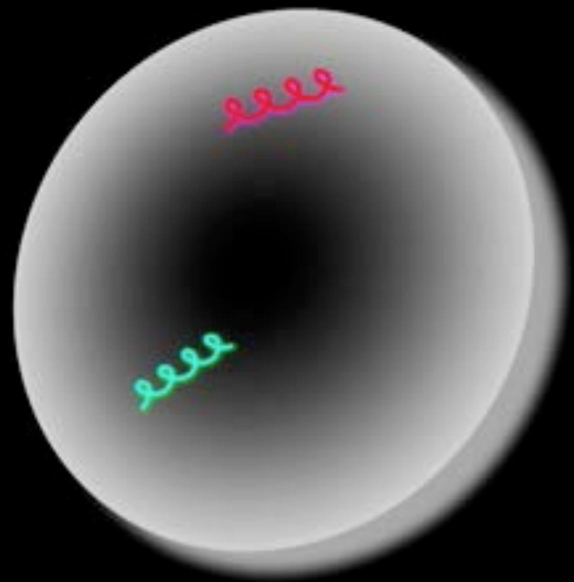
Glueballs – fundamental, exciting and elusive

Ulrich Wiedner, São Paulo, 26. Feb. 2019

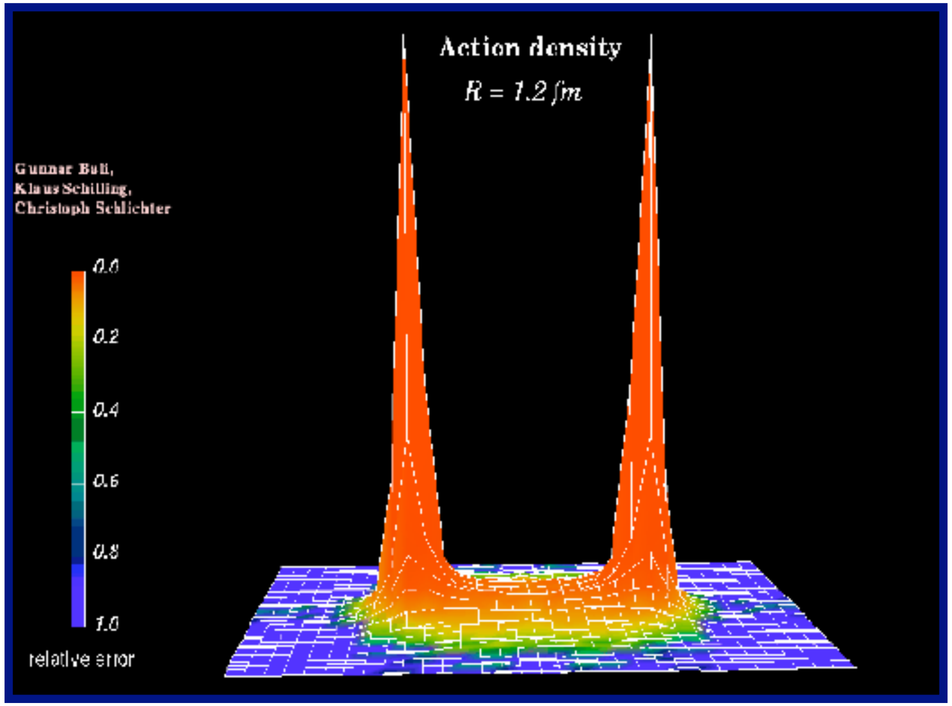
H. Fritzsch and M. Gell-Mann, Current algebra: Quarks and what else?

A troublesome feature of the extended null plane algebra is the apparent absence of operators corresponding to those in the model that contain only gluon field strengths and no quark operators; for a color singlet gluon, the field strength itself would be such an operator, while for a color octet gluon we could begin with bilinear forms in the field strength in order to obtain color singlet operators. Can we obtain these quark–free operators by investigating discontinuities at the coincidence of coordinates characterizing quark and antiquark fields in the model? At any rate, we certainly want these quarkfree operators included in the extended algebra.

Glueballs



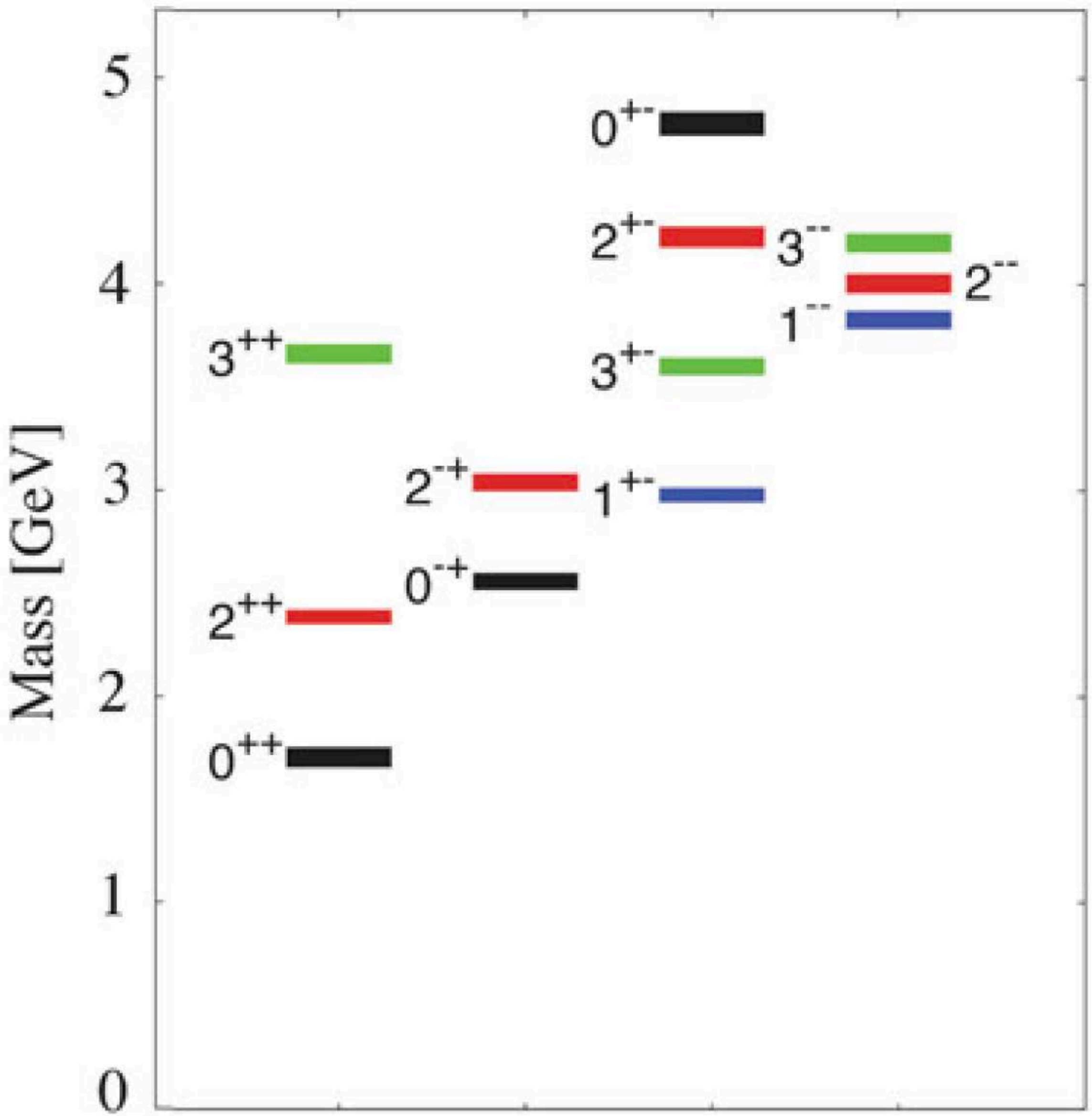
QCD on the computer: lattice calculations



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

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

Glueball predictions in a quenched lattice calculation



AdS/CFT Correspondence

(Maldacena 1997, AdS: Anti de Sitter space, CFT: conformal field theory)

- Duality Quantum Field Theory $\Leftrightarrow$ Gravity Theory
- Arises from String Theory in a particular low-energy limit
- Duality: Quantum field theory at strong coupling

  $\Leftrightarrow$ Gravity theory at weak coupling
- Works for large N gauge theories at large 't Hooft coupling λ

Conformal field theory in four dimensions

$\Leftrightarrow$ Supergravity Theory on $AdS_5 \times S^5$

More information can be found at:

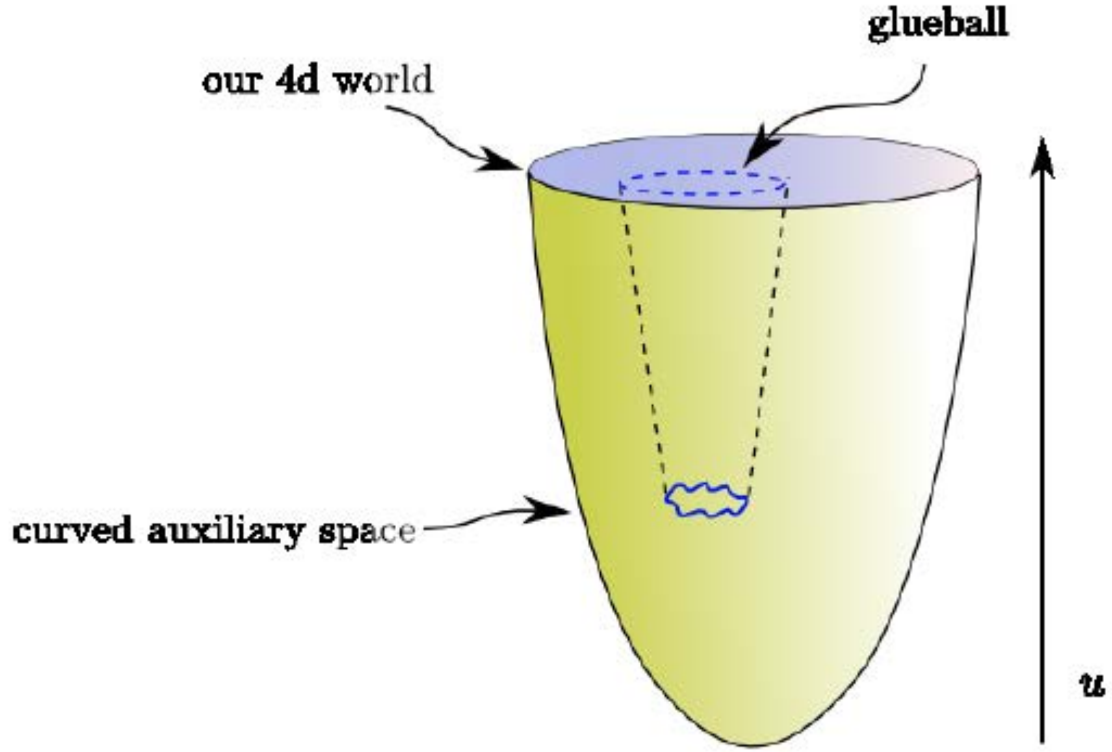
Holography Inspired Stringy Hadrons
Jacob Sonnenschein (Tel Aviv U.). Feb 1, 2016. 49 pp.
Published in **Prog.Part.Nucl.Phys. 92 (2017) 1-49**
TAUP-3021-16
DOI: 10.1016/j.ppnp.2016.06.005
e-Print: **arXiv:1602.00704 [hep-th] | PDF**

Glueballs as rotating folded closed strings
Jacob Sonnenschein, Dorin Weissman (Tel Aviv U.). Jul 6, 2015. 44 pp.
Published in **JHEP 1512 (2015) 011**
DOI: 10.1007/JHEP12(2015)011
e-Print: **arXiv:1507.01604 [hep-ph] | PDF**

Excited mesons, baryons, glueballs and tetraquarks: Predictions of the Holography Inspired Stringy Hadron model
Jacob Sonnenschein, Dorin Weissman (Tel Aviv U.). Dec 4, 2018. 45 pp.
e-Print: **arXiv:1812.01619 [hep-ph] | PDF**

Maldacena correspondence

- The string is ten-dimensional ! Maldacena 1997



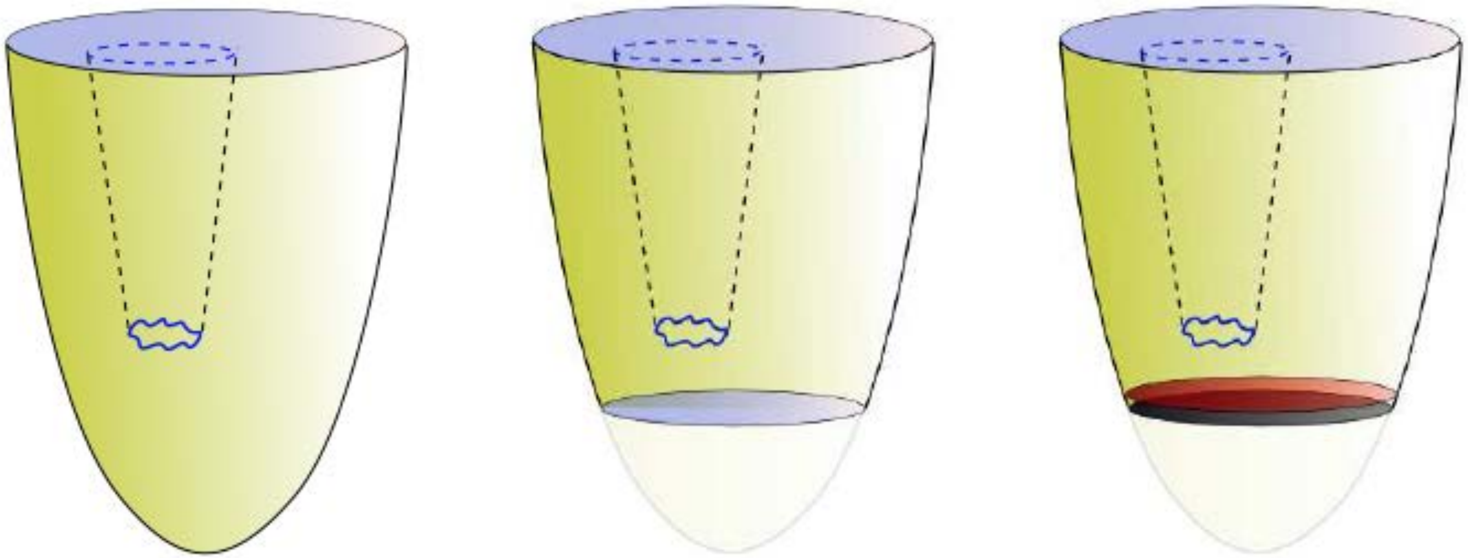
- The curvature in string-size units sets the 't Hooft coupling: $\lambda \sim \left(\frac{R}{l_{\text{string}}}\right)^4$.
- $R \gg l_{\text{string}}$: strings reduce to gravity: gauge/gravity correspondence.
- We will make this relation precise in a moment.

From Ads/CFT to general string(gravity)/gauge duality

- The basic duality relates the string theory on Ads5xS5 to N=4 SYM. Both sides are invariant under the maximal super-conformal symmetries.
- To get to non-susy YM theory we need to break all the supersymmetries .
- The need to introduce a scale in the gauge theory translates to deforming the bulk into a non-Ads one.
- What are bulk geometries that correspond to confining gauge theories? Confining means here admitting an area law Wilson line

Geometry encodes 4d physics

- The 4d physics is encoded in the higher-dimensional geometry.
- We now know which geometries yield confining or finite-T duals.



conformal	confining	thermal
anti de-Sitter	extra scale ("wall")	Hawking-radiating black hole

- $\lambda \sim \left(\frac{R}{l_{\text{string}}}\right)^4$ generalises, but always

small curvature ⟷ strong gauge coupling

Witten's model of confining background

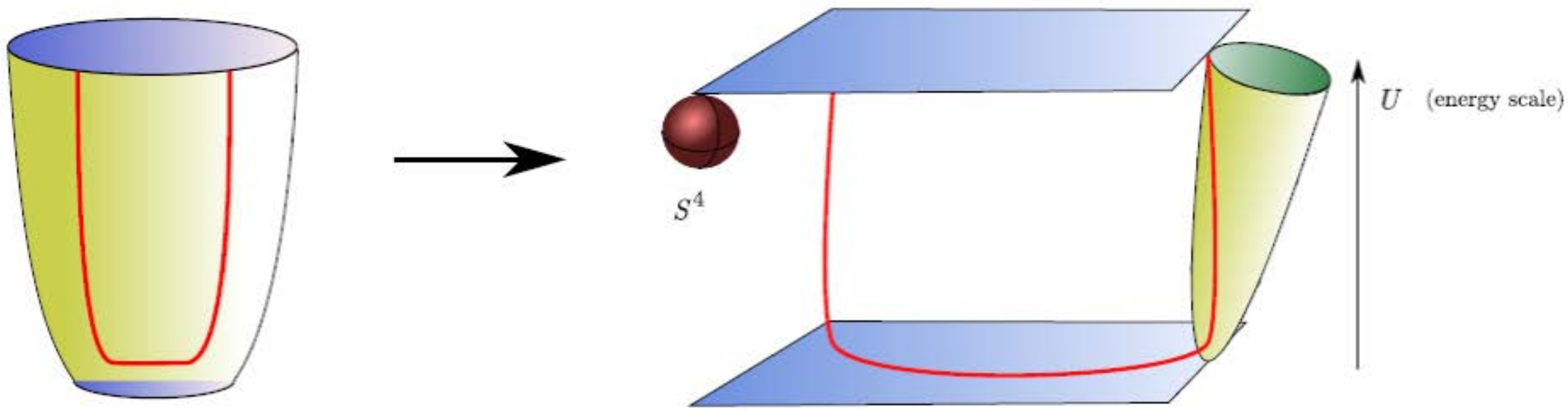
$$ds^2 = \left(\frac{U}{R_{D4}}\right)^{3/2}\left[\eta_{\mu\nu}dX^\mu dX^\nu + f(U)d\theta^2\right] + \left(\frac{R_{D4}}{U}\right)^{3/2}\left[\frac{dU^2}{f(U)} + U^2 d\Omega_4\right]$$

world-volume
our 3+1 world

$f(U) = 1 - \left(\frac{U_\Lambda}{U}\right)^3$

θ is a compact Kaluza-Klein circle

U: radial direction bounded from below $U \geq U_\Lambda$

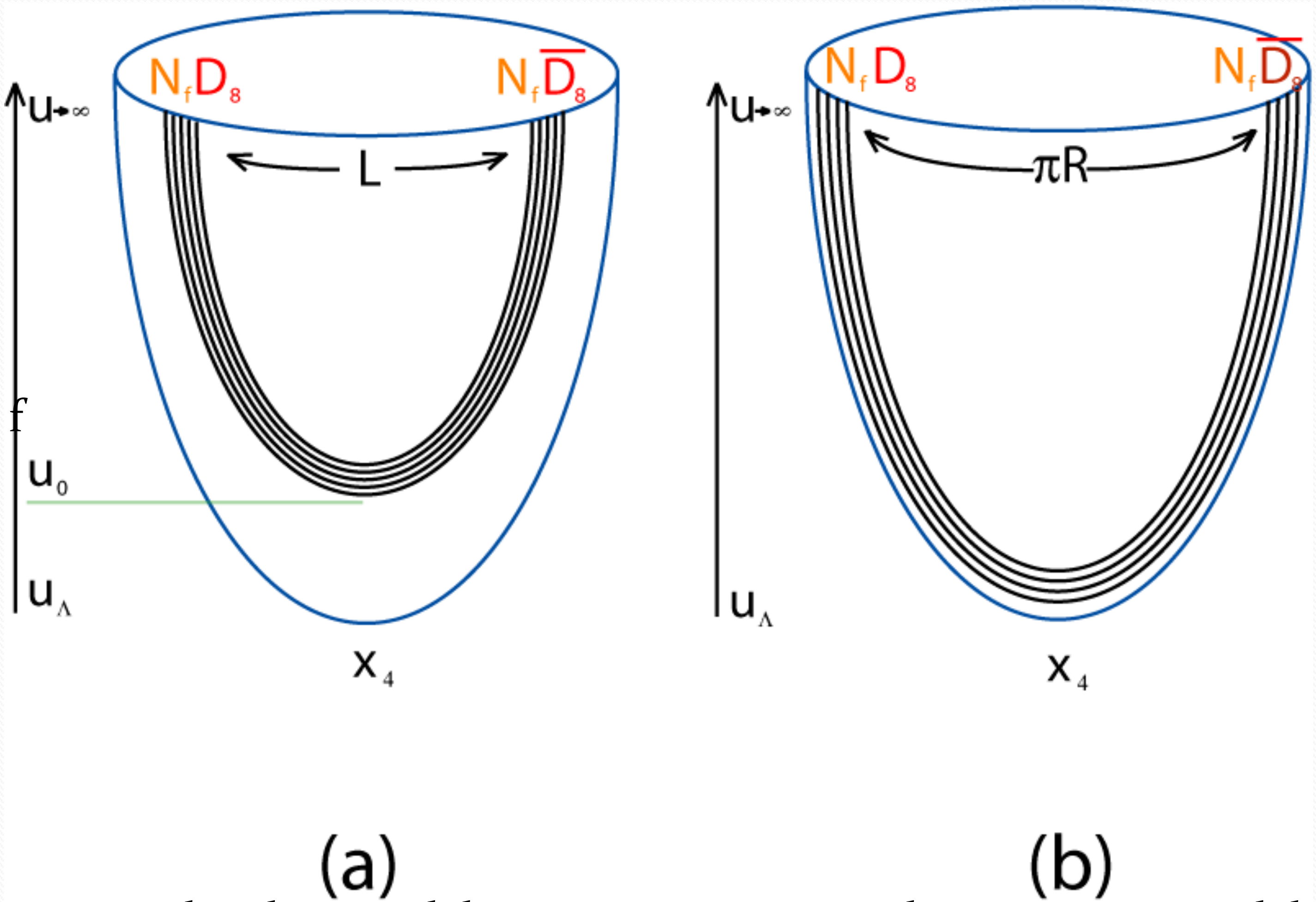


Adding flavor

- We would like to introduce flavor degrees of freedom
- We add N_f flavor branes to a non-supersymmetric confining background.
- A natural candidate is therefore *Witten's model*.
- *For $N_f << N_c$ the flavor brane do not back-react on the background thus they are probe branes*
- To assure chiral symmetry one adds D8 branes and anti D8 branes
- Their U shape profile associate with a spontaneous breaking of the UV *chiral flavor global* symmetry of $U(N_f)xU(N_f)$ to a $U(N_f)_D$ in the IR

