Phenomenology of hadrons in the eLSM

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in collaboration with

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Outline

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Development of the eLSM: general considerations

Meson sector

Baryon sector

Nonzero density

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Development of the eLSM: general considerations

Francesco Giacosa

Objectives

• 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)

Criteria for the construction of the model

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

chiral invariance

and

dilatation symmetry .

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.

These are basic properties of QCD:

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

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Development of the eLSM ($N_f = 3$): mesons

(Pseudo)scalar sector

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

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

$$\Gamma = i\gamma^5$$

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

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

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

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

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

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

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

$K_S^+ = K_0^{*+}(1430) \equiv u\bar{s}$ and not k(800)!!!

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

and not $f_0(500)$!!!

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

and not $f_0(980)$!!!

$$\Phi = S + iP$$
$$\Phi \rightarrow U_L \Phi U_R^+$$

(Axial-)Vector sector

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

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

$$\Gamma=\gamma^{\mu}$$

$$\rho^{+}\equiv u\bar{d},...$$

$$K_{*}^{+}(892)\equiv u\bar{s}$$

$$\omega\approx\omega_{N}\equiv\sqrt{1/2}(\bar{u}u+\bar{d}d)$$

$$\phi\approx\phi_{S}\equiv\bar{s}s$$

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

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

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

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

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

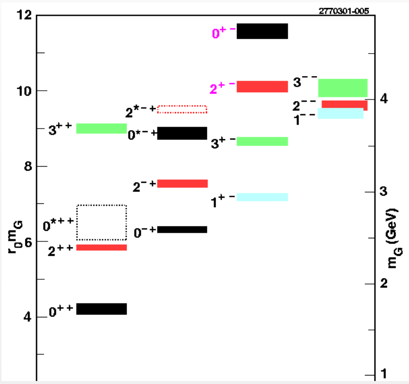
$$f_1(1285) \approx f_{1,N} \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d)$$

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

$$L^{\mu} = V^{\mu} + A^{\mu} \qquad R^{\mu} \rightarrow U_R R^{\mu} U_R^{+}$$

$$R^{\mu} = V^{\mu} - A^{\mu} \qquad L^{\mu} \rightarrow U_L L^{\mu} U_L^{+}$$

Meson sector: how many fields do we have?



Morningstar (1999)

36 + 2 fields

G : Scalar glueball (trace anomaly)

$\tilde{G}$: Pseudoscalar glueball (axial anomaly)

For N_f = 3 there are 38 mesons

36 quark-antiquark fields + 2 glueballs

Model of QCD – eLSM

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

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

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

S. Janowski, D. Parganlija, F. Giacosa, D. H. Rischke, **Phys. Rev. D84, 054007 (2011**) **arXiv: 1103.3238**

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

Basic feature

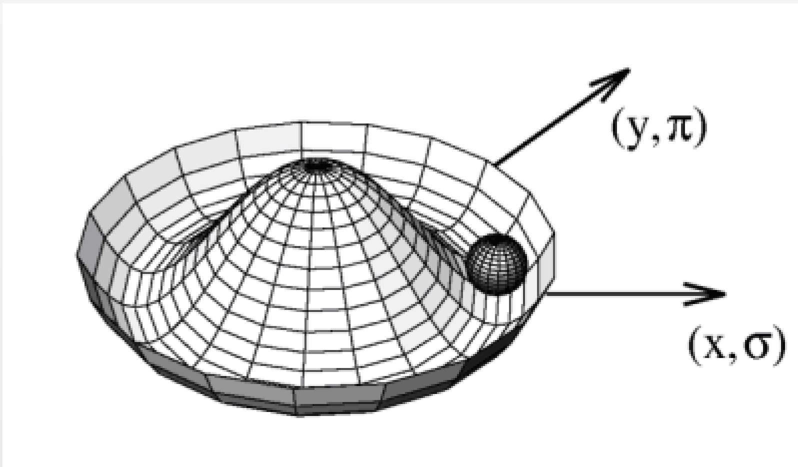
$$V = \frac{m_0^2}{2}\left(\sigma^2 + \pi^2\right) + \frac{\lambda_1 + \lambda_2}{4}\left(\sigma^2 + \pi^2\right)^2$$

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

$\pi = \text{neutral pion}$

Spontaneous Symmetry Breaking (SSB): $\sigma = \sigma_N \equiv \sqrt{1/2}(\bar{u}u + \bar{d}d) \equiv f_0(1370)$

...and not to $f_0(500)$...



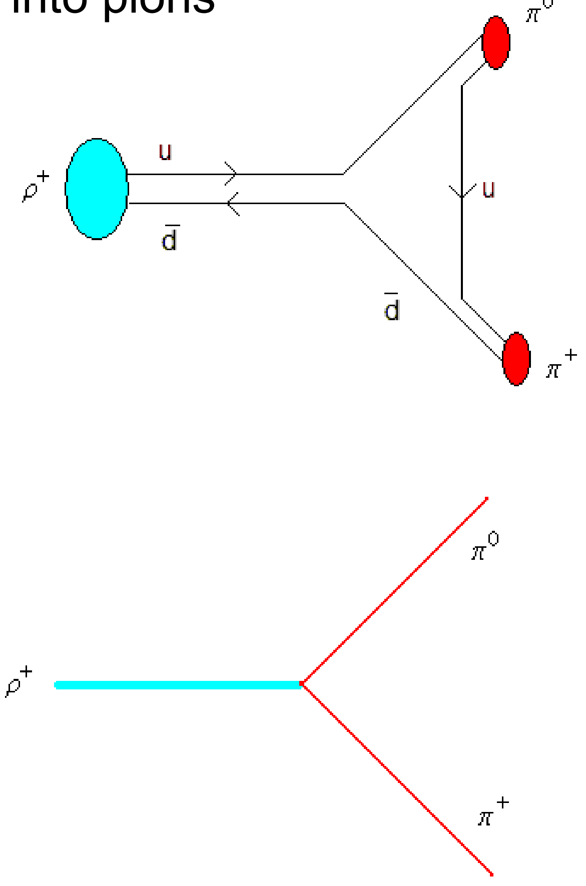
Because of dilatation invariance: only a finite number of terms is present!

