Glueballs - at the heart of QCD
but hard to identify

Ulrich Wiedner
(Ruhr-University Bochum)

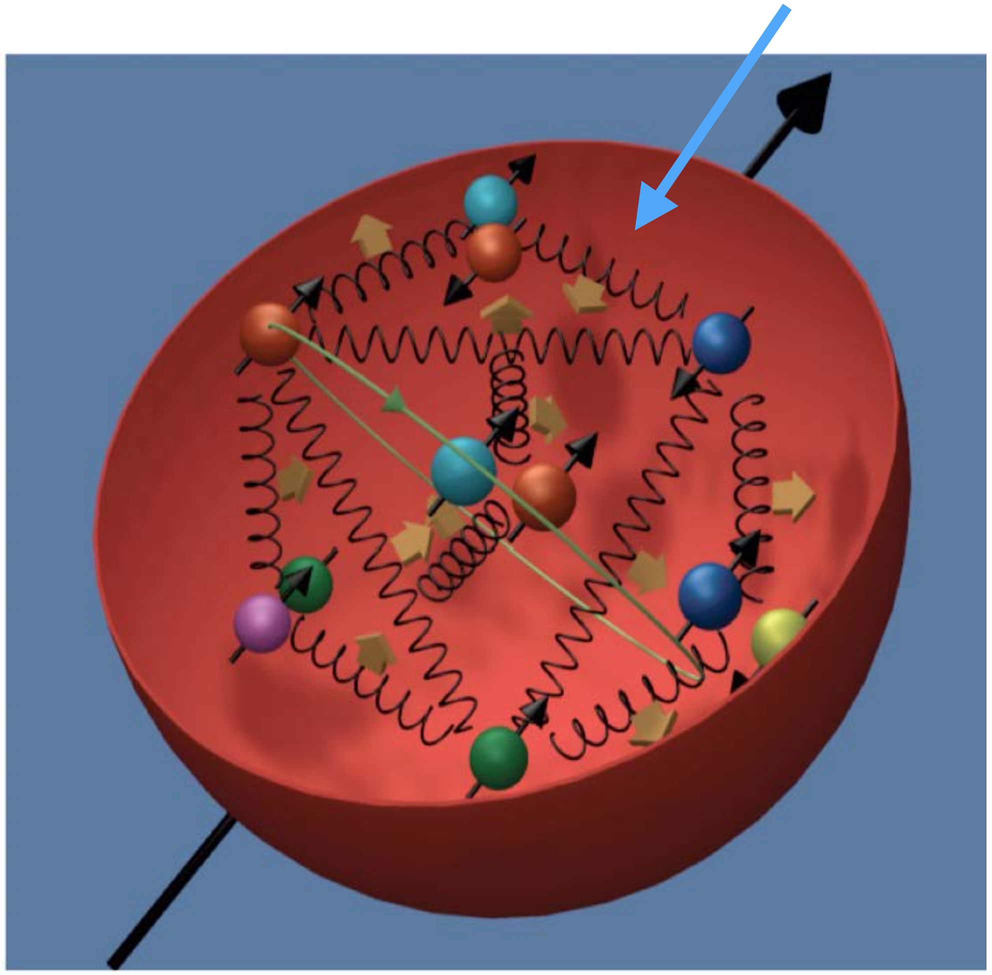
FAIR, Darmstadt, 20.5.2026

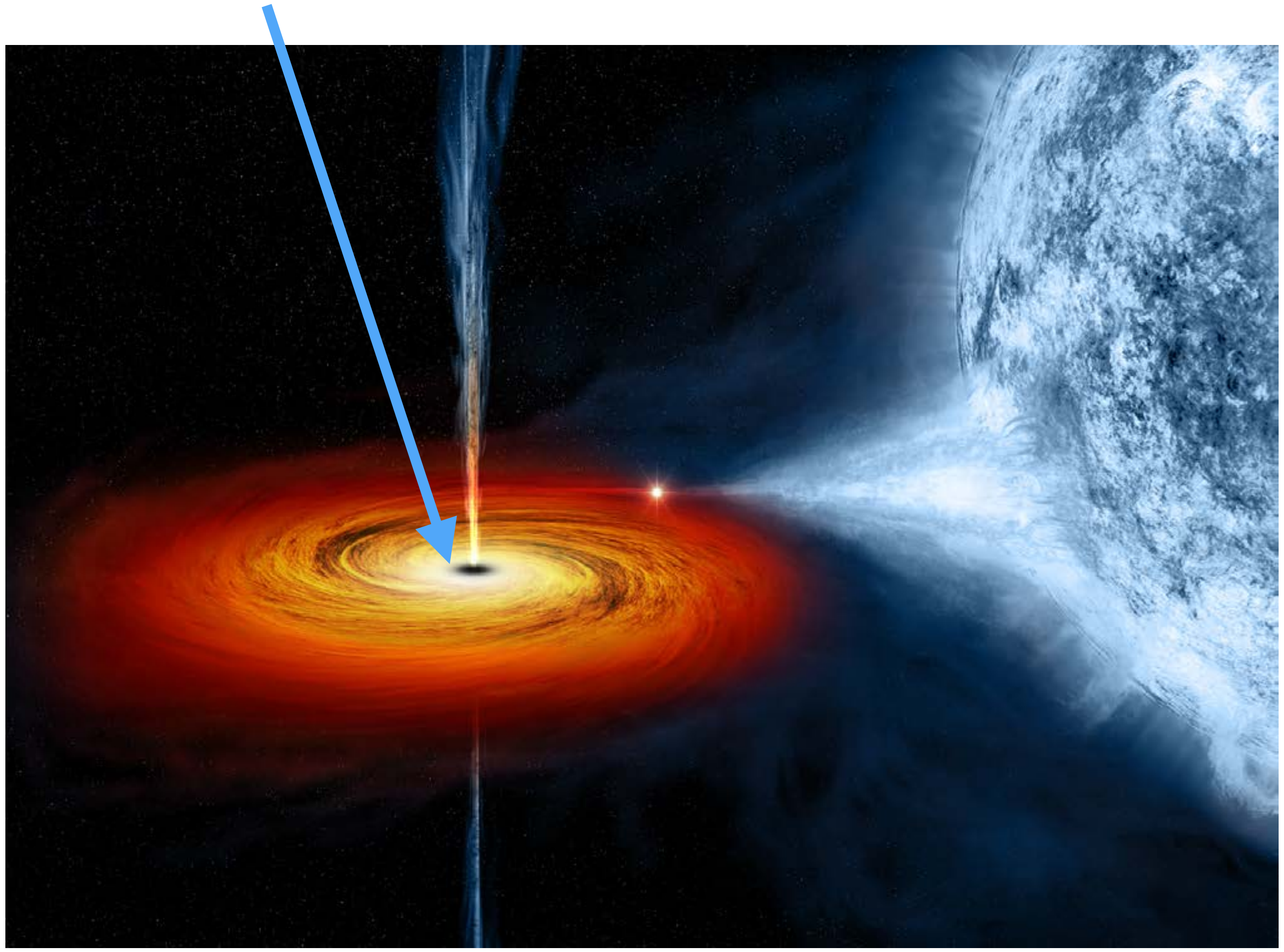
Binding of masses of confined objects

Confining particles:

Massless gluons

Massless gravitons





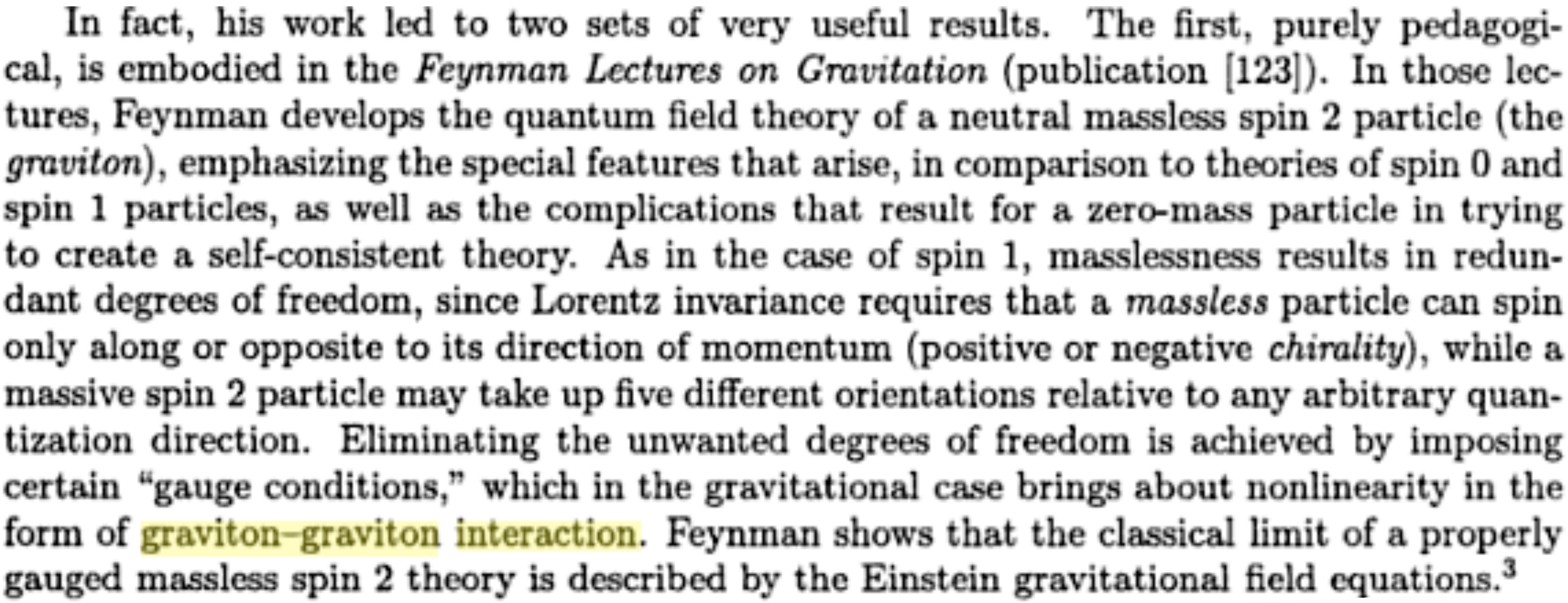
Credits: NASA/CXC/M.Weiss

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.

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]

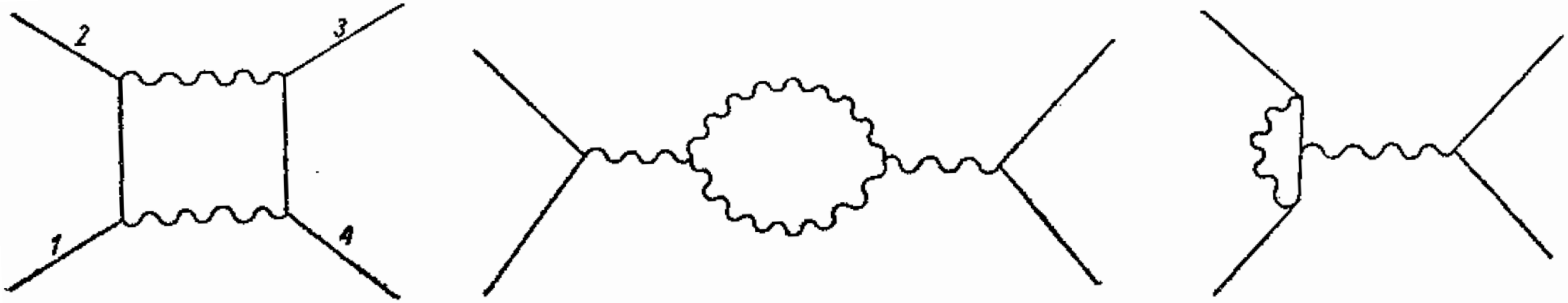


Fig. 5

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

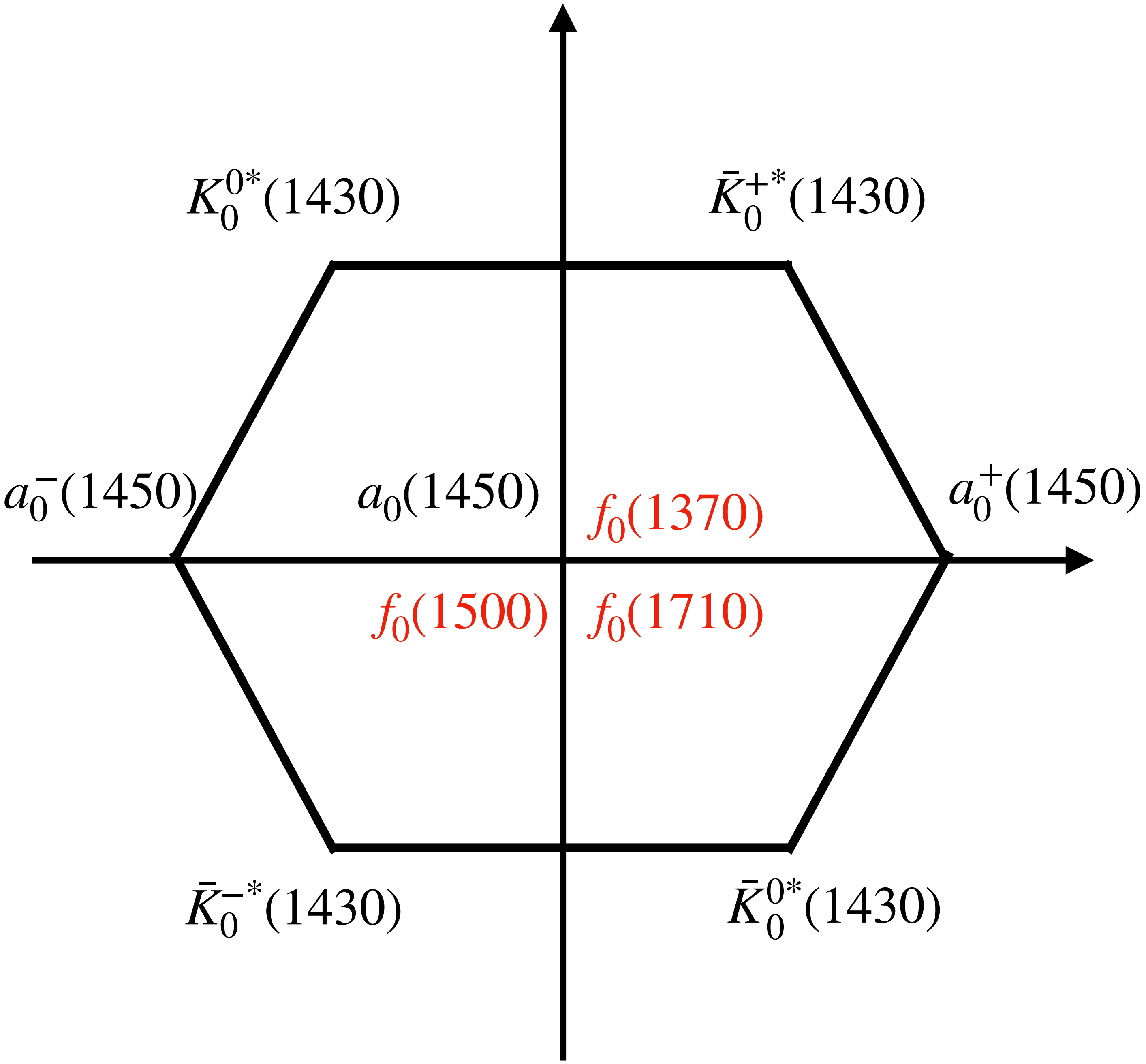
Glueballs decay flavor blind:

➥ study decay patterns to mesons with different quark-(gluon?) content

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

➥ use different beam particles

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



$K_0^{0*}(1430)$ $\bar{K}_0^{+*}(1430)$

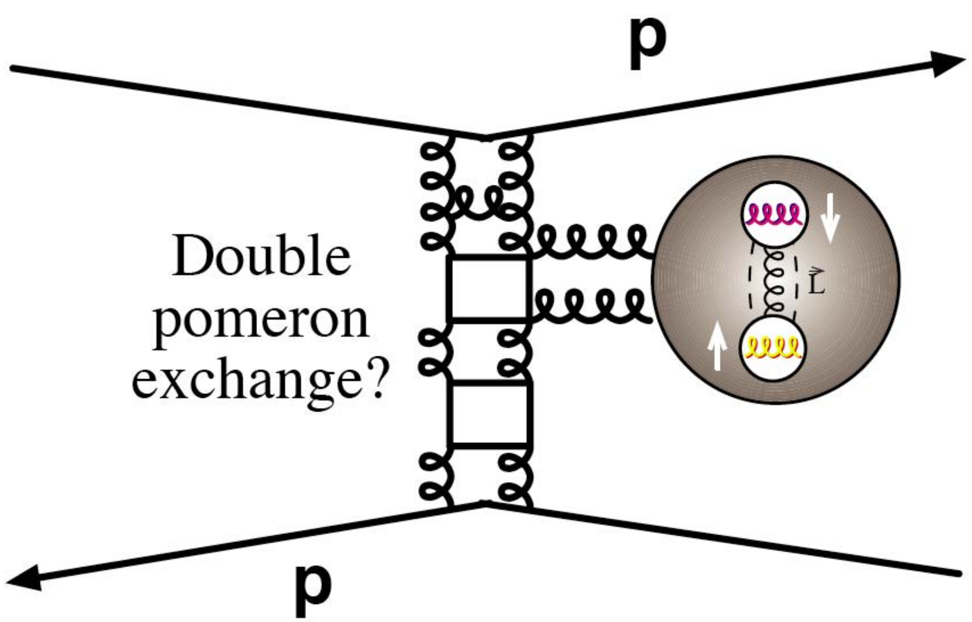
$a_0^-(1450)$ $a_0(1450)$ $f_0(1370)$ $a_0^+(1450)$

$f_0(1500)$ $f_0(1710)$

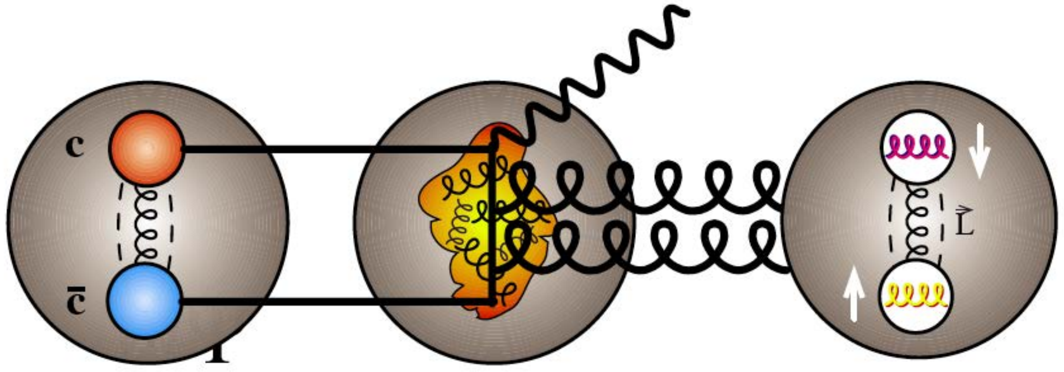
$\bar{K}_0^{-*}(1430)$ $\bar{K}_0^{0*}(1430)$

3 f_0 ?? → 1 particle super numerous ⇒ glueball??

