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Glueballs & Hybrids: Prospects for BES III

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Topics

- Introduction
- Chiral Suppression: $\langle G_0 \mid \bar{q}q \rangle \propto m_q$
- Scalar glueball: three paradigms
- Hybrids
- Conclusion

To be presented at ludicrous speed.

Glueballs dramatically reflect QCD's fundamental properties: local, unbroken, nonAbelian symmetry

- NonAbelian gauge th'y: gauge bosons carry charge
- Unbroken: charge confined in IR

➡ **Gauge bosons form singlet bound states**

Cf QED: $Q_\gamma = 0 \Rightarrow$ IR free $\Rightarrow$ no lightballs

Prediction is simple and fundamental, but difficult to verify.

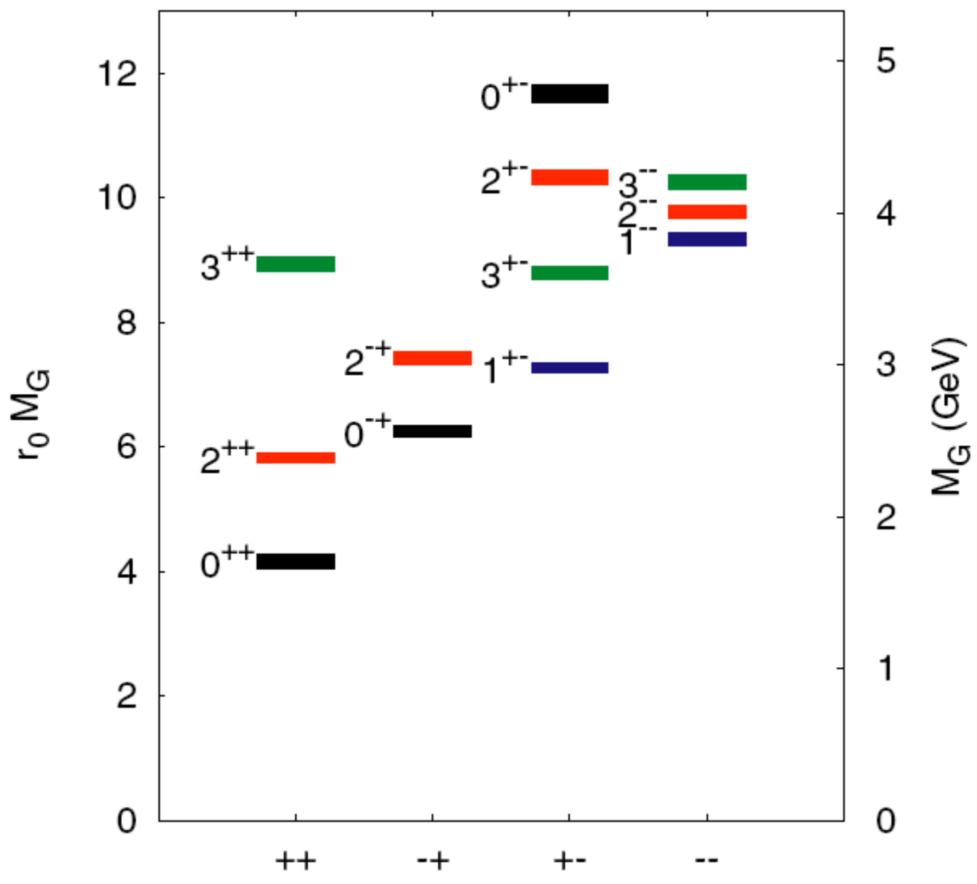
We expect a solution in the coming years:

✓ **BES III** ⇒ definitive Ψ decay data (especially $\Psi \to \gamma X$)

✓ **LQCD** ⇒ unquenched results on spectrum, mixing, decays

➡ Powerful combination of experiment & theory, sufficient to solve the problem.

