Medium modification of charmed meson masses based on an effective chiral model

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@ Reimei Workshop: New exotic hadron matter

(Inha Univ., Incheon, Korea, October 24, 2016)

Based on

- M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, in preparation
- Y. Motohiro, Y. Kim, M.Harada, PRC92, 025201 (2015)
- D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)

1. Introduction

of Hadrons

Origin of Mass ?

of Us

=

One of the Interesting problems of QCD

Chiral Invariant Mass of Hadrons ?

- Parity doublet model for light baryons
  - In [C.DeTar, T.Kunihiro, PRD39, 2805 (1989)], N*(1535) is regarded as the chiral partner to the N(939) having the chiral invariant mass.

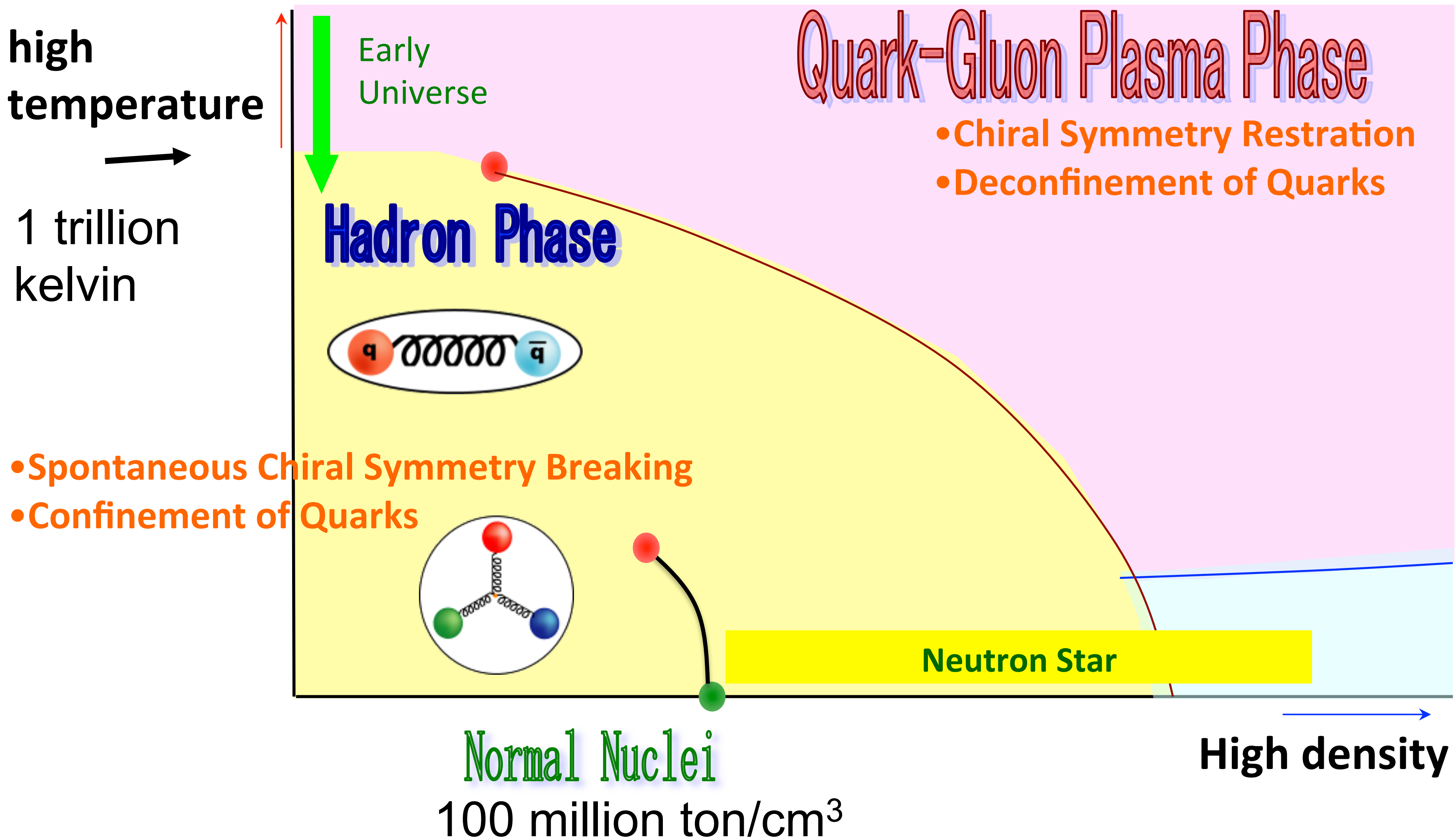
$$m_B = m_{0B} + m_{\langle \bar{q}q \rangle}$$

chiral invariant mass (m_{0B})

