Phenomenology of light mesons within a chiral approach

Francesco Giacosa

In collaboration with

Denis Parganlija, Stanislaus Janowski,

Achim Heinz, Anja Habersetzer, and Dirk Rischke

J. W. Goethe University, Frankfurt am Main

Talk prepared for Meson2012, 4 June 2012, Krakow (Poland)

Motivation

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

- Study of the model for T = μ =0 (spectroscopy in vacuum)

  (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:

- Quark-antiquark mesons: scalar, pseudoscalar, vector and axial-vector quarkonia.
- Additional meson: The scalar glueball
- Baryons: nucleon doublet and its partner

(in the so-called mirror assignment)

How to construct the model:

- Chiral symmetry: $SU_R(N_f) x SU_L(N_f) x U_V(1)$
- Retain operators of fourth order (dilatation invariance)

Counting and listing the fields

$4N_f^2+1$ fields

where Nf is the number of flavors

For $N_f = 2$ there are 17 mesons

16 quark-antiquark fields + 1 Glueball

For $N_f = 3$ there are 37 mesons

36 quark-antiquark fields + 1 Glueball

(Pseudo)scalar sector (Nf = 3): 18 quark-antiquark fields

$$\Phi = S + iP$$

9 pseudoscalar fields

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

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

9 scalar fields

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

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

$$S_{ij} = \overline{q}_j q_i$$

First Problem: which resonances correspond to the scalar mesons?

a_0 is $a_0(980)$ or $a_0(1450)$??? K_S is $K_0^*(800)$ or $K_0^*(1420)$???

Reminder: PDG Data on $J^{PC} = 0^{++}$ isoscalar mesons

$\bar{n}n \propto \bar{u}u + \bar{d}d \quad \bar{s}s$

Five states up to 1.8 GeV (isoscalars)

State	Mass [MeV]	Width [MeV]
$f_0(600)$	400 - 1200	600 - 1000
$f_0(980)$	980 ± 10	40 - 100
$f_0(1370)$	1200 - 1500	200 - 500
$f_0(1500)$	1505 ± 6	109 ± 7
$f_0(1710)$	1720 ± 6	135 ± 8

$\bar{q}\bar{q}qq$ **Glueball** **meson - meson boundstate**

Chiral transformation

$$q = q_R + q_L \rightarrow U_R q_R + U_L q_L \qquad U_R,\ U_L \subset SU(3)$$

$$\Phi = S + iP$$

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

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

(Axial-)Vector sector: 9 vector fields…

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

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

…and 9 axial-vector fields…

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

$$\Gamma = \gamma^{\mu}\gamma^{5} \rightarrow J^{PC} = 1^{++}$$

$f_{1,N}$ (in PDG: $f_1(1285)$)

a_1 (in PDG: $a_1(1260)$)

$f_{1,S}$ (in PDG: $f_1(1420)$)

K_1^+ (in PDG: $K_1(1270)$)

…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 transformation transform as

$$R^{\mu} \rightarrow U_R R^{\mu} U_R^{+}$$

$$L^{\mu} \rightarrow U_L L^{\mu} U_L^{+}$$

Dilaton

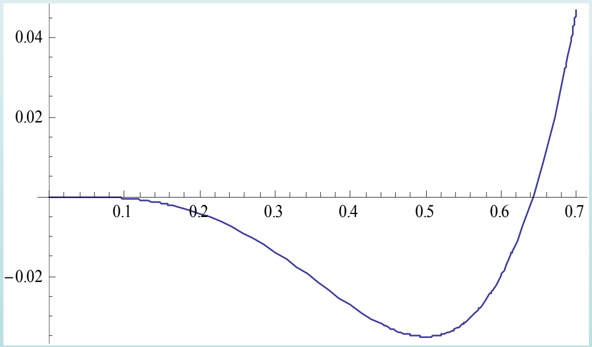
Yang-Mills Lagrangian: classically dilatation invariant

…this symmetry is broken at the quantum level…

At the hadronic level, we moke-up these properties with the following Lagrangian:

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

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



$$G \rightarrow G + \Lambda_G$$

Λ_G dimensionful param.-which breaks dilatation inv.- also in the chiral limit!

