Mass modification of hadrons associated with partial chiral symmetry restoration

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Based on discussions with
- Hiroyuki Sako, Yusuke Takeda, Yong-Liang Ma, Youngman Kim,

See also
- M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, in preparation.
- Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)

Introduction

of Hadrons

Origin of Mass ?

of Us

=

One of the Interesting problems of QCD

Chiral Invariant Mass of Baryons ?

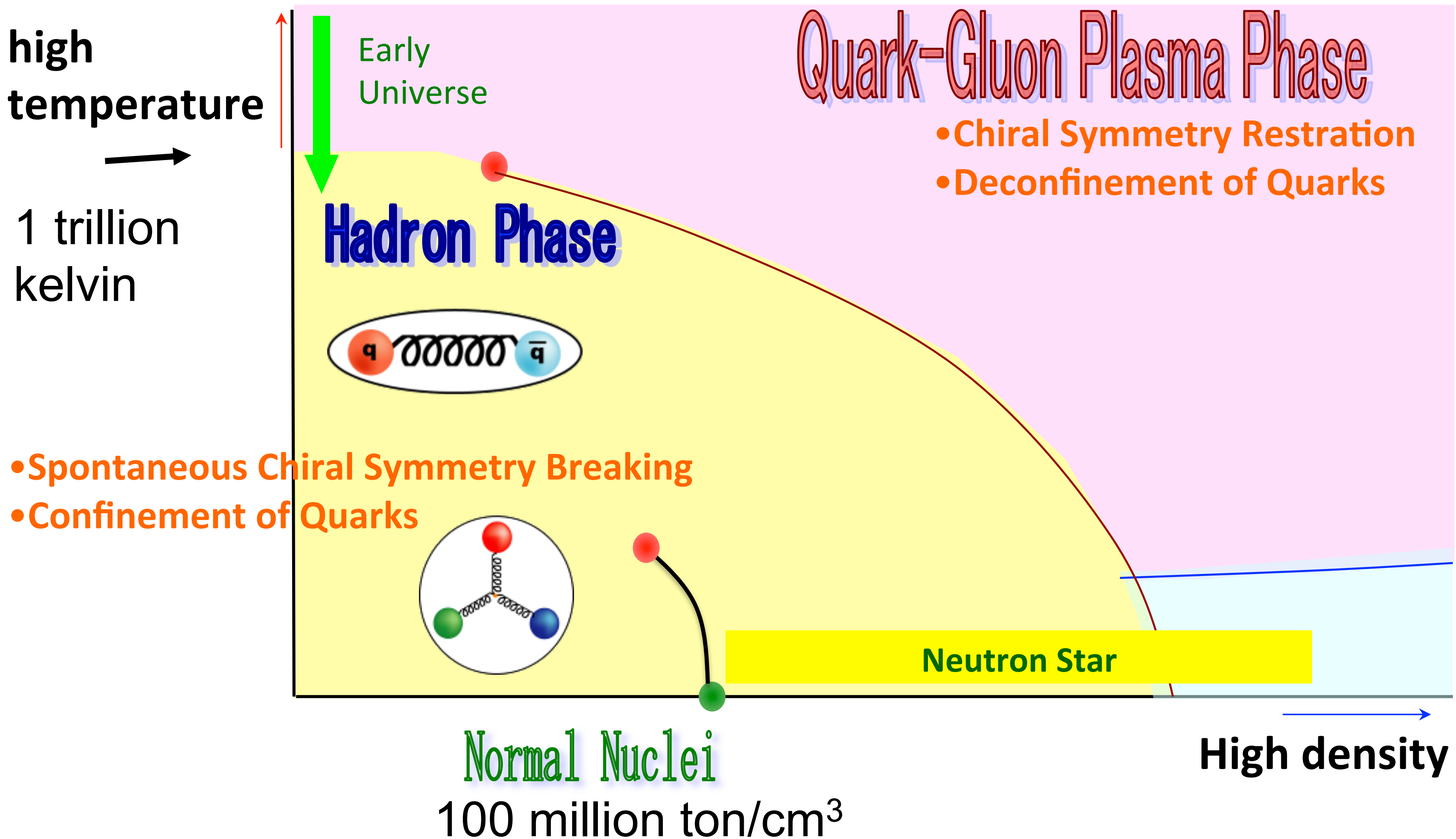
- Parity doublet model for light baryons
  - In [C.DeTar, T.Kunihiro, PRD39, 2805 (1989)], N*(1535) is regarded as the chiral partner to the N(939) having the chiral invariant mass.
  - In [D.Jido, T.Hatsuda, T.Kunihiro, PRL84, 3252 (2000)], Δ(1700) is regarded as the chiral partner to Δ(1232).