LQCD verifies naïve prediction that glueballs should exist:



Spectrum from quenched LQCD

Y. Chen *et al.*
PRD73:014516,2006
(updates Morningstar &
Peardon, ‘99)

0^{++} : 1710 ± 50 ± 80

Also:
1611 ± 30 ± 160   Michael ‘98
1550 ± 50 ± ?   Bali et al. ‘93

But they are not easy to find:

- Not easily distinguished from $\bar{q}q$ or $\bar{q}qg$, with which they can mix
- Dynamics not understood – e.g., widths

Properties

- Extra states, beyond $\bar{q}q$ spectrum – e.g., too many 0^{++}

  Must understand "ordinary" $\bar{q}q$ spectrum very well
  ⇒ need results from many different experiments:
  Ψ decay, πp, $\bar{p}p$, γγ, γN, LEP…

- Big coupling to gluons – Produce in **$\psi \to \gamma G$**
- Small coupling to photons

Sticky

- Flavor singlet ⇒ SU(3) symmetric mixing/decays

OR NOT? → chiral suppression for spin 0?

Special role of radiative J/Ψ decay (& BEPC!)

For heavy quark, pert. th'y implies

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

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

$$B(\Psi \to ggg) \sim B(\Psi_{\text{direct}} \to \text{hadrons}) = 0.71$$

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

~ 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/Ψ decay (2)

- Rough agreement of pert. th'y with ψ → γX data verifies that leading short distance mechanism is ψ → γ + **gg**

- ϒ(9460) can't compete:

$$\frac{N(\Psi \to \gamma X_{1-2\mathrm{GeV}})}{N(\Upsilon \to \gamma X_{1-2\mathrm{GeV}})} \sim \frac{\overline{\sigma}_\Psi}{\overline{\sigma}_\Upsilon} \left(\frac{e_c}{e_b}\right)^2 \cdot \left(\frac{\Gamma(\Psi \to \gamma X_{1-2\mathrm{GeV}})}{\Gamma(\Psi \to \gamma X)}\right) / \left(\frac{\Gamma(\Upsilon \to \gamma X_{1-2\mathrm{GeV}})}{\Gamma(\Upsilon \to \gamma X)}\right)$$

$$\sim 10^2 \bullet 4 \bullet 10 \sim 4000$$

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

Expect glueballs are sticky: $S_G >> S_{M(\bar{q}q)}$

➡ Two-photon physics also interesting for BES III

Radiative ψ decay is the ideal glueball hunting ground

Chiral suppression of $\langle G_0 \mid \bar{q}q \rangle$

MC PRL95:172001,2005

$m_q=0$: $G_0 \to \bar{q}_L q_L + \bar{q}_R q_R \xrightarrow{\textit{helicity}} \bar{q}_+ q_- + \bar{q}_- q_+$

$\Rightarrow \vec{J}\cdot\hat{p}_q = \pm 1 \Rightarrow \langle G_0 \mid \bar{q}q \rangle \xrightarrow[m_q \to 0]{} 0$

Like
$\pi\to\mu\nu/e\nu$

Equivalently, Jacob-Wick helicity amplitude: **$D^0_{\lambda 1} = 0$**

Explicit example: $\mathcal{L}_{eff} = f_0 G_0 G_{a\mu\nu} G_a^{\mu\nu}$

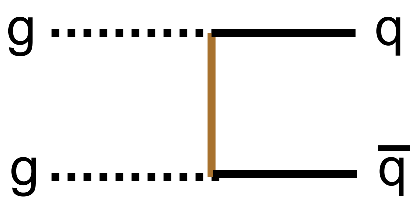
Leading order: $\mathcal{M}(G_0 \to \bar{q}q) = -f_0 \alpha_S \frac{16\pi\sqrt{2}}{3} \frac{m_q}{\beta} \log\frac{1+\beta}{1-\beta} \bar{u}_3 v_4 \delta_{ij}$

Easy to show $\langle G_0 \mid \bar{q}q \rangle \xrightarrow[m_q \to 0]{} 0$ **to all orders in α_S,**

even without assuming specific form of $\mathcal{L}_{\text{eff}}$.

