Heavy glueballs

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Talk prepared for:

Excited QCD 2017

7-13/5/2017, Sintra, Portugal

Outline

From quarks and gluons to hadrons

Glueball's masses

Experiments searching glueball

Glueballs below 2.6 GeV.

The vector glueball

The pseudotensor glueball

Summary

Find t glueball/1

Inspire: find t Glueball: 1393 papers (on 31/5/2016)

Find t glueball/2

Inspire: find t Glueball: 1410 papers (on 12/11/2016)

Find t glueball /3

Inspire: find t Glueball: 1434 papers (on 6/5//2017)

Review papers

Uniwersytet Jana Kochanowskiego w Kielcach

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. **40** (2013) 043001 (68pp) doi:10.1088/0954-3899/40/4/043001

TOPICAL REVIEW

The status of glueballs

Wolfgang Ochs

Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, Föhringer Ring 6, D-80805 München, Germany

Progress in Particle and Nuclear Physics 63 (2009) 74–116

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journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

The experimental status of glueballs

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Int.J.Mod.Phys. E18 (2009) 1-49

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Glueballs are particles whose valence degrees of freedom are gluons and therefore in their description the gauge field plays a dominant role. We review recent results in the physics of glueballs with the aim set on phenomenology and discuss the possibility of finding them in conventional hadronic experiments and in the Quark Gluon Plasma. In order to describe their properties we resort to a variety of theoretical treatments which include, lattice QCD, constituent models, AdS/QCD methods, and QCD sum rules. The review is supposed to be an informed guide to the literature. Therefore, we do not discuss in detail technical developments but refer the reader to the appropriate references.

Previous reviews:

F.E. Close, Rep. Progress Phys. 51 (1988) 833.
C. Amsler, Rev. Modern Phys. 70 (1998) 1293. hep-ex/9708025.
S. Godfrey, J. Napolitano, Rev. Modern Phys. 71 (1999) 1411. hep-ph/9811410.
C. Amsler, N.A. Tornqvist, Phys. Rep. 389 (2004) 61.
A. Masoni, C. Cicalo, G.L. Usai, J. Phys. G32 (2006) R293.

Inspire: f t glueball after 28/2/2013: 93 articles. 'Soon' a new review will be needed.

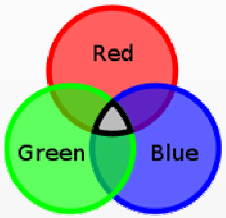
From QCD Lagrangian to baryons and mesons

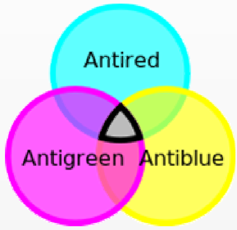
Born	Giuseppe Lodovico Lagrangia 25 January 1736 Turin
Died	10 April 1813 (aged 77) Paris

Francesco Giacosa

The QCD Lagrangian

Quark: u,d,s and c,b,t R,G,B





$$q_i = \begin{pmatrix} q_i^R \\ q_i^G \\ q_i^B \end{pmatrix} ; \; i = u,d,s \,,...$$

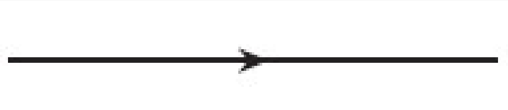
8 type of gluons ($R\bar{G}$,$B\bar{G}$,…)

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

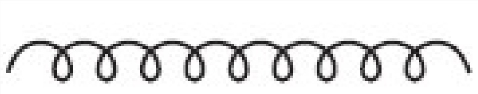
$$A_\mu^a \; ; \; a = 1,..., 8$$

Feynman diagrams of QCD

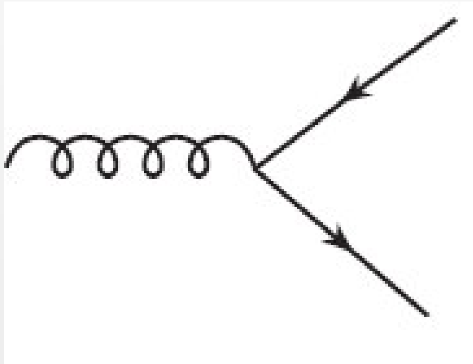
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$



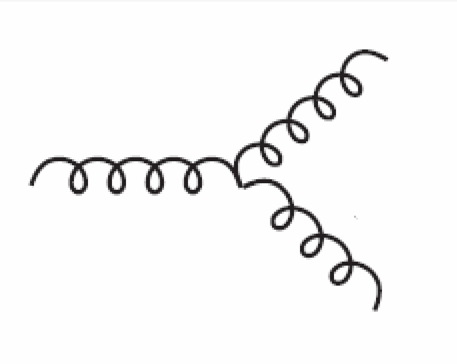
Quark



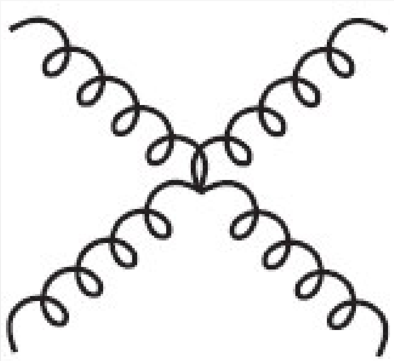
Gluon



Gluon-quark-antiquark vertex



3-gluon vertex



4-gluon vertex

Already here one may ask: what about bound states of gluons???

Symmetries of QCD and breakings

$SU(3)_{color}$: exact. Confinement: you never see color, but only white states.

Dilatation invariance: holds only at a classical level and in the chiral limit. Broken by quantum fluctuations (**trace anomaly**) and by quark masses.

$SU(3)_R \times SU(3)_L$: holds in the chiral limit, but is broken by nonzero quark masses. Moreover, it is **spontaneously** broken to $U(3)_{V=R+L}$

$U(1)_{A=R-L}$: holds at a classical level, but is also broken by quantum fluctuations (**axial anomaly**)

Hadrons

The QCD Lagrangian contains ‘colored’ quarks and gluons. However, no ‚colored‘ state has been seen.

Confinement: physical states are white and are called hadrons.

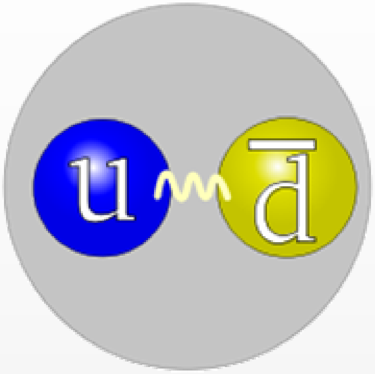
Hadrons can be:

Mesons: bosonic hadrons

Baryons: fermionic hadrons

A meson is **not necessarily** a quark-antiquark state.
A quark-antiquark state is a conventional meson.

Example of conventional quark-antiquark states: the ρ and the π mesons



Rho-meson $m_{\rho^+} = 775 \ \text{MeV}$

Pion $m_{\pi^+} = 139 \ \text{MeV}$

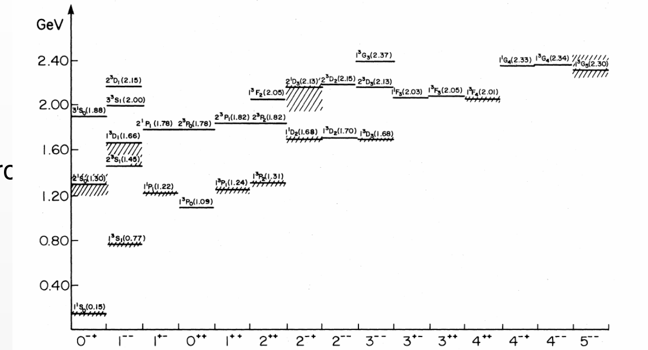
$$m_u + m_d \approx 7 \ \text{MeV}$$

Mass generation in QCD is a nonpert. penomenon based on SSB (mentioned previusly).

Quark model(s) and their QFT extensions

Uniwersytet Jana Kochanowskiego w Kielcach

Mesons in a Relativized Quark Model with Chromodynamics
S. Godfrey, Nathan Isgur
Published in Phys.Rev. D32 (1985) **189-231**



Mesonic loops e.g. included into
A Low Lying Scalar Meson Nonet in a Unitarized Meson Model
E. van Beveren, T. A. Rijken, K. Metzger, C.~Dullemond, G.~Rupp and J. E.~Ribeirc
Z. Phys. C **30** (1986) 615
Meson spectroscopy: too much excitement and too few excitations
G. Rupp, S. Coito and E. van Beveren,
Acta Phys. Polon. Supp. 5 (2012) 1007

QCD phenomenology based on a chiral effective Lagrangian
Tetsuo Hatsuda, Teiji Kunihiro
Phys.Rept. **247** (1994) 221-367

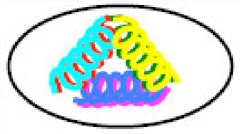
NJL: quark-based model with
chiral symmetry and SSB
chiral condensate
Effective quark mass
Mesons as quarkonia (pion: ok)

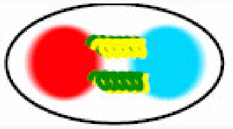
The Infrared behavior of QCD Green's functions: Confinement dynamical symmetry breaking, and hadrons as relativistic bound states
Reinhard Alkofer, Lorenz von Smekal
Phys.Rept. **353** (2001) 281

Baryons as relativistic three-quark bound states
G. Eichmann, H.~ Sanchis-Alepuz, R. Williams, R. Alkofer and C. S. Fischer,
Progr. Part. Nucl. Phys. **91** (2016) 1

DS:
quarks and gluons propagators from QCD
Condensates
Effective quark and gluon masses
Spectra of mesons as quarkonia (pion: ok) and baryons as qqq states

Non-conventional mesons: theoretical expectations

1) Glueballs 

2) Hybrids 

3) Four-quark states

Compact diquark-antidiquark states 

Molecular states (a type of dynamical generation) 

Companion poles (another type of dynamical generation)

Masses of glueballs

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Glueball masses: bag models

A. Chodos, et al., Phys. Rev. D 9 (1974) 3471.
R.L. Jaffe, K. Johnson, Phys. Lett. B60 (1976) 201

ANNALS OF PHYSICS **168**, 344–367 (1986)

Qualitative Features of the Glueball Spectrum*

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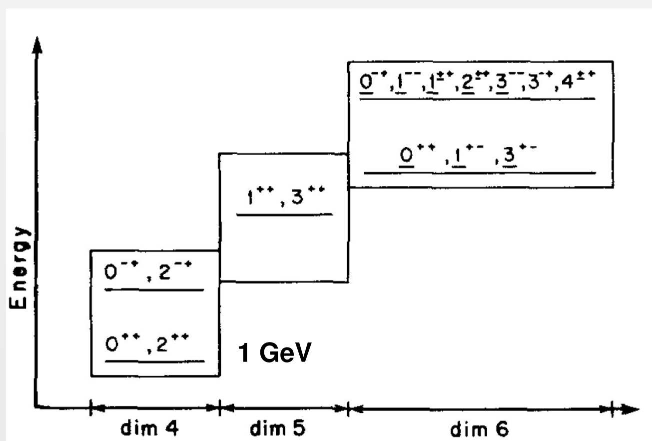
Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received September 13, 1985



Lattice

PHYSICAL REVIEW D **73**, 014516 (2006)

