Scalar resonances and scalar glueball from radiadive J/Ψ decay

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Gatchina, PNPI, 21st October 2021

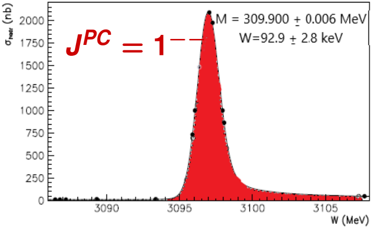
1.5 How to search for glueballs in radiative J/ψ decays

1974: Extremely narrow resonance discovered: J/ψ

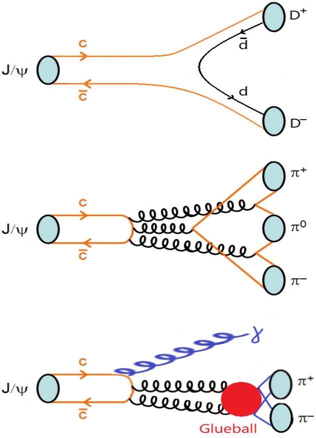
New quark: charm

$$J/\psi = c\bar{c} \rightarrow c\bar{d} + \bar{c}d$$

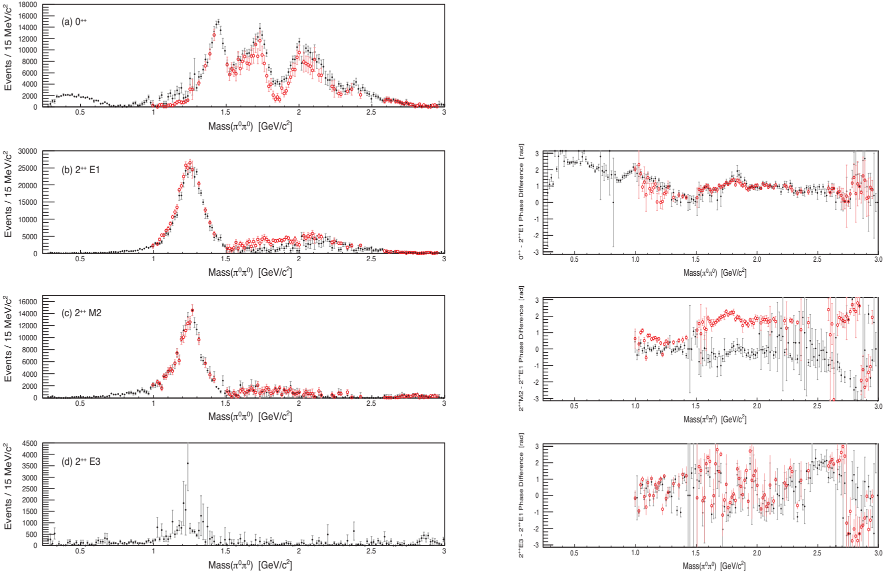
energetically forbidden!



Today: Data from BESIII, $1.3 \cdot 10^9$ J/ψ decays

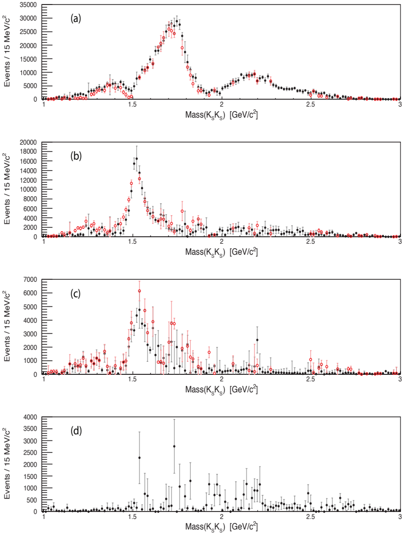


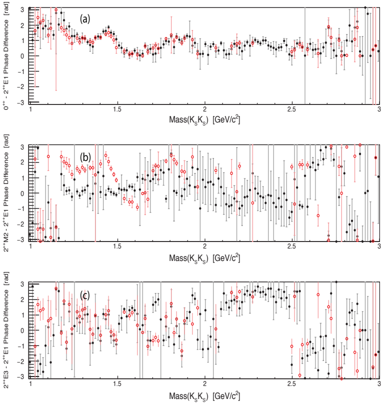
Energy independent analysis for $J/\Psi \to \gamma\pi^0\pi^0$



