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Gluonic States: Glueballs & Hybrids

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Glueballs & Hybrids

- Overview
- "Ordinary" $\bar{q}q$ mesons (in brief)
- Properties of gluonic states
- Glueball candidates
- Hybrid candidates
- Conclusion

Discovery and elucidation of gluonic states is perhaps the most important unsolved problem in QCD:

- The spectrum is traditionally *the* fundamental test of any quantum mechanical theory
- Gluonic states are the sector of the spectrum that tests the unique **nonAbelian** dynamics of QCD:

gluons carry color charge

□ color confinement (& asymptotic freedom)

□ gluon confinement

□ gluonic bound states (glueballs & hybrids)

We can’t be sure we understand QCD until we have discovered and understood gluonic states,

… or, if we cannot find them, until we have understood why not.

<u>“Proof” of existence of glueballs</u> (Bjorken)

- Suppose no light quarks, just one heavy flavor Q

$$m_Q >> \square_{QCD}$$

Consider $e^+e^- \ \square \ \ \square_{\overline{Q}Q}$ $2m_Q < E < 4m_Q$

- Perturbation theory is valid: $\square_{\overline{Q}Q} \ \square$ ggg
- Confinement $\square$ final state must contain glueballs

- Include light quarks u,d,s: glueballs remain in spectrum, though they may mix with light mesons.

All theoretical approaches

LGT (lattice), bag & flux tube models, QCD sum rules

agree that glueballs should exist.

Dynamical question remains: are glueballs narrow enough to be well-defined resonances?

Glueball search: very difficult

- Expt'l search began ~ 1980 when □(1440) was observed in
  □ □ □$\bar{K}K$□ ($J^{PC} = 0^{-+}$, first confused with $J^{PC} = 1^{++}$ "E" = $f_1(1420)$)
- 24 years later it seems very unlikely that □is a glueball:
  - Lattice predicts 0^{-+} glueball mass > 2 GeV
  - Later exp'ts split □(1440) into □(1405) & □(1475)
  - Some new physics may yet be needed in 0^{-+} at ~ 1400
- Current focus on scalars near quenched LGT (lattice) prediction.
  BESII: □ □ □f(1710) □ □$\bar{K}K$ **$J^{PC} = 0^{++}$**

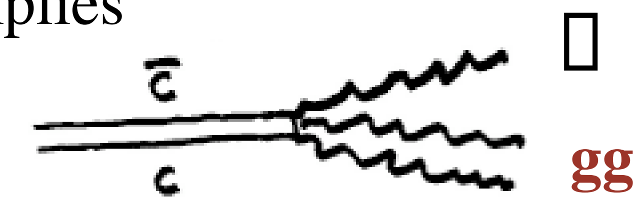
We should not be surprised by the difficulty of the problem:

- Experiment needs high statistics PWA, only becoming available now from BESII.
- Theory needs quantitatively reliable nonperturbative techniques, which LGT is only beginning to provide.

Excellent prospects for BESII, BEPCII/BESIII, and CESR-C

Special role of radiative J/ψ decay

For heavy quark Q, perturbation theory implies



$$\Gamma(V_{\bar{Q}Q} \to \gamma X)_{\text{inclusive}} \approx \Gamma(V_{\bar{Q}Q} \to \gamma gg)$$

→ **color singlet**

$$\Rightarrow \quad \frac{\Gamma(\psi \to \gamma gg)}{\Gamma(\psi \to ggg)} \sim \frac{16\alpha}{5\alpha_S} \sim 0.09$$

MC, Okun-Voloshin

$$B(\psi \to ggg) \sim B(\psi \to \text{hadrons})_{\text{direct}} = 0.71$$

$$\Rightarrow \quad B(\psi \to \gamma X) \approx 0.06$$

~ Consistent w MarkII
No recent measurement

… and **gg** partial waves in pert. th'y are $J^{PC} = 0^{++}, 0^{-+}, 2^{++}$

⇒ **Copious source of γ-tagged color-singlet gg pairs, perfectly matched to expected masses & quantum numbers of low-lying glueballs.**

Radiative J/□ decay (2)

- Rough agreement of pert. th'y with (old) □ □ □X data verifies that leading short distance mechanism is

  □+ gg-color-singlet

- □(□ □ □X) agrees roughly with pert. th'y but not **d□/dE□**, because resonances dominate:

  bad news for testing QCD,

  but good news for glueball hunting.

- Heavier quarkonia like □(9460) cannot compete, because □(3097) has:
  - biggest peak cross section
  - best signal:background
  - factor 4 in B(□ □ □X)/ B(□ □ □X)/ from quark charges
  - glueball region is biggest fraction of radiative decays

Radiative □ decay is the idea glueball hunting ground

Other production channels

- Hadronic scattering: π, K, p, $\bar{p}$ beams
  - High statistics source of all $\bar{q}q$, possible glueball & hybrid production
  - Analyze flavor content by varying production & decay channels.
  - Important results from high statistics PWA,
    e.g., E852, VES, Crystal Barrel, WA102, LASS + …
  - Some might be "gluon rich"
    - $\bar{p}p$ annihilation
    - Pomeron-dominated central production

Maybe(?): not as well understood as $J/\psi \to \gamma X$

- Hadronic J/ψ decay:
  - Analyze flavor content: e.g., $J/\psi \to \phi + \bar{s}s$ or $\omega + (\bar{u}u + \bar{d}d)$ OIZ rule
  - May also be source of glueballs & hybrids
- Two photon scattering: glueball production suppressed

Stickiness: $$S_X = C\,\frac{\Gamma(J/\psi \to \gamma X) \times \text{Phase Space }(X \to \gamma\gamma)}{\Gamma(X \to \gamma\gamma) \times \text{Phase Space }(J/\psi \to \gamma X)}$$ MC

Expect $\mathbf{S_{glueball} >> S_{meson}}$

$$\frac{M(X \to gg)^2}{M(X \to \gamma\gamma)^2}$$

Hybrids

Hybrids were first proposed in the bag model, where valence gluons are as natural as valence quarks. Then

$$| gg > \sim \text{ glueball}$$
$$|(qq)_8 g > \sim \text{ hybrid}$$

In strong coupling limit of LGT, gluonic states are instead collective excitations of soft gluons, but it is conceivable that “valence glue” might emerge in the continuum limit.

In any case, hybrids are expected to exist in all theoretical approaches, including LGT, bag model, flux-tube model, and QCD sum rules.

Hybrids (2)

- Same flavor structure as ordinary $\bar{q}q$ mesons: **flavor nonets**

- Some hybrids have **exotic J^{PC}**, that do not occur in the naïve quark model (NRQM).
  - Can't be confused with ordinary $\bar{q}q$ mesons
  - Can't mix with ordinary $\bar{q}q$ mesons
  - Exotic hybrids might mix with exotic $\bar{q}q\bar{q}q$/ two-meson states, if such exist.

- All approaches

  LGT, bag, flux tube, QCD sum rules

  agree that $\mathbf{J^{PC} = 1^{-+}}$

  is the lightest exotic.

- There is experimental evidence for isovector $\mathbf{J^{PC} = 1^{-+}}$ states.

Theory: the state of play

Models -- flux tube, bag, nonrel. constituent models, … ---
may all be useful sources of "inspiration" & motivation,
but they are all uncontrolled approximations that
cannot be trusted to provide definitive interpretations
of the experimental data. Success for ordinary $\bar{q}q$ & qqq
does not ensure their validity for gluonic states.

LGT (Lattice gauge theory) offers a controlled approximation which may eventually provide definitive theoretical understanding, but not yet:

- Ordinary mesons & baryons OK within few % --- unquenched.
- Quenched glueball mass estimates are credible, but unquenched results are still preliminary: essential to understand glueball-meson mixing, which may be larger than ordinary meson-meson mixing.
- Estimates of decay widths have only just begun -- very preliminary

We can hope that LGT will eventually be definitive.
For now we use simple ideas and models to guide the search.

Huge challenge: *develop analytical methods to complement LGT*.

Simple Ideas

- Glueballs are new degrees of freedom in meson spectrum, **extra states** in addition to ordinary $\bar{q}q$ mesons.
  - To use this simple idea, we must understand the ordinary $\bar{q}q$ spectrum **very well.**
  - Analysis might be greatly complicated by mixing.

- 0^{++}, 2^{++}, 0^{-+} glueballs below ~ 2.5 GeV should be produced at big rates in □ □ □G, with BR $\geq O(10^{-3})$.

- Glueballs are sticky: small □□couplings

- Glueballs decay like $SU(3)_{Flavor}$ singlets.

Warning: might not apply to J = 0.

Ordinary $\bar{q}q$ Mesons

Must understand “old” physics to find the “ new”

- gluonic states overlap complicated $\bar{q}q$ spectrum
- gluonic states & $\bar{q}q$ can mix

Interesting & poorly understood

- why do valence quarks dominate static properties?
- why does naive NRQM (nonrelativistic quark model) work so well?
- why does OIZ rule work so well for light quarks?

High statistics experiments using PWA (partial wave analysis) have made great progress: there are currently **10** nonets that are completely filled with well-established resonances.

Ordinary Mesons: Topics

- A quick look at the spectrum
- Isoscalar mixing & the OIZ rule
  - Models: MNQM & LNQM
  - Examples: ideal vectors, not-ideal pseudoscalars
- A tour of relevant nonets
  - p-wave nonets
  - an extra scalar nonet
  - radially excited pseudoscalars
- Summary

Nonrelativistic $\bar{q}q$ spectrum

$$J = L \oplus S$$

$$S = 1/2 \oplus 1/2 = \begin{cases} 0 & 1/\sqrt{2}\,(\uparrow\downarrow - \downarrow\uparrow) \quad \text{singlet} \\ 1 & \uparrow\uparrow,\ 1/\sqrt{2}\,(\uparrow\downarrow + \downarrow\uparrow),\ \downarrow\downarrow \quad \text{triplet} \end{cases}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+1}\,(-1)^{S+1} = (-1)^{L+S}$$

$L = 0$	$J^{PC} = 0^{-+},\ 1^{--}$
$L = 1$	$J^{PC} = 1^{+-},\ (0,1,2)^{++}$
$L = 2$	$J^{PC} = 2^{-+},\ (1,2,3)^{--}$
$\vdots$	

Radial Quantum Number:

$N = 1$	ground state
$N = 2,3,\ldots$	radial excitations

<u>Observed meson nonets</u>

Complete (orange) | Almost Complete (cyan)

N = 1

L = 0	0^{-+}		1^{--}		770	
L = 1	1^{+-}	0^{++}	1^{++}	2^{++}	1320	*Two* 0^{++}
L = 2	2^{-+}	1^{--} *	2^{--}	3^{--}	1690	*Missing □
L = 3	3^{+-}	2^{++}	3^{++}	4^{++} #	2050	#Missing f_4□

Mass is for leading isovector at each N,L

N = 2

L = 0	0^{-+} **	1^{--}	1450	**K needs confirmation, One extra I = 0 !

Warning: some excited states might be nonexotic hybrids
or mixed with hybrids.

Flavor "nonet"

$$9 = \underset{\sim}{8} + \underset{\sim}{1}$$ SU(3)$_{\text{Flavor}}$ representations

Isoscalars X_0, X_0' mixing depends on OIZ rule:

- OIZ rule valid $\Rightarrow$ ideal mixing

$$X_0 = \frac{u\bar{u} + d\bar{d}}{2}$$

$$X_0' = s\bar{s}$$

- Strong OIZ violation in flavor-singlet channel

$\Rightarrow$ $\underset{\sim}{1}$ - $\underset{\sim}{8}$ mixing

$$X_0 = X_8 = \frac{1}{6}(\bar{u}u + \bar{d}d - 2\bar{s}s)$$

$$X_0' = X_1 = \frac{1}{3}(\bar{u}u + \bar{d}d + \bar{s}s)$$

• $d\bar{s}$ • $u\bar{s}$

• X_0

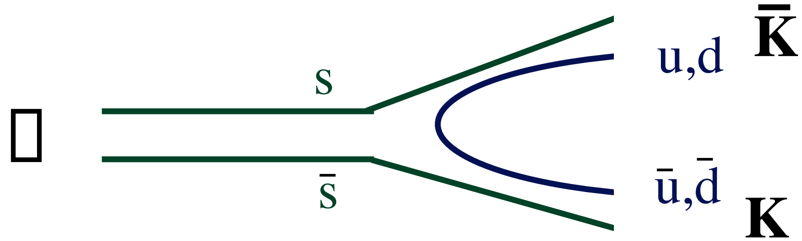
• $d\bar{u}$ • $\frac{u\bar{u} - d\bar{d}}{2}$ • $u\bar{d}$

• X_0'

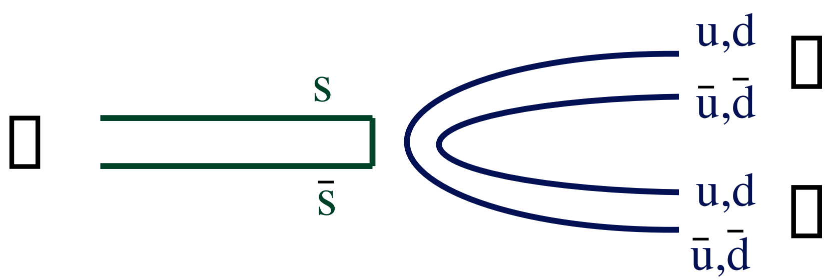
• $s\bar{u}$ • $s\bar{d}$

In general: mixing intermediate between ideal and 1-8.