We calculate: masses, decays, and scattering lengths.

Example: ρ-meson decay into pions

Microscopic

eLSM



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

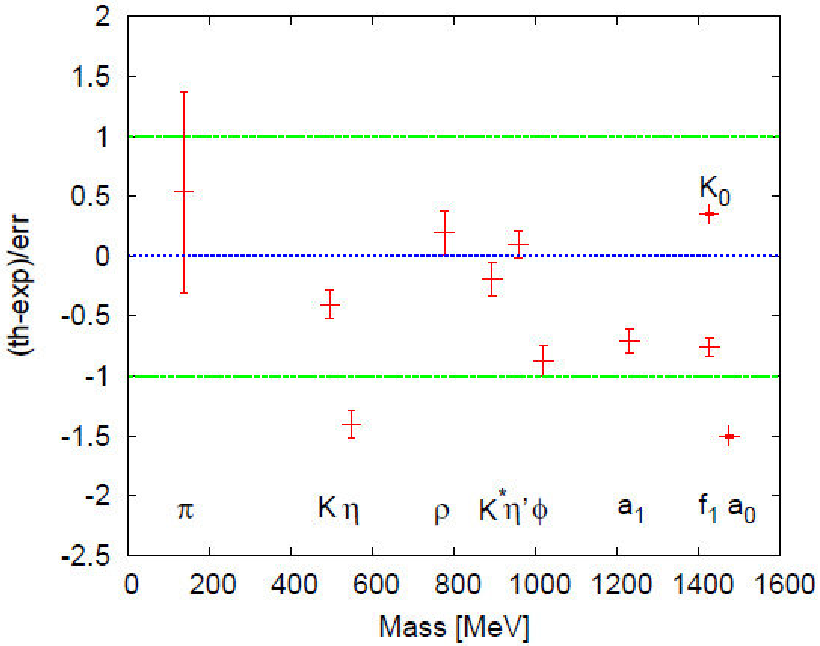
Error from PDG or 5% of exp.
Scalar-isoscalar sector not included.

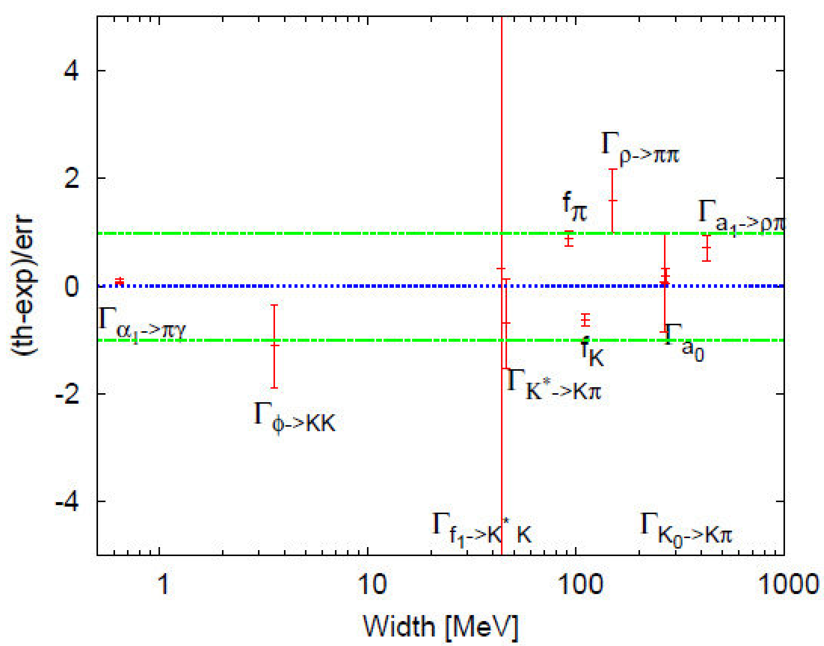
$$\chi^2_{red} = 1.2$$

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_{a0}	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: 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

There are many consequences of the fit.
Example: $a_0(1450)$

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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)

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

An important ongoing work: where is the scalar glueball?

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

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

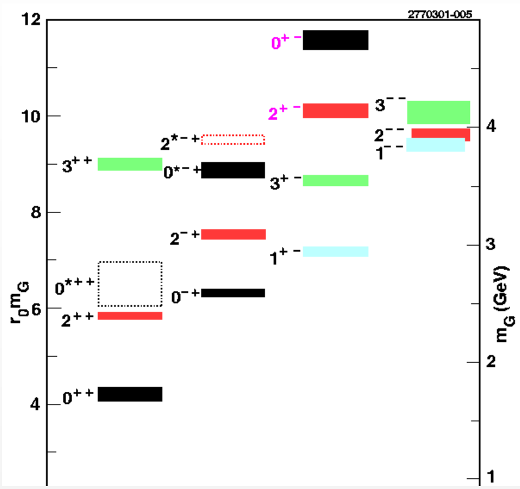
where B is a 3×3 orthogonal matrix

A new entry: the pseudoscalar glueball

$$\mathcal{L}^{int}_{\tilde{G}\text{-mesons}} = i c_{\tilde{G}\Phi} \tilde{G} \left(\det\Phi - \det\Phi^{\dagger} \right) \qquad M_{\tilde{G}} \approx 2.6\,\text{GeV}$$

