Mire használható a kiterjesztett lineáris szigma modell?

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Overview

Based on the paper: arXiv:2407.18348

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High Energy Physics - Phenomenology

[Submitted on 25 Jul 2024]

Ordinary and exotic mesons in the extended Linear Sigma Model

Francesco Giacosa, Péter Kovács, Shahriyar Jafarzade

The extended Linear Sigma Model (eLSM) is a hadronic model based on the global symmetries of QCD and the corresponding explicit, anomalous, and spontaneous breaking patterns. In its basic three-flavor form, its mesonic part contains the dilaton/glueball as well as the nonets of (pseudo)scalar and (axial-)vector mesons, thus chiral symmetry is linearly realized. In the chiral limit and neglecting the chiral anomaly, only one term -- within the dilaton potential -- breaks dilatation invariance. Spontaneous symmetry breaking is implemented by a generalization of the Mexican-hat potential, with explicit symmetry breaking responsible for its tilting. The overall mesonic phenomenology up to 2 GeV is in agreement with the PDG compilation of masses and decay widths. The eLSM was enlarged to include other conventional quark-antiquark nonets (pseudovector and orbitally excited vector mesons, (axial-)tensor mesons, etc.), as well as two nonets of hybrid mesons, the lightest one with exotic quantum numbers $J^{PC}=1^{-+}$ not allowed for $\bar{q}q$ objects such as the resonance $\pi_1(1600)$ and the recently discovered $\eta_1(1855)$. In doing so, different types of chiral multiplets are introduced: heterochiral and homochiral multiplets, which differ in the way they transform under chiral transformations. Moreover, besides the scalar glueball, the tensor, the pseudoscalar and the vector glueballs were coupled to the eLSM: the scalar $f_0(1710)$ turns out to be mostly gluonic, the tensor glueball couples strongly to vector mesons, and the pseudoscalar glueball couples can be assigned to $X(2370)$ or $X(2600)$. The eLSM contains chiral partners on an equal footing and is therefore well suited for studies of chiral symmetry restoration at nonzero temperature and densities. The QCD phase diagram and the location of the critical endpoint were investigated within this framework.

Comments: Review paper about the extended Linear Sigma Model. Prepared for Progress in Particle and Nuclear Physics. 118 pages, 47 tables, 14 figures

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Lattice (hep-lat); High Energy Physics - Theory (hep-th)

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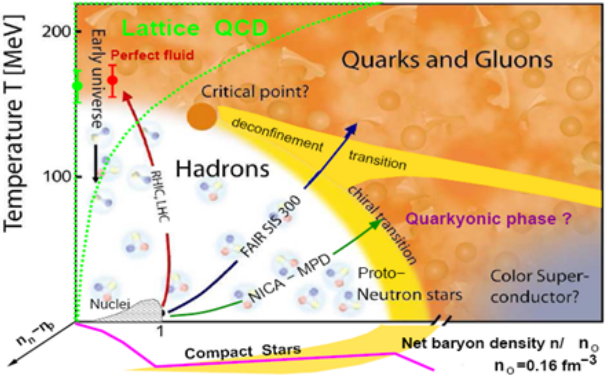
Conventional ($\bar{q}q$) mesons

L	S	$\mathcal{P}=(-1)^{L+1}$	$\mathcal{C}=(-1)^{L+S}$	$J^{\mathcal{PC}}$	$n^{2S+1}L_J$	Resonances
0	0	-1	$+1$	0^{-+}	1^1S_0	π, K, η, η'
1	1	$+1$	$+1$	0^{++}	1^3P_0	$a_0, K_0^*, f_{0,L}, f_{0,H}$
1	0	$+1$	-1	1^{+-}	1^1P_1	$b_1, K_{1,B}, h_{1,L}, h_{1,H}$
0	1	-1	-1	1^{--}	1^3S_1	$\rho, K^*, \omega_{1,L}=\omega, \omega_{1,H}=\phi$
1	1	$+1$	$+1$	1^{++}	1^3P_1	$a_1, K_{1,A}, f_{1,L}, f_{1,H}$
2	1	-1	-1	1^{--}	1^3D_1	$\rho_D, K_{1D}^*, \omega_D, \phi_D$
2	0	-1	$+1$	2^{-+}	1^1D_2	$\pi_2, K_2, \eta_2, \eta_2'$
1	1	$+1$	$+1$	2^{++}	1^3P_2	$a_2, K_2, f_{2,L}=f_2, f_{2,H}=f_2'$
2	1	-1	-1	2^{--}	1^3D_2	$\rho_2, K_2^*, \omega_{2,L}=\omega_2, \omega_{2,H}=\phi_2$
3	1	$+1$	$+1$	2^{++}	1^3F_2	$a_{2F}, K_{2F}, f_{2F,L}, f_{2F,H}$

Non-conventional mesons (like $J^{\mathcal{PC}}=1^{-+}$ do not appear), such exotic quantum numbers can be realized by glueballs and hybrid mesons.
(Note: If $J^{\mathcal{PC}}=1^{-+} \Longrightarrow L=2k$ (from P), $S=0$ (from C and $S\in(0,1)$), thus $J=2\ell$, so $J\neq 1$)

Envisaged phase diagram of QCD



Important details of the phase diagram is still unknown

Properties of the phase diagram especially at finite baryon densities/baryochemical potential can be well investigated with the help of effective field theories of QCD $\longrightarrow$ e.g. details of the phase boundary like existence and location of the CEP, in medium dependence of meson masses, or properties of compact stars etc.

