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Mesons beyond the quark-antiquark picture: glueballs, hybrids, tetraquarks - part 2 -

55 Cracow School of Theoretical Physics

20 -28/26/2015, Zakopane, Poland

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Outline

The origin of hadronic masses.

The building of a chiral model: the eLSM.

Scalar mesons and the scalar glueball.

The pseudoscalar glueball.

The resonance $a_0(980)$ as a companion pole

Discussion about X,Y,Z states

Summary

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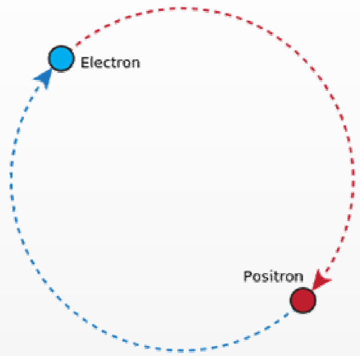
Hadron masses

Positronium mass



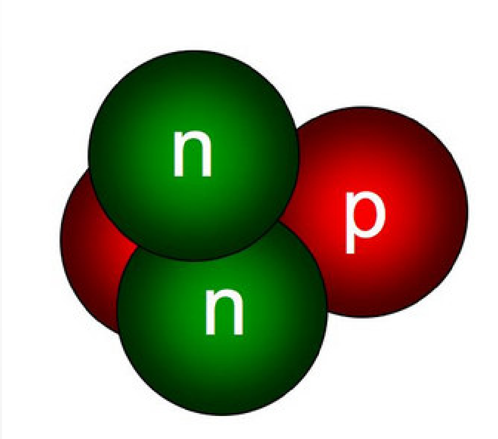
$$m_e = 0.511 \ \text{MeV}$$

$$m_{\text{Positronium}} = 2m_e - 6.8 \cdot 10^{-6} \ \text{MeV}$$

$$m_{\text{Positronium}} \approx 2m_e$$

Mass of the α particle

Nucleus of a Helium-atom



$$m_\alpha = 3.727379240 \text{ GeV}$$

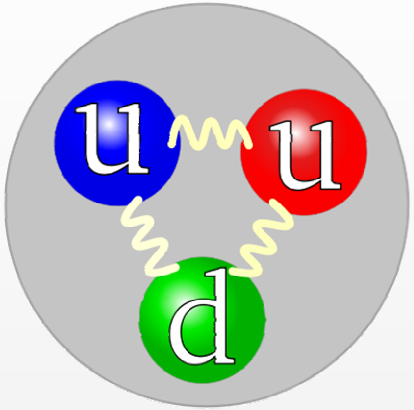
$$m_p = 0.93827 \text{ GeV} \; ; \; m_n = 0.93956 \text{ GeV}$$

$$m_\alpha \approx 2m_p + 2m_n$$

$$m_\alpha = (2m_p + 2m_n) - 28.2956 \text{ MeV}$$

Proton

$$m_p = 938.27\,\text{MeV}$$

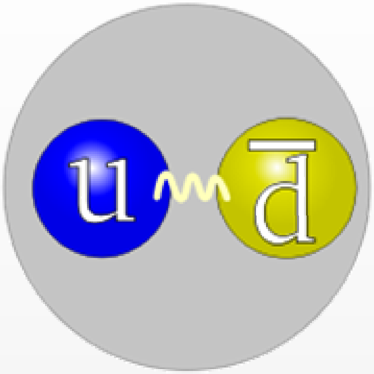


$$m_u = 2.3^{+0.7}_{-0.5}\ \text{MeV}$$

$$m_d = 4.8^{+0.7}_{-0.5}\ \text{MeV}$$

$$m_p >> 2m_u + m_d \approx 10\ \text{MeV}$$

The ρ and the π mesons



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

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

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

Recall: trace anomaly

Emergence of a low-energy scale: $\Lambda_{YM} \approx 250\ \mathrm{MeV}$

Gluon condensate: $\left\langle G^{a}_{\mu\nu} G^{a,\mu\nu} \right\rangle \neq 0$

„Effective“ gluon mass

Analytic Structure of the Landau-Gauge Gluon Propagator
Stefan Strauss, Christian S. Fischer, and Christian Kellermann
Phys. Rev. Lett. **109**, 252001 – Published 19 December 2012

Moreover, the gluon is certainly not a massive particle in the usual sense. [...]
Within the present accuracy we find 600 MeV < mg < 700 MeV.

$$D_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) \frac{Z(p^2)}{p^2}$$

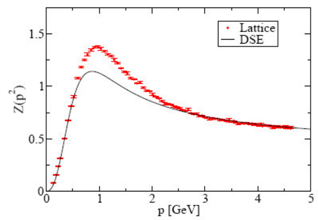
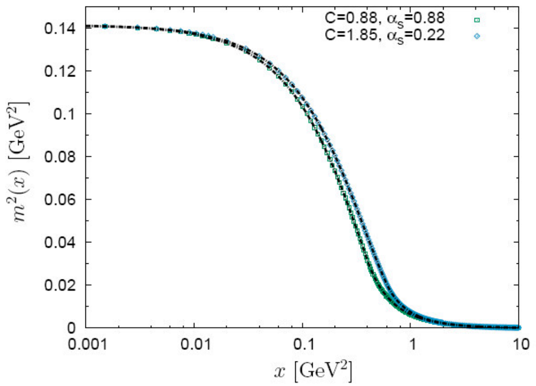


FIG. 2: Results for the gluon dressing function $Z(p^2)$ from lattice calculations [12] compared to the result from DSEs [9].

See also:
All-order equation of the effective gluon mass
D. Binosi, D. Ibañez, and J. Papavassiliou
Phys. Rev. D **86**, 085033 – Published 19 October 2012



Many other works:

A Dynamical gluon mass solution in a coupled system of the Schwinger-Dyson equations
A.C. Aguilar, A.A. Natale (Sao Paulo, IFT). Aug 2004. 17 pp.
Published in **JHEP 0408 (2004) 057**
DOI: 10.1088/1126-6708/2004/08/057
e-Print: **hep-ph/0408254** | **PDF**
•References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
•ADS Abstract Service; JHEP Electronic Journal Server
•Record dettagliato - Citato da 117 record 100+

Off diagonal gluon mass generation and infrared Abelian dominance in the maximally Abelian gauge in lattice QCD
Kazuhisa Amemiya, Hideo Suganuma (Osaka U., Res. Ctr. Nucl. Phys.). Nov 1998. 18 pp.
Published in **Phys.Rev. D60 (1999) 114509**
DOI: 10.1103/PhysRevD.60.114509
e-Print: **hep-lat/9811035** | **PDF**
•References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
•CERN Document Server ; ADS Abstract Service; Phys. Rev. D Server
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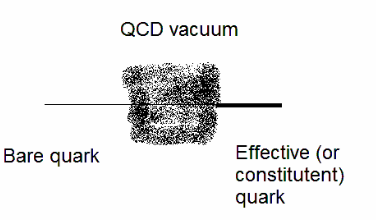
Recall: Spontnaeous Symmetry Breaking (SSB)

