Mesons in nuclei and partial restoration of chiral symmetry

D. Jido

(Tokyo Metropolitan University)

mesons in nuclear matter in the context of chiral symmetry

- introduction
- K^{bar} meson in nuclear medium
- K^+ nucleus scattering revisited
- $\pi^0 \rightarrow \gamma\gamma$ in nuclear medium
- η mesonic nuclei
- η’ in nuclear medium and η’-N interaction

首都大学東京
TOKYO METROPOLITAN UNIVERSITY

Motivation

Why do we study the properties of hadron in nucleus ?

- as **nuclear physics**
  - interested in the nature of the strong interaction
  - study many-body systems governed by the strong force
  - discover new bound systems of the strong interaction
  - exotic states are interesting

- as **hadron physics**
  - in-medium change of hadron properties
  - more fundamental interpretation in terms of QCD
  - one of the key concept is partial restoration of **chiral symmetry**

- for **other research areas**
  - provide basic informations of high density physics
  - important constraints accessible in experiments on earth

In-medium change of hadron properties

medium effects on hadron

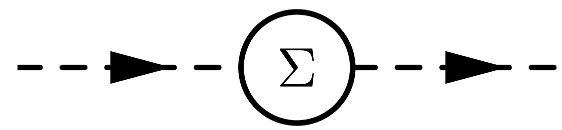
mass modification — mass is given by pole of propagator at rest

vertex correction

wave function renormalization

$$Z = \left(1 - \frac{\partial \Sigma}{\partial p_0^2}\right)^{-1}$$

in-medium self-energy Σ



describes interaction between hadron and nuclear matter.

effective theory, effective model such as, in-medium ChPT

provides fundamental interactions between hadrons and nucleons

describes hopefully nuclear matter out of nucleon correlations (NN, NNN, ⋯)

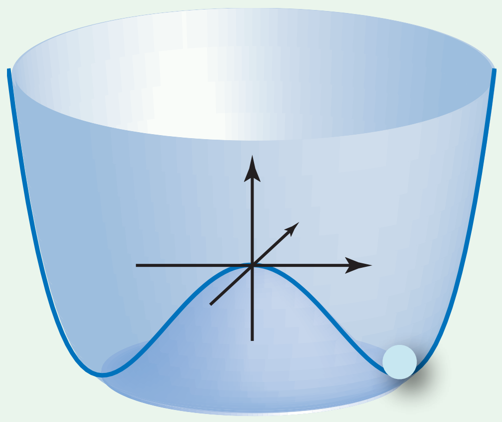
eff. theory —**predict**→ in-medium mass, spectra, bound states, ⋯

parameters ←**feedback**— observation

⇩

more fundamental interpretation in terms of QCD

Chiral Symmetry



- a fundamental symmetry in QCD,
- dynamically broken by physical states
- dynamical ChS breaking determines **vacuum property** and describes **low energy hadron dynamics**
  - most of light hadron properties is affected by ChSB
  - hadrons are excitation modes upon vacuum

light pion mass, mass generation etc.

- DChSB is a **phase transition phenomenon**
  - broken symmetry can be restored at extreme conditions, such as high density, high temp.
  - partial (incomplete) restoration takes in nuclear medium
  - pionic atom experiments and pion nucleus scattering with theoretical consideration have suggested that chiral symmetry is partially restored in nuclear matter with 30% reduction of quark condensate

K. Suzuki et al. PRL92, 072302 (04)

Friedman et al. PRL93, 122302 (04)

Kolomeitsev, Kaiser, Weise, PRL90, 092501 (03).

DJ, Hatsuda, Kunihiro, PLB 670, 109 (08).

Reduction of π decay constant

enhancement of s-wave repulsive interaction

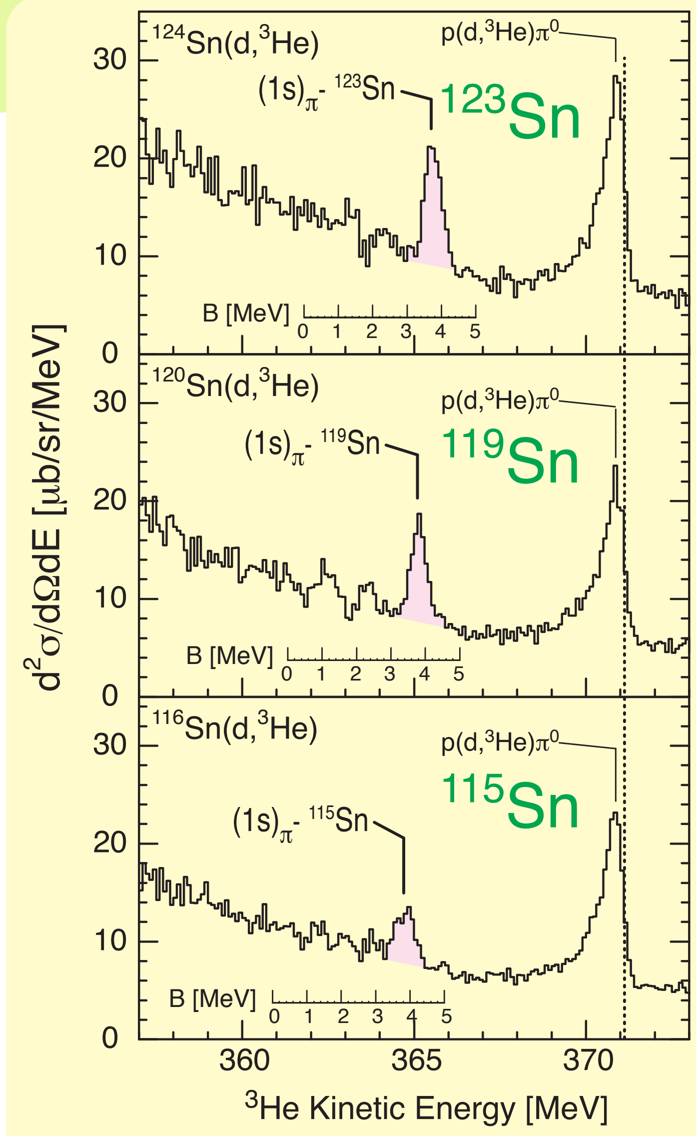
Deeply bound pionic atom K. Suzuki et al. PRL92, 072302 (04)

systematic study of π^- bound states in Sn isotopes

$$b_1^{\text{free}}/b_1 = 0.78 \pm 0.05 \qquad \rho \sim 0.6\ \rho_0$$

Elastic scattering (Friedman et al.)

$$b_1^{\text{free}}/b_1 \sim 0.69$$



related to in-medium reduction of pion decay constant F_π

Weinberg-Tomozawa realtion

in vacuum

$$4\pi\left(1+\frac{m_\pi}{m_N}\right)b_1^{\text{free}} = -\frac{m_\pi}{2F^2}$$

in medium at low-density

$$4\pi\left(1+\frac{m_\pi}{m_N}\right)b_1 = -\frac{m_\pi}{2(F_\pi^t)^2}$$

$$\frac{b_1^{\text{free}}}{b_1} = \left(\frac{F_\pi^t}{F_\pi}\right)^2$$

at low density

DJ, Hatsuda, Kunihiro, PLB 670 (2008), 109.

Chiral Symmetry

expectation in partial restoration of chiral symmetry in nuclear matter

- **reduction of mass difference between parity partners**

  σ-π ρ- a_1 N-N* etc.

  η probes chiral symmetry for N and N*(1535)

- **wave function renormalization for Nambu-Goldstone bosons**

  amplitudes of NG bosons have energy dependence due to chiral symmetry

  $$Z = \left(1 - \frac{\partial \Sigma}{\partial p_0^2}\right)^{-1}$$

  DJ, Hatsuda, Kunihiro, PRD63, 011901(R); PLB 670 (2008), 109.