Chao, He & Ma
hep-ph/051237

BUT…



- Even for $m_G \to \infty$ *t,u* channel is in IR:

We know $\langle G_0 \,|\, \bar{q}q \,\rangle \propto m_q$ to all orders in α_S
but **cannot** estimate magnitude in pert. th'y.

- Nonperturbative chiral sym. breaking *might* lift suppression,
  e.g., instanton interaction,

Zhang & Jin

but neither the instanton amplitude nor the chiral invariant (suppressed) amplitude can be reliably estimated.

Need a **reliable nonperturbative** method
to determine if chiral suppression occurs:
for now **LQCD** is the only game in town.

Challenge: unquenched, near chiral **&** continuum limits.

Consequences *if* chiral suppression occurs

Mixing

- G_0 - $M(\bar{q}q)$ mixing is suppressed, $O(m_q/m_G)$

  Consistent with quenched LQCD study, Lee-Weingarten '99

  must be revisited with modern techniques/computers
- To extent it occurs, G_0 - $M(\bar{q}q)$ mixing dominated by $M(\bar{s}s)$
- G_0 - $H(\bar{q}qg)$ & G_0 - $\bar{q}\bar{q}qq$ unsuppressed

$\Psi \rightarrow \gamma X$: Filter for new physics

- For $J^{PC} = 0^{++}$ $M_0(\bar{q}q)$, $\Psi \rightarrow \gamma M_0$ is suppressed
- To extent it occurs, $M_0(\bar{s}s)$ is favored over $M_0(u\bar{u}+d\bar{d})$
- $J^{PC} = 0^{++}$ $H_0(\bar{q}qg)$ & $\bar{q}\bar{q}qq$ unsuppressed

➡ $\Psi \rightarrow \gamma + X(0^{++})$ selects new physics

Consequences: decays

Heavy G_0 (with discernible jet structure in decay)

- 2 jet decays: leading strange ($< 2m_D$)
  or charm ($> 2m_D$) particles
- 3 jet decays: $SU(3)_{\text{Flavor}}$ symmetric

➡ Study strangeness as function of Thrust/Sphericity

Light G_0 ~ 1.7 GeV (too light for jet-shape analysis?)

- *perhaps* $G_0 \rightarrow \bar{s}s \xrightarrow[\text{hadronization}]{\text{nonperturbative}} G_0 \rightarrow \bar{K}K$

  $\Rightarrow \quad G_0 \rightarrow \bar{K}K \quad \gg G_0 \rightarrow \pi\,\pi$
- *perhaps not*:

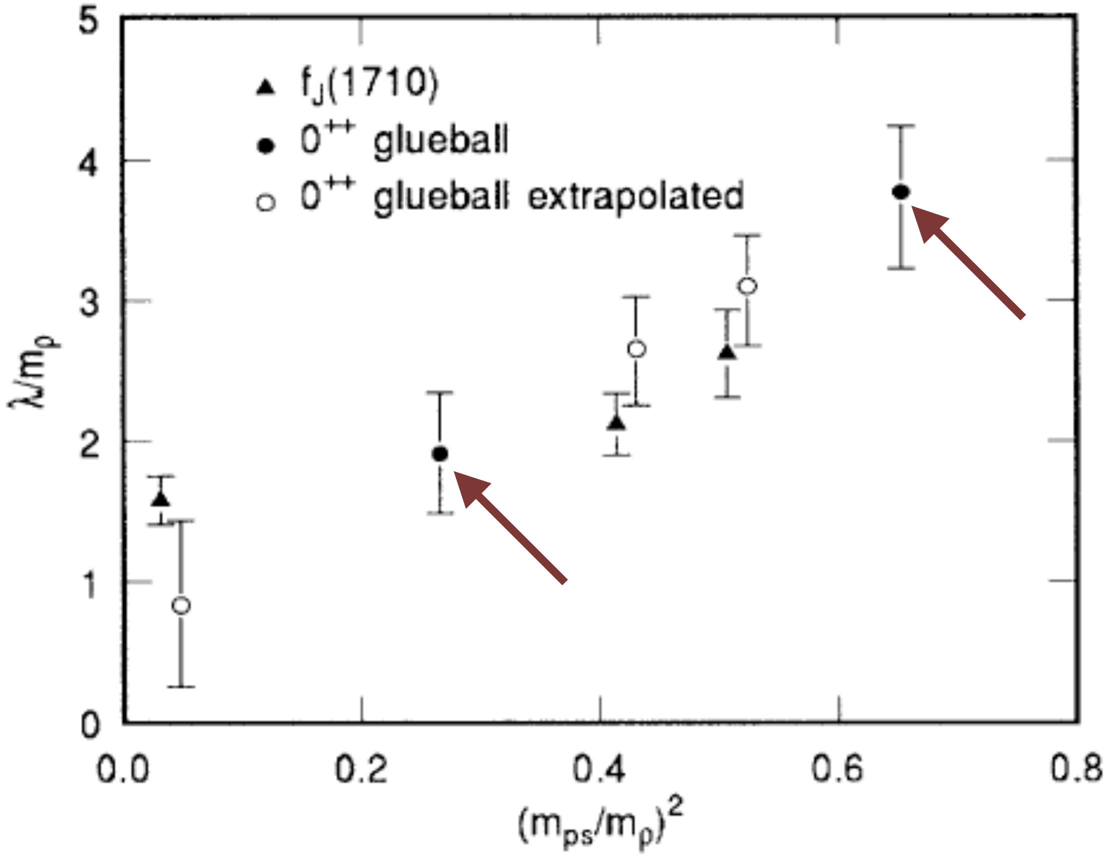
  pert. th'y ⊕ light cone wave f'n models

  Chao,He,Ma

➡ **Need LQCD for reliable determination**

Quenched LQCD

Sexton,
Vaccarino,
Weingarten
PRL75:4563,'95



- Consistent with chiral suppression
- Must be reexamined with modern methods/computers
  (∃ concerns that β=5.7 is near non-QCD critical point)

Scalar Glueball

Quenched LQCD: $m_G = 1710 \pm 50 \pm 80$ MeV

Y. Chen *et al.*
PRD73:014516,2006

“Too many” $I,J^{PC} = 0,0^{++}$ mesons in 1.5 – 2 GeV region:

$f_0(600)$, $f_0(980)$ — Assume Jaffe’s cryptoexotic $\bar{q}\bar{q}qq$; heavier $\bar{q}\bar{q}qq$ fall apart”, $\Gamma \sim m$.

$f_0(1370)$, $f_0(1500)$, $f_0(1710)$ — $G_0 + 2$ p-wave $M(\overline{q}\overline{q}))$

Some mixing likely

He-Liu-Li-Zheng

$f_0(1790)$, $f_0(1812)$ — Hybrids and/or excited M(qq))

⇒ We have observed the groundstate scalar glueball, but cannot yet identify it.

Consider three paradigms:

Paradigm I: $G_0 \sim f_0(1500)$

Mixing from model of observed decays:

Close & Zhao ‘05
Similar: He-Liu-Li -Zheng, ‘06

$$|f_0(1710)\rangle = 0.36|G\rangle + 0.93|s\bar{s}\rangle + 0.09|n\bar{n}\rangle,$$

$$|f_0(1500)\rangle = -0.84|G\rangle + 0.35|s\bar{s}\rangle - 0.41|n\bar{n}\rangle,$$

$$|f_0(1370)\rangle = 0.40|G\rangle - 0.07|s\bar{s}\rangle - 0.91|n\bar{n}\rangle,$$

Problems:

- Unquenched $m_G = 1440 \pm 16$ – *low end of LQCD range*
- BESII: $\Gamma(\Psi \to \omega f_0(1710)) = 5\Gamma(\Psi \to \varphi f_0(1710))$

  but typically DOZI/SOZI << 1, maybe O(1) for J=0

  5 ~ O(1)?
  3 ~ O(∞)?