OIZ rule



OIZ allowed
E.g., □—> K̄K



OIZ forbidden
E.g., □—> □□

Works very well:

$$\frac{g^2_{\phi \overline{K} K}}{g^2_{\phi\rho\pi}} \simeq O(100)$$

As if strong interaction isn't so strong…

The MNQM (The *Most* Naive Quark Model)

$$\mathcal{H}_{MNQM} = \mathcal{H}_{Free} = m(\overline{u}u + \overline{d}d) + m_s\overline{s}s$$

$$< \frac{\overline{u}u + \overline{d}d}{\sqrt{2}} |\mathcal{H}_{Free}| \overline{s}s >= 0$$

Trivial "OIZ" rule

➡ **Ideal mixing:**

$$\boxed{X_0 = \frac{\overline{u}u + \overline{d}d}{\sqrt{2}} \qquad X_0' = \overline{s}s}$$

Masses:

$$m_{I=1} = 2m$$

$$m_{I=\frac{1}{2}} = m + m_s$$

$$m_0 = 2m$$

$$m_0' = 2m_s$$

➡

$$\boxed{\begin{aligned} m_{I=1} &= m_0 \\ m_{I=\frac{1}{2}} &= \frac{m_0 + m_0'}{2} \end{aligned}}$$

To show: OIZ + SU(3) ⬜ same result

The LNQM (The *Less* Naive Quark Model)

$$\mathcal{H}_{LNQM} = \mathcal{H}_{Free} + \mathcal{H}'$$

$$X_0 \simeq \frac{\overline{u}u + \overline{d}d}{\sqrt{2}}$$

~ ideal eigenstates

OIZ: $$< \frac{\overline{u}u + \overline{d}d}{\sqrt{2}} | \mathcal{H}' | \overline{s}s > \simeq 0$$

$$X_0' \simeq \overline{s}s$$

"Theorem": SU(3) symmetry + OIZ rule imply equal 1 & 8 interaction energies

Proof:
$$X_0 = \sqrt{\frac{1}{3}} X_8 + \sqrt{\frac{2}{3}} X_1$$

$$X_0' = -\sqrt{\frac{2}{3}} X_8 + \sqrt{\frac{1}{3}} X_1$$

OIZ □ $$0 =< X_0' | \mathcal{H}' | X_0 >= \frac{\sqrt{2}}{3} (\mathcal{H}_{11}' - \mathcal{H}_{88}' - \frac{1}{\sqrt{2}} \mathcal{H}_{18}' - \sqrt{2} \mathcal{H}_{81}')$$

SU(3) Sym. □ $$0 = \mathcal{H}_{18}' = \mathcal{H}_{81}'$$

□ $$\mathcal{H}_{11}' = \mathcal{H}_{88}'$$

"nonet symmetry" for interaction energy

From "Theorem", $$m_1 = m_0$$

$$m_{\frac{1}{2}} = \frac{m_0 + m_0'}{2}$$

OIZ + SU(3) □ ideal mixing & free quark mass formula

$J^{PC} = 1$□□ : the ideal, ideal nonet

□(776), K*(894), □(783), □(1019)

Average of K^{*0} and K^{*+}

- Ideal mixing & OIZ

$$\frac{g^2_{\phi \overline{K} K}}{g^2_{\phi \rho \pi}} \simeq O(100) \quad \Rightarrow \quad \phi \simeq \overline{s} s, \qquad \omega \simeq \frac{\overline{u} u + \overline{d} d}{\sqrt{2}}$$

- Mass formulas to 1%

770 ~ 783   894 ~ 901

Highest spin complete nonet   **3**□□

□$_3$(1689), K_3*(1776), □$_3$(1667), □$_3$(1854)

Mass formula valid to ~ 1%

OIZ/ideal mixing:

- □$_3$ □ □□, □□□   produced in □p
- □$_3$ □ $\overline{K}$K, $\overline{K}$K*   produced in Kp

(Why do the simple ideas work so well? – *a speculation)*

In the history of QCD very simple ideas have had more success than we might reasonably have expected, e.g.,

- Valence quark description of spectrum
- OIZ rule
- Successes of bag model & NRQM

If nonvalence components were important, wouldn't have simple SU(3) reps & QCD would have been *much* harder to discover.

Maybe the strong interaction is not *so* strong:

There is a growing body of evidence from experiment & theory that $\alpha_S(Q)$ has an IR fixed point at $\alpha_S/\pi \approx 0.3$:

not small enough for precise quantitative control, but perhaps small enough for qualitative/semiquantitative success of simple approaches.

E.g.,

- D-S eqs,: Cornwall +…
- Exp't: Mattingly & Stevenson, Brodsky *et al*. +…
- LGT: Bernard *et al*.

But life is not always ideal: groundstate 0 □+

□(140), K(496), □(548), □(958)

Ideal mass relations? 140 = 548 / 496 = 753 — Poor even by theorist standards

Instead SU(3) mass formula for □$_8$ works better for m$_□$:

$$m_8^2 = \frac{4}{3}m_K^2 - \frac{1}{3}m_\pi^2 = (565)^2 \simeq m_\eta^2$$

Quadratic mass formula follows from chiral symmetry broken by quark masses.

$$\eta \simeq \eta_8 = \frac{1}{\sqrt{6}}(\overline{u}u + \overline{d}d - 2\overline{s}s)$$

Mixing closer to **1 - 8** (□$_{1\text{-}8}$ ~ – 20^o)

$$\eta' \simeq \eta_1 = \frac{1}{\sqrt{3}}(\overline{u}u + \overline{d}d + \overline{s}s)$$

OIZ rule badly broken: $\mathcal{H}_{11} \gg \mathcal{H}_{88}$ — Chiral anomaly, “U(1)” problem…

Warning: *J = 0 can be “different”*

P-wave 2^{++}

a_2(1318), K^*_2(1429), f_2(1275), f_2□(1525)

- Mass formulas valid at 3% & 2%
- f □ □□ & f□□ $\bar{K}K$ dominant

Approximately ideal

Compute conventional quark model mixing angle:

$$M = \begin{pmatrix} m_8 & □ \\ □ & m_1 \end{pmatrix}$$

□, m_1 = free parameters

From SU(3) $$m_8 = \frac{4}{3} m_{K*} - \frac{1}{3} m_{a_2}$$

Diagonalize with □ in ideal basis,

$$f_2 = cos\theta \frac{\overline{u}u + \overline{d}d}{\sqrt{2}} + sin\theta \overline{s}s$$

$$f_2' = -sin\theta \frac{\overline{u}u + \overline{d}d}{\sqrt{2}} + cos\theta \overline{s}s$$

find $$\theta_{Ideal} = -6^o$$

$$(\theta_{1-8} = \theta_{Ideal} + 35^o)$$

P-wave 1^{++} & 1^{+-}

1^{+-}: $b_1(1230)$, K_{b1}(?), $h_1(1170)$, $h_1(1386)$

Looks ~ ideal:
- 1230 ~ 1170
- 1170 produced w □ beam, decays □ □□
- 1386 produced w K beam, decays □ K*K

1^{++}: $a_1(1230)$, K_{a1}(?), $f_1(1282)$, $\left\{ \begin{array}{l} f_1(1426) \\ f_1(1518) \end{array} \right.$ **?**

- 1426 & 1518 both decay □ K*K
- 1426 produced w □ beam, 1518 w K beam

My vote: 1518

Looks ~ ideal:
- f_1, f_1□ production/decay pattern ideal
- but m_1 uncertain ± 40, □ ~ 250 - 600 □ $m_1 = m_0$?

Mass eigenstates $K_1(1270)$ & $K_1(1400)$ are mixtures of K_{a1} & K_{b1} (mixing allowed by SU(3) breaking).

If f_1□= $f_1(1518)$ then $f_1(1426)$ is an **extra** state.

P-wave 0^{++} Two nonets?

$$a_0(1474),\ K_0^*(1412),\ f_0(1370),\ \left\{\begin{matrix} f_0(1507) \\ f_0(1714) \end{matrix}\right. \ \textbf{?}$$

Difficult experimentally:
- nonleading partial waves hard to see
- 1474, 1412, 1370 very broad
  □ masses somewhat ill-defined.

Masses in ~ same range as other p-wave nonets,

Masses do not match pattern of ideal mixing

- $m_a \neq m_{f0}$
- peculiar that $m_a > m_{K^*}$

But these are the broad states with ill-defined masses.

No obvious assignment of $f_0(1507)$ vs. $f_0(1714)$:
plausible to consider that they are G_0-f_0□mixtures, but no nice solution has emerged consistent with the data – more on this to follow.

A Second Scalar Nonet

$a_0(980)$, $K_0{}^*(800)$, $f_0(600)$, $f_0(980)$

Very peculiar if interpreted as $\bar{q}q$ nonet

- $a_0(980)$, $f_0(980)$ couple strongly to KK despite being just below KK threshold.
- $f_0(600) \sim$ "□" & $K_0{}^*(800) \sim$ "□" are *very* broad, **□ ~ O(m)**, but $a_0(980)$, $f_0(980)$ appear to have O(100) MeV widths.
- $m_{a0} = m_{f0(980)}$ looks ideal, *except* that $f_0(980)$ is the heavier isoscalar. Instead $m_{a0} = m_{f0(600)}$ fails badly.

A Second Scalar Nonet (2)

Jaffe 1977

Bag model analysis with $SU(6)_{\text{Color-spin}}$

Low-lying "crypto-exotic" scalar nonet.

$a_0 = (\bar{u}u - \bar{d}d)\bar{s}s$
$f_0 = (\bar{u}u + \bar{d}d)\bar{s}s$
□ $= \bar{u}u\bar{d}d$
□ $= d\bar{s}(\bar{u}u + \bar{d}d)$

Beautifully explains nonet's peculiarities:

- a_0 & f_0 couple strongly to $\bar{K}K$
- $m_{a0} = m_{f0(980)} >> m_{f0(600)}$
- "Fall-apart" decay to two-meson final states
  - □ for □, □ expect □ ~ O(m)
  - □ a_0, f_0 narrow because $\bar{K}K$ kinematically suppressed

Alternative dynamical description: $\bar{K}K$ "molecules"

A Second Scalar Nonet (3)

Cryptoexotic interpretation of a_0, f_0 is supported by recent data:

- Radiative □ decay: □□ □a_0□ □□$_0$□ DAFNE

  □□ □f_0□ □□$_0$□$_0$

  ➡ a_0,f_0 have big $\bar{s}s$ components

- Hadronic □ decay: □(□ □ □□$^+$□$^-$) / □(□ □ □K^+K^-) BES

  ➡ $f_0(980)$ couplings: $\mathbf{g_{KK}/g_{\pi\pi} = 4.21 \pm 0.25 \pm 0.21}$

If there were many $\bar{q}\bar{q}qq$/molecular resonances, the simple $\bar{q}q$ classification would not have worked so well and it might have been much more difficult to discover quarks and QCD.

In cryptoexotic picture other $\bar{q}\bar{q}qq$ are too broad to observe as resonances: explains why ordinary $\bar{q}q$ taxonomy works so well.

Radially excited 0^{-+}

□(1300), K(1460), □(1294) $\left\{ \begin{array}{l} \text{□(1405)} \\ \text{□(1476)} \end{array} \right.$

□(1300): □ ~ 200 – 600, m ~ 1300 ± 100   ill-defined

K(1460): □ ~ 250, mass not well determined

□(1294): □ = 50 ± 5, produced: □p,   decay □ □□□

□(1405) & □(1476): □ = 55 & 87, produced: □p, pp, □ □ □X

dominant decay: □(1405) □ a_0□,   □(1476) □ K*K

DM2 had opposite(?)

Ideal?

– hard to test mass rel'ns since □, K masses poorly known

– if ideal, □(1476) is plausible $\bar{s}s$ □ □(1405) **extra**

- In general, some combination of □(1405) & □(1476) is extra.
- BESII & BESIII/CESR-C pwa of □ □ □KK□/□□□ at 1400-1500 MeV will be *very interesting*

Summary

Tremendous experimental progress in establishing meson spectrum.

NRQM provides a surprisingly good zero’th order description of the spectrum.

Deviations from NRQM spectrum are possible signs of new physics, including gluonic states.

- extra scalar nonet seems to be cryptoexotic $\bar{q}\bar{q}qq$/ “moleculear”.
- Interesting *extra* isoscalars
  - ❅ $f_1(1426)$ & $f_1(1518)$
  - ❅ □(1405) & □(1476)
  - ❅ $f_0(1507)$ & $f_0(1714)$

Other states which seem to have unambiguous $\bar{q}q$ assigments might actually be nonexotic hybrids or meson-hybrid mixtures: *Continued experimental progress with the “ordinary” mesons is essential to understand what might be a very complicated spectrum.*

Theoretical Approaches

Models
- NRQM
- Bag
- Flux tube

Describe & Critique

QCD sum rules – a "good try" to get nonperturbative results from a perturbative method.

Lattice Gauge Theory: a systematically improvable approximation to continuum QCD.
- Glueballs
  - spectrum
  - dynamics
- Hybrids

Nonrelativistic potential models

NRQM assumes $v \ll c$ **&** instantaneous potential

BUT $r \sim 0.8$ fm □ $p \sim 1/r \sim 250$ MeV

□ $v \sim O(c)$ for $m_q \lesssim 300$ MeV

BUT² confining force is not instantaneous

□ additional states from excitation of collective modes of soft confining quanta: *string/cavity/flux-tube excitations*

hybrids

- Reasonable approximation for heavy quarks, not for u,d,s.
- NRQM works surprisingly well (qualitative/semi-quantitative) for u,d,s, — why?

Models with massive nonrelativistic gluon constituents:

- *a priori* no reason to expect they are valid or how to choose mass, potential
- *a posteriori* we'll learn if they have any validity
- limited utility for predicting or interpreting *terra incognita*

Bag Model

Crude relativistic model of confinement

Recipe:

- Assume **fixed spherical** cavity, $\mathbf{V = \infty}$ at boundary
- Solve free field eqs with boundary condition

$$E_i = C_i/R \qquad \begin{array}{ll} \text{Dirac:} & C_q = 2.02 \\ \text{Maxwell} & C_g = 2.79 \quad (1^{-+}) \end{array} \qquad \text{groundstates}$$

- minimize wrto R: $\quad E(R) = \Sigma\, C_i/R + (4/3)\pi R^3 \mathbf{B}$
- Reasonable fit to s-wave mesons & baryons: determines **B**

Valence gluons are as natural as valence quarks

Glueball/hybrid mass predictions significantly below LGT

BUT: actual confining force is dynamical,

not fixed or spherical or infinitely sharp

BUT²: no reason to expect that $B_{glueball} = B_{meson}$

more natural: $B_{glueball} > B_{meson}$ gluon's color charge bigger than quark's

would raise glueball mass predictions

Flux tube model

Model of confinement based on LGT in strong-coupling, coarse-grained phase

- strong-coupling phase assures confinement but is far from true QCD which is at weak-coupling continuum limit.
- quarks treated nonrelativistically, in potential from adiabatic variation of connecting string/tube.

Good description of ordinary meson & baryon spectrum, including excitations.

Does not have valence gluons, but does predict glueballs and hybrids, in which the gluonic components are flux-tube excitations, presumeably due to collective excitations of soft gluons that cause confinement.

Valence Gluons ?

By construction in the bag model, valence gluons occur as naturally as valence quarks and there are no collective excitations of soft modes .

By construction in the flux-tube model, gluonic states reflect collective excitations of soft modes and there are no valence gluons.

BUT - in the bag we follow a fixed cavity *approximation;* we could in principle consider cavity excitations.
- in the flux-tube we *could* put gluons at flux tube ends (massless gluon no more problematic than 5 MeV u-quark).

Q1: Are these complementary descriptions of the same states?

Q2: If not, could both descriptions be correct?
—then we expect gluonic states of both kinds.

Answer could emerge from continuum limit of LGT or by high-p_T scattering from gluonic-states. **:)**

Models and the frailty of mankind

- Models are simple because humans are weak: we design them to be simple enough to solve.

- Simplified models are useful and necessary in theoretical physics, **but** it can be difficult to distinguish genuine predictions from the consequences of simplifying assumptions.

- Examples:
  - Bag: *ad hoc* assumption $B_{glueball} = B_{meson}$ may imply wrong glueball mass scale.
  - Flux tube: hybrid decay selection rule forbidding decays to two s-wave mesons is a consequence of expanding about static quark limit.

Dangerous to rely strongly on details of models for interpretation of the data.

QCD sum rules

An interesting effort to use the part of QCD we do understand,

perturbation theory at short distance,

to obtain information about the part we do not understand,

nonperturbative dynamics at long distance.

