Glueballs, Hybrids, Quarkonia: A Global View

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INT-JLab Workshop 2009

Seattle, Washington

11/09/2009

Outline

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1. Introduction and Motivation
   - The Quark Model of Hadrons
     - Just a few words about baryons ...
   - Meson Spectroscopy
2. Experimental Methods in Meson Spectroscopy
   - Glue-Rich Environments
   - Two-Photon Fusion at e^+e^- Colliders
   - B-Decays, $\pi^- p$-Scattering, Photoproduction
3. Glueballs and Hybrids: A Global View
   - Glueballs and the Quest for the Scalar Glueball
   - Exotic Hybrid Mesons
4. Interpretation and Summary

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

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

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

However, QCD also predicts so-called exotic states

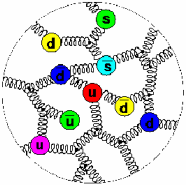
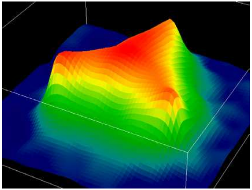
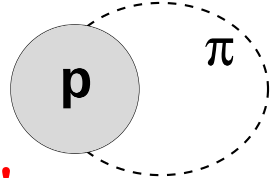
➜ simplest possibility: $\underbrace{q \otimes \bar{q} \otimes q = 15 \oplus 6 \oplus 3 \oplus 3}$ *"SU(3) Color"*

Does not work: color singlets needed !

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

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

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

$\ll 0.1$ fm		0.1 – 1.0 fm		> 1.0 fm
				
pQCD	! ? ↔ ? !	Models	? ! ↔ ! ?	ChPT
q, g, q$\bar{q}$		Quarks and Gluons as Quasiparticles		Nucleon and Mesons

1. What are the relevant degrees of freedom?
2. What are the corresponding effective interactions responsible for hadronic phenomena?

One of the Main Goals of the N^* Program ...

Search for *missing* or yet unobserved resonances

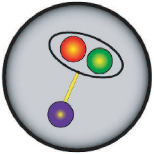
Quark models predict many more baryons than have been observed

	****	***	**	*
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

$\Rightarrow$ according to PDG
(Phys. Rev. **D66** (2002) 010001)
$\Rightarrow$ little known
(many open questions left)

Possible solutions:

1. Quark-diquark structure



one of the internal degrees of freedom is frozen

2. Have not been observed, yet

Nearly all existing data result from πN scattering experiments

➜ If the missing resonances did not couple to Nπ, they would not have been discovered!!

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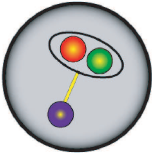

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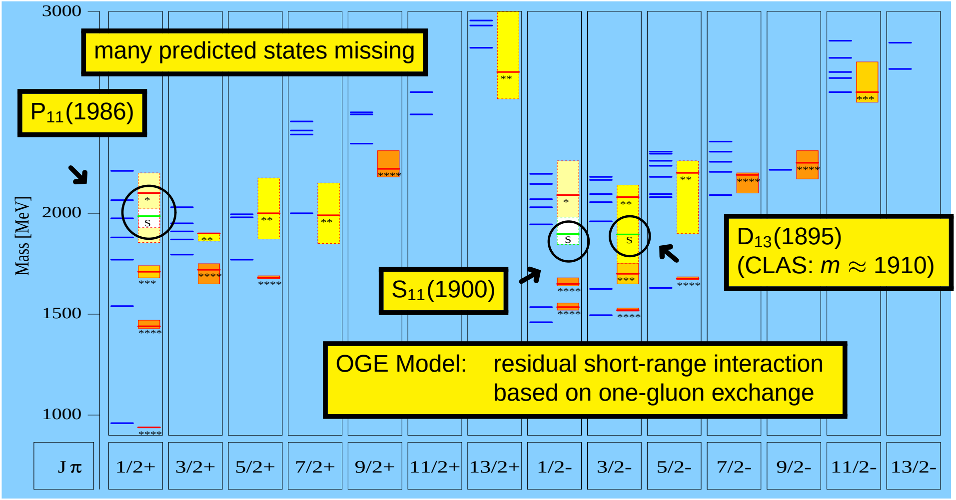
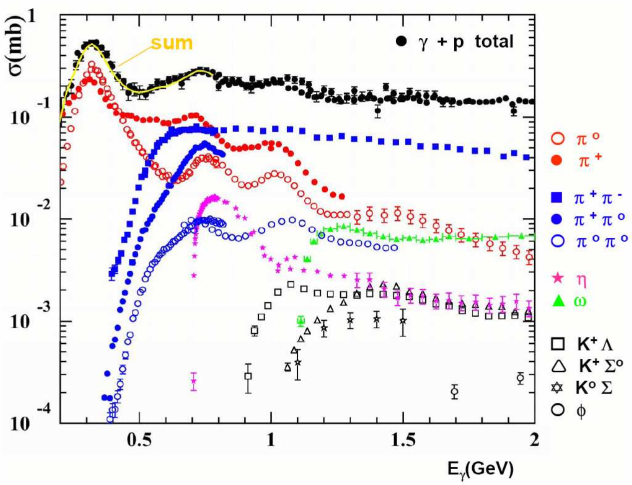
Nucleon Resonances: Status of 2001

