Glueball: to be or not to be?

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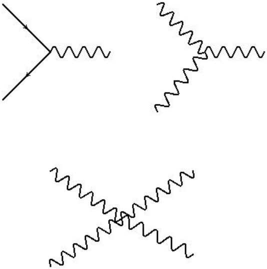
INTRODUCTION

Exotics

QCD = gauge theory with the color group $\mathcal{SU}(3)$
H. Fritzsch, M. Gell-Mann and H. Leutwyler, *Phys. Lett.* B47 (1973) 365.

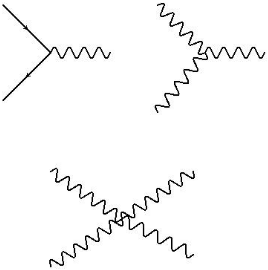


$$
\begin{aligned}
\mathcal{L}_{QCD} &= -\frac{1}{4}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} + \sum \bar{q}(\gamma^{\mu} D_{\mu} - m)q \\
G_{\mu\nu} &= \partial_{\mu} A_{\mu} - \partial_{\nu} A_{\mu} - ig[A_{\mu}, A_{\nu}]
\end{aligned}
$$

Quark = fundamental representation **3**
Gluon = Adjoint representation **8**
Physical state = color singlet **1**

Triality

Mesons:	$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$	$0^{-+}, 1^{--}, \ldots$
Baryons:	$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10}$	$1/2^{\pm}, (3/2)^{\pm}, \ldots$



H. Fritzsch and P. Minkowski, *Nuov. Cim.* **30**A (1975) 393, ventured that a consequence of QCD, would be to abandon Triality

Glueballs:	$\mathbf{8}\otimes\mathbf{8}=(\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{27})\oplus(\mathbf{8}\oplus\mathbf{10}\oplus\overline{\mathbf{10}})$	$0^{\pm +}, 2^{\pm +}, \ldots$
	$\mathbf{8}\otimes\cdots\otimes\mathbf{8}=\mathbf{1}\oplus\mathbf{8}\oplus\ldots$	$0^{\pm -}, 1^{\pm\pm}, 2^{\pm -}, \ldots$
Hybrid Mesons:	$\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\mathbf{8}=\mathbf{1}\oplus\mathbf{8}\oplus\ldots$	$1^{-+}, 0^{--}, \ldots$

Lightest glueball: 0^{++}
Lightest hybrid meson: 1^{-+}

Why Glueballs?

A particularly good test of our understanding of the nonperturbative aspects of QCD is to study particles where the gauge field plays a more important dynamical role than in the standard hadrons. Glueballs, bound states of gluons, represent such a scenario.

Glueballs have not been an easy subject to study due to the lack of phenomenological support and therefore much debate has been associated with their properties. The main achievement of their study has been to understand of the deep relation between the properties of the glueball states and the structure of the QCD vacuum.

It is important to stress, that if they were to exist they would be a beautiful and unique consequence of QCD.

Mathieu, Kochelev and Vento, "The Physics of Glueballs", Int. J. Mod. Phys. E**18** (2009) 1

PURE YANG MILLS

Glueballs

Only glueballs !

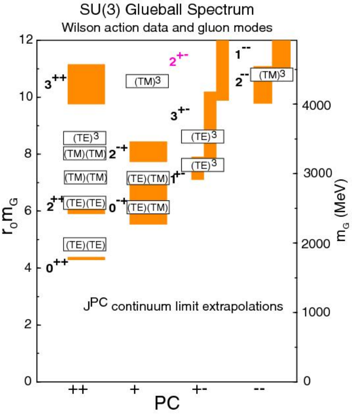
R. L. Jaffe and K. Johnson, Phys. Lett. B 60 (1976) 201

J. Kuti, Nucl. Phys. Proc. Suppl. **73** (1999) 72

Free Particles Confined in a Cavity

Gluonic Modes in a Cavity

TE mode	$J^P = 1^+$	$x_{\rm TE} = 2.74,$
TE mode	$J^P = 2^-$	$x_{\rm TE} = 3.96,$
TM mode	$J^P = 1^-$	$x_{\rm TM} = 4.49.$