BESIII, A. P. Szczepaniak, P. Guo1 Phys. Rev. D 92 no.5, 052003 (2015)

Energy independent analysis for $J/\Psi \to \gamma K_s K_s$





BESIII, Phys. Rev. D 98, no.7, 072003 (2018)

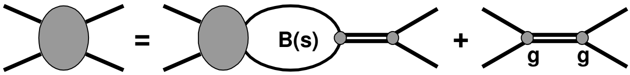
2. Coupled channel analysis

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).

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

N/D-based approach to the description of the scattering amplitude

The scattering amplitude is found by solving the following equation:



$$A_{ij}(s,s) = \sum_m \int\limits_{(m_1+m_2)^2}^{\infty} \frac{ds}{\pi} \frac{A_{im}(s,s')\rho_m(s')K_{mj}(s',s)}{s'-s-i\varepsilon} + K_{ij}(s,s)$$

Here $i, m, j = \pi\pi, KK, \eta\eta, \eta\eta', \omega\phi, \rho\rho, \sigma\sigma$ and $K(s)$ is an interaction kernel:

$$K_{ij} = \sum_\alpha \frac{g_i^\alpha g_j^\alpha}{M_\alpha^2 - s} + f_{ij}(s)\,.$$

where f_{ij} is nonresonant transition part.

P-vector approach

$$T_j(s,s) = \sum_i \int\limits_{(m_1+m_2)^2}^{\infty} \frac{ds}{\pi} \frac{P_i(s,s')\rho_i(s')A_{ij}(s,s')}{s'-s-i\varepsilon} + P_j(s,s)$$

The P-vector of the initial interaction has the form:

$$P_j = \sum_\alpha \frac{\Lambda_\alpha g_j^\alpha}{M_\alpha^2 - s} + F_j(s)$$

Here F_j is a nonresonant production term.
The same set of Λ_α production couplings should describe all final states. For example the same P-vector describes the reactions:

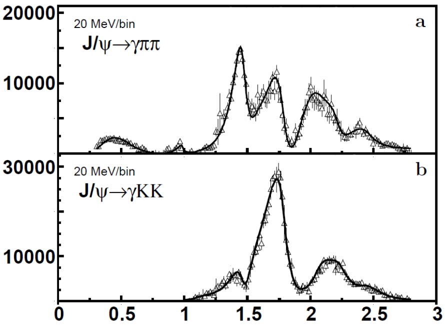
$$\bar{p}p \to \pi^0\pi^0\pi^0, \eta\eta\pi^0, KK\pi$$

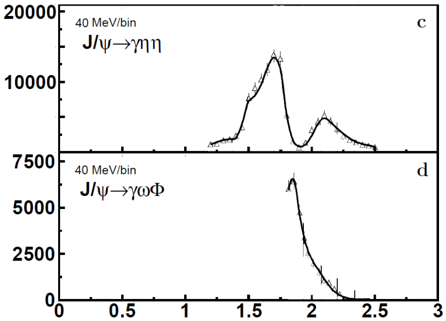
Here the Λ_α and F_j parameters can be complex numbers due to rescattering.
The same P-vector should describe the J/Ψ decay:

$$J/\Psi \to \gamma\pi\pi, \gamma KK, \gamma\eta\eta, \gamma\eta\eta', \gamma\omega\phi$$

Here one can expect that Λ_α and F_j parameters are real numbers.

$J/\psi \to \gamma$ $\pi^0\pi^0$ and 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).