$$\langle T_\mu^\mu \rangle = \left\langle -\frac{1}{4}\frac{m_G^2}{\Lambda_G^2} G^4 \right\rangle = -\frac{1}{4}\frac{m_G^2}{\Lambda_G^2} G_0^4 \equiv -\left\langle \frac{11 N_c}{48}\frac{\alpha_s}{\pi} G_{\mu\nu}^a G^{a,\mu\nu} \right\rangle \, .$$

$$\Lambda_G^2 = \frac{11}{4m_G^2}\left\langle \frac{\alpha_s}{2} G_{\mu\nu}^a G^{a,\mu\nu} \right\rangle \simeq \frac{(0.25\text{-}0.8 \text{ GeV})^4}{m_G^2} = (0.23\text{-}0.7 \text{ GeV})^2 ,$$

Put all the ingredients together

We construct the mesonic Lagrangian accroding to

dilatation symmetry

and

chiral invariance.

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

Moreover, C and P are also taken into account.

Full Lagrangian in the meson sector

$$
\begin{aligned}
\mathcal{L} = {} & \mathcal{L}_{dil} + \mathrm{Tr}\left[\left(D^{\mu}\Phi\right)^{\dagger}\left(D_{\mu}\Phi\right) - m_0^2 \left(\frac{G}{G_0}\right)^2 \Phi^{\dagger}\Phi - \lambda_2 \left(\Phi^{\dagger}\Phi\right)^2 \right] - \lambda_1 \left(\mathrm{Tr}\left[\Phi^{\dagger}\Phi\right]\right)^2 \\
& - c\left(\det\Phi - \det\Phi^{\dagger}\right)^2 - \mathrm{Tr}[H(\Phi^{\dagger} + \Phi)] - \frac{1}{4}\mathrm{Tr}\left[(L^{\mu\nu})^2 + (R^{\mu\nu})^2\right] \\
& + \frac{m_1^2}{2}\left(\frac{G}{G_0}\right)^2 \mathrm{Tr}\left[(L^{\mu})^2 + (R^{\mu})^2\right] + \mathrm{Tr}\left[\delta(L^{\mu})^2 + \delta(R^{\mu})^2\right] \\
& + \frac{h_1}{2}\mathrm{Tr}\left[\Phi^{\dagger}\Phi\right]\mathrm{Tr}\left[(L^{\mu})^2 + (R^{\mu})^2\right] + h_2 \mathrm{Tr}\left[\Phi^{\dagger}(L^{\mu})^2\Phi + \Phi^{\dagger}(R^{\mu})^2\Phi\right] \\
& + h_3 \mathrm{Tr}\left[\Phi^{\dagger}L^{\mu}\Phi R_{\mu}\right] + \ldots
\end{aligned}
$$

$$
D_{\mu}\Phi = \partial_{\mu}\Phi - i g_1\left(L^{\mu}\Phi - \Phi R^{\mu}\right)
$$

In the chiral limit (H=0) two dimensional parameters:

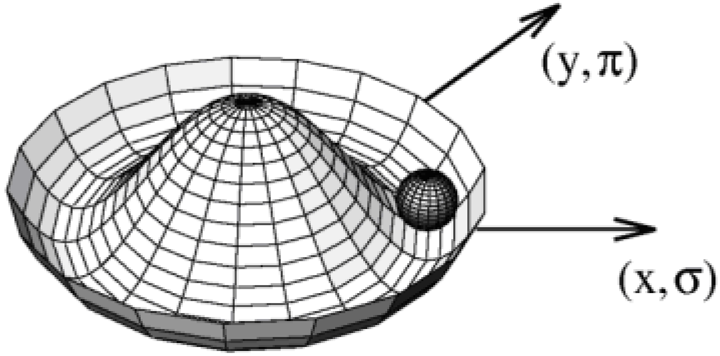
Λ_G (dilatation invariance) and c (anomaly). Both from the gauge sector.

Here the large Nc counting shows that all the state are quarkonia.
Only exception: the glueball. $(\Lambda \propto N_c, \lambda_2 \propto N_c^{-1}, \ldots)$

Details in: Denis Parganlija, F.G., Dirk H. Rischke, **Phys.Rev.D82:054024,2010**; **arXiv:1003.4934** [hep-ph].
S. Janwoski, D. Parganlija, F.G., D. Rischke, to appear in Phys. Rev. D, **arXiv:1103.3238** [hep-ph].

