From η and η' to Glueballs

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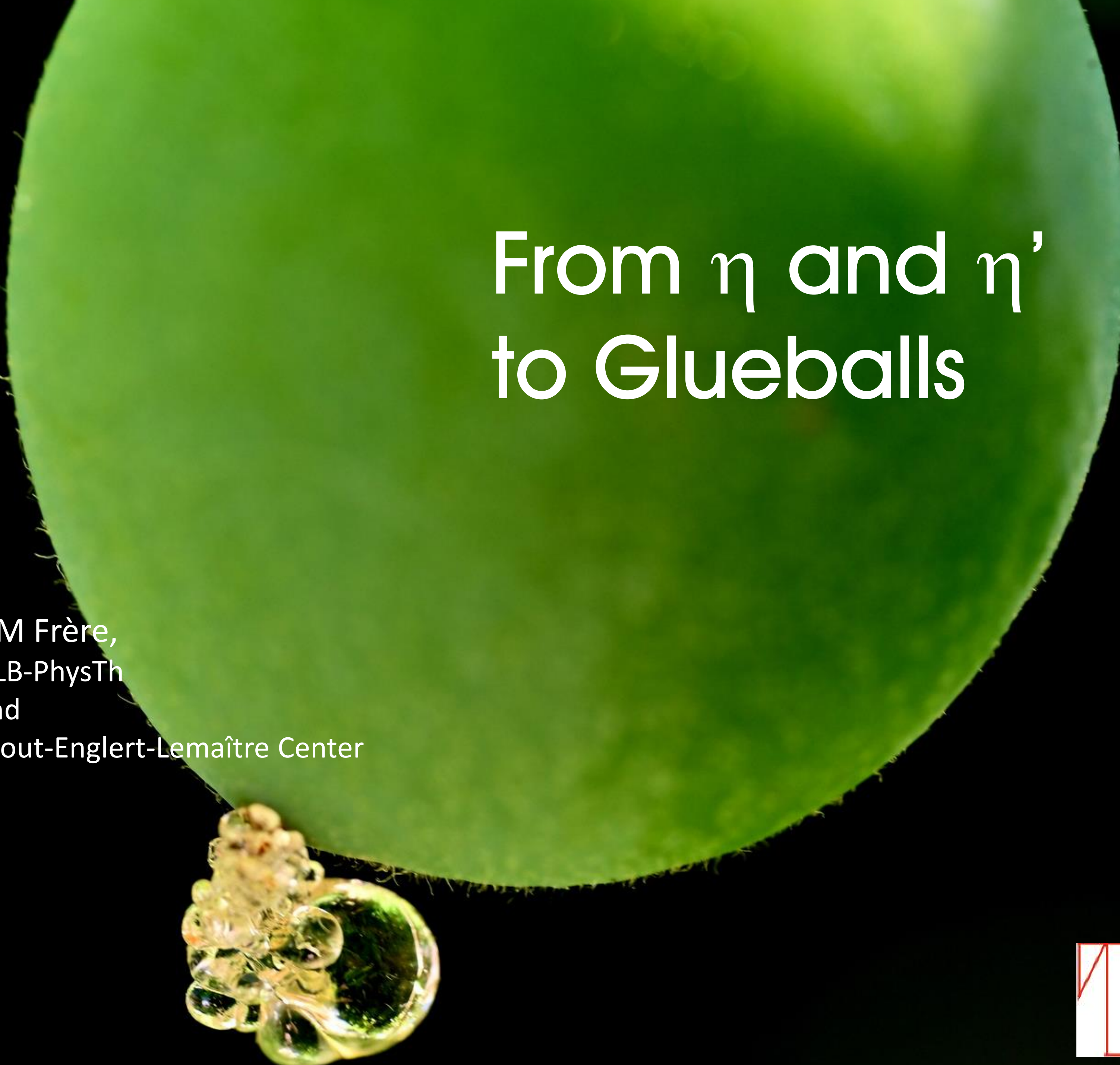


Where have all the Glueballs gone?

One of the most striking predictions of QCD, the materialization of the quark strong interactions by Gluons and its formalization as a gauge theory opens the possibility to “pure glue” states (dubbed Glueballs).

- While we don’t have a complete understanding of the confinement of coloured states, the standard understanding is that
  - Coloured objects cannot be observed as free states
  - Colourless combinations escape confinement (for instance, quark-antiquark states)
- It is thus a logical assumption (and verified by lattice gauge theory) that colourless assembly of gluons (colour octets) both exist (they are the simplest construction of QCD) and should be observable as free states.
- But ... We have ***not seen (or at least uniquely identified) them.***

WHY? ...and why bring this back?