—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809

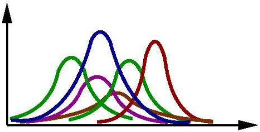


Total Photoproduction Cross Sections



No peak hunting

- Decay into neutral
- and charged particles
- Broad resonances



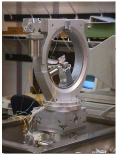
Ingredients

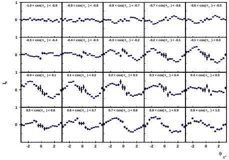
- Measurements off neutron and proton to resolve isospin contributions
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \quad \Longleftrightarrow \quad \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \quad \Longleftrightarrow \quad N^*$
- Re-scattering effects: Large number of measurements (and also final states) needed to define the full scattering amplitude
- Double-polarization measurements

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

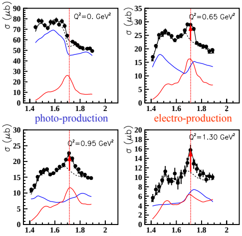
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with the four single-spin observables.

Polarization Program toward Complete Experiments



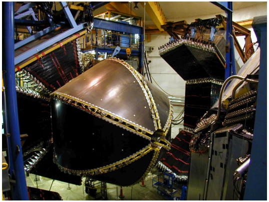


E.g. beam asymmetry in $\gamma p \to p\,\pi^+\pi^-$

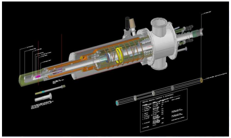


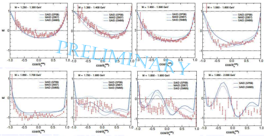
g8b

Frost



Victor Mokeev's talk



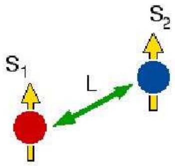


E.g. helicity difference in $\gamma p \to n\,\pi^+$

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 $G = C(-1)^I$

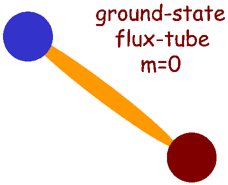


$L = 0,\ S = 1:$

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

$L = 0,\ S = 0:$

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



Ordinary and Exotic Mesons

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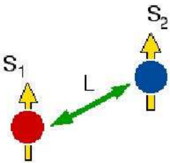

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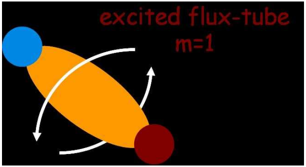

Forbidden States (Exotics):

$J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, \cdots$

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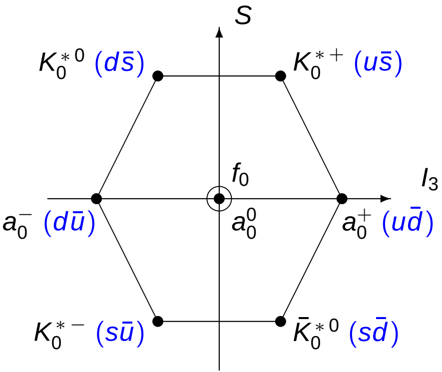
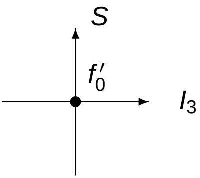
The Nonet of Scalar Mesons with $J^{PC} = 0^{++}$





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 ...