Mass Spectrum

$$E = \frac{4\pi B R^3}{3} + \sum_i n_i \frac{x_i}{R} - \frac{\alpha}{4R}\lambda_1^a \lambda_2^a \vec{S}_1 \cdot \vec{S}_2$$

$$M^2 = E^2 - \sum_i n_i \left(\frac{x_i}{R}\right)^2$$

$$\alpha = 0.5 \qquad B = (280\ \text{MeV})^4$$

Effective gluon mass 740 ± 100 MeV
Donoghue Phys. Rev. D29 (1984) 2559

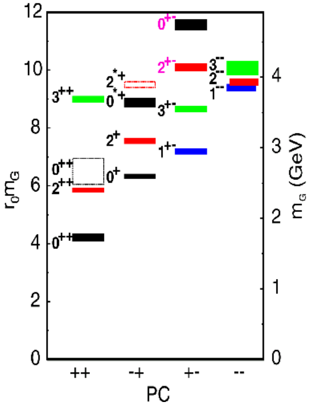
Quenched Results

Investigation of the glueball spectrum (pure gluonic operators) on a lattice by Morningstar and Peardon, Phys. Rev. D**60** (1999) 034509

Identification of 15 glueballs below 4 GeV

$$
\begin{aligned}
M(0^{++}) &= 1.730 \pm 0.130 \text{ GeV} \\
M(0^{-+}) &= 2.590 \pm 0.170 \text{ GeV} \\
M(2^{++}) &= 2.400 \pm 0.145 \text{ GeV}
\end{aligned}
$$

Quenched approximation (gluodynamics) $\rightarrow$ mixing with quarks is neglected



Unquenched Results

Lattice studies with $n_f = 2$ exist. The lightest scalar would be sensitive to the inclusion of sea quarks and mixing but no definitive conclusion.

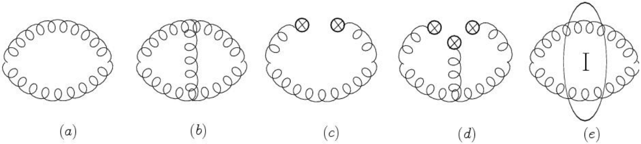
Shifman, Vainshtein and Zakharov, Nucl. Phys. B **147** (1979) 385

Gluonic currents: $J_S(x) = \alpha_S \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu}$ $\quad J_P(x) = \alpha_S \mathrm{Tr}\, G_{\mu\nu} \widetilde{G}^{\mu\nu}$

$$\Pi(Q^2) = i \int d^4x\; e^{iq\cdot x} \langle 0 | T J_G(x) J_G(0) | 0 \rangle = \frac{1}{\pi} \int_0^\infty \frac{\mathrm{Im}\Pi(s)}{s+Q^2} ds$$

Theoretical side (OPE):

$$J_G(x) J_G(0) = C_{(a)+(b)+(e)} \mathbf{1} + C_{(c)} G^a_{\mu\nu} G^{\mu\nu}_a + C_{(d)} f_{abc} G^a_{\alpha\beta} G^b_{\beta\gamma} G^b_{\gamma\alpha} + \cdots$$



Confinement parameterized with condensates $\langle 0 | \alpha_s G^a_{\mu\nu} G^{\mu\nu}_a | 0 \rangle, \ldots$

Phenomenological side:

$$\mathrm{Im}\Pi(s) = \sum_i \pi f^2_{G_i} m^4_{G_i} \delta(s - m^2_{G_i}) + \pi \theta(s - s_0) \mathrm{Im}\Pi(s)^{\mathrm{Cont}}$$

Low Energy Theorems

Let us study in some detail the scalar glueball groundstate, $J^{PC} = 0^{++}$, which would be an ideal state to find since it has many fundamental connotations.

In gluodynamics, as we have seen, the situation that arises from lattice calculations is clear and the masses of the scalar glueballs are large $m > 1$ GeV.

However, when sea quarks are considered no firm conclusion about the scalar spectrum can be drawn.

The theoretical calculations based on QCD SRs and/or low energy theorems lead to contradictory results. Its properties, *i.e.*, mass, decay channels and widths still differ among the various approaches.

- Low mass 500- 700 MeV ; narrow width < 100 MeV; Dominguez and Paver, *Z. Phys. C* **31** (1986) 591; Bordes , Peñarrocha and Giménez *Phys. Lett. B* **223** (1989) 251; Kisslinger and Johnson, *Phys. Lett. B* **523** (2001) 127.
- Medium mass 700-1000 MeV ; wide width 200 MeV $< \Gamma <$ 800 MeV; Narison, Nucl. Phys. Proc. Suppl. **186** (2009) 306.
- Large mass 1250 +/- 200 MeV ; wide width 300 MeV; Forkel Phys. Rev. D**71** (2005) 054008 However, he has some strength at lower masses which he is not able to ascribe to a resonance in the fits.

