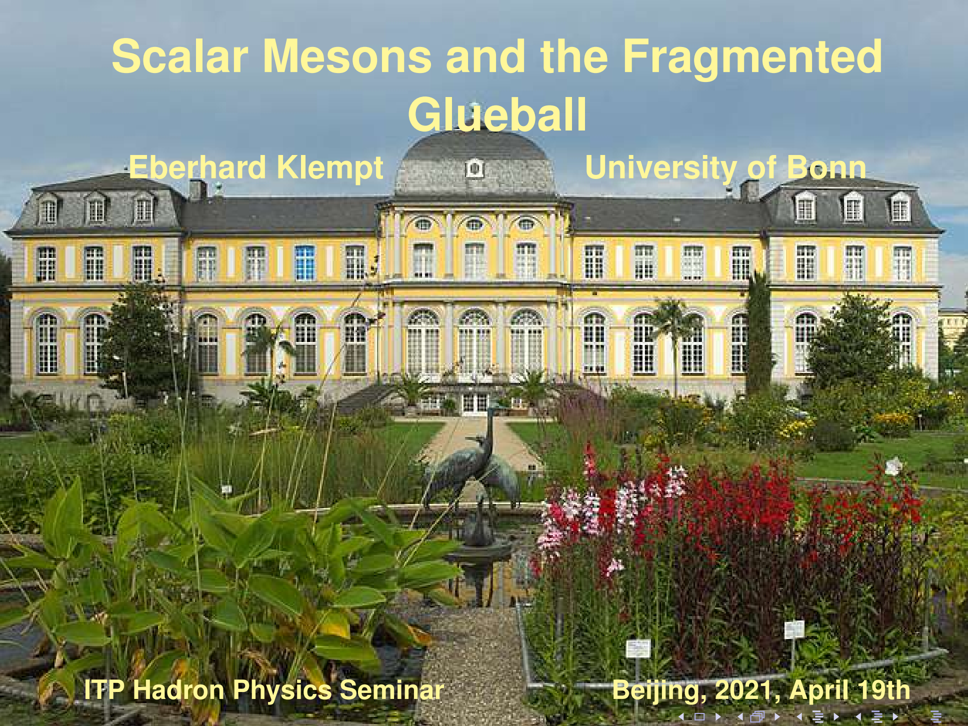
Scalar Mesons and the Fragmented Glueball

Eberhard Klempt University of Bonn



ITP Hadron Physics Seminar Beijing, 2021, April 19th

Scalar mesons and the fragmented glueball

1. The Standard Model
2. How to seacrh for glueballs
3. Coupled channel analysis
4. Results and interpretation
5. Summary

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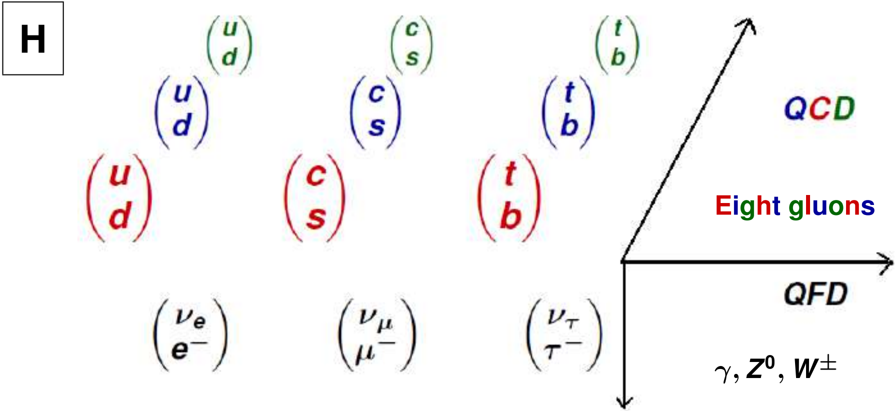
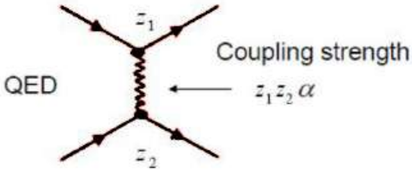
1. The Standard Model

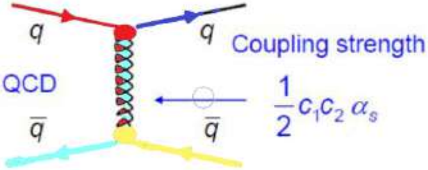
1.1 Particles ...

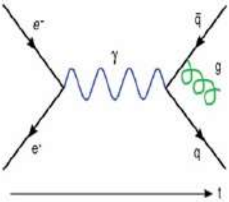
1. **Fermions: Six quarks (in three colours) and six leptons**
2. **Bosons: Eight gluons, three vector bosons, one photon**
3. **The Higgs boson provides the mass**



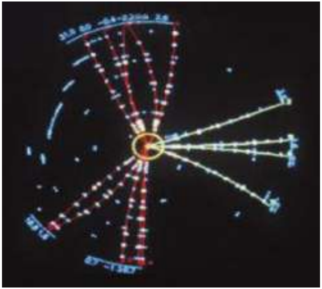
1.2. and interactions

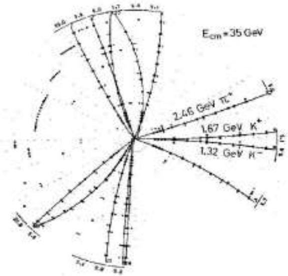






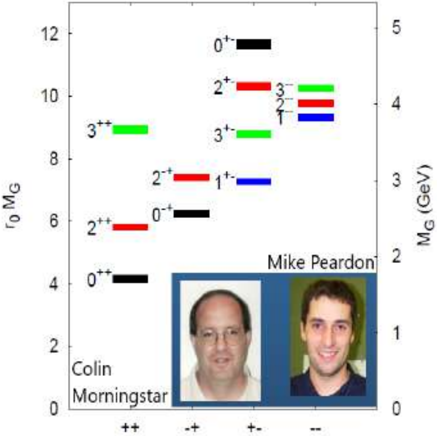
Three-jet events demonstrate the existence of gluons!





1.3 Glueballs

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



0^{++}	$1710 \pm 50 \pm 80$ MeV
2^{++}	$2390 \pm 30 \pm 120$ MeV
0^{-+}	$2560 \pm 35 \pm 120$ MeV

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

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

[2] A. P. Szczepaniak and E. S. Swanson, "The Low lying glueball spectrum," Phys. Lett. B 577, 61-66 (2003).