Basic features:

$$m_0^2 > 0 \rightarrow \text{Mexican hat}$$



Perform Spontaneous Symmetry Breaking (SSB):

$$\sigma_N \rightarrow \sigma_N + \phi_N \;,\; \sigma_S \rightarrow \sigma_S + \phi_S$$

$$H = diag\{h_1, h_2, h_3\} \text{ with } h_i \propto m_i^2$$

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

Parameter c: axial anomaly and eta-prime mass

What we did up to now in the meson sector and what we will be doing…

1) Nf = 2 with „frozen“ glueball ($m_G \mapsto \infty$): done !

2) Nf = 2 with active glueball ($m_G \approx 1.5 \text{ GeV}$): done!

3) Nf = 3 with „frozen“ glueball ($m_G \mapsto \infty$): ongoing (almost done!).

4) Nf = 3 with active glueball ($m_G \approx 1.5 \text{ GeV}$): ongoing.

5) Inclusion of weak bosons and tau decay: ongoing.

6) Generalization to Nf = 4: ongoing.

7) Tetraquark nonet: planned.

8) Study at nonzero temperature (with dilepton emission): planned.

Nf = 2 (with glueball)

Problem of scalars

$$\sigma \quad \text{is} \quad f_0(600) \quad \text{or} \quad f_0(1370) \quad ???$$

$$a_0 \quad \text{is} \quad a_0(980) \quad \text{or} \quad a_0(1450) \quad ???$$

This is an important issue. One shall do the correct assignment.

Many models use σ = $f_0(600)$ (Lσm, NJL). This has been the usual picture at nonzero temperature/density.

However, this assignment is found to be incorrect in many studies at zero temperature (Phenomenology, Large-N_c, Lattice) .

The quantitative effects of scalars both in the vacuum and in a medium are large!

Scenario I: $\sigma \cong f_0(600),\ a_0 \equiv a_0(980)\ ,\ \ G \cong f_0(1500),$

$M_\sigma \leq 550 \quad \text{MeV}$ from $\pi\pi$-scattering.

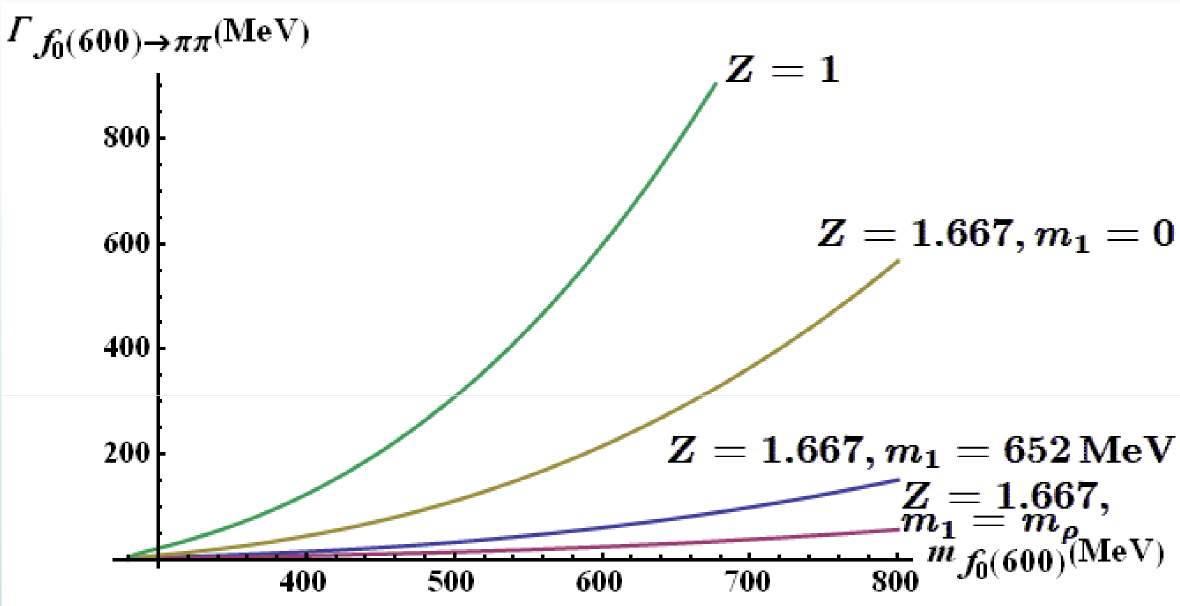
$$\Gamma\left[\sigma \equiv f_0(600) \rightarrow \pi\pi\right] \leq 200 \quad \text{MeV! !!}$$

This is wrong! The experimental value is much larger (500 MeV).
Note, the role of axial-vector mesons is crucial for this result.

