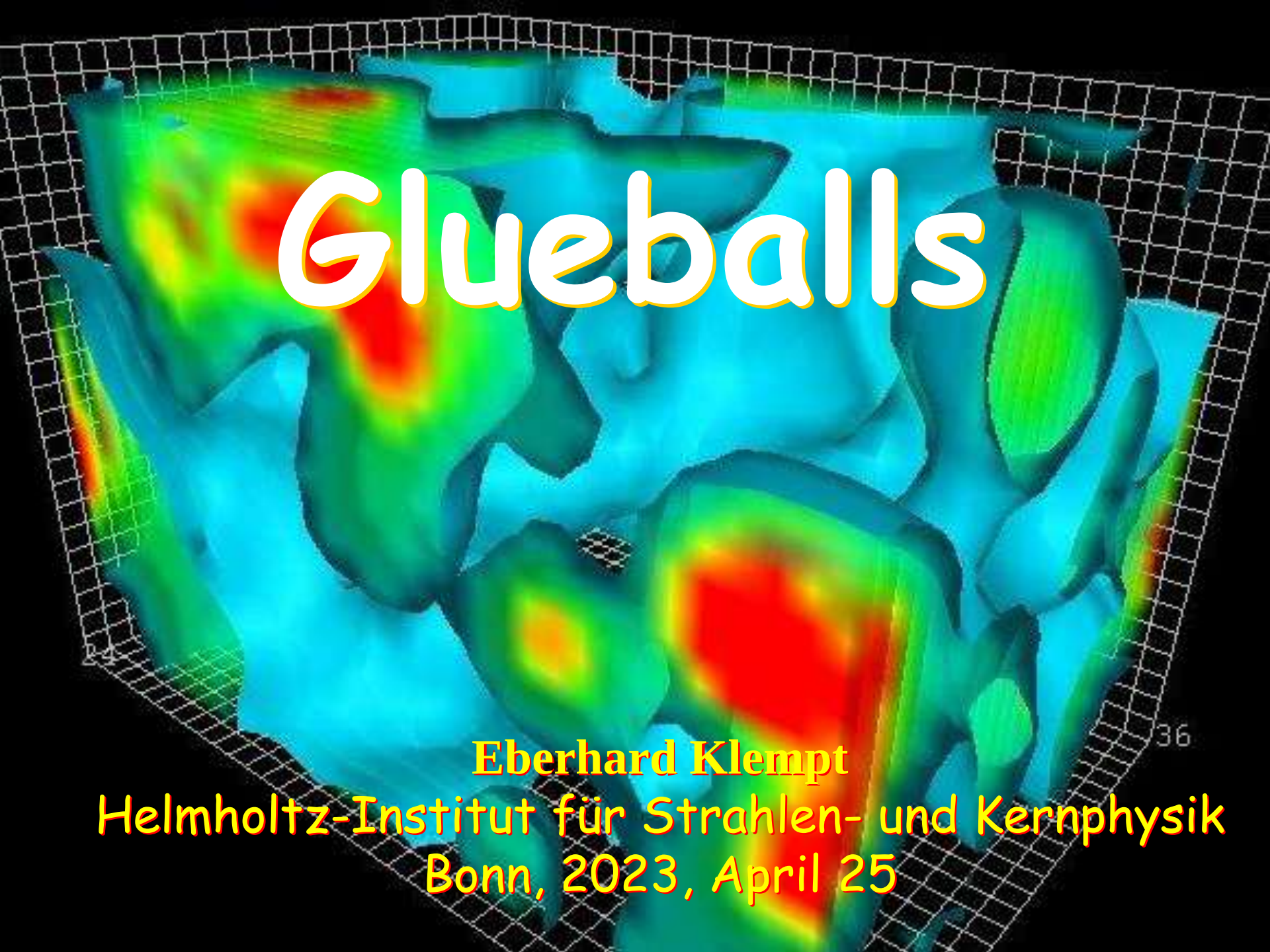


Glueballs

Eberhard Klempt
Helmholtz-Institut für Strahlen- und Kernphysik
Bonn, 2023, April 25

The Path to QCD and Glueballs

Properties of Glueballs

Mass, width, yield
How to search for glueballs
Radiative J/ψ decays (MARKIII, DM2)
NN annihilation (Crystal Barrel at LEAR)
Central production (WA102 experiment at the SPS)

New Data from BESIII

Partial waves from $J/\psi \rightarrow \gamma\pi^0\pi^0$ in slices of the $\pi^0\pi^0$ mass
The scalar waves from $J/\psi \rightarrow \gamma\pi^0\pi^0$ in slices of the $\pi^0\pi^0$ and $\bar{K}K$ mass
The tensor waves from $J/\psi \rightarrow \gamma\pi^0\pi^0$ in slices of the $\pi^0\pi^0$ and $\bar{K}K$ mass

Coupled Channel Analysis

Radiative J/ψ decays into $\pi^0\pi^0$, K_sK_s, $\eta\eta$, and $\omega\phi$
GAMS and BNL data
The CERN-Munich data on $\pi\pi \rightarrow \pi\pi$ elastic scattering
15 Dalitz plots from Crystal Barrel

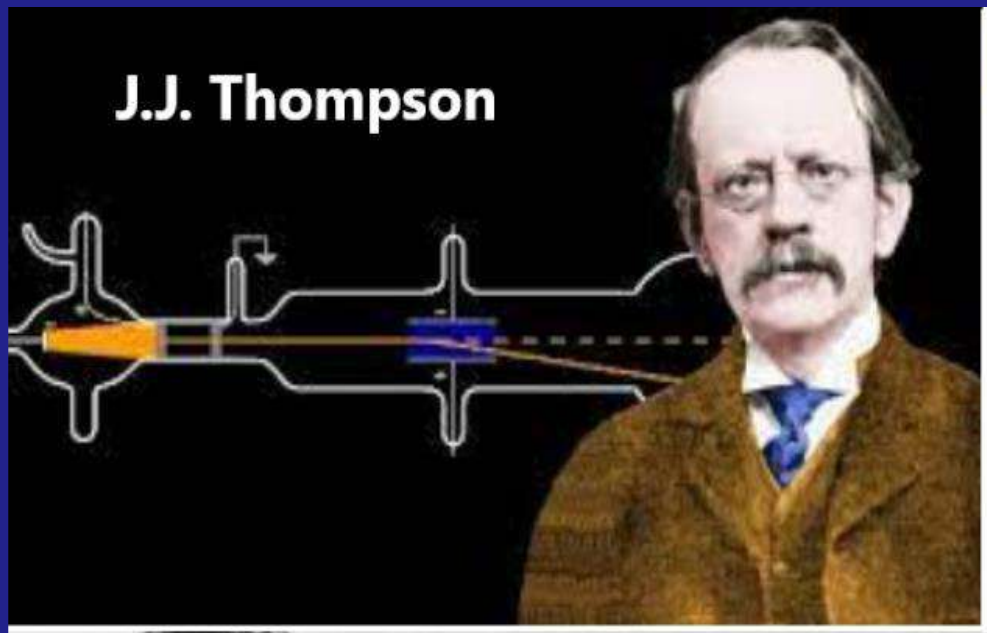
Results and Interpretation

Contributing resonances
The $f_0(1370)$ and $f_0(1500)$ mixing angle
The scalar glueball from production in radiative J/ψ decays
The scalar glueball from a decay analysis
Comparison with LHCb data

Summary

(The hidden tensor glueball)

The Path to QCD and Glueballs



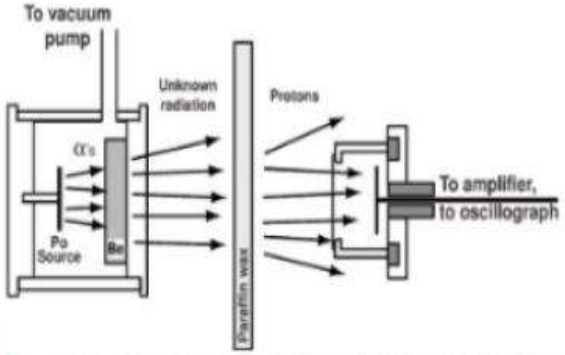
James Chadwick (1891-1974)

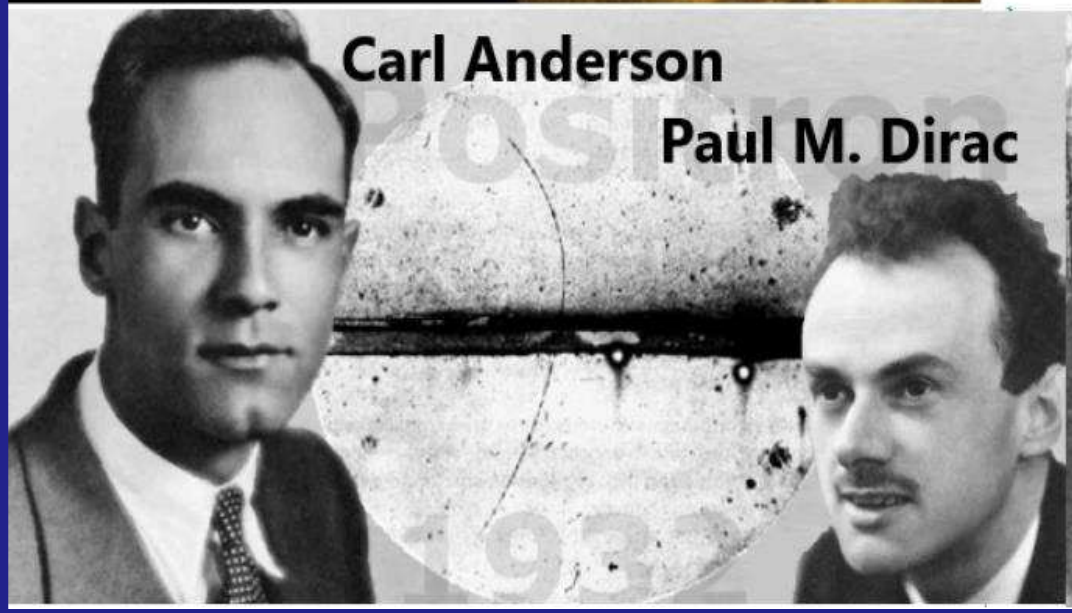
The Existence of a Neutron.

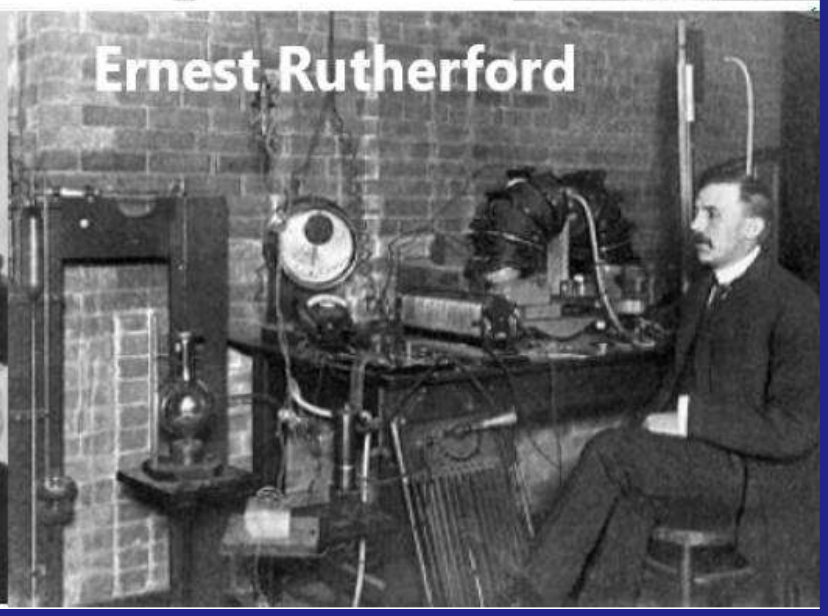
By J. Chadwick, F.R.S.

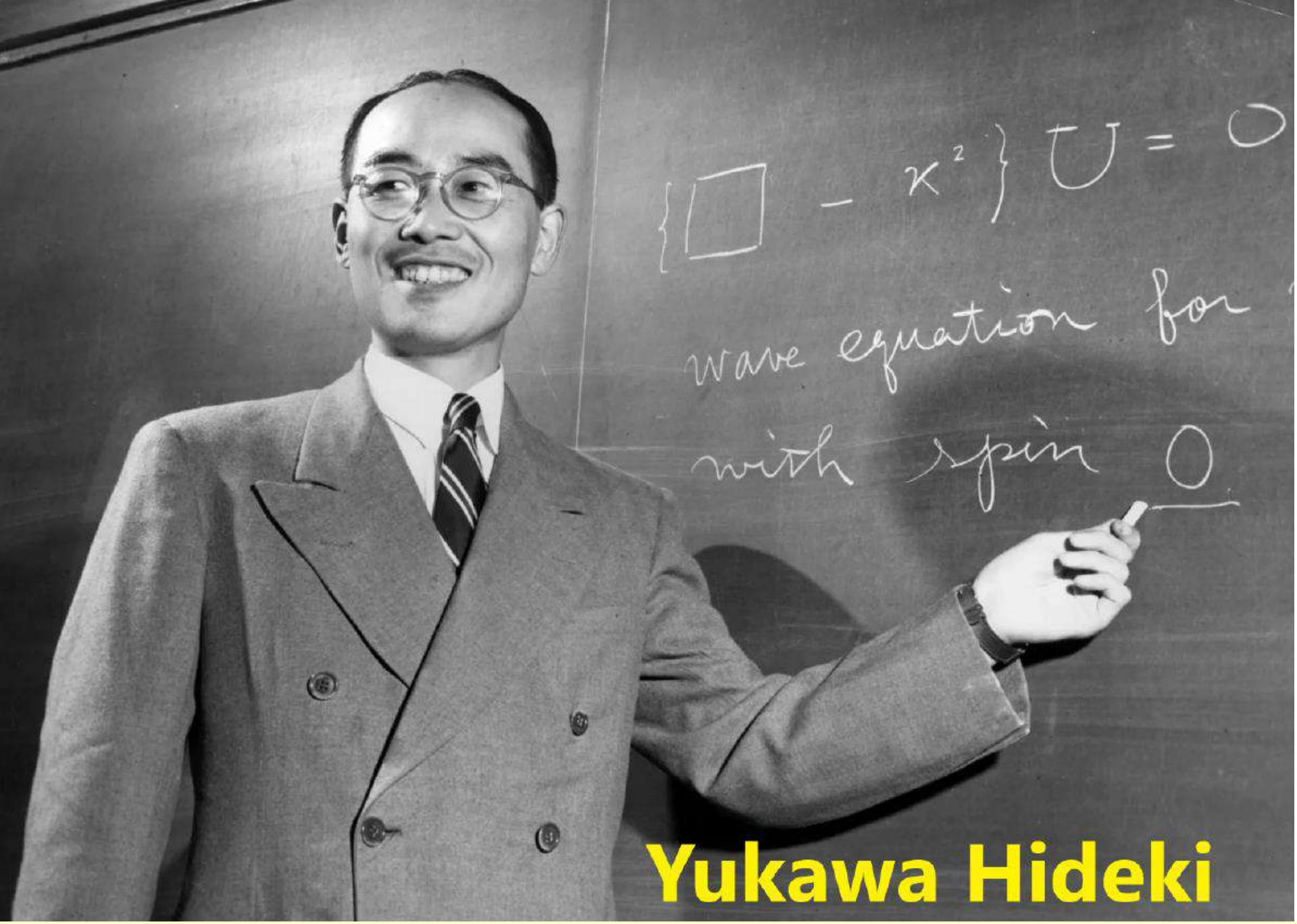
(Received May 10, 1932.)