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



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

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

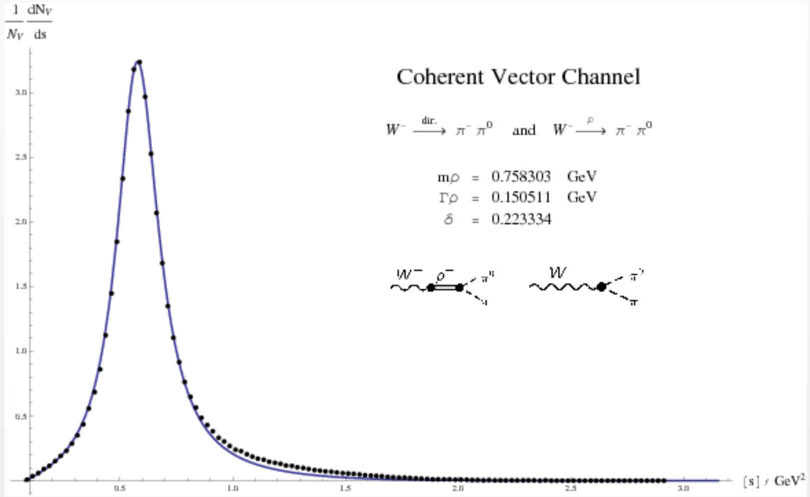
Details in:

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

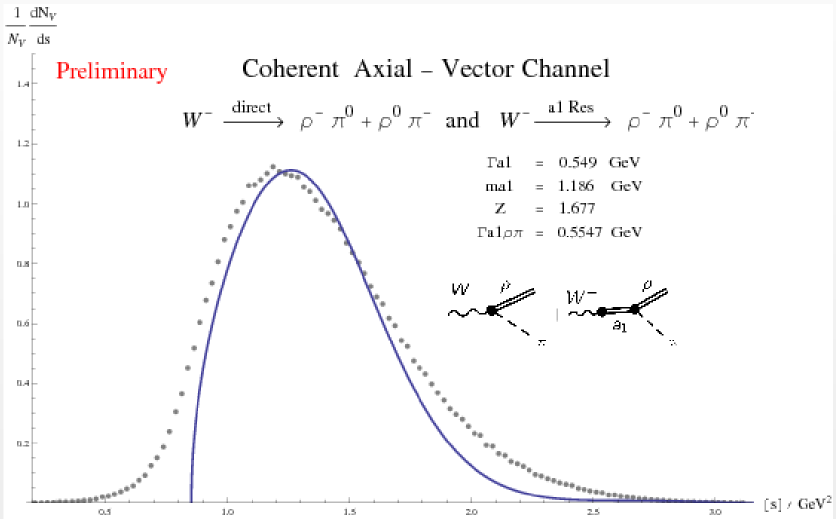
W. Eschraim, S. Janowski, K. Neuschwander, A. Peters, F.G., **Acta Phys. Pol. B**, Prc. Suppl. 5/4, **arxiv: 1209.3976**

The weak tau-decay into mesons

$\tau \rightarrow W^{-}\nu_{\tau} \rightarrow \pi\pi\nu_{\tau}$



$\tau \rightarrow W^{-}\nu_{\tau} \rightarrow \pi\pi\pi\nu_{\tau}$



Thanks to Anja Habersetzer

Development of a hadronic model (N_f =2): baryons

Francesco Giacosa

Baryon sector in the ElSM
(Nf = 2 only)

Nucleon and its chiral partner; chiral symmetry and dilatation invariance

(Axial-)vector mesons are included

Mirror assignment: C. De Tar and T. Kunihiro, **PRD 39 (1989) 2805**)

$$\Psi_{1,R} \to U_R \Psi_{1,R} \qquad \Psi_{1,L} \to U_L \Psi_{1,L}$$

$$\Psi_{2,R} \to U_L \Psi_{2,R} \qquad \Psi_{2,L} \to U_R \Psi_{2,L}$$

A chirally invariant mass-term is possible!

$$m_0 \left(\overline{\Psi}_{1,L} \Psi_{2,R} - \overline{\Psi}_{1,R} \Psi_{2,L} - \overline{\Psi}_{2,L} \Psi_{1,R} + \overline{\Psi}_{2,R} \Psi_{1,L} \right)$$

Lagrangian in the baryon sector

Interaction of baryons with (pseudo)scalar and (axial-)vector mesons

$$\mathcal{L}_{mirror} = \overline{\Psi}_{1L} i\gamma_\mu D^\mu_{1L} \Psi_{1L} + \overline{\Psi}_{1R} i\gamma_\mu D^\mu_{1R} \Psi_{1R} + \overline{\Psi}_{2L} i\gamma_\mu D^\mu_{2R} \Psi_{2L} + \overline{\Psi}_{2R} i\gamma_\mu D^\mu_{2L} \Psi_{2R}$$
$$- \widehat{g}_1 \left(\overline{\Psi}_{1L} \Phi \Psi_{1R} + \overline{\Psi}_{1R} \Phi^\dagger \Psi_{1L} \right) - \widehat{g}_2 \left(\overline{\Psi}_{2L} \Phi^\dagger \Psi_{2R} + \overline{\Psi}_{2R} \Phi \Psi_{2L} \right) + \mathcal{L}_{\text{mass}}$$