Chiral symmetry, chiral models

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

$$\mathcal{G}_{cl} \equiv U(3)_L \times U(3)_R = U(1)_L \times U(1)_R \times \underbrace{SU(3)_L \times SU(3)_R}_{\mathcal{G}_{\text{chiral}}}$$

$$= \underbrace{U(1)_V}_{\text{baryon number}} \times \underbrace{U(1)_A}_{\text{axial}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\mathcal{G}_{\text{chiral}}}$$

$U(1)_V \longrightarrow$ baryon number conservation (exact symmetry of nature)

$U(1)_A \longrightarrow$ axial symmetry (connected to axial anomaly)

$SU(3)_L \times SU(3)_R \longrightarrow$ broken down to $SU(3)_V$ if $m_u = m_d = m_s \neq 0$;
or to $SU(2)_V$ if $m_u = m_d \neq m_s \neq 0$;
or to $U(1)_V$ if $m_u \neq m_d \neq m_s \neq 0$

Since QCD is very hard to solve $\longrightarrow$ low energy effective models $\longrightarrow$ 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))

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Lagrangian of the eLSM model

$\mathcal{L}$ constructed based on linearly realized global $U(3)_L \times U(3)_R$ symmetry and its explicit breaking

$$\begin{aligned}
\mathcal{L} = &\mathrm{Tr}[(D_\mu\Phi)^\dagger(D_\mu\Phi)] - m_0^2\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)^2 \\
&+ c_1(\det\Phi + \det\Phi^\dagger) + \mathrm{Tr}[H(\Phi+\Phi^\dagger)] - \frac{1}{4}\mathrm{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) \\
&+ \mathrm{Tr}\left[\left(\frac{m_1^2}{2}\mathbb{1} + \Delta\right)(L_\mu^2 + R_\mu^2)\right] + i\frac{g_2}{2}(\mathrm{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \mathrm{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
&+ \frac{h_1}{2}\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(L_\mu^2 + R_\mu^2) + h_2\mathrm{Tr}[(L_\mu\Phi)^2 + (\Phi R_\mu)^2] + 2h_3\mathrm{Tr}(L_\mu\Phi R^\mu\Phi^\dagger) \\
&+ \bar{\Psi}\left(i\gamma^\mu D_\mu - g_F(S - i\gamma_5 P)\right)\Psi - g_V\bar{\Psi}\left(\gamma^\mu(V_\mu + \gamma_5 A_\mu)\right)\Psi,
\end{aligned}$$

$$\begin{aligned}
\Phi &= S + iP \equiv \sum_{a=0}^{8}(S_a\lambda_a + iP_a\lambda_a) \\
D^\mu\Phi &= \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu) - ieA_e^\mu[T_3, \Phi], \\
L^{\mu\nu} &= \partial^\mu L^\nu - ieA_e^\mu[T_3, L^\nu] - \{\partial^\nu L^\mu - ieA_e^\nu[T_3, L^\mu]\}, \\
R^{\mu\nu} &= \partial^\mu R^\nu - ieA_e^\mu[T_3, R^\nu] - \{\partial^\nu R^\mu - ieA_e^\nu[T_3, R^\mu]\}, \\
D^\mu\Psi &= \partial^\mu\Psi - iG^\mu\Psi, \quad \text{with} \quad G^\mu = g_s G_a^\mu T_a.
\end{aligned}$$

+ Polyakov loop potential (for $T > 0$)

Particle content

- Vector and Axial-vector meson nonets

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N+\rho^0}{\sqrt{2}} & \rho^+ & K^{\star+} \\ \rho^- & \frac{\omega_N-\rho^0}{\sqrt{2}} & K^{\star 0} \\ K^{\star-} & \bar{K}^{\star 0} & \omega_S \end{pmatrix}^\mu \quad A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N}+a_1^0}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & \frac{f_{1N}-a_1^0}{\sqrt{2}} & K_1^0 \\ K_1^- & \bar{K}_1^0 & f_{1S} \end{pmatrix}^\mu$$

$\rho \to \rho(770), K^\star \to K^\star(894)$
$\omega_N \to \omega(782), \omega_S \to \phi(1020)$

$a_1 \to a_1(1230), K_1 \to K_1(1270)$
$f_{1N} \to f_1(1280), f_{1S} \to f_1(1426)$

- Scalar ($\sim \bar{q}_i q_j$) and pseudoscalar ($\sim \bar{q}_i \gamma_5 q_j$) meson nonets

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\sigma_N+a_0^0}{\sqrt{2}} & a_0^+ & K_0^{\star+} \\ a_0^- & \frac{\sigma_N-a_0^0}{\sqrt{2}} & K_0^{\star 0} \\ K_0^{\star-} & \bar{K}_0^{\star 0} & \sigma_S \end{pmatrix} \quad P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\eta_N+\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N-\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix}$$

multiple possible assignments
mixing in the $\sigma_N - \sigma_S$ sector

$\pi \to \pi(138), K \to K(495)$
mixing: $\eta_N, \eta_S \to \eta(548), \eta'(958)$

Spontaneous symmetry breaking: $\sigma_{N/S}$ acquire nonzero expectation values $\phi_{N/S}$
fields shifted by their expectation value: $\sigma_{N/S} \to \sigma_{N/S} + \phi_{N/S}$

In case of compact stars, also nonzero vector condensates

Determination of the parameters

14 unknown parameters $(m_0, \lambda_1, \lambda_2, c_1, m_1, g_1, g_2, h_1, h_2, h_3, \delta_S, \Phi_N, \Phi_S, g_F) \longrightarrow$ determined by the min. of χ^2:

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

$(x_1,\dots,x_N) = (m_0, \lambda_1, \lambda_2, \dots)$, $Q_i(x_1,\dots,x_N) \longrightarrow$ from the model, $Q_i^{\exp} \longrightarrow$ PDG value, $\delta Q_i = \max\{5\%, \text{PDG value}\}$

multiparametric minimalization $\longrightarrow$ MINUIT

- PCAC $\rightarrow$ 2 physical quantities: f_π, f_K
- Curvature masses $\rightarrow$ 16 physical quantities: $m_{u/d}, m_s, m_\pi, m_\eta, m_{\eta'}, m_K, m_\rho, m_\Phi, m_{K^\star}, m_{a_1}, m_{f_1^H}, m_{K_1}, m_{a_0}, m_{K_s}, m_{f_0^L}, m_{f_0^H}$
- Decay widths $\rightarrow$ 12 physical quantities: $\Gamma_{\rho\to\pi\pi}, \Gamma_{\Phi\to KK}, \Gamma_{K^\star\to K\pi}, \Gamma_{a_1\to\pi\gamma}, \Gamma_{a_1\to\rho\pi}, \Gamma_{f_1\to KK^\star}, \Gamma_{a_0}, \Gamma_{K_S\to K\pi},$ $\Gamma_{f_0^L\to\pi\pi}, \Gamma_{f_0^L\to KK}, \Gamma_{f_0^H\to\pi\pi}, \Gamma_{f_0^H\to KK}$
- Pseudocritical temperature T_c at $\mu_B = 0$

A usual (hybrid) approximation

- D.O.F's: – scalar, pseudoscalar, vector, and axial-vector nonets
  – u, d, s constituent quarks ($m_u = m_d$)
  – (Polyakov loop variables $\Phi, \bar{\Phi}$ with $\mathcal{U}_{\log}^{\mathrm{YM}}$ or $\mathcal{U}_{\log}^{\mathrm{glue}}$)
- no mesonic fluctuations, only fermionic ones
  $\mathcal{Z}=e^{-\beta V\Omega(T,\mu_q)}=\int\limits_{\mathrm{PBC}}\prod_a \mathcal{D}\xi_a \int\limits_{\mathrm{APBC}}\prod_f \mathcal{D}q_f\mathcal{D}q_f^\dagger \exp\left[-\int_0^\beta d\tau\int_V d^3x\left(\mathcal{L}+\mu_q\sum_f q_f^\dagger q_f\right)\right]$ approximated
  as $\Omega(T,\mu_q) = U_{\mathrm{meson}}^{\mathrm{tree}}(\langle M\rangle) + \Omega_{\bar{q}q}^{(0)}(T,\mu_q) + \mathcal{U}_{\log}(\Phi,\bar{\Phi})$, $\tilde{\mu}_q=\mu_q-iG_4$
  $e^{-\beta V\Omega_{\bar{q}q}^{(0)}}=\int\limits_{\mathrm{APBC}}\prod_{f,g}\mathcal{D}q_g\mathcal{D}q_f^\dagger \exp\left\{\int_0^\beta d\tau\int_x q_f^\dagger\left[\left(i\gamma_0\vec{\gamma}\cdot\vec{\nabla}-\frac{\partial}{\partial\tau}+\tilde{\mu}_q\right)\delta_{fg}-\gamma_0\mathcal{M}_{fg}|_{\xi_a=0}\right]q_g\right\}$
- tree-level (axial)vector masses
- fermionic thermal fluctuations included in the (pseudo)scalar curvature masses
- 2 (or 4) coupled T/μ_B-dependent field equations for the condensates $\phi_N, \phi_S, (\Phi, \bar{\Phi})$ at $N_c = 3$
- Polyakov-loops and fermionic vacuum fluctuations

Introduction to Polyakov-loops/Polyakov-loop variables

Definition of Polyakov-loop

$$L(\vec{x}) = \mathcal{P} \exp\left\{ i \int_0^\beta A_4 dt \right\}$$

Polyakov-loop variables:

$$\Phi(\vec{x}) = \frac{1}{N_c}\mathrm{Tr}_c L(\vec{x}), \text{ and } \bar{\Phi}(\vec{x}) = \frac{1}{N_c}\mathrm{Tr}_c L(\vec{x})^\dagger, \text{(non center } (C_n) \text{ symmetric)}$$

If $\Delta F_{q/\bar{q}}$ is a change in the free energy, when an infinitely heavy quark (or antiquark) is added to the system, than

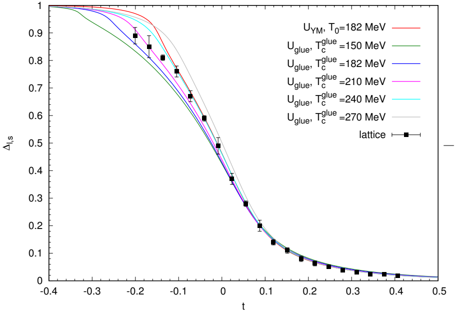
$$\langle\Phi(\vec{x})\rangle_\beta = e^{-\beta\Delta F_q(\vec{x})} \quad , \quad \langle\bar{\Phi}(\vec{x})\rangle_\beta = e^{-\beta\Delta F_{\bar{q}}(\vec{x})}$$ *Phys. Rev. D* 24 (1981) 450

- C_n symm. phase $\rightarrow \langle\Phi(\vec{x})\rangle_\beta = 0 \rightarrow \Delta F_{q/\bar{q}} = \infty \rightarrow$ confinement
- C_n NON symm. phase $\rightarrow \langle\Phi(\vec{x})\rangle_\beta \neq 0 \rightarrow \Delta F_{q/\bar{q}} < \infty \rightarrow$ deconfinement

