Glueball Spectroscopy

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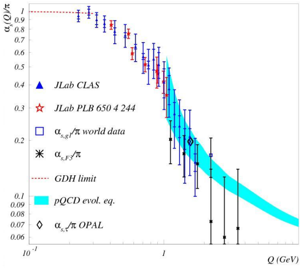
V. M., N. Kochelev, V. Vento,
"The Physics of Glueballs",
Int. J. Mod. Phys. E**18** (2009) 1

A. C. Aguilar, D. Ibañez, V. M. and J. Papavassiliou,
"The Schwinger Mechanism in QCD,"
in preparation

C. Degrande, J.-M. Gérard and V. M.,
in preparation,

Phenomenology - Strong Coupling Constant

Deur, arXiv:0901.2190
Saturation of $\alpha_s(Q^2)$ at large distances



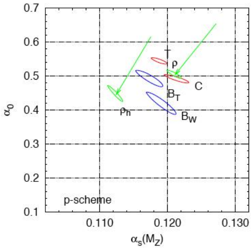
Gribov, Eur. Phys. J., C**10**,71 (1999)

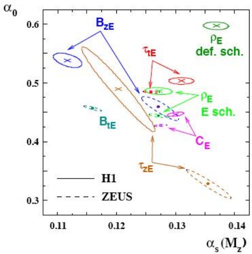
Dokshitzer and Webber,
Phys. Lett., B**352**, 451 ('95)

Dasgupta and Salam,
J. Phys. G **30**, R143 (2004)

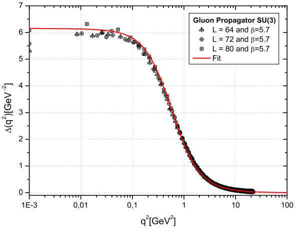
Power correction in event shapes
($\mu_I = 2$ GeV)

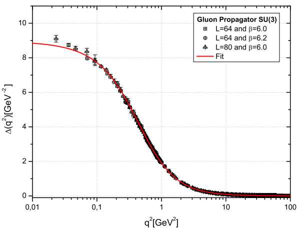
$$\alpha_0 = \mu_I^{-1} \int_0^{\mu_I} \alpha(Q^2) dQ^2 \sim 0.5$$





Gluon propagator from lattice QCD in Landau gauge

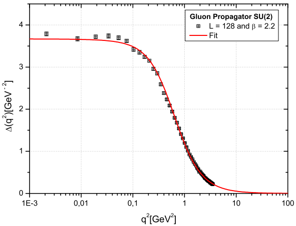




Cucchieri and Mendes,
PoS (Lattice 2007) 297

Bogolubsky *et al.*,
PoS (Lattice 2007) 290

Oliveira and Silva,
PoS (QCD-TNT 2009) 033



Predicted by Cornwall Phys. Rev. D**26**, 1453 (1982)
by introducing a dynamically generated gluon mass

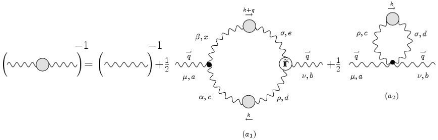
Dynamical Mass Generation

Not a violation of gauge invariance

Schwinger Mechanism like in $(1+1)-$QED
Phys. Rev. **128** (1962) 2425

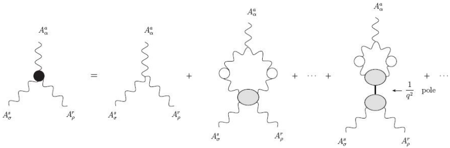
Self-energy gains a dynamical pole

$$\Delta(q^2)_{\mu\nu} = \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) \frac{-i}{q^2 - q^2 \Pi(q^2)}$$



Mass is the residue

$$\Pi(q^2)|_{\text{pole}} = \frac{m^2(q^2)}{q^2}$$

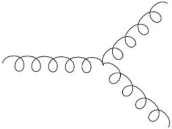


Composite bound state not present in physical processes

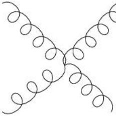
R. Jackiw and K. Johnson, Phys. Rev. D **8**, 2386 (1973)
D. Binosi and J. Papavassiliou, Phys. Rept. **479**, 1 (2009)
A. C. Aguilar, D. Ibañez, V. M. and J. Papavassiliou, “The Schwinger Mechanism in QCD”, in preparation

Glueball ?

