Uniwersytet Jana Kochanowskiego w Kielcach

Status of exotic four-quark mesons

"Collider Physics"
2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society

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Francesco Giacosa

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Outline

Introduction: mesons

Four-quark states in the low-energy sector (< 1 GeV).

Intermezzo: glueballs.

Four-quark states in the high-energy sector (>2 GeV)

Introductory remarks

Hadrons

The QCD Lagrangian contains ‘colored’ quarks and gluons. However, no ‚colored‘ state has been seen.

Confinement: physical states are white and are called hadrons.

Hadrons can be:

Mesons: bosonic hadrons

Baryons: fermionic hadrons

Meson

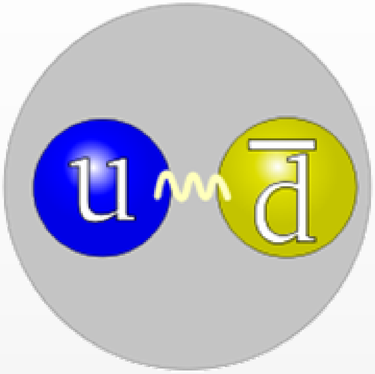
Definition(s):

1) A meson is a strongly interacting particle with integer spin.

2) A meson is a strongly interacting particle with zero baryon number.

A meson is **not necessarily** a quark-antiquark state.
A quark-antiquark state is a conventional meson.

Example of conventional quark-antiquark states: the ρ and the π mesons



Rho-meson $$m_{\rho^+} = 775 \text{ MeV}$$

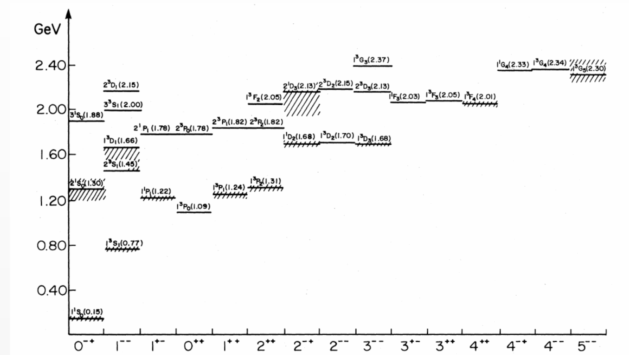
Pion $$m_{\pi^+} = 139 \text{ MeV}$$

$$m_u + m_d \approx 7 \text{ MeV}$$

Mass generation in QCD is a nonpert. penomenon based on SSB.

Quark model(s) and their QFT extensions

Mesons in a Relativized Quark Model with Chromodynamics
S. Godfrey, Nathan Isgur
Published in Phys.Rev. D32 (1985) **189-231**



QCD phenomenology based on a chiral effective Lagrangian
Tetsuo Hatsuda, Teiji Kunihiro
Published in **Phys.Rept. 247 (1994) 221-367**

NJL: quark-based model with
chiral symmetry and SSB
chiral condensate
Effective quark mass
Mesons as quarkonia (pion: ok)

The Infrared behavior of QCD Green's functions: Confinement dynamical symmetry breaking, and hadrons as relativistic bound states
Reinhard Alkofer, Lorenz von Smekal
Published in **Phys.Rept. 353 (2001) 281**

DS:
quarks and gluons propagators
from QCD
Condensates
Effective quark and gluon masses
Spectra of mesons as quarkonia
(pion: ok) and baryons as qqq states

Quark-antiquark states: the large-Nc limit

As Isgur-Godrey have shown, the quark model works. Theoretical justification relies on the large-Nc expansion.

Baryons in the 1/n Expansion
Edward Witten
Published in **Nucl.Phys. B160 (1979) 57**

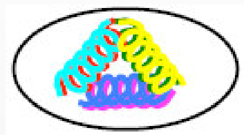
$$|\rho^+\rangle \propto |u\bar{d}\rangle + \frac{1}{N_c}\left(|\pi^+\pi^0\rangle + ...\right)$$

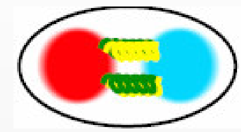
where

$$|u\bar{d}\rangle = |\text{valence } u + \text{valence } \bar{d} + \text{gluons}\rangle$$

Mesons beyond q-qbar: the first term in the first expansion is of non-quarkonium type

Non-conventional mesons: theoretical expectations

1) Glueballs 

2) Hybrids 

3) Four-quark states

Compact diquark-antidiquar states 

Molecular states (a type of dynamical generation) 

Companion poles (another type of dynamical generation)

