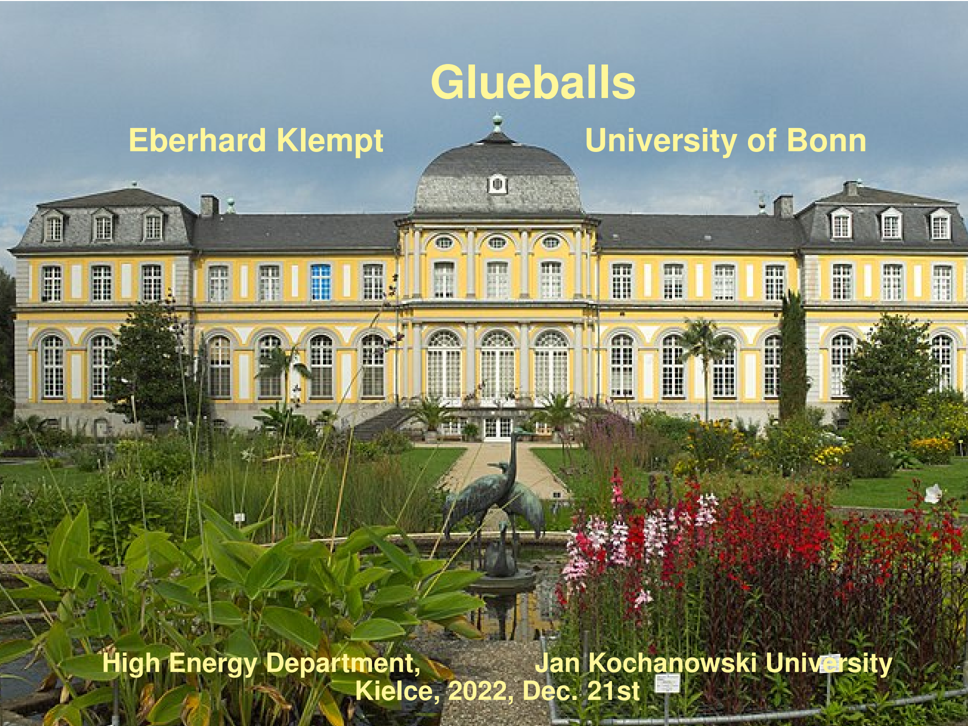
Glueballs

Eberhard Klempt University of Bonn



High Energy Department, Jan Kochanowski University
Kielce, 2022, Dec. 21st

1. **Historical Memories**
2. **Properties of Glueballs**
3. **Coupled Channel Analysis**
4. **Results and Interpretation**
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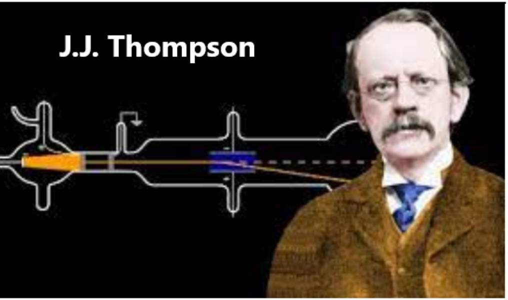
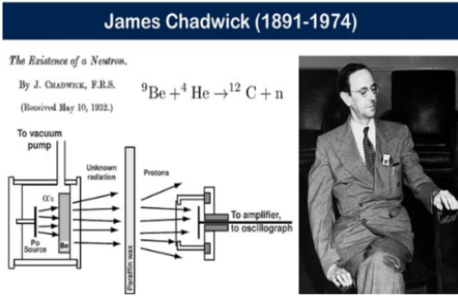
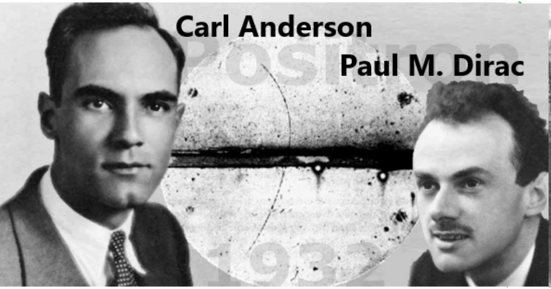
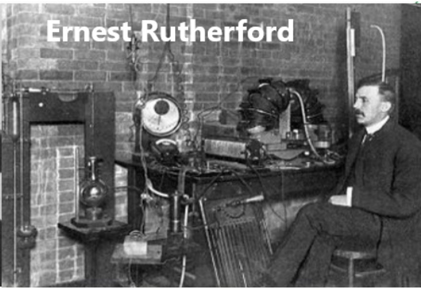
1. Historical Memories









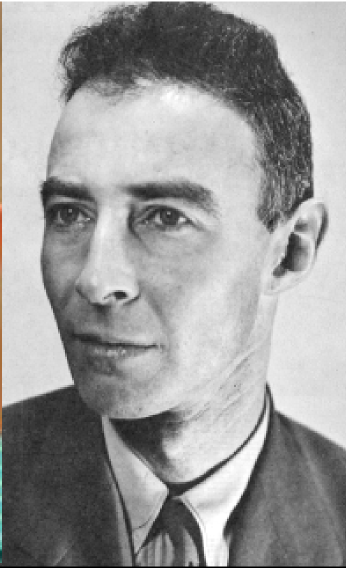
Willis E. Lamb


Murray Gell-Mann


George Zweig

Wolfgang Pauli

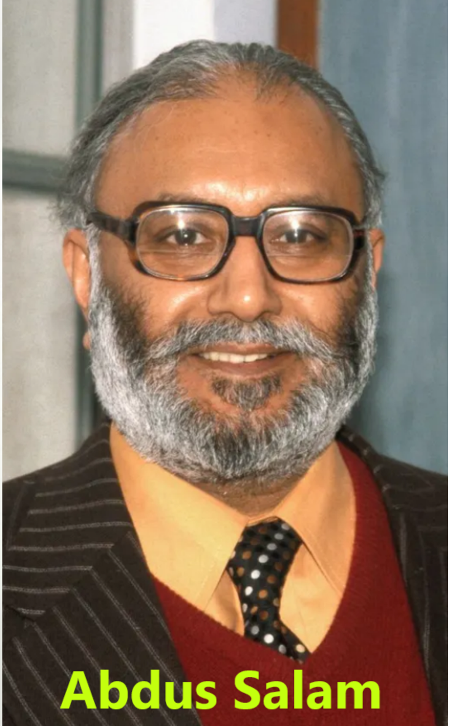
Oscar Greenberg



Robert Oppenheimer


Werner Heisenberg



Steven Weinberg

Abdus Salam


50 years of QuantumChromoDynamics
Harald Fritzsch
Murray Gell-Mann
David Gross
Frank Wilczek
David Politzer

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\gamma^\mu(\partial_\mu + \frac{i}{2}g_s\lambda^A\mathcal{A}^A{}_\mu) - m)\psi - \frac{1}{4}F^A_{\mu\nu}F^{A\,\mu\nu}$$

$$F^{A\,\mu\nu} = \partial_\mu\mathcal{A}^A_\nu - \partial_\nu\mathcal{A}^A_\mu - g_s f_{ABC}\mathcal{A}^B\mathcal{A}^C$$

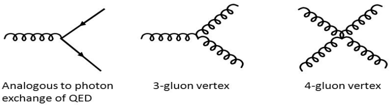
A beautiful equation that cannot be solved with an extremely rich phenomenology

Fritzsch and Gell-Mann (1972):
"$\cdots$ so that meson states would appear that act as if they were made of gluons rather than $q\bar{q}$ pairs".