$$D^\mu_{1R} = \partial^\mu - ic_1 R^\mu, D^\mu_{1L} = \partial^\mu - ic_1 L^\mu$$

$$D^\mu_{2R} = \partial^\mu - ic_2 R^\mu, D^\mu_{2L} = \partial^\mu - ic_2 L^\mu$$

$$\mathcal{L}_{\text{mass}} = -m_0 (\overline{\Psi}_{1L} \Psi_{2R} - \overline{\Psi}_{1R} \Psi_{2L} - \overline{\Psi}_{2L} \Psi_{1R} + \overline{\Psi}_{2R} \Psi_{1L})$$

$$\begin{pmatrix} N \\ N^* \end{pmatrix} = \frac{1}{\sqrt{2\cosh\delta}} \begin{pmatrix} e^{\delta/2} & \gamma_5 e^{-\delta/2} \\ \gamma_5 e^{-\delta/2} & -e^{\delta/2} \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

$$\delta = ar\cosh\left[\frac{M_N + M_{N^*}}{2m_0}\right]$$

$N = N(940)$

$N^* = N^*(1535)$

Mass of the nucleon

$$m_{N,N^*} = \sqrt{m_0^2 + \left(\frac{\widehat{g}_1 + \widehat{g}_2}{4}\right)^2 \phi^2} \pm \frac{(\widehat{g}_1 - \widehat{g}_2)\phi}{4}$$

$N = N(940)$

$N^* = N^*(1535)$

If $m_0 = 0 \rightarrow$ only the quark condensate generates the masses. $\mathrm{m_N} \sim \phi$

$$m_0 = 460 \pm 136 \ \text{MeV}$$

Using $g_A^N = 1.26$ (exp), $g_A^{N^*} \approx 0.2$ (latt) and $\Gamma_{\mathrm{N^* \rightarrow N}\pi} \approx 67$ MeV

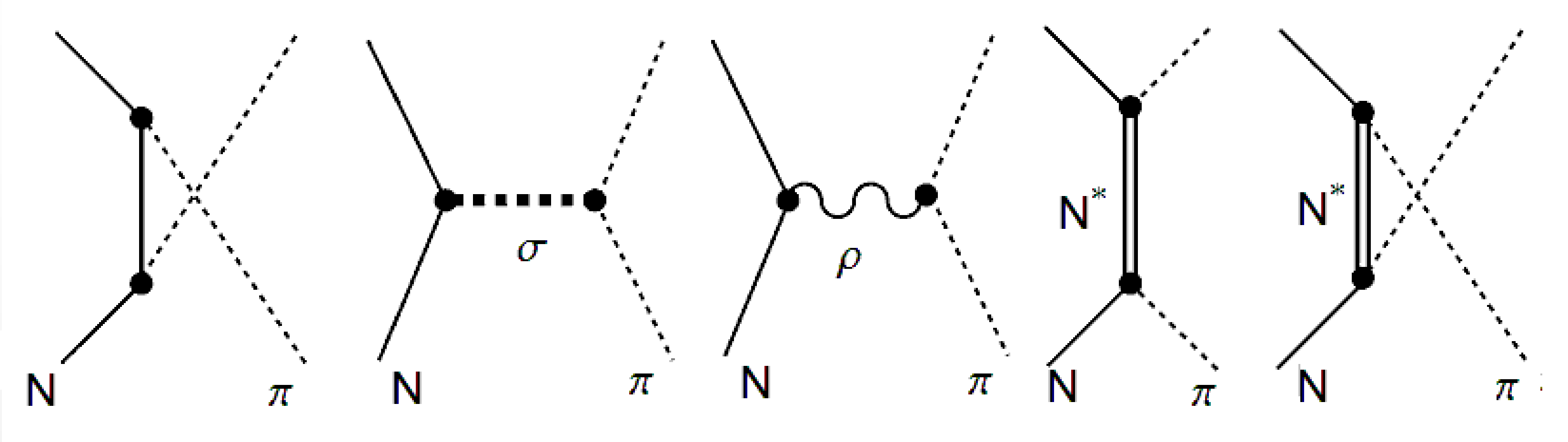
Details in S. Gallas, F. G., D. H. Rischke, **Phys.Rev. D82 (2010) 014004, arXiv:0907.5084**

m_0 parameterizes the contribution which does not stem from the quark condensate

Crucial also at nonzero temperature and density

also in the so-called quarkyonic phase: L. McLerran, R. Pisarski **Nucl.Phys.A796:83-100,2007**

Test: pion-nucleon scattering lengths



$$a_0^- = (6.04 \pm 0.63) \cdot 10^{-4} \text{ MeV}^{-1} \qquad a_0^{-(\text{exp})} = (6.4 \pm 0.1) \cdot 10^{-4} \text{ MeV}^{-1}$$

$$a_0^+ \approx (\text{from} - 20 \text{ to} + 20 \cdot 10^{-4}) \text{ MeV}^{-1} \qquad a_0^{+(\text{exp})} = (-8.8 \pm 7.2) \cdot 10^{-4} \text{ MeV}^{-1}$$

