Mass modification of charmed mesons and Delta baryon in nuclear matter based on a chiral partner structure

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@ APCTP Workshop: Dense Matter from Chiral Effective Theories

(APCTP, Pohang, Korea, December 8, 2016)

Based on

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

Relation with Mannque

- 1990 : I read his papers on HLS
- 1995 : I read his papers on heavy baryons by the bound state approach: Min-Oh-Park-Rho
- 2000 : I visited Mannque at Saclay. This is the first time for me to see him directly.
- 2001 : Mannque hired me at KIAS.
- 2005 : I invited Mannque to have a Japan-Korea mini-workshop in Nagoya. Participants include Dong-Pil Min, Chang-Hwan Lee, Youngman Kim.
- So far, I wrote 10 journal papers with him, during 2002 – 2016.

1. Introduction

of Hadrons

Origin of Mass ?

of Us

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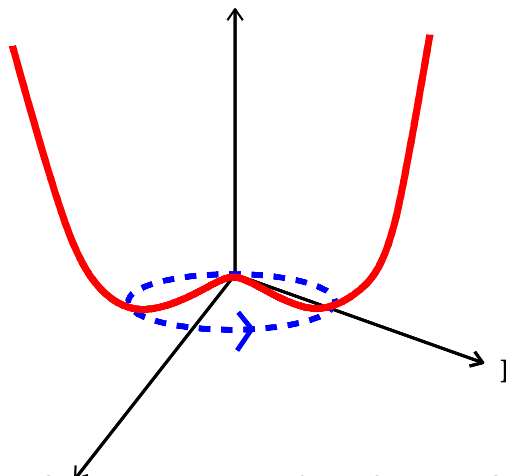
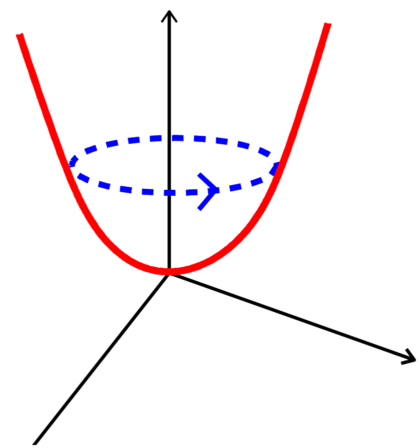
One of the Interesting problems of QCD

Mass generated by the spontaneous chiral symmetry breaking



chiral symmetry broken phase
at vacuum

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

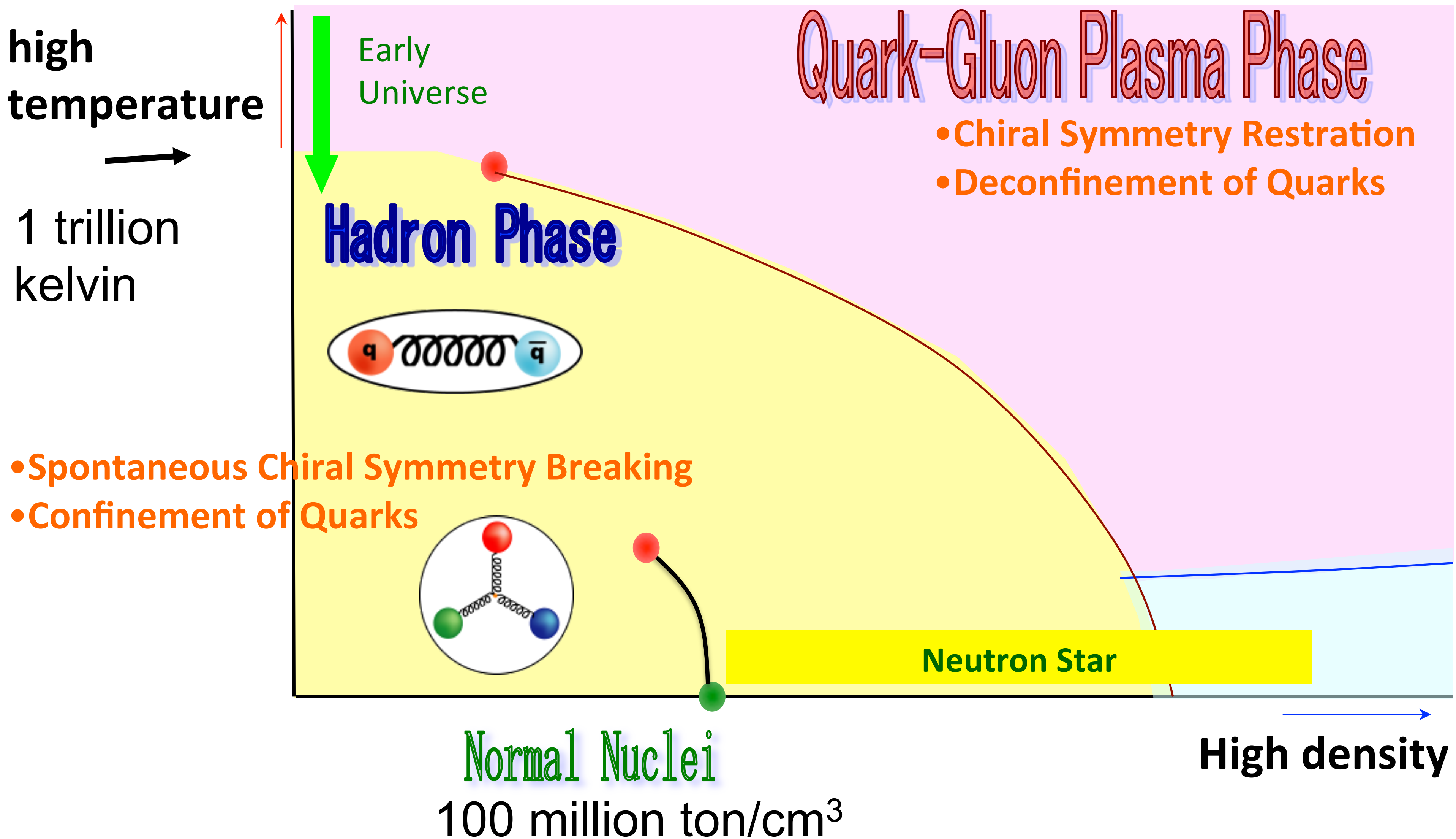


chiral symmetric phase
at high T and/or density

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

- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.