QCD = gauge theory with the color group $\mathcal{SU}(3)$



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



Quark = fundamental representation **3**
Gluon = Adjoint representation **8**
Observable particles = color singlet **1**

Mesons: $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$

Baryons: $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10}$

Glueballs: $\mathbf{8} \otimes \mathbf{8} = (\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27}) \oplus (\mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}})$

$$\mathbf{8} \otimes \cdots \otimes \mathbf{8} = \mathbf{1} \oplus \mathbf{8} \oplus \ldots$$

Three light quarks $\rightarrow$ nine $0^{\pm}$ mesons : $3\pi\ (I=1) \oplus 4K\ (I=1/2) \oplus 2\eta\ (I=0)$

Glueball can mix with two isoscalars $\rightarrow$ glue content in η's wave function and maybe a third isoscalar

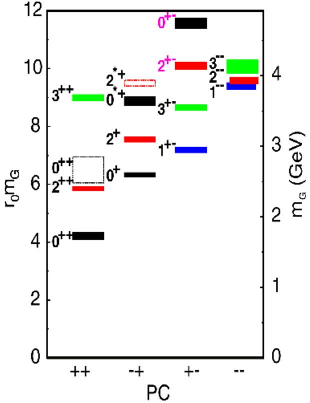
QUENCHED RESULTS

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

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

Quenched approximation (gluodynamics) → 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 but no definitive conclusion.

Theoretical status of glueballs :
V. M., N. Kochelev, V. Vento, "The Physics of Glueballs", Int. J. Mod. Phys. E**18** (2009) 1

Bag Model

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

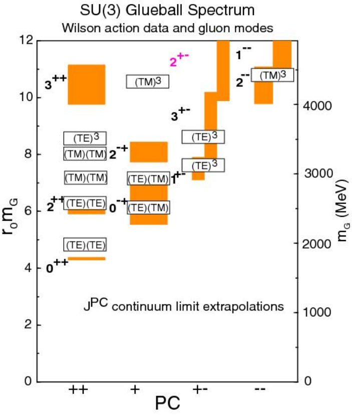
$$\begin{array}{lll} \text{TE mode} & J^P = 1^+ & x_{\text{TE}} = 2.74, \\ \text{TE mode} & J^P = 2^- & x_{\text{TE}} = 3.96, \\ \text{TM mode} & J^P = 1^- & x_{\text{TM}} = 4.49. \end{array}$$

Mass Spectrum

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

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

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



J. F. Donoghue, Phys. Rev. D 29 (1984) 2559
Gluon mass 740 ± 100 MeV in the bag model

Szczepaniak, Swanson, Ji, and Cotanch [Phys. Rev. Lett.**76**, 2011 (1996)]

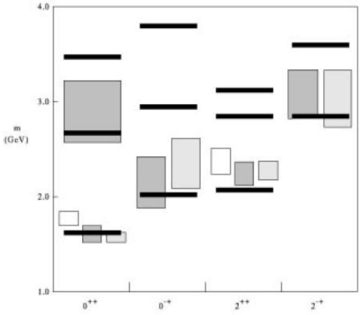
Transverse gluons with 2 helicities $\{-1,+1\}$
Gluon mass given by gap equation

$$\omega^2(k) = k^2 + m^2 e^{-k/\kappa}$$

Relativistic Hamiltonian with

$$V(r) = \frac{9\sigma}{4} r(1 - e^{-\Lambda r}) - \frac{3\alpha_s}{r}$$

No vector state (Yang's theorem)
Agreement with (preliminary) lattice results
without OGE



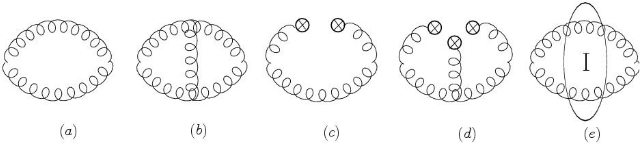
Small gap, 250 MeV, between 0^{++} and 0^{-+}

