The Search for Glueballs

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Rio de Janeiro, 22.09.2023

Feynman lectures on gravitation:

In fact, his work led to two sets of very useful results. The first, purely pedagogical, is embodied in the *Feynman Lectures on Gravitation* (publication [123]). In those lectures, Feynman develops the quantum field theory of a neutral massless spin 2 particle (the *graviton*), emphasizing the special features that arise, in comparison to theories of spin 0 and spin 1 particles, as well as the complications that result for a zero-mass particle in trying to create a self-consistent theory. As in the case of spin 1, masslessness results in redundant degrees of freedom, since Lorentz invariance requires that a *massless* particle can spin only along or opposite to its direction of momentum (positive or negative *chirality*), while a massive spin 2 particle may take up five different orientations relative to any arbitrary quantization direction. Eliminating the unwanted degrees of freedom is achieved by imposing certain "gauge conditions," which in the gravitational case brings about nonlinearity in the form of graviton–graviton interaction. Feynman shows that the classical limit of a properly gauged massless spin 2 theory is described by the Einstein gravitational field equations.[3]

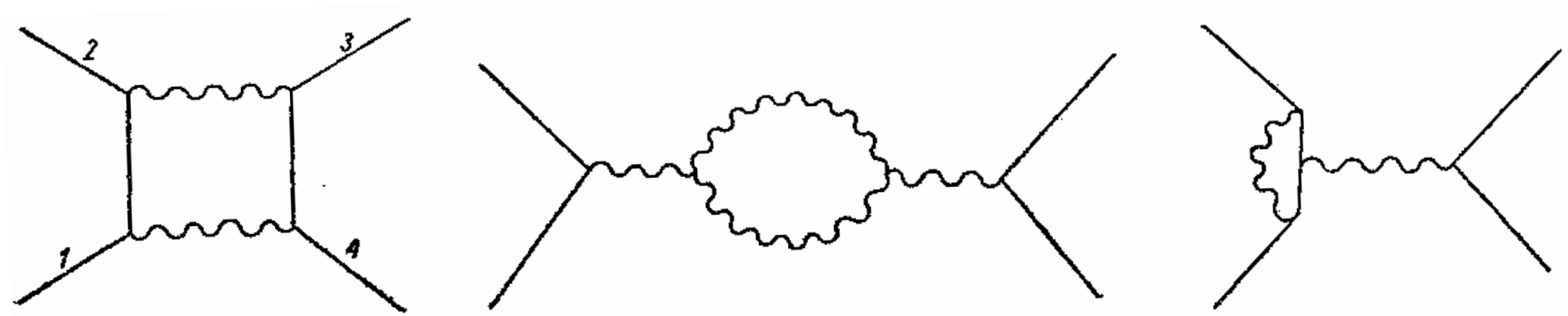


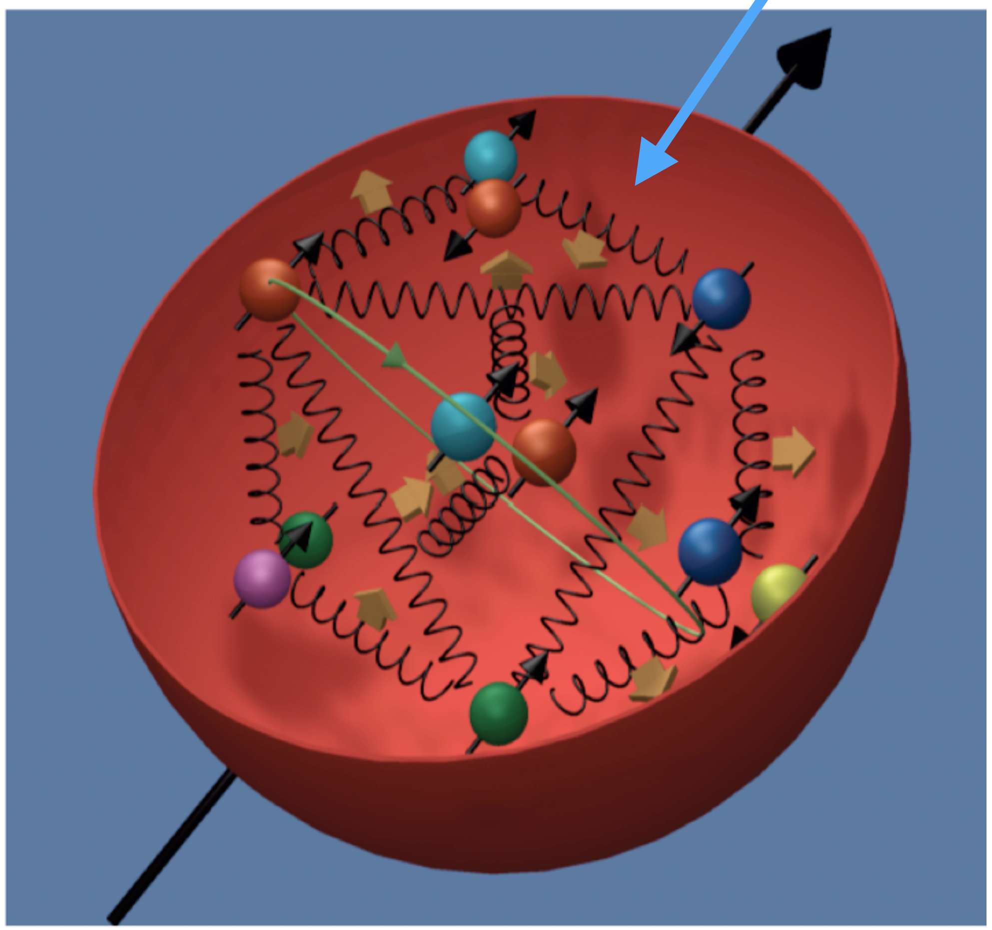
Fig. 5

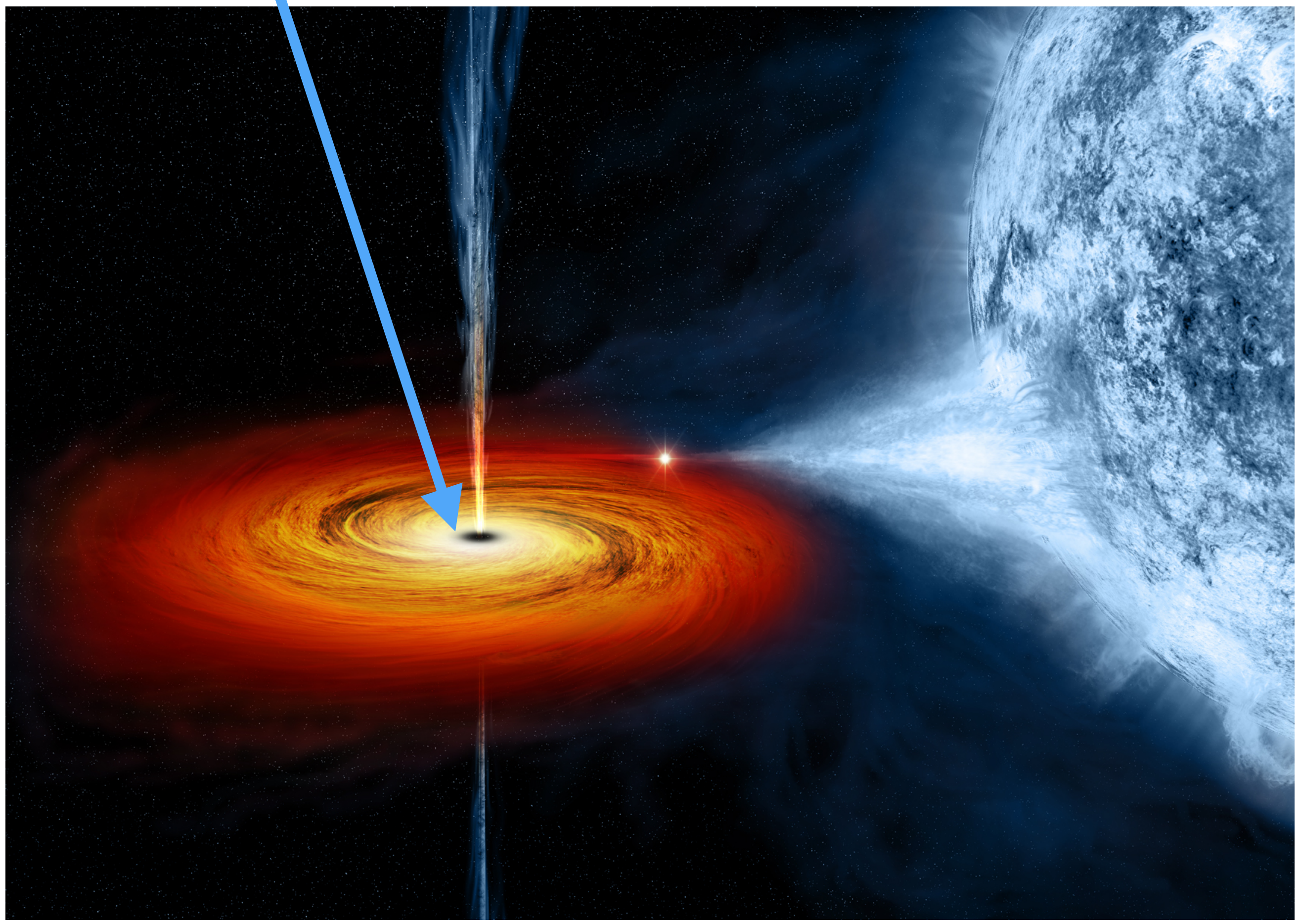
Binding of masses of confined objects

Confining particles:

Massless gluons

Massless gravitons





Credits: NASA/CXC/M.Weiss

Glueballs are one of the most fascinating facets of QCD:

↳ massless gluons come together to form massive states

Hadron physics is the place on earth to study non-Abelian massless gauge boson - gauge boson interaction in a controlled manner.

The glueball hunter’s guide

Use gluon-rich processes to form and find them

Glueballs are super-numerous states among the nonets

➥ precise hadron spectroscopy experiments and analyses

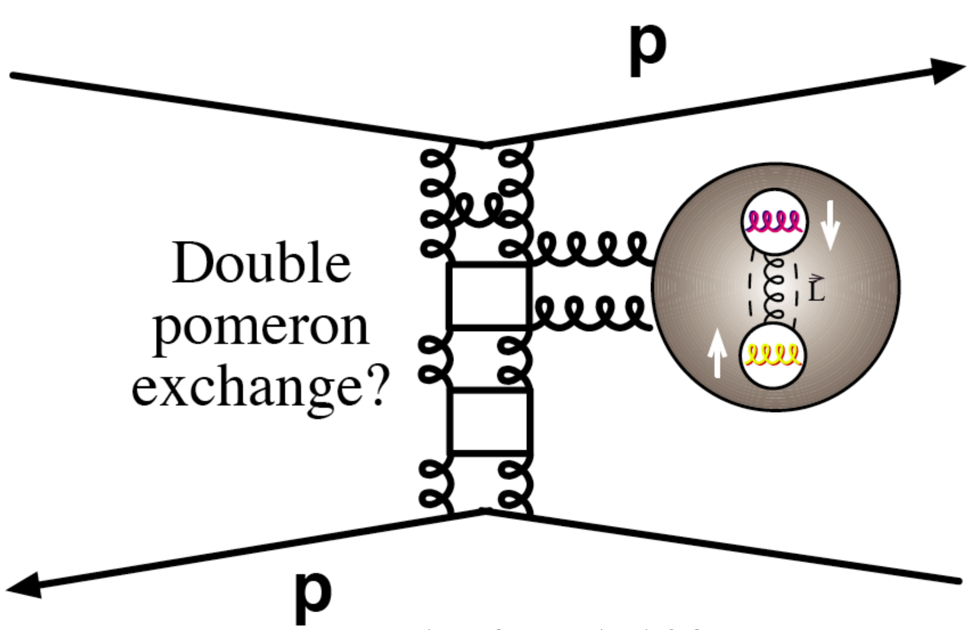
Glueballs decay flavor blind:

➥ study decay patterns

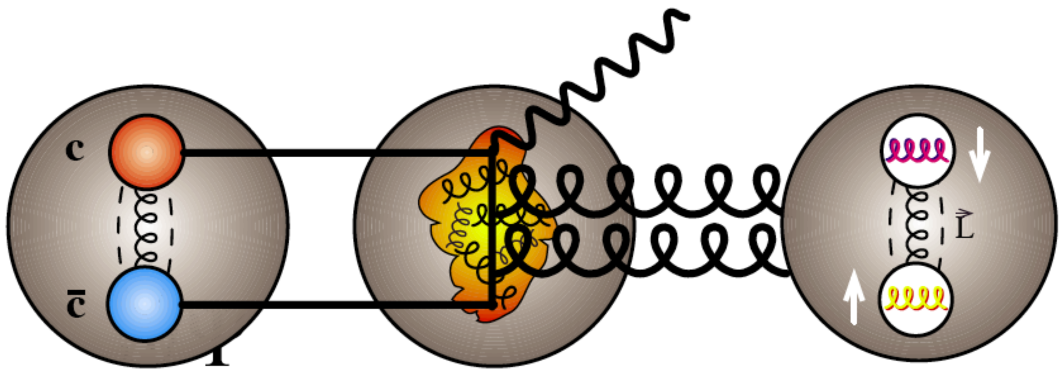
Glueballs do not couple to photons (at least in first order)

➥ use different beam particles

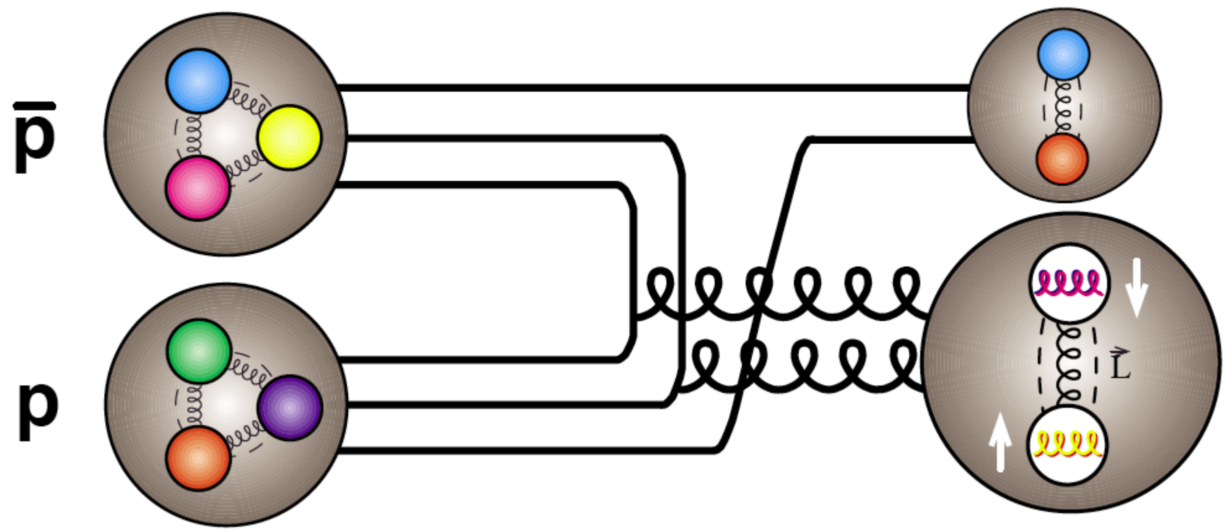
Particle production: “gluon-rich” processes



WA 79, WA 102



MARK III, DM2, BES

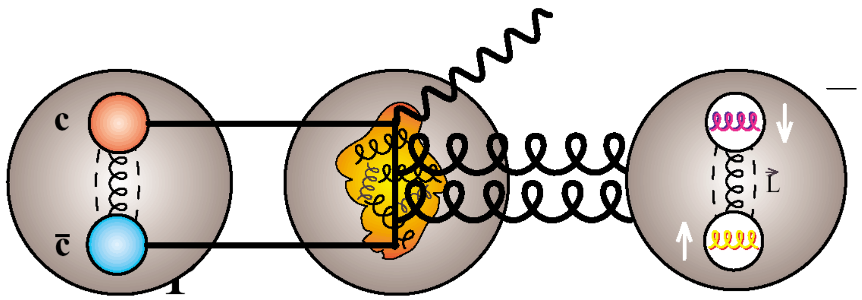


ASTERIX, Crystal Barrel, OBELIX, E835, PANDA

Glueballs

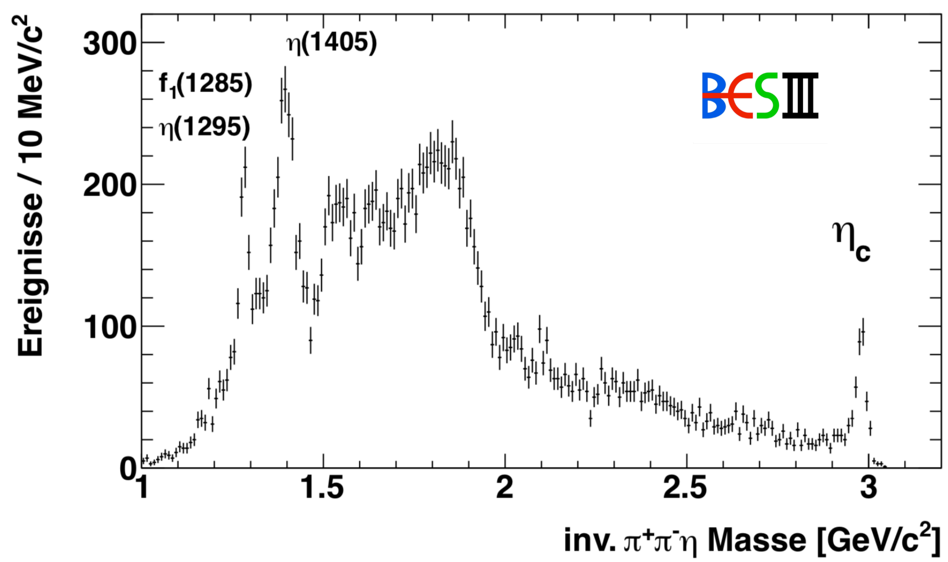
Massless gluons come together to form massive states

Many candidates are proposed and observed in gluon-rich processes:



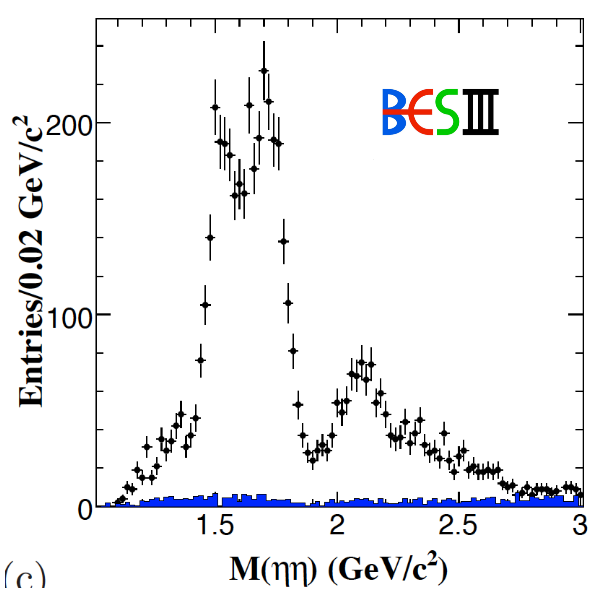
Radiative J/Ψ decays

η(1405)

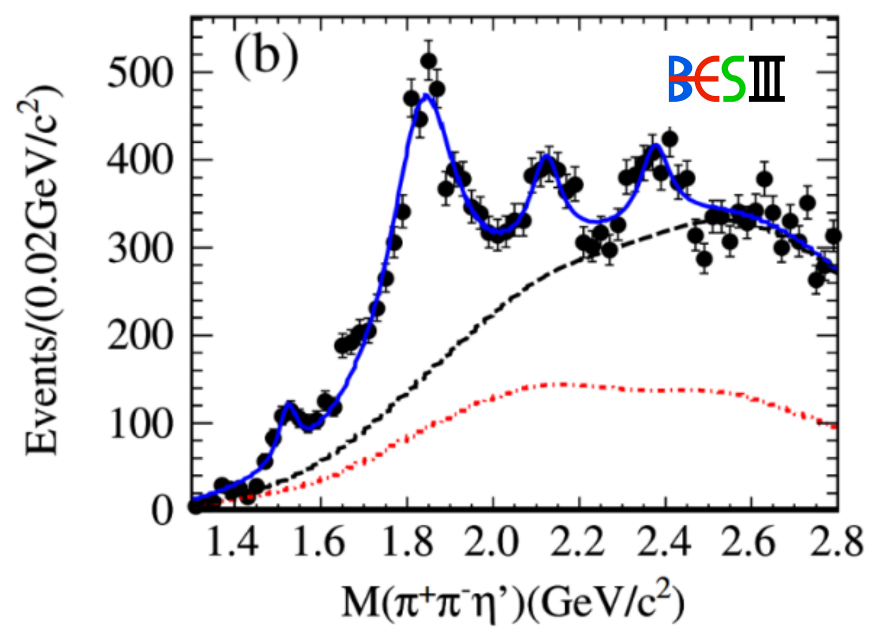


M. Leyhe (Thesis work)

f₀(1500) and f₀(1710)

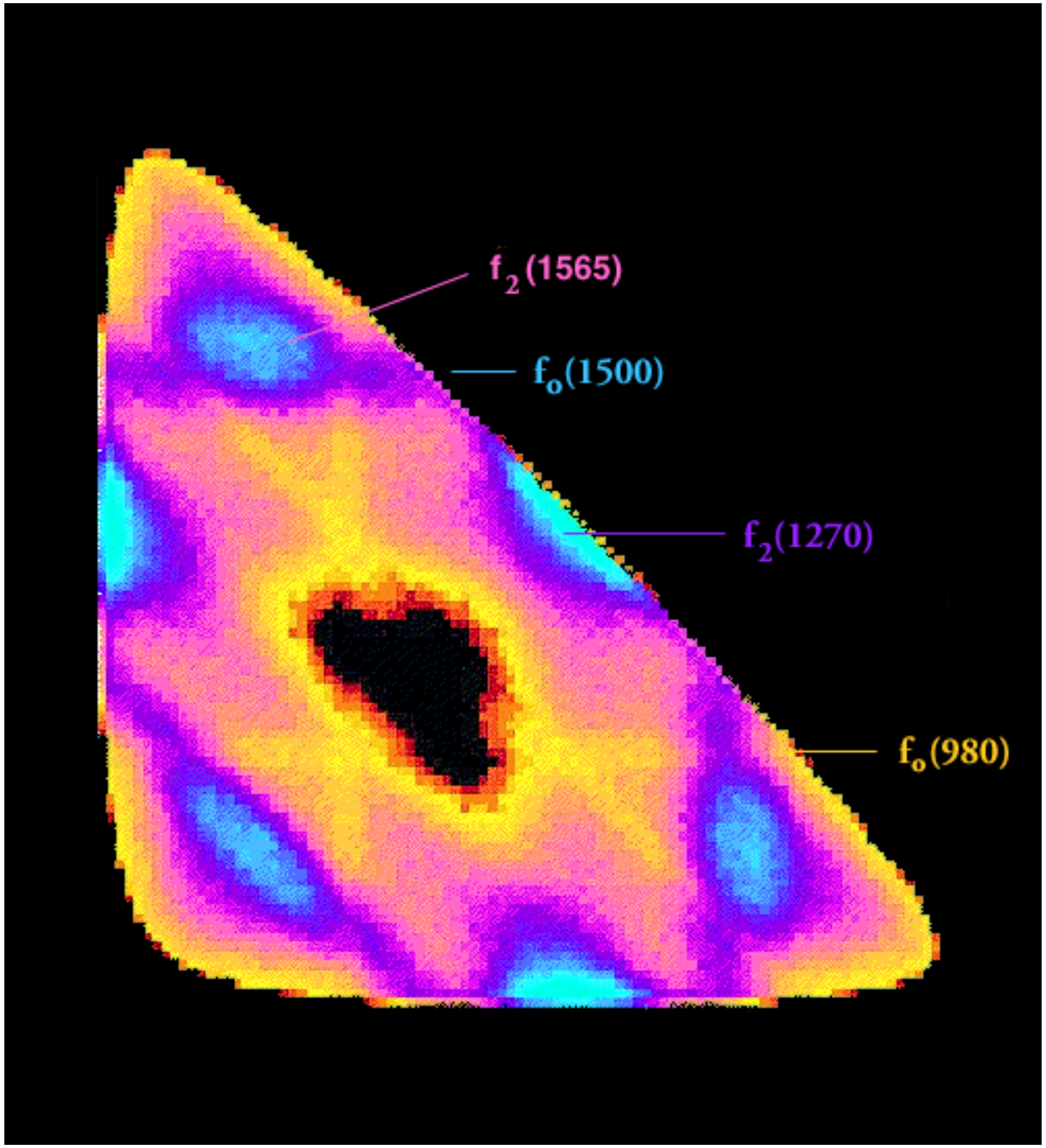


X(1835)



