Scalar Glueball, Scalar Quarkonia, and their Mixing

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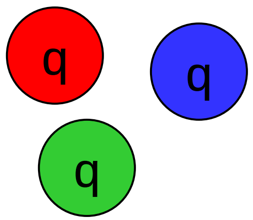
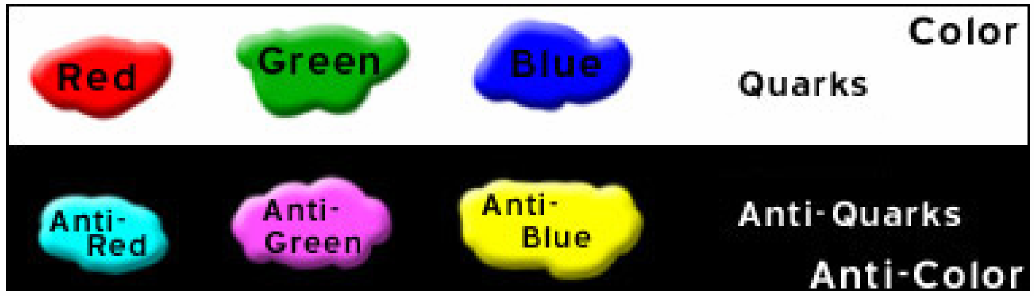
- Each quark has one of three different color charges and antiquark carries an anti-color charge





- Quarks exchange **gluons** and create a very strong color force
- Gluons carry a color and an anti-color and hence can have a self-coupling
- Single quark has not been observed yet. QCD tells it cannot be observed (quark confinement). All naturally occurring particles are **colorless**.

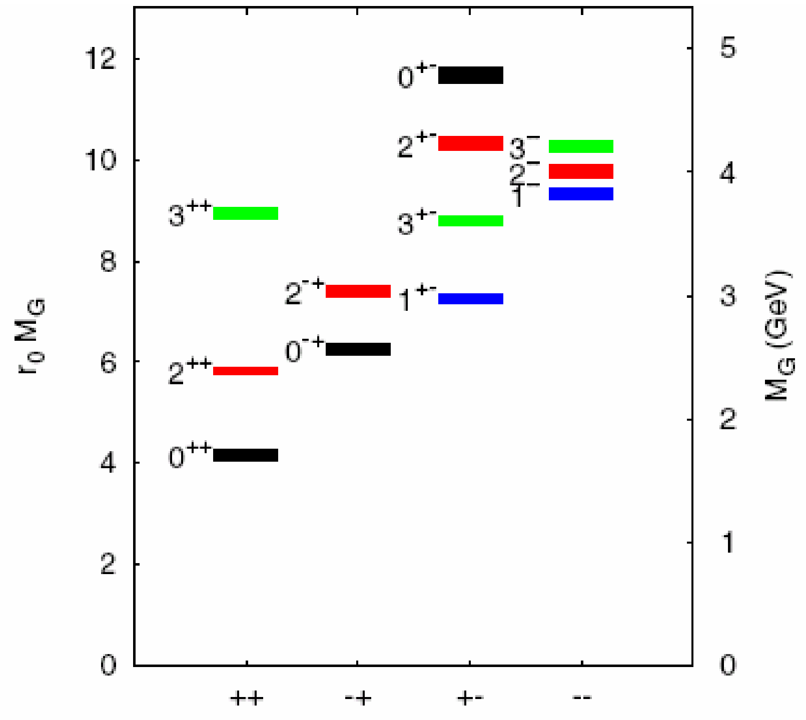
Glueball: color-singlet bound state of gluons as gluons have a self coupling

Lighest glueballs:

$J^{PG}=0^{++}$ 1710±50±80 MeV

$J^{PG}=2^{++}$ 2390±30±120 MeV

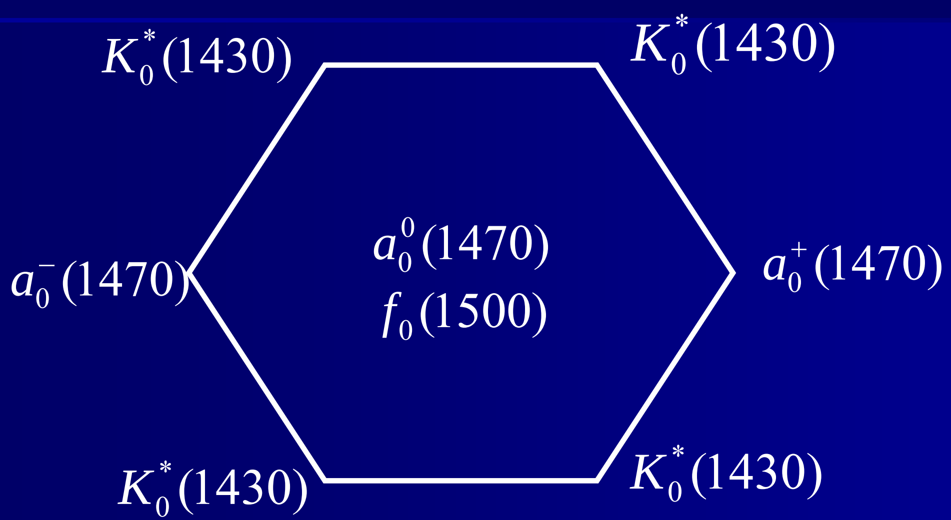
Y. Chen et al. hep-lat/0510074



- $\iota(1440)$ [now $\eta(1405)$] as 0^{-+} glueball
- Amsler & Close (1995) claimed $f_0(1500)$ discovered at LEAR as an evidence for a scalar glueball because its decay to $\pi\pi$,KK,$\eta\eta$,$\eta\eta'$ is not compatible with a simple $q\underline{q}$ picture.
- V.V. Anisovich et al. (2005) claimed evidence of a tensor glueball, namely, $f_2(2000)$