We conclude: the assignment is unfavoured!
One should start from:

$$\sigma \approx f_0(1370) \qquad \text{and} \qquad a_0 \equiv a_0(1450)$$

arXiv:1003.4934 [hep-ph].



Z = 1 corresponds to the (unphysical) decoupling of (axial-)vector mesons.
The reason for the big change is technical: the a1-π mixing.

Scenario II: $\sigma \approx f_0(1370), a_0 \equiv a_0(1450)$ and $G \approx f_0(1500)$

10 free parameters. 6 are fixed through $m_\pi, m_\rho, m_{\eta_N}, m_{a_1}, f_\pi, \Gamma_{a_1 \to \pi\gamma}$

For the remaining 4: fit to 5 exp quantities:

arXiv:1103.3238

Quantity	Our Value [MeV]	Experiment [MeV]
$M_{\sigma'}$	1191 ± 25	1200-1500
$M_{G'}$	1505 ± 5	1505 ± 6
$G' \to \pi\pi$	38 ± 5	38.04 ± 4.95
$G' \to \eta\eta$	5.3 ± 1.3	5.56 ± 1.34
$G' \to KK$	9.3 ± 1.7	9.37 ± 1.69

Fit in the scenario $\{\sigma', G'\} = \{f_0(1370), f_0(1500)\}$. Note that the $f_0(1370)$ mass ranges between 1200 MeV and 1500 MeV [17] and therefore, as an estimate, we are using the value $m_{\sigma'} = (1350 \pm 150)$ MeV in the fit.

$$\begin{pmatrix} f_0(1370) \\ f_0(1500) \end{pmatrix} = \begin{pmatrix} \sqrt{0.75} & \sqrt{0.25} \\ -\sqrt{0.25} & \sqrt{0.75} \end{pmatrix} \begin{pmatrix} \sigma \equiv \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d) \\ G = gg \end{pmatrix}$$

$$C^4 = \langle \tfrac{\alpha_s}{2\pi} G^a_{\mu\nu} G^{a,\mu\nu} \rangle = (698 \pm 39 \text{ MeV})^4$$

to be compared with

$$\langle \tfrac{\alpha_s}{2\pi} G^a_{\mu\nu} G^{a,\mu\nu} \rangle \approx (\underset{\text{sum rules}}{300} \text{ to } \underset{\text{lattice}}{600} \text{ MeV})^4$$

Nf = 3 (still without glueball): toward the real „hard“ world

Possible Assignments

- Isospin 1

$$a_0 = \begin{cases} a_0(980) \\ a_0(1450) \end{cases}$$

- Isospin ½

$$K_S = \begin{cases} K_0^*(800)\ /\ \kappa \\ K_0^*(1430) \end{cases}$$

- Isospin 0 (Isoscalars)

$$\begin{cases} \sigma_N \equiv \bar{n}n \\ \sigma_S \equiv \bar{s}s \end{cases} \rightarrow \begin{cases} f_0^L \equiv \text{predominantly } \bar{n}n \\ f_0^H \equiv \text{predominantly } \bar{s}s \end{cases}$$

$$f_0(600) \qquad f_0(980) \qquad f_0(1370)$$

$$f_0(1500) \qquad f_0(1710)$$

Check all possibilities

Best Fit

Observable	Fit [MeV]	Experiment [MeV]
f_π	92.5	92.4 ± 0.9
f_K	109.6	$155.5/\sqrt{2} \pm 1.1$
m_π	139.0	138 ± 1.4
m_K	503.9	495.6 ± 5.0
m_η	526.5	547.9 ± 5.5
$m_{\eta'}$	967.7	957.8 ± 9.6
m_ρ	767.2	775.5 ± 7.8
$m_{K^\star}$	899.9	893.8 ± 8.9
m_φ	1014.0	1019.5 ± 1.02
m_{a_1}	1178.9	1230 ± 40
m_{K_1}	1296.4	1272 ± 12.7
$m_{f_1(1420)}$	1405.1	1426.4 ± 14.3
m_{a_0}	1441.7	1474 ± 74
$m_{K_0^\star}$	1536.5	1425 ± 71
$m_{f_0^L}$	1214.1	1350 ± 150
$m_{f_0^H}$	1584.1	1720 ± 86

