Development of a hadronic model: general considerations

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Objectives

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• Development of a chirally symmetric model for mesons and baryons including (axial-)vector d.o.f.

'Extended Linear Sigma Model (eLSM)'

• Study of the model for $T = \mu = 0$ (spectroscopy in vacuum)

(Masses, decay, scattering lengths,…)

Interrelation between these two aspects!

• Second goal: properties at nonzero T and μ

(condensates and masses in thermal/matter medium,…)

Fields of the model

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

- Additional mesons: The scalar and the pseudoscalar glueballs

- Baryons: nucleon doublet and its partner

  (in the so-called mirror assignment)

How to construct the eLSM

- Confinement: only hadrons.
- Dilatation invariance and its anomalous breaking
- Chiral symmetry $SU_R(N_f) \times SU_L(N_f) \times U_V(1)$ and its spontaneous as well as explicit breaking.
- Chiral anomaly

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Development of a hadronic model: mesons

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Confinement: from gluons to glueballs

$$m_{gluon} = 0 \rightarrow m^{*}_{gluon} \approx 500 - 800 \text{ MeV}$$

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

Confinement implies glueballs.

Where are they? We are still looking for them.

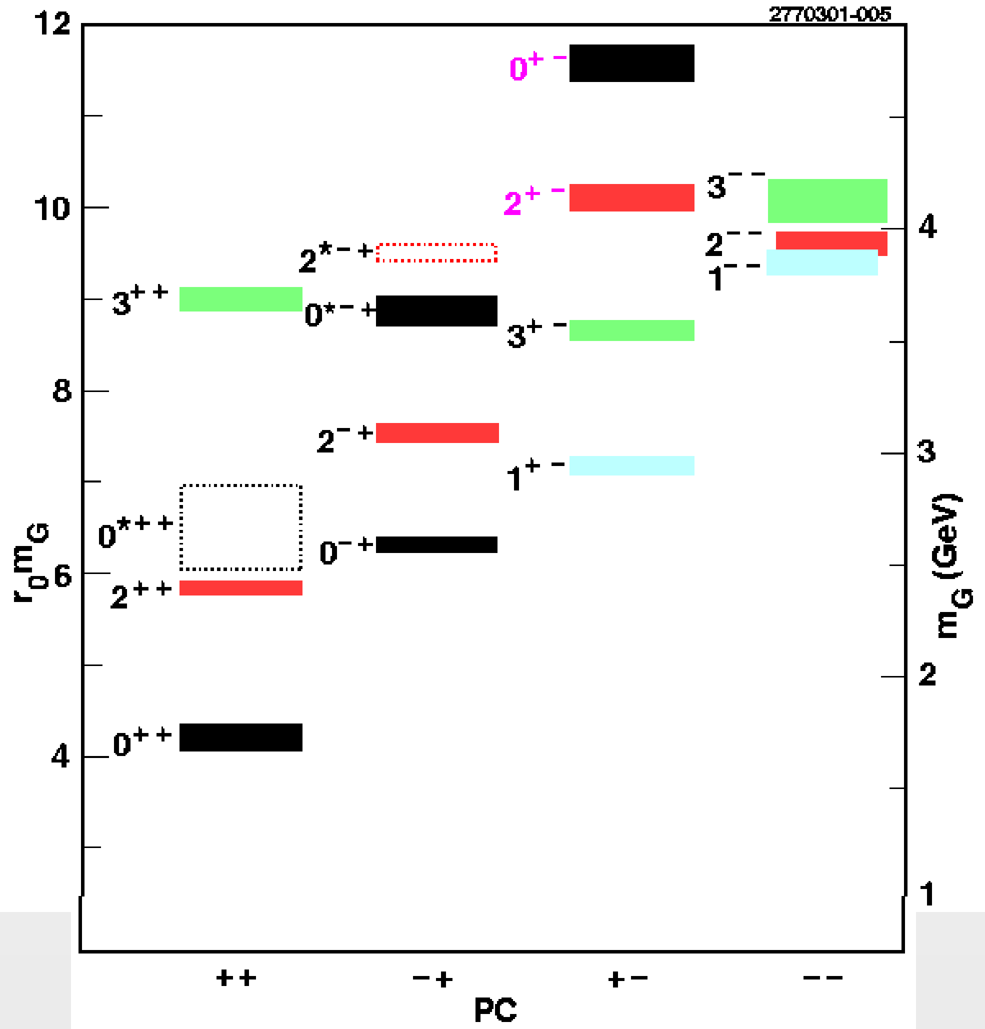
Glueballs from Lattice QCD

$$M_G = 1.6 - 1.8 \text{ GeV}$$

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

$$I = 0$$

lightest predicted glueball



Morningstar (1999)

The lightest glueball is part of an effective Lagrangian which reproduces at a composite level the breaking of dilatation invariance.

