Impact of finite magnetic field and volume on the susceptibilities of conserved charges

INDIA-JINR Workshop, 2023

Nisha Chahal

under the supervision of

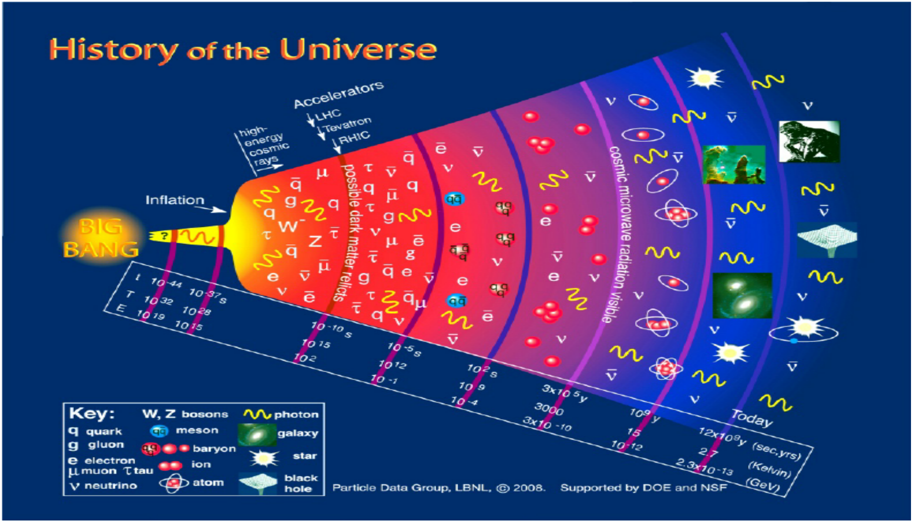
Dr. Suneel Dutt and Dr. Arvind Kumar

Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, India

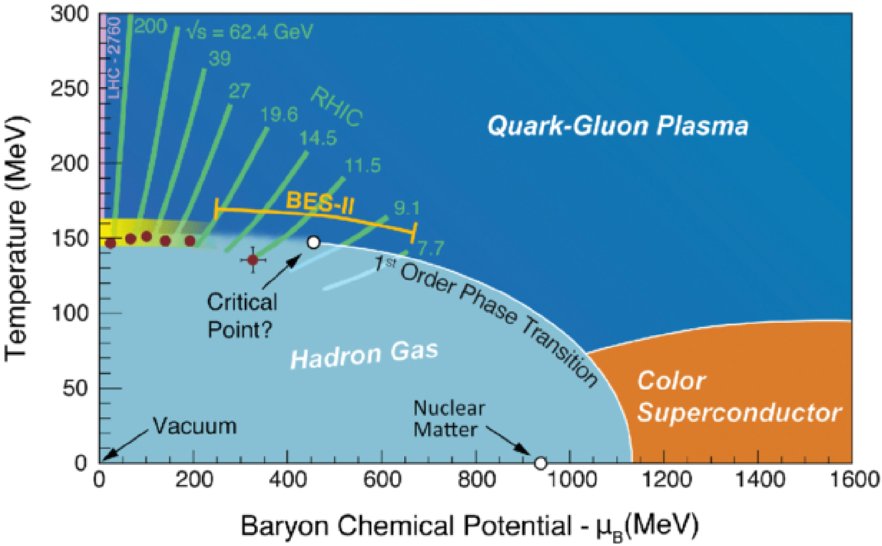
October 17, 2023

Outline

INTRODUCTION



QCD Phase Diagram



Outline

Chiral SU(3) Quark Mean Field Model

Lagrangian density

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{q0} + \mathcal{L}_{qm} + \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{VV} + \mathcal{L}_{SB} + \mathcal{L}_{\Delta m} + \mathcal{L}_{h}. \tag{1}$$

- $\mathcal{L}_{q0}$ is the free part of massless quarks.
- $\mathcal{L}_{qm}$ quark meson interaction term.
- $\mathcal{L}_{\Sigma\Sigma}$ scalar meson self-interaction term (σ, ζ, χ and δ fields).
- $\mathcal{L}_{VV}$ vector meson self-interaction term (ω, ρ and ϕ fields).
- $\mathcal{L}_{SB}$, $\mathcal{L}_{\Delta m}$ and $\mathcal{L}_{h}$ are explicit symmetry breaking terms.