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

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

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

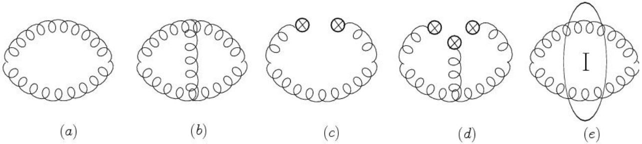
Gluonic currents: $J_S(x) = \alpha_S \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$ $J_P(x) = \alpha_S \mathrm{Tr}\, G_{\mu\nu}\widetilde{G}^{\mu\nu}$

$$\Pi_{\mathcal{O}}(0) = \lim_{q^2\to 0} i \int d^4x\, e^{iq\cdot x} \langle 0|T J_S(x)\mathcal{O}(0)|0\rangle = \frac{8\pi d_{\mathcal{O}}}{b_0}\langle 0|\mathcal{O}|0\rangle$$

$$\begin{aligned} \Pi_S(Q^2=0) &= \frac{32\pi}{b_0}\langle 0|\alpha_s G^a_{\mu\nu}G^{\mu\nu}_a|0\rangle \\ \Pi_P(Q^2=0) &= (8\pi)^2 \frac{m_u m_d}{m_u+m_d}\langle 0|\bar{q}q|0\rangle \end{aligned}$$

Instantons contribution essential for LETs
Forkel, Phys. Rev. D**71** (2005) 054008

$$M(0^{++}) = 1.25 \pm 0.20 \text{ GeV} \quad M(0^{-+}) = 2.20 \pm 0.20 \text{ GeV}$$

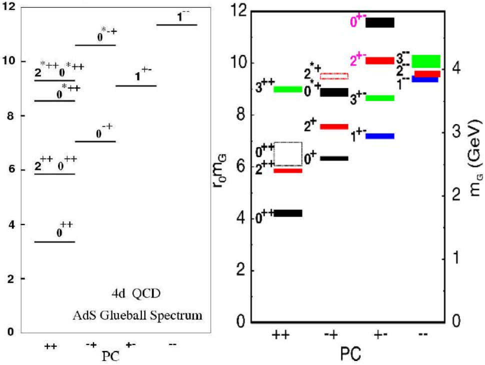


AdS/CFT correspondance:
Correspondance between conformal theories and string theories in AdS spacetime
QCD not conformal → breaking conformal invariance somehow

Introduction of a black hole in AdS to break conformal invariance

Parameter adjusted on 2^{++}

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



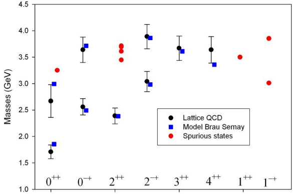
R. C. Brower *et al.*, Nucl. Phys. B**587** (2000) 249

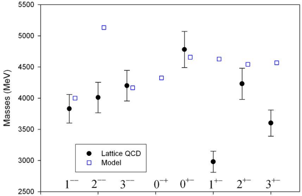
Two Models

$$H_{gg} = 2\sqrt{\boldsymbol{p}^2} + \frac{9}{4}\sigma r - 3\frac{\alpha_s}{r} + V_{\rm OGE}$$

Gluons spin-1 usual rules of spin couplings

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

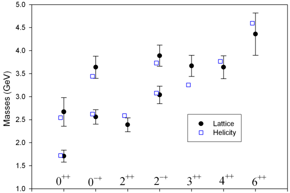




V.M. , PoS [QCD-TNT09], 024 (2009)

Gluons transverse Gluons helicity-1 particles

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



- OGE no needed $V_{\rm OGE} = 0$
- No vector states
- 3 d.o.f. not compatible with J^{+-}
- Instanton contribution

Gluon has only 2 d.o.f in bound state w. f.

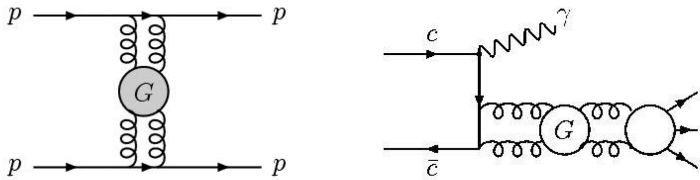
Crede and Meyer, The Experimental Status of Glueballs,
Prog. Part. Nucl. Phys. **63**, 74 (2009)

Production in gluon rich processes (OZI forbidden,...)
Closely linked to the Pomeron: $J = 0.25 M^2 + 1.08$

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

Scalar Candidates:	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$f_0(1810)$	...
Pseudoscalar Candidates:	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$\eta(1760)$	...