Constituent Models

Gluonium models for the low-lying glueballs with Spinless Salpeter Hamiltonian

$$
\begin{aligned}
H_{gg}|\Psi\rangle &= M_G|\Psi\rangle \\
H_{gg} &= 2\sqrt{\boldsymbol{p}^2 + m^2} + V(r) \\
V(r) &= V_{conf}(r) + V_{pQCD}(r) + V_{instantons}(r) + \dots
\end{aligned}
$$

Diagonalization of H_{gg} $\rightarrow$ Construction of the basis.

Quenched calculation: no quark loop effects
The idea to reproduce lattice results and more..

There have been calculations for two and three gluon states. Here we only consider two gluon states
Mathieu , PoS FACESQCD (2010) 002.

Two different schemes

Gluons spin-1 particles with usual rules of spin coupling

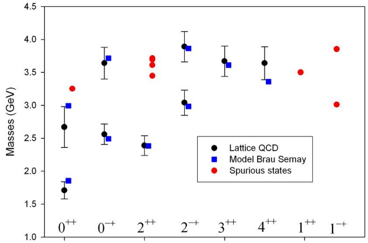
$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S} \text{ with } \quad \boldsymbol{S} = 0, 1, 2$$

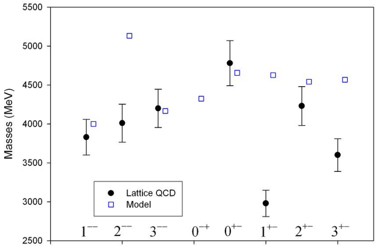
Gluon transverse $p \cdot A = 0$ $\rightarrow$ 2 degrees of freedom helicity-1 particles

$$\boldsymbol{J} \neq \boldsymbol{L} + \boldsymbol{S}$$

Jacob and Wick, Annals Phys. **7** (1959) 404

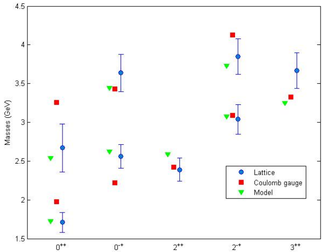
Constituent Models





Spin-1 gluons Models for $C = +$
Agreement with lattice but unwanted vector states

Helicity-1 gluons Models for $C = +$
Agreement with lattice

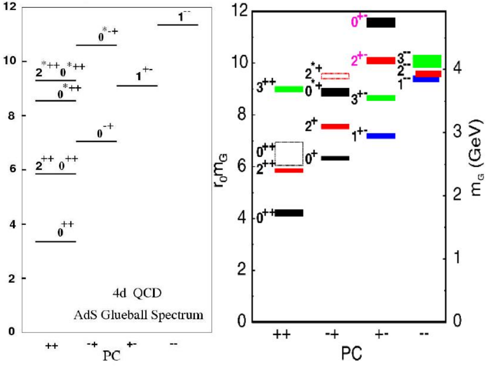


AdS/CFT correspondance:
Correspondance between conformal theories and string theories in AdS spacetime
QCD not conformal → breaking conformal invariance somehow

Introduction of a black hole in AdS to break conformal invariance

Parameter adjusted on 2^{++}

Same hierarchy but missing states (spin 3,...)



R. C. Brower *et al.*, Nucl. Phys. B**587** (2000) 249

EFFECTIVE QCD

Low Energy Theorems and OZID

Analysis, modelled by $\frac{1}{N_c}$ physics, leads to a scenario of broken OZID which produces an intermediate mass glueball and a nearby σ meson.

The glueball is narrow since only its $\sigma\prime$ state component is allowed to decay and the small mixing angle inhibits decays.

It represents a beautiful example of approximate OZID in the decay.
Vento *Phys. Rev. D* **73** (2006) 054006.

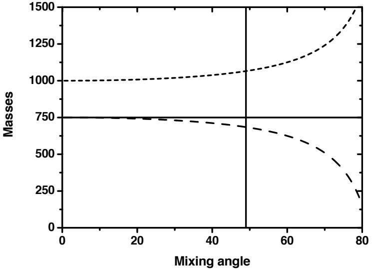


FIGURE: The limiting values for the masses of the physical $\tilde{g}$ (solid–dashed lines) and $\tilde{\sigma}$ (solid–short-dashed lines) are shown as a function of the mixing angle for the range The degenerate initial mass has been taken at $m = 750$ MeV. The vertical line defines the approximate limit of the validity of the $\frac{1}{N_c}$ expansion.