Adding flavor: The Sakai Sugimoto model

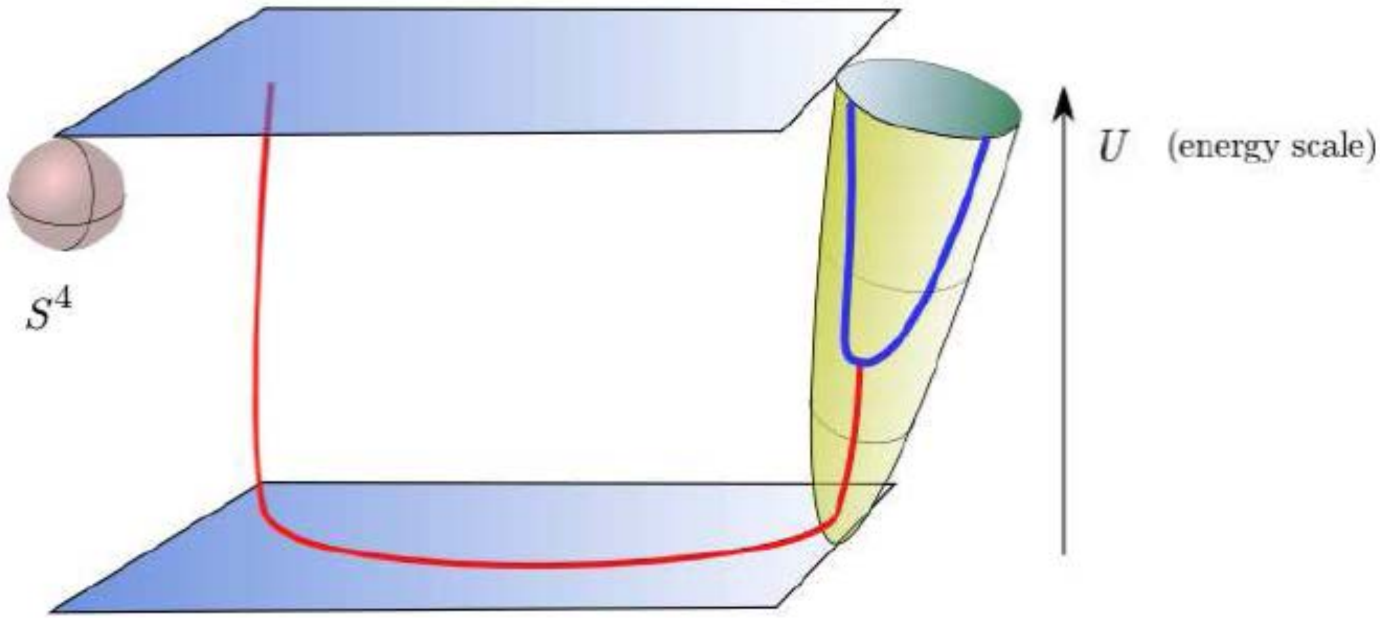
- Adding N_f D8 anti-D8 branes into Witten's model
- In the cigar geometry the flavor brane have a U shape profile



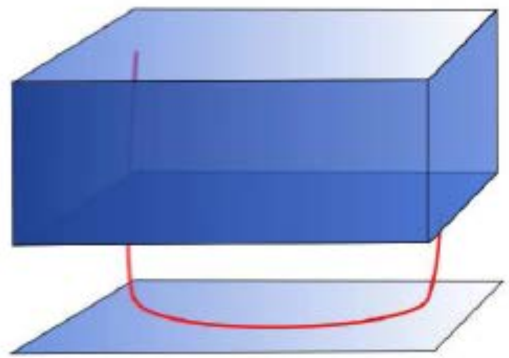
Generalized SS model

Sakai Sugimoto model

Adding flavor: The Sakai Sugimoto model

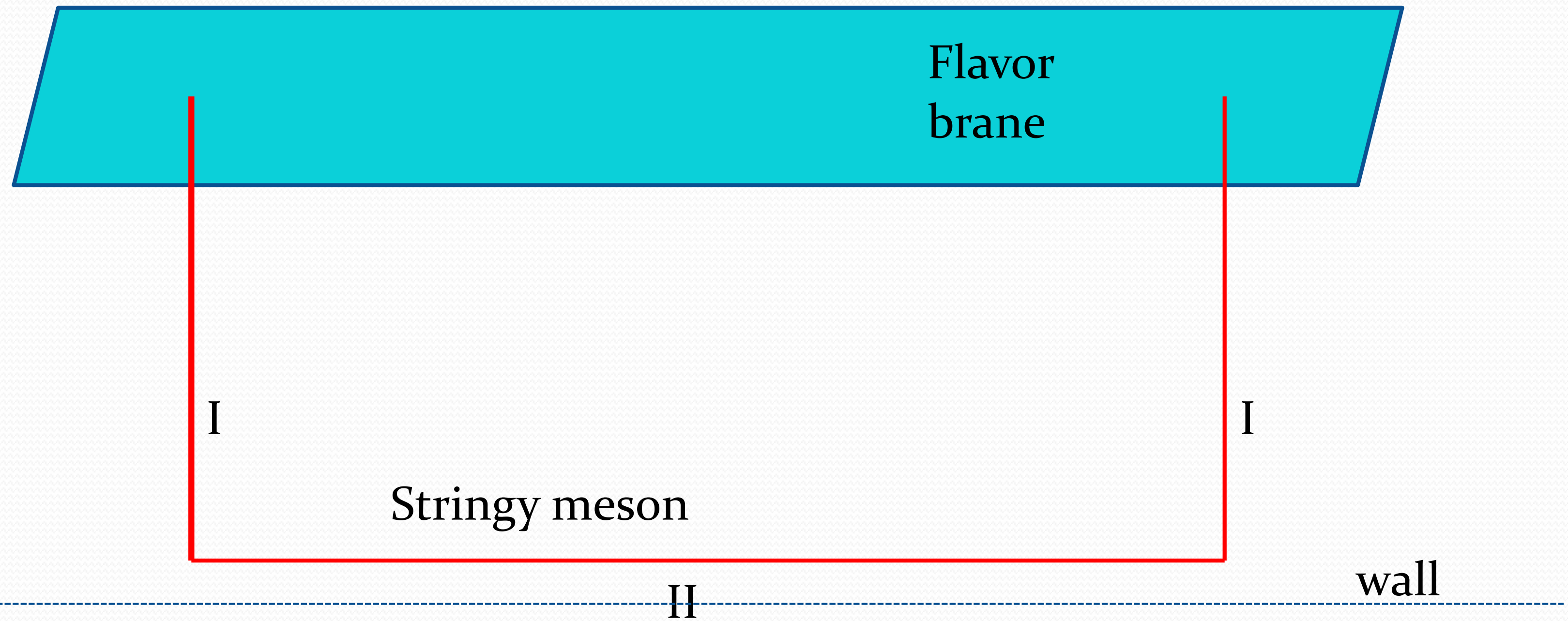


suppressing everything but U
and our 3+1d world:



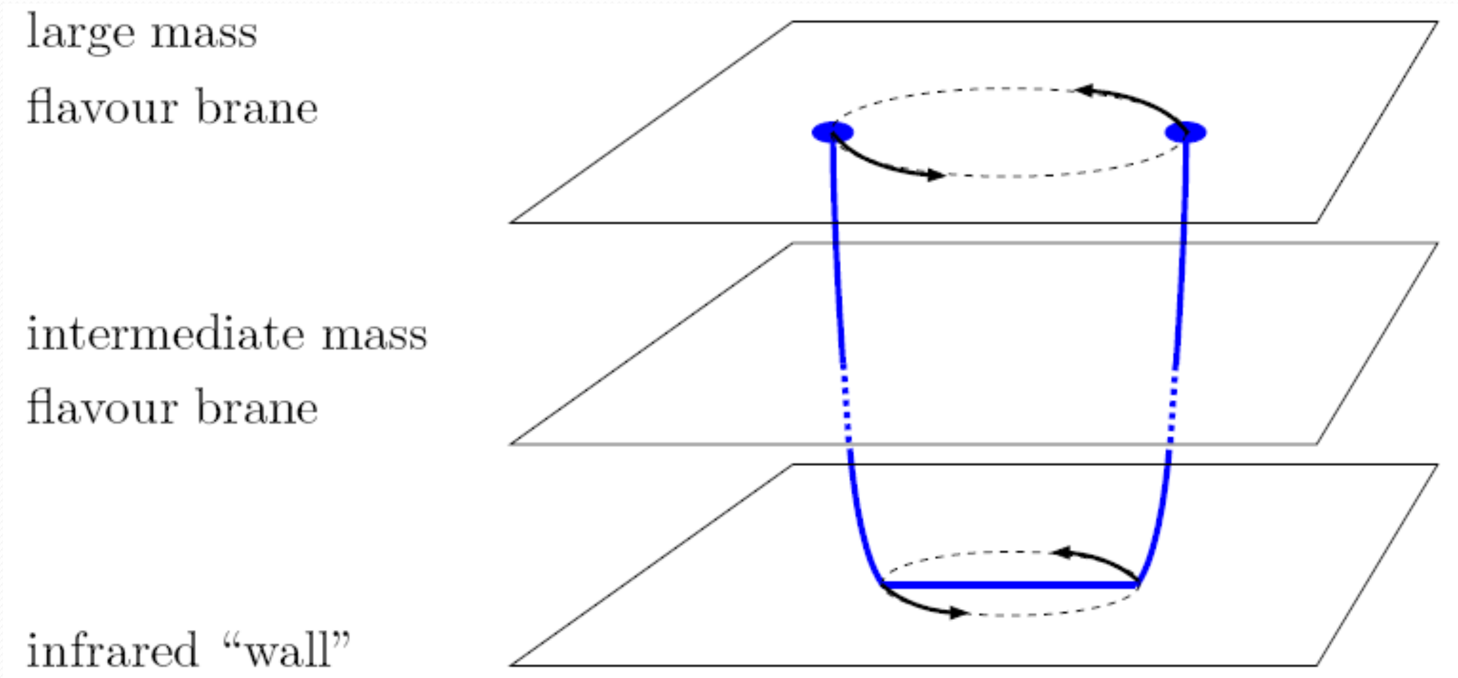
Strings ending on flavor branes

- The space-time of the string/gauge duality is curved and has a holographic dimension truncated at a wall
- A (mesoic) rotating string between two endpoints on a flavor brane does not stretch along the flavor brane
- Instead solving the Nambu Goto EOM we find that the string falls down stretches flatly along the wall and climbs up to the flavor brane.

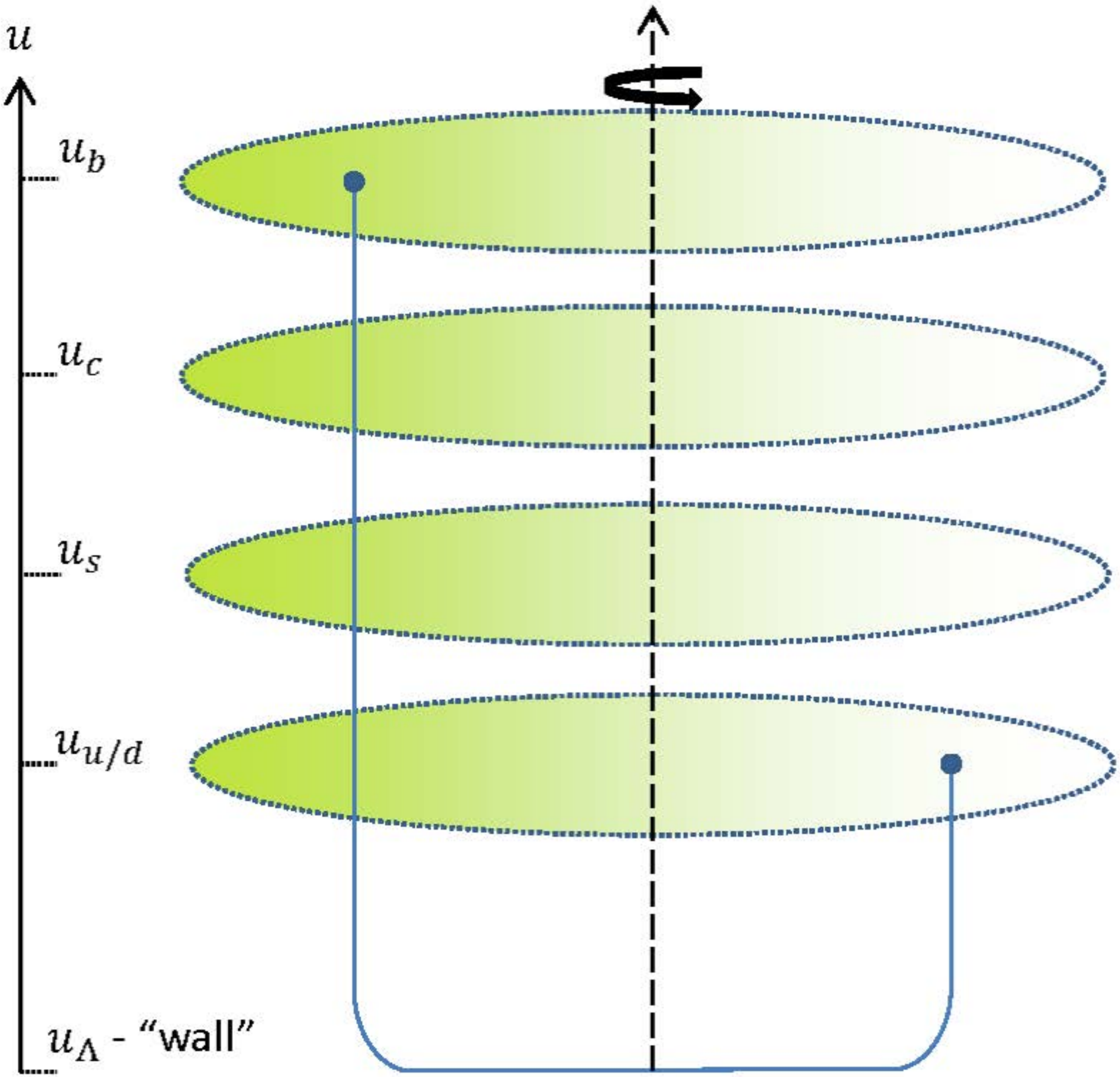


The structure of a rotating holographic string

- Thus the structure of a holographic meson connected to a large mass flavor brane

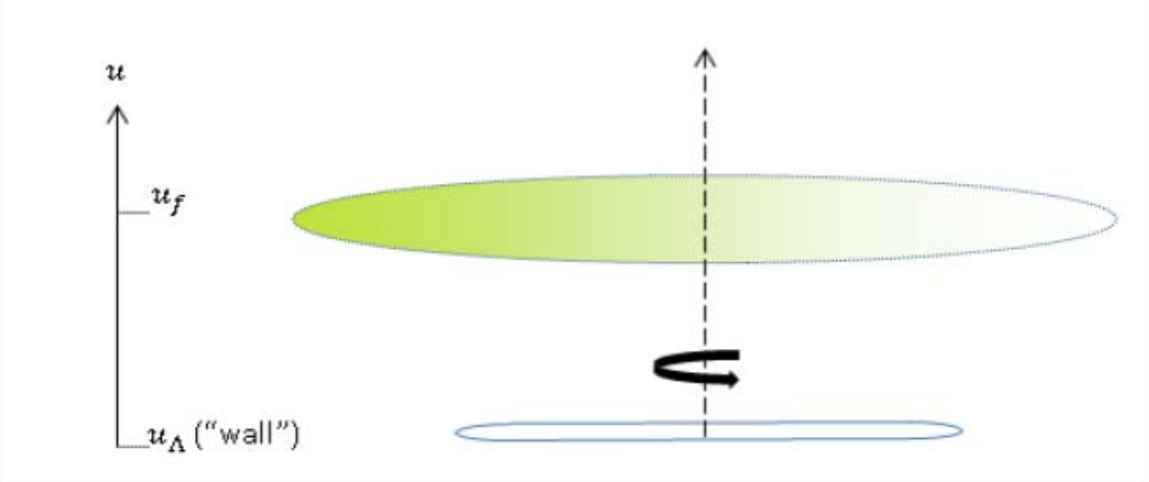


Example: The B meson

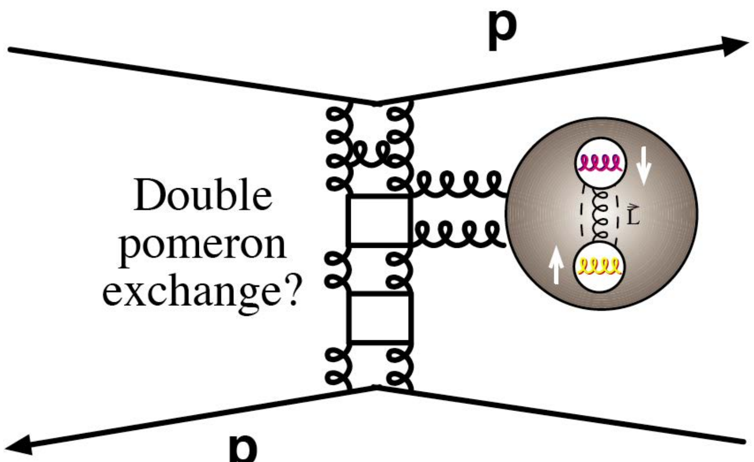


Glueballs as closed strings

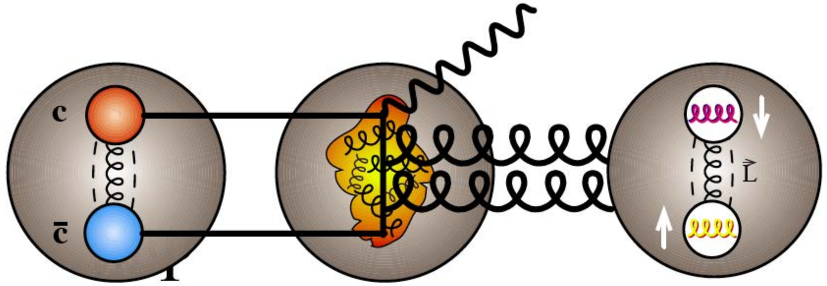
- Mesons are open strings with a massive quark and an anti-quark on its ends.
- Baryons are open strings with a quark on one end and a baryonic vertex and a di-quark on the other end.
- What are glueballs?
- Since they do not incorporate quarks it is natural to assume that they are rotating closed strings
- Angular momentum associates with rotation of folded closed strings



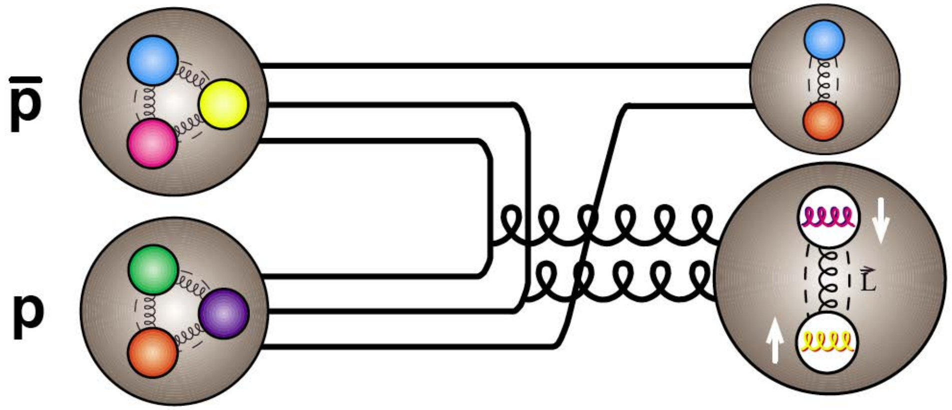
Particle production: “gluon-rich” processes



WA 79, WA 102



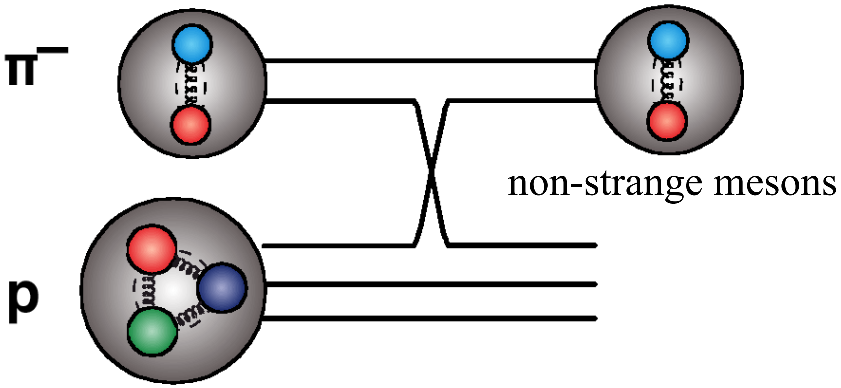
MARK III, DM2, BES

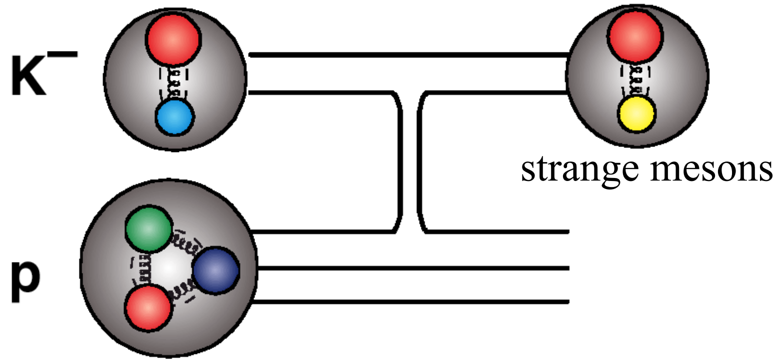


ASTERIX, Crystal Barrel, OBELIX, E835, PANDA

Particle production: “quark-rich” processes

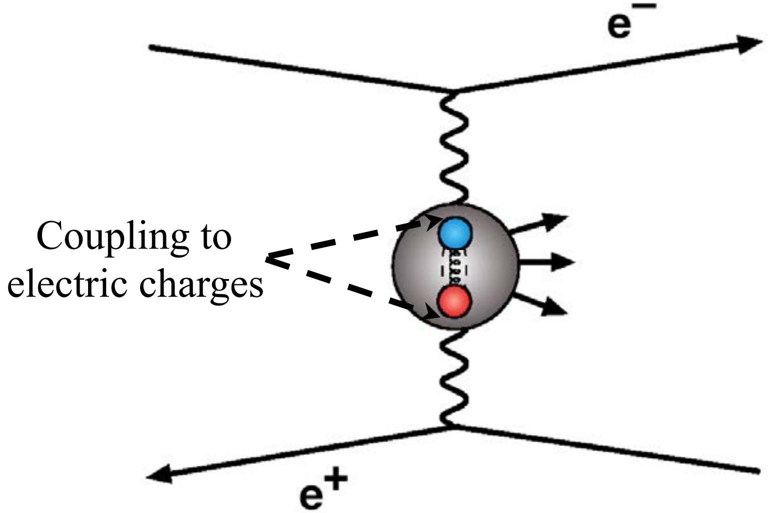
Hadron beams





GAMS (CERN), LASS (SLAC), BNL experiments ...