$$^{9}\mathrm{Be} + ^{4}\mathrm{He} \rightarrow ^{12}\mathrm{C} + \mathrm{n}$$





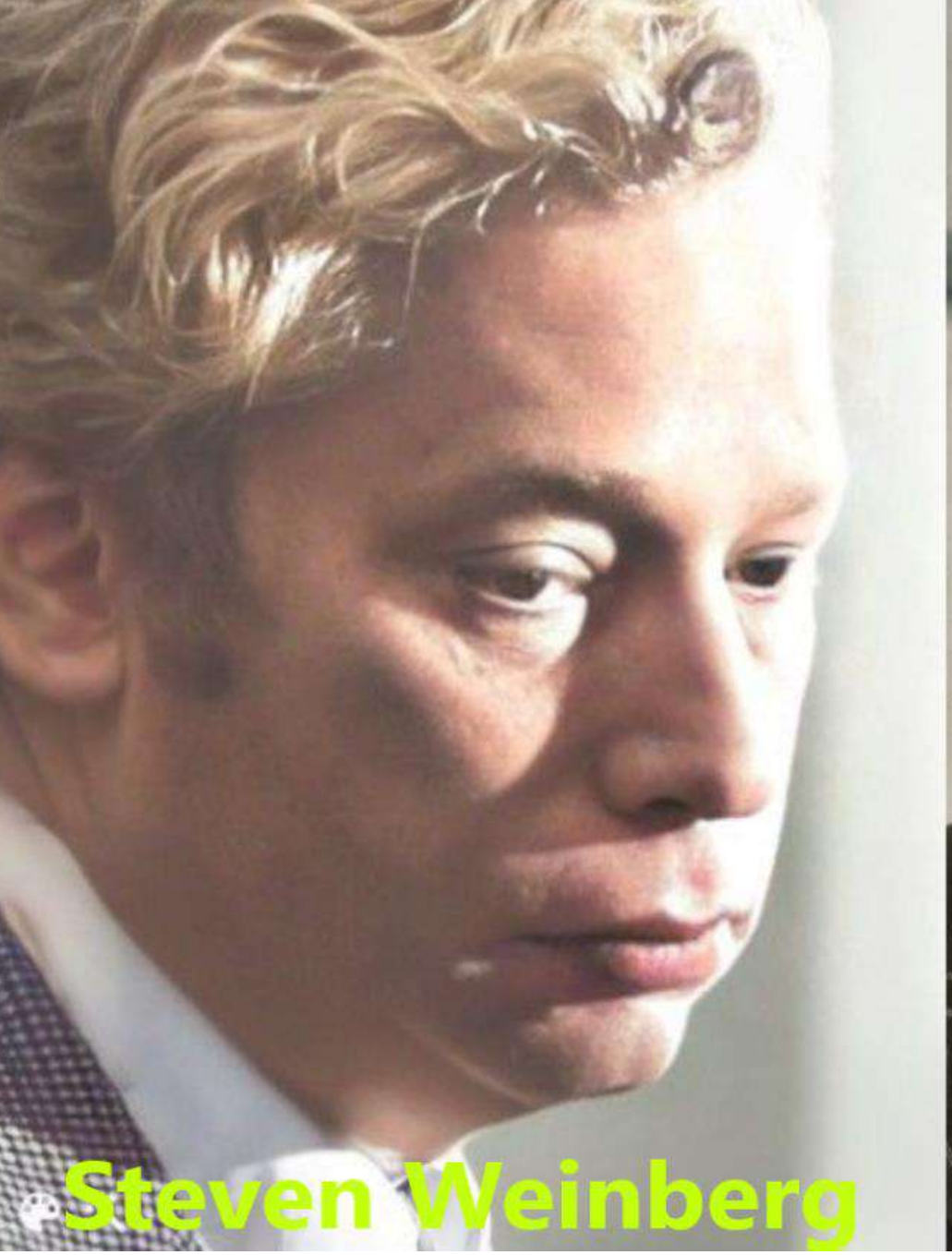


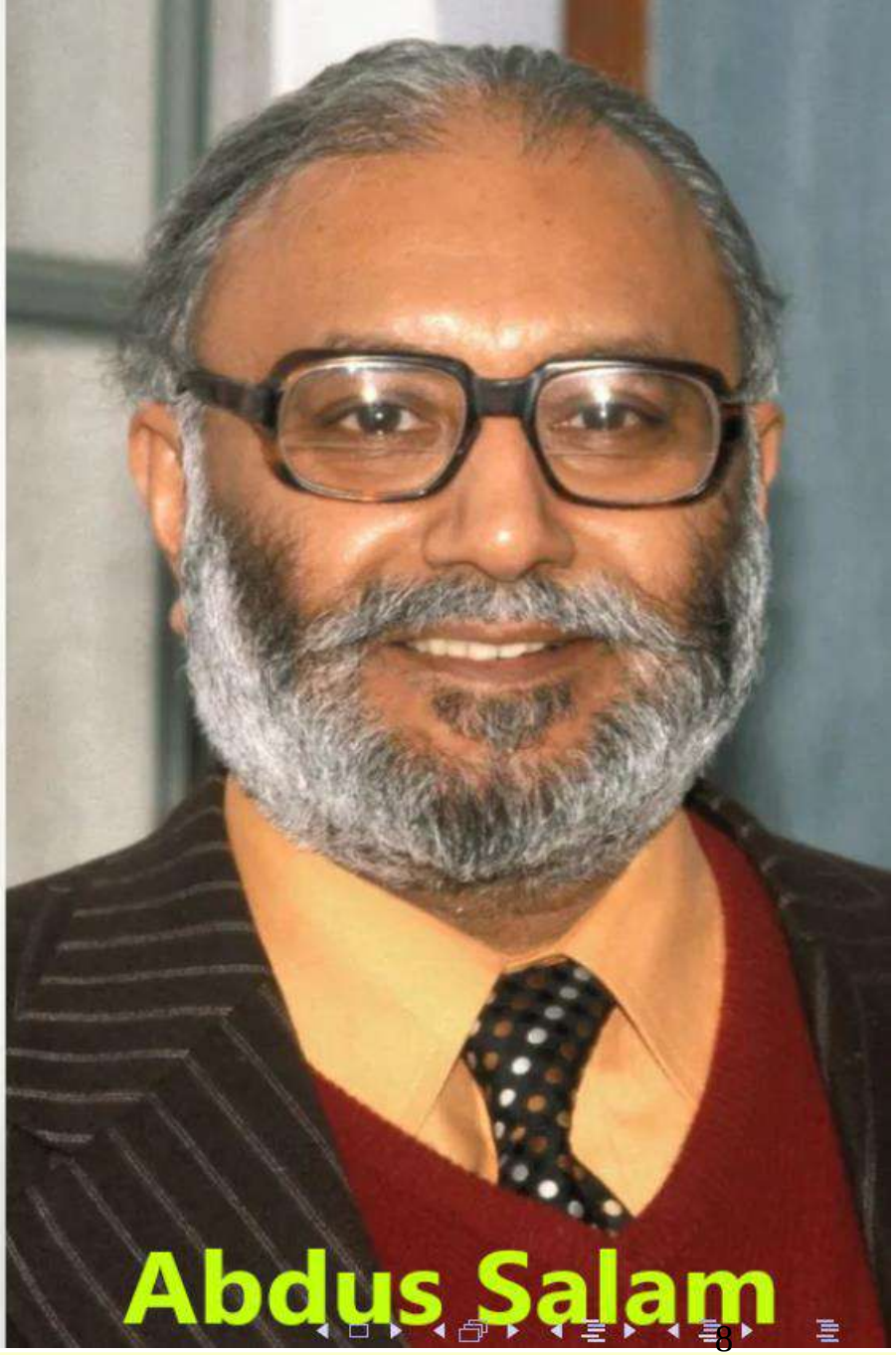


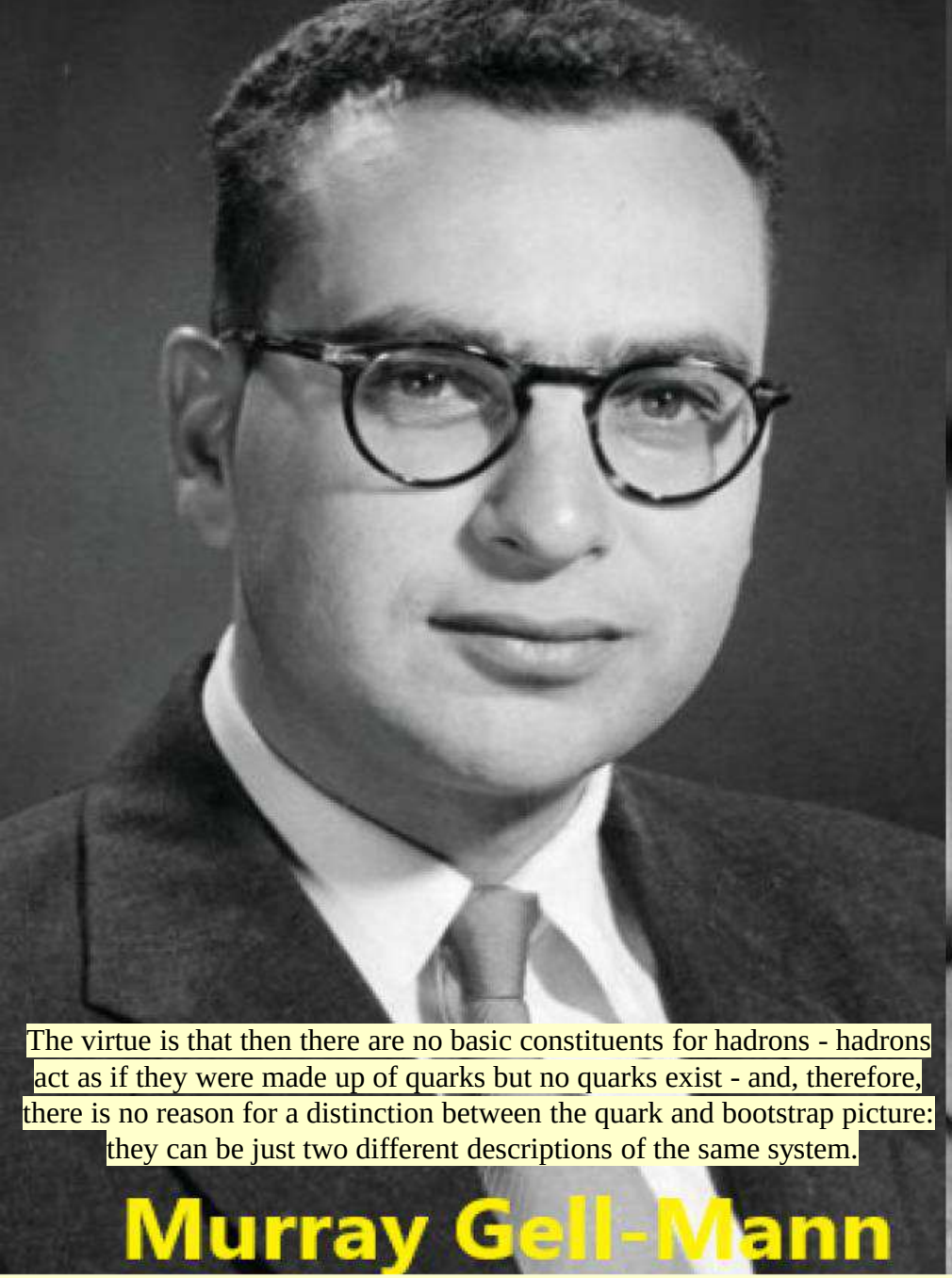
The Path to QCD and Glueballs

The Path to QCD and Glueballs

The Path to QCD and Glueballs


Steven Weinberg


Abdus Salam



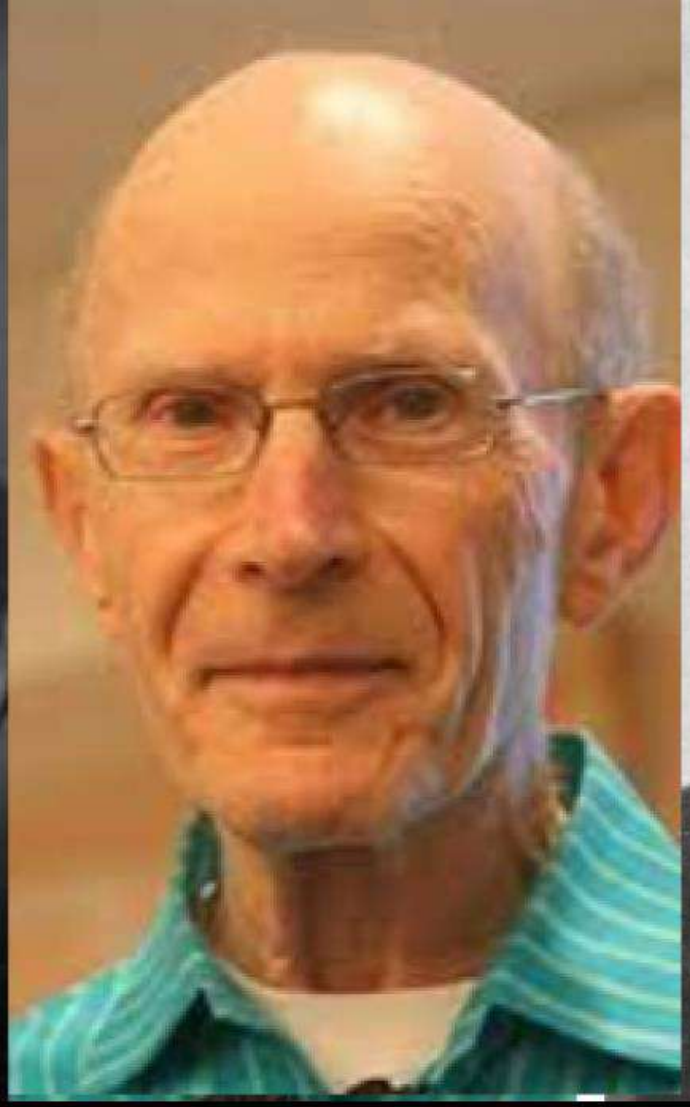
The virtue is that then there are no basic constituents for hadrons - hadrons act as if they were made up of quarks but no quarks exist - and, therefore, there is no reason for a distinction between the quark and bootstrap picture: they can be just two different descriptions of the same system.

Murray Gell-Mann

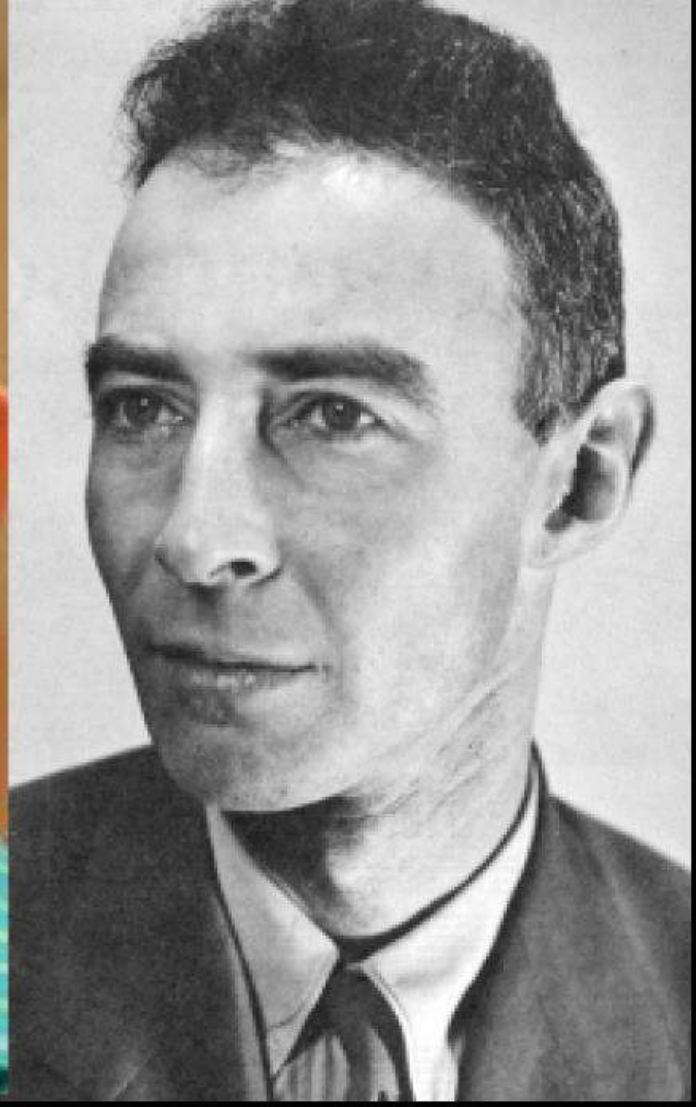
George Zweig

The Path to QCD and Glueballs

Wolfgang Pauli

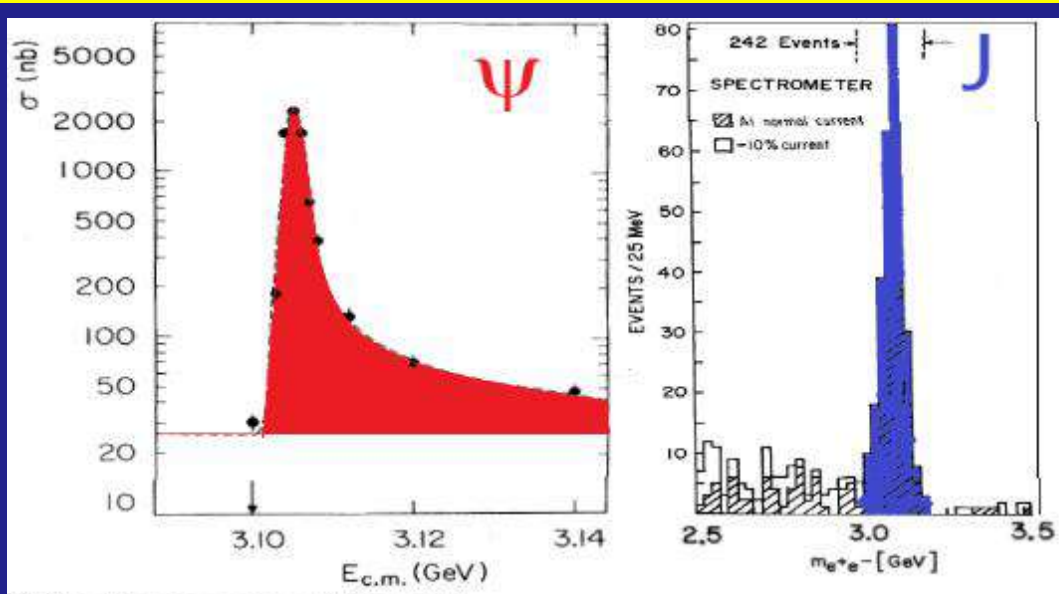


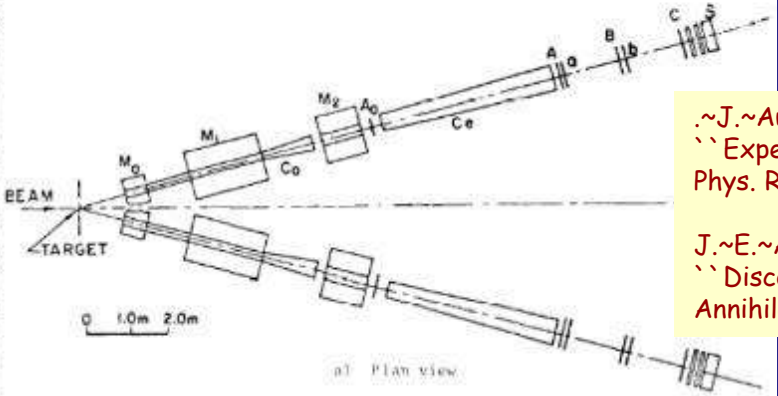
Oscar Greenberg



Robert Oppenheimer

The November Revolution in Particle Physics





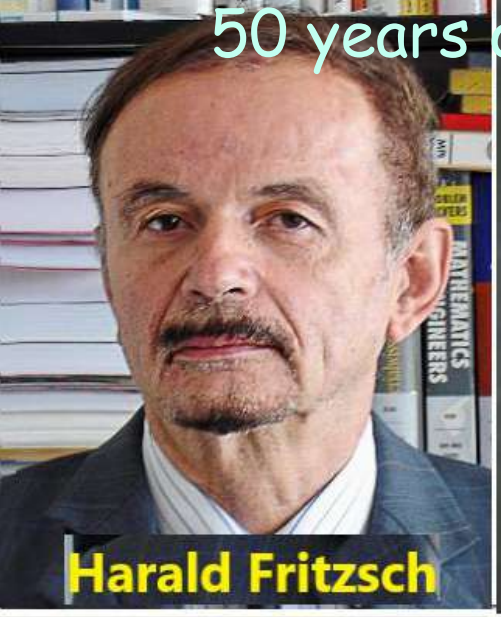
The discovery of the J/ψ

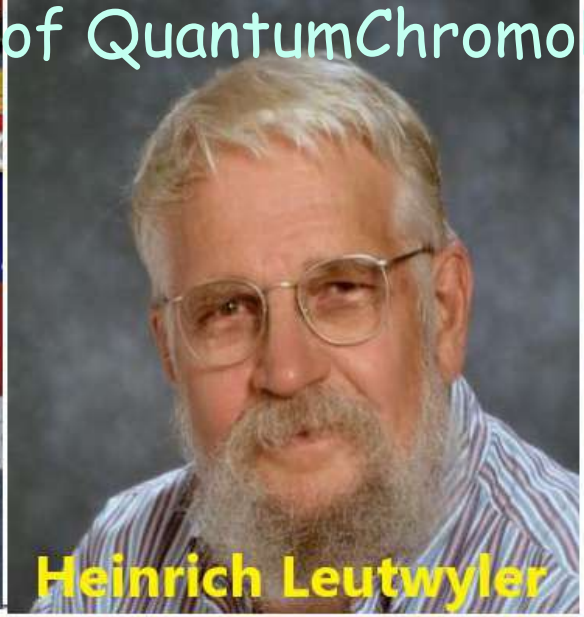
.~J.~Aubert et al. [E598],
``Experimental Observation of a Heavy Particle J,''
Phys. Rev. Lett. 33, 1404-1406 (1974).

