η'(958) bound states in nuclei
and
Partial Restoration of Chiral Symmetry

D. Jido, H. Nagahiro, S. Hirenzaki

京奈 collaboration

- 1. Some Remarks for Motivation
- 2. Description by A Model
- 3. Current Status
- 4. Summary

Some Remarks for Motivation

1, Mass reduction will be equivalent to attractive V in Eq. of Motion..

$$m_{\eta'}^2 \to m_{\eta'}^2(\rho) = (m_{\eta'} + \Delta m_{\eta'}(\rho))^2 \sim m_0^2 + 2m_0\Delta m(\rho)$$

$$\Delta m(\rho) \to V(\rho(r)) = V_0 \frac{\rho(r)}{\rho_0}$$

2, But " Attractive ➔ Mass reduction " is wrong. Ex.) Coulomb case.
Origin of the attraction is important.

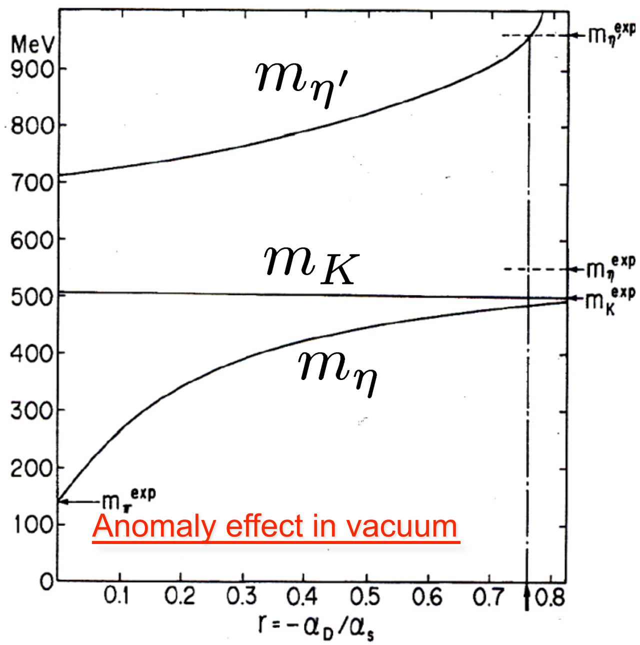
3, Thus, "clear origin" is important to deduce something.

4, For Bound State observation as peaks, ReV>ImV is important.

5, η(958) seems interesting, in these senses.