Four-quark states: low-energy

The light scalar mesons

$$a_0(980) \quad k(800) \quad f_0(980) \quad f_0(500)$$

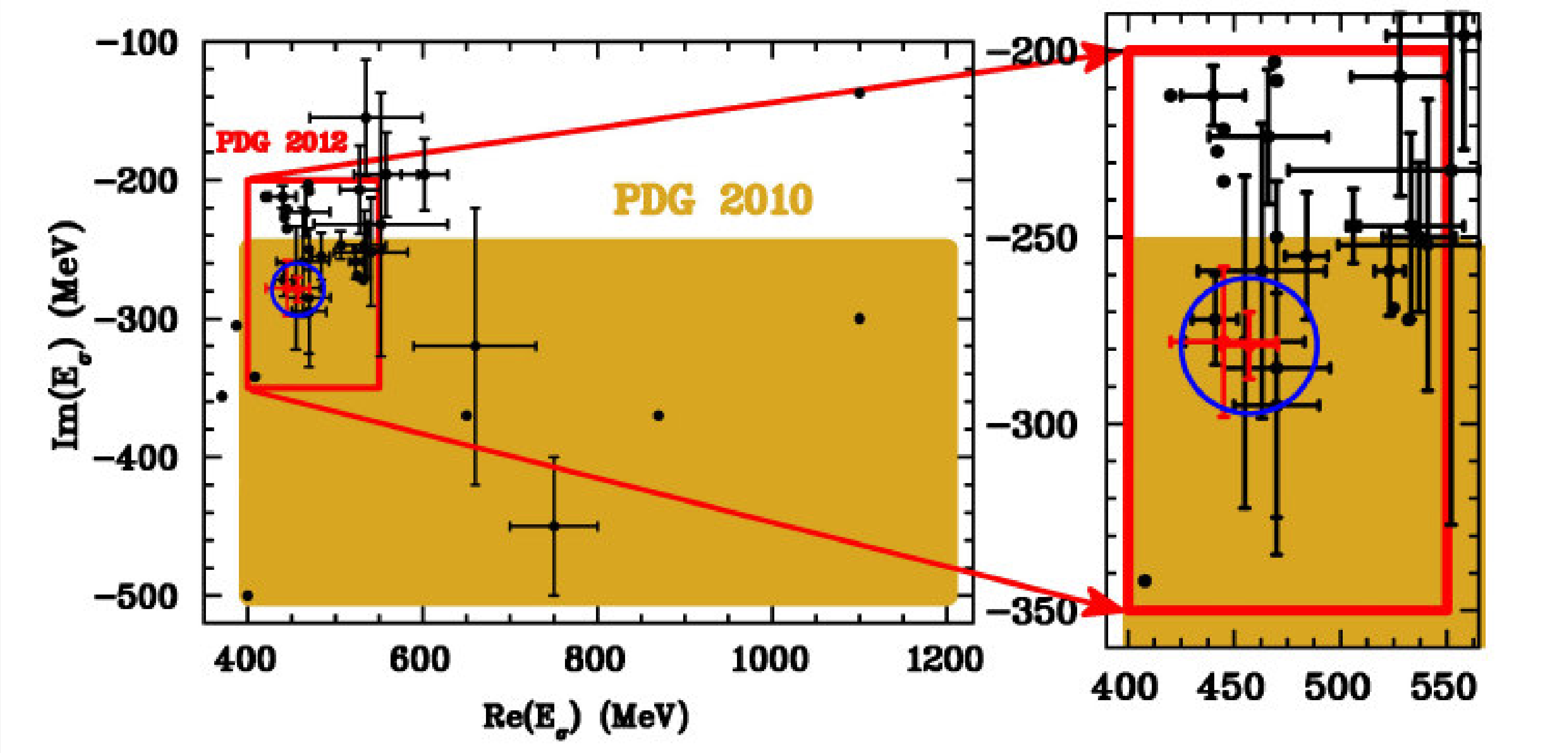
$$J^{PC} = 0^{++}$$

Many low-energy QCD) approaches show that these states are not quark-antiquark states!!!

$J^{PC} = 0^{++}$	M < 1 GeV	Main contribution
$I = 1$	$a_0(980)$	KK
$I = \frac{1}{2}$	$k(800)$	πK
$I = 0$	$f_0(500)$	ππ
	$f_0(980)$	KK

Existence and pole position of f0(500)

From 2010 to 2012: update…



J.R. Pelaez e-Print: **arXiv:1510.00653**
From controversy to precision on the sigma meson:
a review on the status of the non-ordinary f0(500) **resonance**

The very peculiar case of the f0(500)

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

$f_0(500)$ or σ
was $f_0(600)$

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

A REVIEW GOES HERE – Check our WWW List of Reviews

$f_0(500)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(400–550)−*i*(200–350) OUR ESTIMATE			

It is a kind of four-quark object which arises due to pion-pion interaction and due to mesonic loops.

It is NOT a quark-antiquark state (large-Nc, quark-based and hadron based models,…). Hence it is not the chiral partner of the pion.

It has a long, problematic and interesting history.