Method: construct dispersion relation for 2-point function of operators that interpolate the desired bound state, e.g., for *V/A* hybrids:

$$\Pi^{(1,0)}_{V/A}(q^2) = \int_0^\infty \frac{dt}{t - q^2 - i\epsilon} \frac{1}{\pi} \mathrm{Im}\, \Pi^{(1,0)}_{V/A} + \ldots$$

LHS: Choose q^2 in deep-Euclidean so LHS can be evaluated with pert. th'y.
RHS: integral is over physical region:
approximate Im Π by *resonance pole* + *QCD continuum*

In practice,

- typically use Laplace-transformed dispersion relation.
- evaluate *QCD continuum* with perturbation theory

so that *resonance pole* mass can be extracted.

Difficult to quantify errors: as much art as science?

Lattice Gauge Theory

LGT is our best (and, for now, *only*) hope for reliable QCD calculations of the spectrum of gluonic states and, perhaps, eventually, of their dynamical properties, such as decays and mixing.

Computational challenge: need large volume
~ 2.5 fm to contain hadron, even larger to contain light
quarks (e.g., $m_u \sim 5$ MeV) in chiral limit
and small lattice spacing, $a \sim 0.1$ fm, to recover continuum limit
Forced to very large lattices

In practice results are obtained by extrapolating as close as possible
- toward chiral limit $m_q \to 0$
- toward continuum limit $a \to 0$

Until recently most calculations are "quenched", i.e., no "dynamical" quarks / no quark loops.

Lattice Gauge Theory (2)

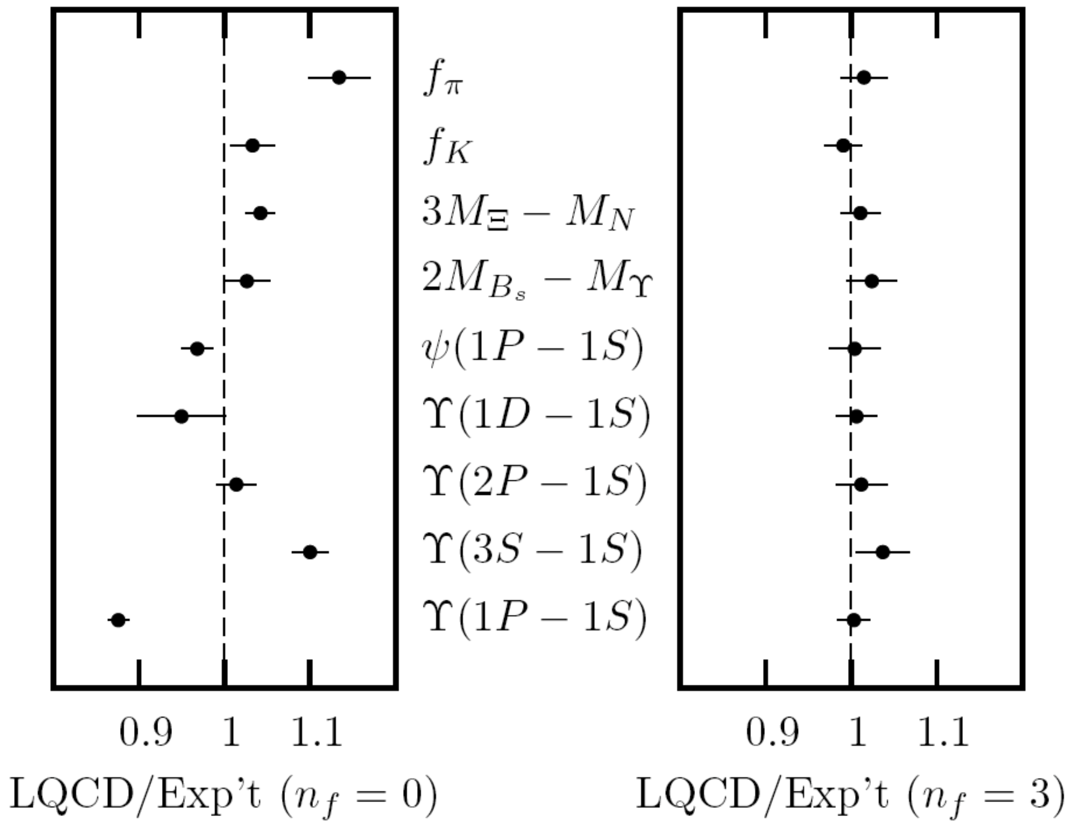
Progress from a combination of increased computing power and clever methods, e.g., “Szymanzik-staggered” fermions, engineered to reduce contribution of lattice artifacts (higher-dim. operators).
Not clear theory so-defined is QCD but seems to work in practice.

Very impressive results have been obtained
- “gold-plated” quantities to within a few percent (*unquenched*),
- pure Yang-Mills (*quenched)* glueball spectrum to a few percent plus ± 10% overall normalization uncertainty

but the remaining challenges are formidable
- unstable hadrons fluctuate into multi-particle decay products that exit boundary
- unquenched glueball/hybrid results still unstable
- study of decays & mixing just beginning.

‘Gold-plated quantities’

From Davies et al.
hep-lat/0304004



Inputs for $n_f = 3$: m_π, m_K, m_{Ds}, $m_{□}$, $m_{□□}$

Theory: the bottom line

In the US Constitution any criminal defendant is
"presumed innocent until proven guilty."

In the attempt to discover gluonic states we should say
"all theorists are presumed guilty until proven innocent."

Q: what about Russell's paradox?

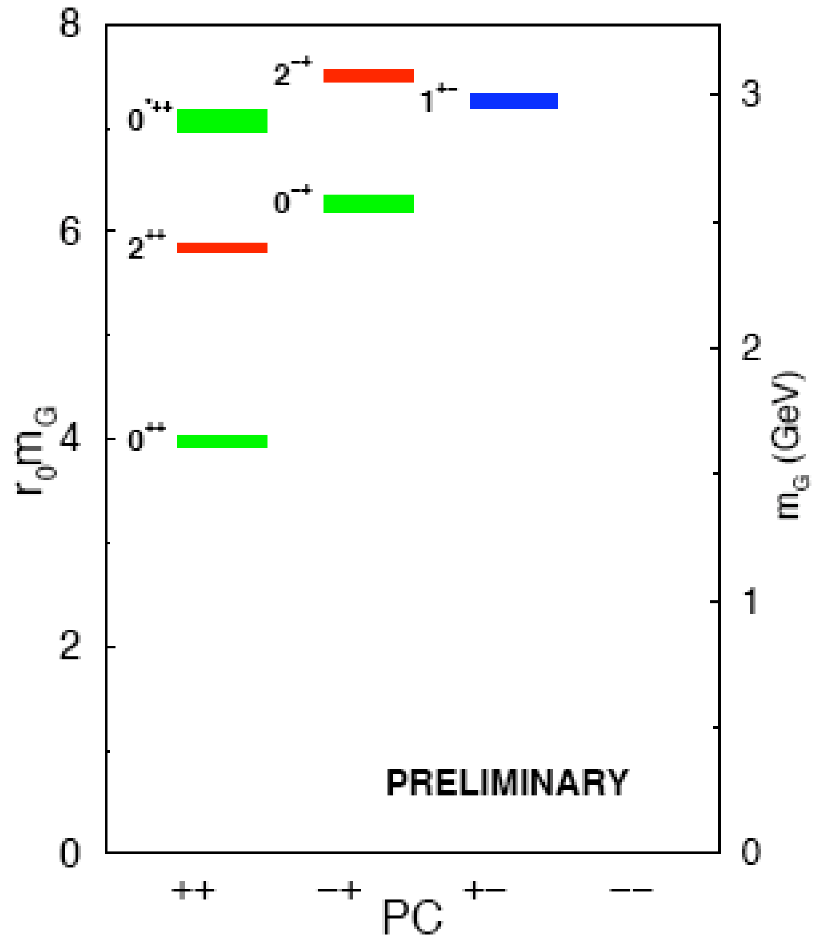
Properties of gluonic states

- Glueball & hybrid spectrum from LGT
- Production in J/ψ decay – radiative & hadronic
- Two photon couplings
  - Glueball stickiness
  - Exotic hybrid production in *tagged* $\gamma\gamma$ scattering
- Decays
  - LGT?
  - Are glueball decays always SU(3) symmetric?
  - Hybrid decays
    - Selection rules?
    - Possible OIZ violating signatures

Glueball spectrum from LGT

For *quenched* SU(3) Yang-Mills
several groups find
$M(0^{++}) \sim 1.6 - 1.7$ GeV
with others heavier
$M(2^{++}) \sim 2.4$ GeV
$M(0^{-+}) \sim 2.6$ GeV

Actual QCD eigenstates,
from unquenched simulations,
could have quite different
masses.



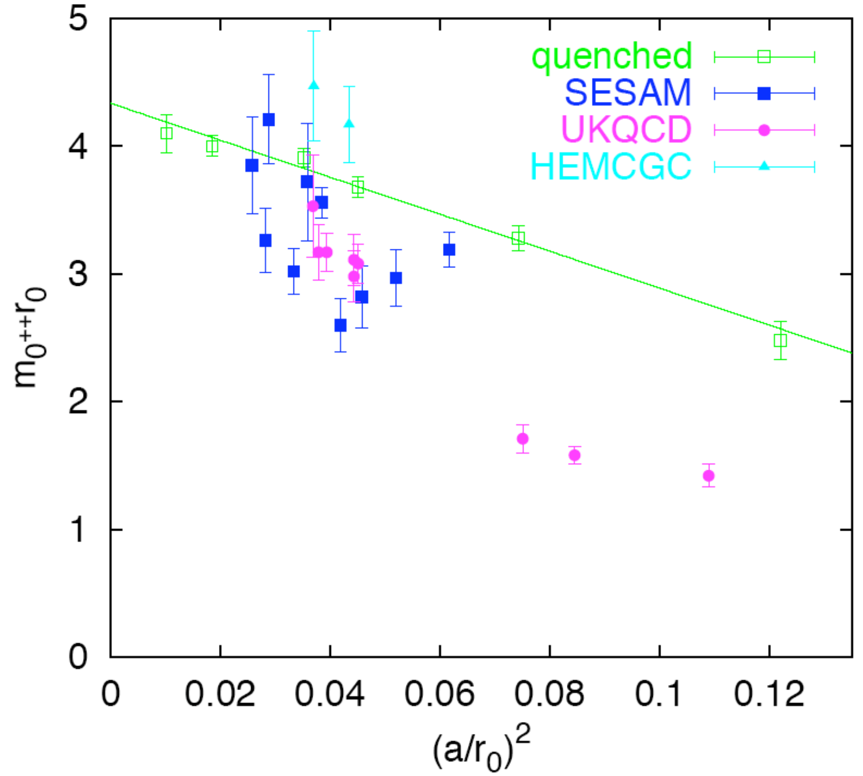
Morningstar & Peardon
nucl-th/0309068

Unquenched

Unquenched simulations will predict all scalar eigenstates, *mixing included*

(and will not by themselves reveal the mixing matrix or the initial unmixed glueball & meson *ur-states*).

Preliminary unquenched studies with 2 quark flavors, $m > m_s/3$, do not give converging results at small lattice spacing *a* for the scalar glueball mass.



Morningstar
nucl-th/0110074

Glueball Decay from LGT

- *Quenched* study of scalar glueball decay finds

$$\square(\ G_0 \longrightarrow 2 \text{ pseudoscalars}) = 108\ (29) \text{ MeV}$$

Lee & Weingarten

for G_0 mass m ~ 1700 MeV

- Consistent with what is known experimentally about $f_0(1710)$, ***if*** it turns out that two-body decays dominate the f_0 width **–** multibody decays have not been found yet but they are also harder to find.

- Result obtained at value of the coupling (□ = 5.7) near a critical point for which the LGT is known *not* to converge to QCD in the continuum limit but to another, different theory.

Morningstar

Hybrid spectrum from quenched LGT

For heavy (static) quarks the lightest hybrids are a set of eight states:

J^{PC}	J^{PC}	J^{PC}	J^{PC}
1^{--}	0^{-+}	1^{-+}	2^{-+}
1^{++}	0^{+-}	1^{+-}	2^{+-}

Of these the lightest exotic is the $J^{PC} = 1^{-+}$

Studies of light quark hybrids also find that $J^{PC} = 1^{-+}$ is the lightest exotic – same result in bag & flux-tube.

Initial quenched study for 1^{-+} $\bar{s}s$"g": m = 2.0 (2) GeV — UKQCD

with expectation that the isovector and light isoscalar are ~ 1.9 GeV

A more recent *quenched* study finds for the isovector

$$m_{I=1} = 1792(139)$$

using □(1020) to set the scale. With other estimates of the scale the result could be as low as 1600 MeV. — Bernard *et al.*

Unquenched results not quantitative but suggest mixing with two-meson molecules/$\bar{q}\bar{q}qq$ may be important.

Mixing from LGT? – the scalar glueball

- One quenched study of scalars finds evidence that $f_0(1710)$ is predominantly (75%) a glueball.

Lee & Weingarten

$$
\begin{aligned}
|f_0(1710)> &= 0.859(54)|g> +0.302(52)|s\bar{s}> +0.413(87)|n\bar{n}>, \\
|f_0(1500)> &= -0.128(52)|g> +0.908(37)|s\bar{s}> -0.399(113)|n\bar{n}>, \\
|f_0(1390)> &= -0.495(118)|g> +0.290(91)|s\bar{s}> +0.819(89)|n\bar{n}> .
\end{aligned}
$$

- Another study finds evidence of larger mixing

UKQCD

Both studies are far from chiral limit – i.e., m_q too big

A question of principle: *can LGT determine glueball-meson mixing?*

- Unquenched gives physical spectrum but no analysis of mixing.
- Quenched approx. allows analysis of mixing, but does not appear to be controllable or systematically improvable.

LGT Summary

Best guidance on masses from quenched simulations:

$G(0^{++})$	$\sim 1.6 - 1.7$
$G(2^{++})$	~ 2.4
$G(0^{-+})$	~ 2.6

$\boxed{H(1^{-+},\ I=1) \quad \sim 1.6 - 1.9}$

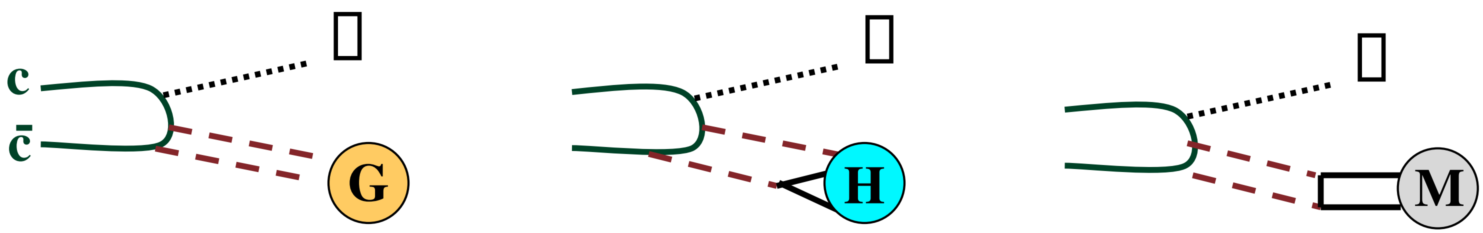
but corrections in full QCD could be sizeable.