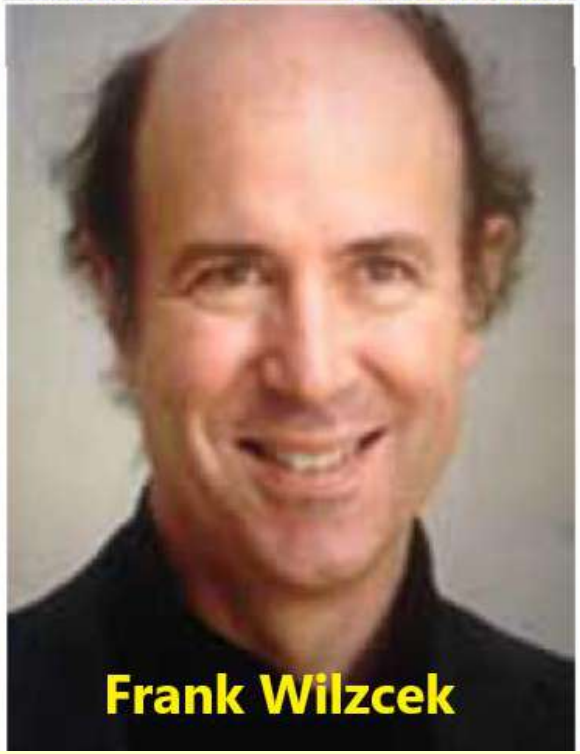
J.~E.~Augustin [SLAC-SP-017]
``Discovery of a Narrow Resonancein e+ e- Annihilation,''Phys. Rev. Lett. 1406-1408 (1974).

Definite verification of the quark model
Discovery of the fourth quark (GIM)

50 years of QuantumChromoDynamics







H.Fritzsch and M.Gell-Mann, ``Current algebra: Quarks and what else?,'' eConf C720906V2} 135 (1972).

H.Fritzsch, M.Gell-Mann and H.Leutwyler, ``Advantages of the Color Octet Gluon Picture,'' Phys. Lett. B 47 365 (1973).

D.J.Gross and F.Wilczek,``Asymptotically Free Gauge Theories,'' Phys. Rev. D 3633 (1973).

H.D.Politzer, ``Reliable Perturbative Results for Strong Interactions?,'' Phys. Rev. Lett. 1346 (1973).

Latter article received 50 years ago: (1973) May, 3rd

The Path to QCD and Glueballs

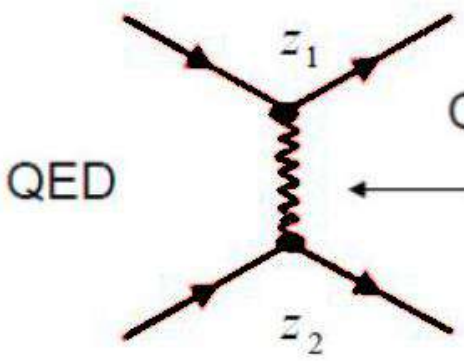
QCD

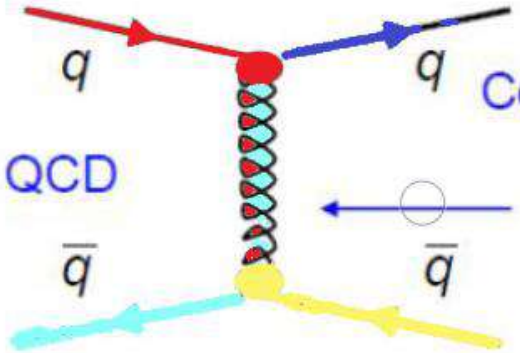
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}(i\gamma^{\mu}(\partial_{\mu} + \frac{i}{2}g_s\lambda^{A}\mathcal{A}^{A}{}_{\mu}) - m)\psi - \frac{1}{4}F^{A}_{\mu\nu}F^{A\,\mu\nu}$$

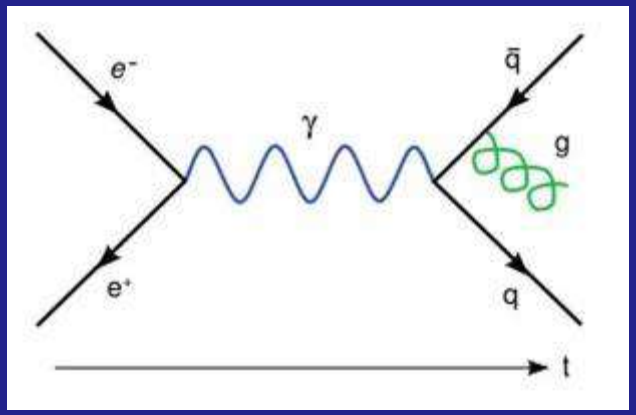
$$F^{A\,\mu\nu} = \partial_{\mu}\mathcal{A}^{A}_{\nu} - \partial_{\nu}\mathcal{A}^{A}_{\mu} - g_s f_{ABC}\mathcal{A}^{B}\mathcal{A}^{C}$$

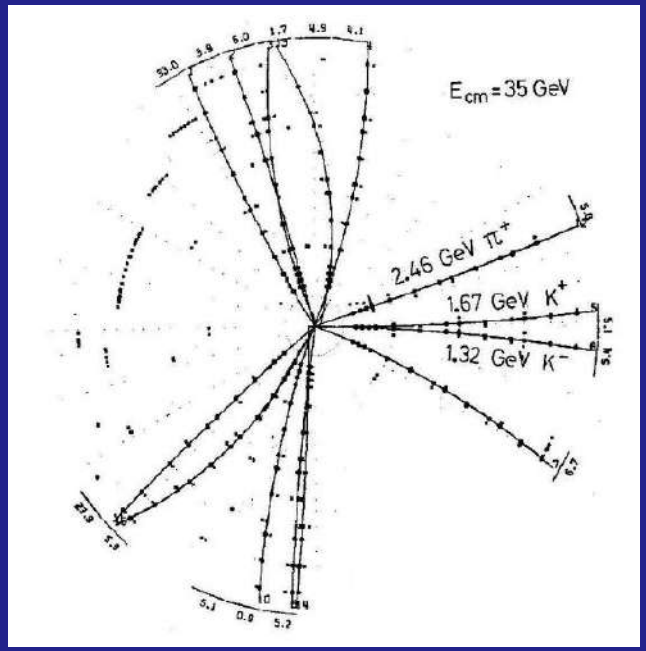
A beautiful equation that cannot be solved with an extremely rich phenomenology

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







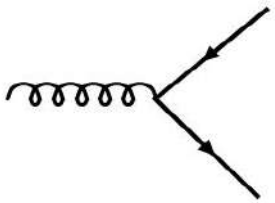


R.~Brandelik et al. [TASSO], ``Evidence for Planar Events in e+ e- Annihilation at High-Energies,'' Phys. Lett. B 86, 243-249 (1979).

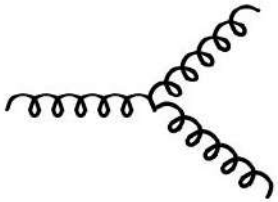
Fritzsch and Gell-Mann (1972):
`` … so that meson states would appear that act as if they were made of gluons rather than $q\bar{q}$ pairs".

Properties of Glueballs

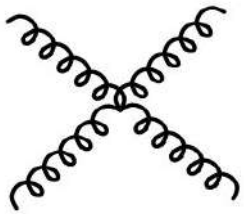
Mass, width and yield



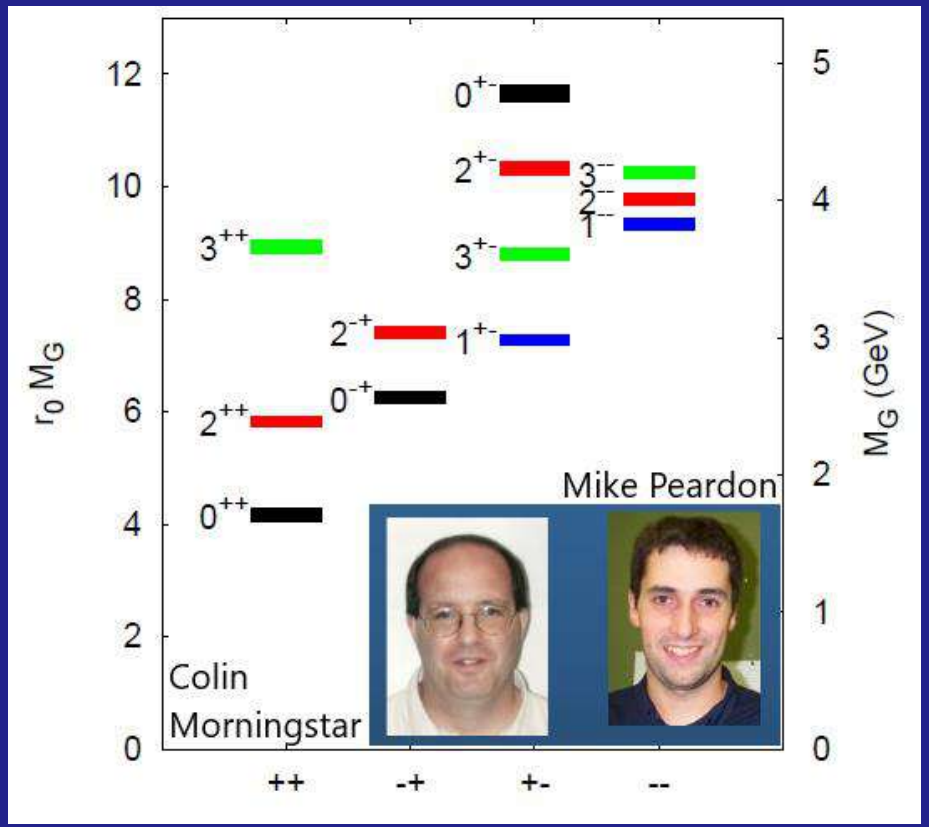
Analogous to photon exchange of QED



3-gluon vertex



4-gluon vertex



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

Glueballs: **Widths** **Yields** **undetermined**

$BR_{J/\psi\to\gamma G_{0^{++}}}$(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]

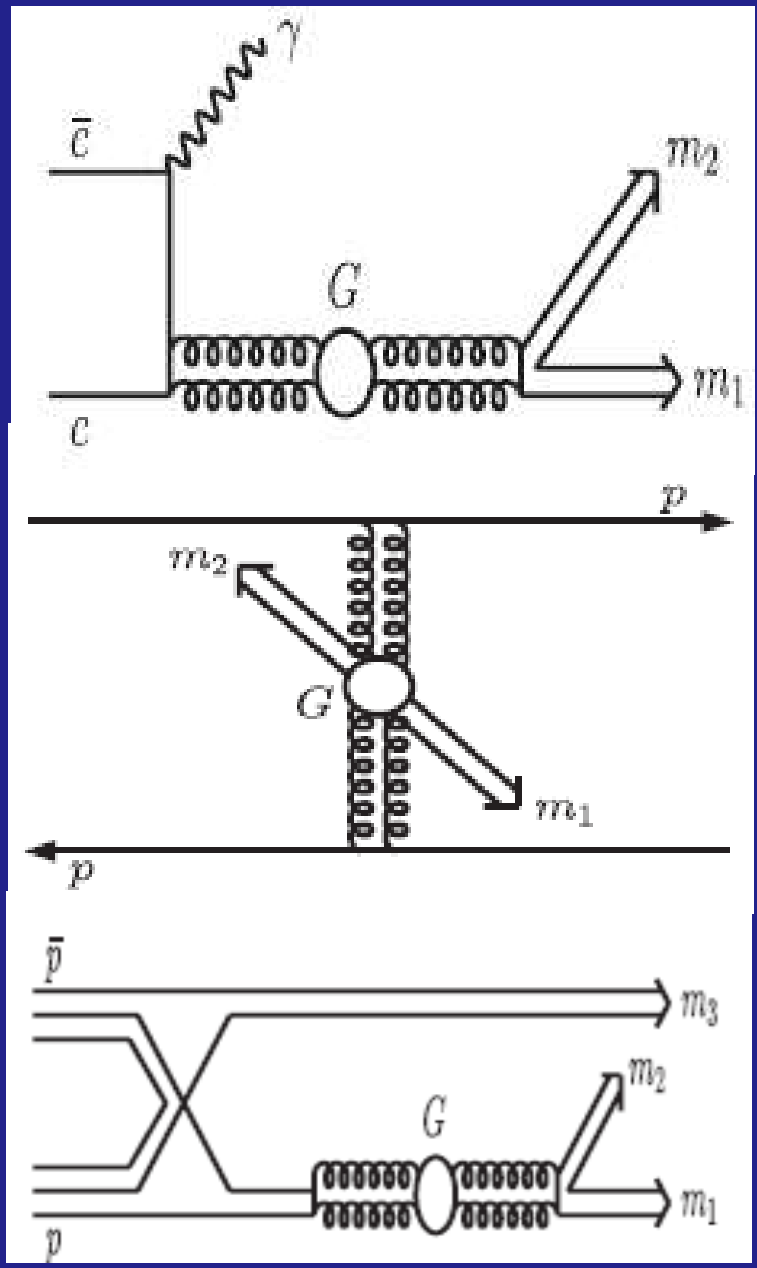
[1] L. C. Gui *et al.* [CLQCD], "Scalar Glueball in Radiative J/ψ Decay on the Lattice," PRL 110, 021601 (2013).
[2] S. Narison, "Masses, decays and mixings of gluonia in QCD," Nucl. Phys. B 509, 312-356 (1998).
[3] Y. Chen *et al.*, "Glueballs in charmonia radiative decays," PoS LATTICE2013, 435 (2014).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

How to search for Glueballs

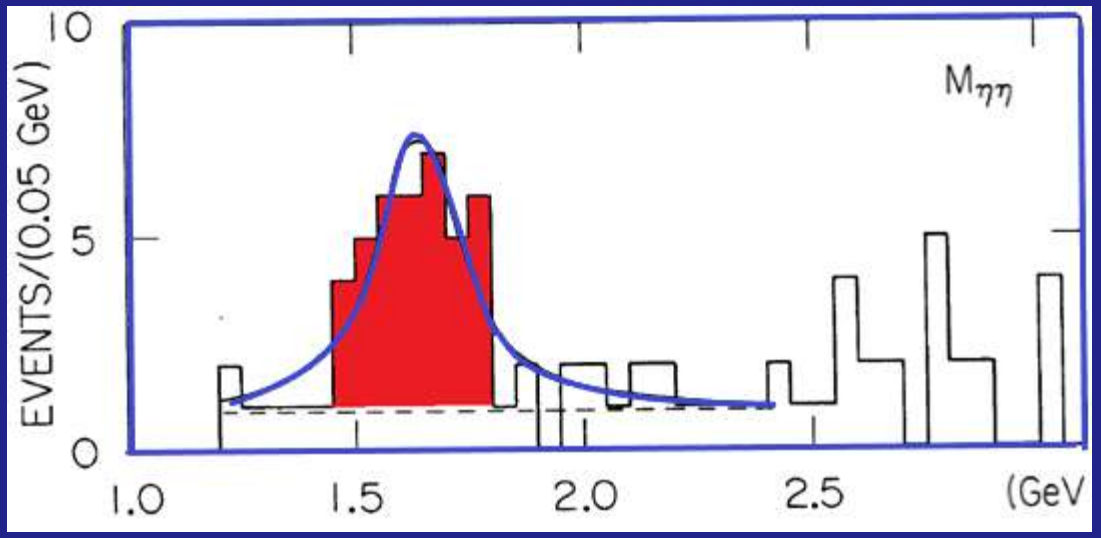
Radiative J/ψ decays

Central Production

$N\bar{N}$ Annihilation



Radiative J/ψ decays

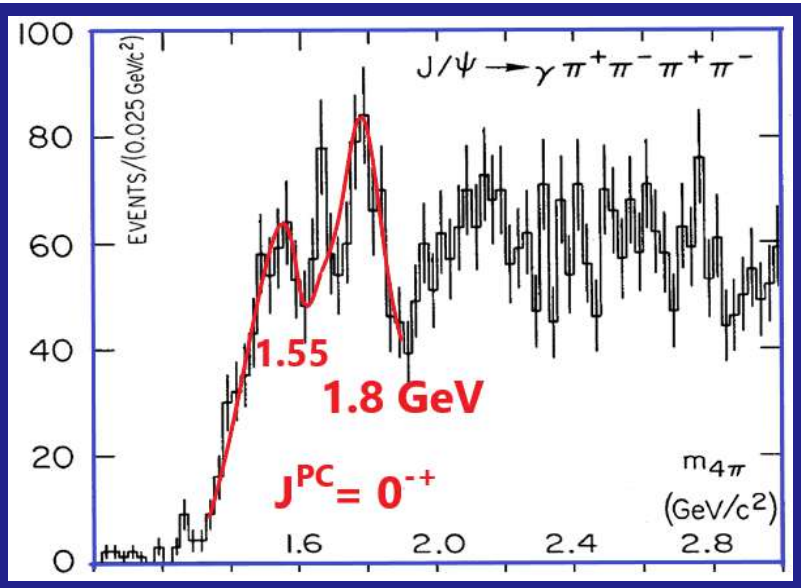


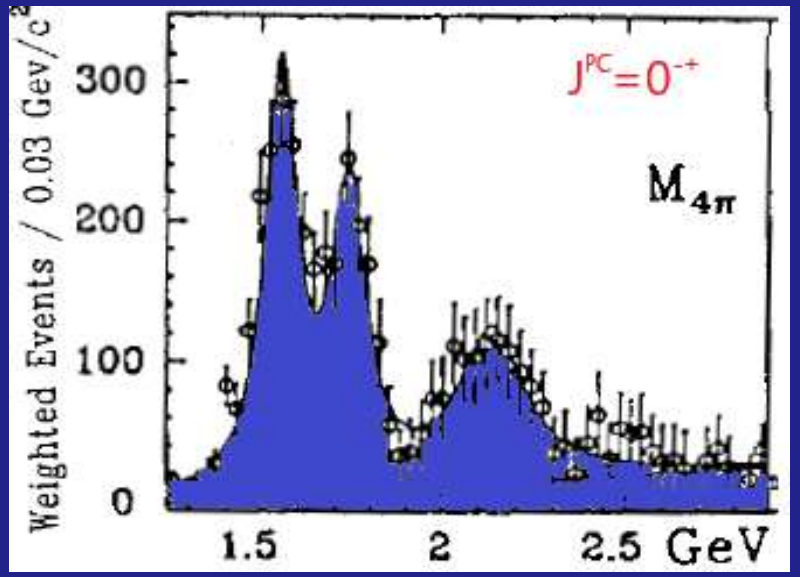
MARKIII: A radiatively produced resonance decaying into $\eta\eta$

The tensor glueball?