Large theoretical uncertainty due to the scalar-isosocalar sector

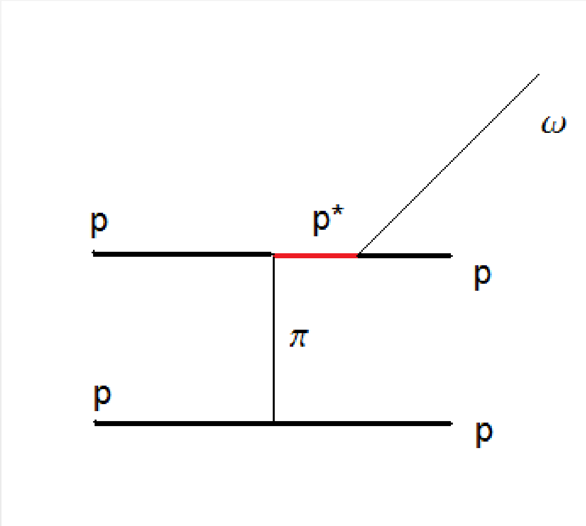
Importance of both vector mesons and mirror assignment in order to get these results

What we are studying rigth now…

$$p + p \rightarrow p + p + X$$

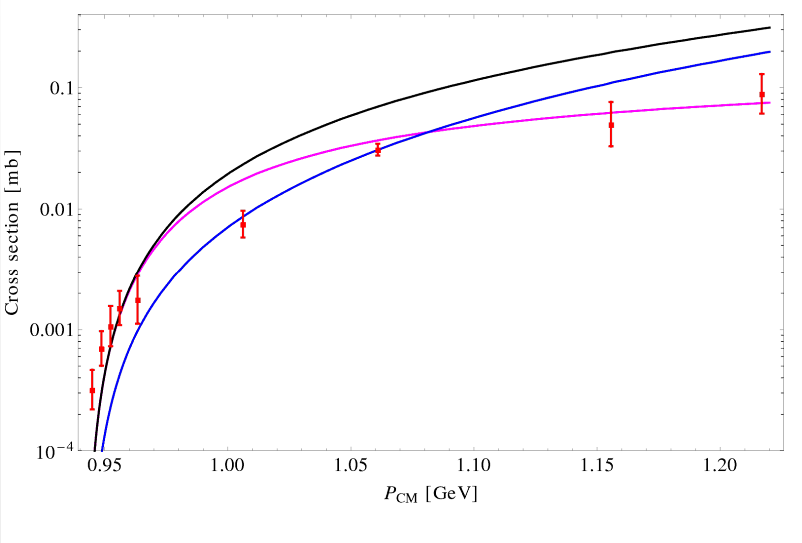
$$X = \omega, \eta, \text{lepton pair,...}$$

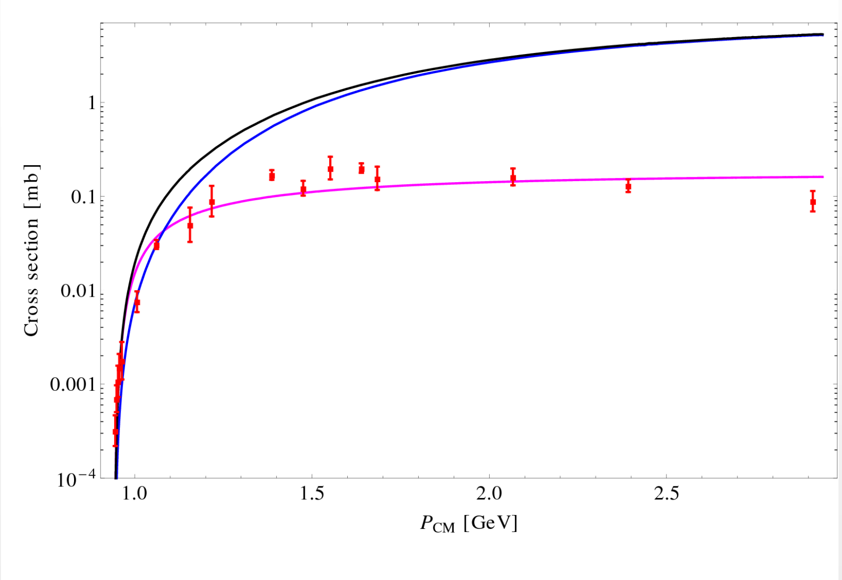
Many diagrams to calculate; the advantage is : chiral symmetry (and also g.i.) built in.



$$p + p \rightarrow p + p + \omega$$

Preliminary!





Thanks to Dr. Khaled Teilab.

Results at nonzero density

Basic considerations for nonzero density

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

The question is: what is $f_0(500)$ and, more in general, what are the scalar states below 1 GeV?

A good phenomenology (masses and decays) is achieved when interpreting the light scalar states as tetraquarks: $f_0(500) \approx [\bar{u},\bar{d}][u,d]$
(bound states of a diquark and an anti-diquark)

Details in: F.G, Phys.Rev. D **75** (2007) 054007

Back to nucleons: where does m_0 comes from?

$$m_0\left(\overline{\Psi}_{1,L}\Psi_{2,R}-\overline{\Psi}_{1,R}\Psi_{2,L}-\overline{\Psi}_{2,L}\Psi_{1,R}+\overline{\Psi}_{2,R}\Psi_{1,L}\right)$$

By requiring dilatation invariance one should modify the mass-term as:

$$a\chi\left(\overline{\Psi}_{1,L}\Psi_{2,R}-\overline{\Psi}_{1,R}\Psi_{2,L}-\overline{\Psi}_{2,L}\Psi_{1,R}+\overline{\Psi}_{2,R}\Psi_{1,L}\right)$$

Tetraquark

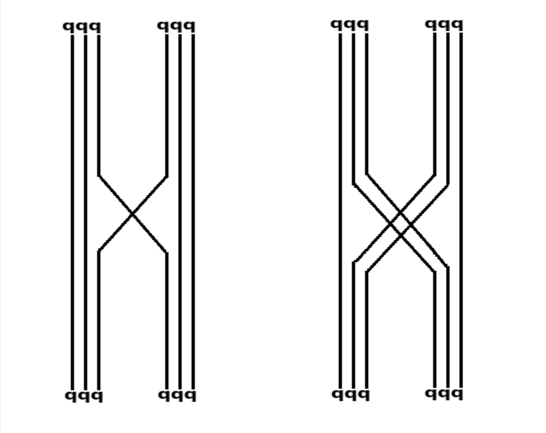
New field: $f_0(500)$

$$\text{By shifting}: \chi \to \chi_0 + \chi \qquad \text{one has}: \quad m_0 = a\chi_0$$

m_0 originates form the tetraquark condensate

.