Reliable results on decays & mixing with two-meson/$\bar{q}\bar{q}qq$ states will be very difficult to obtain.

To understand glueball-meson mixing, LGT can help but may not be definitive – must rely on experiment/phenomenology.

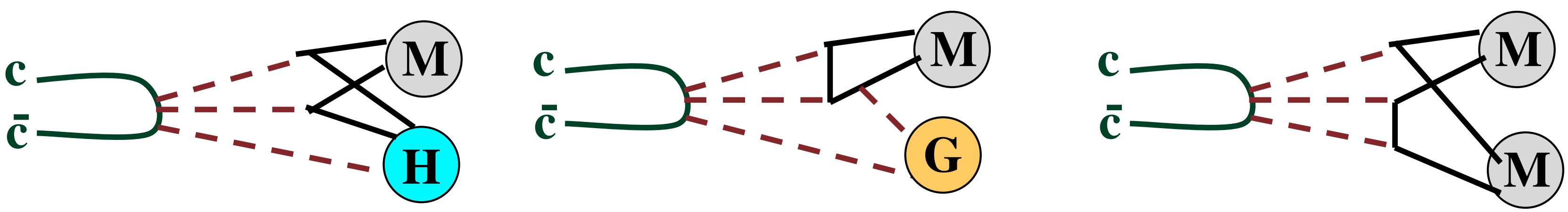
Return now to simple ideas.

G & H production in J/ψ decay: power counting



$\Gamma \sim \quad \alpha\alpha_s^2 \quad > \quad \alpha\alpha_s^3 \quad > \quad \alpha\alpha_s^4$

Glueballs preferred in radiative decay



$\Gamma \sim \quad \alpha_s^5 \quad > \quad \alpha_s^6 \quad \sim \quad \alpha_s^6$

Hybrids preferred in hadronic decay

Glueballs are sticky

Stickiness:

$$S_X = \frac{\Gamma(\Psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)} \times \frac{PS(X \to \gamma\gamma)}{PS(\Psi \to \gamma X)}$$

Measures constituents' color charge:electric charge (wave f'n cancels).

Glueballs should be sticky.

Use **S** to compare states with same J^{PC}, e.g., $f_2(1270)$ & $f_2(1525)$:

$$S_{1270}/S_{1525} = 0.073 \pm 0.02$$

Cf. naïve estimate assuming exact ideal mixing for f_2–f_2':

$$\frac{S_{1270}}{S_{1525}} = 2\frac{\left(\frac{1}{3}\right)^2}{\left[\frac{1}{\sqrt{2}}\left(\frac{4}{9}+\frac{1}{9}\right)\right]^2} = 0.16$$

Order of magnitude as expected, off by factor 2

Order of magnitude agreement is good enough: expect glueballs to be stickier than ordinary mesons by one or more orders of magnitude (except $\eta'(958)$) which has big *gg* coupling from chiral anomaly).

Hadronic J/□ decay: a flavor analyzer

Since □–□ & f_2(1270)–f_2□(1525) are ideally mixed, according to the OIZ rule we may use

$$\square \longrightarrow \square/\square/f_2/f_2\square + X$$

to analyze the flavor content of the isoscalar **X**.

E.g., we expect

$$\square \longrightarrow \square + (\bar{u}u + \bar{d}d) \;\gg\; \square \longrightarrow \square + (\bar{u}u + \bar{d}d)$$

(fig.)

$$\square \longrightarrow \square + (\bar{s}s) \;\gg\; \square \longrightarrow \square + (\bar{s}s)$$

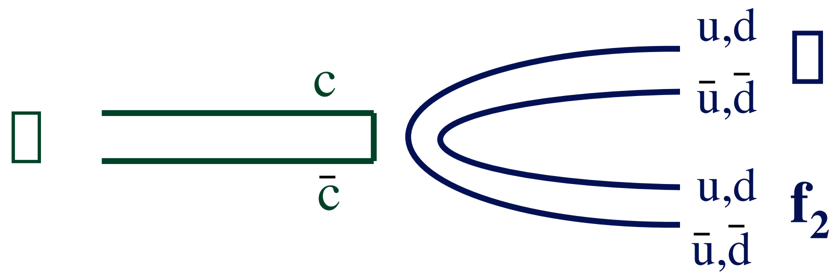
How well does it work? — consider $\square \longrightarrow \square/\square + f_2/f_2\square$

BR(10^{-3}):

$\square + f_2 = 4.3 \pm 0.6$	$\square + f_2\square < 0.22$ (90% CL)
$\square + f_2\square = 0.8 \pm 0.4$	$\square + f_2 < 0.37$ (90% CL)

For □, valid to order of magnitude or better.

OIZ rule (2)



OIZ *once* forbidden

E.g., □ —> □ + $\mathbf{f_2}$

OIZ *twice* forbidden

E.g., □ —> □ + $\mathbf{f_2}$□

Glueball decay: – SU(3) symmetry & perturbation theory

Since glueballs are manifestly $SU(3)_{Flavor}$ singlets, it is assumed that they decay like $SU(3)_{Flavor}$ singlets, but perturbation theory suggests $SU(3)_{Flavor}$ might be badly broken in some glueball decays.

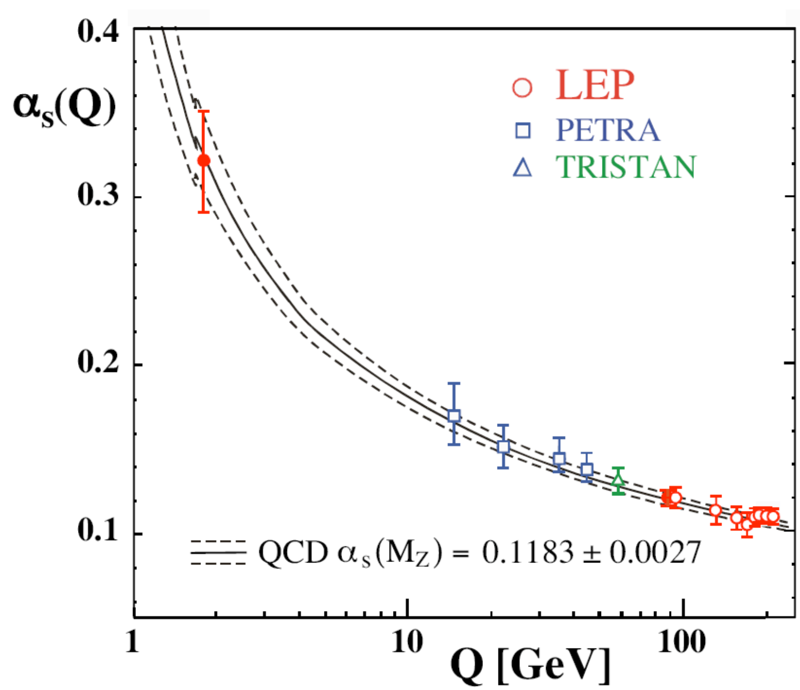
There is a growing body of evidence that perturbation theory may be approximately valid at surprisingly low energy scales:

Perturbation theory at low scale

There is a growing body of evidence that perturbation theory may be approximately valid at surprisingly low energy scales:

- **α_S(1.8 GeV)** from τ decay is consistent with **$\alpha_S(m_Z)$.**

- deep inelastic scattering data (not shown) at
  Q = 0.7 – 0.8 GeV
  is also consistent.



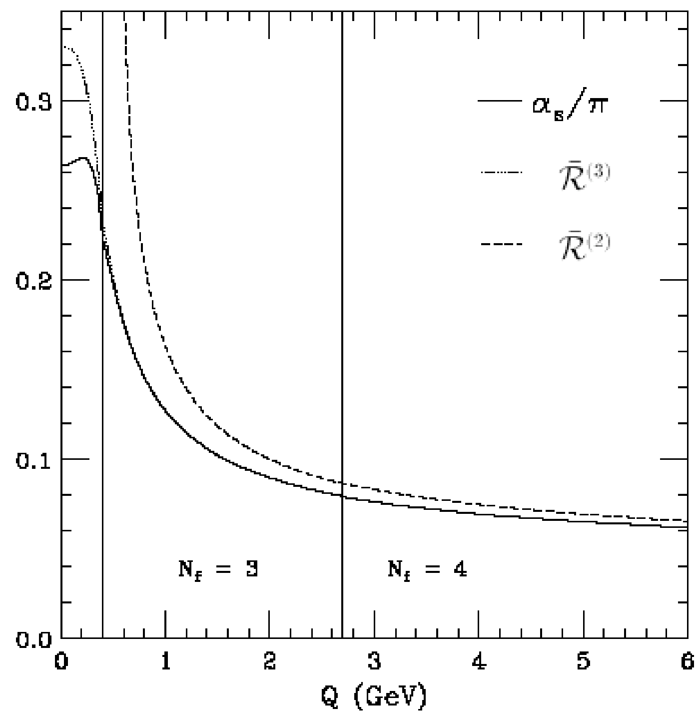
Bethke
04 review

Perturbation theory at low scale (2)

There is a growing body of evidence that perturbation theory may be approximately valid at surprisingly low energy scales:

There is a variety of evidence that α_S approaches an IR fixed point of order $\boldsymbol{\alpha_S(FP)/\pi \sim 0.3}$

- Phenomenological studies (Mattingly-Stevenson, Brodsky et al…)
- Schwinger-Dyson eq
  - → dynamical gluon mass
  - → IR FP (Cornwall +…)
- LGT supports results from Schwinger-Dyson eq (Bernard et al.)



Mattingly & Stevenson

Perturbation theory at low scale (3)

Since glueballs are manifestly $SU(3)_{Flavor}$ singlets, it is assumed that they decay like $SU(3)_{Flavor}$ singlets, but perturbation theory suggests $SU(3)_{Flavor}$ might be badly broken in some glueball decays.

There is a growing body of evidence that perturbation theory may be approximately valid at surprisingly low energy scales:

- $\boldsymbol{\alpha_S}$**(1.8 GeV)** from τ decay and $\boldsymbol{\alpha_S}$**(0.8 GeV)** from DIS are consistent with $\boldsymbol{\alpha_S(m_Z)}$**.**
- There is a variety of evidence that α_S approaches an IR fixed point of order $\boldsymbol{\alpha_S(FP)/\pi \sim 0.3}$:
  - Phenomenological studies (Mattingly-Stevenson, Brodsky et al.,…)
  - Schwinger-Dyson eq ⇒ dynamical gluon mass ⇒ IR FP (Cornwall)
  - LGT supports results from Schwinger-Dyson eq (Bernard et al.)
- **Could explain "mysterious" successes**
  - simple valence quark description of ordinary mesons & baryons
  - why OIZ rule works so well for light hadrons

It cannot be used for precise predictions, but perturbation theory may offer useful guidance about some glueball properties.

Glueball decay & flavor symmetry (2): 0^{++}

Consider $gg \longrightarrow \bar{q}q$ in $J^{PC} = 0^{++}$ channel, at leading order in perturbation theory.

Like $\pi \longrightarrow \mu\nu$, we might expect amplitude m_q, since chirality conservation forbids decay to massless $f\bar{f}$ pair:

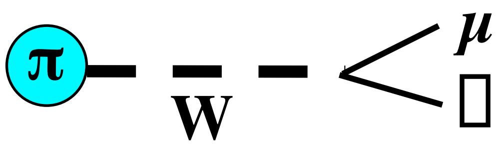
massless f, $\bar{f}$ produced with opposite helicity

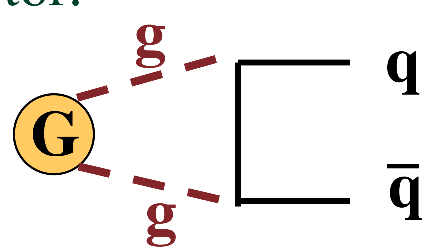
$\Rightarrow$ **Equal** s_Z components in center of mass

$\Rightarrow$ $J_Z = 1$ if $L = 0$.

$\Longrightarrow$ J = 0 decay requires chirality breaking from $m_f \neq 0$

But the analogy is not perfect, since $\pi \longrightarrow \mu\nu$ is mediated by massive **W** boson exchange, while $gg \longrightarrow \bar{q}q$ is mediated by massless quark exchange which might provide an IR singularity to cancel the chirality suppression factor.





Glueball decay & flavor symmetry (3): 0^{++}

Chirality suppression is confirmed by calculation:

$$\Gamma(G_0 \to \overline{q}q) = \frac{16\pi}{3}\alpha_S^2 C_0^2 m_q^2 M_G \beta \log^2 \frac{1+\beta}{1-\beta}.$$

MC – work in progress

where C_0 depends on G_0 wave function, β = quark velocity in CMS.

For running quark masses at scale Q = 2 GeV,

s: 80 MeV **d:** 7 MeV **u:** 3 MeV

From PDG & recent LGT

find

$$\frac{\Gamma(G_0 \to \overline{s}s)}{\Gamma(G_0 \to \overline{u}u + \overline{d}d)} \simeq 30$$

Conclusion: in lowest order perturbation theory, decays to strange quarks dominate by an order of magnitude.

BUT even for strange quark the lowest order amplitude is suppressed

$\Rightarrow$ must consider next order — work in progress.

Glueball decay & flavor symmetry (4): kinematics?

A kinematical speculation:

IF it is sensible to apply perturbation theory to glueball decays, then (except for J = 0 as discussed on previous page) we expect $SU(3)_{Flavor}$ symmetry to apply ***at the quark level***.

We then would expect $SU(3)_{Flavor}$ symmetry to apply ***inclusively***, but not necessarily to exclusive final states.

If strange multiparticle final states are kinematically suppressed then a larger fraction of $\bar{s}s$ events may hadronize as $\bar{K}K$, leading to an enhancement of $\bar{K}K$ relative to $\pi\pi$.

Test? — would be useful to test SU(3) symmetry predictions for ordinary hadrons in 1.5 – 2.5 GeV mass region.

Hybrid decays: OIZ violating signature

Perturbation theory suggests an interesting possible signature for hybrid decays:

Consider isovector or non-strangeonium isoscalar hybrid

$\bar{q}qg \qquad\qquad q = u \text{ or } d$

Gluon g converts flavor symmetrically to $\bar{q}q$ pairs
so 1/3 of the time we have $g \longrightarrow \bar{s}s$

$$(\bar{q}q)_8 g \longrightarrow (\bar{q}q)_8\, (\bar{s}s)_8 \begin{cases} \nearrow (\bar{q}s)_1 + (\bar{s}q)_1 & \text{rearrangement} \\ \searrow (\bar{q}q)_1 + (\bar{s}s)_1 & \text{gluon exchange} \end{cases}$$

➡ Possibility of unique OIZ rule violating decays

(estimate likelihood on lattice?)

Hybrid decays: selection rules?

LGT and flux-tube model predict dominant decays are

Hybrid —> s-wave meson + p-wave meson

Not —> s-wave meson + s-wave meson

E.g., for I = 1, $J^{PC} = 1^{-+}$ exotic:

π_1 —> πb_1 **ALLOWED**

π_1 —> π □, π□ **FORBIDDEN**

BUT the LGT prediction applies in the static quark limit only, with corrections of order $1/m_q$: good approximation for *b*, maybe for *c*, but doubtful for *u,d,s*. Michael

- Flux-tube model expands around static limit of LGT strong-coupling phase, so reflects LGT prediction.
- In flux-tube, point-like excitation of π by chiral current breaks π□ symmetry □ π_1 —> π□ ALLOWED Close-Dudek

CAUTION: selection rules may reflect approximations, not QCD.