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

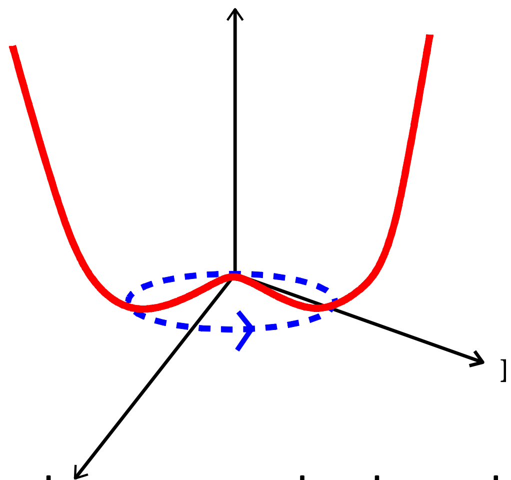
chiral invariant mass (m_{0B}) — spontaneous chiral symmetry breaking ($m_{\langle \bar{q}q \rangle}$)

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

Phase diagram of Quark-Gluon system

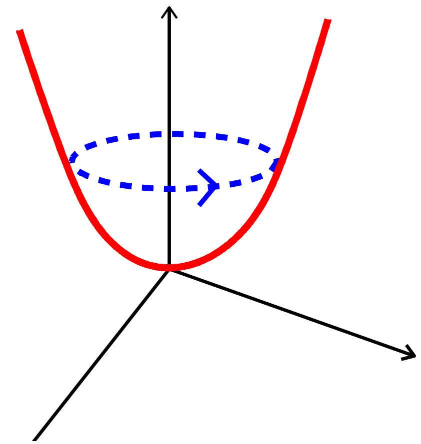


Important for understanding the spontaneous chiral symmetry breaking



chiral symmetry broken phase
at vacuum

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



chiral symmetric phase
at high T and/or density

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

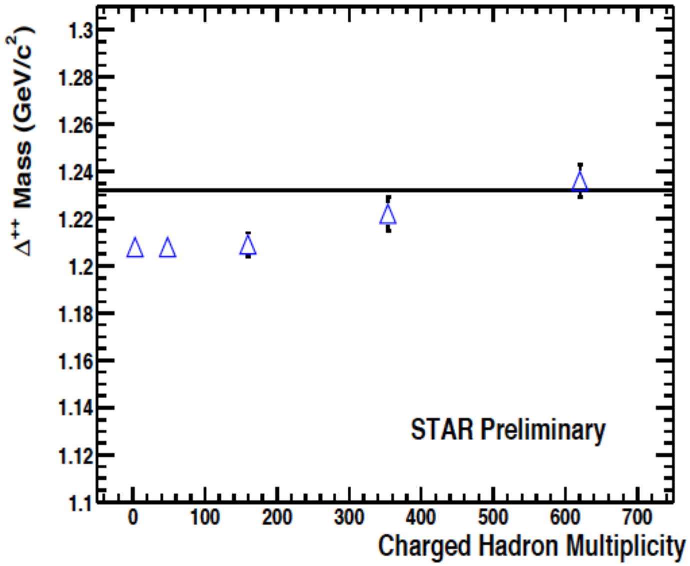
- The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
- It causes mass difference between chiral partners.
- Changing T and/or density will cause some change of hadron masses.

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.

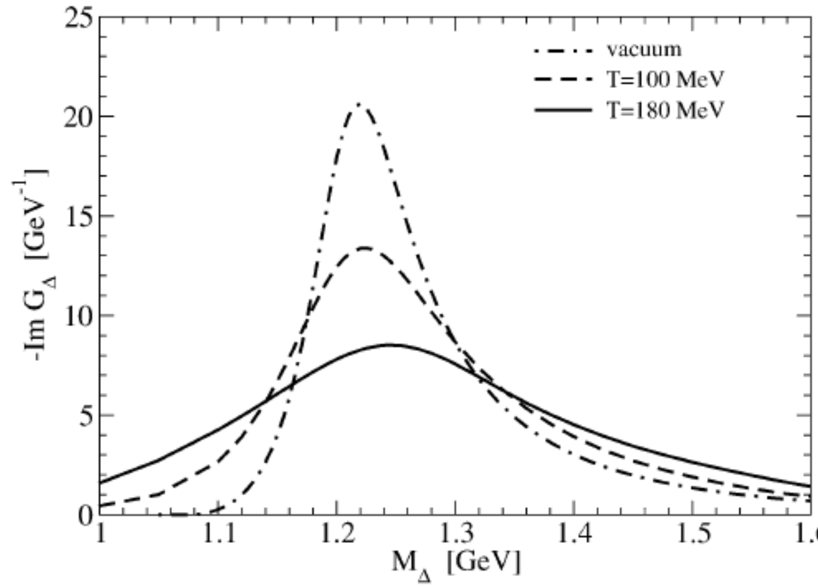
What happens to the mass of Delta baryon ?