Glueball spectrum and matrix elements on anisotropic lattices

Y. Chen,[1,2] A. Alexandru,[2] S. J. Dong,[2] T. Draper,[2] I. Horváth,[2] F. X. Lee,[3,4] K. F. Liu,[2] N. Mathur,[2,4] C. Morni
M. Peardon,[6] S. Tamhankar,[2] B. L. Young,[7] and J. B. Zhang[8]
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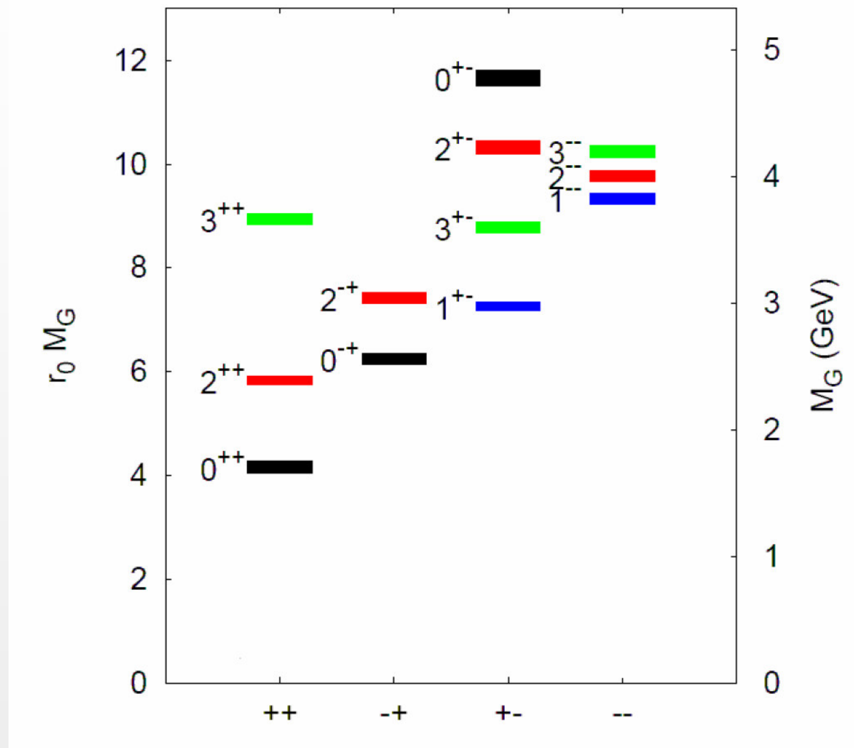
[2]*Department of Physics & Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA*
[3]*Center for Nuclear Studies, Department of Physics, George Washington University, Washington, D.C. 20052 US*
[4]*Jefferson Lab, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*
[5]*Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[6]*School of Mathematics, Trinity College, Dublin, Dublin 2, Ireland*
[7]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[8]*CSSM and Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia*
(Received 13 October 2005; published 26 January 2006)

The glueball-to-vacuum matrix elements of local gluonic operators in scalar, tensor, and pseudoscalar channels are investigated numerically on several anisotropic lattices with the spatial lattice spacing ranging from 0.1–0.2 fm. These matrix elements are needed to predict the glueball branching ratios in J/ψ radiative decays which will help identify the glueball states in experiments. Two types of improved local gluonic operators are constructed for a self-consistent check and the finite-volume effects are studied. We find that lattice spacing dependence of our results is very weak and the continuum limits are reliably extrapolated, as a result of improvement of the lattice gauge action and local operators. We also give updated glueball masses with various quantum numbers.



Quoted by the PDG in the 'Quark Model' review.

See also: Gregory et al, **JHEP 1210 (2012) 170**

Towards the glueball spectrum from unquenched lattice QCD

Conclusions and future prospects: "*The most conservative interpretation of our results is that the masses in terms of lattice representations are broadly consistent with results from quenched QCD. We do not see any evidence for large unquenching effects, however a definitive calculation requires a continuum extrapolation, and the inclusion of fermionic operators.*"

Experiments searching glueballs

Glueball production and decays:

Glueballs should be find in gluon-rich processes
(such as J/ψ decays, proton-antiproton fusion, …)

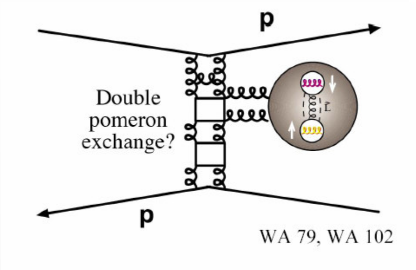
Glueballs should couple to all quark flavors with similar strenght

Moreover, glueballs should have a suppressed (but nonzero!) decay into photons.

Hadronic experiments

Proton-proton

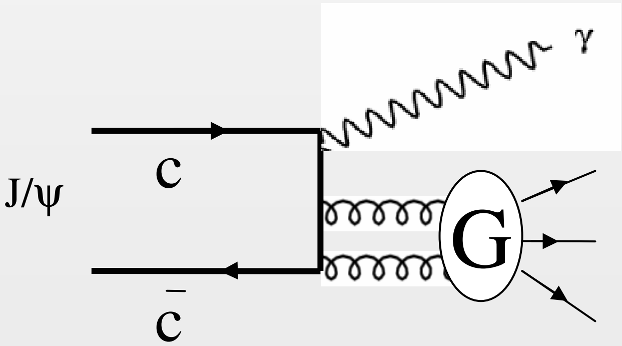
(WA79,WA102,LHC,RHIC)



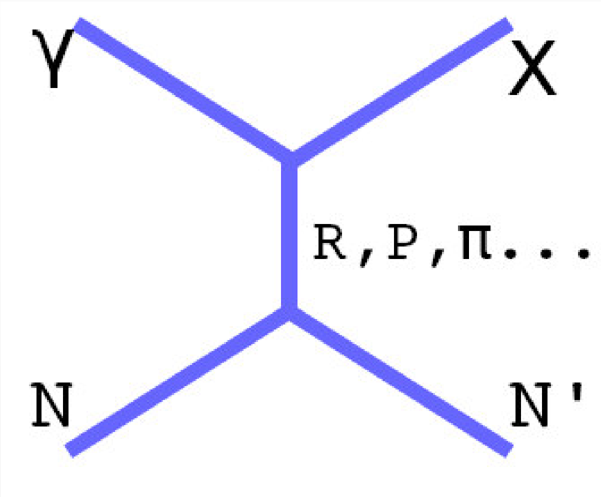
Electron-positron (with strange-antistrange, charm-anticharm or bottom-antibottom formation)

(Belle, Belle II, Babar,

BES, KLOE, KLOEII,...)

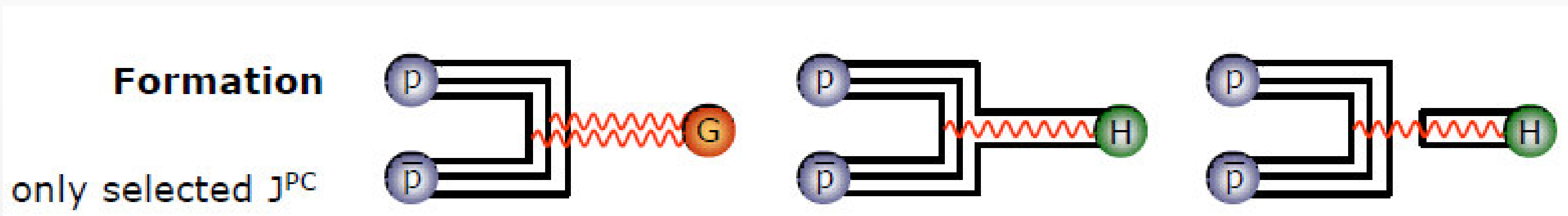


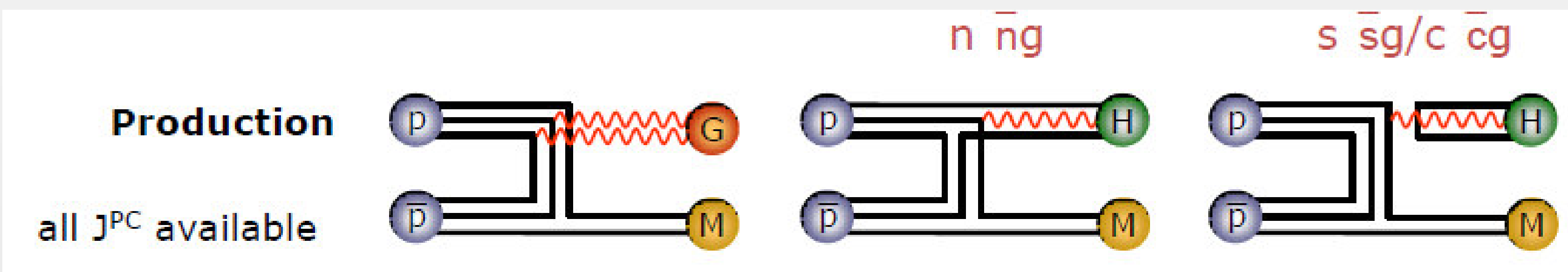
Photoproduction: Compass at CERN (also with pion instead of the photons)
GlueX AND CLAS12 at JLab (start soon)



Proton-antiproton

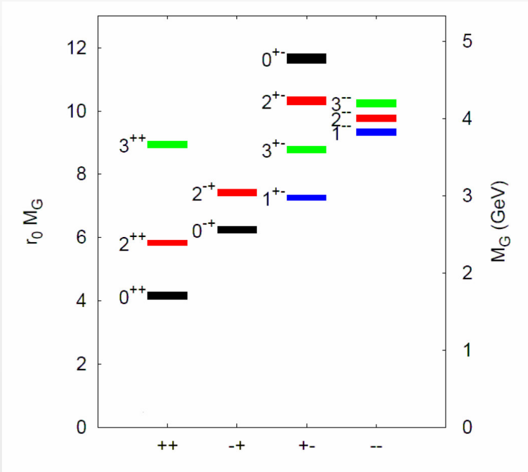
(Lear,Fermilab, and in the future: PANDA)





PANDA mass range: from 2.5 to 4.5 GeV

The scalar glueball



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Mixing pattern

Above 1 GeV one has two quark-antiquark states and a bare glueball.

$$\sqrt{\tfrac{1}{2}}(\bar{u}u + \bar{d}d)$$

$$\bar{s}s$$

$$\text{Glueball: } gg$$

They mix to form the 3 resonances on the right.

Note:

$a_0(980)$ $k(800)$ $f_0(980)$ $f_0(500)$

are regarded as non-quarkonium objects

$f_0(1370)$ $I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-reviews on scalar mesons under $f_0(500)$ (see the index for the page number) and on non-$q\bar{q}$ candidates in PDG 06, Journal of Physics **G33** 1 (2006).

$f_0(1370)$ T-MATRIX POLE POSITION

Note that $\Gamma \approx 2\ \text{Im}(\sqrt{s_{\text{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(1200–1500)−i(150–250) OUR ESTIMATE			

$f_0(1500)$ $I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-reviews on scalar mesons under $f_0(500)$ (see the index for the page number) and on non-$q\bar{q}$ candidates in PDG 06, Journal of Physics **G33** 1 (2006).

$f_0(1500)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1504± 6 OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.		

$f_0(1500)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
109± 7 OUR AVERAGE				

$f_0(1710)$ $I^G(J^{PC}) = 0^+(0^{++})$

See our mini-review in the 2004 edition of this *Review*, Physics Letters **B592** 1 (2004). See also the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$f_0(1710)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1723^{+6}_{-5} OUR AVERAGE		Error includes scale factor of 1.6. See the ideogram below.		

$f_0(1710)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
139 ± 8 OUR AVERAGE		Error includes scale factor of 1.1.		