Chiral SU(3) Quark Mean Field Model

Thermodynamical potential density

$$\Omega = \sum_{i=u,d,s} \frac{-2\mathrm{k_B T}\gamma_\mathrm{i}}{(2\pi)^3} \int_0^\infty d^3k \, [\ln(1 + e^{-(\mathrm{E_i^*(k)} - \nu_\mathrm{i})/\mathrm{k_B T}}) + \ln(1 + e^{-(\mathrm{E_i^*(k)} + \nu_\mathrm{i})/\mathrm{k_B T}})] - \mathcal{L}_M, \quad (2)$$

- $\mathcal{L}_\mathrm{M} = \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_\mathrm{VV} + \mathcal{L}_\mathrm{SB}$.
- $\mathrm{E_i^*(k)} = \sqrt{m_i^{*2} + k^2}$ is the effective single particle energy of quarks.
- $\mathrm{m_i}^* = -\mathrm{g}^\mathrm{i}_\sigma \sigma - \mathrm{g}^\mathrm{i}_\zeta \zeta - \mathrm{g}^\mathrm{i}_\delta \delta + \mathrm{m_{i0}}$ is effective constituent quark mass.
- $\nu_\mathrm{i}^* = \mu_\mathrm{i} - \mathrm{g}^\mathrm{i}_\omega \omega - \mathrm{g}^\mathrm{i}_\phi \phi - \mathrm{g}^\mathrm{i}_\rho \rho$ is effective chemical potential.
- γ_i is spin degeneracy factor for quarks(γ_i=3) and electrons (γ_i=1).

Polyakov Chiral SU(3) quark mean field model

Polyakov loop

$$\Phi(\tilde{x}) = (\mathrm{Tr_c L})/\mathrm{N_C}, \tag{3}$$

and its conjugate

$$\bar{\Phi}(\tilde{x}) = (\mathrm{Tr_c L^\dagger})/\mathrm{N_C}. \tag{4}$$

Total lagrangian density

$$\mathcal{L}_{\mathrm{PCQMF}} = \mathcal{L}_{\mathrm{eff}} \; -$$

Polyakov Chiral SU(3) quark mean field model

Polyakov loop

$$\Phi(\tilde{x}) = (\mathrm{Tr_c L})/\mathrm{N_C}, \tag{3}$$

and its conjugate

$$\bar{\Phi}(\tilde{x}) = (\mathrm{Tr_c L^{\dagger}})/\mathrm{N_C}. \tag{4}$$

Total lagrangian density

$$\mathcal{L}_{\mathrm{PCQMF}} = \mathcal{L}_{\mathrm{eff}} - \mathcal{U}(\Phi(\tilde{x}), \bar{\Phi}(\tilde{x}), \mathrm{T}), \tag{5}$$

Modified thermodynamical potential density

$$\Omega_{\mathrm{PCQMF}} = -2k_BT \sum_{u,d,s} \int_0^{\infty} \frac{d^3k}{(2\pi)^3} [\ln(1 + e^{-3(\mathrm{E_i^*(k)}-\nu_{\mathrm{i}})./\mathrm{k_B T}} + 3\Phi e^{-(\mathrm{E_i^*(k)}-\nu_{\mathrm{i}})./\mathrm{k_B T}} + 3\bar{\Phi} e^{-2(\mathrm{E_i^*(k)}-\nu_{\mathrm{i}})./\mathrm{k_B T})} + \ln(1 + e^{-3(\mathrm{E_i^*(k)}+\nu_{\mathrm{i}})./\mathrm{k_B T}} + 3\bar{\Phi} e^{-(\mathrm{E_i^*(k)}+\nu_{\mathrm{i}})./\mathrm{k_B T}} + 3\Phi e^{-2(\mathrm{E_i^*(k)}+\nu_{\mathrm{i}})./\mathrm{k_B T})}] + \mathcal{U}(\Phi, \bar{\Phi}, \mathrm{T}), \tag{6}$$