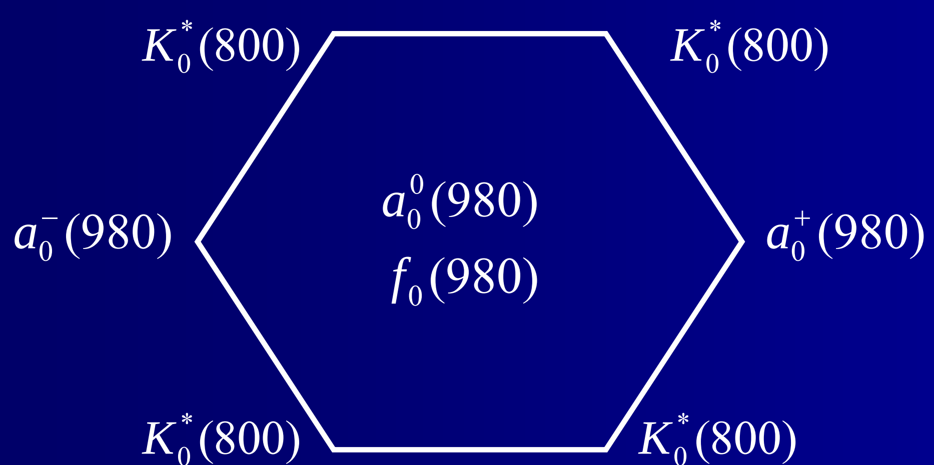
Scalar Mesons ($J^P = 0^+$)

$q\bar{q}$



$+ \quad f_0(1370)$
$f_0(1710)$

$q^2\bar{q}^2$



$+ \quad \sigma(600)$

$f_0(1500)$: dominant scalar glueball ~ 1550 MeV [Bali et al. '93, Amsler et al. '95]

$K\bar{K}/\pi\pi$ ~ 0.25 ⇒ small $s\bar{s}$ content

$f_0(1710)$: $\pi\pi$ is suppressed relative to $K\bar{K}$ ⇒ primarily $s\bar{s}$ dominated

$f_0(1370)$: $K\bar{K}$ is suppressed relative to $\pi\pi$ ⇒ dominated by $n\bar{n}$ states $n\bar{n} = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$

$$\begin{array}{ccc} G & s\bar{s} & n\bar{n} \end{array}$$
$$\begin{pmatrix} M_G & y & \sqrt{2}y \\ y & M_S & 0 \\ \sqrt{2}y & 0 & M_N \end{pmatrix}$$

$$|f_0(1710)\rangle = 0.36|G\rangle + 0.09|N\rangle + 0.93|S\rangle$$
$$|f_0(1500)\rangle = -0.84|G\rangle - 0.41|N\rangle + 0.35|S\rangle$$
$$|f_0(1370)\rangle = 0.40|G\rangle + 0.91|N\rangle - 0.07|S\rangle$$

Amsler, Close, Kirk, Zhao, He, Li…

$M_S > M_G > M_N$ M_G ~ 1500 MeV, $M_S - M_N$ ~ 200-300 MeV

Further support:

- **$f_0(1710)$ is not seen in $p\bar{p} \to \pi^0 f_0$ ⇒ $f_0(1710)$ dominated by $s\bar{s}$**
- **While $f_0(1710)$ is observed in $\gamma\gamma \to K\bar{K}$, $f_0(1500)$ has not been seen in $\gamma\gamma \to K\bar{K}$ or $\pi^+\pi^-$ ⇒ absence of $f_0(1500)$ coupling to 2γ**

  ⇒ glueball structure of $f_0(1500)$

Other scenarios:

Lee, Weingarten (lattice): $f_0(1710)$ glueball ; $f_0(1500)$ $n\underline{n}$;

$f_0(1370)$ $s\underline{s}$

Giacosa et al. (χ Lagrangian): 4 allowed sloutions

PDG (2006): p.168

Experimental evidence is mounting that $f_0(1500)$ has considerable affinity for glue and that the $f_0(1370)$ and $f_0(1710)$ have large $u\underline{u}+d\underline{d}$ and $s\underline{s}$ components, respectively.

F.E. Close (Oxford): a leading figure in hadron spectroscopy

C. Amsler (Zurich): a dominant figure in searching for (exotic)

non-$q\underline{q}$ mesons

author of “Non-$q\underline{q}$ mesons”, Particle Data Group

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Problems:

- **Near degeneracy of $a_0(1450)$ and $K_0^*(1430)$ cannot be explained due to the mass difference between M_S and M_n**
- **Improved LQCD $\Rightarrow$ $M_G \sim 1700$ MeV rather than ~ 1500 MeV**
- **If $f_0(1710)$ is $s\underline{s}$ dominated, $J/\psi \to \phi f_0(1710) >> J/\psi \to \omega f_0(1710)$**

  BES $\Rightarrow \Gamma(J/\psi \to \omega f_0(1710)) = (6.6 \pm 2.7)\ \Gamma(J/\psi \to \phi f_0(1710))$
- **$J/\psi \to \gamma gg$ and glueballs couple strongly to gluons**