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

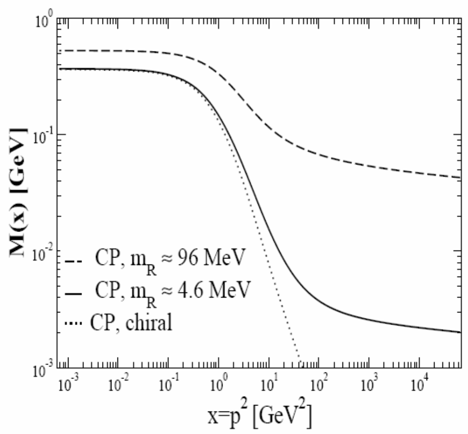
Chiral symmetry → Flavor symmetry

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



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

Nonperturbative propagators, running coupling, and the dynamical quark mass of Landau gauge QCD
C. S. Fischer and R. Alkofer
Phys. Rev. D **67**, 094020 – Published 27 May 2003



Masses revisited

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

$$m_p \approx 3m^*$$

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

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

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

From quarks and gluons to hadrons d.o.f.

Hadrons

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.

Quark model(s) and their QFT extensions

Mesons in a Relativized Quark Model with Chromodynamics
S. Godfrey, Nathan Isgur (Toronto U.). 1985.
Published in **Phys.Rev. D32 (1985) 189-231**
DOI: 10.1103/PhysRevD.32.189
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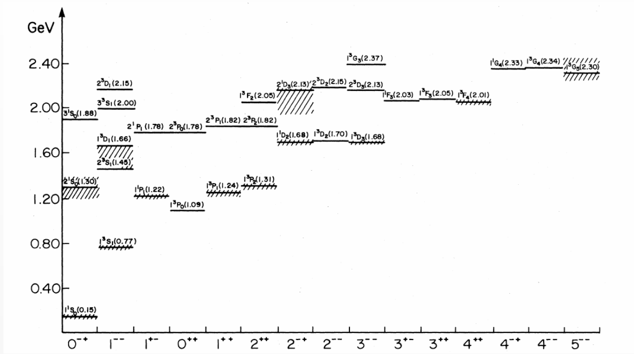


QCD phenomenology based on a chiral effective Lagrangian
Tetsuo Hatsuda (Tsukuba U.), Teiji Kunihiro (Ryukoku U.). Jan 1994. 23 pp.
Published in **Phys.Rept. 247 (1994) 221-367**
UTHEP-270, RYUTHP-94-1
DOI: 10.1016/0370-1573(94)90022-1

Record dettagliato - Citato da 1184 record 1000+

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 (Tubingen U.), Lorenz von Smekal (Erlangen - Nuremberg U., Theorie III). Jul 2000. 212 pp.
Published in **Phys.Rept. 353 (2001) 281**
DOI: 10.1016/S0370-1573(01)00010-2
UNITUE-THEP-00-09, FAU-TP3-00-8
e-Print: **hep-ph/0007355** | **PDF**
Record dettagliato - Citato da 836 record 500+

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 (Harvard U.). Mar 1979. 118 pp.
Published in **Nucl.Phys. B160 (1979) 57**
HUTP-79-A007
DOI: 10.1016/0550-3213(79)90232-3
Record dettagliato - Citato da 2093 record 1000+

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

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

Construction of a chiral model of QCD

Francesco Giacosa

Fields of the eLSM

• Quark-antiquark mesons: scalar, pseudoscalar, vector and axial-vector quarkonia.

• Additional mesons: The scalar glueball and the pseudoscalar glueball

• Baryons: nucleon doublet and its partner (not discussed here!)

(in the so-called mirror assignment)

Criteria

We construct the Lagrangian of model, called Extended Linear Sigma Model (ELSM), according to:

dilatation symmetry

and

chiral invariance.

The breaking of the dilatation symmetry is only included in the „gluonic part“…(scalar glueball and axial anomaly) through a dilaton field.

Moreover, invariance under C and P is also taken into account.

Simiplified discussion of the eLSM

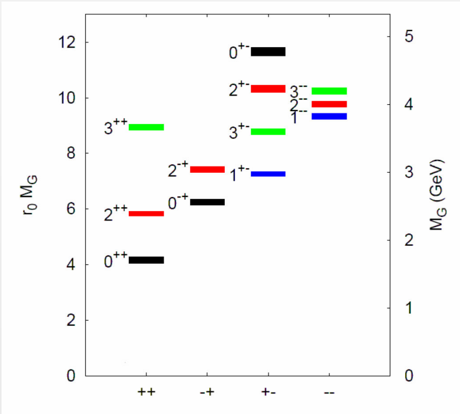
Francesco Giacosa

Dilaton -Scalar glueball/1

We start from the scalar glueball.

The lightest glueball is included as part of the chiral Lagrangian in order to reproduce at a composite level the breaking of dilatation invariance.

Development of a dilaton field and a dilaton potential.



Exotic: 2^+- and 0^+-
They are heavy!

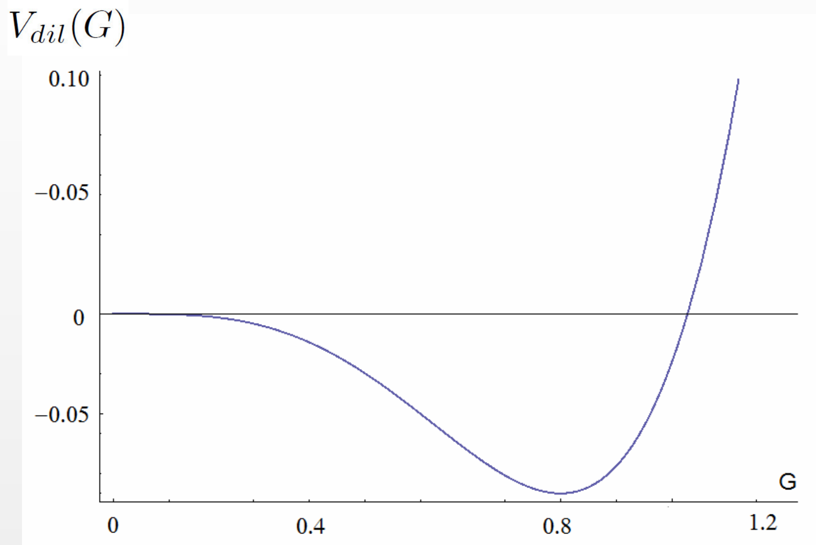
Dilaton - Scalar glueball/2

At the hadronic level, we describe these properties as:

$$G^4 \sim G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\mathcal{L}_{dil} = \frac{1}{2}(\partial_\mu G)^2 - V_{dil}(G)$$

$$V_{dil}(G) = \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left[G^4 \ln\left(\frac{G}{\Lambda_G}\right) - \frac{G^4}{4}\right]$$



