surprisingly successful quantitative description of low-energy QCD with minimal set of parameters

WSS model: almost parameter-free (1 coupling at a certain mass scale)!

Original AdS/CFT correspondence

J. M. Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998)
"pedestrian's guide": S. S. Gubser and A. Karch, Ann. Rev. Nucl. Part . Sci. 59, 145 (2009)

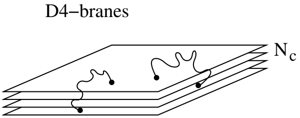


(type IIB) string theory on 5D anti-de Sitter space ($\times S_5$)	$\Leftrightarrow$	$\mathcal{N}=4$ SU(∞) super-YM theory on 4D boundary of AdS$_5$
$\dfrac{(\text{curvature radius})^4}{(\text{string length})^4} = \dfrac{R^4}{\ell_s^4}$	$=$	$g^2_{\mathrm{YM}} N_c \equiv \lambda$ 't Hooft coupling
supergravity limit $\ell_s \ll R$ relatively easy	$\Leftrightarrow$	strong coupling limit $\lambda \gg 1$ impossibly difficult

Witten model: Holographic nonsupersymmetric QCD

E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998):

Type-IIA string theory with $N_c \to \infty$ $D4$ branes dual to $4+1$-dimensional super-Yang-Mills theory



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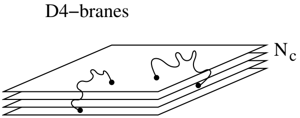

Type-IIA string theory with $N_c \to \infty$ $D4$ branes
dual to $4+1$-dimensional super-Yang-Mills theory

supersymmetry completely broken by compactification
on "thermal-like" circle $x_4 \equiv x_4 + 2\pi/M_{\mathrm{KK}}$ (Kaluza−Klein)

- antisymmetric b.c. for adjoint fermions: masses $\sim M_{\mathrm{KK}}$
- adjoint scalars not protected by gauge symmetry: also masses $\sim M_{\mathrm{KK}}$

$\to$ dual to pure-glue YM theory
3+1-dimensional at scales $\ll M_{\mathrm{KK}}$

but supergravity approximation needs weak curvature,
cannot take limit $M_{\mathrm{KK}} \to \infty$

Glueballs in confined phase

$\exists$ scalar and tensor glueballs corresponding to 5D dilaton Φ and graviton G_{ij}
Csaki, Ooguri, Oz & Terning 1999

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Type-IIA supergravity compactified on x_4-circle many more modes:
Constable & Myers 1999; Brower, Mathur & Tan 2000

Mode Sugra fields J^{PC}	S$_4$ G_{44} 0^{++}	T$_4$ Φ, G_{ij} $0^{++}/2^{++}$	V$_4$ C_1 0^{-+}	N$_4$ B_{ij} 1^{+-}	M$_4$ C_{ij4} 1^{--}	L$_4$ G^α_α 0^{++}
n=0	7.30835	22.0966	31.9853	53.3758	83.0449	115.002
n=1	46.9855	55.5833	72.4793	109.446	143.581	189.632
n=2	94.4816	102.452	126.144	177.231	217.397	277.283
n=3	154.963	162.699	193.133	257.959	304.531	378.099
n=4	228.709	236.328	273.482	351.895	405.011	492.171

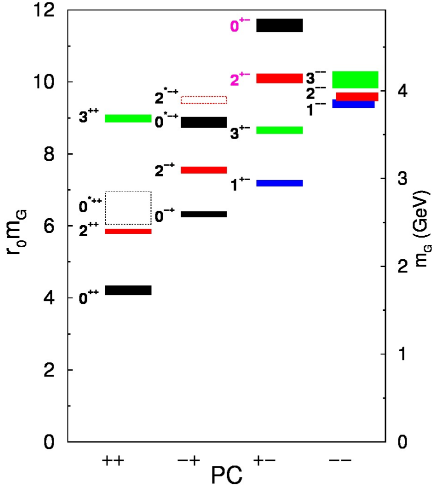
Lowest mode not from dilaton, but from "exotic polarization" – in 11D notation:

$$\underline{\delta g_{44}} = -\frac{r^2}{L^2} f\, H(r) G(x), \quad \delta g_{\mu\nu} = \frac{r^2}{L^2}\left[\frac{1}{4} H(r)\eta_{\mu\nu} - \left(\frac{1}{4} + \frac{3R^6}{5r^6 - 2R^6}\right) H(r) \frac{\partial_\mu \partial_\nu}{M^2}\right] G(x)$$

$$\delta g_{11,11} = \frac{r^2}{L^2}\frac{1}{4} H(r) G(x), \quad \delta g_{rr} = -\frac{L^2}{r^2} f^{-1} \frac{3R^6 H(r) G(r)}{5r^6 - 2R^6}, \quad \delta g_{r\mu} = \frac{90 r^7 R^6 H(r) \partial_\mu G(x)}{M^2 L^2 (5r^6 - 2R^6)^2}$$

Lattice glueballs vs. supergravity glueballs

Morningstar & Peardon hep-lat/9901004:



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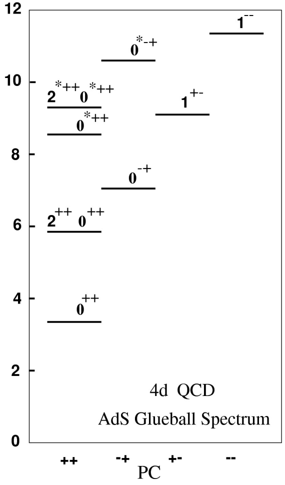
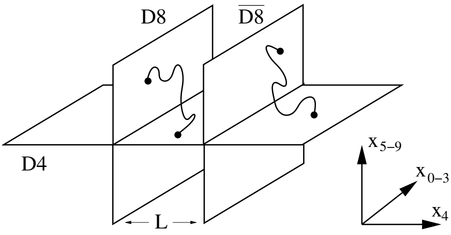


(mass scales matched on 2^{++}) $\to$ seemingly good qualitative agreement!

Sakai-Sugimoto model: Adding chiral quarks

T. Sakai, S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)
add N_f D8- and $\overline{\mathrm{D8}}$-branes, separated in x_4, $N_f \ll N_c$ (probe branes)

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



4-8, 4-$\bar{8}$ strings
$\rightarrow$ fundamental, massless chiral fermions

flavor symmetry
$U(N_f)_L \times U(N_f)_R$

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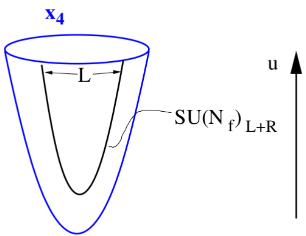

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spontaneously broken because D8-$\overline{\mathrm{D8}}$ have to join in cigar-shaped topology

for now: maximal separation in x_4 (antipodal on x_4 circle): $L = \pi/M_{\mathrm{KK}}$

Quantitative predictions

Parameter-free prediction of (axial-)vector meson mass pattern:

Isotriplet Meson	$\lambda_n = m^2/M_{\rm KK}^2$	m/m_ρ	$(m/m_\rho)^{\rm exp.}$	$(m/m_\rho)^{N\to\infty}$
1^{--} (ρ)	0.669314	1	1	1
1^{++} (a_1)	1.568766	1.531	1.59(5)	1.86(2)
1^{--} (ρ^*)	2.874323	2.072	1.89(3)	2.40(4)
1^{++} (a_1^*)	4.546104	2.606	2.12(3)	2.98(5)

(last column from lattice study by Bali et al. JHEP 06, 071 (2013))

agreement within $\lesssim 20\%$

not bad, given that WSS is not yet large-N QCD (in particular at scales $\gtrsim M_{\rm KK}$)

(near-perfect agreement for m_{a_1}/m_ρ with real QCD certainly fortuitous)

Quantitative predictions

Other predictions depend on value of 't Hooft coupling λ at scale M_{KK}

Matching

1. $m_\rho \approx 776$ MeV fixes $\boxed{M_{\mathrm{KK}} = 949\ \mathrm{MeV}}$ ($\Rightarrow T_{deconf} = 151$ MeV)
2. $f_\pi^2 = \frac{\lambda N_c}{54\pi^4} M_{\mathrm{KK}}^2$ gives $\boxed{\lambda = g_{\mathrm{YM}}^2 N_c \approx 16.63}$ [Sakai&Sugimoto 2005-7]
   (matching instead large-N_c lattice result [Bali et al. 2013] for $m_\rho/\sqrt{\sigma}$ gives $\lambda \approx 12.55$)