Look in all channels, interpret after we have all the data

Hybrid decays: selection rules? (2)

Flavor selection rule: CP odd octet meson *cannot* decay into two octet $J^{PC} = 0^{-+}$ mesons. Lipkin

Then for I = 1, $J^{PC} = 1^{-+}$ exotic hybrid π_1, SU(3) symmetry predicts

π_1 —> π $□_1$	ALLOWED	($□_1$ = SU(3) singlet)
π_1 —> π $□_8$	FORBIDDEN	($□_8$ = SU(3) octet)

so expect □ (π_1 —> π □□) >> □ (π_1 —> π □)

Or maybe not:

- Phase space: PS(π_1 —> π □)/PS(π_1 —> π □□) = 4.5
- □ - □□ mixing not negligible: sin 20^o = 0.34
- SU(3) symmetry breaking could be O(20%);
  if SU(3) breaking amplitude interfered constructively with π_1 —> π $□_1$ component then π_1 —> π □ could be significantly enhanced.

Data: a quick look

Candidates: many nominated, few elected.

- Glueball candidates
  - Scalars
  - Tensor
- Hybrid candidates
  - Exotic 1^{-+}
  - Nonexotic: 1^{++}, 0^{-+}, 1^{--}

Scalar glueball candidates

Best current evidence for glueballs is the evidence for *three* $I = 0$, $J^{PC} = 0^{++}$ resonances in the mass region predicted by LGT:

$$\boxed{f_0(1370),\ f_0(1500),\ f_0(1710)}$$

- $f_0(1370)$ plausible as predominantly $\bar{u}u + \bar{d}d$, p-wave isoscalar.
  Dominant decay: $f_0 \longrightarrow 4\pi$ (□□)
  Very broad □ ~ 200 - 500 MeV PDG

- $f_0(1500)$ & $f_0(1710)$ might be *admixture* of of $\bar{s}s$ p-wave isoscalar and scalar glueball.

- Puzzling observations in hadronic □ decay by Mark III (5.8M □'s) and BESII (58M □'s) makes interpretation even more difficult.

$f_0(1370)$

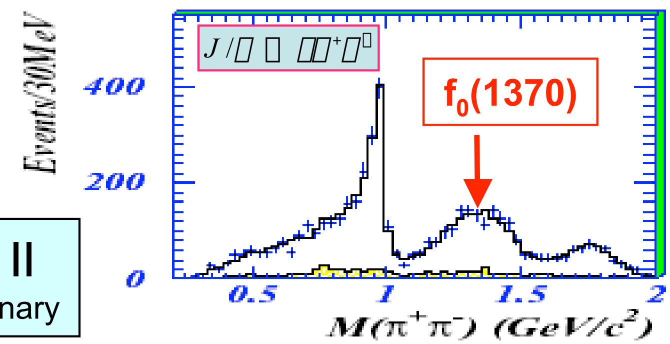
$f_0(1370)$ plausible as predominantly $\bar{u}u + \bar{d}d$, p-wave isoscalar:

- Broad □ ~ 200 - 500 MeV PDG
- Dominant decay: $f_0 \longrightarrow 4\pi$ (□□)

BR's from WA102 $\pi\pi : K\overline{K} : \eta\eta : \boxed{4\pi} = 1 : 0.46 \pm 0.19 : 0.16 \pm 0.07 : \boxed{34.0^{+22}_{-9}}$

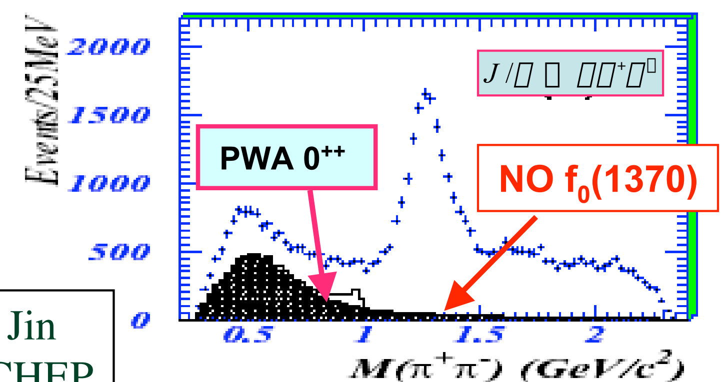
Seen in pp (central), $\bar{p}$p, πp, and □ decay

BES II
Preliminary



<u>BESII reports puzzling result:</u>

- Dominant 4π decay implies **$\bar{u}u + \bar{d}d$** composition
- **BUT** absence in **□ππ**, signal in **□ππ** suggests **$\bar{s}s$??**

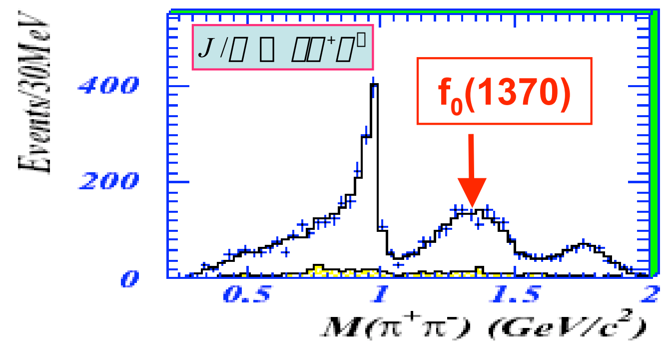


Jin
ICHEP

$f_0(1370) \longrightarrow 4\pi$

BES II $f_0(1370)$ signal appears to be ~ comparable to $f_0(980)$

BES II
Preliminary



Suppose $\quad B(\psi \to \phi f_0^{1370} \to \phi\pi\pi) \sim B(\psi \to \phi f_0^{980} \to \phi\pi\pi)$

Mark I: $\quad B(\psi \to \phi f_0^{980} \to \phi\pi\pi) = (2.0 \pm 0.5)\, 10^{-4}$

WA102: $\quad B(f_0^{1370} \to \pi\pi\pi\pi) \,/\, B(f_0^{1370} \to \pi\pi) = (34\,^{+22}_{-9})$

$$\Longrightarrow \quad B(\psi \to \phi f_0^{1370} \to \phi\pi\pi\pi\pi) \sim (6.8\,^{+4.8}_{-2.5}) \times 10^{-3}$$

$$\boxed{\text{Expect very big signal for } B(\psi \to \phi f_0^{1370} \to \phi\pi\pi\pi\pi)}$$

$f_0(1500)$ & $f_0(1710)$

$f_0(1500)$ studied in pp (central production) & $\bar{p}p$: □ ~ 100 MeV

PDG: BR's: 4π: 2π: KK: □□: □□□ ~ 49: 35: 9: 5: 2 %

$f_0(1710)$ discovered in radiative □ decay
and studied in pp (central) □ ~ 140 MeV (PDG)

BR's from WA102:

$$\pi\pi : K\overline{K} : \eta\eta : \eta\eta' : 4\pi = 1 : 5.0 \pm 0.7 : 2.4 \pm 0.6 :< 0.18\ (90\,\%\ CL) :< 5.4\ (90\,\%\ CL)$$

➡ $\bar{K}K$ is biggest observed mode

Mark III: Clear signal for □ —> □ + $f_0(1710)$
No signal for □ —> □ + $f_0(1710)$

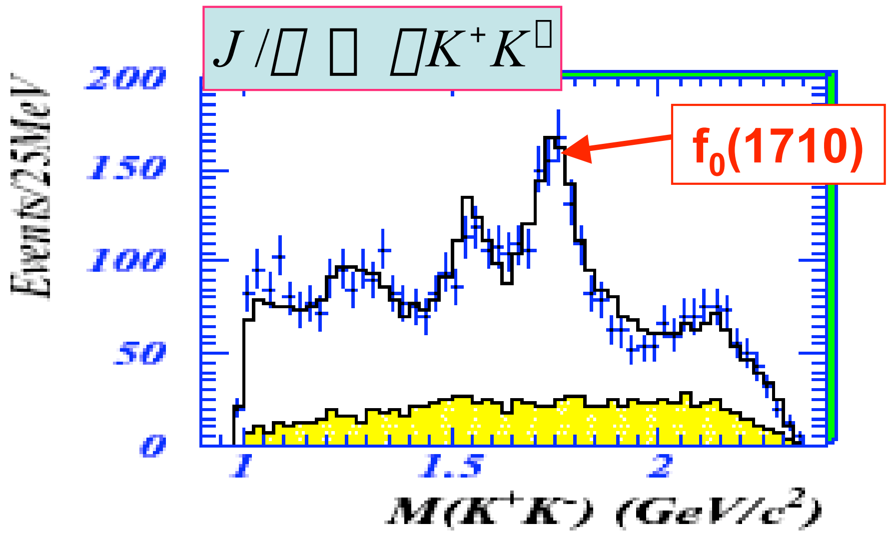
} Another OIZ paradox

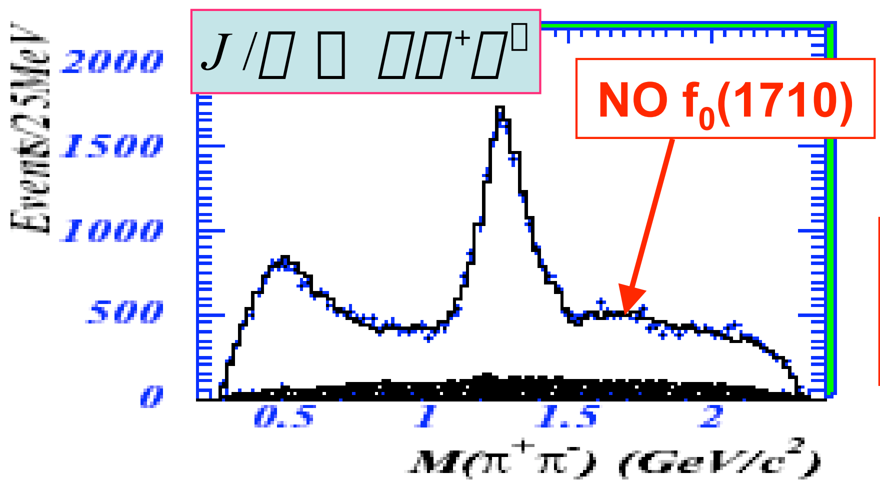
Confirmed by BESII, which also finds from □ —> □ + $f_0(1710)$
that B($\bar{K}K$) > 7.7 □ B(ππ) (95%)

$f_0(1710)$ in hadronic ψ decay BESII

Jin
ICHEP

BES II
Preliminary





- **Clear $f_0(1710)$** peak in J/ψ —> γKK.

$$M = 1740 \pm 30 \ MeV$$
$$\Gamma = 125 \pm 20 \ MeV$$

- **No $f_0(1710)$** observed in J/ψ → γππ!

$$\frac{BR(f_0(1710) \to \pi\pi)}{BR(f_0(1710) \to K\bar{K})} < 0.13 \quad @95\%CL$$

A new scalar: $f_0(1790)$ BESII

BES discovers another scalar
in hadronic ψ decay

$$M = 1790^{+40}_{-30} \quad MeV$$
$$\Gamma = 270^{+60}_{-30} \quad MeV$$

BES II
Preliminary

Jin
ICHEP

with OIZ violating signature:

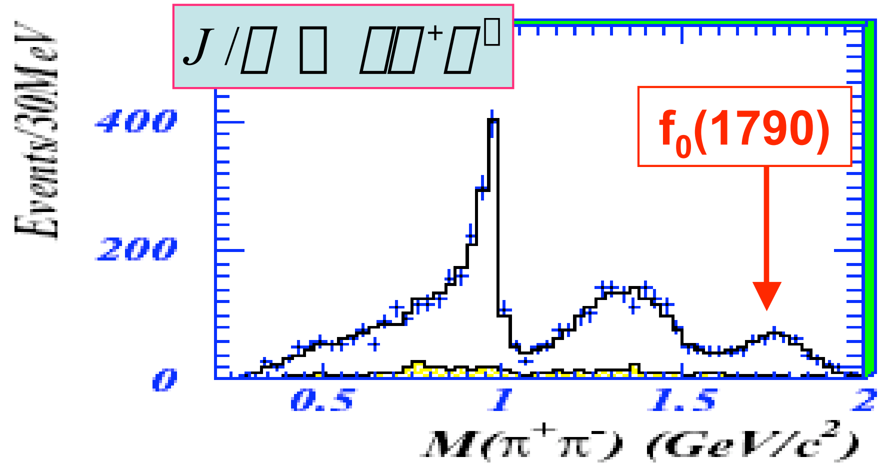
- Production:

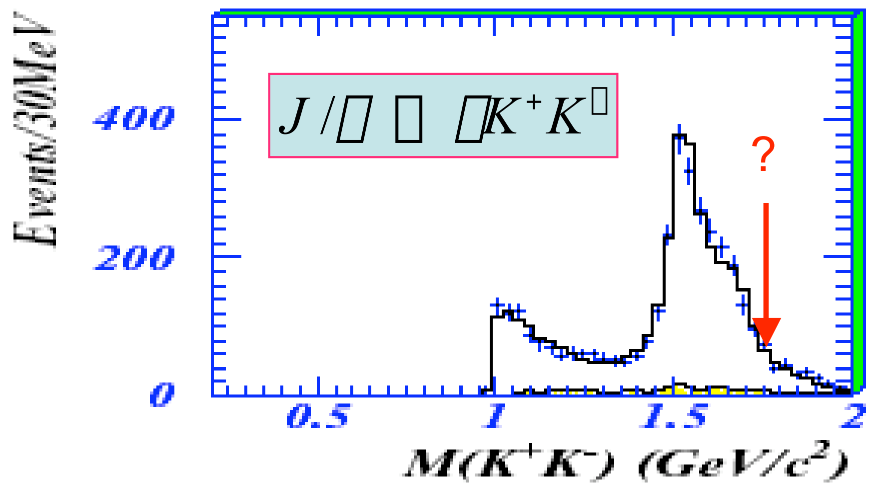
  Signal $\psi \to \phi + f_0(1790)$
  No signal $\psi \to \omega + f_0(1790)$

- Decay:

  Signal $f_0(1790) \to \pi\pi$
  No signal $f_0(1790) \to \bar{K}K$

$f_0(1790)$ dominant decay to $\pi\pi$
$f_0(1710)$ dominant decay to $\bar{K}K$,
==> they must be different states.





Need PWA to reveal if any $f_0(1500)$
or $f_0(1710)$ under $f_2(1525) \to \bar{K}K$ peak.

