

Chiral phase transition in the vectormeson extended linear sigma model

Péter Kovács

Wigner Research Centre for Physics, Budapest

kovacs.peter@wigner.mta.hu

Sept 23, 2014

FAIRNESS 2014

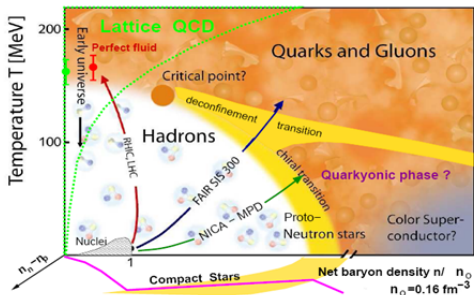
Collaborators: Zsolt Szép , György Wolf

Overview

- 1 Introduction
 - Motivation
 - QCD's chiral symmetry, effective models
- 2 The model
 - Axial(vector) meson extended linear σ -model with constituent quarks and Polyakov-loops
- 3 eLSM at finite T/μ_B
 - Polyakov loop
 - Extremum equations for $\phi_{N/S}$ and $\Phi, \bar{\Phi}$
 - Parametrization at $T = 0$
- 4 Results
 - T dependence of the order parameters
 - T dependence of the (pseudo)scalar masses
- 5 Summary

QCD phase diagram

Phase diagram in the $T - \mu_B - \mu_I$ space



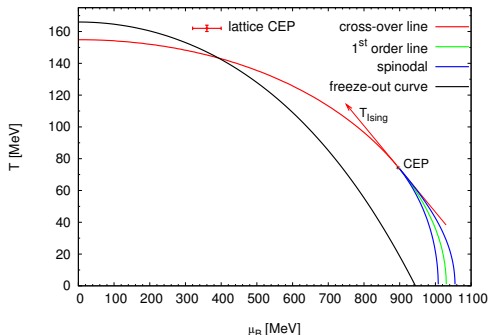
- At $\mu_B = 0$
 $T_C = 151(3)$ MeV
 Y. Aoki, *et al.*, PLB **643**, 46 (2006)
- Is there a CEP?
- At $T = 0$ in μ_B where is the phase boundary?
- Behavior as a function of μ_I/μ_S ?

Details of the phase diagram are heavily studied theoretically (Lattice, EFT), and experimentally (RHIC, LHC, FAIR, NICA)

Previous results (with linear σ -model)

The CEP at the physical point of the mass plane

P. Kovács, Zs. Szép: Phys. Rev. D **75**, 025015



effective model

- $T_c(\mu_B = 0) = 154.84$ MeV
 $\Delta T_c(x\chi) = 15.5$ MeV
- $T_{CEP} = 74.83$ MeV
 $\mu_{B,CEP} = 895.38$ MeV
- $T_c \left. \frac{d^2 T_c}{d\mu_B^2} \right|_{\mu_B=0} = -0.09$

lattice

- $T_c(\mu_B = 0) = 151(3)$ MeV
 $\Delta T_c(\chi_{\bar{\psi}\psi}) = 28(5)$ MeV
Y. Aoki, *et al.*, PLB **643**, 46 (2006)
- $T_{CEP} = 162(2)$ MeV
 $\mu_{B,CEP} = 360(40)$ MeV
- $-0.058(2)$
Z. Fodor, *et al.*, JHEP 0404 (2004) 050

Structure of scalar mesons

	Mass (MeV)	width (MeV)	decays
$a_0(980)$	980 ± 20	$50 - 100$	$\pi\pi$ dominant
$a_0(1450)$	1474 ± 19	265 ± 13	$\pi\eta, \pi\eta', K\bar{K}$
$K_s(800) = \kappa$	682 ± 29	547 ± 24	$K\pi$
$K_s(1430)$	1425 ± 50	270 ± 80	$K\pi$ dominant
$f_0(500) = \sigma$	400–550	400 – 700	$\pi\pi$ dominant
$f_0(980)$	980 ± 20	40 – 100	$\pi\pi$ dominant
$f_0(1370)$	1200–1500	200 – 500	$\pi\pi \approx 250, K\bar{K} \approx 150$
$f_0(1500)$	1505 ± 6	109 ± 7	$\pi\pi \approx 38, K\bar{K} \approx 9.4$
$f_0(1710)$	1722 ± 6	135 ± 7	$\pi\pi \approx 30, K\bar{K} \approx 71$

Possible scalar states: $\bar{q}q, \bar{q}q\bar{q}q$, meson-meson molecules, glueballs

It was shown in: [D. Parganlija et al., Phys. Rev. D87 \(2013\) 014011](#)

→ $q\bar{q} f_0$'s should be above 1 GeV

Addressed problems

- What are the effects of Polyakov loops and (axial)vector mesons on the chiral transition?
- How the order parameters behave at finite temperature/chemical potential?
- Which scalars are the chiral partners of the pseudoscalar nonet (in view of the in medium behavior)?
- What is the effect of the medium on the various masses?