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   (matching instead large-N_c lattice result [Bali et al. 2013] for $m_\rho/\sqrt{\sigma}$ gives $\lambda \approx 12.55$)

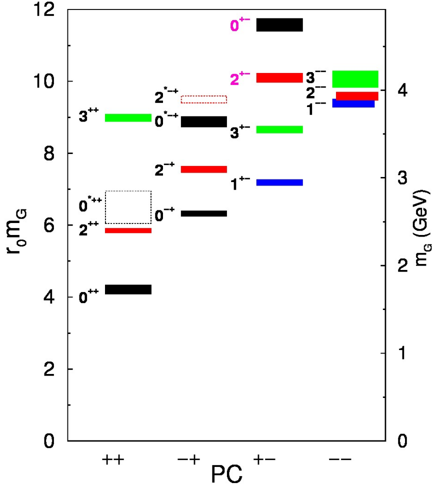
yields (for $N_c = 3$ and $\lambda = 16.63 \ldots 12.55$):

- LO decay rate of ρ meson $\sim \lambda^{-1} N_c^{-1}$
  $\Gamma_{\rho\to 2\pi}/m_\rho = 0.1535 \ldots 0.2034$ (exp.: 0.191(1))
- decay rate for $\omega \to 3\pi$ (from Chern-Simons part of D8 action) $\sim \lambda^{-4} N_c^{-2}$
  $\Gamma_{\omega\to 3\pi}/m_\omega = 0.0033 \ldots 0.0102$ (exp.: 0.0097(1))
- gluon condensate [Kanitscheider, Skenderis & Taylor JHEP 0809]
  $$C^4 \equiv \langle \frac{\alpha_s}{\pi} F_{\mu\nu}^2 \rangle = \frac{4}{3^7 \pi^4} N_c \lambda^2 M_{\rm KK}^4 \simeq 0.0126 \ldots 0.0072 \text{ GeV}^4$$
  classical SVZ value: 0.012 GeV^4 (lattice higher but with large subtraction ambiguities)

Lattice vs. supergravity glueballs

seemingly good qualitative agreement by matching up 2^{++} (but AdS spectrum somewhat stretched and slightly too many 0^{++})

Morningstar & Peardon hep-lat/9901004:



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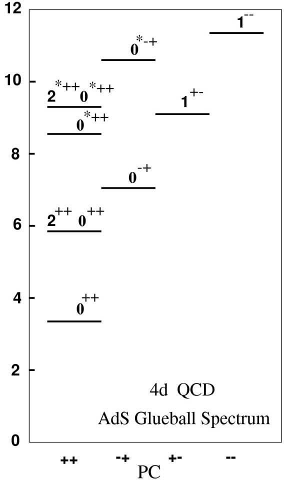

Lattice vs. supergravity glueballs in Sakai-Sugimoto model

Sakai-Sugimoto model: glueball masses $\propto M_{\mathrm{KK}} = 949$ MeV fixed by m_ρ

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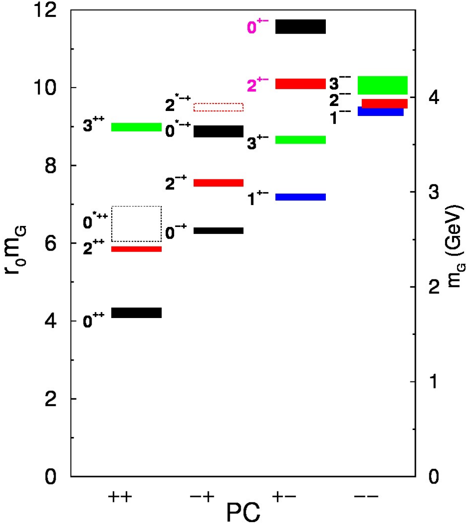