G in the extended Linear Sigma Model (eLSM)

Hadronic model based on the symmetries of QCD: scalar glueball G built in from the very beginning (trace anomaly)

Nonet	L	S	J^{PC}	Current	Assignment
P	0	0	0^{-+}	$P_{ij}=\frac{1}{\sqrt{2}}\bar{q}_j i\gamma^5 q_i$	π, K, η, η'
S	1	1	0^{++}	$S_{ij}=\frac{1}{\sqrt{2}}\bar{q}_j q_i$	$a_0(1450)$, $K_0^*(1430)$, $f_0(1370)$, $f_0(1510)$
V^μ	0	1	1^{--}	$V_{ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j\gamma^\mu q_i$	$\rho(770)$, $K^*(892)$, $\omega(785)$, $\phi(1024)$
A^μ	1	1	1^{++}	$A_{ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j\gamma^5\gamma^\mu q_i$	$a_1(1230)$, $K_{1,A}$, $f_1(1285)$, $f_1(1420)$

Chiral multiplet	Current	$U_R(3)\times U_L(3)$	P	C
$\Phi = S+iP$	$\sqrt{2}\bar{q}_{R,j}q_{L,i}$	$U_L\Phi U_R^\dagger$	$\Phi^\dagger$	Φ^t
$R^\mu = V^\mu - A^\mu$	$\sqrt{2}\bar{q}_{R,j}\gamma^\mu q_{R,i}$	$U_R R^\mu U_R^\dagger$	L_μ	$L^{t\mu}$
$L^\mu = V^\mu + A^\mu$	$\sqrt{2}\bar{q}_{L,j}\gamma^\mu q_{L,i}$	$U_L R^\mu U_L^\dagger$	R_μ	$R^{t\mu}$

$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right] \\
& - m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \lambda_1\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\
& + \left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2}+\Delta\right)\left((L^\mu)^2+(R^\mu)^2\right)\right] \\
& - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2+(R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger+\Phi\right)\right] \\
& + c_1[\det(\Phi)-\det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\
& + h_2 \mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]
\end{aligned}
$$

D. Parganlija, P. Kovacs, G. Wolf, F. G., D. H. Rischke,
Phys. Rev. D 87 (2013) no.1, 014011
[arXiv:1208.0585 [hep-ph]].

eLSM: fit (11 parameters, 21 exp. quantities)

Error from PDG or 5% of exp.
Scalar-isoscalar sector not included.

$$\chi^2_{red} = 1.2$$

Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 51.0
m_{a_1}	1186 ± 6	1230 ± 62
$m_{f_1(1420)}$	1372.5 ± 5.3	1426.4 ± 71.3
m_{a_0}	1363 ± 1	1474 ± 74
$m_{K_0^\star}$	1450 ± 1	1425 ± 71
$\Gamma_{\rho\to\pi\pi}$	160.9 ± 4.4	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.6 ± 1.9	46.2 ± 2.3
$\Gamma_{\phi\to\bar{K}K}$	3.34 ± 0.14	3.54 ± 0.18
$\Gamma_{a_1\to\rho\pi}$	549 ± 43	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.66 ± 0.01	0.64 ± 0.25
$\Gamma_{f_1(1420)\to K^\star K}$	44.6 ± 39.9	43.9 ± 2.2
Γ_{a_0}	266 ± 12	265 ± 13
$\Gamma_{K_0^\star\to K\pi}$	285 ± 12	270 ± 80

arXiv:1208.0585

Scalar glueball in the eLSM

PHYSICAL REVIEW D **90,** 114005 (2014)

Is $f_0(1710)$ a glueball?

Stanislaus Janowski,[1] Francesco Giacosa,[1,2] and Dirk H. Rischke[1]
[1]*Institute for Theoretical Physics, Goethe University, Max-von-Laue-Straße 1, 60438 Frankfurt am Main, Germany*
[2]*Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland*
(Received 26 August 2014; published 2 December 2014)

We study the three-flavor chirally and dilatation invariant extended linear sigma model with (pseudo) scalar and (axial-)vector mesons as well as a scalar dilaton field whose excitations are interpreted as a glueball. The model successfully describes masses and decay widths of quark-antiquark mesons in the low-energy region up to 1.6 GeV. Here we study in detail the vacuum properties of the scalar-isoscalar $J^{PC} = 0^{++}$ channel and find that (i) a narrow glueball is only possible if the vacuum expectation value of the dilaton field is (at tree level) quite large (i.e. larger than what lattice QCD and QCD sum rules suggest) and (ii) only solutions in which $f_0(1710)$ is predominantly a glueball are found. Moreover, the resonance $f_0(1370)$ turns out to be mainly $(\bar{u}u + \bar{d}d)/\sqrt{2}$ and thus corresponds to the chiral partner of the pion, while the resonance $f_0(1500)$ is mainly $\bar{s}s$.

DOI: 10.1103/PhysRevD.90.114005 PACS numbers: 12.39.Fe, 12.39.Mk, 12.40.Yx, 13.25.Jx

Unique assignment is found:

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.91 & -0.24 & 0.33 \\ 0.30 & 0.94 & -0.17 \\ -0.27 & 0.26 & 0.93 \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \bar{s}s \\ \text{Glueball: } gg \end{pmatrix}$$

Clear outcome: $f_0(1710)$ is predominantly gluonic

Lattice result on J/Psi decay into glueball

PRL **110,** 021601 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2

Scalar Glueball in Radiative J/ψ Decay on the Lattice

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(CLQCD Collaboration)

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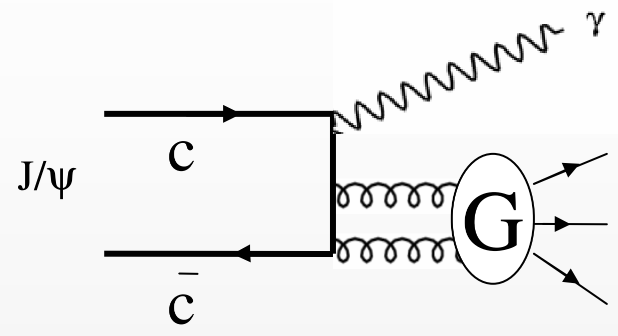
(Received 5 June 2012; published 10 January 2013)

The form factors in the radiative decay of J/ψ to a scalar glueball are studied within quenched lattice QCD on anisotropic lattices. The continuum extrapolation is carried out by using two different lattice spacings. With the results of these form factors, the partial width of J/ψ radiatively decaying into the pure gauge scalar glueball is predicted to be 0.35(8) keV, which corresponds to a branching ratio of $3.8(9) \times 10^{-3}$. By comparing with experiments, out results indicate that $f_0(1710)$ has a larger overlap with the pure gauge glueball than other related scalar mesons.



From the PDG (decay of the j/ψ): the radiative decays into $f_0(1710)$ are larger than into $f_0(1500)$.

$\gamma f_0(1710) \to \gamma K\overline{K}$	$(8.5\ ^{+1.2}_{-0.9}) \times 10^{-4}$
$\gamma f_0(1710) \to \gamma \pi\pi$	$(4.0 \pm 1.0) \times 10^{-4}$
$\gamma f_0(1710) \to \gamma \omega\omega$	$(3.1 \pm 1.0) \times 10^{-4}$
$\gamma f_0(1710) \to \gamma \eta\eta$	$(2.4\ ^{+1.2}_{-0.7}) \times 10^{-4}$

$\gamma f_0(1500) \to \gamma \pi\pi$	$(1.01 \pm 0.32) \times 10^{-4}$
$\gamma f_0(1500) \to \gamma \eta\eta$	$(1.7\ ^{+0.6}_{-1.4}) \times 10^{-5}$

Decays of the scalar glueball in holography

PHYSICAL REVIEW D **91**, 106002 (2015)

Glueball decay rates in the Witten-Sakai-Sugimoto model

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(Received 13 March 2015; published 14 May 2015)

We revisit and extend previous calculations of glueball decay rates in the Sakai-Sugimoto model, a holographic top-down approach for QCD with chiral quarks based on D8-$\overline{\text{D8}}$ probe branes in Witten's holographic model of nonsupersymmetric Yang-Mills theory. The rates for decays into two pions, two vector mesons, four pions, and the strongly suppressed decay into four π^0 are worked out quantitatively, using a range of the 't Hooft coupling which closely reproduces the decay rate of ρ and ω mesons and also leads to a gluon condensate consistent with QCD sum rule calculations. The lowest holographic glueball, which arises from a rather exotic polarization of gravitons in the supergravity background, turns out to have a significantly lower mass and larger width than the two widely discussed glueball candidates $f_0(1500)$ and $f_0(1710)$. The lowest nonexotic and predominantly dilatonic scalar mode, which has a mass of 1487 MeV in the Witten-Sakai-Sugimoto model, instead provides a narrow glueball state, and we conjecture that only this nonexotic mode should be identified with a scalar glueball component of $f_0(1500)$ or $f_0(1710)$. Moreover the decay pattern of the tensor glueball is determined, which is found to have a comparatively broad total width when its mass is adjusted to around or above 2 GeV.

DOI: 10.1103/PhysRevD.91.106002 PACS numbers: 11.25.Tq, 13.25.Jx, 14.40.Be, 14.40.Rt

$f_0(1710)$ fits well into the picture.

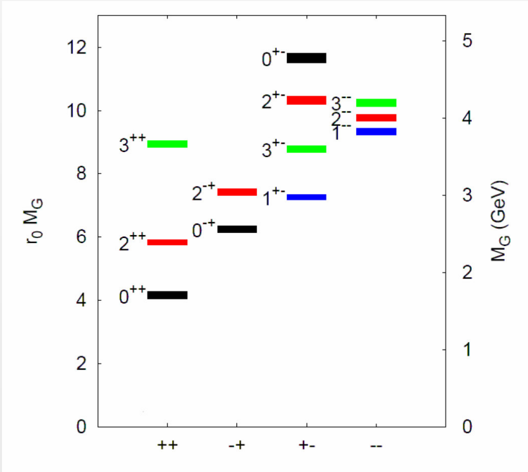
Total width calculated to be about 100 MeV.

Alternative direction to study glueballs.

Summary: scalar glueball - where do we stay?

- Various scenarios exist
- Lattice's help concerning the width of the scalar glueball is expected.
- Decays into gamma-gamma of $f_0(1500)$ and $f_0(1710)$ (both not seen yet). Clarification of $f_0(1370) \to \gamma\gamma$ and $a_0(1450) \to \gamma\gamma$ (seen but no branching ration yet).
- In general, an improvement of the experimental knowledge (such as $a_0(1450) \to \omega\pi\pi$) is welcome

Tensor glueball



Francesco Giacosa

Tensor glueball

Candidate: $f_J(2220)$
It is not on the Regge trajectories

V. V. Anisovich, JETP Lett. 80, 715 (2004) [Pisma Zh. Eksp. Teor. Fiz. 80, 845 (2004)] [arXiv:hep-ph/0412093];
V. V. Anisovich, M. A. Matveev, J. Nyiri and A. V. Sarantsev, arXiv:hep-ph/0506133.

No decay into photon-photon
Two-pion/two-kaon ratio in agreement with flavor blindness.

Details and further refs. in:
C. Amsler and N. A. Tornqvist, Phys. Rept. 389, 61 (2004).

F. G, T.Gutsche, V. E. Lyubovitskij and A.~Faessler,
``*Decays of tensor mesons and the tensor glueball in an effective field approach*,''
Phys. Rev. D 72 (2005) 114021 [hep-ph/0511171].

$$\mathcal{L}_{\rm eff}^G = c_{GPP}\, G_{\mu\nu}\, \langle\, \Theta_P^{\mu\nu}\, \rangle + c_{GVV}\, G_{\mu\nu}\, \langle\, \mathcal{V}^\mu\, \mathcal{V}^\nu\, \rangle$$

$$\pi\pi : \overline{K}K : \eta\eta : \eta\eta' : \eta'\eta' = 1 : 0.79 : 0.17 : 0 : 0.001$$

$$\rho\rho : \overline{K}^* K^* : \omega\omega : \omega\phi : \phi\phi = 1 : 0.84 : 0.32 : 0 : 0.11$$

Tensor glueball

$f_J(2220)$

$I^G(J^{PC}) = 0^+(2^{++} \text{ or } 4^{++})$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See our mini-review in the 2004 edition of this *Review*, PDG 04.