Low Energy Theorems and OZID

	$f_0(600)$	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
mass (MeV)	$400 - 1200$	980 ± 10	$120 - 1500$	1507 ± 5	1714 ± 5
width (MeV)	$600 - 1000$	$40 - 100$	$200 - 500$	109 ± 7	140 ± 10
Decay modes	$\pi\pi$ dominant $\gamma\gamma$ seen	$\pi\pi$ dominant $K\bar{K}$ seen $\gamma\gamma$ seen	$\pi\pi$ seen 4π ... $\rho\rho$ dominant ... other 4π seen $\eta\eta$ seen $K\bar{K}$ seen $\gamma\gamma$ seen	$\pi\pi$ 35% 4π 50% $\eta\eta$ 5% $\eta\eta'$ 2% $K\bar{K}$ 9% $\gamma\gamma$ not seen	$\pi\pi$ seen $K\bar{K}$ seen $\eta\eta$ seen
Spectrum	g and σ	meson	Forkel's gball	AmslerClose	Chanowitz

Table: Interpretations of the scalar Particle Data Group spectrum

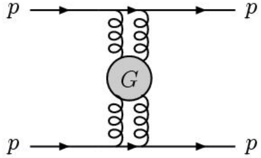
EXPERIMENTAL STATUS

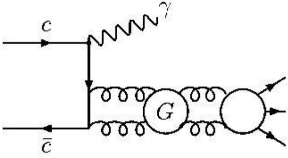
Physical States

Crede and Meyer, The Experimental Status of Glueballs,
Prog. Part. Nucl. Phys. **63**, 74 (2009)

Production:

Pomeron is gluon rich — gluon rich processes (OZI forbidden,...)





Mixing between glueball 0^{++} and light mesons

Scalar Candidates:	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$\ldots$	$f_0(600)$ $f_0(980)$
Pseudoscalar Candidates:	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$\ldots$	

Three light quarks $\rightarrow 3 \times 3 = 9$ (pseudo)scalar mesons
A 10th light meson would be the realization of the glueball

CHIRAL SUPPRESSION

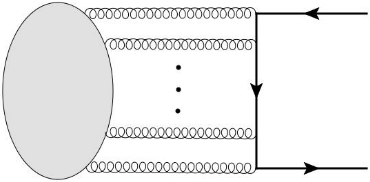
Chanowitz, Phys. Rev. Lett. **95** (1999) 172001

$$A\left(0^{++} \longrightarrow \bar{q}q\right) \propto m_q$$

Decay to $K\bar{K}$ favoured over $\pi\pi$

$$R = \frac{A\left(0^{++} \longrightarrow \bar{K}K\right)}{A\left(0^{++} \longrightarrow \pi\pi\right)} > 1$$

Centerline $f_0(1710)$ good glueball candidate



Results: Crystal Barrel and OBELIX ($p\bar{p}$), WA102 (pp), BES (J/ψ)

Future: Alice (pp) and COMPASS ($\pi^- p$)?

Name	Masse (MeV)	Width (MeV)	Decays	Production
$f_0(1370)$	$1200 - 1500$	$200 - 500$	$\pi\pi, K\bar{K}, \eta\eta$	$p\bar{p} \to PPP$, $pp \to pp(PP)$ weak signal in $J/\psi \to \gamma(PP)$
$f_0(1500)$	1505 ± 6	109 ± 7	$\pi\pi, K\bar{K}, \eta\eta$	$J/\psi \to \gamma(PP)$, $pp \to pp(PP)$ $p\bar{p} \to PPP$
$f_0(1710)$	1720 ± 6	135 ± 8	$\pi\pi, K\bar{K}, \eta\eta$	$J/\psi \to \gamma(PP)$, $pp \to pp(PP)$ not seen in $p\bar{p}$

Belle and BaBar puzzle : $f_0(1500)$ strong coupling to $K\bar{K}$ and weak to $\pi\pi$