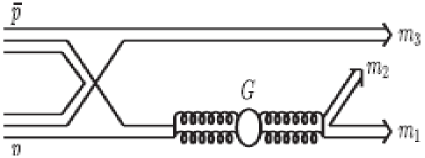
0^{++}	1850 ± 130 MeV
0^{-+}	2580 ± 180 MeV

[3] 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).

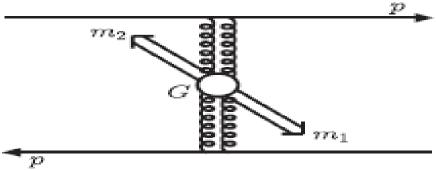
The scalar glueball is expected in the 1700 to 2000 MeV mass range

2. How to search for glueballs

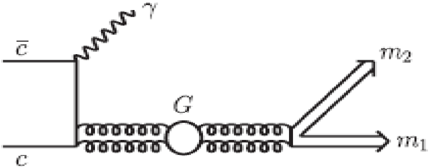
$\bar{N}N$ annihilation



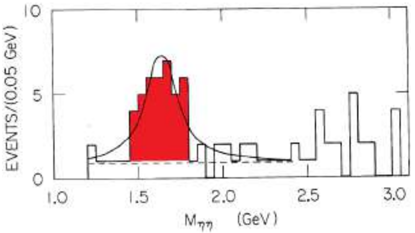
Central production



Radiative J/ψ decays



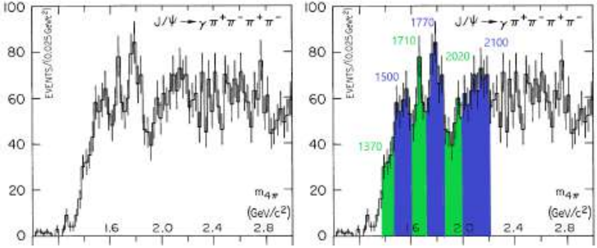
2.1 Radiative J/ψ decays (MARKIII, DM2)

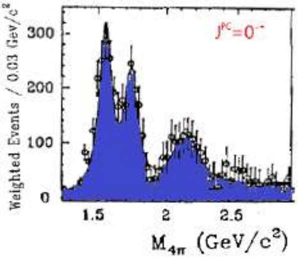


MARKIII: A radiatively produced resonance decaying into $\eta\eta$

The tensor glueball?

C. Edwards *et al.* Phys. Rev. Lett. 48, 458 (1982).



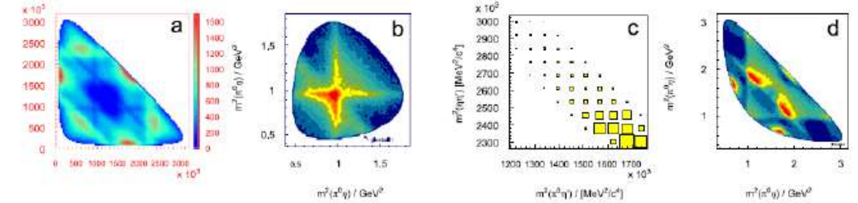


R. M. Baltrusaitis *et al.* [MARK-III], Phys. Rev. D 33, 1222 (1986). (N. Wermes)

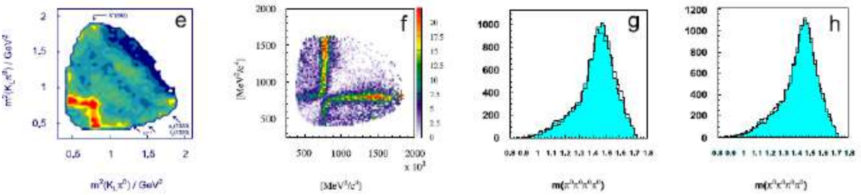
D. Bisello *et al.* [DM2], Phys. Rev. D 39, 701 (1989).

Three resonances at 1500, 1750, and 2100 MeV, first $J^{PC} = 0^{-+}$, D.V. Bugg: $J^{PC} = 0^{++}$

2.2 $\bar{N}N$ annihilation (Crystal Barrel at LEAR)



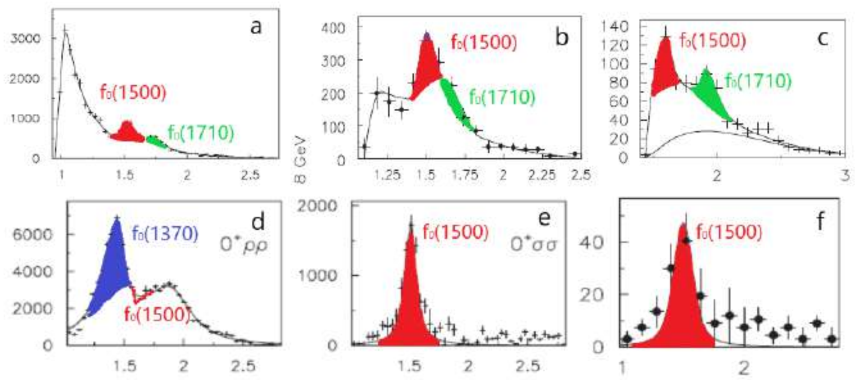
a: $3\pi^0$; J. Brose (Mainz)
b: $\pi^0\eta\eta$; R. Hackmann (Mainz)
c: $\pi^0\eta\eta'$; S. Spanier (Mainz)
d: $\pi^0\pi^0\eta$; S. Spanier (Mainz)



e: $K_L K_L \pi^0$; 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: $f_0(1370)$, $f_0(1500)$, $a_0(1475)$!