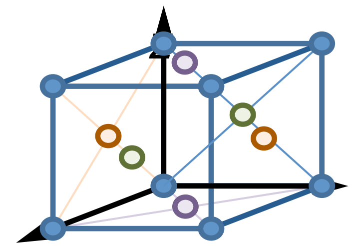
Phase diagram of Quark-Gluon system



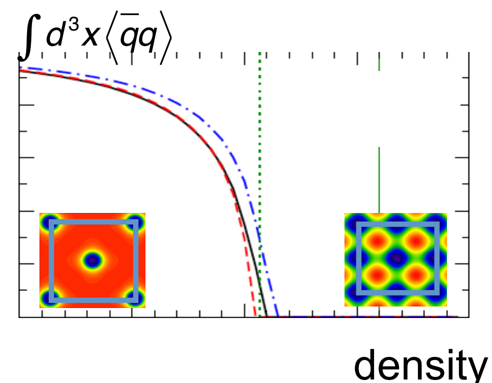
Dense nuclear matter by a Skyrme-crystal model

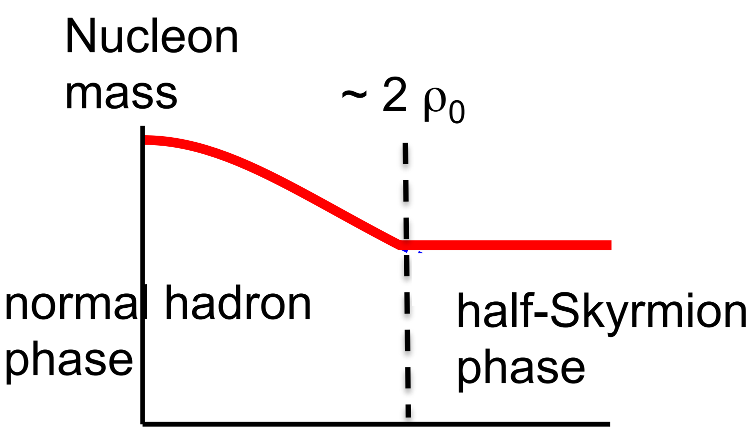
- Y. –L. Ma, M. Harada, H.K. Lee, Y. Oh, B. –Y. Park, M. Rho, PRD88 (2013) 014016
- Y. –L. Ma, M. Harada, H.K. Lee, Y. Oh, B. –Y. Park, M. Rho, PRD90 (2014) 34105

- There exists the “half-Skyrmion phase” where the space-average of the chiral condensate vanishes.



- Nucleon mass decreases with density in the normal phase, while i is stable In the half-Skyrmion phase.





Chiral invariant mass ?

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

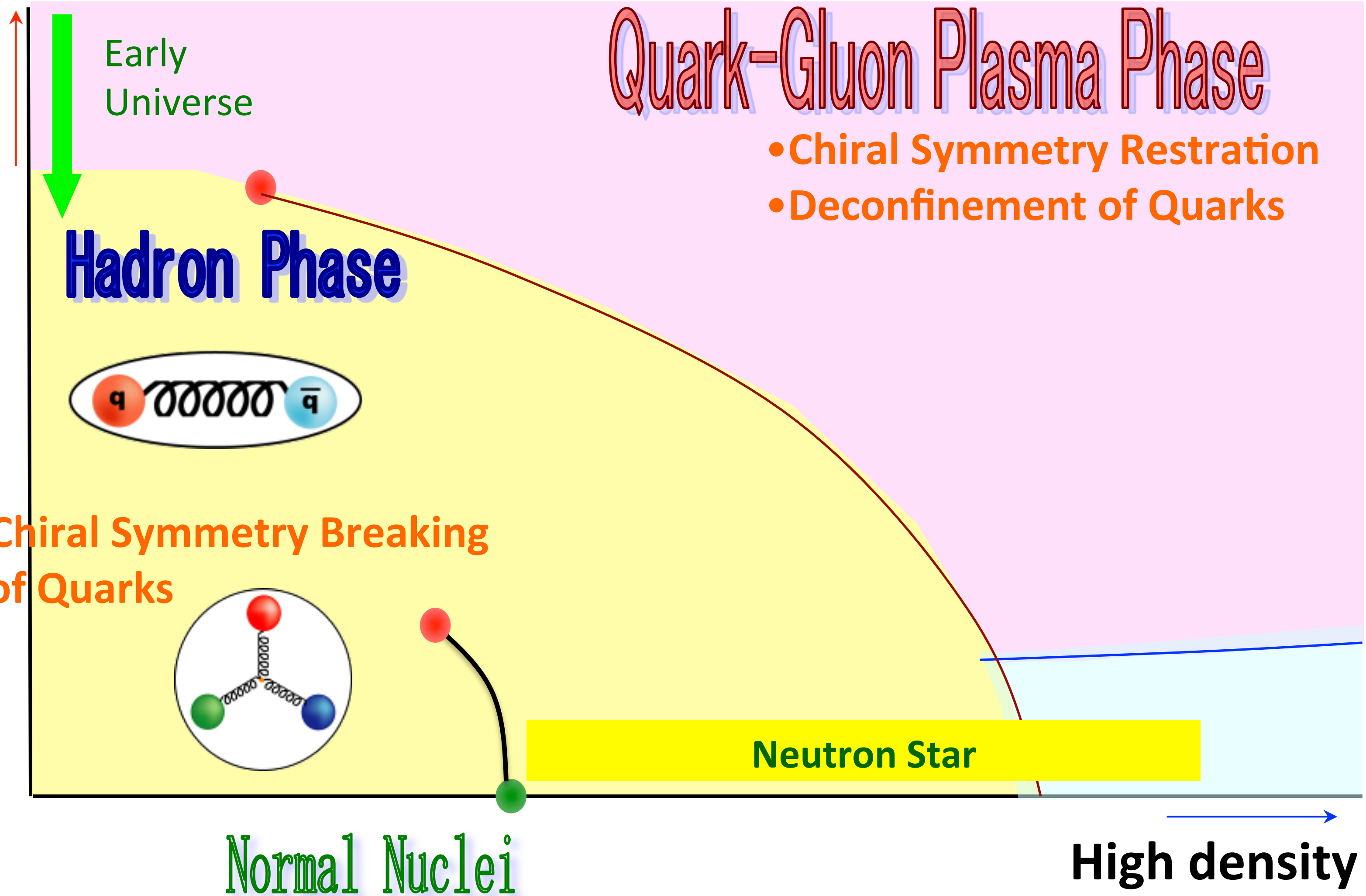
spontaneous chiral symmetry breaking

- 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

high temperature

1 trillion kelvin



100 million ton/cm^3

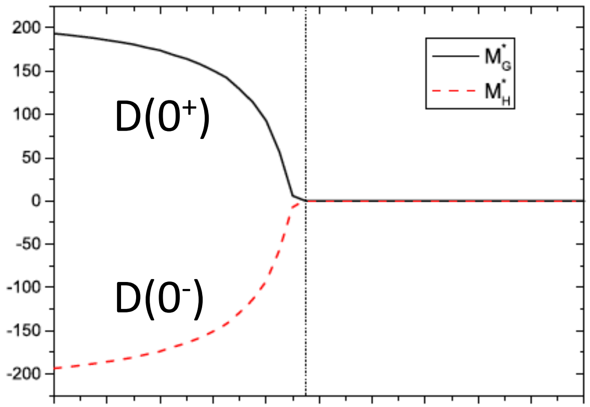
High density

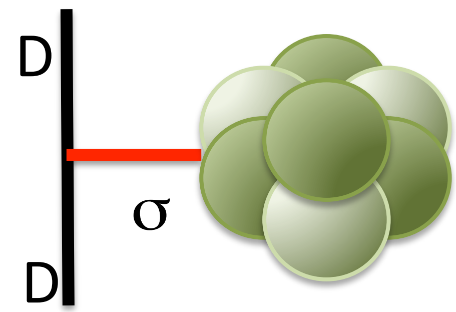
In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we studied nuclear matter using a parity doublet model, and showed some relations between the chiral invariant mass of nucleon and the phase structure. We also presented a density dependence of the nucleon mass, which changes reflecting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