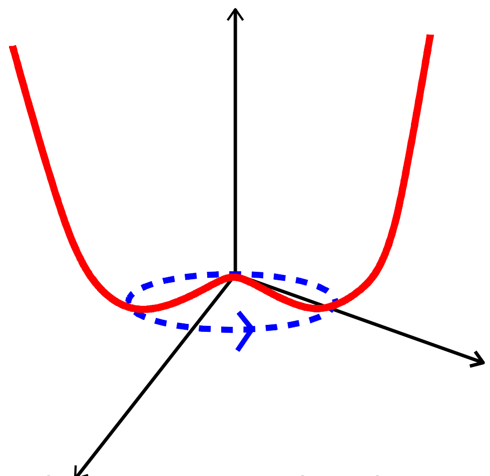
spontaneous chiral symmetry breaking ($m_{\langle \bar{q}q \rangle}$)

- How much mass of nucleon is from the spontaneous chiral symmetry breaking ?
- What is the value of the chiral invariant mass ?

Phase diagram of Quark-Gluon system

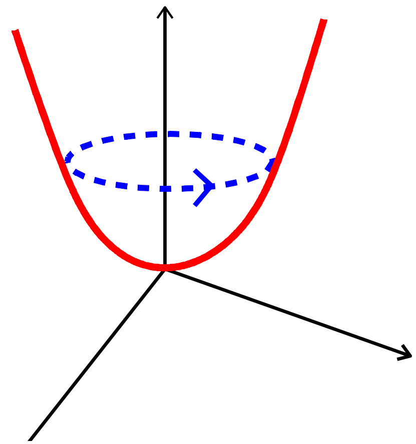


Important for understanding the spontaneous chiral symmetry breaking



chiral symmetry broken phase
at vacuum

$\langle \bar{q}q \rangle \neq 0$ (chiral condensate)



chiral symmetric phase
at high T and/or density

$\langle \bar{q}q \rangle = 0$

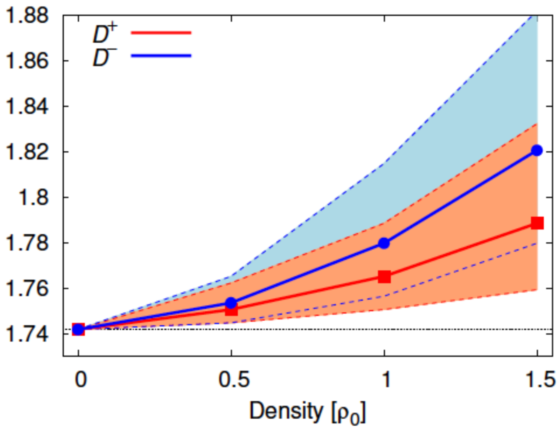
- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.
- Changing T and/or density will cause some change of hadron masses.

In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we studied nuclear matter using a parity doublet model, and showed some relations between the chiral invariant mass of nucleon and the phase structure. We also presented a density dependence of the nucleon mass, which changes reflecting the partial chiral symmetry restoration.

What happens to the masses of charmed hadrons in nuclear matter ?