Today's Specialty: $\eta'(958)$

Kunihiro, Hatsuda, PLB206(88)385, Fig.3



The NJL Model : $J^p = 0^-$

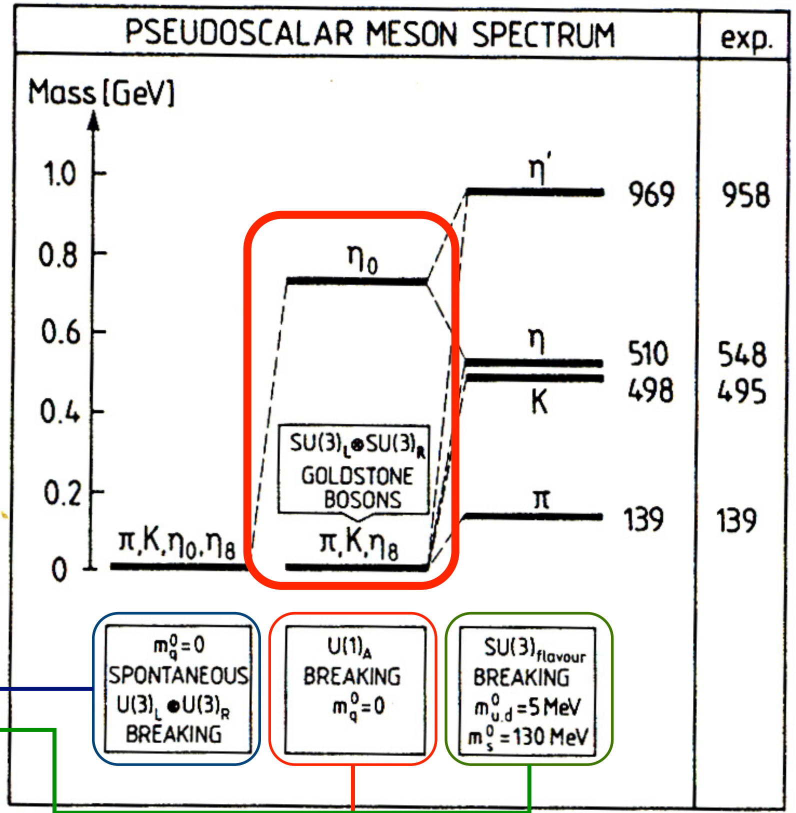
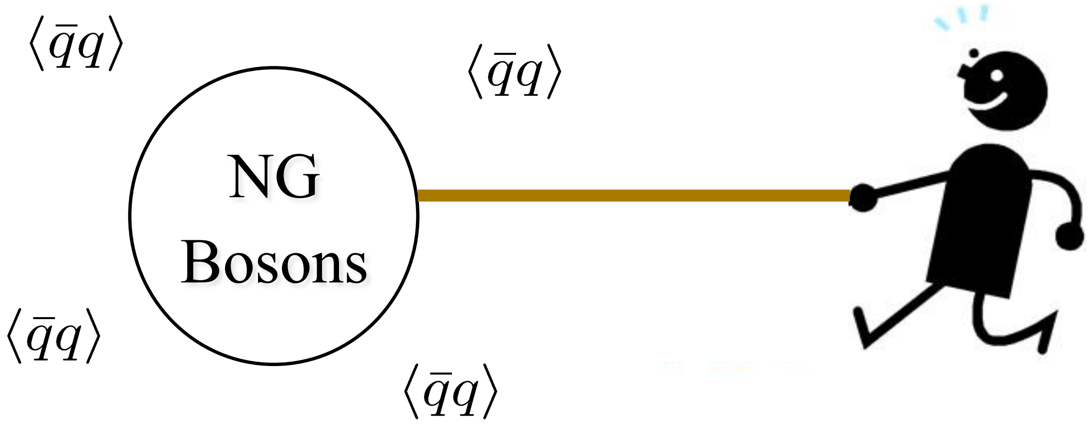
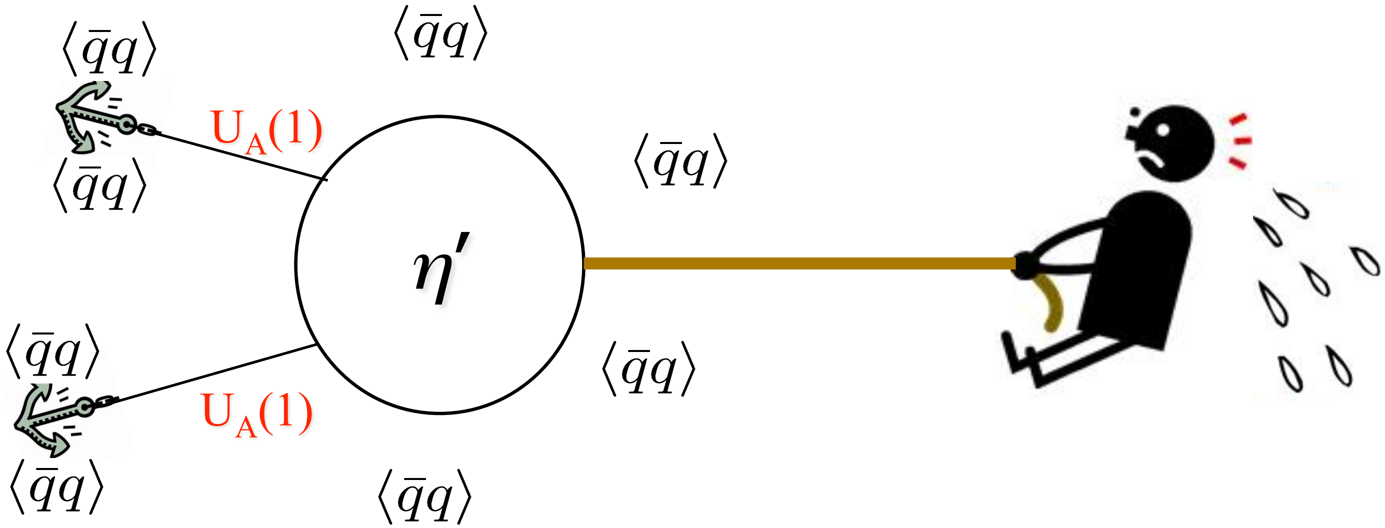


Fig. 10. *Pseudoscalar meson spectrum from the NJL model (Klimt et al. 1990), showing the chiral and flavour symmetry breaking pattern. Calculated and experimental masses are given in MeV.*

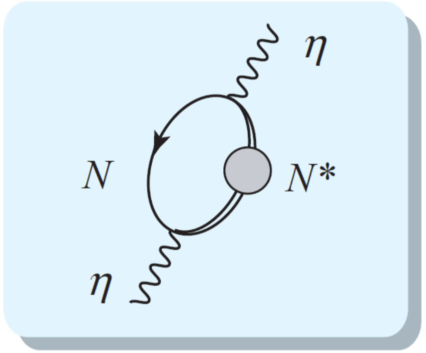
- Higgs mechanism
- Spontaneous Chiral Symmetry Breaking
- $U_A(1)$ Anomaly Effect

Primer plato: Origin of Mass





Segundo: (s-channel) Dispersion



$$\mathrm{Re}V(\omega) = a(\omega_0) + \frac{\omega - \omega_0}{\pi} \mathrm{P} \int d\omega' \frac{\mathrm{Im}V(\omega)}{(\omega' - \omega_0)(\omega' - \omega)}$$

Re and Im, Same Order!! ………. But, We love ReV >> ImV !!!