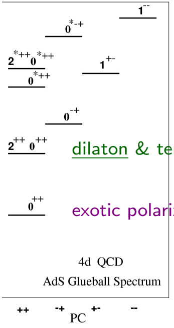

dilaton & tensor 1487 MeV

exotic polarization 855 MeV

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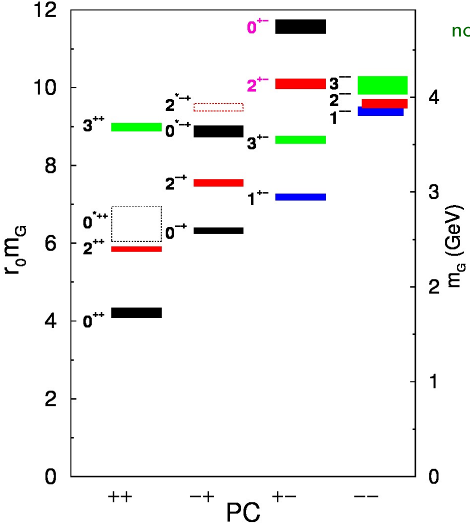
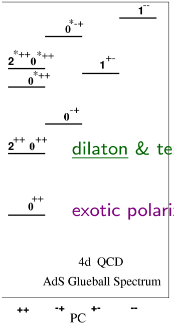


now good match lowest $0^{++} \leftrightarrow$ dilaton



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Should exotic polarization (δG_{44} with x_4 the compactified direction of SYM_{4+1}) be excluded as lowest glueball mode?

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Unrealistic degeneracy of dilatonic 0^{++} and tensor 2^{++} suggests that supergravity approximation insufficient for masses

Take good results for (dimensionless) mesonic Γ/m as encouragement for calculation of relative width of glueballs

Glueball decay rates in Sakai-Sugimoto model

F. Brünner, D. Parganlija, AR, PRD91 (2015) 106002
Full decay pattern of scalar (Dilatonic, as opposed to Exotic) glueball G_D

decay $G_D \to 4\pi$ suppressed (below 2ρ threshold): $\Gamma_{G\to 4\pi}/\Gamma_{G\to 2\pi} \sim \lambda^{-1} N_c^{-1}$,
while $f_0(1500) \to 4\pi$ dominant:

decay	Γ/M (PDG)	$\Gamma/M[G_D]$
$f_0(1500)$ (total)	0.072(5)	0.027...0.037
$f_0(1500) \to 4\pi$	0.036(3)	0.003...0.005
$f_0(1500) \to 2\pi$	0.025(2)	0.009...0.012
$f_0(1500) \to 2K$	0.006(1)	0.012...0.016
$f_0(1500) \to 2\eta$	0.004(1)	0.003...0.004

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$f_0(1710) \to \pi\pi$ OK: $\Gamma^{(\mathrm{ex})}(f_0(1710) \to \pi\pi)/(1722\mathrm{MeV}) \sim 0.01$
but $f_0(1710)$ decays predominantly into $K\bar{K}$!

— not reproduced by (chiral=flavor-symmetric) WSS model,
but may be due to mechanism of "chiral suppression of scalar glueball decay"
(Chanowitz 2005)

Nonchiral enhancement in mass-deformed WSS?

F. Brünner & AR, PRL 115 (2015) 131601 [1504.05815]

Current quark masses can be introduced through deformations of the WSS model by world-sheet instantons [Hashimoto, Hirayama, Liu & Yee 2008] yielding

$$\int d^4x \int_{u_{\rm KK}}^{\infty} du\, h(u)\, \mathrm{Tr}\left(\mathcal{T}(u)\, \underbrace{\mathrm{P}\, e^{-i\int dz A_z(z,x)}}_{U(x)\ \text{(pseudoscalars)}} + h.c. \right),$$

where $h(u)$ includes metric (glueball) fields

Choosing appropriate boundary conditions for $\mathcal{T}$, the quark mass matrix arises through

$$\int_{u_{\rm KK}}^{\infty} du\, h(u)\, \mathcal{T}(u) \propto \mathcal{M} = \mathrm{diag}(m_u, m_d, m_s),$$

thereby realizing a Gell-Mann-Oakes-Renner relation.