Thus $\Phi(\vec{x})$ and $\bar{\Phi}(\vec{x})$ can be used as order parameters for confinement

t-dependence of the condensates compared to lattice results

The subtracted chiral condensate



– subtracted chiral condensate:

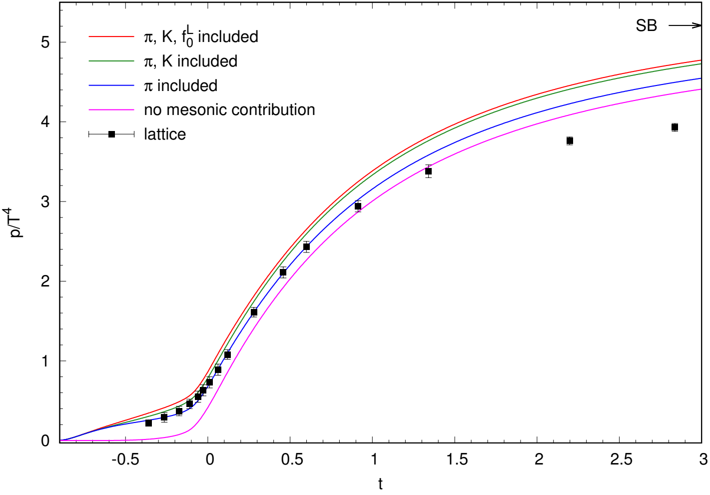
$$\Delta_{l,s} = \frac{\left(\phi_N - \frac{h_N}{h_S} \cdot \phi_S\right)\Big|_T}{\left(\phi_N - \frac{h_N}{h_S} \cdot \phi_S\right)\Big|_{T=0}}$$

– $U^{\text{glue}}_{\text{log}}$ with $T_c^{\text{glue}} \in (210, 240)$ MeV gives good agreement with the lattice result of

Borsányi *et al.*, JHEP 1009, 073 (2010)

here we use the reduced temperature: $t = (T - T_c)/T_c$

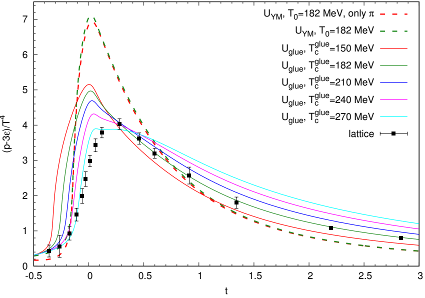
Normalized pressure and the effects of meson contributions



- pions dominate the pressure at small T
- contribution of the kaons is important
- at high T the pressure overshoots the lattice data of Borsányi *et al.*, JHEP 1011, 077 (2010)

Scaled interaction measure, speed of sound and p/ϵ

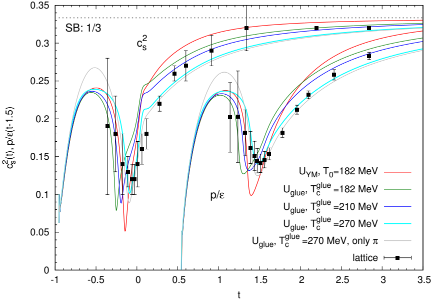
Scaled interaction measure



$$\Delta = \frac{\varepsilon - 3p}{T^4}$$

By properly setting the T_c^{glue} parameter $\longrightarrow$ good agreement with lattice

Speed of sound and p/ϵ



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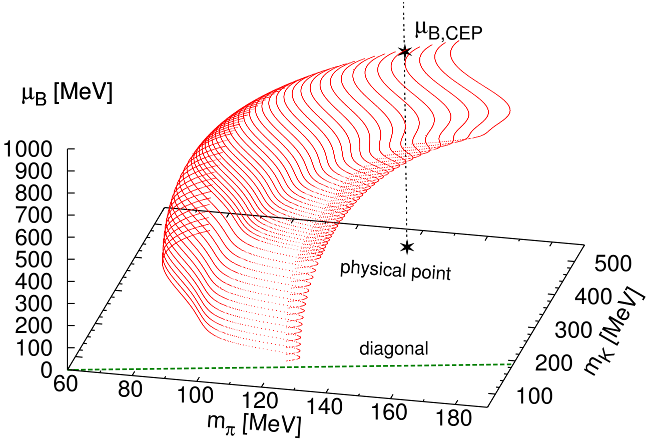
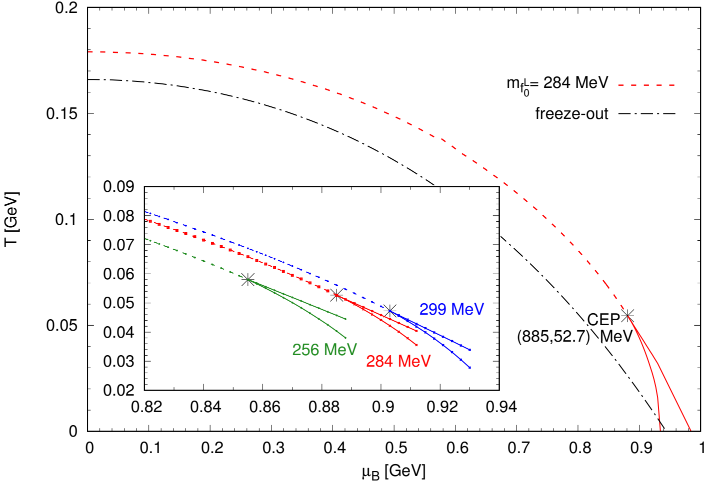
Second order surface in $m_\pi - m_K - \mu_B$