PRL 108, 112003 (2012)
PRL 115, 091803 (2015)

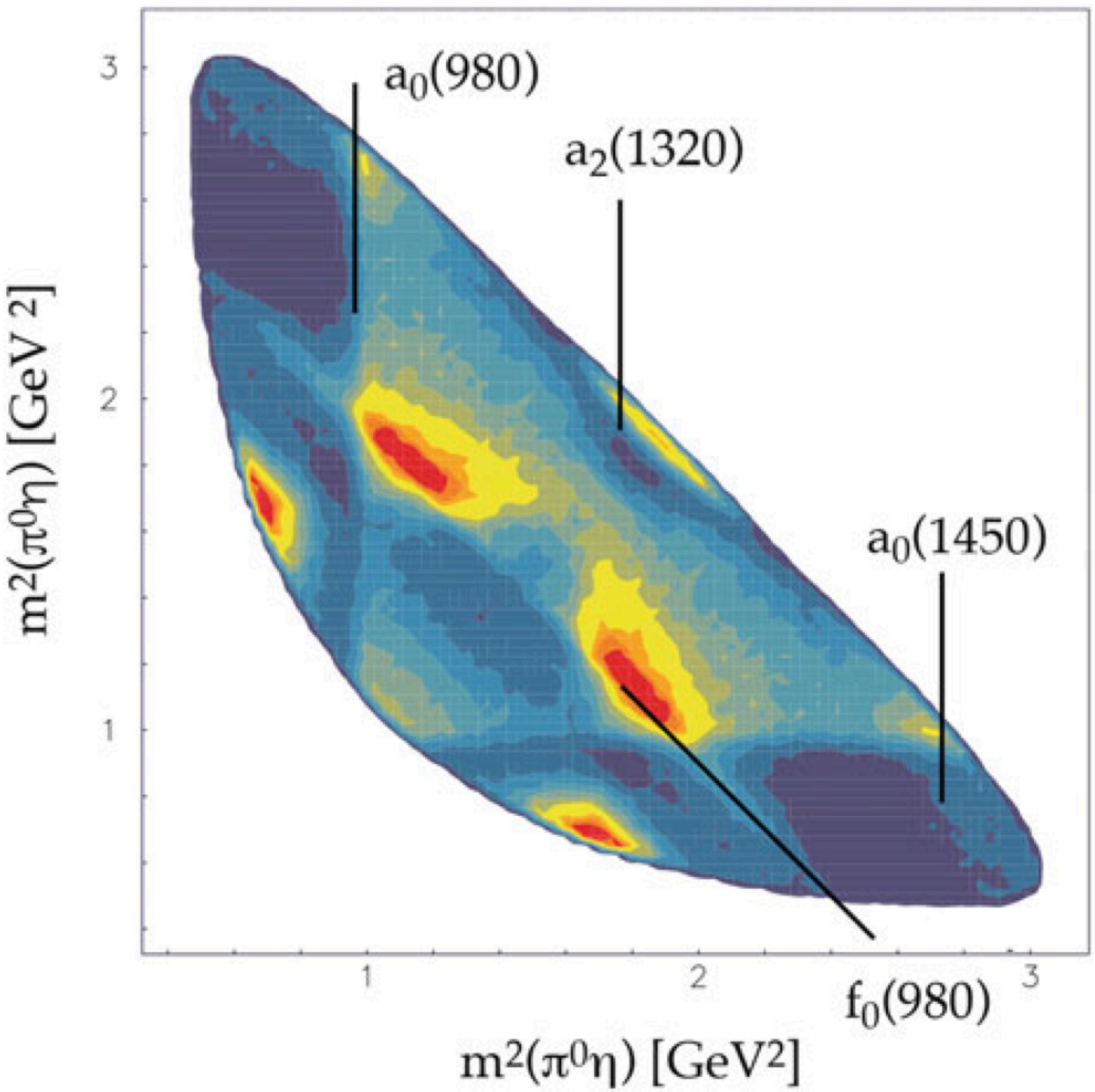
Data: $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ Dalitz plot



Crystal Barrel

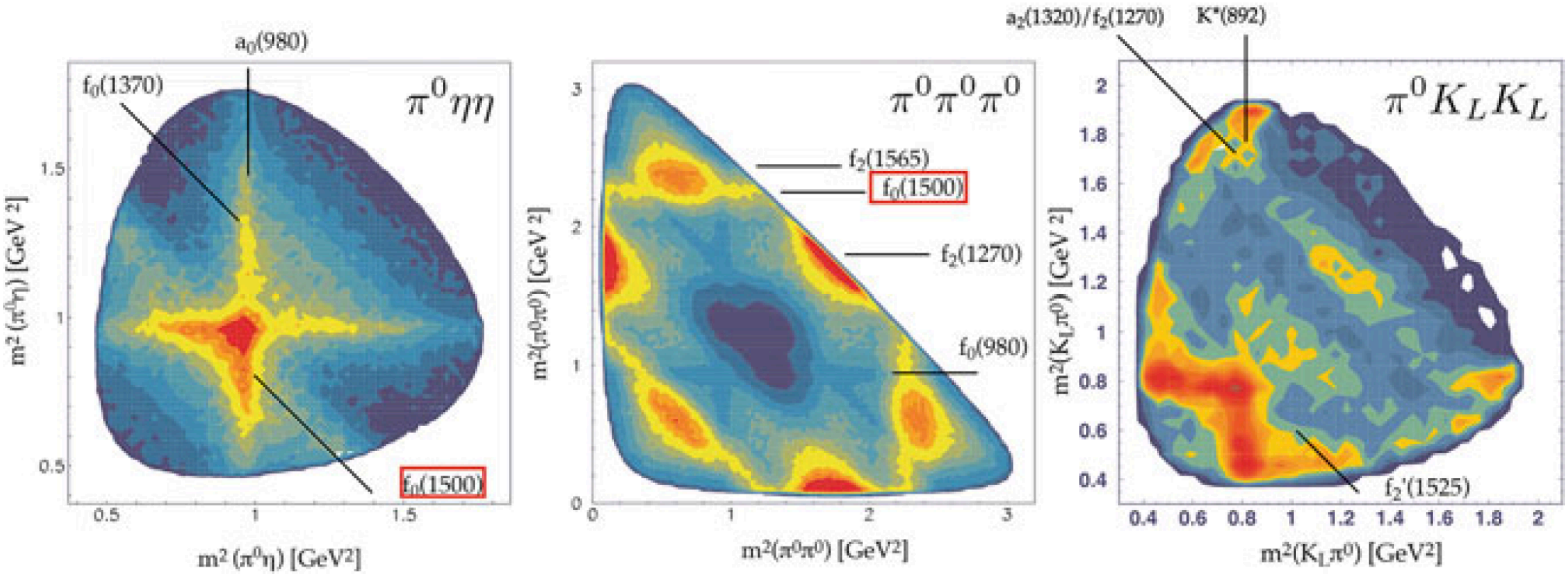
700000 events = 6×700000 entries

Data: $p\bar{p} \rightarrow \pi^0\pi^0\eta$ Dalitz plot



Amsler, C.: Rev. Mod. Phys. 70, 1293 (1998)

Data: pp̄ Dalitz plots



Amsler, C.: Rev. Mod. Phys. 70, 1293 (1998)

Lots of information in the PDG

2018 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)
For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

INSPIRE search

$f_0(1500)$ $I^G(J^{PC}) = 0^+(0^{++})$

See also the mini-reviews on scalar mesons under $f_0(500)$ (see the index for the page number) and on non-$q\bar{q}$ candidates in PDG 2006 , Journal of Physics G33 1 (2006).

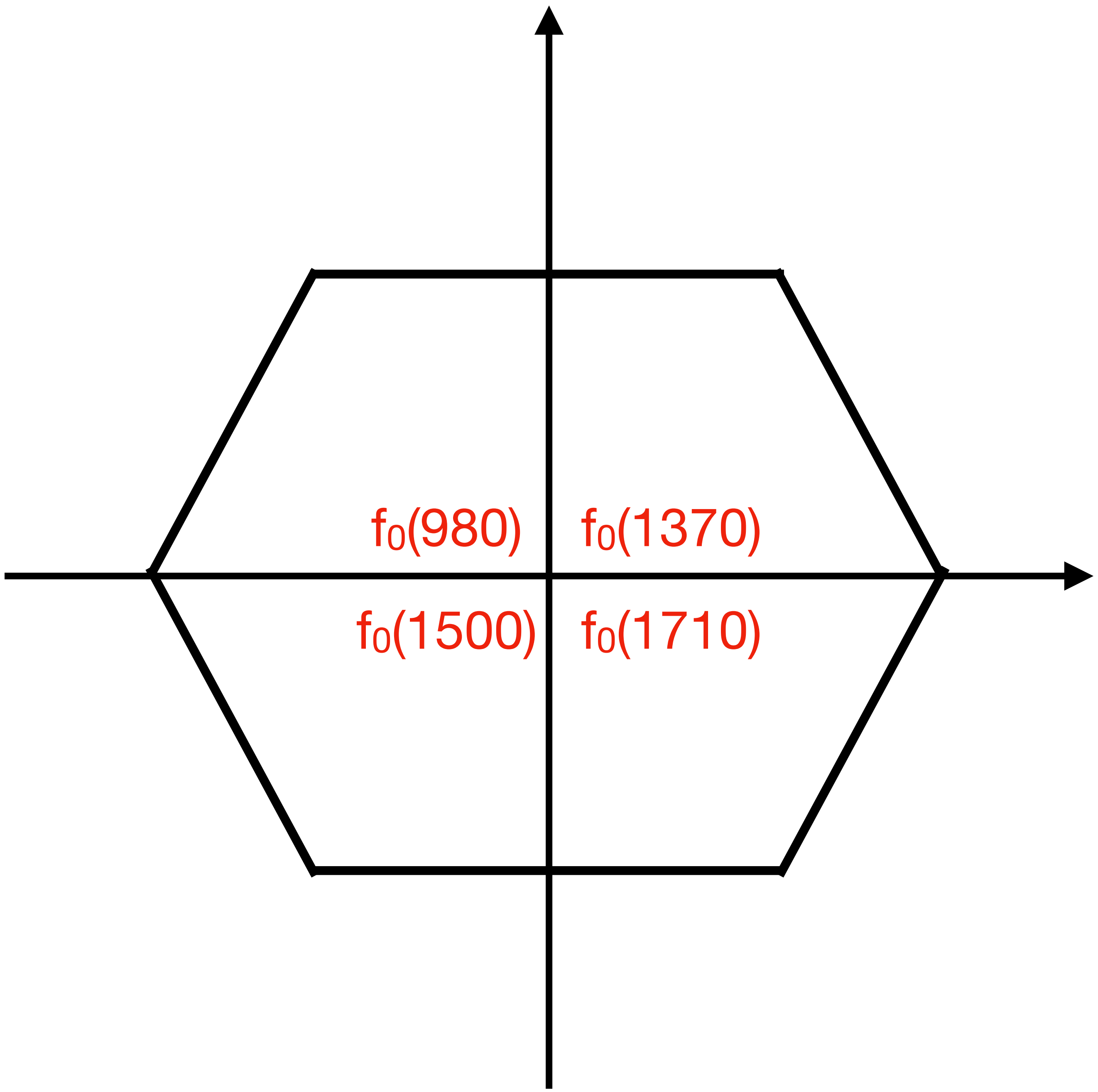
$f_0(1500)$ MASS	1504 ± 6 MeV (S = 1.3)
$f_0(1500)$ WIDTH	109 ± 7 MeV