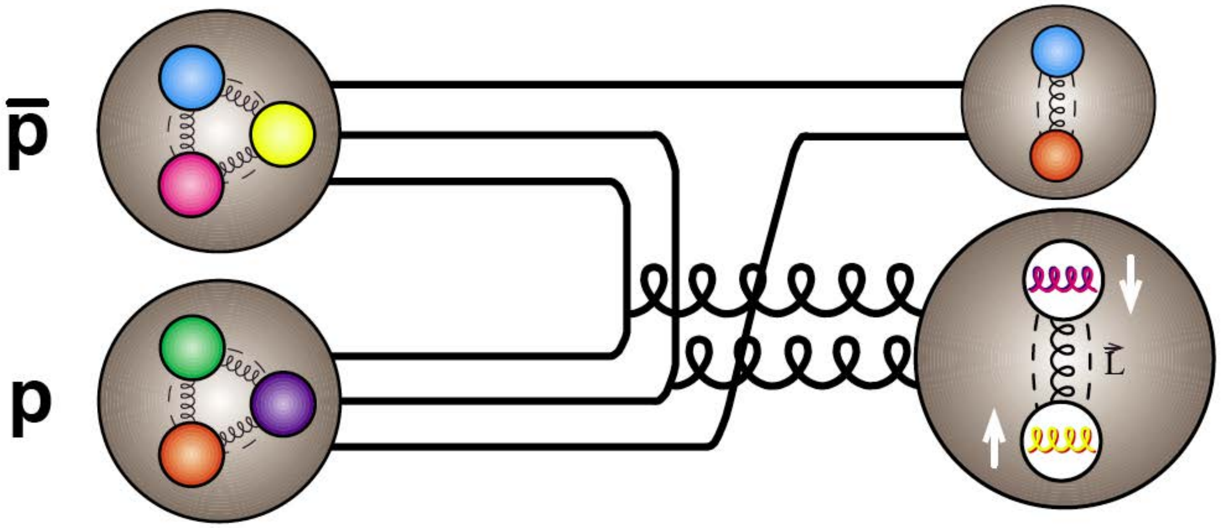
Particle production: “gluon-rich” processes



WA 79, WA 102

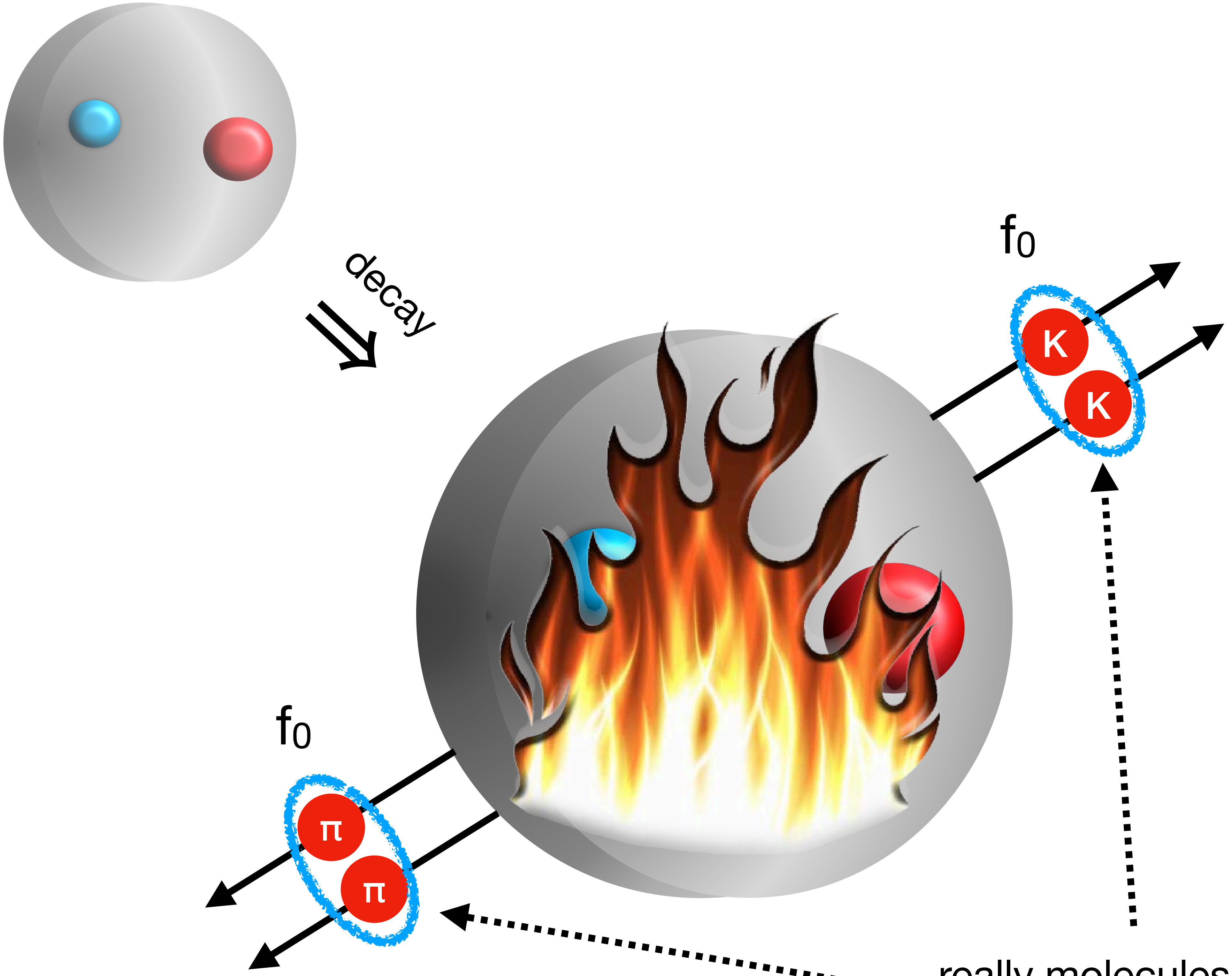


MARK III, DM2, BES



ASTERIX, Crystal Barrel, OBELIX, E835, PANDA

Charmonium decays



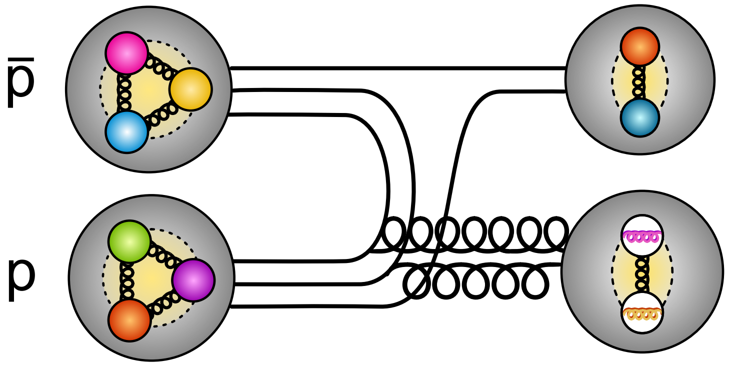
really molecules bound
by a few MeV ??

Glueball searches in gluon-rich reactions

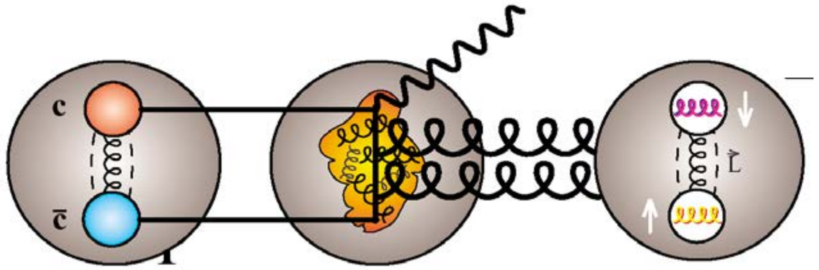
Massless gluons come together to form massive states.

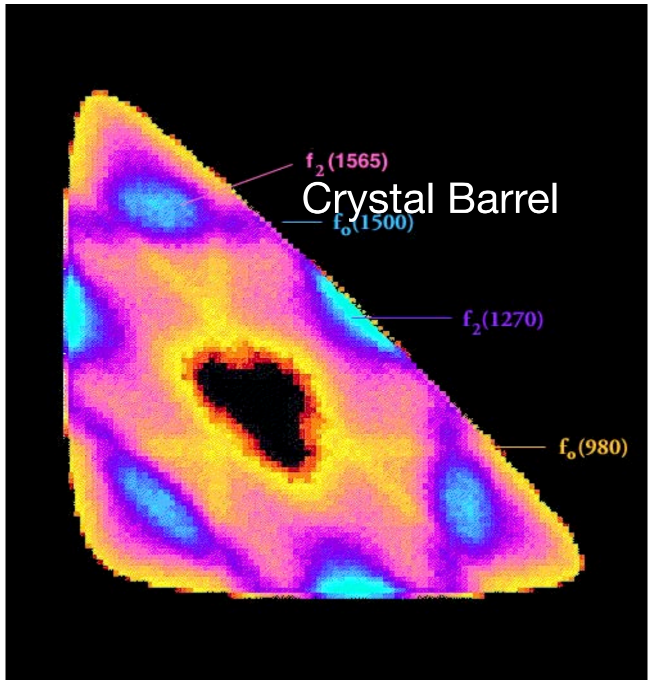
Many candidates are proposed and observed in gluon-rich processes:

p̄p annihilation

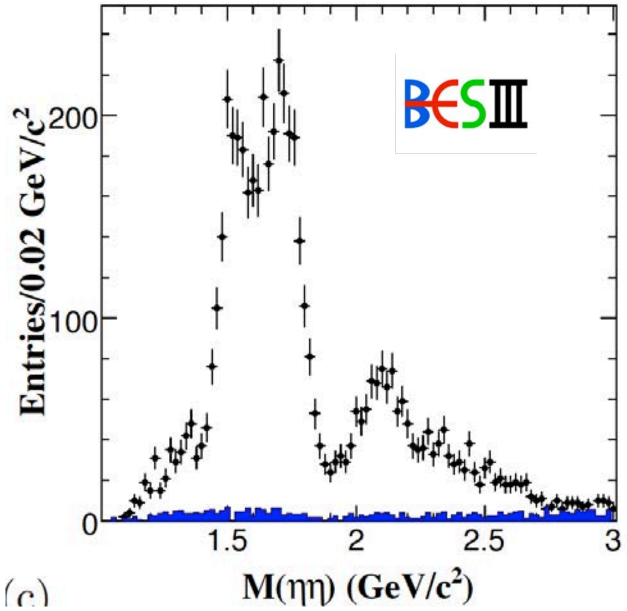


Radiative J/ψ decays





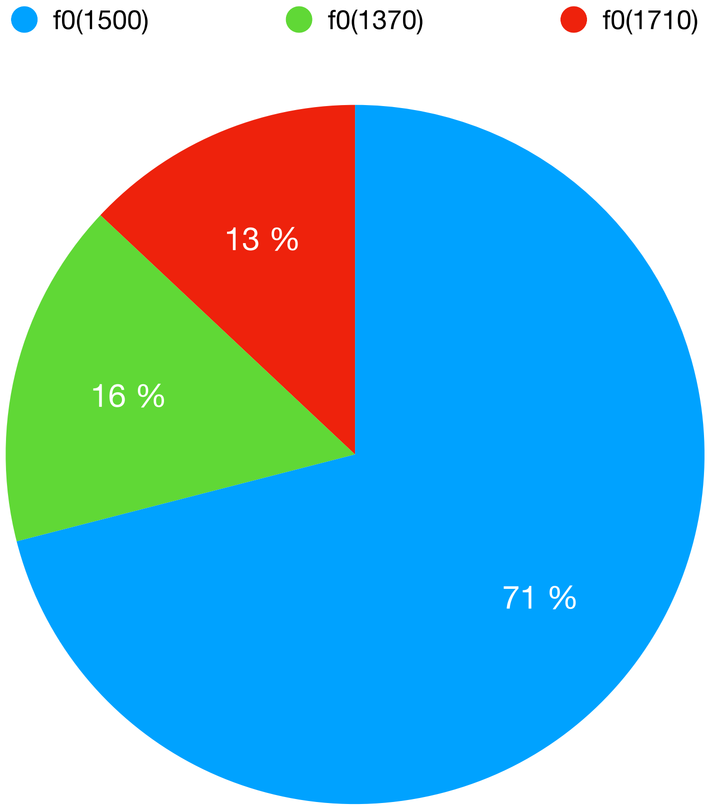
$f_0(1500)$ and $f_0(1710)$



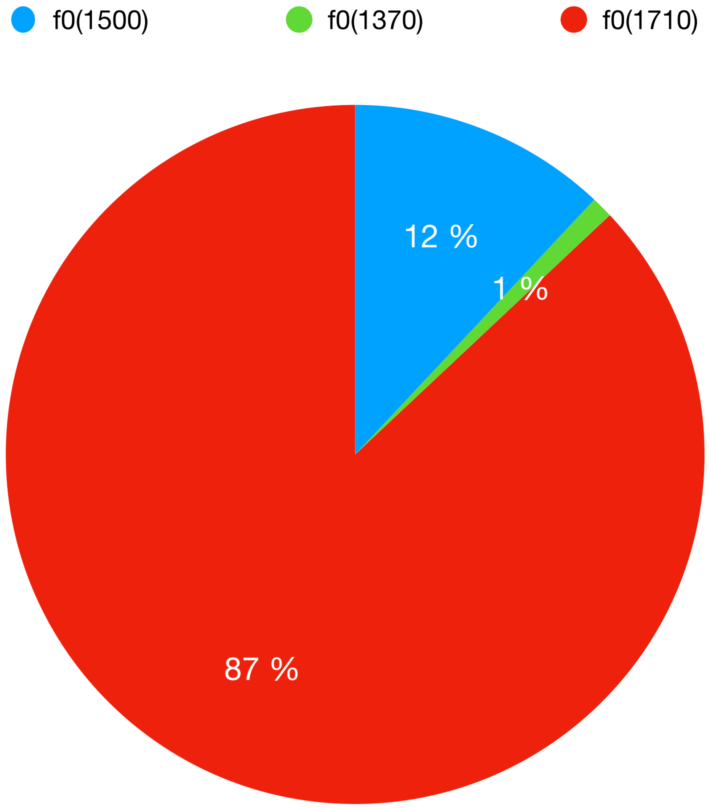
Primitive glueball decays to mesons: ππ : ηη : ηη′ : KK = 3 : 1 : 0 : 4

The mixing of states

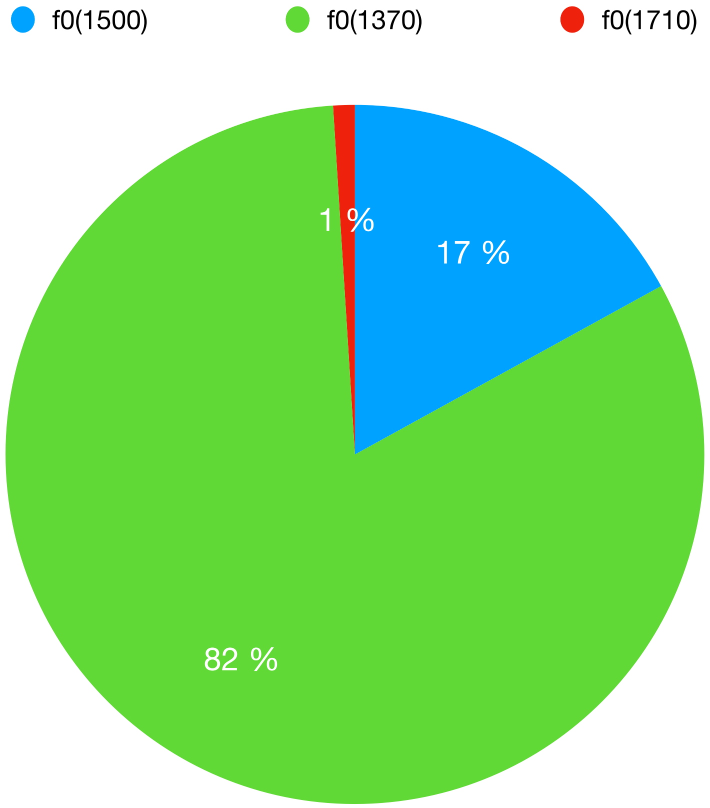
Problem: Overlapping states with the same quantum numbers $q\bar{q}$ or gg can mix.



glue



$s\bar{s}$



$n\bar{n}$

Different mixing schemes exist.