  K^+, π^0 K^+A scattering amplitude is enhanced due to Z

- **mass reduction of hadrons whose mass is generated by spontaneous breaking of chiral symmetry**

  a part of nucleon mass is generated by spontaneous breaking of chiral symmetry

  effective mass of nucleon in nuclear matter is 0.7 m_N.

  η' part of eta' mass is generated by chiral symmetry breaking

K^{bar} meson

$\bar{K}$ in nuclear medium

a lots of studies on in-medium kaon

one of the difficulties in observation

a recent review
Freedman, Gal, Phys.Rept. 425, 89 (2007)

large in-medium absorption

kaon is strongly absorbed in nuclear medium

mesonic $K^{bar}N$ to πY

nonmesonic $K^{bar}NN$ to YN   30% at ρ_0

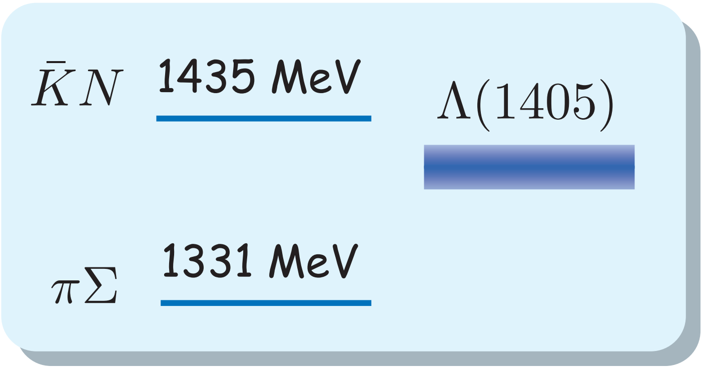
Sekihara, Yamagata-Sekihara, DJ, Kanada-En'yo, PRC86, 065205 (12)

hard to identify K^{bar}-nucleus bound states, even if they exist

$K^{bar}N$ interaction as a fundamental interaction of $K^{bar}A$

Λ(1405) is sitting 30 MeV below the $K^{bar}N$ threshold

nature of Λ(1405) is extremely important to be revealed



chiral symmetry determines low-energy $K^{bar}N$ interaction, but it may play a minor role on the in-medium K^{bar} properties, because dynamics of $K^{bar}N$, or Λ(1405), is more significant

Nature of Λ(1405)

DJ, Oller, Oset, Ramos, Meissner, NPA725, 181 ('03)

a recent review, Hyodo, DJ, Prog. Part. Nucl. Phys. 67, 55 ('12)

- Λ(1405) is most probably a quasi-bound state of K^bar^N

low-energy theorem of chiral symmetry tells that K^bar^N interaction is attractive
(model independent Weinberg-Tomozawa interaction)

how strong ??

the I=0 interaction is enough strong to form a bound state

dynamical calculations of the K^bar^N system with the chiral interaction and without sources of resonances conclude a K^bar^N bound state with 15 MeV binding energy

Λ(1405) appears as a K^bar^N bound state with 15 MeV binding energy

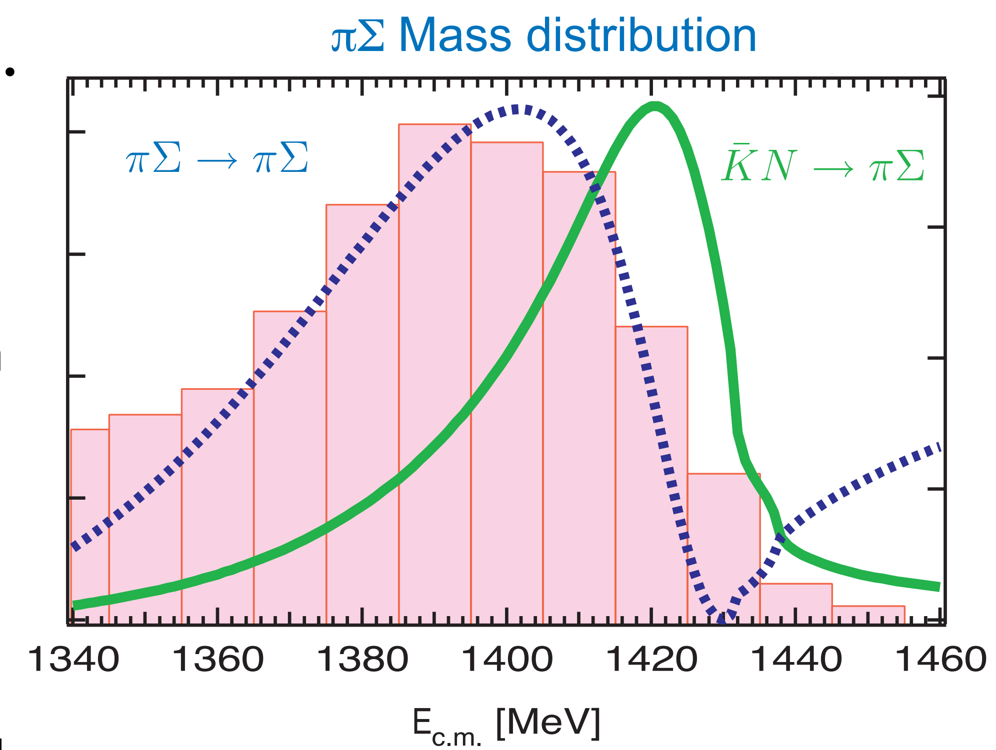
theoretically, K^bar^N interaction is not so strong.

the binding energy is 15 MeV not 30 MeV

two-pole structure

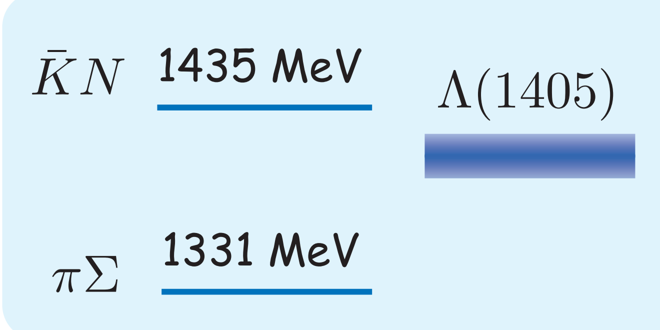
the spectrum of Λ(1405) is explained by interference between two components, K^bar^N bound state and πΣ resonance.

Hyodo, Weise, PRC77, 035204 ('08)



to confirm this scenario,
we observe Λ(1405) produced by K^bar^N channel

Subthreshold amplitude of K^{bar}N



Λ(1405) is located below the K^{bar}N threshold

cannot be produced by direct reaction $\bar{K}N \to \Lambda(1405)$

indirect reaction

use nuclear effect

to see subthreshold amplitude

$$K^- d \to \Lambda(1405) n$$

nuclear effect

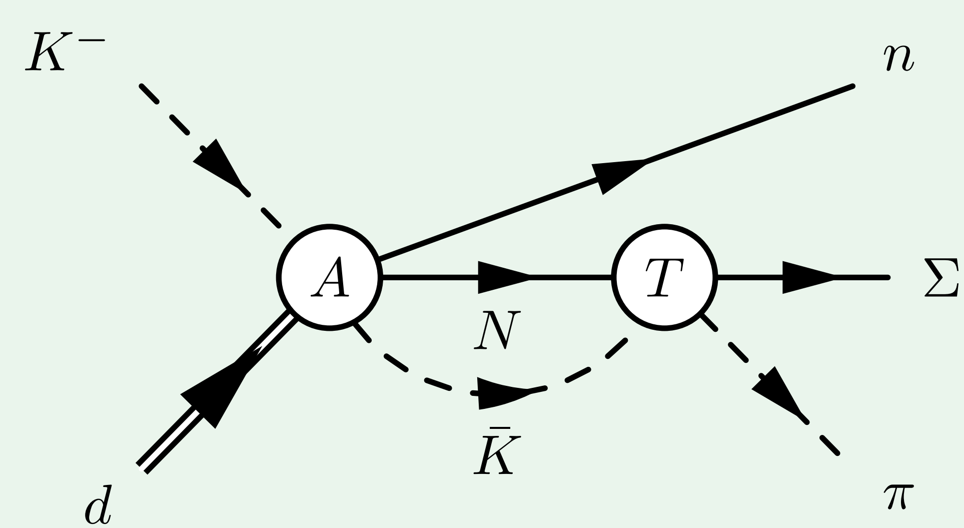
- fermi motion
- two-body effect

K^{bar}N selective production

- strangeness carried by incident kaon

more sophisticated calculations given by Ohnishi and Miyagawa

production mechanism be under control



Want to extract T-amplitude from experiment. For this purpose, need to understand the production mechanism described by A-amplitude.