H. Nagahiro, D. Jido, and S. Hirenzaki, Phy. Rev. C 68 (2003) 035205.

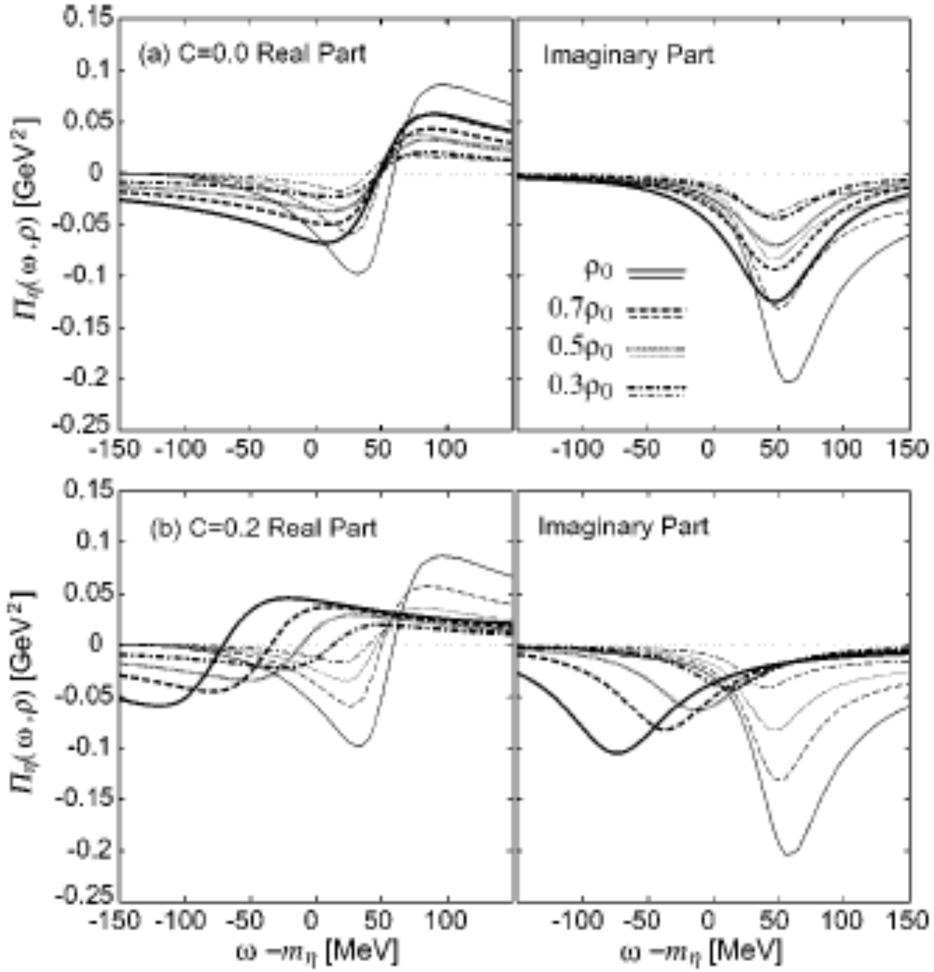
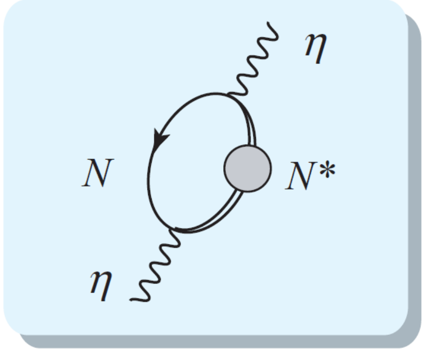


FIG. 1. The η self-energies are plotted as a function of the η energy for four nuclear density cases as indicated in the figure. (a) The self-energies obtained by the chiral doublet model with the mirror assignment for $C=0.0$ (thick lines) and those by the chiral unitary approach (thin lines). (b) Same as (a) except for $C=0.2$ for the chiral doublet model (thick lines). The results with the chiral unitary approach are taken from Fig. 6(c) of Ref. [8(b)] and are the same for both (a) and (b).

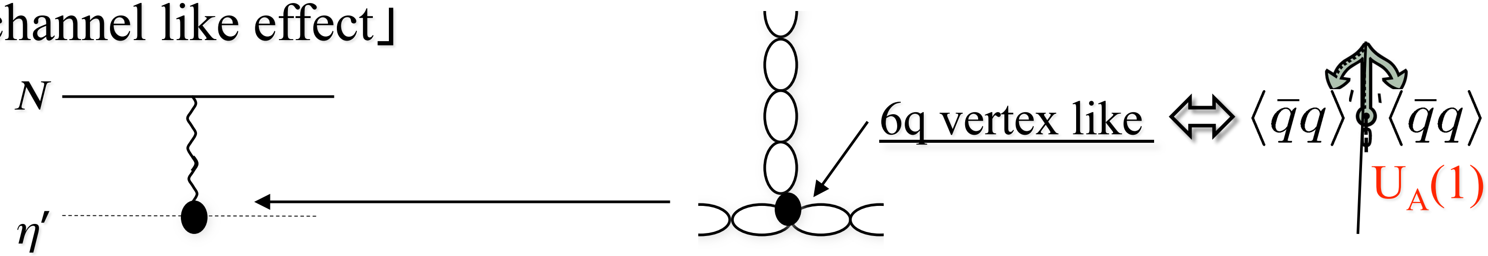
Segundo: (s-channel) Dispersion



$$\mathrm{Re}V(\omega) = a(\omega_0) + \frac{\omega - \omega_0}{\pi} \mathrm{P} \int d\omega' \frac{\mathrm{Im}V(\omega)}{(\omega' - \omega_0)(\omega' - \omega)}$$

Same Order!! ………. But, We love ReV >> ImV !!!