Chiral symmetry

If the quark masses are zero (chiral limit) \implies QCD invariant under the following global transformation (**chiral symmetry**):

$$U(3)_L \times U(3)_R \simeq U(3)_V \times U(3)_A = SU(3)_V \times SU(3)_A \times U(1)_V \times U(1)_A$$

$U(1)_V$ term \longrightarrow baryon number conservation

$U(1)_A$ term \longrightarrow broken through axial anomaly

$SU(3)_A$ term \longrightarrow broken down by any quark mass

$SU(3)_V$ term \longrightarrow broken down to $SU(2)_V$ if $m_u = m_d \neq m_s$

\longrightarrow totally broken if $m_u \neq m_d \neq m_s$ (**realized in nature**)

Since QCD is very hard to solve \longrightarrow **low energy effective models** can be set up \longrightarrow **reflecting the global symmetries of QCD** \longrightarrow **degrees of freedom: observable particles** instead of quarks and gluons

Linear realization of the symmetry \longrightarrow linear sigma model

(nonlinear representation \longrightarrow chiral perturbation theory (ChPT))

Lagrangian (2/1)

$$\begin{aligned}
\mathcal{L}_{\text{Tot}} = & \text{Tr}[(D_\mu \Phi)^\dagger (D_\mu \Phi)] - m_0^2 \text{Tr}(\Phi^\dagger \Phi) - \lambda_1 [\text{Tr}(\Phi^\dagger \Phi)]^2 - \lambda_2 \text{Tr}(\Phi^\dagger \Phi)^2 \\
& - \frac{1}{4} \text{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) + \text{Tr} \left[\left(\frac{m_1^2}{2} + \Delta \right) (L_\mu^2 + R_\mu^2) \right] + \text{Tr}[H(\Phi + \Phi^\dagger)] \\
& + c_1 (\det \Phi + \det \Phi^\dagger) + i \frac{g_2}{2} (\text{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \text{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
& + \frac{h_1}{2} \text{Tr}(\Phi^\dagger \Phi) \text{Tr}(L_\mu^2 + R_\mu^2) + h_2 \text{Tr}[(L_\mu \Phi)^2 + (\Phi R_\mu)^2] + 2h_3 \text{Tr}(L_\mu \Phi R^\mu \Phi^\dagger) \\
& + g_3 [\text{Tr}(L_\mu L_\nu L^\mu L^\nu) + \text{Tr}(R_\mu R_\nu R^\mu R^\nu)] + g_4 [\text{Tr}(L_\mu L^\mu L_\nu L^\nu) \\
& + \text{Tr}(R_\mu R^\mu R_\nu R^\nu)] + g_5 \text{Tr}(L_\mu L^\mu) \text{Tr}(R_\nu R^\nu) + g_6 [\text{Tr}(L_\mu L^\mu) \text{Tr}(L_\nu L^\nu) \\
& + \text{Tr}(R_\mu R^\mu) \text{Tr}(R_\nu R^\nu)] + \bar{\Psi} i \not{\partial} \Psi - g_F \bar{\Psi} (\Phi_S + i\gamma_5 \Phi_{PS}) \Psi \\
& + g_V \bar{\Psi} \gamma^\mu \left(V_\mu + \frac{g_A}{g_V} \gamma_5 A_\mu \right) \Psi
\end{aligned}$$

+ Polyakov loops \longrightarrow through grand canonical potential

Axial(vector) meson extended linear σ -model with constituent quarks and Polyakov-loops

Lagrangian (2/2)

where

$$D^\mu \Phi = \partial^\mu \Phi - ig_1(L^\mu \Phi - \Phi R^\mu) - ieA_e^\mu [T_3, \Phi]$$

$$\Phi = \sum_{i=0}^8 (\sigma_i + i\pi_i) T_i, \quad H = \sum_{i=0}^8 h_i T_i \quad T_i : U(3) \text{ generators}$$

$$R^\mu = \sum_{i=0}^8 (\rho_i^\mu - b_i^\mu) T_i, \quad L^\mu = \sum_{i=0}^8 (\rho_i^\mu + b_i^\mu) T_i$$

$$L^{\mu\nu} = \partial^\mu L^\nu - ieA_e^\mu [T_3, L^\nu] - \{\partial^\nu L^\mu - ieA_e^\nu [T_3, L^\mu]\}$$

$$R^{\mu\nu} = \partial^\mu R^\nu - ieA_e^\mu [T_3, R^\nu] - \{\partial^\nu R^\mu - ieA_e^\nu [T_3, R^\mu]\}$$

$$\bar{\Psi} = (\bar{u}, \bar{d}, \bar{s})$$

non strange – strange base:

$$\varphi_N = \sqrt{2/3}\varphi_0 + \sqrt{1/3}\varphi_8,$$

$$\varphi_S = \sqrt{1/3}\varphi_0 - \sqrt{2/3}\varphi_8, \quad \varphi \in (\sigma_i, \pi_i, \rho_i^\mu, b_i^\mu, h_i)$$

broken symmetry: non-zero condensates $\langle \sigma_N \rangle, \langle \sigma_S \rangle \longleftrightarrow \phi_N, \phi_S$

Axial(vector) meson extended linear σ -model with constituent quarks and Polyakov-loops