Polyakov Chiral SU(3) quark mean field model

here, $\mathcal{U}(\Phi(\tilde{x}), \bar{\Phi}(\tilde{x}), T)$ is temperature dependent Polyakov loop effective potential,

$$\frac{\mathcal{U}(\Phi, \bar{\Phi}, T)}{T^4} = -\frac{a(T)}{2}\bar{\Phi}\Phi + b(T)\ln[1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2], \tag{7}$$

with T-dependent parameters:

$$a(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2, \quad b(T) = b_3\left(\frac{T_0}{T}\right)^3. \tag{8}$$

a_0	a_1	a_2	b_3
3.51	-2.47	15.2	-1.75

Table 1: Parameters in Polyakov effective potential

Outline

Magnetic field and volume effects

- The total thermodynamical potential is altered and the term giving the contribution of quarks and antiquarks interaction is written as

$$\Omega_{q\bar{q}} = -\sum_{i=u,d,s} \frac{|q_i|\, BT}{2\pi} \sum_{k=0}^{\infty} \alpha_k \int_{-\infty}^{\infty} \frac{dp_z}{2\pi} \left(\ln g_i^+ + \ln g_i^-\right). \tag{9}$$

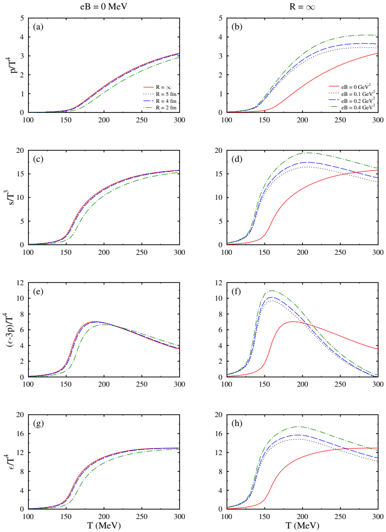
- Total effective energy of the quarks is modified as

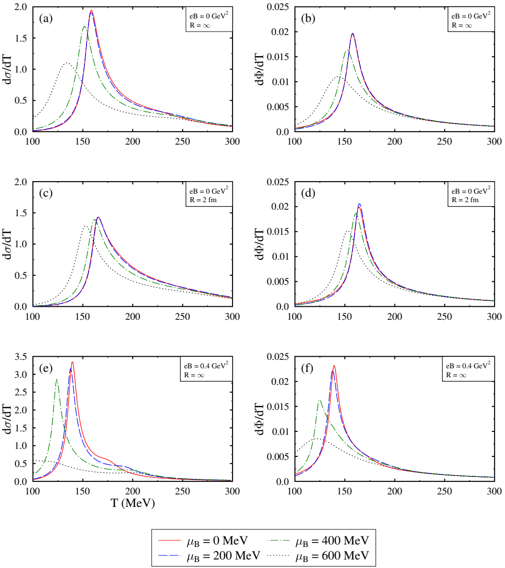
$$E_i^* = \sqrt{p_z^2 + m_i^{*2} + |q_i|\,(2n + 1 - \Upsilon)B}, \tag{10}$$

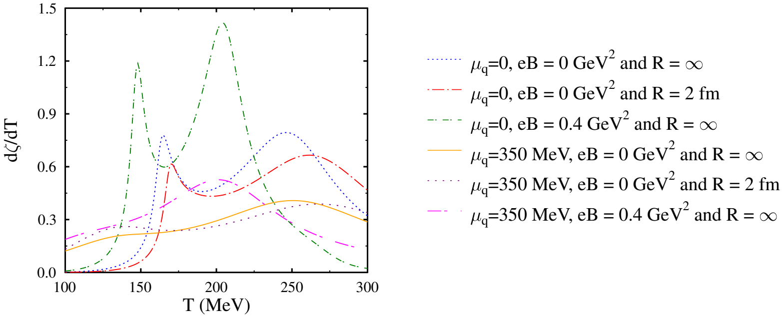
- The impact of the finite size effect is assimilated in the model by using the approximation method defined in by introducing a lower momentum cutoff, p_{min} [MeV] = π/R [MeV] = Λ, where R is the length of a cubic volume.