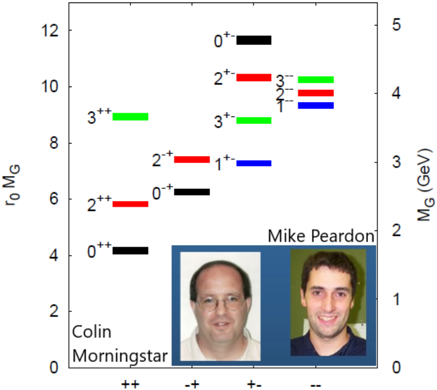
Franz Gross and Eberhard Klempt (eds.), *50 Years Of Quantum Chromodynamics*, **EPJC (2023).**

2. Properties of Glueballs

2.1 M, Γ, Y



The self-interaction between gluons leads to the prediction of glueballs[1]



[1] H. Fritzsch and M. Gell-Mann, "Current algebra: Quarks and what else?," eConf C720906V2, 135 (1972).

0^{++}	$1710 \pm 50 \pm 80$ MeV
	1850 ± 130 MeV
	1980 MeV
	1920 MeV
2^{++}	$2390 \pm 30 \pm 120$ MeV
	2610 ± 180 MeV
	2420 MeV
	2371 MeV
0^{-+}	$2560 \pm 35 \pm 120$ MeV
	2580 ± 180 MeV
	2220 MeV

Y. Chen *et al.* "Glueball spectrum and matrix elements on anisotropic lattices," Phys. Rev. D 73, 014516 (2006).
M. Q. Huber, C. S. Fischer and H. Sanchis-Alepuz, "Spectrum of scalar and pseudoscalar glueballs from functional methods," Eur. Phys. J. C 80, no.11, 1077 (2020).
A. P. Szczepaniak and E. S. Swanson, "The Low lying glueball spectrum," Phys. Lett. B 577, 61-66 (2003).
M. Rinaldi and V. Vento, "Meson and glueball spectroscopy within the graviton soft wall model," [arXiv:2101.02616 [hep-ph]].

Glueballs: **Widths** undetermined

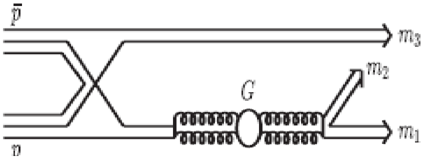
Yields

$BR_{J/\psi\to\gamma G_{0^{++}}}$(TH)	=	(3.8 ± 0.9)	$\cdot 10^{-3}$		[1]
	$\approx$	3	$\cdot 10^{-3}$		[2]
$BR_{J/\psi\to\gamma G_{2^{++}}}(TH)$	=	(11 ± 2)	$\cdot 10^{-3}$		[3]
$BR_{J/\psi\to\gamma G_{0^{-+}}}(TH)$	=	(0.231 ± 0.080)	$\cdot 10^{-3}$	M=2395 MeV	[4]
	=	(0.107 ± 0.037)	$\cdot 10^{-3}$	M=2560 MeV	[4]

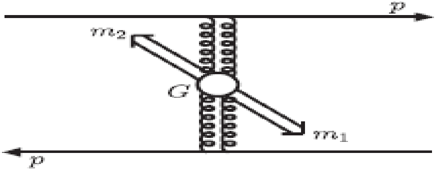
[1] L. C. Gui *et al.* [CLQCD], "Scalar Glueball in Radiative J/ψ Decay on the Lattice," PRL 110, 021601 (2013).
[2] S. Narison, "Masses, decays and mixings of gluonia in QCD," Nucl. Phys. B 509, 312-356 (1998).
[3] Y. Chen *et al.*, "Glueballs in charmonia radiative decays," PoS LATTICE2013, 435 (2014).
[4] L. C. Gui *et al.*, "Study of the pseudoscalar glueball in J/ψ radiative decays," PR D 100, 054511 (2019)].

2.2 How to search for glueballs

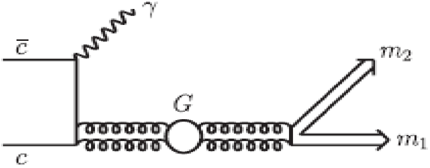
N̄N **annihilation**



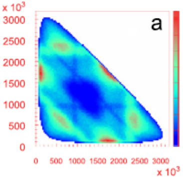
Central production



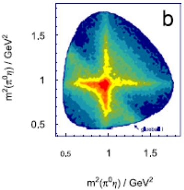
Radiative J/ψ decays



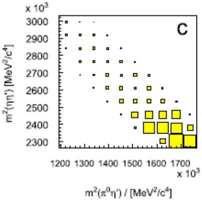
2.3 $\bar{N}N$ annihilation (Crystal Barrel at LEAR)



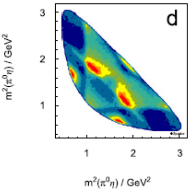
a: $3\pi^0$;
J. Brose (Mainz)



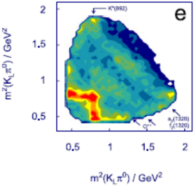
b: $\pi^0\eta\eta$;
R. Hackmann (Mainz)



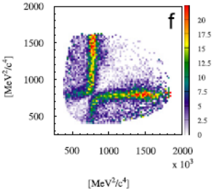
c: $\pi^0\eta\eta'$;
S. Spanier (Mainz)



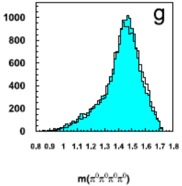
d: $\pi^0\pi^0\eta$;
S. Spanier (Mainz)



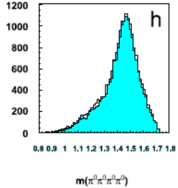
e: $K_LK_L\pi^0$;
A.R. Cooper (London)



f: $K^\pm K_L\pi^\mp$;
C. Völker (Munich)