- BESII: $B(\Psi \to \gamma f_0(1500)) \cdot B(f_0 \to \pi^+\pi^-) = 6.7 \pm 2.8 \cdot 10^{-5}$

  PDG: $B(f_0 \to \pi\,\pi) = 0.349 \pm 0.023$

  ⟹ $B(\Psi \to \gamma f_0(\mathbf{1500})) = \mathbf{2.9 \pm 1.2 \cdot 10^{-4}}$ – ***small for G_0!***

BESII & WA102 } **Cf.**, $B(\Psi \to \gamma\, f_0(\mathbf{1710})) \geq \mathbf{16.2^{+3.0}_{-2.4} \cdot 10^{-4}}$

Paradigm II: $G_0 \sim f_0(1710)$

- Chiral Suppression could explain m_G ~ quenched value,

  $G_0 - M_0(\bar{q}q)$ mixing suppressed ⇒ quenched approx. good

  and decays,

  $B(G_0 \to KK) / B(G_0 \to \pi\pi) > 9$ (95% CL) BES
- $f_0(1710)$ most prominent scalar in radiative Ψ decay:

  BESII: $B(\Psi \to \gamma f_0(1710)) \cdot B(f_0 \to KK) = 11.1^{+1.7}_{-1.2} \cdot 10^{-4}$

  WA102: $B(f_0 \to \eta\eta) / B(f_0 \to KK) = 0.48 \pm 0.15$

  ➡ **$B(\Psi \to \gamma f_0(1710)) \geq 16.2^{+3.0}_{-2.4} \cdot 10^{-4}$**
- Small γγ width: < 0.06 keV (95%) CELLO
- Sticky: 1710:1525:1270 = (≥ 56) : 14 : 1

E.g., Lee-Weingarten,
from quenched
LQCD mixing

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

Paradigm II: problems

- $\Gamma(\Psi \rightarrow \omega f_0(1710)) = 5\Gamma(\Psi \rightarrow \varphi f_0(1710))$ requires DOZI ~ 5 SOZI, same as paradigm I.

- $f_0(1370)$ and $f_0(1500)$ do not decay like I = 0 partners of $\bar{q}q$ $J^{PC} = 0^{++}$ nonet – where is $\bar{s}s$ component?

  PDG: $B(f_0(1500) \rightarrow KK) = (8.6 \pm 1.0)\%$

Question: could $f_0(1500) \rightarrow KK$ be lost under $f_2(1525) \rightarrow KK$?

Paradigm III, a compromise: share the glue

Assume
- G_0 & $M_0(\bar{s}s)$ ~ degenerate before mixing, m ~ 1620 MeV
- G_0 - $\bar{s}s$ *not* suppressed (m_s^{eff} not so small)

⇒ Maximal mixing, $\Theta \approx \pi/4$

⇒ $f_0(1710) \propto G_0 + M_0(\bar{s}s)$

$f_0(1500) \propto G_0 - M_0(\bar{s}s)$

$$\left.\begin{array}{l} gg \rightarrow f_0(1710) \\ f_0(1710) \rightarrow \bar{s}s \end{array}\right\} \quad \text{Constructive}$$

$$\left.\begin{array}{l} gg \rightarrow f_0(1500) \\ f_0(1500) \rightarrow \bar{s}s \end{array}\right\} \quad \text{Destructive}$$

⇒ could explain $\psi \rightarrow \gamma$ + 1500/1710 and 1500/1710 → KK

Hybrids: $H(\bar{q}qg)$

- Expected in all approaches: LQCD, bag, flux-tube, QCD sum rules.
- Some nonets with exotic J^{PC}
  - Can't be confused with or mix with ordinary M(qq) (qqqq ?)
  - All approaches agree $\underline{J}^{PC} = 1^{-+}$ is the lightest exotic
- ∃ exp'tl evidence (πp & pp exp'ts) for I = 1, $J^{PC} = 1^{-+}$ exotics:

$\pi_1(1400)$ → $\eta\pi$ E852, CB (GAMS, KEK)

$\pi_1(1600)$ → $\eta'\pi$, $\rho\pi$, $b_1\pi$, $f_1^{1285}\pi$ E852, CB (VES)

- LQCD: ~ 1900 MeV $\xrightarrow[m_\pi/m_\rho \to 1/3]{\text{Hedditch et al.}}$ ~ 1600 MeV $\xrightarrow[m_\pi/m_\rho \to 1/6]{}$?