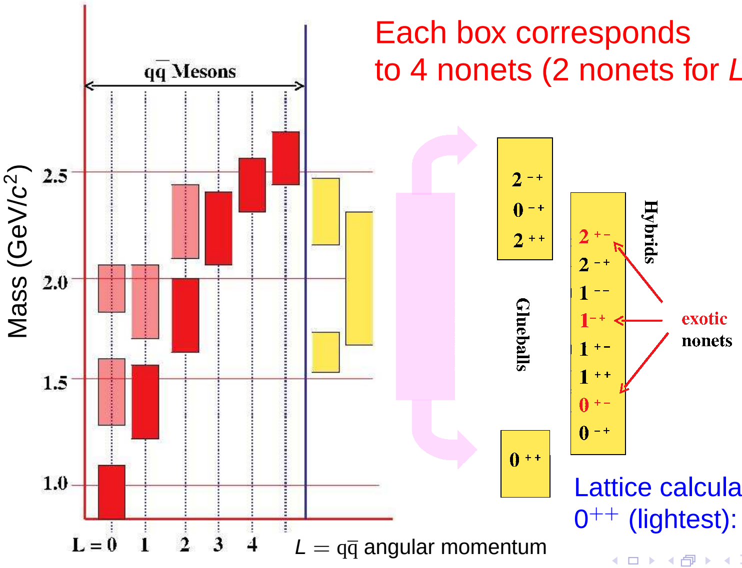
Can we understand bound systems of hadrons within the QCD framework?

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 $L = 0$)

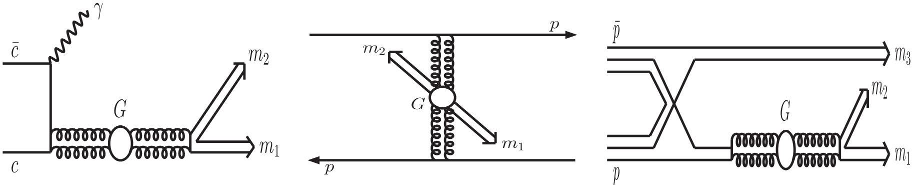


$L = q\bar{q}$ angular momentum

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

Outline

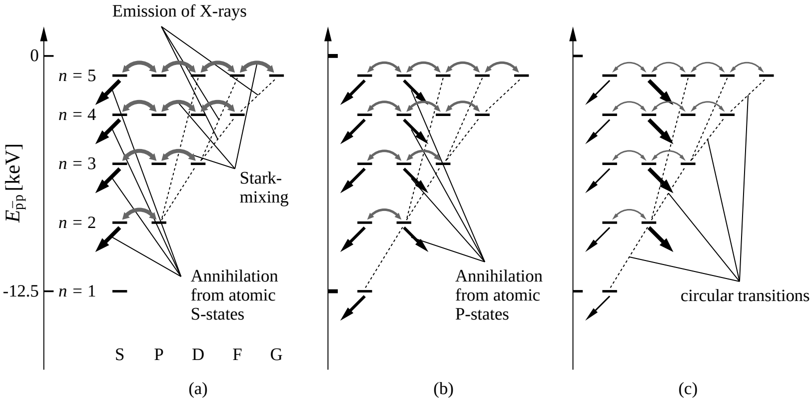
Glue-Rich Environments



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.

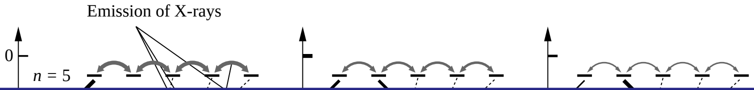
Antiproton-Nucleon Annihilation



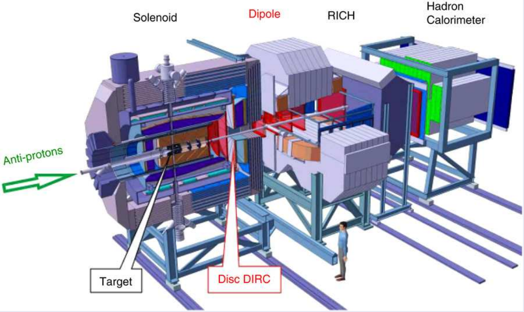
Formation of Protonium (annihilation likely *in production* with recoiling meson):

$$\bar{p} + \mathrm{H}_2 \rightarrow \boxed{p\bar{p}} + \mathrm{H} + e^- \qquad ({}^1S_0,\ {}^3S_1,\ {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2)$$