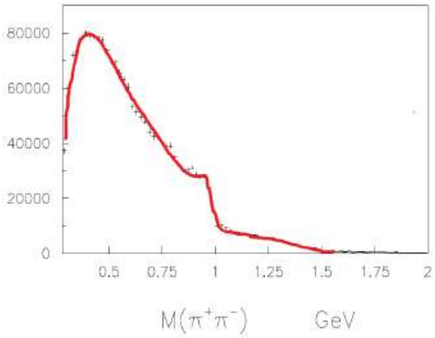
2.3 Central production (WA102 experiment at SPS)

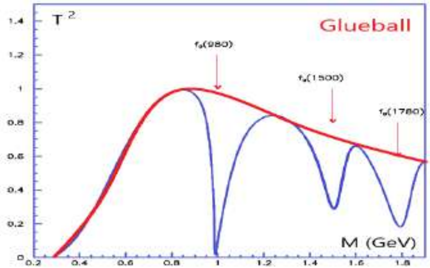


a: $K\bar{K}$; **b:** $\eta\eta$; **c:** $\eta\eta'$;
d: $\rho\rho$; **e:** $\sigma\sigma$; **f:** $4\pi^0$;

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

2.4 A global view of scalar mesons





B. S. Zou, "$\pi\pi$ S-wave interaction and 0^{++} particles," Subnucl. Ser. 34, 579-582 (1997).

Centrally produced $\pi^+\pi^-$ **The $\pi\pi$ S-wave squared amplitude**

Wide "background amplitude" could be the glueball[1].

[1] P. Minkowski and W. Ochs, "Identification of the glueballs and the scalar meson nonet of lowest mass," Eur. Phys. J. C 9, 283-312 (1999).

Or it could be the superposition of a series of SU(3) singlet scalar mesons superimposed by "narrow" SU(3) octet states[2].

[2] E. Klempt and A. Zaitsev, "Glueballs, Hybrids, Multiquarks. Experimental facts versus QCD inspired concepts," Phys. Rept. 454, 1-202 (2007).

2.5 Supernumerosity

$\{a_0(1475), K_0^*(1430), f_0(1710), f_0(1370)\}$ $f_0(1500)$

similar: $\{a_2(1320), K_2^*(1430), f_2'(1525), f_2(1270)\}$

Two scalar isoscalar states expected, three found!

Two $q\bar{q}$ and one glueball with mixing.

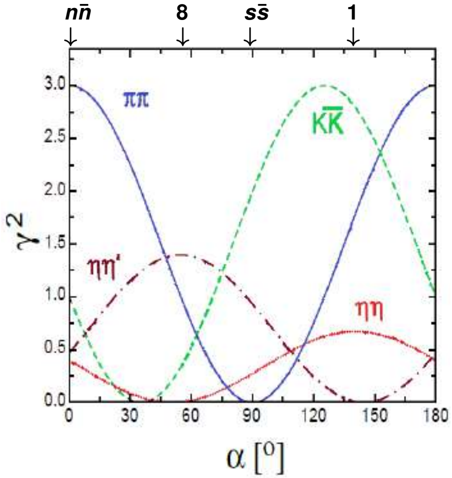
Mixing matrix[1]:

$$\begin{pmatrix} |f_0(1710)\rangle \\ |f_0(1500)\rangle \\ |f_0(1370)\rangle \end{pmatrix} = U \begin{pmatrix} |s\bar{s}\rangle \\ |G\rangle \\ |n\bar{n}\rangle \end{pmatrix} = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{pmatrix} \begin{pmatrix} |s\bar{s}\rangle \\ |G\rangle \\ |n\bar{n}\rangle \end{pmatrix}.$$

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

Large number of follow-up papers

2.6 Decays of scalar mesons



$$\frac{\Gamma(f_0(1370) \to \eta\eta)}{\Gamma(f_0(1370) \to \pi\pi)} = 0.02 \pm 0.02$$

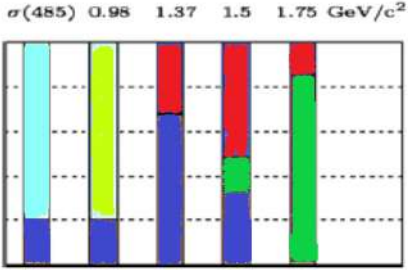
$$\frac{\Gamma(f_0(1370) \to K\bar{K})}{\Gamma(f_0(1370) \to \pi\pi)} = 0.00 - 1.00$$

$$\frac{\Gamma(f_0(1500) \to \eta\eta')}{\Gamma(f_0(1500) \to \eta\eta)} = 0.84 \pm 0.23$$

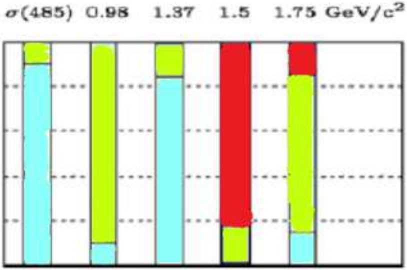
$$\frac{\Gamma(f_0(1500) \to \eta\eta)}{\Gamma(f_0(1500) \to \pi^0\pi^0)} = 0.23 \pm 0.04$$

$$\frac{\Gamma(f_0(1500) \to K\bar{K})}{\Gamma(f_0(1500) \to \pi\pi)} = 0.19 \pm 0.07.$$

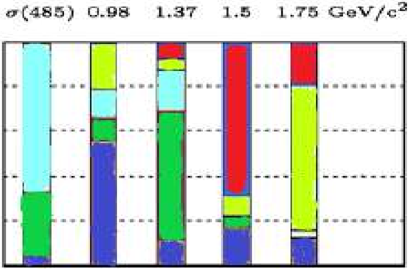
$$\frac{\Gamma(f_0(1710) \to K\bar{K})}{\Gamma(f_0(1710) \to \pi\pi)} = 2.56 \pm 0.92$$



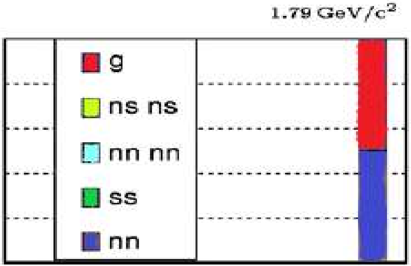
F. E. Close and A. Kirk, Eur. Phys. J. C 21, 531-543 (2001).



L. Maiani *et al.*, Eur. Phys. J. C 50, 609-616 (2007).



A. H. Fariborz, Phys. Rev. D 74, 054030 (2006).



D. V. Bugg, [arXiv:hep-ph/0603018 [hep-ph]].

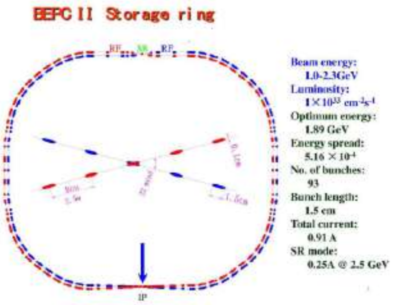
Scalar mesons could have a large tetraquark component!