The tensor amplitudes in the spin-orbital momentum basis $A_2(SL)$:

$$A_2(20) = \epsilon^{\Psi}_{\mu}\epsilon^{\gamma}_{\nu}\tilde{a}_{20}(s)Z_{\mu\nu}(k)$$
$$A_2(02) = (\epsilon^{\Psi}\epsilon^{\gamma})X^{(2)}_{\mu\nu}(k_1^{\perp})\tilde{a}_{02}(s)Z_{\mu\nu}(k)$$
$$A_2(12) = \frac{3}{2}(\epsilon^{\Psi}k_1^{\perp})\epsilon^{\gamma}_{\mu}k^{\perp}_{1\nu}\tilde{a}_{12}(s)Z_{\mu\nu}(k)$$

The correspondence to the helicity basis:

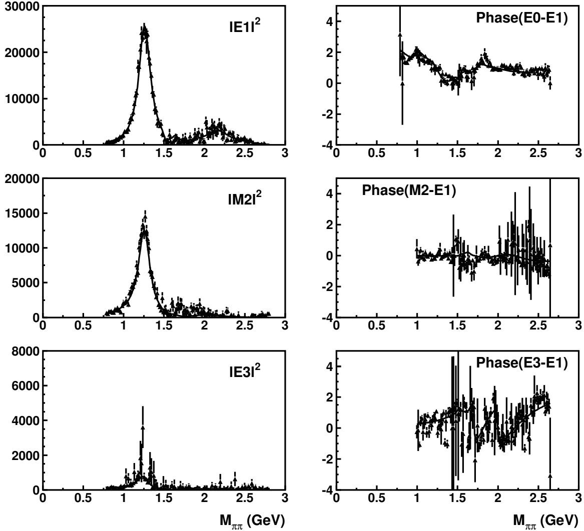
$$E_1 = \frac{1}{\sqrt{5}}\left(\tilde{a}_{02} + \sqrt{3}\tilde{a}_{12} + \tilde{a}_{20}\left(7 + 3\frac{P_0}{\sqrt{s}}\right)\right)$$
$$M_2 = \frac{\sqrt{5}}{3}\left(\sqrt{3}\tilde{a}_{02} + \tilde{a}_{12} - \sqrt{3}\tilde{a}_{20}\left(1 - \frac{P_0}{\sqrt{s}}\right)\right)$$
$$E_3 = \frac{2\sqrt{7}}{3\sqrt{5}}\left(\sqrt{3}\tilde{a}_{02} - 2\tilde{a}_{12} + 2\sqrt{3}\tilde{a}_{20}\left(1 - \frac{P_0}{\sqrt{s}}\right)\right)$$

At high masses:

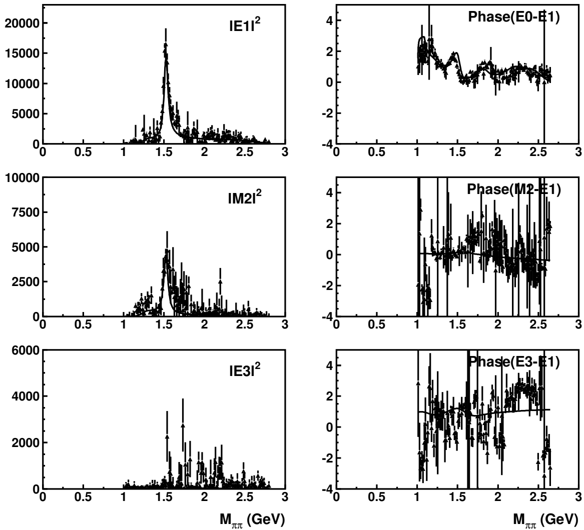
$$\frac{P_0}{\sqrt{s}} \to 1 \qquad E_1 >> M_2 \qquad E_1 >> E_3$$

if $\tilde{a}_{20}(s)$ is a dominant partial wave.