Observable	Fit [MeV]	Experiment [MeV]
$\Gamma_{\rho\to\pi\pi}$	166.5	149.1 ± 7.4
$\Gamma_{K^\star\to K\pi}$	44.3	46.2 ± 2.3
$\Gamma_{a_1\to\rho\pi}$	737	425 ± 175
$\Gamma_{a_1\to\pi\gamma}$	0.650	0.640 ± 0.250
$\Gamma_{f_1(1420)\to K^\star K}$	43.3	43.9 ± 2.2
$\Gamma_{f_0^L\to\pi\pi}$	122.3	250 ± 100
$\Gamma_{f_0^L\to KK}$	125.7	150 ± 100
$\Gamma_{f_0^H\to\pi\pi}$	31.3	29.3 ± 6.5
$\Gamma_{f_0^H\to KK}$	141.6	71.4 ± 29.1

$$\begin{cases} f_0(1370) \text{ predominantly } \bar{n}n \\ f_0(1710) \text{ predominantly } \bar{s}s \end{cases}$$

What We Did Not Find

- **No fit** with $f_0(600)$ and $f_0(980)$ as $\bar{q}q$ states
- **No fit** with $K_0^*(800)$ as $\bar{q}q$ state
- **No** reasonable **fit** with $f_0(600)$ and $f_0(1370)$ as $\bar{q}q$ states
  $\rightarrow m_{K_0^*} \sim 1.1$ GeV or $m_{a_0} \sim 1.2$ GeV

$$\begin{cases} m_{K_0^*(800)\,/\,\kappa} = (676 \pm 40)\text{ MeV} \\ m_{K_0^*(1430)} = (1425 \pm 50)\text{ MeV} \end{cases} \qquad \begin{cases} m_{a_0(980)} = (980 \pm 20)\text{ MeV} \\ m_{a_0(1450)} = (1474 \pm 19)\text{ MeV} \end{cases}$$

Thus: scalar $\bar{q}q$ states above 1 GeV

$\rightarrow f_0(1370)$ predominantly $\bar{n}n$

$\rightarrow f_0(1710)$ predominantly $\bar{s}s$

Summary

Chiral model for hadrons based on dilatation invariance and chiral symmetry

Important role of (axial)vector mesons in all phenomenology

Scalar quarkonium (and glueball) above 1 GeV (effects in the medium)

Overall good phenomenology (also in the baryon sector not discussed here)

Outllok

Include the scalar glueball in the Nf=3 case.

Include the pseudoscalar glueball.