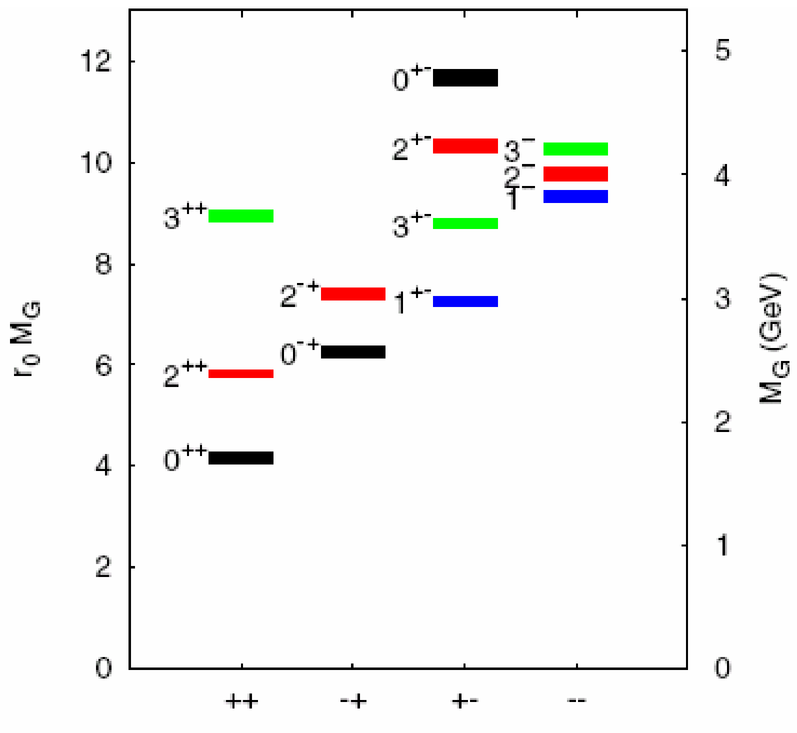
  $\Rightarrow$ **If $f_0(1500)$ is primarily a glueball,**

  $J/\psi \to \gamma f_0(1500) >> J/\psi \to \gamma f_0(1710)$

  Expt $\Rightarrow$ $\Gamma(J/\psi \to \gamma f_0(1710)) \sim 5\ \Gamma(J/\psi \to \gamma f_0(1500))$

In this work we consider two recent lattice inputs for mass matrix:

- glueball spectrum from quenched LQCD
- approximate SU(3) symmetry in scalar meson sector (> 1GeV)



Y. Chen et al. hep-lat/0510074

- improved quenched LQCD calculations based on much larger & finer lattices
- infinite quark mass $\Rightarrow$ no $q\underline{q}$ loops

$M(0^{++})=1710 \pm 50 \pm 80$ MeV

M_G before mixing should be close to 1700 MeV

1650 MeV by Lee, Weingarten

1550 Mev by Bali

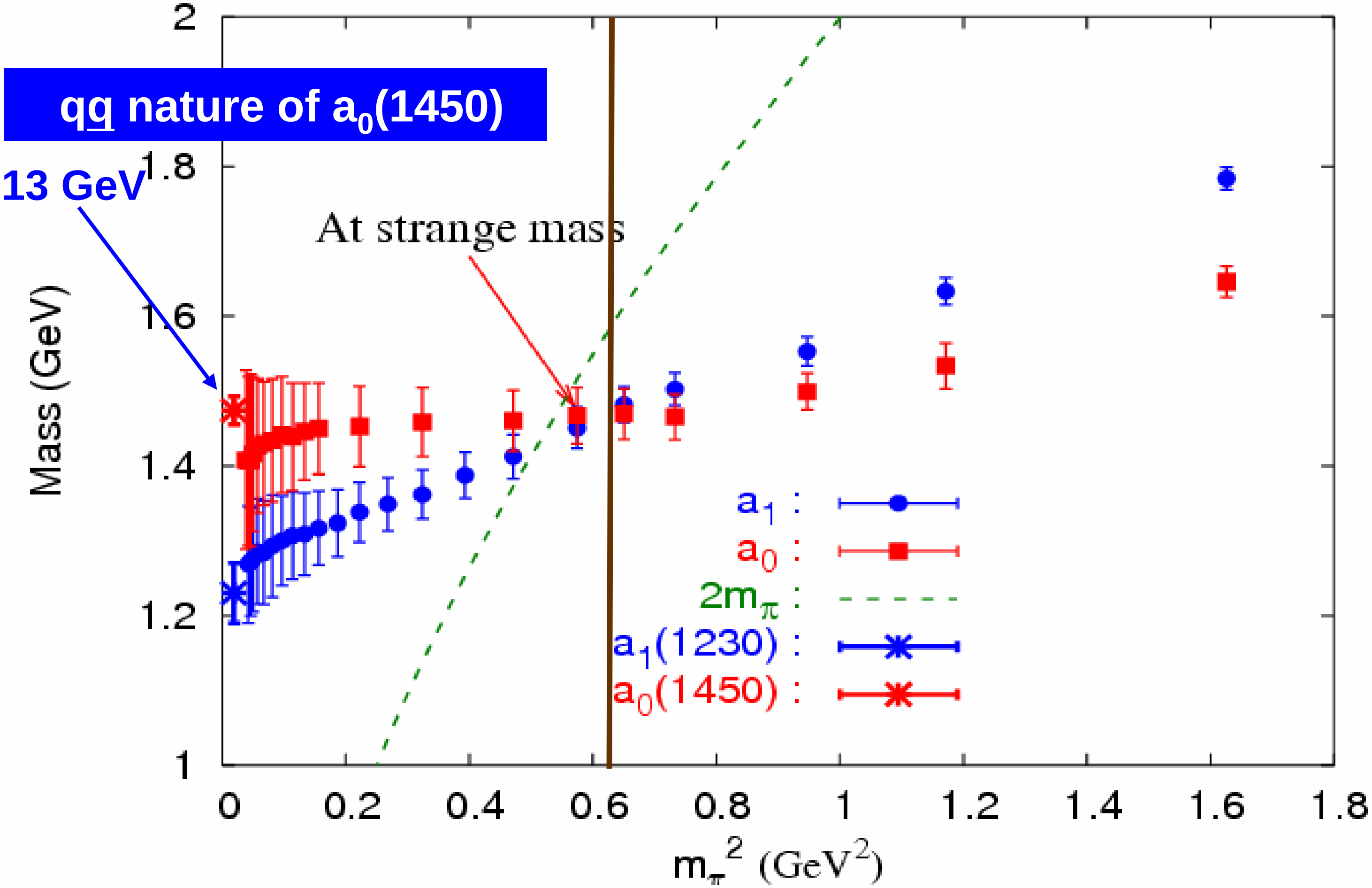
$\bar{\psi}\psi$ $I^G(J^{PC}) \equiv$ $1^-(0^{++})$, $1^-(1^{++})$