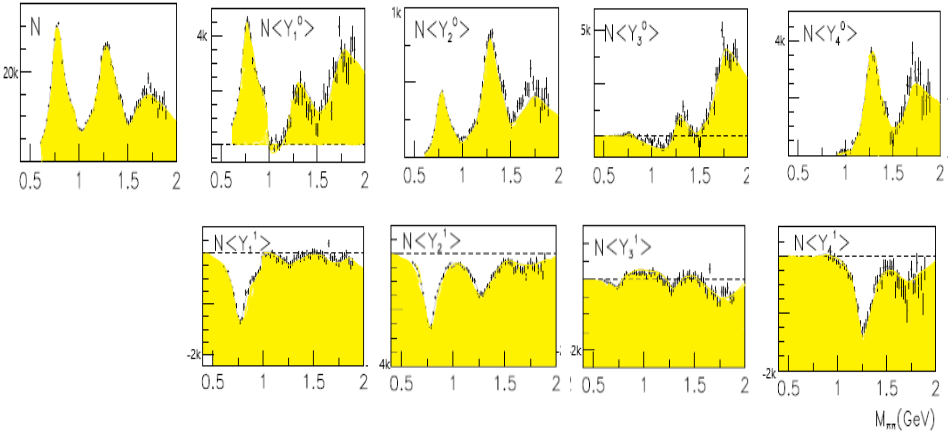
The description of the tensor states in the reaction $J/\Psi \to \gamma\pi\pi$: only ground states are strongly produced.



The description of the tensor states in the reaction $J/\Psi \to \gamma KK$: only ground states are strongly produced.

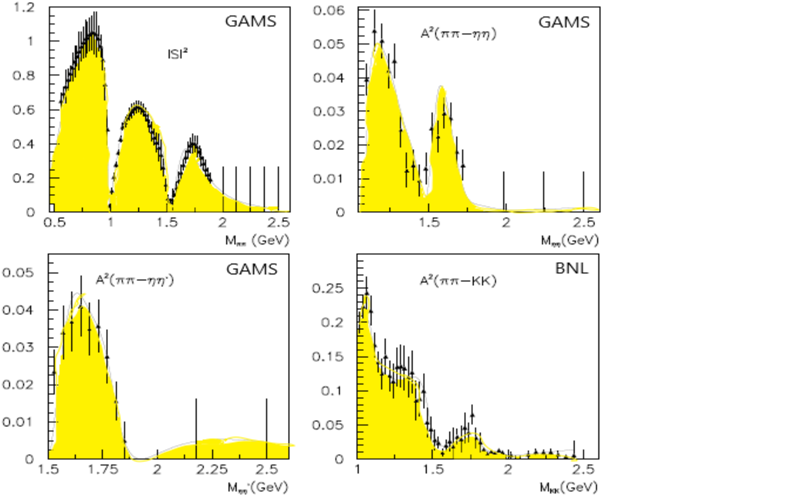


The CERN-Munich data on $\pi\pi \to \pi\pi$ elastic scattering



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).

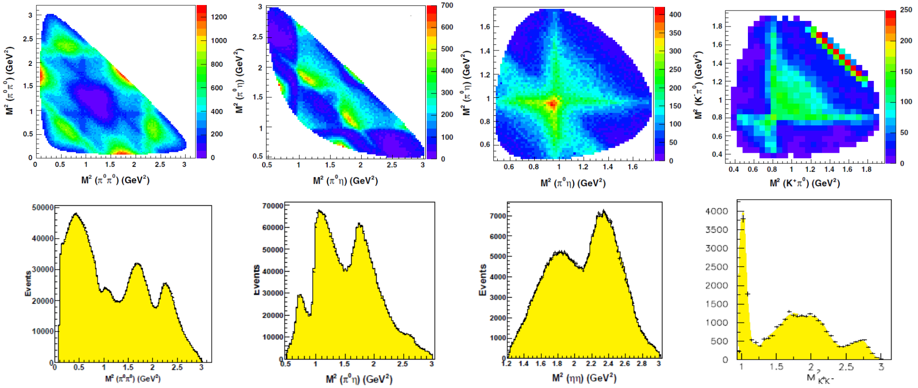
GAMS and BNL data on pion-induced reactions



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).