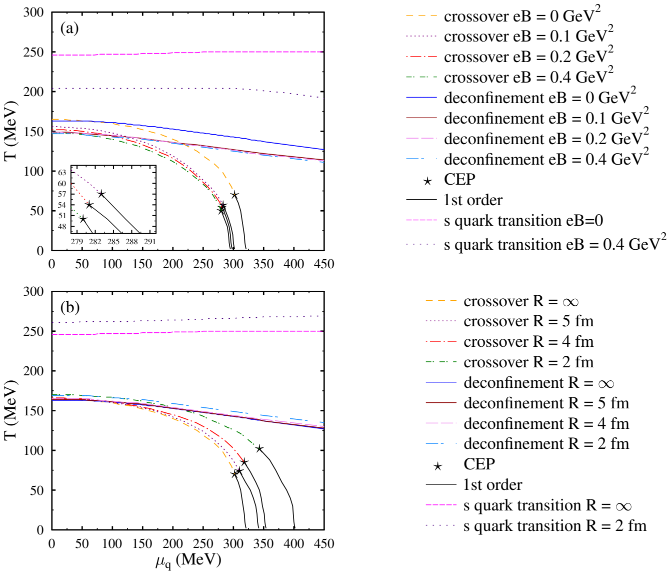
Outline

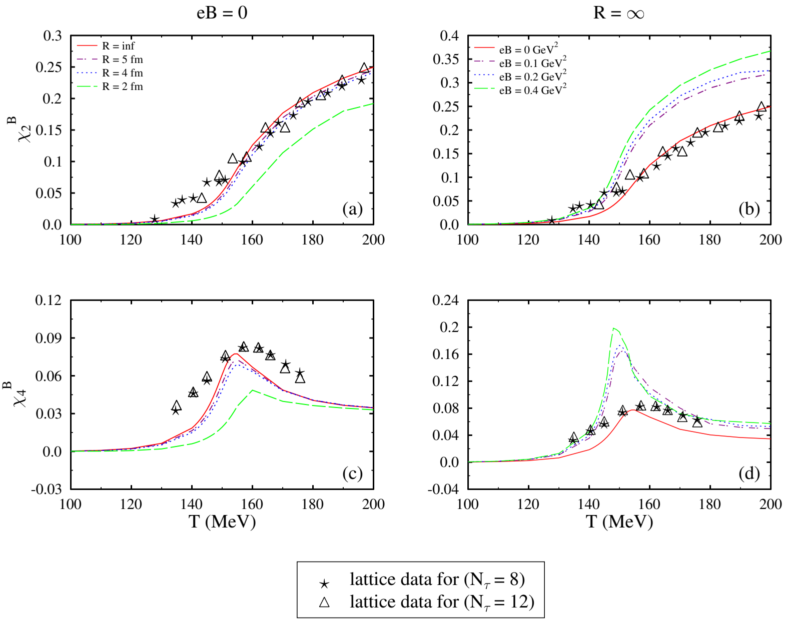
Results

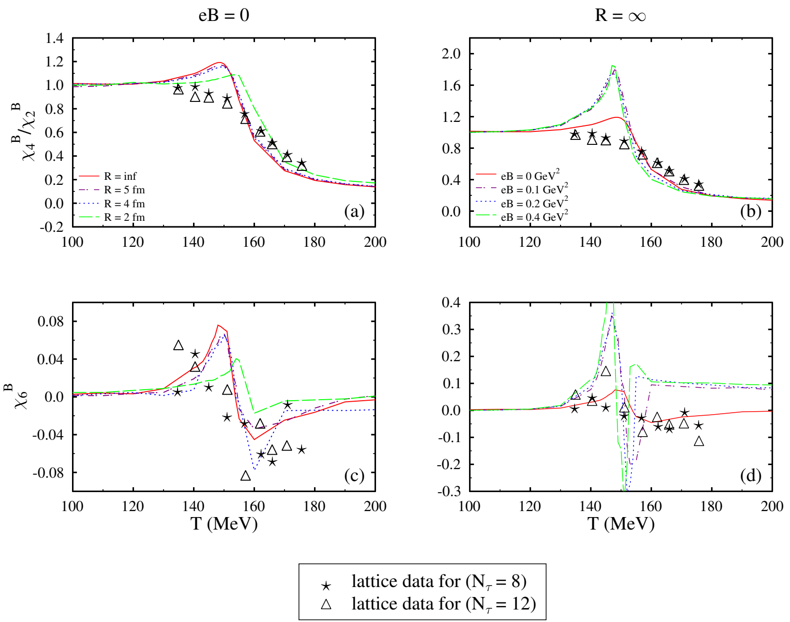

eB = 0 MeV
R = ∞
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
p/T^4
s/T^3
(ϵ-3p)/T^4
ϵ/T^4
T (MeV)
R = ∞
R = 5 fm
R = 4 fm
R = 2 fm
eB = 0 GeV^2
eB = 0.1 GeV^2
eB = 0.2 GeV^2
eB = 0.4 GeV^2