Decay Modes

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$\pi\pi$	$(34.9 \pm 2.3)\%$	S=1.2	740
Γ_2	$\pi^+\pi^-$	seen		739
Γ_3	$2\pi^0$	seen		740
Γ_4	4π	$(49.5 \pm 3.3)\%$	S=1.2	691
Γ_5	$4\pi^0$	seen		691
Γ_6	$2\pi^+2\pi^-$	seen		686
Γ_7	$2(\pi\pi)_{S\text{-wave}}$	seen		
Γ_8	$\rho\rho$	seen		-1
Γ_9	$\pi(1300)\pi$	seen		143
Γ_{10}	$a_1(1260)\pi$	seen		217
Γ_{11}	$\eta\eta$	$(5.1 \pm 0.9)\%$	S=1.4	515
Γ_{12}	$\eta\eta'(958)$	$(1.9 \pm 0.8)\%$	S=1.7	-1
Γ_{13}	$K\bar{K}$	$(8.6 \pm 1.0)\%$	S=1.1	568
Γ_{14}	$\gamma\gamma$	not seen		752

constrained fit information

The glueball ground state (0^{++}) and the scalar nonet



4 ?? → 1 particle super numerous ⇒ which one is the glueball??

The f_0(980) - glueball?

Scalar Glueball–Quarkonium Mixing and the Structure of the QCD Vacuum
John Ellis, Hirotsugu Fujii and Dmitri Kharzeev

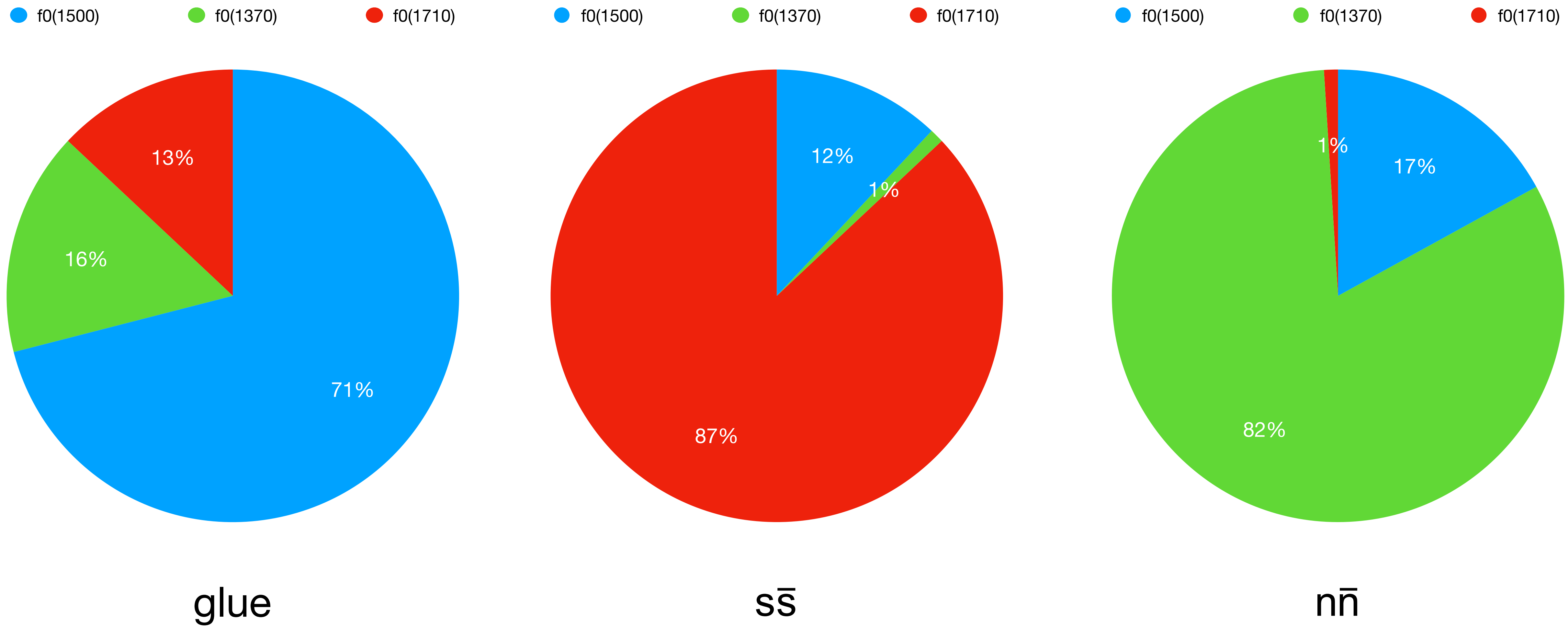
CERN-TH/99-278

Sum rules based on the Ward identities of broken scale invariance:

We have found empirically that the sum rules are probably dominated by the f_0(980) state, with contributions from the lighter and heavier f_0 mesons each contributing around the 10% level. Does this mean that one should identify the f_0(980) as the lightest scalar glueball?

Certainly not until one has analyzed the pattern of mixing with $q\bar{q}$ states, a complicated issue which we approach in this paper.

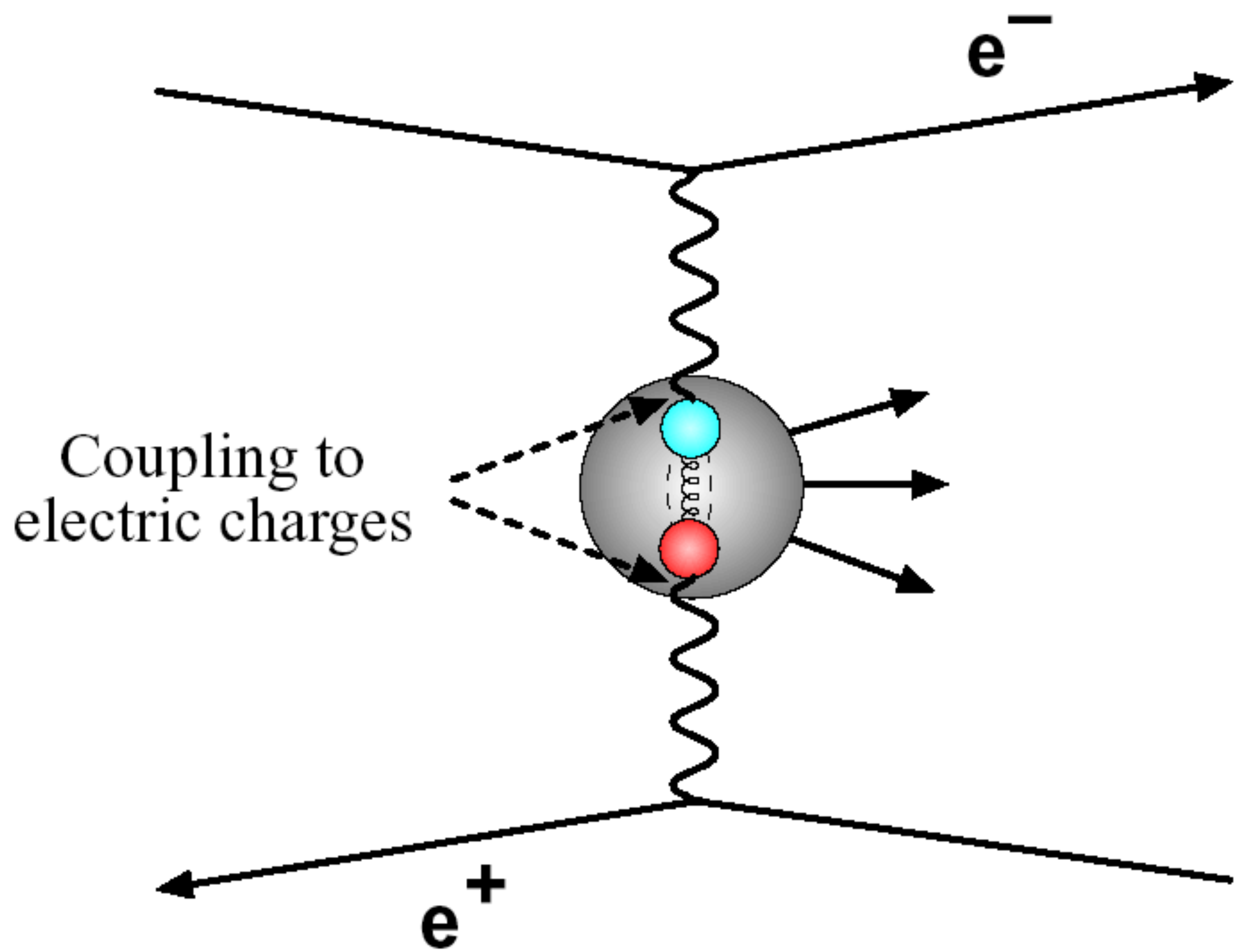
The mixing of states



Different mixing schemes exist.

ISSN 0075-8450 ISSN 1616-6361 (electronic)
Lecture Notes in Physics
ISBN 978-3-319-98526-8 ISBN 978-3-319-98527-5 (eBook)
https://doi.org/10.1007/978-3-319-98527-5