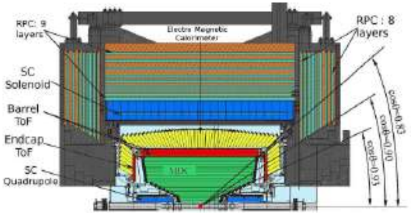
3. Coupled channel analysis

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).

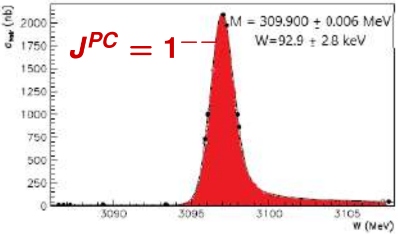
J/ψ	$\rightarrow$	$\gamma\pi^0\pi^0$	$K_S K_S$	$\gamma\eta\eta'$	$\gamma\omega\phi$	BESIII
χ^2/N; N		1.28; 167	1.21, 121	0.8; 21	0.2; 17	
$\bar{p}p$	$\rightarrow$	$3\pi^0$	$\pi^0\pi^+\pi^-$	$2\pi^0\eta$	$\pi^0\eta\eta$	CB (liq. H_2)
χ^2/N, N		1.40; 7110	1.24, 1334	1.23; 3475	1.28; 3595	
$\bar{p}p$	$\rightarrow$	$3\pi^0$		$2\pi^0\eta$	$\pi^0\eta\eta$	CB (gas. H_2)
χ^2/N, N		1.38; 4891		1.24; 3631	1.32; 1182	
$\bar{p}p$	$\rightarrow$	$K_L K_L \pi^0$	$K^+K^-\pi^0$	$K_S K^\pm \pi^\mp$	$K_L K^\pm \pi^\mp$	CB (liq. H_2)
χ^2/N, N		1.08; 394	0.97; 521	2.13; 771	0.76; 737	
$\bar{p}n$	$\rightarrow$	$\pi^+\pi^-\pi^-$	$\pi^0\pi^0\pi^-$	$K_S K^-\pi^0$	$K_s K_S \pi^-$	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

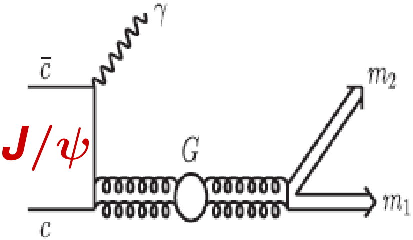
3.1 Data from BESIII



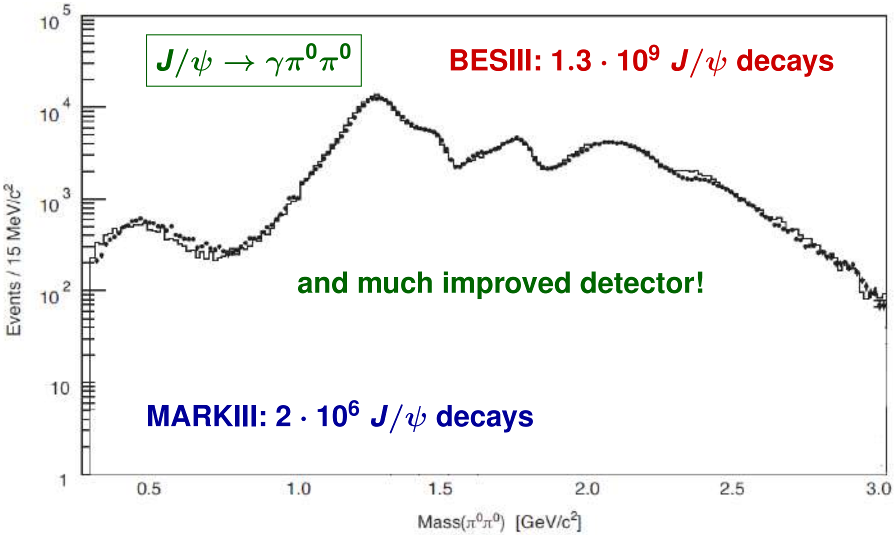


M. Ablikim *et al.* [BESIII],"Design and Construction of the BESIII Detector," Nucl. Instrum. Meth. A 614, 345-399 (2010).

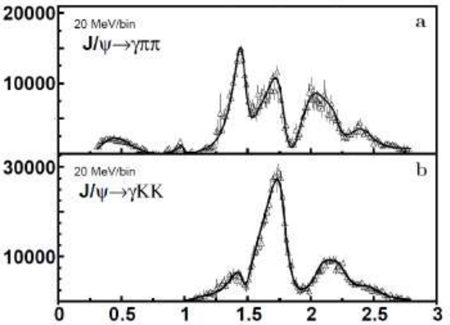


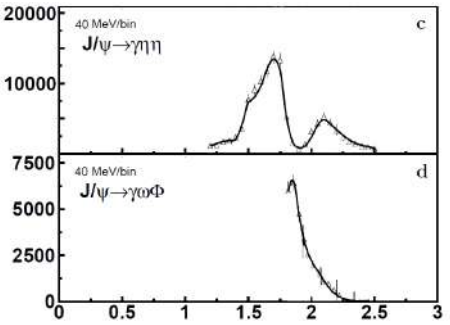


V. V. Anashin *et al.* "Final analysis of KEDR data on J/ψ and $\psi(2S)$ masses," Phys. Lett. B 749, 50-56 (2015).


$J/\psi \to \gamma\pi^0\pi^0$
BESIII: $1.3 \cdot 10^9$ J/ψ decays
and much improved detector!
MARKIII: $2 \cdot 10^6$ J/ψ decays
Events / 15 MeV/c^2
10^5
10^4
10^3
10^2
10
1
0.5
1.0
1.5
2.0
2.5
3.0
Mass($\pi^0\pi^0$) [GeV/c^2]