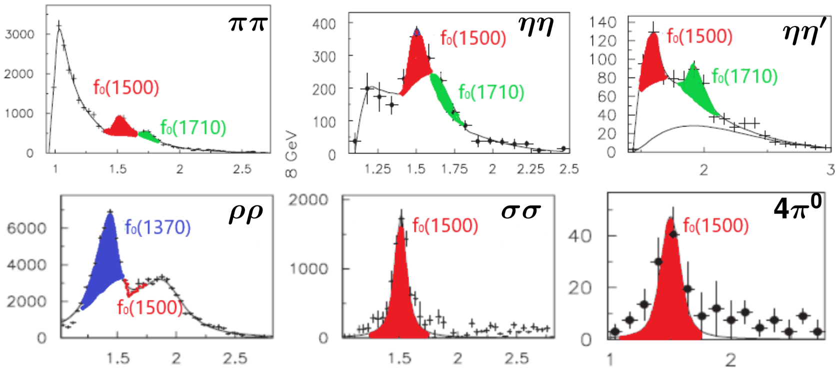
g: $4\pi^0$;
U. Thoma (Bonn)



h: $4\pi^0$
U. Thoma (Bonn)

Three new scalar mesons: $f_0(1370)$, $f_0(1500)$, $a_0(1475)$!

2.4 Central production (WA102 experiment at SPS)



Three scalar isoscalar mesons: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$!

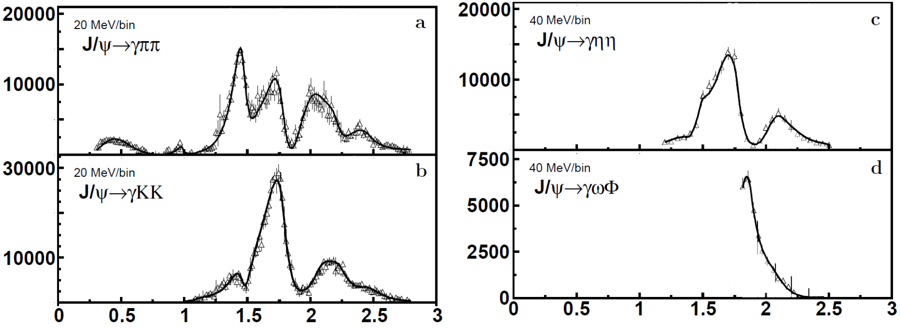
Glueballs: **Mixing**

$$\begin{matrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{matrix} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} \begin{matrix} |n\bar{n}\rangle \\ |s\bar{s}\rangle \\ |gg\rangle \end{matrix}$$

***supernumerous*!**

C. Amsler and F. E. Close, "Evidence for a scalar glueball," Phys. Lett. B 353, 385-390 (1995).
C. Amsler and F. E. Close, "Is $f_0(1500)$ a scalar glueball?," Phys. Rev. D 53, 295-311 (1996).

2.5 Radiative J/ψ decays into $\pi^0\pi^0$, K_sK_s, $\eta\eta$, and $\omega\phi$



$1.3 \cdot 10^9$ events

$0.225 \cdot 10^9$ events

PWA in slices of energy

Amplitude fit to data

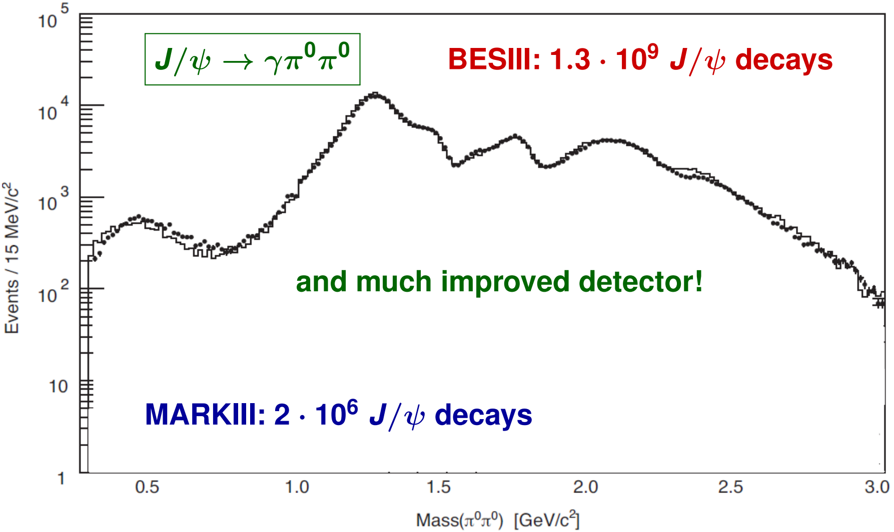
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92 no.5, 052003 (2015).
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the K_SK_S system produced in radiative J/ψ decays," Phys. Rev. D 98 no.7, 072003 (2018).
M. Ablikim *et al.* [BESIII Collaboration], "Partial wave analysis of $J/\psi \to \gamma\eta\eta$," Phys. Rev. D 87, no. 9, 092009 (2013).
M. Ablikim *et al.* [[BESIII Collaboration], "Study of the near-threshold $\omega\phi$ mass enhancement in doubly OZI-suppressed' $J/\psi \to \gamma\omega\phi$ decays," Phys. Rev. D 87 no.3, 032008 (2013).

3. Coupled channel analysis

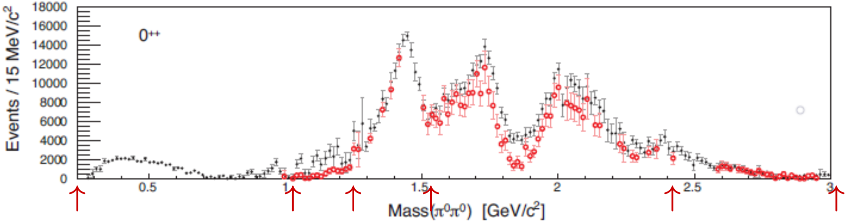
A. V. Sarantsev, I. Denisenko, U. Thoma and E. Klempt,
"Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays,"
Phys. Lett. B 816, 136227 (2021).