$f_J(2220)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
2231.1± 3.5 OUR AVERAGE				

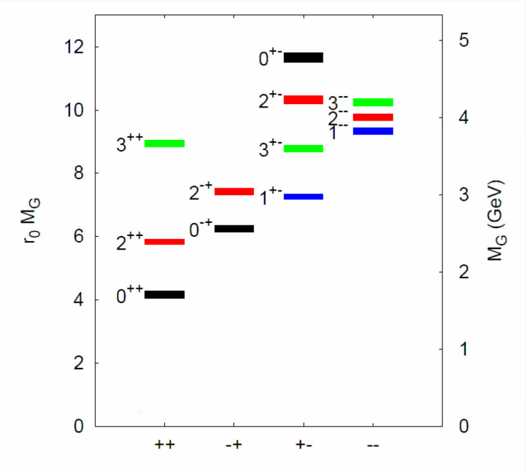
$f_J(2220)$ WIDTH

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*
23^{+8}_{-7} OUR AVERAGE				

$f_J(2220)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi\pi$	seen
Γ_2	$\pi^+\pi^-$	seen
Γ_3	$K\overline{K}$	seen
Γ_4	$p\overline{p}$	
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\eta\eta'(958)$	seen
Γ_7	$\phi\phi$	not seen
Γ_8	$\eta\eta$	not seen

Pseudoscalar glueball



Francesco Giacosa

Pseudoscalar glueball

INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **32** (2006) R293–R335 — doi:10.1088/0954-3899/32/9/R01

TOPICAL REVIEW

The case of the pseudoscalar glueball

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Published 10 August 2006
Online at stacks.iop.org/JPhysG/32/R293

Abstract

Glueballs represent a key requirement of quantum chromodynamics as a non-Abelian field theory. Their search provides one of the strongest motivations for meson spectroscopy. The first glueball candidate was identified in 1980 in the J/Ψ radiative decay. Its discovery actually dates back to 1963 and for four decades about 30 experiments, using six different production mechanisms, were dedicated to studying the pseudoscalar states lying in the 1.4–1.5 GeV$/c^2$ mass region. Today, the presence of two pseudoscalar states and an axial vector can be considered as established (see 2004 edition of the *Review of Particle Properties*). Assuming that $\eta(1295)$ is established and the nonet filled, the lower mass pseudoscalar, $\eta(1405)$, becomes a supernumerary and shows the properties of a non-$\overline{q}q$ state. Here, we review the experimental effort related to this long search, which can be considered a sort of paradigm for light-quark spectroscopy.

Pseudoscalar glueball

The bare states

$$\sqrt{\tfrac{1}{2}}(\bar{u}u + \bar{d}d)$$

$$\bar{s}s$$

$$\text{Glueball: } gg$$

mix and form the 3 resonances.
Usually, in such studies the glueball turns out to sit mostly in the eta(1405) state.

Conflict with Lattice!

$\eta(1295)$ $\quad I^G(J^{PC}) = 0^+(0^{-+})$

See also the mini-review under $\eta(1405)$

$\eta(1295)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1294±4 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.			

$\eta(1405)$ $\quad I^G(J^{PC}) = 0^+(0^{-+})$

A REVIEW GOES HERE – Check our WWW List of Reviews

$\eta(1405)$ MASS

VALUE (MeV)	DOCUMENT ID
1408.8±1.8 OUR AVERAGE	Includes data from the 2 datablocks that follow this one. Error includes scale factor of 2.1. See the ideogram below.

$\eta(1475)$ $\quad I^G(J^{PC}) = 0^+(0^{-+})$

See also the $\eta(1405)$.

$\eta(1475)$ MASS

$K\bar{K}\pi$ MODE ($K^*(892)$ K dominant)

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1476± 4 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.			

Uniwersytet Jana Kochanowskiego w Kielcach

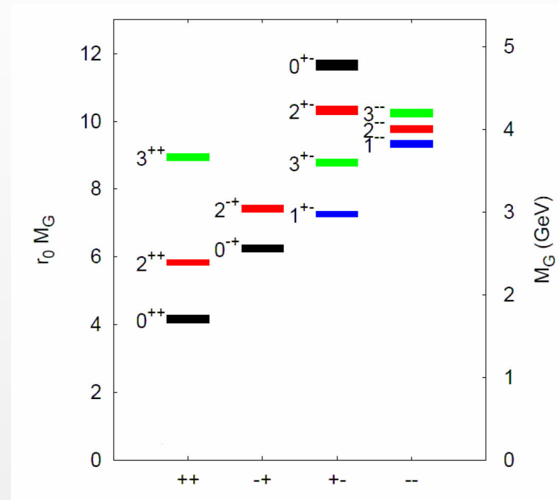
The pseudoscalar glueball: predictions from the eLSM

$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = i c_{\tilde{G}\Phi} \tilde{G} \left(\det\Phi - \det\Phi^{\dagger} \right)$$

Quantity	Value
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma^{tot}_{\tilde{G}}$	0.049
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.019
$\Gamma_{\tilde{G}\to \eta\eta\eta}/\Gamma^{tot}_{\tilde{G}}$	0.016
$\Gamma_{\tilde{G}\to \eta\eta\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.0017
$\Gamma_{\tilde{G}\to \eta\eta'\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.00013
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma^{tot}_{\tilde{G}}$	0.46
$\Gamma_{\tilde{G}\to \eta\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.16
$\Gamma_{\tilde{G}\to \eta'\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.094

$$\Gamma_{\tilde{G}\to\pi\pi\pi} = 0$$

M_G = 2.6 GeV from lattice as been used as an input.



X(2370) found at BESIII is a possible candidate.

Future experimental search, e.g. at BES and PANDA

Details in:

W. Eshraim, S. Janowski, F.G., D. Rischke, **Phys.Rev. D87 (2013) 054036. arxiv: 1208.6474** .

The pseudoscalar glueball from the eLSM/2

Coupling to baryons

$$\frac{\Gamma_{\tilde{G}\to\bar{N}N}}{\Gamma_{\tilde{G}\to\bar{N}^*N+\text{h.c.}}} \simeq 1.96$$

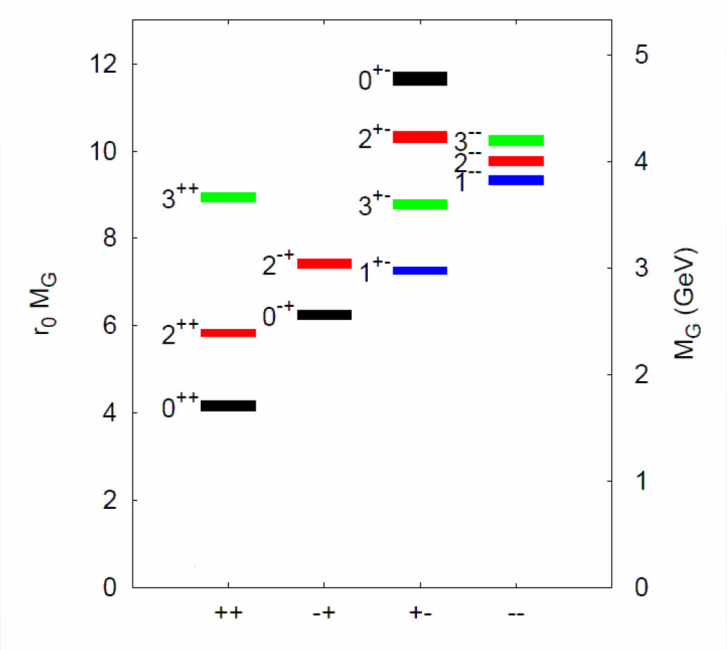
$$p + \bar{p} \to p + \bar{p}(1535) + \text{h.c.}$$

W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

Heavier glueballs: vector and pseudotensor

vector, pseudotensor,... glueballs.

Oddballs.



My personal plan: make predictions for decays of various glueballs (9 to do)

Vector glueball

From arXiv:1607.03640 [hep-ph], to appear in PRD,

Decays of the vector glueball by F.G, J. Sammet, S. Janowski

We predict that the vector glueball decays mostly into:

$\mathcal{O} \rightarrow b_1\pi \rightarrow \omega\pi\pi$ $\mathcal{O} \rightarrow \omega\pi\pi$ $\mathcal{O} \rightarrow \pi K K^*(892)$

The lattice mass of 3.8 GeV has been used; Tables of ratios are in the preprint.

Fields: new entry

Nonet	L	S	J^{PC}	Current	Assignment
P	0	0	0^{-+}	$P_{ij}=\frac{1}{\sqrt{2}}\bar{q}_j i\gamma^5 q_i$	π, K, η, η'
S	1	1	0^{++}	$S_{ij}=\frac{1}{\sqrt{2}}\bar{q}_j q_i$	$a_0(1450),\ K_0^*(1430),\ f_0(1370),\ f_0(1510)$
V^μ	0	1	1^{--}	$V_{ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j\gamma^\mu q_i$	$\rho(770),\ K^*(892),\ \omega(785),\ \phi(1024)$
A^μ	1	1	1^{++}	$A_{ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j\gamma^5\gamma^\mu q_i$	$a_1(1230),\ K_{1,A},\ f_1(1285),\ f_1(1420)$
B^μ	1	0	1^{+-}	$B_{ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j\gamma^5\overleftrightarrow{\partial}^\mu q_i$	$b_1(1230),\ K_{1,B},\ h_1(1170),\ h_1(1380)$
E_{ang}^μ	2	1	1^{--}	$E_{\text{ang},ij}^\mu=\frac{1}{\sqrt{2}}\bar{q}_j i\overleftrightarrow{\partial}^\mu q_i$	$\rho(1700),\ K^*(1680),\ \omega(1650),\ \phi(???)$

Chiral multiplet	Current	$U_R(3)\times U_L(3)$	P	C
$\Phi=S+iP$	$\sqrt{2}\bar{q}_{R,j}q_{L,i}$	$U_L\Phi U_R^\dagger$	$\Phi^\dagger$	Φ^t
$R^\mu=V^\mu-A^\mu$	$\sqrt{2}\bar{q}_{R,j}\gamma^\mu q_{R,i}$	$U_R R^\mu U_R^\dagger$	L_μ	$L^{t\mu}$
$L^\mu=V^\mu+A^\mu$	$\sqrt{2}\bar{q}_{L,j}\gamma^\mu q_{L,i}$	$U_L R^\mu U_L^\dagger$	R_μ	$R^{t\mu}$
$\tilde{\Phi}^\mu=E_{\text{ang}}^\mu-iB^\mu$	$\sqrt{2}\bar{q}_{R,j}i\overleftrightarrow{\partial}^\mu q_{L,i}$	$U_L\tilde{\Phi}^\mu U_R^\dagger$	$\tilde{\Phi}^{\dagger\mu}$	$-\tilde{\Phi}^{t\mu}$

ArXiv: 1607.03640

Vector glueball into pseudoscalar-pseudovector

$$\mathcal{L}_1 = \lambda_{\mathcal{O},1} G \mathcal{O}_\mu Tr\left[\Phi^\dagger \tilde{\Phi}^\mu + \tilde{\Phi}^{\mu\dagger}\Phi\right]$$