★Chance to have ReV >> ImV
「t-channel like effect」



Description by A Model:

Nagahiro, Takizawa, Hirenzaki

PRL **94**, 232503 (2005) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2005

Formation of $\eta'(958)$-Mesic Nuclei and Axial $U_A(1)$ Anomaly at Finite Density

Hideko Nagahiro[1] and Satoru Hirenzaki[2]

[1]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*

[2]*Department of Physics, Nara Women's University, Nara 630-8506, Japan*

PHYSICAL REVIEW C **74**, 045203 (2006)

η- and η'-mesic nuclei and $U_A(1)$ anomaly at finite density

Hideko Nagahiro,[1] Makoto Takizawa,[2] and Satoru Hirenzaki[3]

[1]*Research Center for Nuclear Physics(RCNP), Osaka University, Ibaraki, Osaka, 567-0047, Japan*

[2]*Showa Pharmaceutical University, Machida, Tokyo, 194-8543, Japan*

[3]*Department of Physics, Nara Women's University, Nara, 630-8506, Japan*

(Received 26 June 2006; published 20 October 2006)

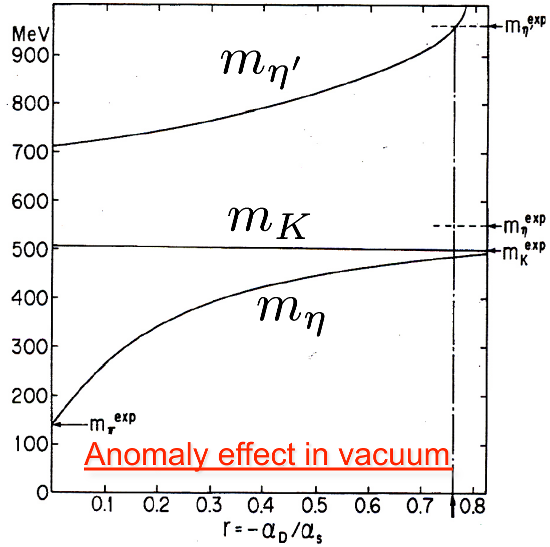
H.Nagahiro., S. H, PRL94(05)232503
H. Nagahiro, M. Takizawa and S. H, PRC74(06)045203

η'(958) mesic nuclei formation

- η'(958) meson … close connection to the $U_A(1)$ anomaly
  - many theoretical works
    - in vacuum / at finite temperature / at finite density
      - R. D. Pisarski, R. Wilczek, PRD29(84)338
      - T. Kunihiro, T. Hatsuda, PLB206(88)385 / T. Kunihi
      - V. Bernard, R.L.Jaffe and U.-G.Meissner, NPB308(1
      - Y. Kohyama, K.Kubodera and M.Takizawa, PLB208
      - K. Fukushima, K.Onishi, K.Ohta, PRC63(01)045203
      - P. Costa *et al.*,PLB560(03)171, PRC70(04)025204, e
  - poor experimental information at finite density

- $U_A(1)$ anomaly in medium from the viewpoint of "mes
  - the η' properties, especially **mass shift**, at finite density

Kunihiro, Hatsuda, PLB206(88)385



Anomaly effect in vacuum

- **Nambu-Jona-Lasinio model** with the **KMT interaction**

$$\mathcal{L} = \bar{q}(i\,\partial\!\!\!/ - m)q + \frac{g_s}{2}\sum_a \left[(\bar{q}\lambda_a q)^2 + (i\bar{q}\lambda_a\gamma_5 q)^2\right]$$
$$+ g_D\left[\det \bar{q}_i(1-\gamma_5)q_j + h.c.\right]$$

explicit breaking the $U_A(1)$ sym.

Kobayashi, Maskawa Prog.Theor.Phys.44, 1422 (70), G. 't Hooft, Phys.Rev.D14,3432 (76)

