Latest News on Glueballs

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Talk prepared for:
2023 Polish Particle and Nuclear Theory Summit
2PiNTS
22-24/11/2023
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23/11/2023

Outline

The QCD Lagrangian.

Glueball's masses

Glueball decays: main features.

A short look at past, ongoing and future experiments.

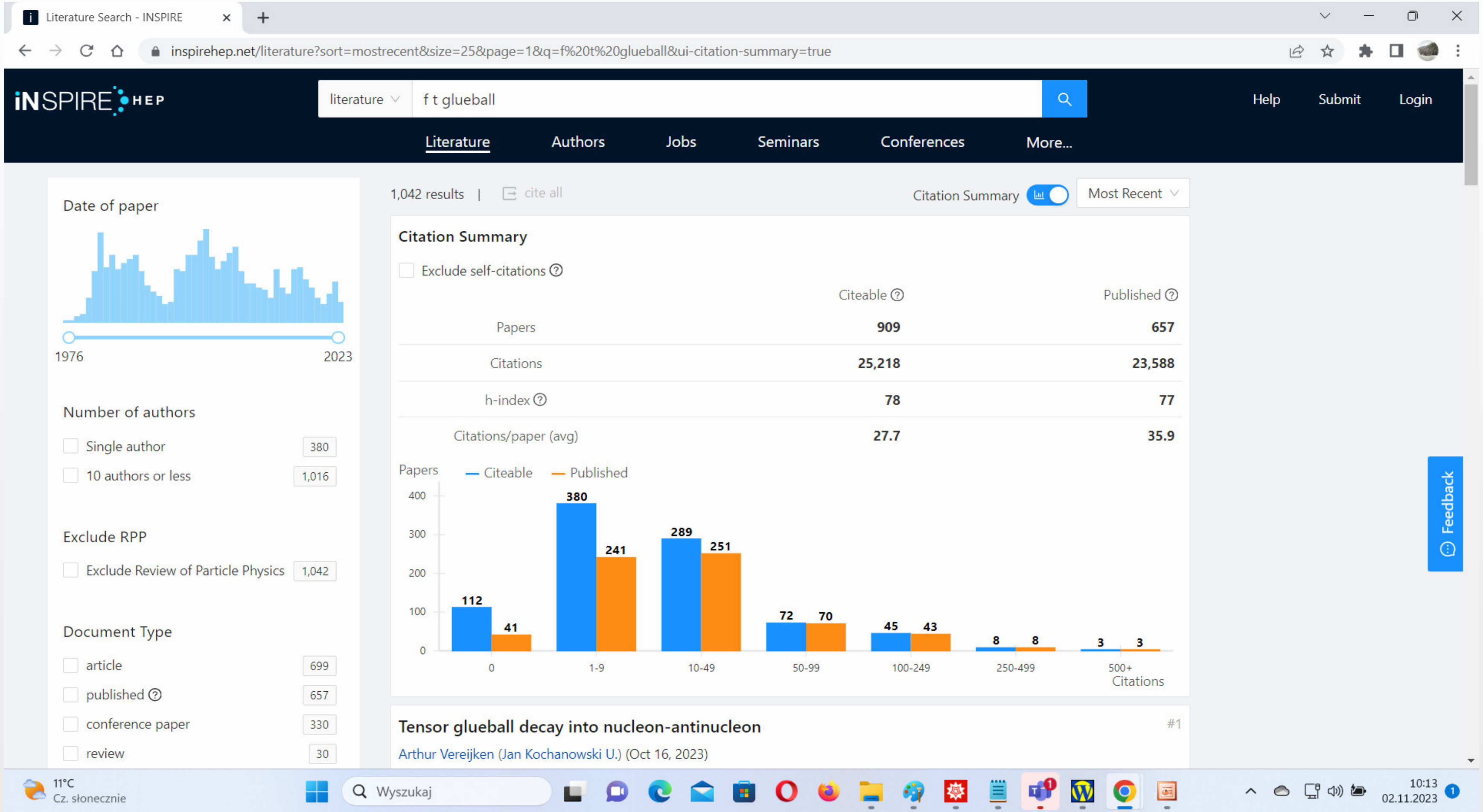
The scalar glueball

The tensor glueball

The pseudoscalar glueball

Other glueballs

Summary



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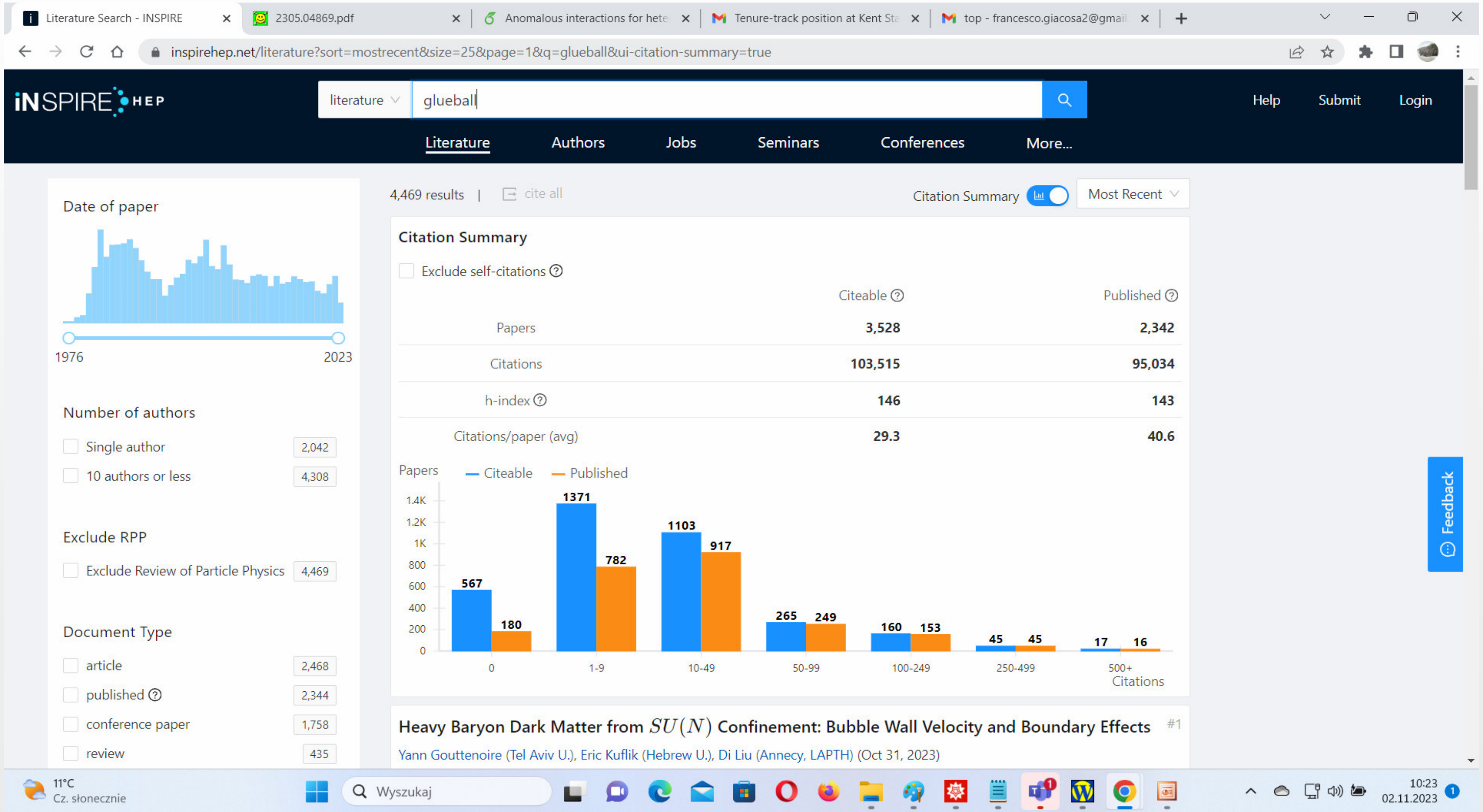

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Review papers

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

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

Contents lists available at ScienceDirect

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Progress in Particle and Nuclear Physics

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

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.

Eur. Phys. J. Spec. Top. (2021) 230:1575–1592
https://doi.org/10.1140/epjs/s11734-021-00143-8

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Check for updates

Review

Uniwersytet Jana Kochanowskiego w Kielcach

Glueballs as the Ithaca of meson spectroscopy

From simple theory to challenging detection

Felipe J. Llanes-Estrada[a]

F. Gross et al.,
50 Years of Quantum Chromodynamics,
[arXiv:2212.11107 [hep-ph]].

A review on Glueball hunting

Davide Vadacchino[a,*]

Lattice review: 2305.04869

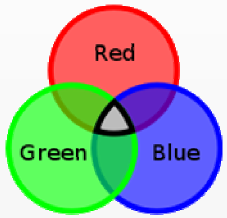
The Lagrangian of QCD and its symmetries

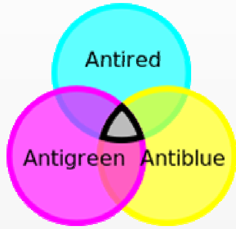
Born	Giuseppe Lodovico Lagrangia 25 January 1736 Turin
Died	10 April 1813 (aged 77) Paris

Francesco Giacosa

The QCD Lagrangian

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





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

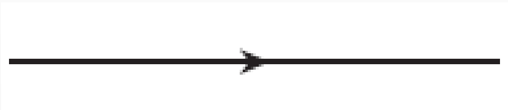
8 type of gluons ($R\overline{G}$, $B\overline{G}$,…)

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

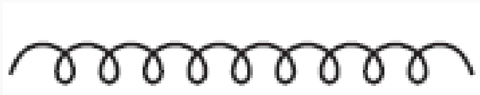
$$A_\mu^a \; ; \; a = 1,..., 8$$

Feynman diagrams of QCD

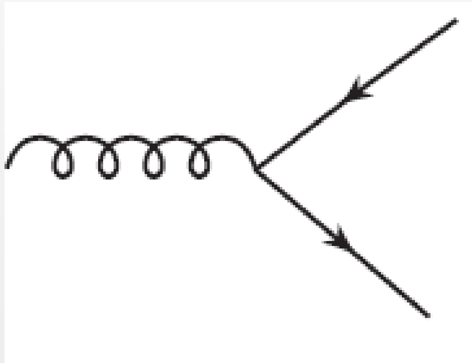
$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$