Quantity	Value
$\frac{\mathcal{O}\to\eta h_1(1170)}{\mathcal{O}\to b_1\pi}$	0.17
$\frac{\mathcal{O}\to\eta h_1(1380)}{\mathcal{O}\to b_1\pi}$	0.11
$\frac{\mathcal{O}\to\eta' h_1(1170)}{\mathcal{O}\to b_1\pi}$	0.15
$\frac{\mathcal{O}\to\eta' h_1(1380)}{\mathcal{O}\to b_1\pi}$	0.10
$\frac{\mathcal{O}\to K K_1(1270)}{\mathcal{O}\to b_1\pi}$	0.75
$\frac{\mathcal{O}\to K K_1(1400)}{\mathcal{O}\to b_1\pi}$	0.30
$\frac{\mathcal{O}\to K_0^*(1430) K^*(1680)}{\mathcal{O}\to b_1\pi}$	0.20
$\frac{\mathcal{O}\to a_0(1450)\rho(1700)}{\mathcal{O}\to b_1\pi}$	0.14
$\frac{\mathcal{O}\to f_0(1370)\omega(1650)}{\mathcal{O}\to b_1\pi}$	0.034

ArXiv: 1607.03640

$$\mathcal{O} \to b_1\pi \to \omega\pi\pi$$

Vector glueball into VPP

$$\mathcal{L}_2 = \lambda_{\mathcal{O},2} \mathcal{O}_\mu Tr \left[L^\mu \Phi \Phi^\dagger + R^\mu \Phi^\dagger \Phi \right]$$

Quantity	Value
$\frac{\mathcal{O} \to KK\rho}{\mathcal{O} \to \omega\pi\pi}$	0.50
$\frac{\mathcal{O} \to KK\omega}{\mathcal{O} \to \omega\pi\pi}$	0.17
$\frac{\mathcal{O} \to KK\phi}{\mathcal{O} \to \omega\pi\pi}$	0.21
$\frac{\mathcal{O} \to \pi K K^*(892)}{\mathcal{O} \to \omega\pi\pi}$	1.2
$\frac{\mathcal{O} \to \eta\eta\omega}{\mathcal{O} \to \omega\pi\pi}$	0.064
$\frac{\mathcal{O} \to \eta\eta'\omega}{\mathcal{O} \to \omega\pi\pi}$	0.019
$\frac{\mathcal{O} \to \eta'\eta'\omega}{\mathcal{O} \to \omega\pi\pi}$	0.019
$\frac{\mathcal{O} \to \eta\eta\phi}{\mathcal{O} \to \omega\pi\pi}$	0.039
$\frac{\mathcal{O} \to \eta\eta'\phi}{\mathcal{O} \to \omega\pi\pi}$	0.011
$\frac{\mathcal{O} \to \eta'\eta'\phi}{\mathcal{O} \to \omega\pi\pi}$	0.011
$\frac{\mathcal{O} \to a_0(1450)a_0(1450)\omega}{\mathcal{O} \to \omega\pi\pi}$	0.00029

Quantity	Value
$\frac{\mathcal{O} \to a_0(1450)\rho}{\mathcal{O} \to \omega\pi\pi}$	0.47
$\frac{\mathcal{O} \to f_0(1370)\omega}{\mathcal{O} \to \omega\pi\pi}$	0.15
$\frac{\mathcal{O} \to K_0^*(1430)K^*(892)}{\mathcal{O} \to \omega\pi\pi}$	0.30
$\frac{\mathcal{O} \to KK}{\mathcal{O} \to \omega\pi\pi}$	0.018

ArXiv: 1607.03640

$\mathcal{O} \to \omega\pi\pi$ $\quad$ $\mathcal{O} \to \pi K K^*(892)$

Vector glueball into VP

$$\mathcal{L}_3 = \alpha\varepsilon_{\mu\nu\rho\sigma}\partial^\rho\mathcal{O}^\sigma Tr\left[L^\mu\Phi R^\nu\Phi^\dagger\right]$$

Quantity	Value
$\frac{\mathcal{O}\to KK^*(892)}{\mathcal{O}\to\rho\pi}$	1.3
$\frac{\mathcal{O}\to\eta\omega}{\mathcal{O}\to\rho\pi}$	0.16
$\frac{\mathcal{O}\to\eta'\omega}{\mathcal{O}\to\rho\pi}$	0.13
$\frac{\mathcal{O}\to\eta\phi}{\mathcal{O}\to\rho\pi}$	0.21
$\frac{\mathcal{O}\to\eta'\phi}{\mathcal{O}\to\rho\pi}$	0.18
$\frac{\mathcal{O}\to\rho a_1(1230)}{\mathcal{O}\to\rho\pi}$	1.8
$\frac{\mathcal{O}\to\omega f_1(1285)}{\mathcal{O}\to\rho\pi}$	0.55
$\frac{\mathcal{O}\to\omega f_1(1420)}{\mathcal{O}\to\rho\pi}$	0.82

ArXiv: 1607.03640

dominant decay modes → $\rho\pi$, $KK^*(892)$, and $\rho a_1(1230)$

Pseudotensor glueball

Uniwersytet
Jana Kochanowskiego w Kielcach

Eur. Phys. J. A (2016) **52**: 356
DOI 10.1140/epja/i2016-16356-x

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Phenomenology of pseudotensor mesons and the pseudotensor glueball

"$G_2(3040)$"	
Branching ratio	Theory
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(K_2^*(1430)\,K + c.c.)$	0.9
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2(1270)\,\eta)$	6.0
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2(1270)\,\eta'(958))$	8.5
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2'(1525)\,\eta)$	9.0
$\Gamma^{\rm th}(a_2(1320)\,\pi)/\Gamma^{\rm th}(f_2'(1525)\,\eta'(958))$	11.0

Table 8: Theoretical branching ratios for the pseudotensor glueball "$G_2(3040)$".

ArXiv: 1608.8777

Still hypothetical states. Need of experiment (PANDA in first place).

Pseudotensor meson: suprising large mixing?

Abstract. We study the decays of the pseudotensor mesons ($\pi_2(1670), K_2(1770), \eta_2(1645), \eta_2(1870)$) interpreted as the ground-state nonet of 1^1D_2 $\bar{q}q$ states using interaction Lagrangians which couple them to pseudoscalar, vector, and tensor mesons. While the decays of $\pi_2(1670)$ and $K_2(1770)$ can be well described, the decays of the isoscalar states $\eta_2(1645)$ and $\eta_2(1870)$ can be brought in agreement with the present experimental data only if the mixing angle between nonstrange and strange states is surprisingly large (about $-42°$, similar to the mixing in the pseudoscalar sector, in which the chiral anomaly is active). Such a large mixing angle is however at odd with all other conventional quark-antiquark nonets:

ArXiv: 1608.8777

$$\begin{pmatrix} \eta_2(1645) \\ \eta_2(1870) \end{pmatrix} = \begin{pmatrix} \cos\theta_{PT} & \sin\theta_{PT} \\ -\sin\theta_{PT} & \cos\theta_{PT} \end{pmatrix} \begin{pmatrix} \eta_{2,N} = \frac{\bar{u}u+\bar{d}d}{\sqrt{2}} \\ \eta_{2,S} = \bar{s}s \end{pmatrix}$$

$$\theta_{PT} \simeq -42°$$

Concluding remarks

- We did not find glueballs yet.
- We have some good candidates for the scalar sector and less good candidates for the tensor and pseudoscalar sector.
- Vector and pseudotensor glueballs: predictions
- Are (at least some) glueballs narrow enough? This is a crucial question. Large-Nc tells so. Help from Lattice would be very welcome!
- Other glueballs can be studied; oddballs and glueballs with J=3 are on my to-do list
- Ongoing and future experiments:

BESIII

COMPASS@CERN - LHCb@CERN

CLAS12@JLAB, GLUEX@JLAB

BELLE2

RHIC/STAR

PANDA@FAIR is very well suited for the search of glueballs.

Concluding remarks

The search for glueballs is an active field.

Expected other 1000 publications in the next 20 years.

Hopefully with conclusive results!

Thank You

Back-up slides

Trace anomaly: the emergence of a dimension

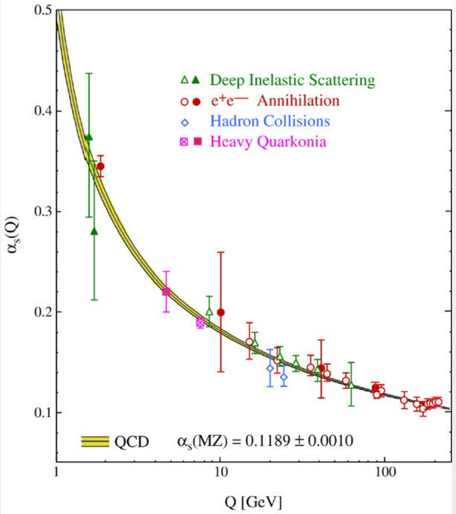
Chiral limit: $m_i = 0$

$$x^\mu \rightarrow x'^\mu = \lambda^{-1} x^\mu$$

is a classical symmetry, which is how broken by quantum fluctuations (trace anomaly)

Dimensional transmutation $\Lambda_{YM} \approx 250 \text{ MeV}$

$$\alpha_S(\mu = Q) = \frac{g^2(Q)}{4\pi}$$



In Yang-Mills (QCD without quarks) it is:

Gluon condensate: $\left\langle G^a_{\mu\nu} G^{a,\mu\nu} \right\rangle \neq 0$

$$\partial_\mu J^\mu = T^\mu_\mu = \frac{\beta(g)}{4g} G^a_{\mu\nu} G^{a,\mu\nu} \neq 0$$

The trace anomaly: addendum

Emergence of a low-energy scale: $\Lambda_{YM} \approx 250\ \mathrm{MeV}$

Gluon condensate: $\left\langle G^{a}_{\mu\nu} G^{a,\mu\nu} \right\rangle \neq 0$

„Effective“ gluon „*mass*“ (better: ‚dressing‘ of the propagator)

Analytic Structure of the Landau-Gauge Gluon Propagator
Stefan Strauss, Christian S. Fischer, and Christian Kellermann
Phys. Rev. Lett. **109**, 252001 – Published 19 December 2012

„Moreover, the gluon is certainly not a massive particle in the usual sense. Within the present accuracy we find 600 MeV < mg < 700 MeV.“

$$D_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)\frac{Z(p^2)}{p^2}$$

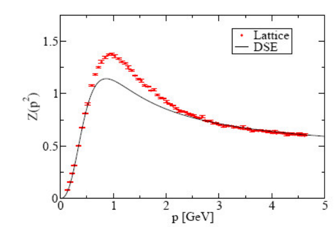
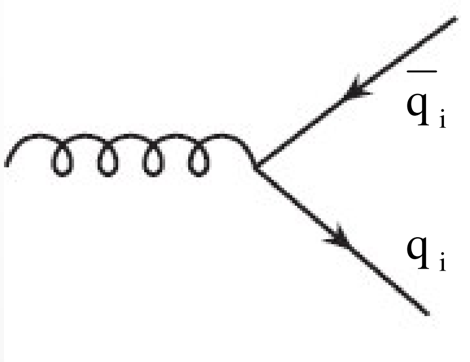


FIG. 2: Results for the gluon dressing function $Z(p^2)$ from lattice calculations [12] compared to the result from DSEs [9].

