Glueballs in Radiative J/ψ Decays

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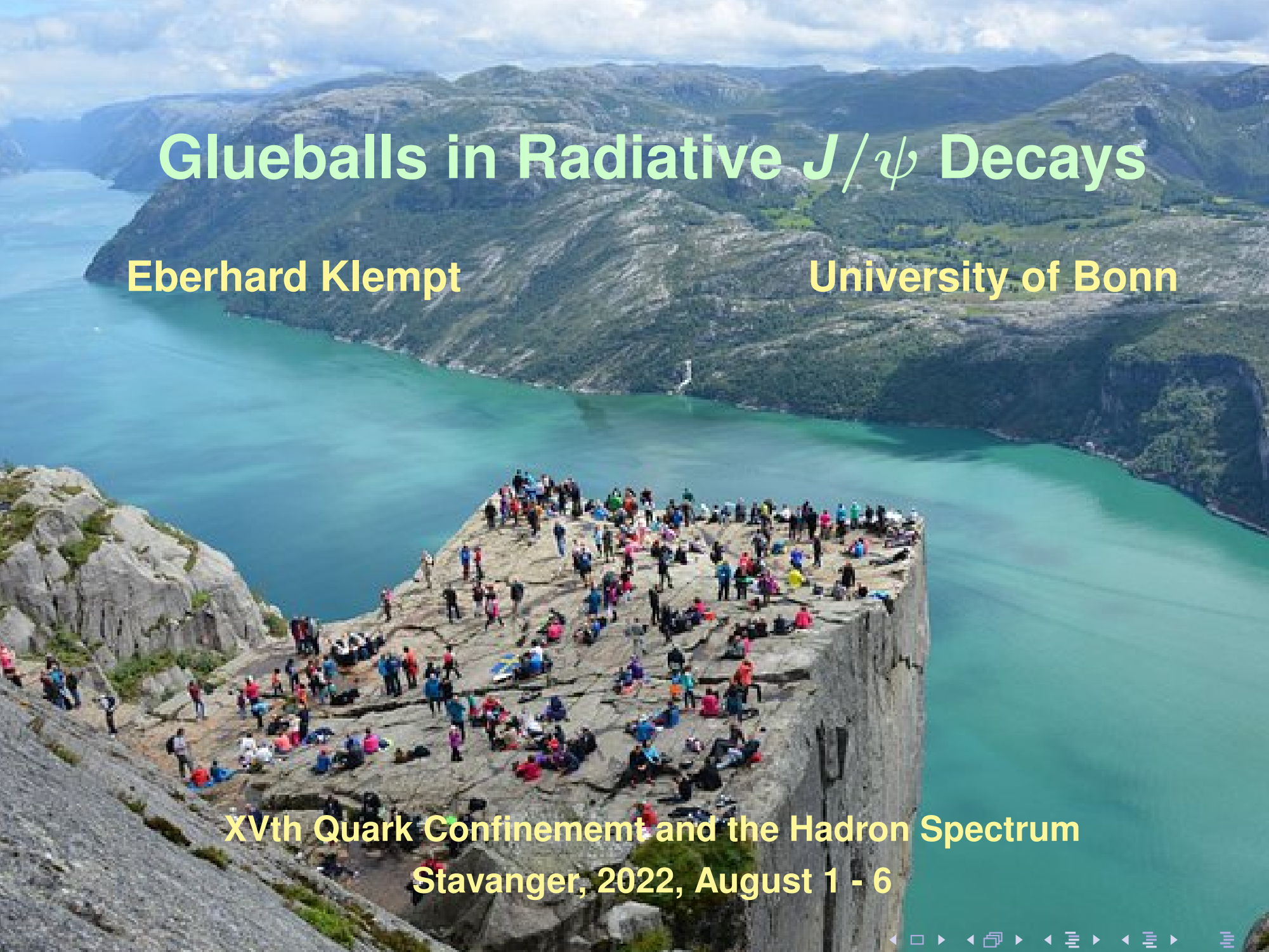


XVth Quark Confinememt and the Hadron Spectrum

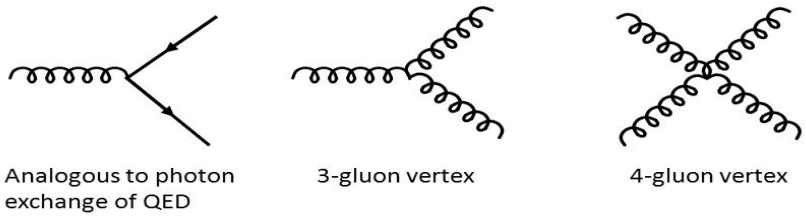
Stavanger, 2022, August 1 - 6

Content

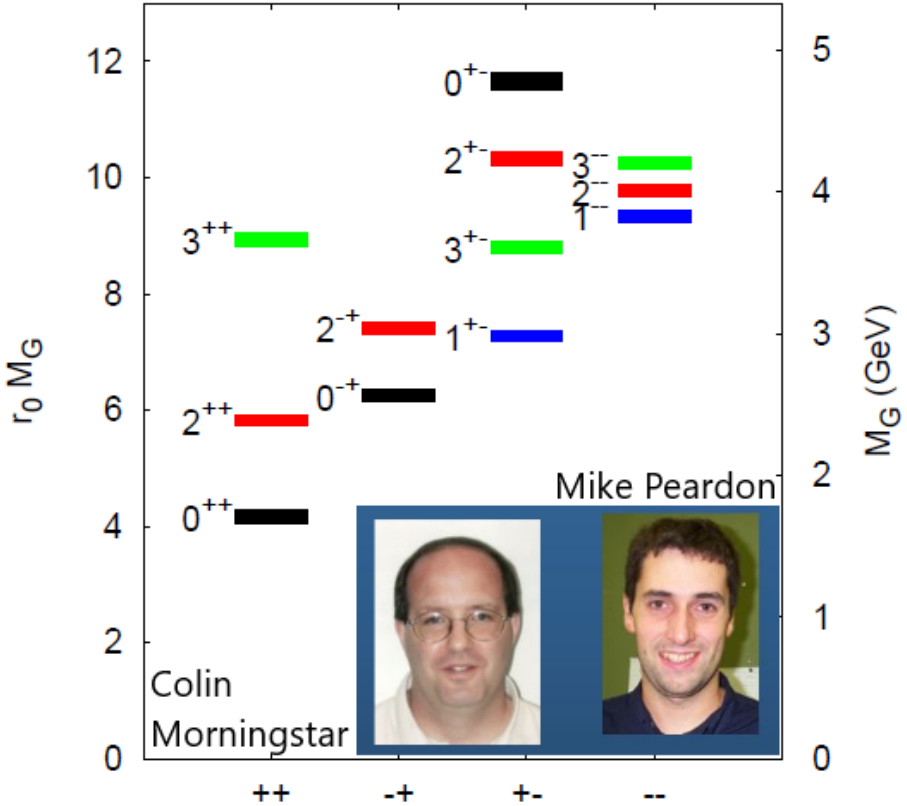
- Glueball expectations
- Observation of the scalar glueball
- Evidence for the tensor glueball
- How to search for the pseudoscalar glueball

1. Glueballs:

Masses



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

Glueballs: 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)].