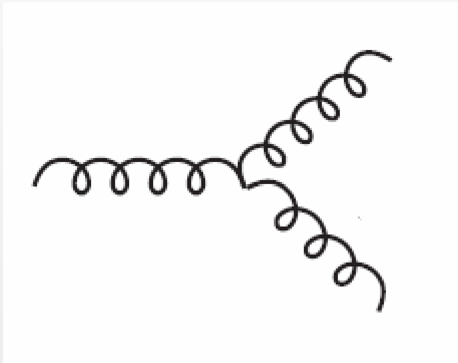
Quark



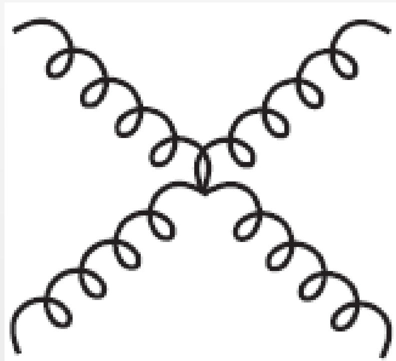
Gluon



Gluon-quark-antiquark vertex



3-gluon vertex



4-gluon vertex

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

Trace anomaly: the emergence of a dimension

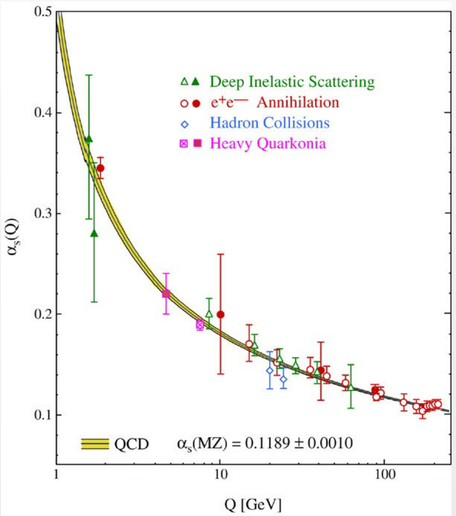
Chiral limit: $m_i = 0$

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

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

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

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

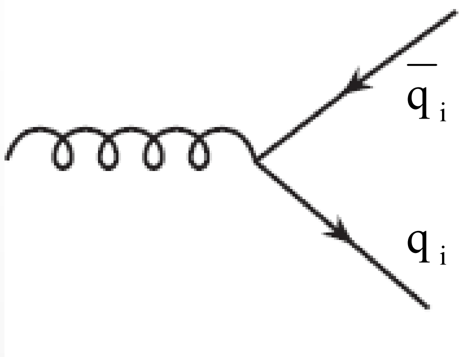


In Yang-Mills (QCD without quarks) it is:

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

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

Flavor symmetry

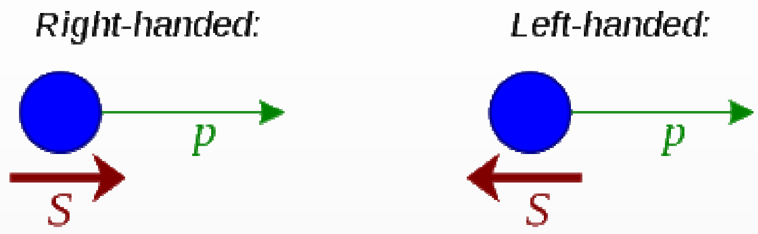


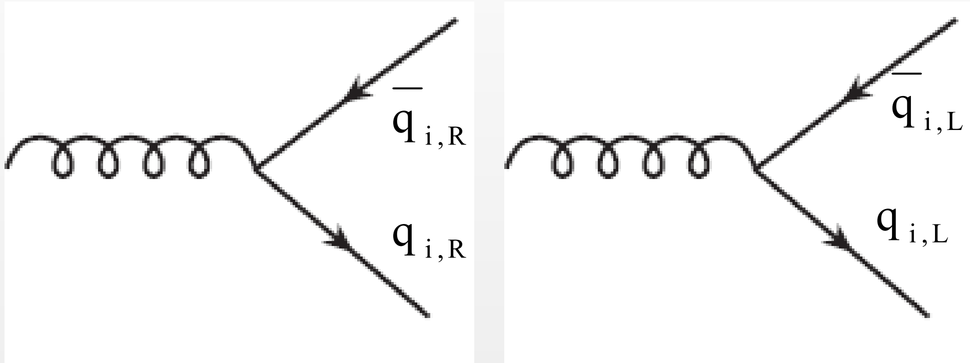
Gluon-quark-antiquark vertex.

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





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

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

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

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

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.

Symmetries of QCD: summary

$SU(3)_{color}$: 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 (chiral anomaly)

From quarks and gluons to hadrons d.o.f.

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

Meson

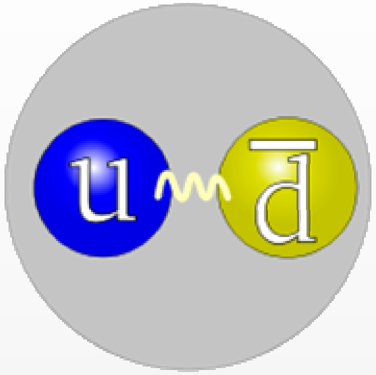
Definition(s):

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.

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



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

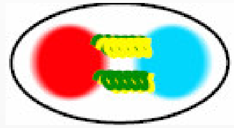
Pion $m_{\pi^+} = 139 \ \text{MeV}$

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

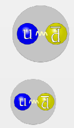
Mass generation in QCD is a nonpert. penomenon based on SSB
(mentioned previusly).

Non-conventional mesons: theoretical expectations

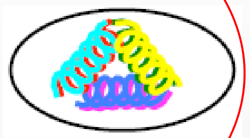
1) Glueballs 

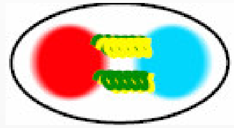
2) Hybrids 

3) Four-quark states

- Compact diquark-antidiquark states 
- Molecular states (a type of dynamical generation) 
- Companion poles (another type of dynamical generation)

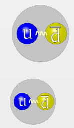
Non-conventional mesons: theoretical expectations

1) Glueballs 

2) Hybrids 

Compact diquark-antidiquark states 

3) Four-quark states

Molecular states (a type of dynamical generation) 

Companion poles (another type of dynamical generation)

Masses of glueballs

Glueball masses: bag models

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

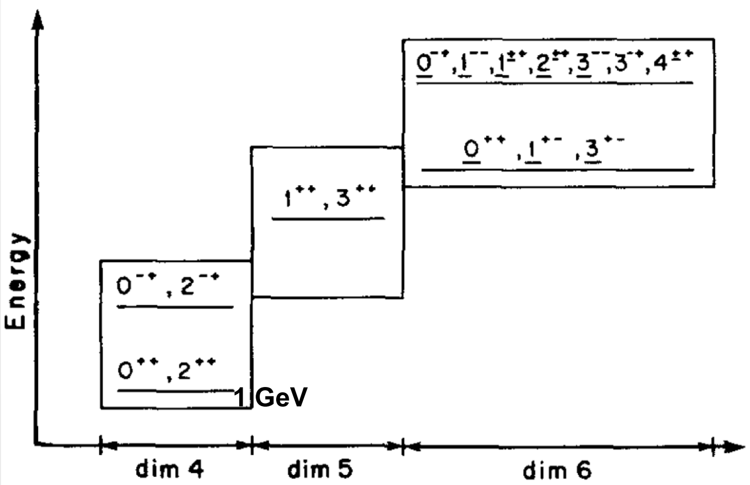
ANNALS OF PHYSICS 168, 344–367 (1986)

Qualitative Features of the Glueball Spectrum*

R. L. JAFFE, K. JOHNSON, AND Z. RYZAK†

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

Received September 13, 1985



Theoretical 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.

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

Theoretical approaches/2

- Flux-tube models

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

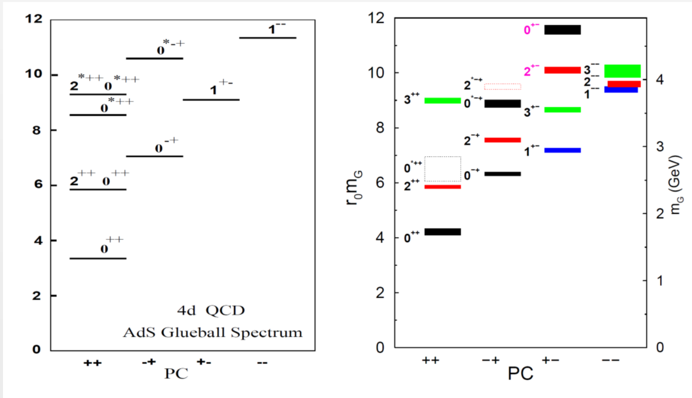
$$M_{0^{++}} \simeq 1.5 \text{ GeV}$$
$$M_{2^{++}} \simeq 2.8 \text{ GeV}$$
$$M_{0^{-+}} \simeq 2.8 \text{ GeV}$$

- Bethe-Salpeter approach

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

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

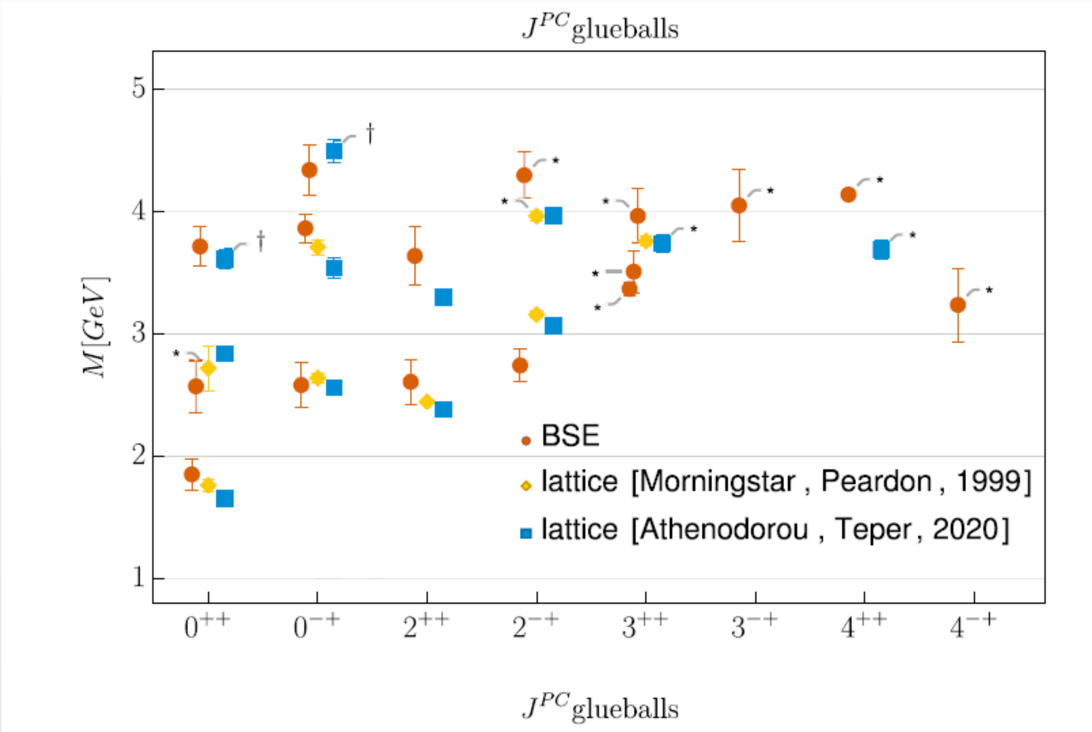
- ADS/QCD



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

Theoretical approaches /3

Bethe-Salpeter results: Huber, Fischer, Sanchis-Alepuz:
Eur.Phys.J.C 81 (2021) 12, 1083 and *Eur.Phys.J.C* 80 (2020) 11, 1077