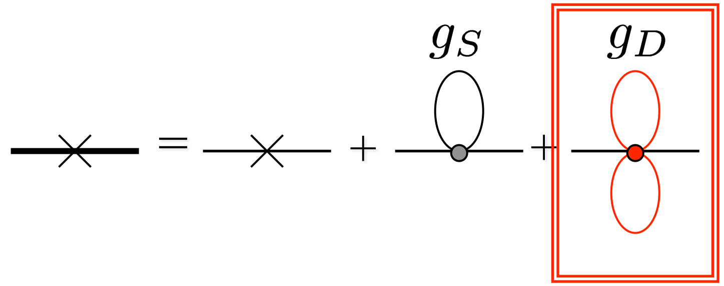
Mesons in finite T/ρ with NJL

T. Kunihiro, PLB219(89)363
P. Costa *et al.*,PLB560(03)171 etc…

Gap equations for quarks

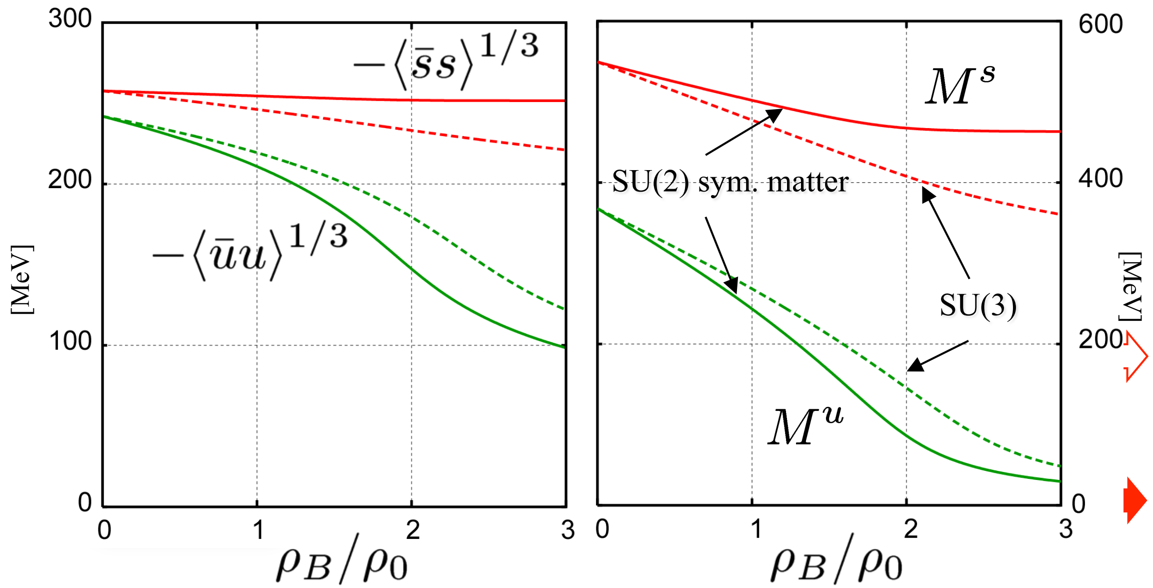
$$\begin{cases} M^u = m^u - 2g_S\langle\bar{u}u\rangle - 2g_D\langle\bar{d}d\rangle\langle\bar{s}s\rangle \\ M^d = m^d - 2g_S\langle\bar{d}d\rangle - 2g_D\langle\bar{s}s\rangle\langle\bar{u}u\rangle \\ M^s = m^s - 2g_S\langle\bar{s}s\rangle - 2g_D\langle\bar{u}u\rangle\langle\bar{d}d\rangle \end{cases}$$

flavor mixing terms



condensate in finite T/ρ

$$\langle\bar{q}q\rangle = -2N_C\int\frac{d^3p}{(2\pi)^3}\frac{M}{E_p}(1-n_p(T,\mu)-\bar{n}_p(T,\mu))$$



$$n(T,\mu) = \frac{1}{e^{(E_p-\mu)/T}+1}$$

Fermi distribution function

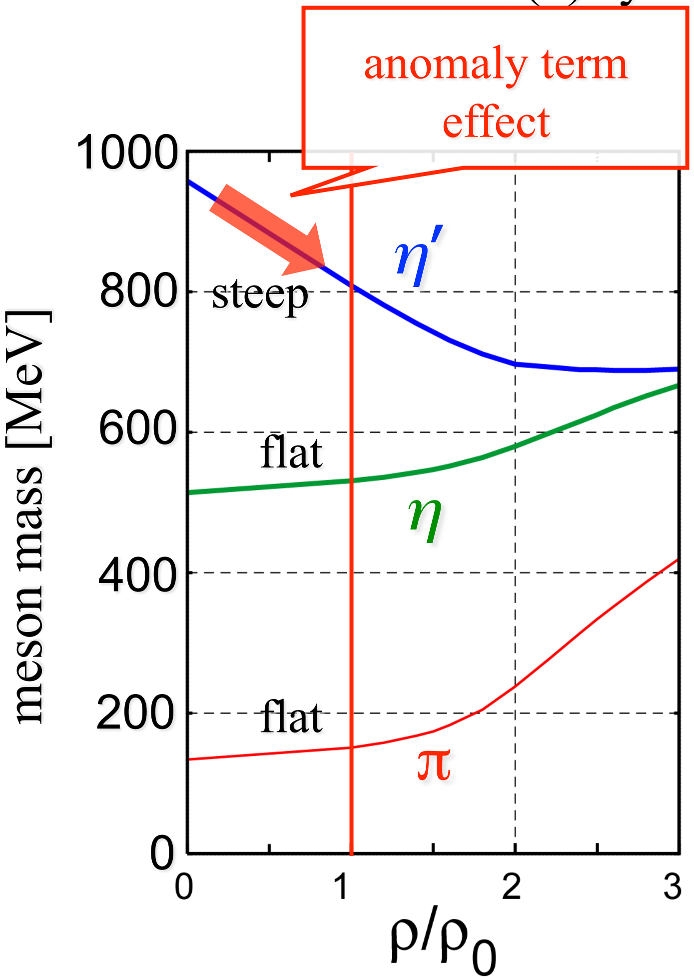
partial restoration in medium

meson properties (mass)

η' mass shift in medium $\rho_u = \rho_d,\ \rho_s = 0$

- we consider the SU(2) sym. matter as the sym. nuclear matter.