Mathur et al.

hep-ph/0607110

qq nature of $a_0(1450)$

1.42±0.13 GeV



$a_0(980)$ is not seen $\Rightarrow$ not a qq state !

$a_0(1450)$ mass is independent of quark mass when $m_q \leq m_s$

$\Rightarrow$ Flavor SU(3) is a good symmetry for scalar meson sector > 1 GeV

$\Rightarrow$ **M_S should be close to M_N**

LQCD $\Rightarrow$ **$K_0^*(1430)=1.41\pm0.12$ GeV**

$\Rightarrow$ **near degeneracy of $K_0^*(1430)$ and $a_0(1450)$**

This unusual behavior is not understood and it serves as a challenge to the existing QM

Near degeneracy also occurs in charm sector, $D_{s0}^*(2317)$ & $D_0^*(2308)$. This is the place where the conventional QM seems not to work.

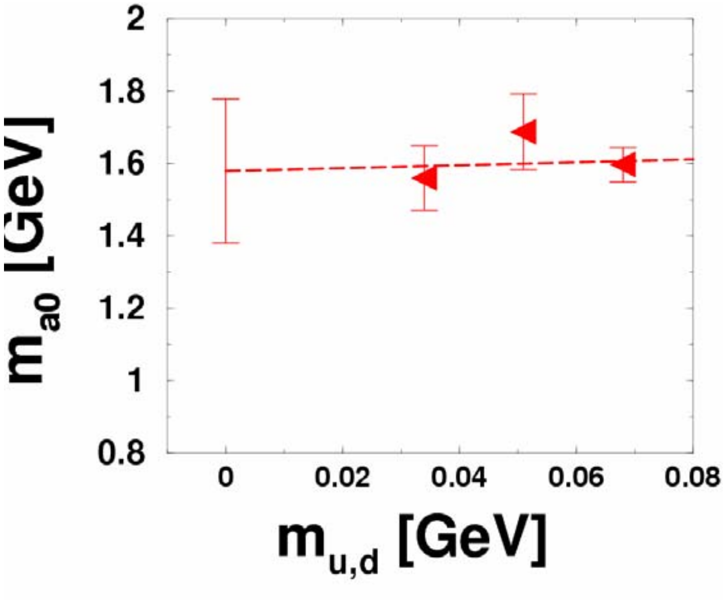
Belle: $2308\pm17\pm32$ MeV for D_0^*

FOCUS: $2407\pm21\pm35$ MeV

Lattice calculations of a_0

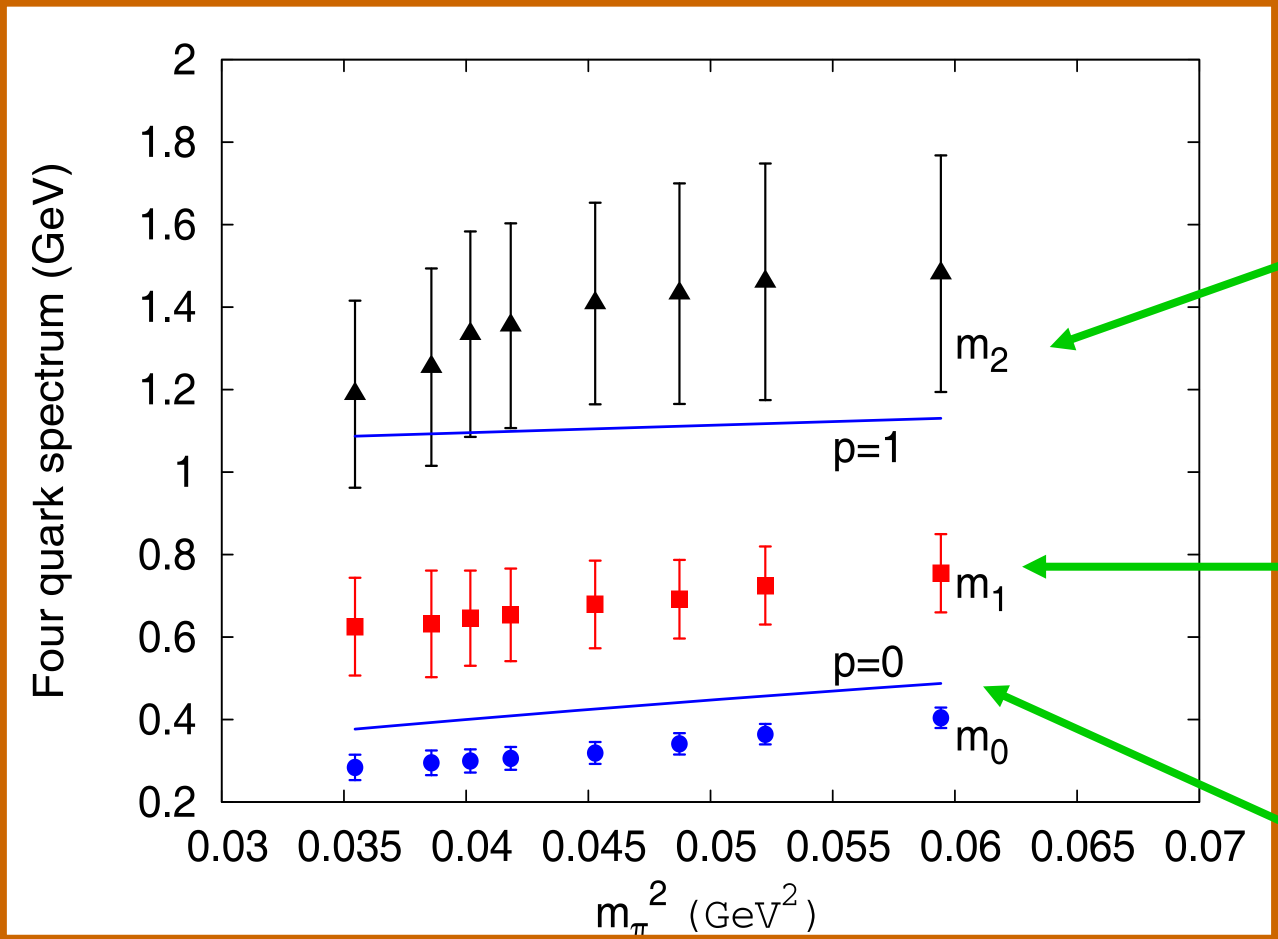
Bardeen et al	Wilson fermion	m_{a0}=1.326±0.086 GeV
RBC	domain wall fermion	m_{a0}=1.43±0.10 GeV m_{a0}=1.58±0.34 GeV
SCALAR Kunihiro et al	dynamical fermion	m_{a0}~ 1.8GeV for m_π/m_ρ~ 0.7
UKQCD(03') UKQCD(06')	dynamical fermion	m_{a0}=1.0±0.2 GeV m_{a0}=1.01±0.04 GeV
BGR		m_{a0} ~ 1.45 GeV
MILC	stagged fermion	indication for a_0
Alford & Jaffe		indication of bound qqqq states