Lattice 2006

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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[5]*Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[6]*School of Mathematics, Trinity College, Dublin, Dublin 2, Ireland*
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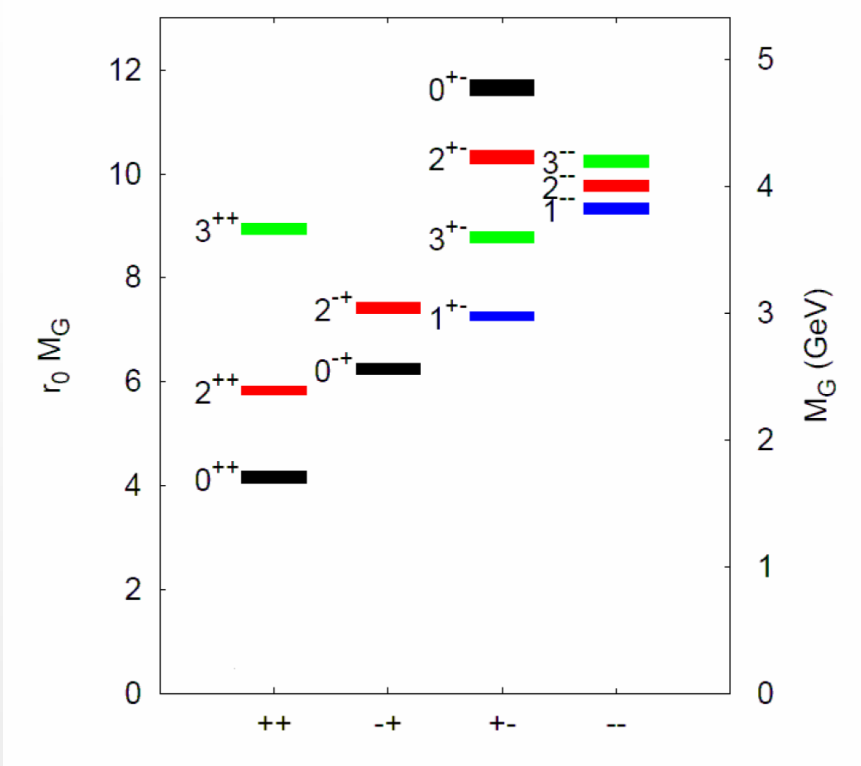
(Received 13 October 2005; published 26 January 2006)

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.

Lattice: comparison

Table 2 The values of the glueball masses as given in three lattice works

$n\ J^{PC}$	M[MeV] Chen et al. [51]	Meyer [52]	A & T [53]	$n\ J^{PC}$	M[MeV] Chen et al. [51]	Meyer [52]	A & T [53]
1 0^{++}	1710(50)(80)	1475(30)(65)	1653(26)	**1 1**$^{--}$	3830(40)(190)	3240(330)(150)	4030(70)
2 0^{++}		2755(30)(120)	2842(40)	**1 2**$^{--}$	4010(45)(200)	3660(130)(170)	3920(90)
3 0^{++}		3370(100)(150)		**2 2**$^{--}$		3740(200)(170)	
4 0^{++}		3990(210)(180)		**1 3**$^{--}$	4200(45)(200)	4330(260)(200)	
1 2^{++}	2390(30)(120)	2150(30)(100)	2376(32)	**1 0**$^{+-}$	4780(60)(230)		
2 2^{++}		2880(100)(130)	3300(50)	**1 1**$^{+-}$	2980(30)(140)	2670(65)(120)	2944(42)
1 3^{++}	3670(50)(180)	3385(90)(150)	3740(70)	**2 1**$^{+-}$			3800(60)
1 4^{++}		3640(90)(160)	3690(80)	**1 2**$^{+-}$	4230(50)(200)		4240(80)
1 6^{++}		4360(260)(200)		**1 3**$^{+-}$	3600(40)(170)	3270(90)(150)	3530(80)
1 0^{-+}	2560(35)(120)	2250(60)(100)	2561(40)	**2 3**$^{+-}$		3630(140)(160)	
2 0^{-+}		3370(150)(150)	3540(80)	**1 4**$^{+-}$			4380(80)
1 2^{-+}	3040(40)(150)	2780(50)(130)	3070(60)	**1 5**$^{+-}$		4110(170)(190)	
2 2^{-+}		3480(140)(160)	3970(70)				
1 5^{-+}		3942(160)(180)					
1 1^{-+}			4120(80)				
2 1^{-+}			4160(80)				
3 1^{-+}			4200(90)				

Table from 2212.03272

51. Y. Chen et al., Glueball spectrum and matrix elements on anisotropic lattices. Phys. Rev. D **73**, 014516 (2006). https://doi.org/10.1103/PhysRevD.73.014516. arXiv:hep-lat/0510074
52. H.B. Meyer, Glueball regge trajectories. arXiv:hep-lat/0508002
53. A. Athenodorou, M. Teper, The glueball spectrum of SU(3) gauge theory in 3 + 1 dimensions. JHEP **11**, 172 (2020). https://doi.org/10.1007/JHEP11(2020)172. arXiv:2007.06422 [hep-lat]

Which masses fit better? According to thermodynamics, the 'AT' ones

Eur. Phys. J. C (2023) 83:390
https://doi.org/10.1140/epjc/s10052-023-11557-0

THE EUROPEAN PHYSICAL JOURNAL C

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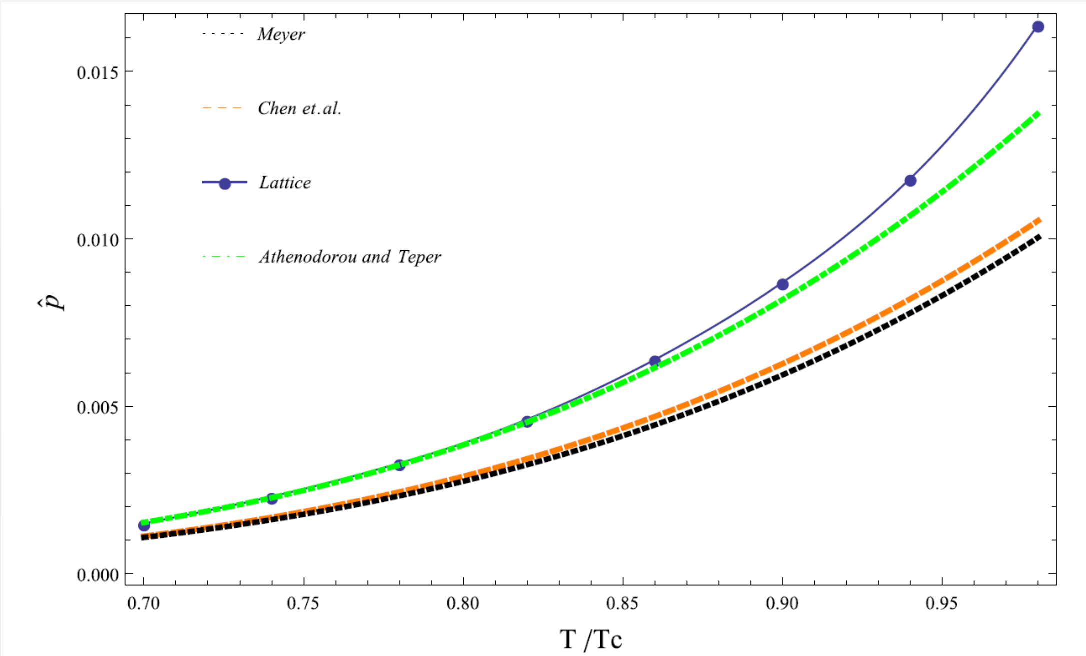
Regular Article - Theoretical Physics

Thermodynamics of the glueball resonance gas

Enrico Trotti[1,a], Shahriyar Jafarzade[1,b], Francesco Giacosa[1,2,c]



Masses: summary

Agreement of different methods.

Lightest state: a scalar glueball between 1.5 - 2 GeV

Next: tensor and pseudoscalar glueballs.