C. Edwards *et al.* "Observation of an $\eta\eta$ Resonance in J/ψ Radiative Decays," Phys. Rev. Lett. 48, 458 (1982).

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

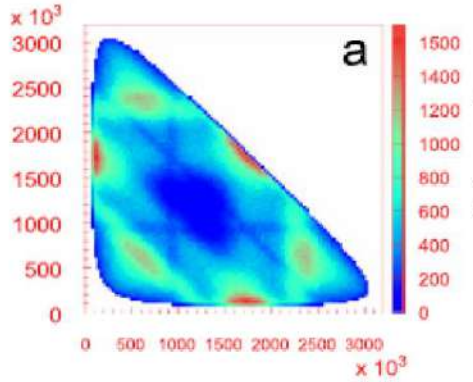


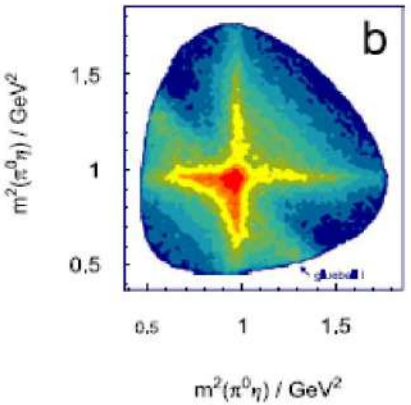


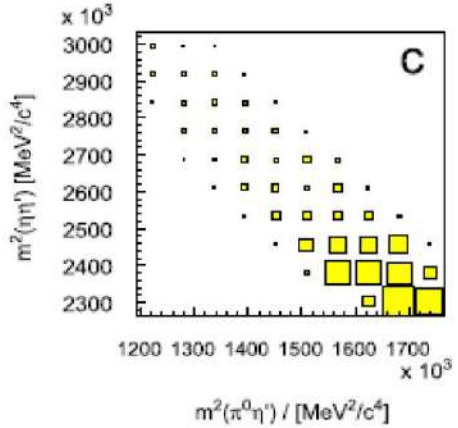
R. M. Baltrusaitis *et al.* [MARK-III], "A Study of the Radiative Decay $J/\psi \to \gamma\rho\rho$," Phys. Rev. D 33, 1222 (1986). (N. Wermes)

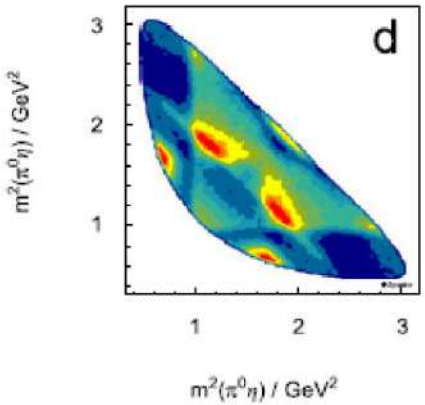
D. Bisello *et al.* [DM2], "First Observation of Three Pseudoscalar States in the $J/\psi \to \gamma\rho\rho$ Decay," Phys. Rev. D 39, 701 (1989).

$\bar{p}p$ Annihilation (Crystal Barrel at LEAR







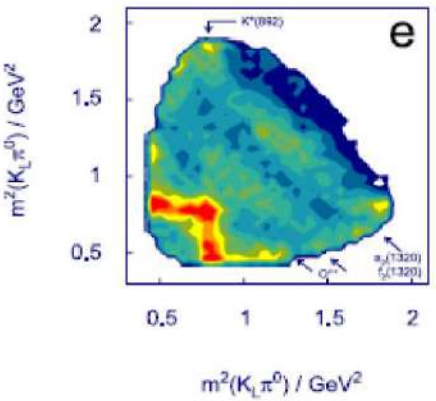


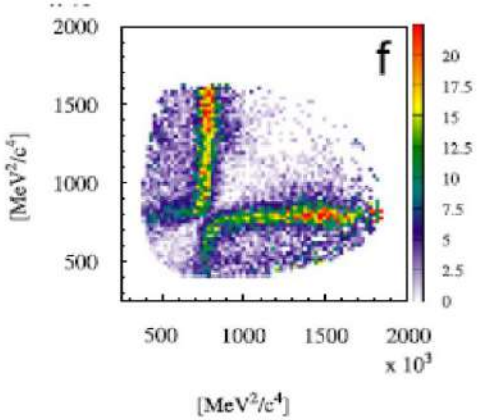
a: $3\pi^0$; J. Brose (Mainz)

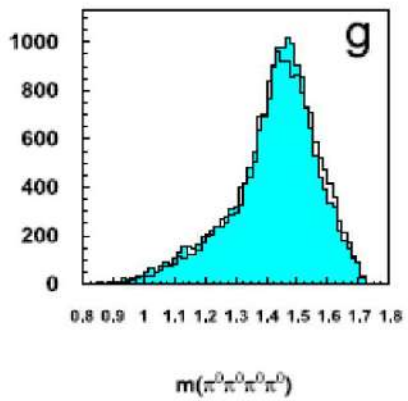
b: $\pi^0\eta\eta$; R. Hackmann (Mainz)

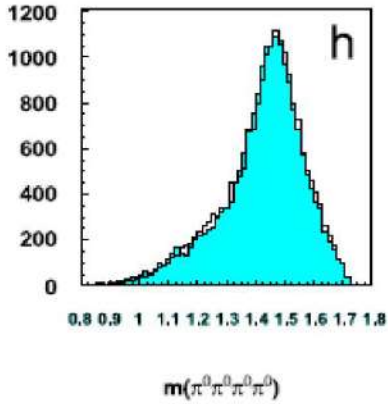
c: $\pi^0\eta\eta'$; S. Spanier (Mainz)

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)

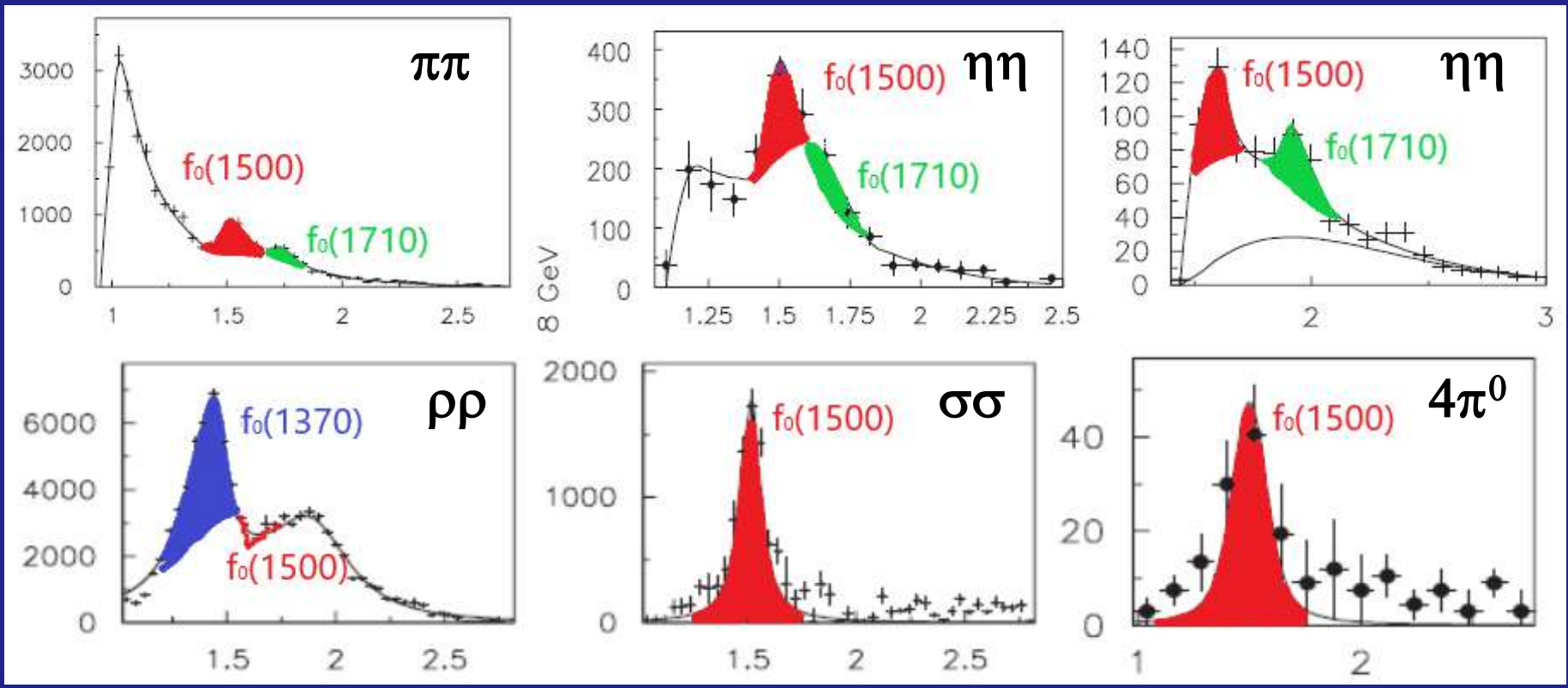
g: $4\pi^0$; U. Thoma (Bonn)

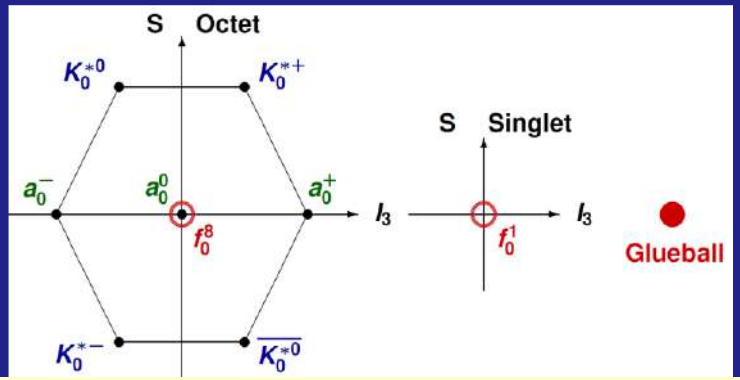
h: $4\pi^0$ U. Thoma (Bonn)

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

Properties of Glueballs

Central production (WA102 experiment, SPS)



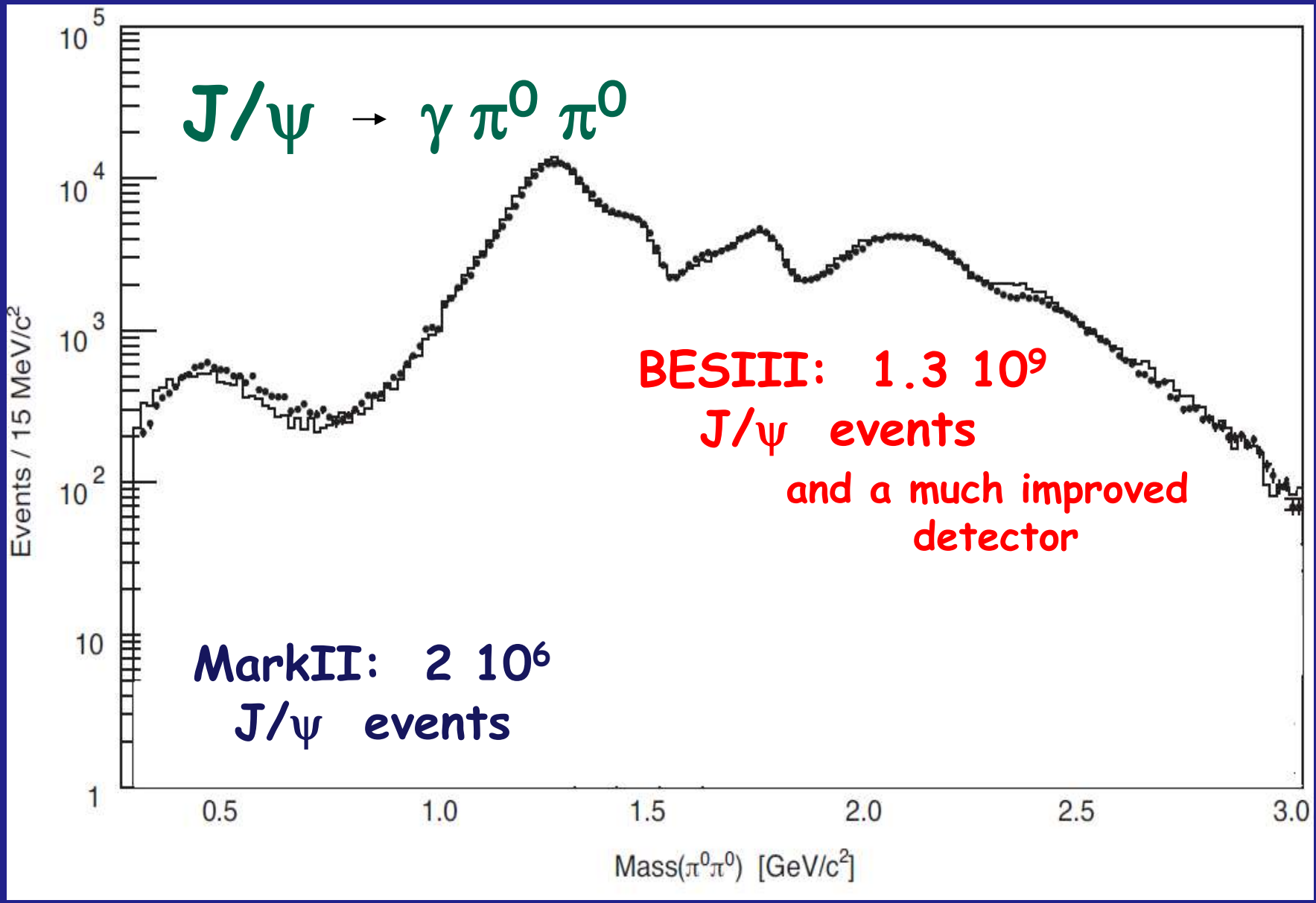


$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{pmatrix} \begin{matrix} |n\bar{n}\rangle \\ |s\bar{s}\rangle \\ |gg\rangle \end{matrix}$$

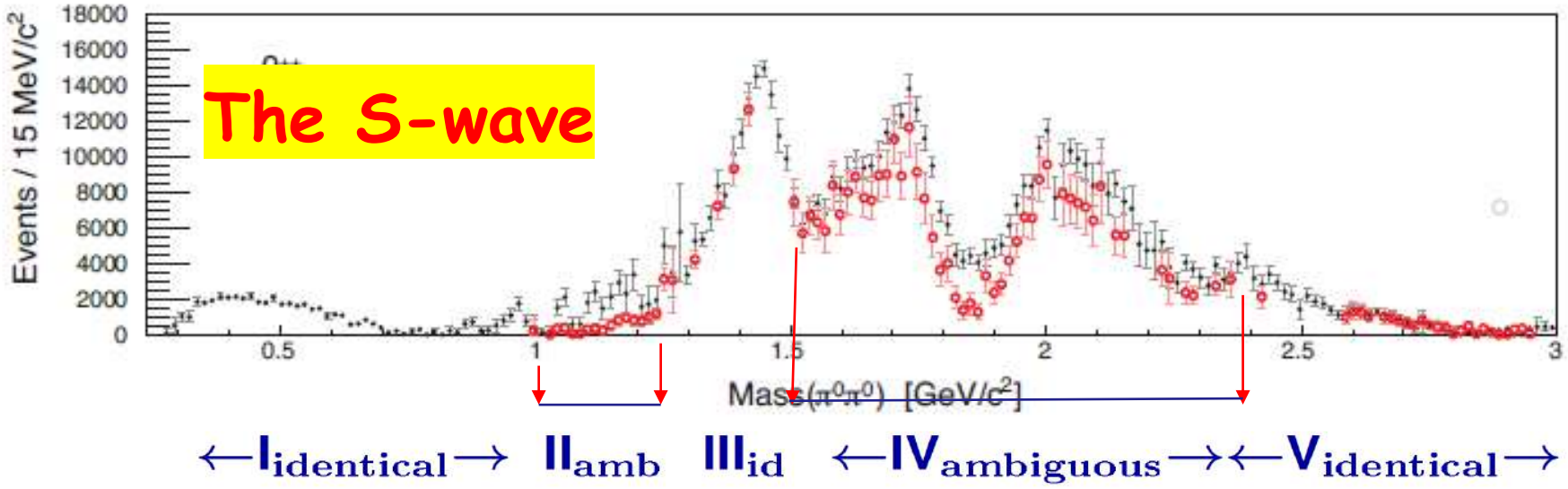
C. Amsler and F. E. Close, "Evidence for a scalar glueball," Phys. Lett. B 353, 385-390 (1995).