γγ collisions



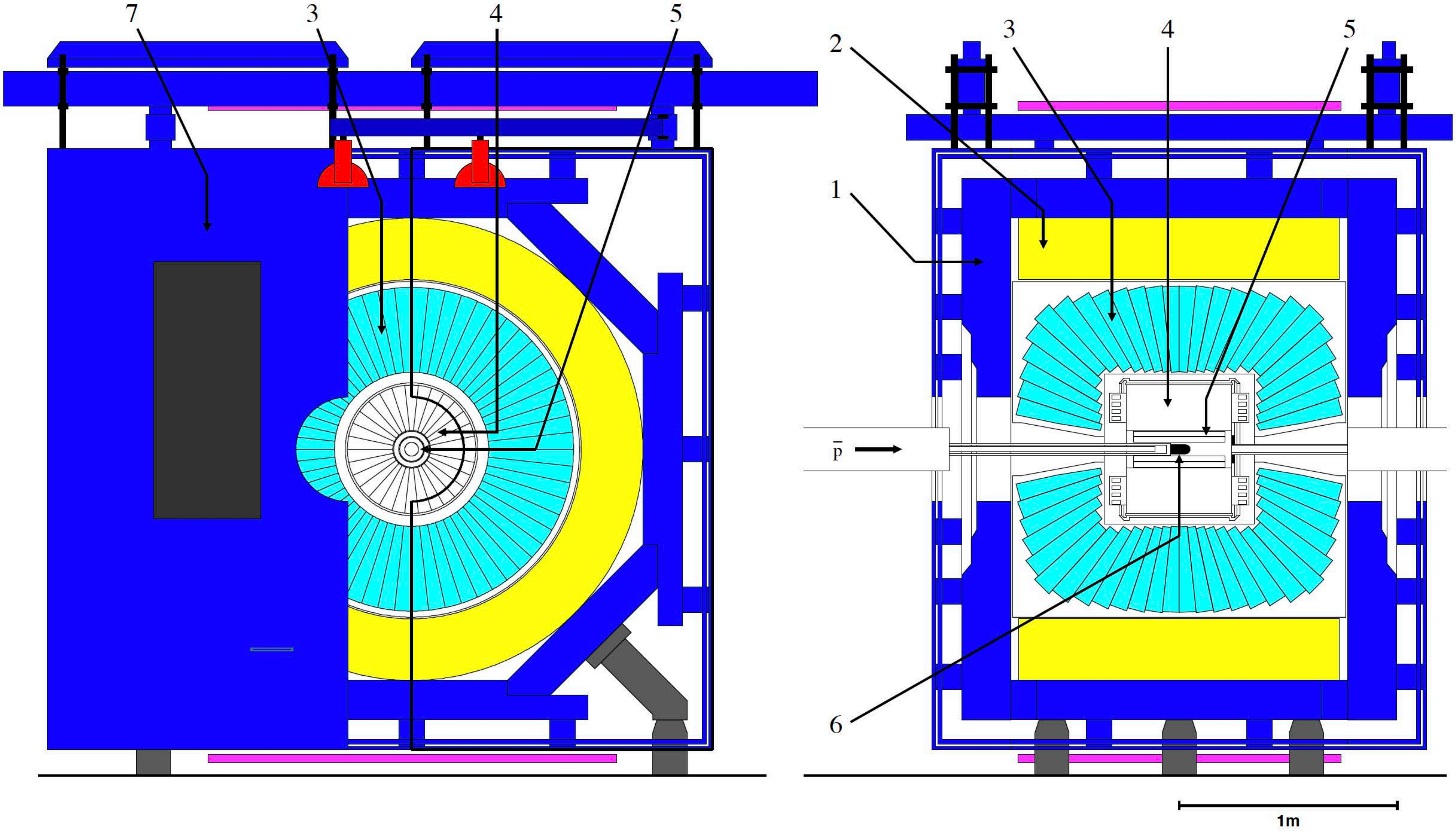
γγ collisions
... act as anti-glueball filter

ARGUS, Crystal Ball, LEP, BaBar, Belle, BESIII experiments ...

The scalar ($J^{PC} = 0^{++}$) particles

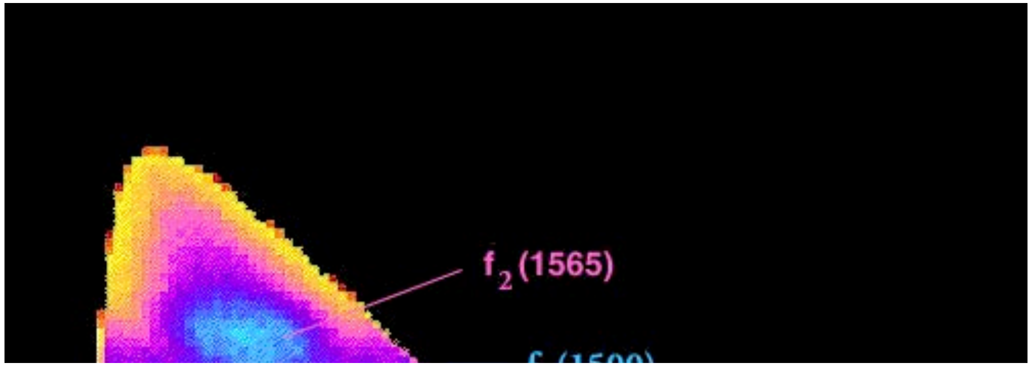
Known scalar mesons

	Γ [MeV]	i
$a_0(980)$	~ 50	1
$f_0(980)$	~ 50	0
$f_0(500)$	~ 800	0
$\kappa(700)$	~ 600	$\frac{1}{2}$
$a_0(1450)$	265	1
$f_0(1370)$	~ 400	0
$f_0(1710)$	125	0
$K_0^*(1430)$	294	$\frac{1}{2}$



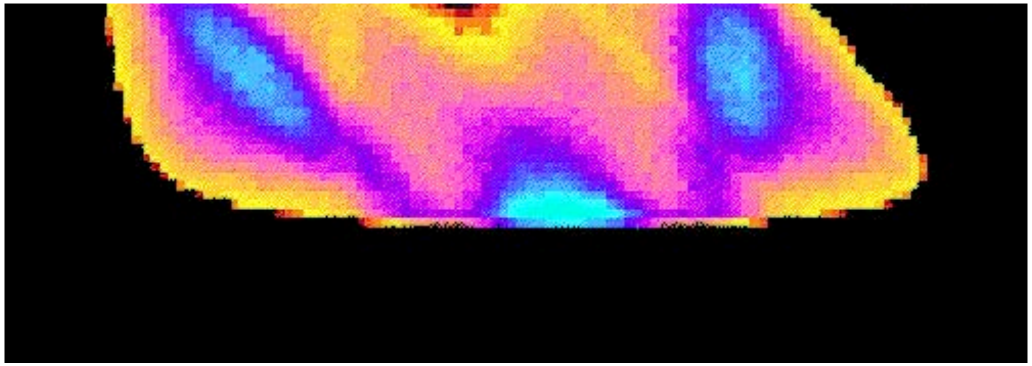
Overall layout of the Crystal Barrel detector showing (1) magnet yoke, (2) magnet coils, (3) CsI barrel, (4) jet drift chamber, (5) proportional chamber, (6) liquid hydrogen target, (7) one half of endplate.

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



The determination of contributing particles and their properties requires refined analysis methods.

The interpretation of the states' nature requires refined theory

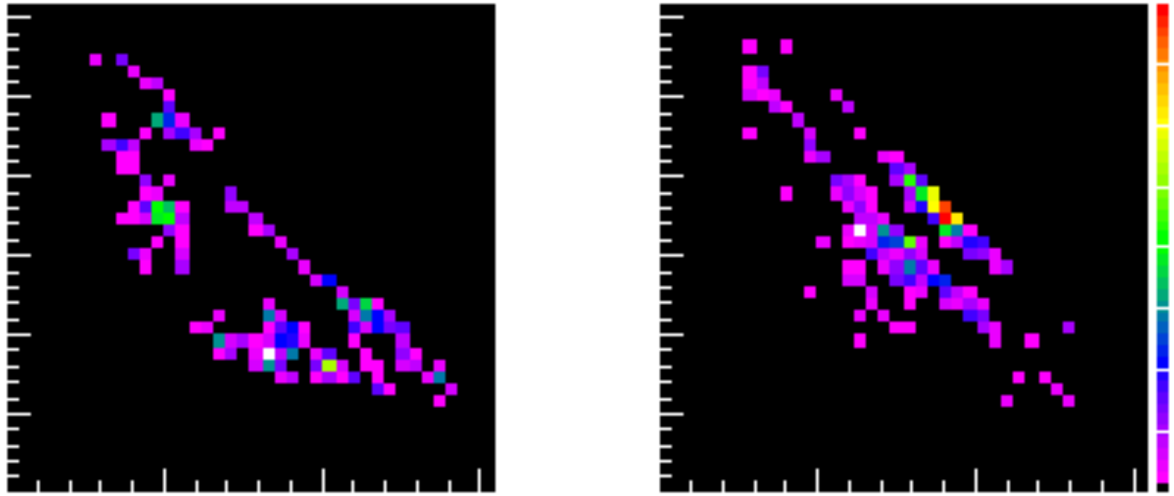


Crystal Barrel @ LEAR

700000 events = 6×700000 entries

Dalitz plot fits

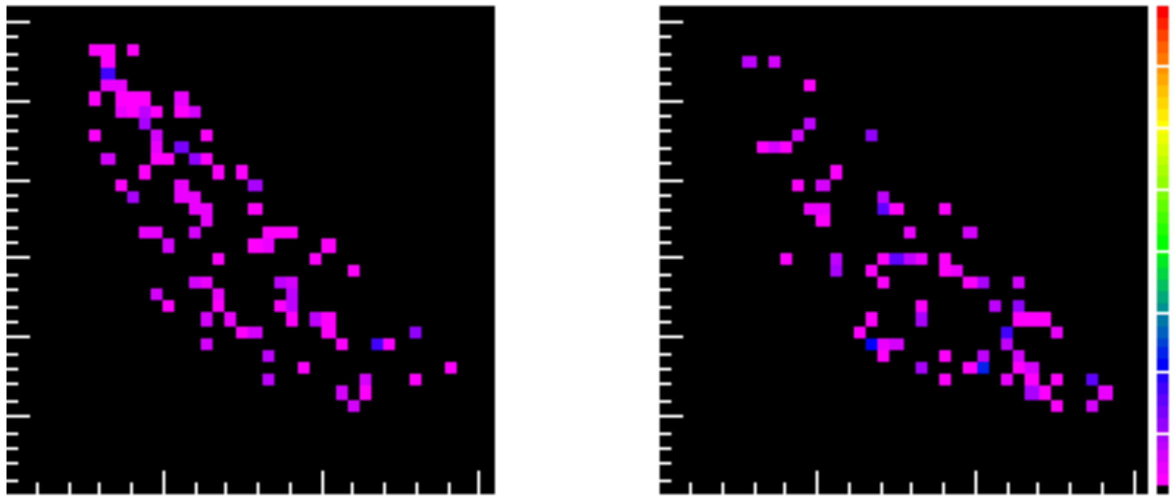
Difference data-fit
with
“standard” resonances
χ^2 / d.o.f = 3.07



Fit exceeds data

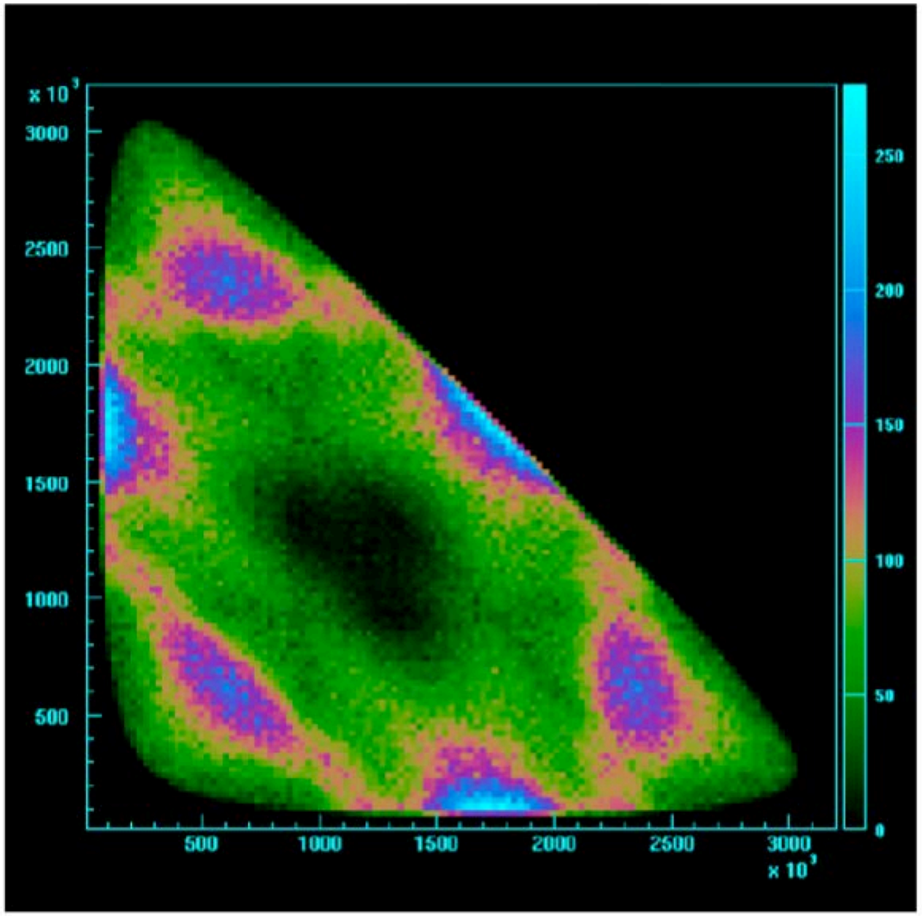
Data exceed fit

Include exotic
$J^{PC} = 1^{-+}$ $\pi_1(1400)$
in fit
χ^2 / d.o.f = 1.29

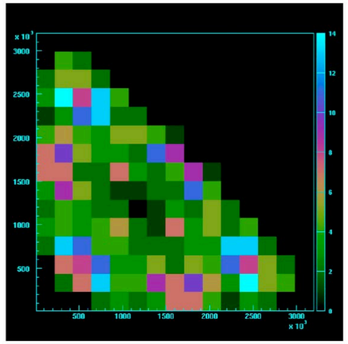


Statistics is important!

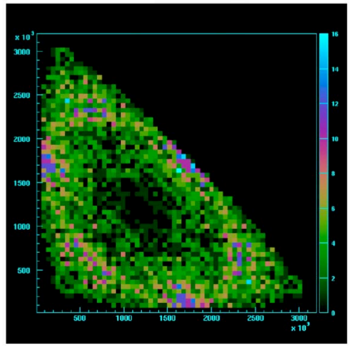
100,000 events



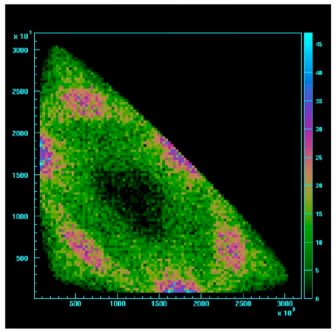
100 events



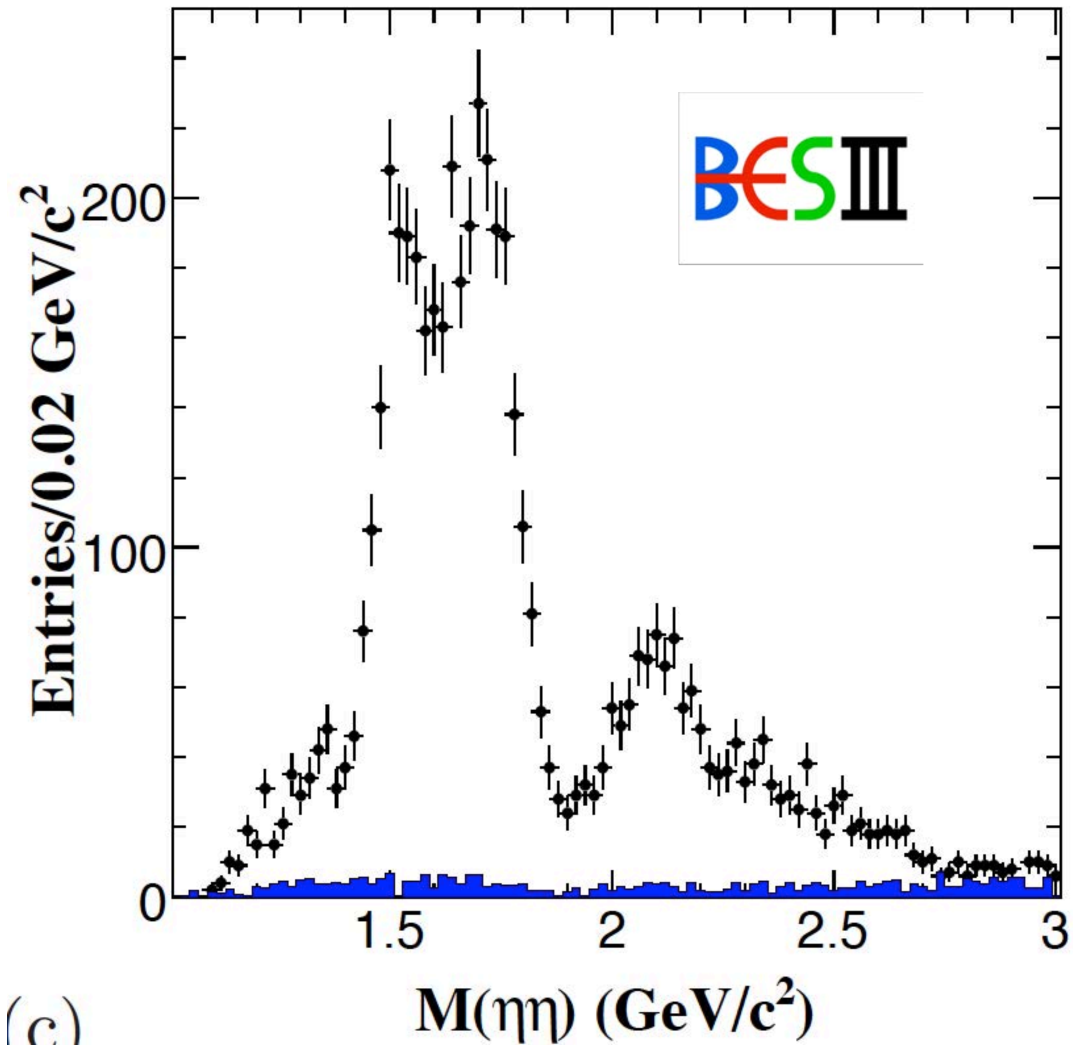
1000 events



10,000 events



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



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

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

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).