0^{++} and 0^{-+} glueballs shared between those states

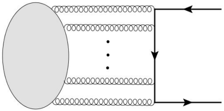


Three light quarks $\rightarrow 3 \times 3 = 9$ (pseudo)scalar mesons
A 10th light mesons would be the realization of the glueball

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 $\pi\pi$

Controversy about m_q (current or constituent mass ?)

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

$f_0(1710)$ good glueball candidate

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

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 $\pi\pi$

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

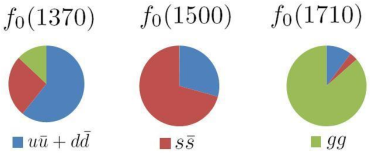
$$|G\rangle = |gg\rangle + \frac{\langle n\bar{n}|gg\rangle}{M_{gg} - M_{n\bar{n}}}\,|n\bar{n}\rangle + \frac{\langle s\bar{s}|gg\rangle}{M_{gg} - M_{s\bar{s}}}\,|s\bar{s}\rangle$$

Analysis of

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

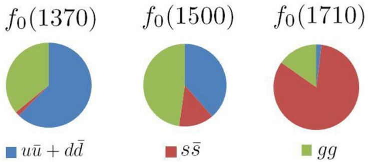
Two mixing schemes

Cheng *et al*, Phys. Rev. D**74** (2006) 094005



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

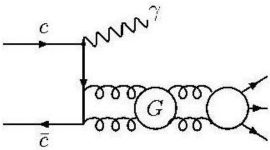
Close and Kirk, PLB**483** (2000) 345



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

Pseudoscalar

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

Possible glue content in η'

$$\frac{\Gamma(J/\psi \to \eta'\gamma)}{\Gamma(J/\psi \to \eta\gamma)} = \left(\frac{\langle 0|G\tilde{G}|\eta'\rangle}{\langle 0|G\tilde{G}|\eta\rangle} \right)^2 \left(\frac{M^2_{J/\psi} - M^2_{\eta'}}{M^2_{J/\psi} - M^2_{\eta}} \right)^3 = 4.81 \pm 0.77$$

Physical Pseudoscalar States

Axial Anomaly $\to$ mixing with η_1

$$\partial^\mu \left(\bar{q}\gamma_\mu\gamma_5 q\right) = 2im\bar{q}\gamma_5 q + \frac{\alpha_S}{4\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} \to \langle gg|\partial^\mu J^1_{\mu 5}|0\rangle \neq 0$$

Mixing Scheme with pseudoscalar glueball

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

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

$V \to P\gamma$ 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)

Where is the physical pseudoscalar glueball $|\eta''\rangle$?

$$\eta(1295), \quad \eta(1405), \quad \eta(1475), \quad \ldots$$

Cheng *et al.*, Phys. Rev D **79** (2008) 014024

QCD = gauge theory with the color group $\mathcal{SU}(3)$

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

Degrees of freedom at High Energies: Quarks q and Gluons A_μ
Degrees of freedom at Low Energies: Pions, Kaons,...

Goldstone bosons of Chiral Symmetry Breaking
(Global) Chiral Symmetry: $U(3)_V \otimes U(3)_A$

$$
\begin{aligned}
U(3)_V : \quad & q \quad \rightarrow \exp(i\theta_a\lambda^a)q \\
U(3)_A : \quad & q \quad \rightarrow \exp(i\gamma_5\theta_{5a}\lambda^a)q
\end{aligned}
$$

$U(3)_A$ broken spontaneously by quark condensate $\langle 0|\bar{q}q|0\rangle \neq 0$
$U(3)_A$ broken explicitly by quark masses m
$\rightarrow$ 9 Goldstone pseudoscalar bosons with a small mass $\propto m\langle 0|\bar{q}q|0\rangle$

$$3\pi,\ 4K \text{ and } 2\eta$$

$U(1)_A$ is not a symmetry of QCD
$\rightarrow \eta'$ is NOT a Goldstone boson $M_{\eta'} \sim 958$ MeV $> M_\eta \sim 548$ MeV