The scalar kaonic resonace K_0*(800)/1

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

$K_0^*(800)$

or κ

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

Needs confirmation. See the mini-review on scalar mesons under $f_0(500)$ (see the index for the page number).

$K_0^*(800)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
682 ±29 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.			

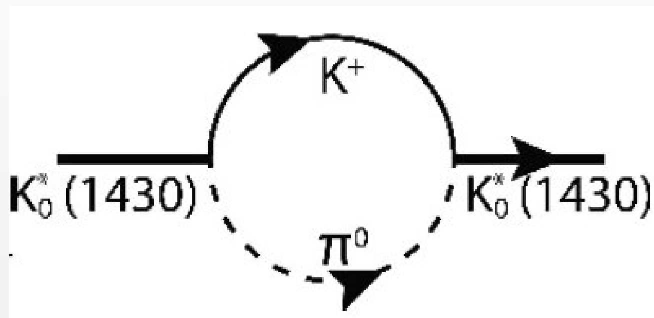
The scalar kaonic resonace K_0*(800)/2

The Lag. contains a
kingle scalar kaon corresponding
to K0*(1430).

$$\mathcal{L}_{int} = aK_0^{*+}K^-\pi^0 + bK_0^{*+}\partial_\mu K^-\partial^\mu\pi^0 + \ldots$$

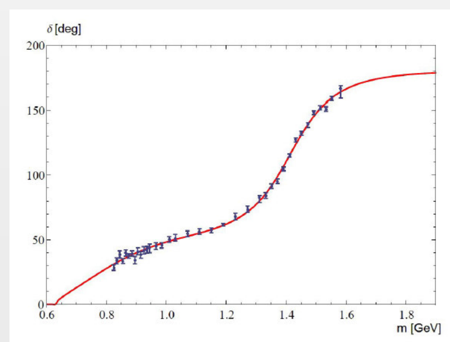
$K_0^*(1430)$ [nn] $\quad I(J^P) = \frac{1}{2}(0^+)$

Mass $m = 1425 \pm 50$ MeV
Full width $\Gamma = 270 \pm 80$ MeV



K0*(800) is not in the Lag.!!!
Role of loops crucial.

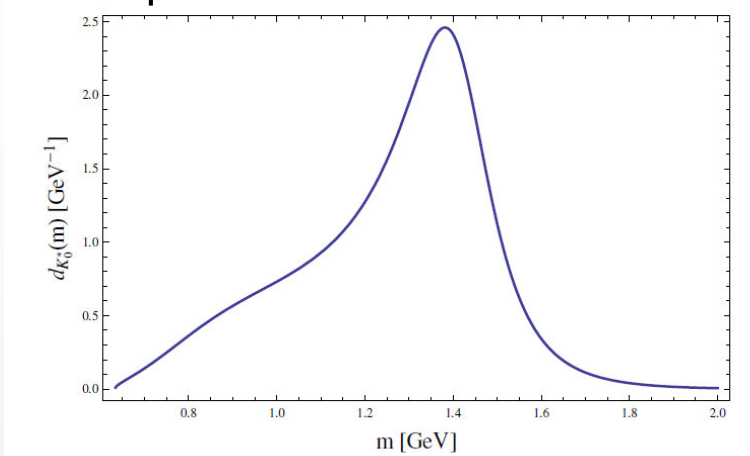
Correct description of pion-kaon scattering data



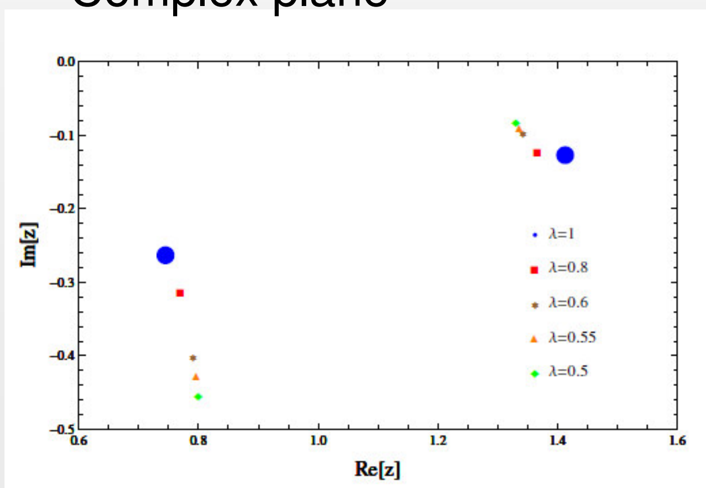
T. Wolkanowski, M. Soltysiak, F. G., arxiv: 1512.01071