Medium modification of charmed meson masses

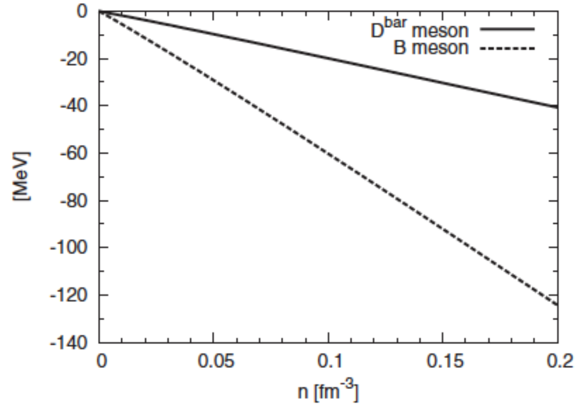
- QCD sum rule



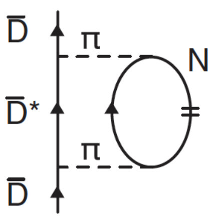
K.Suzuki, P.Gubler, M.Oka, PRC 93, 045209 (2016)

D meson mass is increased at finite density

- One-loop in an effective model

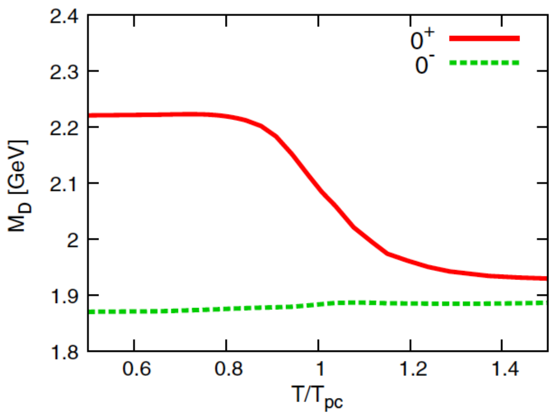


S.Yasui, K.Sudoh, PRC 87, 015202 (2013)

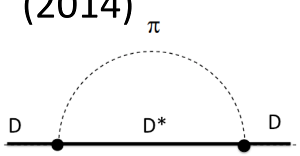


D meson mass is decreased at finite density

- One-loop in an effective model at finite temperature



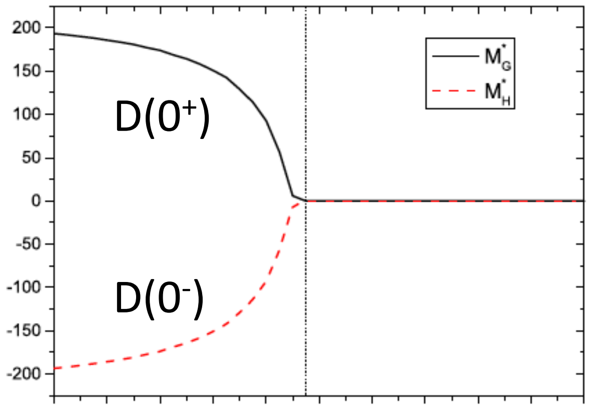
C.Sasaki, PRD 90, 114007 (2014)

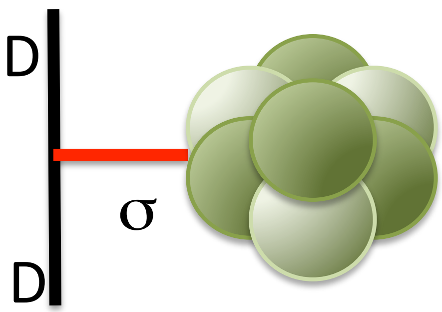


D meson mass is stable at finite temperature

One boson exchange contribution

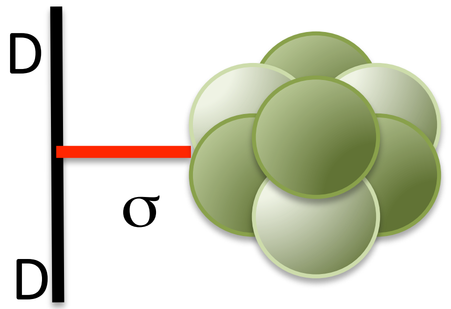
- Effective sigma meson exchange contribution
  - Nuclear matter is created in a Skyrme crystal approach
  - D meson ($J^P=0^-$) is included together with D_0^* ($J^P=0^+$) as the chiral partner
  - D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)

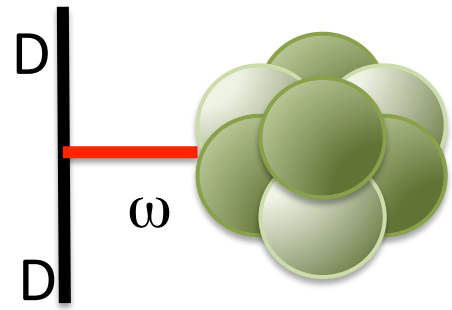




- D meson ($J^P=0^-$) mass is increased,
- D_0* ($J^P=0^+$) mass is decreased.
- They are degenerate when $\langle\sigma\rangle = 0$.