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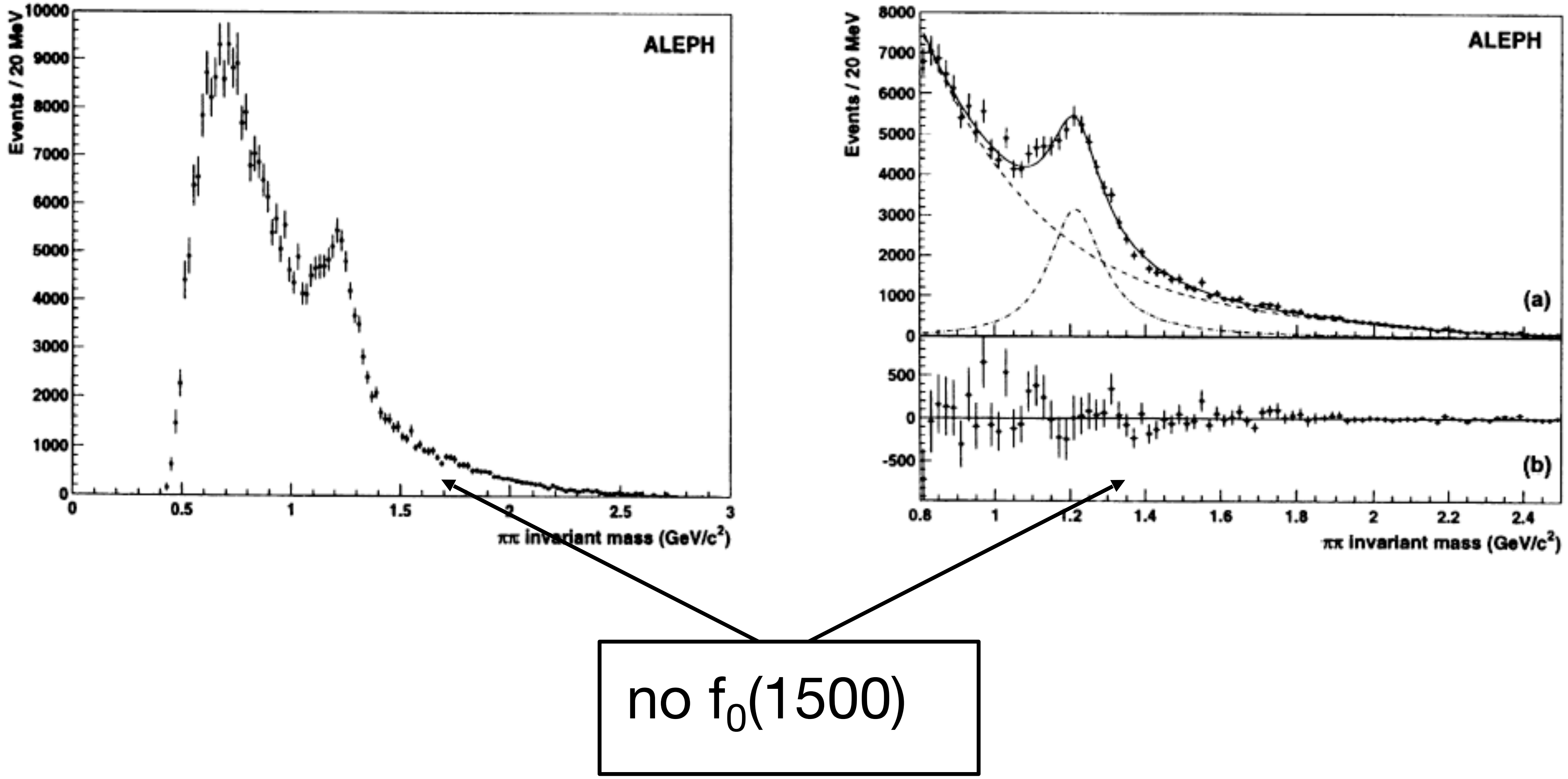
https://doi.org/10.1007/978-3-319-98527-5

γγ collisons from ALEPH

(anti-glueball filter)



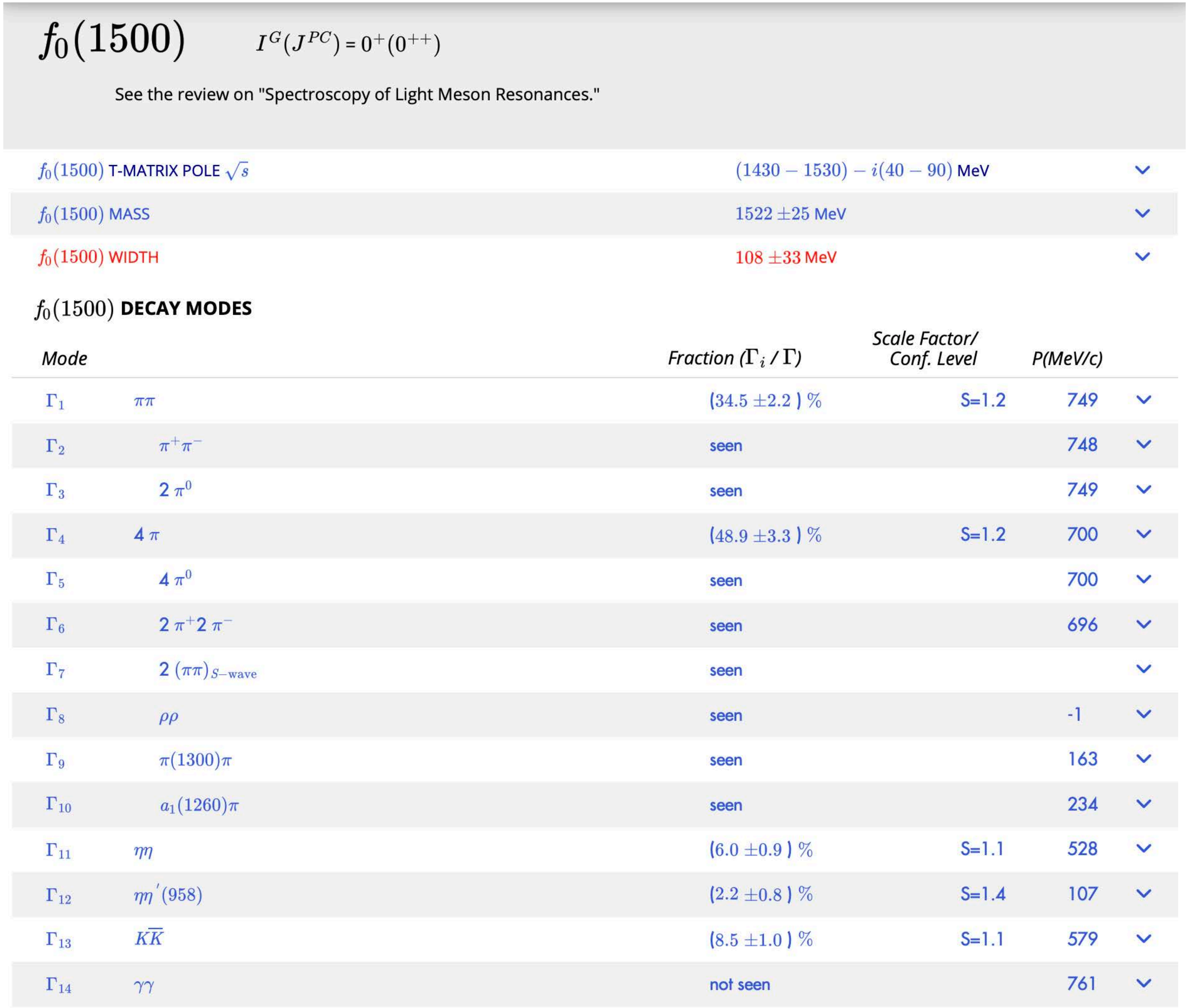
no $f_0(1500)$

upper limit:

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

Phys. Lett. B472 (2000) 189.

Lots of information in the PDG (2025)



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

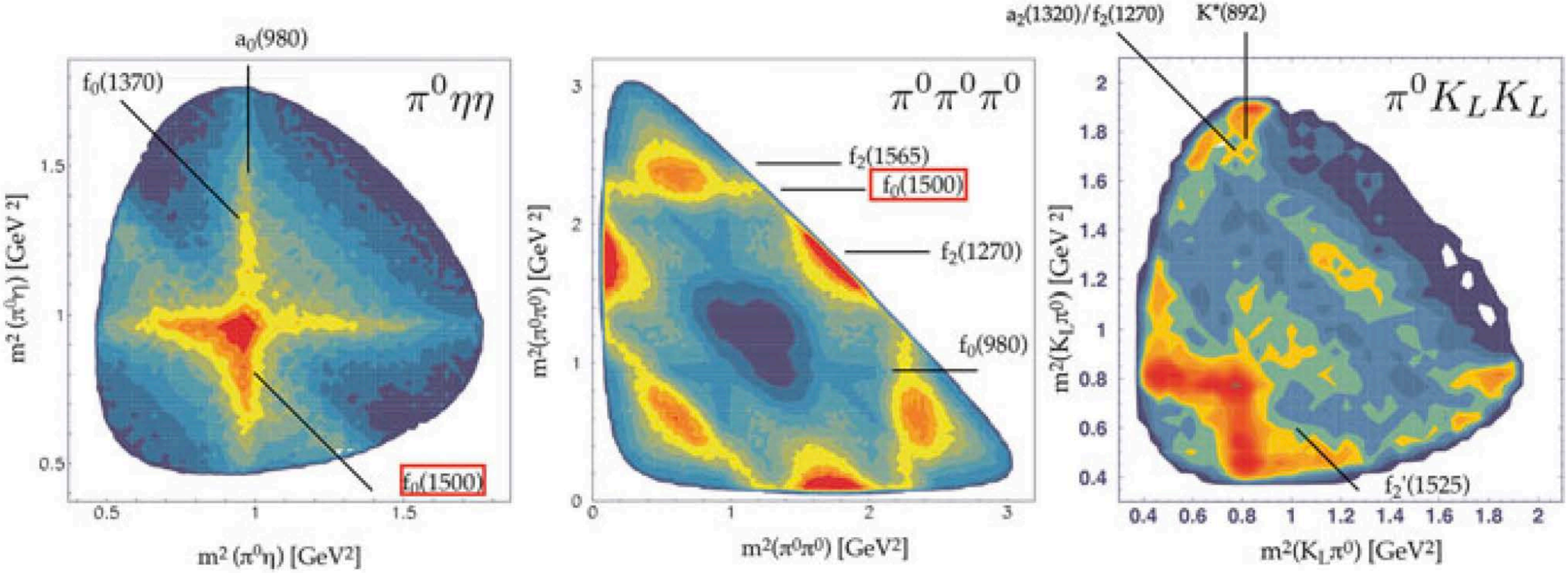
See the review on "Spectroscopy of Light Meson Resonances."

$f_0(1500)$ T-MATRIX POLE $\sqrt{s}$	$(1430-1530)-i(40-90)$ MeV
$f_0(1500)$ MASS	1522 ± 25 MeV
$f_0(1500)$ WIDTH	108 ± 33 MeV

$f_0(1500)$ DECAY MODES

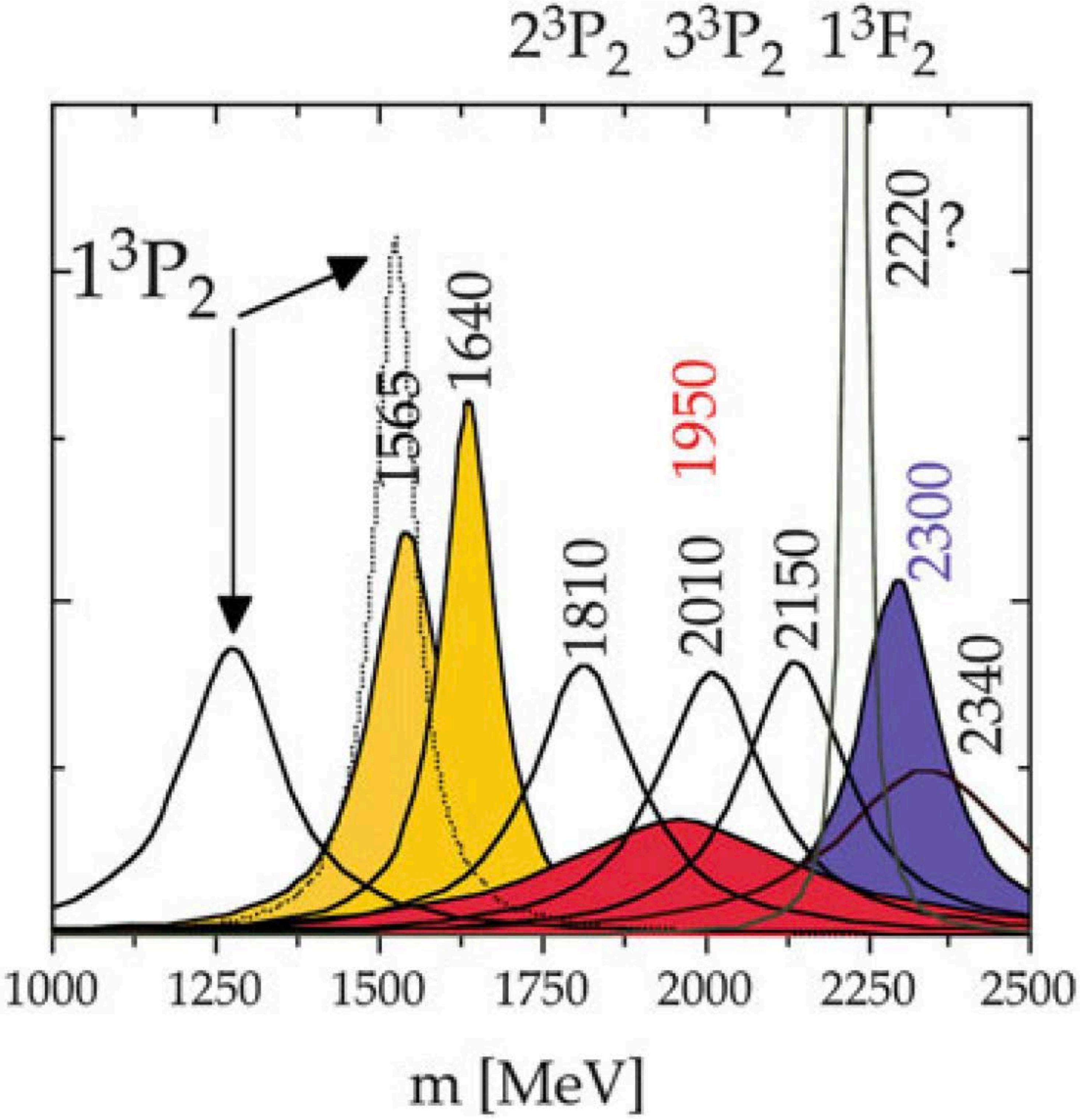
Mode		*Fraction* (Γ_i / Γ)	*Scale Factor/ Conf. Level*	*P(MeV/c)*
Γ_1	$\pi\pi$	(34.5 ± 2.2) %	S=1.2	749
Γ_2	$\pi^+\pi^-$	seen		748
Γ_3	$2\pi^0$	seen		749
Γ_4	4π	(48.9 ± 3.3) %	S=1.2	700
Γ_5	$4\pi^0$	seen		700
Γ_6	$2\pi^+ 2\pi^-$	seen		696
Γ_7	$2(\pi\pi)_{S-\mathrm{wave}}$	seen		
Γ_8	$\rho\rho$	seen		-1
Γ_9	$\pi(1300)\pi$	seen		163
Γ_{10}	$a_1(1260)\pi$	seen		234
Γ_{11}	$\eta\eta$	(6.0 ± 0.9) %	S=1.1	528
Γ_{12}	$\eta\eta'(958)$	(2.2 ± 0.8) %	S=1.4	107
Γ_{13}	$K\overline{K}$	(8.5 ± 1.0) %	S=1.1	579
Γ_{14}	$\gamma\gamma$	not seen		761

Data: pp̄ Dalitz plots



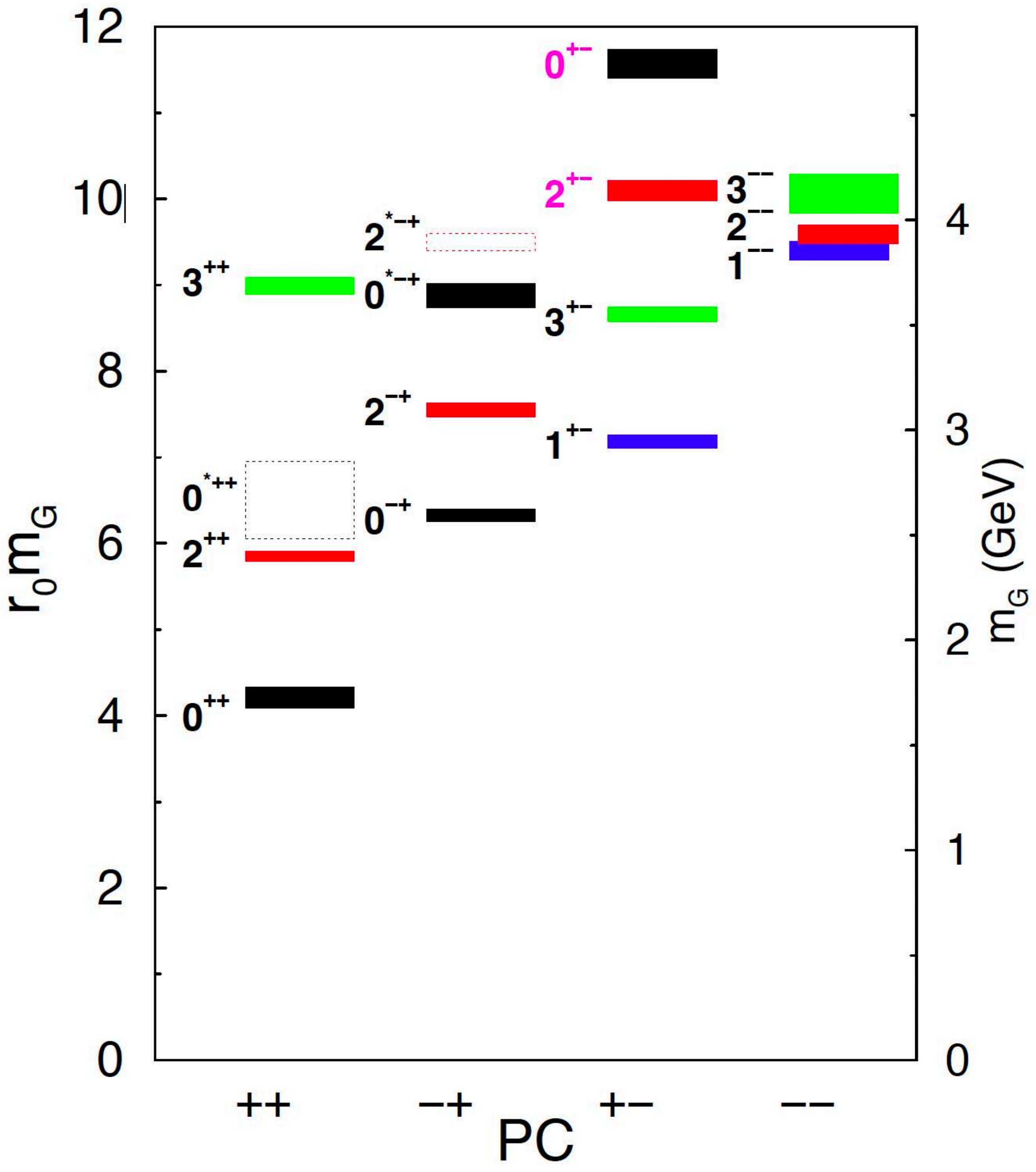
Amsler, C.: Rev. Mod. Phys. 70, 1293 (1998)

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



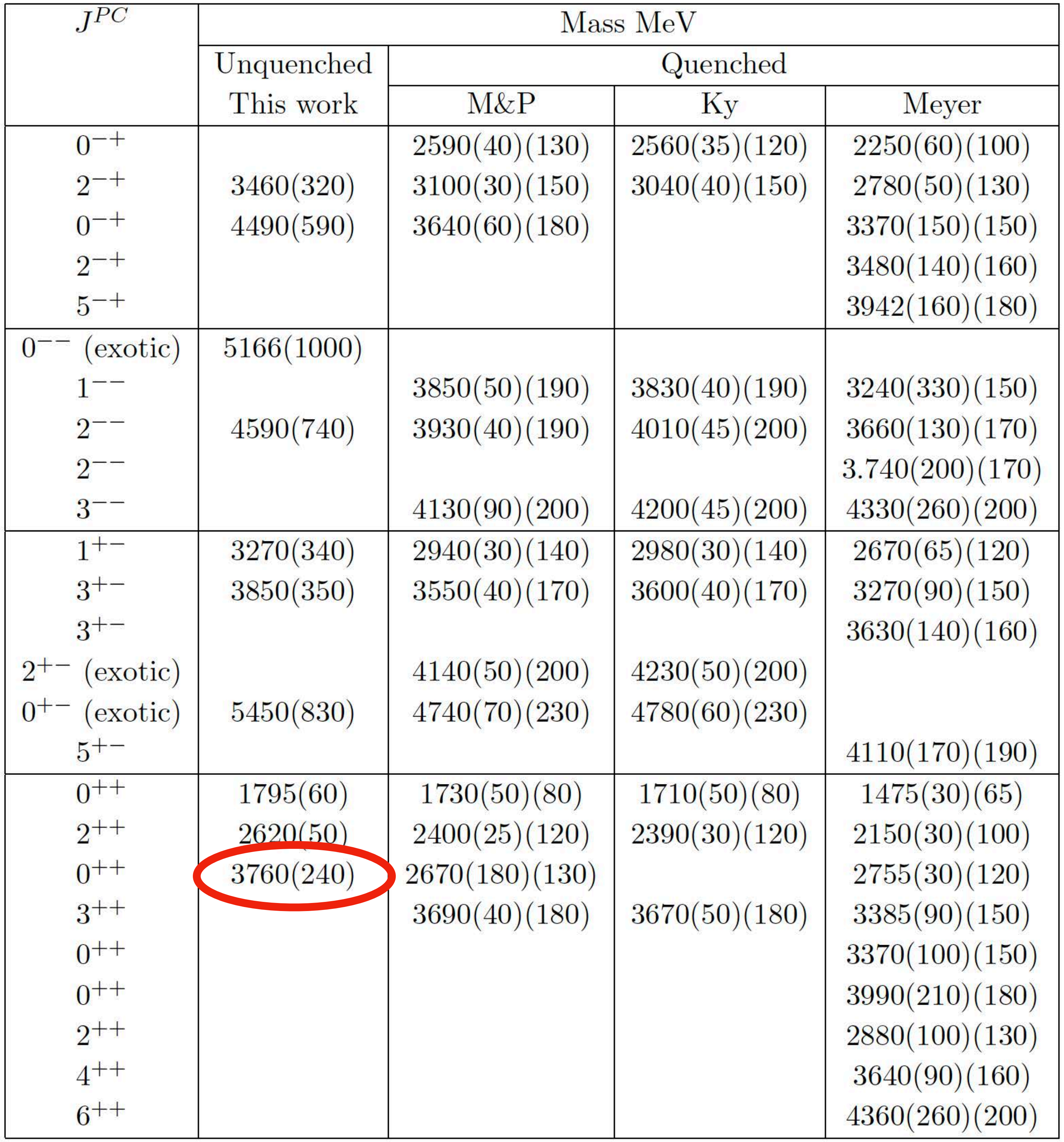
Taken from Claude Amsler: Lecture Notes in Physics
ISBN 978-3-319-98526-8 ISBN 978-3-319-98527-5 (eBook)