ChPT for baryons used to obtain the value of $m_{u,s}$ P. Kovács, Zs. Sz, PRD75 (2007) 025015



The surface bends towards the physical point $\Longrightarrow$ existence of CEP

$T - \mu_B$ Phase Diagram



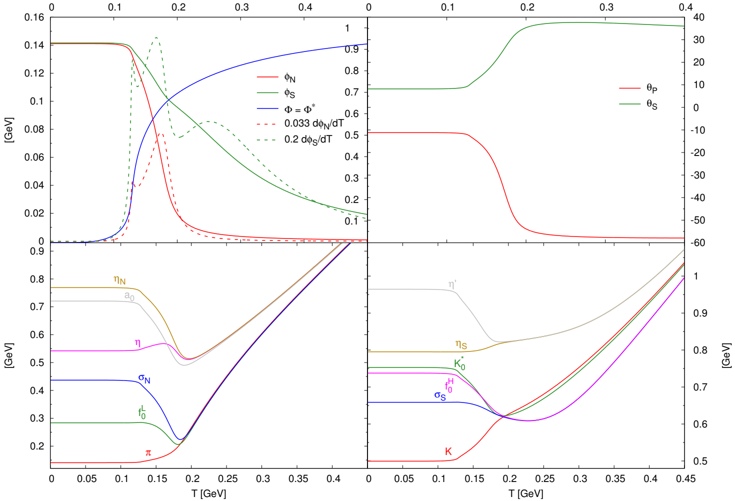
– we used $U_{\log}^{\mathrm{glue}}$ with $T_c^{\mathrm{glue}} = 210$ MeV

– freeze-out curve from Cleymans *et al.*, J.Phys.G 32, S165 (2006)

– curvature κ at $\mu_B = 0$ obtained from the fit $\frac{T_c(\mu_B)}{T_c(\mu_B{=}\mathbf{0})} = 1 - \kappa \left(\frac{\mu_B}{T_c(\mu_B{=}\mathbf{0})} \right)^{\mathbf{2}}$

$\kappa = 0.0193$ obtained, close to the lattice value $\kappa = 0.020(4)$ of Cea *et al.*,PRD93, 014507

T dependence of masses, condensates, mixing angles



- ch. partners (π, f_0^L), (η, a_0) and $(K, K_0^\star)$, (η', f_0^H) become degenerate at high T
- $U(1)_A$ not restored, axial partners (π, a_0) and (η, f_0^L) not become degenerate

Structure of compact stars

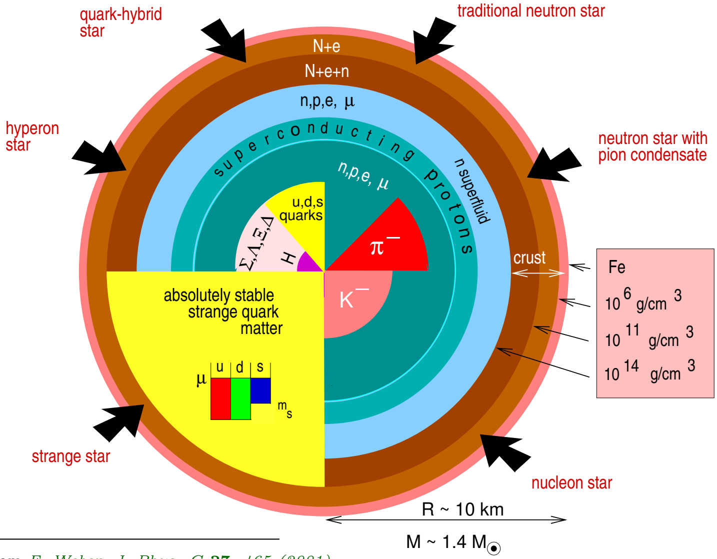
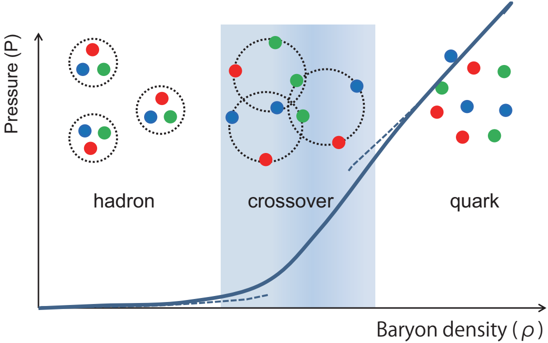


Fig. from *F. Weber, J. Phys. G* **27**, *465 (2001)*

Hybrid EoS for hybrid stars

K. Masuda et al., PTEP **2013** *073D01*



In the crossover region hadrons starts to overlap

⟶ both low and high ρ_B models loose their validity

Gibbs condition (extrapolation from the dashed lines) can be misleading

EoS part I (hadronic part)

Hybrid stars also have a hadronic crust and outer core

- at low densities we use hadronic EoSs:
  - the SFHo EoS to represent soft hadronic EoSs
  - the DD2 to represent stiff hadronic EoSs
- we apply a smooth connection between the two phases: $\varepsilon(n_B)$ interpolation with polynomial

$$\varepsilon(n_B) = \sum_{m=0}^{N} C_m n_B^m \,, \quad n_{BL} < n_B < n_{BU},$$

  the C_m coefficients given by the matching of the ε and its derivatives on the boundary
- we have 4 adjustable parameters:
  - 2 from the constituent quark model: m_σ, g_V
  - 2 describing the concatenation: $\bar{n}$, Γ