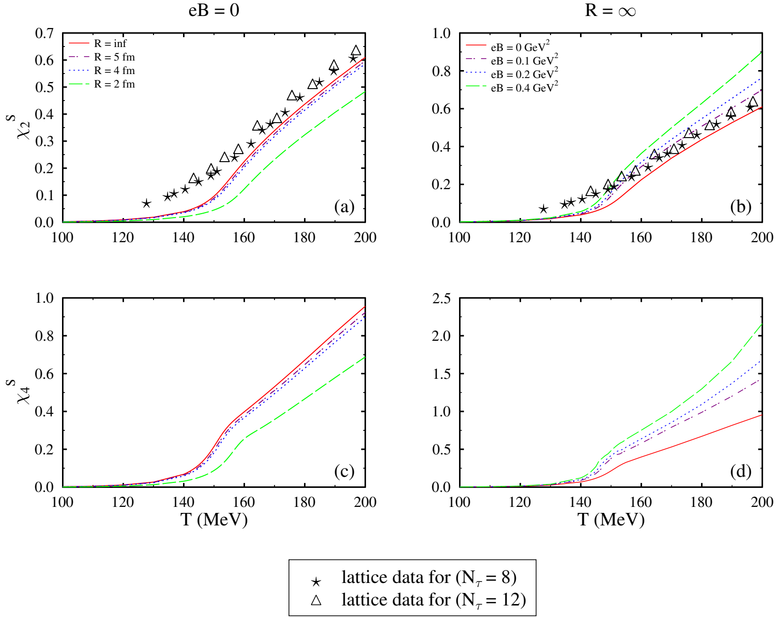

(a)
eB = 0 GeV^2
R = ∞
dσ/dT
(b)
eB = 0 GeV^2
R = ∞
dΦ/dT
(c)
eB = 0 GeV^2
R = 2 fm
dσ/dT
(d)
eB = 0 GeV^2
R = 2 fm
dΦ/dT
(e)
eB = 0.4 GeV^2
R = ∞
dσ/dT
(f)
eB = 0.4 GeV^2
R = ∞
dΦ/dT
T (MeV)
μ_B = 0 MeV
μ_B = 200 MeV
μ_B = 400 MeV
μ_B = 600 MeV

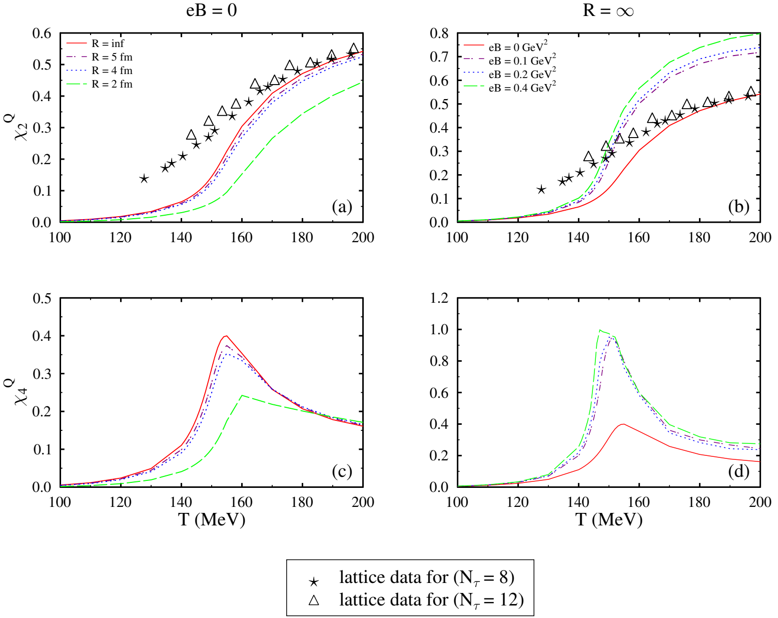

1.5
1.2
0.9
0.6
0.3
0.0
dζ/dT
100
150
200
250
300
T (MeV)
μq=0, eB = 0 GeV2 and R = ∞
μq=0, eB = 0 GeV2 and R = 2 fm
μq=0, eB = 0.4 GeV2 and R = ∞
μq=350 MeV, eB = 0 GeV2 and R = ∞
μq=350 MeV, eB = 0 GeV2 and R = 2 fm
μq=350 MeV, eB = 0.4 GeV2 and R = ∞