But Anomaly vanishes for large N, for a gauge group $SU(N \rightarrow \infty)$

Mass Matrix at Leading Order

Chiral Lagrangian at leading order (in p^2 and $1/N$)

$$\mathcal{L}^{(p^2)} = \frac{f^2}{8} \left\langle \partial_\mu U^\dagger \partial^\mu U + B(mU^\dagger + Um^\dagger) \right\rangle - \frac{1}{2}\alpha_0 \eta_0^2$$

with $U = \exp(i\sqrt{2}\pi/f)$

Isospin Symmetry $m = \text{diag}\ (\tilde{m}, \tilde{m}, \tilde{m}_s) \to m_\pi^2 = B\tilde{m}$ and $m_K^2 = B(\tilde{m} + m_s)/2$

Mass matrix in the flavor basis $(\eta_q - \eta_s)$

$$\mathcal{M}_{qs}^2 = \begin{pmatrix} m_\pi^2 + 2\alpha_0 & \sqrt{2}\alpha_0 \\ \sqrt{2}\alpha_0 & 2m_K^2 - m_\pi^2 + \alpha_0 \end{pmatrix}$$

Anomaly only source of mixing

Rotation to Physical States

$$R^\dagger(\phi)\mathcal{M}_{qs}^2 R(\phi) = \begin{pmatrix} m_\eta^2 & 0 \\ 0 & m_{\eta'}^2 \end{pmatrix}$$

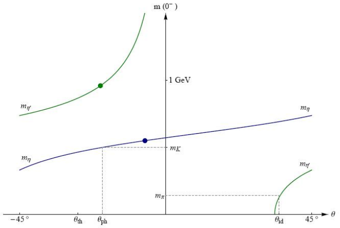
ϕ determines Decay Properties

Only 1 parameter α_0 but 2 states (or 2 invariants)

Trace $\quad \alpha_0 = (m_\eta^2 + m_{\eta'}^2 - 2m_K^2)/3$

Determinant $\quad \alpha_0 = \dfrac{m_\eta^2 m_{\eta'}^2 - m_\pi^2(2m_K^2 - m_\pi^2)}{4m_K^2 - m_\pi^2}$

! Not Equal !



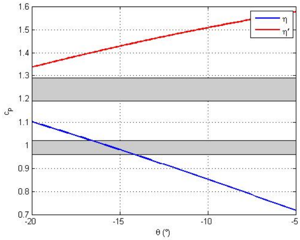
2 photons decays : $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$

Degrande and Gérard, JHEP **0905** (2009) 043

$\theta \sim -(20-15)^\circ$ in the $U(3)$ basis $(\eta_8 - \eta_0)$
$\phi \sim (40-45)^\circ$ in the flavor basis $(\eta_q - \eta_s)$

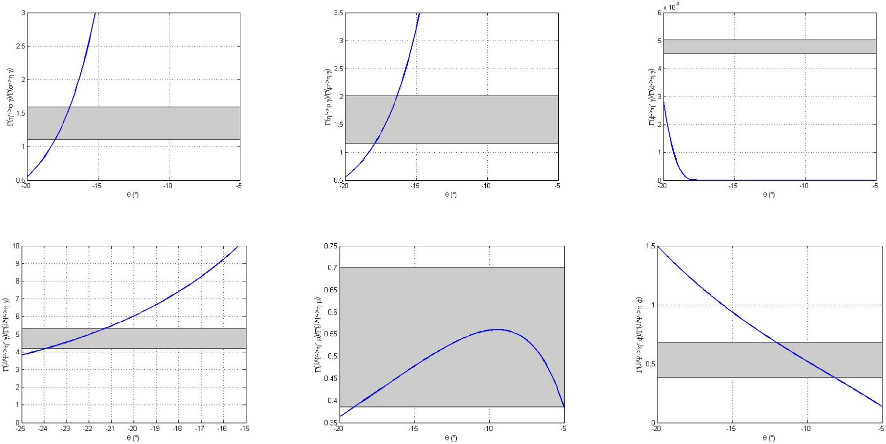
$$\theta = \phi - \theta_i$$

with the ideal mixing angle
$\theta_i = \arccos(1/\sqrt{3}) \sim 54.7^\circ$



Decays with respect to θ

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



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

$\hat{\theta} G_{\mu\nu}\tilde{G}^{\mu\nu}$ $\rightarrow$Glueball $\sim$ massive axion in the chiral Lagrangian