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

Decays of glueballs: simple features

Glueball decays: blindness

Flavour blindness (widely used for the scalar glueball):

$$\left|\frac{A_{G\to\pi\pi}}{A_{G\to KK}}\right|^2=\frac{3}{4}\quad,\quad\left|\frac{A_{G\to\eta\eta}}{A_{G\to KK}}\right|^2=\frac{1}{4}\qquad A_{G\to\eta\eta'}=0$$

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:

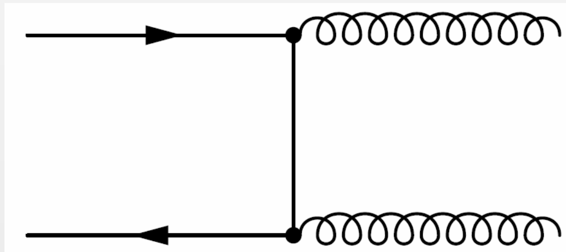
$$A_{M\to M_1 M_2} \propto N_c^{-1/2} \qquad \Gamma_{\mathrm{M}\to M_1 M_2} \propto N_c^{-1}$$

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:

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

`Rough' estimate of the glueball's width/1

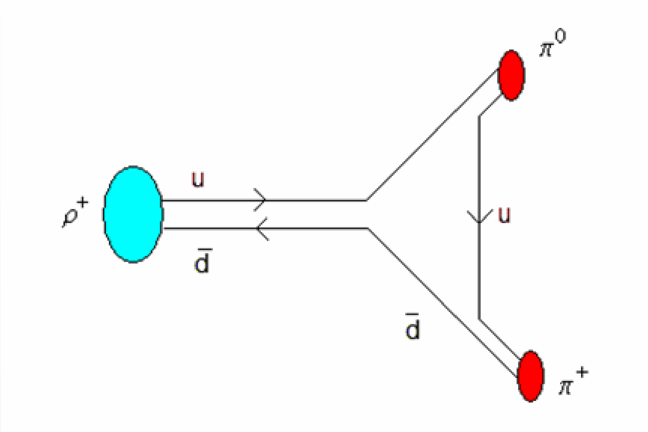
OZI-dominant decays of conventional quark-antiquark mesons:

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

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

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

$$\Gamma_{\psi(3370)\rightarrow DD} \propto \frac{1}{N_c} \text{ and } \Gamma^{\text{exp}}_{\psi(3370)\rightarrow DD} = 87 \text{ MeV}.$$



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

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*":

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

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

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

Experiments

Glueball production and decays: gluon-rich processes

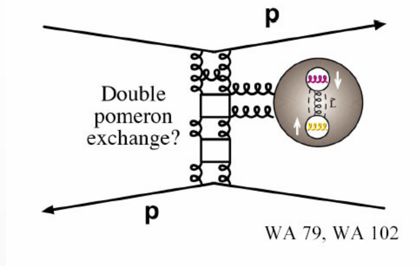
Glueballs should be find in gluon-rich processes (such as J/ψ decays, proton-antiproton fusion, …)

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

Hadronic experiments

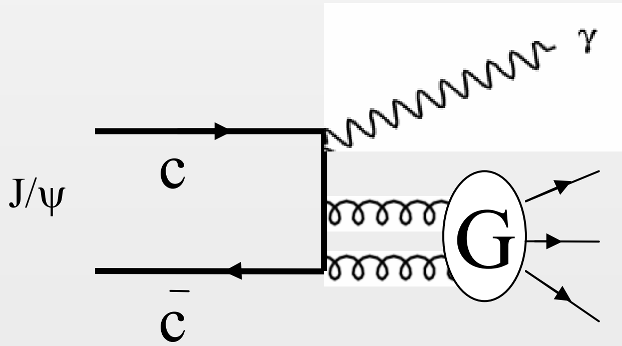
Proton-proton

(WA79,WA102,LHC,RHIC)

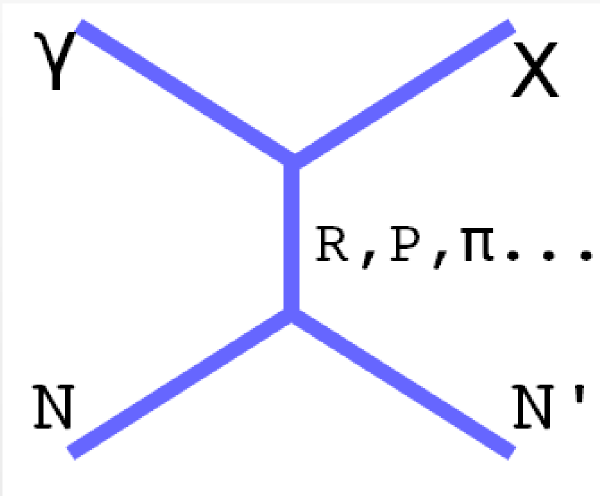


Electron-positron (with strange-antistrange, charm-anticharm or bottom-antibottom formation)

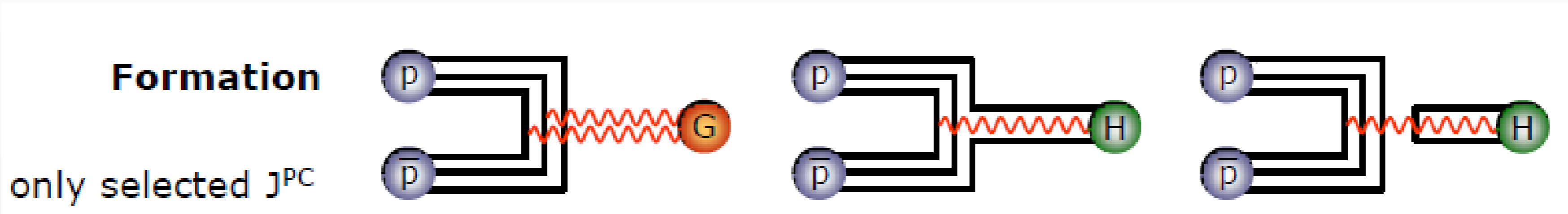
(Belle, Babar, BES, KLOE,…)

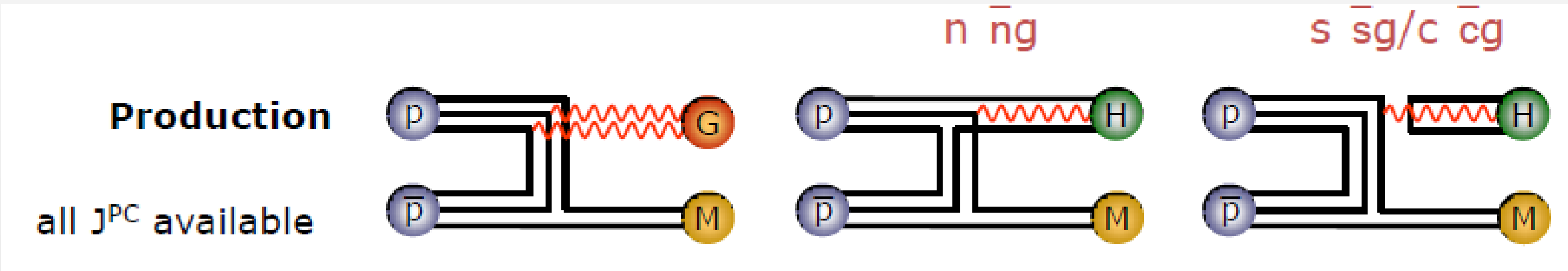


Photoproduction: Compass at CERN (also with pion instead of the photons), Amber
GlueX AND CLAS12 at Jlab
EIC



Proton-antiproton
(Lear,Fermilab, and in the future: **PANDA**)

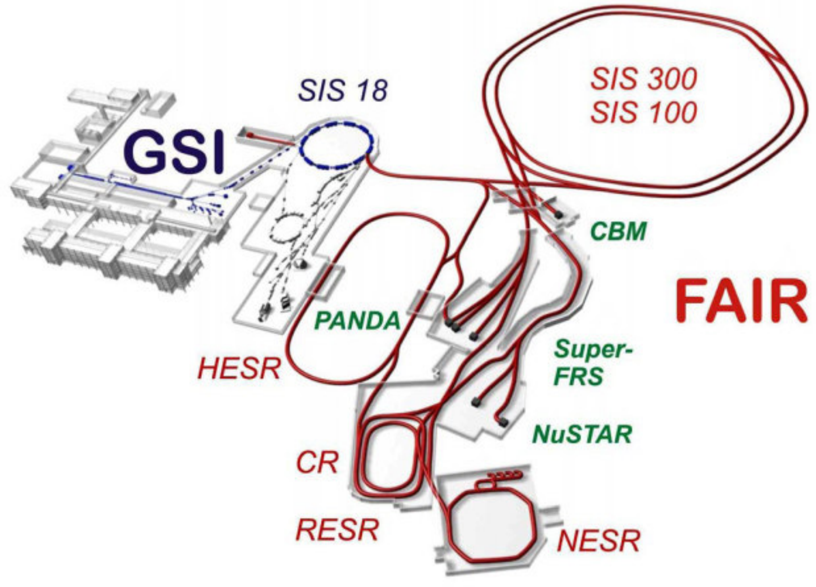


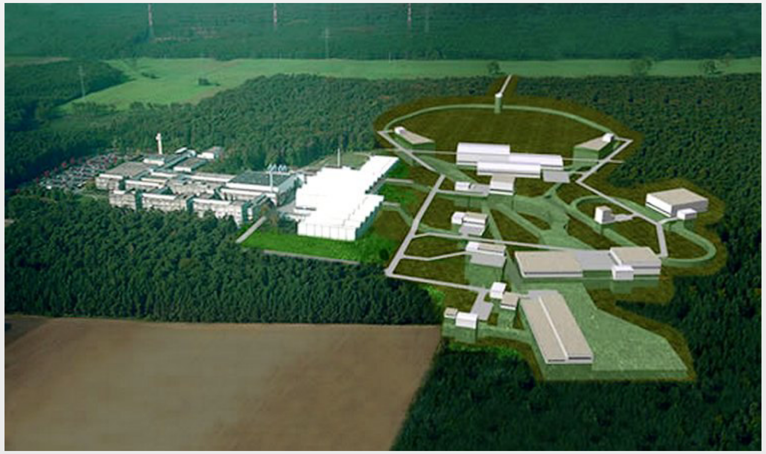


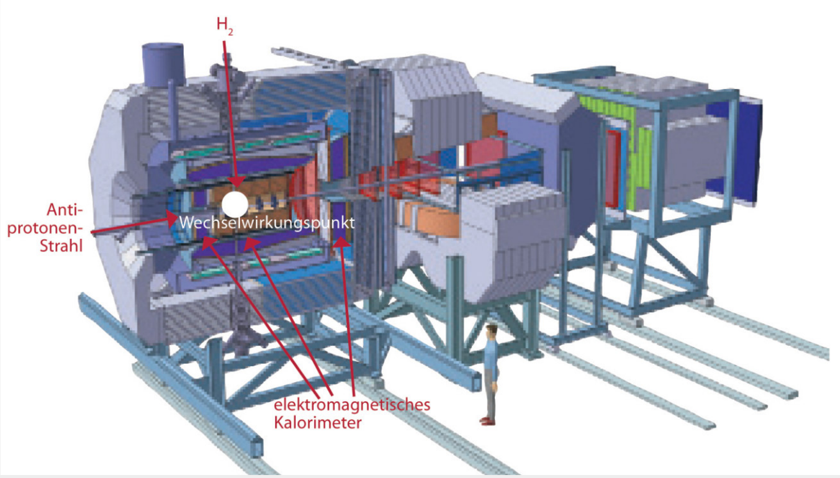
Exoitc quantum numbers:

$$J^{PC} = 0^{+-} \ , 1^{-+} \ , 2^{+-}, \ldots$$

The PANDA experiment







Formation process: the energy range in PANDA

$$\bar{p} + p \rightarrow X$$

…then X decays in something else (pions,kaons,…)