Antiproton-Nucleon Annihilation



Most results come from LEAR experiments: Asterix, Crystal-Barrel, Obelix



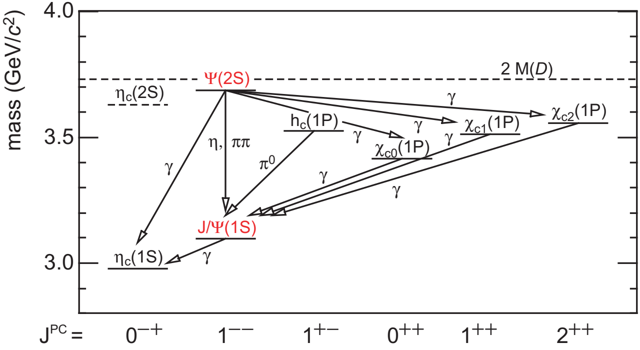
New Facility: PANDA

U. Wiedner
Search for glueballs and hybrids in antiproton annihilations

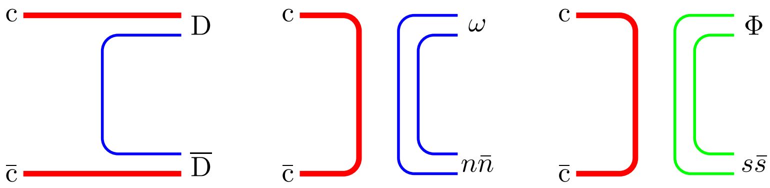
Most Suggestive: Radiative J/ψ Decays

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



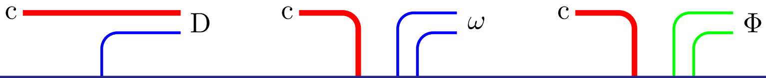
The decay of J/ψ into mesons with open charm (left) is forbidden due to energy conservation.

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

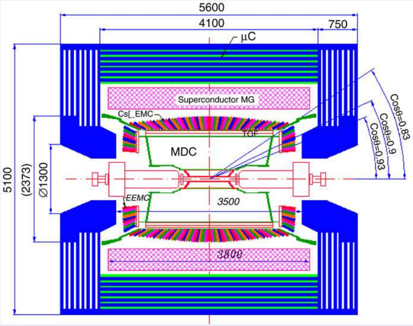
- Recoiling against ω, mesons with $n\bar{n}$ quark structure are expected.
- If a ϕ is observed, we expect mesons with hidden strangeness $s\bar{s}$.

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

The OZI Rule and Flavor-Tagging Approach



Most recent J/ψ data come from BES (older results from Crystal-Ball)



Current (near future) Facility: BES-III

➜ B. Zou, P. Guo

Data on radiative decays from KLOE

➜ B. DiMicco

Production Experiments: Central Production

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

$$\text{hadron}_{\,\text{beam}}\; p \;\longrightarrow\; \text{hadron}_{\,f}\; X\; p_s\,,$$

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.)

Production Experiments: Central Production

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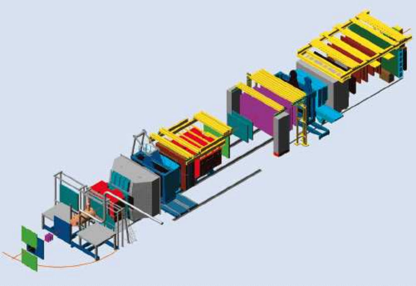
$$\text{hadron}_{\text{beam}}\ p \longrightarrow \text{hadron}_f\ X\ p_s\ ,$$

Most data from CERN experiments: WA102, ...



Current (near future) Facility: COMPASS

➜ S. Neubert
Hadron Spectroscopy at COMPASS

Indirect Glueball Signals (CERN, CLEO, ...

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:

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

Physicists are creative ...

Stickiness (in J/ψ decays)

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

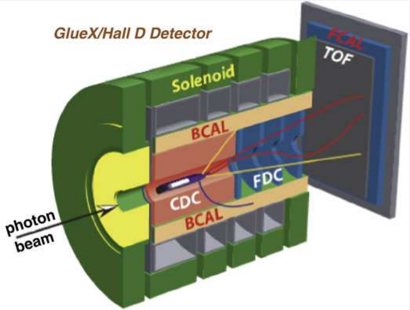
Gluiness

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

Other Important Approaches for Meson Spectroscopy

- Pion- and kaon-induced reactions: LASS, VES, E852, ...
  $\pi^-\ (K^-) + \text{proton} \longrightarrow \text{neutron} + \text{meson}$
- Light-meson spectroscopy at heavy-flavor experiments: Belle, BaBar, ...