Scalar Glueball from Theory

Pure states: $|gg\rangle$, $|n\bar{n}\rangle$, $|s\bar{s}\rangle$

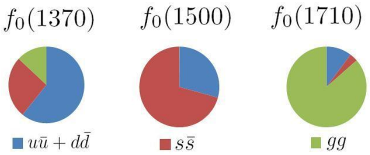
$$|G\rangle = |gg\rangle + \frac{\langle n\bar{n}|gg\rangle}{M_{gg} - M_{n\bar{n}}}\,|n\bar{n}\rangle + \frac{\langle s\bar{s}|gg\rangle}{M_{gg} - M_{s\bar{s}}}\,|s\bar{s}\rangle$$

Analysis of

Production: $J/\psi \to \gamma f_0, \omega f_0, \phi f_0$ Decay: $f_0 \to \pi\pi, K\bar{K}, \eta\eta$

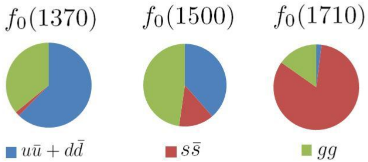
Two mixing schemes

Cheng *et al*, PRD**74** (2006) 094005



$$M_{n\bar{n}} < M_{s\bar{s}} < M_{gg}$$

Close and Kirk, PLB**483** (2000) 345



$$M_{n\bar{n}} < M_{gg} < M_{s\bar{s}}$$

	$f_0(600)$	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
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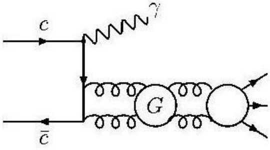
Spectrum	g and σ	meson	Forkel's gball	AmslerClose	Chanowitz

Table: My interpretations of the scalar Particle Data Group spectrum

Pseudoscalar Glueball

Mark III : $J/\psi \to \gamma PPP$
observation of two pseudoscalar states

$\gamma\gamma$ fusion : $\eta(1475)$ seen but not $\eta(1405)$



Results from Crystal Barrel ($p\bar{p}$), OBELIX ($p\bar{p}$)

Name	Masse (MeV)	Width (MeV)	Decays	Production
$\eta(1295)$	1294 ± 4	55 ± 5	$\gamma\gamma, K\bar{K}\pi, a_0\pi$	not seen in $p\bar{p}$
$\eta(1405)$	1409.8 ± 2.5	51.1 ± 3.4	$K\bar{K}\pi, a_0\pi, \eta\pi\pi$	not seen in $\gamma\gamma$
$\eta(1475)$	1476 ± 4	87 ± 9	$\gamma\gamma, K\bar{K}^*, K\bar{K}\pi, a_0\pi$	

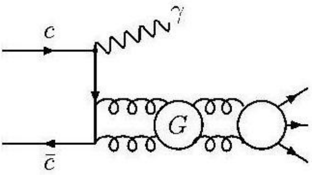
$\eta(1205)$ and $\eta(1475)$ radial excitations of η and η'.
$\eta(1405)$ glueball candidate.
Identification as a glueball requires a theoretical framework for the $\eta(1405)$

Quenched mass: $M_{0-+} = 2.6$ GeV for the correlator $J_P(x) = \mathrm{Tr}\, G_{\mu\nu}\widetilde{G}^{\mu\nu}$

Possible glue content in η'

$$\frac{\Gamma(J/\psi \to \eta'\gamma)}{\Gamma(J/\psi \to \eta\gamma)} = 4.81 \pm 0.77$$

$$= \left(\frac{\langle 0|G\tilde{G}|\eta'\rangle}{\langle 0|G\tilde{G}|\eta\rangle}\right)^2 \left(\frac{M^2_{J/\psi} - M^2_{\eta'}}{M^2_{J/\psi} - M^2_{\eta}}\right)^3$$



Traditional Scheme for η mesons

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} |\eta_8\rangle \\ |\eta_1\rangle \end{pmatrix}$$

Measurement of $\sin^2\phi_G = \langle\eta'|gg\rangle^2$

$V \to P\gamma$ and $P \to V\gamma \to$	0.04 ± 0.09	Escribano and Nadal (2007)
$\frac{\mathrm{Br}(\phi(1020) \to \eta'\gamma)}{\mathrm{Br}(\phi(1020) \to \eta\gamma)} \to$	0.12 ± 0.04	KLOE collaboration (2008)
$J/\psi \to VP \to$	0.28 ± 0.21	Escribano (2008)