C. Amsler and F. E. Close, "Is $f_0(1500)$ a scalar glueball?," Phys. Rev. D 53, 295-311 (1996).

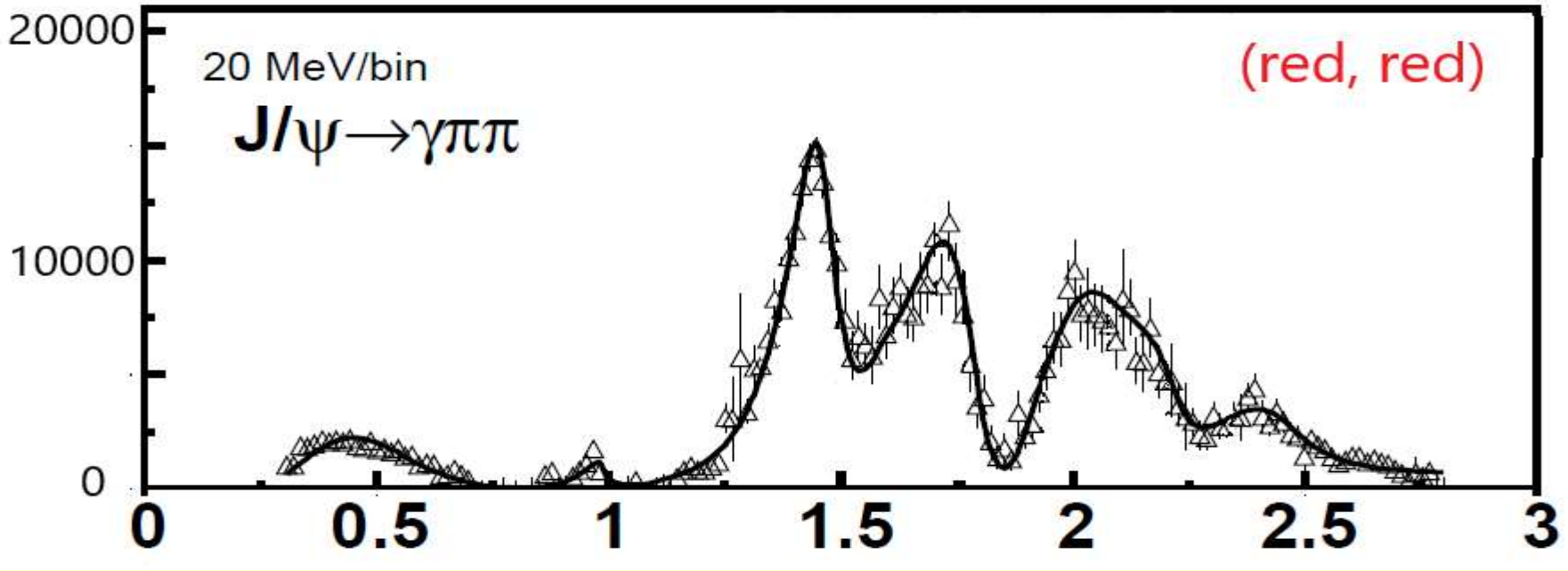
New Data from BESIII



New Data from BESIII

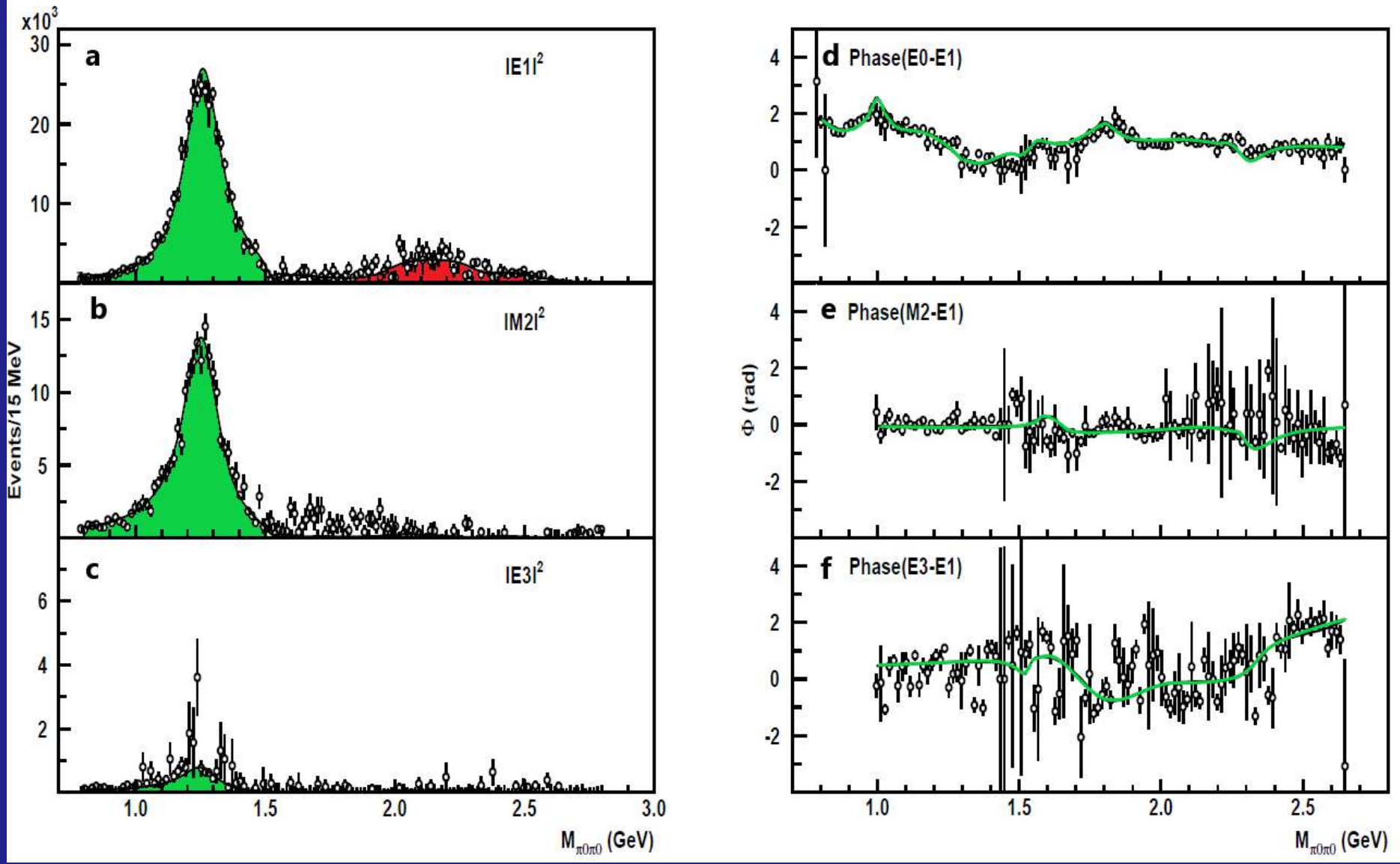


M. Ablikim *et al.* [BESIII], and A.P. Szczepaniak, P. Guo,
"Amplitude analysis of the $\pi^0\pi^0$ system produced in radiative J/ψ decays," Phys. Rev. D 92, no.5, 052003 (2015).



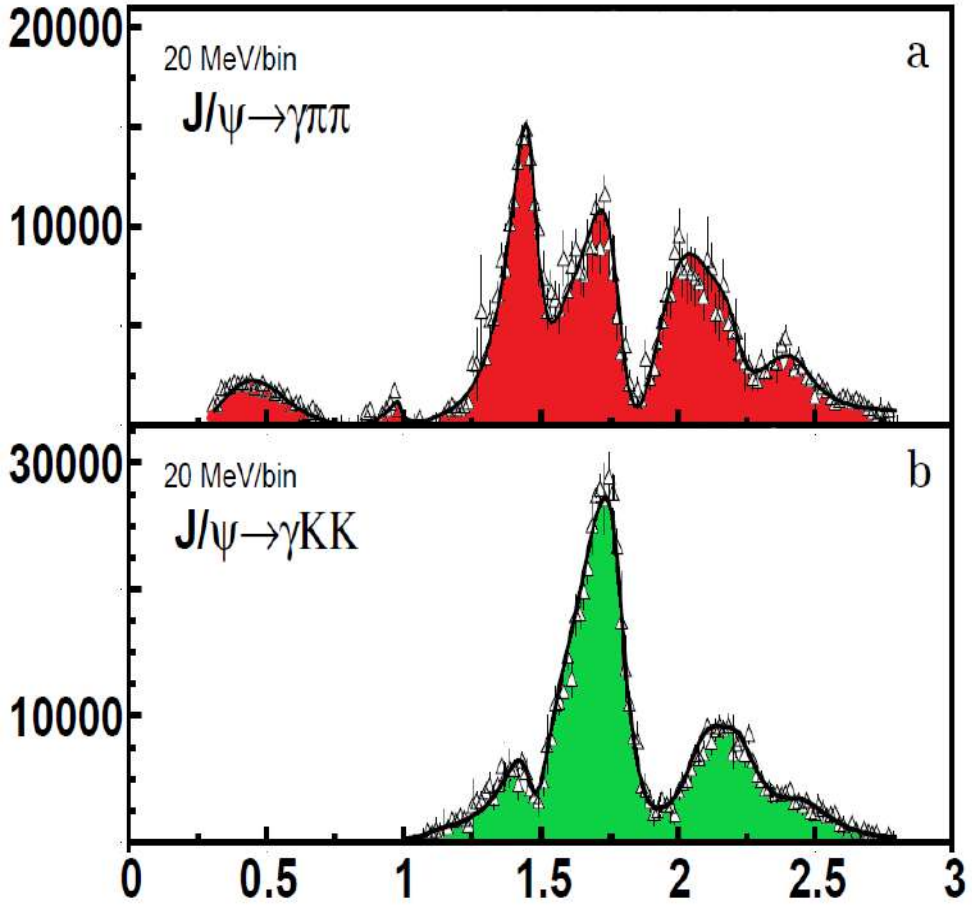
New Data from BESIII

The ππ D-wave



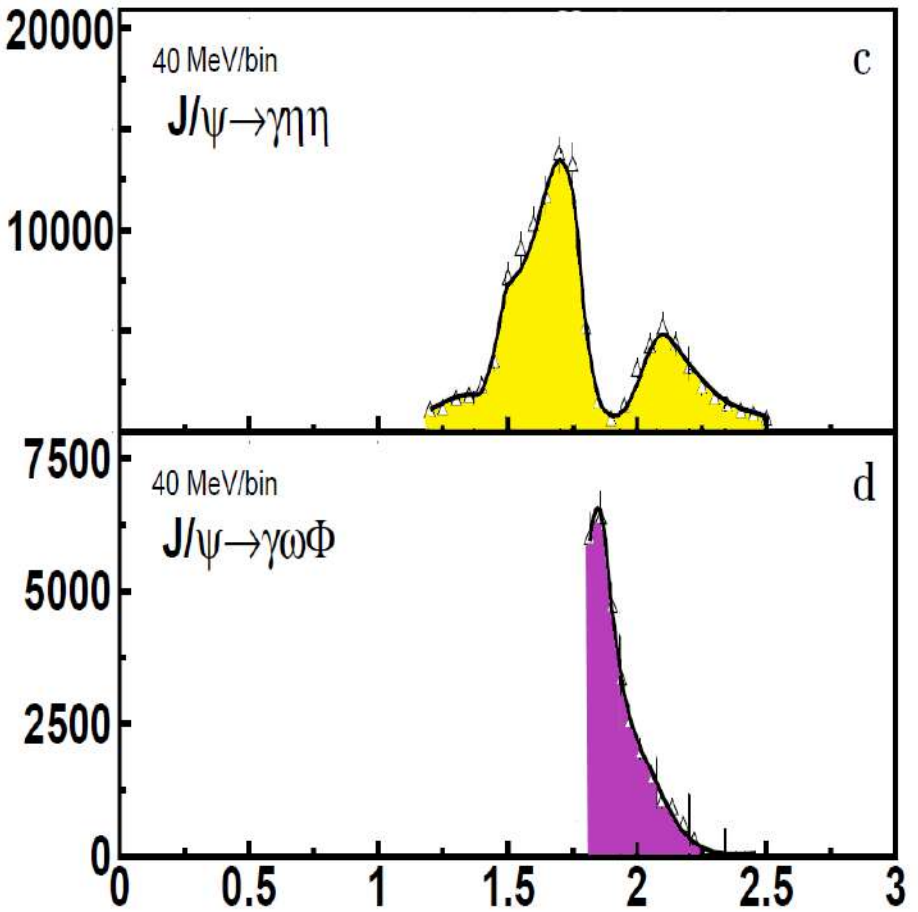
New Data from BESIII

Coupled Channel Analysis



$1.3 \cdot 10^9$ events

PWA in slices of energy



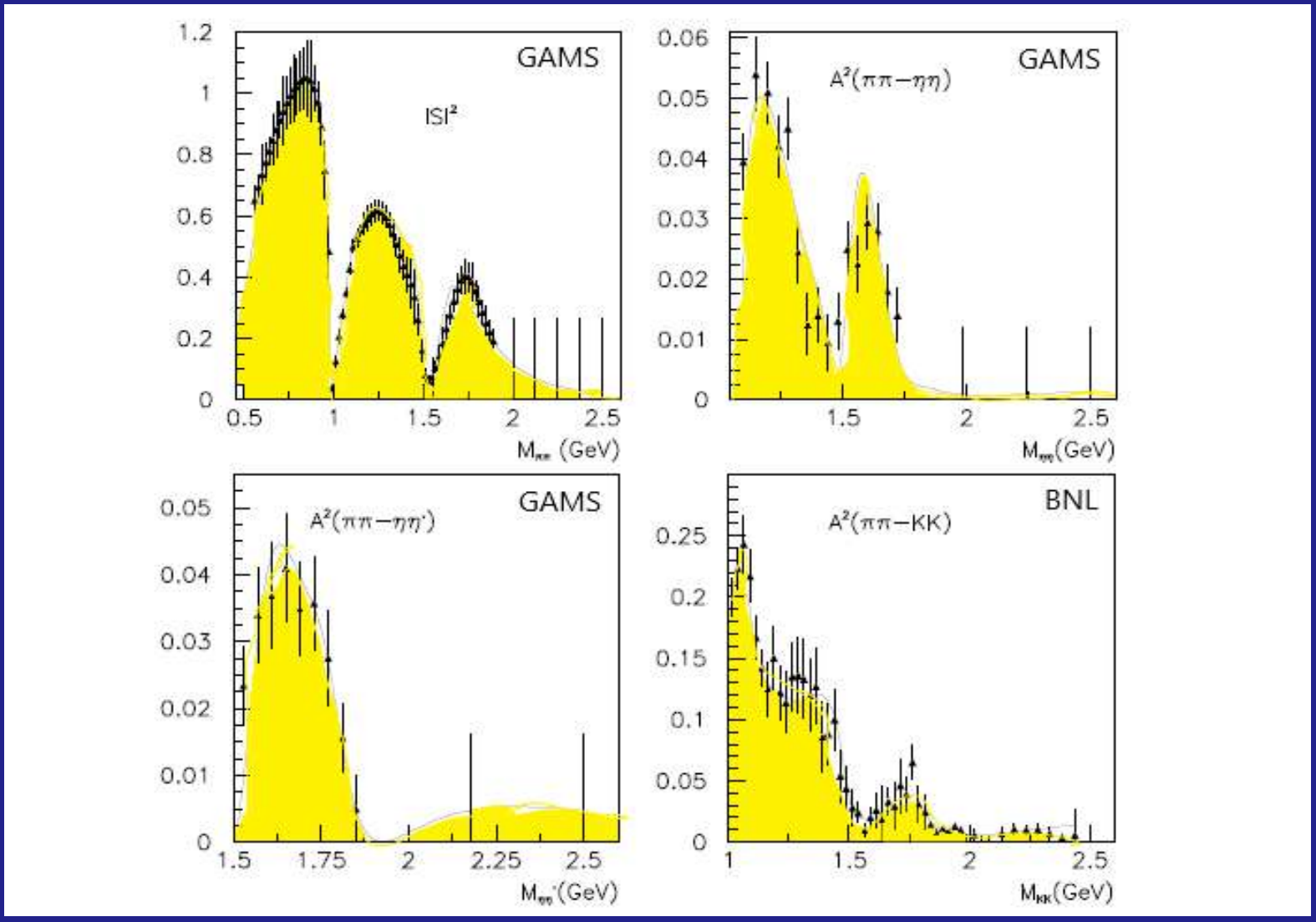
$0.225 \cdot 10^9$ events

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 $K_S K_S$ 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).