The current consensus seems to be that we DID produce glueballs, but that they mix and hide with the quark states.

Most significantly, we have no clear-cut example to help with identifying the others, and there is a lot of uncertainty in the decay mechanisms.

As a result, we get a slow-moving field, which seems to have bored most.

Alternatively, it is worth re-visiting the field from time to time, specially since we can witness (and expect) significant progress from BESIII.

How do we expect glueballs to decay?

For the moment, let us keep to “pure glueballs”, we will deal with exotics later.

The first problem is that they have unremarkable quantum numbers (O^{++} 2^{++} 0^{-+} ,...for the lighter) which means they can hide and mix with quark states in the same mass range (above 1 GeV)

The traditional approach focuses on the decays alone and hopes to characterize them based on various theoretical considerations.

Possible (usual) decay assumptions for glueballs (and comments)

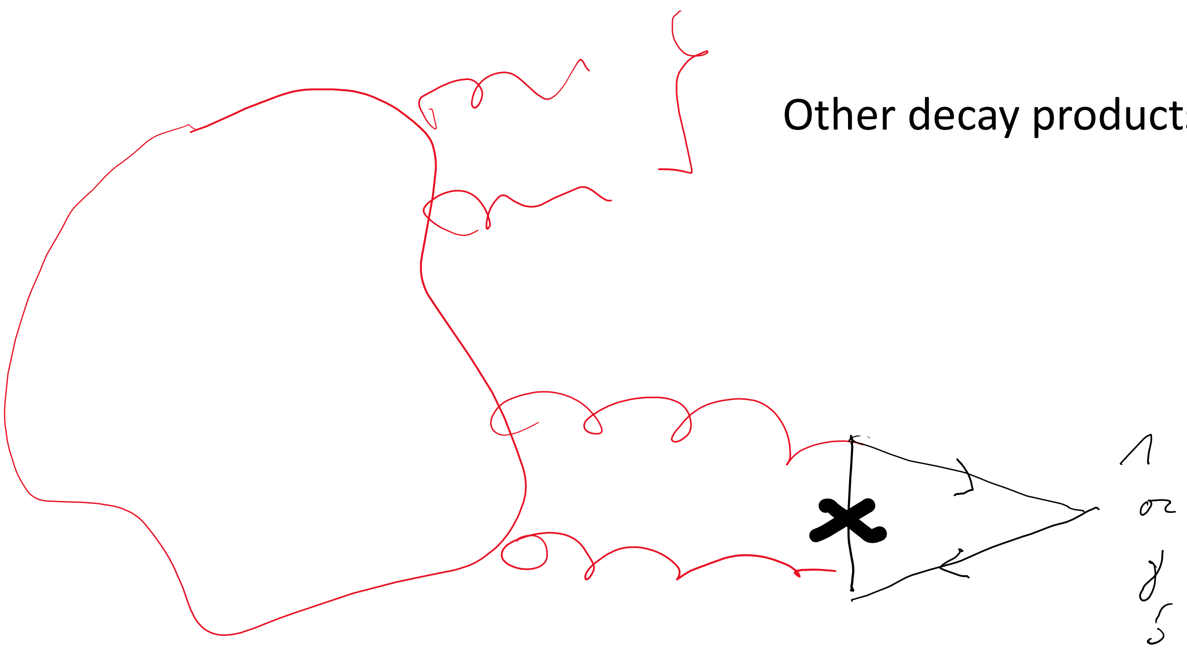
- Glueballs (like gluons) are flavour blind.
  This seems pretty obvious, one would thus expect,
  where it not for phase space, that π and K appear
  equally (taking into account phase space and number of states).

  - Yet, considerations like "wave function overlap" are sometimes introduced to justify, e.g**. a larger BR in the heavier modes.**

  - Even more strikingly, it is often argued that "chiral suppression" acts on the decays into (pseudo-)scalar mesons (see later) , once again **favouring the heavier quarks.**

  - It might happen (we don't know) that decays into multi meson states are favoured (e.g. Through 2 σ resonnances)

Chiral suppression?



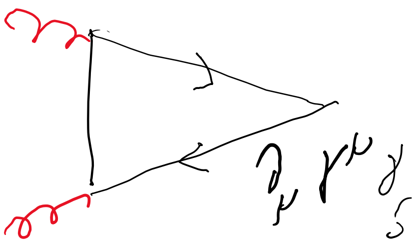
Other decay products

(pseudo-)scalar

✖ Mass insertion ?