The scalar kaonic resonace K0*(800)/3

Spectral function



Complex plane



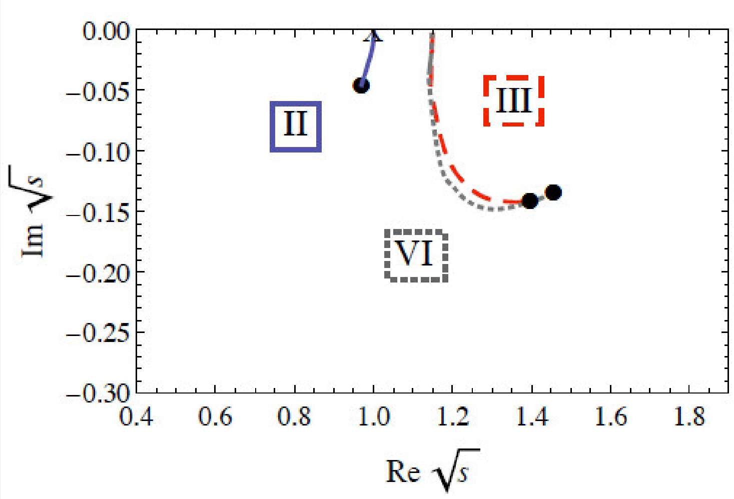
$K_0^*(1430)$: 1.412760 – 0.126770i
$K_0^*(800)$: 0.744805 – 0.263056i

T. Wolkanowski, M. Soltysiak, F. G., arxiv: 1512.01071

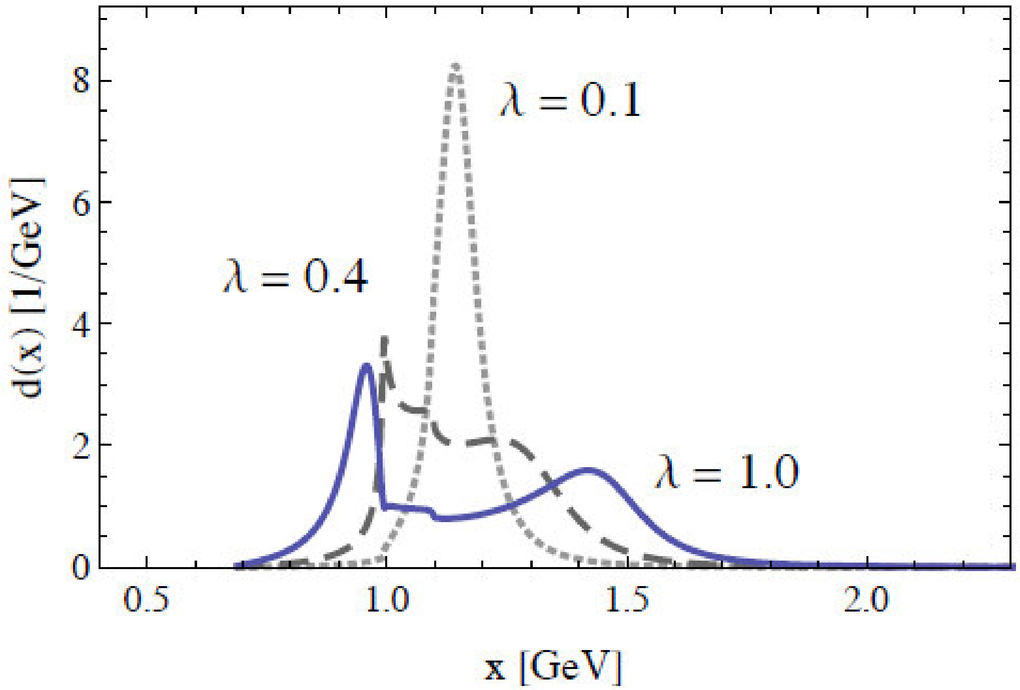
The resonance a0(980) as a companion pole

$$\begin{aligned}
\mathcal{L}_{a_0\eta\pi} &= A_1 a_0^0 \eta\pi^0 + B_1 a_0^0 \partial_\mu \eta \partial^\mu \pi^0 \ , \\
\mathcal{L}_{a_0\eta'\pi} &= A_2 a_0^0 \eta'\pi^0 + B_2 a_0^0 \partial_\mu \eta' \partial^\mu \pi^0 \ , \\
\mathcal{L}_{a_0 K\bar{K}} &= A_3 a_0^0 (K^0\bar{K}^0 - K^- K^+) + B_3 a_0^0 (\partial_\mu K^0 \partial^\mu \bar{K}^0 - \partial_\mu K^- \partial^\mu K^+)
\end{aligned}$$

Here: $a_0 = a_0(1450)$ is the unique seed state present in the Lagrangian.