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

One boson exchange contribution

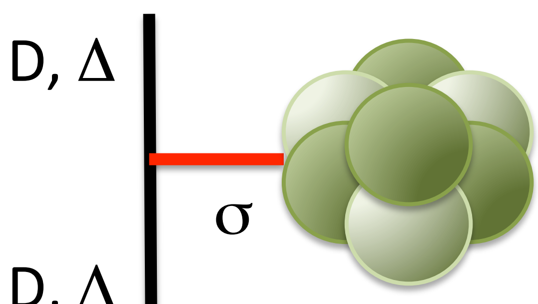
- Effective sigma meson exchange contribution
  - Nuclear matter is created in a Skyrme crystal approach
  - D meson ($J^P=0^-$) is included together with D_0^* ($J^P=0^+$) as the chiral partner
  - D.Suenga, B.R.He, Y.L.Ma. M.Harada, PRD 91, 036001 (2015)

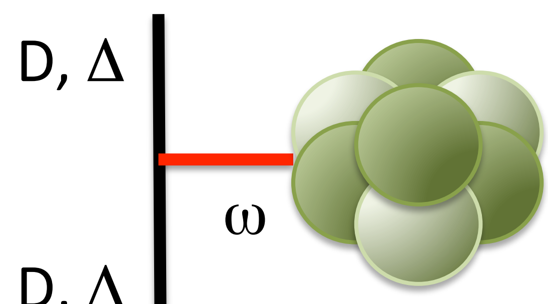




- D meson ($J^P=0^-$) mass is increased,
- D_0* ($J^P=0^+$) mass is decreased.
- They are degenerate when $\langle\sigma\rangle = 0$.

- In this talk, I introduce our recent works.
- Charmed mesons [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, in preparation]
  - Based on the chiral partner structure of charmed mesons, we study effective masses of charmed mesons 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.
- Delta baryons [Y. Takeda, Y. Kim, M. Harada, work in progress]
  - Based on the parity partner structure of Delta baryons, we study effective masses of Delta baryons in nuclear matter.





Outline

1. Introduction
2. A parity doublet model for nucleon
3. Nuclear matter from a parity doublet model
4. Density dependence of effective masses of charmed mesons based on chiral partner structure
5. Density dependence of effective masses of Delta baryons based on parity doublet structure
6. Summary

2. A parity doublet model for nucleon

C.DeTar, T.Kunihiro, PRD39, 2805 (1989)

D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

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

Parity Doublet model for nucleon

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 which is caused by the existence of the sigma condensate, $\langle \sigma \rangle \neq 0$.

Two chiral representations for baryons

- Ordinary baryon $\psi_1 = \psi_{1l} + \psi_{1r}$
  - The transformation property under the chiral group is assigned with the chirality.

$$\gamma_5 \psi_{1l} = -\psi_{1l}; \quad \psi_{1l} \to g_L \psi_{1l}; \quad g_L \in \mathrm{SU}(2)_L$$

$$\gamma_5 \psi_{1r} = +\psi_{1r}; \quad \psi_{1r} \to g_R \psi_{1r}; \quad g_R \in \mathrm{SU}(2)_R$$

- Mirror baryon $\psi_2 = \psi_{2l} + \psi_{2r}$
  - The chiral transformation is assigned oppositely to the chirality

$$\gamma_5 \psi_{2l} = -\psi_{2l}; \quad \psi_{2l} \to g_R \psi_{2l}; \quad g_R \in \mathrm{SU}(2)_R$$

$$\gamma_5 \psi_{2r} = +\psi_{2r}; \quad \psi_{2r} \to g_L \psi_{2r}; \quad g_L \in \mathrm{SU}(2)_L$$

Linear sigma model (2 flavor)

- A scalar-pseudoscalar field $M = \sigma + i\vec{\pi}\cdot\vec{\tau}$
  - Transforms as $M \to g_L M g_R^\dagger$; ; VEV $\langle M \rangle = \sigma_0 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
- A linear sigma model with 2 baryons

$$
\begin{aligned}
\mathcal{L}_N = & \bar{\psi}_{1r} i\gamma^\mu \partial_\mu \psi_{1r} + \bar{\psi}_{1l} i\gamma^\mu \partial_\mu \psi_{1l} \\
& + \bar{\psi}_{2r} i\gamma^\mu \partial_\mu \psi_{2r} + \bar{\psi}_{2l} i\gamma^\mu \partial_\mu \psi_{2l} \\
& - m_0 \left[\bar{\psi}_{1l}\psi_{2r} - \bar{\psi}_{1r}\psi_{2l} - \bar{\psi}_{2l}\psi_{1r} + \bar{\psi}_{2r}\psi_{1l} \right] \\
& - g_1 \left[\bar{\psi}_{1r} M^\dagger \psi_{1l} + \bar{\psi}_{1l} M \psi_{1r} \right] \\
& - g_2 \left[\bar{\psi}_{2r} M \psi_{2l} + \bar{\psi}_{2l} M^\dagger \psi_{2r} \right] ,
\end{aligned}
$$

  - chiral invariant mas m_0 : baryons can have masses even without spontaneous chiral symmetry breaking.
  - Two masses are separated with each other by the effect of spontaneous chiral symmetry breaking.

Determination of the parameters at vacuum

- Masses of parity eigenstates

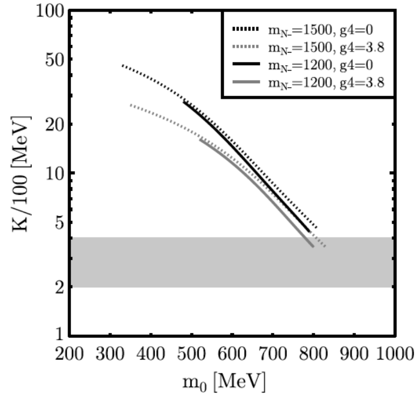
$$m_{\pm} = \frac{1}{2}\left[\sqrt{(g_1 + g_2)^2\,\bar{\sigma}^2 + 4m_0^2} \mp (g_2 - g_1)\,\bar{\sigma}\right]$$

- Determination of parameters at vacuum (D.Jido et al., PTP106, 873 (2001))
  - Inputs : m_+ = 939 MeV, m_- = 1535 MeV, $\sigma_0 = f_\pi$ = 93 MeV, and $g_{\pi N+N-}$ = 0.7 obtained from $\Gamma_{N^* \to \pi N}$ = 75 MeV.
  - Outputs : m_0 = 270 MeV , g_1 = 9.8 , g_2 = 16 .
- Global fit in an extended model (S.Gallas et al., PRD82, 014004 (2010)) shows m_0 = 460 +- 136 MeV.