Change of Delta at RHIC ?

STAR: arXiv:nucl-ex/040301



In-medium spectral funcion of Δ
by Hees-Rapp, PLB606, 59 (2005)



These show that medium effects push up the Δ mass at high temperature.

- What happens at high density ?
- What is the relation to the partial chiral symemtry restoration ?

- In this talk, I will show a preliminary study of the mass of Δ baryon at high density, based on a parity doublet structure.

Outline

1. Introduction
2. Nuclear matter from a parity doublet model
3. Density dependence of effective mass of Delta baryon
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.
- In this model, the origin of our mass is not only the chiral symmetry breaking.

Determination of the parameters at vacuum

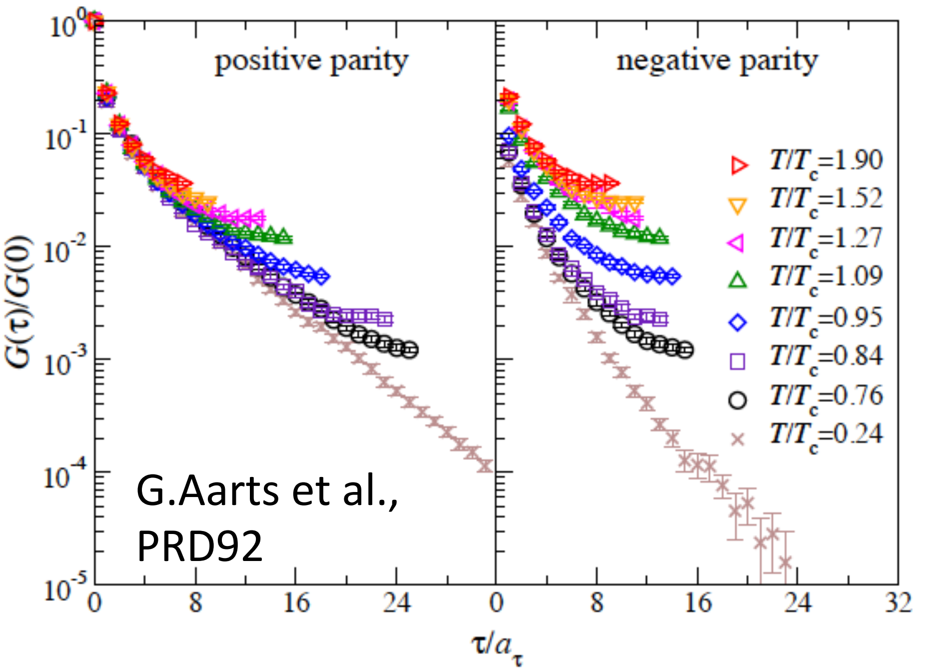
- Masses of parity eigenstates

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

- 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.

Lattice analysis

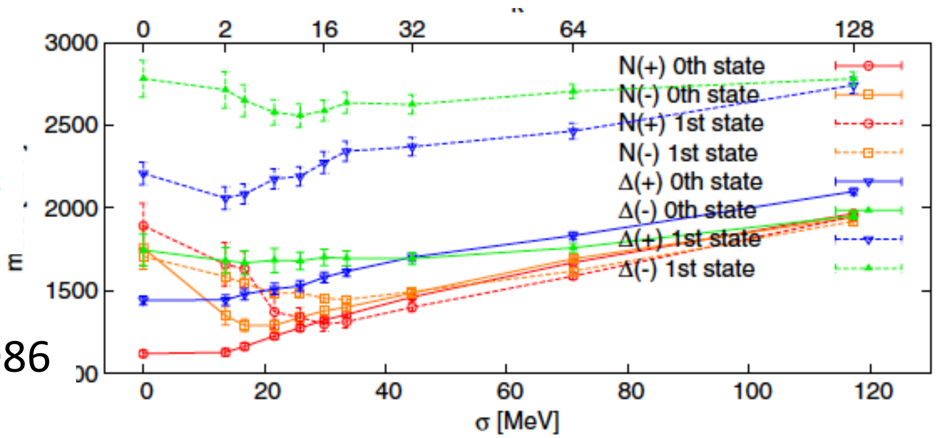
- The result in [G. Aarts, C. Allton, S. Hands, B. Jaeger, C. Praki, and J. I.Skullerud, Phys. Rev. D 92, 014503 (2015)] and [L.Y.Glozman, C.B.Lang, M. Schrock, Phys. Rev. D86, 014507 (2012)] seems to show the existence of large chiral invariant mass.