Λ_G dimensionful param that breaks dilatation inv!

$$\langle G \rangle = G_0 = \Lambda_G \propto \Lambda_{YM}$$

$$\partial_\mu J^\mu = T^\mu_\mu = -\frac{1}{4}\frac{m_G^2}{\Lambda_G^2} G^4$$

In Yang-Mills (QCD wo quarks) it is:

$$\partial_\mu J^\mu = T^\mu_\mu = \frac{\beta(g)}{4g} G^a_{\mu\nu} G^{a,\mu\nu} \neq 0$$

J. Schechter et al,
Phys. Rev. D 24, 2545 (1981)

M. Migdal and Shifman,
Phys. Lett. 114B, 445 (1982)

Glueball, pion, and sigma

$\pi = \pi^0 \equiv \sqrt{1/2}(\bar{u}u - \bar{d}d)$ neutral pion

$\sigma \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$

Chiral transformation: $\sigma \leftrightarrow \pi$

$$\pi_i \longrightarrow \pi_i + \Theta_i \sigma$$
$$\sigma \longrightarrow \sigma - \Theta_i \pi_i$$

Chirally symmetric and dilatation-invariant potential (besides the dilaton):

$$V(G, \sigma, \vec{\pi}) = \frac{a}{2} G^2 (\sigma^2 + \vec{\pi}^2) + \frac{\lambda}{4} (\sigma^2 + \vec{\pi}^2) + V_{dil}(G)$$

At first, σ and π have no masses.

G condenses to G_0

$$\langle G \rangle = G_0 = \Lambda_G \propto \Lambda_{YM}$$

If $a > 0$:

$$m_\sigma^2 = m_\pi^2 = a G_0^2$$

and

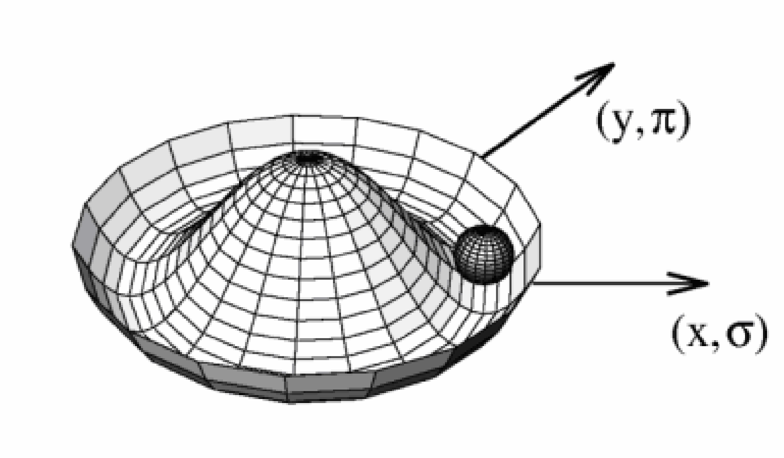
$$\langle \sigma \rangle = 0$$

But if $a < 0$:

$$\langle \sigma \rangle = \sigma_0 = \sqrt{\frac{-a}{\lambda}} G_0$$

$$m_\pi = 0$$

$$m_\sigma^2 = -2aG_0^2 = 2\lambda\sigma_0^2$$



This is what we have in reality.
Masses are combinations of the gluon and the quark condensates.

The full vs of the chiral model eLSM in the three-flavor case

(and with (axial-)vector mesons)

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(Pseudo)scalar sector

$$P = P_a \lambda^a = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_N}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_N}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix}$$

$$\Gamma = i\gamma^5$$
$$J^{PC} = 0^{-+}$$

$$S = S_a \lambda^a = \begin{pmatrix} \frac{a_0^0}{\sqrt{2}} + \frac{\sigma_N}{\sqrt{2}} & a_0^+ & K_S^+ \\ a_0^- & -\frac{a_0^0}{\sqrt{2}} + \frac{\sigma_N}{\sqrt{2}} & K_S^0 \\ K_S^- & \bar{K}_S^0 & \sigma_S \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix}$$

$$\Gamma = 1$$
$$J^{PC} = 0^{++}$$

$a_0^+ = a_0(1450) \equiv u\bar{d}$ and not $a_0(980)$!!!

$\sigma_N \equiv \sqrt{1/2}(u\bar{u} + d\bar{d}) \approx f_0(1370)$ and not $f_0(500)$!!!

Chiral transformation of (pseudo)scalar mesons

$$q_i = q_{i,R} + q_{i,L} \rightarrow (U_R)_{ij} q_{j,R} + (U_L)_{ij} q_{j,L} \qquad U_R,\ U_L \subset U(3)$$

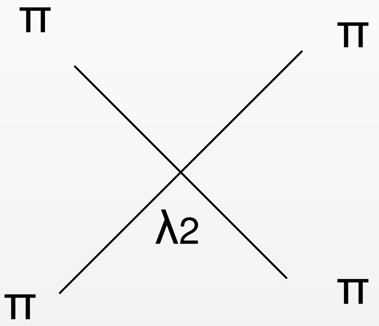
$$\Phi = S + iP$$

$$\Phi_{ij} = \bar{q}_j q_i + i\bar{q}_j i\gamma^5 q_i = \sqrt{2}\,\bar{q}_{R,j} q_{L,i}$$

$$\Phi \rightarrow U_L \Phi U_R^+$$

Example of an invariant term

$$\Phi \rightarrow U_L \Phi U_R^+ \qquad U_R,\ U_L \subset SU(3)$$



$$\lambda_2 Tr\left[\Phi^+ \Phi \Phi^+ \Phi\right] \rightarrow$$

$$\lambda_2 Tr\left[U_R \Phi^+ U_L^+ U_L \Phi U_R^+ U_R \Phi^+ U_L^+ U_L \Phi U_R^+\right] = \lambda_2 Tr\left[\Phi^+ \Phi \Phi^+ \Phi\right]$$

$$U_L^+ U_L = 1\ ,\ U_R^+ U_R = 1$$

(Axial-)Vector sector

$$V^\mu = V^\mu{}_a \lambda^a = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega_N}{\sqrt{2}} & \rho^+ & K_*(892)^+ \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega_N}{\sqrt{2}} & K_*(892)^0 \\ K_*(892)^- & \overline{K}_*(892)^0 & \phi_S \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix}$$