The lattice glueball spectrum



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]



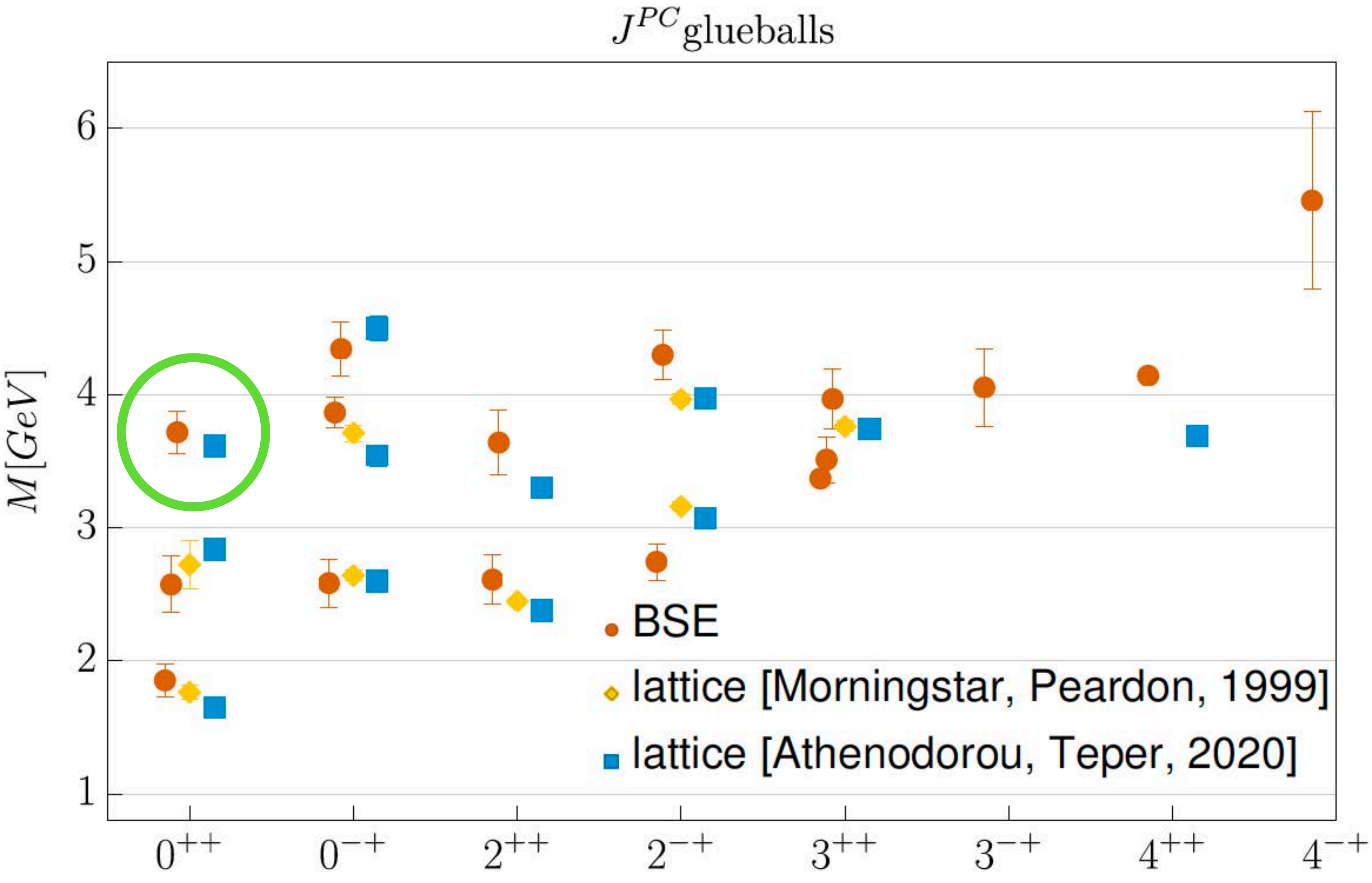
J^{PC}	Mass MeV			
	Unquenched	Quenched		
	This work	M&P	Ky	Meyer
0^{-+}		2590(40)(130)	2560(35)(120)	2250(60)(100)
2^{-+}	3460(320)	3100(30)(150)	3040(40)(150)	2780(50)(130)
0^{-+}	4490(590)	3640(60)(180)		3370(150)(150)
2^{-+}				3480(140)(160)
5^{-+}				3942(160)(180)
0^{--} (exotic)	5166(1000)			
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.

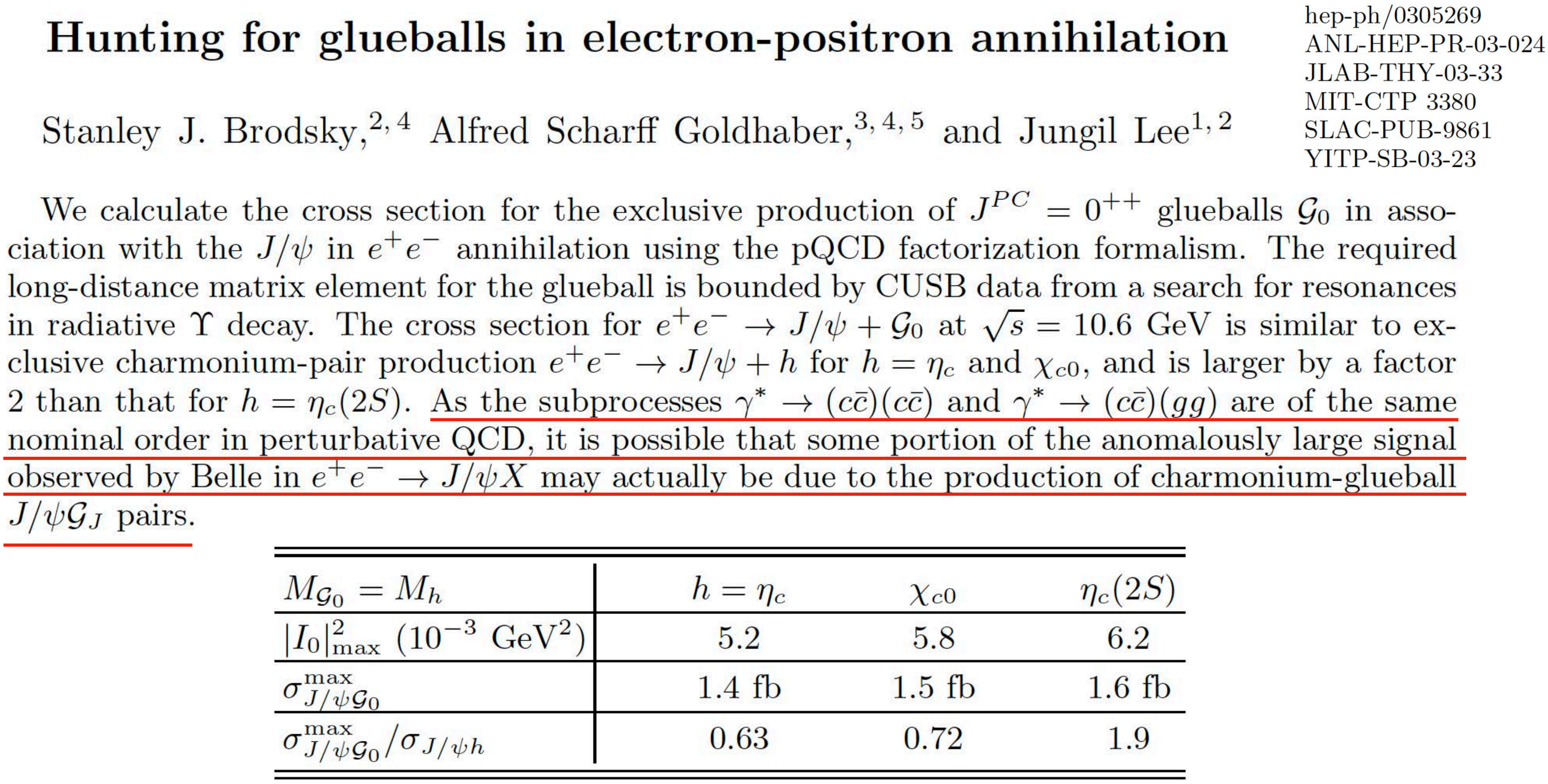
Glueballs from functional methods



M.Q.Huber, Fischer, Sanchis Alepuz, Eur.Phys.J.C 85, 2503.03821 (2025)

New approach on scalar glueballs

Look for the excited 0^{++} glueball among the charmonium states.



Hunting for glueballs in electron-positron annihilation

hep-ph/0305269
ANL-HEP-PR-03-024
JLAB-THY-03-33
MIT-CTP 3380
SLAC-PUB-9861
YITP-SB-03-23

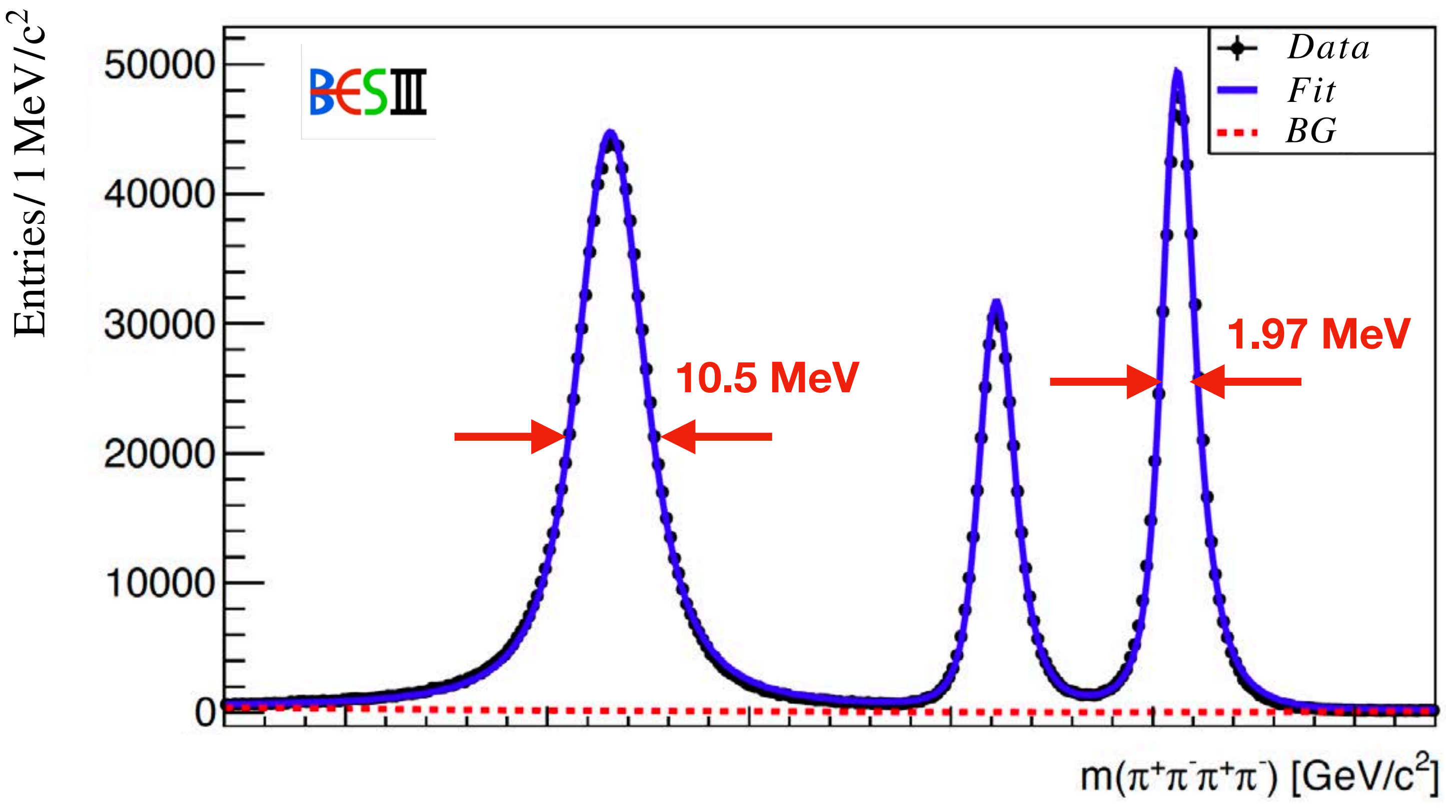
Stanley J. Brodsky,[2, 4] Alfred Scharff Goldhaber,[3, 4, 5] and Jungil Lee[1, 2]

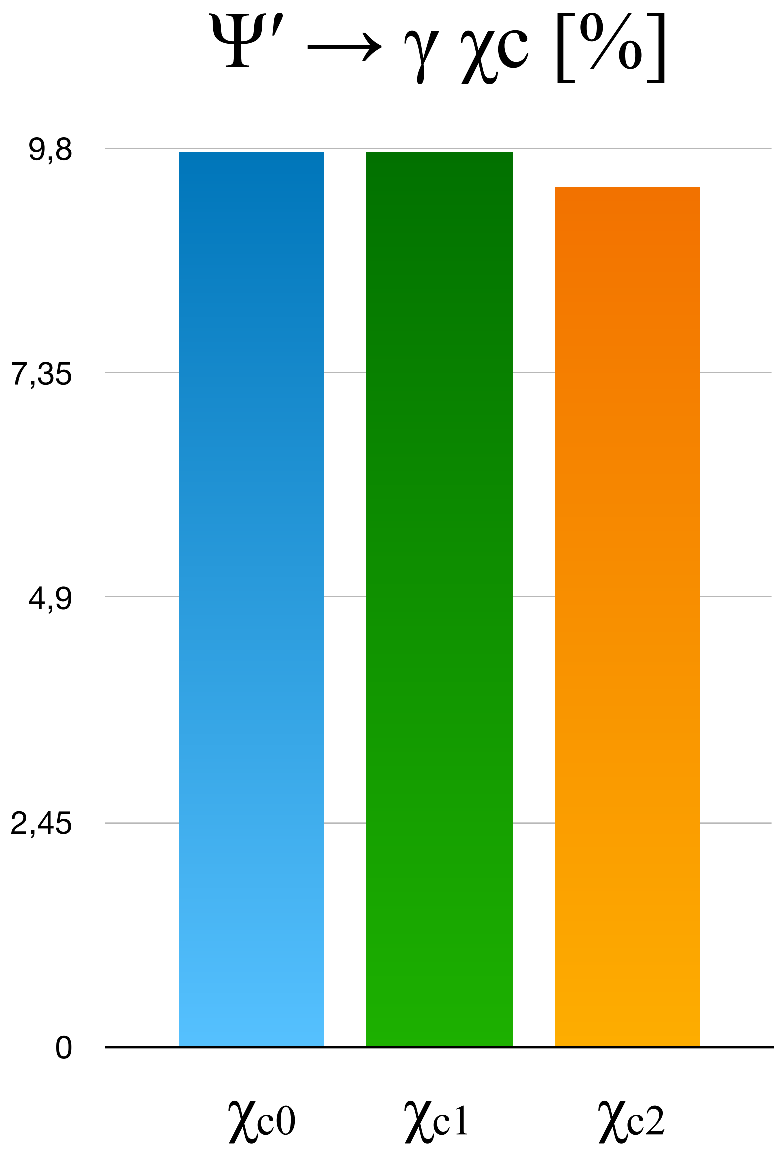
We calculate the cross section for the exclusive production of $J^{PC} = 0^{++}$ glueballs $\mathcal{G}_0$ in association with the J/ψ in e^+e^- annihilation using the pQCD factorization formalism. The required long-distance matrix element for the glueball is bounded by CUSB data from a search for resonances in radiative Υ decay. The cross section for $e^+e^- \to J/\psi + \mathcal{G}_0$ at $\sqrt{s} = 10.6$ GeV is similar to exclusive charmonium-pair production $e^+e^- \to J/\psi + h$ for $h = \eta_c$ and χ_{c0}, and is larger by a factor 2 than that for $h = \eta_c(2S)$. As the subprocesses $\gamma^* \to (c\bar{c})(c\bar{c})$ and $\gamma^* \to (c\bar{c})(gg)$ are of the same nominal order in perturbative QCD, it is possible that some portion of the anomalously large signal observed by Belle in $e^+e^- \to J/\psi X$ may actually be due to the production of charmonium-glueball $J/\psi\mathcal{G}_J$ pairs.