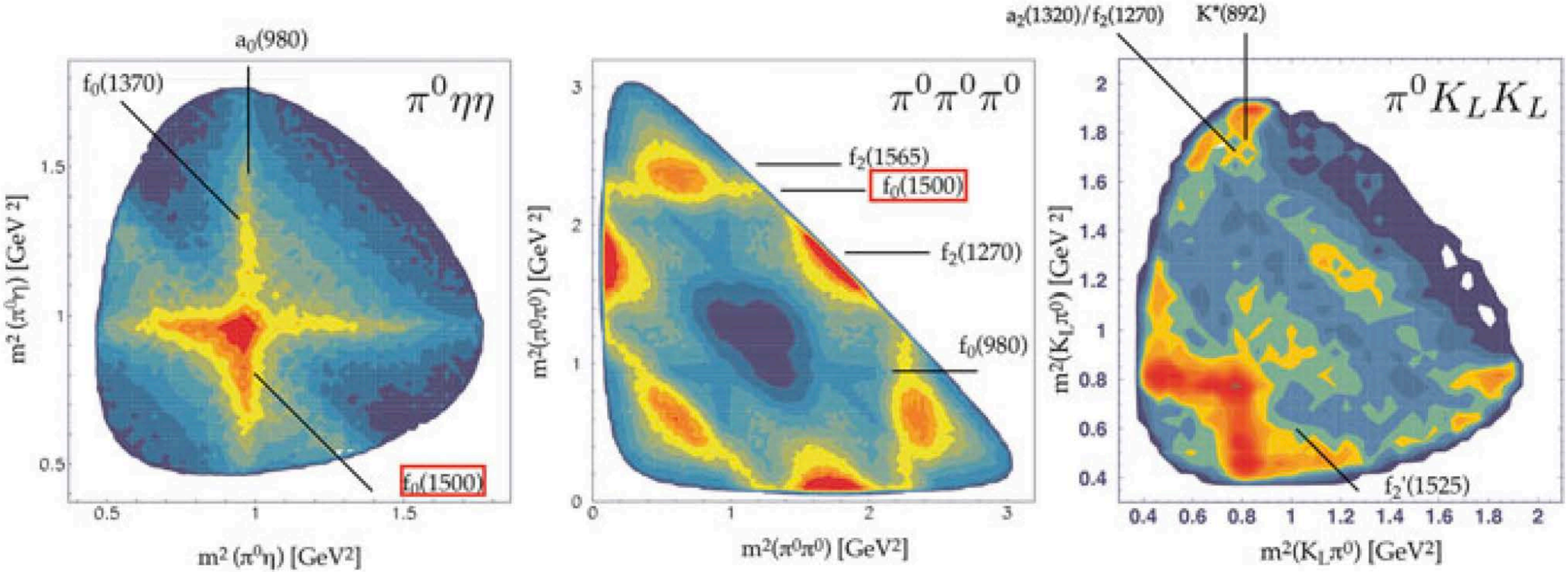
$f_0(1500)$ MASS	1504 ± 6 MeV (S = 1.3)
$f_0(1500)$ WIDTH	109 ± 7 MeV

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

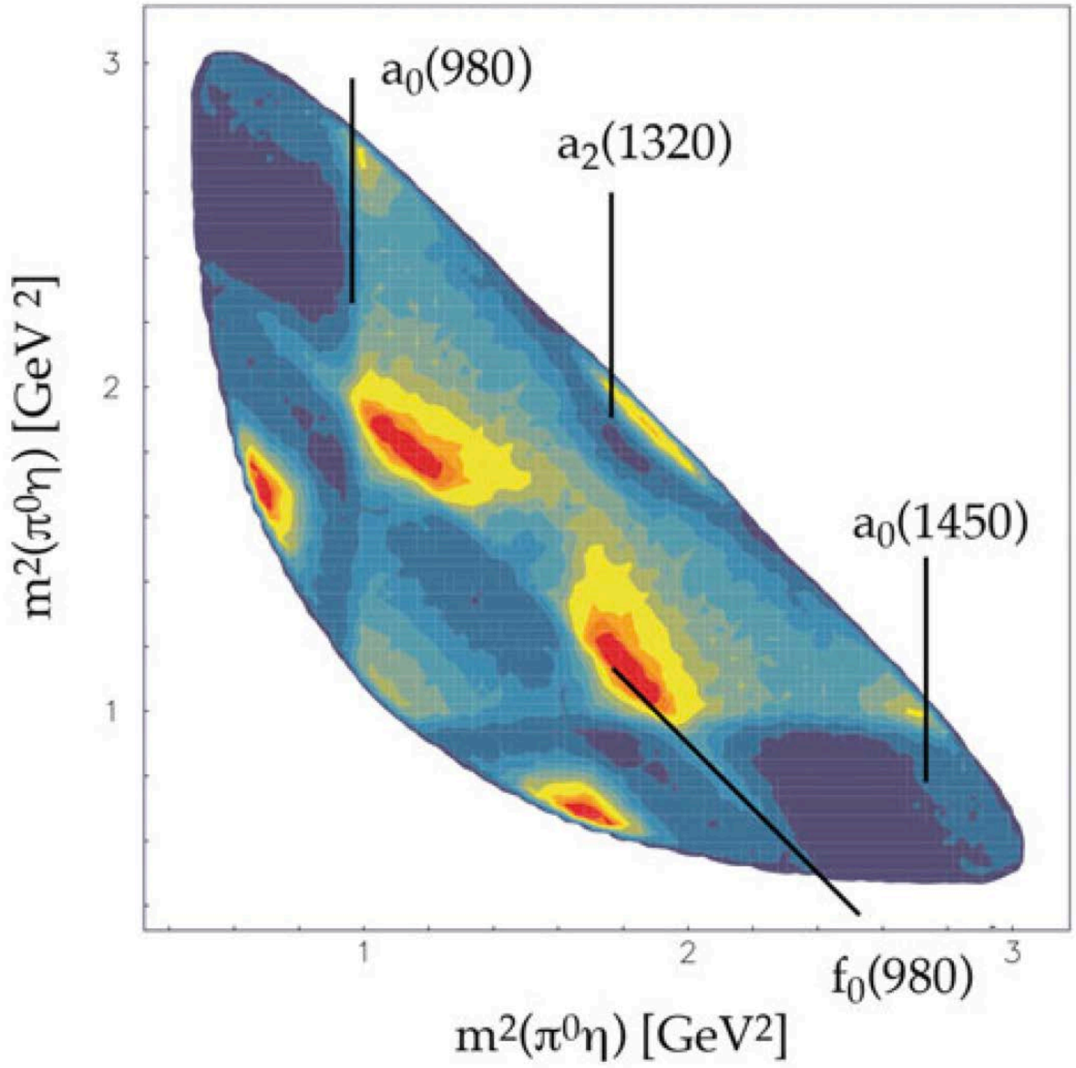
constrained fit information

Best use the same experiment to determine the properties of a particle



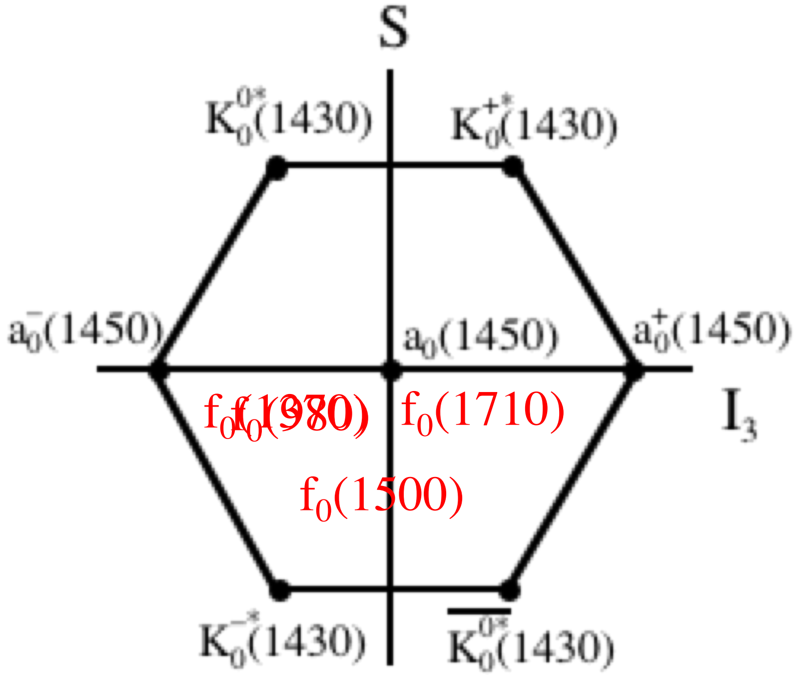
Crystal Barrel @ LEAR

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



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

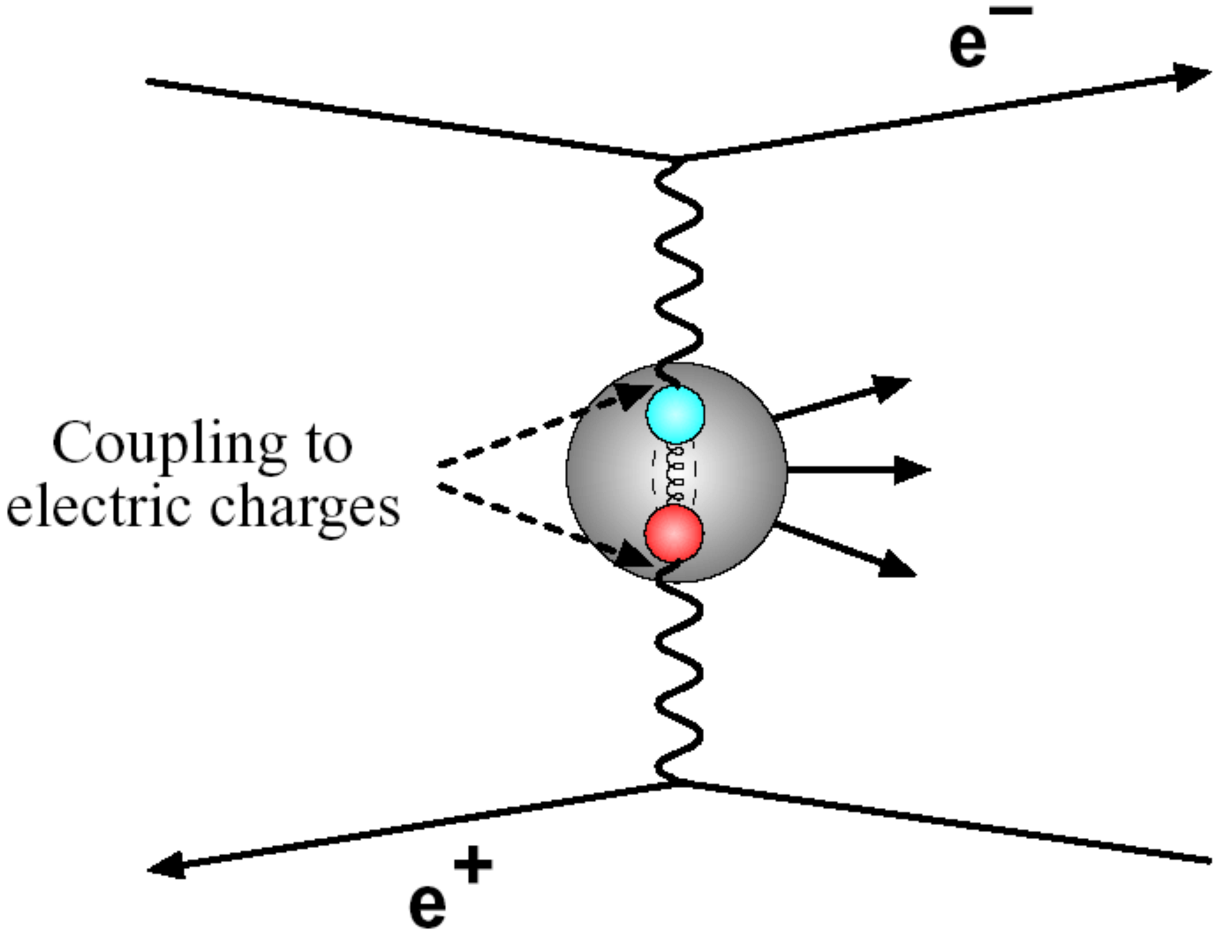
A possible nonet of scalar ($J^{PC} = 0^{++}$) mesons



One particle is supernumerous!

Which is the glueball?

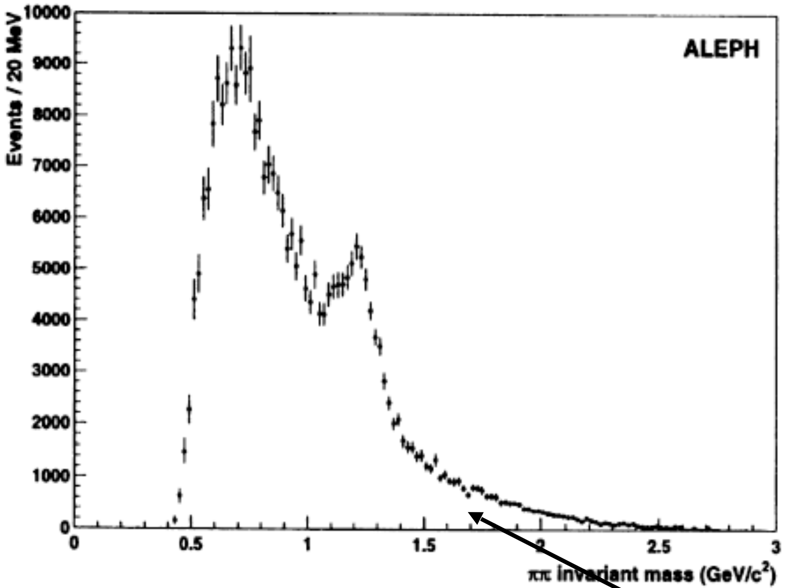
Meson production in $\gamma\gamma$ collisions

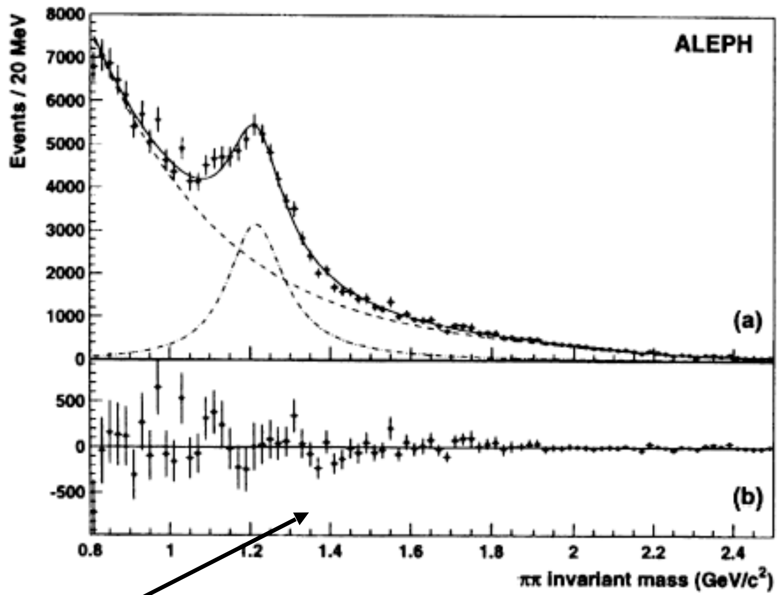


… act as anti-glueball filter

$\gamma\gamma$ collisons from ALEPH

(anti-glueball filter)





no $f_0(1500)$

upper limit:

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

Phys. Lett. B472 (2000) 189.

Study the decay pattern!

$$G \rightarrow \pi\pi, K\overline{K}, \eta\eta, \eta\eta' = 3 : 4 : 1 : 0$$

Experimental observation:

$f_0(1380) \rightarrow n\overline{n}$
$f_0(1500) \rightarrow$ much more into π than $K\overline{K}$
$f_0(1710) \rightarrow$ mainly observed in decays to $K\overline{K}$

???

Mixing of particles with the same quantum numbers !

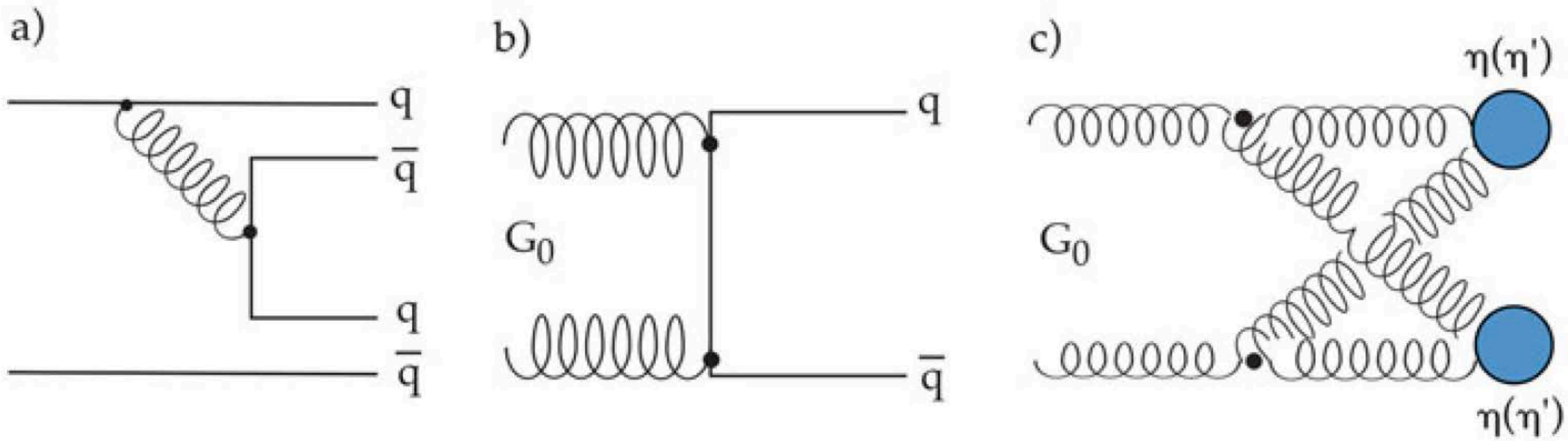


Fig. 11.8 Decay in first order perturbation of a $q\overline{q}$ meson (**a**), mixing of a glueball G_0 with $q\overline{q}$ (**b**) and G_0 decay into two glueballs (**c**)

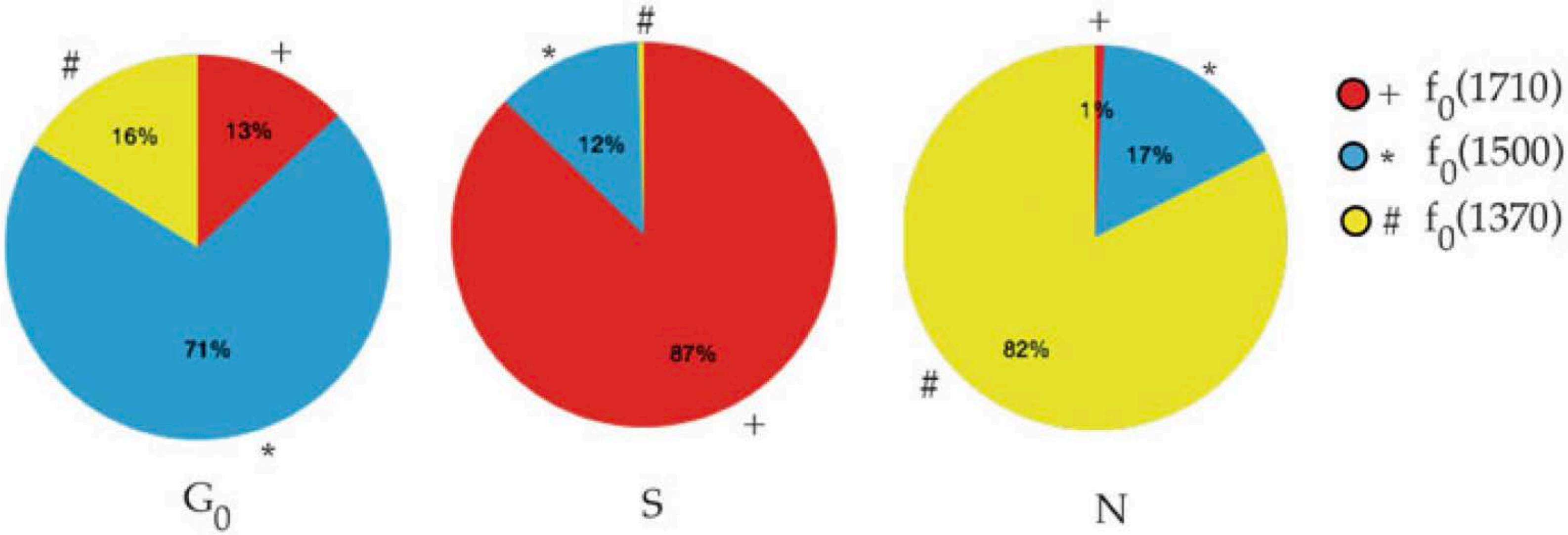


Fig. 11.9 Distribution of glue (G_0), $s\overline{s}$ (S) and $n\overline{n}$ (N) pairs in the $f_0(1710)$, $f_0(1500)$ and $f_0(1370)$ wavefunctions from central collisions and J/ψ decay (extracted from the analysis [23])

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

A possible scenario

	Γ [MeV]	i	Structure
$a_0(980)$	~ 50	1	$qq\bar{q}\bar{q} \leftrightarrow K\bar{K}$
$f_0(980)$	~ 50	0	$qq\bar{q}\bar{q} \leftrightarrow K\bar{K}$
$f_0(500)$	~ 800	0	$qq\bar{q}\bar{q} \leftrightarrow \pi\pi$
$\kappa(700)$	~ 600	$\frac{1}{2}$	$qq\bar{q}\bar{q} \leftrightarrow K\pi$
$a_0(1450)$	265	1	$q\bar{q}$
$f_0(1370)$	~ 400	0	$q\bar{q}$
$f_0(1710)$	125	0	$q\bar{q}$
$K_0^*(1430)$	294	$\frac{1}{2}$	$q\bar{q}$
$f_0(1500)$	109	0	glueball (?)

VI. SUMMARY OF CONCLUSIONS

Our interpretation of the LHCb data on $B_{d,s} \to J/\psi 2\pi; 4\pi$ leads to the following qualitative conclusions.

1. The $f_1(1285)$ is consistent with the flavor mixture $f_1(1285) \sim 0.9n\bar{n} - 0.4s\bar{s}$ [8].

2. The data on $B_{d,s} \to J/\psi 4\pi$ show that $f_0(1370)$ and $f_0(1500)$ interfere, and that $s\bar{s}$ is more prominent in $f_0(1500)$ than in $f_0(1370)$ [7].

3. The data on $B_s \to J/\psi 2\pi$ show that there is a large $s\bar{s}$ component in $f_0(1710)$ and that this scalar interferes with the other scalar states and the S-wave background.

5. Thus we expect a prominent signal for $f_0(1710)$ in $B_{d,s} \to J/\psi K\bar{K}$. Evidence for a peak in $K\bar{K}$ spectrum is consistent with the parameters of the $f_0(1710)$ [1]

In conclusion: the LHCb data appear to be consistent with the picture of scalar mesons below 1 GeV being tetraquark states, and those above 1 GeV being a canonical nonet mixed with a scalar glueball.

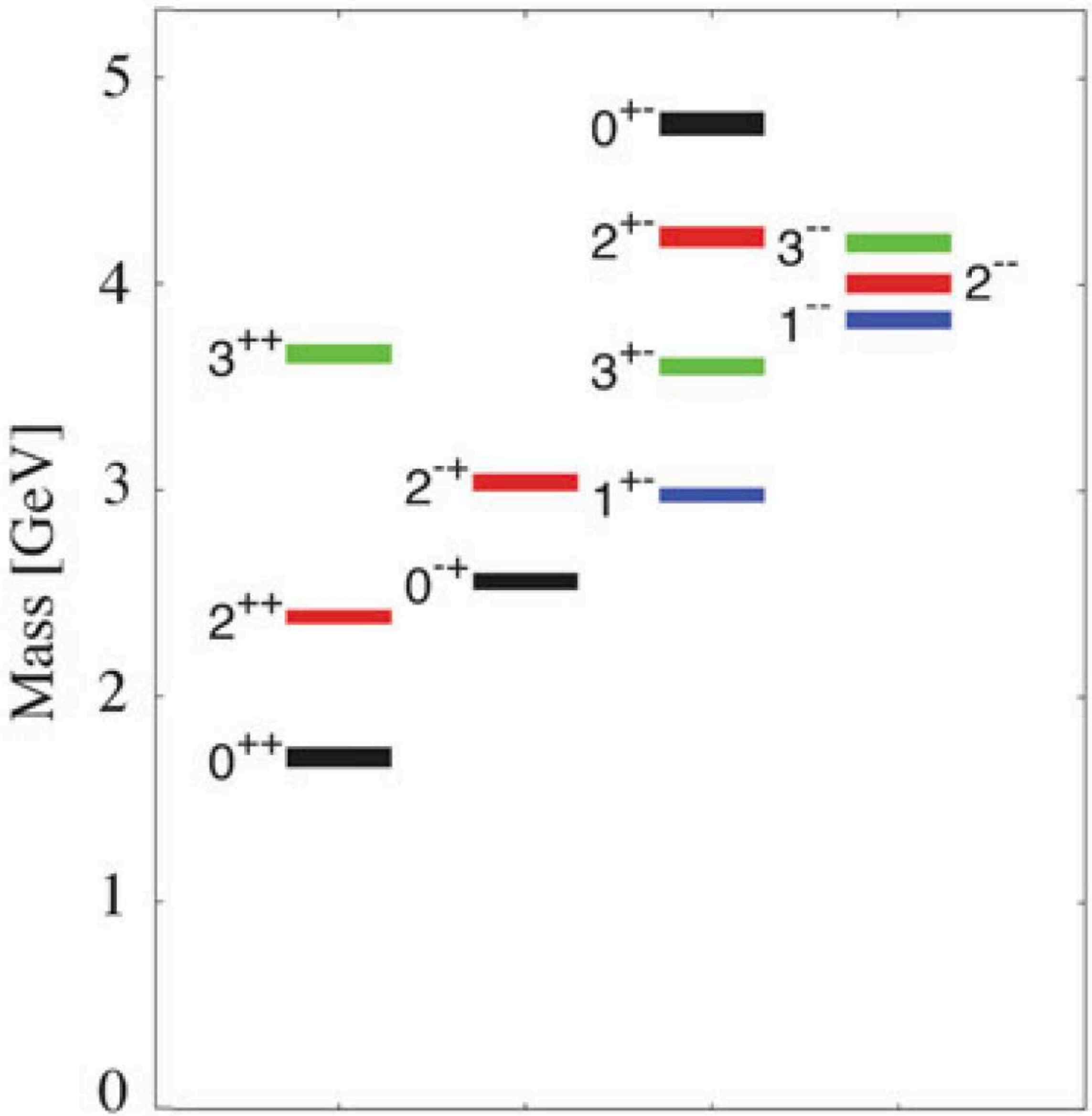
LHCb now made a fit to their acceptance corrected data taking into account our scenario. As the nature of the scalar mesons is so fundamental, not least in connection with the isolation of a scalar glueball degree of freedom in this mass region, the picture presented here merits serious examination.