EoS part II (quark part)

For large density the e(P)QM model is used

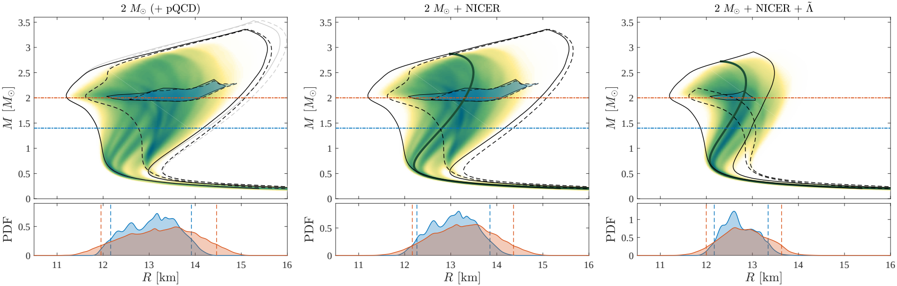
- nonzero scalar condensates: $\phi_N = \langle \sigma_N \rangle$, $\phi_S = \langle \sigma_S \rangle$
- nonzero vector condensates: $\langle (\rho^0)^0 \rangle = \phi_\rho$, $\langle (\omega)^0 \rangle = \phi_\omega$, $\langle (\Phi)^0 \rangle = \phi_\Phi$
- free electron gas + β-equilibrium
- modified chemical potentials:

$$\mu_u = \mu_q - \frac{2}{3}\mu_e - \frac{1}{2}g_V(\phi_\omega + \phi_\rho)$$
$$\mu_d = \mu_q + \frac{1}{3}\mu_e - \frac{1}{2}g_V(\phi_\omega - \phi_\rho)$$
$$\mu_s = \mu_q + \frac{1}{3}\mu_e - \frac{1}{\sqrt{2}}g_V\phi_\Phi$$

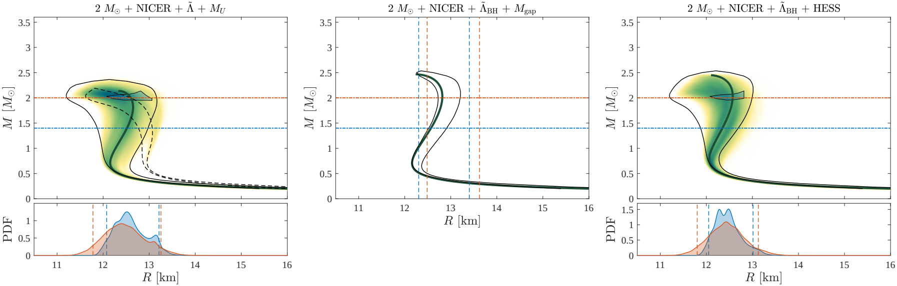
- charge neutrality: $\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$
- field equations (FEs):

$$\frac{\partial \Omega_{tot}}{\partial \phi_N} = \frac{\partial \Omega_{tot}}{\partial \phi_S} = \frac{\partial \Omega_{tot}}{\partial \phi_\rho} = \frac{\partial \Omega_{tot}}{\partial \phi_\omega} = \frac{\partial \Omega_{tot}}{\partial \phi_\Phi} = 0 \quad \to p(\varepsilon)\text{curve}$$

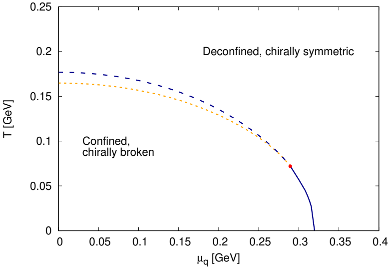
Restriction of $M-R$ curves with Bayesian analysis I

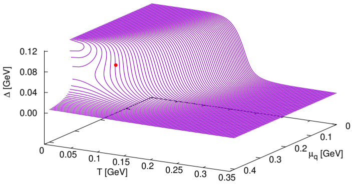


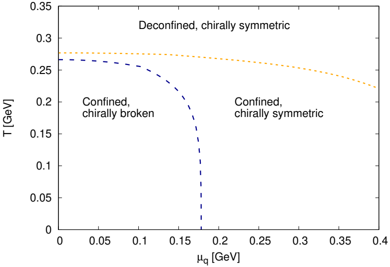
Restriction of $M - R$ curves with Bayesian analysis II

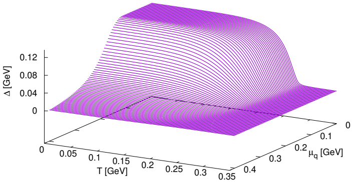


Phase boundary for different N_cs *I.*



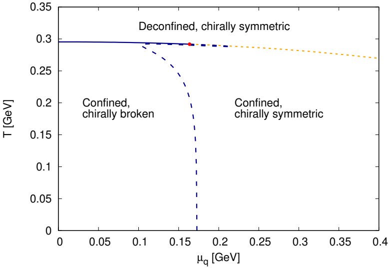


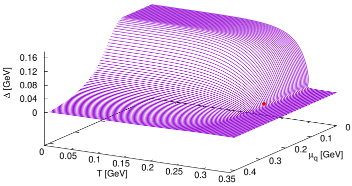




top: $N_c = 3$, CEP exist, crossover for small T; *bottom* : $N_c = 33$ crossover everywhere