Note, also, a tetraquark exchange naturally arises in nucleon-nucleon interactions



Nuclear matter saturation and compressibilty

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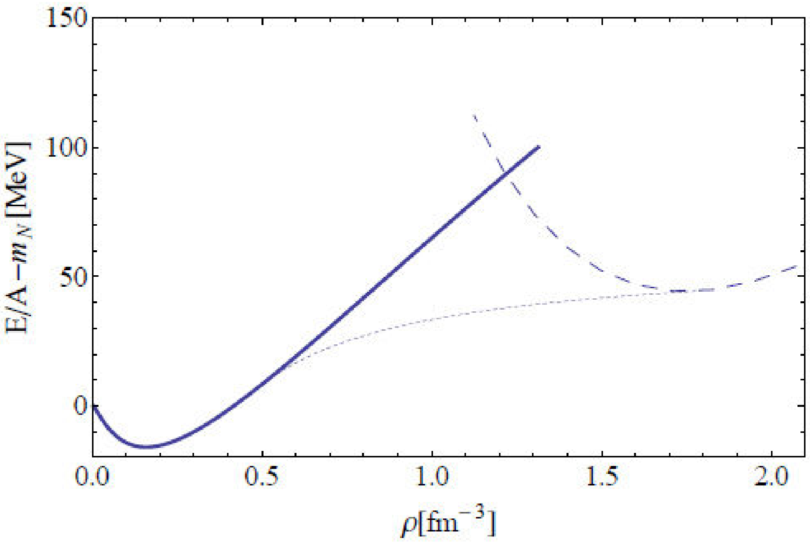
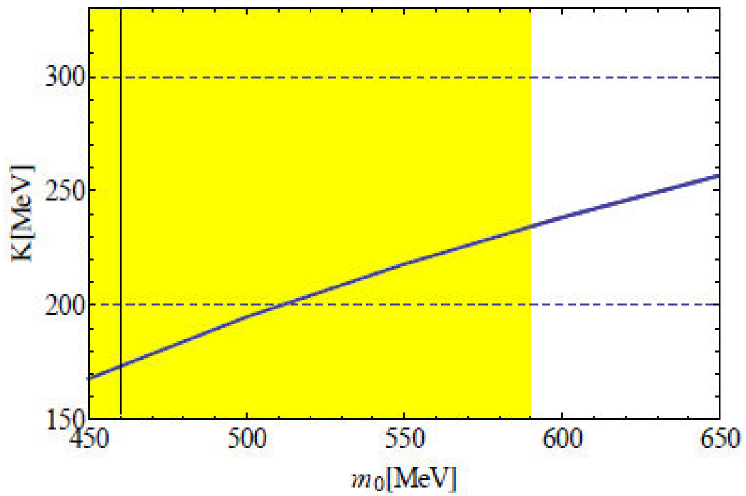




Details in: S. Gallas, F. G:, G. Pagliara, **Nucl.Phys. A872 (2011) 13-24 arXiv:1105.5003**

Nuclear matter: why does it bind?

The resonance $f_0(500)$, here interpreted as a tetraquark, plays an important role for the stability of nuclear matter.

Related 'amusing' question: does nuclear matter binds at large Nc?

As soon as the lightest scalar $f_0(500)$ is not a quarkonium, nuclear matter ceases to exist already for Nc=4.

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

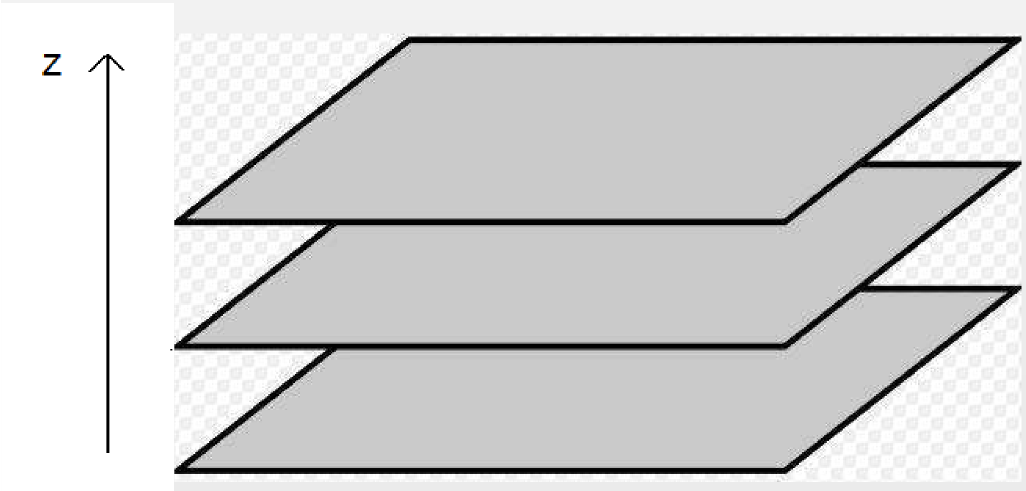
Inhomogeneous condensation at nonzero density