DJ, Oset, Sekihara, Eur.Phys.J.A. 42, 257 (2009).
Yamagata-Sekihara, Sekihara, DJ, PTEP 2013, 043D02

Λ(1405) in $K^{bar}N$ channel

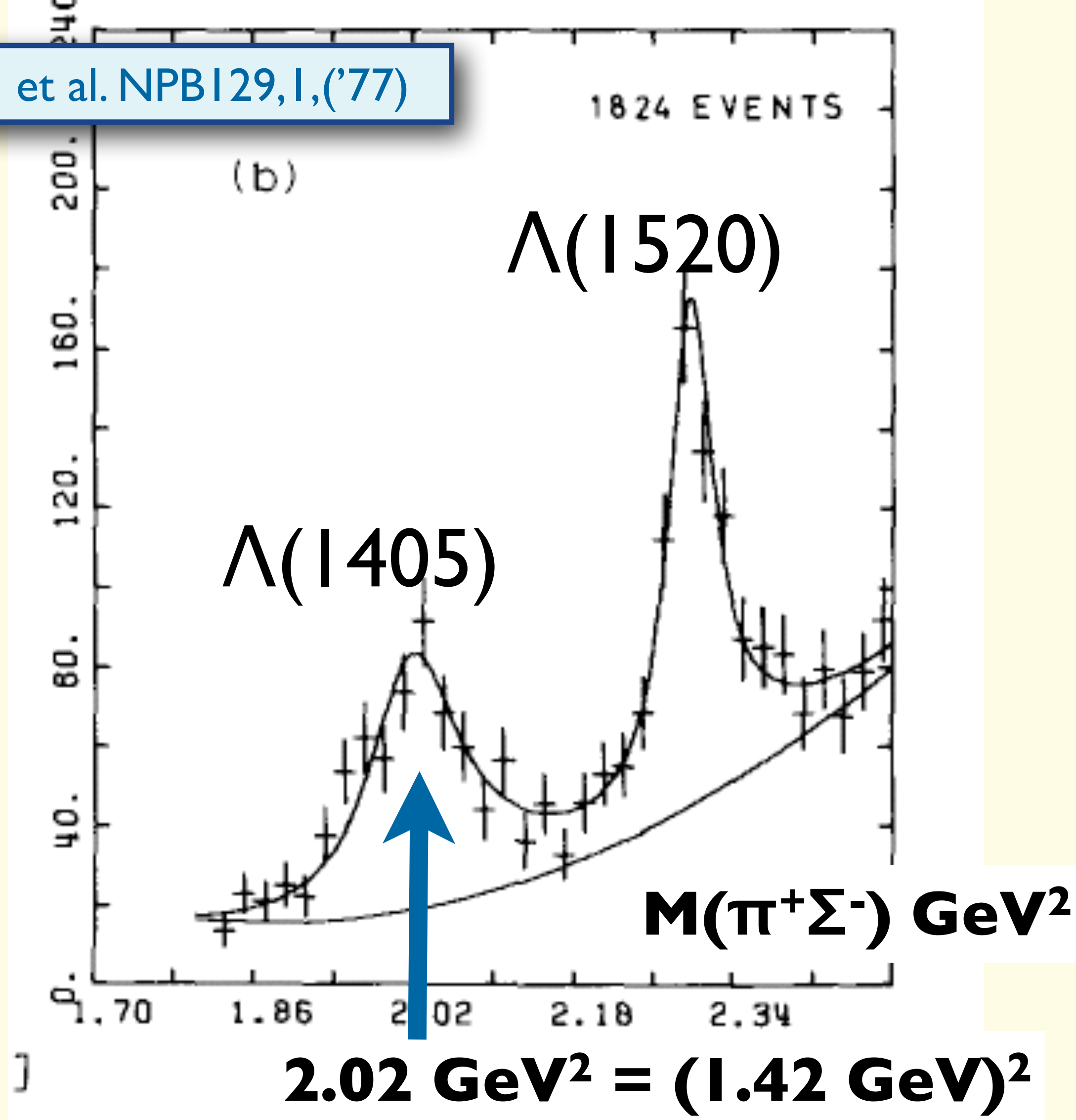
DJ, Oset, Sekihara, Eur.Phys.J.A. 42, 257 (09); ibid. A49, 95
Yamagata-Sekihara, Sekihara, DJ, PTEP 2013, 043D02