Spectral function of the a_0 sector



The $a_0(980)$ revisited

Thomas Wolkanowski[a], Francesco Giacosa[a,b] and Dirk H. Rischke[a]

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[b]*Institute of Physics, Jan Kochanowski University, 25406 Kielce, Poland*

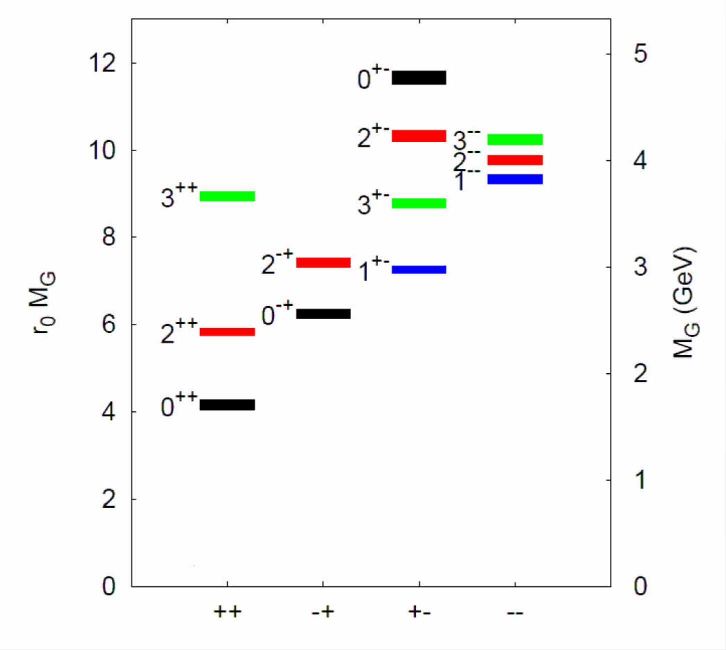
Phys.Rev. D93 (2016) no.1, 014002

Here, $a_0(980)$ is
a threshold-effect at the
kaon-kaon threshold
but corresponds to a pole!
It is a state, it is a kind of
molecular object.

Intermezzo - Gueballs

Glueballs

Bound state of gluons. Where are they?



Scalars above 1 GeV and scalar glueball candidate

$f_0(1370)$ is compatible with a quark-antiquark substructure.

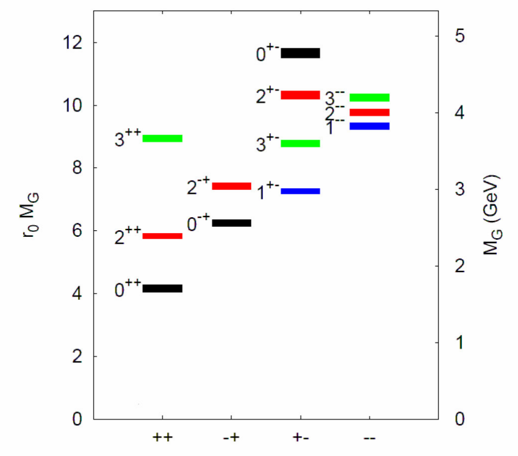
Yet, a large glueball component is expected in $f_0(1500)$ and/or in $f_0(1710)$.

Latest studies actually point toward $f_0(1710)$ as being predominantly gluonic.

The scalar glueball

The calculation within a chiral model (eLSM)of the full mixing problem in the I=J=0 sector shows that:

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} 0.91 & -0.24 & 0.33 \\ 0.30 & 0.94 & -0.17 \\ -0.27 & 0.26 & 0.93 \end{pmatrix} \begin{pmatrix} \sigma_N \equiv \bar{n}n = \sqrt{1/2}(\bar{u}u + \bar{d}d) \\ \sigma_S \equiv \bar{s}s \\ G \equiv gg \end{pmatrix}$$



Ergo: f0(1710) is predominantly a glueball!
…and f0(1370) is the chiral partner of the pion
f0(1500) is predominantely a hidden-strange state

Details in S. Janowski, F.G, D. H. Rischke, **Phys.Rev. D90 (2014) 11, 114005** arXiv: 1408.4921

See also: L. -C. Gu et al, **Phys. Rev. Lett. 110 (2013) 021601** [arXiv:1206.0125 [hep-lat]]

Pseudoscalar glueball

Up to now we do not know where it is. A light pseudoscalar glueball was not found yet. Here also the candidates are not so easily found.