- In this talk, I introduce our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, in preparation], where we study the charmed meson masses in nuclear matter through the exchange of sigma and omega mesons.
- In this talk, I focus on the density dependence in the matter described by the parity doublet model.





Outline

1. Introduction
2. Nuclear matter from a parity doublet model
3. Density dependence of effective masses of charmed mesons
4. Summary

2. Nuclear matter from a parity doublet model

Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)

Parity Doublet model

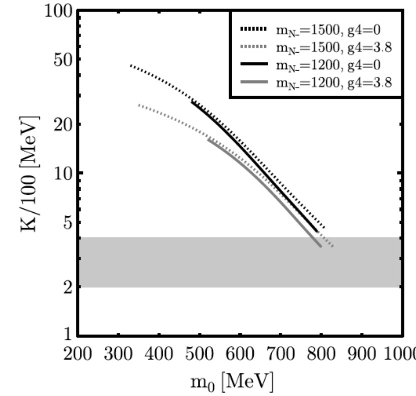
C.DeTar, T.Kunihiro, PRD39, 2805 (1989)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

- An excited nucleon with negative parity such as N*(1535) is regarded as the chiral partner to the N(939) which has the positive parity.
- These nucleons have a chiral invariant mass in addition to the mass generated by the spontaneous chiral symmetry breaking.
- The chiral symmetry is spontaneously broken by the sigma condensate, $< \sigma > \neq 0$.

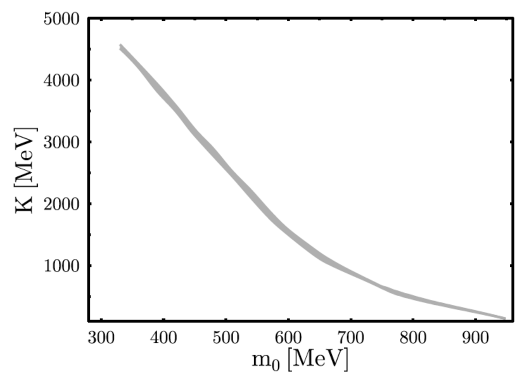
Nuclear matter in parity doublet models

- A parity doublet model including omega meson with 4-point interaction is used in a Walecka-type mean field analysis.
  - Large value of m_0 is needed to reproduce the incompressibility.
- Rho meson is further included with 4-point interaction.
  - $m_0 > 800$ MeV is needed to have $100 < K < 400$ MeV
- In our analysis [Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we construct a model with a 6-point interaction of sigma, but without 4-point interaction for vector mesons.
- Our results show that K = 240 MeV is reproduced for $m_0 > 500$ MeV.

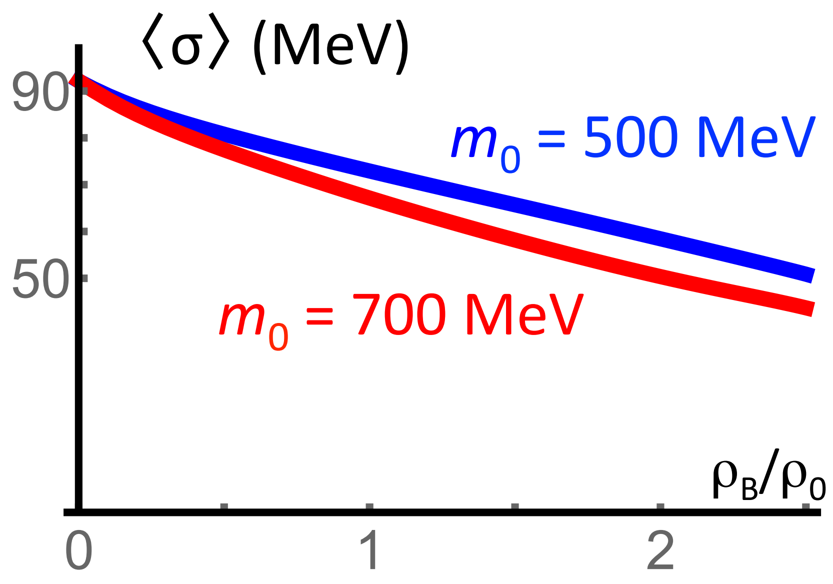
D.Zschiesche et al., PRC75, 055202 (2007)