Experiment bubble chamber initial K momentum 686 ~ 844 MeV/c

πΣ invariant mass spectrum

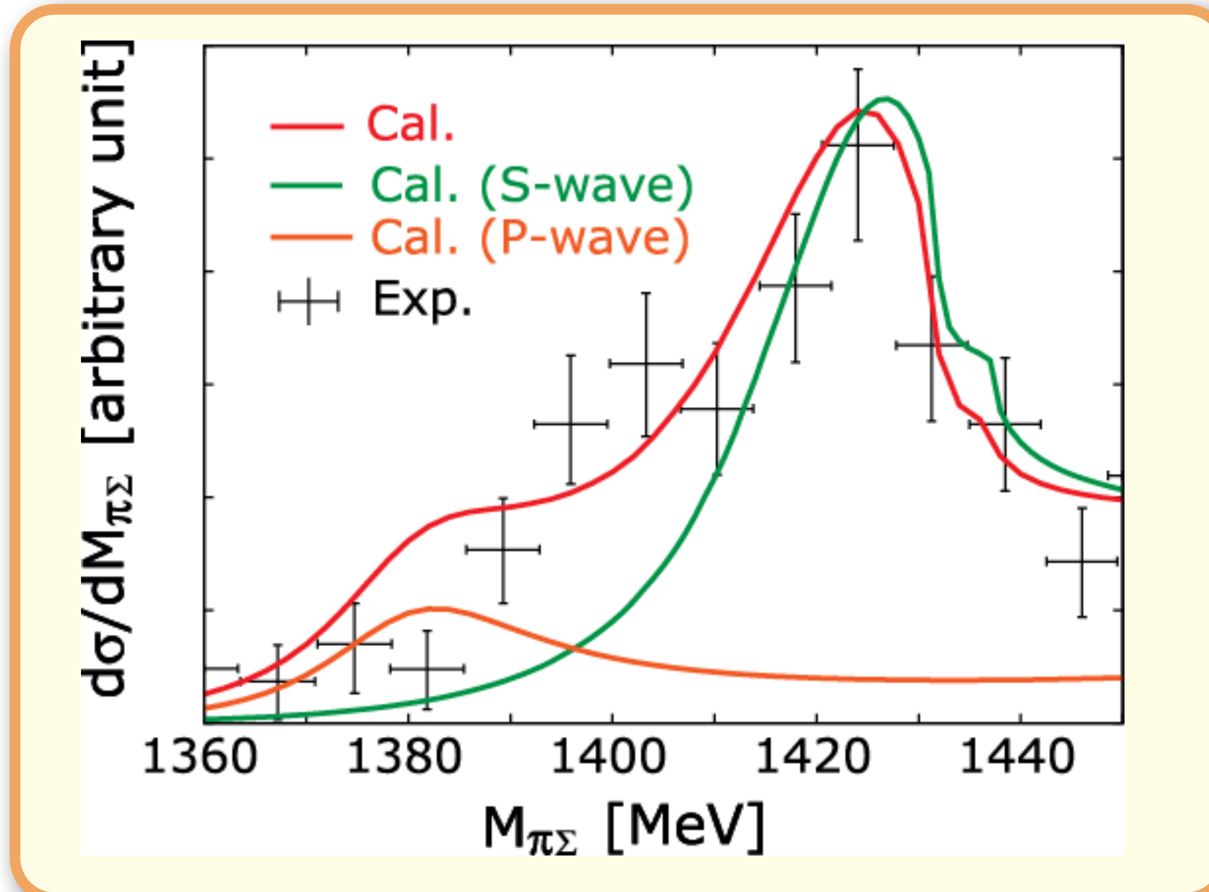
$$K^- d \to \pi^+ \Sigma^- n$$

Braun et al. NPB129,1,('77)



peak position 1420 MeV

theoretical calculation in ChUM



production cross section of Λ(1405)

385 μb @ 800MeV/c (exp. 410 ± 100 μb)

agrees with data in shape and size

inclusion of Σ* does not distort the shape.

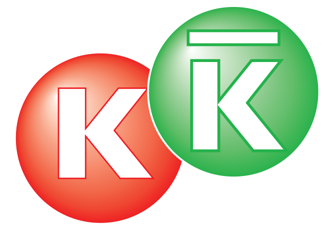
brand-new experiment at J-PARC (E31)

Family of kaonic few-body systems

Λ(1405)

BE ~10 MeV (30 MeV)

f_0(980), a_0(980)



BE ~10 MeV

DJ, Kanada-En'yo, **PRC78, 035203 (08).**
Martinez Torres, DJ, **PRC82, 038202 (10).**
Martinez Torres, DJ, Kanada-En'yo, **PRC83 065205 (11).**

K^{bar}NN

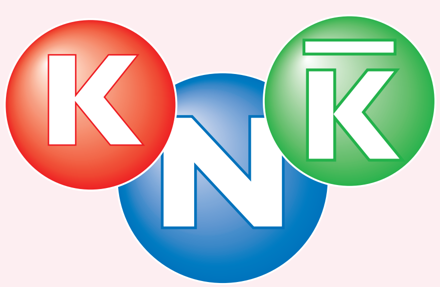
BE ~20 MeV

or more

K^{bar}KN

N*

$J^P=1/2^+$



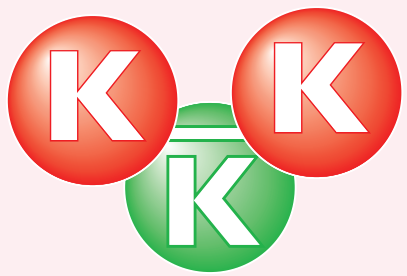
a new N* resonance N(1910)

BE ~20 MeV

K^{bar}KK

K*

$J^P=0^-$



1420 ~ 1465 MeV

BE 20~60 MeV

and more	K^{bar}K^{bar}N	K^{bar}NNN	K^{bar}K^{bar}NN
	Kanada-En'yo, DJ	Akaishi, Yamazaki, Dote,..	Barnea, Gal, Liverts,

K^{bar}N and **K^{bar}K** Weinberg-Tomozawa interactions are "similar" in a sense of chiral dynamics

pion is too light to be bound in range of strong interaction

K^+ meson

K^+ - nucleus scattering revisited

Aoki, DJ, on going

review articles
Dover, Walker, Phys. Rept. 89, 1 (1982)
Freedman, Gal, Phys.Rept. 425, 89 (2007)

Kaon in nucleus

- KN interaction is repulsive, and KN cross section is small
- mean free path of K in nuclear medium is around 5 fm
- Kaon has been consider to be a clean probe to investigate nuclear matter
- no strong resonances in KN channel
- relatively easy to investigate **in-medium effects on kaon**

breakdown of linear density approximation

thanks to large mean free path, K^+A scatting could be written well by single step

$$\sigma_{K^+A} \simeq A\,\sigma_{K^+N} \qquad p_{\rm lab.} < 800\ {\rm MeV/c}$$

the ratio of the cross sections is known to be larger than unity

$$\frac{\sigma_{K^{+\,12}{\rm C}}}{6\sigma_{K^+d}} > 1.0$$

K^+ - nucleus scattering revisited

Aoki, DJ, on going

breakdown of τρ approximation

$$2m_K^+ V_{\rm opt} \simeq -\rho T_{K^+N}$$ linear density approximation

$$T_{K^+N} = -\frac{4\pi E_{\rm c.m.}}{M_N} b_0$$

$p_{\rm lab}$	$V_{\rm opt}$	Re b_0(fm)	Im b_0(fm)	
488	$t\rho$	−0.203(26)	0.172(7)	**obtained by χsq fitting**
	$t_{\rm free}\rho$	−0.178	0.153	**free KN**

Friedman, Gal, Phys.Rept. 425, 89 (2007)

15% enhancement in in-medium KN scattering

possible explanation

- nucleon-nucleon correlation
- "swelling" of nucleon
- mass reduction of vector mesons

etc.

K^+ - nucleus scattering revisited

Aoki, DJ, on going

in the aspect of chiral symmetry

the 15% enhancement can be explained by wave function renormalization

argument by Kolomeitsev et al. for pion

Kolomeitsev, Kaiser, Weise, PRL90, 092501 (03)

See also, DJ, Hatsuda, Kunihiro, PRD63, 011901(R); PLB 670 (2008), 109.

when self-energy is energy-dependent,
equivalent energy-independent optical potential can be obtain as follows

- consider in-medium dispersion relation $\omega^2 - m^2 - \Sigma(\omega) = 0$
- expanding self-energy around $\omega = m$

$$2mV_{\rm opt}(m^*) = \Sigma(m) + (\omega^2 - m^2)\frac{\partial \Sigma}{\partial \omega^2} + \cdots$$

$$\simeq \left(1 + \frac{\partial \Sigma}{\partial \omega^2}\right)\Sigma(m) \simeq Z\Sigma(m)$$

$$2mV_{\rm opt} = -Z\rho T_{K+N}$$

one of the higher order corrections

$$Z = 1 + 0.1\frac{\rho}{\rho_0}$$

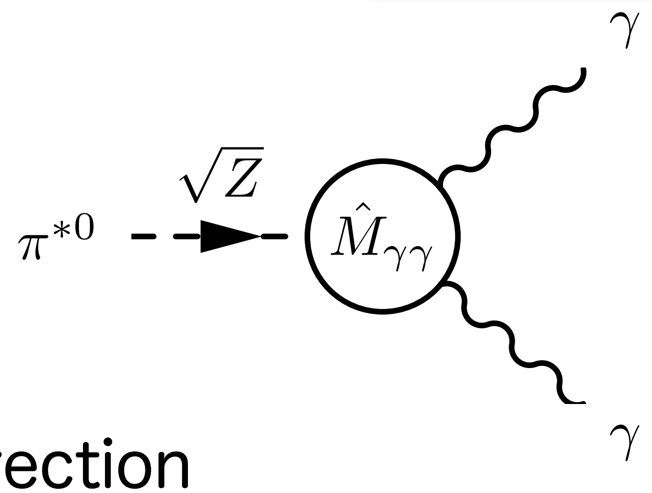
leading order chiral perturbation theory calculation

