The Experimental Status of Glueballs

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Outline

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The Quark Model of Hadrons

- Mesons ($q\bar{q}$) $\quad q \otimes \bar{q} = 3 \otimes \bar{3} = 8 \oplus 1$

- Baryons (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter ...

The Quark Model of Hadrons

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- Baryons (qqq) $q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter, however, QCD also predicts so-called exotic states

➜ simplest possibility: $\underbrace{q \otimes \bar{q} \otimes q = 15 \oplus 6 \oplus 3 \oplus 3}$

Does not work: color singlets needed !

➜ multiple of (qqq) and ($q\bar{q}$) necessary

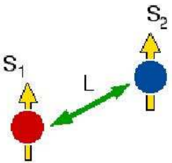
- Glueballs: $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus \boxed{1}$
- Hybrids: $q \otimes \bar{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus \boxed{1}$ ➜ $\boxed{(q\bar{q})^{l}((q)^{3})^{m}(g)^{n}}$,

$l + m \geq 1$ for n = 1

Ordinary Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

- Parity $P = (-1)^{L+1}$
- Charge conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = C(-1)^I$

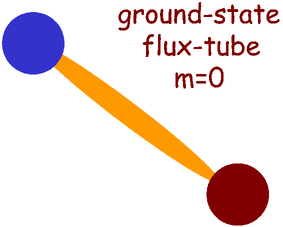


$L = 0,\ S = 1:$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 0,\ S = 0:$

e.g. $\pi\ (J^{PC} = 0^{-+})$



Mesons and their Quantum Numbers

		J^{PC}	$^{2S+1}L_J$	$I=1$	$I=0\ (n\bar{n})$	$I=0\ (s\bar{s})$	Strange
$L=0$	$S=0$	0^{-+}	$^1S_0$	π	η	η'	K
	$S=1$	1^{--}	$^3S_1$	ρ	ω	ϕ	K^*
$L=1$	$S=0$	1^{+-}	$^1P_1$	b_1	h_1	h'_1	K_1
	$S=1$	0^{++}	$^3P_0$	a_0	f_0	f'_0	K^*_0
	$S=1$	1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
	$S=1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2

Notation

1. J^{PC} s are measured quantities
2. $^{2S+1}L_J$ s are internal quantum numbers in a non-relativistic quark model

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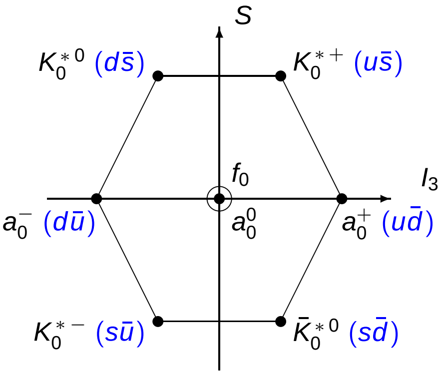
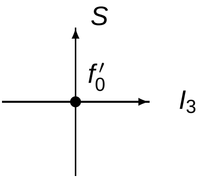
The Nonet of Scalar Mesons with $J^{PC} = 0^{++}$





Properties of Quarks

Classification	d	u	s
Charge	-1/3	2/3	-1/3
Isospin I	1/2	1/2	0
I_3	-1/2	1/2	0

From large energies to large distances ...

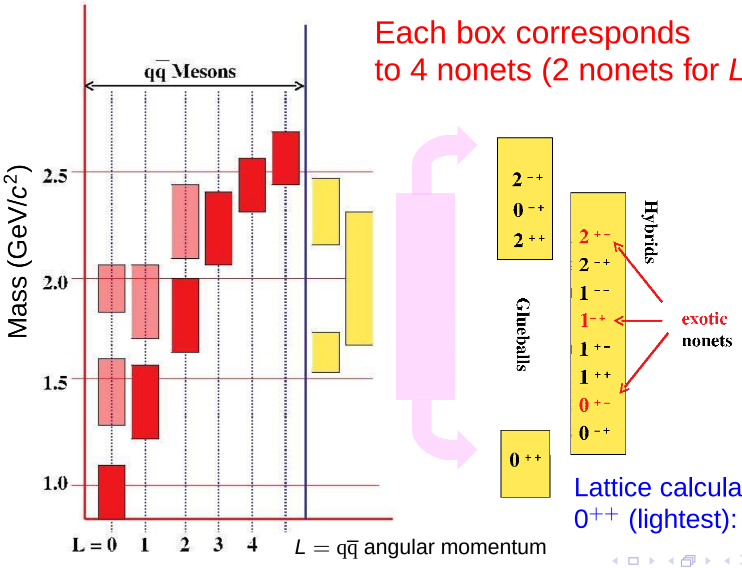
Can we understand bound systems of hadrons within the QCD framework?