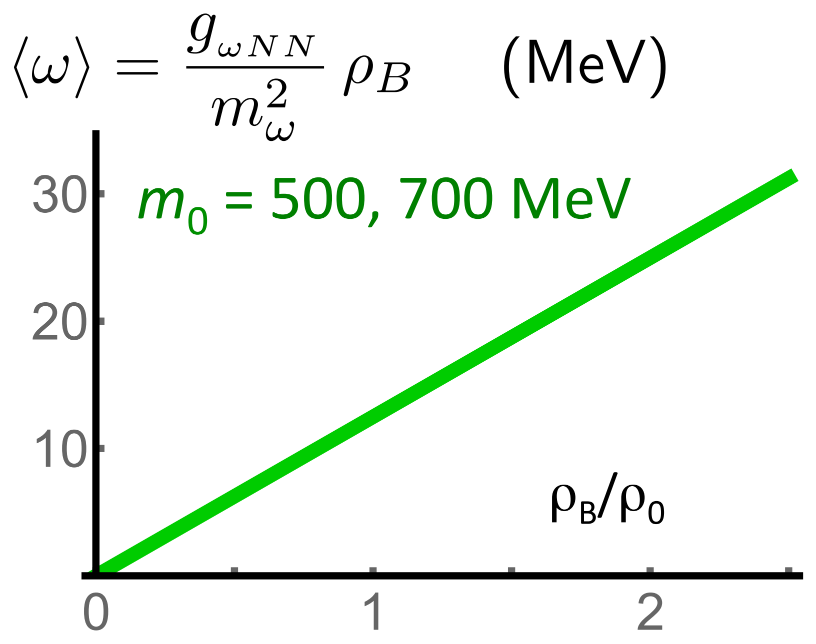
V.Dexheimer et al., PRC77, 025803 (2008)



Mean fields



⟨σ⟩ (MeV)
90
50
m_0 = 500 MeV
m_0 = 700 MeV
ρ_B/ρ_0
0
1
2



$\langle\omega\rangle = \frac{g_{\omega NN}}{m_\omega^2}\,\rho_B$ (MeV)
30
20
10
m_0 = 500, 700 MeV
ρ_B/ρ_0
0
1
2

3. Density dependence of effective masses of charmed mesons

M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, in preparation

Chiral partner structure for charmed mesons

- M.A.Nowak, M.Rho and I.Zahed, PRD48, 4370 (1993)
- W.A.Bardeen and C.T.Hill, PRD49, 409 (1994)

- 2 heavy quark multiplets with J_l=1/2 are regarded as the chiral partner:

$$\left[D(0^-), D^*(1^-)\right] \xleftrightarrow[\text{chiral partner}]{} \left[D_0^*(0^+), D_1(1^+)\right]$$

- Mass difference is generated by the chiral condensate, and the value is roughly equal to the constituent quark mass.
- Experimental value implies that the chiral partner structure seems to work:

$$m\left(0^+\right) - m\left(0^-\right) \approx m\left(1^+\right) - m\left(1^-\right) \approx 0.43\,\text{GeV}$$

An effective Lagrangian

- 2 Heavy meson doublets for $J^P = (0^-, 1^-), (0^+, 1^+)$ mesons

$$H = \frac{1 + v^\mu \gamma_\mu}{2} \left[D^*_\mu \gamma^\mu + i D \gamma_5 \right] \ , \quad G = \frac{1 + v^\mu \gamma_\mu}{2} \left[D^*_0 - i \gamma^\mu D'_{1\mu} \gamma_5 \right]$$