$M_{\mathcal{G}_0} = M_h$	$h = \eta_c$	χ_{c0}	$\eta_c(2S)$
$\lvert I_0\rvert^2_{\max}$ (10^{-3} GeV^2)	5.2	5.8	6.2
$\sigma^{\max}_{J/\psi\mathcal{G}_0}$	1.4 fb	1.5 fb	1.6 fb
$\sigma^{\max}_{J/\psi\mathcal{G}_0}/\sigma_{J/\psi h}$	0.63	0.72	1.9

⇒ Study χ_{c0} decays (admixture of glueball component)

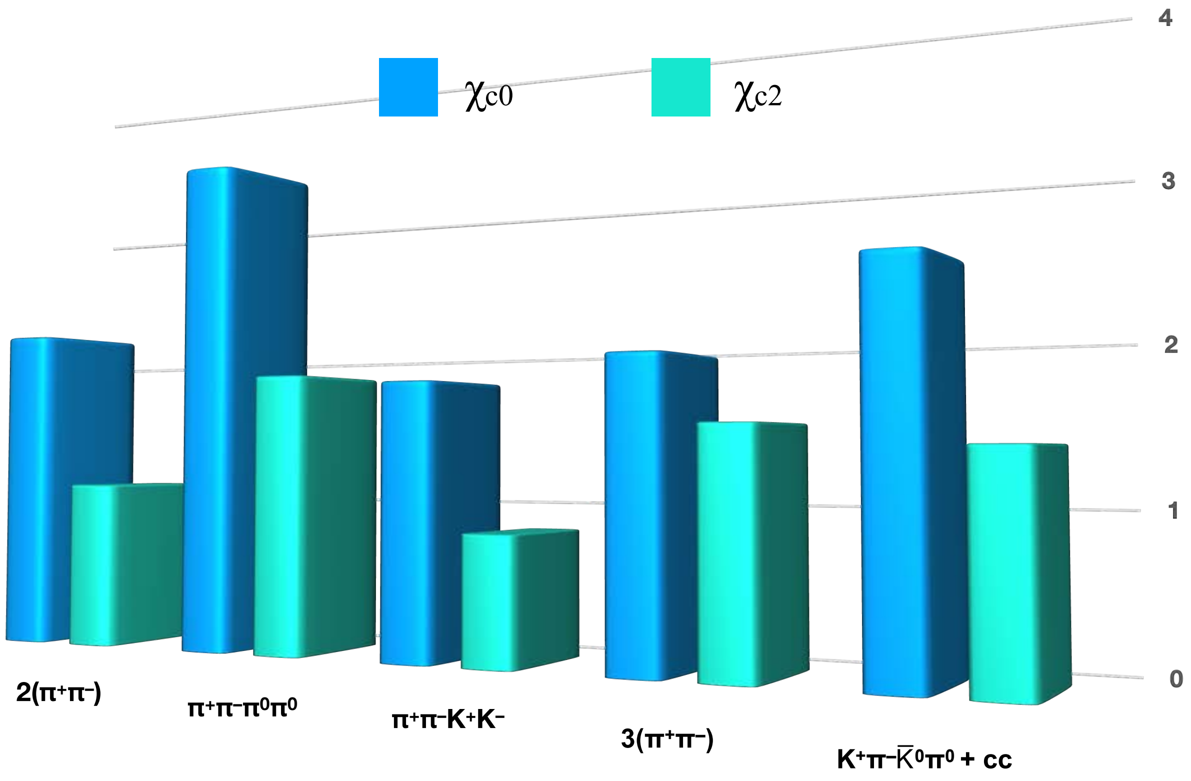
The χ_{cJ} states in radiative $\psi(2S)$ BESIII data





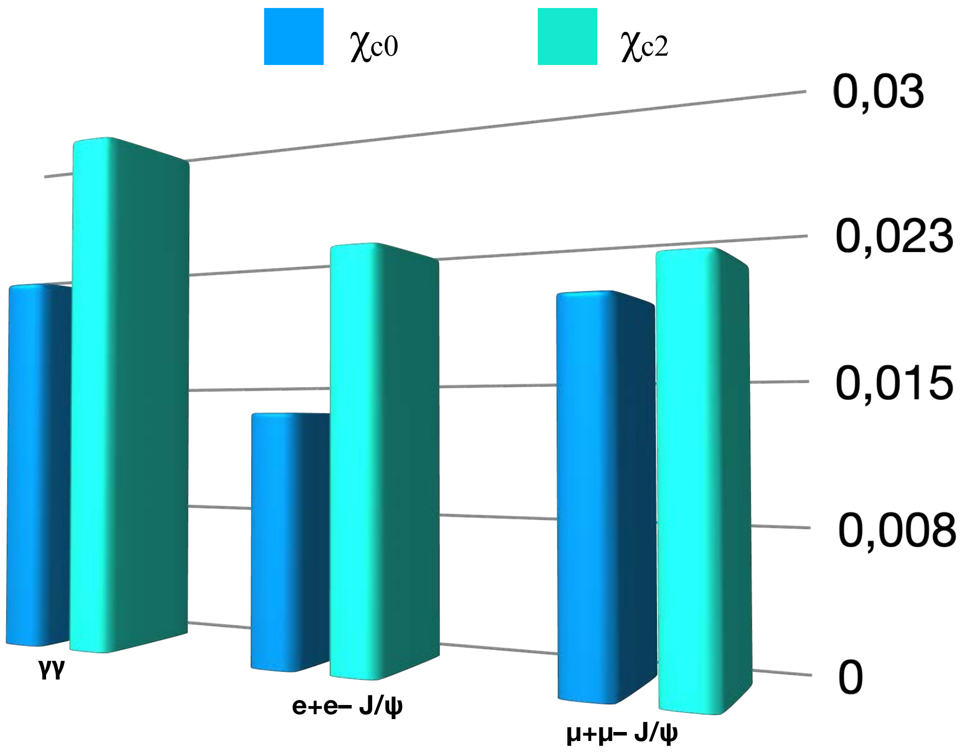
Decay B.F. of χ_{cJ} states

Most prominent hadronic decays of χ_{c0} and χ_{c2}



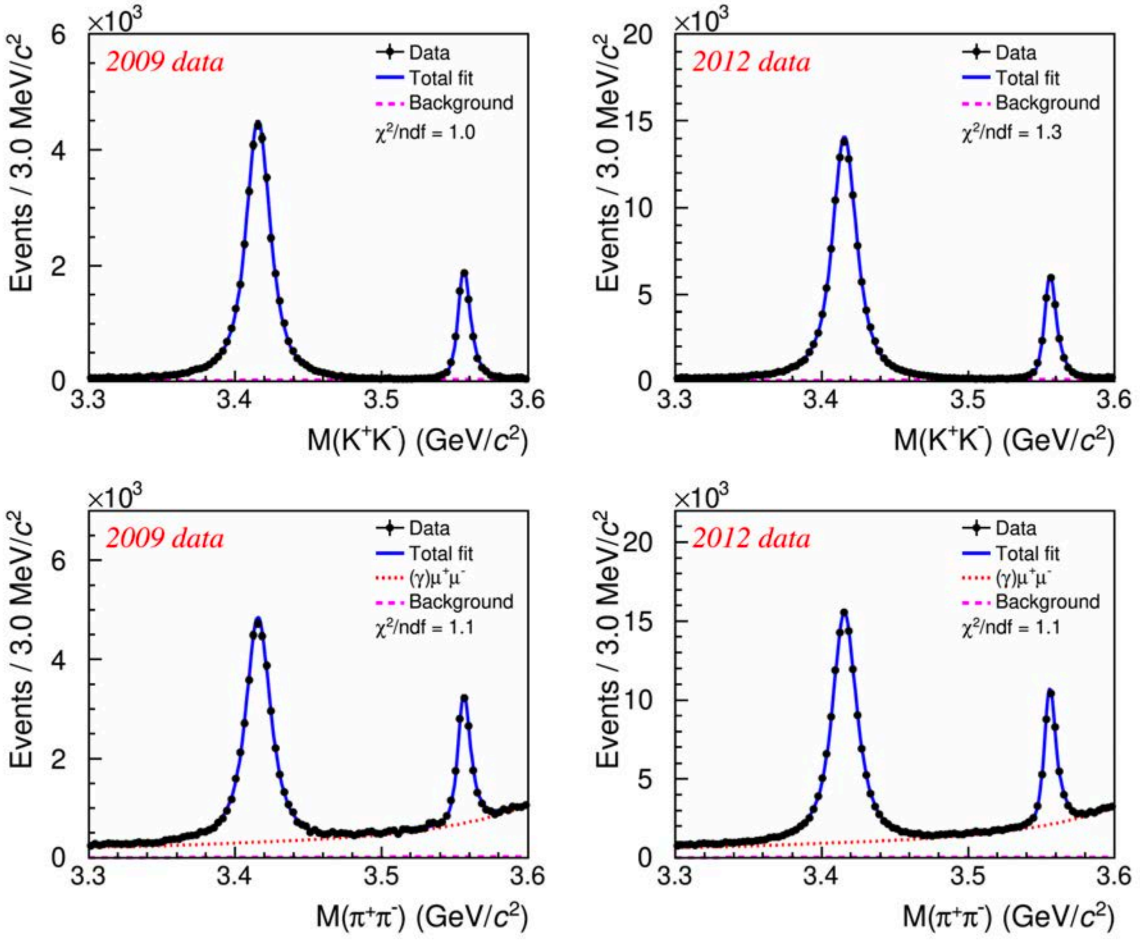
B.F. % of decay channel

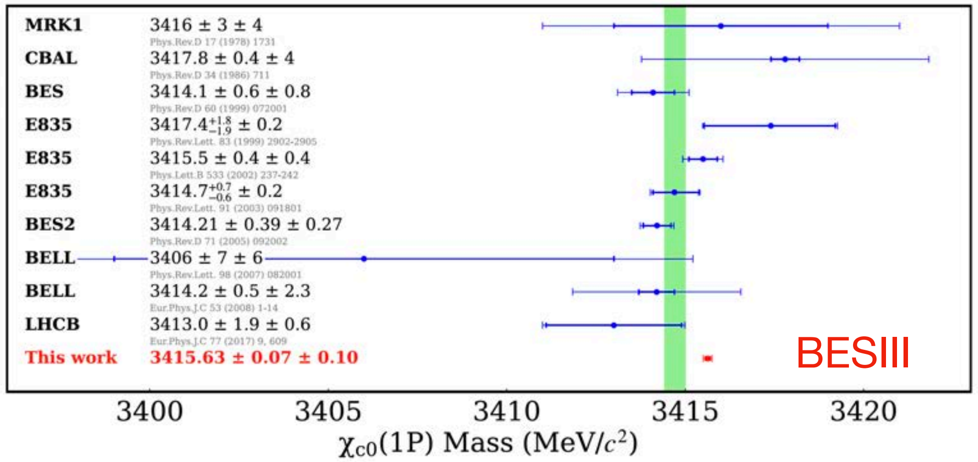
Electroweak decays of χ_{c0} and χ_{c2}

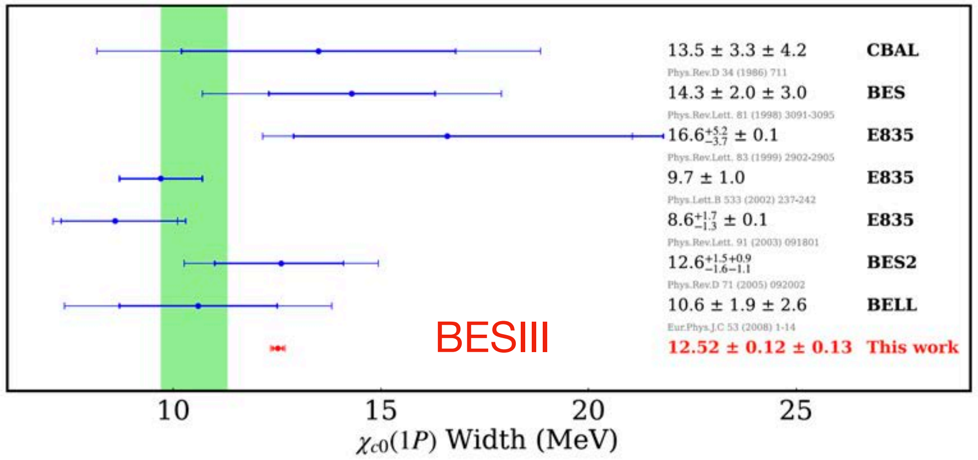


B.F. % of decay channel

Precision charmonium physics and decay B.F. of χ_{cJ} states







$$\mathcal{B}(\chi_{c0} \to K^+K^-) = (6.36 \pm 0.02 \pm 0.08 \pm 0.13) \times 10^{-3}$$

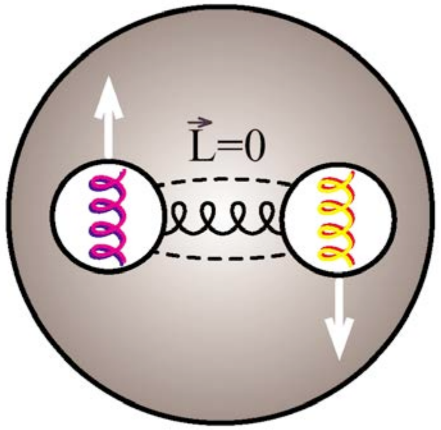
$$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-) = (6.06 \pm 0.02 \pm 0.07 \pm 0.13) \times 10^{-3}$$

$$\mathcal{B}(\chi_{c2} \to K^+K^-) = (1.22 \pm 0.01 \pm 0.02 \pm 0.03) \times 10^{-3}$$

$$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-) = (1.61 \pm 0.01 \pm 0.02 \pm 0.04) \times 10^{-3}$$

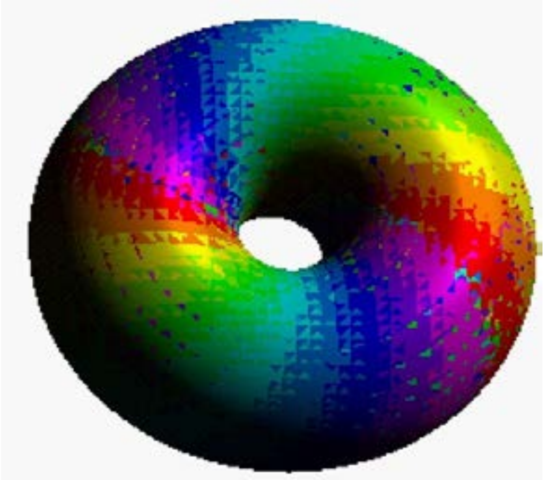
https://arxiv.org/abs/2502.08929

The structure of glueballs



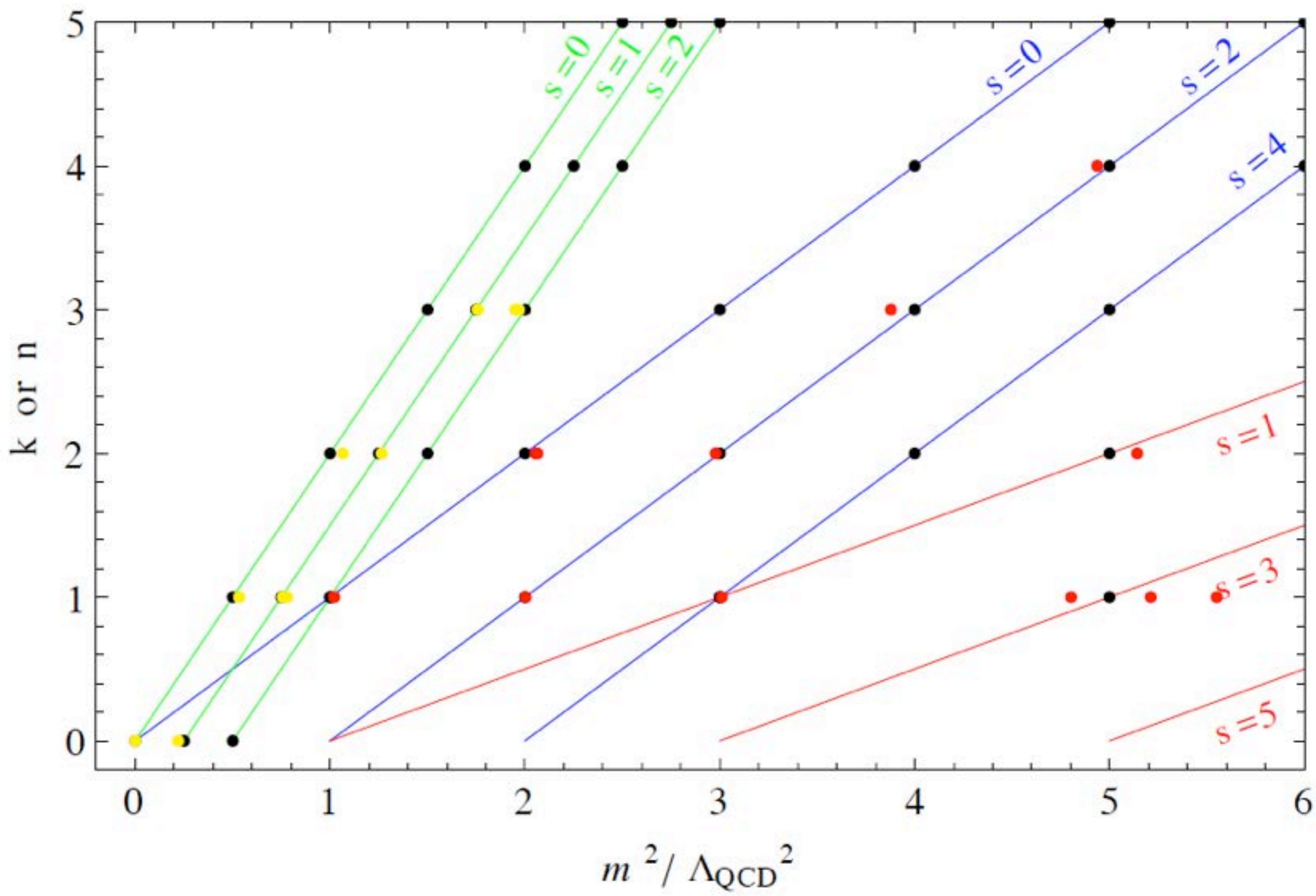
Glueball (gg)

Are glueballs configurations of twisted or knotted colored flux?



GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner
Phys.Rev.D70:114033, 2004

Glueballs on Regge trajectories like mesons?