Included fields - pseudoscalar and scalar meson nonets

$$\Phi_{PS} = \sum_{i=0}^8 \pi_i T_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\eta_N + \pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N - \pi^0}{\sqrt{2}} & K^0 \\ K^- & K^0 & \eta_S \end{pmatrix} (\sim \bar{q}_i \gamma_5 q_j)$$

$$\Phi_S = \sum_{i=0}^8 \sigma_i T_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\sigma_N + a_0^0}{\sqrt{2}} & a_0^+ & K_S^+ \\ a_0^- & \frac{\sigma_N - a_0^0}{\sqrt{2}} & K_S^0 \\ K_S^- & K_S^0 & \sigma_S \end{pmatrix} (\sim \bar{q}_i q_j)$$

Particle content:

Pseudoscalars: $\pi(138)$, $K(495)$, $\eta(548)$, $\eta'(958)$ Scalars: $a_0(980 \text{ or } 1450)$, $K_0^*(800 \text{ or } 1430)$, $(\sigma_N, \sigma_S) : 2 \text{ of } f_0(500, 980, 1370, 1500, 1710)$

Axial(vector) meson extended linear σ -model with constituent quarks and Polyakov-loops

Included fields - vector meson nonets

$$V^\mu = \sum_{i=0}^8 \rho_i^\mu T_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N + \rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega_N - \rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & K^{*0} & \omega_S \end{pmatrix}^\mu$$

$$A^\mu = \sum_{i=0}^8 b_i^\mu T_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N} + a_1^0}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & \frac{f_{1N} - a_1^0}{\sqrt{2}} & K_1^0 \\ K_1^- & K_1^0 & f_{1S} \end{pmatrix}^\mu$$

Particle content:

Vector mesons: $\rho(770)$, $K^*(894)$, $\omega_N = \omega(782)$, $\omega_S = \phi(1020)$ Axial vectors: $a_1(1230)$, $K_1(1270)$, $f_{1N}(1280)$, $f_{1S}(1426)$

Spontaneous symmetry breaking

Interaction is approximately chiral symmetric, spectra not, so SSB:

$$\sigma_{N/S} \rightarrow \sigma_{N/S} + \phi_{N/S} \quad \phi_{N/S} \equiv \langle \sigma_{N/S} \rangle$$

For tree level masses we have to select all terms quadratic in the new fields. Some of the terms include mixings arising from terms like $\text{Tr}[(D_\mu \Phi)^\dagger (D_\mu \Phi)]$:

$$\begin{aligned}
 \pi_N - a_{1N}^\mu &: -g_1 \phi_N a_{1N}^\mu \partial_\mu \pi_N, \\
 \pi - a_1^\mu &: -g_1 \phi_N (a_1^{\mu+} \partial_\mu \pi^- + a_1^{\mu 0} \partial_\mu \pi^0) + \text{h.c.}, \\
 \pi_S - a_{1S}^\mu &: -\sqrt{2} g_1 \phi_S a_{1S}^\mu \partial_\mu \pi_S, \\
 K_S - K_\mu^* &: \frac{ig_1}{2} (\sqrt{2} \phi_S - \phi_N) (\bar{K}_\mu^{*0} \partial^\mu K_S^0 + K_\mu^{*-} \partial^\mu K_S^+) + \text{h.c.}, \\
 K - K_1^\mu &: -\frac{g_1}{2} (\phi_N + \sqrt{2} \phi_S) (K_1^{\mu 0} \partial_\mu \bar{K}^0 + K_1^{\mu+} \partial_\mu K^-) + \text{h.c.}
 \end{aligned} \tag{1}$$

Polyakov loops in Polyakov gauge

Polyakov loop variables: $\Phi(\vec{x}) = \frac{\text{Tr}_c L(\vec{x})}{N_c}$ and $\bar{\Phi}(\vec{x}) = \frac{\text{Tr}_c \bar{L}(\vec{x})}{N_c}$ with

$$L(x) = \mathcal{P} \exp \left[i \int_0^\beta d\tau A_4(\vec{x}, \tau) \right]$$

→ signals center symmetry (\mathbb{Z}_3) breaking at the deconfinement transition

low T : confined phase, $\langle \Phi(\vec{x}) \rangle, \langle \bar{\Phi}(\vec{x}) \rangle = 0$

high T : deconfined phase, $\langle \Phi(\vec{x}) \rangle, \langle \bar{\Phi}(\vec{x}) \rangle \neq 0$

Polyakov gauge: the temporal component of the gauge field is time independent and can be gauge rotated to a diagonal form in the color space

$$A_{4,d}(\vec{x}) = \phi_3(\vec{x})\lambda_3 + \phi_8(\vec{x})\lambda_8; \quad \lambda_3, \lambda_8 : \text{Gell-Mann matrices.}$$