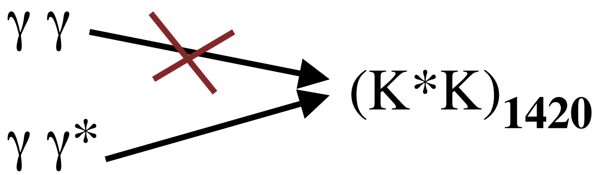
➡ **to confirm interpretation, must find nonet partners.**

➡ Consider hints of **$\eta_1(1400)$: $_1$** →

$\gamma\gamma^* \to \eta_1$, $\psi \to \omega\eta_1$, $\psi \to \gamma\eta_1$

$\gamma\,\gamma^* \to$ "$\mathrm{f}_1(1420)$" & $\Psi \longrightarrow \omega +$ "$\mathrm{f}_1(1420)$"

TPC
Mark II
L3



$\gamma\,\gamma$
$\gamma\,\gamma^*$
$(K^*K)_{1420} \Longrightarrow J^C = 1^+$

Landau-Yang
Theorem

Might be $\mathrm{f}_1(1420)$ – Also see $\gamma\,\gamma^* \longrightarrow \mathrm{f}_1(1285) \longrightarrow \eta\pi\pi$ $J^{PC} = 1^{++}$

Data:

$$\tilde{\Gamma}_{\gamma\gamma} = \lim_{Q^2\to 0}\frac{M^2}{Q^2}\Gamma^{TS}_{\gamma\gamma^*} = \left\{\begin{array}{lll} 2.8 \pm 1.2\ \text{keV} & 1285 & \text{PDG} \\ 3.8 \pm 1.3\ \text{keV} & 1420 & \text{My average} \end{array}\right.$$

$$\tilde{\Gamma}_{\gamma\gamma}(1420)/\tilde{\Gamma}_{\gamma\gamma}(1285) \sim \left\{\begin{array}{ll} \mathbf{1.4} & \underline{\text{Data}} \\ 2/25 \times 1420/1285 \sim \mathbf{0.1} & \underline{\text{Ideal mixing prediction}} \end{array}\right.$$

$\mathrm{f}_1^{\,1285}(\bar{u}u + \bar{d}d)$
$\mathrm{f}_1^{\,1420}(\bar{s}s)$,

Data indicates **big $\gamma\,\gamma$ coupling** for $\mathrm{f}_1(1420)$, **like $\bar{u}u + \bar{d}d$**.

AND:

$B(\Psi \longrightarrow \omega + \mathrm{f}_1(1420)) = (6.8 \pm 2.4)\ 10^{-4}$
$B(\Psi \longrightarrow \phi + \mathrm{f}_1(1420)) < 1.1\ 10^{-4}$ (90%)

Mk III

also as if $\mathrm{f}_1(1420) \sim \bar{u}u + \bar{d}d$.

$\gamma\,\gamma^* \rightarrow \eta_1(1420)$ & $\Psi \longrightarrow \omega + \eta_1(1420)$?

MC
PLB187:409

Suppose: "$f_1(1420)$" in $\gamma\gamma^* \longrightarrow$ "f_1" and $\Psi \longrightarrow \omega +$ "f_1"

is not 1^{++} $f_1(1420)$ $\bar{s}s$ observed in hadronic reactions,

but is 1^{-+} $\eta_1(1420)$ $(\bar{u}u + \bar{d}d)g$ partner of **$\pi_1(1400)$.**

➡ Explains puzzling large rates in both channels

<u>BUT</u> why does $\boldsymbol{\eta_1(1420)}$ $(\bar{u}u + \bar{d}d)g$ decay to K^*K, not $\eta\pi\pi$?