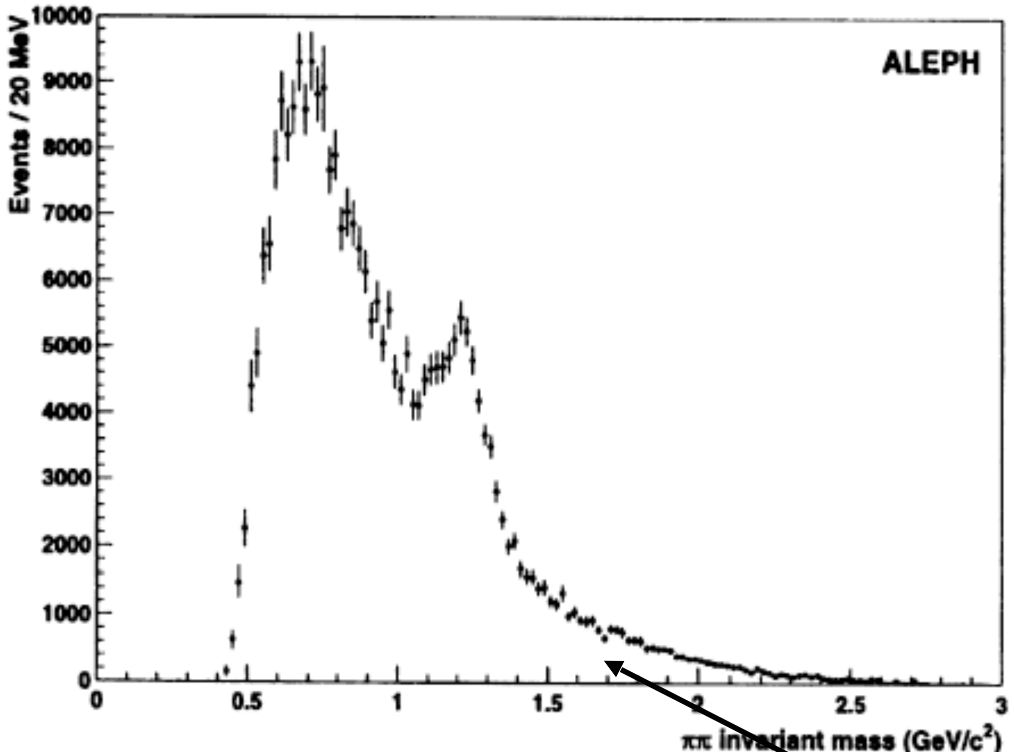
Meson production in γγ collisions

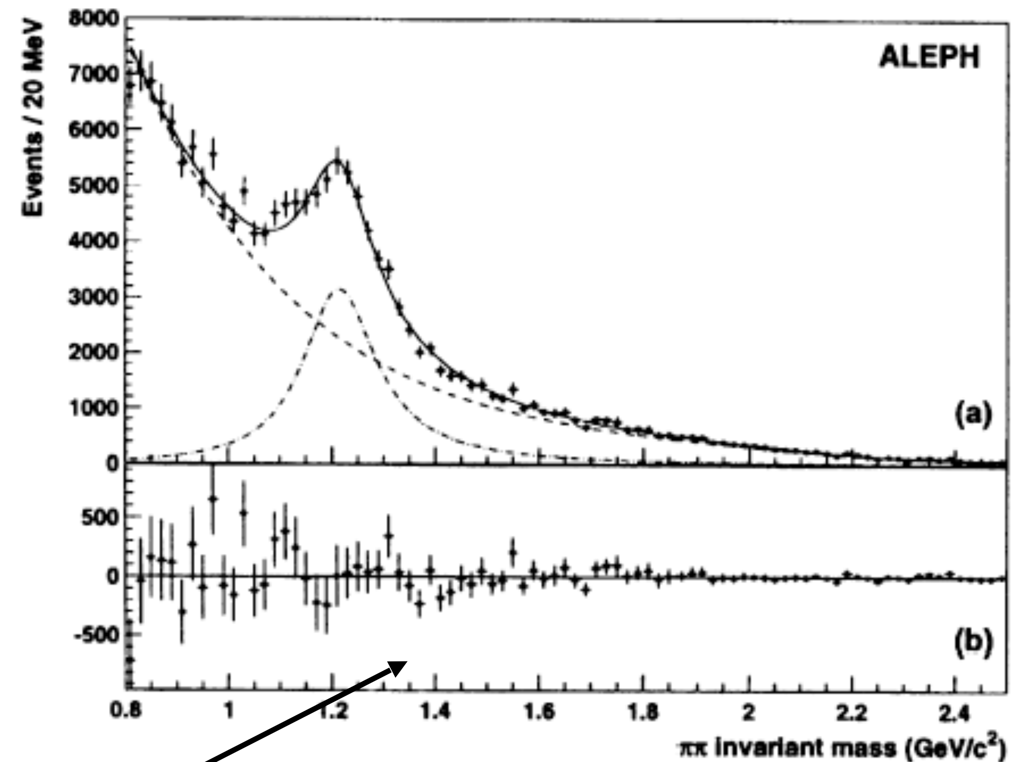


… act as anti-glueball filter

$\gamma\gamma$ collisons from ALEPH

(anti-glueball filter)





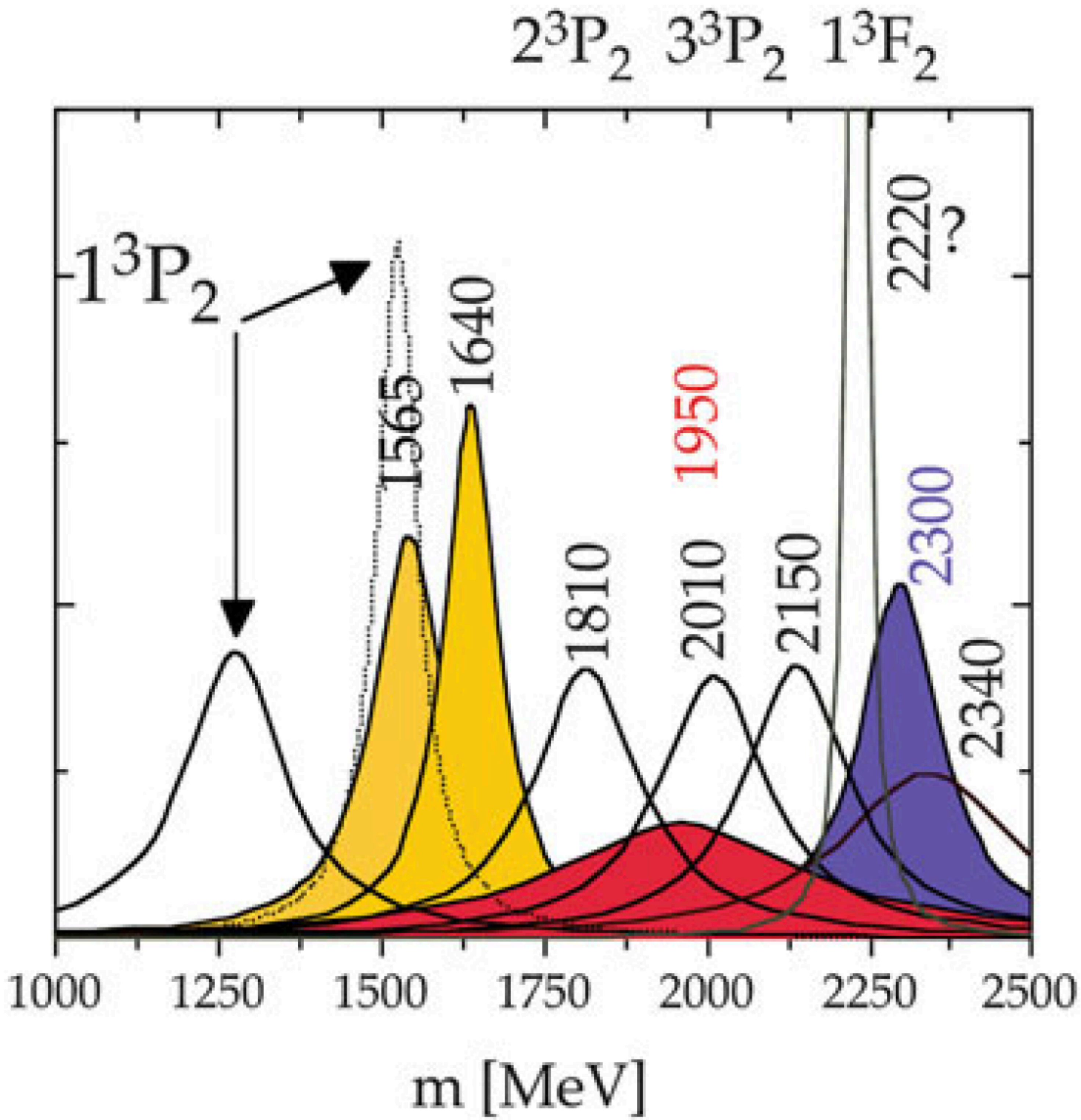
no $f_0(1500)$

upper limit:

$$\Gamma(\gamma\gamma \rightarrow f_0(1500)) \cdot \mathit{BR}\,(f_0(1500) \rightarrow \pi^+\pi^-) < 0.31 \text{ keV}$$

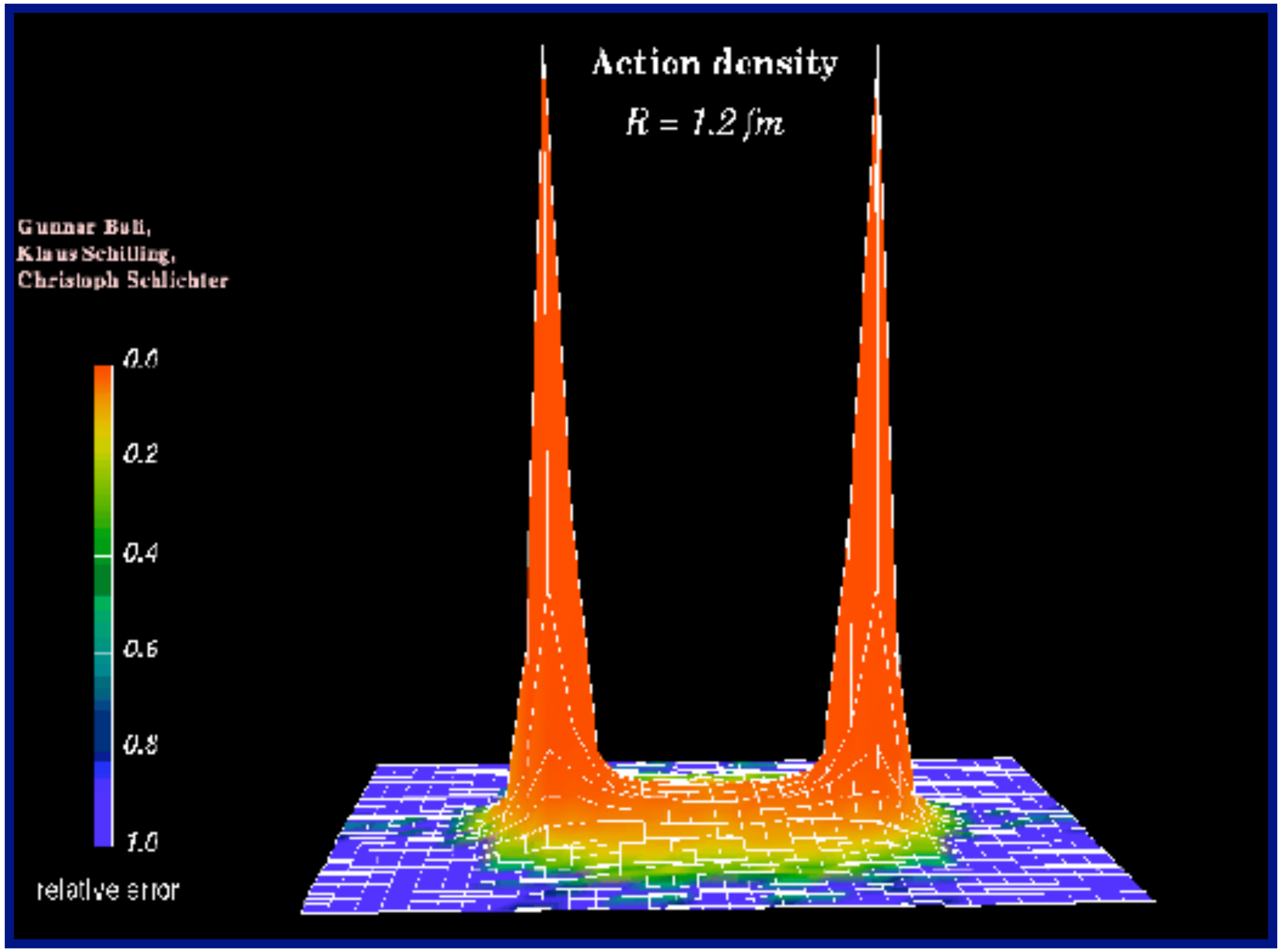
Phys. Lett. B472 (2000) 189.

The tensor ($J^{PC} = 2^{++}$) particles



Taken from Claude Amsler: Lecture Notes in Physics
ISBN 978-3-319-98526-8 ISBN 978-3-319-98527-5 (eBook)

QCD on the computer: lattice calculations



Quark separation: 1.2 fm; string tension (OGE) : 16 t !