- Chiral fields

$$\mathcal{H}_R = \frac{1}{\sqrt{2}} \left[G + i H \gamma_5 \right] \ , \quad \mathcal{H}_L = \frac{1}{\sqrt{2}} \left[G - i H \gamma_5 \right] \ , \quad \omega_\mu \ , \quad M = \sigma + i \sum_{a=1}^{3} \pi_a \tau_a$$

$$\mathcal{H}_{R,L} \to \mathcal{H}_{R,L} \, g^\dagger_{R,L} \quad \omega_\mu \to \omega_\mu \quad M \to g_L M g^\dagger_R \ , \quad \left(g_{R,L} \in \mathrm{SU}(2)_{R,L} \right)$$

- Spontaneous chiral symmetry breaking : $\langle \sigma \rangle \neq 0$

- An effective Lagrangian invariant under chiral symmetry

$$\begin{aligned} \mathcal{L}/m =& \mathrm{tr} \left[\mathcal{H}_L (i v \cdot \partial) \bar{\mathcal{H}}_L \right] + \mathrm{tr} [\mathcal{H}_R (i v \cdot \partial) \bar{\mathcal{H}}_R] \\ & - g_{\omega DD} \, \mathrm{Tr} \left[\mathcal{H}_L v^\mu \omega_\mu \bar{\mathcal{H}}_L + \mathcal{H}_R v^\mu \omega_\mu \bar{\mathcal{H}}_R \right] \\ & + \frac{\Delta_M}{2 f_\pi} \mathrm{tr} \left[\mathcal{H}_L M \bar{\mathcal{H}}_R + \mathcal{H}_R M^\dagger \bar{\mathcal{H}}_L \right] \\ & - i \frac{g_A}{2 f_\pi} \mathrm{tr} \left[\mathcal{H}_R \gamma_5 \gamma^\mu \partial_\mu M^\dagger \bar{\mathcal{H}}_L - \mathcal{H}_L \gamma_5 \gamma^\mu \partial_\mu M \bar{\mathcal{H}}_R \right] \end{aligned}$$

Masses of charmed mesons in nuclear matter

- Relevant interactions for D($J^P=0^-$), D($J^P=0^+$)

$$\mathcal{L}/m = -2D\left[v^\mu\left(i\partial_\mu + g_{\omega DD}\omega_\mu\right) - \frac{1}{2}\Delta_M\frac{\sigma}{f_\pi}\right]D^\dagger$$
$$+ 2D_0^*\left[v^\mu\left(i\partial_\mu + g_{\omega DD}\omega_\mu\right) + \frac{1}{2}\Delta_M\frac{\sigma}{f_\pi}\right](D_0^*)^\dagger$$

- Effective masses for D($J^P=0^-$), D($J^P=0^+$) in nuclear matter

$$m_{D(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$
$$m_{D(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle$$

- Effective masses for anti-charmed mesons

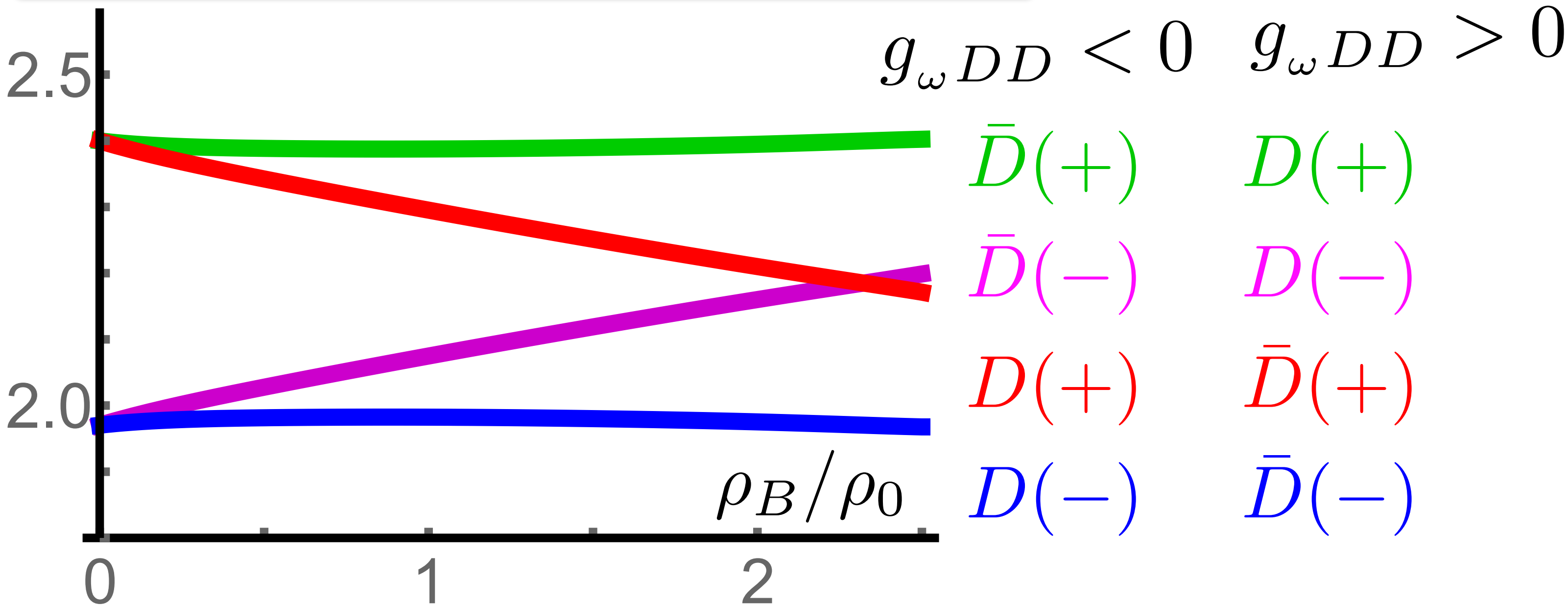
$$m_{\bar{D}(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$
$$m_{\bar{D}(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