Prelovsek, Dawson, Izubuchi, Orginos, Soni PR, D70, 094503 (2004); hep-ph/0511110: domain wall fermions



Mass for lightest nonsinglet two-quark $a_0 = 1.58 \pm 0.34$ GeV, which can be identified with $a_0(1450)$

$\bar{\psi}\gamma_5\psi\,\bar{\psi}\gamma_5\psi\,[\pi\pi, I^G(J^{PC}) \equiv 0^+(0^{++})]$



Scattering states

$E_\pi(p=1) + E_\pi(p=1)$

Possible BOUND state
$\sigma(600)$?

$E_\pi(p=0) + E_\pi(p=0)$

Scattering states
(Negative scattering length)

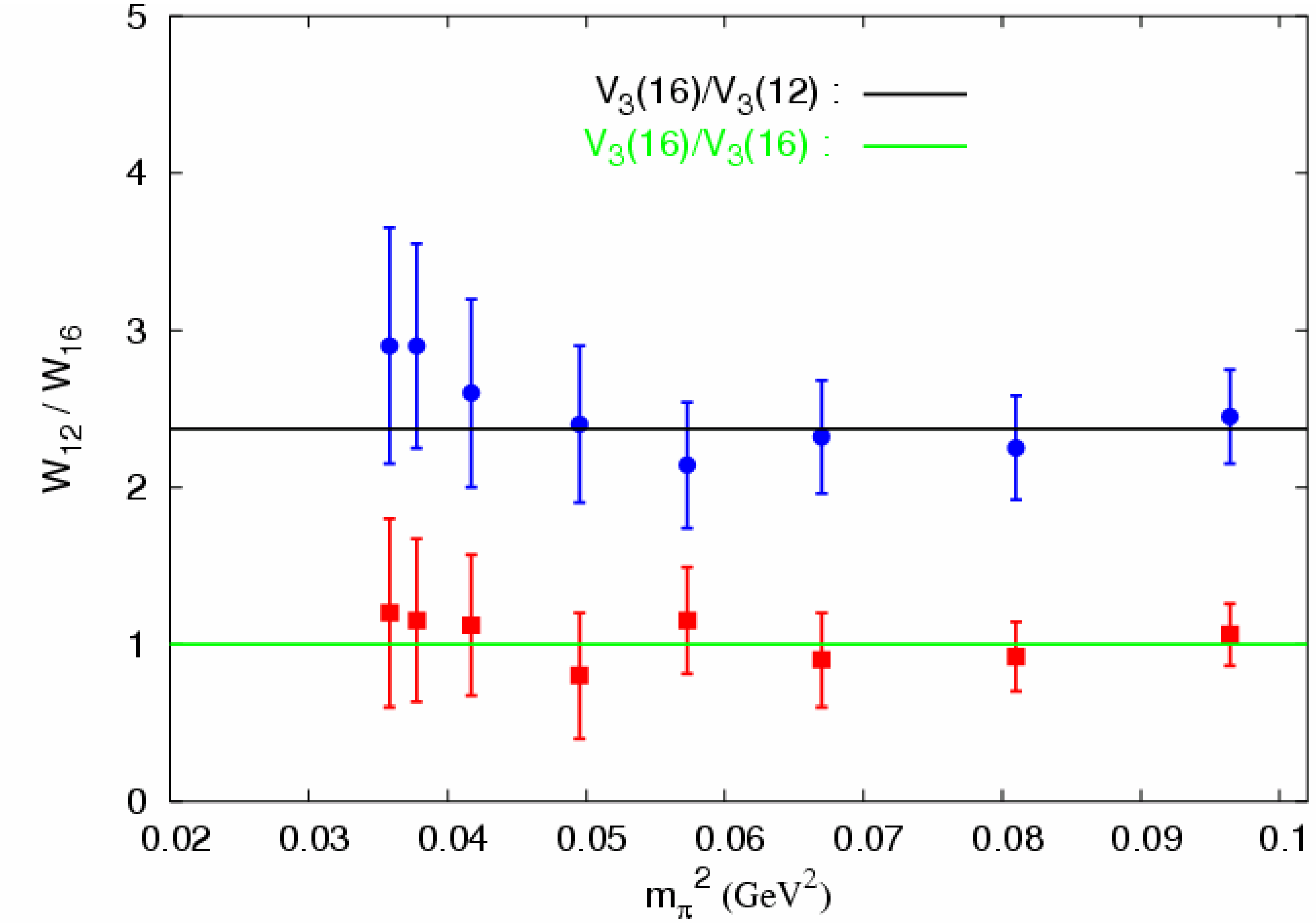
In chiral limit, m_σ=540±170 MeV

Need to check the volume dependence of the observed states

Two lattice sizes : 12^3x28, 16^3x28

For two-particle state, $W_{12}/W_{16}=V_3(16)/V_3(12)=16^3/12^3=2.37$