Development of a dilaton potential.

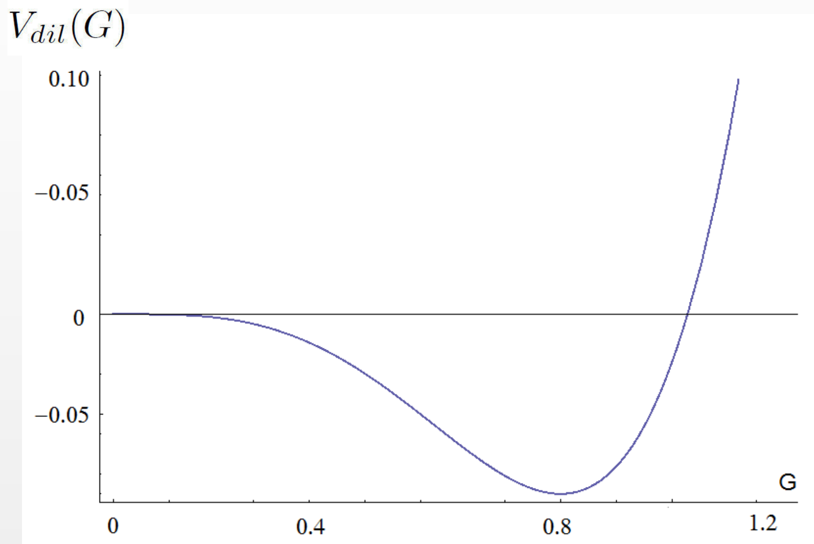
Dilaton / Scalar glueball

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!

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

In QCD it is:

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

Dilaton / Scalar glueball (2)

Where is the glueball G in the PDG ???

(Too many) candidates, most notably: $f_0(1500)$ and $f_0(1710)$

Quark-Antiquark mesons

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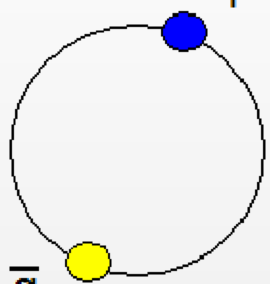
Quark: u,d,s R,G,B

Quark-antiquark bound states: conventional mesons



$$\left| color \right\rangle = \sqrt{1/3}\,(\bar{R}R + \bar{B}B + \bar{G}G)$$

$$\vec{L}, \vec{S} \Longrightarrow P = -(-1)^{L} \quad C = (-1)^{L+S}$$

$$\vec{L}, \vec{S} \Longrightarrow \vec{J} = \vec{L} + \vec{S} \qquad J^{PC}$$

(Pseudo)scalar sector

9 pseudoscalar fields: $L = S = 0 \Rightarrow J^{PC} = 0^{-+}$

$$P = P_a \lambda^a = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_N}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_N}{\sqrt{2}} & K^0 \\ K^- & \overline{K}^0 & \eta_S \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix} \qquad \Gamma = i\gamma^5$$

$$\pi^+ \equiv u\bar{d}$$

$$K^+ \equiv u\bar{s}$$

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_\eta & \sin\theta_\eta \\ -\sin\theta_\eta & \cos\theta_\eta \end{pmatrix} \begin{pmatrix} \eta_N \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \\ \eta_S \equiv \bar{s}s \end{pmatrix}$$

$$-36^\circ < \theta_\eta < -45^\circ$$

…and 9 scalar fields: $L = S = 1 \rightarrow J^{PC} = 0^{++}$

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$$S = S_a \lambda^a = \begin{pmatrix} \frac{a_0^0}{\sqrt{2}} + \frac{\sigma_N}{\sqrt{2}} & a_0^+ & K_S^+ \\ a_0^- & -\frac{a_0^0}{\sqrt{2}} + \frac{\sigma_N}{\sqrt{2}} & K_S^0 \\ K_S^- & \bar{K}_S^0 & \sigma_S \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix} \qquad \Gamma = 1$$

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

$K_S^+ = K_0^{*+}(1430) \equiv u\bar{s}$ and not k(700)!!!