$J/\psi \to \gamma$ $\pi^0\pi^0$ and K_sK_s $\eta\eta$ and $\omega\phi$





$1.3 \cdot 10^9$ events

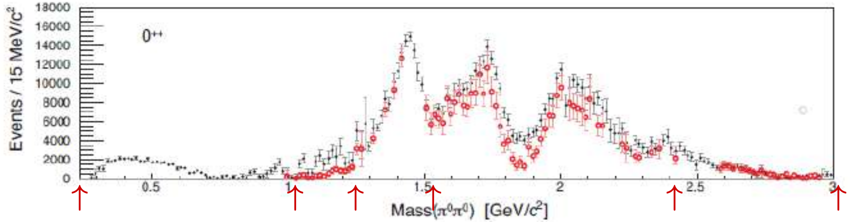
$0.225 \cdot 10^9$ events

PWA in slices of energy

Amplitude fit to data

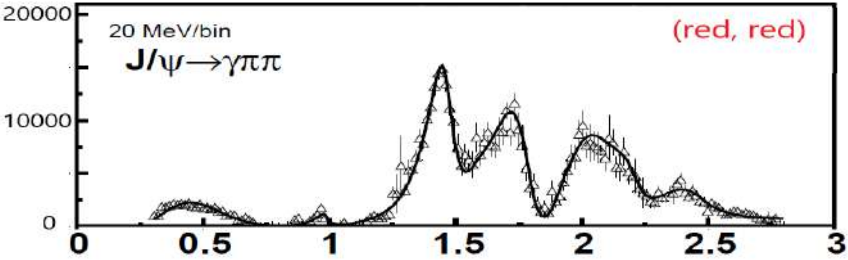
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92 no.5, 052003 (2015).
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the K_SK_S system produced in radiative J/ψ decays," Phys. Rev. D 98 no.7, 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).

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

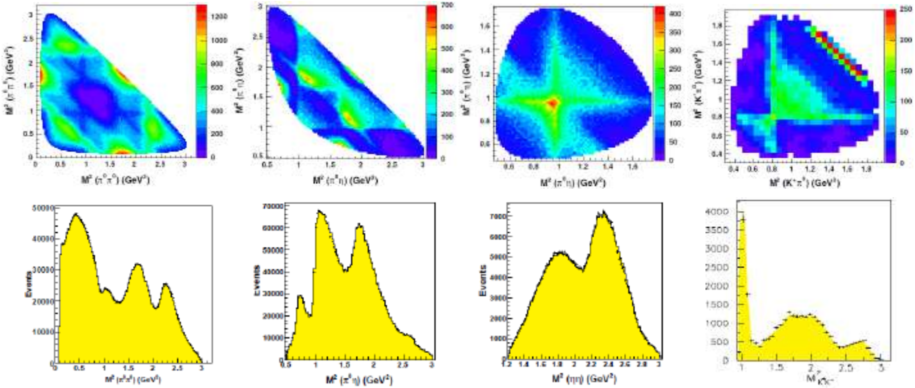


$\leftarrow \mathrm{I}_{\text{identical}} \rightarrow$ II_{amb} III_{id} $\leftarrow \mathrm{IV}_{\text{ambiguous}} \rightarrow \leftarrow \mathrm{V}_{\text{identical}} \rightarrow$

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).



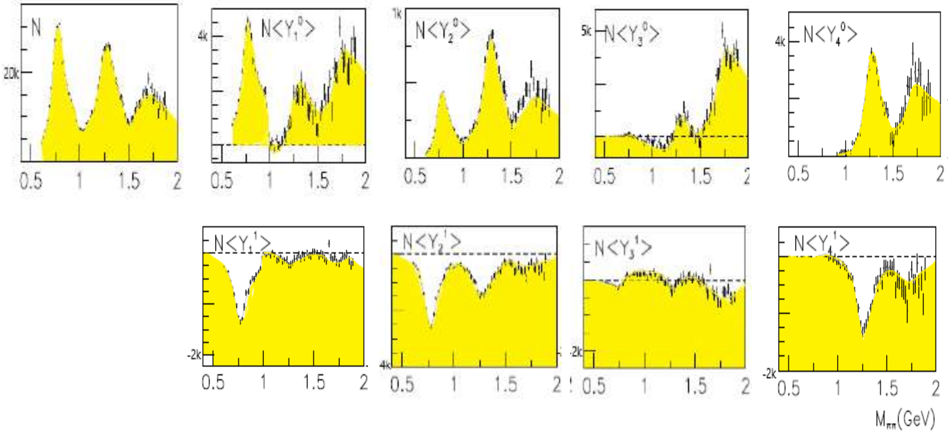
3.2 The Crystal Barrel data



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

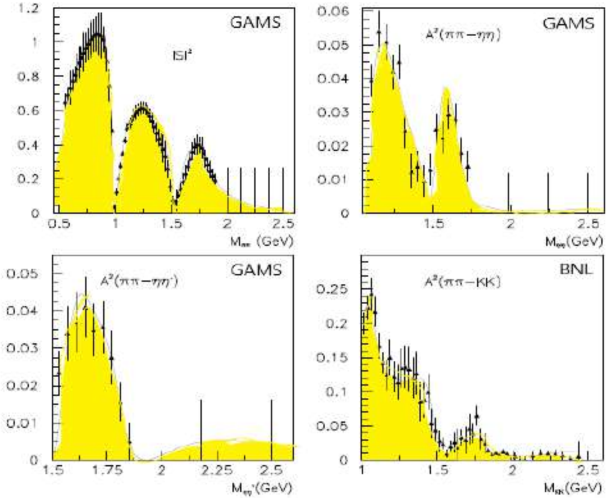
$\cdots$ **and further Dalitz plots.**

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).

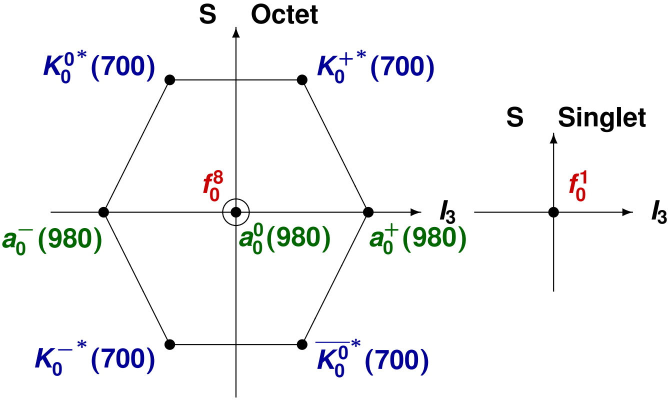
4. Results and interpretation

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
	$400\to550$	$1200\to1500$	1704 ± 12	1992 ± 16	2187 ± 14
Γ	480 ± 30	390 ± 40	255 ± 25	320 ± 35	150 ± 30
	$400\to700$	$100\to500$	123 ± 18	442 ± 60	$\sim$ 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
	$10\to100$	112 ± 9		284^{+60}_{-32}	250 ± 20