η(1405) and η(1475)

(but much lighter than the lattice value of 2.6 GeV)

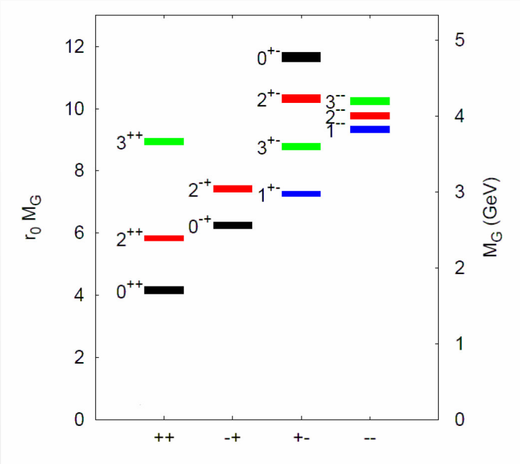
X(2370) (BES)

The pseudoscalar glueball

$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = ic_{\tilde{G}\Phi}\tilde{G}\left(\det\Phi - \det\Phi^{\dagger}\right)$$

Quantity	Value
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma^{tot}_{\tilde{G}}$	0.049
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.019
$\Gamma_{\tilde{G}\to\eta\eta\eta}/\Gamma^{tot}_{\tilde{G}}$	0.016
$\Gamma_{\tilde{G}\to\eta\eta\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.0017
$\Gamma_{\tilde{G}\to\eta\eta'\eta'}/\Gamma^{tot}_{\tilde{G}}$	0.00013
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma^{tot}_{\tilde{G}}$	0.46
$\Gamma_{\tilde{G}\to\eta\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.16
$\Gamma_{\tilde{G}\to\eta'\pi\pi}/\Gamma^{tot}_{\tilde{G}}$	0.094

Quantity	Value
$\Gamma_{\tilde{G}\to KK_S}/\Gamma^{tot}_{\tilde{G}}$	0.059
$\Gamma_{\tilde{G}\to a_0\pi}/\Gamma^{tot}_{\tilde{G}}$	0.083
$\Gamma_{\tilde{G}\to\eta\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.028
$\Gamma_{\tilde{G}\to\eta\sigma_S}/\Gamma^{tot}_{\tilde{G}}$	0.012
$\Gamma_{\tilde{G}\to\eta'\sigma_N}/\Gamma^{tot}_{\tilde{G}}$	0.019



$$\Gamma_{\tilde{G}\to\pi\pi\pi} = 0$$

Future experimental search, e.g. at BES and PANDA

Details in:

W. Eshraim, S. Janowski, F.G., D. Rischke, **Phys.Rev. D87 (2013) 054036. arxiv: 1208.6474** .
W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

Other glueballs

Here it is fog…

The resonance $f_J(2220)$ could be a candidate, if J=2 will be confirmed.

So on for the other glueballs…definitely, both experiment and theory are needed.

Plan: make predictions for decays of (almost all) glueballs in the list.

Discussion on heavy non-quarkonium mesons

Francesco Giacosa

X(3872)

X(3872) $M_X = 3871.52 \pm 0.2\ \text{MeV},\ \Gamma = 1.3 \pm 0.6\ \text{MeV},\ J^{PC} = 1^{++}$

Various works (see Brambilla et al, EPJ C (2011) 71):
tetraquark or molecular states the most probable intepretations.
(Mass too light when compared to quark-antiquark predictions)

Possibilities: tetraquark? a D-D* molecular state? It could arise due to mesonic loops as a companion pole. The starting seed state is a regular charm-anticharm object. Loops do the rest.

Four-quark states above 2 GeV

Francesco Giacosa

$D^*_{s0}(2317)$

$D^*_{s0}(2317)$: too light to be a $c\bar{s}$, $\bar{c}s$ quarkonium.

$J^P = 0^+$, Mass $= 2317.8 \pm 0.6$ MeV

It is a good candidate to be a molecular state / dynamically generated state…

In arXiv: 1405.5861 we find that the quarkonium state of 2.47 GeV and a very large width. Loop effects and companion pole?

X(3872)

X(3872) $M_X = 3871.52 \pm 0.2 \text{ MeV}, \Gamma = 1.3 \pm 0.6 \text{ MeV}, J^{PC} = 1^{++}$

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tetraquark or molecular states the most probable intepretations.
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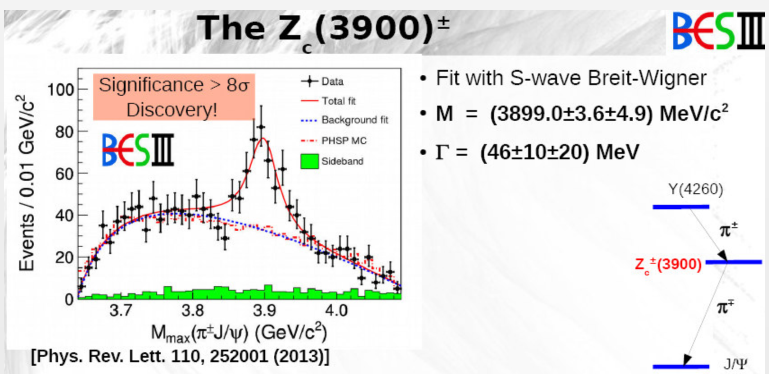
X,Y,Z states