J/ψ	$\rightarrow$	$\gamma\pi^0\pi^0$	K_SK_S	$\gamma\eta\eta'$	$\gamma\omega\phi$	BESIII
χ^2/N; N		1.28; 167	1.21, 121	0.8; 21	0.2; 17	
$\bar{p}p$	$\rightarrow$	$3\pi^0$	$\pi^0\pi^+\pi^-$	$2\pi^0\eta$	$\pi^0\eta\eta$	CB (liq. H_2)
χ^2/N, N		1.40; 7110	1.24, 1334	1.23; 3475	1.28; 3595	
$\bar{p}p$	$\rightarrow$	$3\pi^0$		$2\pi^0\eta$	$\pi^0\eta\eta$	CB (gas. H_2)
χ^2/N, N		1.38; 4891		1.24; 3631	1.32; 1182	
$\bar{p}p$	$\rightarrow$	$K_LK_L\pi^0$	$K^+K^-\pi^0$	$K_SK^\pm\pi^\mp$	$K_LK^\pm\pi^\mp$	CB (liq. H_2)
χ^2/N, N		1.08; 394	0.97; 521	2.13; 771	0.76; 737	
$\bar{p}n$	$\rightarrow$	$\pi^+\pi^-\pi^-$	$\pi^0\pi^0\pi^-$	$K_SK^-\pi^0$	$K_sK_S\pi^-$	CB (liq. D_2)
χ^2/N, N		1.39; 823	1.57; 825	1.33; 378	1.62; 396	
$\pi^+\pi^-$	$\rightarrow$	$\pi^+\pi^-$	$\pi^0\pi^0$	$\eta\eta$	$\eta\eta'$	K^+K^-
χ^2/N, N		1.32; 845	0.89; 110	0.67; 15	0.23; 9	1.06; 35
		CERN-Munich		GAMS		BNL

3.1 Data from BESIII

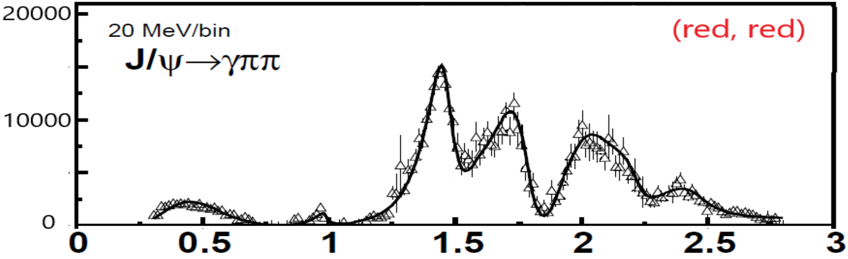


Partial waves from $J/\psi \to \pi^0\pi^0$ in slices of the $2\pi^0$ mass

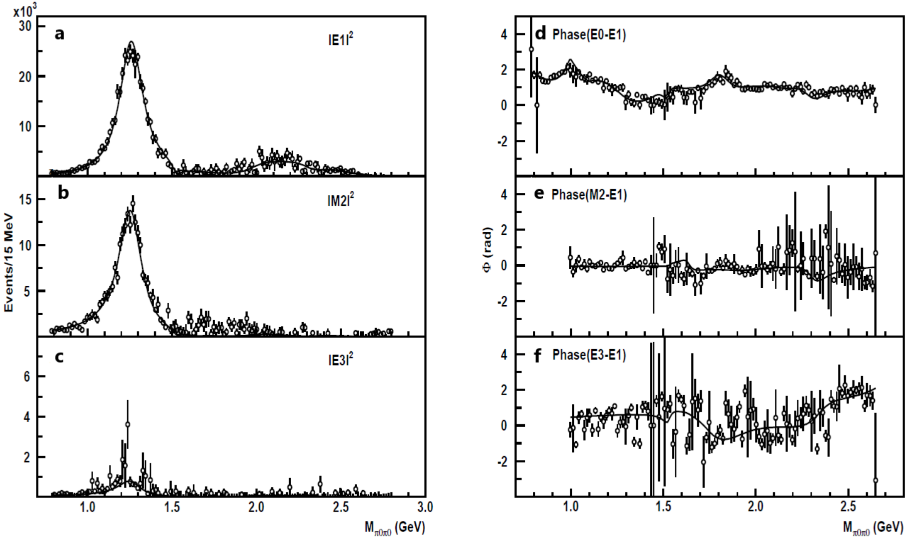


$\leftarrow \mathbf{I}_{\mathrm{identical}} \rightarrow$ $\mathbf{II}_{\mathrm{amb}}$ $\mathbf{III}_{\mathrm{id}}$ $\leftarrow \mathbf{IV}_{\mathrm{ambiguous}} \rightarrow \leftarrow \mathbf{V}_{\mathrm{identical}} \rightarrow$

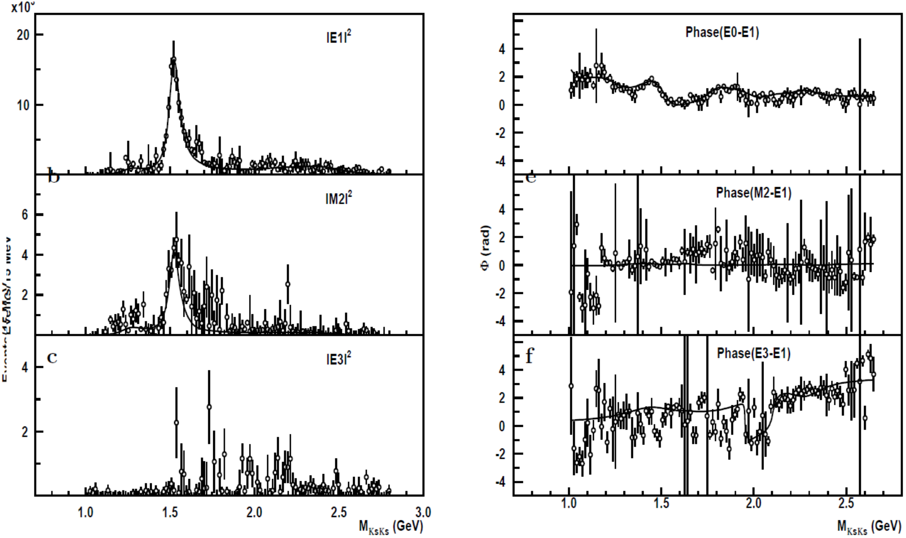
M. Ablikim *et al.* [BESIII], and A.P. Szczepaniak, P. Guo,
"Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92, no.5, 052003 (2015).