$$\Gamma = \gamma^\mu$$

$$J^{PC}_{\Gamma=\gamma^\mu\gamma^5} = 1^{--}$$

$$A^\mu = A^\mu{}_a \lambda^a = \begin{pmatrix} \frac{a_1^0}{\sqrt{2}} + \frac{f_{1,N}}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & -\frac{a_1^0}{\sqrt{2}} + \frac{\omega_N}{\sqrt{2}} & K_1^0 \\ K_1^- & \overline{K}_1^0 & f_{1,S} \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix}$$

$$\Gamma = \gamma^\mu \gamma^5$$

$$J^{PC} = 1^{++}$$

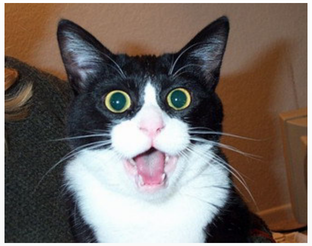
$$a_1^+ = a_1^+(1260) \equiv u\bar{d}$$

$$K_1^+ = K_1^+(1270) \equiv u\bar{s}$$

$$L^\mu = V^\mu + A^\mu \qquad R^\mu \to U_R R^\mu U_R^+$$

$$R^\mu = V^\mu - A^\mu \qquad L^\mu \to U_L L^\mu U_L^+$$

Model of QCD – eLSM with scalar Glueball



$$
\begin{aligned}
\mathcal{L} \;=\;& \frac{1}{2}(\partial_\mu G)^2 - \frac{1}{4}\frac{m_G^2}{\Lambda^2}\left(G^4 \ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right) + \mathrm{Tr}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right] \\
& -m_0^2\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\Phi^\dagger\Phi\right] - \lambda_1(\mathrm{Tr}\left[\Phi^\dagger\Phi\right])^2 - \lambda_2 \mathrm{Tr}\left[(\Phi^\dagger\Phi)^2\right] \\
& +\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)\left((L^\mu)^2 + (R^\mu)^2\right)\right] \\
& -\frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] + \mathrm{Tr}\left[H\left(\Phi^\dagger + \Phi\right)\right] \\
& +c_1[\det(\Phi) - \det(\Phi^\dagger)]^2 + \frac{h_1}{2}\mathrm{Tr}[\Phi^\dagger\Phi]\mathrm{Tr}[L_\mu L^\mu + R_\mu R^\mu] \\
& +h_2\mathrm{Tr}[\Phi^\dagger L_\mu L^\mu \Phi + \Phi R_\mu R^\mu \Phi^\dagger] + 2h_3 \mathrm{Tr}[\Phi R_\mu \Phi^\dagger L^\mu]
\end{aligned}
$$

$$
\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\
a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\
K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S + i\eta_S
\end{pmatrix}
$$

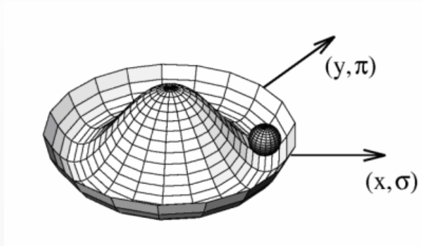
$$
L^\mu, R^\mu = \frac{1}{\sqrt{2}}\begin{pmatrix}
\frac{\omega_N \pm \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \pm a_1^0}{\sqrt{2}} & \rho^+ \pm a_1^+ & K^{\star +} \pm K_1^+ \\
\rho^- \pm a_1^- & \frac{\omega_N \mp \rho^0}{\sqrt{2}} \pm \frac{f_{1N} \mp a_1^0}{\sqrt{2}} & K^{\star 0} \pm K_1^0 \\
K^{\star -} \pm K_1^- & \bar{K}^{\star 0} \pm i\bar{K}_1^0 & \omega_S \pm f_{1S}
\end{pmatrix}
$$

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**)
D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011**
W. I. Eshraim, F.G., D.H. Rischke, arXiv: 1405.5861

Technical remarks

The dilaton field condense: <G> = G0

SSB implies:



$$\sigma_N \to \sigma_N + \phi_N \quad , \quad \sigma_S \to \sigma_S + \phi_S$$

Explicit symmetry breaking terms:

$$H = diag\{h_1, h_2, h_3\} \text{ with } h_i \propto m_i \qquad m_\pi^2 \propto (m_u + m_d)\langle \bar{q}q \rangle$$

$$\delta = diag\{\delta_1, \delta_2, \delta_3\} \text{ with } \delta_i \propto m_i^2$$

Parameter c: axial anomaly and eta-prime mass

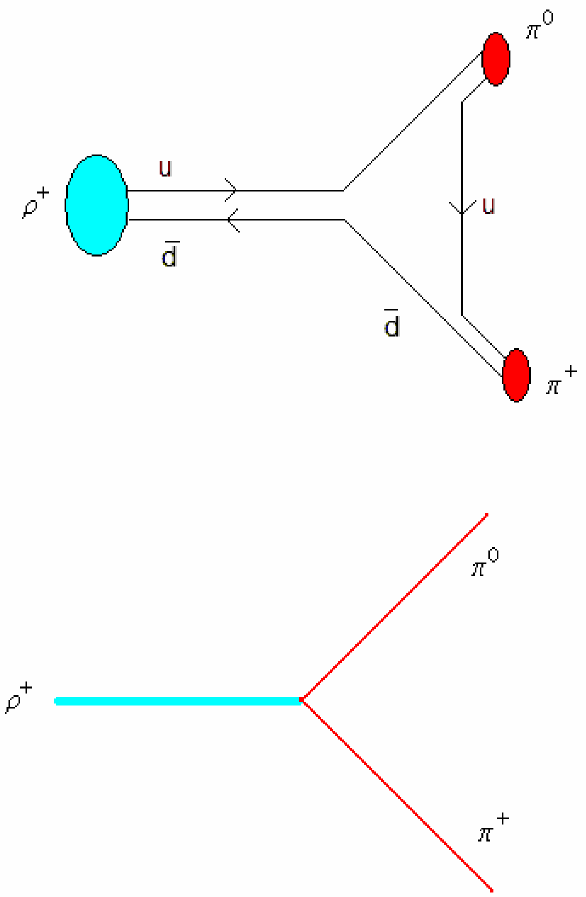
But: only a finite number of terms is allowed!

We can calculate: masses, decays, and scattering lengths.