Witten-Veneziano mass term

Already in chiral model:

WSS contains (fully determined) Witten-Veneziano mass term for singlet η_0 pseudoscalar from U(1)$_A$ anomaly contributions $\sim 1/N_c$

$$m_0^2 = \frac{N_f}{27\pi^2 N_c}\lambda^2 M_{\mathrm{KK}}^2$$

from $S_{C_1} = -\frac{1}{4\pi(2\pi l_s)^6}\int d^{10}x\sqrt{-g}|\tilde{F}_2|^2$ with

$$\tilde{F}_2 = \frac{6\pi u_{\mathrm{KK}}^3 M_{\mathrm{KK}}^{-1}}{u^4}\left(\theta + \frac{\sqrt{2N_f}}{f_\pi}\eta_0\right) du \wedge dx^4,$$

where θ is the QCD theta angle and $\eta_0(x) = \frac{f_\pi}{\sqrt{2N_f}}\int dz\,\mathrm{Tr}A_z(z,x)$.

With $N_f = N_c = 3$, $M_{\mathrm{KK}} = 949$ MeV, $\lambda = 16.63\ldots12.55$: $\boxed{m_0 = 967\ldots730 \text{ MeV}}$

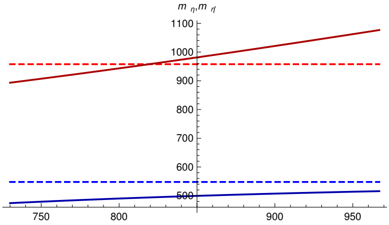
Witten-Veneziano mass term

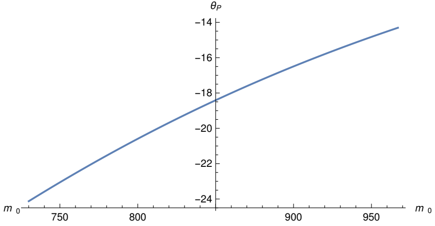
With finite quark masses η_0 and η_8 no longer mass eigenstates.

Diagonalizing:

$N_f = N_c = 3$, $M_{\mathrm{KK}} = 949$ MeV, $\lambda = 16.63 \ldots 12.55$: $\boxed{m_0 = 967 \ldots 730 \text{ MeV}}$,
(with $\mathcal{M} = \mathrm{diag}(\hat{m}, \hat{m}, m_s)$, fixing $m_\pi = 140$ MeV and $m_K = 497$ MeV) $\rightarrow$

$$m_\eta = 518 \ldots 476 \text{ MeV}, \quad m_{\eta'} = 1077 \ldots 894 \text{ MeV},$$
$$\theta_P = -14.4^\circ \ldots - 24.2^\circ,$$





nice ballpark:

light meson decays values favors [Ambrosini 2009, Pham 2015]: $\theta_P \approx -14^\circ$
radiative charmonium decay [Gerard 2004,2013]: $\theta_P \approx -21^\circ$
$\Gamma(\eta' \to 2\gamma)/\Gamma(\eta \to 2\gamma)$ leads to [PDG]: $\theta_P = (-18 \pm 2)^\circ$

Nonchiral enhancement in mass-deformed WSS!

Holographic realization of mass terms leads to:
additional vertices between glueballs and pseudoscalars

rigorously calculable for $G_D \eta_0^2$:

$$\mathcal{L}^{\text{chiral}}_{G_D \eta_0 \eta_0} = \frac{3}{2} d_0 m_0^2\, \eta_0^2 G_D, \qquad d_0 \approx \frac{17.915}{\lambda^{1/2} N_c M_{\text{KK}}}$$

but not (yet) fixed for octet

Parametrize uncertainty by free parameter x:

$$\mathcal{L}^{\text{massive}}_{G_D \pi\pi} = \frac{3}{2} d_m G_D \mathcal{L}^{\mathcal{M}}_m, \qquad d_m \equiv x d_0$$

Most symmetric choice $x = 1$ ($\Leftrightarrow$ no $G_D \to \eta\eta'$)
$\to$ relatively strong enhancement factor for kaons and η mesons:

$$\Gamma^{\text{chiral}}_{G\to PP} \to \Gamma^{\text{chiral}}_{G\to PP} \times \left(1 - 4\frac{m_P^2}{M_G^2}\right)^{1/2} \left(1 + 8.480\frac{m_P^2}{M_G^2}\right)^2$$