QCD flux tube (LGT, G.Bali et al.; hep-ph/010032)

Towards the glueball spectrum from unquenched lattice QCD

E. Gregory, A. Irving, B. Lucini, C. McNeile, A. Rago, C. Richards, E. Rinaldi, JHEP10 (2012) 170, arXiv:1208.1858 [hep-lat]

J^{PC}	Mass MeV			
	Unquenched	Quenched		
	This work	M&P	Ky	Meyer
0^{-+}		2590(40)(130)	2560(35)(120)	2250(60)(100)
2^{-+}	3460(320)	3100(30)(150)	3040(40)(150)	2780(50)(130)
0^{-+}	4490(590)	3640(60)(180)		3370(150)(150)
2^{-+}				3480(140)(160)
5^{-+}				3942(160)(180)
0^{--} (exotic)	5166(1000)			
1^{--}		3850(50)(190)	3830(40)(190)	3240(330)(150)
2^{--}	4590(740)	3930(40)(190)	4010(45)(200)	3660(130)(170)
2^{--}				3.740(200)(170)
3^{--}		4130(90)(200)	4200(45)(200)	4330(260)(200)
1^{+-}	3270(340)	2940(30)(140)	2980(30)(140)	2670(65)(120)
3^{+-}	3850(350)	3550(40)(170)	3600(40)(170)	3270(90)(150)
3^{+-}				3630(140)(160)
2^{+-} (exotic)		4140(50)(200)	4230(50)(200)	
0^{+-} (exotic)	5450(830)	4740(70)(230)	4780(60)(230)	
5^{+-}				4110(170)(190)
0^{++}	1795(60)	1730(50)(80)	1710(50)(80)	1475(30)(65)
2^{++}	2620(50)	2400(25)(120)	2390(30)(120)	2150(30)(100)
0^{++}	3760(240)	2670(180)(130)		2755(30)(120)
3^{++}		3690(40)(180)	3670(50)(180)	3385(90)(150)
0^{++}				3370(100)(150)
0^{++}				3990(210)(180)
2^{++}				2880(100)(130)
4^{++}				3640(90)(160)
6^{++}				4360(260)(200)

M&P: C. J. Morningstar and M. J. Peardon, The glueball spectrum from an anisotropic lattice study, Phys. Rev. D60 (1999) 034509, [hep-lat/9901004].

Ky: Y. Chen et al., Glueball spectrum and matrix elements on anisotropic lattices, Phys. Rev. D73 (2006) 014516, [hep-lat/0510074].

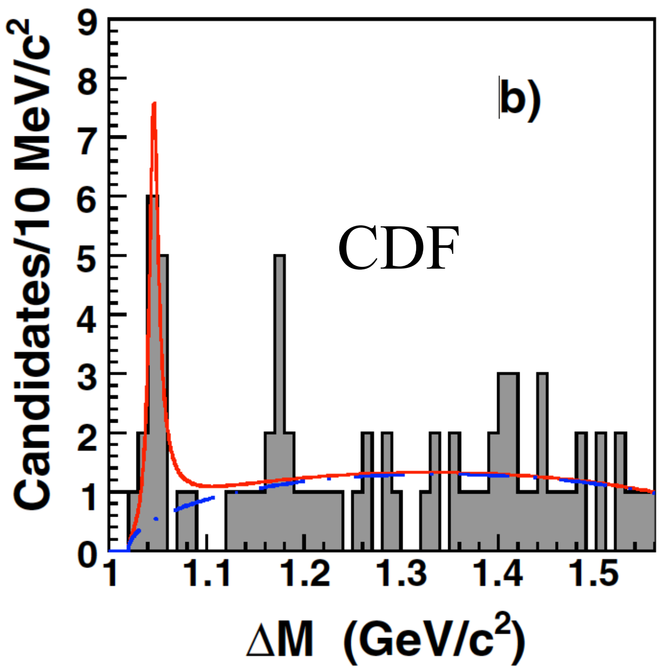
H. B. Meyer, Glueball Regge trajectories, hep-lat/0508002. Ph.D. Thesis.

Glueballs

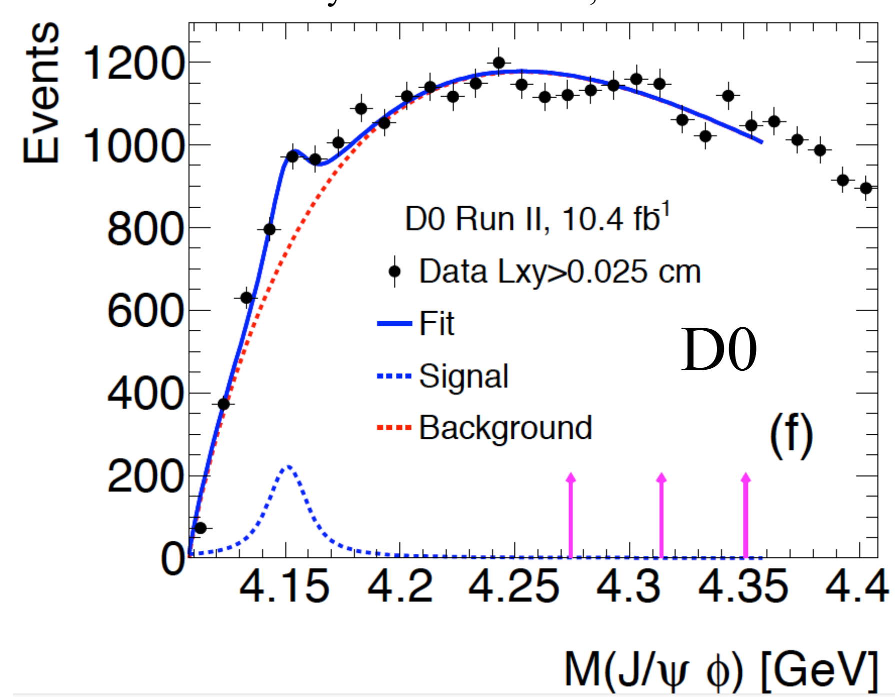
My personal glueball candidate for 1⁺⁺ glueball: X(4140) M= 4147 MeV/c², Γ = ~19 MeV

↳ decay mode J/ψ ϕ (flavor blind)