Mixing Scheme with pseudoscalar glueball

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |\eta''\rangle \end{pmatrix} = \begin{pmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_G & -\sin\phi_G \\ 0 & \sin\phi_G & \cos\phi_G \end{pmatrix} \begin{pmatrix} |\eta_8\rangle \\ |\eta_1\rangle \\ |gg\rangle \end{pmatrix}$$

$\hat{\theta} G_{\mu\nu}\tilde{G}^{\mu\nu} \rightarrow$Glueball $\sim$ massive axion in the chiral Lagrangian
Inclusion of a gluonic state *via* the $\theta-$term and the anomaly

$$\mathcal{L}^{(p^2)} = \frac{f^2}{8}\left\langle \partial_\mu \pi^\dagger \partial^\mu \pi + B(m\pi^\dagger + \pi m^\dagger)\right\rangle - \frac{\alpha}{2}(\eta_1+\theta)^2 - \frac{1}{2}m_\theta^2\theta^2 + \frac{1}{2}\partial_\mu\theta\partial^\mu\theta$$

$\pi = \{\pi, K, \eta_8, \eta_1\}$ contains 9 Golstone bosons (in the large N limit)

$$\mathcal{M}^2_{qsg} = \begin{pmatrix} m_\pi^2 + 2\alpha & \sqrt{2}\alpha & \sqrt{2}\beta \\ \sqrt{2}\alpha & 2m_K^2 - m_\pi^2 + \alpha & \beta \\ \sqrt{2}\beta & \beta & \gamma \end{pmatrix} \rightarrow \mathcal{R}^\dagger \mathcal{M}^2_{qsg}\mathcal{R} = \begin{pmatrix} M_\eta^2 & & \\ & M_{\eta'}^2 & \\ & & M_{\eta''}^2 \end{pmatrix}$$

Three unknowns α, β, γ but three rotation invariants

$$\alpha,\beta,\gamma \equiv F(M_\eta^2, M_{\eta'}^2, M_{\eta''}^2) \qquad \Rightarrow \mathcal{R}(M_\eta^2, M_{\eta'}^2, M_{\eta''}^2) \Rightarrow \text{Decays}(M_{\eta''}^2)$$

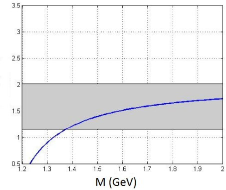
$$\beta^2 \geq 0 \longrightarrow M_{\eta''}^2 \geq (\sim 1.2 \text{ GeV})^2$$

$$M_\eta^2 \sim (500 \text{ MeV})^2 \qquad M_{\eta'}^2 \sim (1000 \text{ MeV})^2$$

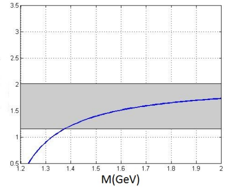
Rosenzweig, Salomone, and Schechter, Phys. Rev. D**24**, 2545 (1981)
Mathieu and Vento, Phys. Rev. D**81**, 034004 (2010)

Decays for $M_\eta = 530$ MeV and $M_{\eta'} = 1030$ MeV

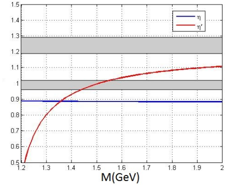
$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)}$$

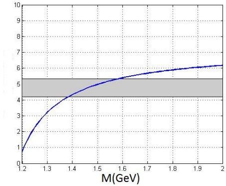


$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)}$$

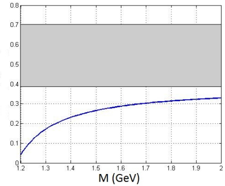


$$\frac{\Gamma(\eta(') \to \gamma\gamma)}{\Gamma(\pi \to \gamma\gamma)}$$

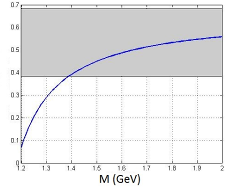




$$\frac{\Gamma(J/\Psi \to \eta'\gamma)}{\Gamma(J/\Psi \to \eta\gamma)}$$



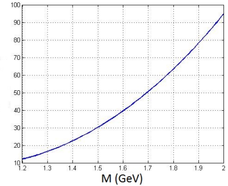
$$\frac{\Gamma(J/\Psi \to \rho\eta')}{\Gamma(J/\Psi \to \rho\eta)}$$