Additonal tetraquark states needed(?), weak decays, Nf=4, …

Systematic studies of the phase diagrams of QCD

Thank You

for the

attention

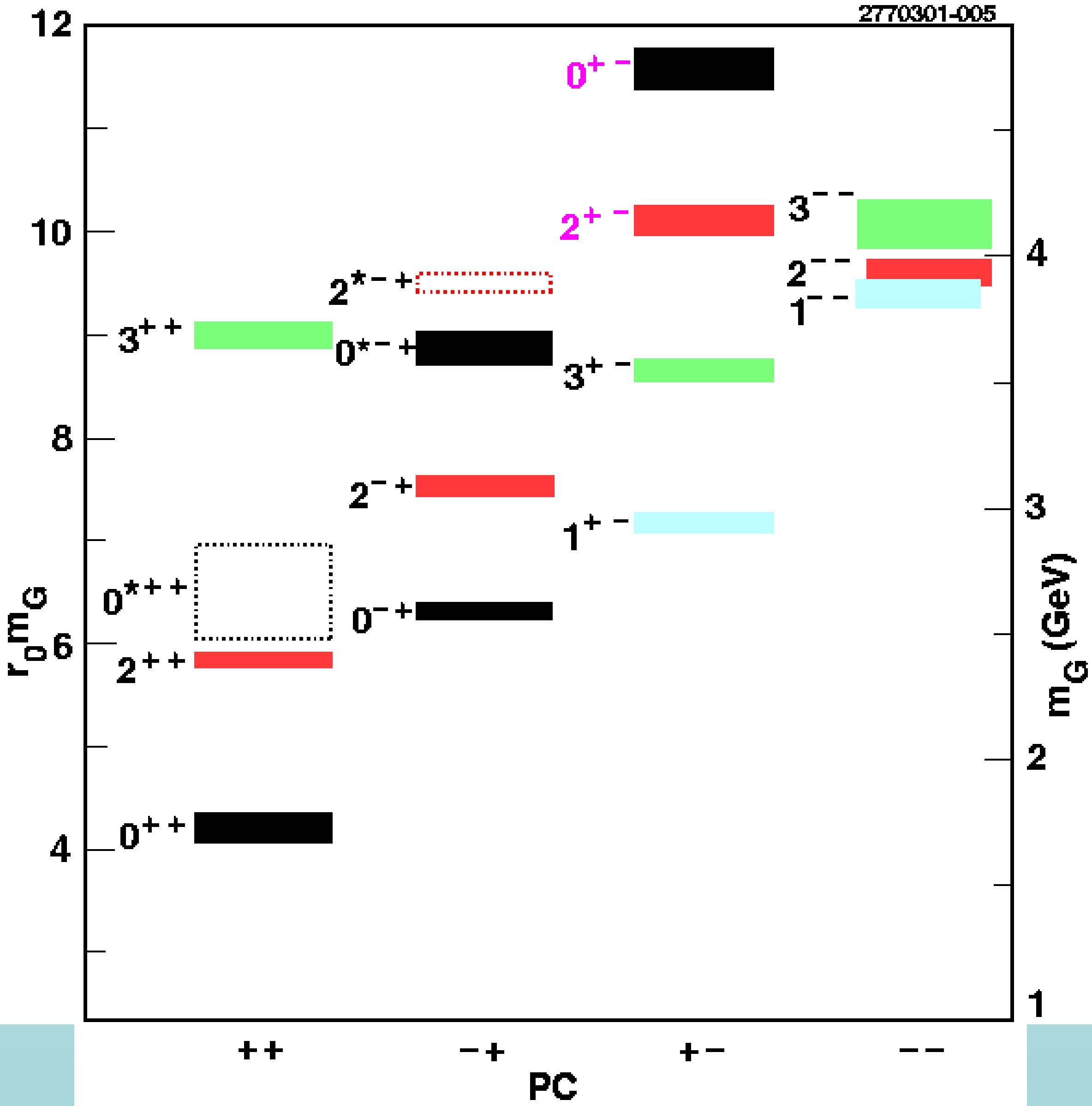
Lattice:

$$M_G = 1.4 - 1.8 \text{ GeV}$$

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

$$I = 0$$

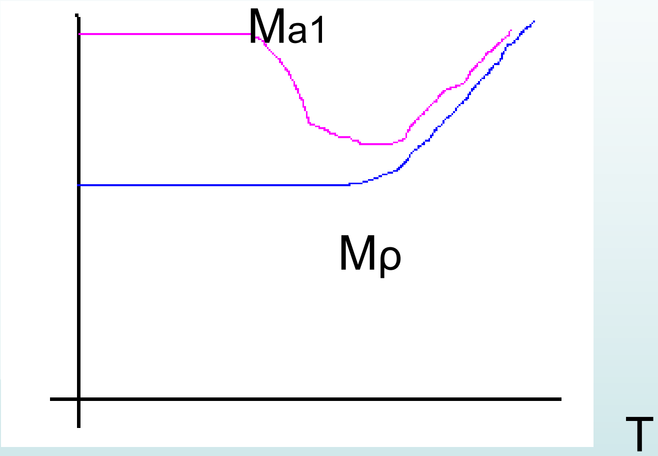
lightest predicted glueball



Morningstar (1999)

Digression: 3 scenarios for the ρ-meson at nonzero T

$$M_\rho^2 = \underbrace{\phi^2}_{\text{quark condensate}} (\ldots) + \underbrace{G_0^2}_{\text{gluon condensate}} (\ldots)$$