Charmed meson masses

$$m_{D(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \qquad m_{\bar{D}(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

$$m_{D(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \qquad m_{\bar{D}(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

An example $|g_{\omega DD}| = 3.4$

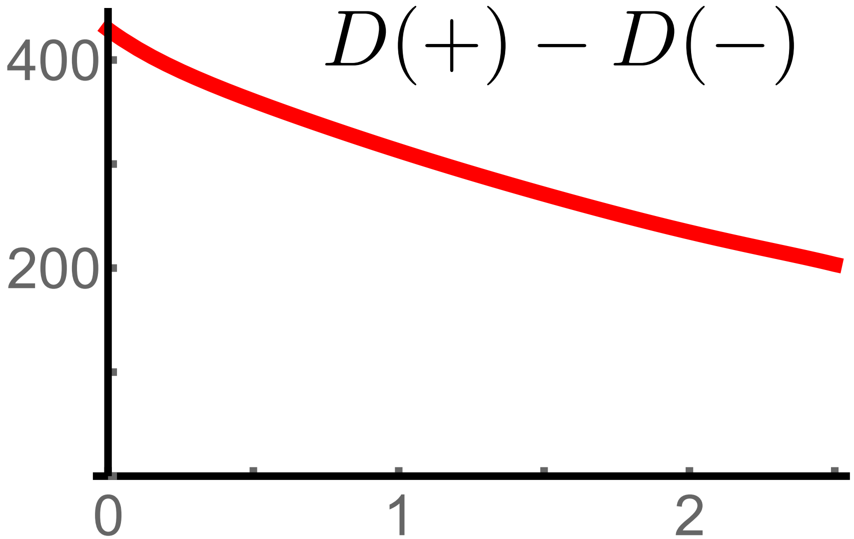


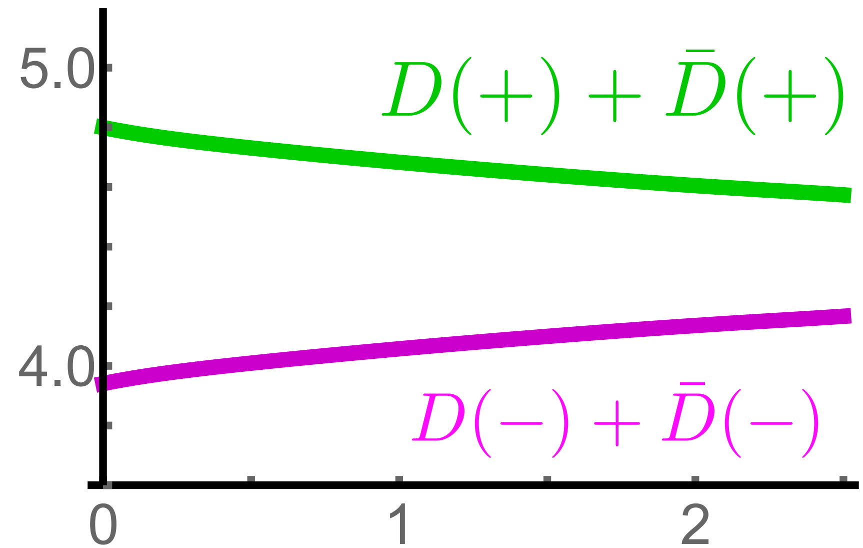
Increasing or decreasing of pseudo-scalar D(-) meson mass only is not enough for measuring the partial chiral symmetry restoration.