Future Facility: Photoproduction at GlueX



➜ C. Meyer
The physics of GlueX

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	$150^{+300}_{-60} \pm 60$	$K\bar{K}K\bar{K}$

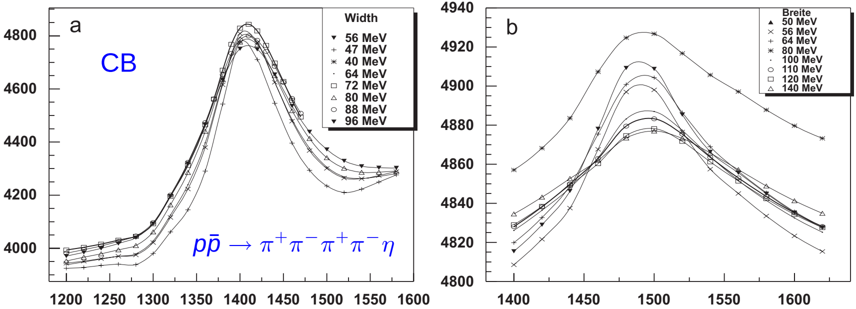
Five pseudoscalar states < 1500 MeV/c^2 listed in the PDG summary table

➜ 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 $\eta(1295)$



The Search for the Lightest Pseudoscalar Glueball

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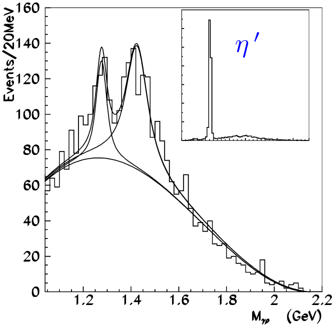
- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?
- In 2005, CLEO published (high-statistics) negative results on both states.

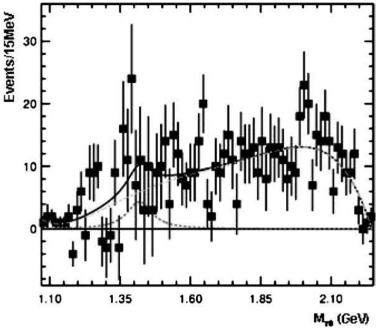
The Flavor Filter in the Decay $J/\psi \to \gamma[\gamma V]$

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

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

  ➜ Glueball should decay to both final states.

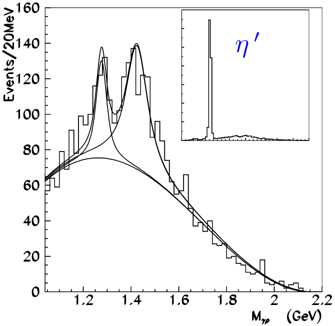


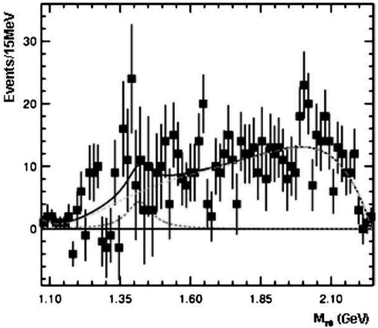


The Search for the Lightest Pseudoscalar Glueball

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!

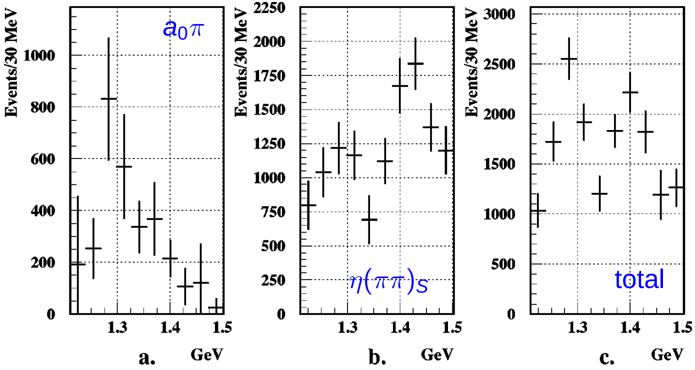




What about the $\eta(1295)$?