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

and not $f_0(500)$!!!

$\sigma_S \equiv u\bar{s} \approx f_0(1500)$ or $f_0(1710)$

and not $f_0(980)$!!!

Chiral transformation of (pseudo)scalar mesons

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

$$\Phi = S + iP$$

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

$$\boxed{\Phi \rightarrow U_L \Phi U_R^+}$$

Example of an invariant term

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

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

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

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

(Axial-)Vector sector

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9 vector fields… $L = 0, S = 1 \rightarrow J^{PC} = 1^{--}$

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

$$\rho^{+} \equiv u\bar{d} \qquad \omega \approx \omega_N \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d)$$

$$K_{*}^{+}(892) \equiv u\bar{s} \qquad \phi \approx \phi_S \equiv \bar{s}s$$

…and 9 axial-vector fields… $L = S = 1 \rightarrow J^{PC} = 1^{++}$

$$A^{\mu} = A^{\mu}{}_{a}\lambda^{a} = \begin{pmatrix} \frac{a_1^0}{\sqrt{2}} + \frac{f_{1,N}}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & -\frac{a_1^0}{\sqrt{2}} + \frac{\omega_N}{\sqrt{2}} & K_1^0 \\ K_1^- & \bar{K}_1^0 & f_{1,S} \end{pmatrix} \equiv \begin{pmatrix} \bar{u}\Gamma u & \bar{d}\Gamma u & \bar{s}\Gamma u \\ \bar{u}\Gamma d & \bar{d}\Gamma d & \bar{s}\Gamma d \\ \bar{u}\Gamma s & \bar{d}\Gamma s & \bar{s}\Gamma s \end{pmatrix} \qquad \Gamma = \gamma^{\mu}\gamma^{5}$$

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

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

$$f_1\,(1285) \approx f_{1,N} \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d)$$

$$f_1\,(1510) \approx f_{1,S} \equiv \bar{s}s$$

…where A and V are coupled in the following way:

$$L^{\mu} = V^{\mu} + A^{\mu}$$

$$R^{\mu} = V^{\mu} - A^{\mu}$$

which under chiral transformations transform as

$$\boxed{\begin{gathered} R^{\mu} \rightarrow U_R R^{\mu} U_R^{+} \\ L^{\mu} \rightarrow U_L L^{\mu} U_L^{+} \end{gathered}}$$

Examples of further invariant objects:

$$G^2 Tr\left[L_\mu^+ L_\mu + R_\mu^+ R_\mu\right]$$

$$Tr\left[\Phi R_\mu \Phi^+ L_\mu\right]$$

$$\ldots$$

Meson sector: how many fields do we have?

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$4N_f^2 + 2$ fields

For $N_f = 3$ there are 38 mesons

36 quark-antiquark fields + 2 glueballs

Criteria (repetita juvant!)

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

dilatation symmetry

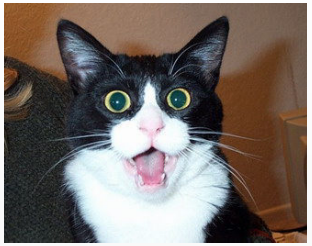
and

chiral invariance.