No !

Solution: QCD-inspired models

- Bag models
- Flux-tube models
- Instanton interactions
- QCD sum rules
- Lattice QCD

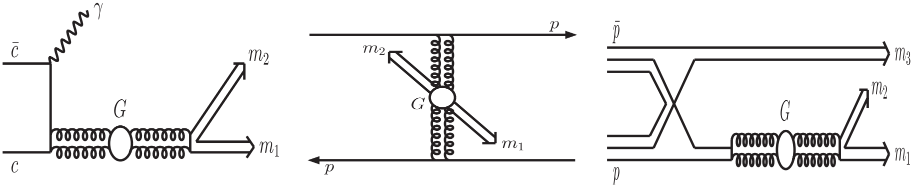
Each box corresponds to 4 nonets (2 nonets for $L = 0$)



Lattice calculations:
0^{++} (lightest): ≈ 1.55 GeV/c^2

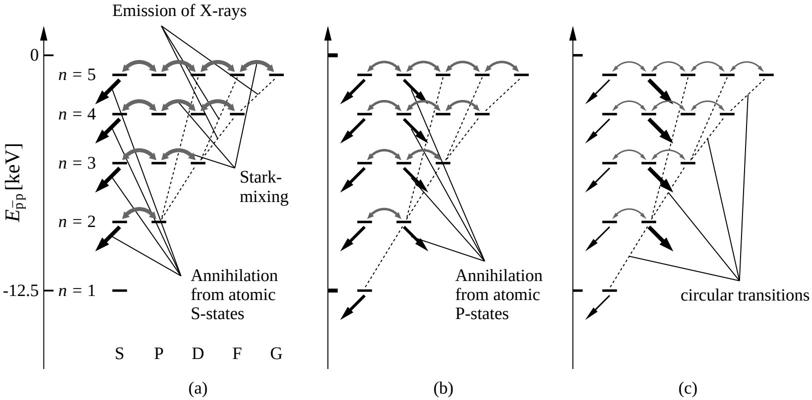
Outline

Glue-Rich Environments



Different Production Mechanisms

1. J/ψ may convert into two gluons and a photon.
2. In central production, two hadrons scatter diffractively; no valence quarks are exchanged.
3. In $p\bar{p}$ annihilation, quark-antiquark pairs annihilate into gluons forming glueballs.



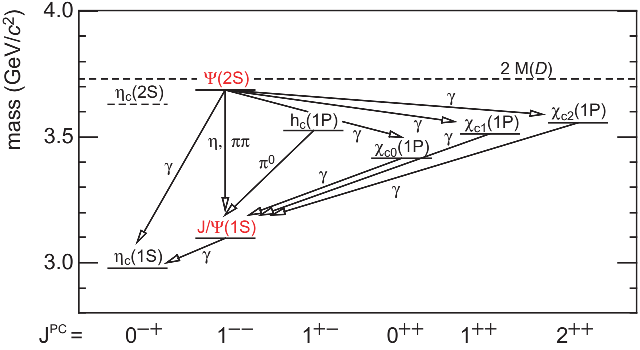
Formation of Protonium (annihilation likely *in production* with recoiling meson):

$$\bar{p} + H_2 \rightarrow \boxed{p\bar{p}} + H + e^- \qquad ({}^1S_0,\ {}^3S_1,\ {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2)$$

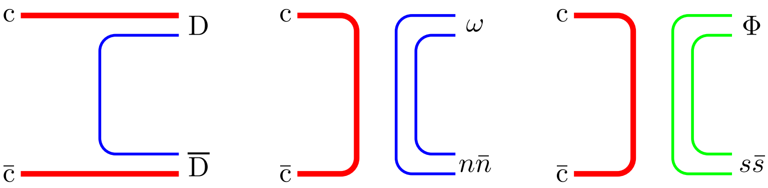
Most Suggestive: Radiative J/ψ Decays

Radiative decays of $c\bar{c}$ states can best be studied *in formation* at e^+e^- colliders via a virtual photon in the process:

$$e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$$



The OZI Rule and Flavor-Tagging Approach



The decay of J/ψ into mesons with open charm (left) is forbidden due to energy conservation.