Scalars in □ —> □$\bar{K}K$

Consistent with Mk III-Dunwoodie

- Clear signal for $f_0(1710)$
  BESII bin-by-bin fit:
  m = 1722 (17) □ = 167 +37 -29

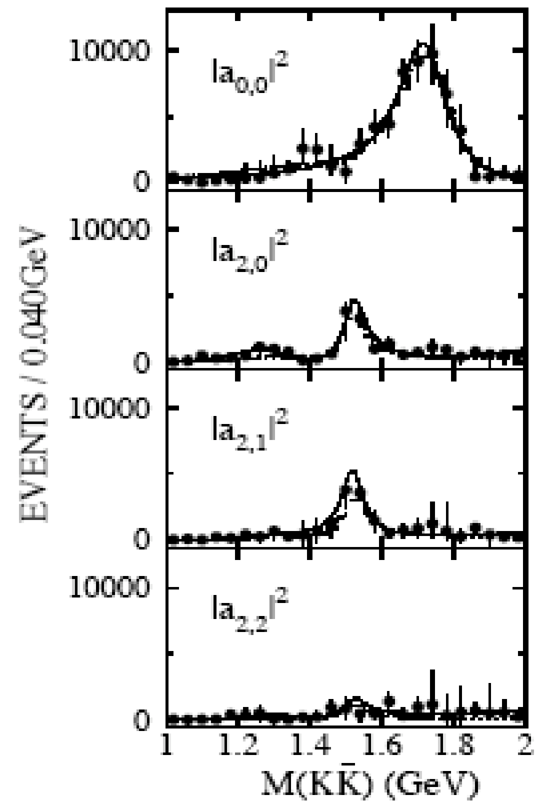
  $B(□ \longrightarrow □ f_0 \longrightarrow □\bar{K}K) = 11.1^{+1.7}_{-1.2}\ 10^{-4}$

  From WA102, *roughly*

  $0.4 \leq B(f_0^{1710} \to \bar{K}K) \leq 0.6$

  $1.8\ 10^{-3} < B(□ \longrightarrow □ f_0^{1710}) < 3.1\ 10^{-3}$

  – Large BR, ~ O(5%) of all □ —> □X



BESII bib-by-bin fit
PRD**68**:052003, 2003

- Hint of $f_0(1370)$? — not included in fit.
- No significant signal for $f_0(1500)$ (1.3 - 2.2 □ in fits)

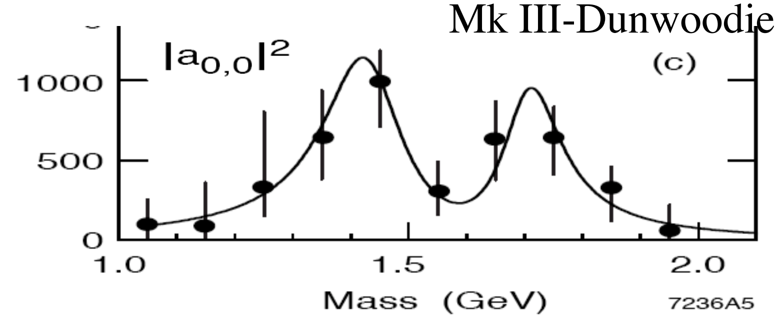
Scalars in □ —> □π π

Mark III:

0^{++} structures at 1430 & 1700

$m = 1429\ ^{+43}_{-37}$ □ $= 169\ ^{+111}_{-76}$

$m = 1704\ ^{+16}_{-23}$ □ $= 124\ ^{+52}_{-44}$



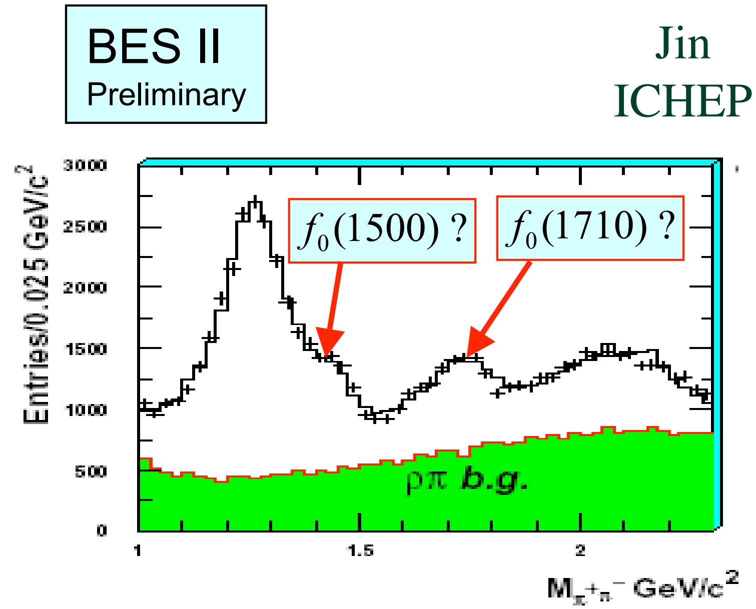
- Lower state lies between $f_0(1370)$ & $f_0(1500)$ and has no significant signal in □ —> □KK

- Upper state consistent with $f_0(1710)$ as seen in □ —> □KK with

$$BR(\pi\pi)/BR(KK) = 0.268\ ^{+0.169}_{-0.120}$$

Scalars in □ —> □π π (2)

Jin
ICHEP



BESII also sees two 0^{++} structures in □ —> □π π.

Like Mark III data, the lower is between $f_0(1370)$ & $f_0(1500)$,

$$m = 1466 \pm 6 \pm 16 \text{ MeV}$$

□ not quoted, looks broader than □ = 109 ± 7 for $f_0(1500)$

Upper structure is heavier than $f_0(1710)$,

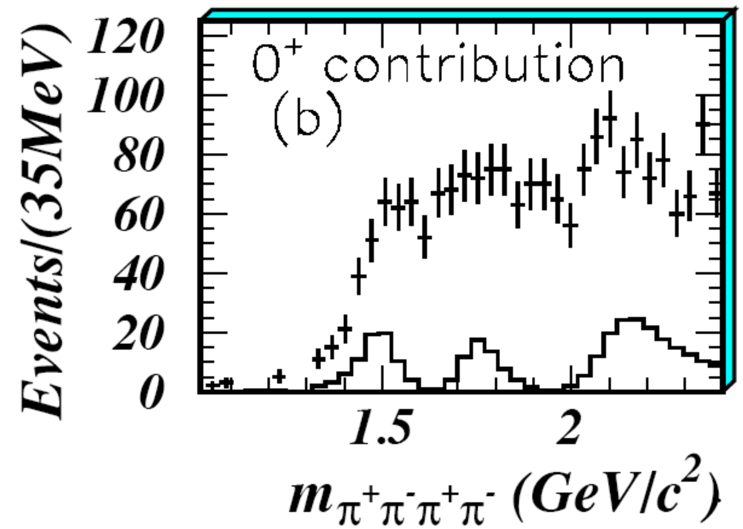
$$m \sim 1765$$

⇒ Interference of $f_0(1710)$ & $f_0(1790)$**?**

Scalars in □ —> □+ 4π

Bai *et al.*
PLB **472**:207,'00

Only other evidence for □ –> □f_0(1500)
is from BES I analysis of □ –> □+ 4π



Complicated analysis with several isobars,
finds 0++ —> □□ —> 4π:

$$Br(J/\psi \to \gamma f_0(1500)) \times Br(f_0(1500) \to \pi^+\pi^-\pi^+\pi^-) \quad = \quad (3.1 \pm 0.2 \pm 1.1) \times 10^{-4}$$

which implies B(□ —> □f_0(1500) —> □ππ) ~ 9/4 □ 2/3 □ 3.1 10^{-4} ~ 5 10^{-4}.
twice as big as Mark III measurement of B(□ —> □f_0(1370 - 1500) —> □ππ)

- *Probably* inconsistent with BR(□ –> □f_0(1500) –> □ππ) (*what is BESII BR?)*
- BES II statistics offer better prospects for such a complex analysis.

Scalars in □ —> □+ 4π (2)

Data for □ —> □+ 4π can help resolve the □ —> □+ ππ puzzle

WA102 finds

$$BR(f_0(1370) \longrightarrow 4\pi)/BR(f_0(1370) \longrightarrow 2\pi) = 34.0^{+22}_{-9} >> 1$$

Crystal Barrel & WA102 agree for $f_0(1500)$ that $4\pi/2\pi \sim 1.5 - 2$

$$BR(f_0(1500) \longrightarrow 4\pi)/BR(f_0(1500) \longrightarrow 2\pi) = 1.42 \pm 0.09 \qquad \text{PDG}$$

If structure in □ —> □+ ππ at ~1450 has comparable contributions from $f_0(1370)$ & $f_0(1500)$, the $f_0(1370)$ component would be more prominent in □ —> □+ 4π, and the inclusive rate BR(□ —> □+ $f_0(1370)$) would be very large

– large enough(?) to set off the glueball alarm, even though 1370 is much lighter than expected in LGT.

Scalar Summary

□ decay:
□ —> V + f
V = □ or □

	f_J Decay:	$\pi\pi$	KK
	□	$f_2(1270)$	$f_0(1710)$
	□	$f_0(980)$ $f_0(1370)$ $f_0(1790)$	$f_0(980)$ $f_2(1525)$

Tensors obey OIZ
Scalars violate OIZ

- $f_0(980)$ understandable as $(\bar{u}u + \bar{d}d)\bar{s}s$ cryptoexotic
- $f_0(1710)$ might be understandable as scalar glueball with chirally enhanced $\bar{s}s$ decay
  ==> expect B(□ —> □$f_0(1710)$) ~ 1/2 B(□ —> □$f_0(1710)$)
- No explanation for $f_0(1370)$ and $f_0(1790)$ decay pattern **==> interesting**!

Tensor candidate: $f_J/\xi(2230)$

If it exists, it is an interesting glueball candidate.

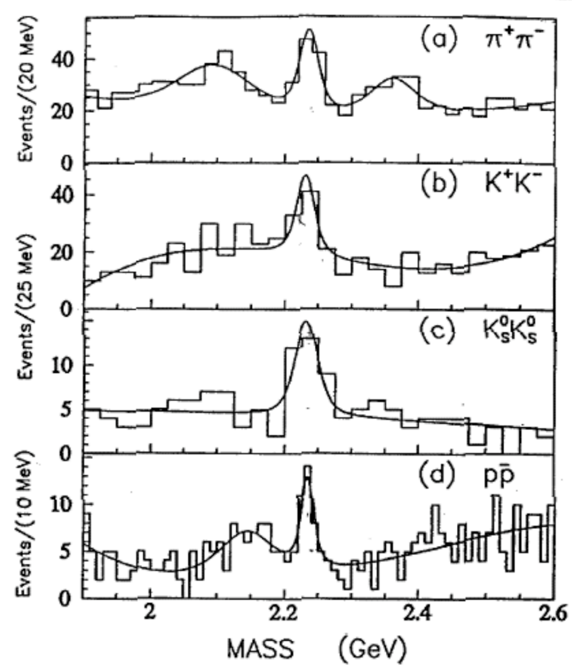
History:

- Seen by Mark III in $\psi \longrightarrow \gamma K^+K^-$
- Not seen by DM2 – but DM2 had poorer K identification (TOF)
- Seen by BESI in $\psi \longrightarrow \gamma \bar{K}K/\pi\pi/pp$
- BESII preliminary: *not* confirmed (ICHEP 02)

PDG

$$M = 2231 \pm 3$$
$$\Gamma = 23 \pm 8$$

Mass consistent with LGT estimate for 2^{++} glueball



Evidence for glueball interpretation based on two *failures* to observe f_J, in $\gamma\gamma \rightarrow \xi$ & $\bar{p}p \rightarrow \xi$

Tensor candidate: $f_J/\xi(2230)$ (2)

BESI:

TABLE I. Mass, width, and branching ratios of $\xi(2230)$. The first error is statistical and the second is systematic.

Decay mode	M_ξ (MeV)	Γ_ξ (MeV)	$B(J/\psi \to \gamma\xi)B(\xi \to X)$ (10^{-5})
$\pi^+\pi^-$	$2235 \pm 4 \pm 6$	$19^{+13}_{-11} \pm 12$	$5.6^{+1.8}_{-1.6} \pm 2.0$
K^+K^-	$2230^{+6}_{-7} \pm 16$	$20^{+20}_{-15} \pm 17$	$3.3^{+1.6}_{-1.3} \pm 1.2$
$K^0_S K^0_S$	$2232^{+8}_{-7} \pm 15$	$20^{+25}_{-16} \pm 14$	$2.7^{+1.1}_{-0.9} \pm 0.8$
$p\overline{p}$	$2235 \pm 4 \pm 5$	$15^{+12}_{-9} \pm 9$	$1.5^{+0.6}_{-0.5} \pm 0.5$

And also seen in $\pi^0\pi^0$:

$$B(J/\psi \to \gamma\xi(2230)) \times B(\xi(2230) \to \pi^0\pi^0) = (4.5 \pm 2.6 \pm 1.3) \times 10^{-5}$$

Tensor candidate: f_J/□(2230) (3)

Two interesting failures:

1) Not observed in two-photon scattering

□(□–> □□)B(□–> $K_S K_S$) < 1.1 eV (95%)

CLEO, L3

Assume J= 2 and
s-wave phase space

$$S_X \propto \frac{\Gamma(\Psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)} \times \frac{m_X}{k_\gamma}$$