Glueballs: Mixing

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

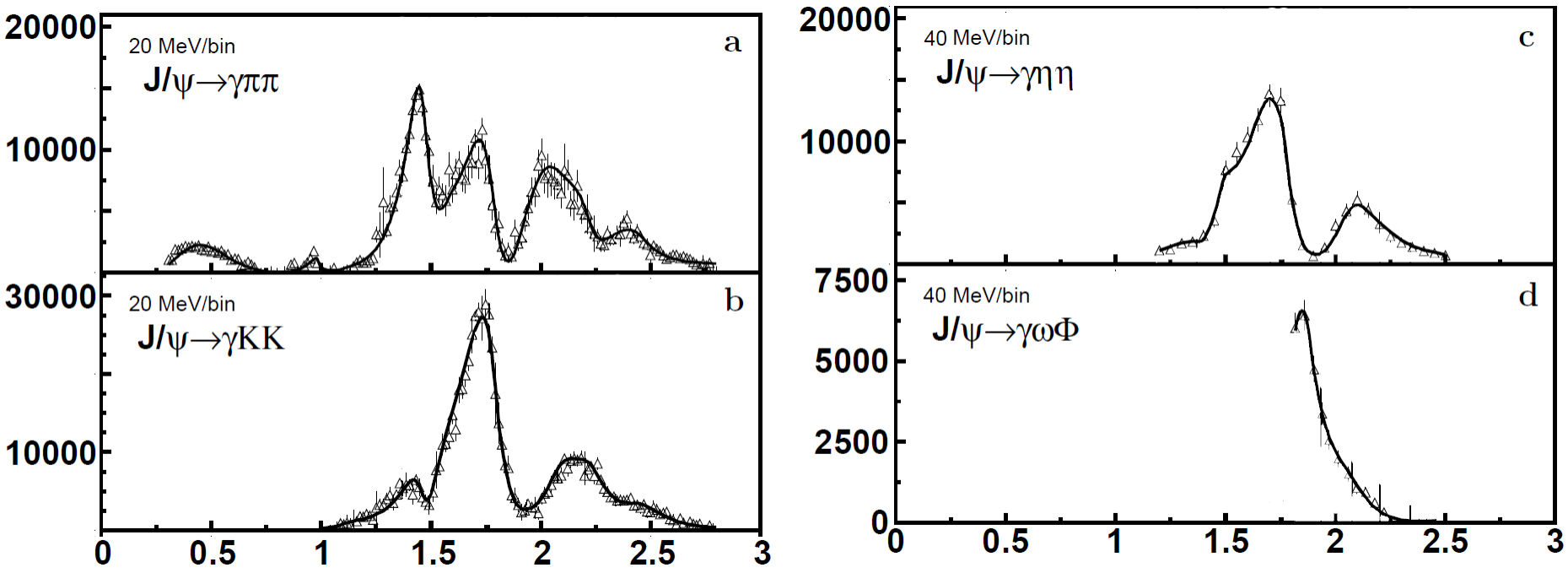
supernumerous!

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. Data and coupled channel analysis

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

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

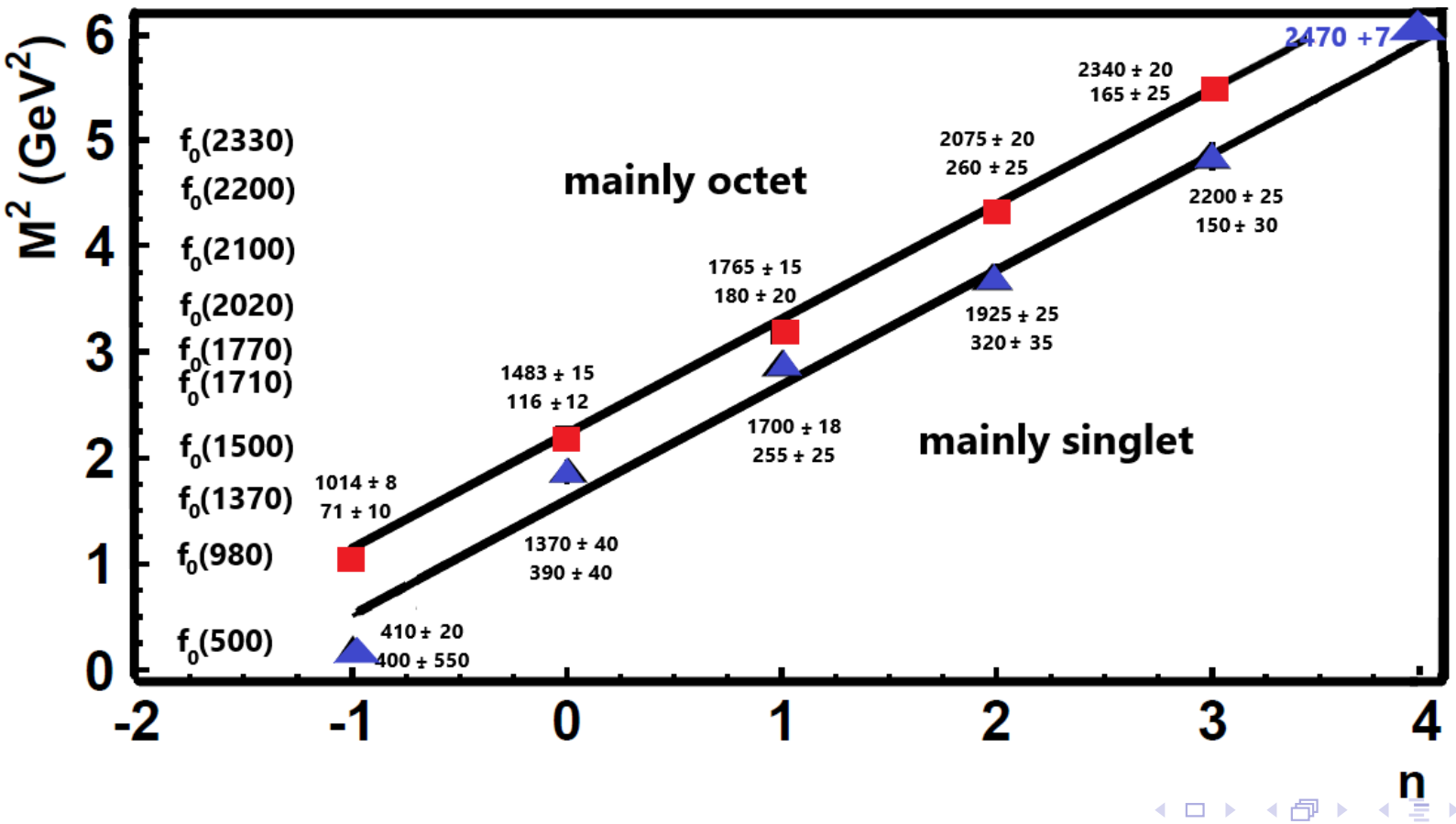


M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92 no.5, 052003 (2015).
M. Ablikim *et al.* [BESIII Collaboration], "Amplitude analysis of the K_SK_S system produced in radiative J/ψ decays," Phys. Rev. D 98 no.7,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

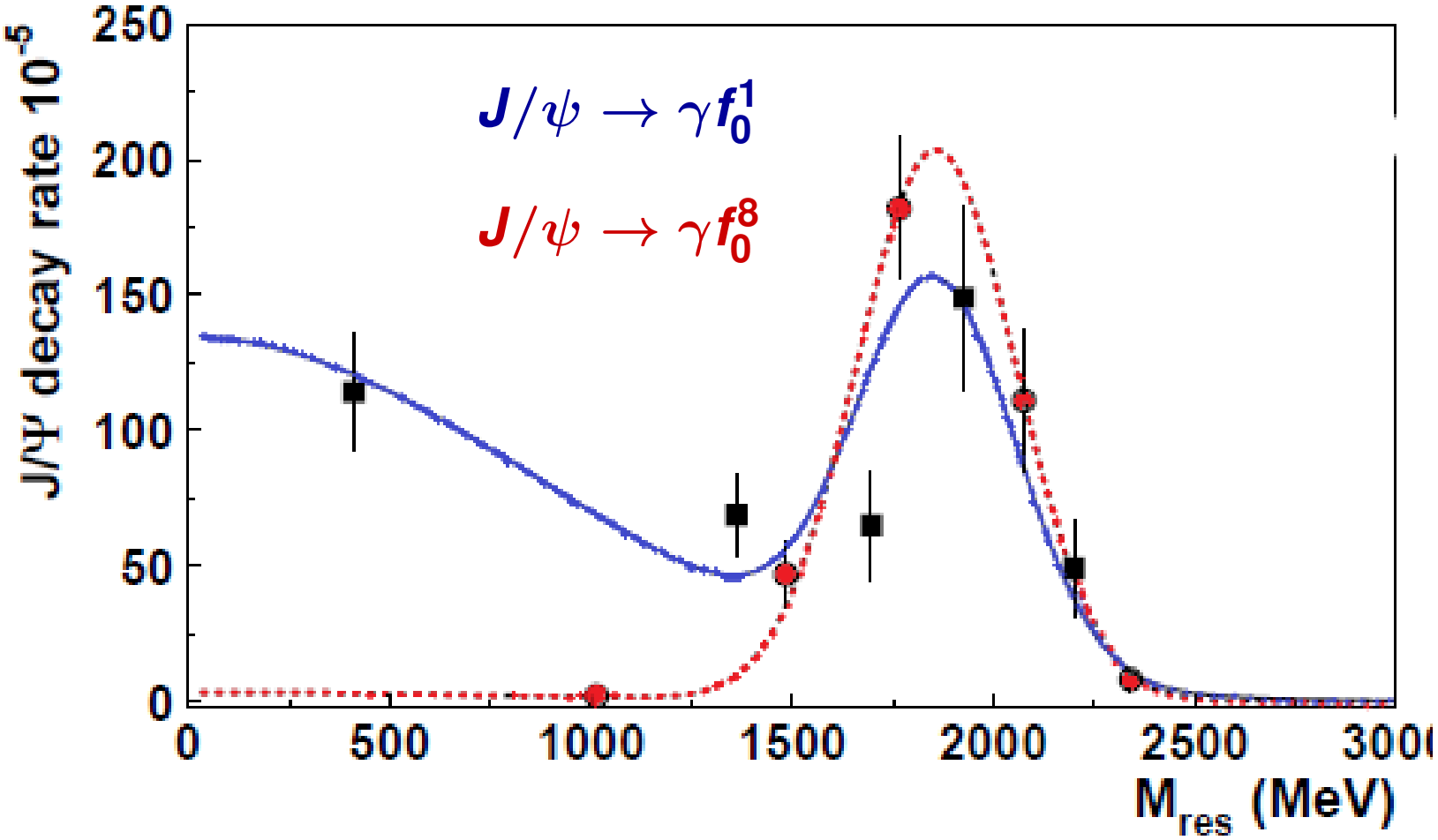
Further data used in the coupled-channel analysis:

1. 15 Dalitz plots from the Crystal Barrel experiment at LEAR/CERN
2. CERN-Munich data on $\pi\pi$ phase shifts
3. GAMS data on $\pi^- p \to \pi^0\pi^0 n$
4. BNL data on $\pi^- p \to K^0\bar{K}^0 n$
5. Low-mass $\pi\pi$ interactions from $K^\pm \to \pi\pi e^\pm \nu$ decay (NA48/2)

M. Ablikim *et al.*, "Partial wave analysis of $J/\psi \to \gamma\eta'\eta'$," PR D 105, 072002 (2022). $f_0(2470) \to \eta'\eta'$



3. The scalar glueball in production

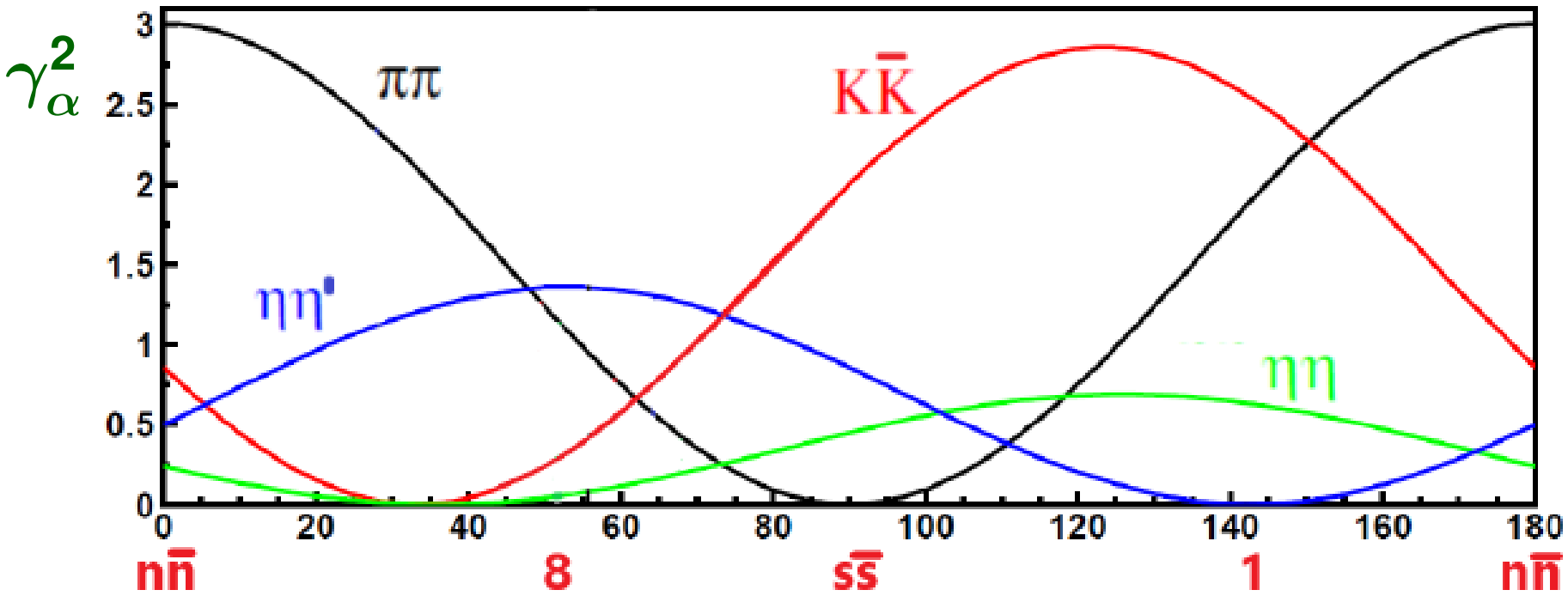


$$M_{glueball} = (1865 \pm 25)\,\mathrm{MeV},\ \Gamma_{glueball} = (370 \pm 50^{+30}_{-20})\,\mathrm{MeV}$$

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

4. The decays of the scalar glueball

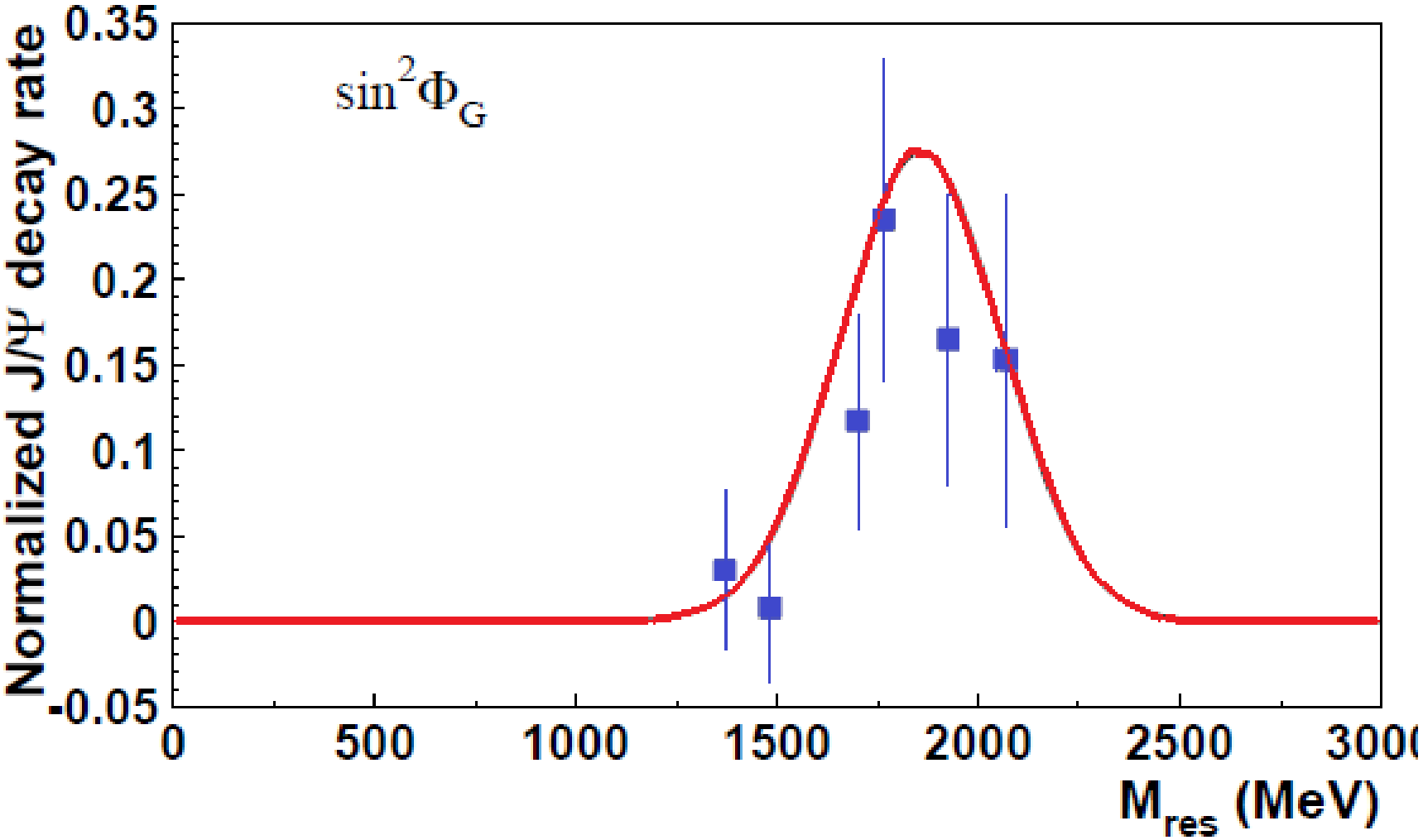
0



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

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

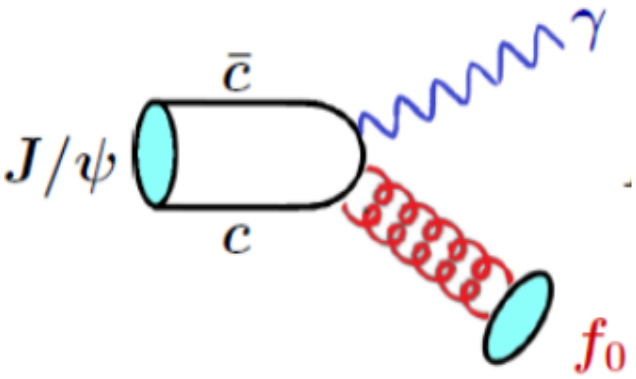
$$g_\alpha = c_{\mathrm{n}}\gamma_\alpha^q + c_G\gamma_\alpha^G$$