The two right diagrams requires annihilation of $c\bar{c}$ into gluons:

- Recoiling against ω, mesons with $n\bar{n}$ quark structure are expected.
- If a ϕ is observed, we expect mesons with hidden strangeness $s\bar{s}$.

➜ OZI rule, e.g. ratio $\phi\eta'/\omega\eta' \sim$ ratio of $s\bar{s}/n\bar{n}$ in η' w.f.

Production Experiments

In central production, it was suggested that glueballs would be produced copiously in the process:

$$\text{hadron}_{\text{beam}}\ p \rightarrow \text{hadron}_f\ X\ p_s\ ,$$

where the final-state hadrons carry large fractions of the initial-state hadron momenta.

At sufficiently high energies:

- Process expected to be dominated by double-Pomeron exchange
- Pomeron: carries no (color) charge, positive parity/charge conjugation
  - ➜ Double-Pomeron exchange should favor production of isoscalar particles with positive *G*-parity in a glue-rich environment (no valence quark are exchanged)

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Close-Kirk Glueball Filter:

- Observation: significant enhancement of glueball candidates over the production of conventional $q\bar{q}$ mesons at small transverse momenta
- No dynamical explanation, yet
  - ➜ Just a momentum filter?
    (It may suppress angular momentum and enhance scalar mesons.)

Indirect Glueball Signals

Glueball production should be strongly suppressed in $\gamma\gamma$ fusion:

➜ There is no valence charge to couple to photons.

The collision of two photons can best be studied in *inelastic Bhabha* scattering at e^+e^- colliders via the reaction:

$$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^- X$$

Physicists are creative ...

Stickiness (in J/ψ decays)

$$S = C\left(\frac{M(h)}{k_\gamma}\right)^{2l+1}\frac{\Gamma(\psi\to\gamma h)}{\Gamma(h\to\gamma\gamma)}$$

Gluiness

$$G = \frac{9e_Q^4}{2}\left(\frac{\alpha}{\alpha_s}\right)^2\frac{\Gamma_{R\to gg}}{\Gamma_{R\to\gamma\gamma}}$$

Outline

The $I = 0$, $J^{PC} = 0^{-+}$ (Pseudoscalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$\eta(548)$ $*$	547.51 ± 0.18	$1.30 \pm .07$ keV	$\gamma\gamma$, 3π
$\eta'(958)$ $*$	957.78 ± 0.14	0.203 ± 0.016	$\eta\pi\pi$, $\rho\gamma$, $\omega\gamma$, $\gamma\gamma$
$\eta(1295)$ $*$	1294 ± 4	55 ± 5	$\eta\pi\pi$, $a_0\pi$, $\gamma\gamma$, $\eta\sigma$, $K\bar{K}\pi$
$\eta(1405)$ $*$	1409.8 ± 2.5	51.1 ± 3.4	$K\bar{K}\pi$, $\eta\pi\pi$, $a_0\pi$, $f_0\eta$, 4π
$\eta(1475)$ $*$	1476 ± 4	87 ± 9	$K\bar{K}\pi$, $K\bar{K}^* + cc$, $a_0\pi$, $\gamma\gamma$
$\eta(1760)$	1760 ± 11	60 ± 16	$\omega\omega$, 4π
$\eta(2225)$	2220 ± 18	$150^{+300}_{-60} \pm 60$	$K\bar{K}K\bar{K}$

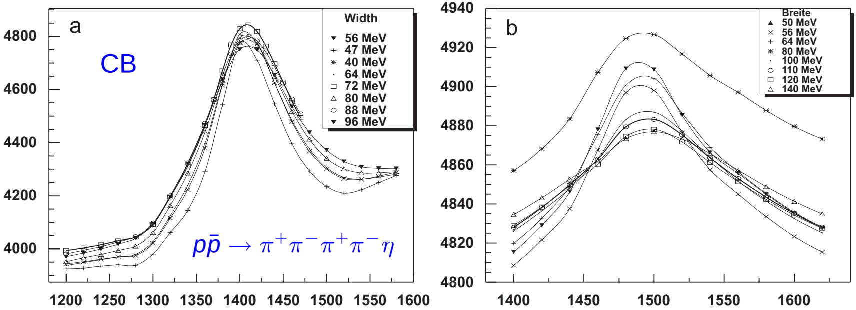
Five pseudoscalar states < 1500 MeV/c^2 listed in the PDG summary table

➜ Too many for two nonets!!