$$\text{Up to now} : \phi = const$$

…but one can have a Chiral Density Wave:

$$\phi(z) = \phi \cos(2fz)$$

$$\left\langle \pi^0 \right\rangle = \phi \sin(2fz) / Z$$

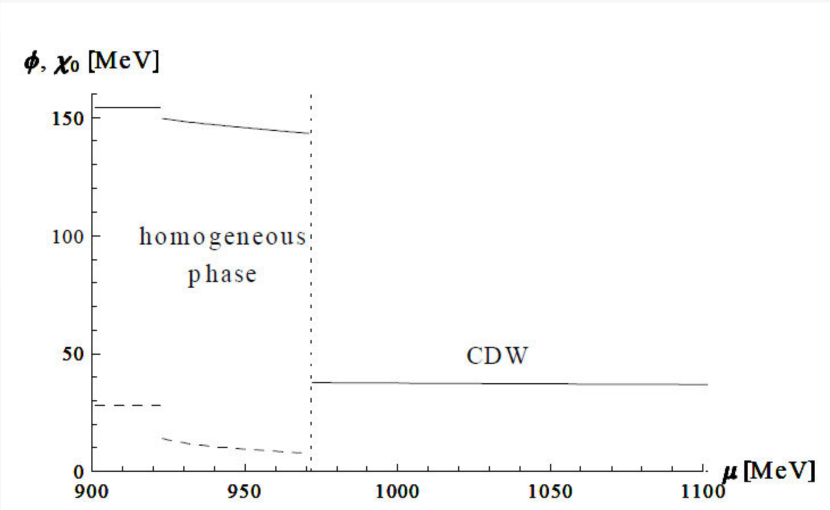


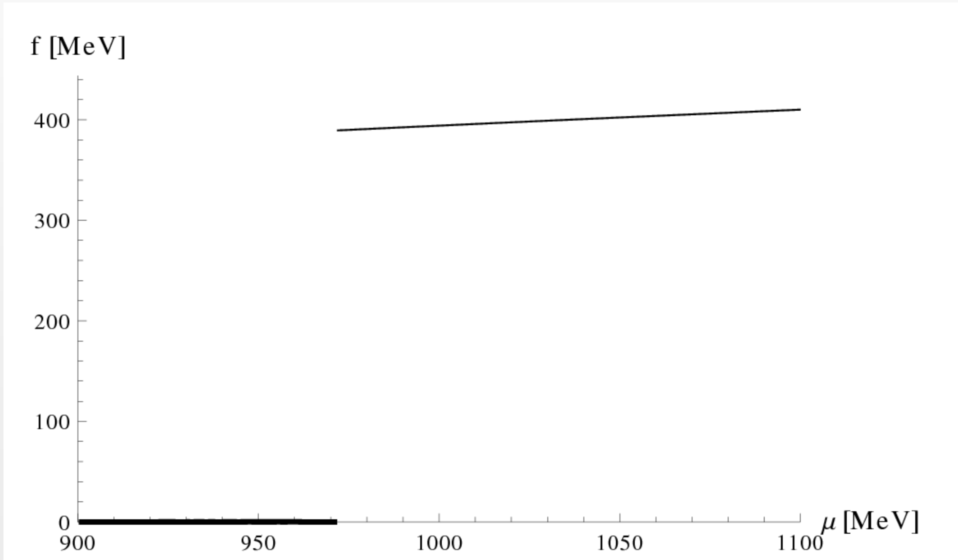
Inhomogeneous condensation/2

$$\phi(z) = \langle \sigma \rangle = \phi \cos(2fz)$$

$$\langle \pi^0 \rangle = \phi \sin(2fz)/Z$$

$m_0 = 460$ MeV





$$\rho_{CDW}/\rho_0 = 2.4$$

A. Heinz, F.G., D. H. Rischke, in preparation.

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Summary

Summary

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Hadronic Theory (eLSM) based on chiral symmetry and dilatation invariance

Important role of (axial-)vector mesons in all phenomenology

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

Nucleon mass contribution which does not stem from the chiral condensate
(but from the tetraquark and glueball condensates)

Ongoing works: $N_f = 4$, additional tetraquark states, weak decays, proton-proton scattering, unitarization (loops)…

Planned: nonzero temperature

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Thank You

Tetraquark: outlook and short excursus at nonzero T

A possibility is to interpret the light scalar states below 1 GeV
[$f_0(600)$, $k(800)$, $f_0(980)$ and $a_0(980)$]
as diquark-antidiquark objects: these are the Jaffe's tetraquarks.

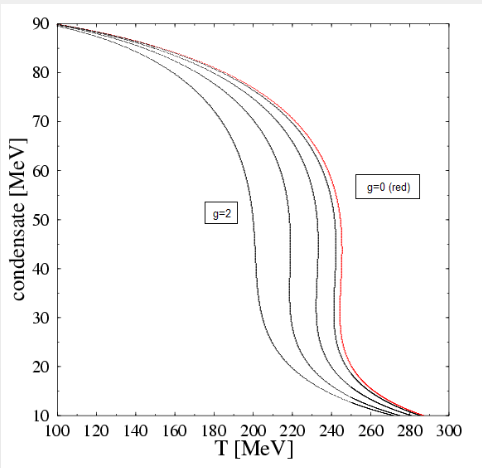
The $N_f=3$ case is an outlook. Mixing of these tetraquark-quarkonioa takes place.