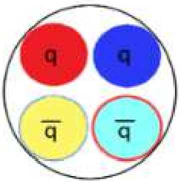
4.1 The low-mass scalar mesons

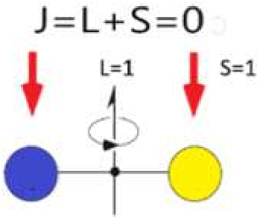


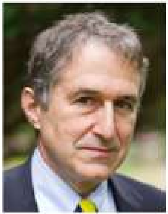
$$f_0(500) = \sin\theta \; f_0^8 + \cos\theta \; f_0^1$$

$$f_0(980) = \cos\theta \; f_0^8 - \sin\theta \; f_0^1$$

Tetraquarks







The energy to excite $q\bar{q}$ to L = 1 is approximately equivalent to the creation of a new $q\bar{q}$ pair.[1]

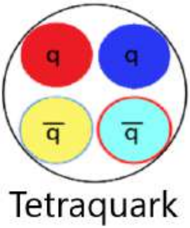
[1] R. L. Jaffe, "Multi-Quark Hadrons. 1. The Phenomenology of ($2Q2\bar{Q}$) Mesons," Phys. Rev. D 15, 267 (1977).

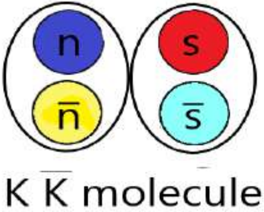
Scalar mesons are ideally mixed

with $f_0(500) = u\bar{u}d\bar{d}$ and

$$f_0(980) = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})s\bar{s}$$

Dynamical generated scalar mesons[1]





Nathan Isgur

[1] J. D. Weinstein and N. Isgur, "$K\bar{K}$ Molecules," Phys. Rev. D 41, 2236 (1990).

Scalar mesons are dynamically generated

with $f_0(500) = \pi\pi$ and

$f_0(980) = K\bar{K}$

The $f_0(500) - f_0(980)$ mixing angle

$$
\begin{aligned}
g(f_0(500) \to \pi\pi) &= -\frac{\sqrt{3}}{4}\cos\theta g_1 - \sqrt{\frac{3}{10}}\sin\theta g_8 \,, \\
g(f_0(500) \to K\bar{K}) &= -\frac{1}{2}\cos\theta g_1 + \frac{1}{\sqrt{10}}\sin\theta g_8 \,, \\
g(f_0(500) \to \eta_8\eta_8) &= \frac{1}{4}\cos\theta g_1 - \frac{1}{\sqrt{10}}\sin\theta g_8 \,, \\
g(f_0(980) \to \pi\pi) &= \frac{\sqrt{3}}{4}\sin\theta g_1 - \sqrt{\frac{3}{10}}\cos\theta g_8 \,, \\
g(f_0(980) \to K\bar{K}) &= \frac{1}{2}\sin\theta g_1 + \frac{1}{\sqrt{10}}\cos\theta g_8 \,, \\
g(f_0(980) \to \eta_8\eta_8) &= -\frac{1}{4}\sin\theta g_1 - \frac{1}{\sqrt{10}}\cos\theta g_8 \,.
\end{aligned}
$$

$\theta = (19 \pm 5)^\circ$

J. A. Oller, "The Mixing angle of the lightest scalar nonet," Nucl. Phys. A 727, 353-369 (2003).

$f_0(500) \approx$ singlet;

$f_0(980) \approx$ octet

$(19 \pm 5)^\circ$	$(39\pm6)^\circ$	$(17 \pm 3)^\circ$	$(1^{+15}_{-9})^\circ$	$(12\pm4)^\circ$	$(32\pm3)^\circ$
[1]	[2]	[3]	[4]	[5]	[6]

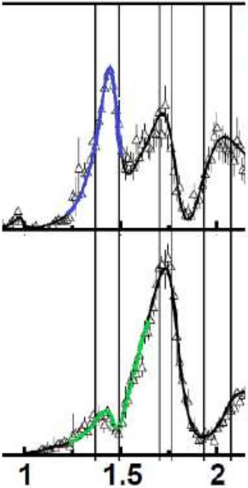
$\approx 10^\circ$	$(3\pm8)^\circ$	$(12 \pm 3)^\circ$	$(0 \pm 5)^\circ$	$(8 \pm 2)^\circ$
[7]	[8]	$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to \pi^0\pi^+\pi^-$	$J/\psi \to \gamma\pi\pi$

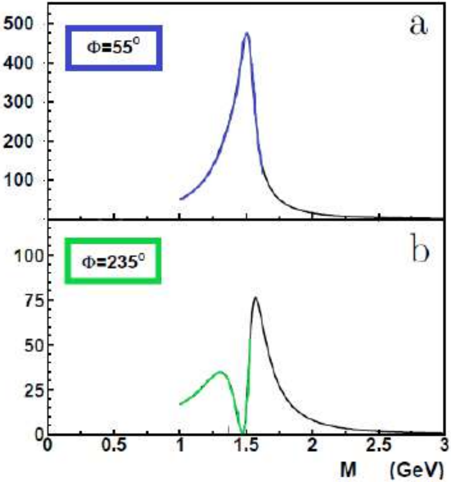
$\theta = (14 \pm 4)^\circ$

E. K., "Scalar mesons and the fragmented glueball", in preparation.

[1] J. A. Oller, Nucl. Phys. A 727, 353 (2003). [2] A. V. Anisovich *et al.*, Eur. Phys. J. A 12, 103 (2001). [3] W. Ochs, J. Phys. G 40, 043001 (2013). [4] J. W. Li *et al.*, Eur. Phys. J. C 72, 2229 (2012). [5] R. Aaij *et al.* [LHCb], Phys. Rev. D 92, 032002 (2015). [6] R. Aaij *et al.* [LHCb], Phys. Rev. D 89, 092006 (2014). [7] X. Liu, Z. T. Zou, Y. Li and Z. J. Xiao, Phys. Rev. D 100, 013006 (2019). [8] N. R. Son *et al.*, Phys. Rev. D 102, 016013 (2020).