$$\mathcal{L}^{(p^2)} = \frac{f^2}{8}\left\langle \partial_\mu U^\dagger \partial^\mu U + B(mU^\dagger + Um^\dagger)\right\rangle - \frac{\alpha}{2}(\eta_0 + \theta)^2 - \frac{1}{2}m_\theta^2\theta^2 + \frac{1}{2}\partial_\mu\theta\partial^\mu\theta$$

Inclusion of a gluonic state *via* the $\theta-$term and the anomaly

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

Rosenzweig, Salomone, and Schechter, Phys. Rev. D**24** (1981) 2545
Degrande, V.M., Gérard, in preparation
What are the theoretical constraints on R ?

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |G\rangle \end{pmatrix} = \mathcal{R}\begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \\ |gg\rangle \end{pmatrix}$$

Inclusion of a gluonic state *via* the $\theta-$term and the anomaly

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

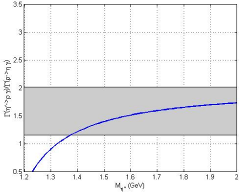
Diagonalization

$$\mathcal{R}^\dagger \mathcal{M}^2_{qsg}\mathcal{R} = \mathcal{D}$$

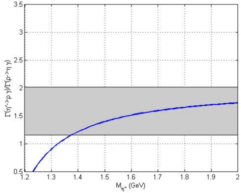
$\mathcal{D} = \text{diag}\ (M_\eta^2, M_{\eta'}^2, M_G^2)$ with M_G^2 unknown

DECAY WITH GLUEBALL FOR $M_\eta = 530$ MEV AND $M_{\eta'} = 1030$ MEV

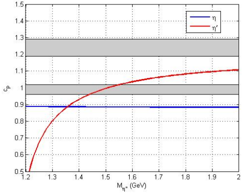
$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)}$$

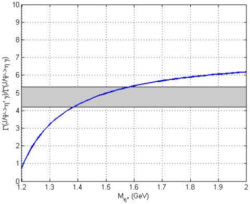


$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)}$$

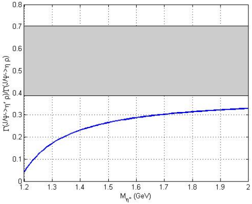


$$\frac{\Gamma(\eta(') \to \gamma\gamma)}{\Gamma(\pi \to \gamma\gamma)}$$

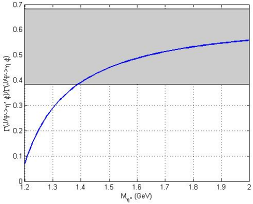




$$\frac{\Gamma(J/\Psi \to \eta'\gamma)}{\Gamma(J/\Psi \to \eta\gamma)}$$



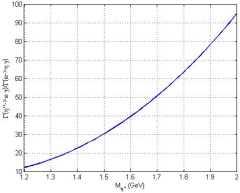
$$\frac{\Gamma(J/\Psi \to \rho\eta')}{\Gamma(J/\Psi \to \rho\eta)}$$

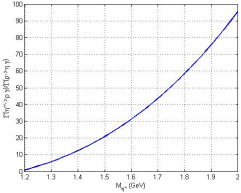


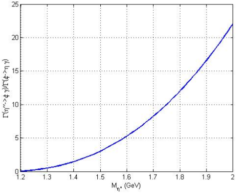
$$\frac{\Gamma(J/\Psi \to \phi\eta')}{\Gamma(J/\Psi \to \phi\eta)}$$

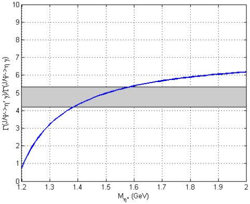
$\eta'' = \eta(1405)$? decays for $M_\eta = 530$ MeV and $M_{\eta'} = 1030$ MeV