Using central values,

$$S_{2230} : S_{1525} : S_{1270} \sim (> 116) : 14 : 1$$

2) Not observed in $\bar{p}p$ annihilation

B(□–> $K_S K_S$)B(□–> $\bar{p}p$) < $7.5\ 10^{-5}$

PS185
JETSET

BES BR's for □ –> □□–> □+ $K_S K_S/\bar{p}p$ then imply

B(□ –> □□) > $2.3^{+0.7}_{-1.3}\ 10^{-3}$

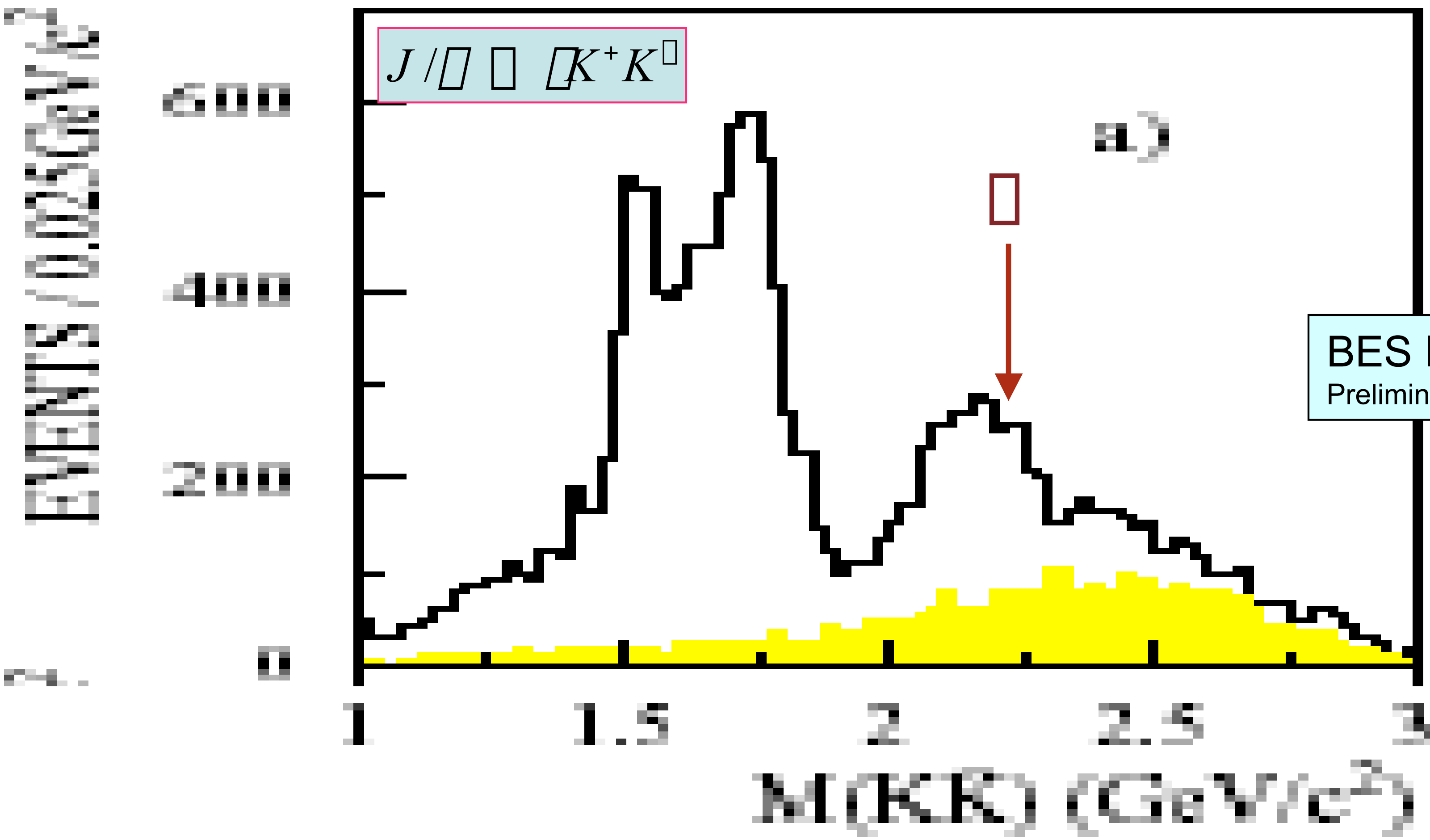
Similar from
Crystal Barrel
in $\bar{p}p \to \pi^0 \pi^0$/□□

➡ many unobserved multibody decay modes
& large (glueball'ish) rate for □ –> □□.

OR *it just doesn't exist…*

Tensor candidate: $f_J/\xi(2230)$ (4)

Jin
ICHEP



ξ(2230) not apparent in raw histogram

Hybrid candidates

Best prospects in exotic channels

- can’t be ordinary mesons
- can’t mix with ordinary mesons
- $J^{PC} = 1^{-+}$ predicted to be lightest exotic

Exciting experimental signals in exotic $I = 1$, $J^{PC} = 1^{-+}$ channel:

- $\pi_1(1400)$ —> □π
- $\pi_1(1600)$ —> □□π, □π, $b_1\pi$, $f_1^{1285}\pi$
- $\pi_1(2000)$ —> $b_1\pi$, $f_1^{1285}\pi$

Perhaps the $J^{PC} = 1^{-+}$ exotic states could be our ‘Hydrogen atom’

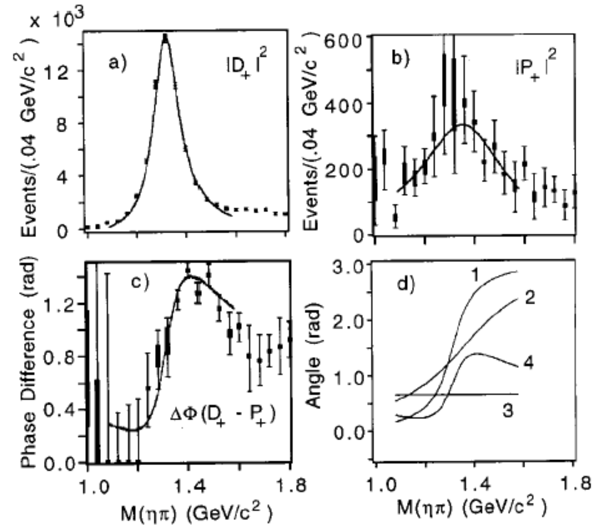
— the system which gives us the best chance to test our understanding of gluonic hadrons.

$\pi_1(1400)$

Early indications: forward-backward asymmetry in Gottfried-Jackson frame for M –> $\eta\pi$ decay at 1400 MeV.

GAMS `88, KEK `93

`96 - `98: compelling evidence from two different production mechanisms



E852:

$\pi^- p \longrightarrow \eta\pi^- p$

Crystal Barrel: Liquid deuterium

$\bar{p}\, n \longrightarrow \eta\pi^- \pi^0$

Initial state	Intermediate state	Rate (%)
$^3S_1$ (66.4%)	$\rho^-(770)\eta$	30.0 ± 3.5
	$a_2(1320)\pi$	11.1 ± 1.0
	$(\eta\pi)_P\pi$	7.9 ± 1.0
$^1P_1$ (33.6%)	$\rho^-(770)\eta$ ($L=0$)	10.3 ± 3.0
	($L=2$)	17.3 ± 1.2
	$a_2(1320)\pi$	3.8 ± 0.8
	$(\eta\pi)_P\pi$ ($L=0$)	2.8 ± 1.3
	($L=2$)	0.5 ± 0.5

<u>Good agreement on m, Γ:</u>

E852	$1370 \pm 16^{+50}_{-30}$	$385 \pm 40^{+65}_{-105}$
Crystal Barrel	$1400 \pm 20 \pm 20$	$310 \pm 50^{+50}_{-30}$

$\pi_1(1400)$ (2)

Barnes-Close
MC-Sharpe

m = 1400 agrees with old bag model prediction

probably coincidence: since glueball predictions seem much too low (LGT), can't take hybrid predictions seriously. I.e., if $B_G \neq B_M$, can't assume $B_G = B_H$.

m = 1400 *disagrees* with other theoretical expectations

- LGT
  - first predictions: m ~ 1900 — UKQCD
  - recently: m ~ 1700, maybe consistent with 1600 — Bernard *et al.*
- Dynamical selection rule (flux-tube model)

$$H \not\longrightarrow M_{S\text{-}WAVE} + M_{S\text{-}WAVE}$$
$$H \longrightarrow M_{S\text{-}WAVE} + M_{P\text{-}WAVE}$$

- Flavor selection rule — Lipkin

$$H_{OCTET}\,(CP = -) \not\longrightarrow M_{OCTET}(0^{-+}) + M_{OCTET}(0^{-+})$$

Problems motivate alternative explanations:

- $\bar{q}\bar{q}qq$ — Close-Lipkin
- nonresonant interpretations — Dzierba *et al.*, Szczepaniak *et al.*

π_1(1400) (3)

BUT remember our slogan:

All theorists presumed guilty until proven innocent.

Theoretical objections to π_1(1400) are not conclusive:

- LGT prediction could shift to ~ 1600 — maybe eventually 1400? We must wait for definitive unquenched results with sufficiently light u,d quarks.
- Dynamical selection rule: flux-tube model prediction based on LGT, but selection rule only follows from LGT for heavy, static quarks **==>** not a QCD prediction but test of model which could be right or wrong **==>** *experiment should decide*.
- Flavor selection rule: could be evaded by combined effect of singlet component of □(548) and SU(3) breaking.

➡ Keep an open mind, continue to investigate 1400 MeV region.

Q: is there evidence for other members of π_1(1400) nonet?

□$_1$(1420) ?

TPC Mark II L3	$\cancel{□□} \longrightarrow (K^*K)_{1420}$ $□□^* \longrightarrow (K^*K)_{1420}$	$\Longrightarrow$ $J^C = 1^+$

Landau-Yang Theorem

Might be $f_1(1420)$ – Also see □□* —> $f_1(1285)$—> □ππ $J^{PC} = 1^{++}$

Data: $\tilde{\Gamma}_{\gamma\gamma} = \lim_{Q^2 \to 0} \frac{M^2}{Q^2} \Gamma^{TS}_{\gamma\gamma^*}$ $= \begin{cases} 2.8 \pm 1.2 \text{ keV} & 1285 \\ 3.8 \pm 1.3 \text{ keV} & 1420 \end{cases}$

2.8 ± 1.2 keV	1285	PDG
3.8 ± 1.3 keV	1420	My average

$\tilde{\Gamma}_{\gamma\gamma}(1420)/\tilde{\Gamma}_{\gamma\gamma}(1285) \sim \begin{cases} 1.4 & \text{data} \\ 2/25 \; □ \; 1420/1285 \sim 0.1 \end{cases}$

1.4 data

2/25 □ 1420/1285 ~ 0.1 Ideal mixing prediction

$f_1^{1285}(\bar{u}u + \bar{d}d)$
$f_1^{1420}(\bar{s}s)$,

➡ Data indicates big □□coupling for $f_1(1420)$, like $\bar{u}u + \bar{d}d$.

<u>AND</u>: B(□ —> □ + $f_1(1420)$) = $(6.8 \pm 2.4)\ 10^{-4}$
No signal for □ —> □ + $f_1(1420)$, $< 1.1\ 10^{-4}$
also as if $f_1(1420) \sim \bar{u}u + \bar{d}d$.

Large for $\bar{s}s$

□$_1$(1420)? (2)

Hypothesis: "f_1(1420)" observed in □□* —> "f_1" and □ —> □ + "f_1"

is not the 1^{++} meson observed in hadronic reactions, but

is the $J^{PC} = 1^{-+}$ **□$_1$(1420)** $(\bar{u}u + \bar{d}d)g$ partner of **π_1(1400).**

MC
PLB187:409

Problem: why does **□$_1$(1420)** $(\bar{u}u + \bar{d}d)$ decay to K*K, not □ππ?

Solution: Isospin **+** Kinematics

□$_1$ —> K*K **p-wave**

□$_1$ —> □ππ **L = 4, ππ d-wave**

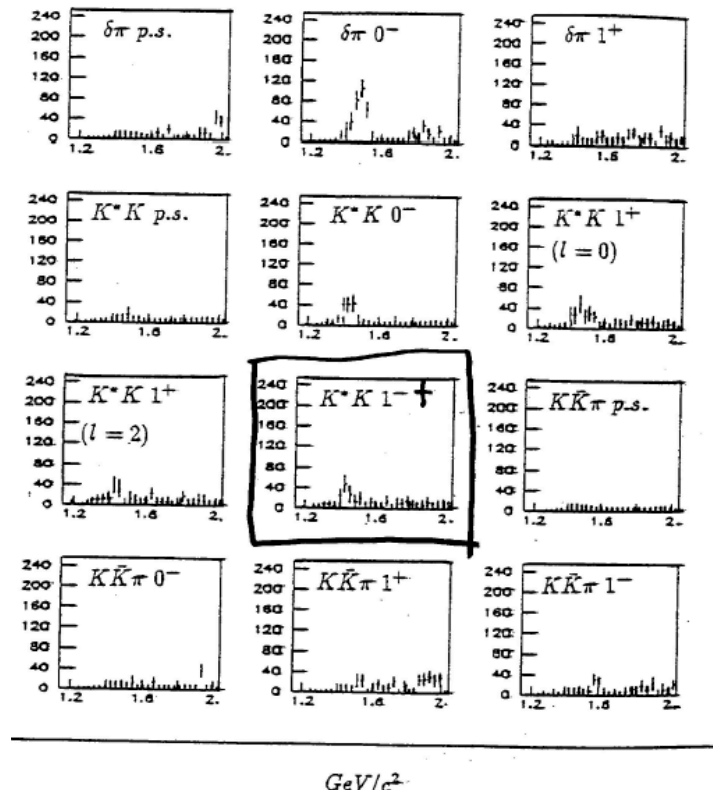
□$_1$$(\bar{u}u + \bar{d}d)$ —> K*K strongly favored by phase space.

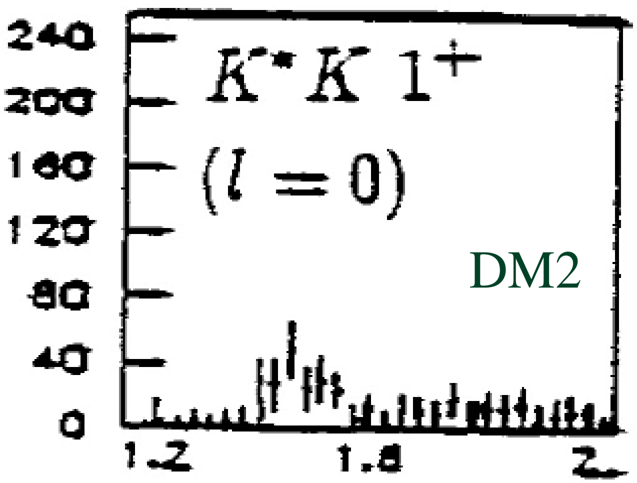
Test: measure "f_1(1420)" parity in □□* —> "f_1" and □ —> □/□ + "f_1"

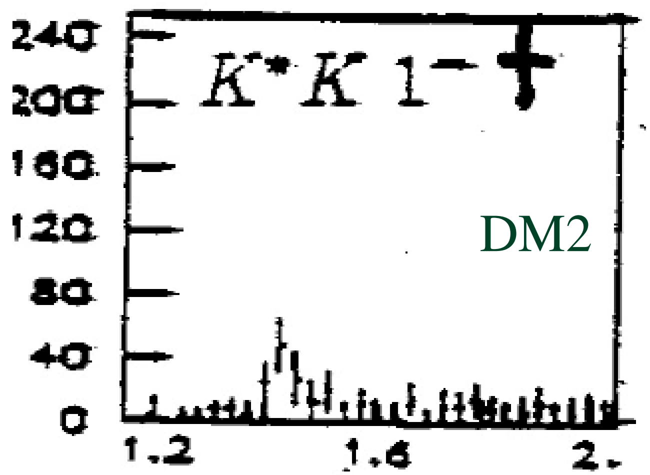
$\square_1$(1420)? (3)

Few experiments which observe $f_1(1420)$ include 1^{-+} partial wave in fits: *if they had,* perhaps they'd see both 1^{-+} and 1^{++} at ~ 1400.

One of the few experiments (DM2) that did include 1^{-+} sees small structure in □ **–> □+ K*K**







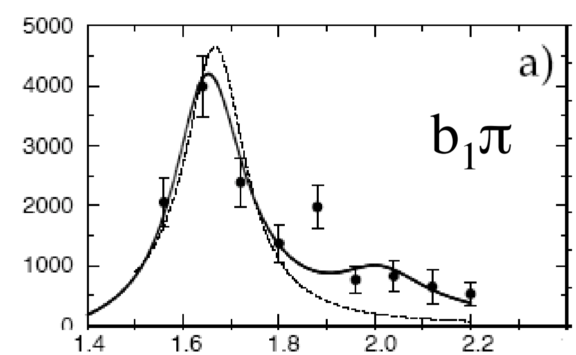
$\pi_1(1600)$ & $\pi_1(2000)$

Compelling evidence in four decay channels from E852, some corroborated by VES & Crystal Barrel:

□π	$1593 \pm 8 +29/-47$	$168 \pm 20 +150/-12$	E852	
□□π	$1597 \pm 10 +45/-10$	$340 \pm 40 \pm 50$	E852	
	1555 ± 50	200 ± 100	CB	Preliminary
$b_1\pi$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 28$	E852	
	~ 1600	~ 330	VES	Preliminary
$f_1^{1285}\pi$	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	E852	

E852 also observes smaller signal with $I,J^{PC} = 1,1^{-+}$ at 2 GeV, $\pi_1(2000)$:

$b_1\pi$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$
$f_1^{1285}\pi$	$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$



Three π_1 states?