Example: ρ-meson decay into pions

Microscopic view

eLSM



Results of the fit/1 (11 parameters, 21 exp. quantities)

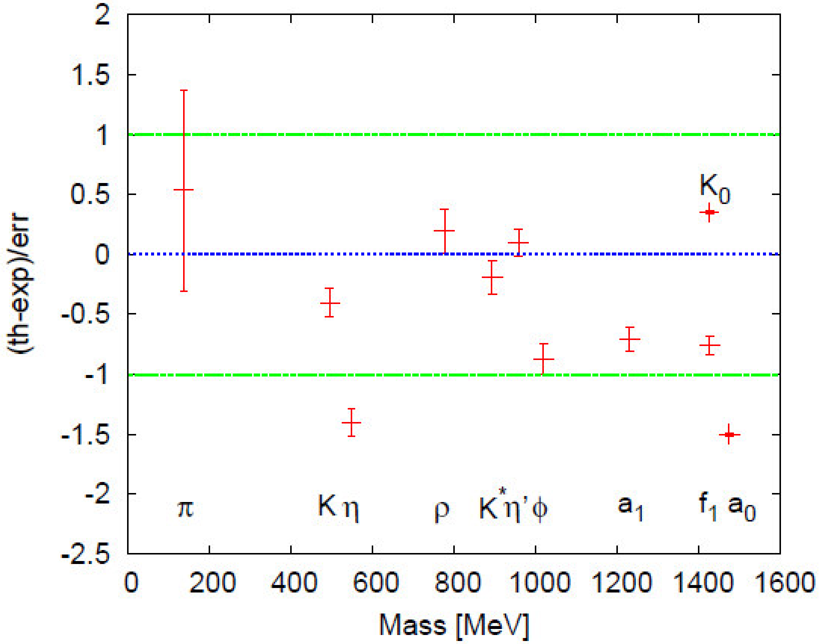
Error from PDG or 5% of exp.
Scalar-isoscalar sector not included.

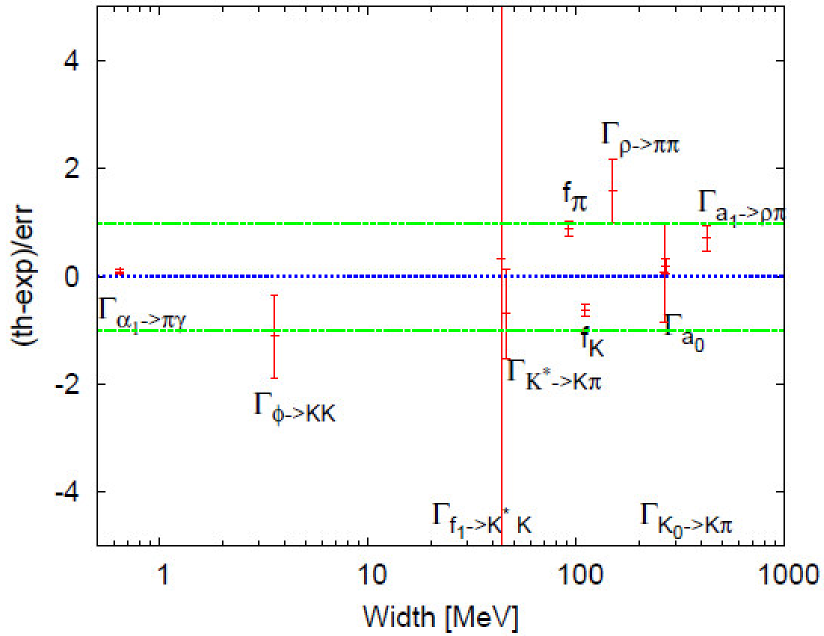
$$\chi^2_{red} = 1.2$$

Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 51.0
m_{a_1}	1186 ± 6	1230 ± 62
$m_{f_1(1420)}$	1372.5 ± 5.3	1426.4 ± 71.3
m_{a_0}	1363 ± 1	1474 ± 74
$m_{K_0^\star}$	1450 ± 1	1425 ± 71
$\Gamma_{\rho\to\pi\pi}$	160.9 ± 4.4	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.6 ± 1.9	46.2 ± 2.3
$\Gamma_{\phi\to\bar{K}K}$	3.34 ± 0.14	3.54 ± 0.18
$\Gamma_{a_1\to\rho\pi}$	549 ± 43	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.66 ± 0.01	0.64 ± 0.25
$\Gamma_{f_1(1420)\to K^\star K}$	44.6 ± 39.9	43.9 ± 2.2
Γ_{a_0}	266 ± 12	265 ± 13
$\Gamma_{K_0^\star\to K\pi}$	285 ± 12	270 ± 80

arXiv:1208.0585

Results of the fit/2 (11 parameters, 21 exp. quantities)





arXiv:1208.0585

Overall phenomenology is good (many more quantities can be calculated)

Scalar mesons $a_0(1450)$ and $K_0(1430)$ above 1 GeV and are quark-antiquark states.

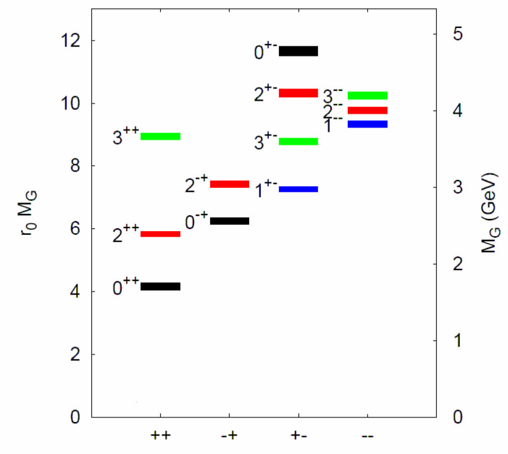
Importance of the (axial-)vector mesons.

Large-Nc: except from G, all states scale as quark-antiquark states.

The scalar glueball

The calculation 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

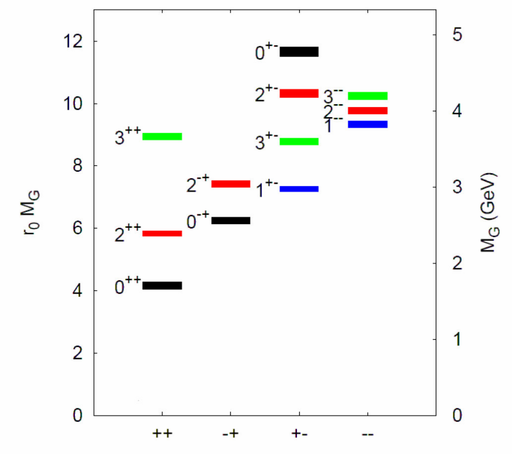
See also: L. -C. Gu et al, **Phys. Rev. Lett. 110 (2013) 021601** [arXiv:1206.0125 [hep-lat]]

The pseudoscalar glueball

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

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:

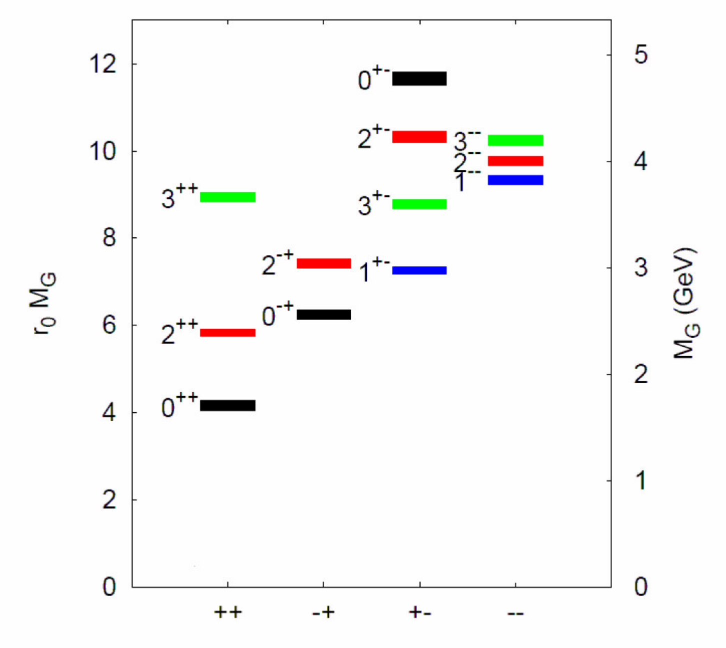
W. Eshraim, S. Janowski, F.G., D. Rischke, **Phys.Rev. D87 (2013) 054036. arxiv: 1208.6474** .

W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

Other glueballs

Calculation of branching ratios for the other glueball states.

Ongoing studies: **vector**, tensor, and pseudotensor glueballs.



The light scalar mesons

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

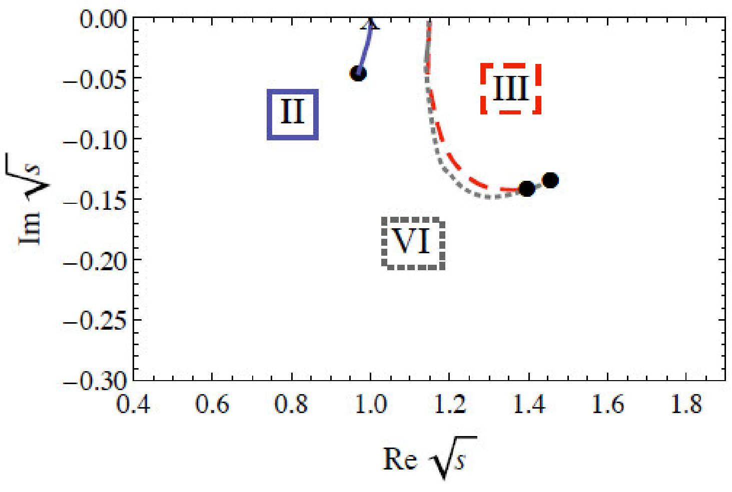
$$J^{PC} = 0^{++}$$

We saw that they are not quark-antiquark states:
(in our approach this is achieved by exclusion,
but this result is common to many others in low-energy QCD)!!!

The resonance $a_0(980)$ as a companion pole
(a very peculiar type of molecular state)

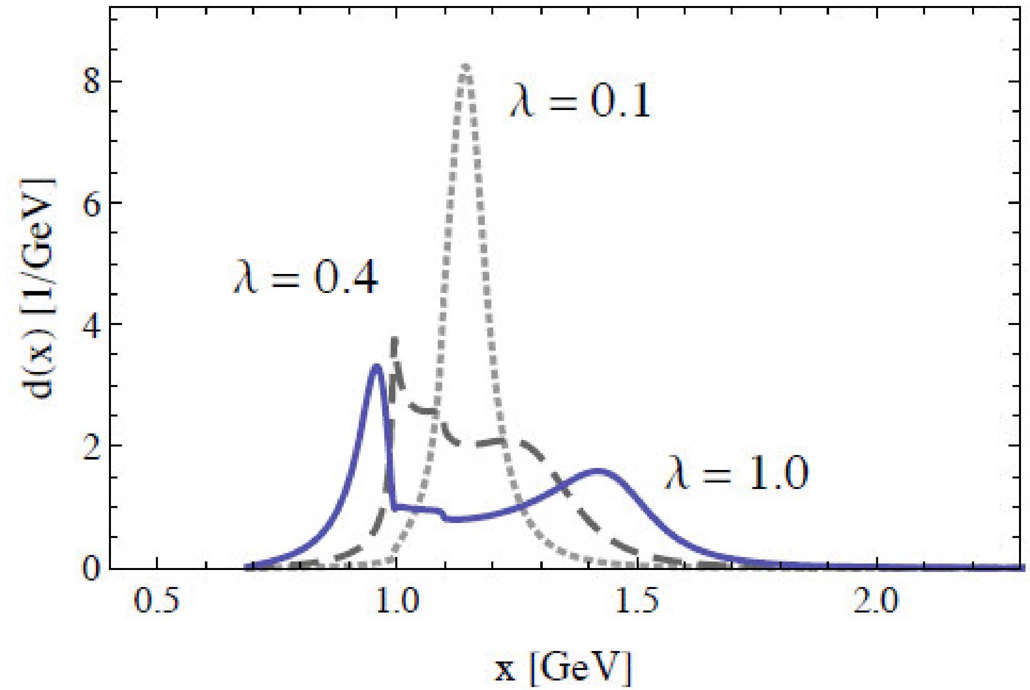
$$\mathcal{L}_{a_0\eta\pi} = A_1 a_0^0 \eta\pi^0 + B_1 a_0^0 \partial_\mu\eta\partial^\mu\pi^0 \ ,$$
$$\mathcal{L}_{a_0\eta'\pi} = A_2 a_0^0 \eta'\pi^0 + B_2 a_0^0 \partial_\mu\eta'\partial^\mu\pi^0 \ ,$$
$$\mathcal{L}_{a_0K\bar{K}} = A_3 a_0^0 (K^0\bar{K}^0 - K^-K^+) + B_3 a_0^0 (\partial_\mu K^0\partial^\mu\bar{K}^0 - \partial_\mu K^-\partial^\mu K^+)$$

Here: $a_0 = a_0(1450)$ is the unique seed state



Spectral function of the a_0 sector

…but there are two states in the spectrum



In preparation:

The $a_0(980)$ revisited

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

[a]*Institut für Theoretische Physik, Goethe-Universität Frankfurt am Main, 60438 Frankfurt am Main, Germany*
[b]*Institute of Physics, Jan Kochanowski University, 25406 Kielce, Poland*

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.

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,…)

It has a long, problematic and interesting history. (Definitely not an easy childhood).