$\pi^0 \to \gamma\gamma$ decay in nuclear medium

Goda, DJ, PTEP 2014, 033D03 (2014).
Nebreda, DJ, in preparation.

in-medium decay amplitude

$$M^*_{\gamma\gamma} = \sqrt{Z}\hat{M}_{\gamma\gamma}$$



Z wave function renormalization

$\hat{M}_{\gamma\gamma}$ 1-particle irreducible vertex correction

no correction in the linear density ← Meissner, Oller, Wirzbz, AnnPhys297, 27 (02)

in-medium change of the amplitude

$$\frac{M^*_{\gamma\gamma}}{M_{\gamma\gamma}} = \sqrt{Z}$$

$$\frac{\Gamma^*_{\gamma\gamma}}{\Gamma_{\gamma\gamma}} = Z \simeq 1 + 0.4\frac{\rho}{\rho_0}$$

40% enhancement in nuclear density

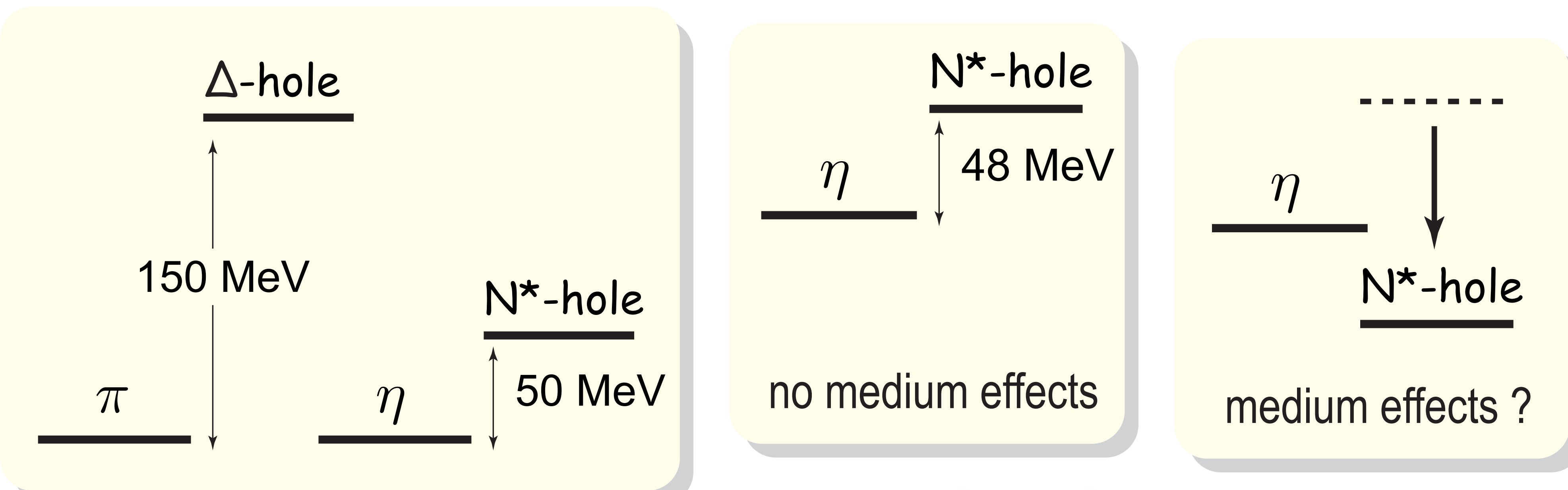
η meson

η mesonic nuclei

- eta N couples strongly to N*(1535)
- N*(1535) is the first excited state with the opposite parity of nucleon
- can be a chiral partner of nucleon
- eta mesonic nuclei can prove chiral symmetry of N and N*

chiral double picture for nucleons

- nucleon and N*(1535) are chiral partners (**chiral doublet**)
- masses of chiral doublets tend to degenerate when ChS is being restored
- mass difference of N and N* decreases in nuclear medium