Expect a suppression $(m/M)^2$
for light (m) versus heavy quarks (M) ....an argument used against η, η'

The η and η’ case



Of course, the previous slide was drawn in a provocative way, since this is precisely the chiral anomaly!

$$\partial^\mu A^8_\mu = \frac{2}{\sqrt{6}}(m_u \bar{u} i\gamma_5 u + m_d \bar{d} i\gamma_5 d - 2m_s \bar{s} i\gamma_5 s) \ ,$$

$$\partial^\mu A^0_\mu = \frac{2}{\sqrt{3}}(m_u \bar{u} i\gamma_5 u + m_d \bar{d} i\gamma_5 d + m_s \bar{s} i\gamma_5 s) + \boxed{\frac{1}{\sqrt{3}}\frac{3\alpha_s}{4\pi} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}}$$

$$\eta(x) = \frac{1}{m^2_\eta}\frac{f^0_{\eta'}\partial^\mu A^8_\mu(x) - f^8_{\eta'}\partial^\mu A^0_\mu(x)}{f^0_{\eta'}f^8_\eta - f^8_{\eta'}f^0_\eta} \ ;$$

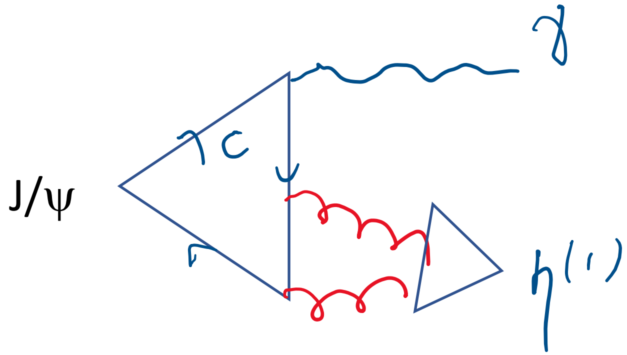
$$\eta'(x) = \frac{1}{m^2_{\eta'}}\frac{f^0_\eta \partial^\mu A^8_\mu(x) - f^8_\eta \partial^\mu A^0_\mu(x)}{f^0_\eta f^8_{\eta'} - f^8_\eta f^0_{\eta'}} \ .$$

A first illustration of the role of η and η’ in connexion with glueballs.

While we will conbenttrate on glueballs, the previous slide is a particular exemple of the gain obtained fron the transition to a relativistic approach.

In particular, in ref (1) *we showed long ago how all the radiative decays of the type V-> γ P or P-> V γ could be predicted by anomaly-type diagrams, avoiding the introduction of "quark magnetic moments" from the non-relativistic approach, and also successfully included the η and η' in the discussion, which validates the following approach.

The first suggestion of this was probably by S.S. Gershtein, who proposed a similar mechanism to explain the somewhat paradoxical J/ψ radiative decay



$$R_{J/\psi} \equiv \frac{\Gamma(J/\psi \to \eta'\gamma)}{\Gamma(J/\psi \to \eta\gamma)} = 4.8$$

$$R_{J/\psi} = \left| \frac{\langle 0|G\tilde{G}|\eta'\rangle}{\langle 0|G\tilde{G}|\eta\rangle} \right|^2 \left(\frac{p_{\eta'}}{p_\eta} \right)^3$$

Not only does this diagram explicit **the connexion of glue states to light quarks**, it also serves as a valuable hint on where to look for glueballs:

Radiative decays of J/ψ (or similar heavy quark systems) provide a "glue-rich" environment.

Strategy and Early results

The strategy then becomes clear:
- Concentrate on “glue-rich” environments,
- Study decay processes, with special attention to “glue-rich” modes, like η and η'

Some early results came from the GAMS experiments (CERN and Serpukhov), namely a lead glass wall detecting photons in fixed target in a pion beam and only sensitive to neutral modes.

States were identified in (η η), (η η') and also in (η' π) (the latter being an Exotic, see later) initially called G(1590), now most probably f_0 1500 and M(1406), now probably π1(1400)

These states have been variably seen since, but a definitive study in a glueball context was calling for high statistics in J/ψ radiative decays...
SLAC stopped, and the studies continued at BES, but we had to wait for BESIII for sufficient resolution in multi-photon states.