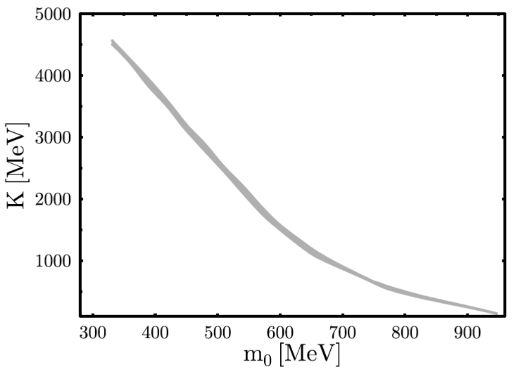
Nuclear matter in parity doublet models

- 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 - 900 MeV.

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



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



3. Nuclear matter from a parity doublet model

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

Model parameters : Inputs from vacuum phenomenology

- We include sigma and omega mesons as well as the pion and rho meson in our model
- We have 11 parameters.
  - 3 parameters in the scalar potential

$$\bar{\mu}\,,\ \lambda\,,\ \lambda_6\ :\ V_\sigma = \frac{1}{2}\bar{\mu}^2\sigma^2 + \frac{1}{4}\lambda\sigma^4 - \frac{1}{6}\lambda_6\sigma^6$$

  - 3 masses for π, ρ, ω : $m_\pi\,,\ m_\rho\,,\ m_\omega$
  - 5 parameters in the baryon sector

    m_0 : chiral invariant mass ; $g_1\,,\ g_2$: Yukawa couplings

    $g_{\rho NN}\,,\ g_{\omega NN}$: ρNN and ωNN couplings

- We determine 10 parameters for a given value of the chiral invariant mass m_0 .
- We use the following 6 inputs at vacuum

m_+	m_-	m_ω	m_ρ	f_π	m_π
939	1535	783	776	93	140

Inputs from medium property

- We calculate the thermodynamic potential in the nuclear medium in our model, using the mean field approximation.
- Then, we determine the 4 remaining parameters from the following physical inputs for a given value of the chiral invariant mass m_0.
  - Nuclear saturation density

$$\rho(\mu_B^* = 923 \text{ MeV}) = \rho_0 = 0.16\,\mathrm{fm}^{-3}$$

  - Binding energy at normal nuclear density

$$\left[\frac{E}{A} - m_+\right]_{\rho_0} = \left[\frac{\epsilon}{\rho_B} - m_+\right]_{\rho_0} = -16 \text{ MeV}$$

  - Incompressibility

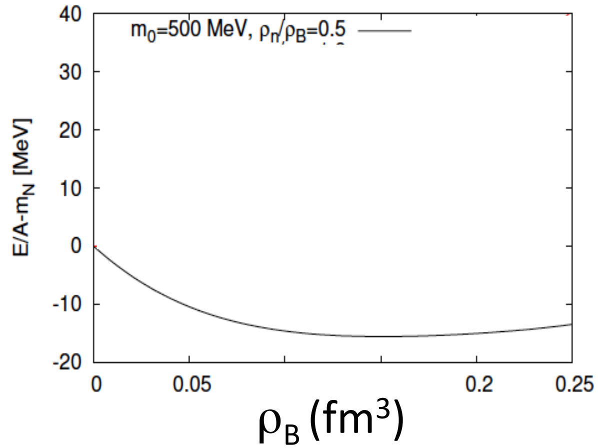
$$K = 9\rho_0^2 \frac{\partial^2 (E/A)}{\partial \rho^2}\bigg|_{\rho_0} = 9\rho_0 \frac{\partial \mu_B}{\partial \rho}\bigg|_{\rho_0} = 240 \text{ MeV}$$