Flavor symmetry

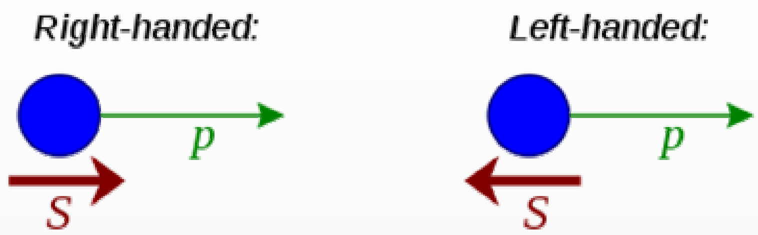


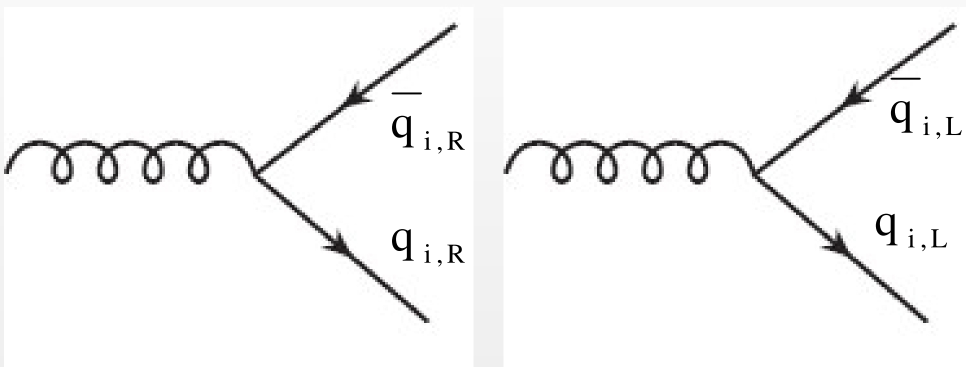
Gluon-quark-antiquark vertex.

The gluon is democratic! It couples to each flavor with the same strength.

$$q_i \rightarrow U_{ij} q_j \qquad \mathrm{U} \in \mathrm{U}(3)_{\mathrm{V}} \rightarrow \mathrm{U}^{+}\mathrm{U} = 1$$

Chiral symmetry





$$q_i = q_{i,R} + q_{i,L}$$

$$q_{i,R} = \frac{1}{2}(1+\gamma^5)q_i$$

$$q_{i,L} = \frac{1}{2}(1-\gamma^5)q_i$$

$$q_i = q_{i,R} + q_{i,L} \rightarrow U_{ij}^{R} q_{j,R} + U_{ij}^{L} q_{j,L}$$

Even more: the gluon couples with the same strength to quarks with different chiralities.

$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

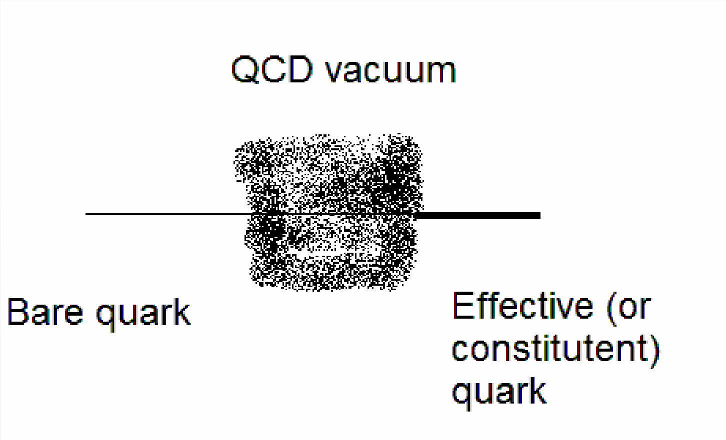
In the chiral limit (m_i=0) chiral symmetry is exact.

Spontaneous breaking of chiral symmetry

$$U(3)_R \times U(3)_L = U(1)_{R+L} \times U(1)_{R-L} \times SU(3)_R \times SU(3)_L$$

$$\mathrm{SSB:}\ \mathrm{SU(3)_R \times SU(3)_L \rightarrow SU(3)_{V=R+L}}$$

Chiral symmetry → Flavor symmetry



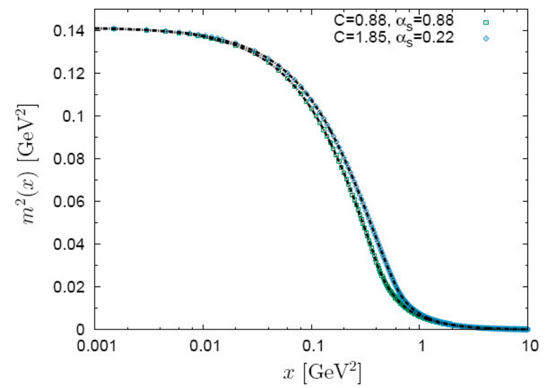
$$\left\langle \bar{q}_i q_i \right\rangle = \left\langle \bar{q}_{i,R} q_{i,L} + \bar{q}_{i,L} q_{i,R} \right\rangle \neq 0$$

$$\mathrm{m \approx m_u \approx m_d \approx 5\ MeV \rightarrow m^* \approx 300\ MeV}$$

$$\mathrm{m_{\rho-meson} \approx 2m^*}$$

$$\mathrm{m_{proton} \approx 3m^*}$$

See also:
All-order equation of the effective gluon mass
D. Binosi, D. Ibañez, and J. Papavassiliou
Phys. Rev. D **86**, 085033 (2012)



Many other works:

A Dynamical gluon mass solution in a coupled system of the Schwinger-Dyson equations
A.C. Aguilar, A.A. Natale
Published in **JHEP 0408 (2004) 057**

Off diagonal gluon mass generation and infrared Abelian dominance in the maximally Abelian gauge in lattice QCD
Kazuhisa Amemiya, Hideo Suganuma
Published in **Phys.Rev. D60 (1999) 114509**

Meson

Definition(s):

1) A meson is a strongly interacting particle with integer spin.

2) A meson is a strongly interacting particle with zero baryon number.

A meson is **not necessarily** a quark-antiquark state.
A quark-antiquark state is a conventional meson.

Quark-antiquark states: the large-Nc limit

As Isgur-Godfrey have shown, the quark model works.
Theoretical justification relies on the large-Nc expansion.
G. 't Hooft, Nucl. Phys. B **72** (1974) 461

For comprehensive reviews on Nc:

Baryons in the 1/n Expansion
Edward Witten
Published in **Nucl.Phys. B160 (1979) 57**

S. R. Coleman, Lectures given at 17th International School of Subnuclear Physics: Pointlike Structures Inside and Outside Hadrons 31 Jul - 10 Aug 1979. Erice, Italy. SLAC-PUB-2484.
R. F. Lebed, Czech. J. Phys. **49** (1999) 1273 [nucl-th/9810080].

$$\left|\rho^+\right\rangle \propto \left|u\bar{d}\right\rangle + \frac{1}{N_c}\left(\left|\pi^+\pi^0\right\rangle + ...\right)$$

where

$$\left|u\bar{d}\right\rangle = \left|\text{valence } u + \text{valence } \bar{d} + \text{gluons}\right\rangle$$

Mesons beyond q-qbar: the first term in the first expansion is of non-quarkonium type

Other approaches/1

QCD Sum rules

H. G. Dosch and S. Narison, Nucl. Phys. Proc. Suppl. 121 (2003) 114 [arXiv:hep-ph/0208271].
H. Forkel, Phys. Rev. D 71, 054008 (2005) [arXiv:hep-ph/0312049].

$$M_{0++} \simeq 1.3 \text{ GeV}$$
$$M_{2++} \simeq 2.0 \text{ GeV}$$
$$M_{0-+} \simeq 2.2 \text{ GeV}$$

Hamiltonian QCD

A.P. Szczepaniak, E.S. Swanson, Phys. Lett. B577 (2003) 61. hep-ph/0308268.

$$M_{0++} \simeq 1.9 \text{ GeV}$$
$$M_{2++} \simeq 2.4 \text{ GeV}$$
$$M_{0-+} \simeq 2.2 \text{ GeV}$$

Masses: summary

Agreement of different methods.

Lightest state: a scalar glueball between 1- 2 GeV

Next: tensor and pseudoscalar glueballs.

Glueballs with exotic quantum numbers (oddballs) are also predicted to exist.

Ellis-Lanik warning (1984)

IS SCALAR GLUONIUM OBSERVABLE?

John ELLIS
CERN, Geneva, Switzerland

and

Jozef LÁNIK
JINR, Dubna, USSR

Received 26 October 1984

We discuss couplings of scalar gluonium σ on the basis of the low energy theorems of broken chiral symmetry and the anomalous trace of the energy–momentum tensor, implemented using a phenomenological lagrangian. Taking the ITEP value of the gluon consensate as input, we find $\Gamma(\sigma \to \pi\pi) \simeq 0.6$ GeV $\times (m_\sigma/1$ GeV$)^5$ and $\Gamma(\sigma \to \gamma\gamma) \simeq 90$ eV $\times (m_\sigma/1$ GeV$)^5$, while m_σ is undetermined. These results suggest that if the scalar gluonium mass is above 1 GeV, it is probably unobservably wide, while production in $\gamma\gamma$ collisions is probably too small to be detectable if $m_\sigma < 1.5$ GeV. We comment on the observability of $J/\psi \to \sigma + \gamma$ and on the relevance of our results to other gluonia.

Physics Letters 150 B, 1984

Dilaton Lagrangian which mimics the trace anomaly: very large glueball is found. Decay into pion reads:

$$\Gamma = 0.6(M_G/1\,\mathrm{GeV})^5\ \mathrm{GeV}$$

For a glueball of about 1.5 GeV in mass, one gets a width of about 4.5 GeV!

Disagreement with the large-Nc expectation

M. Migdal and Shifman, Phys. Lett. 114B, 445 (1982)

J. Schechter et al, Phys. Rev. D 24, 2545 (1981)

Other approaches/2

- Flux-tube models

N. Isgur, J.E. Paton,
Phys. Lett. B124 (1983) 247

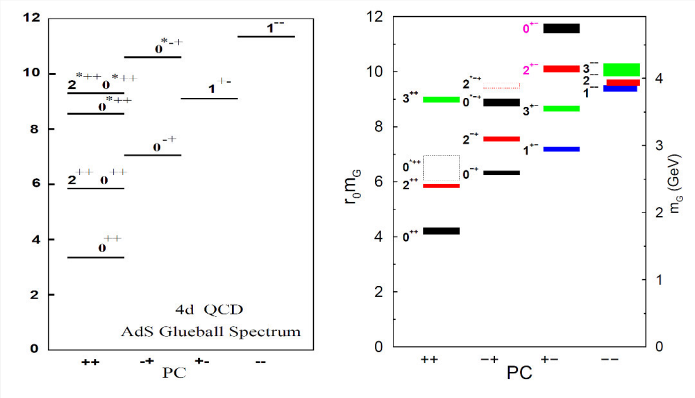
$$M_{0^{++}} \simeq 1.5 \text{ GeV}$$
$$M_{2^{++}} \simeq 2.8 \text{ GeV}$$
$$M_{0^{-+}} \simeq 2.8 \text{ GeV}$$

- Bethe-Salpeter approach

Sanchis-Alepuz et al,
Phys. Rev. D 92, 034001 (2015)

$$M_{0^{++}} \simeq 1.6 \text{ GeV}$$
$$M_{0^{-+}} \simeq 4.5 \text{ GeV}$$

- ADS/QCD



R. C. Brower, S. D. Mathur and C. I. Tan, *Nucl. Phys. B* **587** (2000) 249 [arXiv:hep-th/0003115]

The light scalar mesons

$$a_0(980) \quad k(800) \quad f_0(980) \quad f_0(500)$$

$$J^{PC} = 0^{++}$$

We saw that they are not quark-antiquark states:
(in our approach this is achieved by exclusion,
but this result is common to many others in low-energy QCD)!!!