For one-particle state, $W_{12}/W_{16}=1$



scattering states

σ state

- Scalar $q\bar{q}$ meson has a unit of orbital angular momentum

) a higher mass above 1 GeV

$f_0(1370)$, $a_0(1450)$, $K^*_0(1430)$ and $f_0(1500)/f_0(1710)$ form a P-wave $q\bar{q}$ nonet with some possible mixing with glueballs, supported by lattice.

- Four-quark $qq\bar{q}\bar{q}$ scalar meson can be lighter due to

  (i) absence of the orbital angular momentum barrier in S-wave 4-quark state.

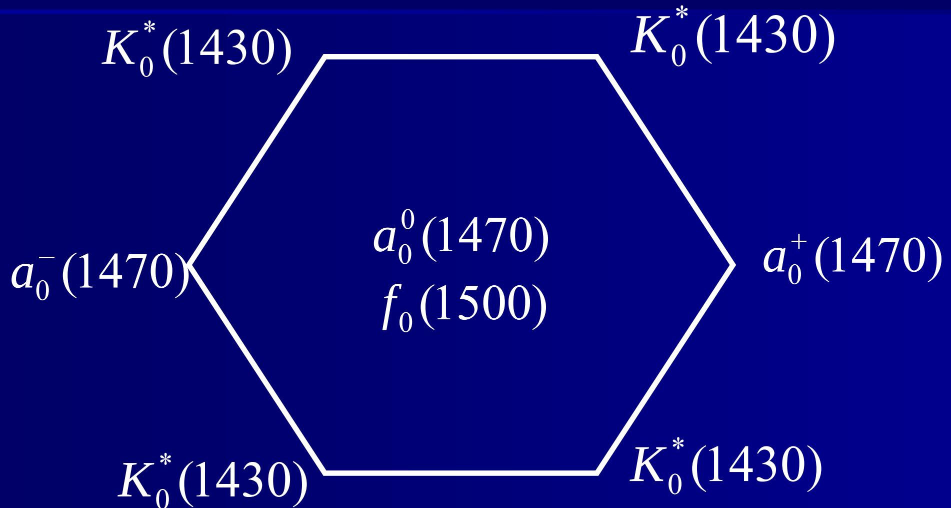
  (ii) a strong attraction between $(qq)_{\bar{3}}$ and $(\bar{q}\bar{q})_3$

) a mass near or below 1 GeV

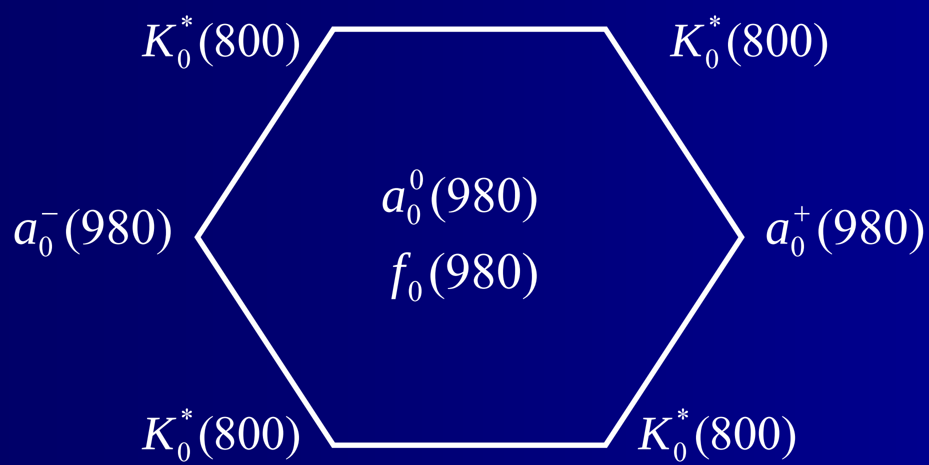
  Light scalar mesons σ, κ, $f_0(980)$, $a_0(980)$, form an **S-wave** nonet