We have given some further tests of our hypothesis, such as the production of a_0 in $B_d \to J/\psi X$. A further test of these ideas will come if neutrals can be detected and ηs reconstructed. The spectrum for $B_{d,s} \to J/\psi\eta\eta$ would thus be valuable as an independent test of the flavour-glue mixing in the scalar mesons above 1 GeV. A study of $B^{o,-} \to J/\psi\eta\pi$ is also relevant, for understanding the $a_0(980)$ production.

In conclusion: the LHCb data appear to be consistent with the picture of scalar mesons below 1GeV being tetraquark states, and those above 1 GeV being a canonical nonet mixed with a scalar glueball.

F. E. Close and A. Kirk, Interpretation of scalar and axial mesons in LHCb from a historical perspective, Phys. Rev. D91 (2015) 114015, [arXiv:1503.06942]

Glueball predictions in a quenched lattice calculation



Closed strings versus open strings

- The spectrum of states of a closed string admits

$$M^2 = \frac{2}{\alpha'}\left(N + \tilde{N} + A + \tilde{A}\right)$$

- The spectrum of an open string

$$M^2_{open} = \frac{1}{\alpha'}(N + A)$$

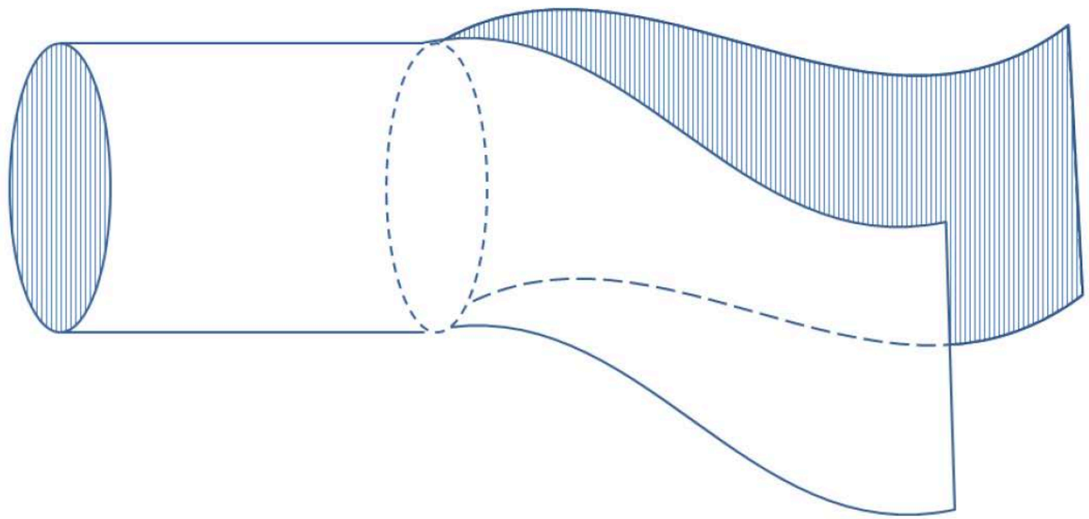
- **The slope of the closed string is ½ of the open**
- The closed string ground states has

$$M^2 = \frac{2}{\alpha'}(A + \tilde{A}) = \frac{2 - D}{6\alpha'}$$

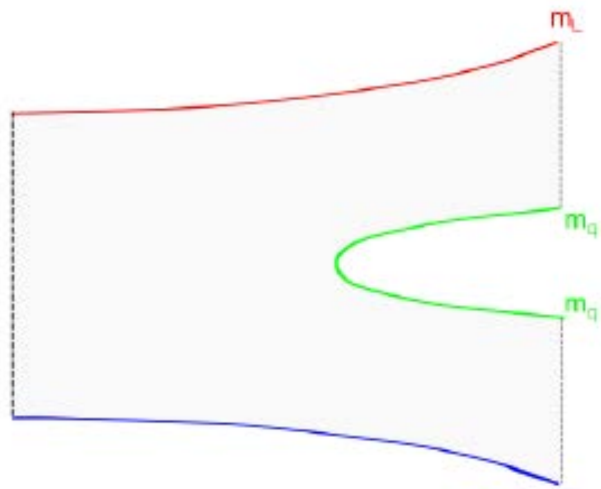
- The intercept is 2 that of an open string

The decay of a long string

- The decay of a hadron is in fact the **breaking of a string into two strings**
- A type I open string can undergo such a split



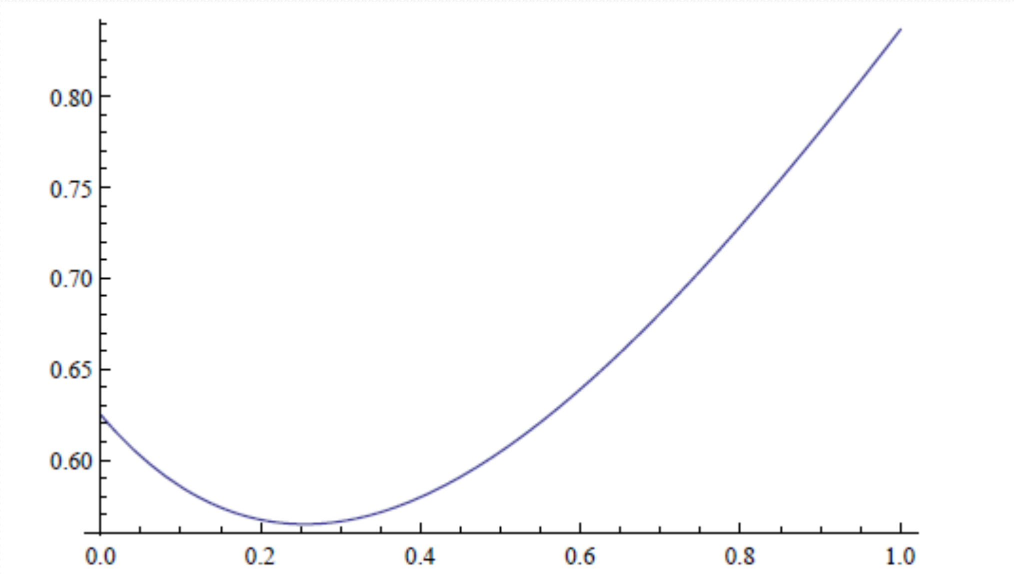
- A split of a string with massive Endpoints



The decay of a long string

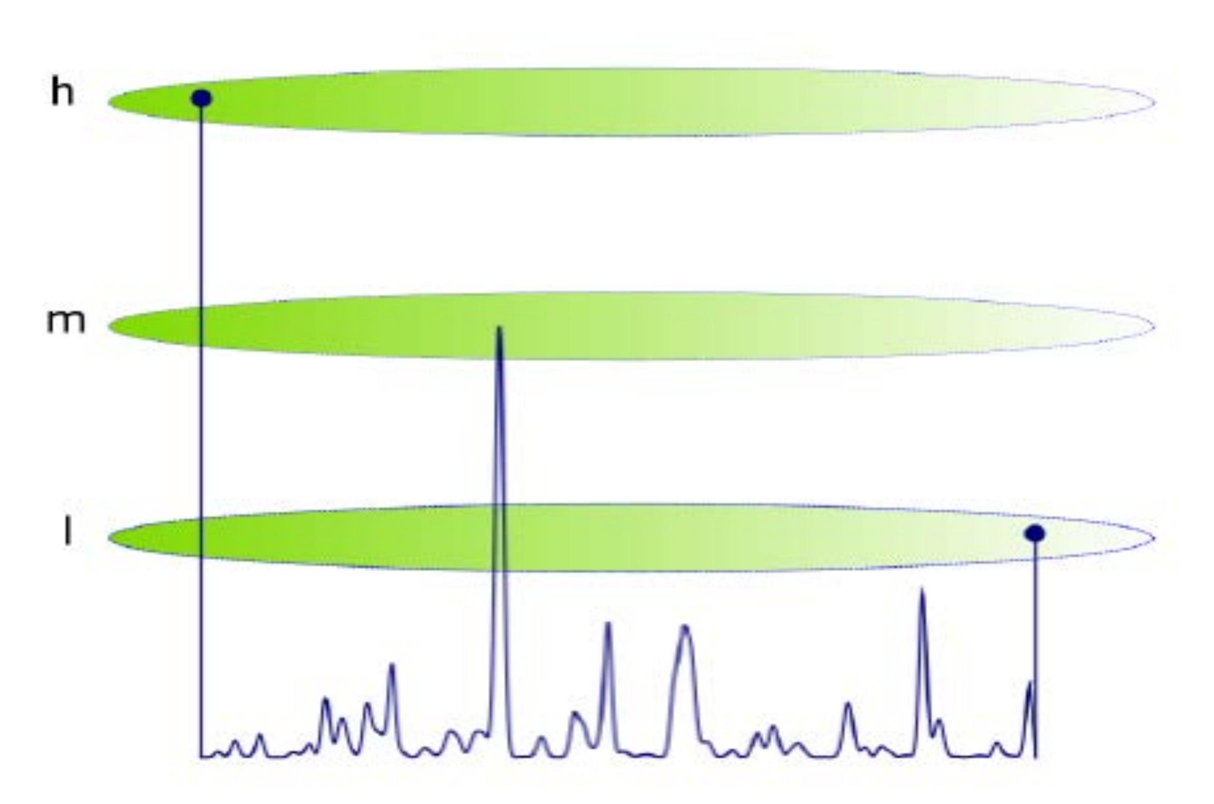
- One calculates the string amplitude first for a string in flat d=26 . Then for a sting in non-critical d=4 and finally for a string with massive endpoints.
- The result is that the decay width is **linear** with the **length of the string**

$$\Gamma \propto \frac{\pi}{4}TL + \frac{\pi}{4}m - \frac{2\sqrt{2}}{3}m^{3/2}(TL)^{-1/2} + \mathcal{O}(L^{-3/2})$$



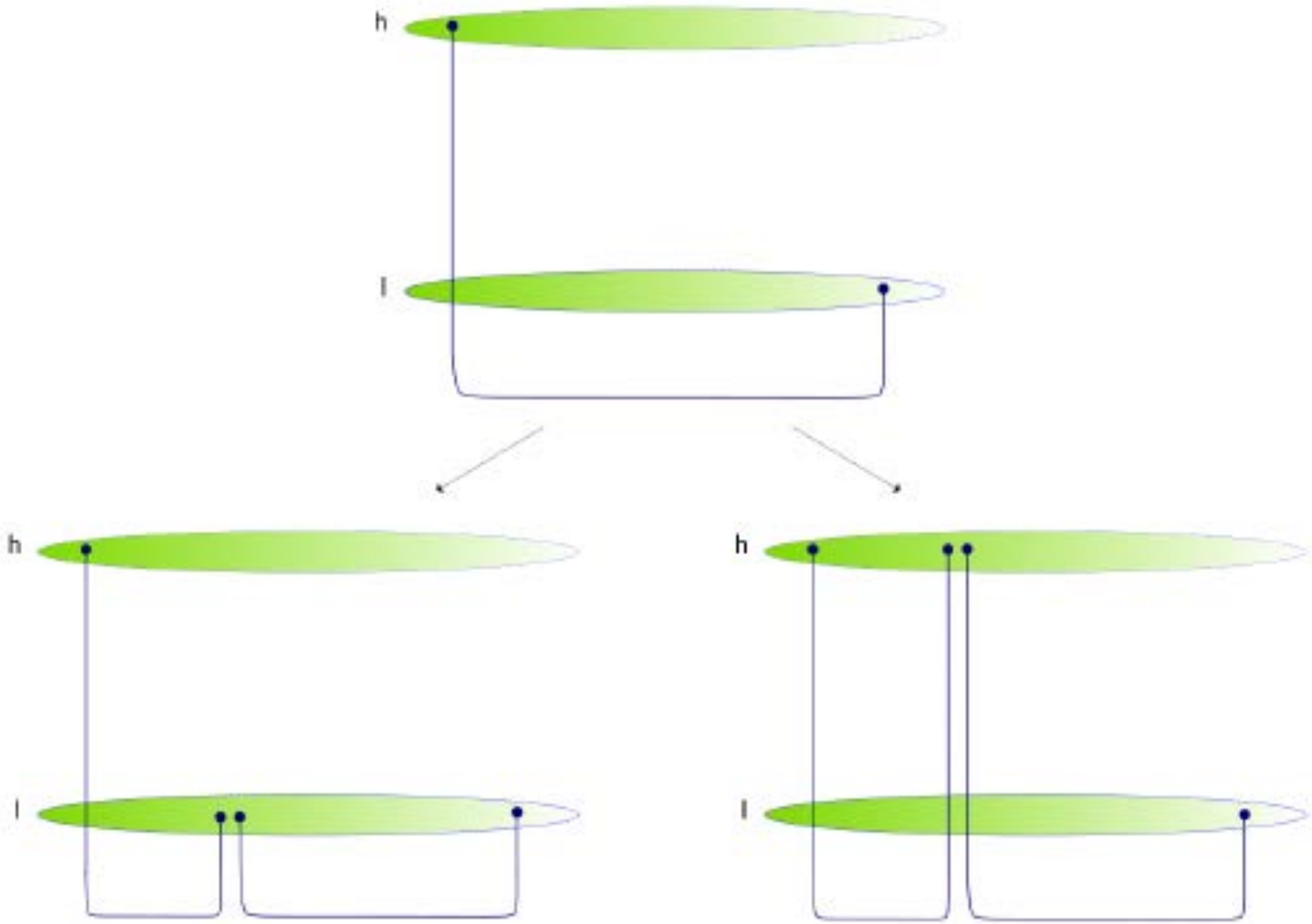
The suppression factor for stringy holographic hadrons

- The horizontal segment of the stringy hadron **fluctuates** and can reach flavor branes
- When this happens the string may **break up** , and the two new endpoints connect to a flavor brane



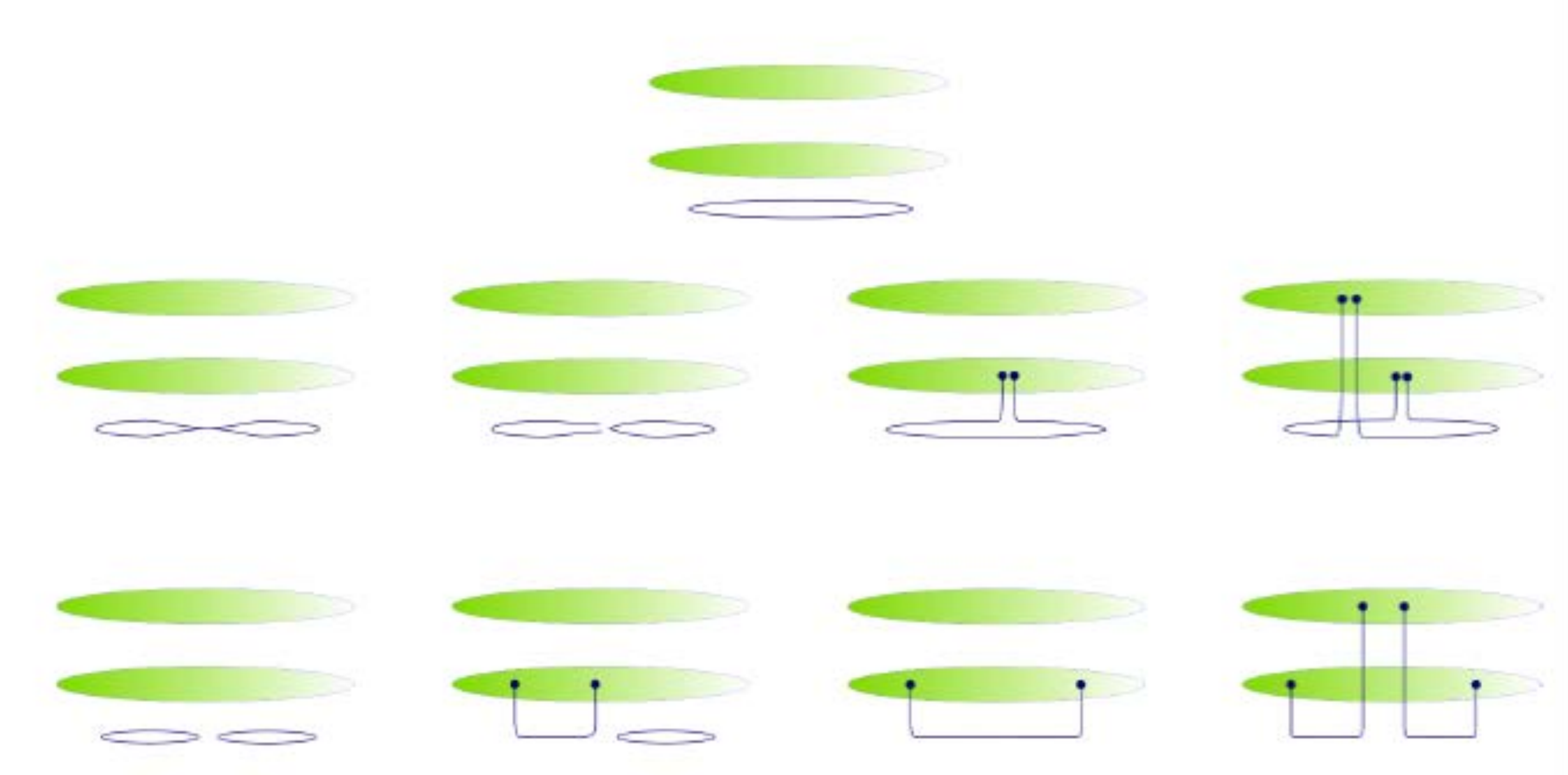
The suppression factor for stringy holographic hadrons

- There are in fact several possible **breakup patterns**



Decay of glueballs

- The glueball which is a folded rotating closed string can decay



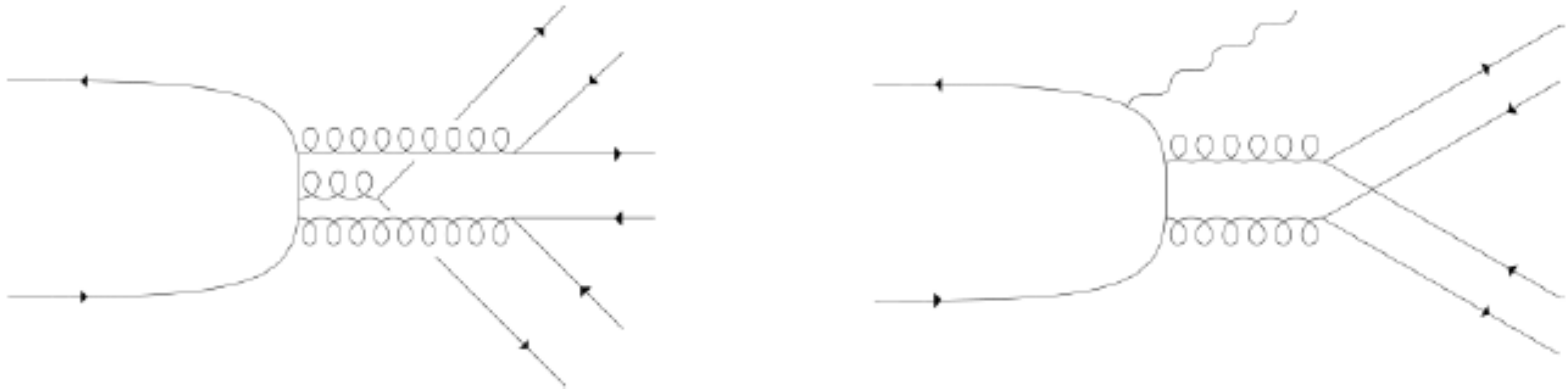
- The width

$$\Gamma_a \sim L\Gamma_{\text{cross}} \qquad \Gamma_b \sim L\Gamma_{\text{cross}} e^{-2\pi C m_{sep}^2/T}$$