Coupled Channel Analysis

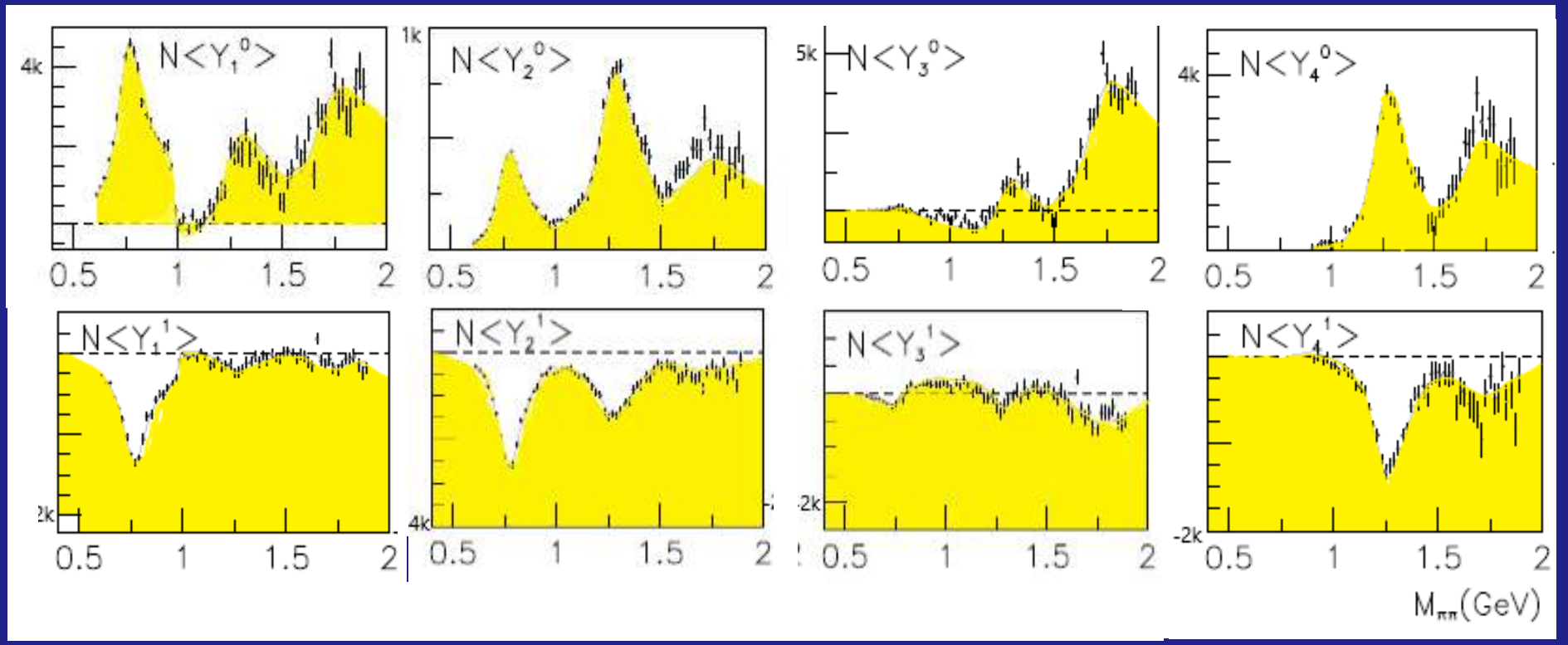
GAMS and BNL data on pion-induced reactions



GAMS: D. Alde et al., ``Study of the $\pi\pi$ 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 2GeV", Phys. Lett. B \textbf{274}, 492 (1992).

Coupled Channel Analysis

CERN Munich data on $\pi\pi \rightarrow \pi\pi$ elastic scattering



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

plus 15 Dalitz plots from Crystal Barrel at LEAR

Coupled Channel Analysis

J/ψ	$\to$	$\gamma\pi^0\pi^0$	K_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	
$\bar{p}p$	$\to$	$3\pi^0$	$\pi^0\pi^+\pi^-$	$2\pi^0\eta$	$\pi^0\eta\eta$	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	
$\pi^+\pi^-$	$\to$	$\pi^+\pi^-$	$\pi^0\pi^0$	$\eta\eta$	$\eta\eta'$	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

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).

Coupled Channel Analysis

Results and Interpretation

Contributing Resonances

Name	$f_0(500)$	$f_0(1370)$	$f_0(1710)$	$f_0(2020)$	$f_0(2200)$
M	410 ± 20 $400 \rightarrow 550$	1370 ± 40 $1200 \rightarrow 1500$	1700 ± 18 1704 ± 12	1925 ± 25 1992 ± 16	2200 ± 25 2187 ± 14
Γ	480 ± 30 $400 \rightarrow 700$	390 ± 40 $100 \rightarrow 500$	255 ± 25 123 ± 18	320 ± 35 442 ± 60	150 ± 30 ~ 200

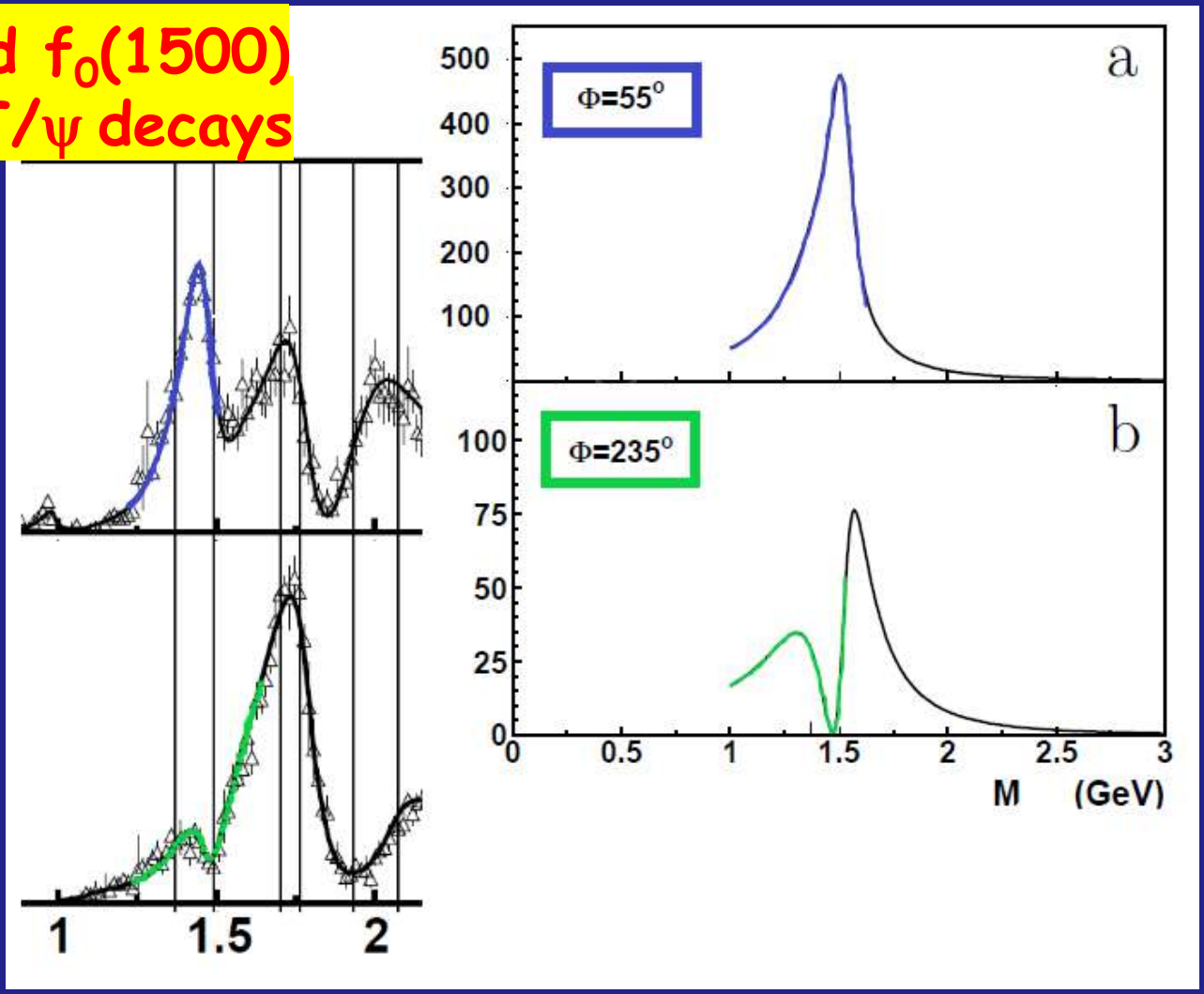
Name	$f_0(980)$	$f_0(1500)$	$f_0(1770)$	$f_0(2100)$	$f_0(2330)$
M	1014 ± 8 990 ± 20	1483 ± 15 1506 ± 6	1765 ± 15	2075 ± 20 2086^{+20}_{-24}	2340 ± 20 ~ 2330
Γ	71 ± 10 $10 \rightarrow 100$	116 ± 12 112 ± 9	180 ± 20	260 ± 25 284^{+60}_{-32}	165 ± 25 250 ± 20

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

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

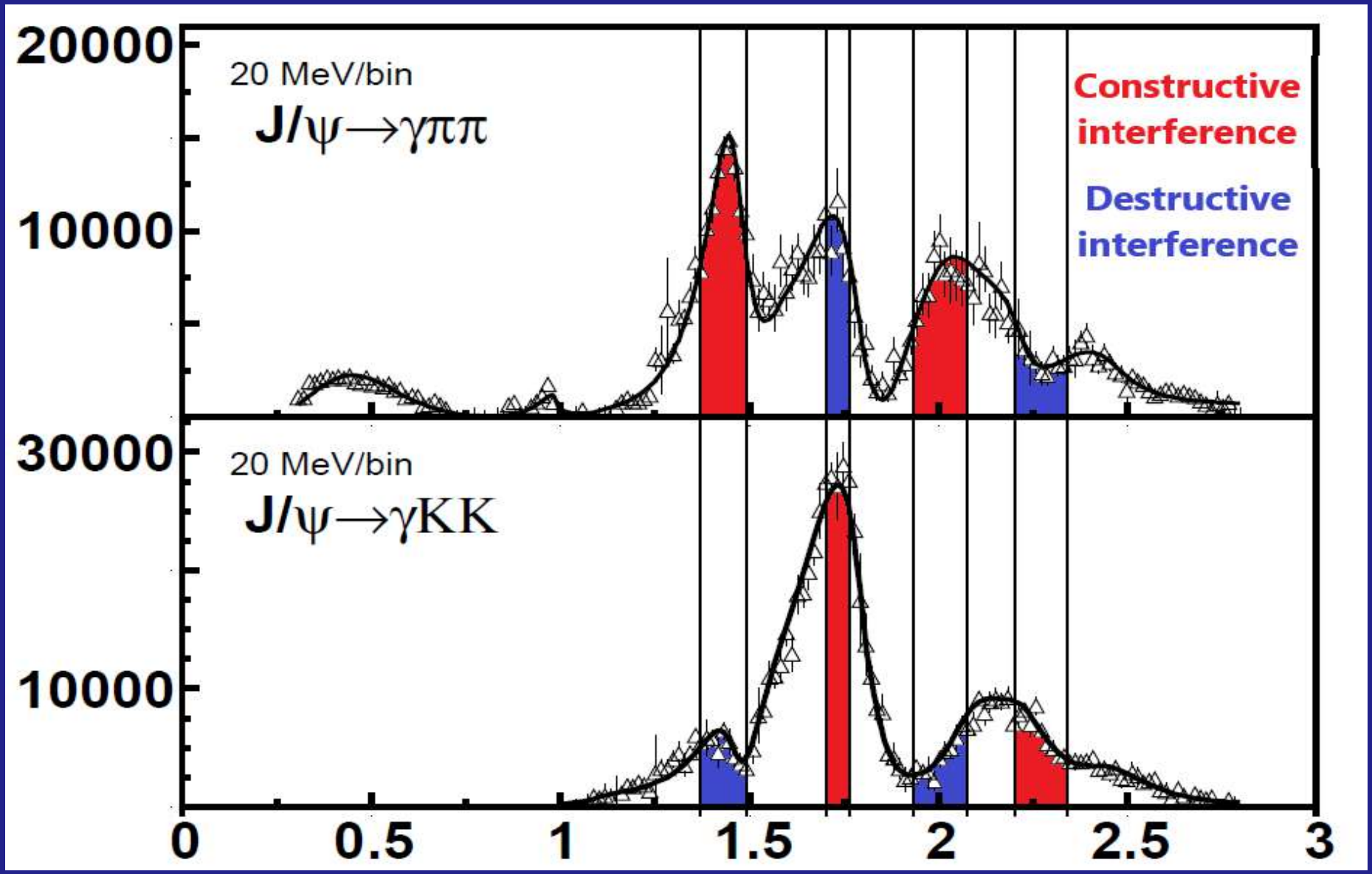
$BR_{J/\psi\to\gamma f_0\to}$	$\gamma\pi\pi$	$\gamma K\bar{K}$	$\gamma\eta\eta$	$\gamma\eta\eta'$	$\gamma\omega\phi$	missing $\gamma 4\pi$ $\gamma\omega\omega$	total
$f_0(500)$	105 ± 20	5 ± 5	4 ± 3	~0	~0	~0	114 ± 21
$f_0(980)$	1.3 ± 0.2	0.8 ± 0.3	~0	~0	~0	~0	2.1 ± 0.4
$f_0(1370)$	38 ± 10	13 ± 4 42 ±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

The $f_0(1370)$ and $f_0(1500)$ mixing angle from J/ψ decays



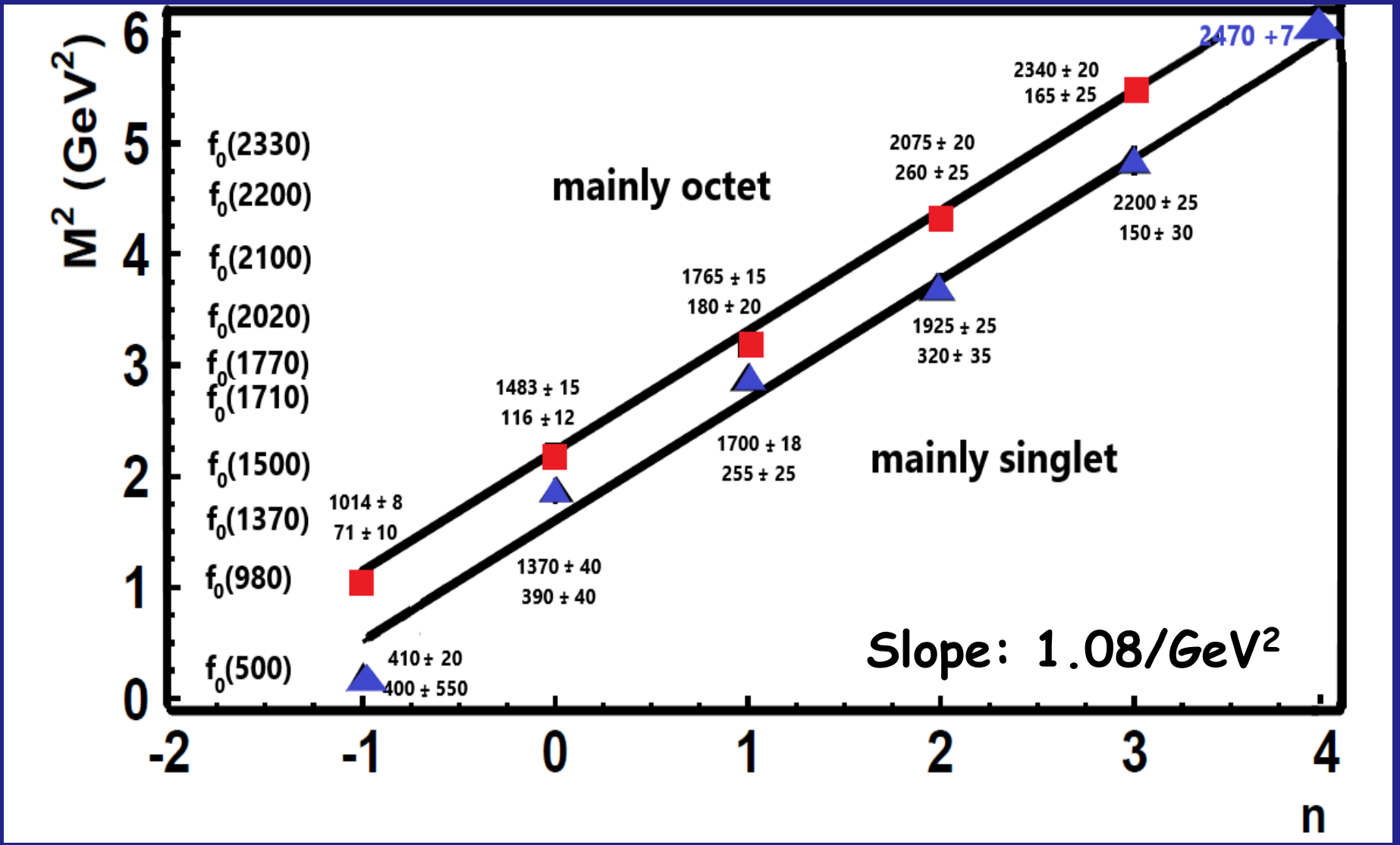
Phase difference between $\pi\pi$ and KK the decay mode is 180^0: $\bar{n}n$-$\bar{s}s$ and $\bar{n}n$+$\bar{s}s$! $f_0(1370)$ and $f_0(1500)$ are SU(3) singlet and SU(3) octet-like and not $\bar{n}n$ and $\bar{s}s$!