4.2 The $f_0(1370) - f_0(1500)$ mixing angle

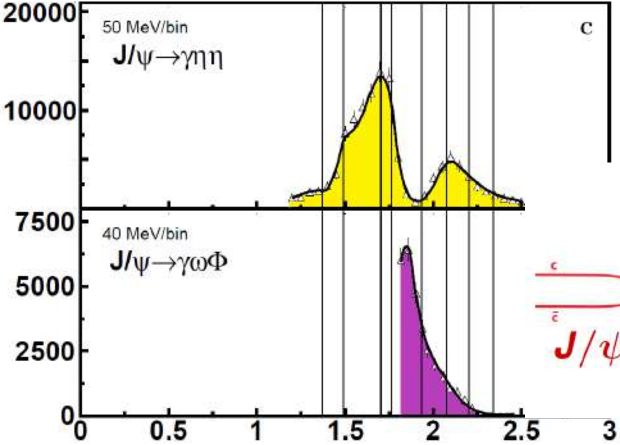




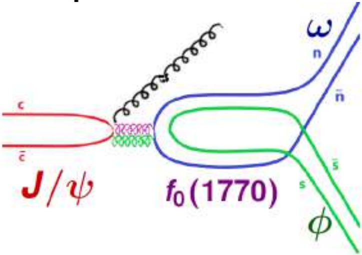
Phase difference between $\pi\pi$ and $K\bar{K}$ decay mode is 180°: $n\bar{n} + s\bar{s}$ and $n\bar{n} + s\bar{s}$!

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

4.3 The $f_0(1770)$ wave function



$$c\bar{c} \rightarrow \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) + s\bar{s}$$

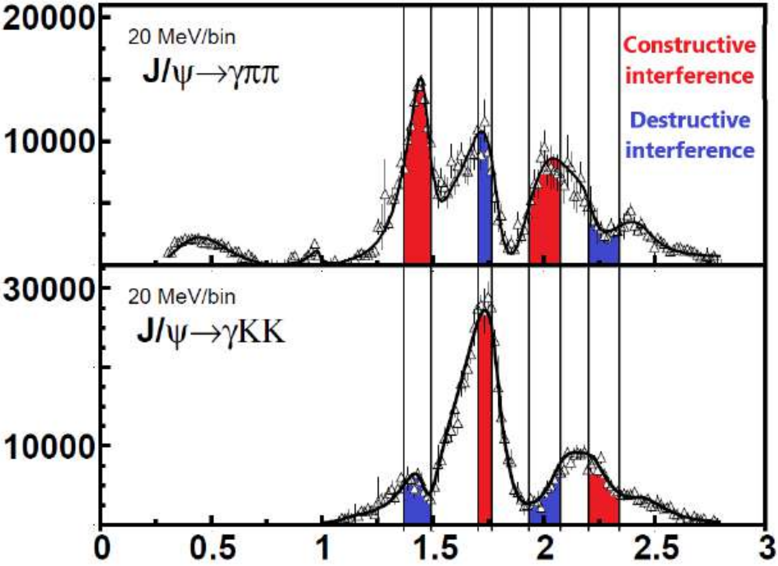


Doubly OZI rule violating and strong yield !

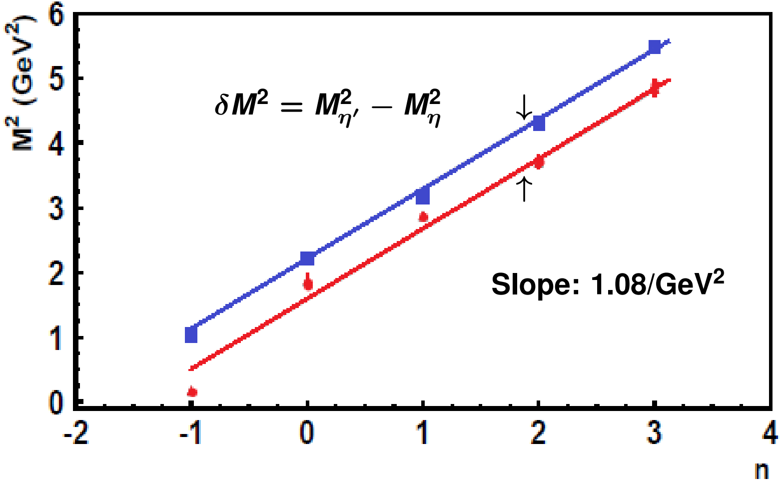
$f_0(1770) \rightarrow \omega\phi$ decay mode proceeds via the $f_0(1770)$ SU(3) octet component

Tetraquark component in the $f_0(1770)$ wave function !

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

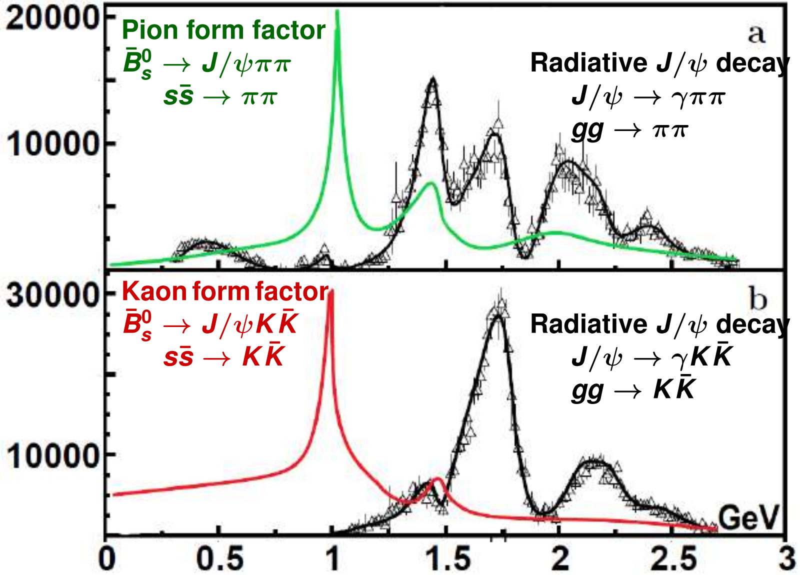


4.5 (M^2, n) trajectories of scalar mesons



$\cdots$ and where is the scalar glueball ?