In this gauge the Polyakov loop operator is

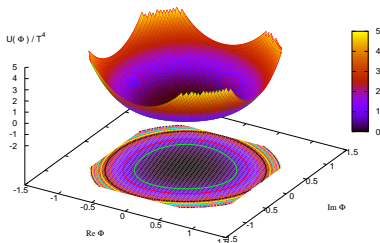
$$L(\vec{x}) = \text{diag}(e^{i\beta\phi_+(\vec{x})}, e^{i\beta\phi_-(\vec{x})}, e^{-i\beta(\phi_+(\vec{x})+\phi_-(\vec{x}))})$$

where $\phi_{\pm}(\vec{x}) = \pm\phi_3(\vec{x}) + \phi_8(\vec{x})/\sqrt{3}$

Polyakov loop potential

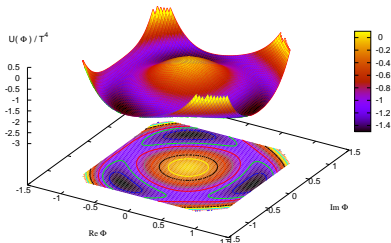
“Color confinement”

$\langle \Phi \rangle = 0 \rightarrow$ no breaking of \mathbb{Z}_3
one minimum



“Color deconfinement”

$\langle \Phi \rangle \neq 0 \rightarrow$ spontaneous breaking of \mathbb{Z}_3
minima at $0, 2\pi/3, -2\pi/3$
one of them spontaneously selected



from H. Hansen et al., PRD75, 065004 (2007)

Form of the potential

I.) Simple **polynomial potential** invariant under \mathbb{Z}_3 and charge conjugation: R.D.Pisarski, PRD 62, 111501

$$\frac{\mathcal{U}_{\text{poly}}(\Phi, \bar{\Phi})}{T^4} = -\frac{b_2(T)}{2} \bar{\Phi} \Phi - \frac{b_3}{6} (\Phi^3 + \bar{\Phi}^3) + \frac{b_4}{4} (\bar{\Phi} \Phi)^2$$

with
$$b_2(T) = a_0 + a_1 \frac{T_0}{T} + a_2 \frac{T_0^2}{T^2} + a_3 \frac{T_0^3}{T^3}$$

II.) **Logarithmic potential** coming from the $SU(3)$ Haar measure of group integration
K. Fukushima, Phys. Lett. **B591**, 277 (2004)

$$\frac{\mathcal{U}_{\text{log}}(\Phi, \bar{\Phi})}{T^4} = -\frac{1}{2} a(T) \Phi \bar{\Phi} + b(T) \ln \left[1 - 6 \Phi \bar{\Phi} + 4 (\Phi^3 + \bar{\Phi}^3) - 3 (\Phi \bar{\Phi})^2 \right]$$

with
$$a(T) = a_0 + a_1 \frac{T_0}{T} + a_2 \frac{T_0^2}{T^2}, \quad b(T) = b_3 \frac{T_0^3}{T^3}$$

$\mathcal{U}(\Phi, \bar{\Phi})$ models the free energy of a pure gauge theory

→ the parameters are fitted to the pure gauge lattice data

Effects of Polyakov loops on FD statistics

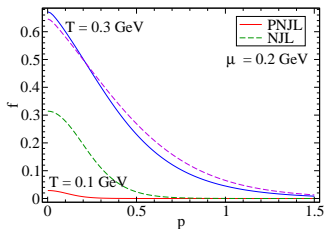
Inclusion of the Polyakov loop modifies the Fermi-Dirac distribution function

$$f(E_p - \mu_q) \longrightarrow f_{\Phi}^+(E_p) = \frac{(\bar{\Phi} + 2\Phi e^{-\beta(E_p - \mu_q)}) e^{-\beta(E_p - \mu_q)} + e^{-3\beta(E_p - \mu_q)}}{1 + 3(\bar{\Phi} + \Phi e^{-\beta(E_p - \mu_q)}) e^{-\beta(E_p - \mu_q)} + e^{-3\beta(E_p - \mu_q)}}$$

$$f(E_p + \mu_q) \longrightarrow f_{\Phi}^-(E_p) = \frac{(\Phi + 2\bar{\Phi} e^{-\beta(E_p + \mu_q)}) e^{-\beta(E_p + \mu_q)} + e^{-3\beta(E_p + \mu_q)}}{1 + 3(\Phi + \bar{\Phi} e^{-\beta(E_p + \mu_q)}) e^{-\beta(E_p + \mu_q)} + e^{-3\beta(E_p + \mu_q)}}$$

$$\Phi, \bar{\Phi} \rightarrow 0 \implies f_{\Phi}^{\pm}(E_p) \rightarrow f(3(E_p \pm \mu_q)) \quad \Phi, \bar{\Phi} \rightarrow 1 \implies f_{\Phi}^{\pm}(E_p) \rightarrow f(E_p \pm \mu_q)$$

three-particle state appears: mimics confinement of quarks within baryons



the effect of the Polyakov loop
is more relevant for $T < T_c$

at $T = 0$ there is no difference between
models with and without Polyakov loop:

$$\Theta(3(\mu_q - E_p)) \equiv \Theta((\mu_q - E_p))$$

H. Hansen et al., PRD75, 065004

Extremum equations for $\phi_{N/S}$ and $\Phi, \bar{\Phi}$

T/μ_B dependence of the Polyakov-loops

By deriving the grand canonical potential for Polyakov loops (Ω) according to Φ and $\bar{\Phi}$ and equate to zero (extremum eqn.)