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

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

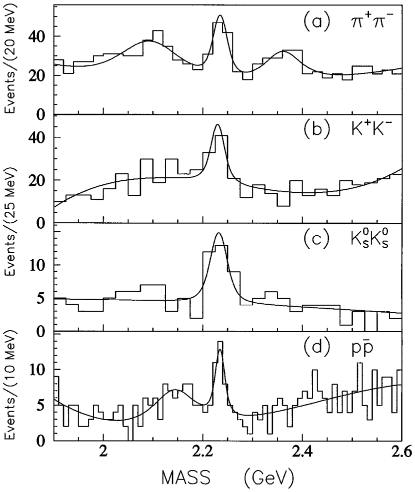
The 2^{++} Tensor Glueball

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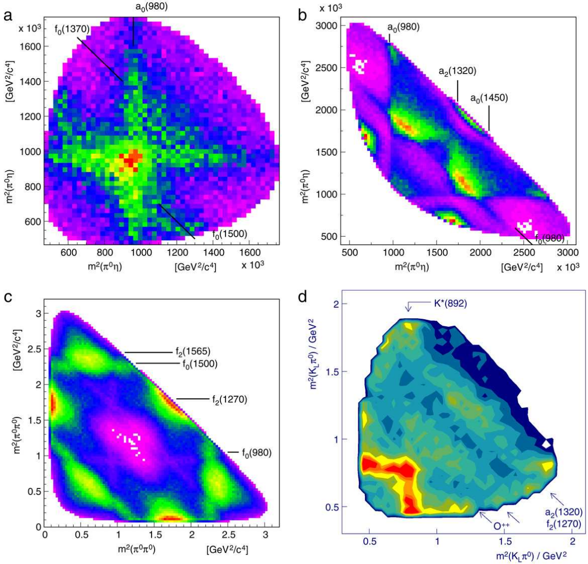
The $I = 0$, $J^{PC} = 0^{++}$ (Scalar) Mesons

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 $p\bar{p} \to \pi^0\eta\eta$

b $p\bar{p} \to \pi^0\pi^0\eta$

c $p\bar{p} \to \pi^0\pi^0\pi^0$

d $p\bar{p} \to \pi^0 K_L K_L$

Good description with

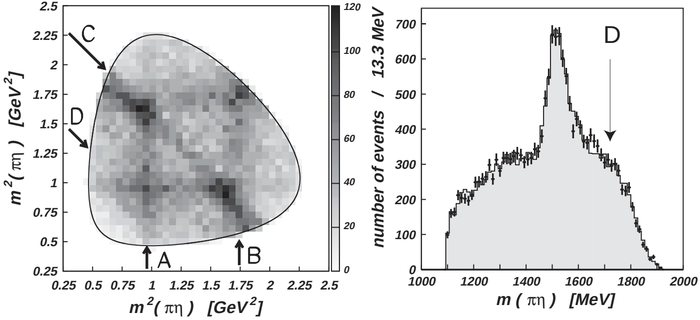
- Two isoscalar states: $f_0(1370)$ / $f_0(1500)$
- In addition: Both have dominant 4π decay modes.

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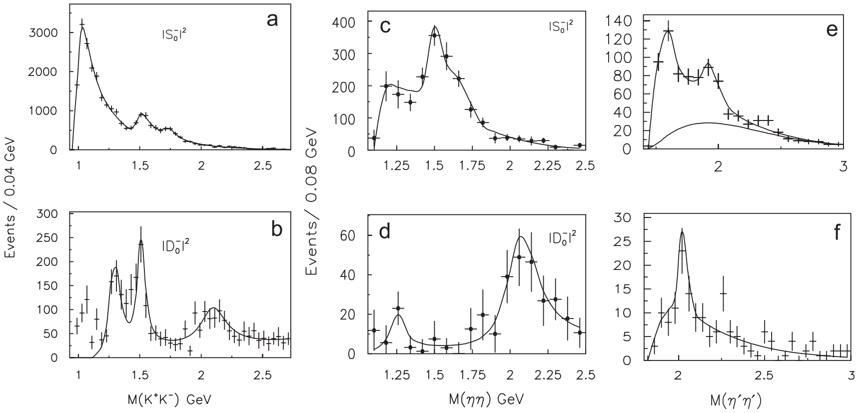
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$
- Consistent with a dominant $s\bar{s}$ assignment
  - ➜ Confirmed by WA102 reporting a much stronger $K\bar{K}$ coupling of $f_0(1710)$ than $\pi\pi$ coupling

Scalar Mesons in Central Production

M(K^+K^-) M($\eta\eta$) M($\eta\eta'/\eta'\eta'$)