G.Aarts et al., PRD92

G. Aarts et al., PRD92

T/T_c	$a_\tau m_+$	$a_\tau m_-$	m_+ [GeV]	m_- [GeV]
0.24	0.213(5)	0.33(5)	1.20(3)	1.9(3)
0.76	0.209(16)	0.28(3)	1.18(9)	1.6(2)
0.84	0.192(17)	0.28(2)	1.08(9)	1.6(1)
0.95	0.198(25)	0.22(4)	1.12(14)	1.3(2)

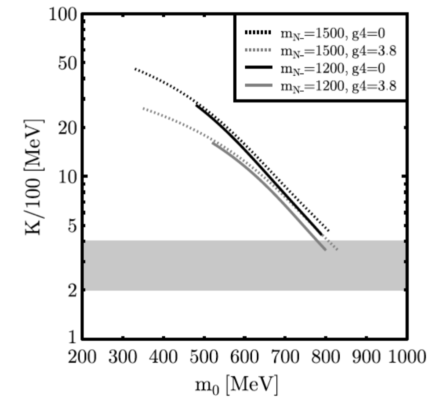


Y.L. Glozman et al., PRD86

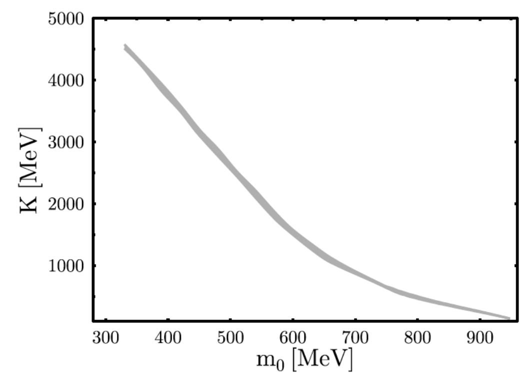
Nuclear matter in parity doublet models

- 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
- Different values of m_0 are preferred at vacuum and in medium ?
  - We construct a model with a 6-point interaction of sigma, but without 4-point interaction for vector mesons.
  - We obtain K = 240 MeV for $m_0 > 500$ MeV.

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



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



Inputs from medium property

- We calculate the thermodynamic potential in the nuclear medium in our model, using the mean field approximation.
- Then, we determine 4 parameters from the following physical inputs for a given value of the chiral invariant mass m_0 ($500 \leqq m_0 \leqq 900$ MeV).
  - Nuclear saturation density

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

  - 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

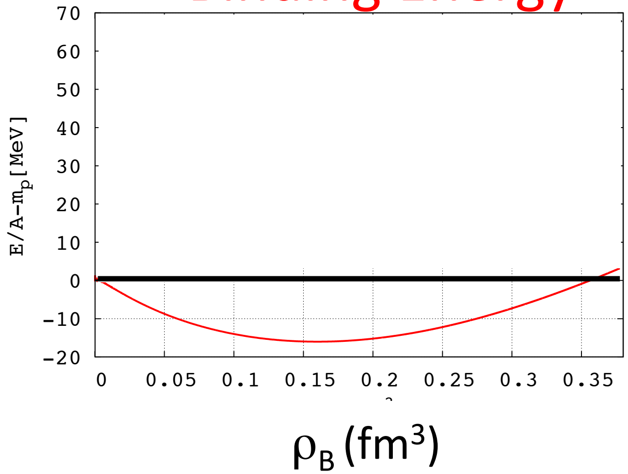
$$K = 9\rho_0^2 \frac{\partial^2 (E/A)}{\partial \rho^2}\bigg|_{\rho_0} = 9\rho_0 \frac{\partial \mu_B}{\partial \rho}\bigg|_{\rho_0} = 240 \text{ MeV}$$