The tensor waves from $J/\psi \to \pi^0\pi^0$ in slices of the $2\pi^0$ mass

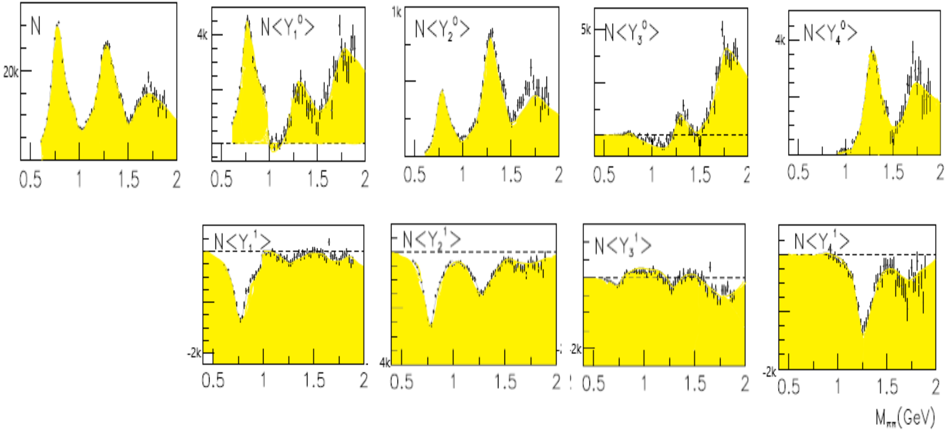


The tensor waves from $J/\psi \to K_s^0 K_s^0$ in slices of the $K_s^0 K_s^0$ mass



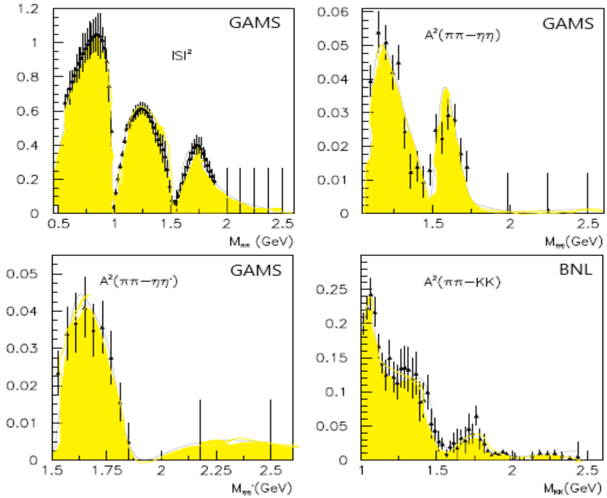
3.2 15 Dalitz plots from Crystal Barrel (partly shown above)

3.3 The CERN-Munich data on $\pi\pi \to \pi\pi$ elastic scattering



The CERN-Munich data have different PWA solutions. The ambiguity is resolved by the GAMS data on $\pi^- p \to \pi^0\pi^0 n$ (at 200 GeV/c pion momenta).

3.4 GAMS and BNL data on pion-induced reactions



GAMS: D. Alde *et al.*, "Study of the $\pi^0\pi^0$ system with the GAMS-4000 spectrometer at 100 GeV/c," Eur. Phys. J. A 3, 361 (1998).

BNL: S. J. Lindenbaum and R. S. Longacre, "Coupled channel analysis of $J^{PC} = 0^{++}$ and 2^{++} isoscalar mesons with masses below 2 GeV," Phys. Lett. B 274, 492 (1992).

4. Results and interpretation

4.1 Contributing resonances

Pole masses and widths (in MeV) of scalar mesons. The RPP values are listed as small numbers for comparison.

Name	$f_0(500)$	$f_0(1370)$	$f_0(1710)$	$f_0(2020)$	$f_0(2200)$
M	410 ± 20 $400\to550$	1370 ± 40 $1200\to1500$	1700 ± 18 1704 ± 12	1925 ± 25 1992 ± 16	2200 ± 25 2187 ± 14
Γ	480 ± 30 $400\to700$	390 ± 40 $100\to500$	255 ± 25 123 ± 18	320 ± 35 442 ± 60	150 ± 30 ~ 200
Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M	1014 ± 8 990 ± 20	1483 ± 15 1506 ± 6	1765 ± 15	2075 ± 20 2086^{+20}_{-24}	2340 ± 20 ~2330
Γ	71 ± 10 $10\to100$	116 ± 12 112 ± 9	180 ± 20	260 ± 25 284^{+60}_{-32}	165 ± 25 250 ± 20

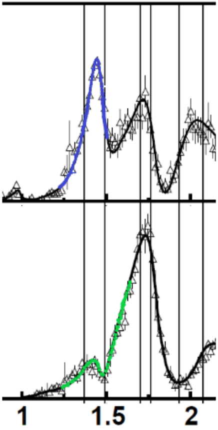
Yields in radiative J/ψ decays (in units of 10^{-5})

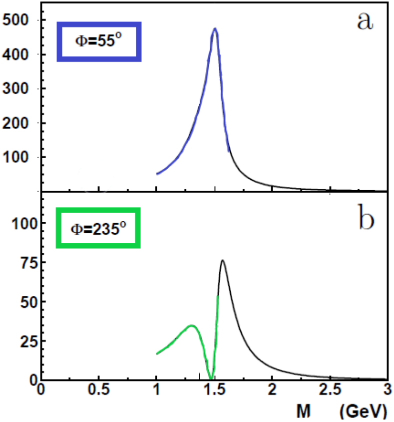
$BR_{J/\psi\to\gamma f_0\to}$	$\gamma\pi\pi$	$\gamma K\bar{K}$	$\gamma\eta\eta$	$\gamma\eta\eta'$	$\gamma\omega\phi$	missing ($\gamma 4\pi$ / $\gamma\omega\omega$)	total
$f_0(500)$	105±20	5±5	4±3	∼0	∼0	∼0	114±21
$f_0(980)$	1.3±0.2	0.8±0.3	∼0	∼0	∼0	∼0	2.1±0.4
$f_0(1370)$	38±10	13±4	3.5±1	0.9±0.3	∼0	14±5	69±12
		42±15				$\gamma 4\pi$: 27±9	
$f_0(1500)$	9.0±1.7	3±1	1.1±0.4	1.2±0.5	∼0	33±8	47±9
	10.9±2.4	2.9±1.2	$1.7^{+0.6}_{-1.4}$	$6.4^{+1.0}_{-2.2}$		$\gamma 4\pi$: 36±9	
$f_0(1710)$	6±2	23±8	12±4	6.5±2.5	1±1	7±3	56±10
$f_0(1770)$	24±8	60±20	7±1	2.5±1.1	22±4	65±15	181±26
$f_0(1750)$	38±5	99^{+10}_{-6}	24^{+12}_{-7}		25±6	$\gamma 4\pi$: 97±18; $\gamma\omega\omega$: 31±10	
$f_0(2020)$	42±10	55±25	10±10			(38±13)	145±32
$f_0(2100)$	20±8	32±20	18±15			(38±13)	108±25
$f_0(2200)$	5±2	5±5	0.7±0.4			(38±13)	49±17
$f_0(2100)/f_0(2200)$	62±10	109^{+8}_{-19}	$11.0^{+6.5}_{-3.0}$			$\gamma 4\pi$: 115±41	
$f_0(2330)$	4±2	2.5±0.5	1.5±0.4				8±3
		20±3					

4.2 Scalar mixing angles

From $f_0(500)$ and $f_0(980)$ decays: $f_0(980)$ is approx. a SU(3) octet state!
(The molecular $K\bar{K}$ interpretation could be a peripheral phenomenon).