Scalar Mesons and Glueball

glueball $f_0(1710)$



$q\bar{q}$ $+$ $f_0(1370)$



$q^2\bar{q}^2$ $+$ $\sigma(600)$

$$
\begin{array}{c}
 \begin{array}{cccc} u\underline{u} & d\underline{d} & s\underline{s} & G \end{array} \\
M = \begin{pmatrix} M_U & 0 & 0 & 0 \\ 0 & M_D & 0 & 0 \\ 0 & 0 & M_S & 0 \\ 0 & 0 & 0 & M_G \end{pmatrix} + \begin{pmatrix} x & x & x_s & y \\ x & x & x_s & y \\ x_s & x_s & x_{ss} & y_s \\ y & y & y_s & 0 \end{pmatrix}
\end{array}
$$

x: quark-antiquark annihilation

y: glueball-quarkonia mixing

first order approximation: exact SU(3) $\Rightarrow$ $M_U=M_D=M_S=M$, $x=x_s=x_{ss}$, $y_s=y$

$$
\begin{array}{c}
\begin{array}{cccc} a_0 & \text{octet} & \text{singlet} & G \end{array} \\
\begin{pmatrix} M & 0 & 0 & 0 \\ 0 & M & 0 & 0 \\ 0 & 0 & M+3x & \sqrt{3}y \\ 0 & 0 & \sqrt{3}y & M_G \end{pmatrix}
\end{array}
\Rightarrow \begin{cases} a_0 = (u\bar{u} - d\bar{d})/\sqrt{2} = 1474, \quad M_U = M_D = 1474 \pm 19 \text{ MeV} \\ f_0(1500) = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} = 1474 \\ f_0(1370) \text{ and glueball are slightly mixed} \end{cases}
$$

- **y=0, $f_0(1710)$ is a pure glueball, $f_0(1370)$ is a pure SU(3) singlet with mass = M+3x** $\Rightarrow$ x = -33 MeV
- $y \neq 0$, slight mixing between glueball & SU(3)-singlet qq. For |y| ~| x|, mass shift of $f_0(1370)$ & $f_0(1710)$ due to mixing is only ~ 10 MeV

$\Rightarrow$ In SU(3) limit, M_G is close to 1700 MeV

SU(3) Breaking

- **Need SU(3) breaking in mass matrix to lift degeneracy of $a_0(1450)$ and $f_0(1500)$**
- **Need SU(3) breaking in decay amplitudes to accommodate observed strong decays**

e.g. $f_0(1500) = \alpha(|u\bar{u}\rangle + |d\bar{d}\rangle) + \beta|s\bar{s}\rangle$

$$R_1 = \frac{\Gamma(f_0(1500) \to K\bar{K})}{\Gamma(f_0(1500) \to \pi\pi)} = \frac{1}{3}\left(1 + \frac{\beta}{\alpha}\right)^2 \frac{p_K}{p_\pi}, \qquad R_2 = \frac{\Gamma(f_0(1500) \to \eta\eta)}{\Gamma(f_0(1500) \to \pi\pi)} = \frac{1}{27}\left(2 + \frac{\beta}{\alpha}\right)^2 \frac{p_\eta}{p_\pi}$$

For SU(3) octet $f_0(1500)$, $\beta = -2\alpha$ $\Rightarrow$ $R_1=0.21$ vs. 0.246 ± 0.026 (expt)

$R_2=0$ vs. 0.145 ± 0.027 (expt)

LQCD [Lee, Weingarten] $\Rightarrow$ $y= 43\pm31$ MeV, $y/y_s=1.198\pm0.072$

y and x are of the same order of magnitude !

SU(3) breaking effect is treated perturbatively

Chiral suppression in scalar glueball decay

If $f_0(1710)$ is primarily a glueball, how to understand its decay to PP ?

If G→PP coupling is flavor blind, $\Gamma(G \to \pi\pi)/\Gamma(G \to K\bar{K}) = 0.91$

$$\frac{\Gamma(f_0(1710) \to \pi\pi)}{\Gamma(f_0(1710) \to K\bar{K})} = \begin{cases} 0.20 \pm 0.04 & \text{WA102} \\ < 0.13 & \text{BES from } J/\psi \to \omega(K\bar{K}, \pi\pi) \\ 0.41^{+0.11}_{-0.17} & \text{BES from } J/\psi \to \gamma(K\bar{K}, \pi\pi) \end{cases}$$

chiral suppression: A(G→$q\bar{q}$) ∝ m_q/m_G in chiral limit **[Chanowitz]**

$$\Gamma(G \to \pi\pi)/\Gamma(G \to K\bar{K}) \propto m_u^2 / m_s^2 \ \ ?$$

Chiral suppression at hadron level is probably not so strong due to nonperturbative chiral symmetry breaking and hadronization

[Chao, He, Ma] : m_q is interpreted as chiral symmetry breaking scale

[Zhang, Jin]: instanton effects may lift chiral suppression

LQCD [Sexton, Vaccarino, Weingarten] ⇒

$$g^{\pi\pi} : g^{K\bar{K}} : g^{\eta\eta} = 0.834^{+0.603}_{-0.579} : 2.654^{+0.372}_{-0.402} : 3.099^{+0.364}_{-0.423}$$

	Experiment	fit (i)	fit (ii)
$M_{f_0(1710)}$ (MeV)	1718 ± 6 [18]	1718	1718
$M_{f_0(1500)}$ (MeV)	1507 ± 5 [18]	1510	1504
$M_{f_0(1370)}$ (MeV)	1350 ± 150	1348	1346
$\frac{\Gamma(f_0(1500)\to\eta\eta)}{\Gamma(f_0(1500)\to\pi\pi)}$	0.145 ± 0.027 [18]	0.068	0.081
$\frac{\Gamma(f_0(1500)\to K\bar{K})}{\Gamma(f_0(1500)\to\pi\pi)}$	0.246 ± 0.026 [18]	0.26	0.27
$\frac{\Gamma(f_0(1710)\to\pi\pi)}{\Gamma(f_0(1710)\to K\bar{K})}$	0.30 ± 0.20(see text)	0.21	0.34
$\frac{\Gamma(f_0(1710)\to\eta\eta)}{\Gamma(f_0(1710)\to K\bar{K})}$	0.48 ± 0.15 [20]	0.26	0.51
$\frac{\Gamma(a_0(1450)\to K\bar{K})}{\Gamma(a_0(1450)\to\pi\eta)}$	0.88 ± 0.23 [18]	1.10	1.12
$\frac{\Gamma(a_2(1320)\to K\bar{K})}{\Gamma(a_2(1320)\to\pi\eta)}$	0.34 ± 0.06 [18]	0.45	0.46
$\frac{\Gamma(f_2(1270)\to K\bar{K})}{\Gamma(f_2(1270)\to\pi\pi)}$	$0.054^{+0.005}_{-0.006}$ [18]	0.056	0.057
χ^2/d.o.f.		2.6	2.5