Comparison with $f_0(1710)$

decay	Γ/M **(PDG)**	$\Gamma/M[G_D]$ (chiral)	$\Gamma/M[G_D]$ (massive)
$f_0(1710)$ (total)	**0.081(5)**	0.059...0.076	0.083...0.106
$f_0(1710) \to 2K$	$(^*)$ 0.029(10)	0.012...0.016	0.029...0.038
$f_0(1710) \to 2\eta$	0.014(6)	0.003...0.004	0.009...0.011
$f_0(1710) \to 2\pi$	$0.012(^{+5}_{-6})$	0.009...0.012	0.010...0.013
$f_0(1710) \to 2\rho, \rho\pi\pi \to 4\pi$	?	0.024...0.030	0.024...0.030
$f_0(1710) \to 2\omega$	$0.010(^{+6}_{-7})$	0.011...0.014	0.011...0.014
$f_0(1710) \to \eta\eta'$	?	0	if 0 : $\Uparrow$
$\Gamma(\pi\pi)/\Gamma(K\bar{K})$	$\mathbf{0.41}^{+0.11}_{-0.17}$	**3/4**	**0.35**
$\Gamma(\eta\eta)/\Gamma(K\bar{K})$	$\mathbf{0.48}\pm 0.15$	$1/4$	0.28

* PDG ratios for decay rates + $\mathrm{Br}(f_0(1710) \to KK) = 0.36(12)$ [Albaladejo&Oller 2008]

- decays into 2 pseudoscalars: massive WSS perfectly compatible with PDG data!
- significant decay into 4 pions (after extrapolation to beyond 2ρ threshold): falsifiable prediction of this model!
  ($f_0(1710) \to 2\rho^0$ hopefully from CEP experiments at LHC!)

Tensor glueball decay rates in Sakai-Sugimoto model

Tensor glueball in WSS, and extrapolated to higher mass:

decay	M	$\Gamma/M[T(M)]$
$T \to 2\pi$	1487	0.013...0.018
$T \to 2K$	1487	0.004...0.006
$T \to 2\eta$	1487	0.0005...0.0007
T (total)	1487	$\approx 0.02 \ldots 0.03$
$T \to 2\rho \to 4\pi$	2000	0.135...0.178
$T \to 2K^* \to 2(K\pi)$	2000	0.119...0.177
$T \to 2\omega \to 6\pi$	2000	0.045...0.059
$T \to 2\pi$	2000	0.014...0.018
$T \to 2K$	2000	0.010...0.013
$T \to 2\eta$	2000	0.0018...0.0024
T (total)	2000	$\approx 0.3 \ldots 0.45$
T (total)	2400	$\approx 0.45 \ldots 0.6$

Very **broad tensor glueball**, if at 2.4 GeV (probably unobservable)

With a mass of 2 GeV, width larger but perhaps comparable with that of the rather broad tensor meson $f_2(1950)$, which has $\Gamma/M = 0.24(1)$.

Very narrow (unconfirmed) candidate $f_J(2220)$ not compatible with WSS

Pseudoscalar glueball in Witten-Sakai-Sugimoto model

Pseudoscalar glueballs described by fluctuations of

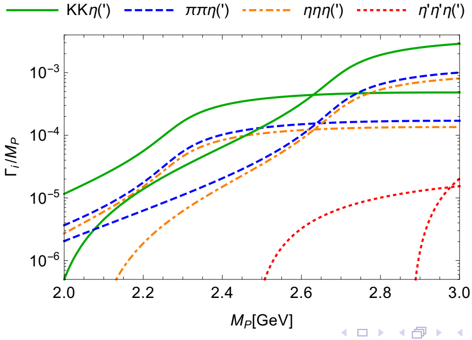
$$\text{RR field } \tilde{F}_2 = dC_1' + \frac{c}{U^4}\left(\theta + \frac{\sqrt{2N_f}}{f_\pi}\eta_0(x)\right) dU \wedge d\tau \qquad \text{(anomaly inflow)}$$

If no mixing with η_0:

only relevant vertex G-$\tilde{G}$-$\eta_0 \propto \sqrt{\frac{N_f}{N_c}}\frac{\sqrt{\lambda}}{N_c}$ from $-\frac{1}{4\pi(2\pi\ell_s)^6}\int d^{10}x\sqrt{-g}|\tilde{F}_2|^2$

$\rightarrow$ *very narrow (pure) pseudoscalar glueball* with dominant decay pattern

$$\tilde{G} \;\rightarrow\; G(=f_0(1710)) + \eta(') \rightarrow \; P\,P\,\eta(')$$



$\lambda = (12.55 + 16.63)/2$

Pseudoscalar glueball production

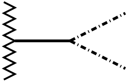
As with decay, production of (nonmixing) $\tilde{G}$ involves $G+\eta(')$ or G+another $\tilde{G}$

(would explain why not yet observed in radiative J/ψ decays; needs excited ψ or Υ?)