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	References
$X(3872)$	3871.69±0.17	<1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [10, 32], BaBar [36], LHCb [34, 72]
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [31, 73, 74], D0 [75]
				$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BES III [76]
				$B \to K(\omega J/\psi)$	Belle [77], BaBar [33]
				$B \to K(D^{*0}\bar{D}^0)$	Belle [38, 78], BaBar [37]
				$B \to K(\gamma J/\psi)$ and $B \to K(\gamma\psi(2S))$	Belle [29], BaBar [30], LHCb [40]
$Z_c(3900)^+$	3888.7 ± 3.4	35±7	1^+	$e^+e^- \to (J/\psi\ \pi^+)\pi^-$	Belle [43], BES III [55]
				$e^+e^- \to (D\bar{D}^*)^+\pi^-$	BES III [56]
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [79], BaBar [33]
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [80], BaBar [81]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(DD^*)$	Belle [82]
				$e^+e^- \to J/\psi\ (...)$	Belle [83]
$Y(4008)$	3891 ± 42	255±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [42, 43]
$Z_c(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [53], BaBar [54]
$X(4050)^+$	4054 ± 3	45	?	$e^+e^- \to (\pi^+\psi(2S))\pi^-$	Belle [84]
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [71],D0 [85]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [82]
$Z_c(4200)^+$	4196^{+35}_{-32}	370^{+99}_{-149}	?	$B \to K(\pi^+ J/\psi)$	Belle [86]
$Z_c(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [53], BaBar [54]
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BaBar [41, 87], CLEO [88], Belle [42, 43]
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [47], BES III [56]
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [47]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$?^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [89]
$Y(4360)$	4361 ± 13	74±18	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BaBar [44], Belle [45, 84]
$Z_c(4430)^+$	4485^{+36}_{-25}	200^{+49}_{-58}	1^+	$B \to K(\pi^+\psi(2S))$	Belle [49, 51, 52], BaBar [50], LHCb [21]
				$B \to K(\pi^+ J/\psi)$	Belle [86], BaBar [50]
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [90]
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [45]
$Z_b(10610)^+$	10607.2±2.0	18.4±2.4	1^+	$e^+e^- \to (b\bar{b}\ \pi^+)\pi^-$	Belle [20]
$Z_b(10610)^0$	10609±4±4	N.A.	1^{+-}	$e^+e^- \to (\Upsilon(2,3S)\pi^0)\pi^0$	Belle [23]
$Z_b(10650)^+$	10652.2±1.5	11.5±2.2	1^+	$e^+e^- \to (b\bar{b}\ \pi^+)\pi^-$	Belle [20]
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [60, 62]

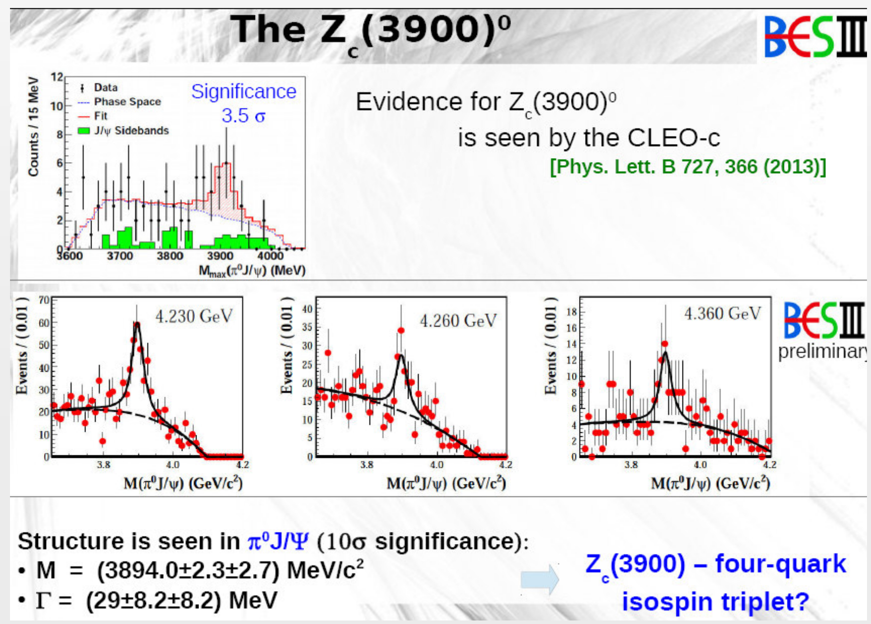
Hosaka et al, arxiv: 1603.09229

Z states

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
$Z_c^+(3885)$	3883.9 ± 4.5	24.8 ± 11.5	$1^{+?}$	$D^{*+}\bar{D}^0,\ D^+\bar{D}^{*0}$	BESIII 2013
$Z_c^+(3900)$	3898 ± 5	51 ± 19	$?^{?-}$	$J/\psi\,\pi^+$	BESIII 2013
$Z_c^+(4020)$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$h_c(1P)\,\pi^+,\ D^{*+}\bar{D}^{*0}$	BESIII 2013
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	1^{+-}	$\psi(2S)\,\pi^+$	Belle 2007



From M. Kavatsyuk for BES, eQCD 2015



States beyond the quark-antiquark picture have been experimentally found!!!