P. Costa et al.,PLB560(03)171, PRC70(04)025204, etc …



parameters (in vacuum)

P. Rehberg, et al., PRC53(96)410.

Λ = 602.3 [MeV]
$g_S \Lambda^2$ = 3.67
$g_D \Lambda^5$ = -12.36
$m_{u,d}$ = 5.5 [MeV]
m_s = 140.7 [MeV]

$M_{u,d}$ = 367.6 [MeV]
M_s = 549.5 [MeV]
$\langle \bar{u}u \rangle^{1/3}$ = -241.9 [MeV]
$\langle \bar{s}s \rangle^{1/3}$ = -257.7 [MeV]
$m_{\eta'}$ = 958 [MeV]
m_η = 514 [MeV]
m_π = 135 [MeV]

η and η' mass shifts @ ρ_0

$$\Delta m_{\eta'} \sim -150 \text{ MeV @ } \rho_0$$
$$\Delta m_{\eta} \sim +20 \text{ MeV @ } \rho_0$$

We can see the large medium effect even at normal nuclear density.

η'(958) mesic nuclei by (π,N) reaction (Missing mass like Pionic Atom)

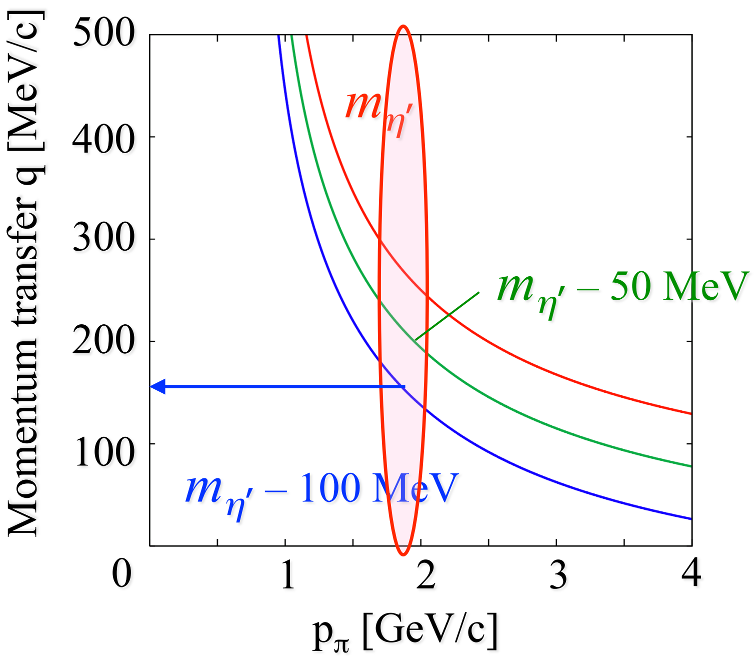
- Potential description

Real Part V_0 … evaluated by possible η' mass shift at ρ_0

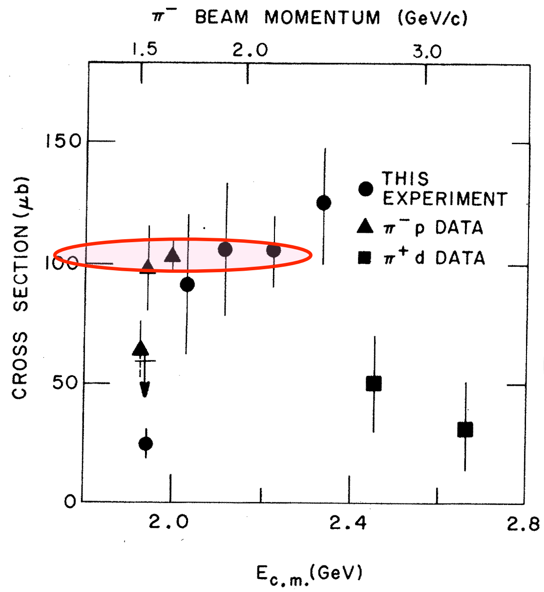
$$\Delta m(\rho) \rightarrow V(\rho(r)) = V_0 \frac{\rho(r)}{\rho_0}$$