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

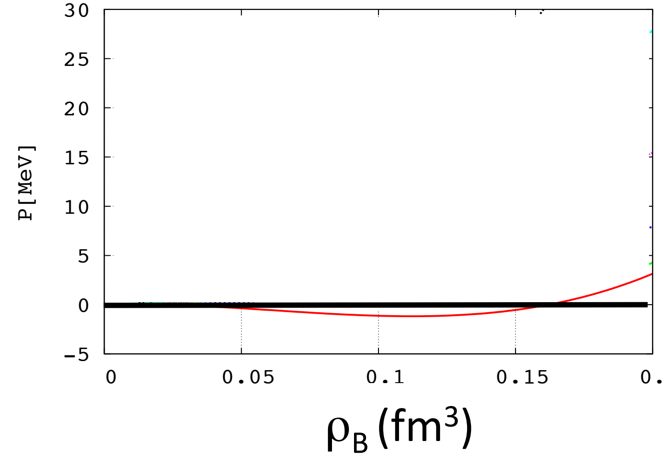
Binding Energy, Pressure, Mean fields

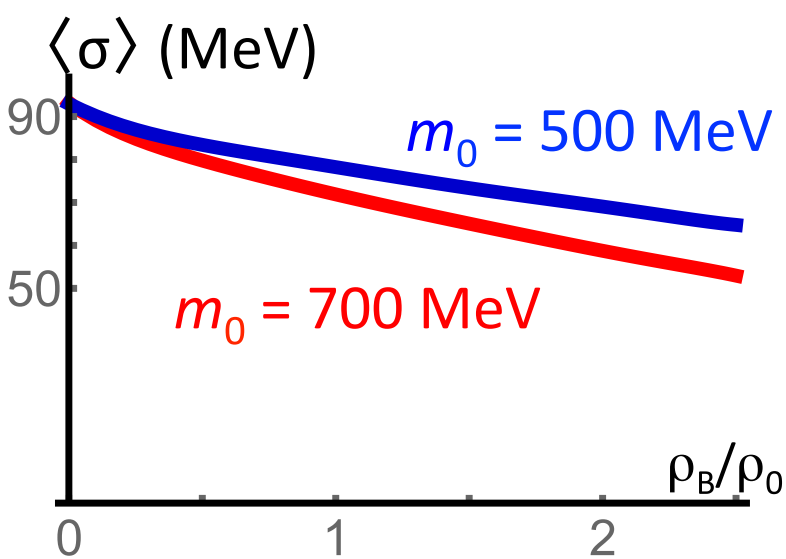
m_0 = 500 MeV

Binding Energy

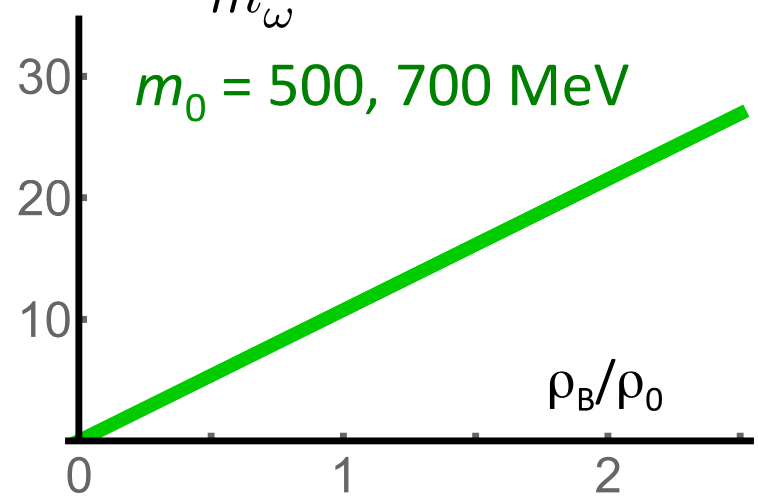


Pressure



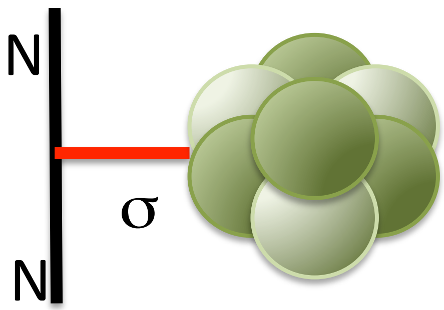


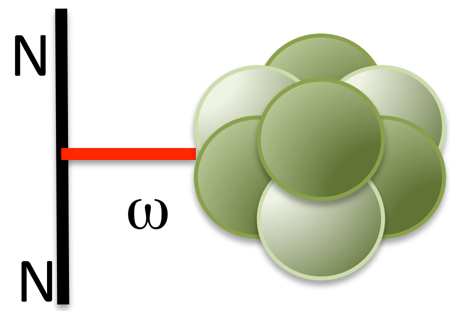
$$\langle\omega\rangle = \frac{g_{\omega NN}}{m_\omega^2}\,\rho_B \quad \text{(MeV)}$$



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].