Close-Amsler (1995 and 1996)

Uniwersytet Jana Kochanowskiego w Kielcach

C. Amsler and F.E. Close Phys. Lett. **B353** (1995) 385

C. Amsler and F.E. Close Phys. Rev. **D53**, 295 (1996)

Is $f_0(1500)$ a scalar glueball?

Claude Amsler*
Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland

Frank E. Close†
Particle Theory, Rutherford-Appleton Laboratory, Chilton, Didcot OX11 0QX, United Kingdom
(Received 24 July 1995)

Following the discovery of two new scalar mesons $f_0(1370)$ and $f_0(1500)$ at the Low Energy Antiproton Ring at CERN, we argue that the observed properties of this pair are incompatible with them both being $Q\bar{Q}$ mesons. We show instead that $f_0(1500)$ is compatible with the ground state glueball expected around 1500 MeV mixed with the nearby states of the $0^{++}Q\bar{Q}$ nonet. Tests of this hypothesis include the prediction of a further scalar state f_0' (1500–1800) which couples strongly to $K\bar{K}$, $\eta\eta$, and $\eta\eta'$. Signatures for a possible tensor glueball at ~ 2 GeV are also considered.

Decuplet: nonet+glueball.
3P0 model for decay.
Flavour symmetry.
Fit to data on decays.

$$\begin{pmatrix} \mathrm{f}_0(1370) \\ \mathrm{f}_0(1500) \\ \mathrm{f}_0(1710) \end{pmatrix} = \begin{pmatrix} -0.91 & 0.07 & 0.40 \\ -0.41 & 0.35 & -0.84 \\ 0.09 & 0.93 & 0.36 \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \bar{s}s \\ \text{Glueball: } gg \end{pmatrix}$$

Lee and Weingarten (1999)

PHYSICAL REVIEW D, VOLUME 61, 014015

Scalar quarkonium masses and mixing with the lightest scalar glueball

W. Lee* and D. Weingarten
IBM Research, P.O. Box 218, Yorktown Heights, New York 10598
(Received 18 August 1999; published 10 December 1999)

We evaluate the continuum limit of the valence (quenched) approximation to the mass of the lightest scalar quarkonium state, for a range of different quark masses, and to the mixing energy between these states and the lightest scalar glueball. Our results support the interpretation of $f_0(1710)$ as composed mainly of the lightest scalar glueball.

One of the first lattice studies. Coupling of the glueball to pions and kaons (via mixing)

$$\begin{pmatrix} \mathbf{f}_0(\mathbf{1370}) \\ \mathbf{f}_0(\mathbf{1500}) \\ \mathbf{f}_0(\mathbf{1710}) \end{pmatrix} = \begin{pmatrix} \mathbf{0.82} & \mathbf{0.29} & \mathbf{-0.49} \\ \mathbf{-0.40} & \mathbf{0.91} & \mathbf{-0.13} \\ \mathbf{0.41} & \mathbf{0.30} & \mathbf{0.85} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{d}}\mathbf{d}) \\ \bar{\mathbf{s}}\mathbf{s} \\ \textbf{Glueball: gg} \end{pmatrix}$$

My PhD time (2005)

PHYSICAL REVIEW D **72,** 094006 (2005)

Scalar nonet quarkonia and the scalar glueball: Mixing and decays in an effective chiral approach

F. Giacosa, Th. Gutsche, V. E. Lyubovitskij, and Amand Faessler

Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14,D-72076 Tübingen, Germany

(Received 22 September 2005; published 9 November 2005)

We study the strong and electromagnetic decay properties of scalar mesons above 1 GeV within a chiral approach. The scalar-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 scalar resonances and to the issue of the glueball decays. A comparison to other experimental results and to other theoretical approaches in the scalar meson sector is discussed.

$$
\begin{aligned}
\mathcal{L}_{\rm eff} = {} & \frac{F^2}{4}\langle D_\mu U D^\mu U^\dagger + \chi_+\rangle + \frac{1}{2}\langle D_\mu S D^\mu S - M_S^2 S^2 \\
& + \frac{1}{2}(\partial_\mu G \partial^\mu G - M_G^2 G^2) + c_d^s\langle S u_\mu u^\mu\rangle \\
& + c_m^s\langle S\chi_+\rangle + \frac{c_d^g}{\sqrt{3}} G\langle u_\mu u^\mu\rangle + \frac{c_m^g}{\sqrt{3}} G\langle\chi_+\rangle \\
& + c_e^s\langle S F_{\mu\nu}^+ F^{+\mu\nu}\rangle + \frac{c_e^g}{\sqrt{3}} G\langle F_{\mu\nu}^+ F^{+\mu\nu}\rangle + \mathcal{L}_{\rm mix}^P
\end{aligned}
$$

Starting point: Lagrangian (with both derivative and non-derivative terms is in agreement with ChPt; nonlinear real. of chiral symmetry)

Flavour symmetry is crucial.

Fit to all available PDG data.

$$
\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.86 & 0.24 & 0.45 \\ -0.45 & -0.06 & 0.89 \\ -0.24 & 0.97 & -0.06 \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \bar{s}s \\ \text{Glueball: } gg \end{pmatrix}
$$

My PhD time (2005)/2

But we found also an alternative solution:

$$\begin{pmatrix} \mathbf{f_0(1370)} \\ \mathbf{f_0(1500)} \\ \mathbf{f_0(1710)} \end{pmatrix} = \begin{pmatrix} \mathbf{0.81} & \mathbf{0.19} & \mathbf{0.54} \\ \mathbf{-0.49} & \mathbf{0.72} & \mathbf{0.49} \\ \mathbf{-0.30} & \mathbf{0.67} & \mathbf{-0.68} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\mathbf{\bar{u}u} + \mathbf{\bar{d}d}) \\ \mathbf{\bar{s}s} \\ \mathbf{Glueball:\ gg} \end{pmatrix}$$

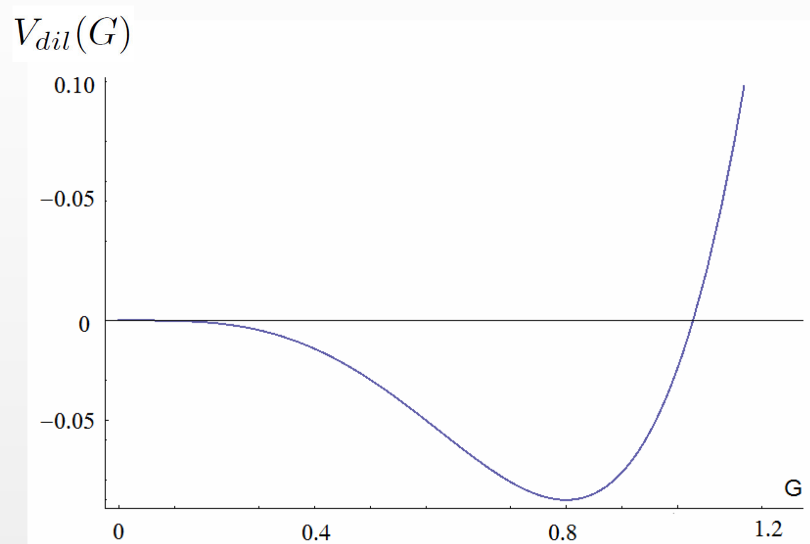
Scalar glueball: often described as a dilaton

At the hadronic level, we describe these properties as:

$$G^4 \sim G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\mathcal{L}_{dil} = \frac{1}{2}(\partial_\mu G)^2 - V_{dil}(G)$$

$$V_{dil}(G) = \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left[G^4 \ln\left(\frac{G}{\Lambda_G}\right) - \frac{G^4}{4}\right]$$



Λ_G dimensionful param that breaks dilatation inv!

$$\langle G \rangle = G_0 = \Lambda_G \propto \Lambda_{YM}$$

$$\partial_\mu J^\mu = T^\mu_\mu = -\frac{1}{4}\frac{m_G^2}{\Lambda_G^2} G^4$$

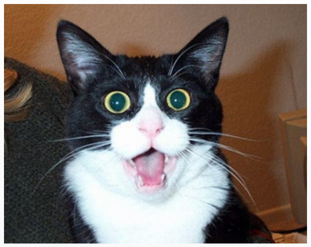
In Yang-Mills (QCD wo quarks) it is:

$$\partial_\mu J^\mu = T^\mu_\mu = \frac{\beta(g)}{4g} G^a_{\mu\nu} G^{a,\mu\nu} \neq 0$$

J. Schechter et al,
Phys. Rev. D 24, 2545 (1981)

M. Migdal and Shifman,
Phys. Lett. 114B, 445 (1982)

Model of QCD – eLSM with scalar Glueball



$$
\begin{aligned}
\mathcal{L} \;=\; & \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu \Phi)^\dagger (D_\mu \Phi)\right] \\
& - m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger \Phi\right] - \lambda_1 (\mathrm{Tr}\left[\Phi^\dagger\Phi\right])^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\
& + \left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)\left((L^\mu)^2 + (R^\mu)^2\right)\right] \\
& - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger + \Phi\right)\right] \\
& + c_1[\det(\Phi) - \det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\
& + h_2 \mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]
\end{aligned}
$$

$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\
a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\
K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S + i\eta_S
\end{pmatrix}
$$

$$
L^\mu, R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{\omega_N \pm \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \pm a_1^0}{\sqrt{2}} & \rho^+ \pm a_1^+ & K^{\star +} \pm K_1^+ \\
\rho^- \pm a_1^- & \frac{\omega_N \mp \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \mp a_1^0}{\sqrt{2}} & K^{\star 0} \pm K_1^0 \\
K^{\star -} \pm K_1^- & \bar{K}^{\star 0} \pm i\bar{K}_1^0 & \omega_S \pm f_{1S}
\end{pmatrix}
$$

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**)
D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011**

Results of the fit/1 (11 parameters, 21 exp. quantities)

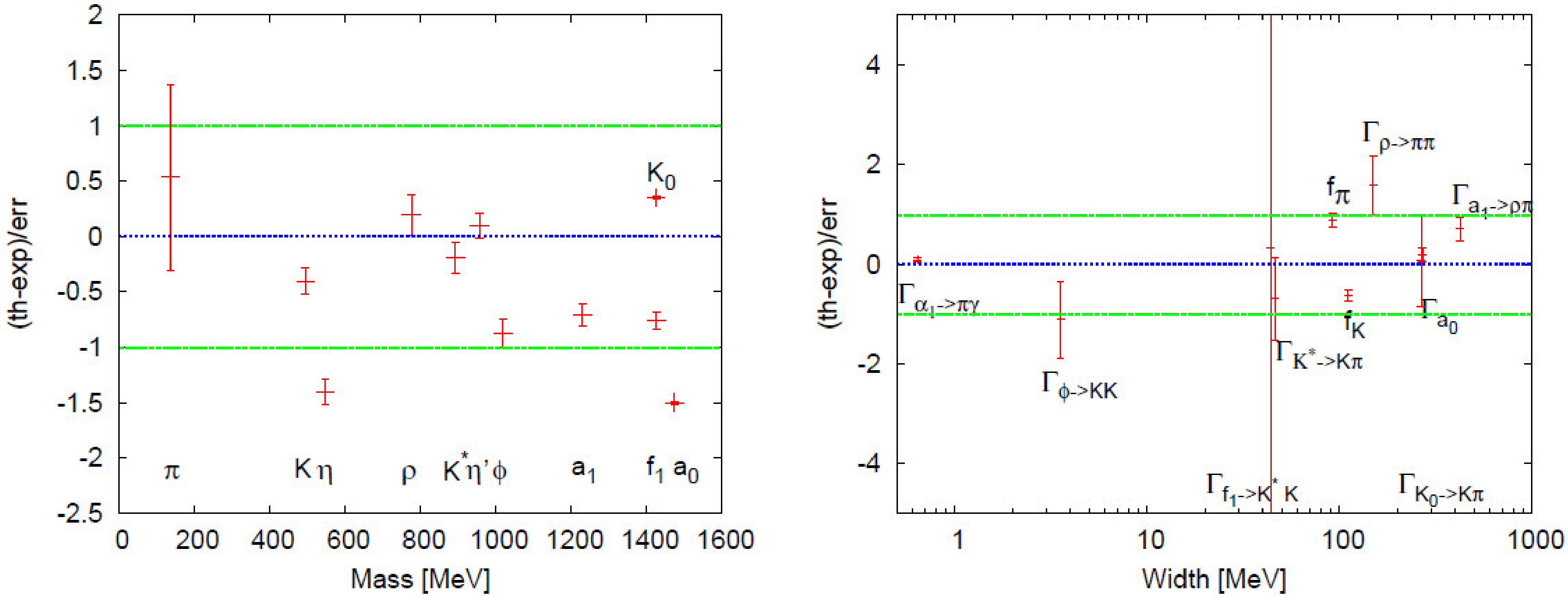
Error from PDG or 5% of exp. Scalar-isoscalar sector not included.