Imaginary part W_0 … *unknown* → 20 MeV, *for example*

momentum transfer



elementary cross section $\pi^+ n \rightarrow \eta' p$



R.K.Rader *et al.*, PRD6(72)3059

$\sigma(\pi^+ n \rightarrow \eta' p) \sim 100\ \mu b$

↓

$$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 10 \sim 100 \mu b/sr$$

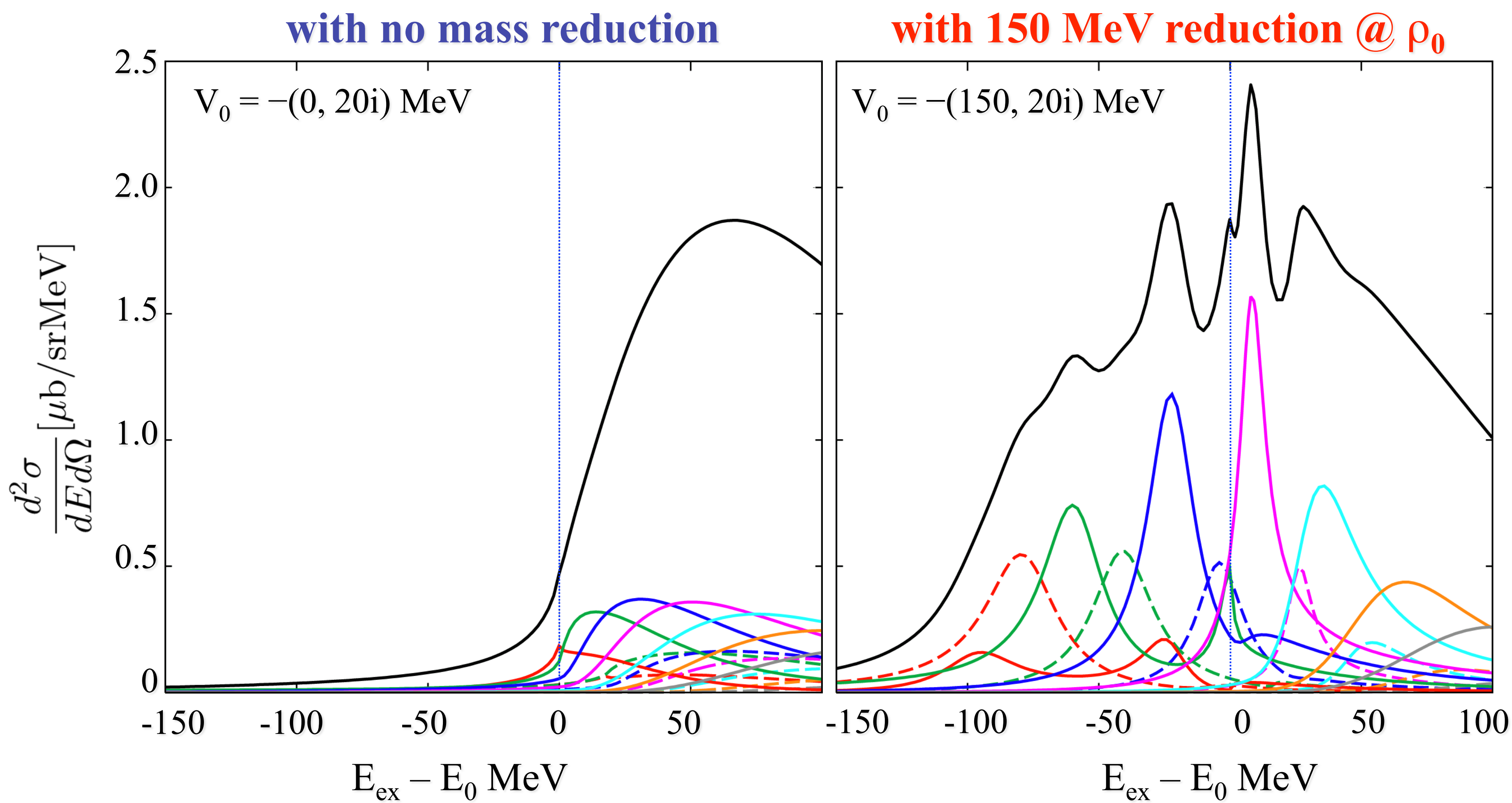
η'-mesic nuclei formation spectra : ^{12}C target : (π^+,p) reaction

- p_π = 1.8 GeV/c
- proton angle = 0 deg.

$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 100\mu b/sr$ case

By H. Nagahiro

PTP Suppl. 186(2010)316.



Current Status

- Experimental Report

1. RHIC: PHENIX/STAR (Low energy pion)
   by T. Csörgö *et al*., Phys. Rev. Lett. 105 (2010) 182301.
   $\Delta m_{\eta'} \sim 200$ MeV (Consistent to NJL)

2. CBELSA/TAPS (transparency)
   by M. Nanova, Talk at BARYONS10;
   $\Gamma\ (\rho_0, \langle \vec{p}_{\eta'} \rangle \sim 0.9$ GeV/c$) \approx 25 - 30$ MeV (Reasonably smaller than $\Delta m_{\eta'}$)