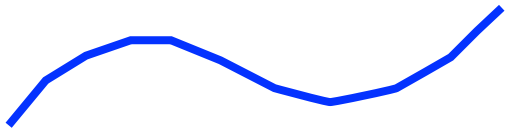


Marco Bochicchio; arXiv:1308.2925

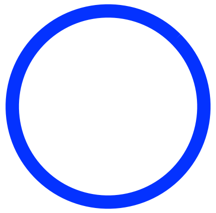
Harvey B. Meyer, Michael J. Teper; Phys.Lett. B605 (2005) 344-354

G. S. Bali et al.; arXiv:1302.1502; PoS ConfinementX (2012) 278

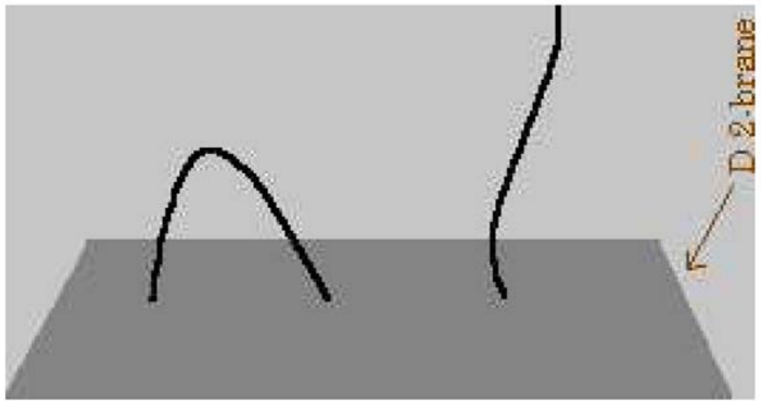
Open Strings



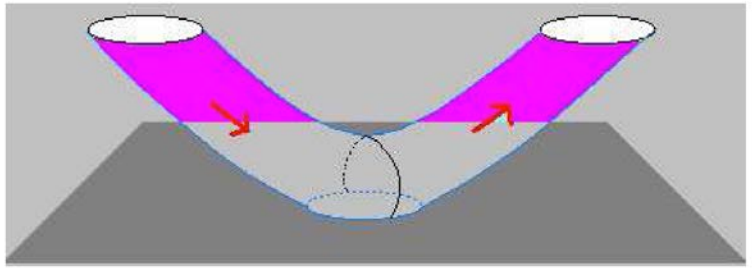
Closed Strings



String World

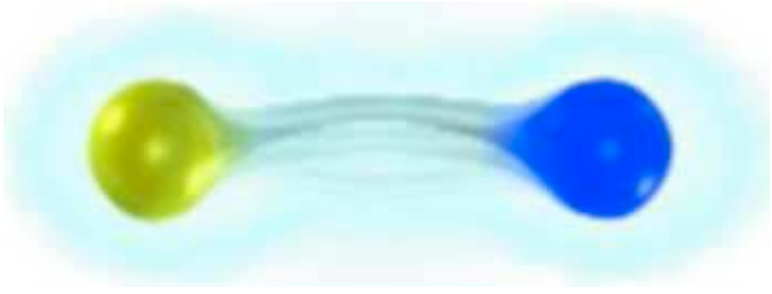


representing gauge theories

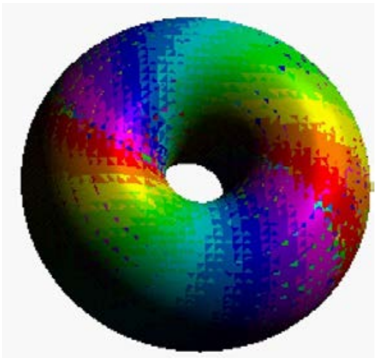


representing gravitation

Hadron World

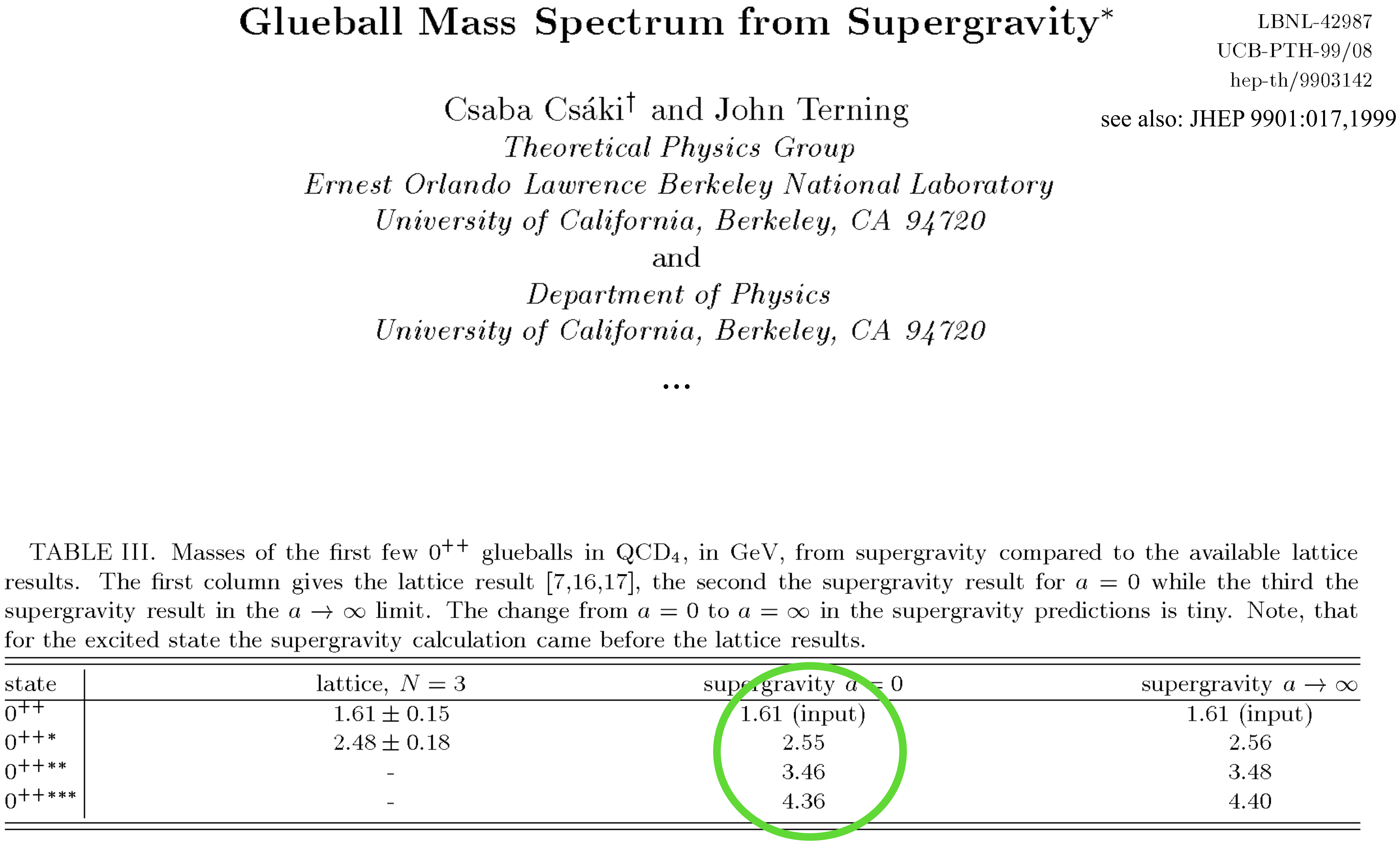


meson



glueball ?

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
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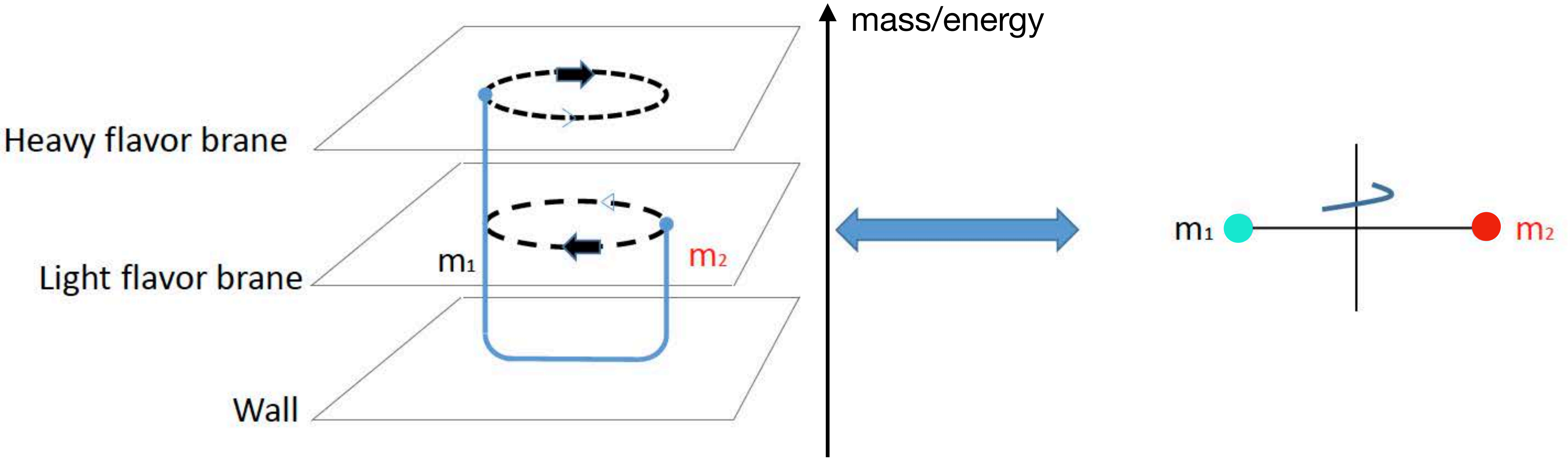
University of California, Berkeley, CA 94720
and
Department of Physics
University of California, Berkeley, CA 94720

…

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.

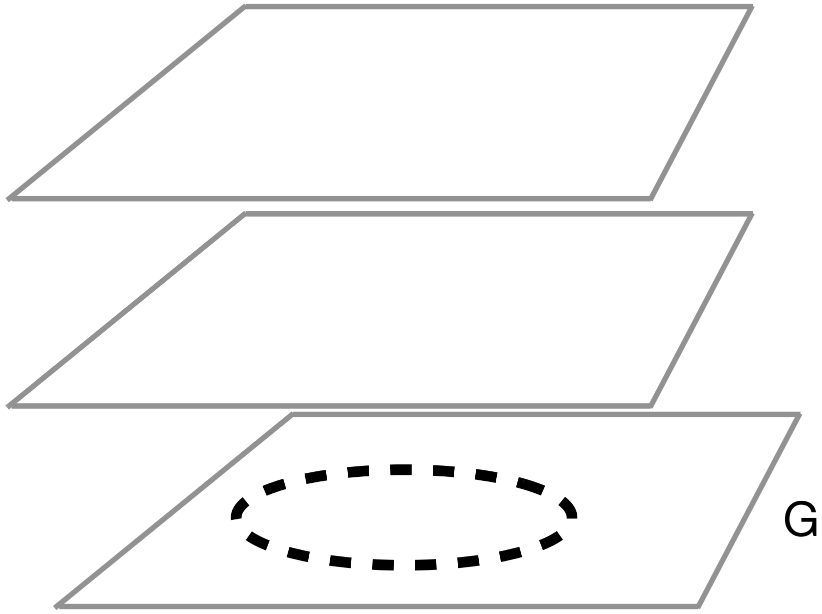
state	lattice, $N = 3$	supergravity $a = 0$	supergravity $a \to \infty$
0^{++}	1.61 ± 0.15	1.61 (input)	1.61 (input)
0^{++*}	2.48 ± 0.18	2.55	2.56
0^{++**}	-	3.46	3.48
0^{++***}	-	4.36	4.40

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

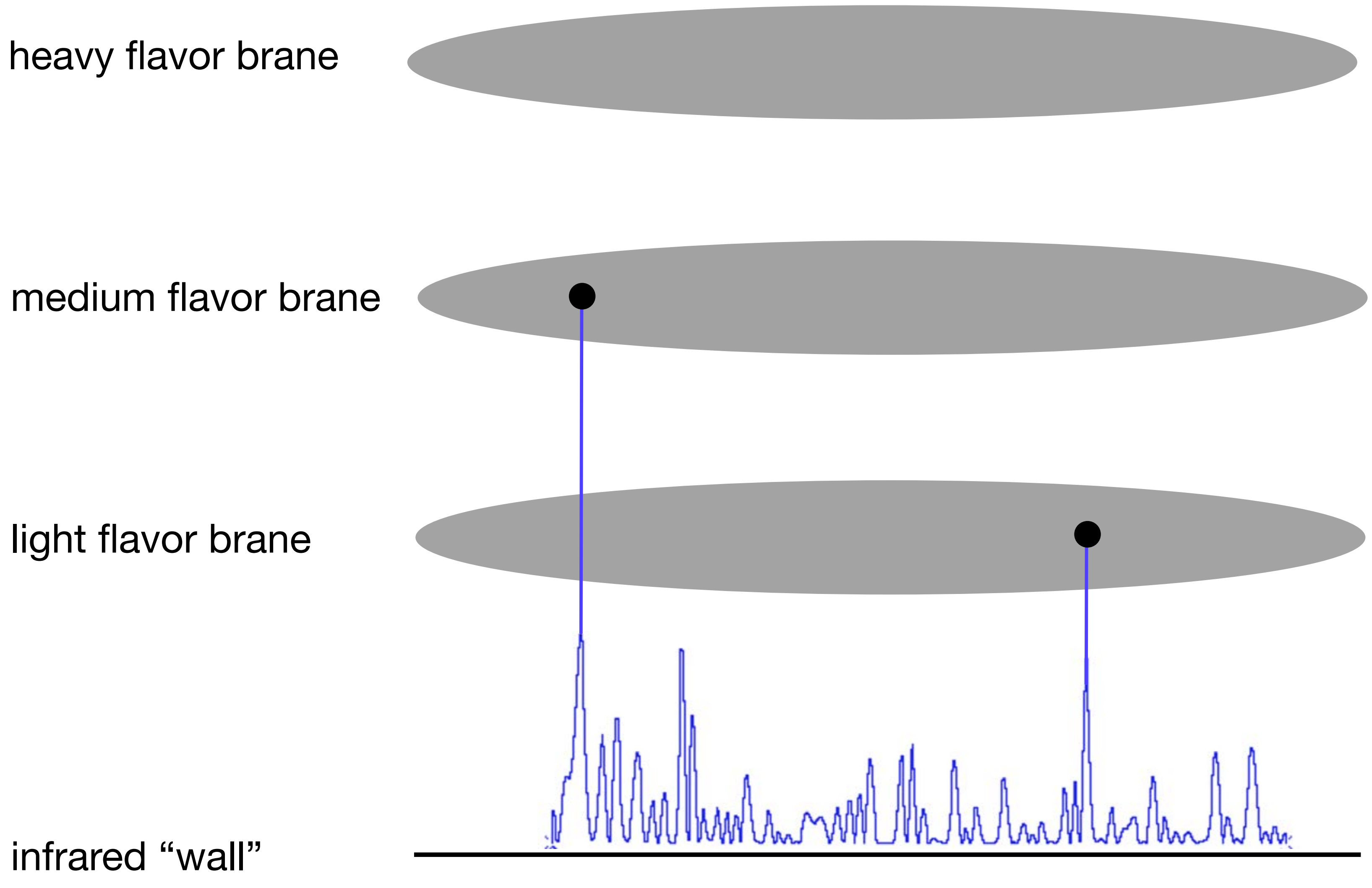
confinement: infrared “wall”

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: decays



Fluctuations of the gluon string reaching flavor branes cause decays

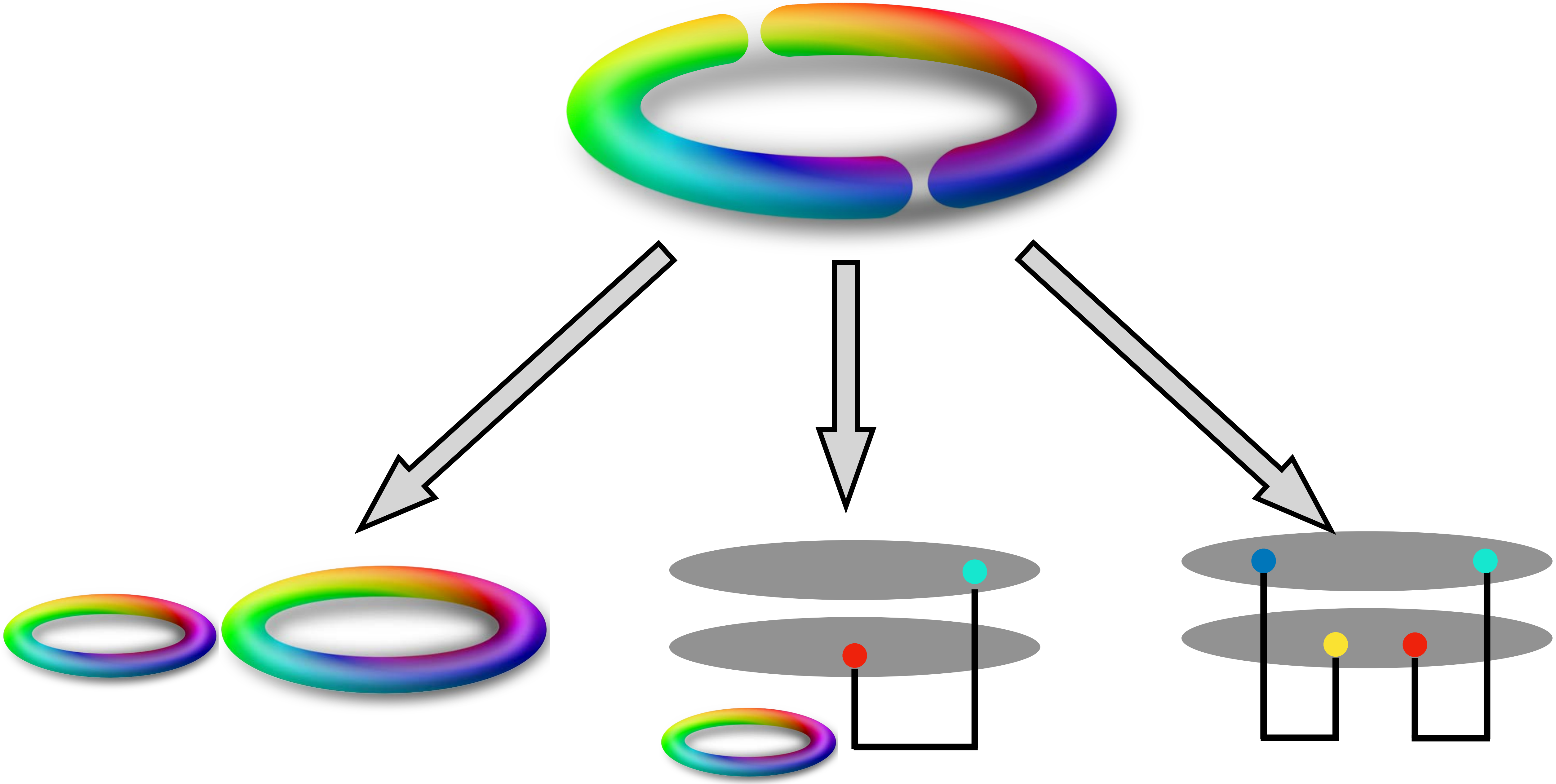
Jacob Sonnenschein, Dorin Weissman, JHEP 1512 (2015) 011, arXiv:1507.01604.