  - Symmetry energy : $E_{sym}(\rho_0) = 31$ MeV

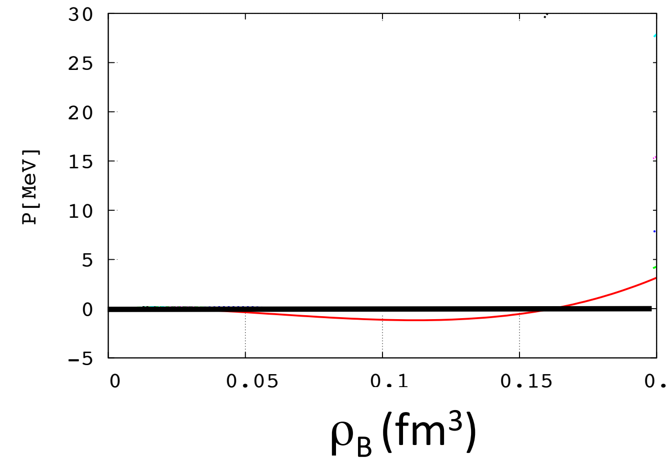
Binding Energy, Pressure, Mean fields

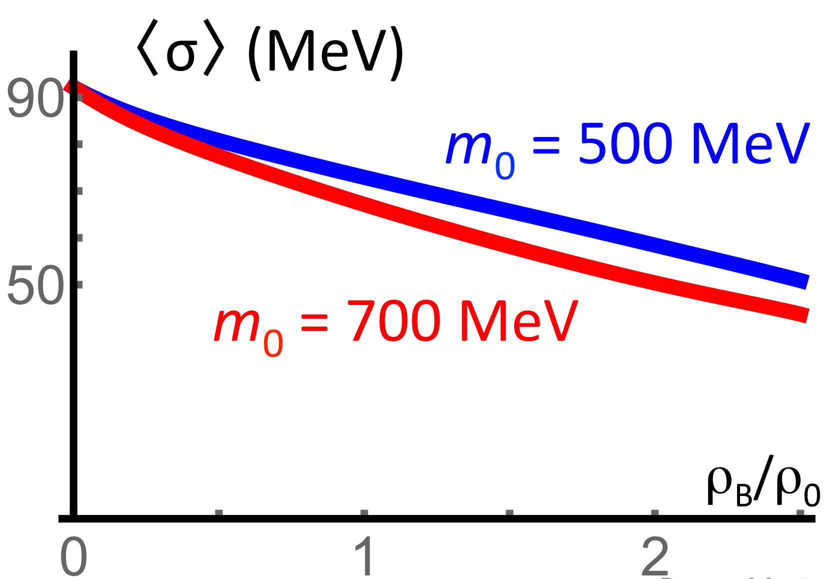
m_0 = 500 MeV

Binding Energy

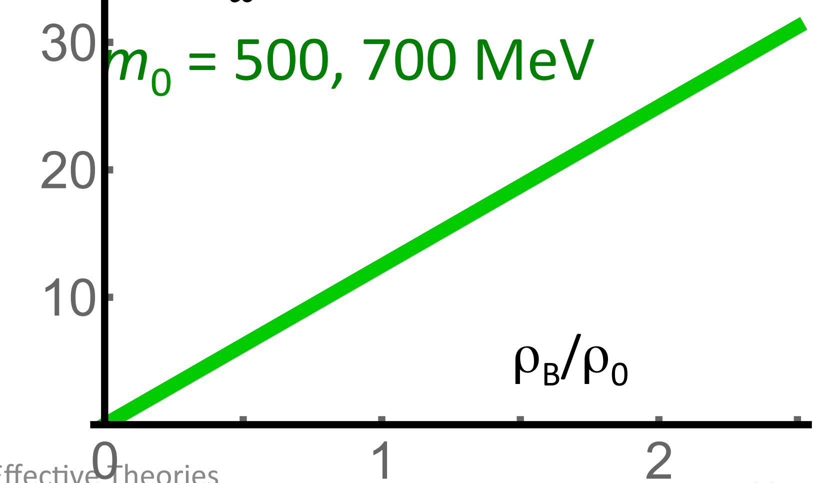


Pressure



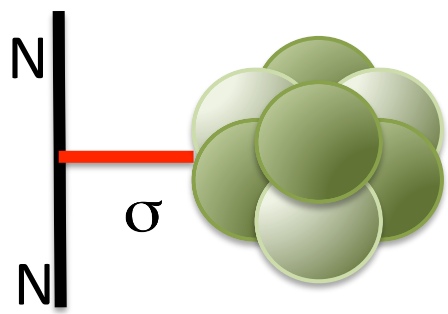


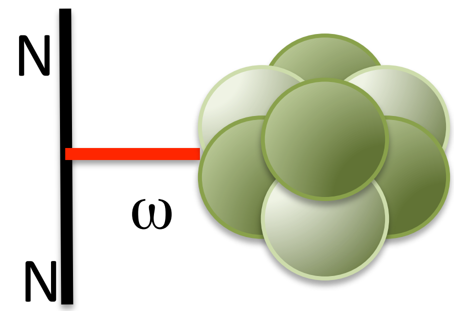
$$\langle\omega\rangle = \frac{g_{\omega NN}}{m_\omega^2}\,\rho_B \qquad \text{(MeV)}$$



Effective masses of nucleons

- In this talk, I define effective masses of nucleons by including effects of exchanging the sigma and omega mesons in the mean field approximation, following our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, in preparation].





$$m_{\pm}^{(\mathrm{eff})} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2-g_1)\langle\sigma\rangle\right] + g_{\omega NN}\langle\omega\rangle \quad \text{(nucleon)}$$

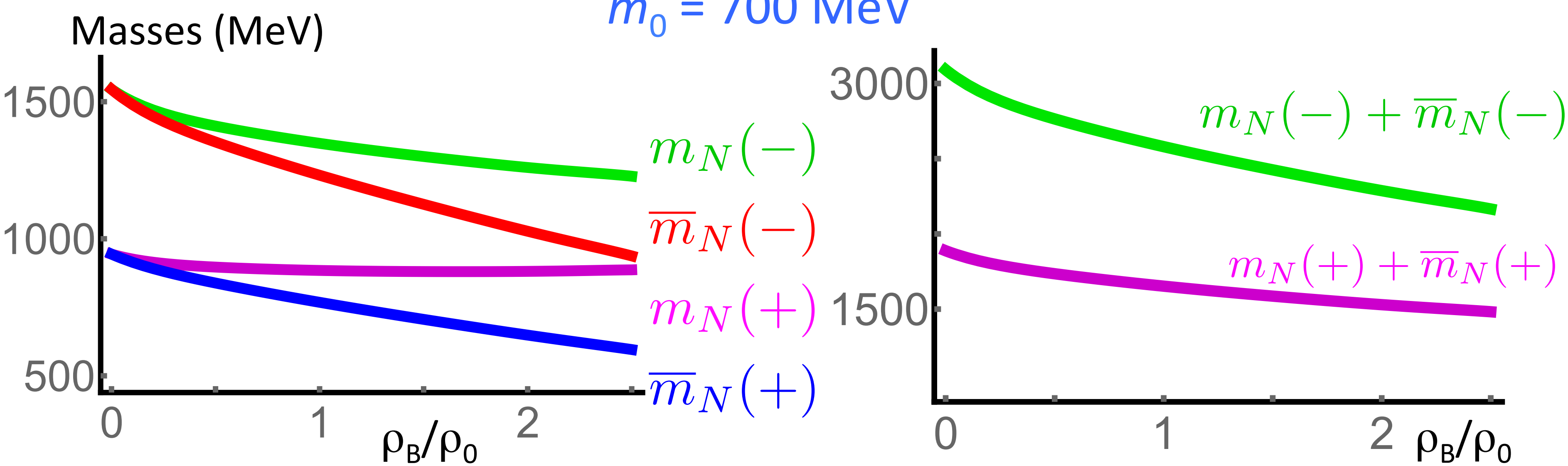
$$\overline{m}_{\pm}^{(\mathrm{eff})} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2-g_1)\langle\sigma\rangle\right] - g_{\omega NN}\langle\omega\rangle \quad \text{(anti-nucleon)}$$

Density dependence of effective masses

$$m_{\pm}^{(\mathrm{eff})} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2-g_1)\langle\sigma\rangle\right] + g_{\omega NN}\langle\omega\rangle \quad \text{(nucleon)}$$

$$\overline{m}_{\pm}^{(\mathrm{eff})} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2-g_1)\langle\sigma\rangle\right] - g_{\omega NN}\langle\omega\rangle \quad \text{(anti-nucleon)}$$

m_0 = 700 MeV



- Sum of masses of nucleon and anti-nucleon decreases toward m_0 reflecting the partial chiral symmetry restoration.
- Studying effective masses will give a clue for m_0.