Phase boundary for different N_cs *II.*

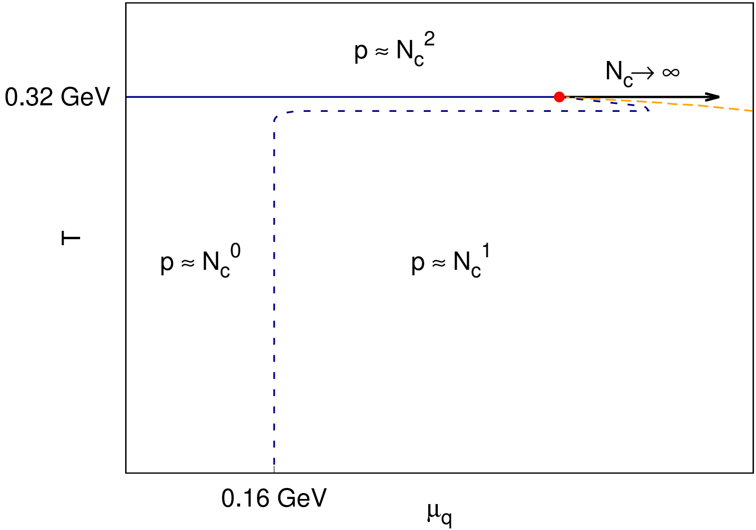




$N_c = 63$ CEP exist again, crossover for large T

$$\Delta(T, \mu_q^{\text{fix}}) = \frac{(\phi_N - \frac{h_N}{h_S}\phi_S)|_{T,\mu_q^{\text{fix}}}}{(\phi_N - \frac{h_N}{h_S}\phi_S)|_{T=0,\mu_q^{\text{fix}}}} \qquad (1)$$

Schematic phase structure for large N_c (conclusion)



see: Phys. Rev. D **106**, 116016

Conclusion

- eLSM can be used to study the properties of various meson nonnets, such as their masses or decay widths, based on the global chiral symmetries of QCD.
- eLSM can be used in the vacuum or at finite temperature and baryon chemical potentials, and it is free from the sign problem found on the Lattice.
- In recent years, more and more precise observations, e.g. mass, radius, tidal deformability, have been made, from which in-medium properties of strongly interacting matter can be inferred, which can be studied with eLSM.
- The $M - R$ curves calculated so far are consistent with current observations when certain parameters of the model are constrained (e.g. $2.5 < g_V < 4.3$)
- The phase diagram at large N_c can also be studied within the eLSM. Three different scaling regions of the pressure can be found, while the CEP interestingly disappears along the μ_B axis and reappears along the T axis as N_c is increased.
- For more details, see https://arxiv.org/abs/2407.18348

Thank you for your attention!

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L. Kassák: Image architecture

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Tolman-Oppenheimer-Volkoff (TOV) equation

Solving the Einstein's equation for spherically symmetric case and homogeneous matter $\longrightarrow$ TOV eqs.:

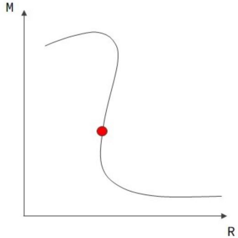
$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{[p(r)+\varepsilon(r)]\,[M(r)+4\pi r^3 p(r)]}{r[r-2M(r)]} \tag{2}$$

where

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \varepsilon(r)$$

These are integrated numerically for a specific EoS ($p(\varepsilon)$):

- For a fixed ε_c central energy density Eq. (2) is integrated until $p = 0$
- Varying ε_c a series of compact stars is obtained (with given M and R)
- Once the maximal mass is reached, the stable series of compact stars ends



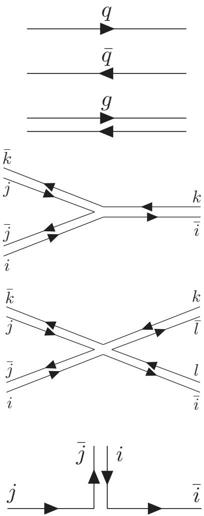
Basics of Large N_c I.

G. 't Hooft. (1974), Nucl. Phys. B 72:461

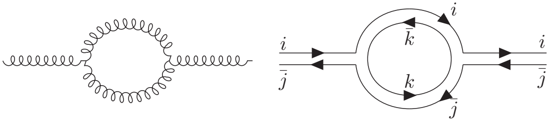
G. 't Hooft. (1974), Nucl. Phys. B 75:461–470

E. Witten. (1979), Nucl. Phys. B 160:57–115

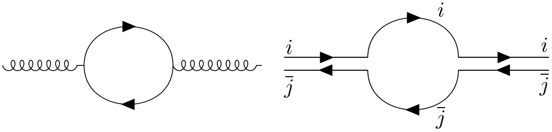
- No expansion parameter in QCD if $m_{u/d/s} \approx 0 \longrightarrow$ not so obvious expansion parameter: N_c
- $SU(3) \longrightarrow SU(N_c)$
- double line notation based on color structure of gluons: $A^{\mu;\,i}_{j} \sim q^i \bar{q}_j$
- 3-coupling: $A^i_{\mu;\,j} A^j_{\nu;\,k} \partial^\mu A^{\nu;\,k}_i$
- 4-coupling: $A^i_{\mu;\,j} A^j_{\nu;\,k} A^{\mu;\,k}_l A^{\nu;\,l}_i$
- quark - gluon vertex: $\bar{q}_i \gamma^\mu q^j A^i_{\mu;\,j}$



Basics of Large N_c II.



N_c combinatorial factor due to closed color loop $\implies$ $g \sim \frac{1}{\sqrt{N_c}}$



Quark loops are $1/N_c$ suppressed.