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 decay by string breaking



glueball → 2 glueballs

glueball → meson + glueball

glueball → 2 mesons

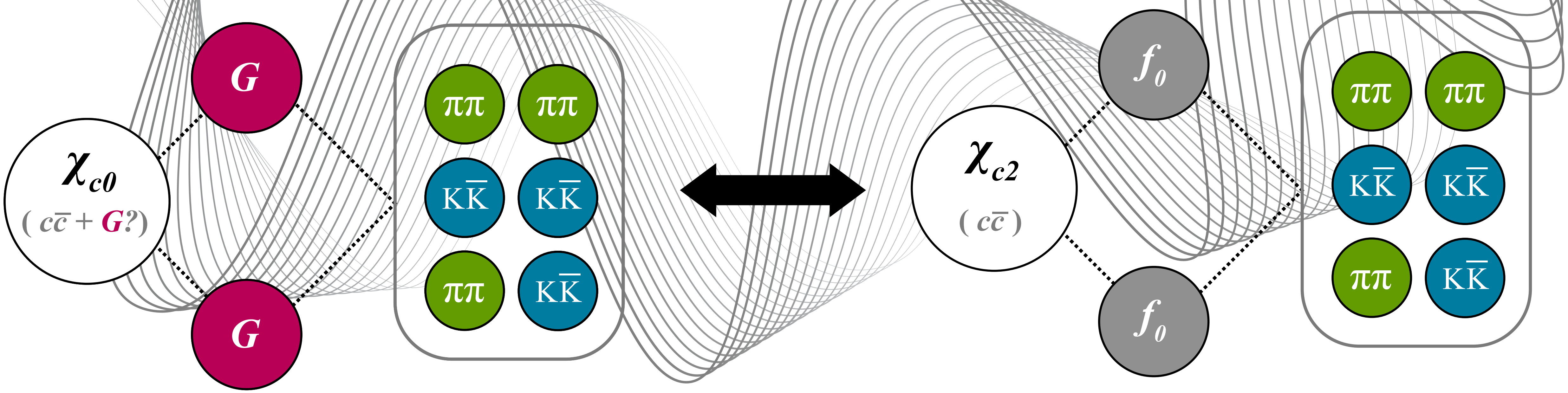
Possible (leading order?) decays of χ_{cJ}

χ_{c0} with suspected glueball admixture	χ_{c2} no glueball admixture
$f_0(980) + f_0$ (or f_2)	$f_0 + f_2(1270)$
$f_0(1370) + f_0$ (or f_2)	$f_0 + f_2'(1525)$
$f_0(1500) + f_0$ (or f_2)	$f_0 + f_2(1565)$
$f_0(1710) + f_0$ (or f_2)	$f_0 + f_2(1640)$
$f_0(1770) + f_0$ (or f_2)	$f_0 + f_2(1810)$
$f_0(2020) + f_0$ (or f_2)	

suspected glue content

Strategy for improved analysis

- χ_c channels have not been investigated since 2008 by CLEO
- χ_{c0} could contain a gluonic admixture due to the presence of a nearby glueball
- Glueballs might decay also into lighter glueballs…
- Measure the coupling of χ_{c0} to $f_0(X)f_0(Y)$, …, and ➔ compare it to χ_{c2} couplings



Investigated channels

⇒ Investigate χ_{cJ} decays to (gluon-rich) $f_0 f_0$. Interesting channels are:

- $\chi_{cJ} \rightarrow \pi^+\pi^-\pi^0\pi^0$
- $\chi_{cJ} \rightarrow 2(\pi^+\pi^-)$
- $\chi_{cJ} \rightarrow \pi^0\pi^0\pi^0\pi^0$
- $\chi_{cJ} \rightarrow \eta\eta\pi^0\pi^0$
- $\chi_{cJ} \rightarrow \eta\eta'\pi^0\pi^0$

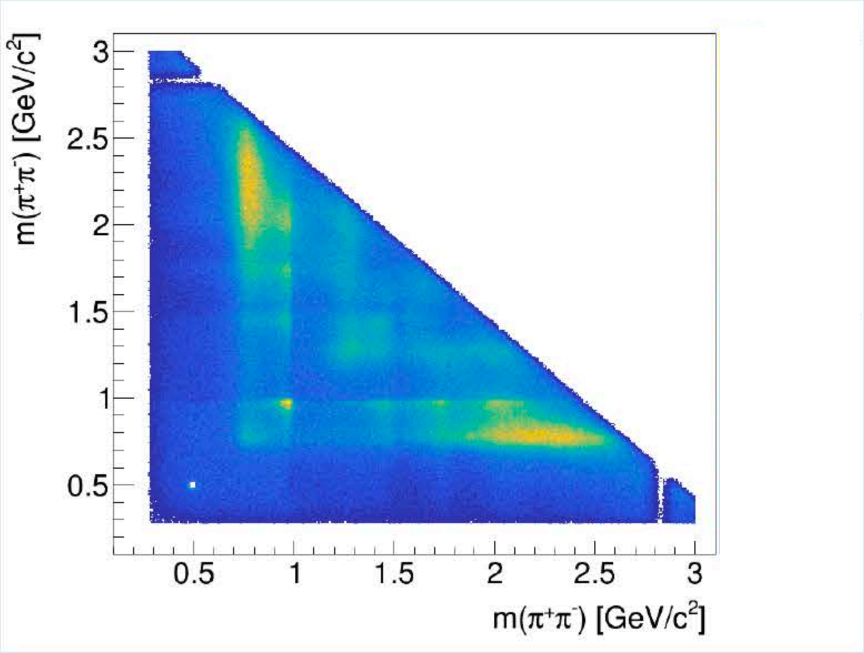
- $\chi_{cJ} \rightarrow K^+K^-\pi^0\pi^0$
- $\chi_{cJ} \rightarrow K^+K^-\pi^+\pi^-$
- $\chi_{cJ} \rightarrow K^+K^-K_S^0K_S^0$
- $\chi_{cJ} \rightarrow K^+K^-\pi^0\pi^0\pi^0\pi^0$

Analyses done in Bochum with the goal of comparison of χ_{c0} to χ_{c2} decays.

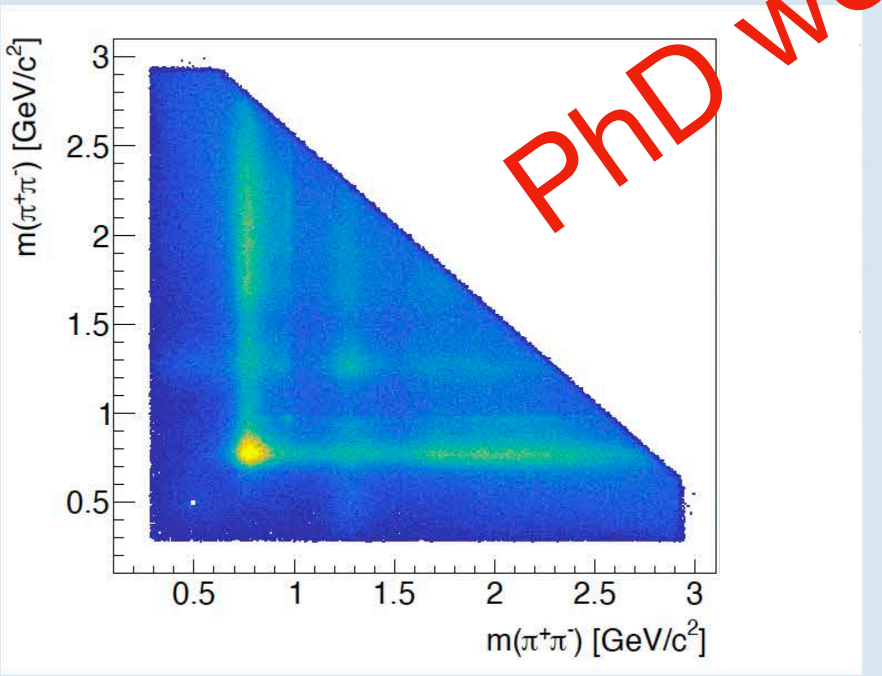
U.Wiedner, 2604.12895, https://doi.org/10.1016/j.jspc.2026.100387

$\chi_{cJ} \to 2(\pi^+\pi^-)$

$\chi_{c0} \to (\pi^+\pi^-)(\pi^+\pi^-)$

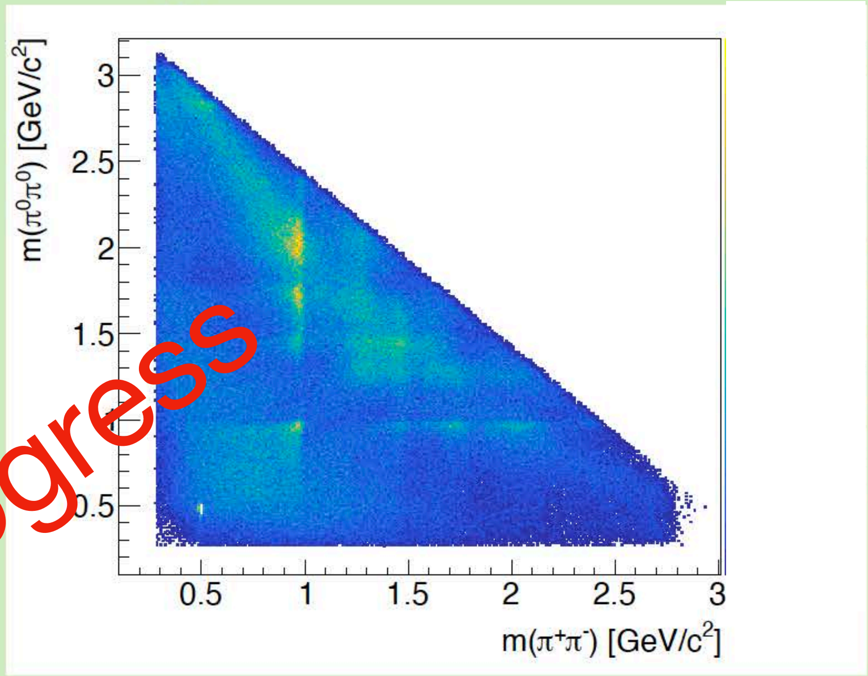


$\chi_{c2} \to (\pi^+\pi^-)(\pi^+\pi^-)$

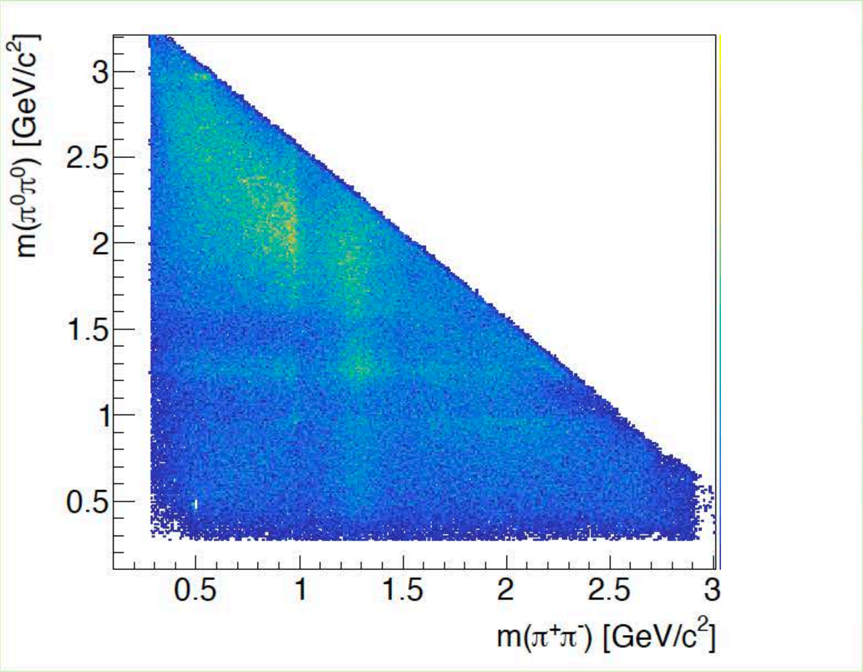


$\chi_{cJ} \to (\pi^+\pi^-\pi^0\pi^0)$

$\chi_{c0} \to (\pi^+\pi^-)(\pi^0\pi^0)$

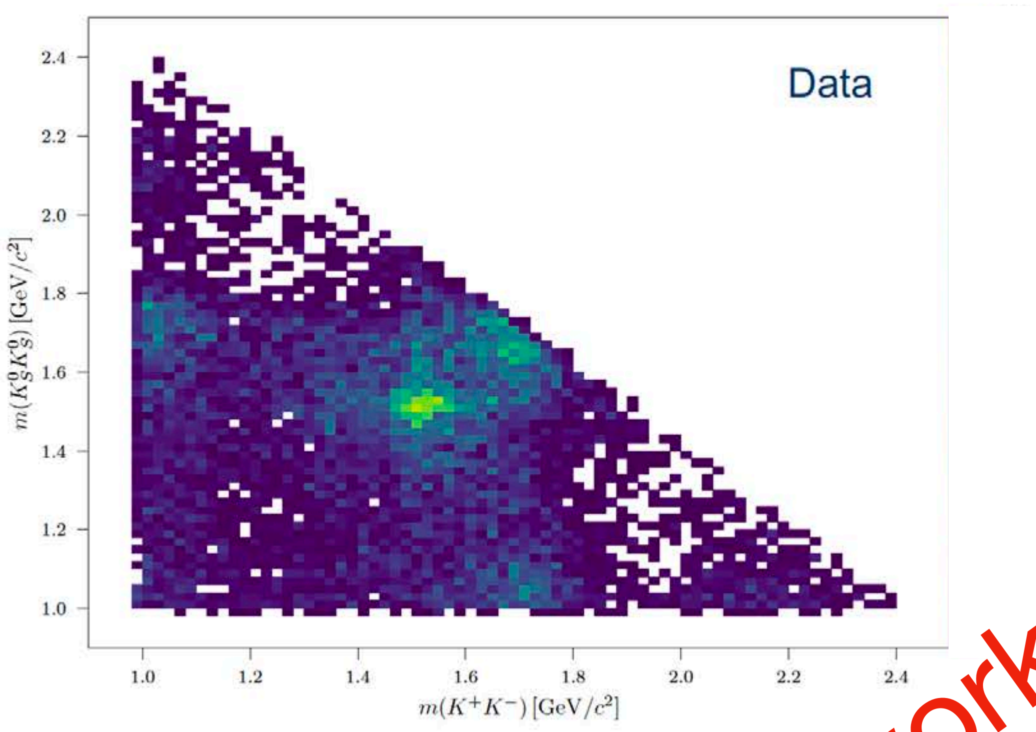


$\chi_{c2} \to (\pi^+\pi^-)(\pi^0\pi^0)$

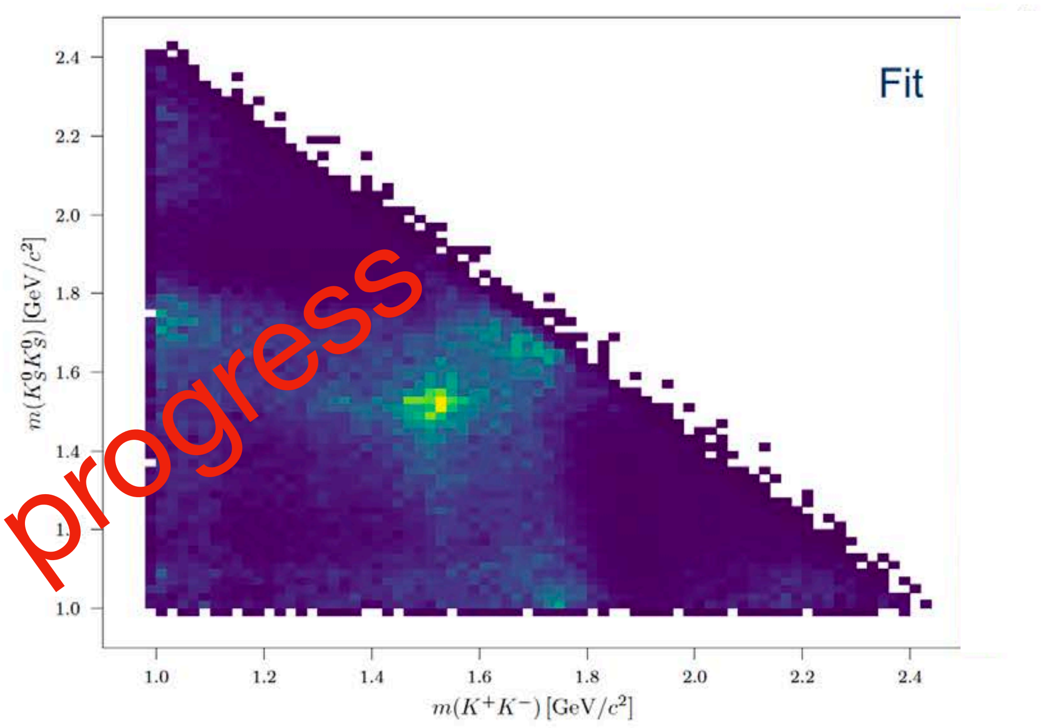


Data and Fit for $\chi_{cJ} \rightarrow K^+K^-K_S^0K_S^0$

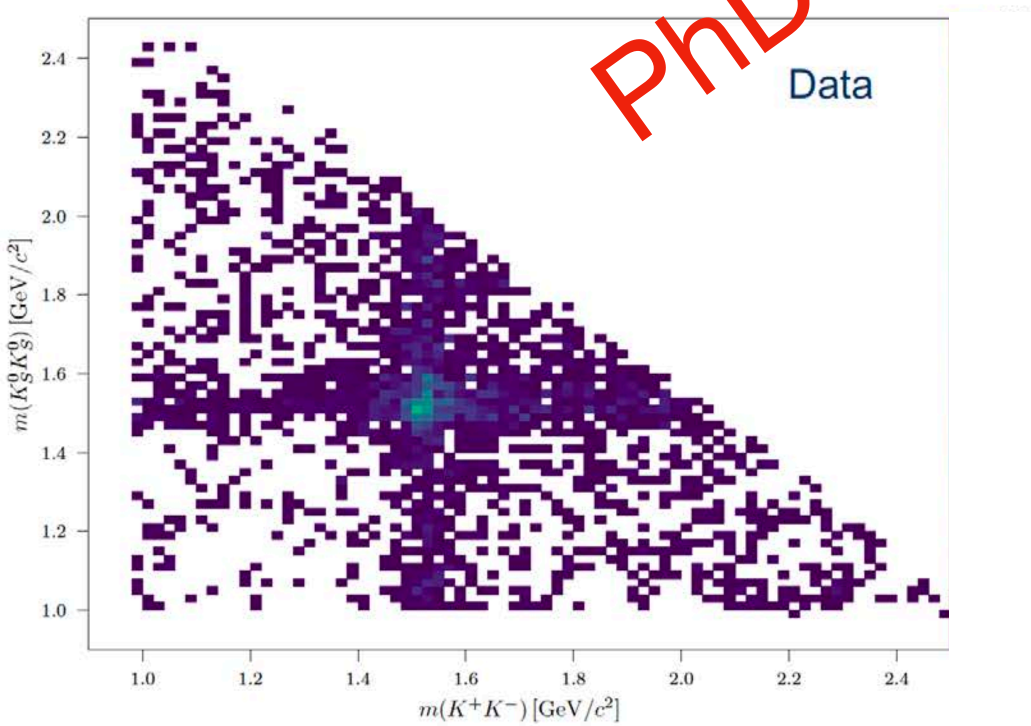
Data $\chi_{c0} \rightarrow (K^+K^-K_S^0K_S^0)$



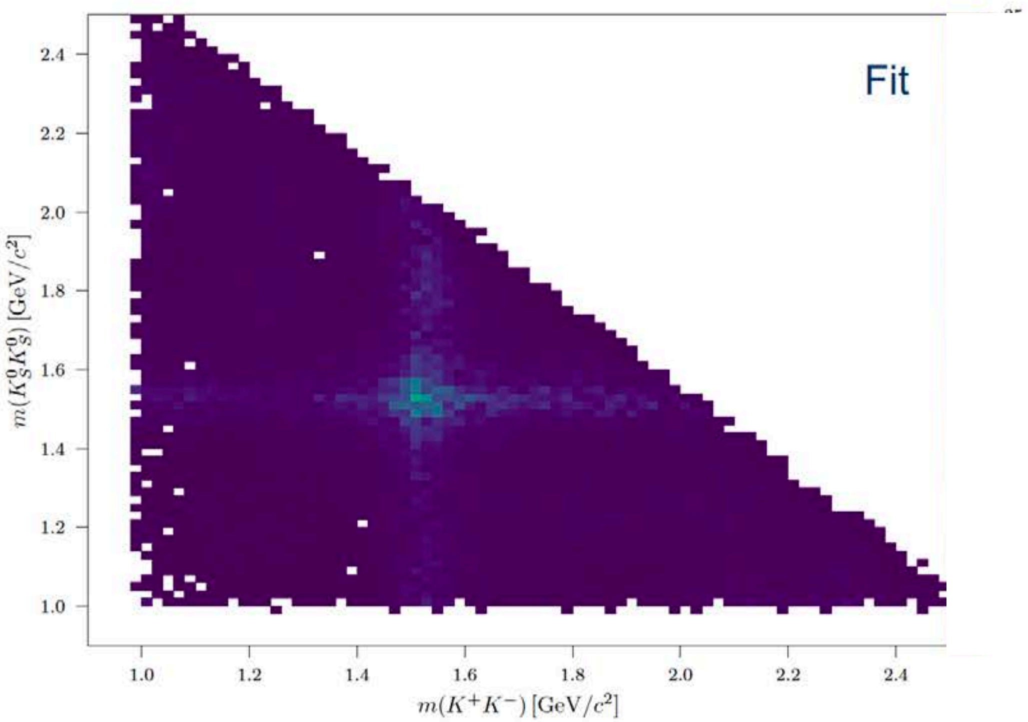
Fit $\chi_{c0} \rightarrow (K^+K^-K_S^0K_S^0)$