4. Density dependence of effective masses of charmed mesons based on chiral partner structure

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

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

- Chiral fields

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

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

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

- An effective Lagrangian invariant under chiral symmetry

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

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

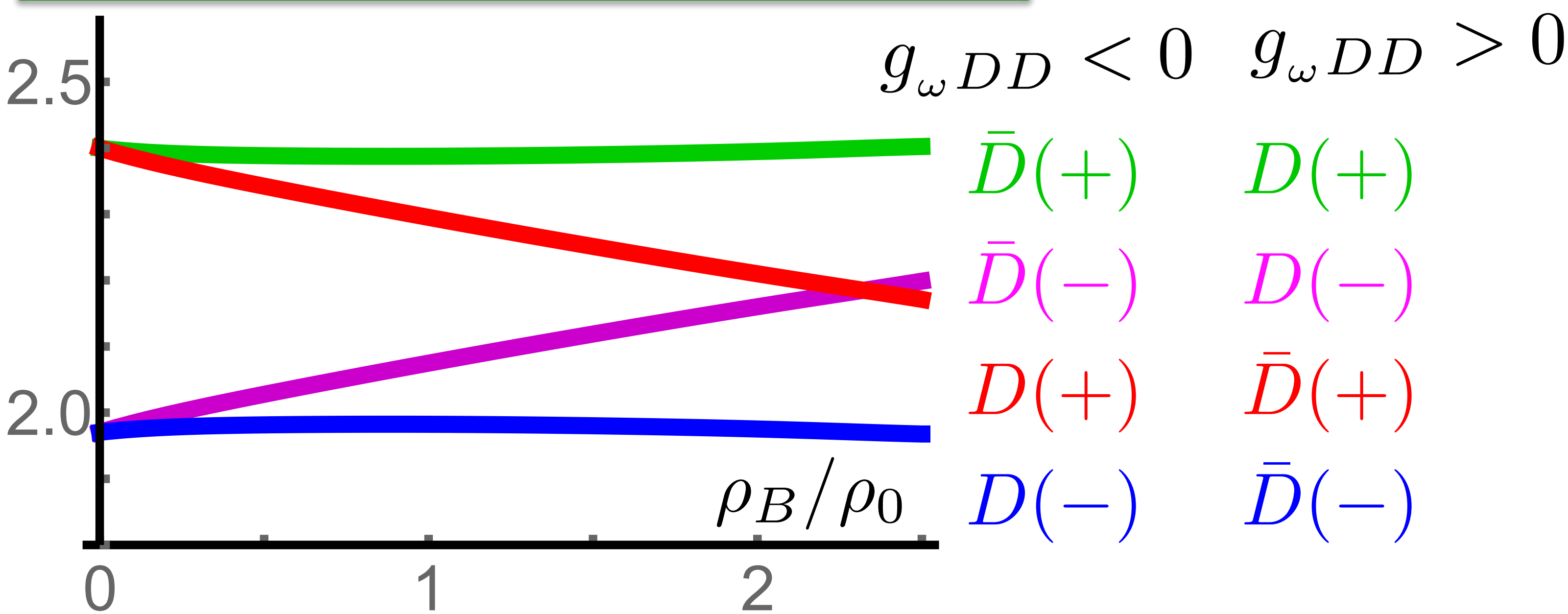
$$m_{\bar{D}(-)}^{(\mathrm{eff})} = m - \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$
$$m_{\bar{D}(+)}^{(\mathrm{eff})} = m + \frac{1}{2}\Delta_M\frac{\langle\sigma\rangle}{f_\pi} - g_{\omega DD}\langle\omega_0\rangle$$

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

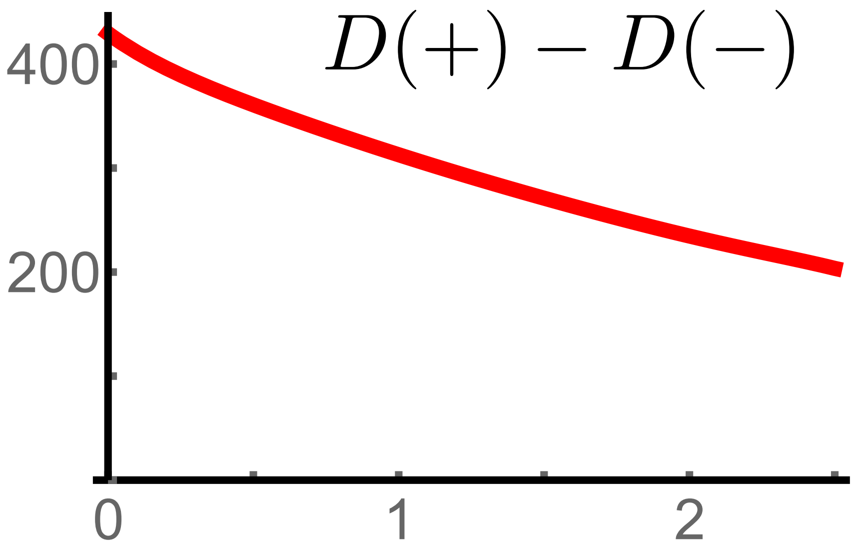


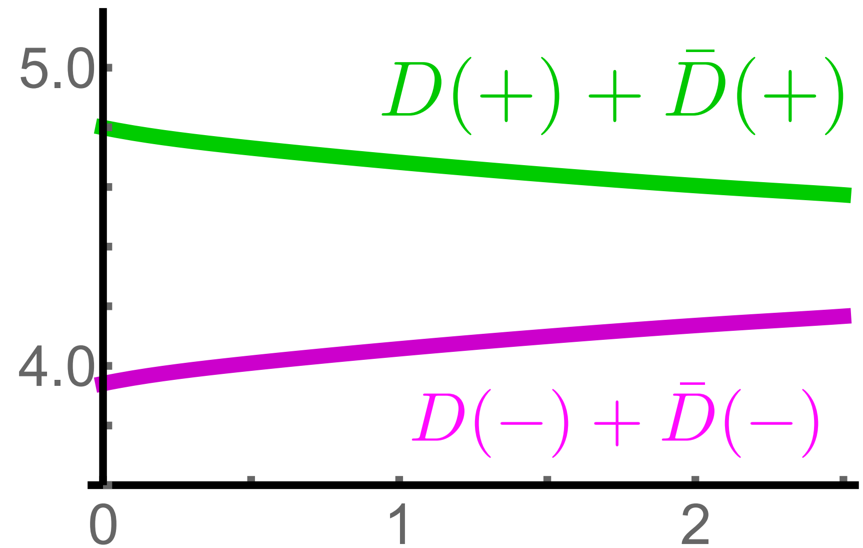
Increasing or decreasing of pseudo-scalar D(-) meson mass only is not enough for measuring the partial chiral symmetry restoration.

Partial chiral symmetry restoration

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

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





- 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.

5. Density dependence of effective masses of Delta baryons based on parity doublet structure

Y. Takeda, Y. Kim, M. Harada, work in progress

Parity Doublet Structure for Delta baryons

D.Jido, T.Hatsuda, T.Kunihiro, PRL84, 3252 (2000)
D.Jido, M.Oka, A.Hosaka, PTP106, 873 (2001)

- Δ(1232) and Δ(1700) are regarded as parity partners.

$$m_{\Delta\pm} = \sqrt{(\bar{g}_1 + \bar{g}_2)^2 \langle \sigma \rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1 - \bar{g}_2) \langle \sigma \rangle$$