Solution: Isospin **+** Kinematics } ➡

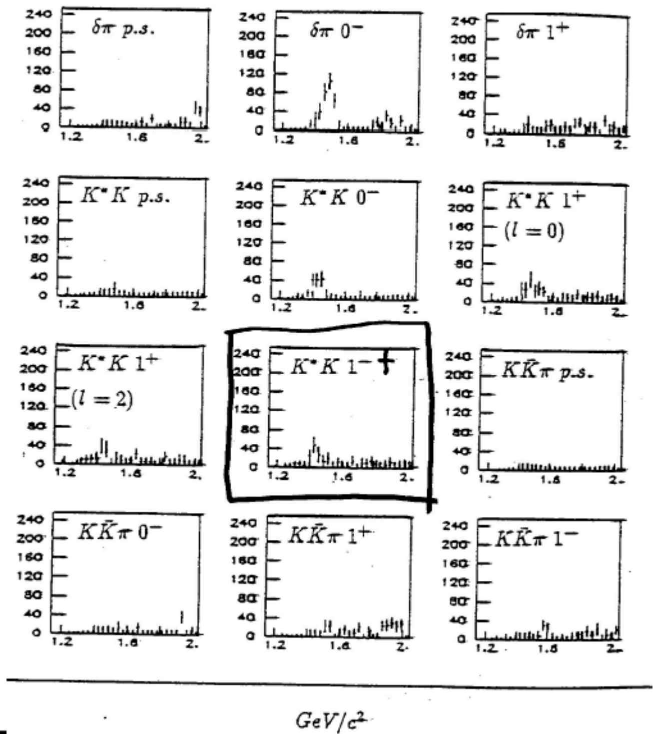
$\eta_1 \longrightarrow K^*K$ **p-wave**

$\eta_1 \longrightarrow \eta\pi\pi$ **L = 4, $\pi\pi$ d-wave**

➡ $\eta_1(\bar{u}u + \bar{d}d)g \longrightarrow K^*K$ strongly favored by phase space.

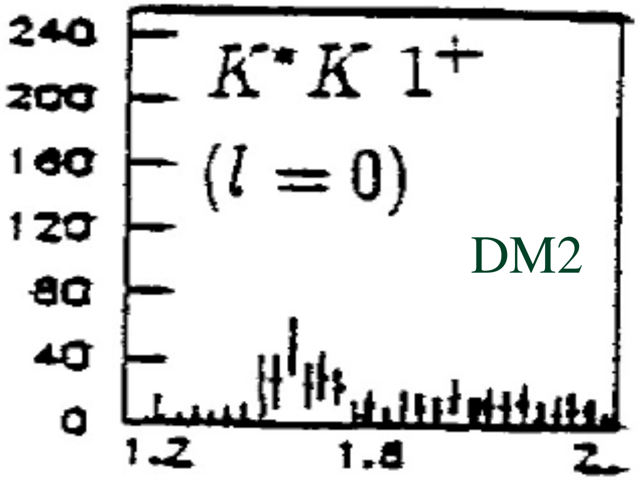
Test: measure "$f_1(1420)$" parity in $\gamma\,\gamma^* \longrightarrow$ "f_1" and $\Psi \longrightarrow \gamma/\omega +$ "f_1"

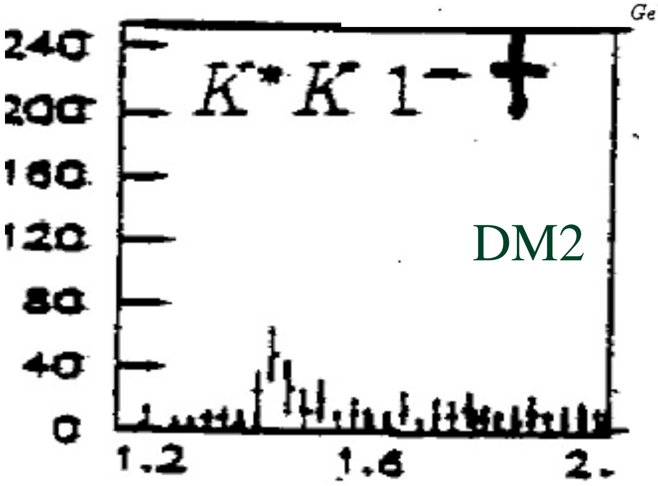
$\Psi \rightarrow \gamma\eta_1(1420)$?