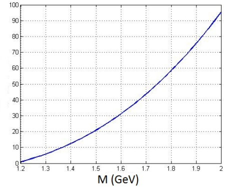


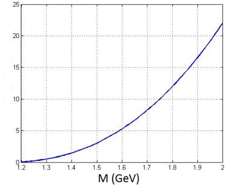
$$\frac{\Gamma(J/\Psi \to \phi\eta')}{\Gamma(J/\Psi \to \phi\eta)}$$

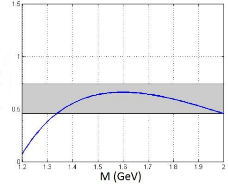
DECAYS FOR $M_{\eta''} = 1405$ MEV

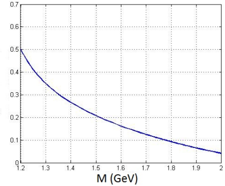
$$\frac{\Gamma(\eta'' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)} \qquad \frac{\Gamma(\eta'' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)} \qquad \frac{\Gamma(\eta'' \to \phi\gamma)}{\Gamma(\phi \to \eta\gamma)}$$

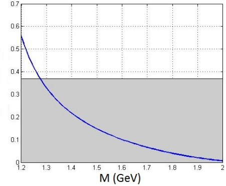












$$\frac{\Gamma(J/\Psi \to \eta''\gamma)}{\Gamma(J/\Psi \to \eta\gamma)} \qquad \frac{\Gamma(J/\Psi \to \rho\eta'')}{\Gamma(J/\Psi \to \rho\eta)} \qquad \frac{\Gamma(J/\Psi \to \phi\eta'')}{\Gamma(J/\Psi \to \phi\eta)}$$

Kiesewetter and Vento, Phys. Rev. D **82** (2010) 034003

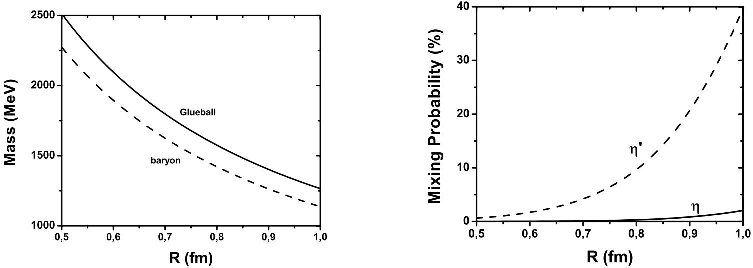


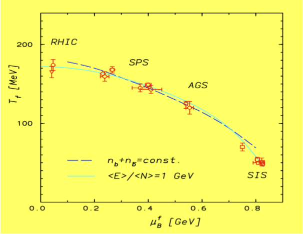
FIGURE: Left: Variation of glueball and baryon masses with bag radius. Right: η-glueball and η'-glueball probabilities as a function of bag radius.

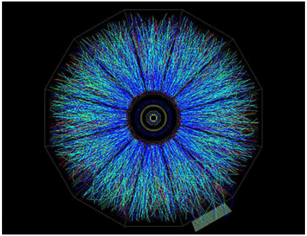
HOT MATTER

Relativistic heavy-ion collisions might be a tool to produce glueballs. It is conceivable that glueball production becomes a dominant part in central nucleon collisions.

Two scenarios have been analyzed

- **Quark Gluon Plasma phase**: one expects that at some point above a certain critical temperature a plasma of quarks and gluons, named quark-gluon plasma (QGP) is formed. This phase is characterized by a large amount of thermal gluons. As the QGP cools down the gluons can form singlet configurations via the color interaction. Bohr and Nielsen, H. B. (1977) Nuclear Physics B 128 (2): 275.
- **Strong Coulomb phase**: experiments in ultra relativistic heavy ion collisions at RHIC can be interpreted by a strenghtening of the color Coulomb interaction between the constituents a therefore a large number of binary (even color) bound states are formed. The QGP phase occurs at a much higher temperature $T_{QGP} > (2-3)T_C$ when the bound states dissolve. Shuryak and Zahed, Phys. Rev. D**69** (2004) 046005.





The high-T phase of QCD commonly known as the Quark-Gluon Plasma, is a weakly interacting gas of "quasiparticles"(quarks and gluons: at very high temperatures asymptotic freedom causes the electric coupling to be small and the QGP to be weakly interacting.

It is conceivable that glueball production becomes dominant in central nuclear collisions since the existence of QGP provides a gluon rich environment especially at high energy density.

Idea: during the hadronization process in this gluon rich environment the gluons combine due to the strong force into glueballs.