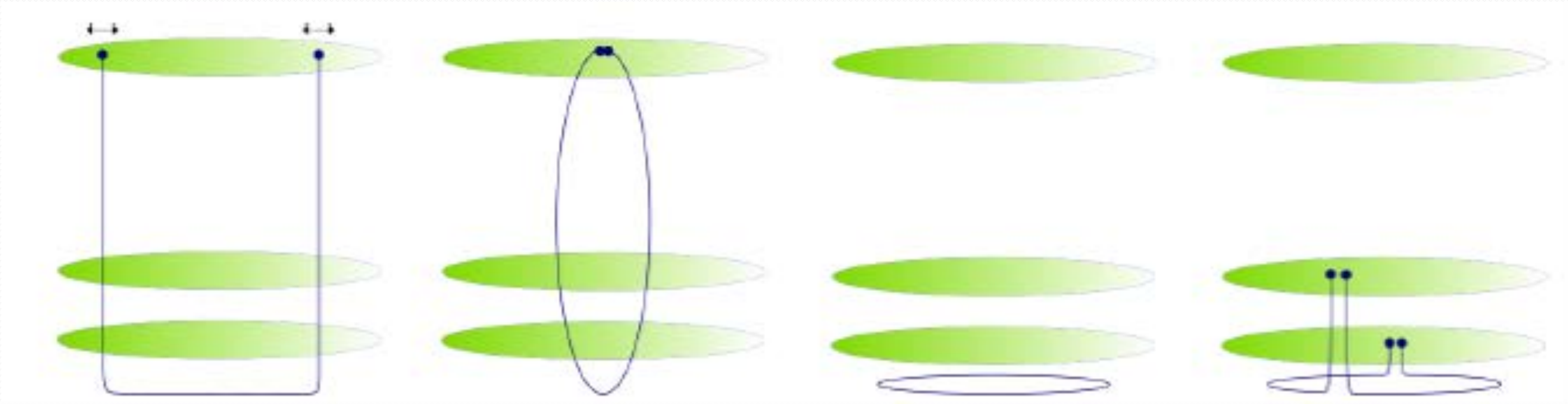
$$\Gamma_c \sim L e^{-2\pi C m_{sep}^2/T} \qquad \Gamma_d \sim L^2 e^{-2\pi C m_{sep}^2/T} e^{-2\pi C m_{sep}'^2/T}$$

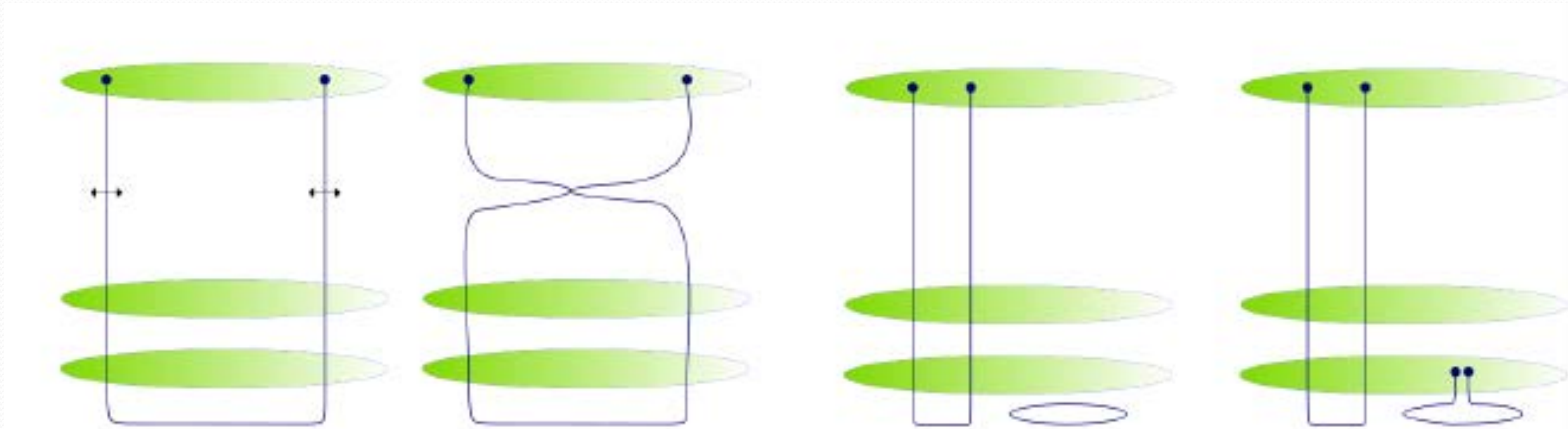
Zweig suppressed decay channels

- Certain heavy quarkonia mesons, build out of $c\bar{c}$ or $b\bar{b}$ decay via the mechanism of breaking apart of the horizontal string
- In QCD the decay based of the annihilation of the pair into 3 gluons or 2 gluons and a photon

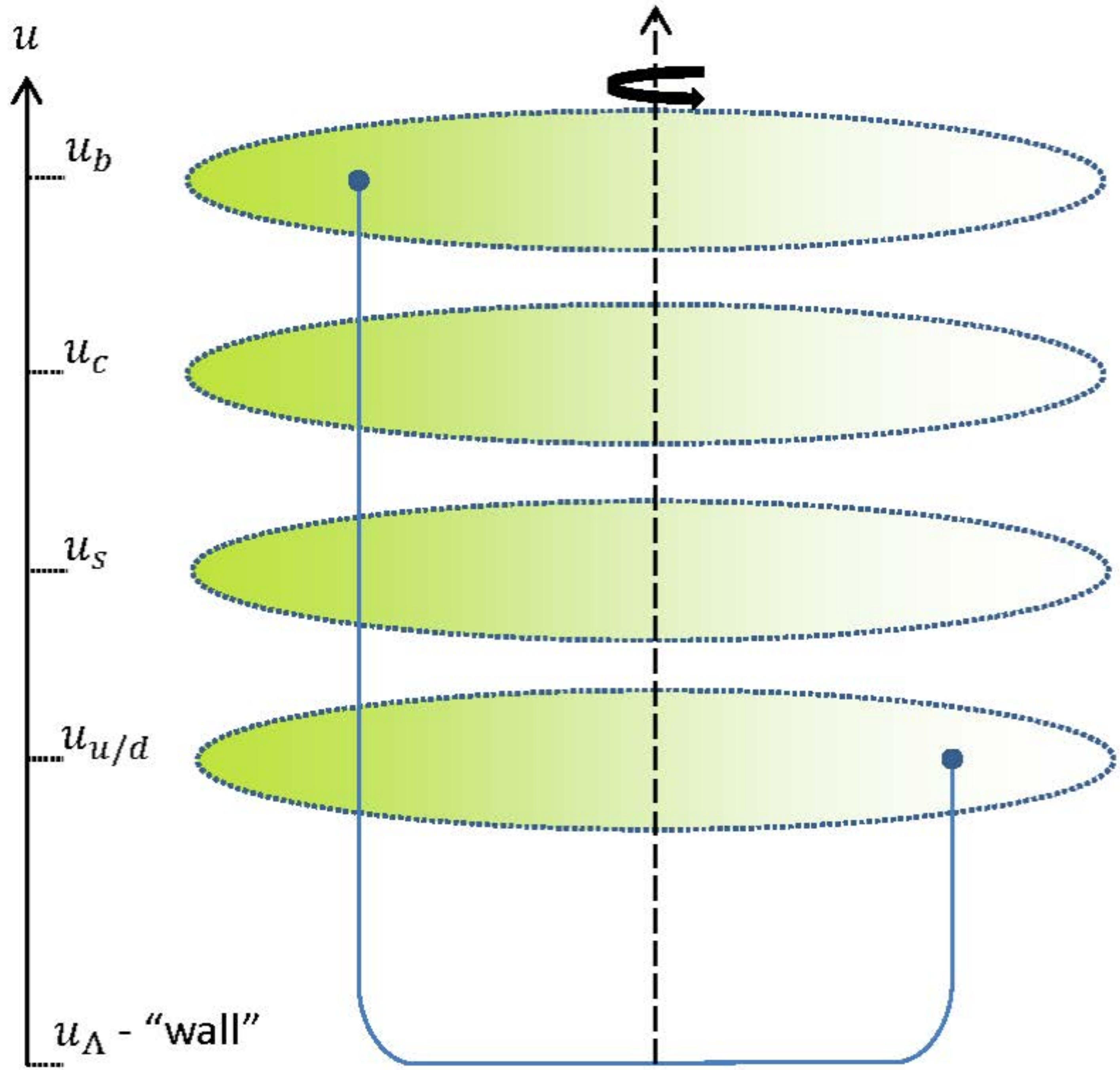


Zweig suppressed decay channels





Example: The B meson



String end-point mass

- We define the string end-point quark mass

$$m_{sep} = T\int_{u_0}^{u_f} g(u)du = T\int_{u_0}^{u_f}\sqrt{G_{00}G_{uu}}du$$

- The boundary equation of motion is

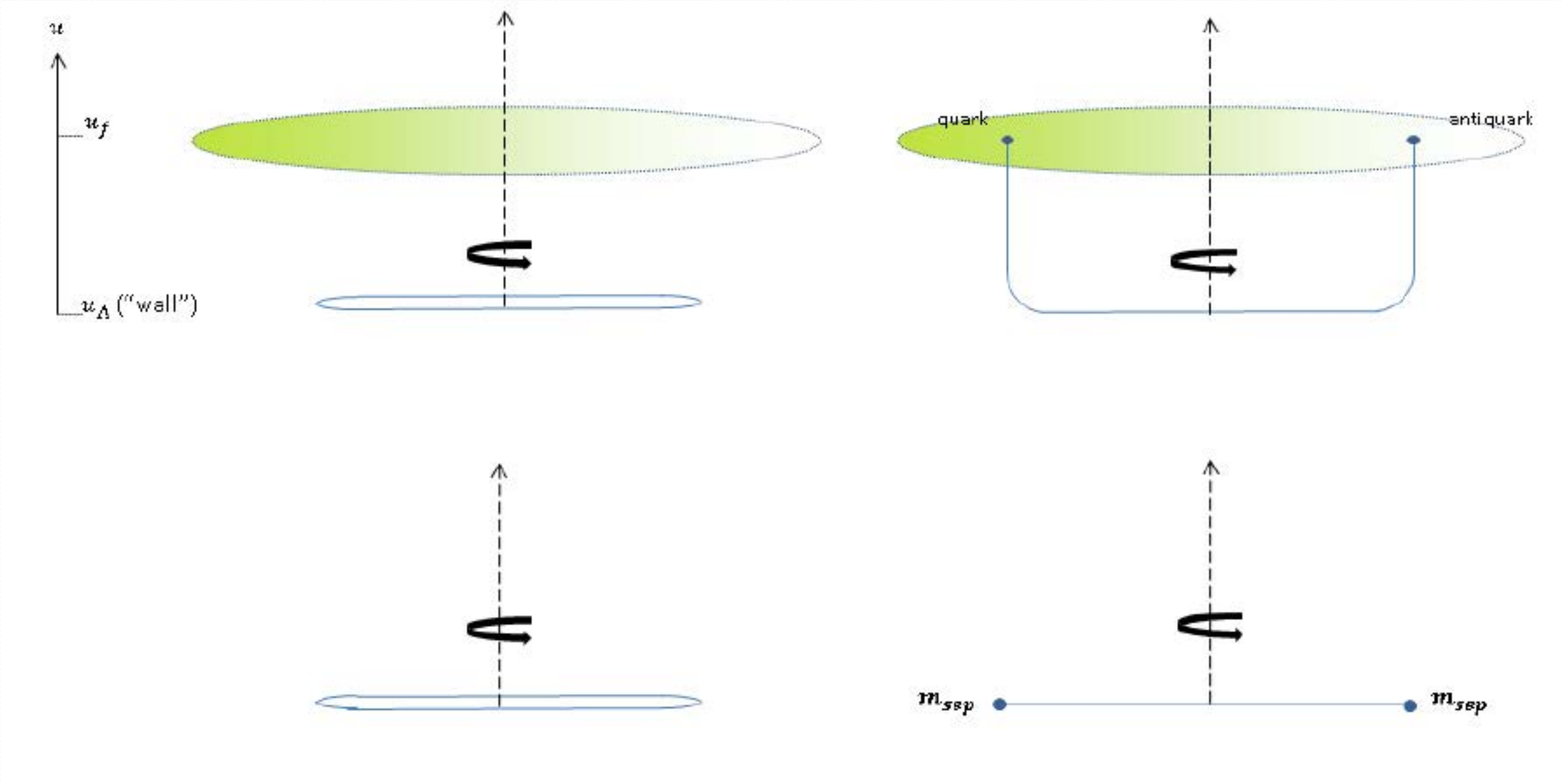
$$T_{eff}(1-v^2) = m_q\omega^2 R_0$$

$$T_{eff} = Tf = TG_{00}$$

$$\frac{T_{eff}}{\gamma} = m_{sep}\gamma\omega^2 R_0$$

- This simply means that the tension is balanced by the (relativistic) centrifugal force.

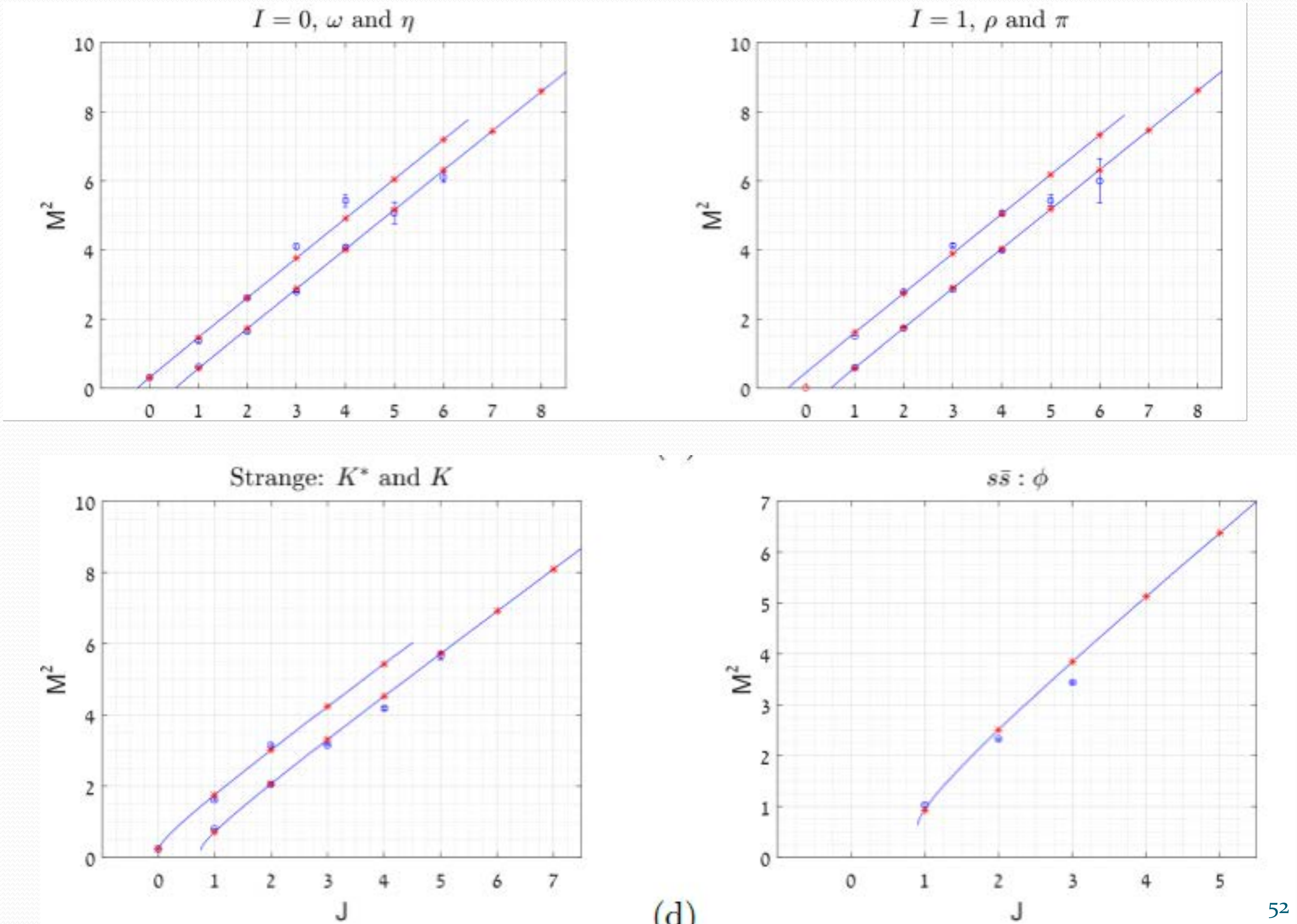
Holographic mesons and glueballs and their map



Fits and predictions of the HISH model

- Next we compare the predictions of the HISH model with the PDG data. We extract the optimal values of the tension (or α') , endpoints masses, and intercepts
- We determine the chi square of the fits of the spectra
- Mesons
- Baryons
- Glueballs
- Exotic Hadrons
- We fit the total decay width of hadrons including Zweig suppressed decays
- We determine branching ratios

Fitted trajectories of mesons



(d)

Fits of (potential) glueball spectra

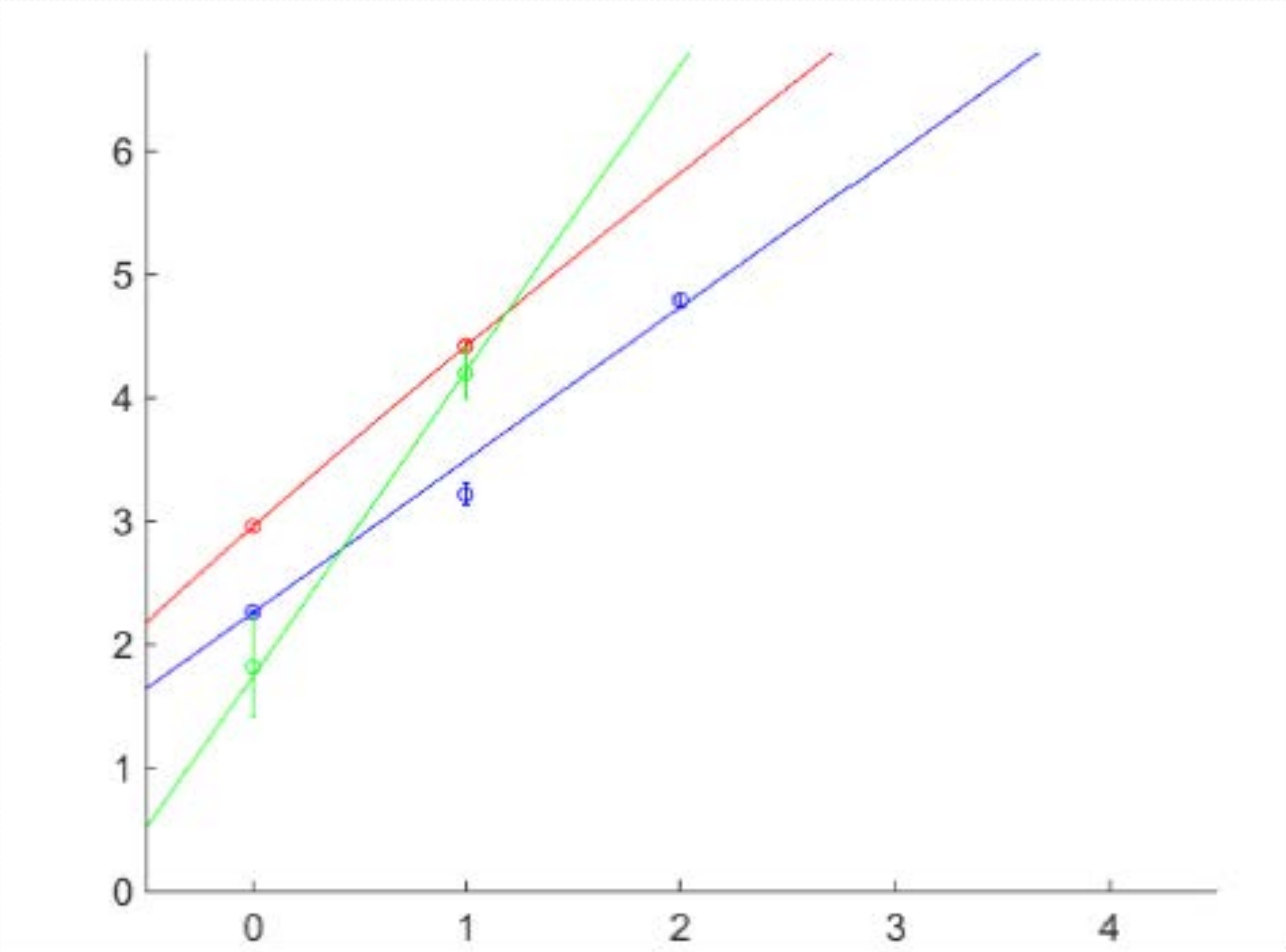
- A rotating and exciting folded closed string admits in flat space-time a linear Regge trajectory

$$J + n = \alpha'_{gb} M^2 + a \qquad \alpha'_{gb} = \tfrac{1}{2}\alpha'$$

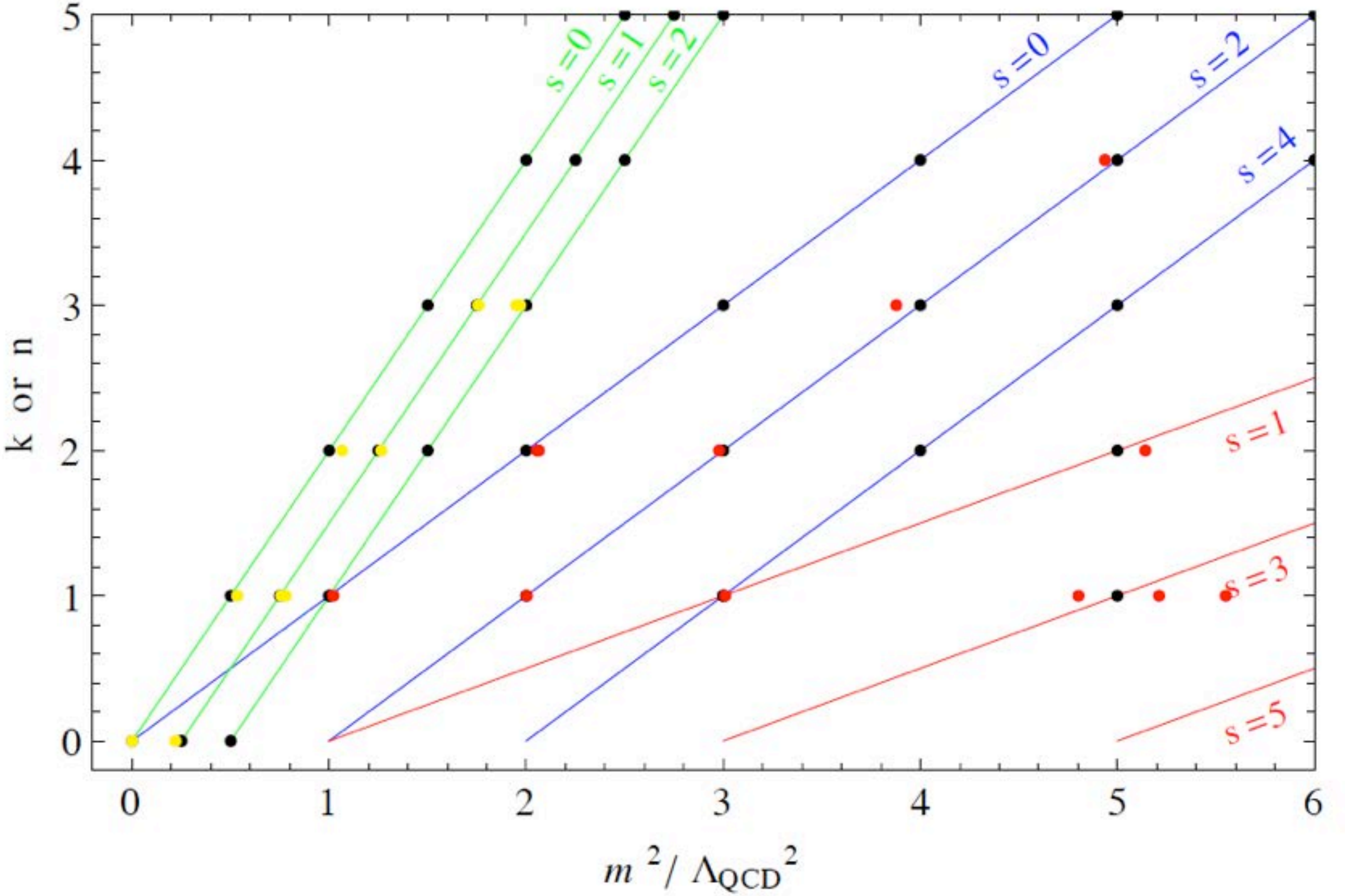
- The basic candidates of glueballs are flavorless hadrons f_0 of 0++ and f_2 of 2++. There are 9 (+3) fo and 12 (+5) f2.
- The question is whether one can fit all of them into meson and separately some glueball trajectories.
- We found various different possibilities of fits.