$$- \frac{d}{d\Phi} \left(\frac{U(\Phi, \bar{\Phi})}{T^4} \right) + \frac{2N_c}{T^3} \sum_{q=u,d,s} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \left(\frac{e^{-\beta E_q^-(p)}}{g_q^-(p)} + \frac{e^{-2\beta E_q^+(p)}}{g_q^+(p)} \right) = 0$$

$$- \frac{d}{d\bar{\Phi}} \left(\frac{U(\Phi, \bar{\Phi})}{T^4} \right) + \frac{2N_c}{T^3} \sum_{q=u,d,s} \int \frac{d^3\mathbf{p}}{(2\pi)^3} \left(\frac{e^{-\beta E_q^+(p)}}{g_q^+(p)} + \frac{e^{-2\beta E_q^-(p)}}{g_q^-(p)} \right) = 0$$

$$g_q^+(p) = 1 + 3 \left(\bar{\Phi} + \Phi e^{-\beta E_q^+(p)} \right) e^{-\beta E_q^+(p)} + e^{-3\beta E_q^+(p)}$$

$$g_q^-(p) = 1 + 3 \left(\Phi + \bar{\Phi} e^{-\beta E_q^-(p)} \right) e^{-\beta E_q^-(p)} + e^{-3\beta E_q^-(p)}$$

$$E_q^\pm(p) = E_q(p) \mp \mu_B/3, \quad E_{u/d}(p) = \sqrt{p^2 + m_{u/d}^2}, \quad E_s(p) = \sqrt{p^2 + m_s^2}$$

Extremum equations for $\phi_{N/S}$ and $\Phi, \bar{\Phi}$

T/μ_B dependence of the condensates ($\phi_{N/S}$)

Extremum equation: $\left\langle \frac{\partial \mathcal{L}_{\text{Tot}}}{\partial \sigma_{N/S}} \right\rangle_T = 0$ (after the SSB)

Hybrid approach: fermions at one-loop, mesons at tree-level (their effects are much smaller)

$$m_0^2 \phi_N + \left(\lambda_1 + \frac{1}{2} \lambda_2 \right) \phi_N^3 + \lambda_1 \phi_N \phi_S^2 - h_N + \frac{g_F}{2} N_c (\langle u\bar{u} \rangle_T + \langle d\bar{d} \rangle_T) = 0$$

$$m_0^2 \phi_S + (\lambda_1 + \lambda_2) \phi_S^3 + \lambda_1 \phi_N^2 \phi_S - h_S + \frac{g_F}{\sqrt{2}} N_c \langle s\bar{s} \rangle_T = 0$$

$$\langle q\bar{q} \rangle_T = -4m_q \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{2E_q(p)} (1 - f_\Phi^-(E_q(p)) - f_\Phi^+(E_q(p)))$$

Determination of the parameters of the Lagrangian

16 unknown parameters ($m_0, \lambda_1, \lambda_2, c_1, m_1, g_1, g_2, h_1, h_2, h_3, \delta_S, \Phi_N, \Phi_S, \mathbf{g}_F, \mathbf{g}_V, \mathbf{g}_A$) \longrightarrow Determined by the **min. of χ^2** :

$$\chi^2(x_1, \dots, x_N) = \sum_{i=1}^M \left[\frac{Q_i(x_1, \dots, x_N) - Q_i^{\text{exp}}}{\delta Q_i} \right]^2,$$

where $(x_1, \dots, x_N) = (m_0, \lambda_1, \lambda_2, \dots)$, $Q_i(x_1, \dots, x_N)$ calculated from the model, while Q_i^{exp} taken from the PDG

multiparametric minimalization \longrightarrow **MINUIT**

- PCAC \rightarrow 2 physical quantities: f_π, f_K

- Tree-level masses \rightarrow 16 physical quantities:

$m_{u/d}, m_s, m_\pi, m_\eta, m_{\eta'}, m_K, m_\rho, m_\Phi, m_{K^*}, m_{a_1}, m_{f_1^H}, m_{K_1}, m_{a_0}, m_{K_s}, m_{f_0^L}, m_{f_0^H}$

- Decay widths \rightarrow 12 physical quantities:

$\Gamma_{\rho \rightarrow \pi\pi}, \Gamma_{\Phi \rightarrow KK}, \Gamma_{K^* \rightarrow K\pi}, \Gamma_{a_1 \rightarrow \pi\gamma}, \Gamma_{a_1 \rightarrow \rho\pi}, \Gamma_{f_1 \rightarrow KK^*}, \Gamma_{a_0}, \Gamma_{K_S \rightarrow K\pi}, \Gamma_{f_0^L \rightarrow \pi\pi}, \Gamma_{f_0^L \rightarrow KK}, \Gamma_{f_0^H \rightarrow \pi\pi}, \Gamma_{f_0^H \rightarrow KK}$