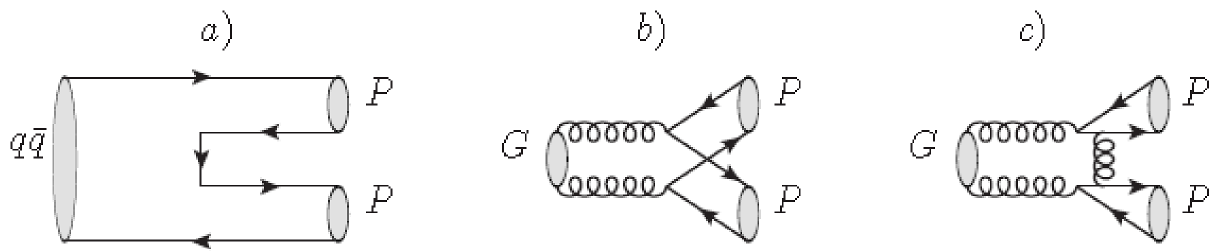
A first significant re-analysis, including results from BESSIII took place in 2015 (Chen, Chua, Liu), mainly centered on the ππ , KK and η η modes. We extended it to include the anomaly contributions to the latter decay.

The main difficulty stems from the use of chiral suppression (favouring K over π), ***even after observing that it does not apply to the singlet η(')*** **.**
Namely, which mass should one use for evalutating this suppression : current mass, constituent mass, ...?)

$f_0(1370)$	1350 ± 150	350 ± 150
$f_0(1500)$	1505 ± 6	109 ± 7
$f_0(1710)$	1722 ± 6	135 ± 7
η	547.86 ± 0.02	$(1.31 \pm 0.05) \times 10^{-3}$
η'	957.78 ± 0.06	0.23 ± 0.02

TABLE I: Some relevant masses and widths [25].

Those analysis (of which there are quite a few) rely on the topologies
(these are not real Feynman diagrams, more like templates for combinatorics,
and their phase combination is unknown), applied to assumed mixed states
of quarkonia and glueballs;



A key element is also the BR of the radiative decay (suggesting the glue coupling)

$$\frac{\Gamma(J/\psi \to \gamma f_0(1710))}{\Gamma(J/\psi \to \gamma f_0(1500))} = 10.5 \pm 6.5$$

The conclusion at that time was

and their decay properties. We consider the present attempt mainly as a preparation for the interpretation of future data. Nevertheless, in both fits we find that $f_0(1710)$ has the largest admixture of the 0^{++} glueball, whereas $f_0(1500)$ comes out close to the octet flavour structure. The very small rate of $f_0(1370) \to PP$ is particularly concerning, even though $f_0(1370) \to 4\pi$ is expected to make up most of the width. The coupling of the glueball to η_0 plays an important role in both fits and is numerically large, making η and η' final states crucial testing grounds. We certainly expect $f_0(1710) \to \eta\eta'$ to be visible in BESIII, which will hopefully clarify some of the issues. It may also be surprising to some that we


And Now?

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A recent partial wave analysis by BESIII provides even more puzzles with the expected η η' modes! !

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
	$f_0(1500)$	1506	112	1506	112	3.05 ± 0.07	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	0.07 ± 0.01	7.6σ
	$f_0(2020)$	1935 ± 5	266 ± 9	1992	442	1.67 ± 0.07	11.0σ
	$f_0(2100)$	2109 ± 11	253 ± 21	2086	284	0.33 ± 0.03	5.2σ
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(2330)$	2327 ± 4	44 ± 5	2314	144	0.07 ± 0.01	8.5σ

Even considering the possibility that the 1810 and 1710 would be confused (as the study attempts) ,
we see that the critical test, namely the product of the radiative decay into a gluon rich channel, times the decay into gluon-related ηη or (here) ηη' completely misses it ! (with a ratio .007/3.05)

The f0 (1500) is a strange beast indeed!

$f_0(1500)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor	(MeV/c)
$\pi\pi$	(34.5 ± 2.2) %	1.2	741
$\pi^+\pi^-$	seen		740
$2\pi^0$	seen		741
4π	(48.9 ± 3.3) %	1.2	692
$\eta\eta$	(6.0 ± 0.9) %	1.1	517
$\eta\eta'(958)$	(2.2 ± 0.8) %	1.4	20
$K\overline{K}$	(8.5 ± 1.0) %	1.1	569
$\gamma\gamma$	not seen		753

We have already mentioned the possibility of decay into other 0++ states, like the ill-defined σ , which would lead to 4π decays, here more abundant than 2 π but,
since the start (GAMS) the very high ratio of ηη’ to ηη decay
is surprising, ...remember the phase space for the latter is very small
(a naïve ratio would give 1/25, but this must be calculated with realistic width) ....
Still this reminds us very much of the starting point, J/ψ -> γ η vs γη’

A word about Exotics

$I^G J^{PC}$ notation

The Parity of a q-antiqark system is given by $(-)^{l+1}$ with l the angular momentum, while the Charge conjugation is given by $(-)^{l+s}$, so the 1^{-+} state is forbidden in a strict 2-quark state.