Glueball 0++ fits of experimental data

- The meson and glueball trajectories based on $f_0(1380)$ as a glueball lowest state.



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

Possible scalar glueball trajectories

Trajectories			Predicted states					
α'	Type	Assigned states	n	Mass	Width	n	Mass	Width
0.78	Glueball	**980**	2	2470	180	4	3350	240
	Light	1370, 1710, 2100, 2330	4	2620	200	4	2850	250
	$s\bar{s}$	1500, 2020	2	2300	300	3	2590	300
0.89	Glueball	**1370**	2	2510	> 700	4	3290	> 900
	Light	1500, *1800, 2100, 2330	4	2580	200	5	2790	250
	$s\bar{s}$	1710, 2200	2	2390	200	3	2630	250
0.89	Glueball	**1500**	2	2600	180	4	3350	240
	Light	1370, *1800, 2020, 2330	4	2540	350	5	2760	400
	$s\bar{s}$	1710, 2100	2	2360	250	3	2610	250
0.82	Glueball	**1710**	2	2800	220	4	3570	280
	Light	1370, *1800, 2100, 2330	4	2610	300	5	2840	300
	$s\bar{s}$	1500, 2020, 2200	3	2270	350	4	2550	350

Table 5: The different assignments of the f_0 into radial trajectories and predicted higher states. The slope α' (in units of GeV^{-2}) was fitted for each assignment separately, as was done in [4], but is common to all three types of trajectories. Widths are provided as estimates, based on proportionality of the width to the string length.

for glueball with f0(1500) ground state

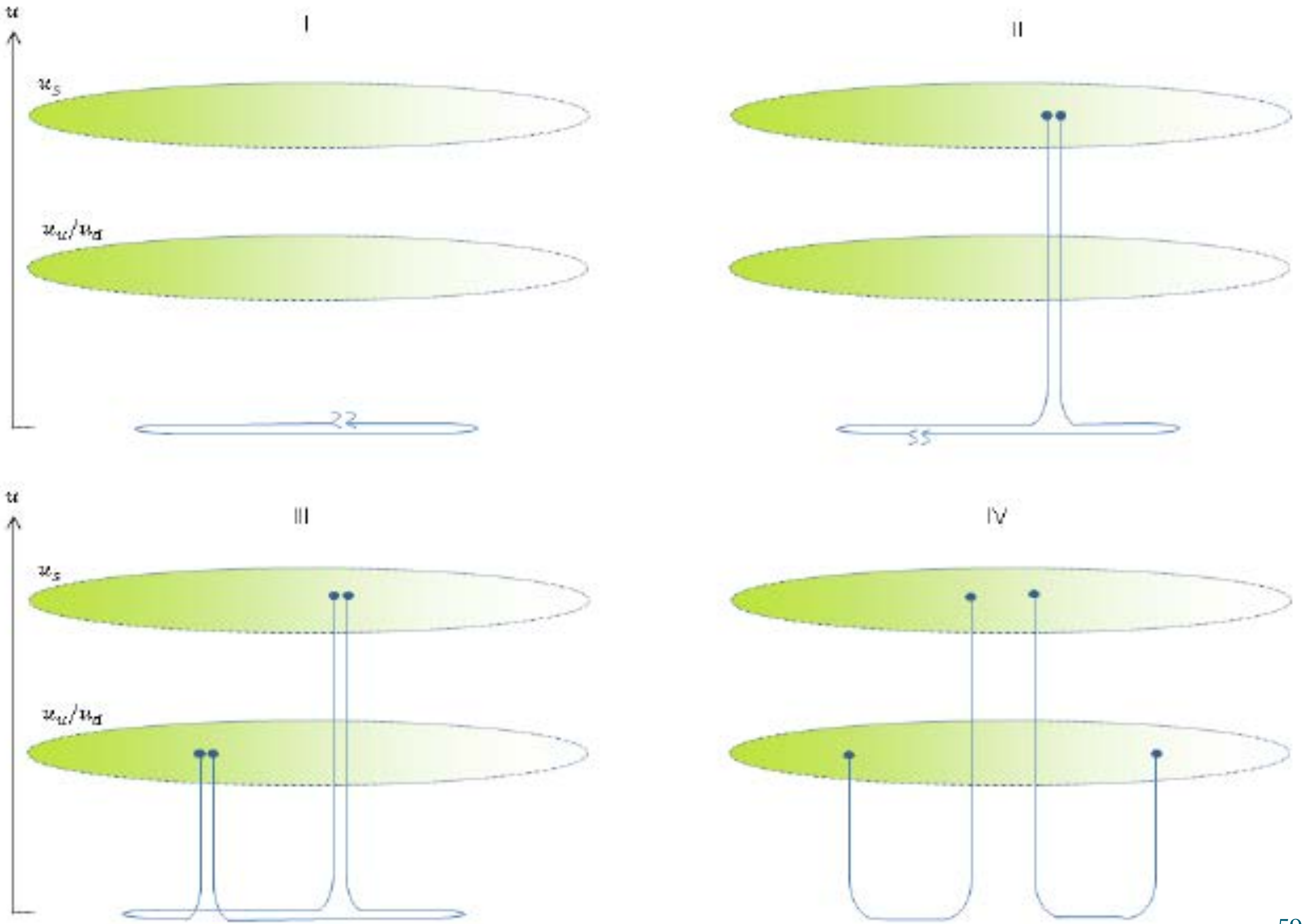
n or J	Mass	Width
0	1505 ± 6	109 ± 7
2	2640 ± 80	335 ± 30
4	3415 ± 100	560 ± 50
6	4050 ± 120	790 ± 70
8	4590 ± 135	1015 ± 90

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

On the identification of glueball trajectory

- Unfortunately there exists no unambiguous way to assign the known flavorless hadrons into trajectories of mesons and glueballs,
- But it is clear that one cannot sort all the known resonances into meson trajectories alone.
- One of the main problems in identifying glueball trajectories is simply the lack of experimental data, particularly in the mass region between 2.4 GeV and the cc threshold, where we expect the first excited states of the glueballs to be found.
- It is because of this that we cannot find a glueball trajectory in the angular momentum plane.

Decays of glueballs versus mesons



Decays of glueballs

- Recall that the width of the decay of a meson into two mesons is

$$\Gamma \propto L e^{-m_q^2/T}$$

- In a similar way the width for the decay of a glueball into two mesons is

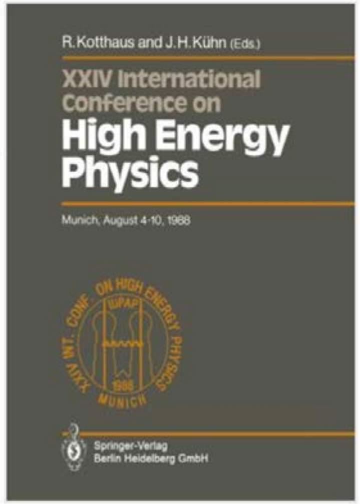
$$\Gamma \propto L \exp(-\frac{m_q^2}{T}) \exp(-\frac{m_{q'}^2}{T})$$

- Thus we get the following hierarchy for the decay of glueballs

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

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

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



A Review of Experimental Progress in Gluonia

S.J. Lindenbaum

Brookhaven National Laboratory, Upton, New York 11973 U.S.A.
and
City College of New York, New York, New York 10031 U.S.A.

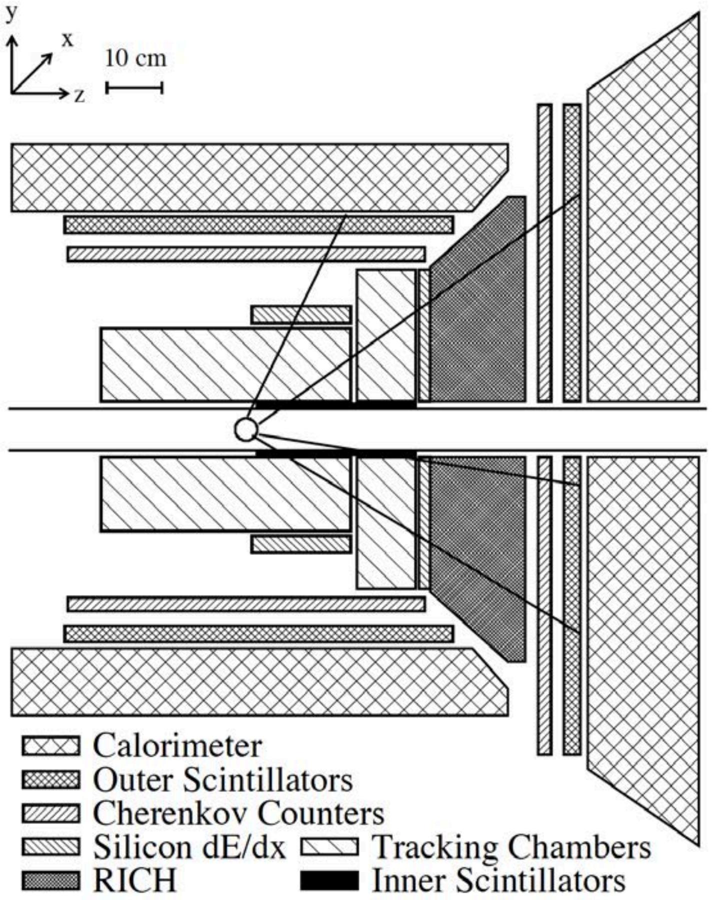
1. Introduction

There has been considerable progress in gluonia investigations and their analysis. As requested by the Convenor, Rich Galik, I will cover the highlights of various conference papers and related work in an integrated manner which incorporates a review of the present state of glueballs (gluonia) to the extent space limitations allow.

There are four general methods of searching for glueballs:

1. J/ψ radiative decay [iota, θ, $\xi(2.2)$]
2. OZI violating (g_T, g_T', g_T'') ⟷ $\pi^- p \to \phi\phi n$
3. Hadronic interaction pattern recognition of extra isosinglet states in addition to $q\bar{q}$ nonets, iota, G, $S^{*\prime}$, g_S.
4. Double Pomeron exchange.

Jetset (PS 202)

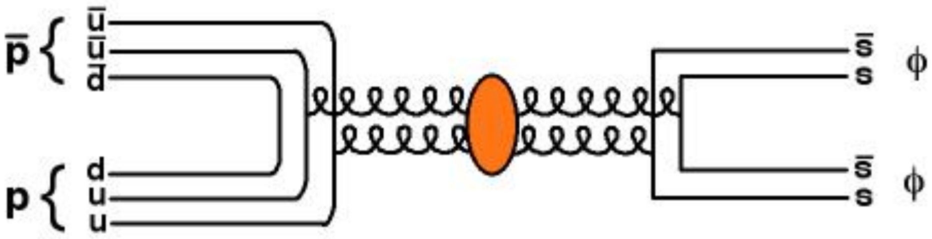


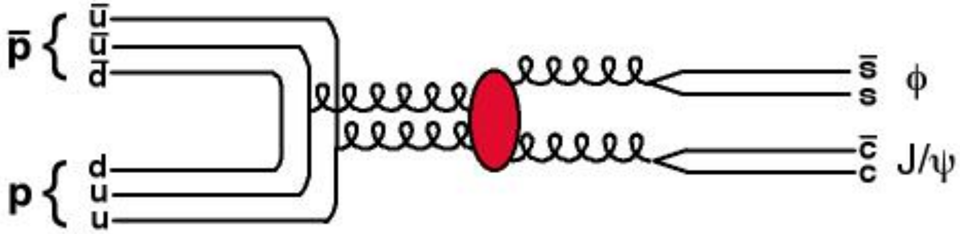
Results:

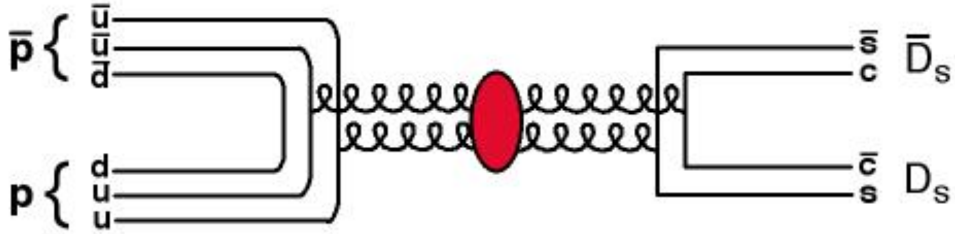
(The JETSET Collaboration)
(18 February 1998)

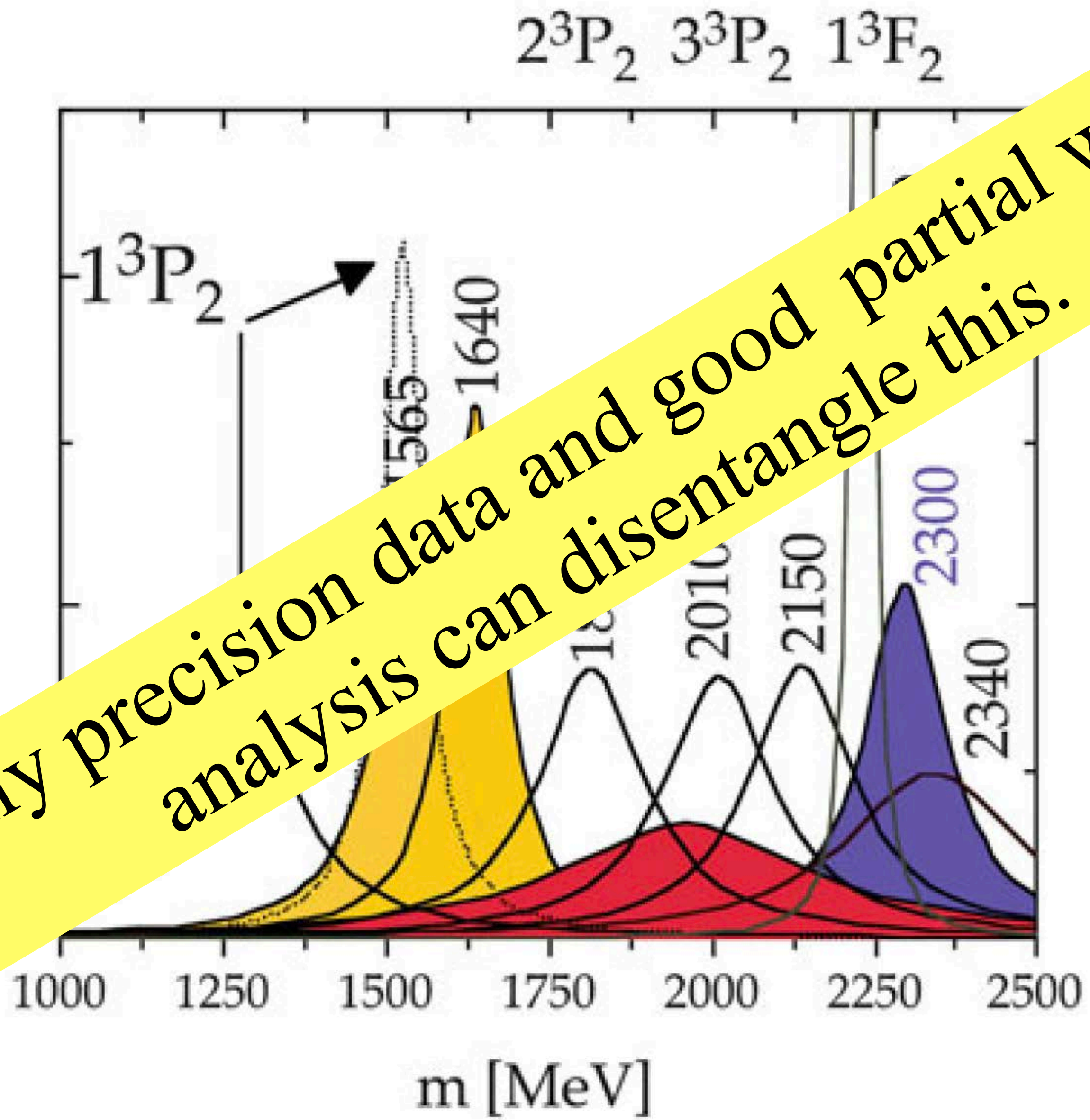
A study has been performed of the reaction $\bar{p}p \to 4K^{\pm}$ using in-flight antiprotons from 1.1 to 2.0 GeV/c incident momentum interacting with a hydrogen jet target. The reaction is dominated by the production of a pair of ϕ mesons. The $\bar{p}p \to \phi\phi$ cross section rises sharply above threshold and then falls continuously as a function of increasing antiproton momentum. The overall magnitude of the cross section exceeds expectations from a simple application of the OZI rule by two orders of magnitude. In a fine scan around the $\xi/f_J(2230)$ resonance, no structure is observed. A limit is set for the double branching ratio $B(\xi \to \bar{p}p) \times B(\xi \to \phi\phi) < 6 \times 10^{-5}$ for a spin 2 resonance of $M = 2.235$ GeV and $\Gamma = 15$ MeV.

OZI-violating processes to be studied at $\bar{\text{P}}$ANDA









Only precision data and good partial wave analysis can disentangle this.

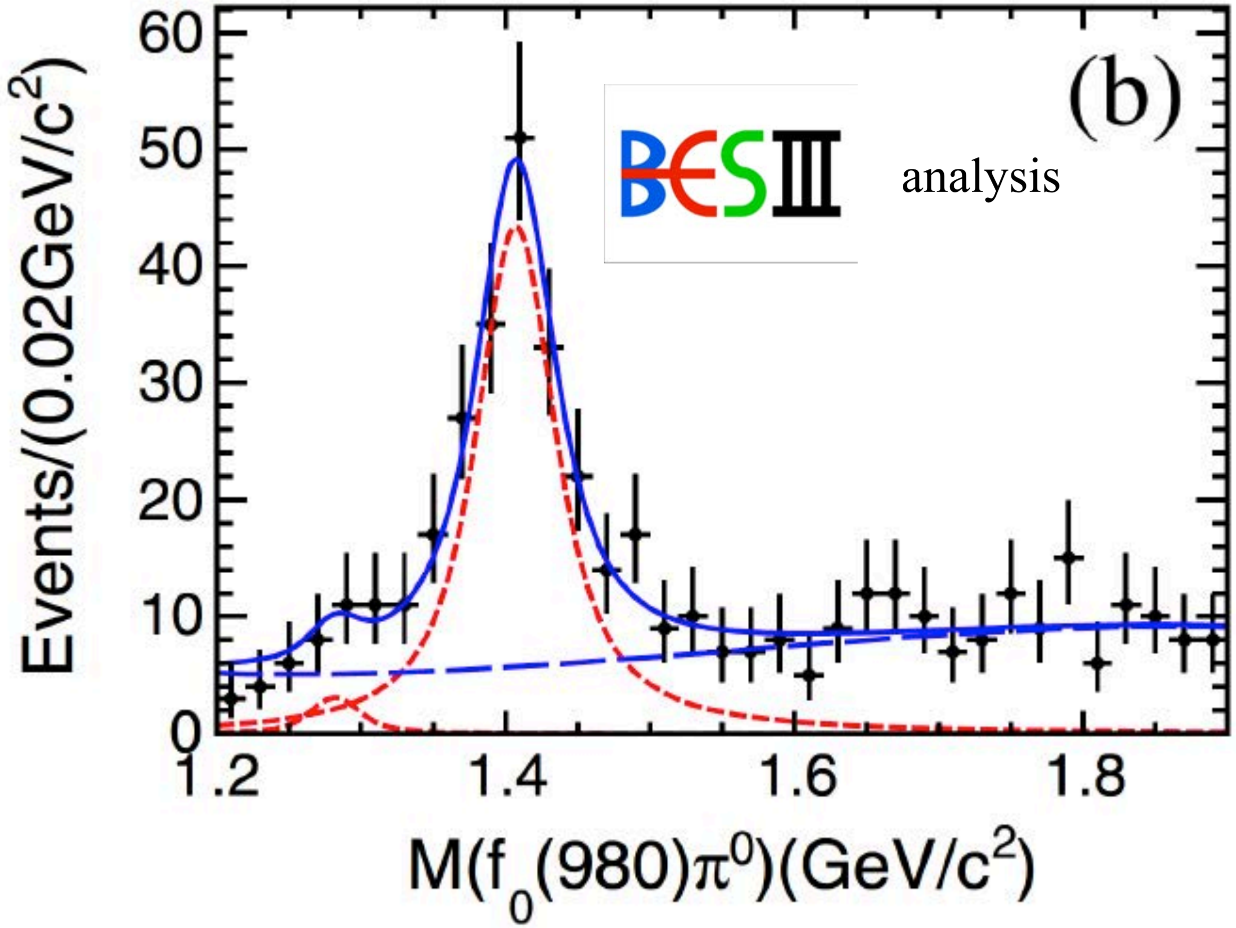
Taken from Claude Amsler: Lecture Notes in Physics

ISBN 978-3-319-98526-8 ISBN 978-3-319-98527-5 (eBook)