[1] J. A. Oller, “The Mixing angle of the lightest scalar nonet,” Nucl. Phys. A 727, 353-369 (2003).

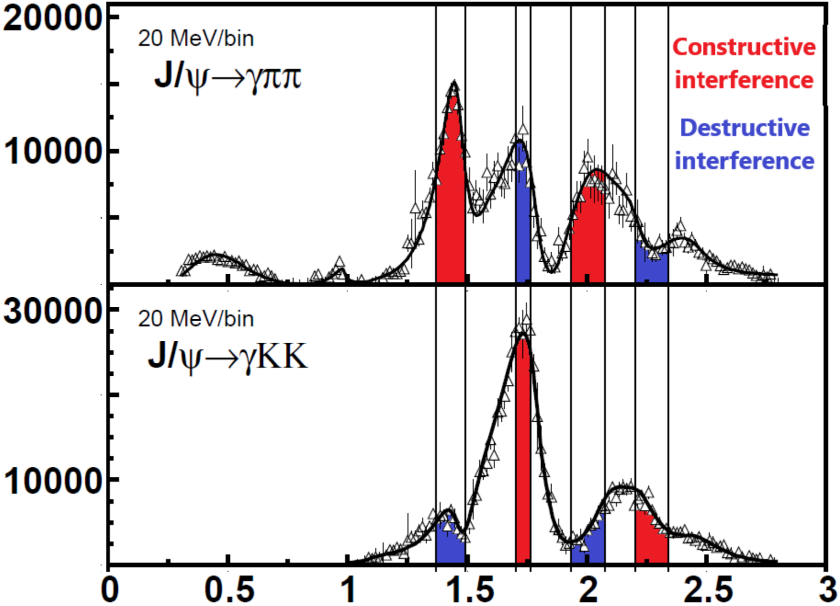




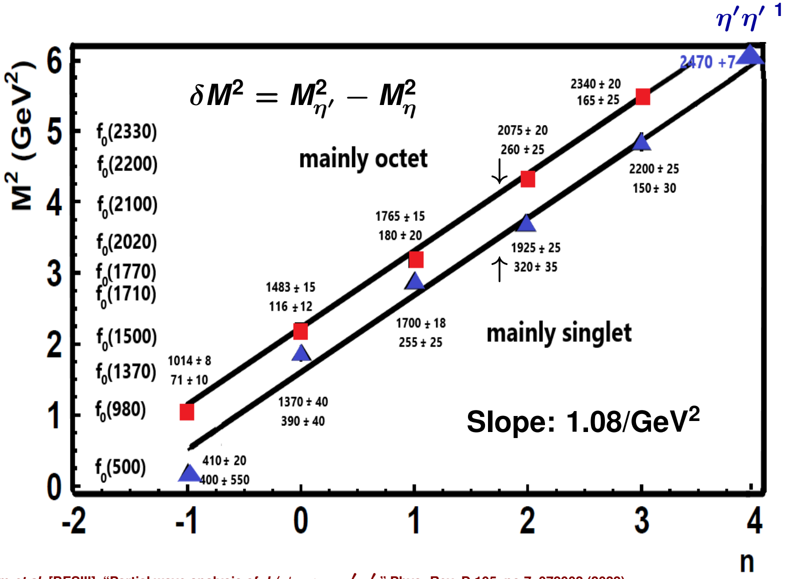
Phase difference between $\pi\pi$ and $K\bar{K}$ decay mode is 180°: $n\bar{n} - s\bar{s}$ and $n\bar{n} + s\bar{s}$!

$f_0(1370)$ and $f_0(1500)$ are SU(3) singlet and SU(3) octet-like and not $n\bar{n}$ and $s\bar{s}$!

Interference in $\pi\pi$ and $K\bar{K}$

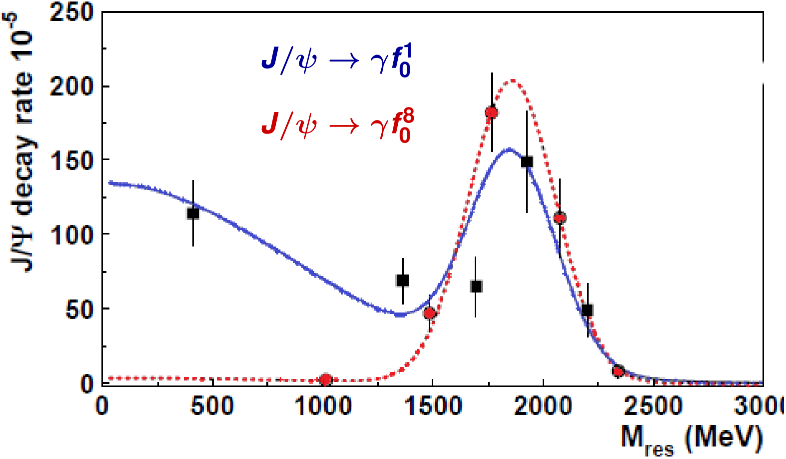


(M^2, n) trajectories of scalar mesons



[1] M. Ablikim *et al.* [BESIII], "Partial wave analysis of $J/\psi \to \gamma\eta'\eta'$," Phys. Rev. D 105, no.7, 072002 (2022).

4.3 The scalar glueball

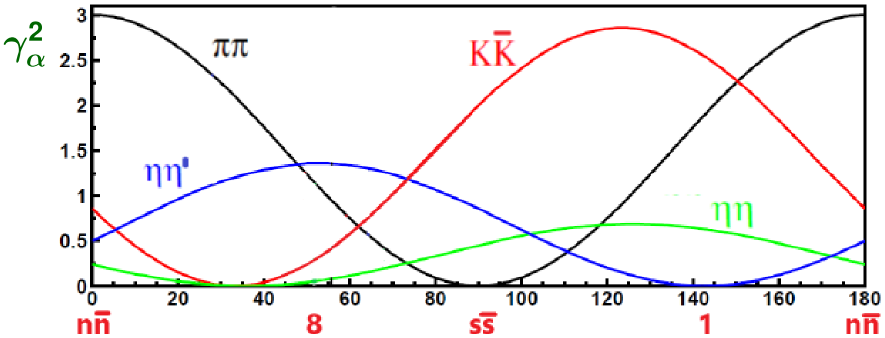


$$\mathrm{M_{glueball}} = (1865 \pm 25)\,\mathrm{MeV},\ \Gamma_{\mathrm{glueball}} = (370 \pm 50^{+30}_{-20})\,\mathrm{MeV}$$