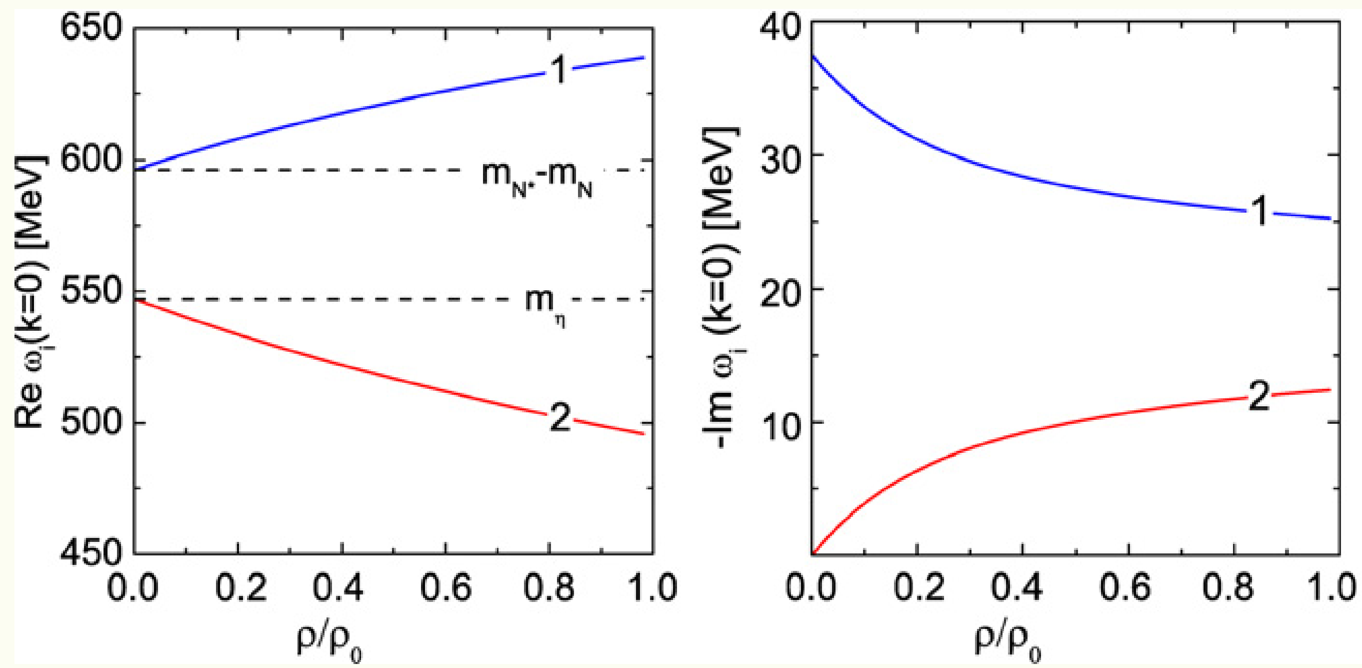


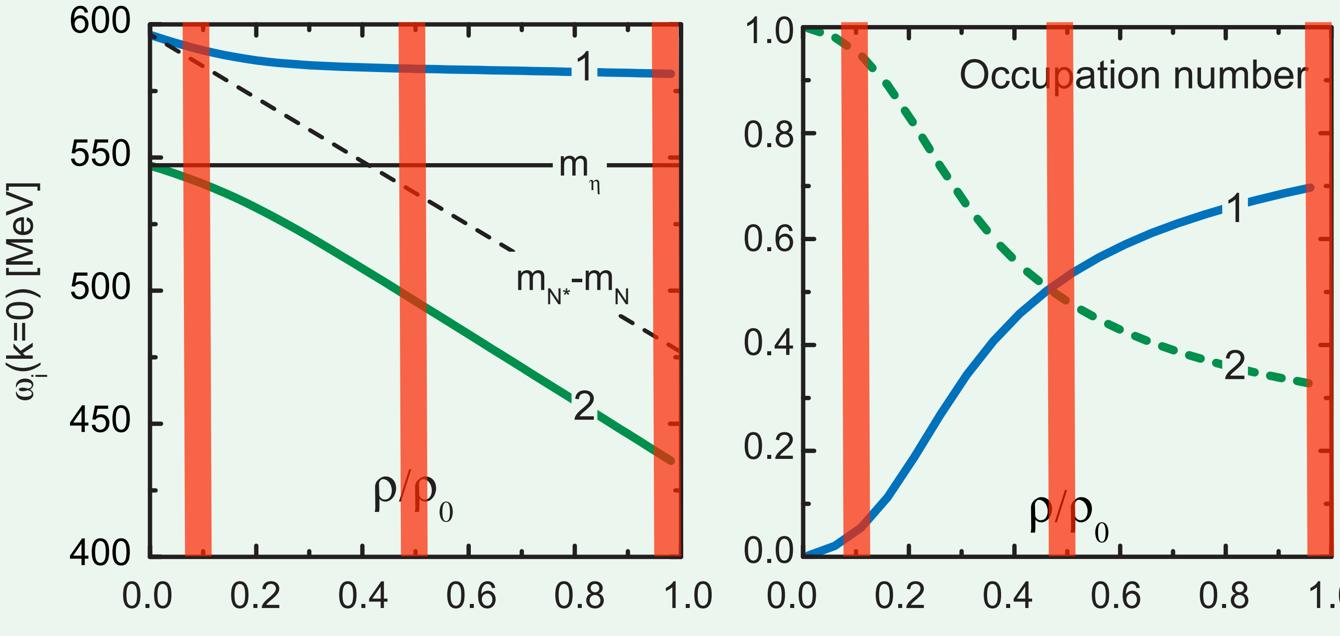
level crossing

Spectral function of in-medium eta meson

density dependence of two levels

Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA811,158 (2008)



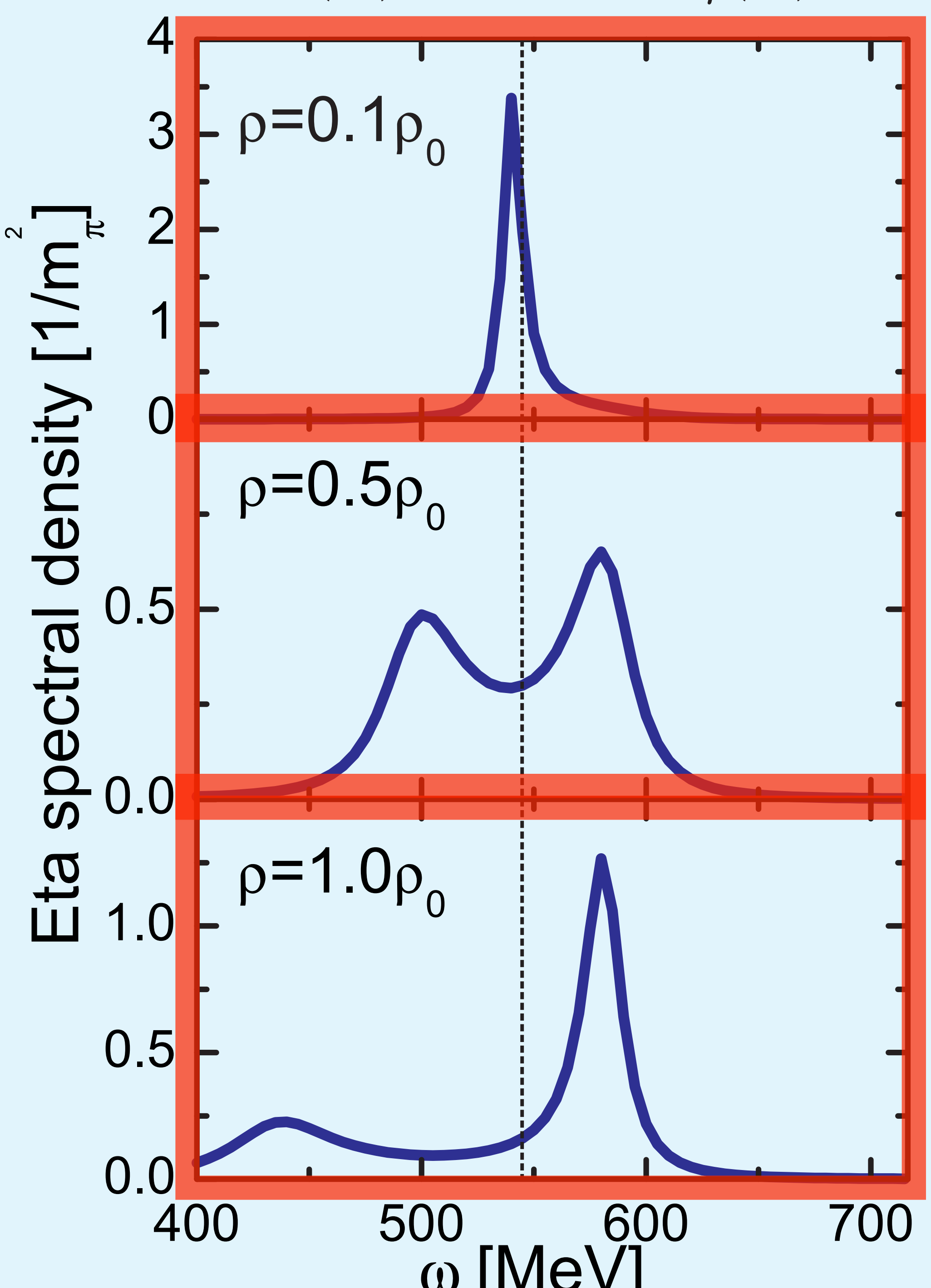


$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i}$$

$$Z_i = \left(1 - \frac{\partial V_\eta(\omega)}{\partial \omega}\bigg|_{\omega=\omega_i}\right)^{-1}$$

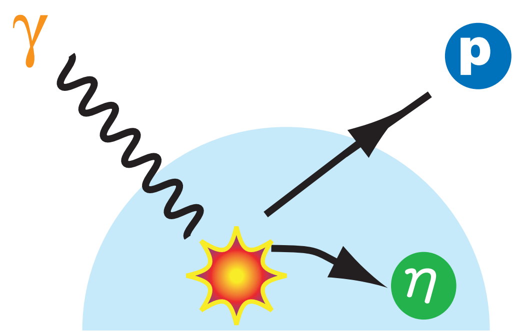
Spectral function

$$S(\omega) = -\mathrm{Im}\, G_\eta(\omega)$$



Eta mesic nuclei

Nagahiro, Jido, Hirenzaki, PRC68, 035805 (03); NPA761, 92 (05)
Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA811,158 (08)