Partial chiral symmetry restoration

$$m^{(\mathrm{eff})}_{D(-)} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \qquad m^{(\mathrm{eff})}_{\bar{D}(-)} = m - \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

$$m^{(\mathrm{eff})}_{D(+)} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} + g_{\omega DD}\langle\omega_0\rangle \qquad m^{(\mathrm{eff})}_{\bar{D}(+)} = m + \frac{1}{2}\Delta_M \frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

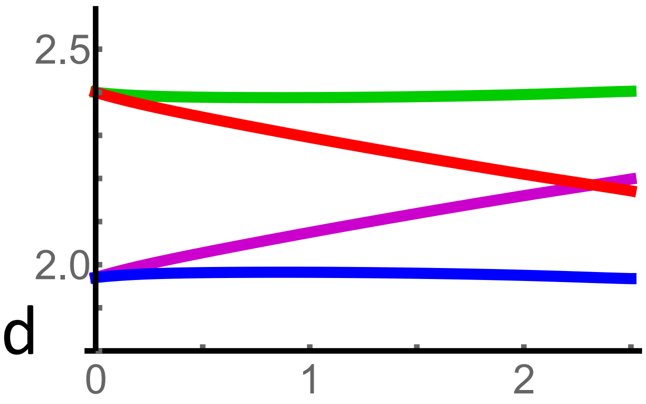


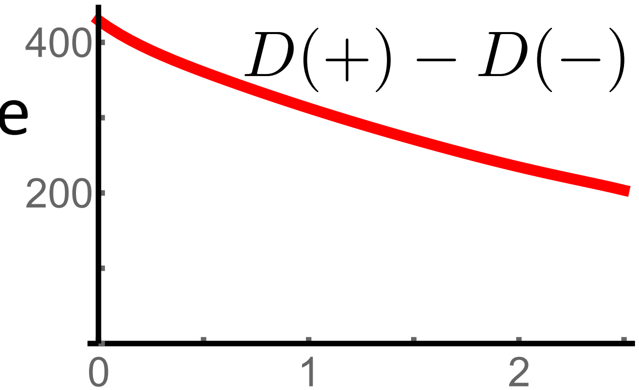


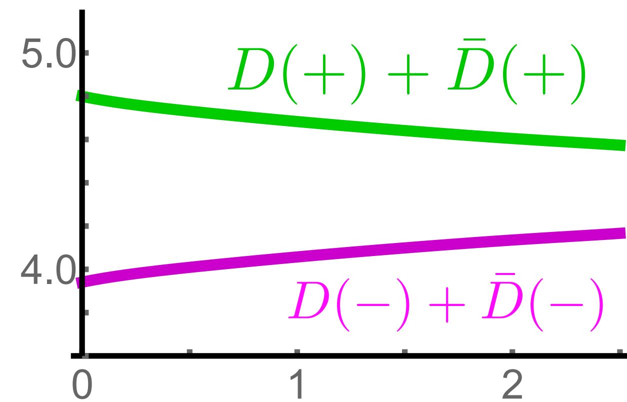
- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.
- Threshold energy for production of D and anti-D meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.

4. Summary

- We studied density dependence of charmed meson masses from the mean field contributions of sigma and omega mesons in the nuclear medium described in the parity doublet model.
- Increasing or decreasing of D(-) meson mass only is not enough for measure the chiral symmetry restoration.
- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.
- Threshold energy for production of D and anti-D meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.







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