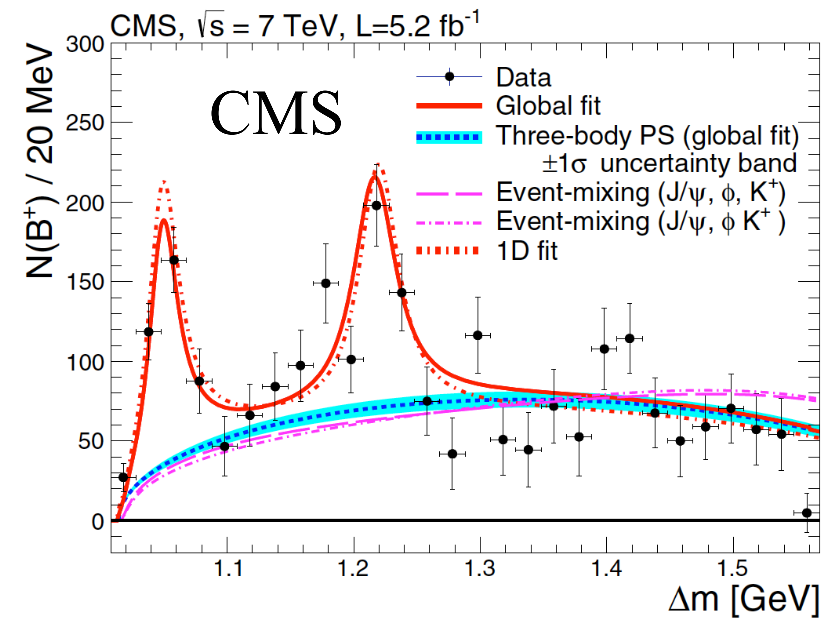
Phys.Rev.Lett. 102 (2009) 242002

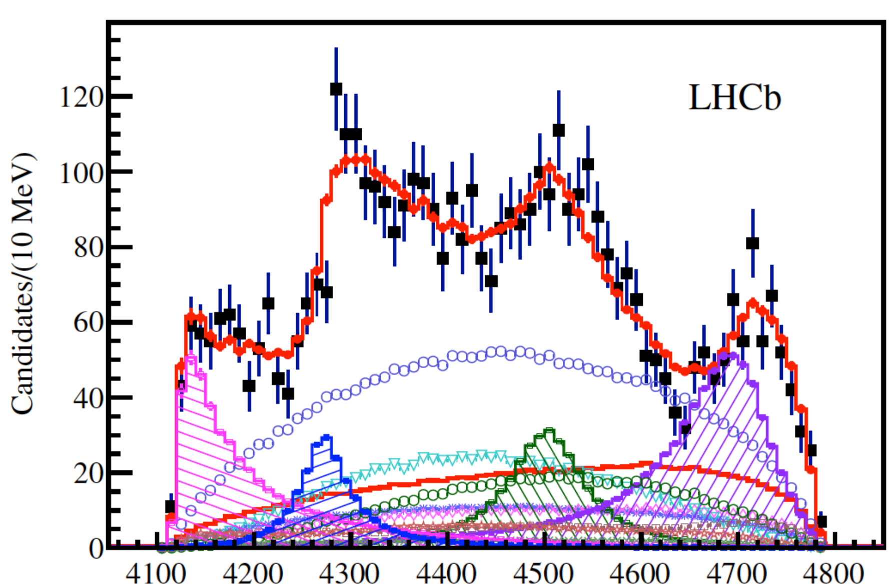


Phys. Rev. Lett. 115, 232001

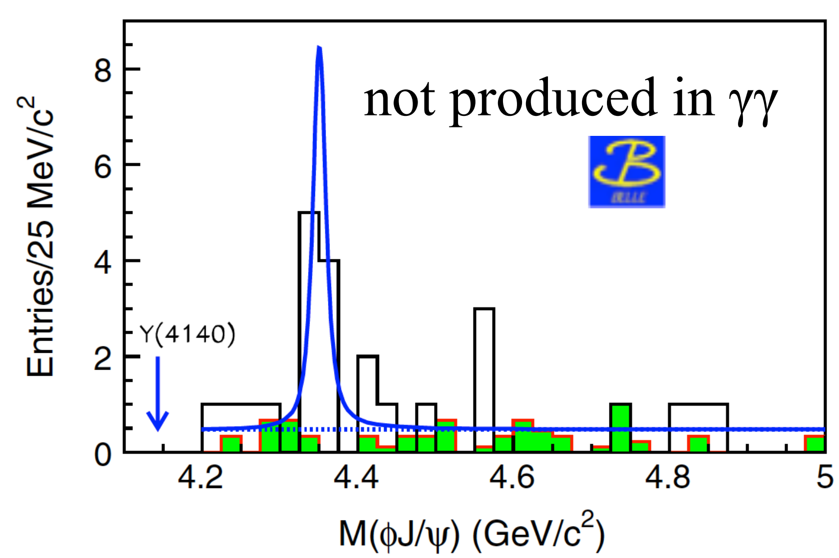


Phys.Lett. B734 (2014) 261-281

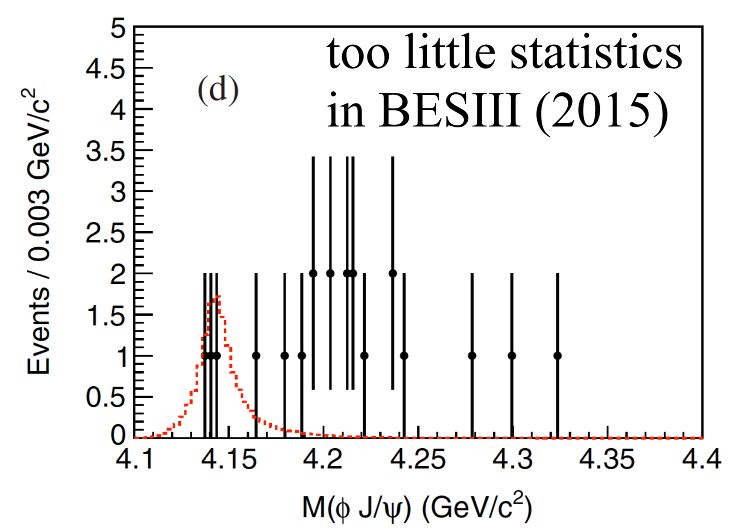




Phys.Rev.Lett. 118 (2017) no.2, 022003

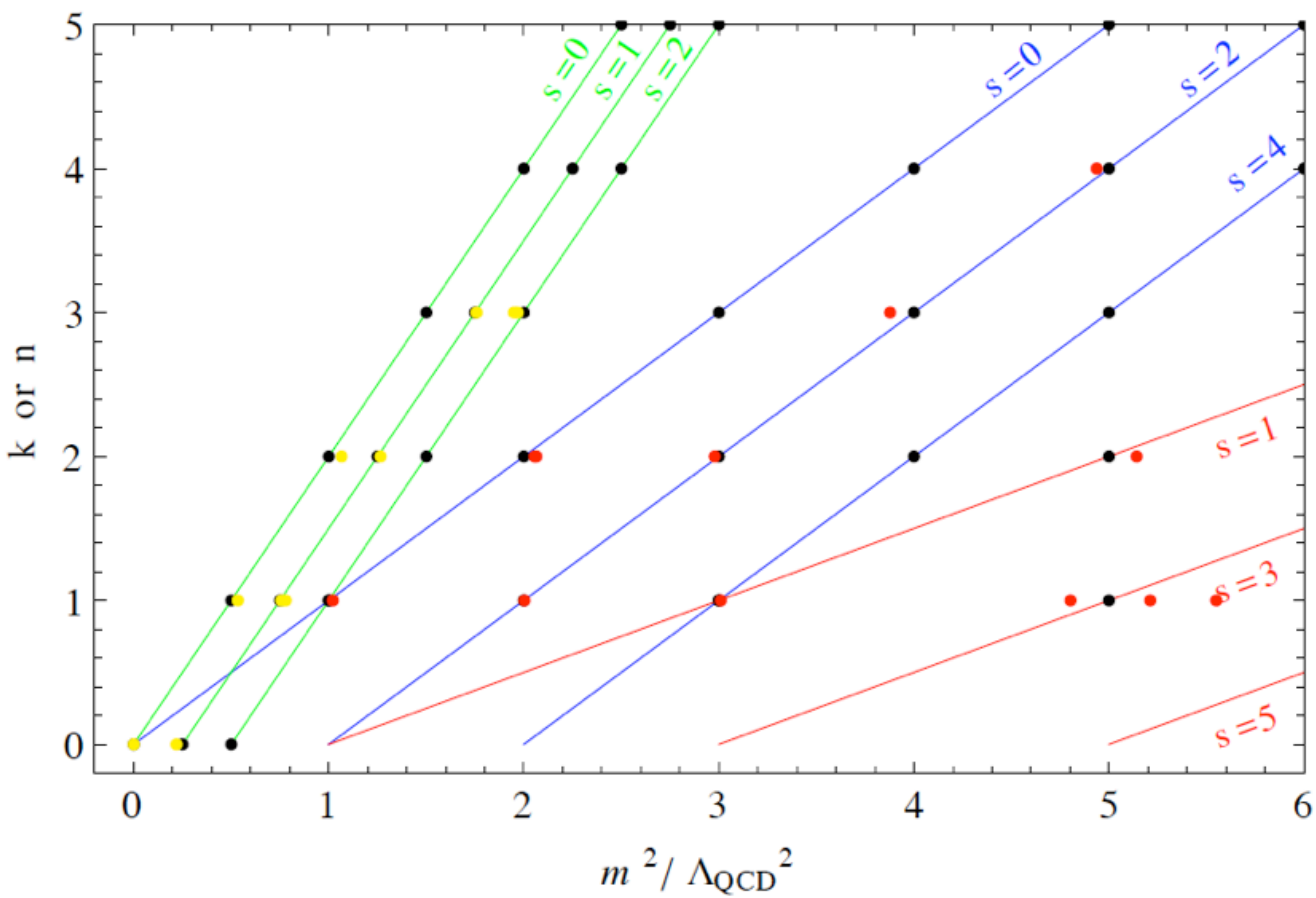


Phys.Rev.Lett. 104 (2010) 112004



Phys.Rev. D91 (2015) no.3, 032002

Glueballs on Regge trajectories like mesons?

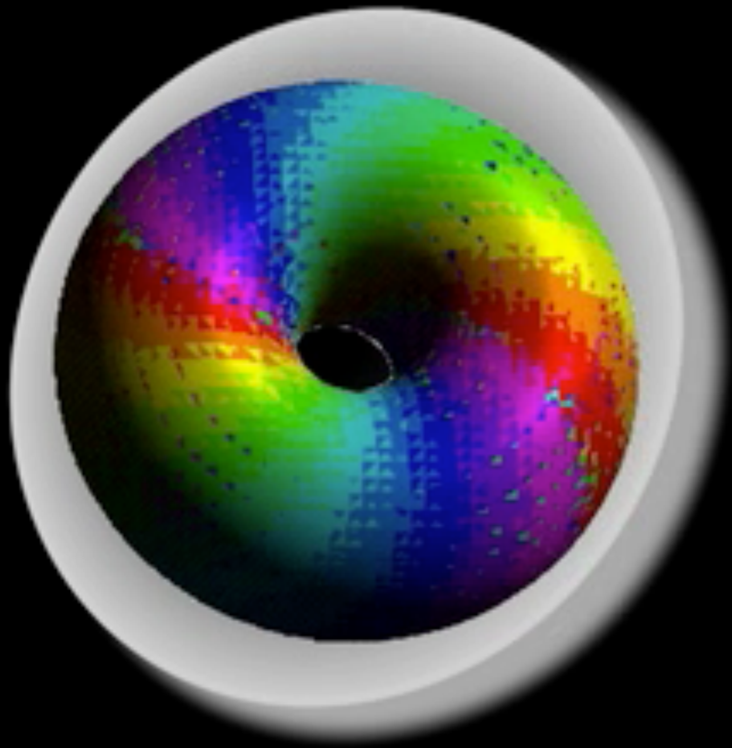


Marco Bochicchio; arXiv:1308.2925

Harvey B. Meyer, Michael J. Teper; Phys.Lett. B605 (2005) 344-354

G. S. Bali et al.; arXiv:1302.1502

Glueballs



Glueballs, closed fluxtubes and $\eta(1440)$

Ludvig Faddeev, Antti Niemi and Ulrich Wiedner

Phys.Rev.D70:114033, 2004

String theory adds new component through ADS/CFT

Glueball Mass Spectrum from Supergravity*

LBNL-42987
UCB-PTH-99/08
hep-th/9903142
see also: JHEP 9901:017,1999

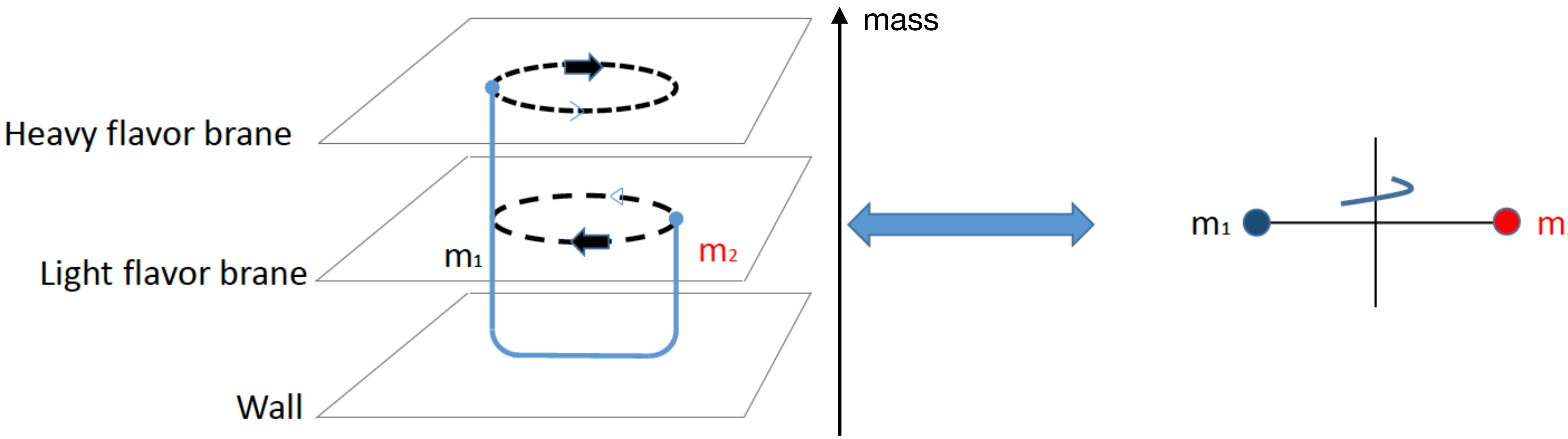
Csaba Csáki† and John Terning
Theoretical Physics Group
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720
and
Department of Physics
University of California, Berkeley, CA 94720

...

TABLE III. Masses of the first few 0^{++} glueballs in QCD_4, in GeV, from supergravity compared to the available lattice results. The first column gives the lattice result [7,16,17], the second the supergravity result for $a = 0$ while the third the supergravity result in the $a \to \infty$ limit. The change from $a = 0$ to $a = \infty$ in the supergravity predictions is tiny. Note, that for the excited state the supergravity calculation came before the lattice results.

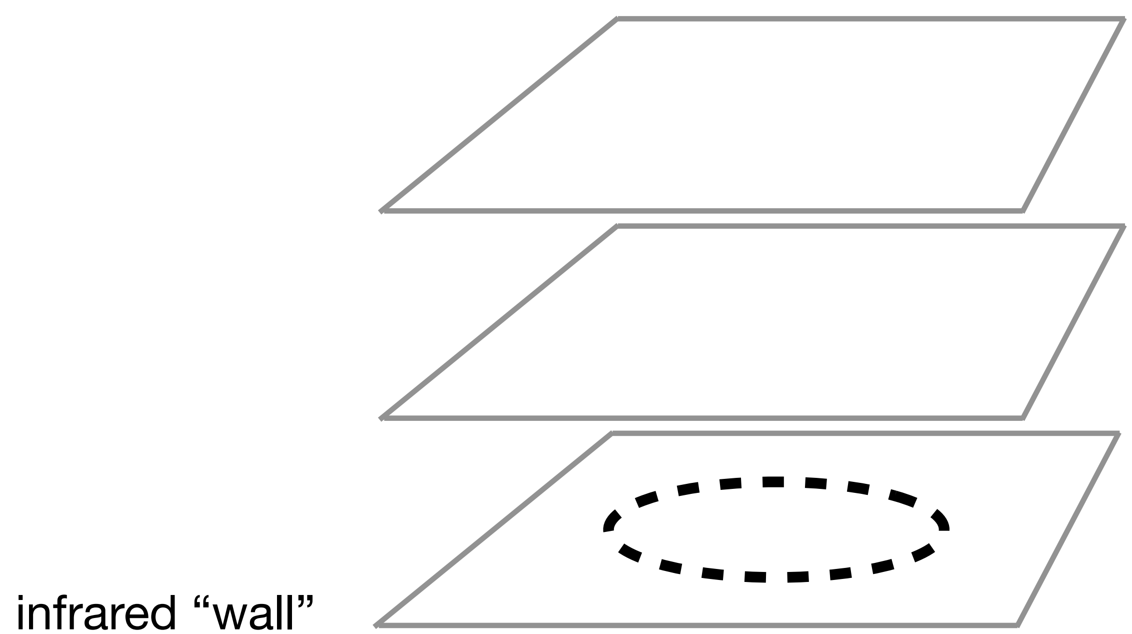
state	lattice, $N = 3$	supergravity $a = 0$	supergravity $a \to \infty$
0^{++}	1.61 ± 0.15	1.61 (input)	1.61 (input)
0^{++*}	2.48 ± 0.18	2.55	2.56
0^{++**}	-	3.46	3.48
0^{++***}	-	4.36	4.40