The Search for the Lightest Pseudoscalar Glueball

In 1990, Mark III reported two pseudoscalar states in the 1400 MeV/c^2 region in radiative J/ψ decays (with $J/\psi \to a_0(980)\pi$ and $J/\psi \to K^*K$).

- Both states confirmed by Crystal Barrel and Obelix at LEAR
- But: CB did NOT observe the $\eta(1295)$



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In 2001, L3 observed $\eta(1475) \to K\bar{K}\pi$ in two-photon collisions.

- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?

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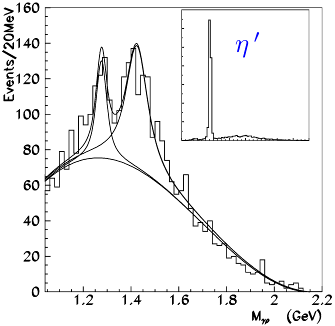
- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?
- In 2005, CLEO published (high-statistics) negative results on both states.

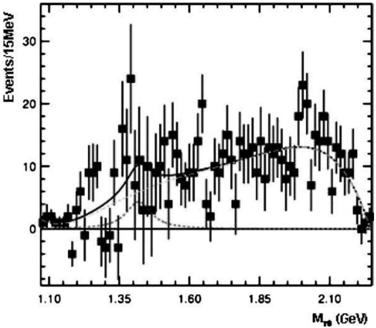
The Flavor Filter in the Decay $J/\psi \rightarrow \gamma[\gamma V]$

BES-II studied $J/\psi \rightarrow \gamma\gamma V(\rho, \phi)$

- Clear observation of peak at $M \approx 1424$ MeV/c^2 in $X(1424) \rightarrow \gamma\rho$ (left)
- No observation of $X(1424) \rightarrow \gamma\phi$ (right)!

  ➜ Glueball should decay to both final states.



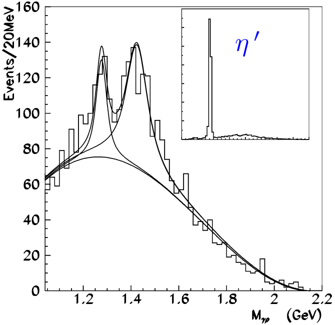


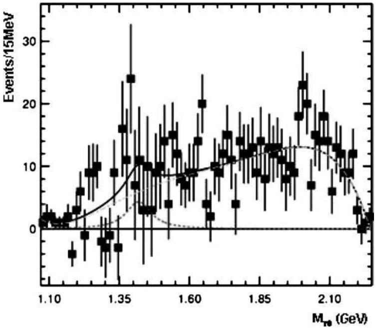
The Search for the Lightest Pseudoscalar Glueball

Common conclusion:

- The X(1424) observed by BES is not the $\eta(1430)$!
- Mark III cannot distinguish between pseudoscalar states and $f_1(1420)$

  ➜ No extra state, no Glueball!

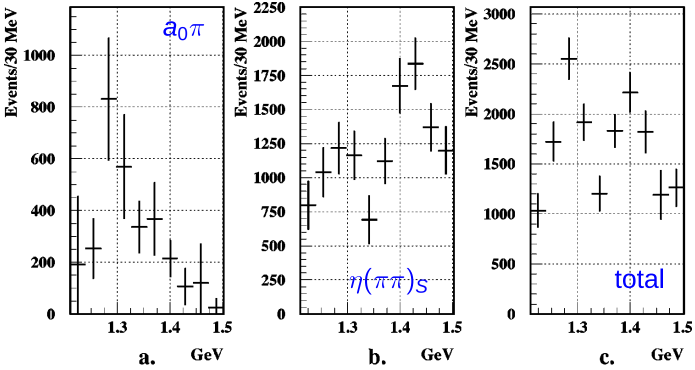




What about the $\eta(1295)$?

Often interpreted as first radial excitation of the η meson.

- Ideal mixing: degenerate in mass with $\pi(1300)$
- Problem: only observed in pion-induced reactions!