- Another possibility: Central Exclusive Production in high-energy hadron collisions!

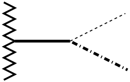
Parametric orders of the production amplitudes of pseudoscalar glueballs in double Pomeron or double Reggeon exchange

$\underline{\tilde{G}\tilde{G}}$:



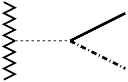
$\sim \lambda^{-1} N_c^{-2}$

$\underline{\eta(')\tilde{G}}$:



$\sim \lambda^{0} N_f^{1/2} N_c^{-5/2}$

$G\tilde{G}$:



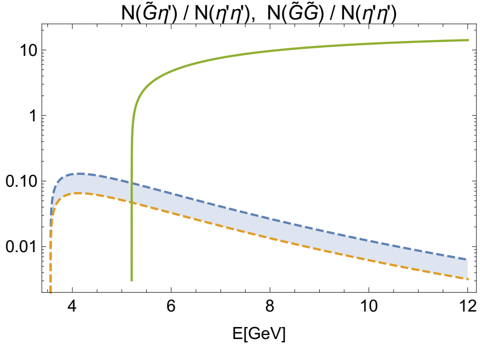
$\sim \lambda^{-1} N_f^{1} N_c^{-3}$ ... suppressed

(in the uppermost diagram the full line stands for G or G_T)

Production of $\tilde{G}\tilde{G}$ and $\tilde{G}\eta'$ pairs versus $\eta'\eta'$

Production from a virtual scalar glueball

(plotted as functions of the c.o.m. energy of the produced pair, assuming $m(\tilde{G}) = 2.6$ GeV)



The full line gives $N(\tilde{G}\tilde{G})/N(\eta'\eta')$, which is independent of the 't Hooft coupling; upper and lower dashed lines correspond to $N(\tilde{G}\eta')/N(\eta'\eta')$ with 't Hooft coupling 12.55 and 16.63, respectively.

CEP of $\eta'\eta'$ in Durham model [Harland-Lang et al. 2013]:

$$\sigma(\eta'\eta')/\sigma(\pi^0\pi^0) \sim 10^3 \ldots 10^5 \text{ at } \sqrt{s} = 1.96 \text{ TeV}$$

Kinetic mixing of pseudoscalar glueball $\tilde{G}$ with η, η'

J. Leutgeb, AR, in preparation:

Indeed no mixing from topological susceptibility terms in potential,
but (parametrically small, numerically important) kinetic mixing of $\tilde{G}$ and η_0

$$\sin(\theta)\partial_\mu \eta_0 \partial^\mu \tilde{G}$$

with $\theta = 0.0056\sqrt{\frac{N_f}{N_c}}\lambda = 0.070 \ldots 0.093 \; (4.0^\circ \ldots 5.3^\circ)$

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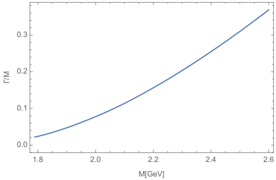
- dominant decay through natural-parity violating $\eta_0\rho\rho$ and $\eta_0\omega\omega$ coupling

$\rightarrow$ relatively broad decay width into 4 and 6 pions

esp. when (naively) extrapolated to larger glueball mass predicted by lattice



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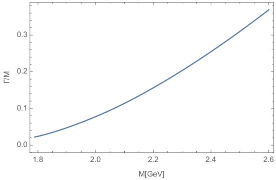
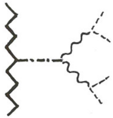




- CEP additionally through:
  natural-parity violating vertex $\eta_0 G_T G_T$

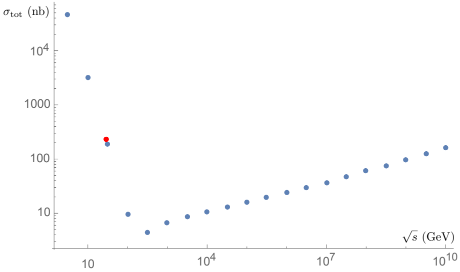
in preparation: production rate calculation along the lines of
N. Anderson, S. K. Domokos, N. Mann: "Central production of η via double Pomeron exchange and double Reggeon exchange in the Sakai-Sugimoto model", PRD96 (2017) 046002