(a)
T (MeV)
0
50
100
150
200
250
300
350
400
450
crossover eB = 0 GeV^2
crossover eB = 0.1 GeV^2
crossover eB = 0.2 GeV^2
crossover eB = 0.4 GeV^2
deconfinement eB = 0 GeV^2
deconfinement eB = 0.1 GeV^2
deconfinement eB = 0.2 GeV^2
deconfinement eB = 0.4 GeV^2
CEP
1st order
s quark transition eB=0
s quark transition eB = 0.4 GeV^2
(b)
T (MeV)
μ_q (MeV)
crossover R = ∞
crossover R = 5 fm
crossover R = 4 fm
crossover R = 2 fm
deconfinement R = ∞
deconfinement R = 5 fm
deconfinement R = 4 fm
deconfinement R = 2 fm
CEP
1st order
s quark transition R = ∞
s quark transition R = 2 fm


eB = 0
R = ∞
R = inf
R = 5 fm
R = 4 fm
R = 2 fm
eB = 0 GeV²
eB = 0.1 GeV²
eB = 0.2 GeV²
eB = 0.4 GeV²
(a)
(b)
(c)
(d)
χ_2^B
χ_4^B
T (MeV)
T (MeV)
lattice data for (N_τ = 8)
lattice data for (N_τ = 12)


eB = 0
R = ∞
χ4B/χ2B
χ6B
R = inf
R = 5 fm
R = 4 fm
R = 2 fm
eB = 0 GeV²
eB = 0.1 GeV²
eB = 0.2 GeV²
eB = 0.4 GeV²
(a)
(b)
(c)
(d)
T (MeV)
T (MeV)
lattice data for (Nτ = 8)
lattice data for (Nτ = 12)


eB = 0
R = ∞
R = inf
R = 5 fm
R = 4 fm
R = 2 fm
eB = 0 GeV^2
eB = 0.1 GeV^2
eB = 0.2 GeV^2
eB = 0.4 GeV^2
χ_2^S
χ_4^S
(a)
(b)
(c)
(d)
T (MeV)
lattice data for (N_τ = 8)
lattice data for (N_τ = 12)


eB = 0
R = ∞
R = inf
R = 5 fm
R = 4 fm
R = 2 fm
eB = 0 GeV²
eB = 0.1 GeV²
eB = 0.2 GeV²
eB = 0.4 GeV²
χ_2^Q
χ_4^Q
T (MeV)
(a)
(b)
(c)
(d)
lattice data for (N_τ = 8)
lattice data for (N_τ = 12)

Outline

Summary

- We have analyzed the impact of finite volume and external magnetic field on the thermodynamic properties using Polyakov loop extended chiral SU(3) quark mean field model in the asymmetric quark matter.
- The impact of external magnetic field and finite system size on the phase diagram of QCD has been investigated by inspecting the variation of scalar and vector fields.
- Susceptibilities of conserved charges are found to be enhanced in the regime of critical point.
- These fluctuations can be deduced from event-by-event inspection of the experimental data and hence play significant role in determination of CEP.

Thank you!

References I

- P. Wang et al., Phys. Rev. C **67**, 015210 (2003).
- Manisha Kumari and Arvind Kumar, Eur. Phys. J. Plus **136**, 19 (2021).
- . N. Tawfik and N. Magdy, Phys. Rev. C **90**, 015204 (2014).
- M. Ferreira, P. Costa, O. Louren co, T. Frederico, and C. Providencia, Phys. Rev. D **637** 89, 116011 (2014).
- B.-J. Schaefer, M. Wagner, and J. Wambach, Phys. Rev. D **81**, 074013 (2010).633
- S. Rossner, C. Ratti, and W. Weise, Phys. Rev. D **75**, 034007 (2007).