The pseudoscalar ($J^{PC} = 0^{-+}$) particles

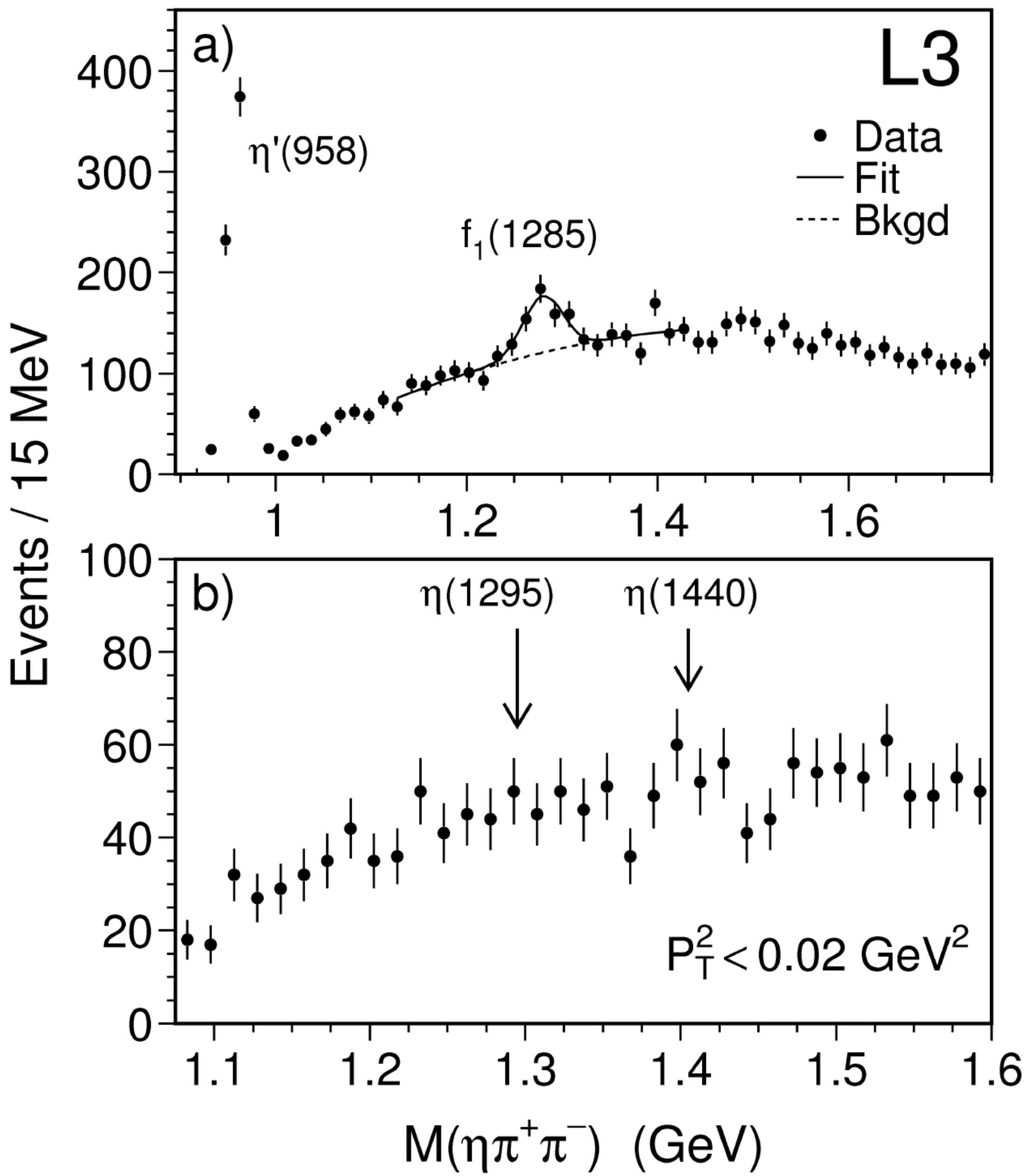
Gluon-rich channel:

$J/\psi \to \gamma\, \pi^0\, \pi^0\, \pi^0$

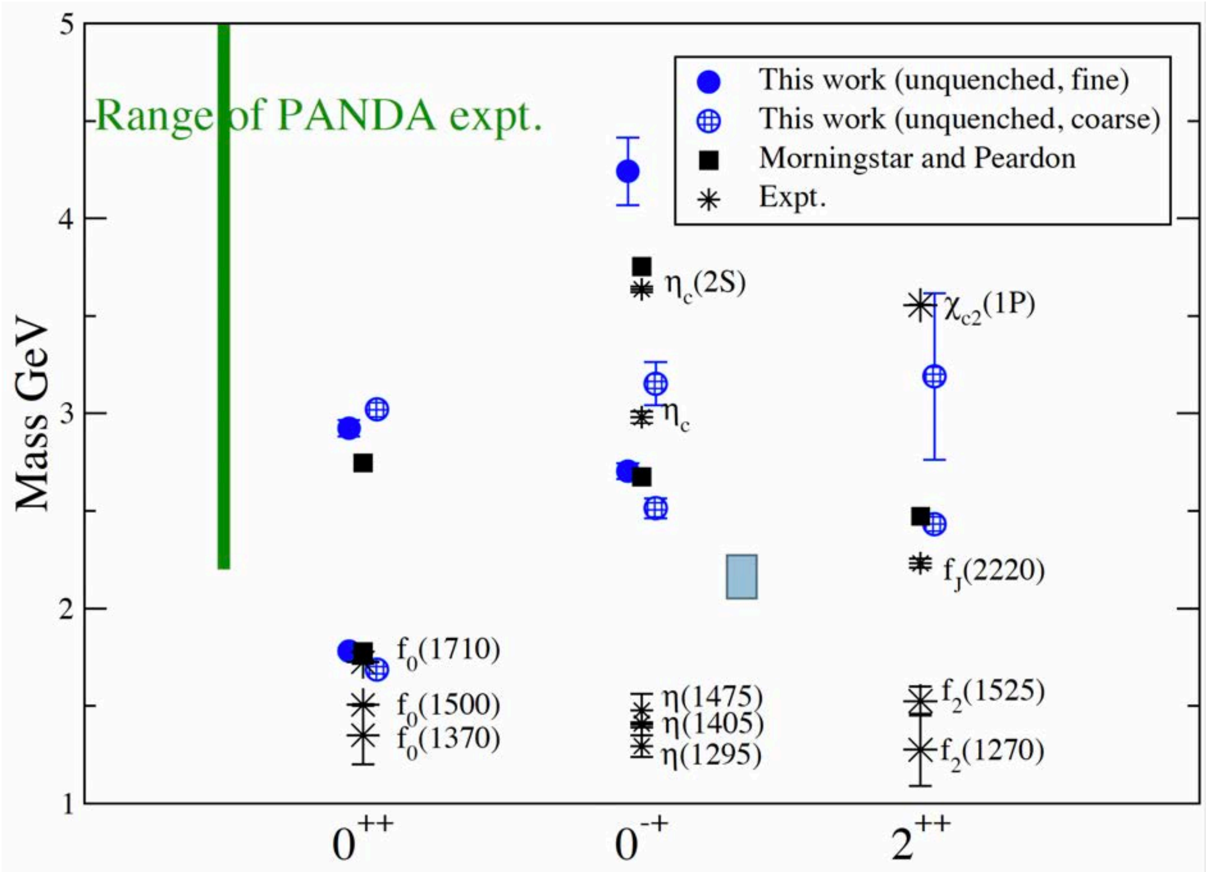


BES3, PRL108 (2012)182001

Gluon-suppressing channel: γγ collisions at L3



Quenched vs. unquenched results



UKQCD Collaboration, C. M. Richards, A. C. Irving, E. B. Gregory, and C. McNeile, Glueball mass measurements from improved staggered fermion simulations, Phys. Rev. D82 (2010) 034501, [arXiv:1005.2473].

UKQCD Collaboration, C. M. Richards, A. C. Irving, E. B. Gregory, and C. McNeile, Glueball mass measurements from improved staggered fermion simulations, Phys. Rev. D82 (2010) 034501, [arXiv:1005.2473].

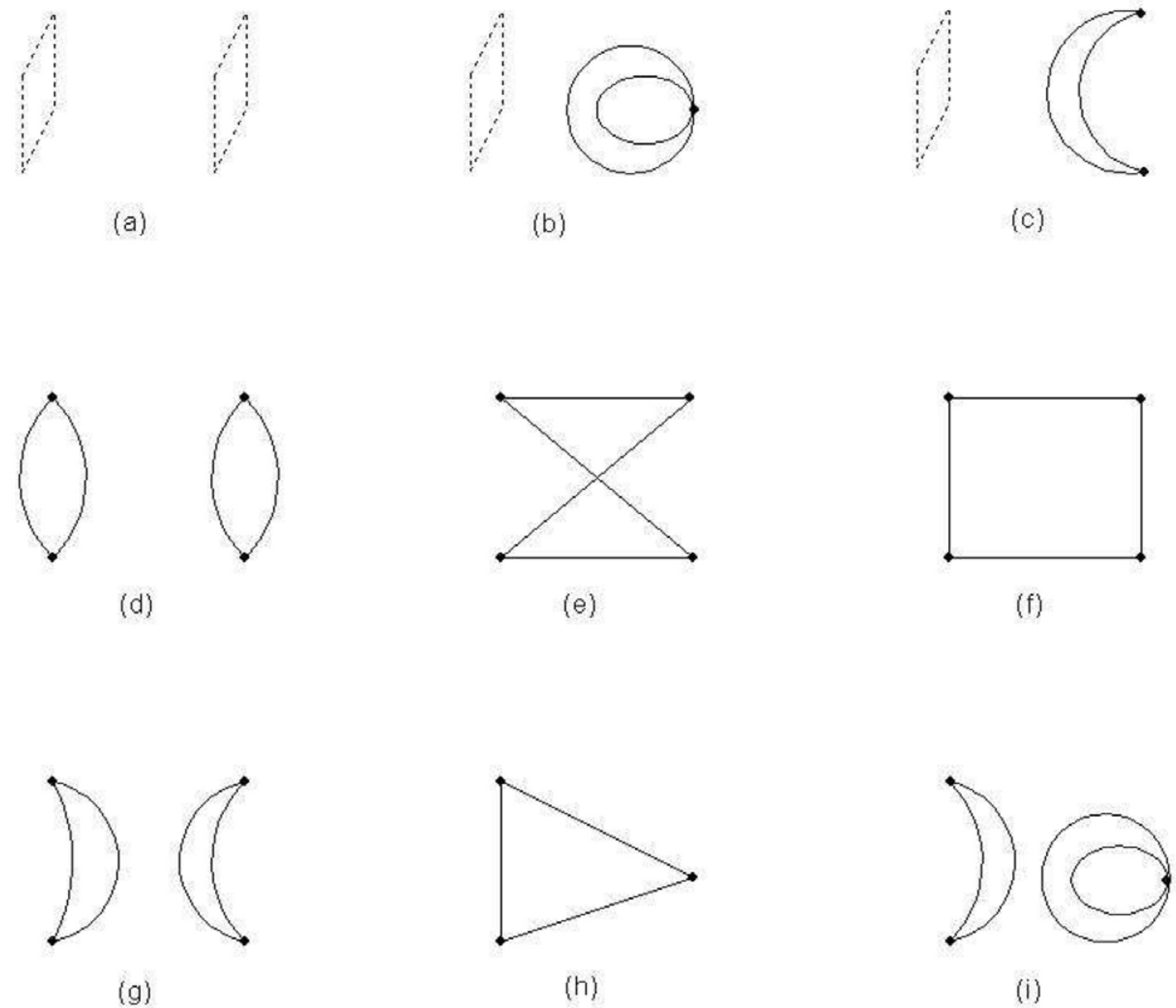


FIG. 13: Schematic mixing diagrams for the full glue, meson, and two meson mixing problem in the $I = 0$ scalar channel. The dashed rectangles represent the glue operators $\mathcal{P}^{A_1^{++}}$ and the solid lines represent quark propagators. Euclidean time runs horizontally.

Comparison quenched/unquenched lattice calculations

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)

E. Gregory, A. Irving, B. Lucini, C. McNeile, A. Rago, et al., Towards the glueball spectrum from unquenched lattice QCD, JHEP 1210 (2012) 170, [arXiv:1208.1858].

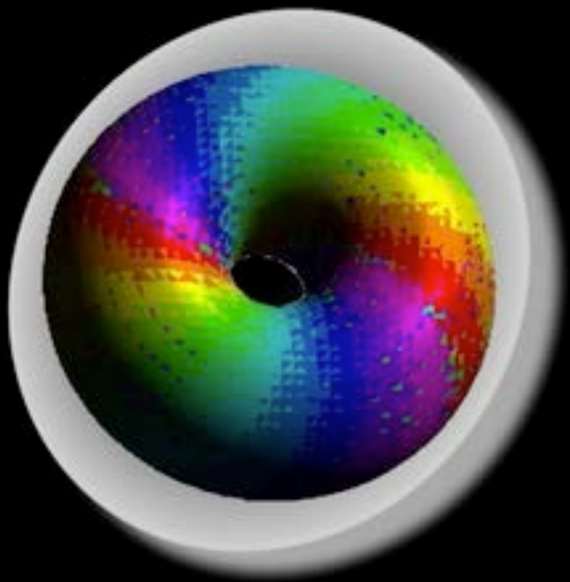
"One analysis [13] of the decay properties of the 0^{-+} states suggested that large unquenching effects moved the quenched 0^{-+} glueball from 2.6 GeV to 1.4(1) GeV, close to the experimental mass of the η(1405) meson."

Pseudoscalar glueball mass from η-η'-G mixing

Hai-Yang Cheng[1],* Hsiang-nan Li[1,2,3],† and Keh-Fei Liu[4]‡
[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China*
[2] *Department of Physics, Tsing-Hua University, Hsinchu, Taiwan 300, Republic of China*
[3] *Department of Physics, National Cheng-Kung University, Tainan, Taiwan 701, Republic of China and*
[4] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506*

We deduce the mass of the pseudoscalar glueball G from an η-η'-G mixing formalism based on the anomalous Ward identity for transition matrix elements. With the inputs from the recent KLOE experiment, we find a solution for the pseudoscalar glueball mass around (1.4 ± 0.1) GeV, which is fairly insensitive to a range of inputs with or without Okubo-Zweig-Iizuka-rule violating effects. This affirms that $\eta(1405)$, having a large production rate in the radiative J/Ψ decay and not seen in $\gamma\gamma$ reactions, is indeed a leading candidate for the pseudoscalar glueball. Other relevant quantities including the anomaly and pseudoscalar density matrix elements are obtained. The decay widths for $G \to \gamma\gamma$, $\ell^+\ell^-$ are also predicted.

H.-Y. Cheng, H.-n. Li, and K.-F. Liu, Pseudoscalar glueball mass from eta - eta-prime - G mixing , Phys.Rev. D79 (2009) 014024, [arXiv:0811.2577].



Glueballs, closed fluxtubes and η(1440)

Ludvig Faddeev, Antti Niemi and Ulrich Wiedner

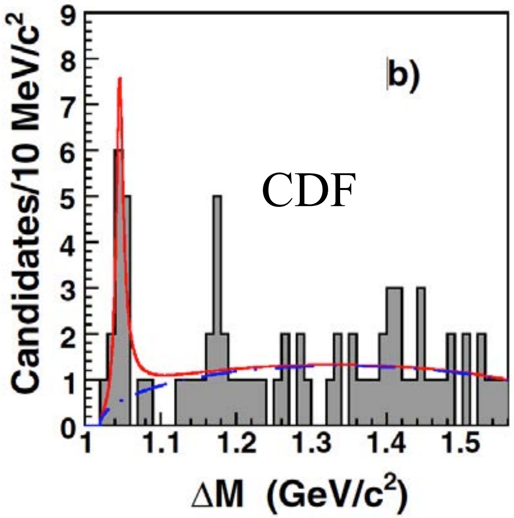
Phys.Rev.D70:114033, 2004

Other glueballs?

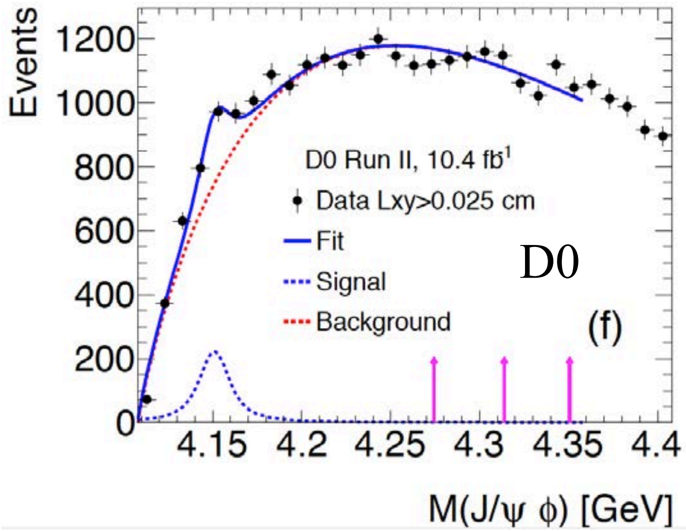
My personal glueball candidate for 1^{++} glueball: X(4140) M= 4147 MeV/c^2 , Γ = ~19 MeV

↳ decay mode $J/\psi\ \phi$ (flavour blind)

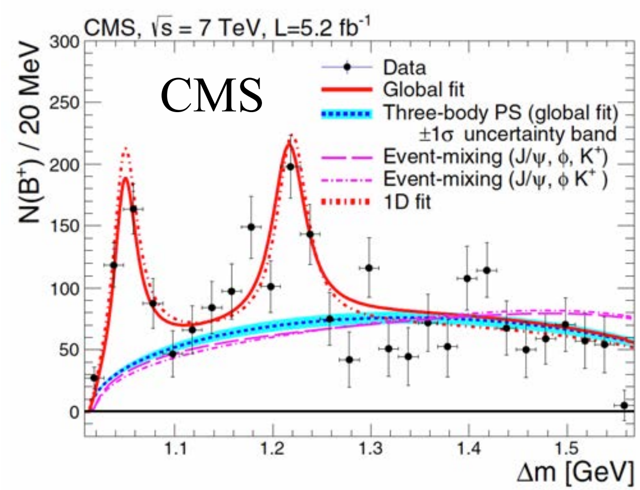
Phys.Rev.Lett. 102 (2009) 242002

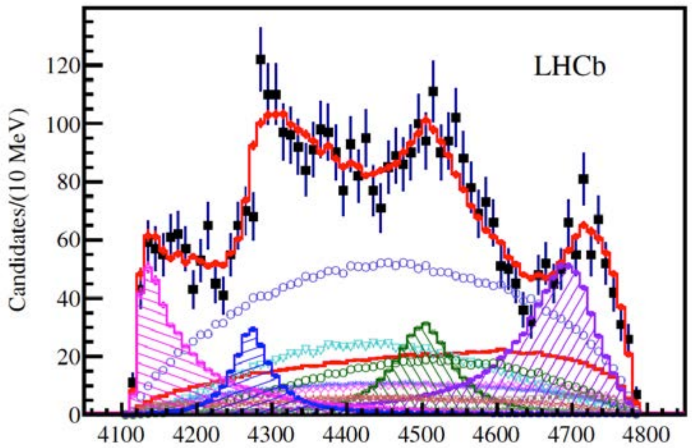


Phys. Rev. Lett. 115, 232001

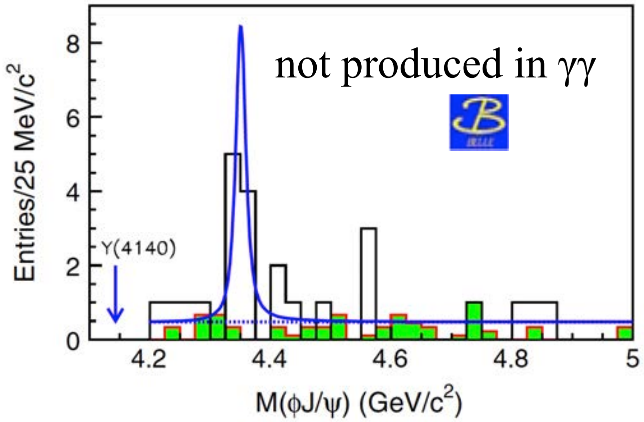


Phys.Lett. B734 (2014) 261-281

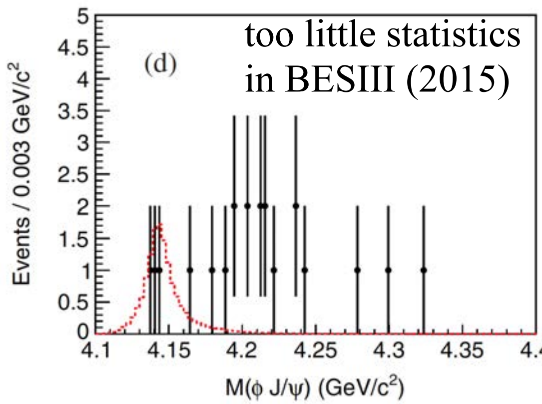




Phys.Rev.Lett. 118 (2017) no.2, 022003



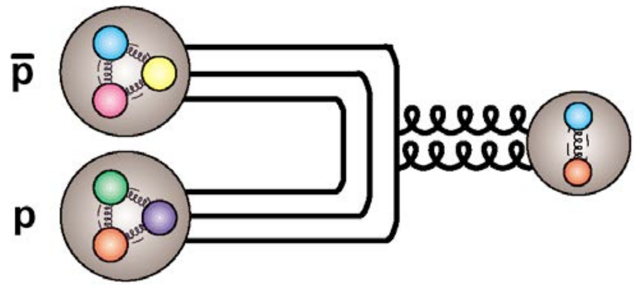
Phys.Rev.Lett. 104 (2010) 112004



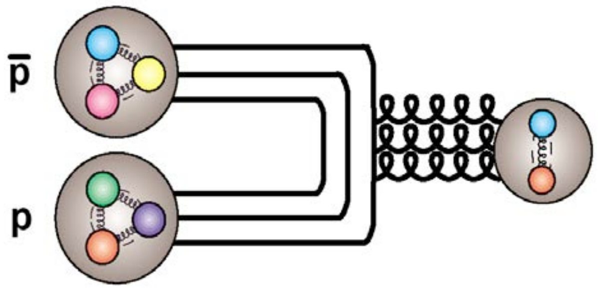
Phys.Rev. D91 (2015) no.3, 032002

The advantage of antiproton annihilations:

- gluon-rich
- high-spin states possible without limitations on q.n.



J = 0, 2, ...
C = +



J = 1
C = –

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]

Thanks a lot!

Muito obrigado!