E852

$\eta \rightarrow a_0(980)\pi$

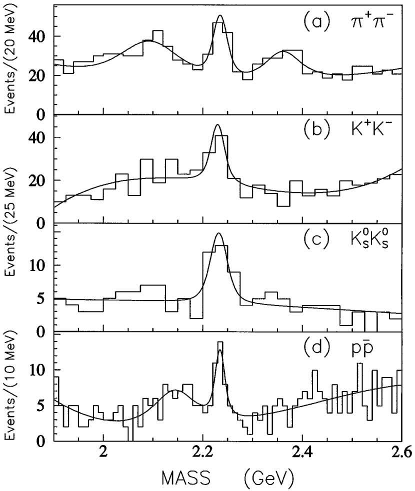
The 2^{++} Tensor Glueball

Evidence essentially non-existent!

- Two quark configurations yield 2^{++}:
  1. $L = 1,\ S = 1,\ J = 2:\ {}^3P_2$ ➜
  2. $L = 3,\ S = 1,\ J = 2:\ {}^3F_2$
- For both nonets, radial excitations are expected.
- Situation premature: none of the states can be assigned definitely to any of the above nonets.

Name	Mass [MeV/c^2]
$f_2(1270)\ *$	1275.4 ± 1.1
$f_2(1430)$	1430
$f_2'(1525)\ *$	1525 ± 5
$f_2(1565)$	1546 ± 12
$f_2(1640)$	1638 ± 6
$f_2(1810)$	1815 ± 12
$f_2(1910)$	1915 ± 7
$f_2(1950)\ *$	1944 ± 12
$f_2(2010)\ *$	2011^{+60}_{-80}
$f_2(2150)$	2156 ± 11
$f_2(2300)\ *$	2297 ± 28
$f_2(2340)\ *$	2339 ± 60

The $f_J(2220)$ or $\xi(2230)$ observed by BES



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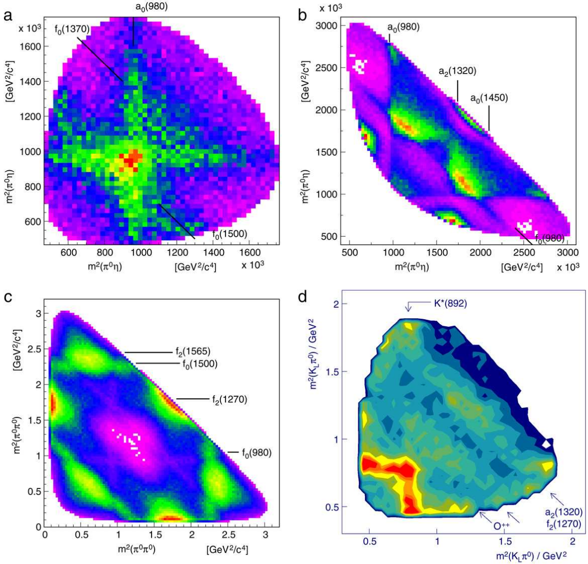
The $I = 0$, $J^{PC} = 0^{++}$ (Scalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ *	$400 - 1200$	$600 - 1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ *	980 ± 10	$40 - 100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ *	$1200 - 1500$	$200 - 500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ *	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ *	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$



Crystal Barrel

- a $p\bar{p} \rightarrow \pi^0\eta\eta$
- b $p\bar{p} \rightarrow \pi^0\pi^0\eta$
- c $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$
- d $p\bar{p} \rightarrow \pi^0 K_L K_L$

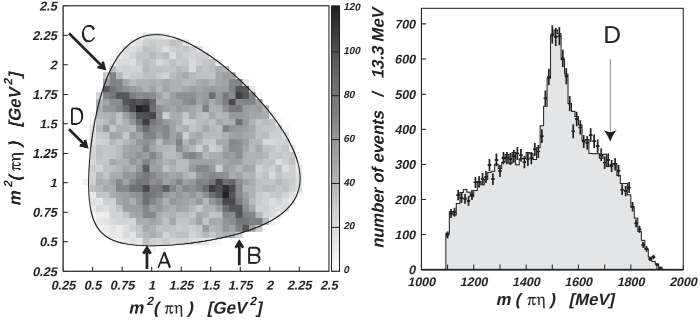
Good description with

- Two isoscalar states: $f_0(1370)$ / $f_0(1500)$
- In addition:
  Both have dominant 4π decay modes.
  ➜ $n\bar{n}$ structure

The $f_0(1710)$ Scalar Meson in Crystal Barrel

First discovered by Crystal-Ball in radiative J/ψ decays into $\eta\eta$

- Spin ($J = 0$ or 2) remained controversial for a long time
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$