Exotics, for instance resulting from an additional gluon upset this rule.

Even if finding an exotic might be a very good hint at a “valence glue” state,

we must keep in mind that a gluon can always be mimicked by a coloured quark-antiquark vector combination (→ molecular state),

and only detailed analysis (molecules would offer more “flavour” structure, for instance) can conclude

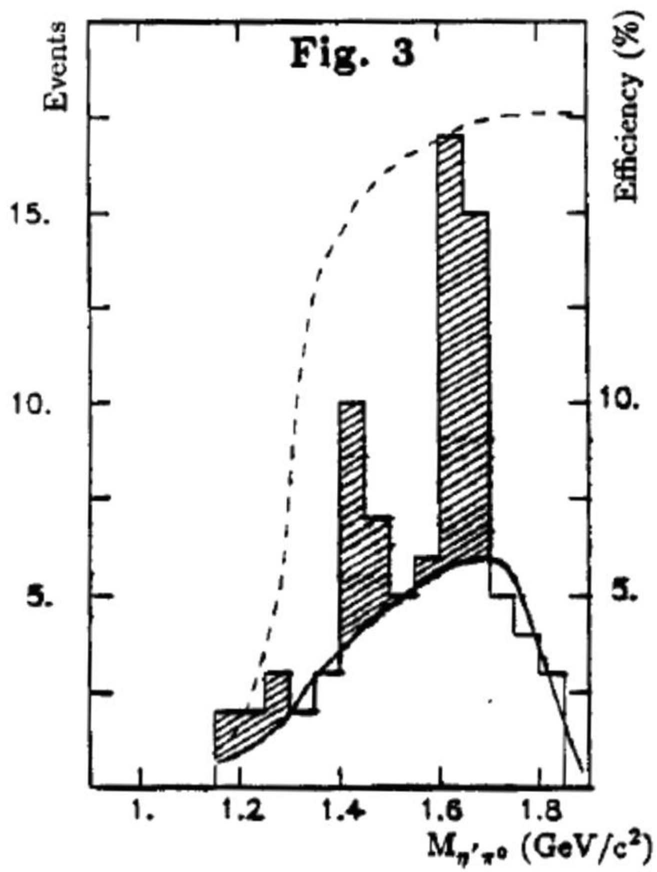
Here also, the prejudice of chiral suppression has played ...
And once again, η(') gives an exception!

"Our results support the interpretation of the η1(1855) recently observed by BESIII as the $\bar{s}sg$ hybrid meson of $I^G J^{PC} = 0^+ 1^{-+}$.

The QCD axial anomaly ensures the $\eta\eta'$ decay mode to be a characteristic signal of the hybrid nature of the η_1(1855)."

(H X Chen, N Su, L Zhu arXiv2202.04918)

It is interesting to compare this to an excess in the $\eta' \pi$ channel seen at GAMS (with excesses at 1400 and 1600, now listed as π_1 in PDG), where we had similarly advocated an evasion of the chiral suppression.



[Evidence for a 1-+ Exotic Meson](#)
D. Alde(Los Alamos Published in: *Phys.Lett.B* 205 (1988) 397

Here, there is again some suspense,
as we are expecting the analysis of the $\eta(')\ \pi$ channels in BESSIII

Returning to the f0(1500) – f0(1710) dilemma...an aftterthought

Remember : the 1710 seemed favoured by a larger J/ψ → 1710 γ BR , but was later not prominent in $\eta'\eta$

One possibility is that we are "missing" states or their BR in J/ψ if they decay importantly into other channels.
For instance, the 1500 is seen to decay mostly into 4π, (6π or more have not been checked) possibly a sign of gg → $\sigma\ \sigma$ → 4π , and the 1710 has not been observed yet in 4π

Suggested homework : rather than trying uncreatively difficult channels, attempt a comparison of the contribution of the reconstructed modes with the inclusive J/ψ decay spectrum

A study of this spectrum has been performed by Cleo using tagged J/ψ from ψ(2s) decays in 2008, ...


If chromodynamics were really about colour!
pictures by jmf+kbr

Some references on a long path...And references therein ...

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Partial wave analysis of J/ψ→γηη’J/\psi\ ->\gamma\eta\eta’ arXiv 2202.00623 (BESIII)

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