Interference between pattern in ππ and K̄K

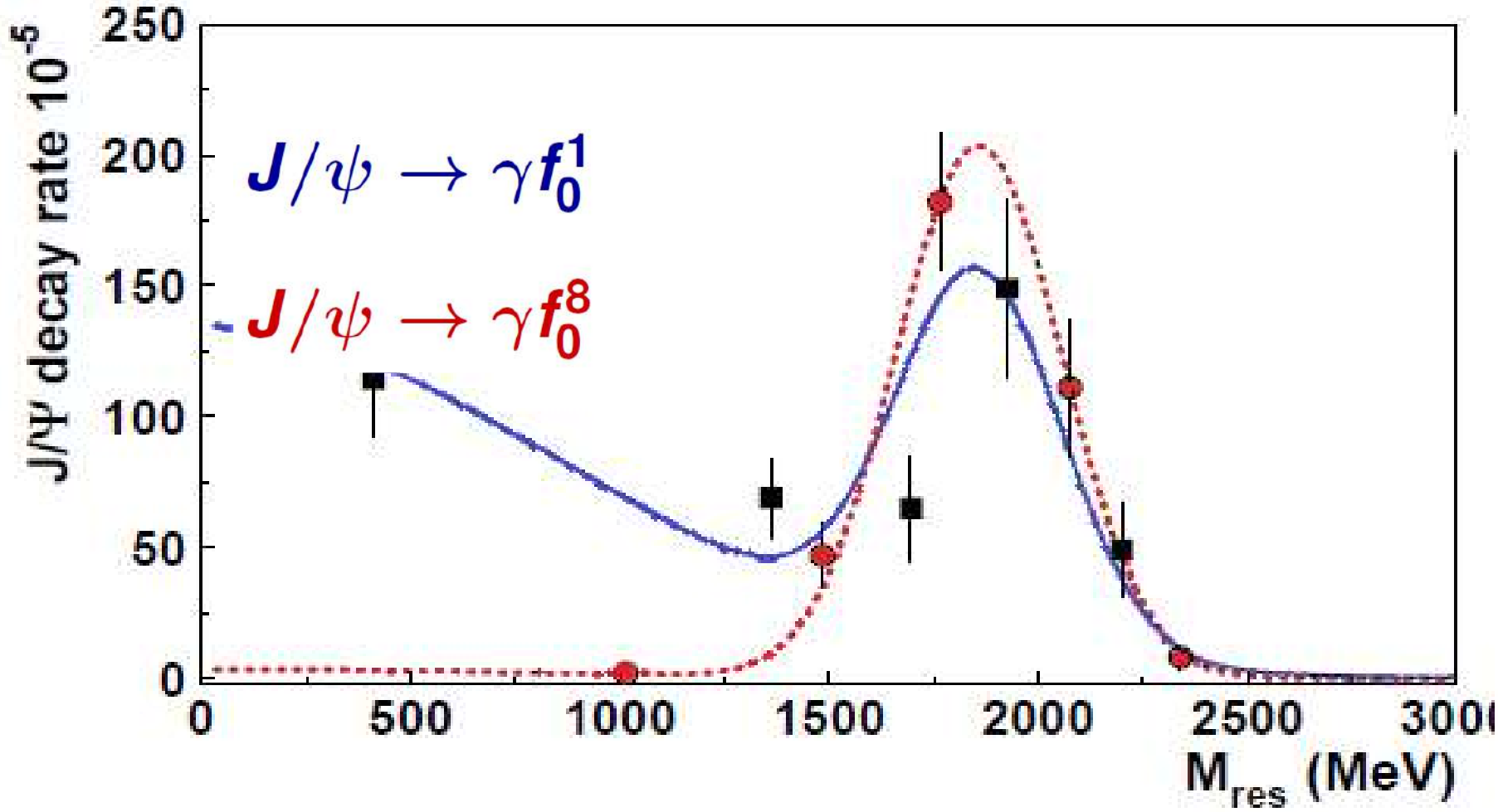


Results and Interpretation

(M^2,n) trajectories of scalar mesons



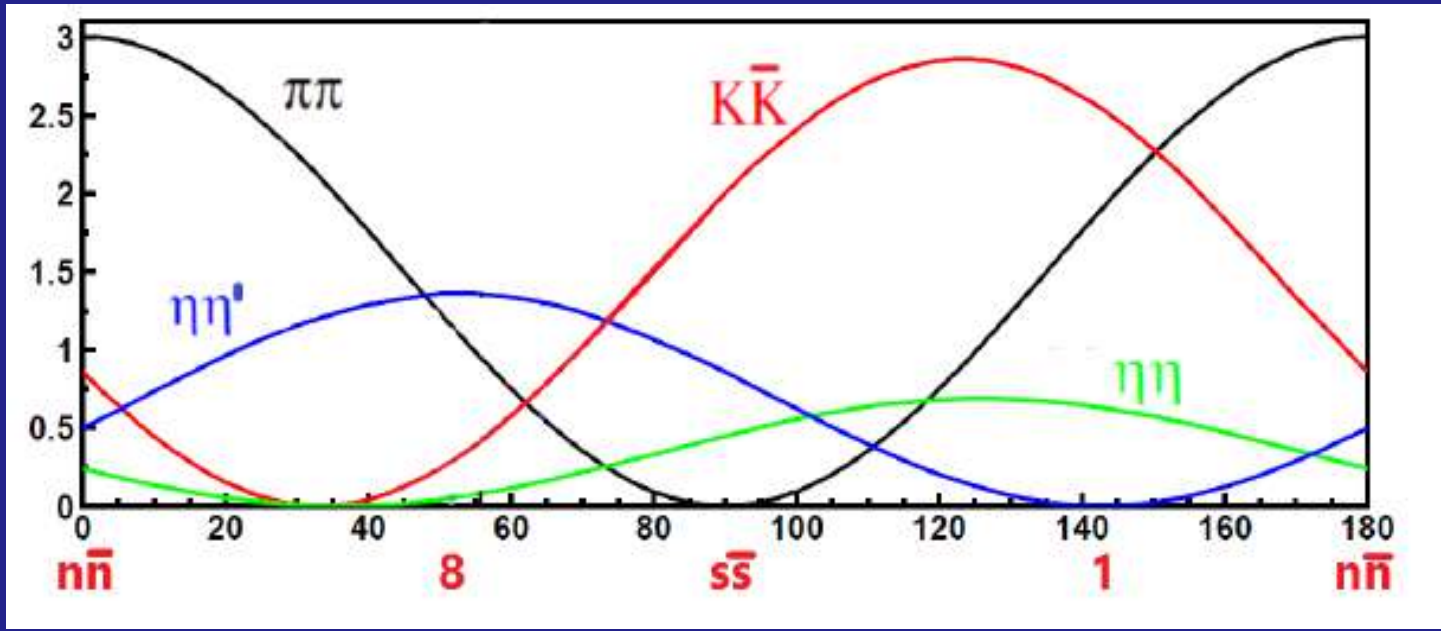
The scalar glueball from production in radiative J/ψ decays



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

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

The scalar glueball from a decay analyis

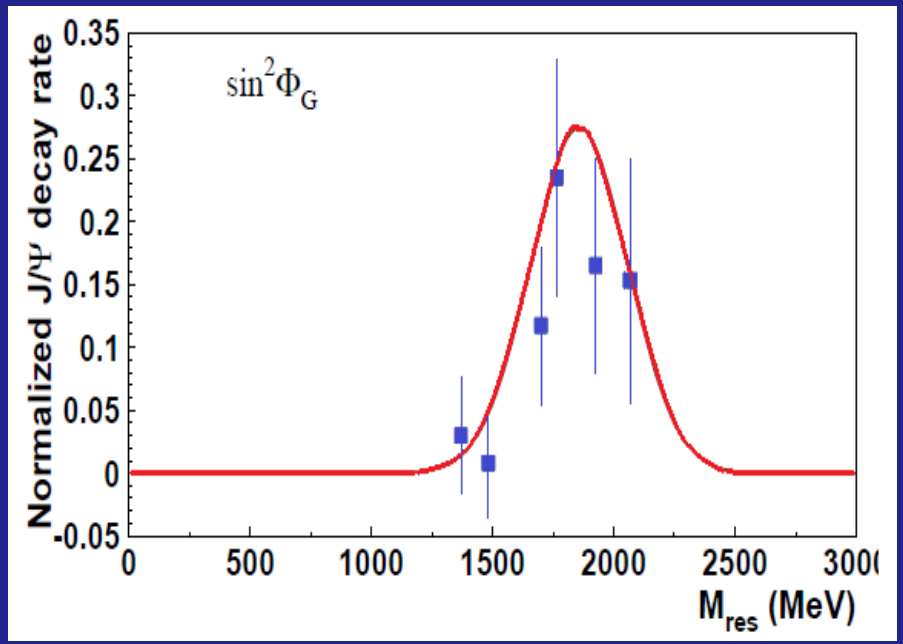


$$f_0^{\rm nH}(xxx) = (n\bar{n}\cos\varphi_{\rm n}^{\rm s} - s\bar{s}\sin\varphi_{\rm n}^{\rm s})\cos\phi_{\rm nH}^{G} + G\sin\phi_{\rm nH}^{G}$$
$$f_0^{\rm nL}(xxx) = (n\bar{n}\sin\varphi_{\rm n}^{\rm s} + s\bar{s}\cos\varphi_{\rm n}^{\rm s})\cos\phi_{\rm nL}^{G} + G\sin\phi_{\rm nL}^{G}$$

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

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

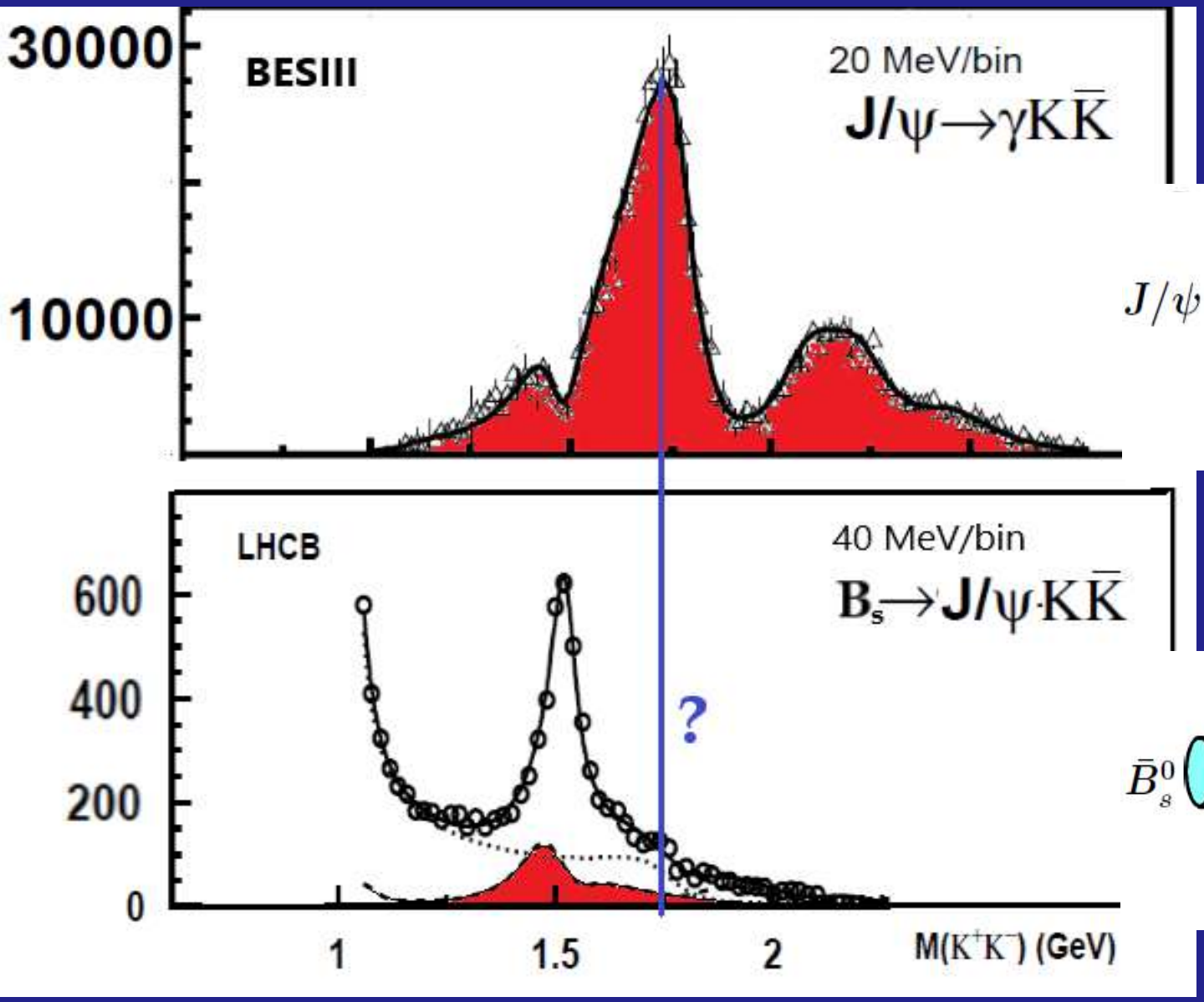
$$\sum_3^8 \sin^2\phi_G = 0.78 \pm 0.18$$

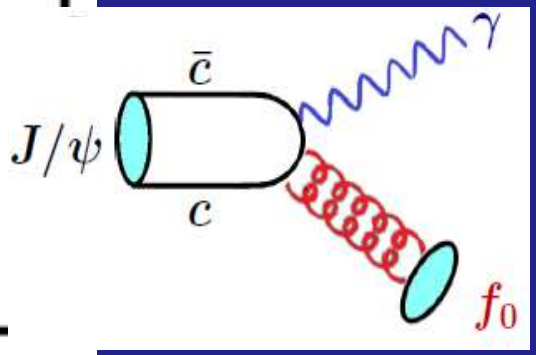


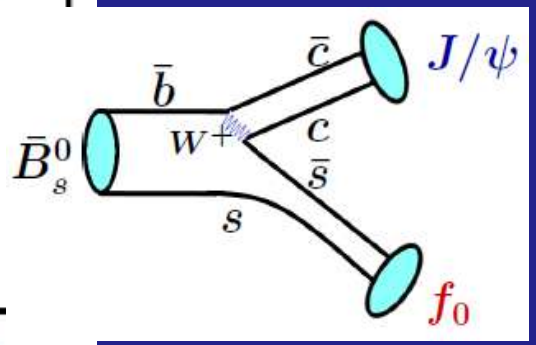
E. Klempt and A. V. Sarantsev, ``Singlet-octet-glueball mixing of scalar mesons,'' Phys. Lett. B 826, 136906 (2022).

Results and Interpretation

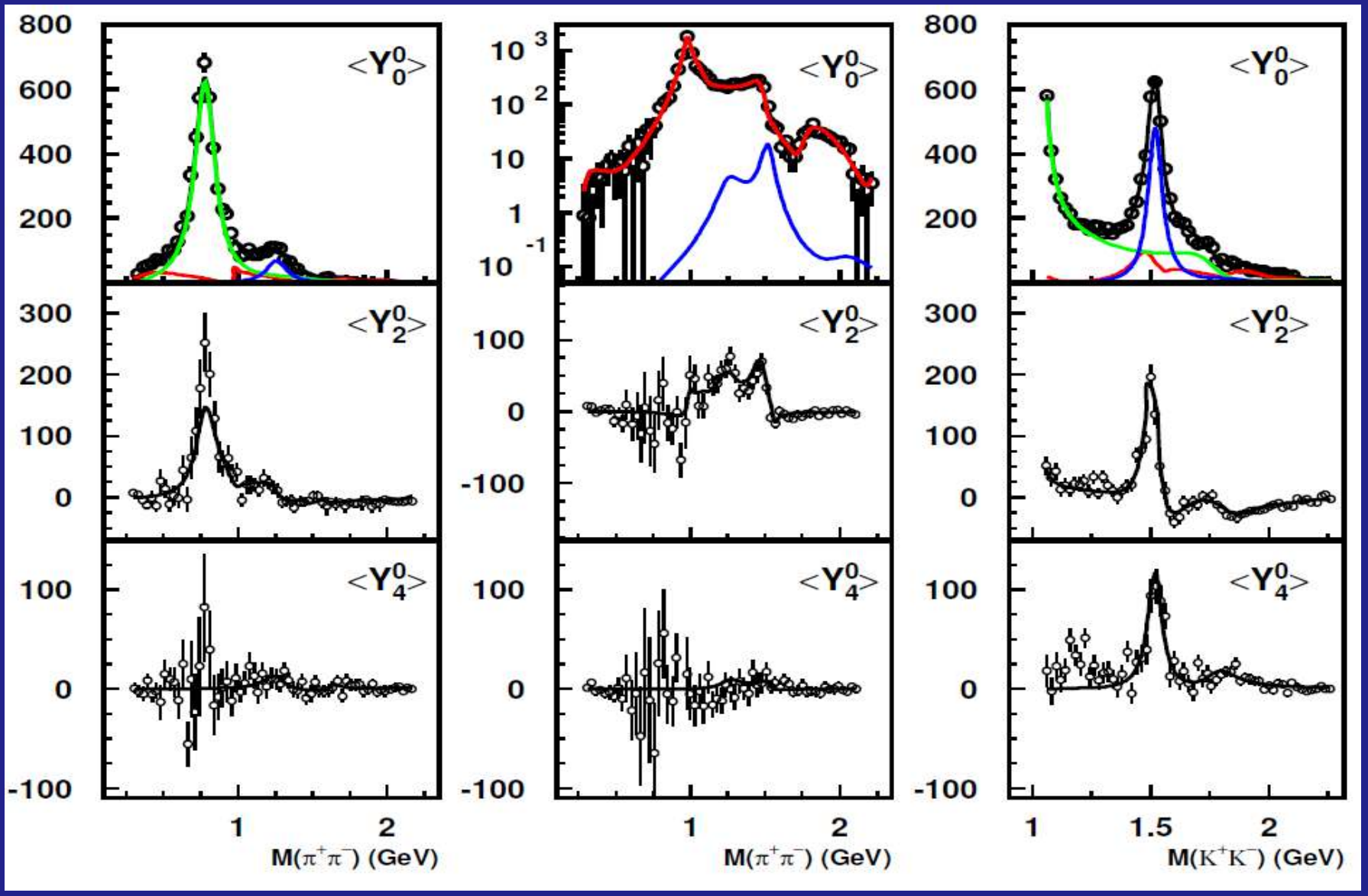
Comparison of $J/\psi \to \gamma f_0$ and $B_s \to J/\psi f_0$ (LHCb)