Leading diagrams are palanar diagrams with minimum number of quark loops

Investigation of N-point functions of quark bilinears ($J = \bar{q}q,\ \bar{q}\gamma^\mu q$) leads to the large N_c properties of mesons

Properties of mesons and baryons for Large N_c

- mesons are free, stable, and non-interacting
- mesons are pure $q\bar{q}$ states for large N_c
- meson masses $\sim N_c^0$
- meson decay amplitudes $\sim 1/\sqrt{N_c}$
- for one meson creation: $< 0|J|m > \sim \sqrt{N_c}$
- k meson vertex $\sim N_c^{1-k/2}$. Specifically, the three- and four-meson vertices are $\sim 1/\sqrt{N_c}$ and $\sim 1/N_c$, respectively
- baryon masses $\sim N_c$. Consequently constituent quark masses $\sim N_c^0$

N_c scaling of the Lagrange parameters

The parameters are: $m_0, \lambda_1, \lambda_2, c_1, m_1, g_1, g_2, h_1, h_2, h_3, \delta_S,\ \Phi_N, \Phi_S, g_F,\ h_{N/S}$

- $m_0^2,\ m_1^2,\ \delta_s \sim N_c^0$, because terms of tree level meson masses
- $g_1,\ g_2 \sim \frac{1}{\sqrt{N_c}}$, three couplings
- $\lambda_2,\ h_2,\ h_3 \sim \frac{1}{N_c}$, four couplings
- $\lambda_1,\ h_1 \sim \frac{1}{N_c^2}$, four couplings with different trace structure
- $c_1 \sim \frac{1}{N_c^{3/2}}$ $U_A(1)$ anomaly term has extra $1/N_c$ suppression
- $h_{N/S} \sim \sqrt{N_c}$, Goldstone-theorem: $m_\pi^2 \Phi_N = Z_\pi^2 h_N$ + PCAC: $\Phi_N = Z_\pi f_\pi$
- $g_F \sim \frac{1}{\sqrt{N_c}},\ m_{u/d} = g_F \Phi_N$

We expect $\Phi_{N/S} \sim \sqrt{N_c}$, since $\Phi_N = Z_\pi f_\pi,\ f_\pi \sim \sqrt{N_c}$, but have to check!

practically: $g_1 \longrightarrow g_1\sqrt{\frac{3}{N_c}},\ h_{N/S} \longrightarrow h_{N/S}\sqrt{\frac{N_c}{3}} \ldots$ *etc.*

Parameter sets at $N_c = 3$

Parameter	Set A	Set B
ϕ_N [GeV]	0.1411	0.1290
ϕ_S [GeV]	0.1416	0.1406
m_0^2 [GeV^2]	2.3925_{E-4}	-1.2370_{E-2}
m_1^2 [GeV^2]	6.3298_{E-8}	0.5600
λ_1	-1.6738	-1.0096
λ_2	23.5078	25.7328
c_1 [GeV]	1.3086	1.4700
δ_S [GeV^2]	0.1133	0.2305
g_1	5.6156	5.3295
g_2	3.0467	-1.0579
h_1	37.4617	5.8467
h_2	4.2281	-12.3456
h_3	2.9839	3.5755
g_F	4.5708	4.9571
M_0 [GeV]	0.3511	0.3935

- Set A: $m_\sigma = 290$ MeV from Phys.Rev.D 93 (2016) 11, 114014
- Set B: similar m_σ mass and additional constraint, $3h_1 + 2h_2 + 2h_3 < 0$ from Phys.Rev.D 105 (2022) 10, 103014

Polyakov-loop variables at large N_c (I.)

Polyakov gauge → A_4 is diagonal and time independent
→ further simplification: homogeneous gluon filed

$$L = e^{i\beta A_4} = \mathrm{diag}\left(e^{iq_1}, \ldots, e^{iq_{N_c}}\right), \quad q_j \in \mathbb{R}, \quad \sum_j q_j = 0$$

$N_c - 1$ independent diagonal $SU(N_c)$ matrix → Φ and $\bar{\Phi}$ above are not enough

$$\Phi_n = \frac{1}{N_c}\mathrm{Tr}_c L^n, \quad \bar{\Phi}_n = \frac{1}{N_c}\mathrm{Tr}_c L^{\dagger n}, \quad n \in \left(1, \ldots, \lfloor\frac{N_c}{2}\rfloor\right),$$ Phys. Rev. D 86, 105017 (2012)

our approx. → quarks prop. on a const. gluon background → color dep. chem. pot.

$$\Omega^{(0)}_{\bar{q}q}(T, \mu_q) = \Omega^{(0)\mathrm{v}}_{\bar{q}q} + \Omega^{(0)\mathrm{T}}_{\bar{q}q}(T, \mu_q),$$

$$\Omega^{(0)\mathrm{T}}_{\bar{q}q}(T, \mu_q) = -2T\sum_f \int \frac{d^3p}{(2\pi)^3}\left[\ln g_f^+(p) + \ln g_f^-(p)\right]$$

$$\ln g_f^+(p) \equiv \mathrm{Tr}_c \ln\left[\mathbb{1} + L^\dagger e^{-\beta(E_f(p)-\mu_q)}\right] = \ln \mathrm{Det}_c\left[\mathbb{1} + L^\dagger e^{-\beta(E_f(p)-\mu_q)}\right]$$

$$\ln g_f^-(p) \equiv \mathrm{Tr}_c \ln\left[\mathbb{1} + L e^{-\beta(E_f(p)+\mu_q)}\right] = \ln \mathrm{Det}_c\left[\mathbb{1} + L e^{-\beta(E_f(p)+\mu_q)}\right]$$