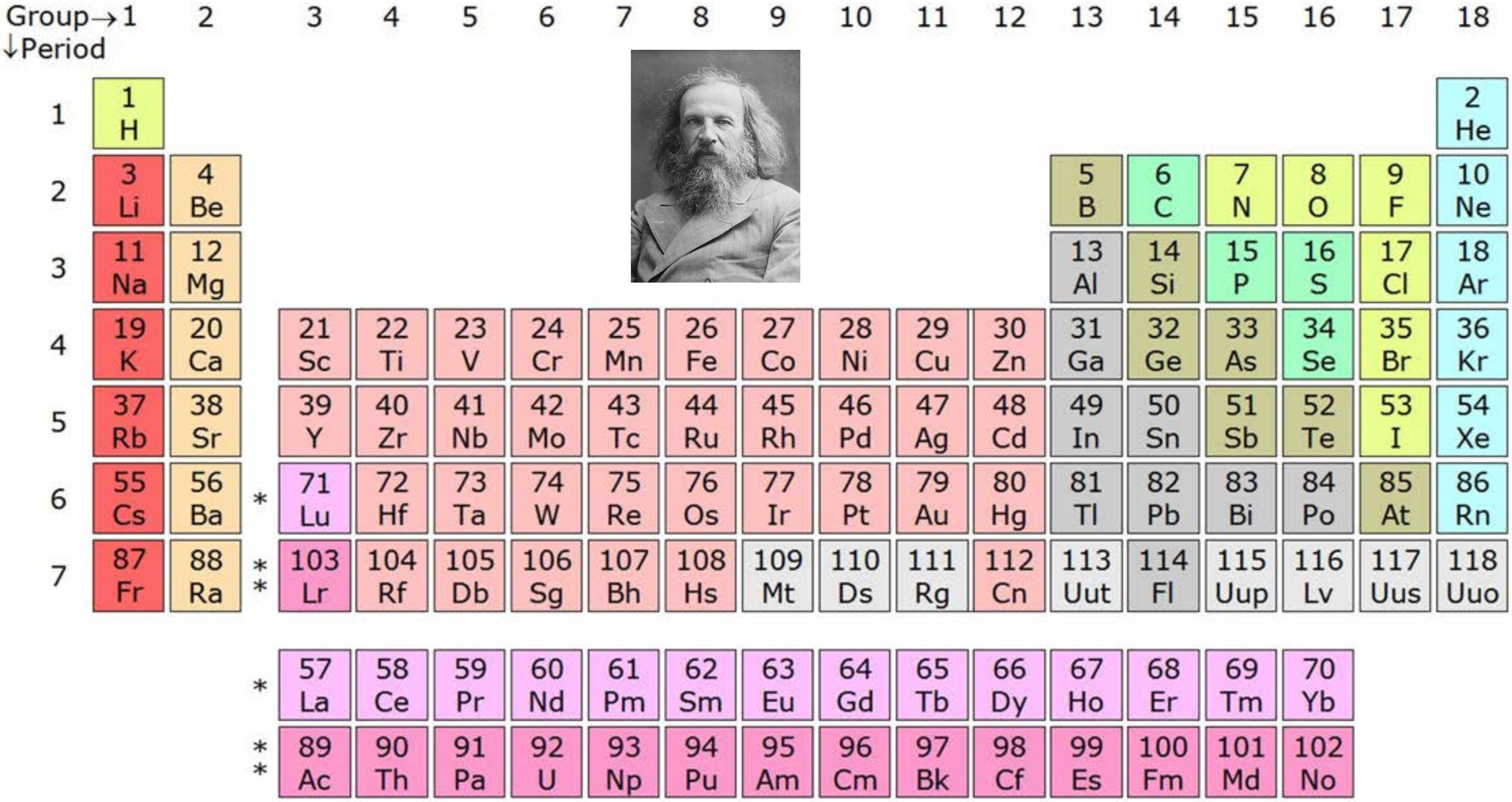
Data $\chi_{c2} \rightarrow (K^+K^-K_S^0K_S^0)$



Fit $\chi_{c2} \rightarrow (K^+K^-K_S^0K_S^0)$



We learned about the nature of the atom due to the periodic system

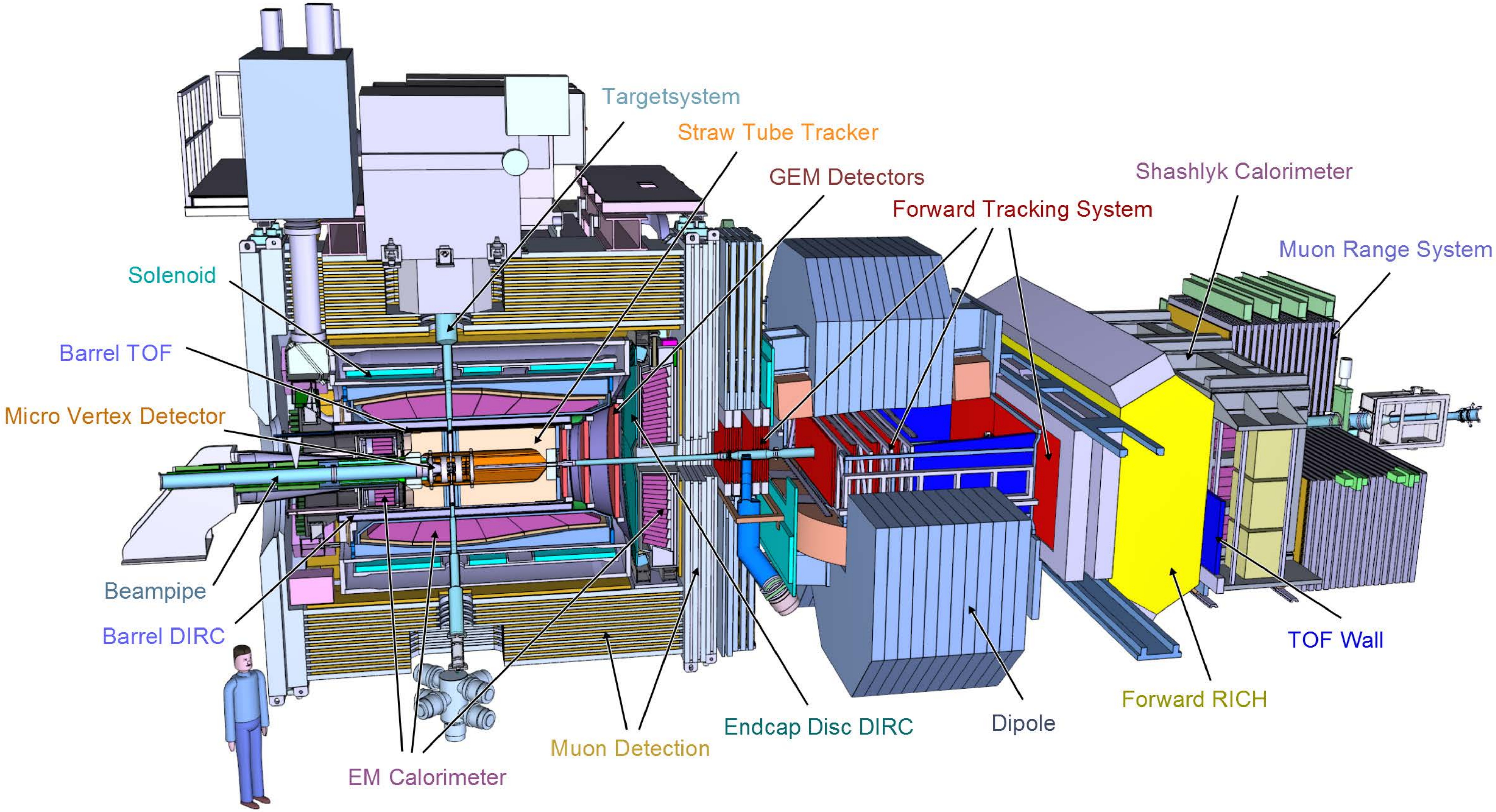


Group→ ↓Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Do precision hadron spectroscopy experiments to understand the glueballs!

PANDA @ FAIR

- gluon-rich due to antiprotons-proton annihilations
- no limitations on q.n. of glueballs (even exotic)
- glueballs (and other particles) up to 5.5 GeV
- line shape of resonances

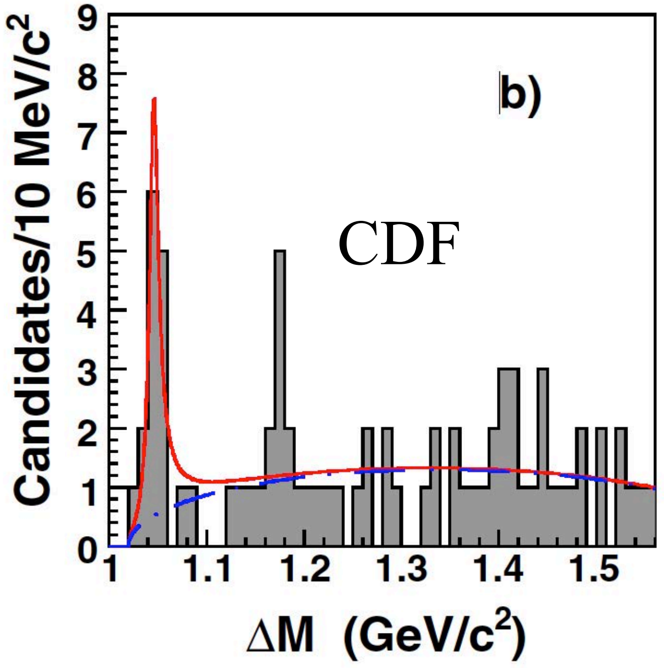


Glueballs

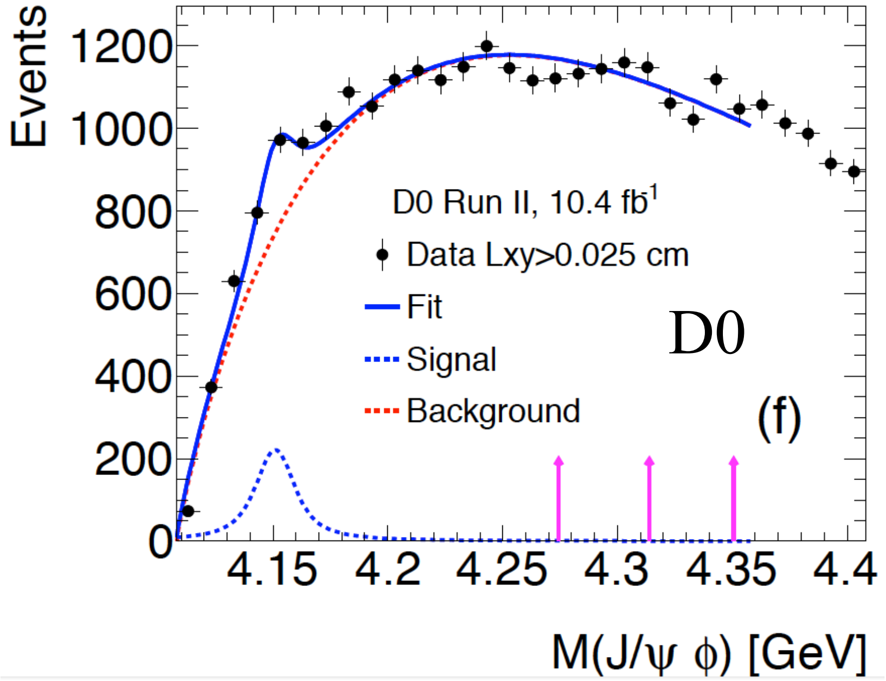
My personal glueball candidate for 1^{++} glueball: X(4140) M= 4147 MeV/c^2 , Γ = ~19 MeV

↳ decay mode J/ψ ϕ (flavor blind)

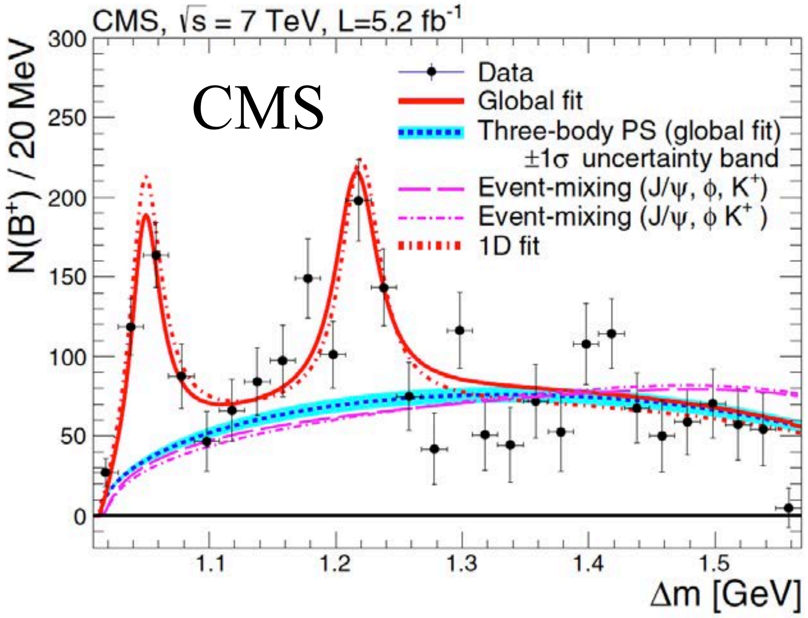
Phys.Rev.Lett. 102 (2009) 242002

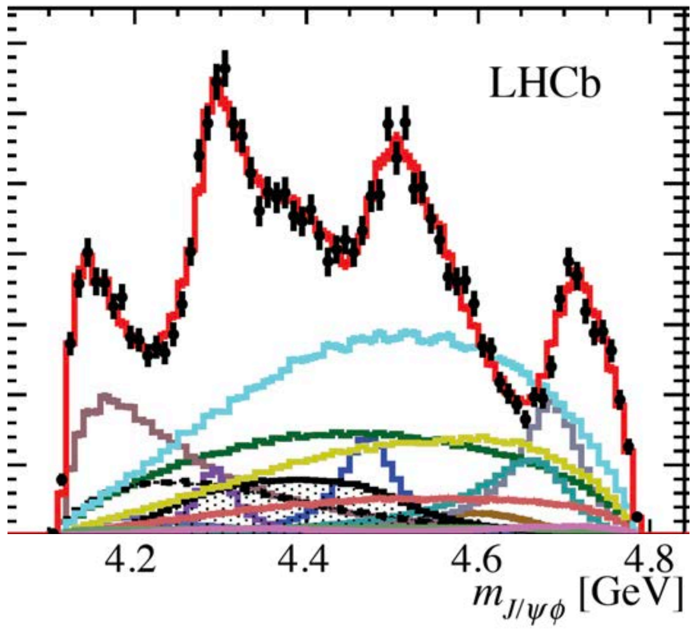


Phys. Rev. Lett. 115, 232001



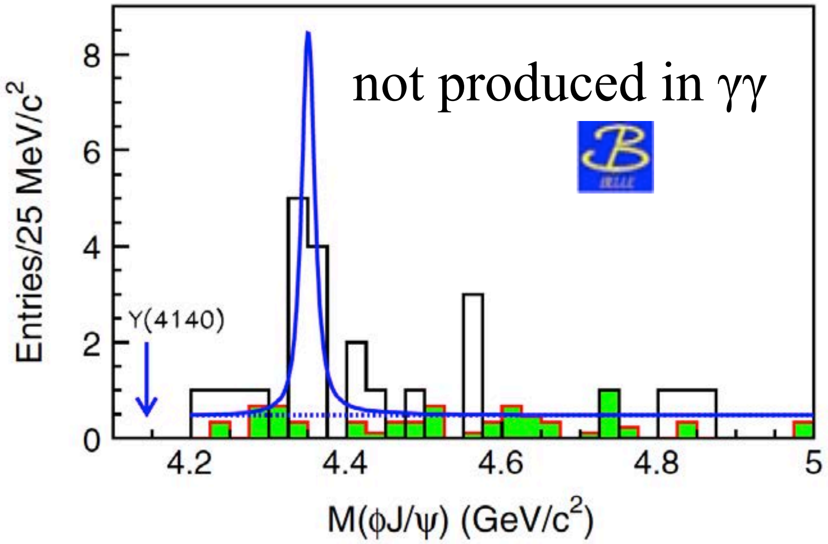
Phys.Lett. B734 (2014) 261-281





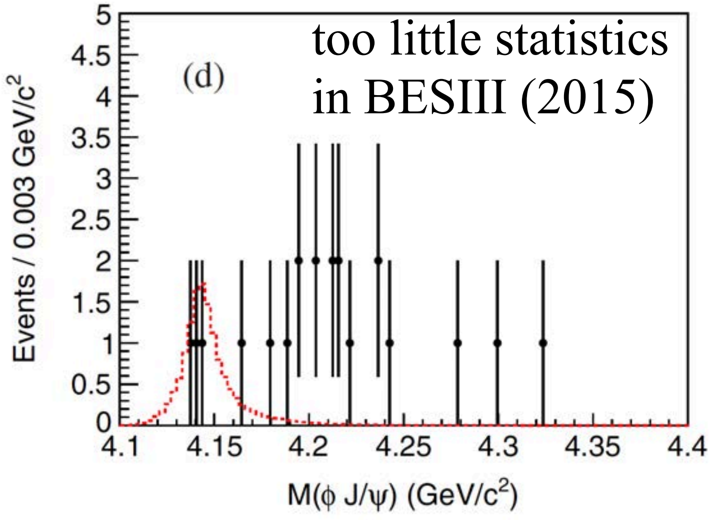
Phys. Rev. Lett. 127, 082001 (2021), arXiv: 2103.01803

not produced in γγ



Phys.Rev.Lett. 104 (2010) 112004

too little statistics in BESIII (2015)



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

Summary and conclusions

BESIII offers the best opportunity to study glueballs at the moment.

➥ full structure and spectrum to be studied in future by $\bar{\text{p}}$anda

There are strong hints for the excited scalar glueball and we have to proof it.

➥ a broad study of 4-body final states is underway.

We might be able to establish glueball to glueball decays.

Our studies will lead to a better understanding of the ground state scalar glueball.

Glueballs are fundamental for understanding mass creation!

Thank you for your attention!