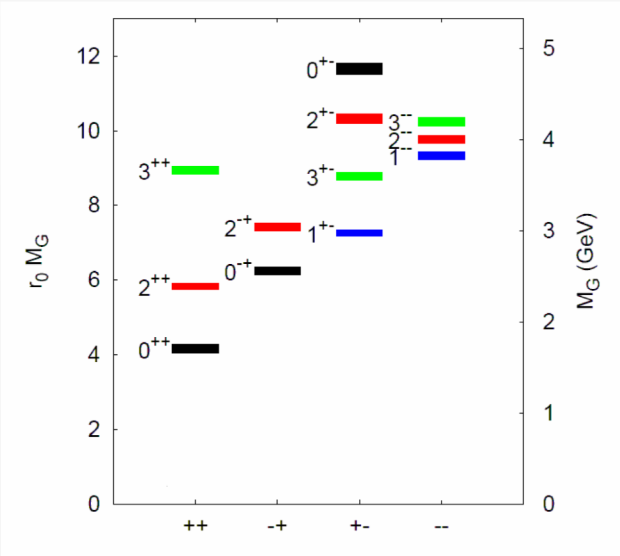
Antiprotons move, protons at rest

$$E_{\bar{p}} = \sqrt{\vec{q}^{\,2} + m_p^2}$$

$$m_X = \sqrt{2 m_p (m_p + E_{\bar{p}})}$$

$$\text{Using } \left|\vec{q}\right| = 1.5 - 10 \text{ GeV}: \ m_X = 2.25 - 4.53 \text{ GeV}$$

The scalar glueball



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 $\Gamma \approx 2\,\mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

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.		

Close-Amsler (1995 and 1996)

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*
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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.

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

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)

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.82 & 0.29 & -0.49 \\ -0.40 & 0.91 & -0.13 \\ 0.41 & 0.30 & \circled{0.85} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ \bar{s}s \\ \text{Glueball: } gg \end{pmatrix}$$

F.G., Guetsche, et al.., Tuebingen (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

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

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.

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

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

Janowski et al (2014)

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

Based on the
extended Linear Sigma Model: **eLSM**
Chiral model with (pseudo)scalar and (axial-)vector mesons.
Dilaton built in.

We did not study the scalar sector alone
but as part of a larger picture.

Unique assignment is found:

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

Details of the model:
D. Parganlija, P. Kovacs, G. Wolf , F. G., D. H. Rischke, **Phys.Rev. D87 (2013) 014011 arXiv:1208.0585**

Lattice result on J/Psi decay into glueball

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

Scalar Glueball in Radiative J/ψ Decay on the Lattice

Long-Cheng Gui,[1,2] Ying Chen,[1,2,*] Gang Li,[3] Chuan Liu,[4] Yu-Bin Liu,[5] Jian-Ping Ma,[6]
Yi-Bo Yang,[1,2] and Jian-Bo Zhang[7]

(CLQCD Collaboration)

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[2]*Theoretical Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
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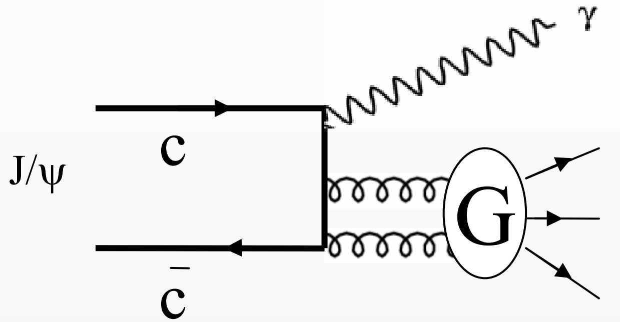
[4]*School of Physics and Center for High Energy Physics, Peking University, Beijing 100871, People's Republic of China*
[5]*School of Physics, Nankai University, Tianjin 300071, People's Republic of China*
[6]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China*
[7]*Department of Physics, Zhejiang University, Zhejiang 310027, People's Republic of China*
(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 f0(1710) are larger than into f0(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

Frederic Brünner, Denis Parganlija, and Anton Rebhan

Institut für Theoretische Physik, Technische Universität Wien,
Wiedner Hauptstrasse 8-10, A-1040 Vienna, Austria

(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-$\bar{\text{D}}$8 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.

See also:
F. Hechenberger et al., Radiative meson and glueball decays in the Witten-Sakai-Sugimoto model,'
Phys. Rev. D 107 (2023) no.11 [arXiv:2302.13379 [hep-ph]].

J. Leutgeb and A. Rebhan,
Witten-Veneziano mechanism and pseudoscalar glueball-meson mixing in holographic QCD,
Phys. Rev. D 101 (2020) no.1, [arXiv:1909.12352 [hep-th]].

Recent BES results

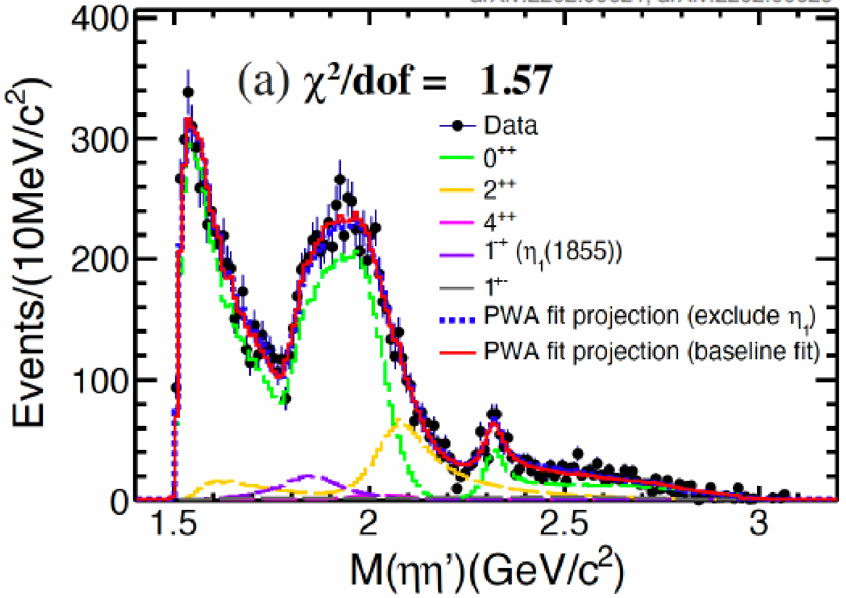
Radiative J/ψ decays

- scalar glueball decays to $\eta\eta'$ expected to be suppressed $\frac{B(G\to\eta\eta')}{B(G\to\pi\pi)} < 0.04$

PRD 92, 121902 (2015)

- significant $f_0(1500)$ contribution, but no $f_0(1710)$ (there is a small $f_0(1810)$ in the fit)
- $\frac{B(f_0(1500)\to\eta\eta')}{B(f_0(1500)\to\pi\pi)} = (8.96^{+2.95}_{-2.87})\times10^{-2}$,
- $\frac{B(f_0(1710)\to\eta\eta')}{B(f_0(1710)\to\pi\pi)} < 1.61\times10^{-3}$ (90% CL)
- $\frac{B(f_0(1810)\to\eta\eta')}{B(f_0(1710)\to\pi\pi)} = (1.39^{+0.62}_{-0.52})\times10^{-2}$

arXiv:2202.00621, arXiv:2202.00623



Nils Hüsken
on behalf of the BESIII collaboration

Workshop: Recent results and perspectives in hadron physics
Orsay, October 17th, 2022

Uniwersytet Jana Kochanowskiego w Kielcach

$J/\psi \to \gamma\eta'\eta$

- PWA of $J/\psi \to \gamma\eta\eta'$ using 10 Billion J/ψ events
- Veto ϕ in $\gamma\eta$ system
- 15000 signal events and $\sim$ 8-13% background events remaining
- All kinematically allowed resonances as listed in the PDG considered
  - $J^{PC} = 0^{++}$, 2^{++} and 4^{++} ($\eta'\eta$ system)

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	3.05 ± 0.07	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	0.07 ± 0.01	7.6σ
	$f_0(2020)$	1935 ± 5	266 ± 9	1992	442	1.67 ± 0.07	11.0σ
	$f_0(2100)$	2109 ± 11	253 ± 21	2086	284	0.33 ± 0.03	5.2σ
	$f_0(2330)$	2327 ± 4	44 ± 5	2314	144	0.07 ± 0.01	8.5σ
	$f_2(1565)$	1542	122	1542	122	0.20 ± 0.03	6.2σ
	$f_2(1810)$	1815	197	1815	197	0.37 ± 0.03	7.0σ
	$f_2(2010)$	2022 ± 6	212 ± 8	2011	202	1.36 ± 0.10	8.8σ
	$f_2(2340)$	2345	322	2345	322	0.25 ± 0.04	6.5σ
	$f_4(2050)$	2018	234	2018	234	0.11 ± 0.02	5.6σ

Fragmented scalar glueball?

Sarantsev, Denisenko, Thoma, Klempt,
PLB 816 (2021) 136227

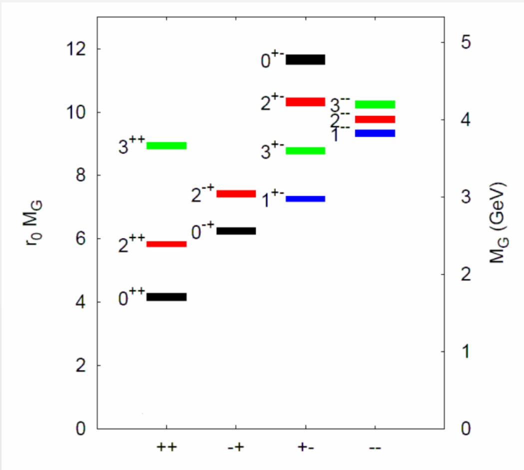
Rather broad glueball (370 MeV) with about 1.86 GeV

The glueball peak extends over over several
scalar glueballs.
See also Klempt, PLB 820 (2021) 136512

Summary: scalar glueball - where do we stay?