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

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

Model of QCD – eLSM with scalar Glueball



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

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

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

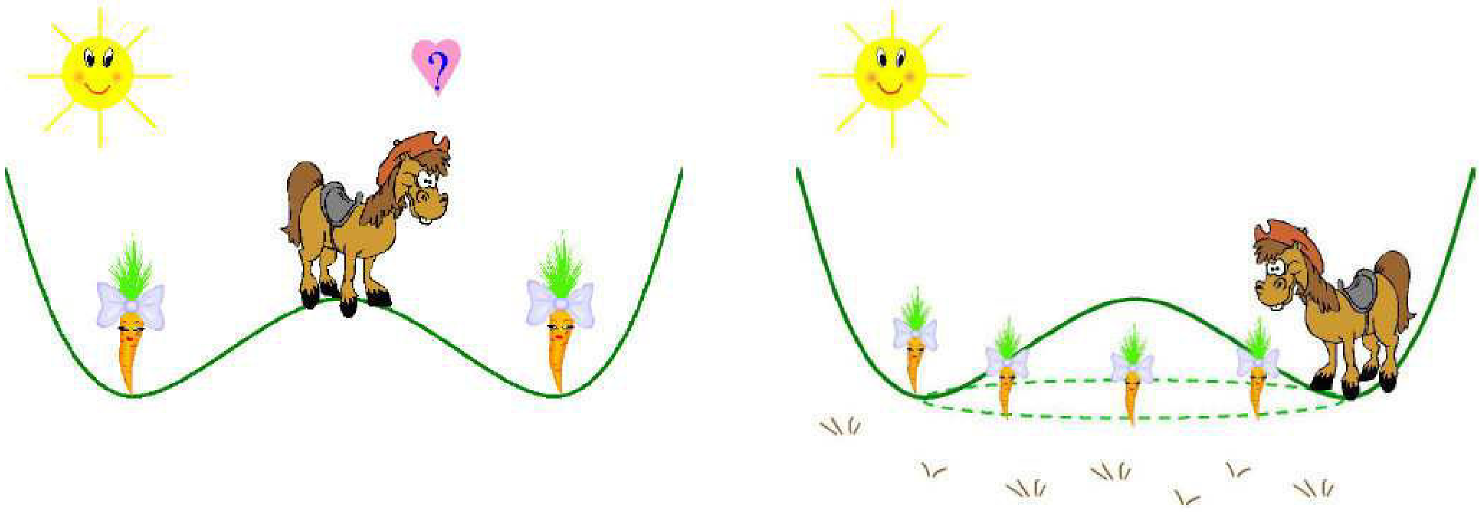
S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011)**

D. Parganlija, P. Kovacs, G. Wolf , F. Giacosa, D. H. Rischke, **Phys.Rev. D87 (2013) 014011 arXiv:1208.0585**

The donkey of Buridan

Jean Buridan (in Latin, *Johannes Buridanus*) (ca. 1300 – after 1358)

Spontaneous Symmetry Breaking



Although Nicolás likes the symmetric food configuration, he must break the symmetry deciding which carrot is more appealing. In three dimensions, there is a continuous valley where Nicolás can move from one carrot to the next without effort.

Technical remarks

Perform Spontaneous Symmetry Breaking (SSB):

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

Explicit symmetry breaking terms:

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

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

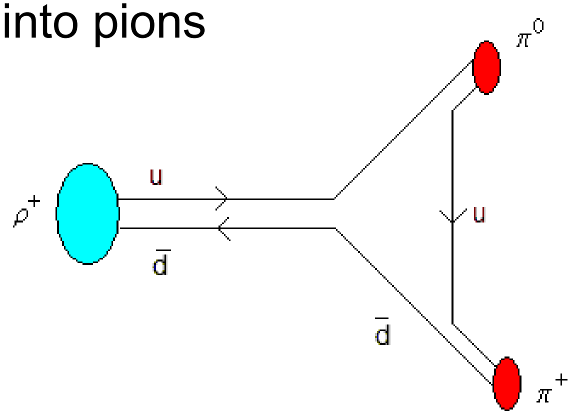
Parameter c: axial anomaly and eta-prime mass

But: only a finite number of terms is allowed!

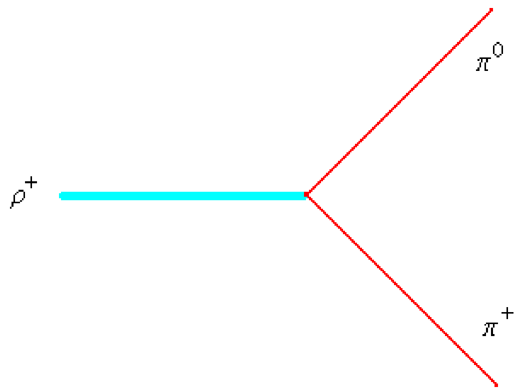
We can calculate: masses, decays, and scattering lengths.