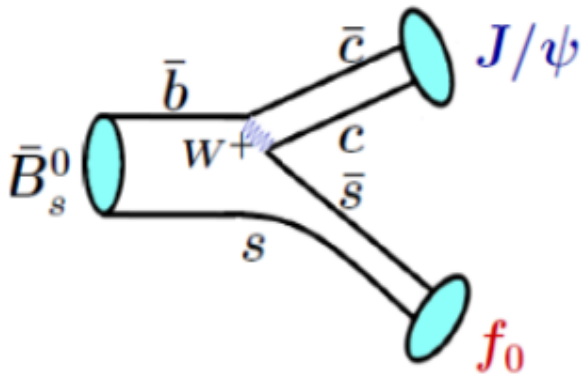
3	4	5	6	7	8
$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$f_0(1770)$	$f_0(2020)$	$f_0(2100)$
$(5\pm4)\%$	$< 5\%$	$(12\pm6)\%$	$(25\pm10)\%$	$(16\pm9)\%$	$(17\pm8)\%$

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

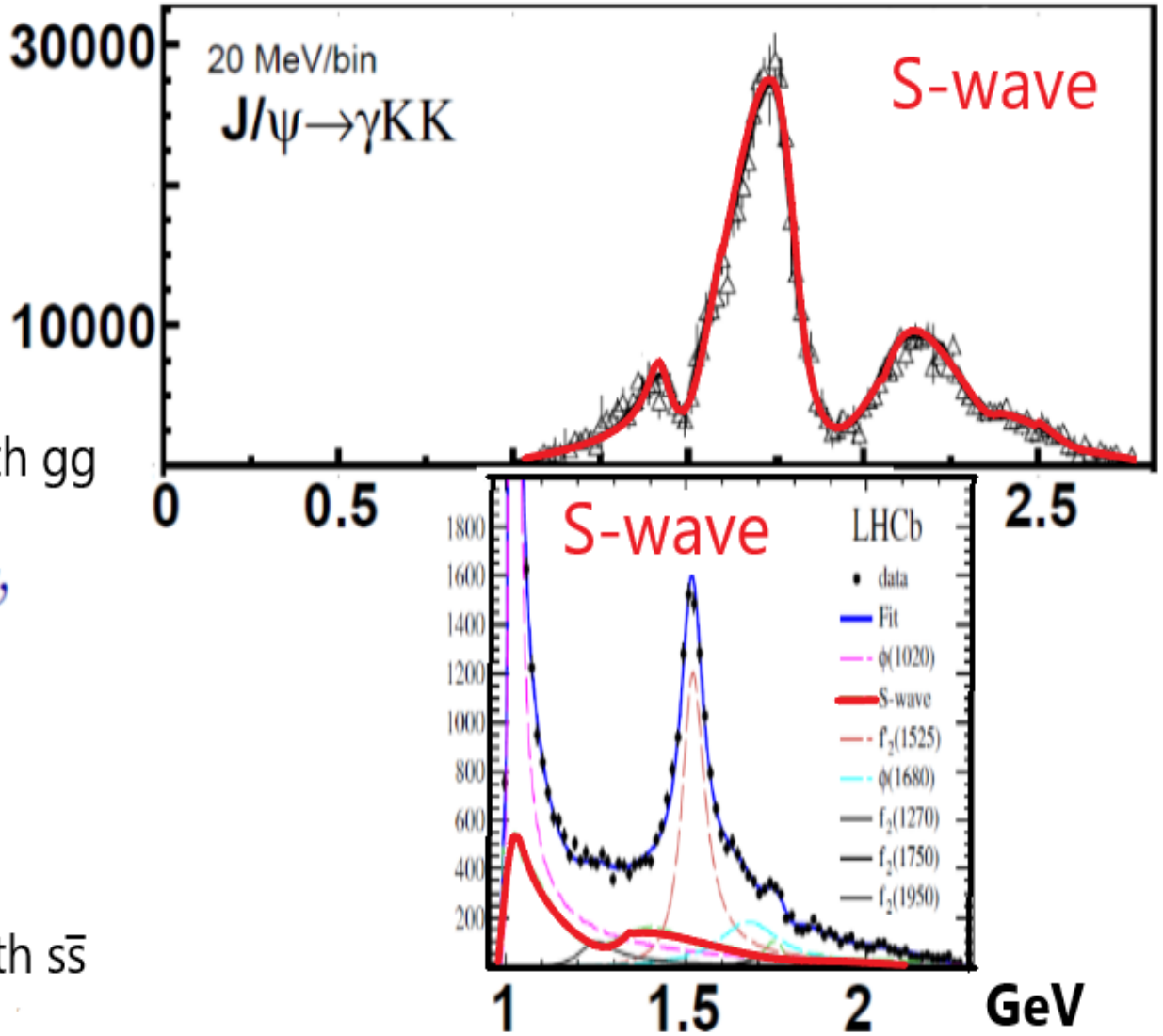
Compare:



Central overlap of f_0 wf with gg



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



5. Discussion

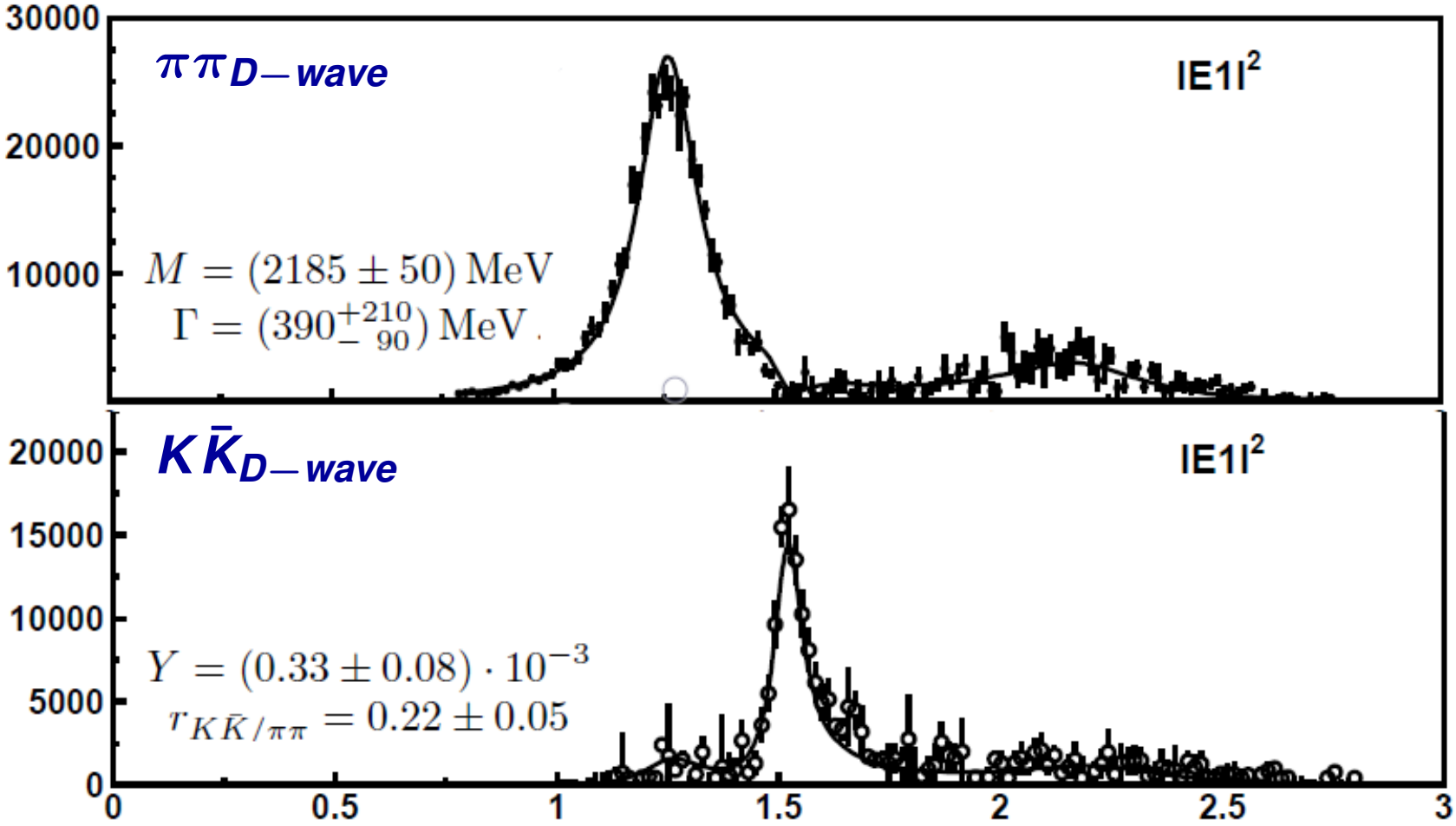
$G_0(1865)$ $\cdots$

1. Its mass is compatible with QCD expectations
2. It is abundantly produced in radiative J/ψ decays with two gluons in the initial state
3. The yield in radiative J/ψ decays is compatible with QCD expectation
4. It is not produced under similar kinematic conditions with $s\bar{s}$ in the intitial state
5. The decays of scalar mesons require a glueball contribution
6. The sum of fractional glueball contributions to scalar mesons is compatible with 1

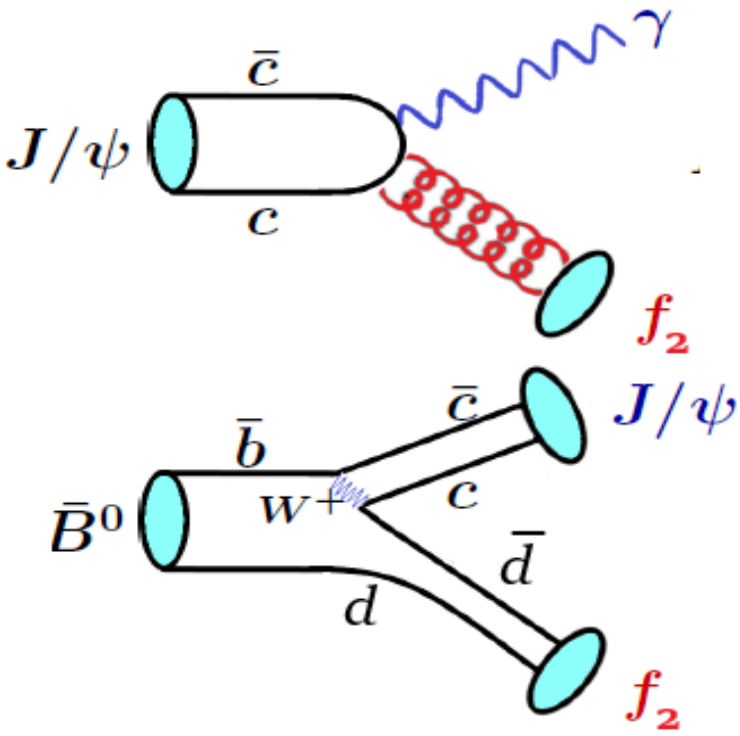
$\cdots$ is the scalar glueball of lowest mass

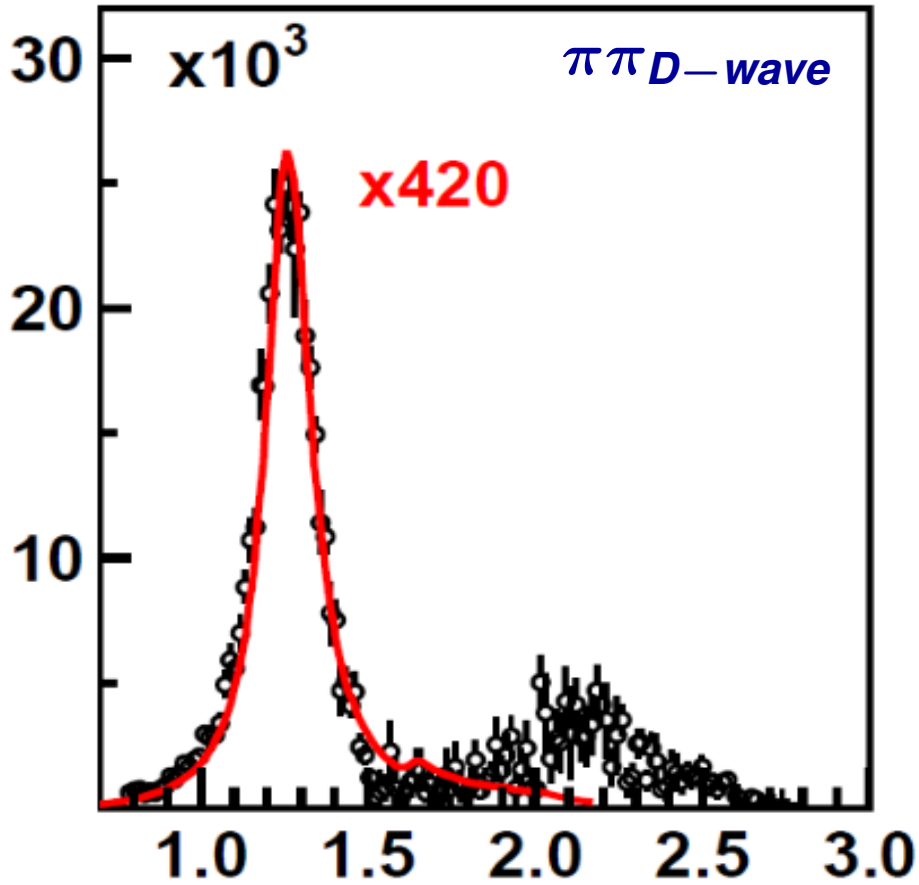
One caveat:	$G_0(1865)$ is not (yet proven to be) a resonance!

5. 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**





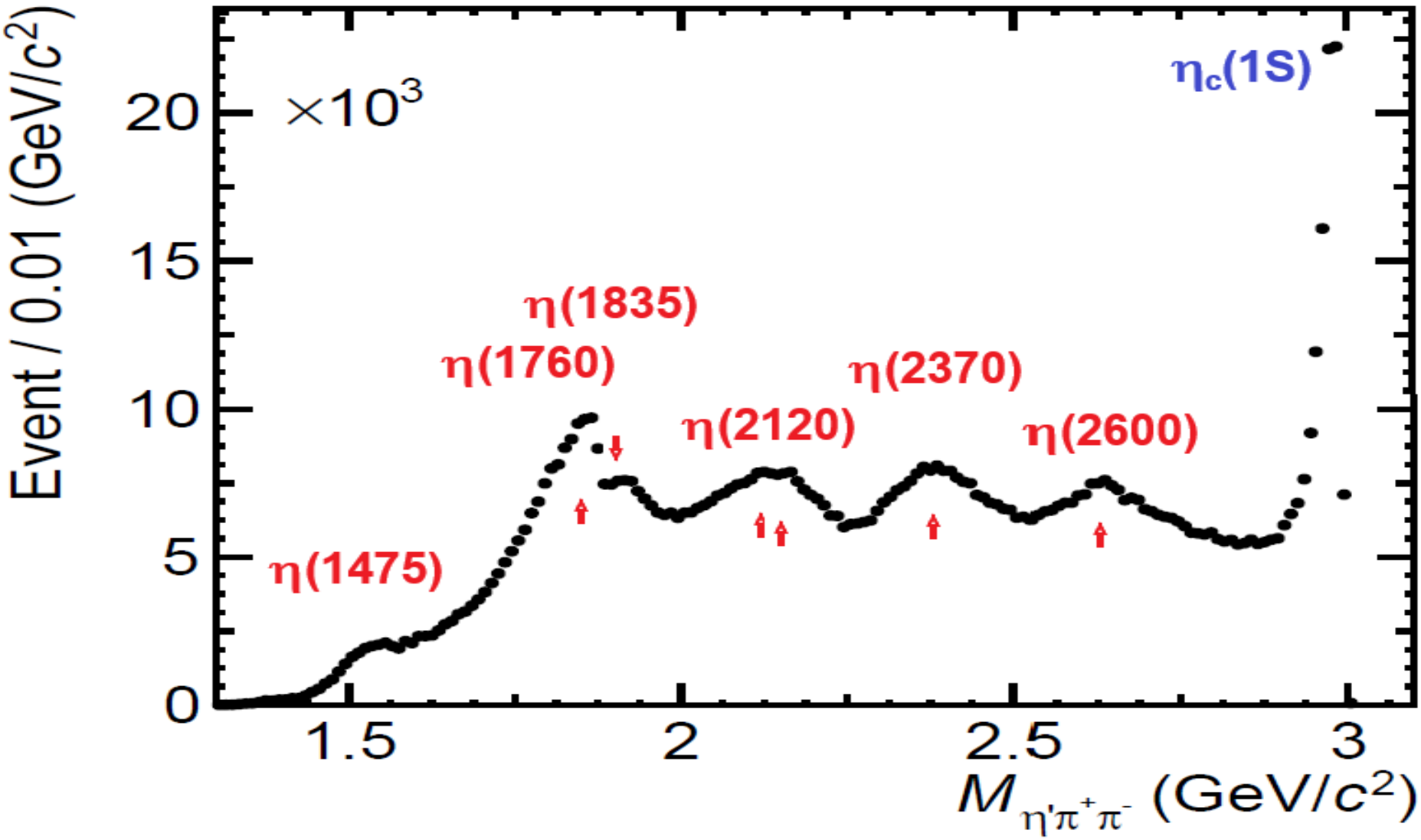
Again, high-mass tensor mesons are produced in radiative J/ψ decays in not in B decays. The yield is, however, much too low.