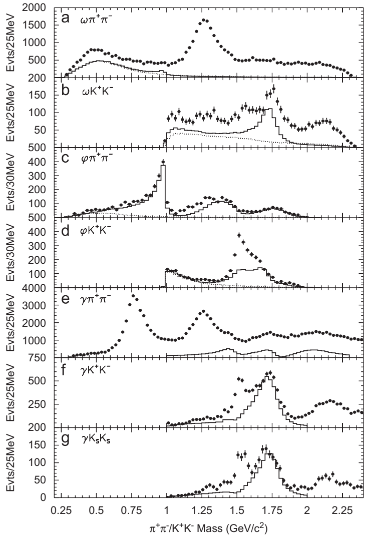
Scalar Mesons in Central Production

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

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

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

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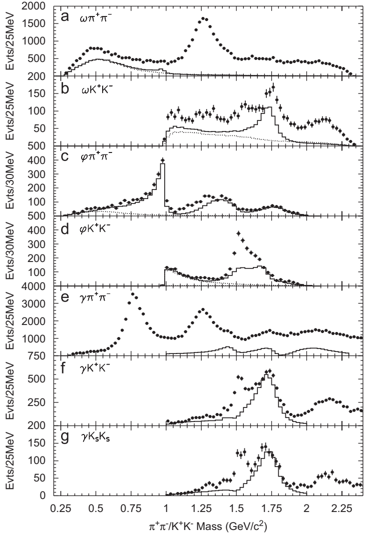


Flavor Tagging

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

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

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

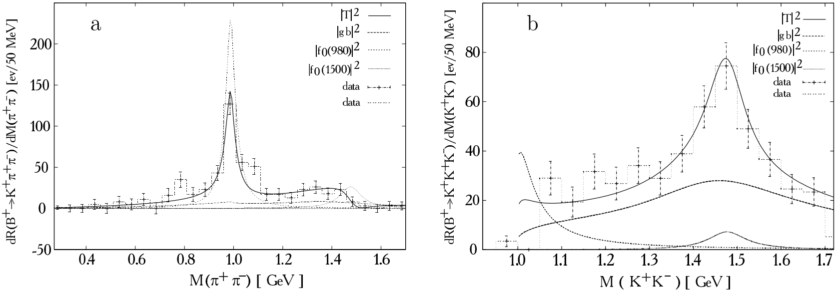
Solution: Two distinct scalar states

- The known $f_0(1710)$ 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)!

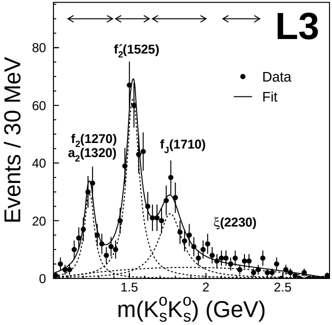


Results on Scalar Mesons from $\gamma\gamma$ Fusion

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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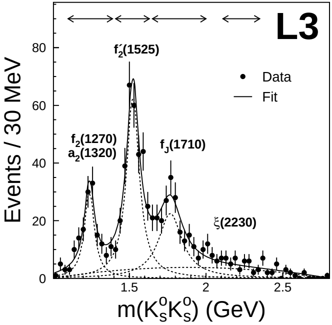

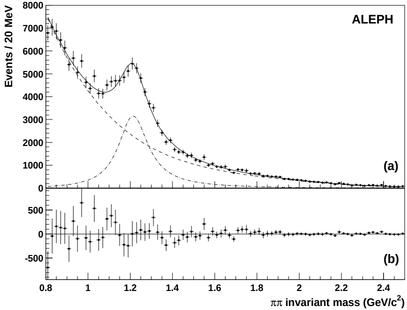

Scalar Mesons: Key Questions

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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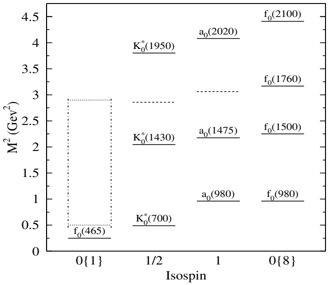

Reaction	expected		observed
$J/\psi \to \omega f_0$	$\bar{n}n$	$f_0(1710) \to K\bar{K}$	$\bar{s}s$
$J/\psi \to \phi f_0$	$\bar{s}s$	$f_0(1790) \to \pi\pi$	$\bar{n}n$
$J/\psi \to \gamma f_0$	Glueball	$f_0(1750) \to \sigma\sigma$	$\bar{n}n$
$J/\psi \to \gamma f_0$	Glueball	$f_0(1810) \to \phi\omega$	SU(3) 8