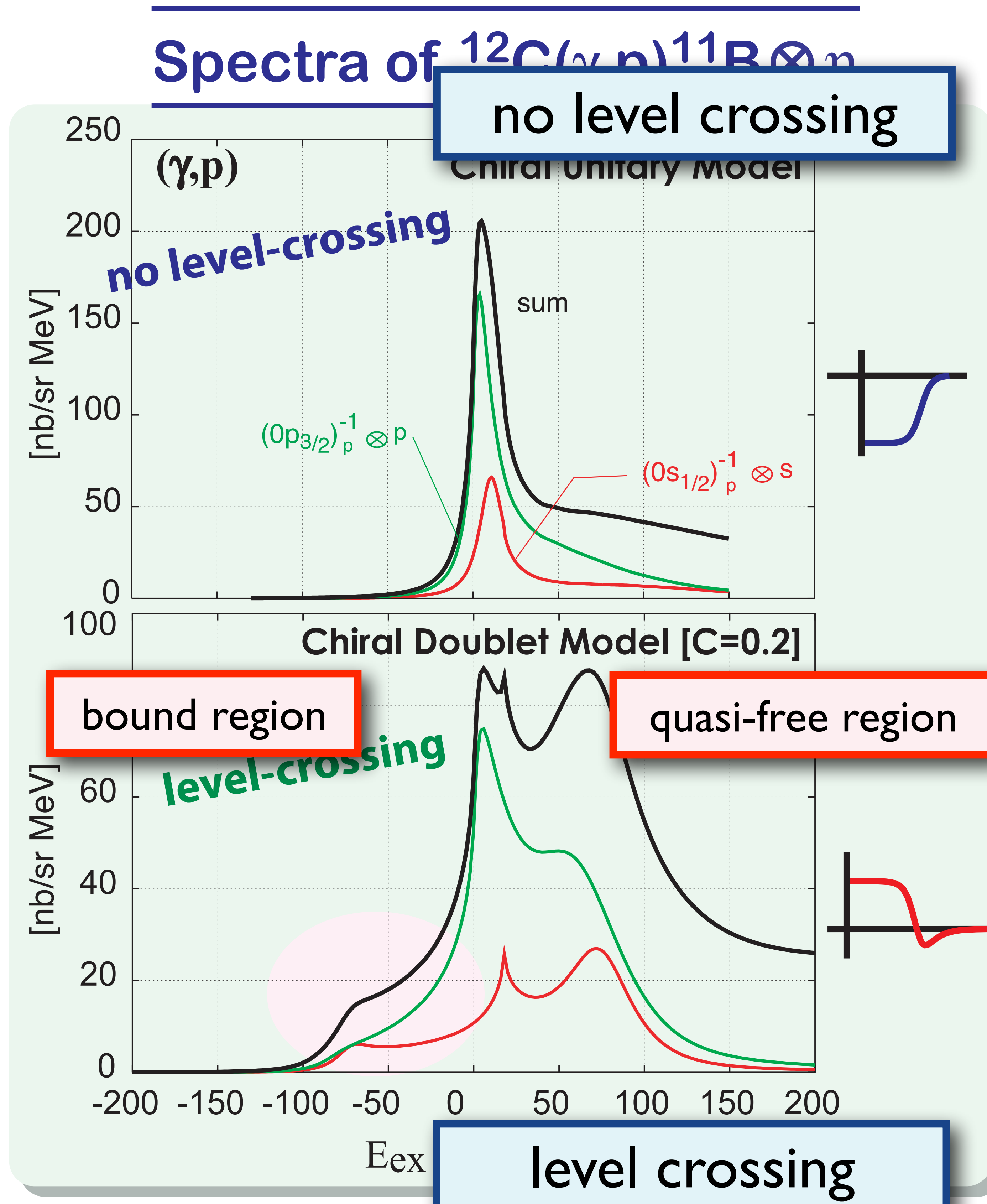
(γ,p) reaction

missing mass spectra of emitted proton

^{12}C target

in recoilless condition
(no momentum transfer)

level crossing effect can be seen in quasi-free region as repulsive shift of eta meson



η' meson

η' meson and chiral symmetry

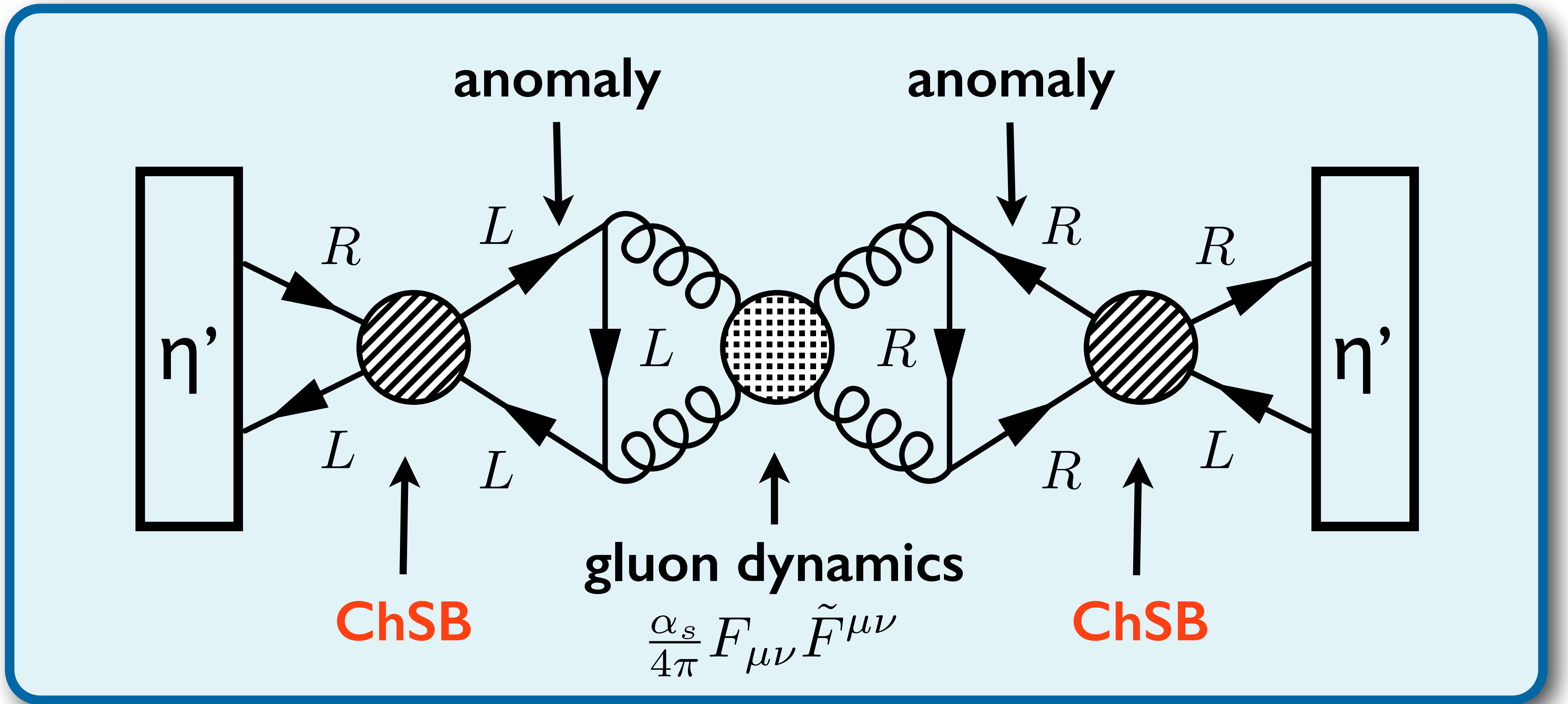
DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

Large eta' mass stems from quantum anomaly, which breaks axial U(1) symmetry. eta' failed to get a Nambu-Goldstone boson due to anomaly.

η′(958) $I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

eta' meson has a strong connection also to chiral symmetry breaking.
in order that $U_A(1)$ anomaly affects the η' mass,
chiral symmetry is necessarily broken spontaneously and/or explicitly.



nonchiral gluon field cannot couple to pseudoscalar states without chiral symmetry breaking.