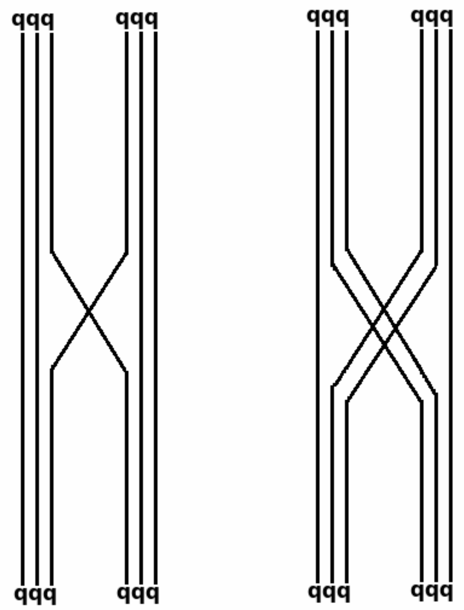
$f_0(500)$

The σ-field of the eLSM corresponds to the resonance $f_0(1370)$
…and not to the lightest scalar resonance $f_0(500)$.

$f_0(500)$ is a four-quark state.
Pion-loops and, eventually, a diquark-antidiquark
Contribute to this structure.

Interaction between nuclei naturally emerges.

The scalar attraction is often modelled through
an exchange of $f_0(500)$.



Nuclear matter binding

Related amusing and philosophical question:

does nuclear matter bind at large Nc?

As soon as the lightest scalar f0(500) is not a quarkonium, nuclear matter ceases to exist already for Nc=4.

Luca Bonanno and F.G., **Nucl.Phys.A859:49-62,2011**. **arXiv:1102.3367** [hep-ph]

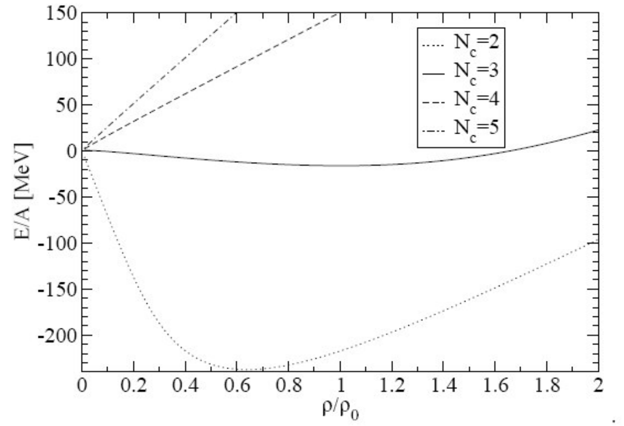


Figure 5: Binding energy per nucleon as a function of baryon density for the case in which the light quark-antiquark σ meson is replaced by a tetraquark state. In this case it is clear that nuclear matter is unbound already for $N_c = 4$.

Discussion on heavy non-quarkonium mesons

X,Y states

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$\chi_{c1}\gamma$	Belle 2013
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^+\pi^-\pi^0$ $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$ $J/\psi\,\gamma$, $\psi(2S)\,\gamma$	Belle 2003
$X(3915)$	3917.5 ± 1.9	20 ± 5	0^{++}	$J/\psi\,\omega$, $(\gamma\gamma)$	Belle 2004
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$D\bar{D}$, $(\gamma\gamma)$	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D^*\bar{D}$, $D\bar{D}^*$	Belle 2007
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$D\bar{D}$, (e^+e^-)	*BABAR* 2007
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$J/\psi\,\pi^+\pi^-$, (e^+e^-)	Belle 2007
$Y(4140)$	4144.5 ± 2.6	$15^{+11}_{-\ 7}$	$?^{?+}$	$J/\psi\,\phi$	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D^*\bar{D}^*$	Belle 2007
$Y(4220)$	4216 ± 7	39 ± 17	1^{--}	$h_c(1P)\,\pi^+\pi^-$, (e^+e^-)	BESIII 2013
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^0\pi^0$ $Z_c(3900)\,\pi$, (e^+e^-)	*BABAR* 2005
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$J/\psi\,\phi$	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$J/\psi\,\phi$, $(\gamma\gamma)$	Belle 2009
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$\psi(2S)\,\pi^+\pi^-$, (e^+e^-)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$, (e^+e^-)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\psi(2S)\,\pi^+\pi^-$, (e^+e^-)	Belle 2007

Models with: tetraquarks and molecular interpretations.

Quarkonium at the Frontiers of High Energy Physics: A Snowmass White Paper

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[6] *Carnegie-Mellon University, Pittsburgh, PA 15213, USA*

(Dated: August 15, 2013)

Abstract

In this Snowmass White Paper, we discuss physics opportunities involving heavy quarkonia at the intensity and energy frontiers of high energy physics. We focus primarily on two specific aspects of quarkonium physics for which significant advances can be expected from experiments at both frontiers. The first aspect is the spectroscopy of charmonium and bottomonium states above the open-heavy-flavor thresholds. Experiments at e^+e^- colliders and at hadron colliders have discovered many new, unexpected quarkonium states in the last 10 years. Many of these states are surprisingly narrow, and some have electric charge. The observations of these charged quarkonium states are the first definitive discoveries of manifestly exotic hadrons. These results challenge our understanding of the QCD spectrum. The second aspect is the production of heavy quarkonium states with large transverse momentum. Experiments at the LHC are measuring quarkonium production with high statistics at unprecedented values of p_T. Recent theoretical developments may provide a rigorous theoretical framework for inclusive production of quarkonia at large p_T. Experiments at the energy frontier will provide definitive tests of this framework. Experiments at the intensity frontier also provide an opportunity to understand the exclusive production of quarkonium states.

…but alslo quantum loops are important: some of the newly discovered states can emerge upon meson-meson dressing.

Example: X(3872).

One expects a charnomium with the same quantum number (1^++) with a mass of about 4 GeV. Then, opn loops, X(3872) can arise as a companion pole (just as a0(980) in the light sector.

Recent and ongoing work in this direction.

See for intance Coito et al, **Eur.Phys.J. C73 (2013) 3, 2351**

Z states

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1^{st} 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

Z(4430)

Uniwersytet Jana Kochanowskiego w Kielcach

Observation of the Resonant Character of the Z(4430)– State
R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **112**, 222002 – Published 4 June 2014

CERN-PH-EP-2014-061
LHCb-PAPER-2014-014
7 April 2014

arXiv:1404.1903v1 [hep-ex] 7 Apr 2014

Observation of the resonant character of the $Z(4430)^-$ state

The LHCb collaboration†

Abstract

Resonant structures in $B^0 \to \psi' \pi^- K^+$ decays are analyzed by performing a four-dimensional fit of the decay amplitude, using pp collision data corresponding to 3 fb^{-1} collected with the LHCb detector. The data cannot be described with $K^+\pi^-$ resonances alone, which is confirmed with a model-independent approach. A highly significant $Z(4430)^- \to \psi'\pi^-$ component is required, thus confirming the existence of this state. The observed evolution of the $Z(4430)^-$ amplitude with the $\psi'\pi^-$ mass establishes the resonant nature of this particle. The mass and width measurements are substantially improved. The spin-parity is determined unambiguously to be 1^+.