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

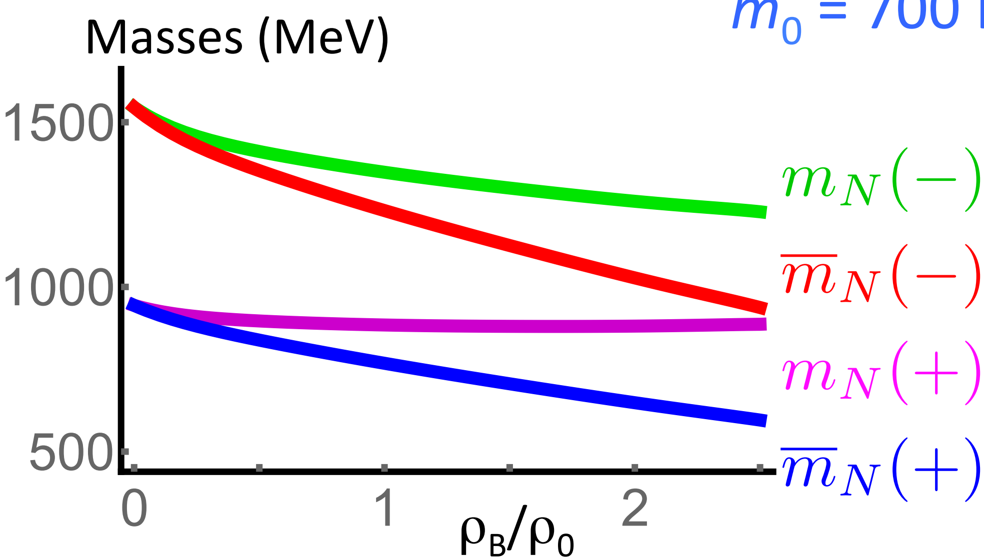
$$\overline{m}_{\pm}^{(\mathrm{eff})} = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\langle\sigma\rangle^2 + 4m_0^2} \mp (g_2 - g_1)\langle\sigma\rangle\right] - g_{\omega NN}\langle\omega\rangle \quad \text{(anti-nucleon)}$$

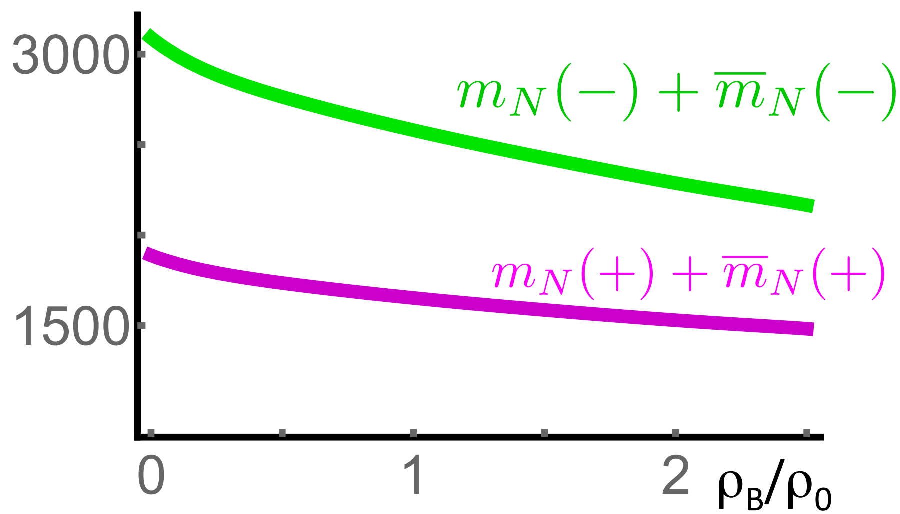
Density dependence of effective masses

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

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

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.

3. Density dependence of effective mass of Delta baryon

Chiral Partner Structure of Delta

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 chiral partners.