Black et al, **Phys. Rev. D 64** (2001), F.G., **Phys.Rev.D 75**,(2007)

For $N_f=2$ only one tetraquark survives. In this case we studied a simplified system at nonzero T.

$$\text{The resonance } f_0(1370) \approx \sigma \equiv \sqrt{\frac{1}{2}}(\bar{u}u + \bar{d}d) \text{ is the chiral partner of the pion } \vec{\pi}.$$

$$\text{The resonance } f_0(600) \approx \chi \equiv \frac{1}{2}[u,d][\bar{u},\bar{d}] \text{ is an extra-scalar state}$$



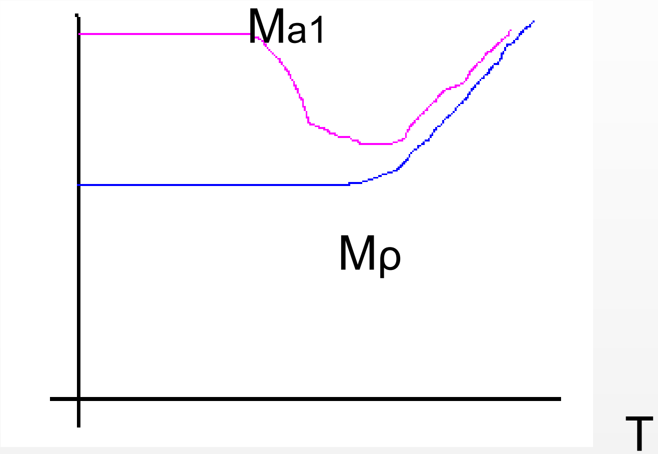
Increasing of mixing:

1) T_c decreases
2) First order softened
3) Cross-over obtained for g large enough

Achim Heinz, Stefan Strube, F.G., Dirk H. Rischke
Phys.Rev.D79:037502,2009; **arXiv:0805.1134** [hep-ph]

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

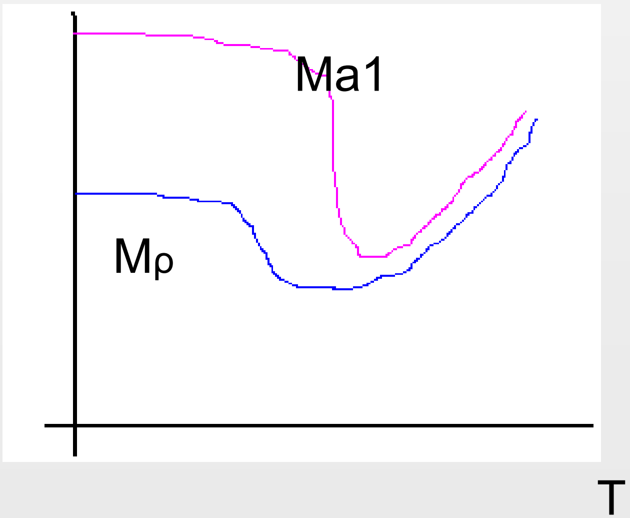
$$M_\rho^2 = \underbrace{\phi^2}_{\text{quark condensate}} (\ldots) + \underbrace{G_0^2}_{\text{gluon condensate}} (\ldots)$$



Case A: G0-term dominates

In our case: both terms comparables.

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



Case B: both terms are similar

Case C: the condensate dominates

QCD and its symmetries

$$\mathcal{L}_{QCD} = \sum_{i=1}^{N_f} \overline{q}_i (i\gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

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$SU(3)_{color}$: exact. Confinement: you never see color, but only white states.

Dilatation invariance: holds only at a classical level and in the chiral limit. Broken by quantum fluctuations (trace anomaly) and by small quark masses

$SU(3)_R \times SU(3)_L$: holds in the chiral limit, but is broken by nonzero quark masses. Moreover, it is spontaneously broken to $U(3)_{V=R+L}$

$U(1)_{A=R-L}$: holds at a classical level, but is also broken by quantum fluctuations (chiral anomaly)

C and P: charge conjugation and parity: exact.

Dilaton / Scalar glueball

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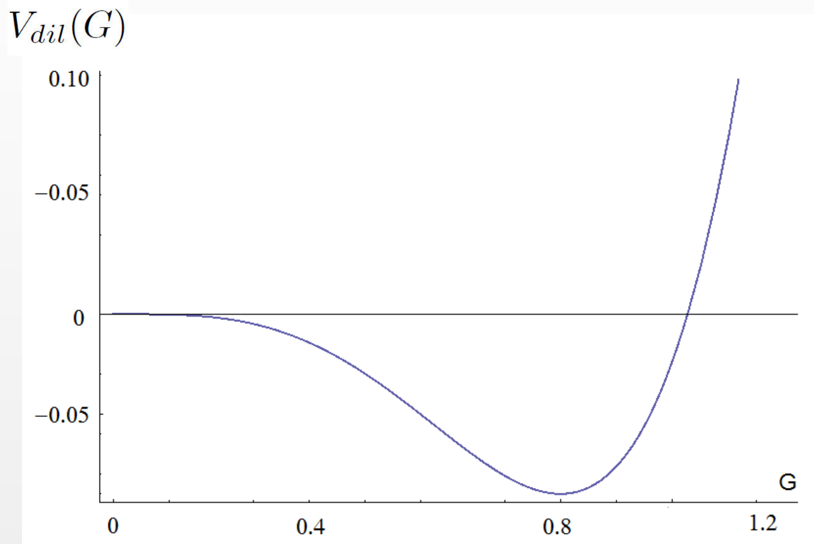
At the hadronic level, we describe these properties as:

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

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

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



Λ_G dimensionful param that breaks dilatation inv!

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

In QCD it is:

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