$$\chi^2_{red} = 1.2$$

Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 51.0
m_{a_1}	1186 ± 6	1230 ± 62
$m_{f_1(1420)}$	1372.5 ± 5.3	1426.4 ± 71.3
m_{a_0}	1363 ± 1	1474 ± 74
$m_{K_0^\star}$	1450 ± 1	1425 ± 71
$\Gamma_{\rho\to\pi\pi}$	160.9 ± 4.4	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.6 ± 1.9	46.2 ± 2.3
$\Gamma_{\phi\to\bar{K}K}$	3.34 ± 0.14	3.54 ± 0.18
$\Gamma_{a_1\to\rho\pi}$	549 ± 43	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.66 ± 0.01	0.64 ± 0.25
$\Gamma_{f_1(1420)\to K^\star K}$	44.6 ± 39.9	43.9 ± 2.2
Γ_{a_0}	266 ± 12	265 ± 13
$\Gamma_{K_0^\star\to K\pi}$	285 ± 12	270 ± 80

arXiv:1208.0585

Results of the fit/2 (11 parameters, 21 exp. quantities)



arXiv:1208.0585

Overall phenomenology is good (many more quantities can be calculated)

Scalar mesons $a_0(1450)$ and $K_0(1430)$ above 1 GeV and are quark-antiquark states.

Importance of the (axial-)vector mesons.

Large-Nc: except from G, all states scale as quark-antiquark states.

eLSM and scalar glueballs: details

$$\sigma_N \equiv (\bar{u}u + \bar{d}d)/\sqrt{2} \cong f_0(1370) \quad \sigma_S \equiv \bar{s}s \cong f_0(1500) \quad G \equiv gg \cong f_0(1710)$$

χ^2/d.o.f. = 0.35

Parameter	Value
Λ_{dil}	3297 [MeV]
m_G	1525 [MeV]
λ_1	6.25
h_1	−3.22
ϵ_S	0.421×10^6 [MeV^2]

Λ_{dil} → C ≈ 1.8 GeV

Quantity	Fit [MeV]	Exp. [MeV]
$M_{f_0(1370)}$	1444	1200-1500
$M_{f_0(1500)}$	1534	1505 ± 6
$M_{f_0(1710)}$	1750	1720 ± 6
$f_0(1370) \to \pi\pi$	423.6	-
$f_0(1500) \to \pi\pi$	39.2	38.04 ± 4.95
$f_0(1500) \to K\bar{K}$	9.1	9.37 ± 1.69
$f_0(1710) \to \pi\pi$	28.3	29.3 ± 6.5
$f_0(1710) \to K\bar{K}$	73.4	71.4 ± 29.1

$$\sigma_N \equiv (\bar{u}u + \bar{d}d)/\sqrt{2} \cong f_0(1370) \quad \sigma_S \equiv \bar{s}s \cong f_0(1500) \quad G \equiv gg \cong f_0(1710)$$

Decay Channel	Our Value [MeV]	Experiment [MeV]
$f_0(1370) \to KK$	117.5	–
$f_0(1370) \to \eta\eta$	43.3	–
$f_0(1370) \to \rho\rho \to 4\pi$	13.8	–
$f_0(1500) \to \eta\eta$	4.7	5.56 ± 1.34
$f_0(1500) \to \rho\rho \to 4\pi$	0.2	$> 54.0 \pm 7.1$
$f_0(1710) \to \eta\eta$	57.9	34.3 ± 17.6
$f_0(1710) \to \rho\rho \to 4\pi$	0.5	–

Gluonium content in η'

Eur. Phys. J. C (2010) 68: 619–681
DOI 10.1140/epjc/s10052-010-1351-1

THE EUROPEAN PHYSICAL JOURNAL C

Review

Physics with the KLOE-2 experiment at the upgraded DAΦNE

$|q\bar{q}\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle + |d\bar{d}\rangle)$ $\quad |s\bar{s}\rangle$

$$|\eta'\rangle = \cos\psi_G \sin\psi_P\, |q\bar{q}\rangle + \cos\psi_G \cos\psi_P\, |s\bar{s}\rangle + \sin\psi_G\, |GG\rangle\,,$$

$$|\eta\rangle = \cos\psi_P\, |q\bar{q}\rangle - \sin\psi_P\, |s\bar{s}\rangle\,,$$

$$Z_G^2 = \sin^2\psi_G$$

In general, one has a 3-body mixing.
Chiral anomaly important.
However, the mixing should be suppressed by the large glueball mass (2.6 GeV).

Results not conclusive yet...

Table 12 Fit to the gluonium content in η' assuming 1% error on the η' branching fractions. The $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$ constraint is used (not used) in the left (right) column

	with $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$	without $\eta' \to \gamma\gamma/\pi^0 \to \gamma\gamma$
Z_G^2	0.11 ± 0.03	0.11 ± 0.04

JHEP

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On the gluon content of the η and η' mesons

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Abstract: A phenomenological analysis of radiative $V \to P\gamma$ and $P \to V\gamma$ decays is performed with the purpose of determining the gluonic content of the η and η' wave functions. Our results show that within our model there is no evidence for a gluonium contribution in the η, $Z_\eta^2 = 0.00 \pm 0.12$, or the η', $Z_{\eta'}^2 = 0.04 \pm 0.09$. In terms of a mixing angle description this corresponds to $\phi_P = (41.4 \pm 1.3)^\circ$ and $|\phi_{\eta' G}| = (12 \pm 13)^\circ$. In addition, the η-η' mixing angle is found to be $\phi_P = (41.5 \pm 1.2)^\circ$ if we don't allow for a gluonium component.

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Situation not clarified yet.

According to Lattice, the pseudoscalar glueball has a mass of about 2.6 GeV.

Mixing should be suppressed.

Glueball decays: blindness

Flavour blindness (widely used for the scalar glueball):

$$\left|\frac{A_{G\to\pi\pi}}{A_{G\to KK}}\right|^2=\frac{3}{4}\qquad\left|\frac{A_{G\to\eta\eta}}{A_{G\to KK}}\right|^2=\frac{3}{4}\qquad A_{G\to\eta\eta'}=0$$

Even more: chiral blindness (could be relevant for heavier glueballs):

$$\left|\frac{A_{G\to\rho\rho}}{A_{G\to a_1(1230)a_1(1230)}}\right|^2=1$$

Glueball decay: Large-Nc

Glueball masses are Nc-indipentent for large-Nc
(just a convetional quark-antiquark mesons)

$$M_G \propto N_c^0$$

Decay amplitude of a glueball into (conventional) mesons scales as:

$$A_{G \to M_1 M_2} \propto N_c^{-1} \qquad \Gamma_{G \to M_1 M_2} \propto N_c^{-2}$$

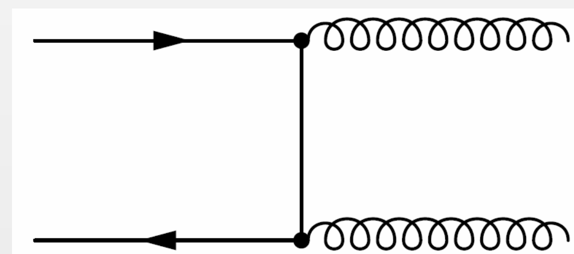
Recall that for a conventional quark-antiquark state:

$$A_{M \to M_1 M_2} \propto N_c^{-1/2} \qquad \Gamma_{\mathrm{M} \to M_1 M_2} \propto N_c^{-1}$$

Glueball-quarkonium: mixing and large-Nc

The picture is complicated by mixing.
A glueball with conventional quantum numbers mix with nearby quark-antiquark states.

$$|\bar{q}q\rangle \longleftrightarrow |gg\rangle$$



Mixing suppressed in large-Nc but phenom. relevant

$$A_{G\text{-}M} \propto N_c^{-1/2}$$

For comparison:

$$A_{\sqrt{\frac{1}{2}}(\bar{\mathbf{u}}\mathbf{u}+\bar{\mathbf{d}}\mathbf{d})\text{-}\bar{\mathbf{s}}\mathbf{s}} \propto N_c^{-1}$$

Estimate of the glueball's width/1

OZI-dominant decays of conventional quark-antiquark mesons:

$$\Gamma_{\rho\to\pi\pi} \propto \frac{1}{N_c} \text{ and } \Gamma^{\text{exp}}_{\rho\to\pi\pi} = 148 \text{ MeV}.$$

$$\Gamma_{f_2(1270)\to\pi\pi} \propto \frac{1}{N_c} \text{ and } \Gamma^{\text{exp}}_{f_2(1270)\to\pi\pi} = 157 \text{ MeV}$$

$$\Gamma_{f_2'(1525)\to KK} \propto \frac{1}{N_c} \text{ and } \Gamma^{\text{exp}}_{f_2'(1525)\to KK} = 65 \text{ MeV}$$

$$\Gamma^{\text{OZI-allowed}}_{\bar{q}q\to MM} \propto \frac{1}{N_c} \text{ and } \Gamma^{\text{OZI-allowed}}_{\bar{q}q\to MM} \sim 100 \text{ MeV}.$$

Estimate of the glueball's width/2

OZI-suppressed decays of conventional quark-antiquark mesons:

$$\Gamma_{f_2'(1525)\to\pi\pi} \propto \frac{1}{N_c^3} \text{ and } \Gamma^{\text{exp}}_{f_2'(1525)\to\pi\pi} = 0.6 \text{ MeV}$$

$$\Gamma_{j/\psi\to\text{hadrons}} \propto \frac{1}{N_c^3} \text{ and } \Gamma^{\text{exp}}_{j/\psi\to\text{hadrons}} = 0.08 \text{ MeV}$$

$$\Gamma^{\text{OZI-suppressed}}_{\bar{q}q\to MM} \propto \frac{1}{N_c^3} \text{ and } \Gamma^{\text{OZI-suppressed}}_{\bar{q}q\to MM} \lesssim 1 \text{ MeV}$$

Hence, for glueballs we *guess*:

$$\Gamma_{G\to MM} \propto \frac{1}{N_c^2} ,$$

$$1 \text{ MeV} \sim \Gamma^{\text{OZI-suppressed}}_{\bar{q}q\to MM} \propto \frac{1}{N_c^3} < \Gamma_{G\to MM} \propto \frac{1}{N_c^2} < \frac{1}{N_c} \propto \Gamma^{\text{OZI-allowed}}_{\bar{q}q\to MM} \sim 100 \text{ MeV}.$$

$$\Gamma_{G\to MM} \sim 10 \text{ MeV}.$$

The PANDA experiment