$$\mathrm{Y}_{J/\psi\rightarrow\gamma G_0} = (5.8 \pm 1.0)\cdot 10^{-3}$$

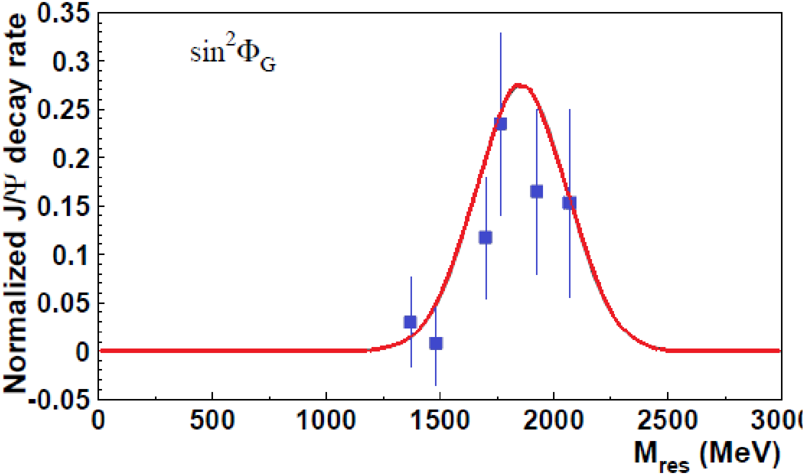
The decays of the scalar glueball

0



$$f_0^{\rm nH}(xxx) = (n\bar{n}\cos\varphi_{\rm n}^{\rm s} - s\bar{s}\sin\varphi_{\rm n}^{\rm s})\cos\phi_{\rm nH}^G + G\sin\phi_{\rm nH}^G$$
$$f_0^{\rm nL}(xxx) = (n\bar{n}\sin\varphi_{\rm n}^{\rm s} + s\bar{s}\cos\varphi_{\rm n}^{\rm s})\cos\phi_{\rm nL}^G + G\sin\phi_{\rm nL}^G$$

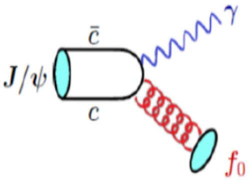
$$g_\alpha = c_{\rm n}\gamma_\alpha^q + c_G\gamma_\alpha^G$$



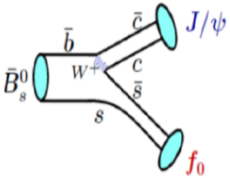
3	4	5	6	7	8
$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$f_0(1770)$	$f_0(2020)$	$f_0(2100)$
$(5\pm4)\%$	$< 5\%$	$(12\pm6)\%$	$(25\pm10)\%$	$(16\pm9)\%$	$(17\pm8)\%$

$$\sum_3^8 \sin^2 \phi_G = 0.78 \pm 0.18$$

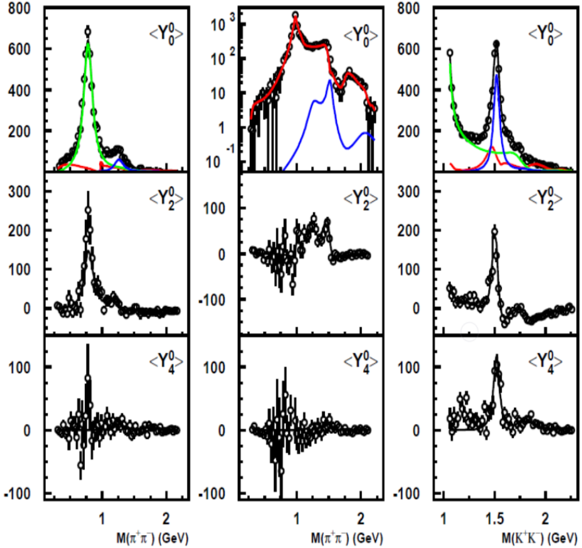
Compare:



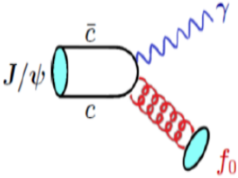
Central overlap of f_0 wf with gg



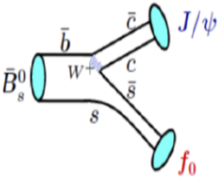
Central overlap of f_0 wf with $s\bar{s}$



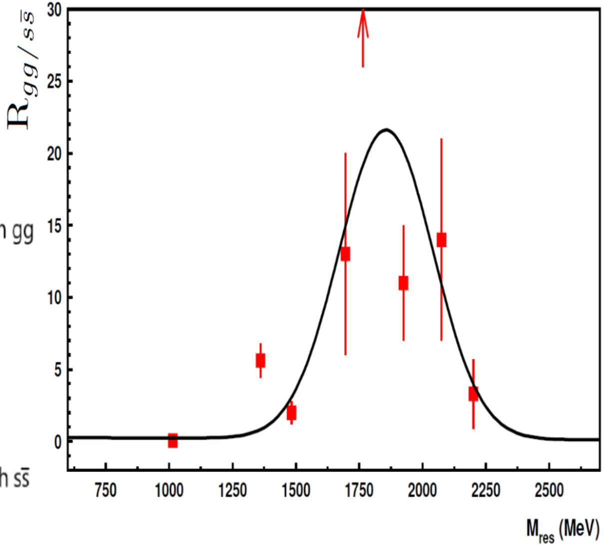
Compare:



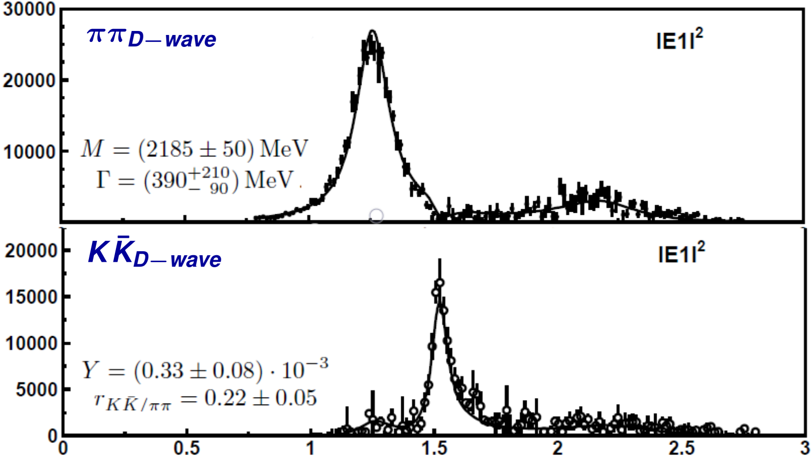
Central overlap of f_0 wf with gg



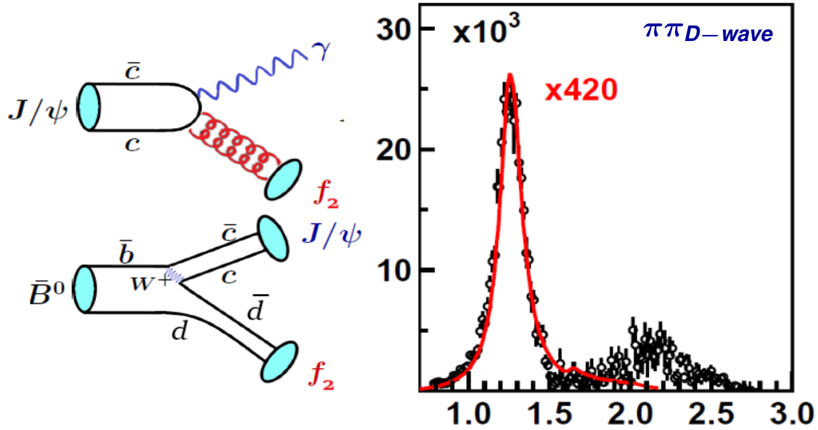
Central overlap of f_0 wf with $s\bar{s}$