	Experiment	fit (i)	fit (ii)
$\frac{\Gamma(f_0(1370)\to K\bar{K})}{\Gamma(f_0(1370)\to\pi\pi)}$	see text	1.27	0.79
$\frac{\Gamma(f_0(1370)\to\eta\eta)}{\Gamma(f_0(1370)\to K\bar{K})}$	0.35 ± 0.30 [18]	0.21	0.12
$\frac{\Gamma(f_2(1270)\to\eta\eta)}{\Gamma(f_2(1270)\to\pi\pi)}$	0.003 ± 0.001 [27]	0.005	0.005
$\frac{\Gamma(J/\psi\to\omega f_0(1710))}{\Gamma(J/\psi\to\phi f_0(1710))}$	6.6 ± 2.7 [21, 31, 32]	3.8	4.1
$\frac{\Gamma(J/\psi\to\omega f_0(1500))}{\Gamma(J/\psi\to\phi f_0(1500))}$		0.44	0.47
$\frac{\Gamma(J/\psi\to\omega f_0(1370))}{\Gamma(J/\psi\to\phi f_0(1370))}$		2.85	2.56
$\Gamma_{f_0(1710)\to PP}$ (MeV)	$< 137 \pm 8$ [18]	84	133
$\Gamma_{f_0(1370)\to PP}$ (MeV)		404	146

In absence of chiral suppression (i.e. $g^{\pi\pi}=g^{KK}=g^{\eta\eta}$), the predicted $f_0(1710)$ width is too small (< 1 MeV) $\Rightarrow$ importance of chiral suppression in G→PP decay

Consider two different cases of chiral suppression in G→PP:

(i) $g^{\pi\pi} : g^{K\bar{K}} : g^{\eta\eta} = 1 : 1.55 : 1.59$

(ii) $g^{\pi\pi} : g^{K\bar{K}} : g^{\eta\eta} = 1 : 3.15 : 4.74$

Scenario (ii) with larger chiral suppression is preferred

Amseler-Close-Kirk

$$|f_0(1710)\rangle = 0.93|G\rangle + 0.32|N\rangle + 0.17|S\rangle$$
$$|f_0(1500)\rangle = 0.03|G\rangle - 0.54|N\rangle + 0.84|S\rangle$$
$$|f_0(1370)\rangle = -0.36|G\rangle + 0.78|N\rangle + 0.52|S\rangle$$

$$|f_0(1710)\rangle = 0.36|G\rangle + 0.09|N\rangle + 0.93|S\rangle$$
$$|f_0(1500)\rangle = -0.84|G\rangle - 0.41|N\rangle + 0.35|S\rangle$$
$$|f_0(1370)\rangle = 0.40|G\rangle - 0.91|N\rangle - 0.07|S\rangle$$

M_N=1474 MeV, M_S=1498 MeV, M_G=1666 MeV, $M_G>M_S>M_N$

- **M_S-M_N ~ 25 MeV is consistent with LQCD result**

  $\Rightarrow$ near degeneracy of $a_0(1450)$, $K_0^*(1430)$, $f_0(1500)$

- **Because $n\bar{n}$ content is more copious than $s\bar{s}$ in $f_0(1710)$,**

  $\Gamma(J/\psi\to\omega f_0(1710)) = 4.1\ \Gamma(J/\psi\to\phi f_0(1710))$ versus 6.6±2.7 (expt)

  If $f_0(1710)=s\bar{s}$, one needs large doubly OZI ~ 5 OZI [Close, Zhao]

- **$\Gamma(J/\psi\to\gamma f_0(1710)) >> \Gamma(J/\psi\to\gamma f_0(1500))$**

  in good agreement with expt.

  $\Gamma(J/\psi\to\gamma f_0(1710)) \sim 5\ \Gamma(J/\psi\to\gamma f_0(1500))$

- **$f_0(1710)$ is not seen in $p\bar{p}\to\pi^0 f_0$ at LEAR (2002), but now observed in $p\bar{p}\to\pi^0\eta\eta$ at Fermilab (2006)**
- **2γ-quarkonium coupling**

  $f_0(1370)$: $f_0(1500)$: $f_0(1710)$ = 9.3 : 1.0 : 1.5

  2γ coupling of $f_0(1500)$ is weak even if it has no glue content

Conclusions

- We use two recent lattice results to constrain mixing matrix of $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$: (i) scalar glueball mass ~ 1700 MeV, (ii) SU(3) symmetry in scalar meson sector > 1 GeV

- Exact SU(3) $\Rightarrow$ $f_0(1500)$ is an SU(3) octet, $f_0(1370)$ is an SU(3) singlet with small mixing with glueball. This feature remains to be true even when SU(3) breaking is considered

- Chiral suppression in $G \to PP$ decays is essential. Hadronic and radiative J/ψ decays all indicate prominent glueball nature of $f_0(1710)$