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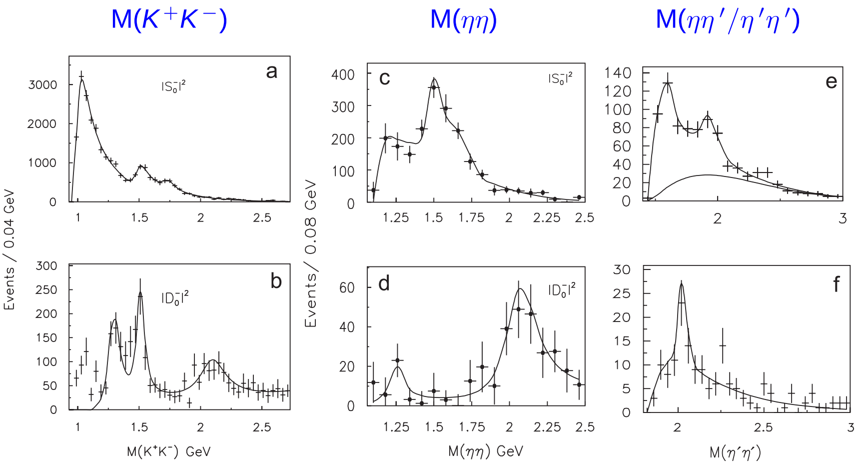
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$
- Consistent with a dominant $s\bar{s}$ assignment
  - ➜ Confirmed by WA102 reporting a much stronger $K\bar{K}$ coupling of $f_0(1710)$ than $\pi\pi$ coupling

Scalar Mesons in Central Production



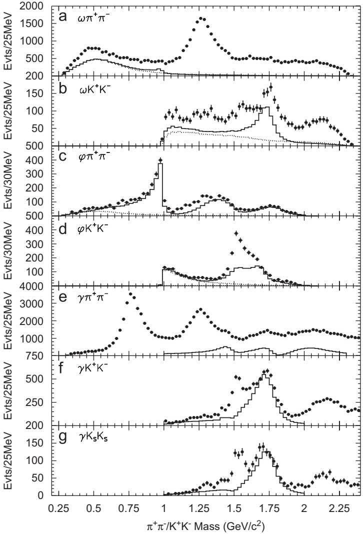
Scalar Mesons in Central Production

Scalar	$\pi\pi/K\bar{K}$	$\rho\rho/2[\pi\pi]_S$	$\rho\rho/4\pi$	$\sigma\sigma/4\pi$
$f_0(1370)$	2.17 ± 0.90		~ 0.9	~ 0
$f_0(1500)$	3.13 ± 0.68	2.6 ± 0.4 [1]	0.74 ± 0.03	0.26 ± 0.03
		3.3 ± 0.5 [2]		
$f_0(1710)$	0.20 ± 0.03			

CB

Ratio	$f_0(1370)$	$f_0(1500)$
$\mathcal{B}(K\bar{K}) \,/\, \mathcal{B}(\pi\pi)$	(0.37 ± 0.16) to (0.98 ± 0.42)	0.186 ± 0.066
$\mathcal{B}(\rho\rho) \,/\, \mathcal{B}(4\pi)$	0.260 ± 0.070	0.130 ± 0.080
$\mathcal{B}(\sigma\sigma) \,/\, \mathcal{B}(4\pi)$	0.510 ± 0.090	0.260 ± 0.070
$\mathcal{B}(\rho\rho) \,/\, \mathcal{B}(2[\pi\pi]_S)$		0.500 ± 0.340
$\mathcal{B}(4\pi) \,/\, \mathcal{B}_{\text{tot}}$	0.800 ± 0.050	0.760 ± 0.080

BES spoils the Glueball Picture ...



Flavor Tagging

$\omega K^+ K^-$ ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi K^+ K^-$ ➜ No peak around 1700 MeV/c^2

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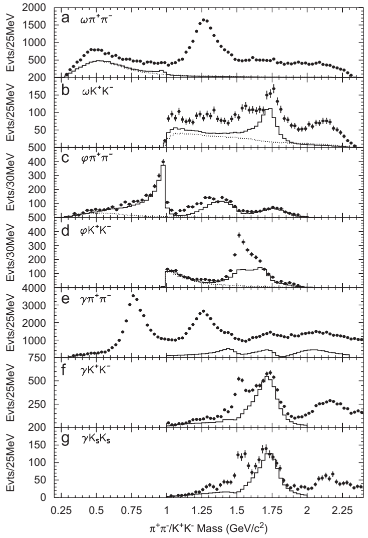