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

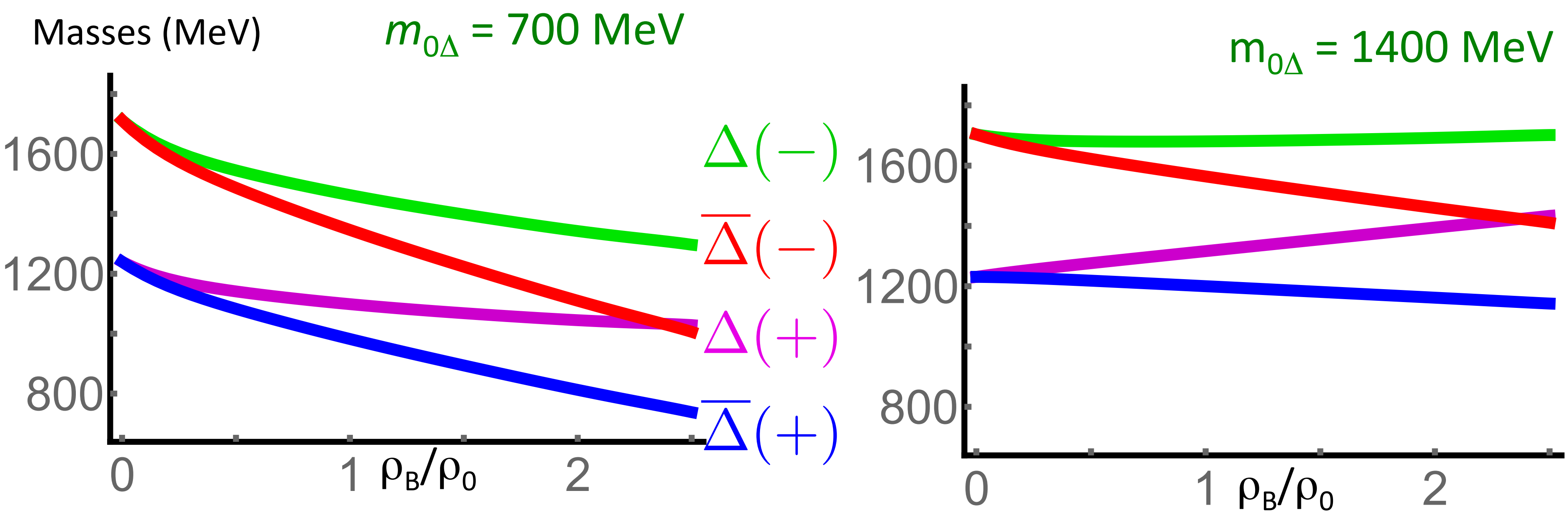
- I use masses of Δ(1232) and Δ(1700) as inputs.
- $m_{0\Delta}$ must lie $m_{0\Delta} \leqq 1460$ MeV.
- In the following analysis, I use $m_{0\Delta} = 1400, 700$ MeV as typical examples.

Density dependence of effective masses

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

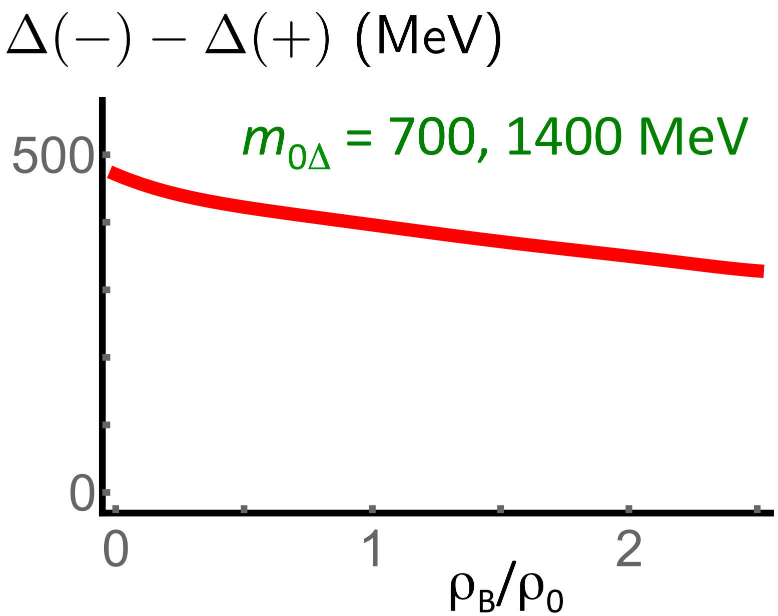
$$\overline{m}_{\Delta\pm} = \sqrt{(\bar{g}_1+\bar{g}_2)^2\langle\sigma\rangle^2 + m_{0\Delta}^2} \mp (\bar{g}_1-\bar{g}_2)\langle\sigma\rangle - g_{\omega\Delta\Delta}\langle\omega\rangle \quad (\text{anti-}\Delta)$$

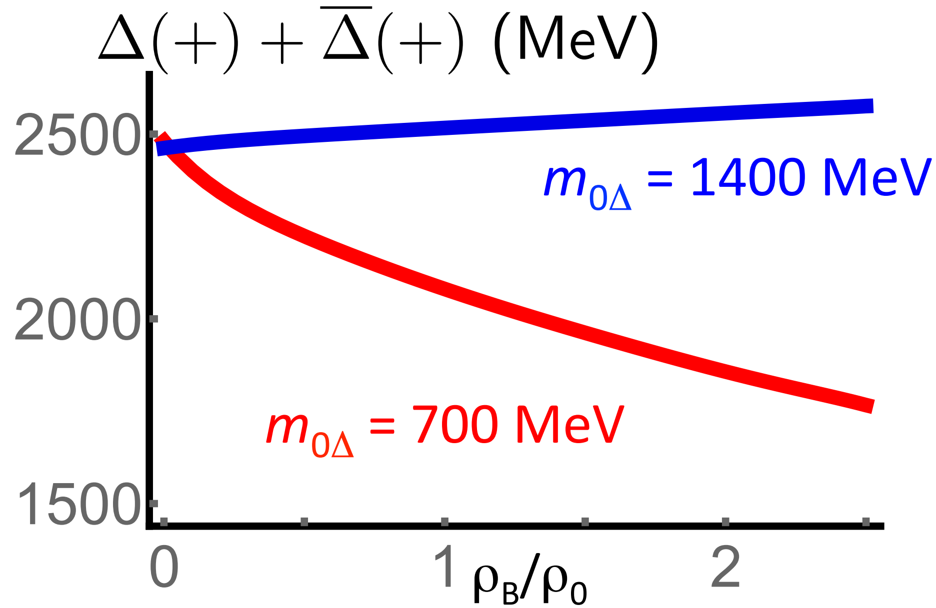
I use $g_{\omega\Delta\Delta} = g_{\omega NN} = 5.4$ as a typical example.