Parameters

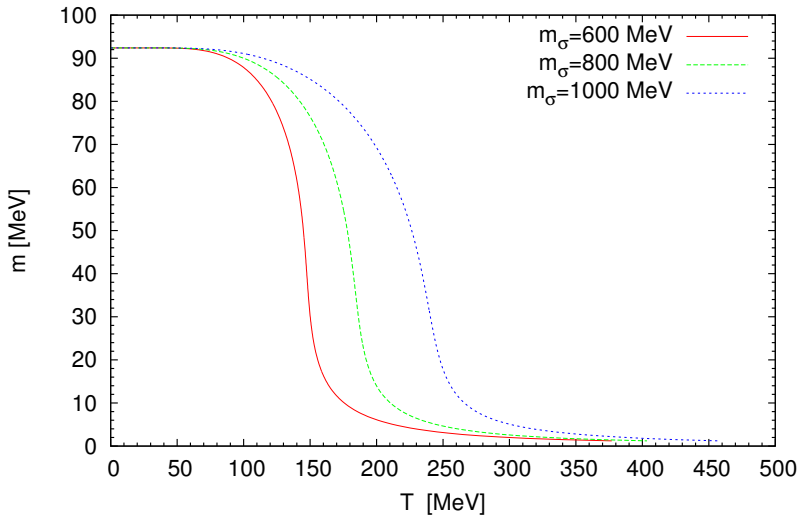
Parameter	Value
ϕ_N [GeV]	0.1622
ϕ_S [GeV]	0.1262
C_1 [GeV ²]	-0.7537
C_2 [GeV ²]	0.3953
λ_1	undetermined
λ_2	65.3221
h_1	undetermined
h_2	11.6586
h_3	4.7028
δ_S [GeV ²]	0.1534
c_1 [GeV]	1.12
g_1	-5.8943
g_2	-2.9960
g_F	4.9429

- inclusion of vector particles effects the parameters (directly they are not present in the equations solved at finite T)
- with this set $f_0^L = 1303$ GeV
- by setting $\lambda_1 \rightarrow f_0^L$ mass can be lowered

T dependence of the order parameters

$\phi_N(T)$ *without* Polyakov loop and vector mesons

B.-J. Schaefer, M. Wagner (PRD 79 014018 (2009)) m_σ dependence of T_c



Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,

Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,

Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,
- constituent quarks

Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,
- constituent quarks
- Four order parameters $(\phi_N, \phi_S, \Phi, \bar{\Phi}) \rightarrow$ four T/μ -dependent equations

Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,
- constituent quarks
- Four order parameters $(\phi_N, \phi_S, \Phi, \bar{\Phi}) \rightarrow$ four T/μ -dependent equations
- Fermion vacuum fluctuations

Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,
- constituent quarks
- Four order parameters $(\phi_N, \phi_S, \Phi, \bar{\Phi}) \rightarrow$ four T/μ -dependent equations
- Fermion vacuum fluctuations
- Fermion **thermal** fluctuations

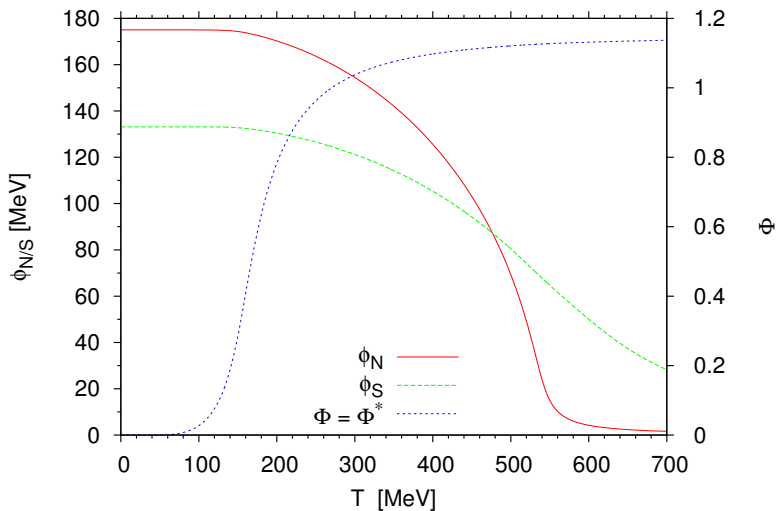
Features of our approach

- D.O.F's: scalar, pseudoscalar, vector, axial vector nonets,
- Polyakov loop variables,
- constituent quarks
- Four order parameters $(\phi_N, \phi_S, \Phi, \bar{\Phi}) \rightarrow$ four T/μ -dependent equations
- Fermion vacuum fluctuations
- Fermion **thermal** fluctuations
- Fermion contributions to the tree-level meson masses