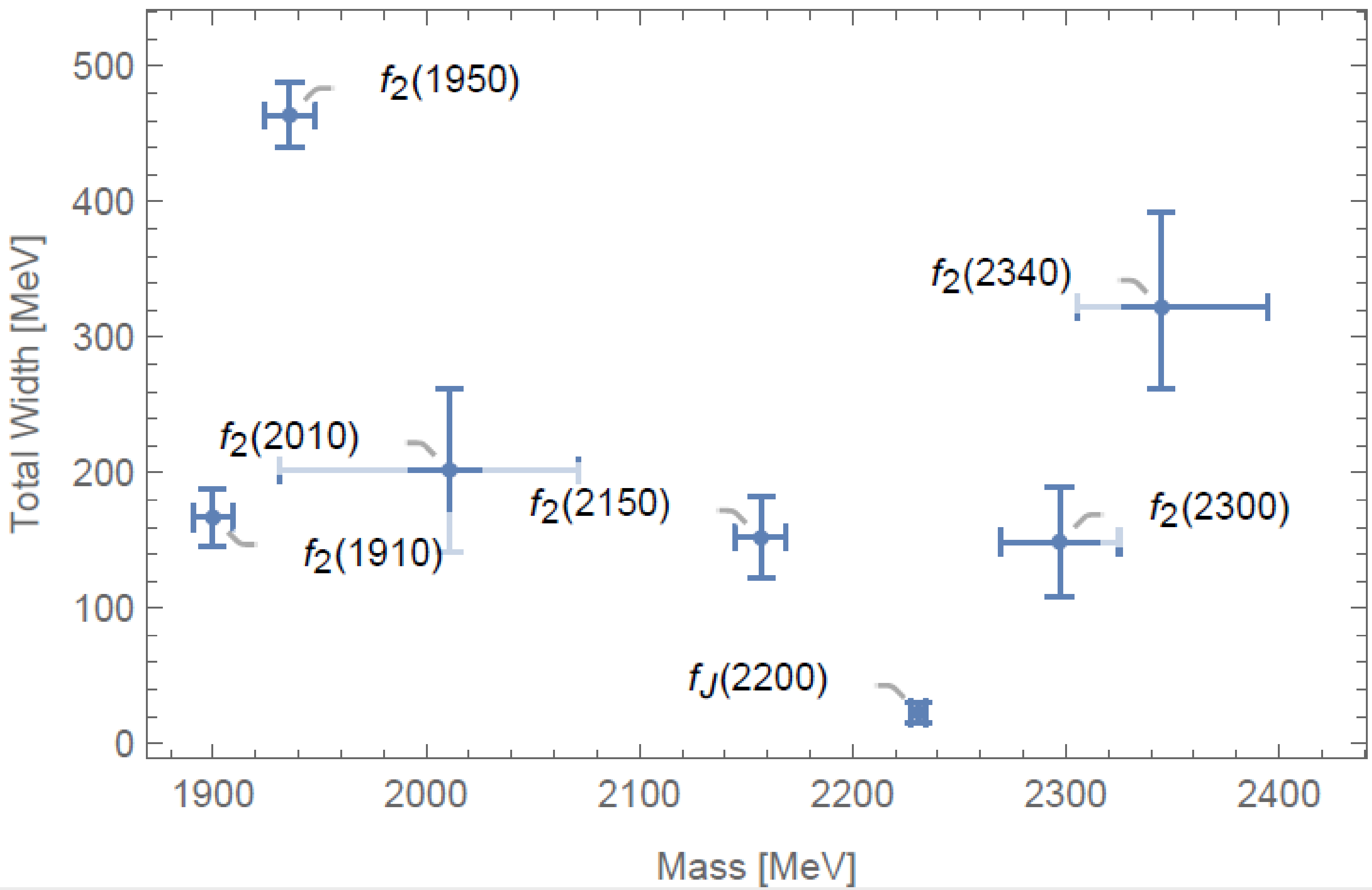
- Various scenarios exist: Lattice's help concerning the width of the scalar glueball is expected.
- Decays into gamma-gamma of $f_0(1500)$ and $f_0(1710)$ (both not seen yet). Clarification of $f_0(1370)\to\gamma\gamma$ and $a_0(1450)\to\gamma\gamma$ (seen but no branching ration yet).
- In general,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

Tensor glueball



Francesco Giacosa

Isoscalar tensor resonances: status



Tensor glueball within the eLSM

PHYSICAL REVIEW D **108,** 014023 (2023)

Is $f_2(1950)$ the tensor glueball?

Arthur Vereijken,[1,*] Shahriyar Jafarzade,[1,†] Milena Piotrowska,[1,‡] and Francesco Giacosa[1,2,§]
[1]*Institute of Physics, Jan Kochanowski University, ul. Uniwersytecka 7, 25-406, Kielce, Poland*

Decay ratios

- Coupling constant is not known so we can only compute decay ratios
- Computation is done for a tensor glueball mass of 2210 MeV (later other masses)
- Vector channels are dominant, in particular $\rho\rho$ and K^*K^*

Decay Ratio	theory
$\frac{G_2(2210)\longrightarrow \bar{K}\,K}{G_2(2210)\longrightarrow \pi\,\pi}$	0.4
$\frac{G_2(2210)\longrightarrow \eta\,\eta}{G_2(2210)\longrightarrow \pi\,\pi}$	0.1
$\frac{G_2(2210)\longrightarrow \eta\,\eta'}{G_2(2210)\longrightarrow \pi\,\pi}$	0.004
$\frac{G_2(2210)\longrightarrow \eta'\,\eta'}{G_2(2210)\longrightarrow \pi\,\pi}$	0.006
$\frac{G_2(2210)\longrightarrow \rho(770)\,\rho(770)}{G_2(2210)\longrightarrow \pi\,\pi}$	55
$\frac{G_2(2210)\longrightarrow \bar{K}^*(892)\,K^*(892)}{G_2(2210)\longrightarrow \pi\,\pi}$	46
$\frac{G_2(2210)\longrightarrow \omega(782)\,\omega(782)}{G_2(2210)\longrightarrow \pi\,\pi}$	18
$\frac{G_2(2210)\longrightarrow \phi(1020)\,\phi(1020)}{G_2(2210)\longrightarrow \pi\,\pi}$	6
$\frac{G_2(2210)\longrightarrow a_1(1260)\,\pi}{G_2(2210)\longrightarrow \pi\,\pi}$	0.24
$\frac{G_2(2210)\longrightarrow K_{1,A}\,K}{G_2(2210)\longrightarrow \pi\,\pi}$	0.08
$\frac{G_2(2210)\longrightarrow f_1(1285)\,\eta}{G_2(2210)\longrightarrow \pi\,\pi}$	0.02
$\frac{G_2(2210)\longrightarrow f_1(1420)\,\eta}{G_2(2210)\longrightarrow \pi\,\pi}$	0.01

$$\mathcal{L} = \lambda G_{\mu\nu}\left(\mathrm{Tr}\left[\{L^\mu, L^\nu\}\right] + \mathrm{Tr}\left[\{R^\mu, R^\nu\}\right]\right)$$

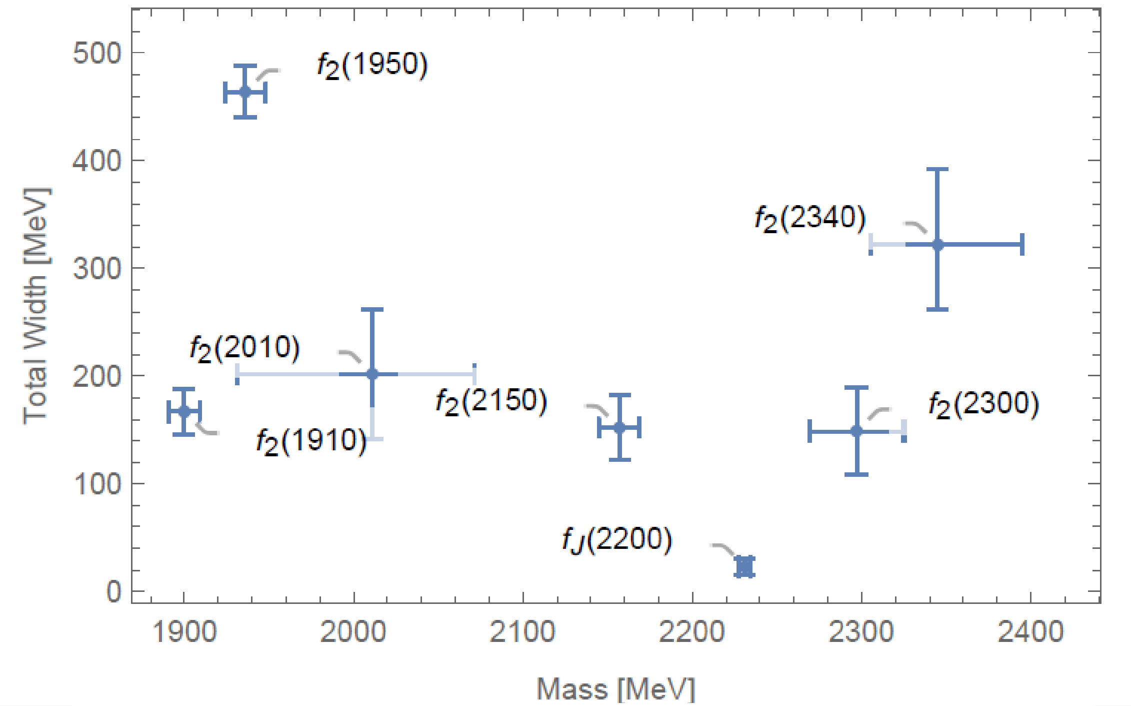
ρ ρ dominant!

Similar result in holographic approach, see e.g.

Brünner,Parganlija Rebhan Phys.Rev.D91,no.10,106002(2015)

Hechenberger, Leutgeb, Rebhan Phys. Rev. D 107 (2023) no.11, 114020

Isoscalar tensor resonances: comparison

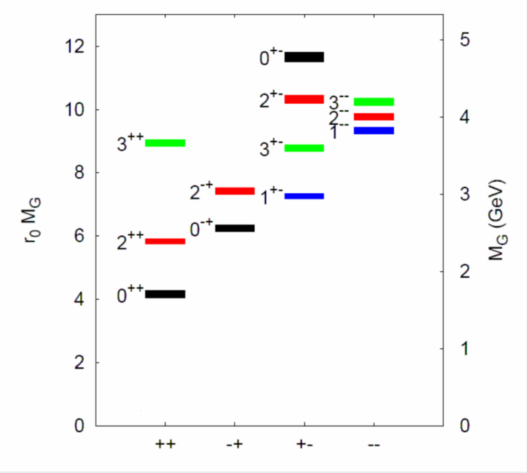


Resonance	Decay Ratio	PDG	Model Prediction
$f_2(1910)$	$\rho\rho/\omega\omega$	2.6 ± 0.4	3.1
$f_2(1910)$	$f_2(1270)\eta/a_2(1320)\pi$	0.09 ± 0.05	0.07
$f_2(1910)$	$\eta\eta/\eta\eta'$	< 0.05	~ 8
$f_2(1910)$	$\omega\omega/\eta\eta'$	2.6 ± 0.6	~ 200
$f_2(1950)$	**$\eta\eta/\pi\pi$**	**0.14 ± 0.05**	**0.081**
$f_2(1950)$	**$K\bar{K}/\pi\pi$**	**~ 0.8**	**0.32**
$f_2(1950)$	**$4\pi/\eta\eta$**	**> 200**	**> 700**
$f_2(2150)$	$f_2(1270)\eta/a_2(1320)\pi$	0.79 ± 0.11	0.1
$f_2(2150)$	$K\bar{K}/\eta\eta$	1.28 ± 0.23	~ 4
$f_2(2150)$	$\pi\pi/\eta\eta$	< 0.33	~ 10

Decay ratios for the decay channels with available data.