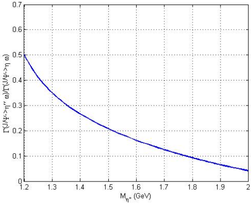
$$\frac{\Gamma(\eta'' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)} \qquad \frac{\Gamma(\eta'' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)} \qquad \frac{\Gamma(\eta'' \to \phi\gamma)}{\Gamma(\phi \to \eta\gamma)}$$

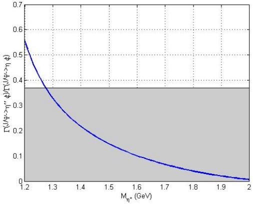












$$\frac{\Gamma(J/\Psi \to \eta''\gamma)}{\Gamma(J/\Psi \to \eta\gamma)} \qquad \frac{\Gamma(J/\Psi \to \rho\eta'')}{\Gamma(J/\Psi \to \rho\eta)} \qquad \frac{\Gamma(J/\Psi \to \phi\eta'')}{\Gamma(J/\Psi \to \phi\eta)}$$

Preliminary Results

Degrande, V.M., Gérard, in preparation

Glueball $\sim$ massive axion in the chiral Lagrangian

$$\mathcal{L}^{(p^2)} = \frac{f^2}{8}\left\langle \partial_\mu U^\dagger \partial^\mu U + B(mU^\dagger + Um^\dagger)\right\rangle - \frac{\alpha}{2}(\eta_0 + \theta)^2 - \frac{1}{2}m_\theta^2\theta^2 + \frac{1}{2}\partial_\mu\theta\partial^\mu\theta$$

Decays in better agreement with data but very sensitive to M_η

$$\begin{array}{ccc} \theta = -11.4^\circ & \varphi_G = (4.7 \pm 0.3)^\circ & \varphi = (46.8 \pm 1.8)^\circ \\ M_\eta = 530 \text{ MeV} & M_{\eta'} = 1030 \text{ MeV} & M_G = 1400 - 1500 \text{ MeV} \end{array}$$

$\eta(1405)$ would be the third state, mainly gluonic !
BUT only leading order

Gérard and Kou, Phys. Rev. Lett. **97** (2006) 261804

Other anomalous decays

$$\text{Br}(B^0 \to K^0\eta') = 65\ 10^{-6}, \qquad \text{Br}(B^0 \to K^0\eta) < 2\ 10^{-6}, \qquad \text{Br}(B^0 \to K^0\pi^0) = 10\ 10^{-6}.$$

$$\eta' : \eta : \pi = 3 : 0 : 1$$

via Penguin diagram

Summary

Pure Yang-Mills

- Various models reproduce lattice spectrum
- Dynamical gluon mass generation BUT only 2 d.o.f. in wave function
- Instanton effects $\rightarrow$ mass difference between 0^{++} and 0^{-+}

Scalar Mesons

- Chiral suppression $A\left(0^{++} \longrightarrow \bar{q}q\right) \propto m_q$
  $\rightarrow$ $f_0(1710)$ realization of the glueball ?
- Not without controversy
- A confirmation of three f_0 is required
- Accurate data about their productions and decays would improve the understanding of their structure.

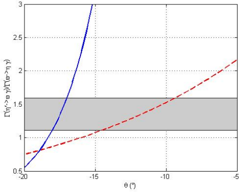
Pseudoscalar Mesons

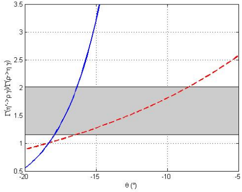
- Anomaly in pseudoscalar $\rightarrow$ no ideal mixing for η and η'
- Chiral Lagrangian at LO not enough to describe η and η'
  $\rightarrow$ Inclusion of glueball in chiral Lagrangian
- Preliminary results favor $\eta(1405)$ realisation of the glueball
- Prediction for η'' decays $\rightarrow$ need experimental confirmation !