The Crystal Barrel data



$\pi^0\pi^0\pi^0$ $\pi^0\pi^0\eta$ $\pi^0\eta\eta$ $K^+K^-\pi^0$

$\cdots$ **and further Dalitz plots.**

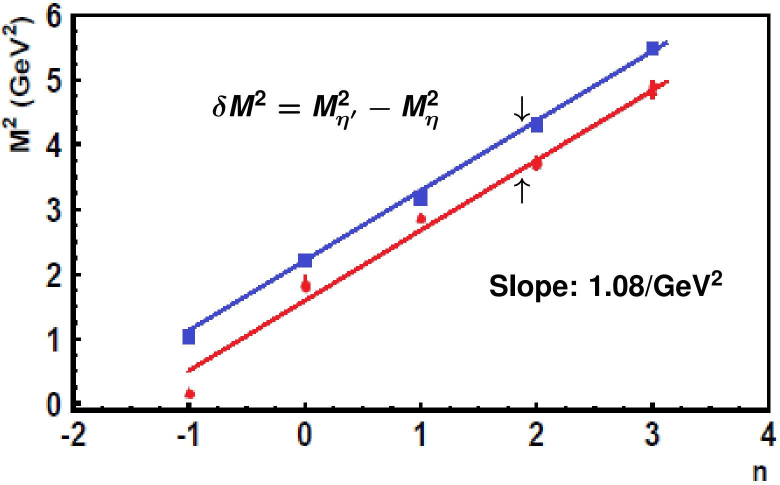
Results and interpretation

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	1370±40	1700±18	1925±25	2200±25
	400→550	1200→1500	1704±12	1992±16	2187±14
Γ	480±30	390±40	255±25	320±35	150±30
	400→700	100→500	123±18	442±60	∼ 200

Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M	1014±8	1483 ± 15	1765±15	2075±20	2340±20
	990±20	1506 ± 6		2086^{+20}_{-24}	∼2330
Γ	71±10	116±12	180±20	260±25	165±25
	10→100	112±9		284^{+60}_{-32}	250±20

(M^2, n) trajectories of scalar mesons



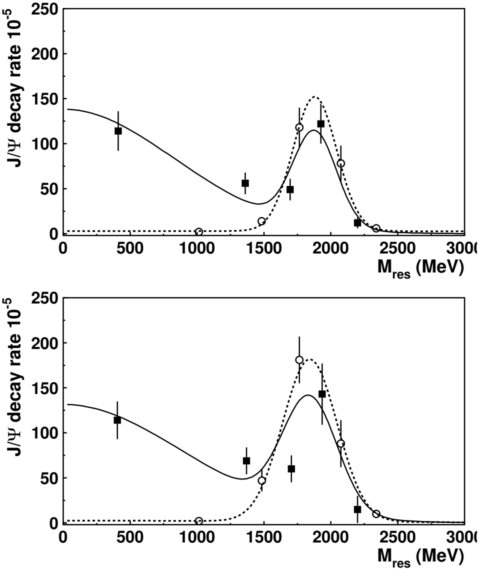
$\cdots$ and where is the scalar glueball ?

The fragmented glueball

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		total
						$\gamma 4\pi$	$\gamma\omega\omega$	
$f_0(500)$	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				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	$1.7^{+0.6}_{-1.4}$	$6.4^{+1.0}_{-2.2}$		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	97 ± 18	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}	$11.0^{+6.5}_{-3.0}$			115 ± 41		
$f_0(2330)$	4 ± 2	2.5 ± 0.5	1.5 ± 0.4					8 ± 3
		20 ± 3						

Is this the scalar glueball?

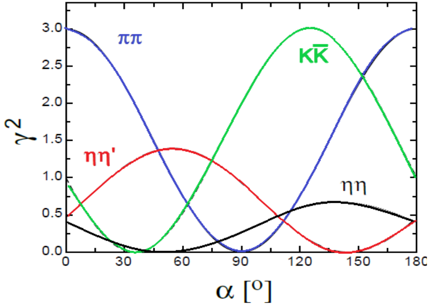


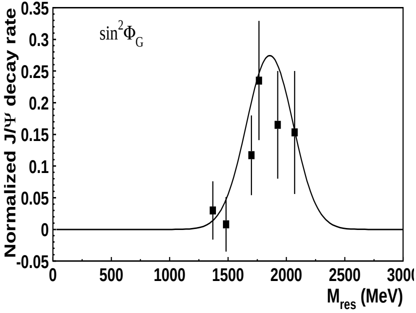
$$M = 1865 \pm 25^{+10}_{-30} \text{ MeV}$$