4.4. The hidden tensor glueball



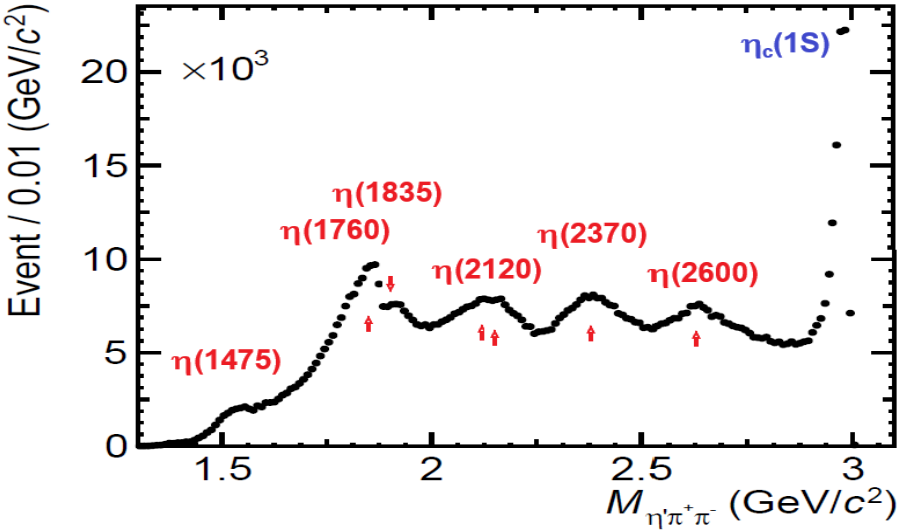
Too low in mass:	Limited phase space?	Use $\psi(2S)$ radiative decays
Yield too low:	Unseen decays?	Analyse $J/\psi \to \gamma 4\pi, K^*\bar{K}$
Decay modes: $n\bar{n}$	Sum of many f_2 and f_2'?	Higher statistics

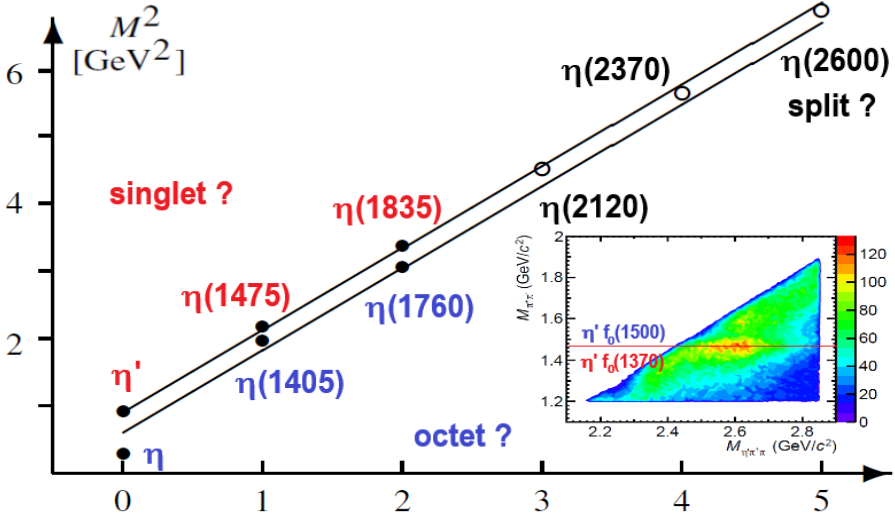


Again, high-mass tensor mesons are produced in radiative J/ψ decays in not in *B* decays. The yield is, however, much too low.
Add yield of all tensor mesons above 1.9 GeV:
$f_2(1910)$, $f_2(1950)$, $f_2(2010)$, $f_2(2300)$, $f_2(2340)$:

$$Y_{\rm Tensor\ mesons\ 1.9-2.4\,GeV} = (3.0 \pm 0.6)\cdot 10^{-3}$$

4.5 How to find the pseudoscalar glueball:



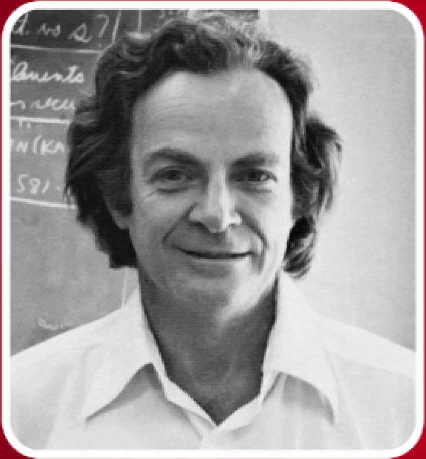


M^2 [GeV^2]
6
4
2
0
1
2
3
4
5
η(2370)
η(2600)
split ?
singlet ?
η(1835)
η(2120)
η(1475)
η(1760)
η'
η(1405)
octet ?
η
η' f_0(1500)
η' f_0(1370)
$M_{\pi\pi}$ (GeV/c^2)
$M_{\eta'\pi^+\pi}$ (GeV/c^2)

5. Summary

- **The scalar glueball has been identified in BESIII data on radiative J/ψ decays. It is spread over several resonances.**
  1. **High-mass scalar mesons are produced via due to their gluonic component.**
  2. **They are absent in hadronic reactions.**
  3. **The decay analysis reveals an inert (glueball) component.**
- **The tensor glueball likely hides itself in a large number of $^3P_2$ and $^3F_2$ $n\bar{n}$ and $s\bar{s}$ states produced in radiative J/ψ decays.**
- **The pseudoscalar glueball should be searched for by a decay analysis of pseudoscalar mesons above 1.6 GeV. It is expected to be spread over several resonances.**

What is this for?



“Physics Is Like Sex: Sure, It May Give Some Practical Results, but That’s Not Why We Do It.”

Richard Feynman