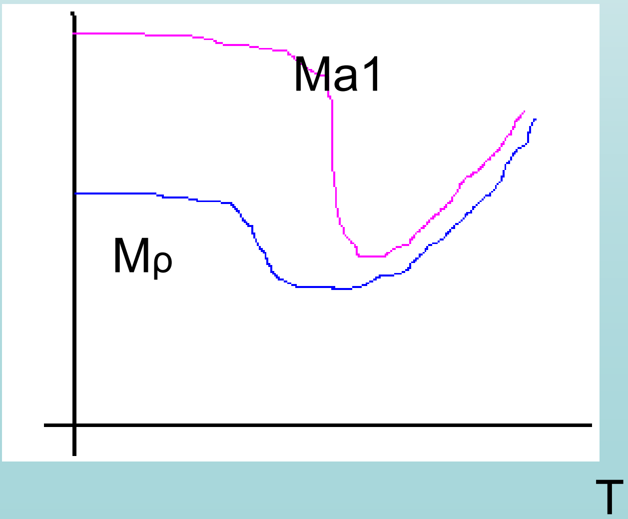


Case A: G0-term dominates

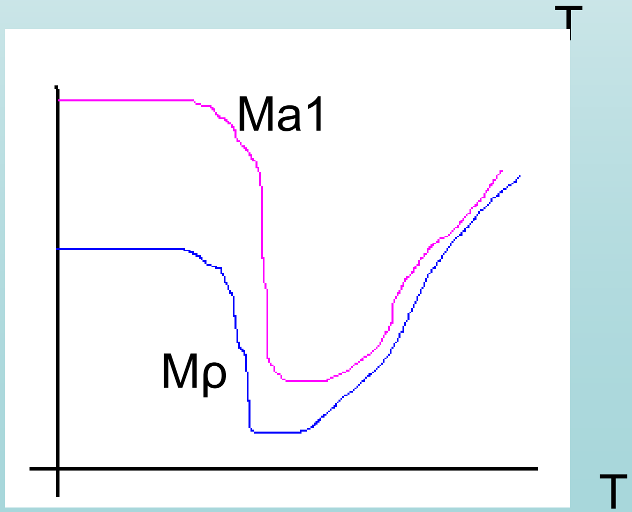
In our case: $\underbrace{G_0^2}_{\text{gluon condensate}} (\ldots) \approx (600\ \text{MeV})^2$

We expect case A to hold;
small drop of the masses in the medium

However: Achtung, Minen!!!



Case B: both terms are similar



Case C: the condensate dominates

$J^{PC} = 0^{++}$	M < 1 GeV	1 GeV < M < 1.8 GeV
$I = 1$	$a_0(980)$	$a_0(1450)$
$I = \frac{1}{2}$	$k(800)$	$K(1450)$
$I = 0$	$f_0(600)$ $f_0(980)$	$f_0(1370)$ $f_0(1500)$ $f_0(1710)$

Too many resonances than expected from quark-antiquark states

$J^{PC}=0^{++}$	M < 1 GeV	Tetraquark interpretation
$I=1$	$a_0(980)$	$[u,s][\bar{d},\bar{s}]$, $[\bar{u},\bar{s}][d,s]$, $([u,s][\bar{u},\bar{s}]-[d,s][\bar{d},\bar{s}])$
$I=\frac{1}{2}$	$k(800)$	$[u,d][\bar{d},\bar{s}]$, $[\bar{u},\bar{d}][d,s]$, $[u,d][\bar{u},\bar{s}]$, $[\bar{u},\bar{d}][u,s]$
$I=0$	$f_0(600)$	$\approx[\bar{u},\bar{d}][u,d]$
	$f_0(980)$	$\approx([u,s][\bar{u},\bar{s}]+[d,s][\bar{d},\bar{s}])$

Indeed, mixing will occur, thus the scenario changes slightly as:

$J^{PC}=0^{++}$	M < 1 GeV	1 GeV < M < 1.8 GeV
$I=1$	$a_0(980)$	$a_0(1450)$
$I=\frac{1}{2}$	$k(800)$	$K(1450)$
$I=0$	Not the chiral partner of pion! $f_0(600) \approx [\bar{u},\bar{d}][u,d]$ $f_0(980)$	Chiral partner of pion! $f_0(1370) \approx \frac{1}{2}(\bar{u}u+\bar{d}d)$ $f_0(1500)$ $f_0(1710)$

These are predominantly tetraquarks (but not only!)

These are predominantly quarkonia (with glueball-intrusion) (but not only!)