Most experiments omit
1^{-+} partial wave in PWA.

DM2 included 1^{-+} and
saw structure in **Ψ –> γ + K*K:**





Selection rules for hybrid decays?

LQCD & Flux tube }
$H \not\rightarrow$ s-wave + s-wave, e.g., $\pi_1 \rightarrow \eta\pi$ *forbidden*
$H \rightarrow$ p-wave + s-wave, e.g., $\pi_1 \rightarrow b_1\pi$ *allowed*

BUT LQCD selection rule applies to static quark limit:
good approximation for *b,* maybe for *c,* doubtful for *u,d,s.*

Michael

Flux tube model is based on static limit of LQCD in strong coupling phase, hence subject to same limitations.

Flavor selection rule }
CP odd octet meson cannot decay into two octet $J^{PC} = 0^{-+}$ mesons. ➡ $\pi_1 \rightarrow \eta'\pi \;\gg\; \pi_1 \rightarrow \eta\pi$

Lipkin

BUT:

- Phase space favors $\pi_1 \rightarrow \eta\pi \,/\, \pi_1 \rightarrow \eta'\pi = 4.5$
- η-η' mixing angle not negligible: sin 20º = 0.34
- Constructive interference of SU(3) breaking & $\pi_1 \rightarrow \eta_1\pi$ could significantly enhance $\pi_1 \rightarrow \eta\pi$

➡ Selection rules may reflect approximations, not QCD.
Look in all channels, interpret after we have all the data

Nonexotic hybrids

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

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

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

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

- Increase number of 'ordinary' J^{PC} nonets & mix with ordinary $\bar{q}q$
- Could be 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

    and even more 1^{-} K_1^* from 1^{-+} exotic nonet.

  -might explain "iota" region with too many isoscalars:

    η(1295), η(1405), η(1475)

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

Hybrid decays: OIZ violating signature

Naïve perturbation theory suggests possible signature:

Consider I=1 or I=0 $\bar{u}u + \bar{d}d$ hybrid: $H = \bar{q}qg$, $q = u$ or d

Gluon g converts to qq pairs so 1/3 of the time

$$g \longrightarrow \bar{s}s$$

(or > 1/3 for TM modes in bag model MC-Sharpe)

$$\begin{tikzcd}
 & & (q\bar{s})_1 + (s\bar{q})_1 \\
(\bar{q}q)_8 g \arrow[r] & (\bar{q}q)_8\,(\bar{s}s)_8 \arrow[ur, "\text{rearrangement}"] \arrow[dr, "\text{soft}", "\text{gluon exch.}"'] & \\
 & & \boldsymbol{(q\bar{q})_1 + (s\bar{s})_1}
\end{tikzcd}$$

Possibility of unique OIZ rule violating decays

Has BES just seen this?

Chao

$$B(\psi \rightarrow \gamma f_0(1812)) \cdot B(f_0(1812) \rightarrow \omega\varphi) \sim 2.6\ 10^{-4}$$

BES
PRL96:162002,06

Conclusion

Important to know if chiral suppression is relevant:

Two old LQCD studies – of decays & of mixing – appear to be consistent with chiral suppression, but definitive LQCD studies are needed.

BES III is at the threshold of a very rich program, with unique capability to perform PWA in channels that are critical for the discovery of gluonic states:

- $\psi \rightarrow \gamma$ + hadrons
- $\psi \rightarrow$ hadrons
- $\gamma\,\gamma \rightarrow$ hadrons, including (tagged) $\gamma\,\gamma^* \rightarrow$ hadrons

Together with anticipated progress in LQCD, BEPC II/BES III can show the way to the gluonic sector of the QCD spectrum.