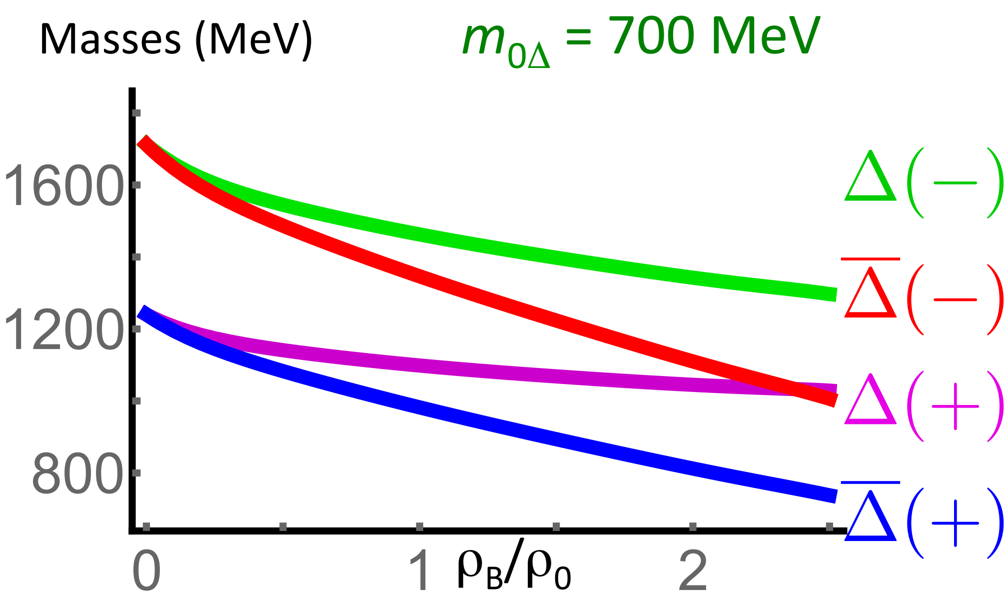
- I use masses of Δ(1232) and Δ(1700) as inputs.
- $m_{0\Delta}$ must lie $m_{0\Delta} \leqq 1460$ MeV.
- In the following analysis, I use $m_{0\Delta}$ = 1400, 700 MeV as typical examples.

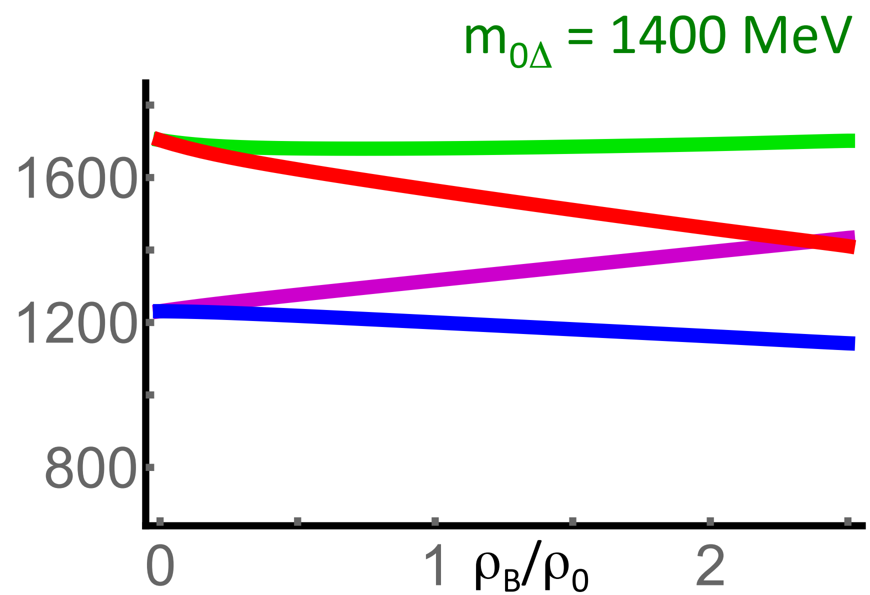
Density dependence of effective masses

$$m_{\Delta\pm} = \sqrt{(\bar{g}_1+\bar{g}_2)^2\langle\sigma\rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1-\bar{g}_2)\langle\sigma\rangle + g_{\omega\Delta\Delta}\langle\omega\rangle \quad (\Delta)$$

$$\overline{m}_{\Delta\pm} = \sqrt{(\bar{g}_1+\bar{g}_2)^2\langle\sigma\rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1-\bar{g}_2)\langle\sigma\rangle - g_{\omega\Delta\Delta}\langle\omega\rangle \quad (\text{anti-}\Delta)$$

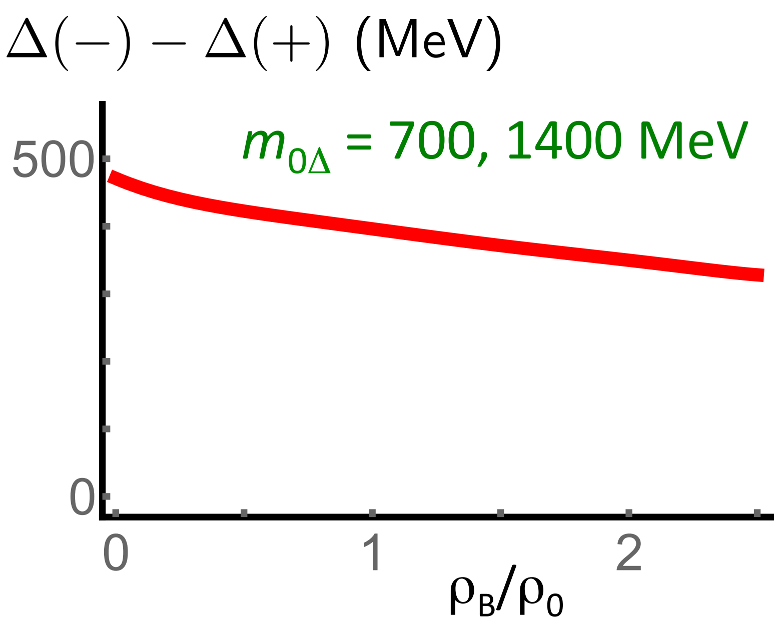
I use $g_{\omega\Delta\Delta} = g_{\omega NN} = 5.4$ as a typical example.

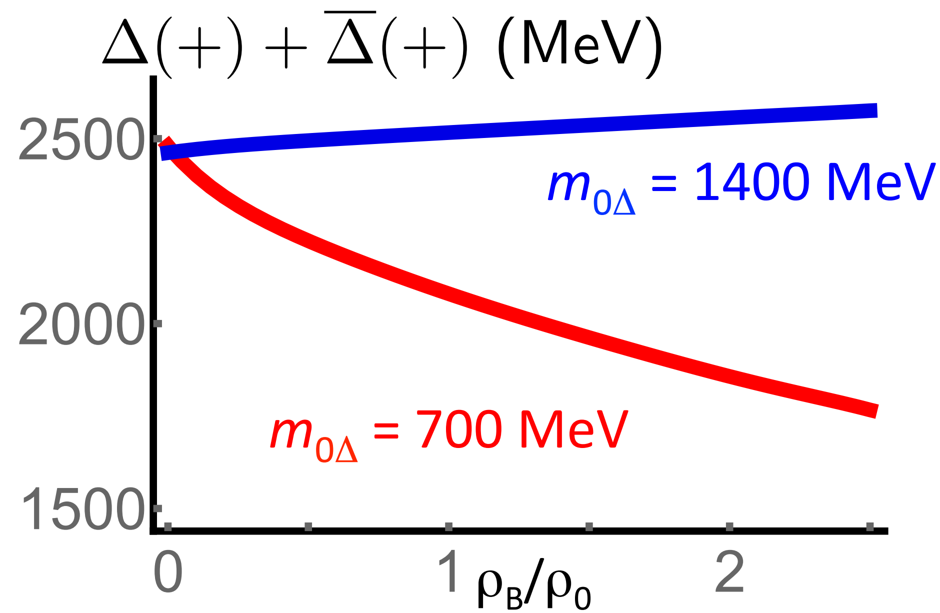




Increasing or decreasing of $\Delta(+)$ baryon mass only is not enough for measuring the chiral symmetry restoration.