Theoretical models have to be improved to describe them

Exotic Hadrons with Heavy Flavors – X, Y, Z and Related States –

March 31, 2016

Atsushi Hosaka[1,2], Toru Iijima[3,4], Kenkichi Miyabayashi[5], Yoshihide Sakai[6,7], Shigehiro Yasui[8]

arxiv:1603.09229

The hidden-charm pentaquark and tetraquark states

Hua-Xing Chen[1a,b], Wei Chen[1c], Xiang Liu[d,e,*], Shi-Lin Zhu[a,f,g,**]

arxiv:1601.02092

Summary

QCD: well defined part of the Standard Model

…still: resonances long since long time are not yet understood (light scalar states).

On the contrary, many theoretically expected resonances have not been found.
Glueballs: still missing!. The state $f_0(1710)$ is a good candidate.
Many others shall be found.

Region of charm-anticharm states:
experimental proof of non-quarkonium states
(Z states are four-quark states!) … but different models exist.

In conclusion: Ongoing and future experiment.
Active theoretical activity (both from lattice and modelling).

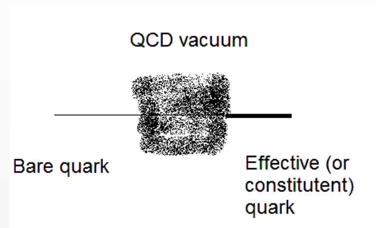
Thank You

Recall: Spontnaeous Symmetry Breaking (SSB)

$$\mathrm{SSB:}\ \mathrm{SU(3)_R \times SU(3)_L \rightarrow SU(3)_{V=R+L}}$$

Chiral symmetry → Flavor symmetry

$$\left\langle \bar{q}_i q_i \right\rangle = \left\langle \bar{q}_{i,R} q_{i,L} + \bar{q}_{i,L} q_{i,R} \right\rangle \neq 0$$



$$\mathrm{m \approx m_u \approx m_d \approx 5\ MeV \rightarrow m^* \approx 300\ MeV}$$

Nonperturbative propagators, running coupling, and the dynamical quark mass of Landau gauge QCD
C. S. Fischer and R. Alkofer
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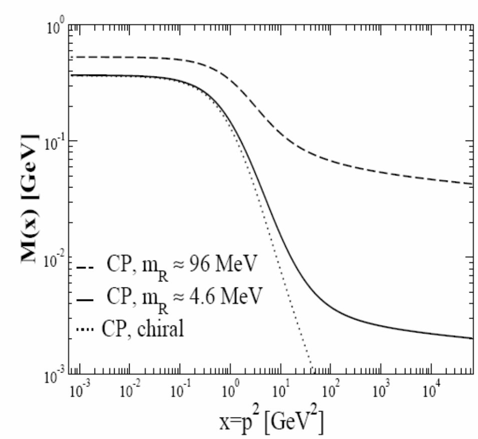

Masses revisited

$$m^* \approx 300\,\mathrm{MeV}$$

$$m_p \approx 3m^*$$

$$m_\rho \approx 2m^*$$

$$m_\pi << 2m^*$$

Pion: (quasi) Goldstone boson. $m_\pi^2 \propto (m_u + m_d)\langle \overline{q}q \rangle$

$J^{PC} = 0^{++}$	M < 1 GeV	Tetraquark interpretation
$I = 1$	$a_0(980)$	$[u,s][\bar{d},\bar{s}],\ [\bar{u},\bar{s}][d,s],$ $([u,s][\bar{u},\bar{s}]-[d,s][\bar{d},\bar{s}])$
$I = \frac{1}{2}$	$k(800)$	$[u,d][\bar{d},\bar{s}],\ [\bar{u},\bar{d}][d,s],$ $[u,d][\bar{u},\bar{s}],\ [\bar{u},\bar{d}][u,s]$
$I = 0$	$f_0(500)$	$\approx [\bar{u},\bar{d}][u,d]$
	$f_0(980)$	$\approx ([u,s][\bar{u},\bar{s}]+[d,s][\bar{d},\bar{s}])$

The light scalars can be interpeted as tetraquark state

A tetraquark is the bound state of two diquarks

An example of „good diquark" is:

$$\left|qq\right\rangle = \left|Space : L = 0\right\rangle \left|Spin : (\uparrow\downarrow - \downarrow\uparrow\right\rangle \left| f : (ud - du)\right\rangle \left|c : (RB - BR)\right\rangle$$

Example: $a_0^+(980) = -[\bar{d},\bar{s}][u,s]$ (and not $u\bar{d}$)