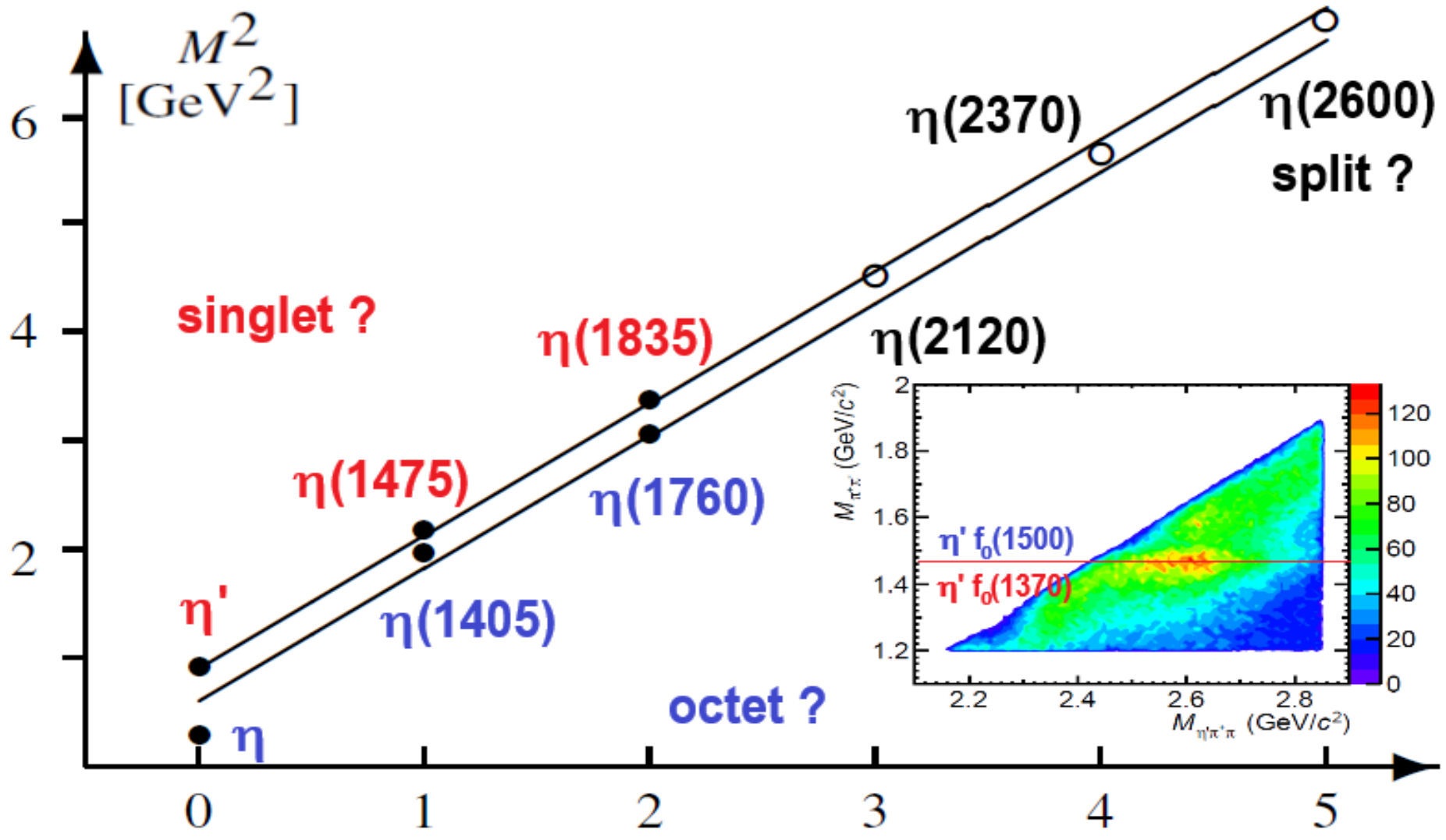
Add yield of all tensor mesons above 1.9 GeV:

$f_2(1910)$, $f_2(1950)$, $f_2(2010)$, $f_2(2300)$, $f_2(2340)$:

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

6. How to find the pseudoscalar glueball:



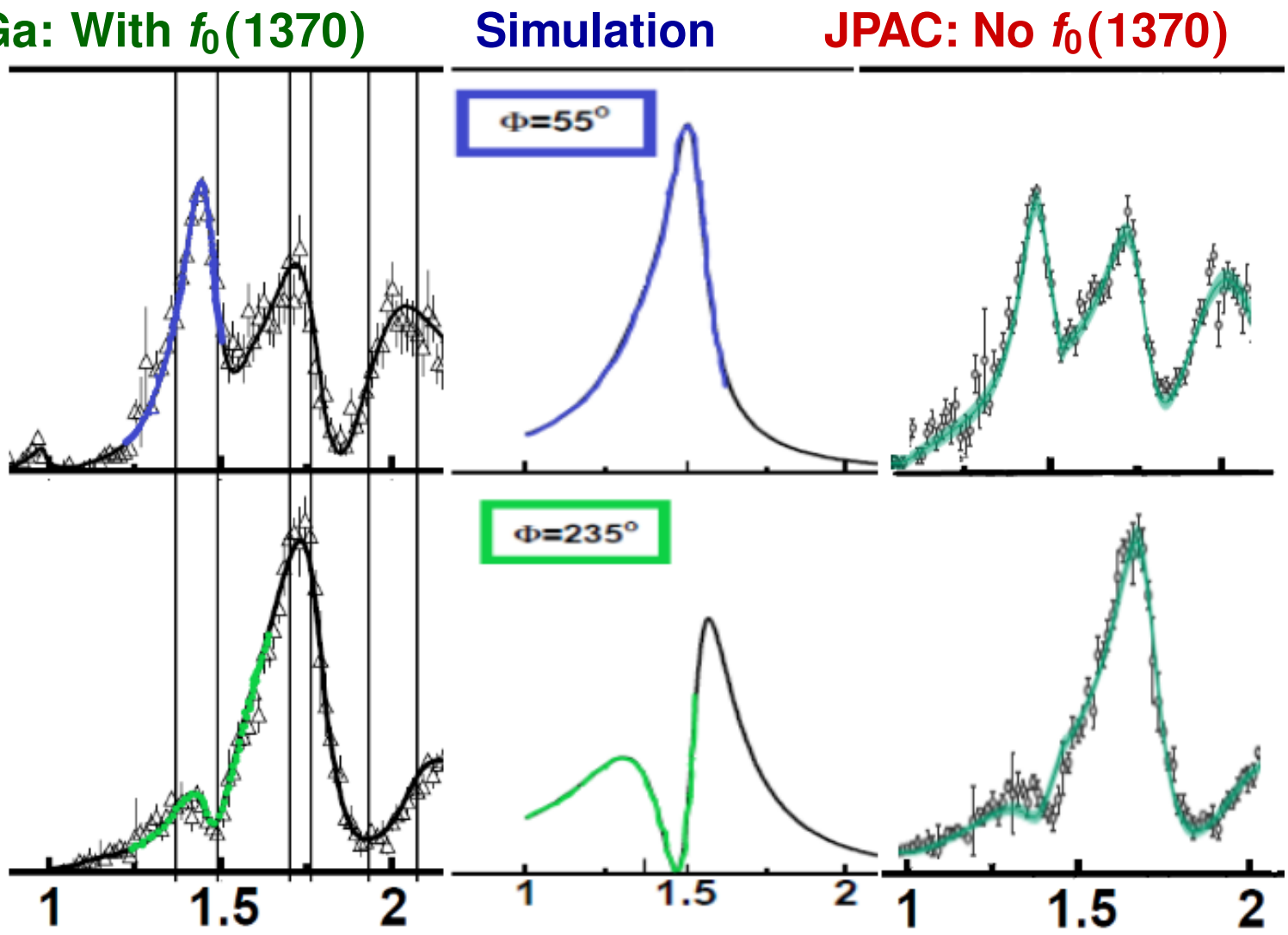

M^2 [GeV^2]
6
4
2
0
1
2
3
4
5
η(2370)
η(2600)
split ?
singlet ?
η(1835)
η(2120)
η(1475)
η(1760)
η'
η(1405)
octet ?
η
η' f0(1500)
η' f0(1370)
$M_{\pi\pi}$ (GeV/c^2)
$M_{\eta'\pi'\pi}$ (GeV/c^2)
2.2
2.4
2.6
2.8
1.2
1.4
1.6
1.8
2
120
100
80
60
40
20
0

7. 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.**

Thank you for your patience!

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 $s\bar{s}$!

The scalar glueball in production

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

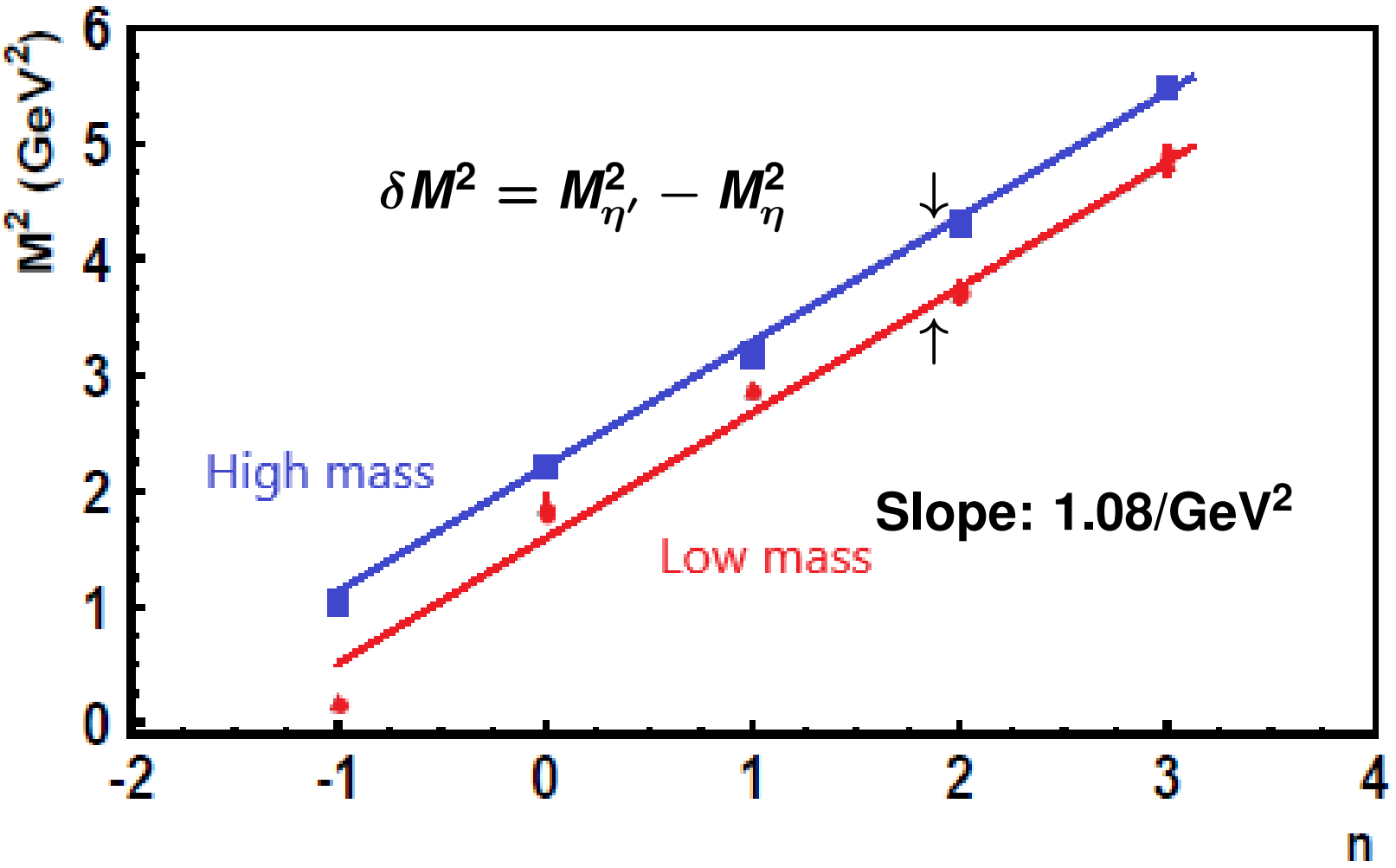
Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M	1014 ± 8 990 ± 20	1483 ± 15 1506 ± 6	1765 ± 15	2075 ± 20 2086^{+20}_{-24}	2340 ± 20 ~ 2330
Γ	71 ± 10 $10 \to 100$	116 ± 12 112 ± 9	180 ± 20	260 ± 25 284^{+60}_{-32}	165 ± 25 250 ± 20

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						

(M^2, n) trajectories of scalar mesons



$\cdots$ and where is the scalar glueball ?

Notes on the number of states

$N(1535)1/2^-$ or $N(1535)S_{11}$ can be interpreted in two ways $\cdots$

Quark models:

$N(1535)1/2^-$ is composed of three constituent quarks with an effective mass. One quark is orbitally excited with $L = 1$.

Effective field theories:

Meson-baryon $N\bar{K}$, $\Sigma\pi$, $N\eta$ coupled-channel dynamics generate $N(1535)1/2^-$ dynamically.

$\cdots$ but there is only one state!