Klempt, Nucl. Phys. **B** (Proc. Suppl.) 186 (2009), 355

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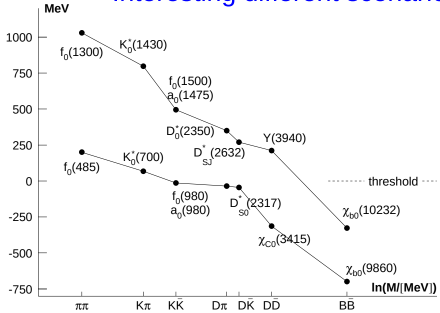
4. Are the two states, $f_0(1710)$ and $f_0(1790)$ distinct states?
5. ...
6. What about the heavy-mass scalars?

The Spectrum of Scalar Mesons

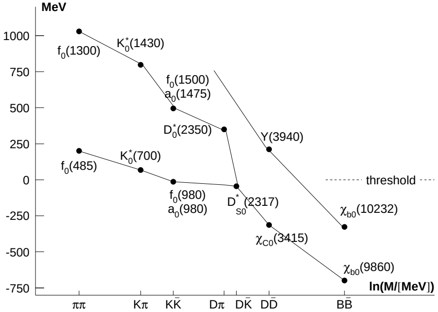
Mesonic flavor wave function of $a_0^+(980)$:

$$|a_0(980)^+\rangle = \alpha|u\bar{d}\,\rangle + \beta|u\bar{d}s\bar{s}\,\rangle + \gamma|K^+\bar{K}^0\,\rangle + \cdots$$

Interesting different scenario!



Conventional scenario



E. Klempt and A. Zaitsev, Phys. Rept. 454:1-202, 2007

The $J^{PC} = 1^{-+}$ Exotic Wave

There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.
➜ The interpretation remains controversial.

Exotic waves are (all) observed in diffraction-like reactions;
➜ Observation of $\pi_1(1400) \to \eta\pi$ in $p\bar{p}$ remains exception

In summary:

1. $\pi_1(1400) \to \eta\pi \neq \pi_1'(1400) \to \rho\pi$ (CB & Obelix, not published)
   ➜ Tetraquark? (too low in mass for hybrid, decuplet state)

   $\pi_1(1400) \to \eta\pi$

   - E852, Phys. Rev. D 60 (1999) 092001.
   - VES, Phys. Atom. Nuc. D 68 (2005) 3.
   - Crystal Barrel, Phys. Lett. B 423 (1998) 175.
   - E852 (IU), Phys. Rev. Lett. 91 (2003) 092002.

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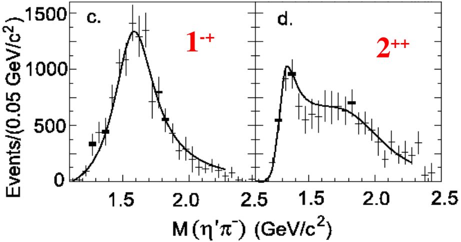

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2. $\pi_1(1600)[\to \eta'\pi, \to f_1(1285)\pi] \neq \pi_1'(1600)[\to \rho\pi, \to b_1(1235)\pi]$
   - $\to \eta'\pi^-$: dominant 1^{-+} partial wave (E852, VES)
   - $\to \rho^0\pi^-$: small relative structure with leakage from other waves
     Evidence: E852, Compass (arXiv:0910.5842v1 [hep-ex])
   - $\to b_1(1235)\pi$: structure in 1^{-+} partial wave (E852, VES)
   - $\to f_1(1285)\pi$: structure in 1^{-+} partial wave (E852, VES)

Outline

Summary and Interpretation

Good chance that $\pi_1(1600)[\rightarrow \eta' \pi, \rightarrow f_1(1285)\pi]$ is lowest mass hybrid

1. Mass agrees fairly well with predictions for a $\sim$ 1900 MeV state.
2. $\pi_1(1400) \rightarrow \eta\pi$ is not a hybrid meson
   - Flux-Tube Model: Hybrid $\rightarrow q\bar{q}\,(L=1) + q\bar{q}\,(L=0)$
     ➜ Decay mode $\eta\pi$ should be suppressed; mass too low
   - Exotic wave may originate from diffractive meson-meson scattering
     ➜ P-wave in $\eta_8\pi$ belongs to SU(3) decuplet: Tetraquark?
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Gluonic excitations likely found in scalar sector, but no clear state:

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

V.C. and C. Meyer, Prog. Part. Nucl. Phys. 63 (2009), pp. 74-116