Partial chiral symmetry restoration





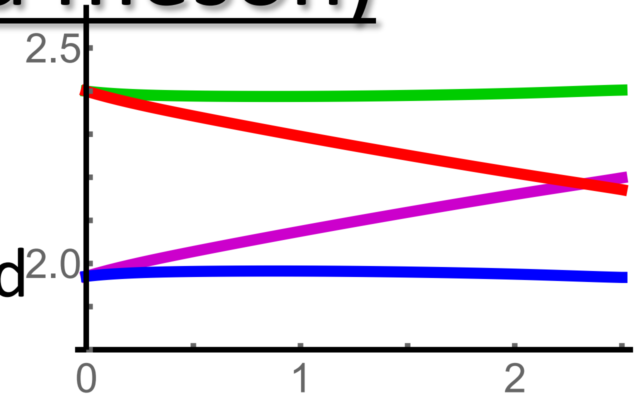
- Studying the mass difference of parity partners gives a clue for partial chiral symmetry restoration, independently of the value of $m_{0\Delta}$.
- Taking sum of particle and anti-particle will give a clue for chiral invariant mass.

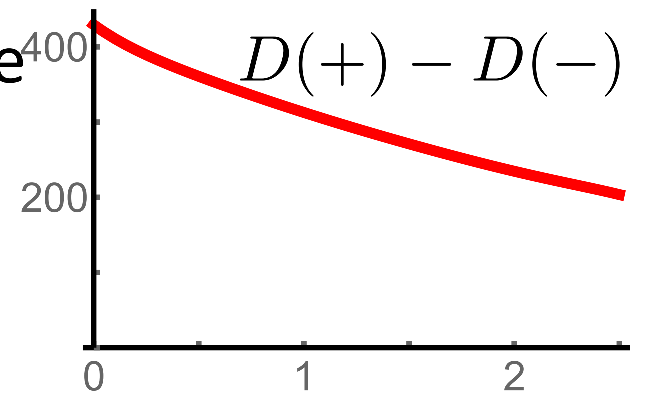
$$m_{\Delta\pm} = \sqrt{(\bar{g}_1 + \bar{g}_2)^2 \langle\sigma\rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1 - \bar{g}_2)\langle\sigma\rangle + g_{\omega\Delta\Delta}\langle\omega\rangle \quad (\Delta)$$

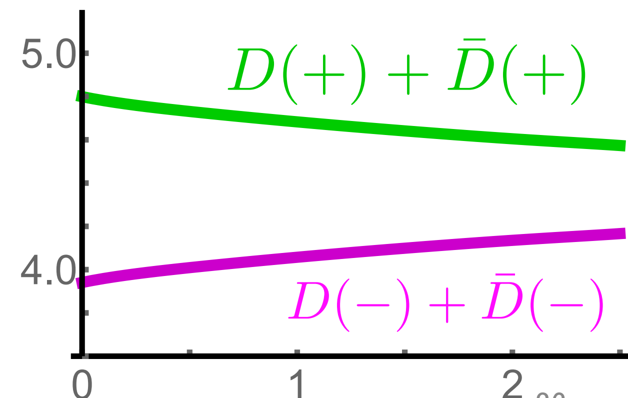
$$\overline{m}_{\Delta\pm} = \sqrt{(\bar{g}_1 + \bar{g}_2)^2 \langle\sigma\rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1 - \bar{g}_2)\langle\sigma\rangle - g_{\omega\Delta\Delta}\langle\omega\rangle \quad (\text{anti-}\Delta)$$

6. Summary 1 (charmed meson)

- 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.

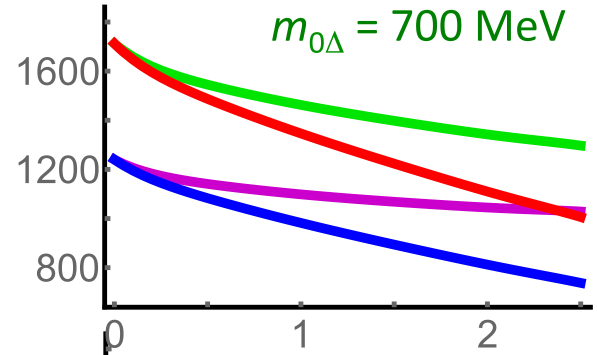


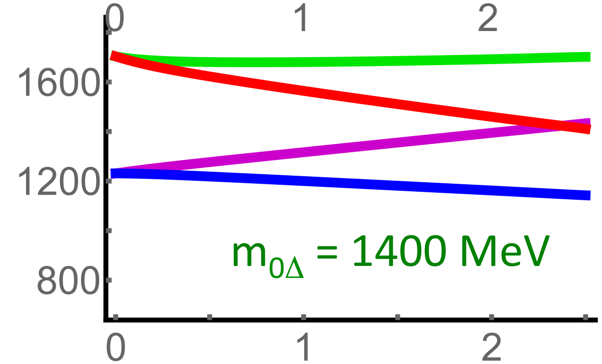


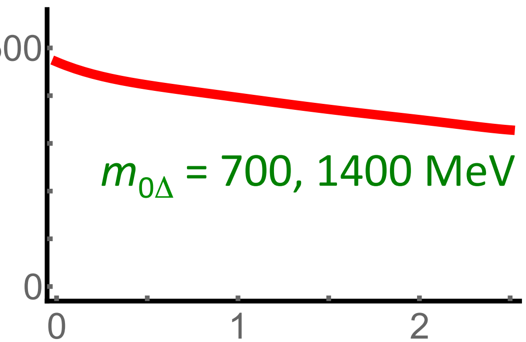


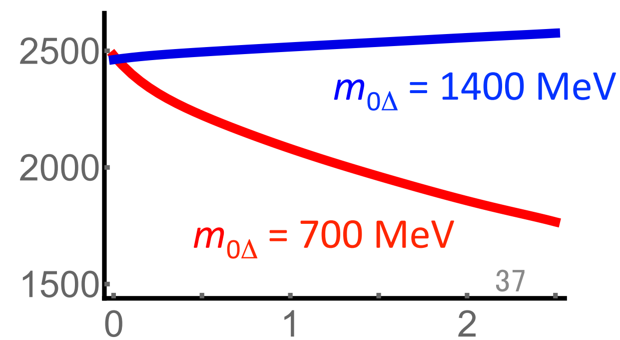
6. Summary 2 (Delta baysons)

- We studied density dependence of Delta baryon masses from the mean field contributions of sigma and omega mesons.
- Increasing or decreasing of $\Delta(+)$ baryon mass only is not enough for measuring the chiral symmetry restoration.
- Studying the mass difference of chiral partners gives a clue for partial chiral symmetry restoration, independently of the value of $m_{0\Delta}$.
- Taking sum of particle and anti-particle will give a clue for the chiral invariant mass m_{0D}.









The End