Z(4430) and a new paradigm for spin interactions in tetraquarks
L. Maiani, F. Piccinini, A.D. Polosa, and V. Riquer
Phys. Rev. D **89**, 114010 – Published 6 June 2014

Born-Oppenheimer approximation for the XYZ mesons
Eric Braaten, Christian Langmack, and D. Hudson Smith
Phys. Rev. D **90**, 014044 – Published 24 July 2014

Tetraquark vs Molecule for Z(4430)

"We hate each other," said Antonio Polosa,
a theorist at Sapienza University of Rome
who takes the latter stance, chuckling about the rival factions.
"We really hate each other."

AUTHOR: NATALIE WOLCHOVER, QUANTA MAGAZINE.NATALIE WOLCHOVER, QUANTA MAGAZINE SCIENCE
DATE OF PUBLICATION: 09.09.14.09.09.14
TIME OF PUBLICATION: 6:30 AM.6:30 AM
NEWLY DISCOVERED 'TETRAQUARK' FUELS QUANTUM FEUD

http://www.wired.com/2014/09/tetraquark-quantum-feud/

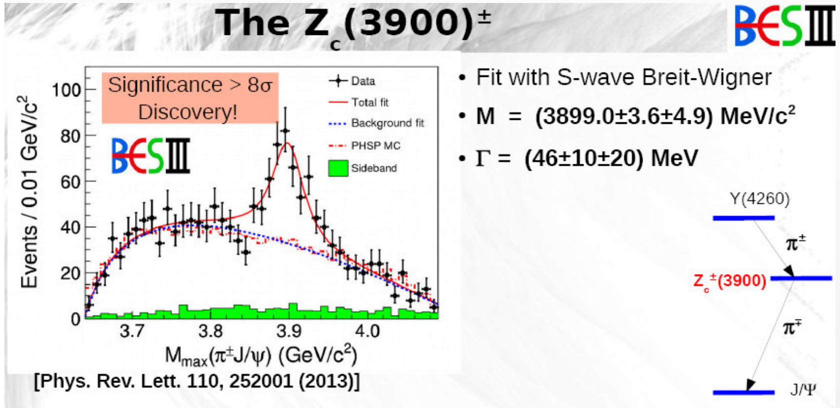
Z(3900)

Observation of a Charged Charmoniumlike Structure in e+e−→π+π−J/ψ at s√=4.26 GeV
M. Ablikim *et al.*
Phys. Rev. Lett. **110**, 252001 – Published 17 June 2013

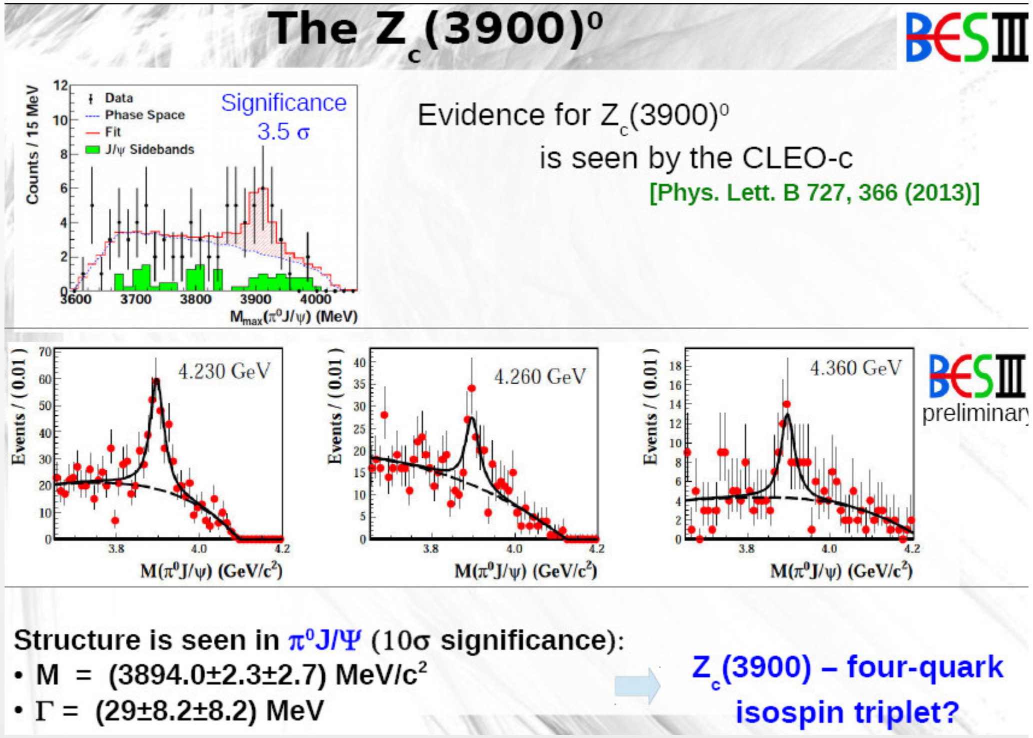
Study of e+e−→π+π−J/ψ and Observation of a Charged Charmoniumlike State at Belle
Z. Q. Liu *et al.*
Phys. Rev. Lett. **110**, 252002 – Published 17 June 2013

What a new jumbo particle reveals about extreme matter
Updated 15:50 24 June 2013 by **Lisa Grossman**
For similar stories, visit the **Cosmology** and **Quantum World** Topic Guides
We're used to scientists making ever bigger atoms. Now it seems subatomic particles can be pushed to similar extremes to create new forms of matter.
Researchers at two particle detectors reported on Monday the strongest evidence yet for a particle made of more than three quarks, the subatomic building blocks of matter.
What does that mean for understanding of matter – and why does that matter? New Scientist investigates

The neutral Z(3900) at BES



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

Summary

QCD: well defined part of the Standard Model

…still: many theoretically expected resonances have not been found
while many have been observed, but we do not know what they are.

Glueballs: still missing!. The state $f_0(1710)$ is a good candidate
for the scalar glueball. 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: Many ongoing experiments and future experiments to come.
Active theoretical activity (both from lattice and modelling).

Thank You

Spontaneous symmetry breaking at the meson level

$$\pi = \pi^0 \equiv \sqrt{1/2}(\bar{u}u - \bar{d}d) \quad \text{neutral pion}$$

$$\sigma \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$$

Chiral transformation: $\sigma \leftrightarrow \pi$

$$V = \frac{m_0^2}{2}\left(\sigma^2 + \pi^2\right) + \frac{\lambda}{4}\left(\sigma^2 + \pi^2\right)^2$$

$m_0^2 < 0 \quad \rightarrow$ Mexican hat

SSB: $\langle \sigma \rangle \propto \langle u\bar{u} + d\bar{d} \rangle \neq 0$