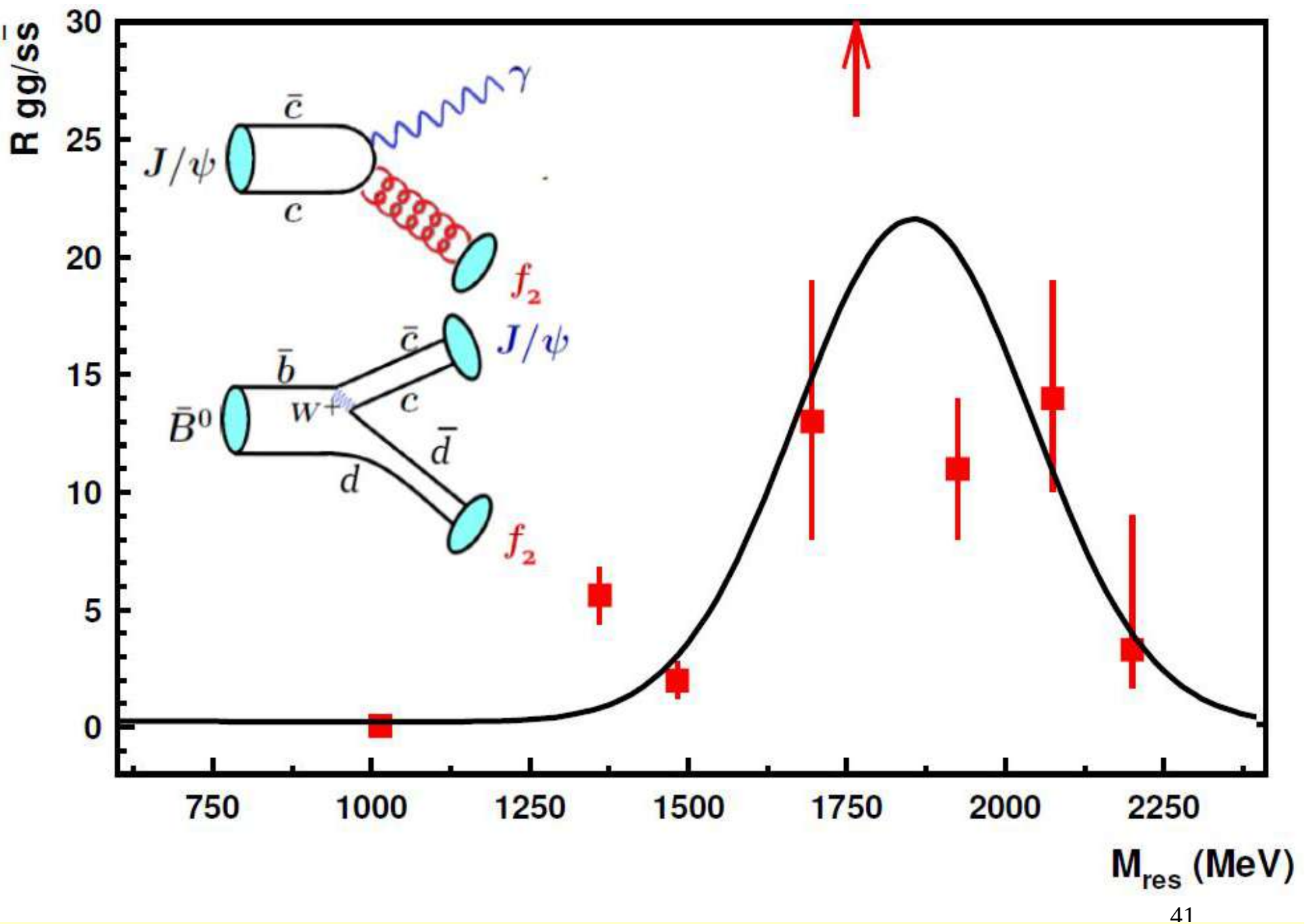


Results and Interpretation



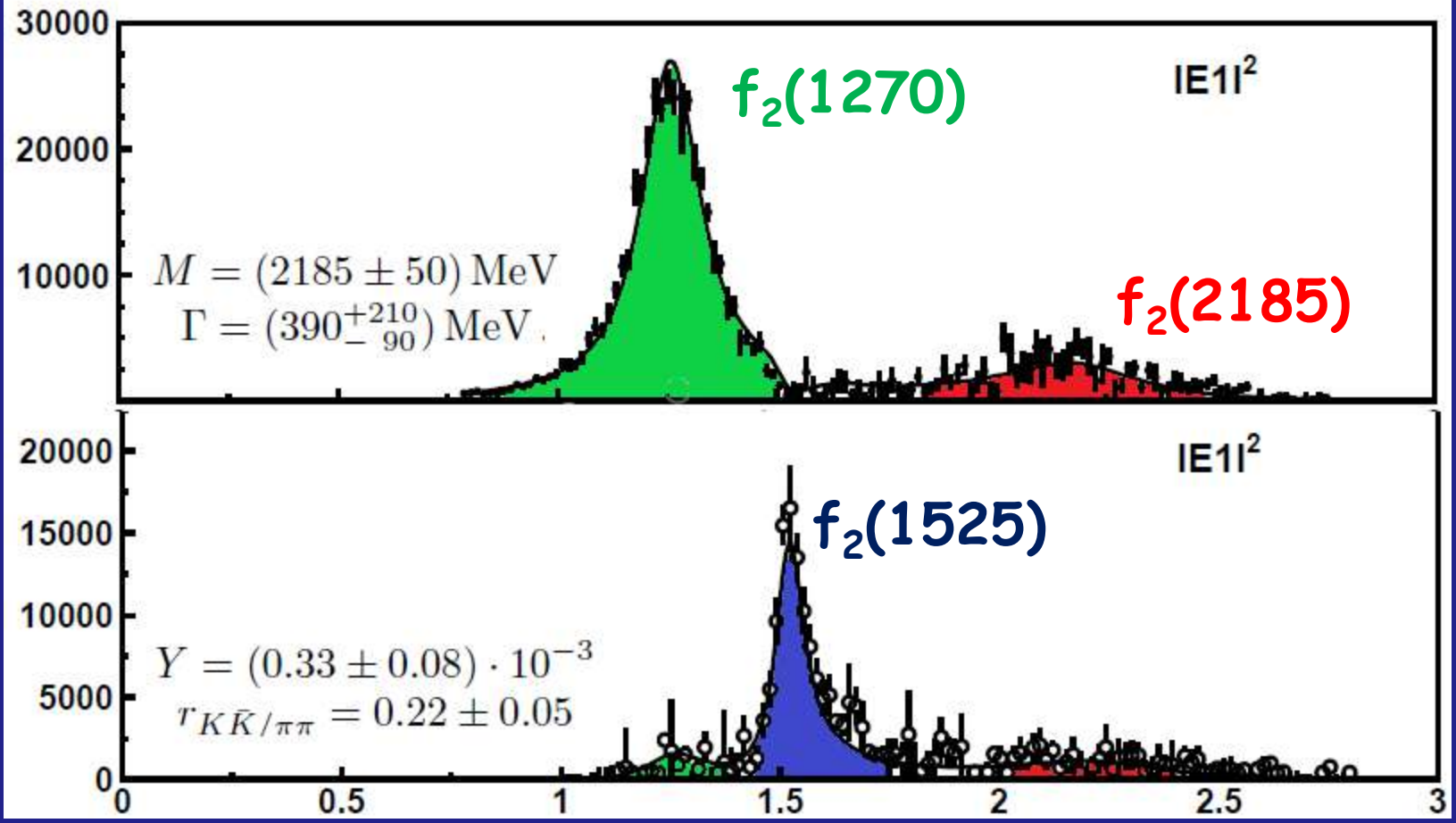
R. Aaij *et al.* [LHCb], "Measurement of the resonant and CP components in $B^0 \to J/\psi\pi^+\pi^-$ decays," Phys. Rev. D 90, no.1, 012003 (2014).
R. Aaij *et al.* [LHCb], "Resonances and *CP* violation in B_s^0 and $\overline{B}_s^0 \to J/\psi K^+K^-$ decays in the mass region above the $\phi(1020)$," JHEP 08, 037 (2017).

Results and Interpretation



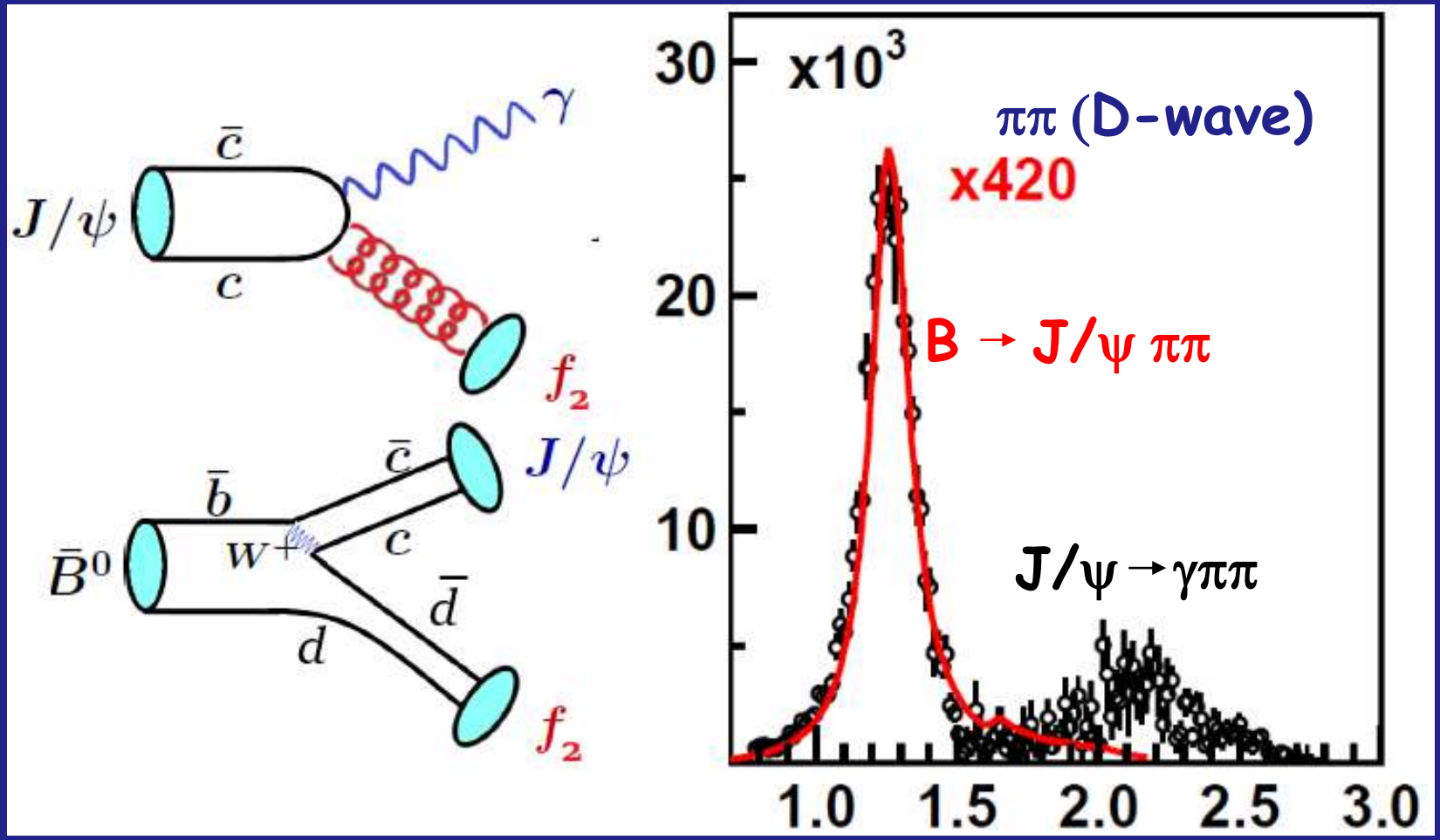
Results and Interpretation

The hidden tensor glueball



	Expected:	Experiment:
Mass	2400 MeV	2185 MeV
Yield	11 10^{-3}	0.33 10^{-3}

Results and Interpretation



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:

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

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

Summary

The scalar glueball has been identified in BESIII data on radiative J/ψ decays. It is spread over several resonances.

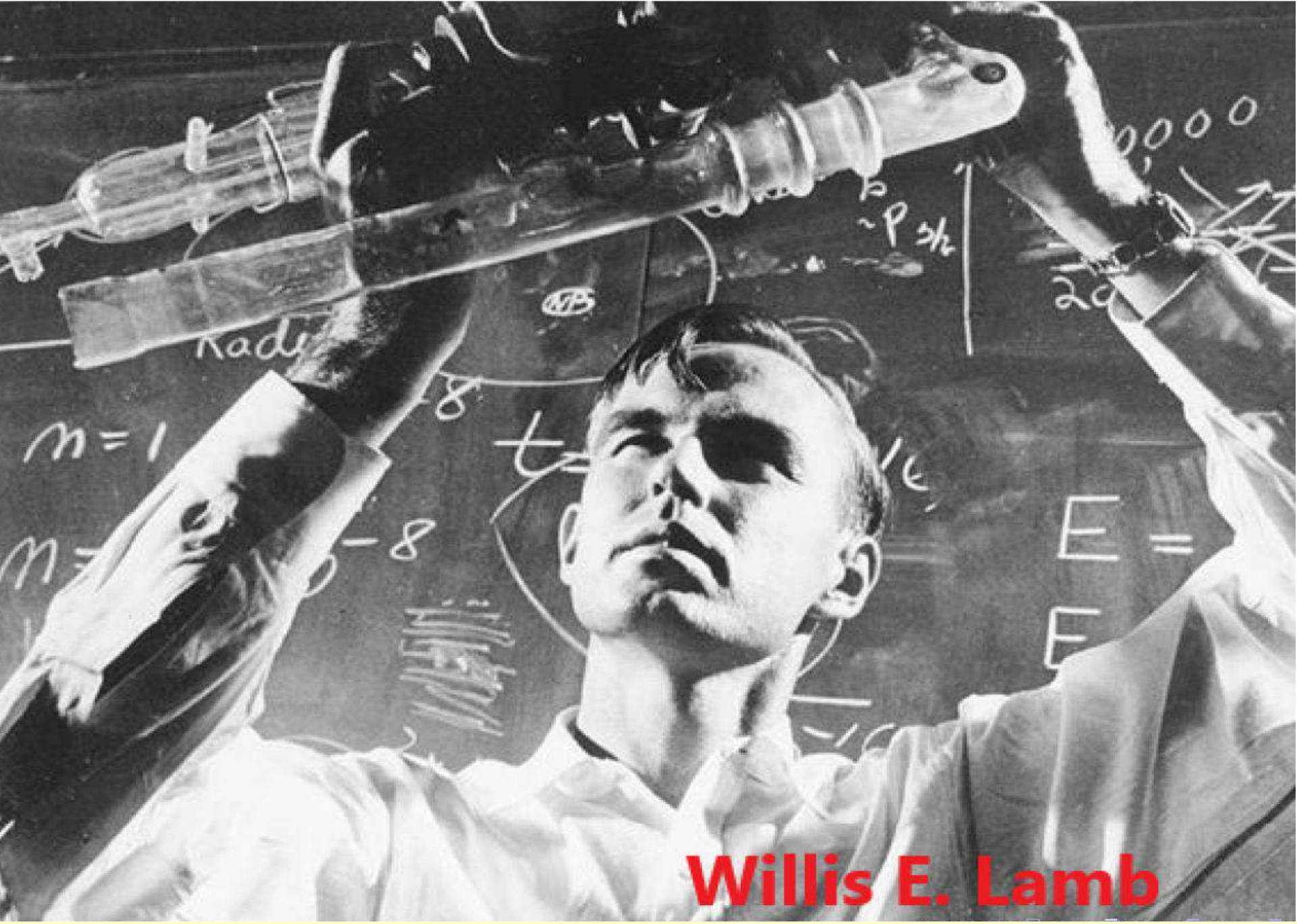
Scalar mesons can be grouped into mainly-singlet and mainly-octet mesons.

The production strength of scalar mesons in radiative J/ψ decays shows a strong peak at 1865 MeV.

The decay pattern of scalar mesons reveal a small glueball component. The glueball fractions peak at 1865 MeV.

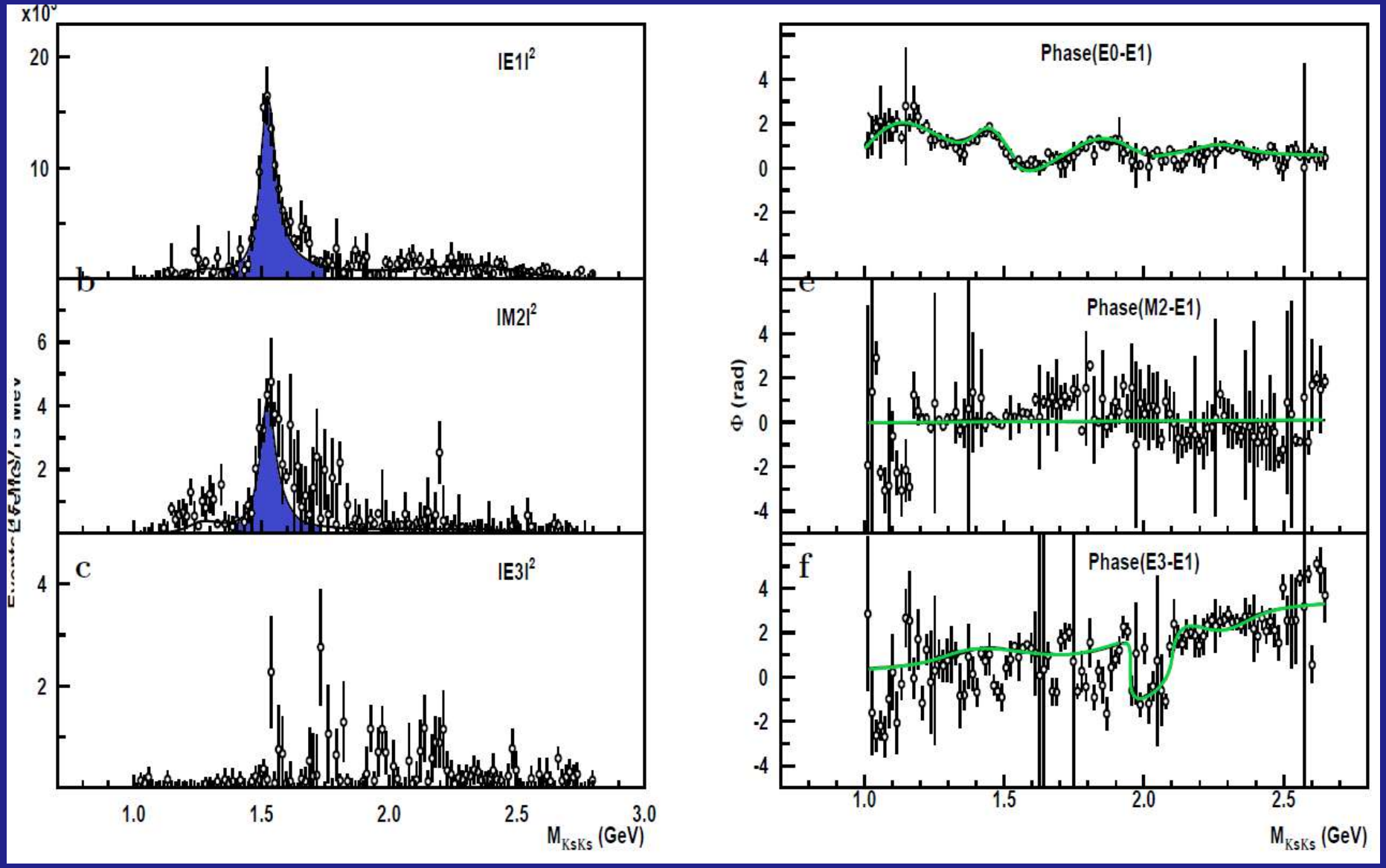
LHCb data on $B_s \rightarrow J/\psi f_0$ show no peak structure at 1865 MeV.

Thank you



The Path to QCD and Glueballs

The $\bar{K}K$ D-wave



New Data from BESIII