Example: ρ-meson decay into pions

Microscopic



eLSM



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

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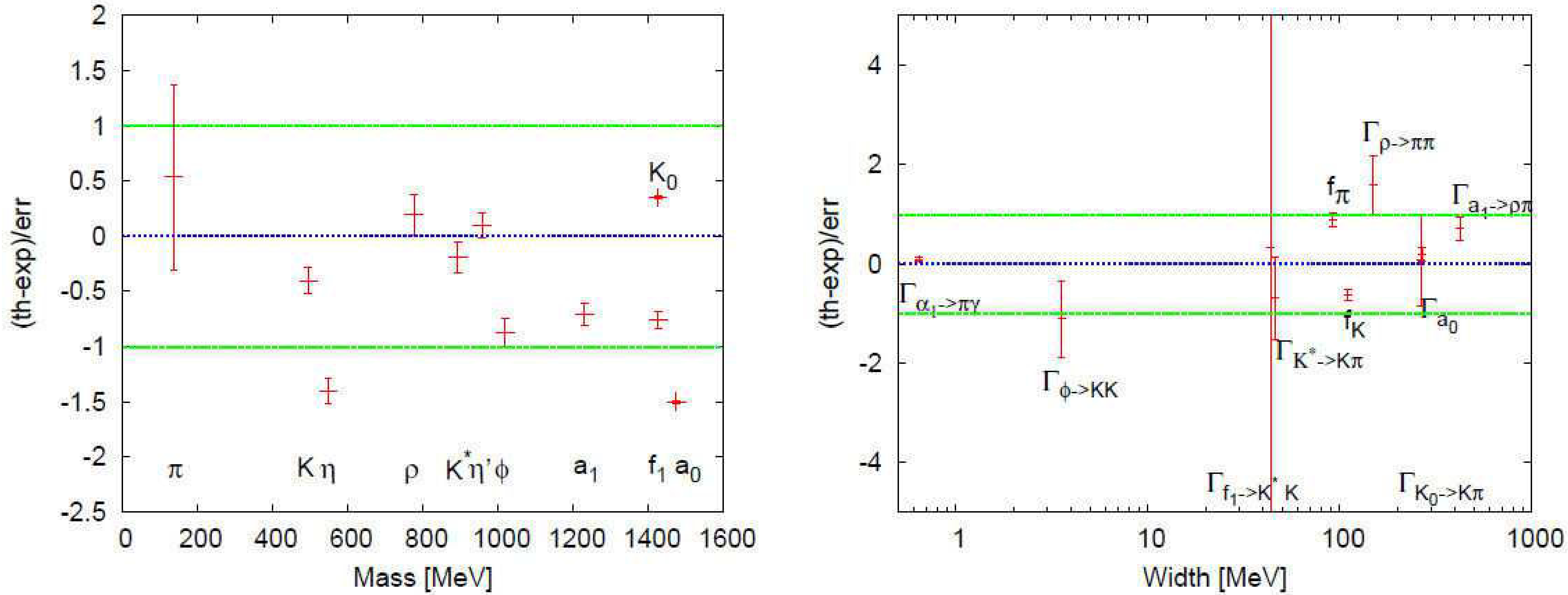
Observable	Fit [MeV]	Experiment [MeV]
f_π	96.3 ± 0.7	92.2 ± 4.6
f_K	106.9 ± 0.6	110.4 ± 5.5
m_π	141.0 ± 5.8	137.3 ± 6.9
m_K	485.6 ± 3.0	495.6 ± 24.8
m_η	509.4 ± 3.0	547.9 ± 27.4
$m_{\eta'}$	962.5 ± 5.6	957.8 ± 47.9
m_ρ	783.1 ± 7.0	775.5 ± 38.8
$m_{K^\star}$	885.1 ± 6.3	893.8 ± 44.7
m_ϕ	975.1 ± 6.4	1019.5 ± 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

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

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

arXiv:1208.0585

Results of the fit: pictorial representation



arXiv:1208.0585

Overall phenomenology is good.