Different view:
Klempt, Sarantsev, Denisenko,Nikonov
PLB 830 (2022) 137171
Similar ‘fragmeted’ glueball scenario in the tensor sector

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

A Masoni[1,2], C Cicalò[1,2] and G L Usai[1,2]

[1] INFN, Sezione di Cagliari, Cagliari, Italy
[2] Dipartimento di Fisica, Università di Cagliari, Cagliari, Italy

Received 20 January 2006
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

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

$$\bar{s}s$$

$$\text{Glueball: } gg$$

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!

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

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

η(1295) MASS

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

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

A REVIEW GOES HERE – Check our WWW List of Reviews

η(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.

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

See also the $\eta(1405)$.

η(1475) MASS

$K\overline{K}\pi$ 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.			

Pseudoscalar glueball

Issues with both approaches (one should at least try a 5-mixing) and with the very existence of two separated pseudoscalar resonances between 1.4-1.5 GeV.

Severe conflict with Lattice expectations!
Pseudoscalar glueball much heavier.

Pseudoscalar glueball

PHYSICAL REVIEW LETTERS **129**, 042001 (2022)

Observation of a State $X(2600)$ in the $\pi^+\pi^-\eta'$ System in the Process $J/\psi \to \gamma\pi^+\pi^-\eta'$

$\pi^+\pi^-$ invariant mass spectrum. A simultaneous fit on the $\pi^+\pi^-\eta'$ and $\pi^+\pi^-$ invariant mass spectra with the two η' decay modes indicates that the mass and width of the $X(2600)$ state are $2618.3 \pm 2.0^{+16.3}_{-1.4}$ MeV$/c^2$ and $195 \pm 5^{+26}_{-17}$ MeV, where the first uncertainties are statistical, and the second systematic.

PHYSICAL REVIEW D **87**, 054036 (2013)

Decay of the pseudoscalar glueball into scalar and pseudoscalar mesons

Walaa I. Eshraim,[1] Stanislaus Janowski,[1] Francesco Giacosa,[1] and Dirk H. Rischke[1,2]

Quantity	$M_{\tilde{G}} = 2.6$ GeV
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.049
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.019
$\Gamma_{\tilde{G}\to \eta\eta\eta}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.016
$\Gamma_{\tilde{G}\to \eta\eta\eta'}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.0017
$\Gamma_{\tilde{G}\to \eta\eta'\eta'}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.00013
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.47
$\Gamma_{\tilde{G}\to \eta\pi\pi}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.16
$\Gamma_{\tilde{G}\to \eta'\pi\pi}/\Gamma^{\text{tot}}_{\tilde{G}}$	0.095

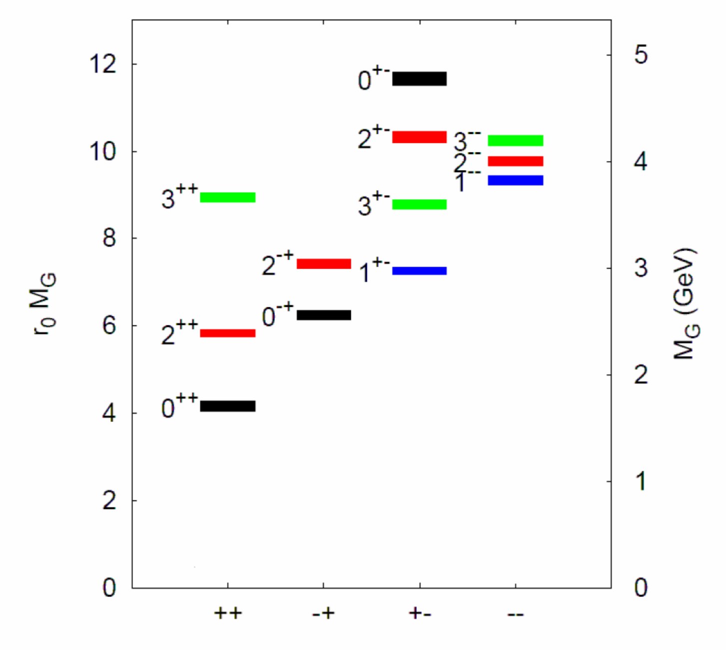
Chiral-anomaly driven decays!

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

Other glueballs: vector and pseudotensor

vector, pseudotensor,... glueballs.

Oddballs.



Vector glueball

Decays of the vector glueball
F.G, J. Sammet, S. Janowski
Phys.Rev.D 95 (2017) 11, 114004
arXiv:1607.03640 [hep-ph]

We predict that the vector glueball decays mostly into:

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

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

The lattice mass of 3.8 GeV has been used;
Warning: only ratios possible!
Example: decay into pseudovector-pseudoscalar mesons:

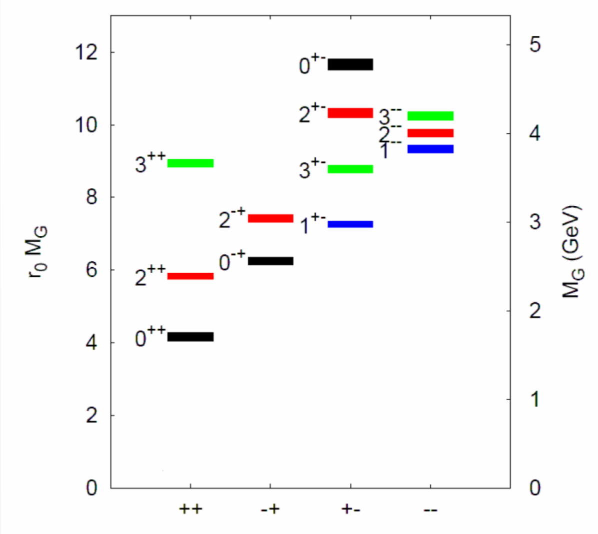
Quantity	Value
$\frac{\mathcal{O}\to\eta h_1(1170)}{\mathcal{O}\to b_1\pi}$	0.181
$\frac{\mathcal{O}\to\eta h_1(1380)}{\mathcal{O}\to b_1\pi}$	0.111
$\frac{\mathcal{O}\to\eta' h_1(1170)}{\mathcal{O}\to b_1\pi}$	0.174
$\frac{\mathcal{O}\to\eta' h_1(1380)}{\mathcal{O}\to b_1\pi}$	0.111
$\frac{\mathcal{O}\to K K_1(1270)}{\mathcal{O}\to b_1\pi}$	0.771
$\frac{\mathcal{O}\to K K_1(1400)}{\mathcal{O}\to b_1\pi}$	0.298
$\frac{\mathcal{O}\to K_0^*(1430) K^*(1680)}{\mathcal{O}\to b_1\pi}$	0.224
$\frac{\mathcal{O}\to a_0(1450)\rho(1700)}{\mathcal{O}\to b_1\pi}$	0.163
$\frac{\mathcal{O}\to f_0(1370)\omega(1650)}{\mathcal{O}\to b_1\pi}$	0.061

Pseudotensor glueball

From arxiv: 1608.8777 [hep-ph],
Phenomenology of pseudotensor mesons and the pseudotensor glueball
by A. Koenigstein and F.G.
Eur.Phys.J.A 52 (2016) 12, 356

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

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



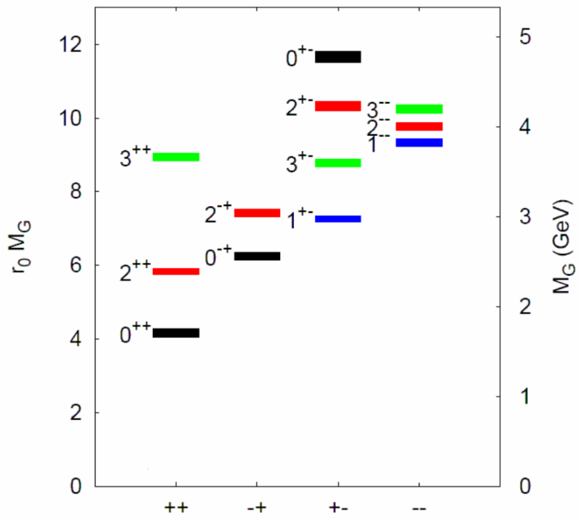
Warning: only ratios possible!
Still hypothetical states. Need of experiment (PANDA in first place).

Glueball with J = 3^--

S. Jafarzade, A. Koenigstein and F. Giacosa,
Phys. Rev. D 103 (2021) no.9, 096027
[arXiv:2101.03195 [hep-ph]].

TABLE XIV. Predictions for the branching ratios of glueball $G_3(4200) \to V_1 + P$.

Branching ratio	Theory
$\frac{\Gamma_{G_3(4200)\to \bar{K}^*(892)K}}{\Gamma_{G_3(4200)\to\rho(770)\pi}}$	1.11
$\frac{\Gamma_{G_3(4200)\to \omega(782)\eta}}{\Gamma_{G_3(4200)\to\rho(770)\pi}}$	0.17
$\frac{\Gamma_{G_3(4200)\to \omega(782)\eta'(958)}}{\Gamma_{G_3(4200)\to\rho(770)\pi}}$	0.089
$\frac{\Gamma_{G_3(4200)\to \phi(1020)\eta}}{\Gamma_{G_3(4200)\to\rho(770)\pi}}$	0.098
$\frac{\Gamma_{G_3(4200)\to \phi(1020)\eta'(958)}}{\Gamma_{G_3(4200)\to\rho(770)\pi}}$	0.11



Warning: only ratios possible!