CEP cross section of mixed pseudoscalar glueball from holographic QCD

N. Anderson, S. K. Domokos, N. Mann: "Central production of η via double Pomeron exchange and double Reggeon exchange in the Sakai-Sugimoto model", PRD96 (2017) 046002

Holographic QCD prediction for CEP cross section of η:

(protons by skyrmions in SS model, couplings as in SS model,
but Reggeized Pomeron and Reggeon propagators with slopes and intercepts from pheno)



for pseudoscalar glueball mixing with η_0 expect similar shape but larger values

Conclusions – mesons and glueballs

• With just one dimensionless parameter, top-down holographic QCD model of Witten, Sakai and Sugimoto very predictive and surprisingly successful quantitatively:

Meson spectrum and dynamics:
— vector and axial vector mesons masses, ρ and ω decay rates, anomalous m'_η, ...
with typically 10–30% errors

Glueball spectrum:
— if "exotic mode" discarded, scalar glueball mass close to lattice QCD prediction
tensor and pseudoscalar glueball ~ 30 % too light

• WSS model also perhaps good guide for glueball signatures

Scalar glueball decay pattern consistent with $f_0(1710)$ as nearly pure glueball, if predictions for 4π and $\eta\eta'$ decays confirmed

Tensor glueball predicted as perhaps unobservably broad if at 2.4 GeV
(if at 2 GeV, marginally consistent with glueball candidate $f_2(1950)$)

Particularly interesting: Pseudoscalar glueball and its interplay with U(1)$_A$

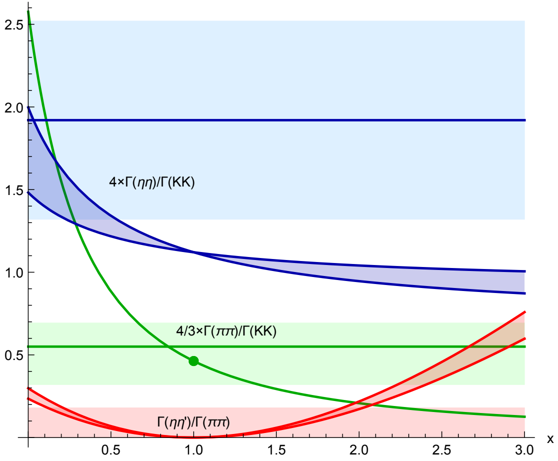
CEP production calculation with couplings from WSS model in preparation

BACKUP SLIDES

Constraints on $\eta\eta'$ rates for $f_0(1710)$ as ≈pure glueball

Relaxing $x = 1$: [F. Brünner & AR, PRD92, 1510.07605]

WSS model gives *flavor asymmetries* consistent with experimental results for $f_0(1710)$ in as long as $\Gamma(G \to \eta\eta')/\Gamma(G \to \pi\pi) \lesssim 0.04$ (upper limit from WA102: < 0.18)



Pseudovector glueball

Next heavier glueball: 1^{+-} (lattice prediction $\sim$ 3 GeV)

In Witten model: **Kalb-Ramond tensor field**, lowest mass eigenvalue 2.3 GeV

coupling to D8 branes and thus mesons determined by DBI+CS structure,
dominant decays from Chern-Simons terms (DBI negligible):

decay channel	Γ/M
$\pi\rho$	0.3624 ... 0.4803
KK^*	0.1945 ... 0.2578
$\eta\omega$	0.0530 ... 0.0941
$\eta\phi$	0.0086 ... 0.0076
$\eta'\omega$	0.0168 ... 0.0203
$\eta'\phi$	0.0020 ... 0.0079
$\pi\rho\rho$	0.2595 ... 0.4556
$\pi K^* K^*$	0.0213 ... 0.0375
$KK^*\rho$	0.0032 ... 0.0056
$KK^*\omega$	0.0011 ... 0.0019
total	**0.9225 ... 1.3685**

very broad resonance!

[F. Brünner, J. Leutgeb, AR, PLB788 (2019) 431]