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

Partial chiral symmetry restoration





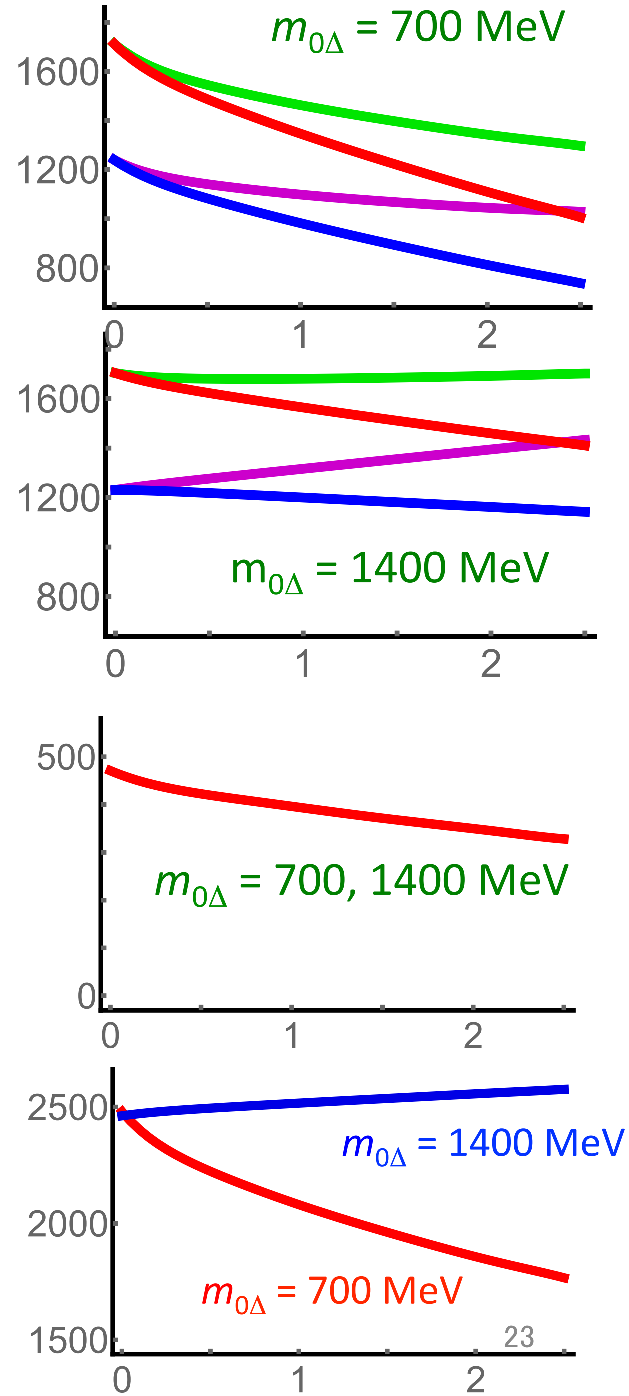
- Studying the mass difference of chiral partners gives a clue for partial chiral symmetry restoration, independently of the value of $m_{0\Delta}$.
- Taking sum of particle and anti-particle will give a clue for chiral invariant mass.

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

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

4. Summary

- We studied density dependence of Delta baryon masses from the mean field contributions of sigma and omega mesons.
- Increasing or decreasing of Δ(+) 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}.



Discussions

- For more realistic study of Δ mass in matter, we should check the effect of π-N loop, which is needed to study the in-medium spectral function.
- There seems still a difference of the estimated value of the chiral invariant mass of nucleon between the one at vacuum and the one in the matter.
- The analysis in the 3-flavor parity doublet model shows that the chiral partner of the positive parity nucleon, N(939), is not N*(1535), but a mixture of N*(1440), N*(1535), N*(1650), … [H.Nishihara and M.Harada, Phys. Rev. D92, 054022 (2015), and work in preparation.]
- It is interesting to include 2 parity doublets for nucleon into a model.

The End