Is three π_1 states too much of a good thing?

- QCD sum rules find 200 MeV splitting between π_1 and π_1□
  - consistent with $\pi_1(1400)$ and π_1□(1600)
- Theoretical prejudice favors $\pi_1(1600)$ and $\pi_1(2000)$
  - masses and decays in better agreement with theory, but theory is still in early days.

Best to rely on experiment as much as possible
- more data can help us decide

Q: Can we find nonet partners for the three π_1's?

At BESII/III & CESR-C, look for

□ —> □/□ + $□_1$ & □ —> □ + π_1
□□* —> $□_1$ / π_1

With PWA

For example, □ —> □ + □π/ □□π/ □π/ $b_1\pi$ Li-Yu-Shen

Strange partners? — 1^{-+} may mix with 1^{--} by SU(3) breaking

==> in any case there is an excess of K*'s relative to vector nonets.

Other exotic hybrids

Low-lying hybrid nonets from LGT include three exotics:

J^{PC}	J^{PC}	J^{PC}	J^{PC}
1^{--}	0^{-+}	1^{-+}	2^{-+}
1^{++}	0^{+-}	1^{+-}	2^{+-}

1^{-+}, 0^{+-}, 2^{+-}

Mass ratios from quenched LGT:

$$\begin{cases} 0^{+-} / 1^{-+} \sim 1.1 \pm 0.09 \\ 2^{+-} / 1^{-+} \sim 1.3 \pm 0.1 \end{cases}$$

UKQCD

Very interesting to search for 0^{+-}, 2^{+-}

Decay modes for I = 1 include

$2^{+-} \longrightarrow (\pi\ \square)$, $(\square\ \square)$ *d-wave* — Most useful experimentally

$0^{+-} / 2^{+-} \longrightarrow (a_2\ \square)$, $(f_2\ \square)$ $(f_1\ \square)$ *p-wave*

$\longrightarrow (f_1\ b_1)$ *s-wave* — High thresholds

Results will illuminate interpretation of π_1 candidates.

Nonexotic hybrids

J^{PC}	J^{PC}	J^{PC}	J^{PC}
1^{--}	0^{-+}	1^{-+}	2^{-+}
1^{++}	0^{+-}	1^{+-}	2^{+-}

Five of the eight low-lying hybrid nonets expected from LGT are not exotic:

$$\boxed{0^{-+},\ 1^{--},\ 1^{+-},\ 1^{++},\ 2^{-+}}$$

to which the bag model appends $\boxed{0^{++},\ 2^{++}}$

- Nonexotic hybrids increase the number of 'ordinary J^{PC}' nonets and can mix with the ordinary $\bar{q}q$ nonets.
- If lower hybrid mass estimates are correct,
  - many are in the mass range of first radial excitations of $\bar{q}q$
  - for 1^{--} there are **3** categories of excited states @ 1 – 2 GeV:

    ==> radial excitations, d-wave excitations, and hybrids
  - there will be even more 1^{--} K_1^* states, arising from 1^{-+} exotic nonet.

□ decay is good place to find/analyze hybrid components of nonexotics, since hybrid production is naively expected to be favored in hadronic and radiative □ decay.

Nonexotic hybrids $J^{PC} = 1^{++}$

Too many I = 0 candidates: **f_1(1285), f_1(1420), f_1(1530)**

f_1(1285): good candidate for $\bar{u}u + \bar{d}d$

- produced in πp scattering, not in Kp
- dominant decays —> □ππ, 4π   B(KKπ) = 9.0 ± 0.4%

f_1(1420): "established" but interpretation unclear

- dominant decay —> K*K
- produced in πp, $pp_{CENTRAL}$, $\bar{p}p$, e^+e^-, □ decay
- **not** established in Kp: claimed observation (Lepton-F) based on a bump in KKπ at ~ 1420 *without* J^P determination (low statistics)

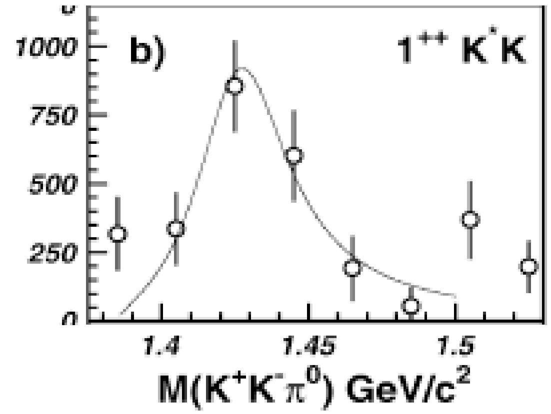
==> could certainly be □(1405) $J^{PC} = 0^{-+}$

Nonexotic hybrids $J^{PC} = 1^{++}$ (2)

f_1(1530): "not established" – PDG

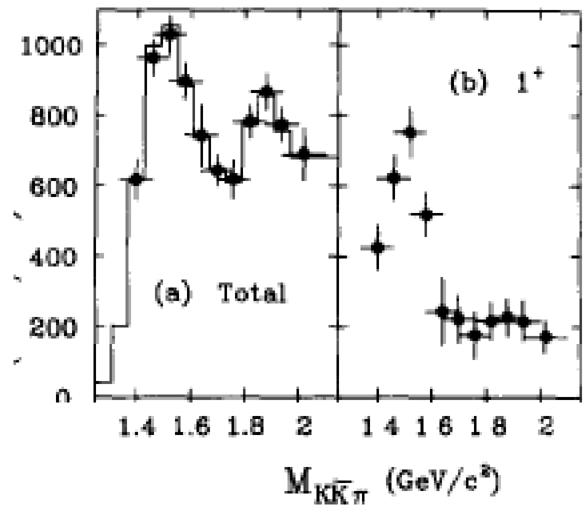
- only observed decay —> K*K
- best seen in Kp (LASS) with no indication of f_1(1420): LASS has 10 □ statistics of Lepton-F
- small signal in πp (E852), with bigger signal for f_1(1420).

E852



Hypothesis: f_1(1285) and f_1(1530) are the $\bar{u}u + \bar{d}d$ and $\bar{s}s$ isoscalars of the approximately ideal 1^{++} nonet.

LASS



Q: could f_1(1420) be a $(\bar{u}u + \bar{d}d)g$ 1^{++} hybrid?

- might explain □ –> □ + f_1(1420)

  and □ –> □+ f_1(1420)

But then why is f_1(1420) —> KK* dominant?

Nonexotic hybrids $\quad J^{PC} = 0^{-+}$

Too many I = 0 candidates: **□(1295), □(1405), □(1475)**

- all "established" (PDG)

□(1295): good candidate for predominantly $\bar{u}u + \bar{d}d$ radial excitation

- produced in πp scattering
- dominant decay —> □ππ

□(1405) & □(1475): split descendants of □(1440) seen in □ –> □□ both seen in radiative □ decay, πp, and pp annihilation.

- **1405** decays to □ππ & KKπ
- **1475** decays predominantly to K*K, no evidence for □ππ

Started glueball mania!

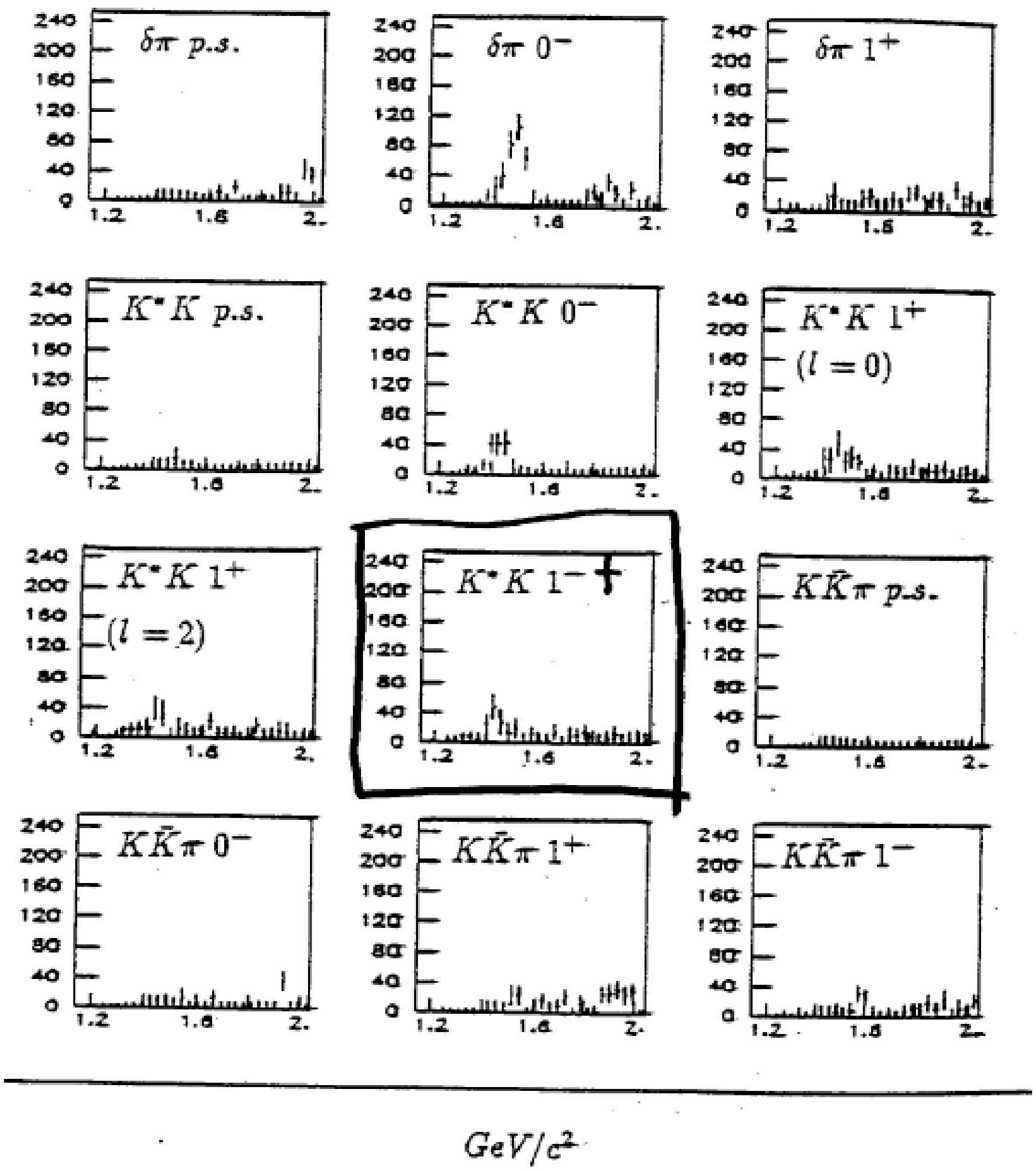
MC Ishikawa

Except DM2: 1405 –> K*K

BESI fits with a single state □ –> □□(1440) —> □ππ/KKπ using mass-dependent widths adjusted to phase space for each channel.

Complicated structure requiring greater statistics than previously available in □ –> □+ □ππ/KKπ **===> eagerly await BESII analysis.**

□ –> □+ KKπ PWA from DM2



Nonexotic hybrids $J^{PC} = 1^{-\square}$

Too many □ excitations? — possibly 5 □□s from 1200 - 2100 MeV

"Established" (PDG)

□(1450): m = 1465 ± 25 □ = 400 ± 60 radial excitation (?)

□(1700): m = 1720 ± 20 □ = 250 ± 100 d-wave (?) (cf. $\square_3$(1690)

History of hints for □(1200 - 1250) — for example:

Crystal Barrel $\bar{p}n \longrightarrow \square\pi^-\pi^0$ Poor fit with only 1450 & 1700

Need □(1200) —> □π : m ~ 1180 ± 70 □ ~ 220 +

LASS $K^-p \longrightarrow \pi^+\pi^-\square$

Need □(1300) —> ππ : m = 1302 ± 28 □ = 140 ± 48 (~5% elasticity)

Mark III $\square \longrightarrow \pi^+\pi^-\pi^0$ Small signal for □(1300)

dominated by □(1600) m = 1600 ± 28 ±? □ = 383 ± 25 ±?

AND two heavy □□s:

E687 □(1900) $\square p \longrightarrow 3\pi^+3\pi^-p$ m = 1910 ± 10 □ = 37 ± 13

PDG □(2150) —> ππ,KK,6π,□π,□□π m = 2149 ± 17 □ = 363 ± 50

BUT no evidence yet for extra □ or K* } □(1420) & □(1650) K*(1410) & K*(1680) ➡ Plausible partners for □(1450) & □(1700)

Nonexotic hybrids $J^{PC} = 1^{-\square}$ (2)

SPECIAL NEWS BULLETIN

Beijing, Wednesday, Sept. 29, 2004

- Wang Zheng reports BESII analysis of □ □□ **πππ**
- Dominant signal π + □(2150)
- Also π + □(770)
- **No indication of** □(1200), □(1450), □(1700), or □(1910)

Reporter's memory is failing: what is m, □ of Zheng state?
□ consistent with PDG? – m = 2149 ± 17 □ = 363 ± 50

Strongly produced in hybrid-favored channel although kinematically disfavored, while lighter, established 1450 &1700 are not seen at all.

Is the hybrid bell ringing?

Nonexotic hybrids $J^{PC} = 1^{-□}$ (3)

Questions I wish I had Wednesday asked about □ □□ π + □(2150):

- fully reconstructed 4C fit?
- could 2150 be faked by reflections from π + □(770)?
- signal/limit for □ □ π + □(2150)?
  - phase space smaller by 3 for □ compared to □ □

Important to look for other decays: KK, 6π, □π, □□π

- o different systematics
- o see if m, □ is reproduced

Conclusion

- Results from high statistics experiments,
  BESII, E852, Crystal Barrel, Obelix, WA102, LASS
  clarify and extend our picture of the $q\bar{q}$ spectrum,
  with evidence for what may be the first discovered gluonic states.

- With the world's largest sample of radiative and hadronic □ decays, BESII has a unique role to play: we look forward to more partial wave analyses, including multibody decay channels, such as

  □□ □/ □/ □/ π + □ππ / KKπ / ππππ /KKππ …

- Hybrids? – NONETS, NONETS, NONETS, NONETS, …

- With future precision results from unquenched LGT simulations and (multi-) giga-event □ decay samples from BESIII & CESR-C, we anticipate definitive studies of the spectrum of gluonic states.

Don't prejudge the outcome: we may find what we expect OR we may find that strong nonAbelian dynamics in the gluonic sector produces surprises.