As the QGP cools further these glueballs decays into conventional hadrons giving rise to signatures of their existence. It has been claimed that the existence of glueballs alters the K/π ratio in the final state.

For the experimental identification of glueballs one can use the decay modes $G \to K\bar{K}$, $G \to \gamma\gamma$ and $G \to 2\pi l^+ l^-$.

Despite of small branching ratio, the 2γ channel has the important advantage that photons have practically no rescattering in the hadronic medium.

Strong Coulomb Phase

At intermediate temperatures there is new and growing evidence that the QGP is not weakly coupled. In this region QCD seems to be close to *a strongly coupled Coulomb regime*, with an effective coupling constant $\alpha \approx 0.5$-1 and multiple *bound states* of quasiparticles.

Caveat: this description is not universally accepted since some lattice calculations do not to find bound states above the transition.

In SCP despite deconfinement the color Coulomb interaction between the constituents is strong and a large number of binary (even color) bound states.
With this input, the scenario for glueballs is as follows Vento, Phys.Rev. D75 (2007) 055012:

The strong Coulomb phase is crowded with gluon bound states and the lightest is the scalar glueball. As the system cools towards the confining phase, color and singlet states decay into the conventional low lying glueballs, in particular the scalar glueball. Thus the number of them becomes large.

The ratio of glueball to meson channels goes from 1 to 8 below the phase transition to 1 to 2 above.Thus the number of scalar glueballs is much larger in SCP than in the cold world.

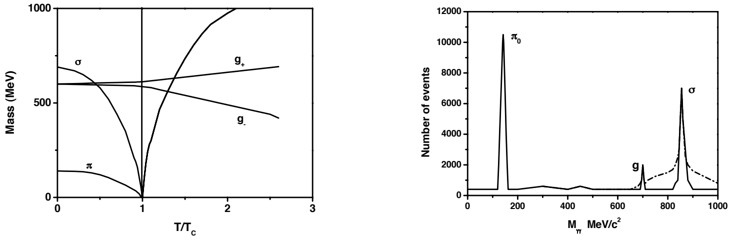


Figure: Left: Behavior of the masses of σ,π and g across the phase transition. Right:Expected fit to the two-photon invariant mass spectrum in central Pb-Pb collisions after substraction from the background. The 2γ decays should allow for a clear separation of g and σ.

The physical g is able to decay, once the σ component is attained, only to 2γ.
Enhancement in the number of g's with respect to the hadronic phase arises because of the larger population of glueballs in the SCP and because these particles are stable in the medium against the dominating hadronic decays.

Thus a clear signal for the existence of a low mass scalar glueball and a confirmation of the SCP scenario would be two 2γ peaks corresponding to g and the σ-meson.

CONCLUDING REMARKS

Concluding Remarks

Scalar Glueballs

- Quenched Lattice Resuts and Constituent Models give large masses > 1.5 GeV
- Sum rules produce a low mass glueball < 1.2 GeV (they can accomodate large masses as excitations).
- Unquenched lattice with mixing lower the glueball masses.
- Approximate QCD allows for lower masses < 1.2GeV (it can accomodate large masses as excitations).
- Specific production and decay dynamics of glueballs still unsolved.
- Accurate data would improve the understanding of their structure.

Pseudoscalar Glueball

- Quenched lattice calculation produce huge masses > 2.6 GeV. Unquenching and mixing necessary.
- Chiral Lagrangian at LO not enough to describe η and η'. Inclusion of glueball necessary.
- Experiments favor $\eta(1405)$ as the lowest mass glueball. Prediction for $\eta(1405)$ decays need experimental confirmation

Hot Matter

- Large amount of gluons allow the formation of large number of glueballs.
- The most favored decay in the hot fire ball $\gamma\gamma$.
- Pseudoscalar glueball mass decreases (Kochelev) giving interesting phenomenology.

Conclusion

The study of glueballs is intimately related to the quantitative understanding of confinement in QCD, i.e. understanding the soft gluonic modes responsible for binding the hadrons and the structure of the QCD vacuum.

Lattice QCD, is the tool, to confirm our suspicions. Unquenching, mixings and decays are the most difficult and expensive calculations one can perform. All efforts up to now, highly questioned by other experts, lead to a lower of the masses and the widths depend on the amount of mixing, in the line of approximate QCD.

Do glueballs exist?

There are strong indications that they do, but no unquestioned confirmation.