4.6 Evidence for strong glue-glue interactions

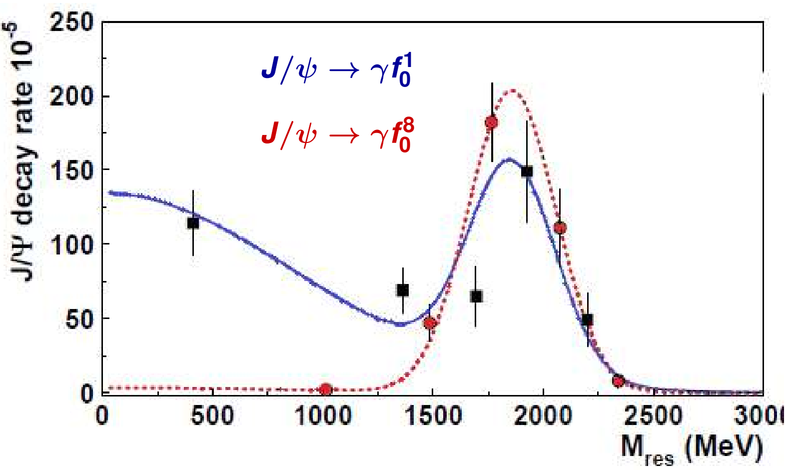


S. Ropertz, C. Hanhart and B. Kubis, "A new parametrization for the scalar pion form factors," Eur. Phys. J. C 78, no.12, 1000 (2018)

4.7 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						



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

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

4.8 The wave function of scalar mesons

$$
\begin{aligned}
f_0(1500) &= \alpha \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \\
&+ \beta \frac{1}{\sqrt{6}}(u\bar{u}s\bar{s} + d\bar{d}s\bar{s} - 2u\bar{u}d\bar{d}) \\
&+ \gamma \cdot (\text{meson} - \text{meson cloud}) \\
&+ \delta(gg) \\
&+ \epsilon(q\bar{q}g) \\
&+ \cdots \qquad \text{and some singlet contribution} \\
&+ \{\alpha' \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) + \beta' \frac{1}{\sqrt{3}}(u\bar{u}s\bar{s} + d\bar{d}s\bar{s} + u\bar{u}d\bar{d})\}
\end{aligned}
$$

The five Fock states are not realized independently as five mesons !

They are components of the mesonic wave functions.

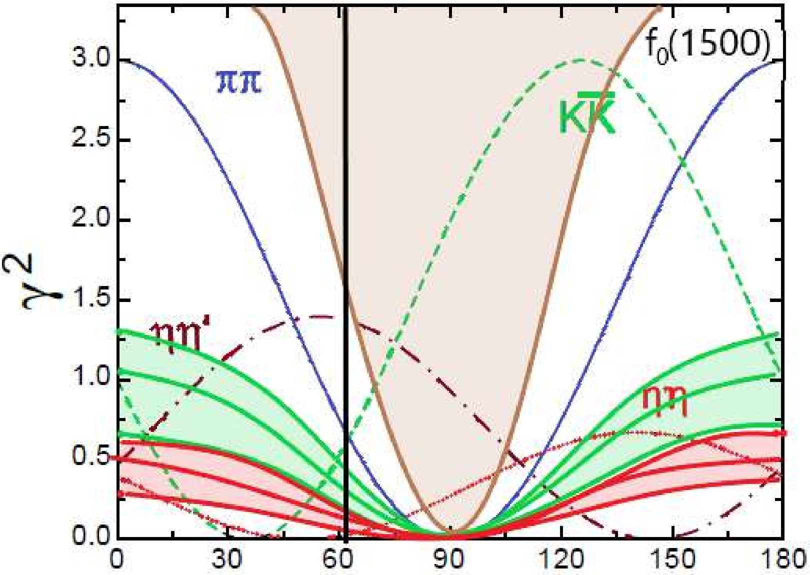
There is no scalar glueball that intrudes the spectrum of scalar mesons

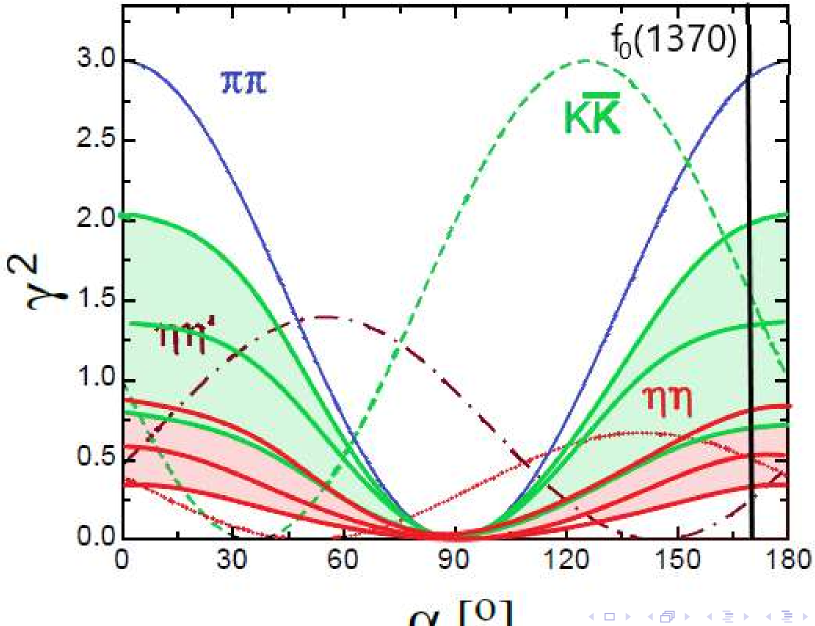
5. Summary

- The BESIII collaboration reported data on radiative J/ψ decays with unprecedented statistics
- The data reveal high intensities in the yield of scalar mesons
- The data can be fit with ten scalar isoscalar resonances.
- The scalar resonances can be grouped into a class of mainly-singlet and mainly-octet states
- The two groups fall onto linear (n, M^2)-trajectories
- Octet scalar isoscalar resonances are produced mainly in the 1700 - 2100 MeV mass range
- Singlet scalar resonances are produced over the full mass range. Their intenisty peaks in the 1700 - 2100 MeV mass range
- The enhanced production of scalar mesons in the 1700 - 2100 MeV mass range is due to gluon-gluon in the initial state
- The peak is the scalar glueball of lowest mass.

Thank you for your patience!

The scalar mixing angle





f0(1370)
ππ
KK̄
ηη'
ηη
γ2
α [o]
0
30
60
90
120
150
180
0.0
0.5
1.0
1.5
2.0
2.5
3.0