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

Importance of the (axial-)vector mesons

Consequences/1: $a_0(1450)$

Theory

$$\frac{\Gamma_{a_0\to\eta'\pi}}{\Gamma_{a_0\to\eta\pi}} = 0.19 \pm 0.02\ , \quad \frac{\Gamma_{a_0\to KK}}{\Gamma_{a_0\to\eta\pi}} = 1.12 \pm 0.07$$

Exp (PDG)

$$\frac{\Gamma_{a_0(1450)\to\eta'\pi}}{\Gamma_{a_0(1450)\to\eta\pi}} = 0.35 \pm 0.16\ , \quad \frac{\Gamma_{a_0(1450)\to KK}}{\Gamma_{a_0(1450)\to\eta\pi}} = 0.88 \pm 0.23\ .$$

Consequences/2: pseudoscalar mixing angle

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_\eta & \sin\theta_\eta \\ -\sin\theta_\eta & \cos\theta_\eta \end{pmatrix} \begin{pmatrix} \eta_N \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \\ \eta_S = \bar{s}s \end{pmatrix}_S$$

Theory $\theta_\eta = -44^\circ$

Exp (KLOE) $\theta_\eta \cong -41^\circ$

Consequences/3: ρ-mass

$$m_\rho^2 = m_1^2 + \frac{1}{2}(h_1 + h_2 + h_3)\phi_N^2 + \frac{h_1}{2}\phi_S^2$$

$$m_1^2 \propto G_0^2 \qquad m_1 = 0.643 \text{ GeV}$$

$$\sqrt{(h_2 + h_3)/2}\phi_N = 0.447 \text{ GeV}$$

Thus, the ρ-mass emerges from the interplay of both the chiral and gluon condensates!

Consequences/4: scalar-isoscalar quarkonia

$$\sigma \equiv \sigma_N \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \qquad \sigma_S = \bar{s}s$$

Theory $m_{\sigma_N} = 1360 \text{ MeV} \qquad \mathrm{m}_{\sigma_S} = 1530 \text{ MeV}$

Exp (PDG)

$$m_{f_0(1370)} = 1350 \pm 150 \text{ MeV} \quad m_{f_0(1500)} = 1505 \pm 6 \text{ MeV} \quad m_{f_0(1710)} = 1720 \pm 6 \text{ MeV}$$

It then follows: the chiral partner of the pion is (predominantly) $f_0(1370)$ and not $f_0(500)$

The scalars below 1 GeV ($f_0(500)$, k(700), $f_0(980)$, $a_0(980)$) are not quarkonia. Possibility: tetraquarks.
(F. G. **Phys.Rev. D75 (2007) 054007,** hep-ph/0611388. **)**

An important ongoing work:

The calculation of the full mixing problem in the I=J=0 sector is ongoing:

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = B \begin{pmatrix} \sigma_N \equiv \bar{n}n = \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \\ G \equiv gg \\ \sigma_S \equiv \bar{s}s \end{pmatrix}$$

where B is a 3×3 orthogonal matrix

Our result within the Nf=2 case was:

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{pmatrix} = \begin{pmatrix} \sqrt{0.76} & \sqrt{0.24} & 0 \\ -\sqrt{0.24} & \sqrt{0.76} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_N \equiv \bar{n}n \\ G \equiv gg \\ \sigma_S \equiv \bar{s}s \end{pmatrix}$$

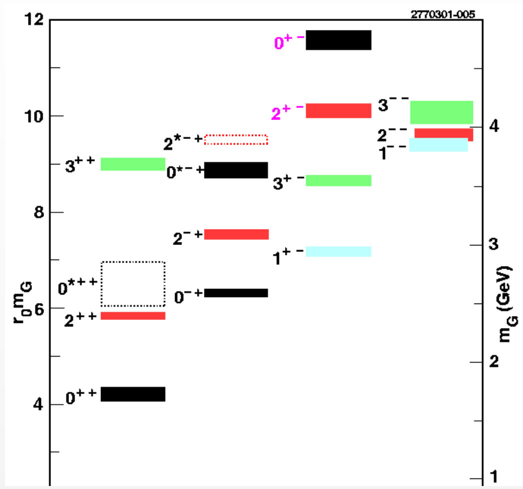
Details in S. Janowski, D. Parganlija, F.G., D. Rischke, **Phys.Rev. D84 (2011) 054007, arXiv:1103.3238**

A new entry: 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



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

PANDA/FAIR will be able to scan the energy above 2.5 GeV

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**