T dependence of the order parameters

$\phi_{N/S}(T), \Phi/\bar{\Phi}(T)$ *with* Polyakov loop $m_{f_0^L} = 1326$ MeV

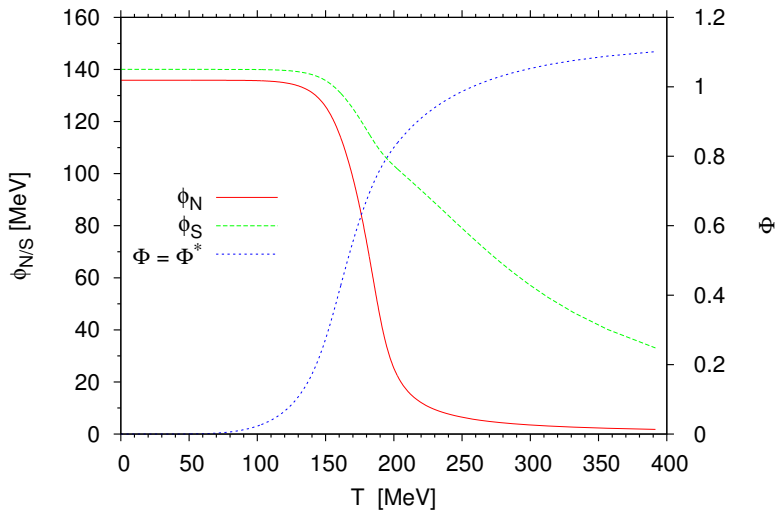
Condensates and Polyakov loop variables with vacuum fluctuations



T dependence of the order parameters

With low mass scalars, $m_{f_0^L} = 402 \text{ MeV}$

Condensates and Polyakov loop variables with vacuum fluctuations



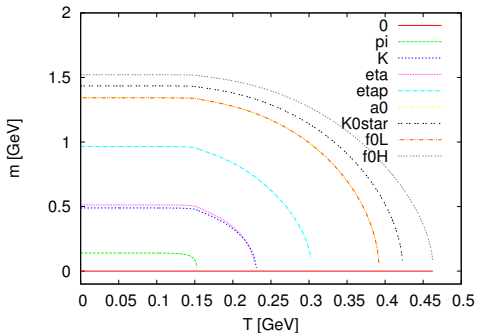
T dependence of the (pseudo)scalar masses

Curvature masses

Tree-level masses (e.g. pion mass):

$$m_\pi^2 = Z_\pi^2 [m_0^2 + \Lambda_N \Phi_N^2 + \lambda_1 \Phi_S^2]$$

$$Z_\pi = \frac{m_{a_1}}{\sqrt{m_{a_1}^2 - g_1^2 \phi_N^2}}$$



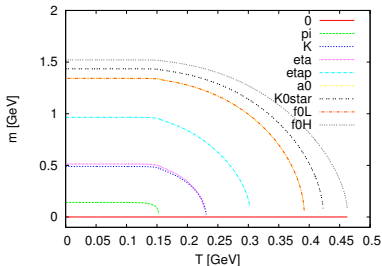
T dependence of the (pseudo)scalar masses

Curvature masses

“Dressed” masses (e.g. pion mass):

$$m_{\pi}^2 = Z_{\pi}^2 [m_0^2 + \Lambda_N \Phi_N^2 + \lambda_1 \Phi_S^2] + \text{something}$$

$$Z_{\pi} = \frac{m_{a_1}}{\sqrt{m_{a_1}^2 - g_1^2 \phi_N^2}}$$



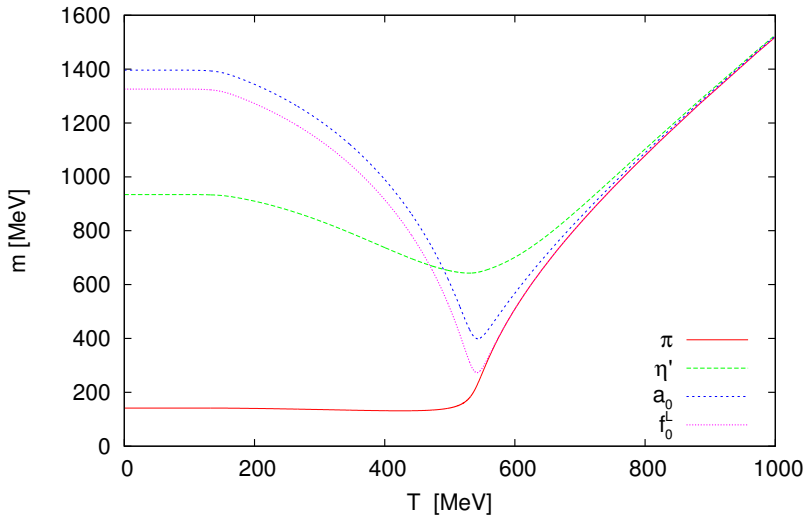
curvature mass contribution from the fermion grand canonical potential:

$$+ \frac{\partial^2 \Omega_q}{\partial \pi_a \partial \pi_b} \quad (2)$$

T dependence of the (pseudo)scalar masses

π, η', a_0, f_0^L masses with $m_{f_0^L} = 1326$ MeV

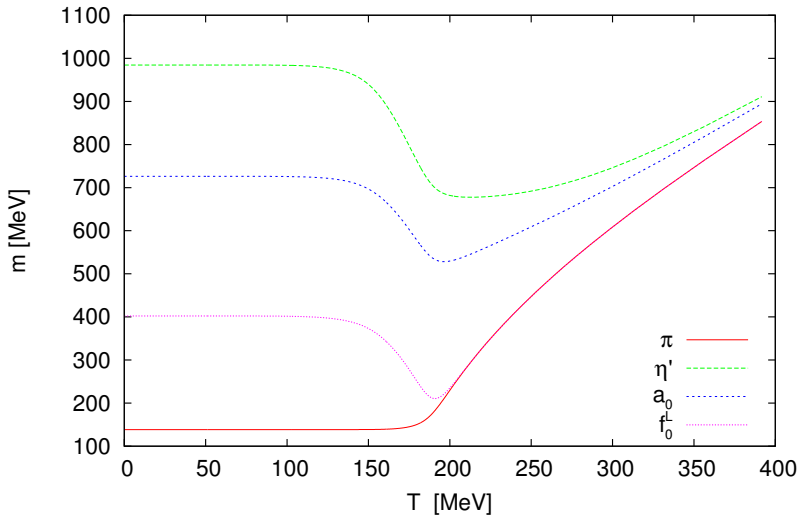
Masses with vacuum fluctuation



T dependence of the (pseudo)scalar masses

π, η', a_0, f_0^L masses with $m_{f_0^L} = 402$ MeV

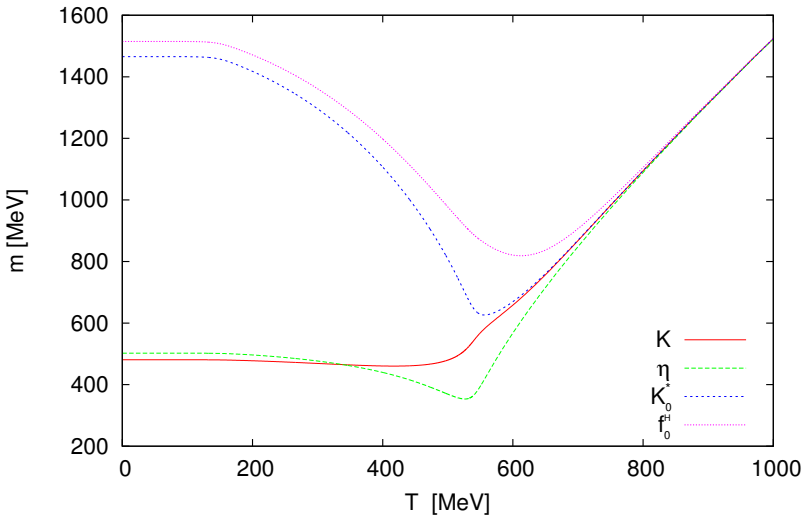
Masses with vacuum fluctuation



T dependence of the (pseudo)scalar masses

K, η, K^*, f_0^H masses with $m_{f_0^L} = 1326$ MeV

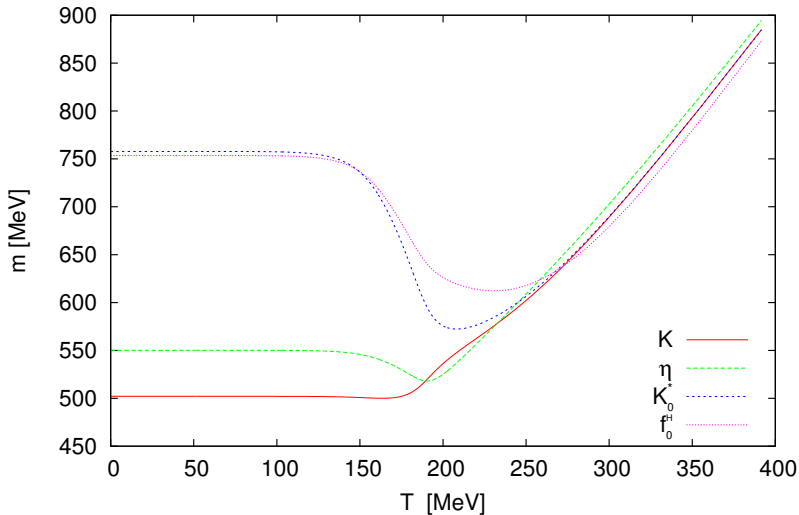
Masses with vacuum fluctuation



T dependence of the (pseudo)scalar masses

K, η, K^*, f_0^H masses with $m_{f_0^L} = 402$ MeV

Masses with vacuum fluctuation



Summary

- An extended linear σ -model was shown with constituent quarks and Polyakov-loops
- The meson phenomenology was very well described by scalars above 1 GeV
- We used hybrid approach at $T = 0$: only fermion loops, since it has the largest contribution
- At finite T/μ_B there was 4 coupled equations for the 4 order parameters
- The correct pseudocritical temperature requires low f_0 mass

Summary

- An extended linear σ - model was shown with constituent quarks and Polyakov - loops
 - The meson phenomenology was very well described by scalars above 1 GeV
 - We used hybrid approach at $T = 0$: only fermion loops, since it has the largest contribution
 - At finite T/μ_B there was 4 coupled equations for the 4 order parameters
 - The correct pseudocritical temperature requires low f_0 mass
- To do ...
- Explore the phase diagram for finite chemical potential as well, CEP
- Improve the vacuum phenomenology by tetraquarks (and glueballs)

Thank you for your attention!