Flavor Tagging

$\omega K^+ K^-$ ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

$\phi K^+ K^-$ ➜ No peak around 1700 MeV/c^2

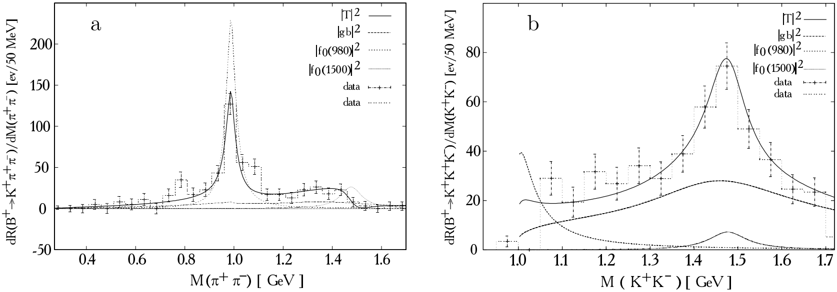
Solution: Two distinct scalar states

- The known $f_0(1790)$ decaying to $K\bar{K}$
- New broad $f_0(1790)$ coupling strongly to $\pi\pi$
  - Not confirmed by other experiments!
  - Mystery why $s\bar{s}$ recoils against ω

Belle makes it even worse ...

Belle measured scalar mesons in $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$
(Results essentially confirmed by BaBar)

- No peak at 1500 MeV/c^2 for the $f_0(1500)$ (left),
- But a clear peak around 1500 MeV/c^2 decaying to K^+K^-
  ➜ Structure of $f_0(1500)$ remains unclear (or two states)!

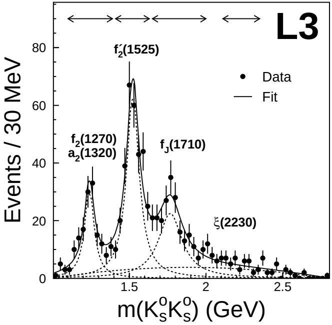


Results on Scalar Mesons from $\gamma\gamma$ Fusion

Results were reported by the LEP collaborations at CERN:

- Three clear peaks in the $K_S^0 K_S^0$ mass by L3 (dominated by tensors)
- No peak for the $f_0(1500)$

➜ Consistent with known small $s\bar{s}$ component! What about $\pi\pi$ spectrum?



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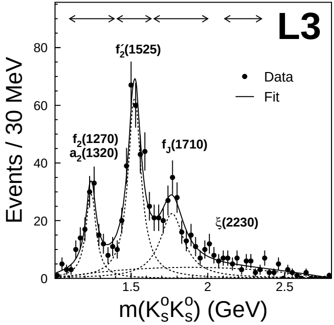

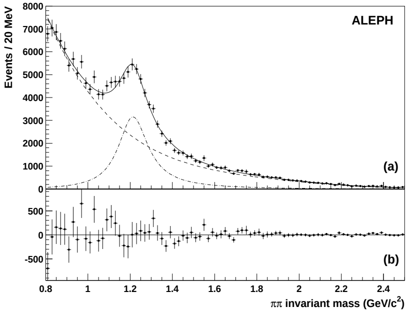

Outline

Scalar Mesons: Key Questions

The following key questions account for the major differences in the models on scalar mesons and need to be addressed in the future:

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4. Are the two states, $f_0(1710)$ and $f_0(1790)$ distinct states?

Summary

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I don't know ... http://dx.doi.org/10.1016/j.ppnp.2009.03.001

1. The tensor glueball
   ➜ No evidence so far.
2. The pseudoscalar glueball
   ➜ Very weak evidence, not likely.
3. The scalar glueball
   ➜ Best evidence, but no clear state. Physical states can mix:

$$\begin{pmatrix} |\, f_0(1370)\,\rangle \\ |\, f_0(1500)\,\rangle \\ |\, f_0(1710)\,\rangle \end{pmatrix} = \begin{pmatrix} M_{1n} & M_{1s} & M_{1g} \\ M_{2n} & M_{2s} & M_{2g} \\ M_{3n} & M_{3s} & M_{3g} \end{pmatrix} \cdot \begin{pmatrix} |\, n\bar{n}\,\rangle \\ |\, s\bar{s}\,\rangle \\ |\, G\,\rangle \end{pmatrix}$$