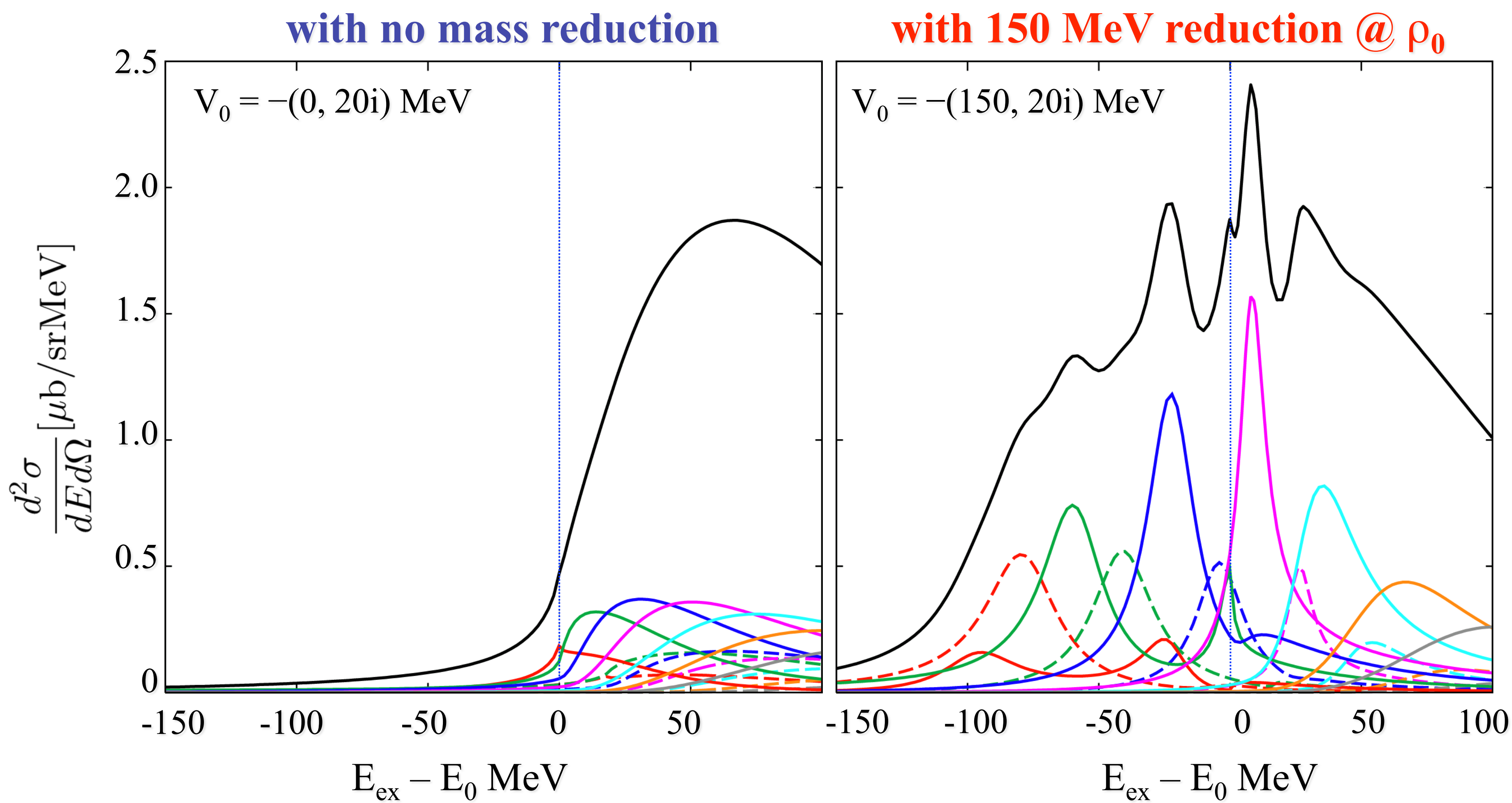
η'-mesic nuclei formation spectra : ^{12}C target : (π^+,p) reaction

- p_π = 1.8 GeV/c
- proton angle = 0 deg.

$\left(\frac{d\sigma}{d\Omega}\right)^{Lab.} = 100\mu b/sr$ case

By H. Nagahiro

PTP Suppl. 186(2010)316.



A small (large?) bone stuck in throat

- Experimental Report

1. RHIC: PHENIX/STAR (Low energy pion)
   by T. Csörgö *et al*., Phys. Rev. Lett. 105 (2010) 182301.
   $\Delta m_{\eta'} \sim 200$ MeV (Consistent to NJL)

2. CBELSA/TAPS (transparency)
   by M. Nanova, Talk at BARYONS10;
   $\Gamma\,(\rho_0, \langle \vec{p}_{\eta'} \rangle \sim 0.9$ GeV/c$) \approx 25 - 30$ MeV (Reasonally smaller than $\Delta m_{\eta'}$)

3. COSY (final state interaction)
   by P. Moskal *et al*., Phys. Lett. B 482 (2000) 356.
   $a_{\eta' p} \sim 0.1$ fm ($V(\rho_0) \sim 10$ MeV)
   (Consistent to E. Oset, A. Ramos, arXiv: 1010. 5603[nucl-th])
   $\cdots$ However, large t-channel like contribution to $a_{\eta' p}$ is expected.

Summary

- Clear origin is of great importance.

- $\eta'(958)$ is Special.
  - » Clear Mass Reduction by $\langle \bar{q}q \rangle$ with help of $U_A(1)$
  - » $\Delta m >> \mathrm{Im}V$, thanks to $U_A(1)$

- Narrow Peak for η' Mesic Nuclei Formation, Missing mass spectra.