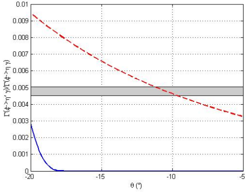
Backup Slides

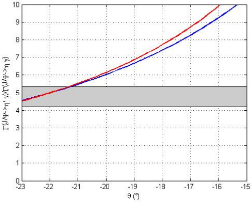
Decays with respect to θ

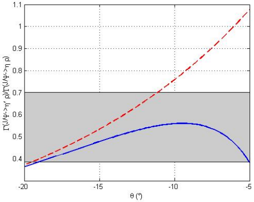
$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)} \qquad \frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)} \qquad \frac{\Gamma(\phi \to \eta'\gamma)}{\Gamma(\phi \to \eta\gamma)}$$

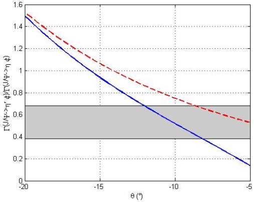






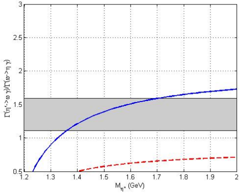




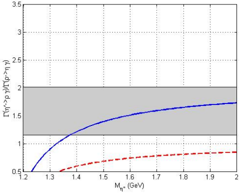


$$\frac{\Gamma(J/\Psi \to \eta'\gamma)}{\Gamma(J/\Psi \to \eta\gamma)} \qquad \frac{\Gamma(J/\Psi \to \rho\eta')}{\Gamma(J/\Psi \to \rho\eta)} \qquad \frac{\Gamma(J/\Psi \to \phi\eta')}{\Gamma(J/\Psi \to \phi\eta)}$$

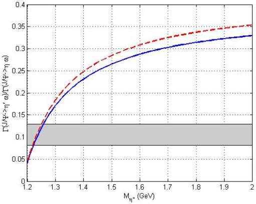
$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)}$$

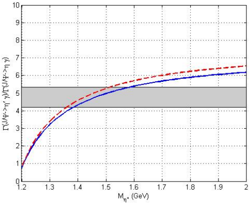


$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)}$$

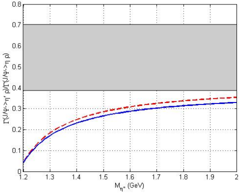


$$\frac{\Gamma(J/\Psi \to \omega\eta')}{\Gamma(J/\Psi \to \omega\eta)}$$

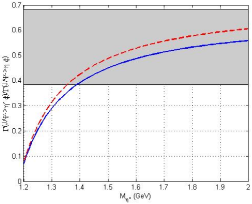




$$\frac{\Gamma(J/\Psi \to \eta'\gamma)}{\Gamma(J/\Psi \to \eta\gamma)}$$



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



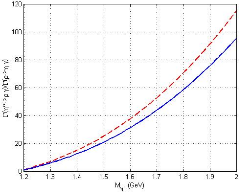
$$\frac{\Gamma(J/\Psi \to \phi\eta')}{\Gamma(J/\Psi \to \phi\eta)}$$

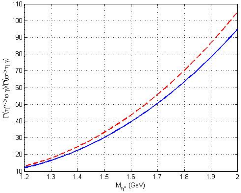
η'' Decays

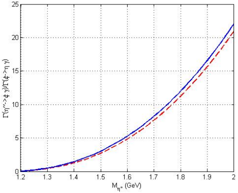
$$\frac{\Gamma(\eta'' \to \rho\gamma)}{\Gamma(\rho \to \eta\gamma)}$$

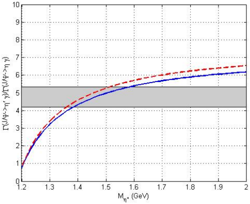
$$\frac{\Gamma(\eta'' \to \omega\gamma)}{\Gamma(\omega \to \eta\gamma)}$$

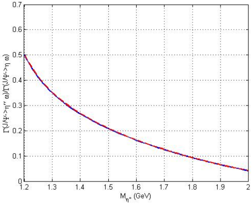
$$\frac{\Gamma(\eta'' \to \phi\gamma)}{\Gamma(\phi \to \eta\gamma)}$$

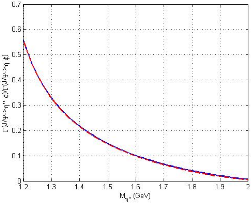












$$\frac{\Gamma(J/\Psi \to \eta''\gamma)}{\Gamma(J/\Psi \to \eta\gamma)}$$

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

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