$$\Gamma = 370 \pm 50^{+30}_{-20} \text{ MeV}$$

3.5 Glueball content of scalar mesons

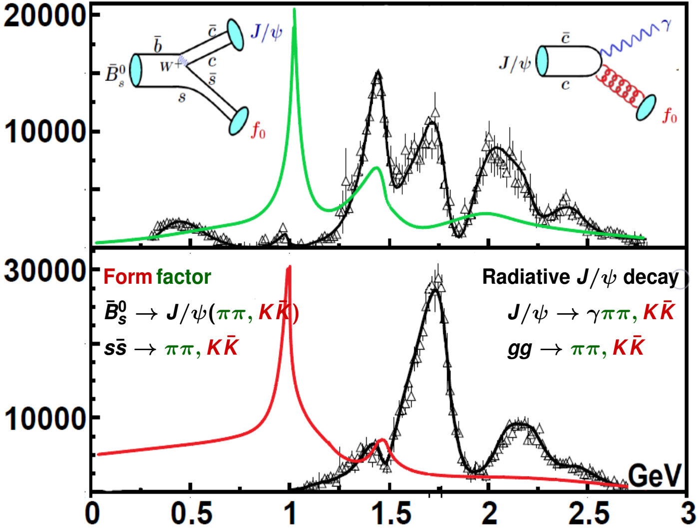
$$|f_0(1770)>= \cos\phi_g(n\bar{n}\cos\alpha - s\bar{s}\sin\alpha)\gamma_{q\bar{q}} + \sin\phi_g\gamma_1$$
$$|f_0(1710)>= \cos\varphi_g(n\bar{n}\sin\alpha + s\bar{s}\cos\alpha)\gamma_{q\bar{q}} + \sin\varphi_g\gamma_1$$





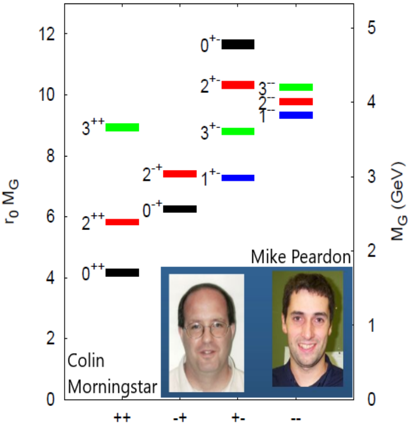
Glueball content from J/ψ radiative production is (nearly) consistent with glueball content from the decays of scalar mesons!

3.4 Evidence for strong glue-glue interactions



S. Ropertz, C. Hanhart and B. Kubis, Eur. Phys. J. C 78, no.12, 1000 (2018).
R. Aaij *et al.* [LHCb], Phys. Rev. D 89, R. Aaij *et al.* [LHCb], JHEP 08, 037 (2017).

1.3 Glueballs:



The scalar glueball is expected in the mass range

from 1700 to 2000 MeV

0^{++}	$1710\pm50\pm$ 80 MeV
2^{++}	$2390\pm30\pm120$ MeV
0^{-+}	$2560\pm35\pm120$ MeV

Y. Chen *et al.* "Glueball spectrum and matrix elements on anisotropic lattices," Phys. Rev. D 73, 014516 (2006).

0^{++}	1980 MeV	1920 MeV
2^{++}	2420 MeV	2371 MeV
0^{-+}	2220 MeV	

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," Phys. Rev. D 104, no.3, 034016 (2021).

0^{++}	1850 ± 130 MeV
0^{-+}	2580 ± 180 MeV

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).

Summary

- We have performed the combined analysis of the J/Ψ radiative decay data together with $\pi\pi$ scattering data and the LEAR data from the anti-proton nucleon annihilation at rest.
- The P-vector analysis reveals 10 scalar states which fall onto linear (n, M^2)-trajectories
- Only the ground states of the tensor mesons are strongly produced. There is some indication for the states in the mass region 1800-2100 MeV. The tensor states are produced dominantly with the orbital momentum $L = 0$ as well as the scalar states.
- The only relevant explanation for the enhanced production of scalar mesons in the mass range 1700 - 2100 MeV and a strong suppression for the production of the tensor states is the mixture of the scalar states with a scalar glueball.
- The intensity for the production of the scalar states reveal the lowest scalar glueball.