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.
- Are (at least some) glueballs narrow enough? This is a decisive information. Large-Nc tells so. Help from Lattice would be very welcome!
- Ongoing and future experiments:

  BESIII

  COMPASS&AMBER@CERN - LHCb@CERN …

  CLAS12@JLAB, GLUEX@JLAB

  BELLE2

  EIC

  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

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 $\times$ $(m_\sigma/1\ \mathrm{GeV})^5$ and $\Gamma(\sigma \to \gamma\gamma) \simeq 90$ eV $\times$ $(m_\sigma/1\ \mathrm{GeV})^5$, 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)

Meson phenomenology - literature

1) N_f = 2 (with frozen glueball): Parganlija FG DHR **PRD82 (2010) 054024**

2) Nf = 2 (with glueball): Janowski Parganlija FG DHR **PRD84 (2011) 054007**

3) N_f = 3 (with frozen glueball): Parganlija Kovacs Wolf FG DHR **PRD87 (2013) 014011**

4) Nf = 3 (with glueball): Janowski FG DHR **PRD90 (2014) 114005**

5) Pseudoscalar glueball: Eshraim Janowski FG DHR **PRD87 (2013) 054036** Eshraim Schramm **PRD95 (2017) 014028**

6) Nf =4: Eshraim FG DHR **EPJ.A51 (2015) no.9,** Eshraim Fischer **112 EPJ A54 (2018) 139**

7) Vector glueball: Sammet Janowski FG **PRD95 (2017) no.11, 114004**

8) Excited (pseudo)scalar mesons: Parganlija FG **Eur.Phys.J. C77 (2017) 450**

9) Consistency with ChPT: Divotgey Kovacs FG DHR **Eur.Phys.J. A54 (2018) 5**

10) f_0(500) as a four-quark in the vacuum: Lakaschus Mauldin FG DHR **arxiv: 1807.03735**

11) Hybrid mesons Eshraim et al., **EPJ+135 (2020) no.12, 945 arXiv:2001.06106**

12) Tensor mesons and tensor glueballs Vereijken et al, **PRD108 (2023) no.1, 014023 arXiv:2304.05225**
SJafarzade et al. **PRD106 (2022) no.3, 036008 [arXiv:2203.16585**

Baryon phenomenology - literature

1) Baryonic eLSM for $N_f = 2$: Gallas FG DHR **PRD82 (2010) 014004,** Gallas FG **IJMP.A29 (2014) 1450098**

2) Nucleon-nucleon scattering: Teilab Deinet FG DHR **Phys.Rev. C94 (2016) 044001**

3) $N_f = 3$ (with four multiplets): Olbrich Zetenyi FG DHR **Phys.Rev. D93 (2016) 034021**

4) Nf = 3 and axial-anomaly for baryons: Olbrich Zetenyi FG DHR **Phys.Rev. D97 (2018) no.1, 014007**

5) Nuclear matter: Gallas Pagliara FG **Nucl.Phys. A872 (2011) 13-24**

6) Inhomogenous condensation in nuclear matter: Heinz FG DHR **Nucl.Phys. A933 (2015) 34-42**

7) $N_f = 3$ Olbrich et al**, PRD93 (2016) no.3, 034021 ;PRD97 (2018) no.1, 014007**

Nonzero temperature and density (and critical endpoint) - literature

Kovacs et al., **PRD93 (2016) no.11, 114014 ; PRD106 (2022) no.11, 116016**

New development: glueball-glueball scattering

Eur. Phys. J. C (2022) 82:487
https://doi.org/10.1140/epjc/s10052-022-10403-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

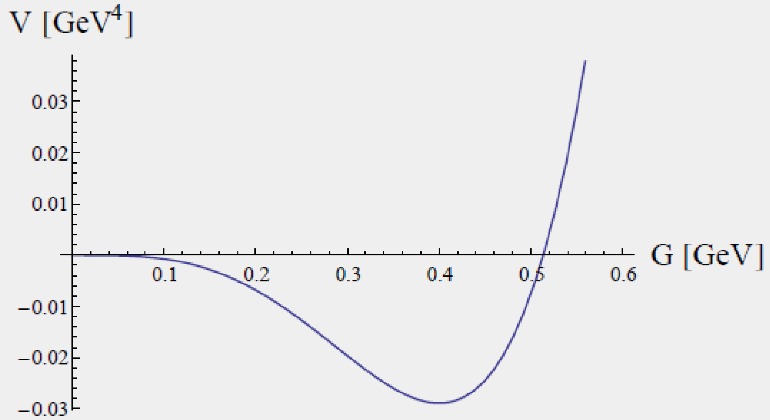
Glueball–glueball scattering and the glueballonium

Francesco Giacosa[1,2], Alessandro Pilloni[3,4], Enrico Trotti[1,a]

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

with

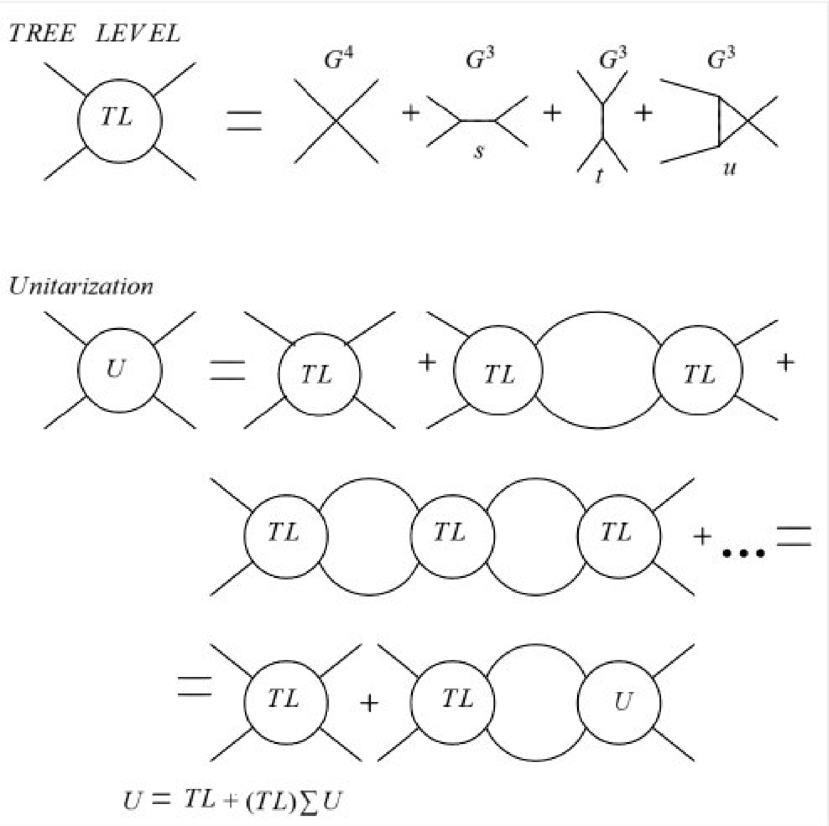
$$V(G) = \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left(G^4 \ln\left|\frac{G}{\Lambda_G}\right| - \frac{G^4}{4}\right).$$

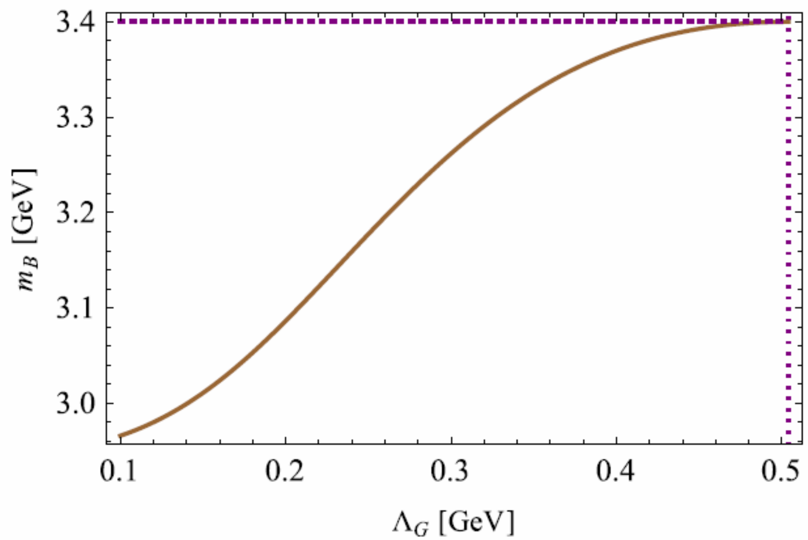


A. A. Migdal and M. A. Shifman, "Dilaton Effective Lagrangian in Gluodynamics," Phys. Lett.B114, 445 (1982)

Glueballonium mass

$$V(G) = V(\Lambda_G) + \frac{1}{2}m_G^2 G^2 + \frac{1}{3!}\left(5\frac{m_G^2}{\Lambda_G}\right)G^3 + \frac{1}{4!}\left(11\frac{m_G^2}{\Lambda_G^2}\right)G^4 + \frac{1}{5!}\left(6\frac{m_G^2}{\Lambda_G^3}\right)G^5 + \ldots$$





Can one see that? In YM-lattice, probably yes.
In experiment? Hard, but…
Extension: **Higgsonium**!
Eur.Phys.J.C 83 (2023) 8, 713 2212.01272

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

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

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

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

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

Tensor glueball

Historical candidate was: fJ(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].

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

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

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

The pseudoscalar glueball: predictions from the eLSM

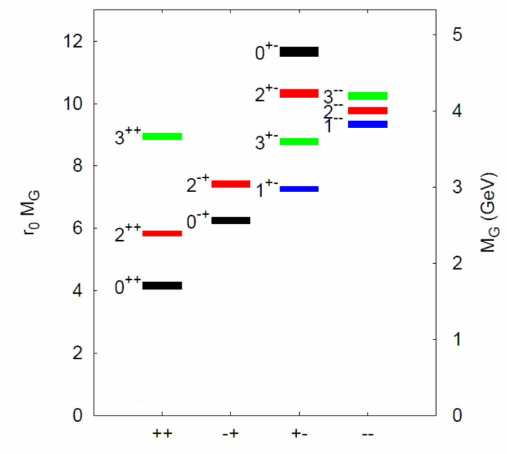
$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = ic_{\tilde{G}\Phi}\tilde{G}\left(\det\Phi - \det\Phi^{\dagger}\right)$$

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.

Quantity	Value
$\Gamma_{\tilde{G}\to KK_S}/\Gamma^{tot}_{\tilde{G}}$	0.059
$\Gamma_{\tilde{G}\to a_0\pi}/\Gamma^{tot}_{\tilde{G}}$	0.083
$\Gamma_{\tilde{G}\to\eta\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.028
$\Gamma_{\tilde{G}\to\eta\sigma_S}/\Gamma^{tot}_{\tilde{G}}$	0.012
$\Gamma_{\tilde{G}\to\eta'\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.019



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** .

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