Holography Inspired Stringy Hadron model



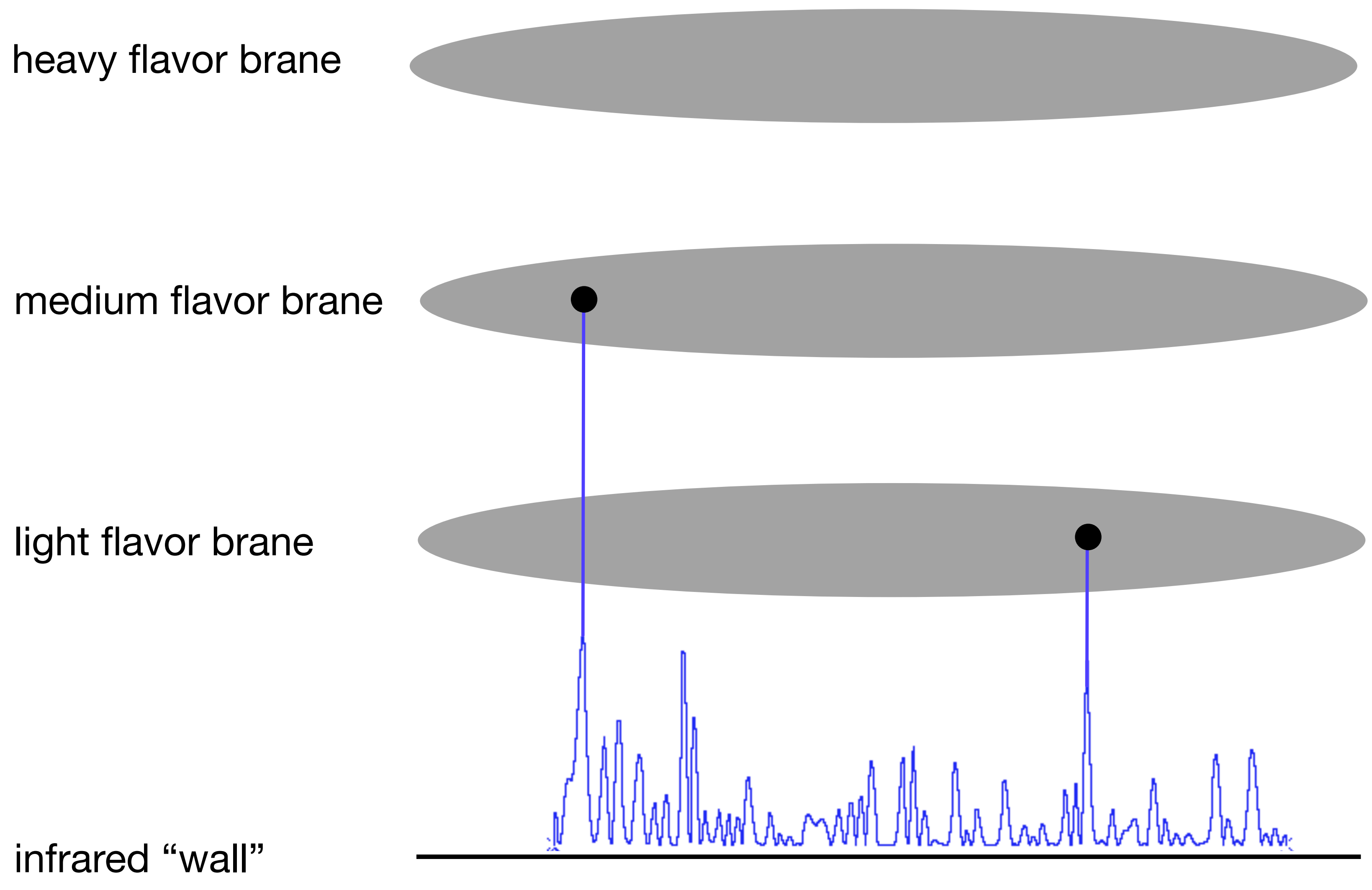
Rotating holographic string
Connected to different flavor branes

Rotating string in flat space-time
with massive endpoints



Glueball as closed rotating string

Holography Inspired Stringy Hadron model: decays



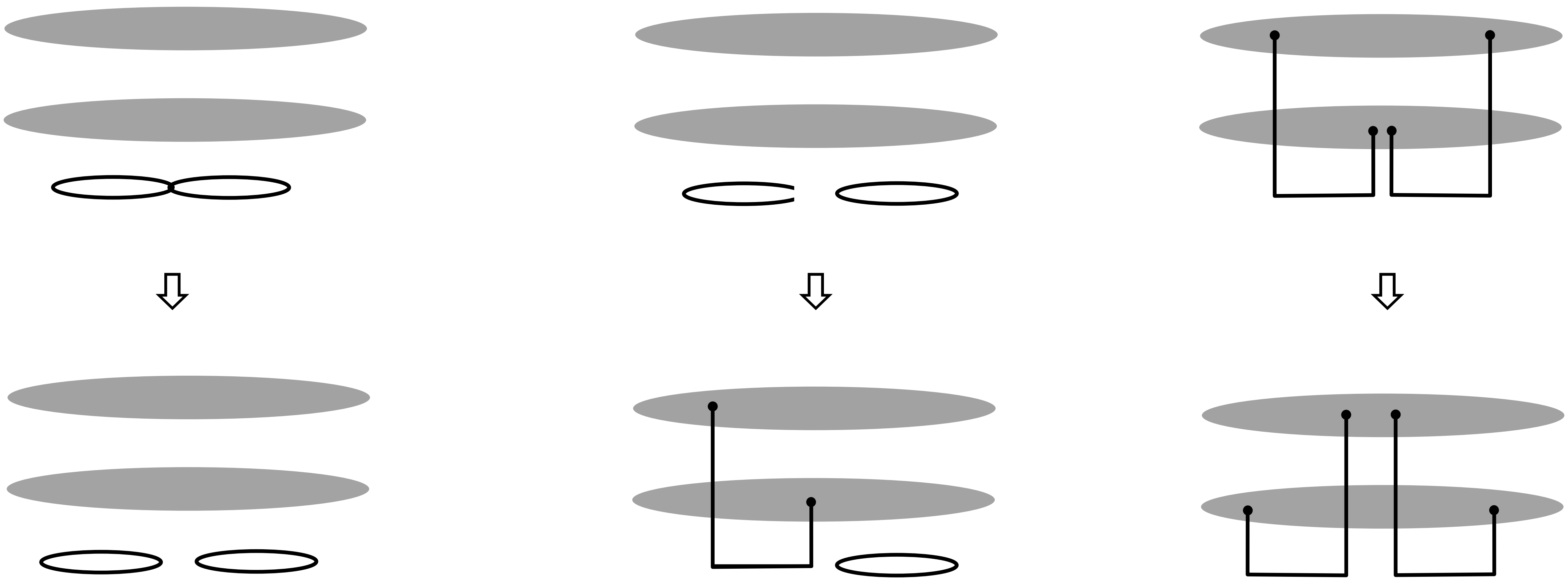
Fluctuations of the gluon string reaching flavor branes cause decays

Jacob Sonnenschein, Dorin Weissman, JHEP 1512 (2015) 011, arXiv:1507.01604.

Jacob Sonnenschein, Dorin Weissman, *Eur.Phys.J.C* 79 (2019) 4, 326 • e-Print: 1812.01619 [hep-ph]

Jakob Sonnenschein, *Prog.Part.Nucl.Phys.* 92 (2017) 1-49 • e-Print: 1602.00704 [hep-th]

Holography Inspired Stringy Hadron model: decay patterns



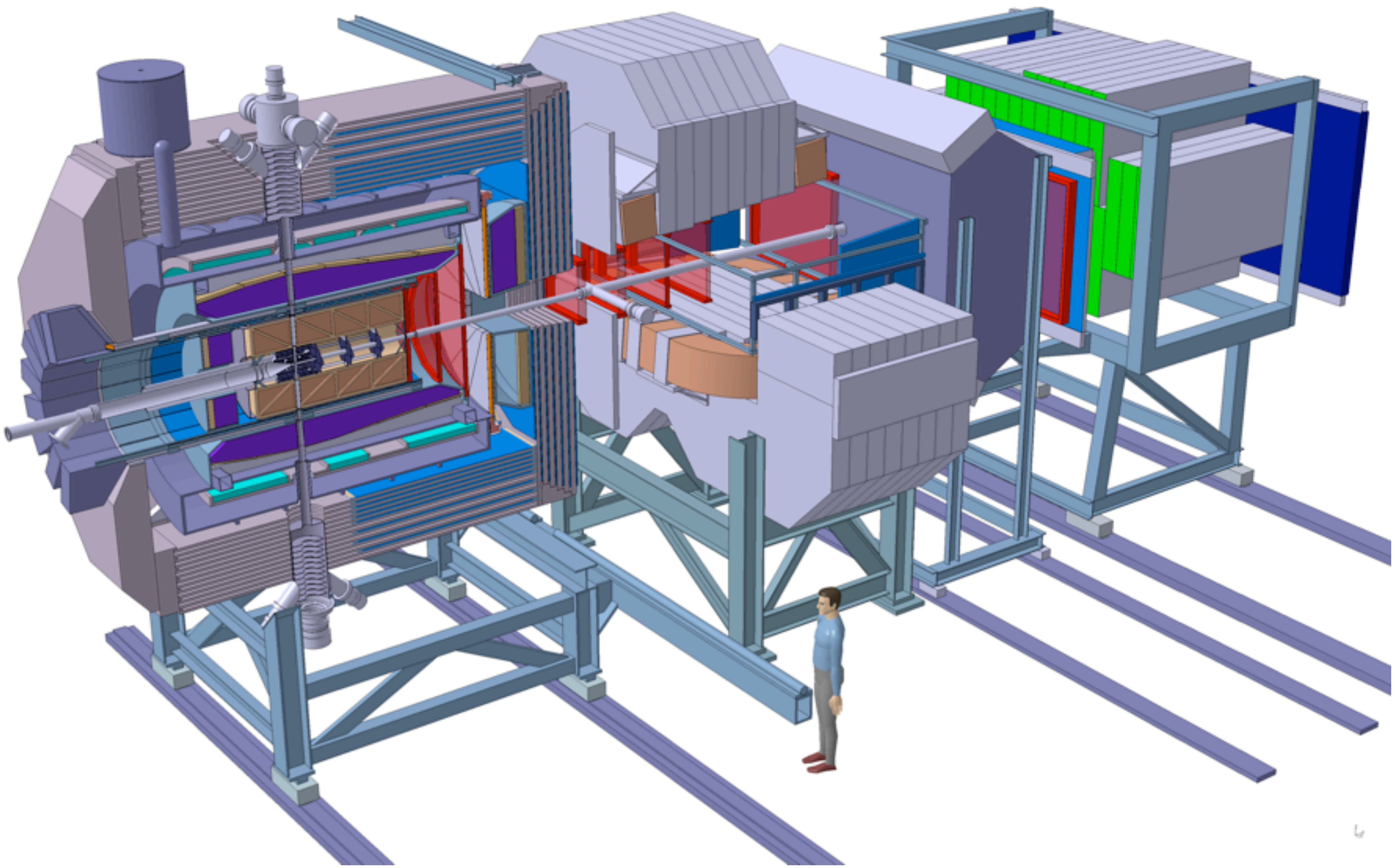
glueball → 2 glueballs   glueball → meson + glueball   glueball → 2 mesons

$$\Gamma(Gb \to 2\ \mathrm{light}) : \Gamma(Gb \to K\bar{K}) : \Gamma(Gb \to \phi\phi) = 1\ : e^{-1}\ : e^{-2}$$

$$\Gamma(GB \to \omega\omega) : \Gamma(GB \to K^{*0}K^{*0}) : \Gamma(GB \to \phi\phi) = 1 : 0.30 : 0.07.$$

PANDA @ FAIR

- gluon-rich (antiprotons)
- no limitations on q.n. of glueballs (even exotic)
- glueballs (and other particles) up to 5.4 GeV
- excitation curve of resonances



Thank you for your attention!