$X(3872)$ can be interpreted in two ways $\cdots$

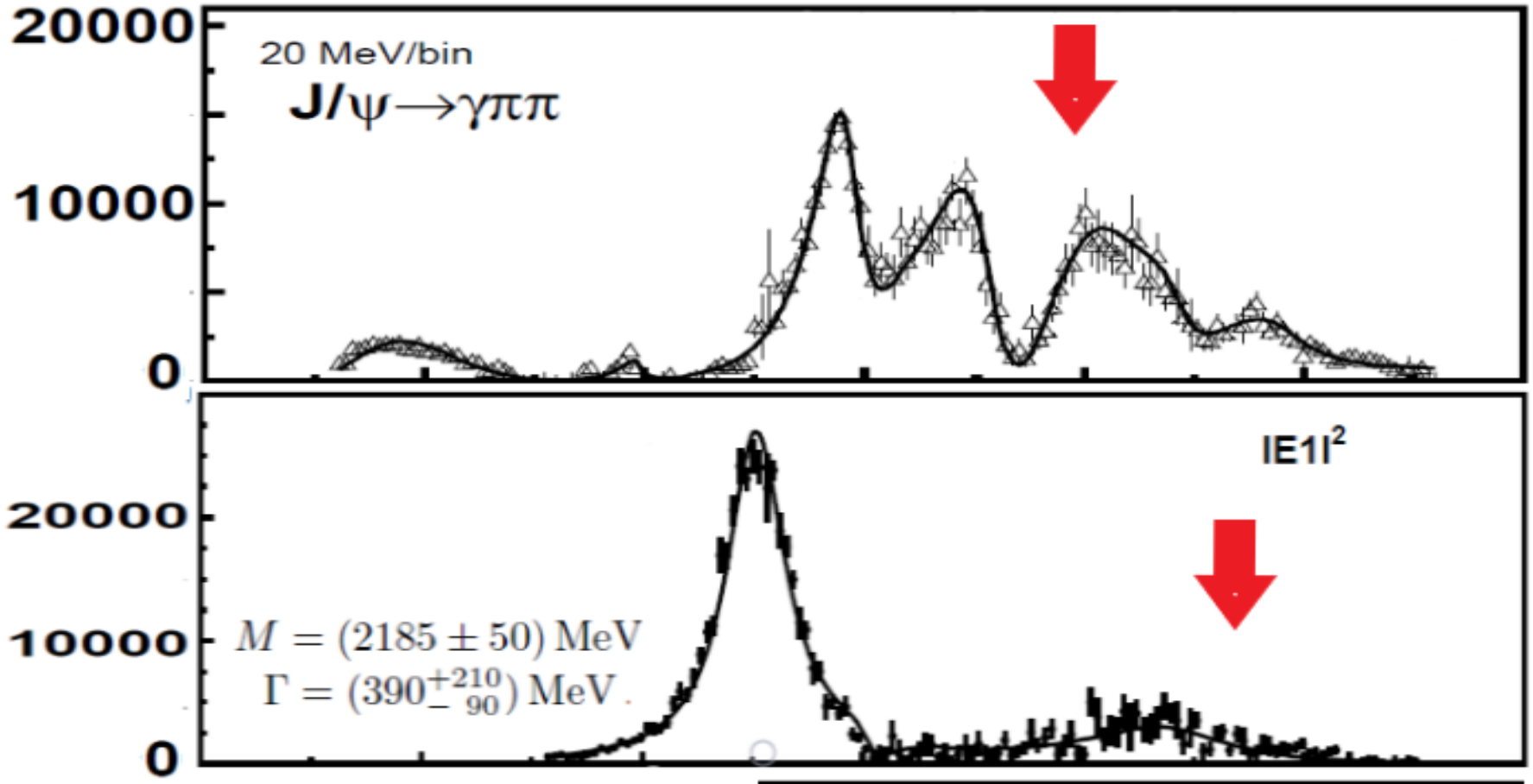
Quark models:

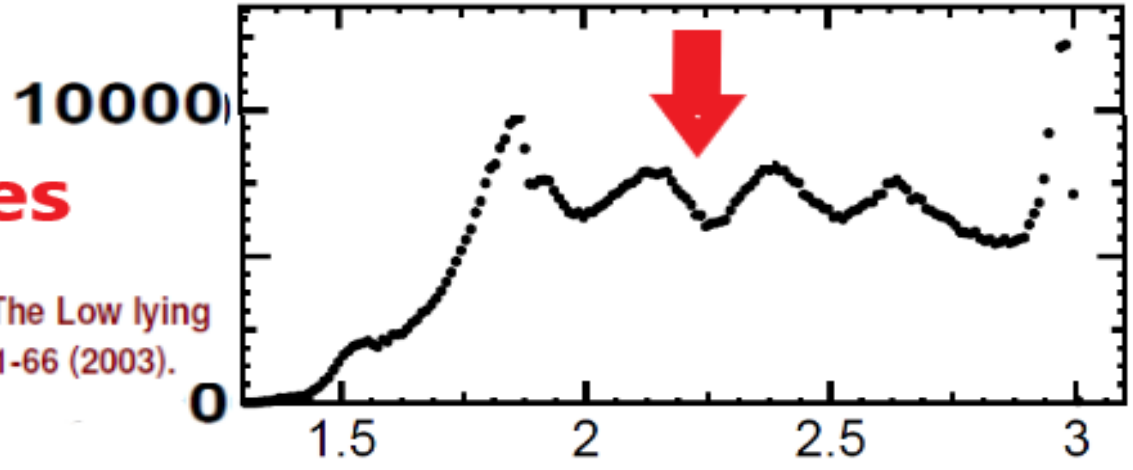
$X(3872)$ could be $\chi_{c1}(2P)$, the radial excitation of $\chi_{c1}(1P)$.

Effective field theories:

$X(3872)$ could be a $D^{0*}\bar{D}^0$ + c.c. molecule.

$\cdots$ are there one or two states?





Expected glueball masses

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

The wave function of scalar mesons

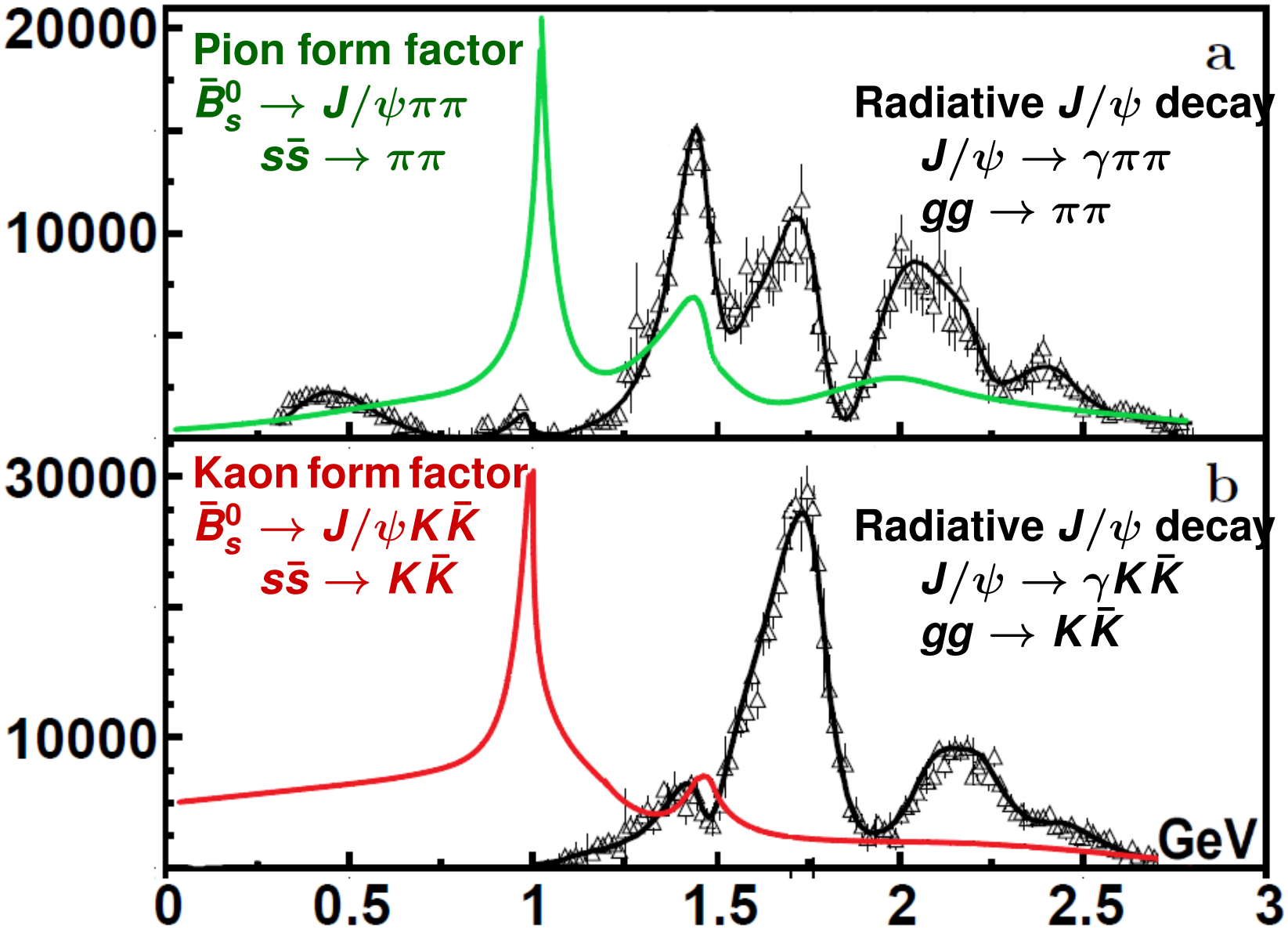
$$
\begin{aligned}
f_0(1500) &= \alpha\frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-2s\bar{s}) \\
&+ \beta\frac{1}{\sqrt{6}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s}-2u\bar{u}d\bar{d}) \\
&+ \gamma\cdot(\text{meson}-\text{meson cloud}) \\
&+ \delta(gg) \\
&+ \epsilon(q\bar{q}g) \\
&+ \cdots \qquad \text{and some singlet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

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

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)