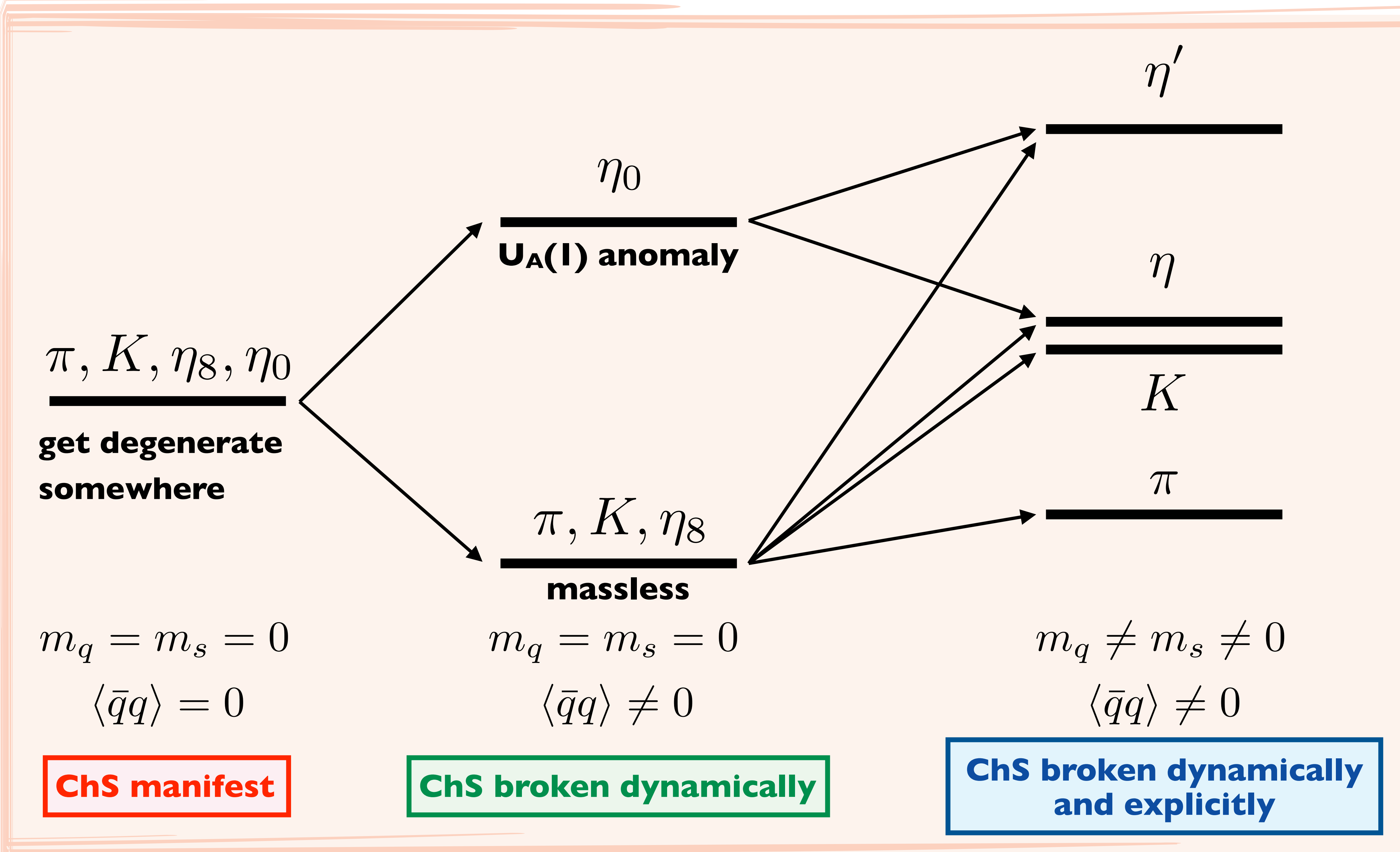
when chiral symmetry is restored, η and η' should degenerate due to SU(3) chiral symmetry. thus, η - η' mass difference is generated by chiral symmetry breaking

η' meson in chiral restoration

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R); Nagahiro, DJ, Fujioka, Itahashi, Hirenzaki, PRC87 (12) 045201

When chiral symmetry is restored... as a consequence of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

9 PS π, K, η_8, η_0 9 S σ, a_0, κ, f_0 get degenerate



in order that $U_A(1)$ anomaly affects the η' mass, chiral symmetry is **necessarily** broken spontaneously and/or explicitly.

η′ meson in nuclear matter

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

the mass gap of η' and η is generated by chiral symmetry breaking

the η′ mass get reduced when chiral symmetry is being restored in nuclear medium

a simple order estimation

linear dependence of quark condensate on η′-η mass difference (400 MeV)

partial restoration of ChS takes place with 35% at ρ_0

we expect strong η′ mass reduction $\Delta m_{\eta'} \sim 100$ MeV @ $\rho = \rho_0$

chiral effective theories tell similar results.

linear sigma model

Sakai, DJ, PRC88 (13) 064906

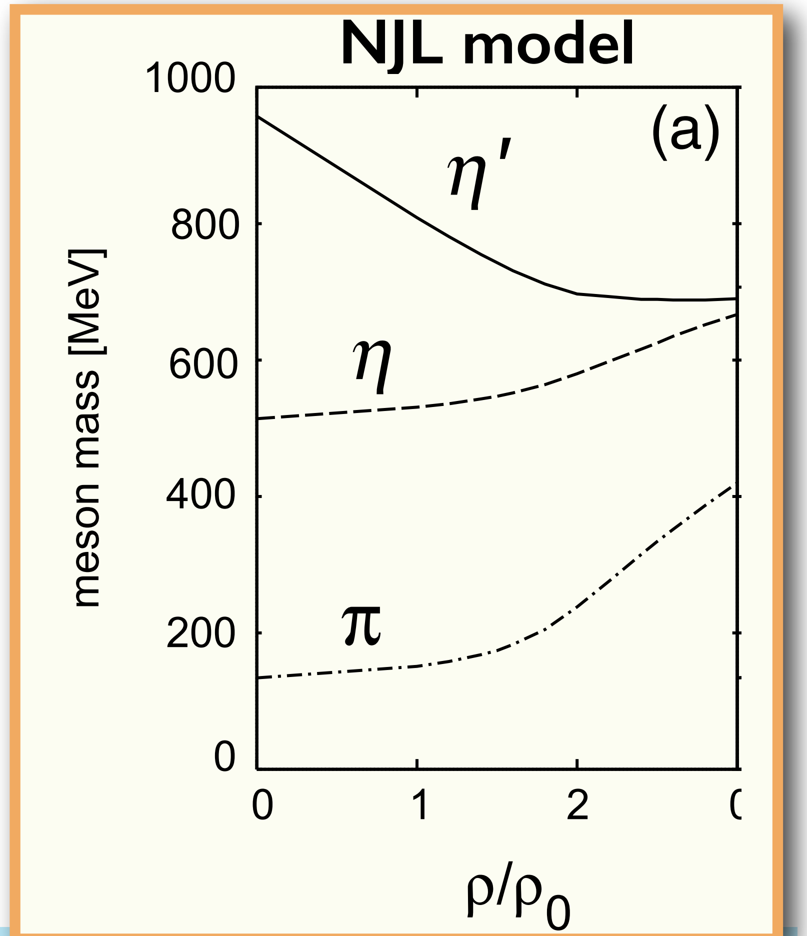
$\Delta m_{\eta'} \sim 80$ MeV @ $\rho = \rho_0$

$m_{\eta'} - m_\eta \sim 130$ MeV @ $\rho = \rho_0$

NJL model

P. Costa, M. C. Ruivo, and Y. L. Kalinovsky, PLB560, 171 (03).
Nagahiro, Takizawa, Hirenzaki, PRC74,045203 (2006)

$\Delta m_{\eta'} \sim 150$ MeV @ $\rho = \rho_0$



Possible bound state spectra

DJ, Nagahiro, Hirenzaki, PRC85 (12) 032201(R)

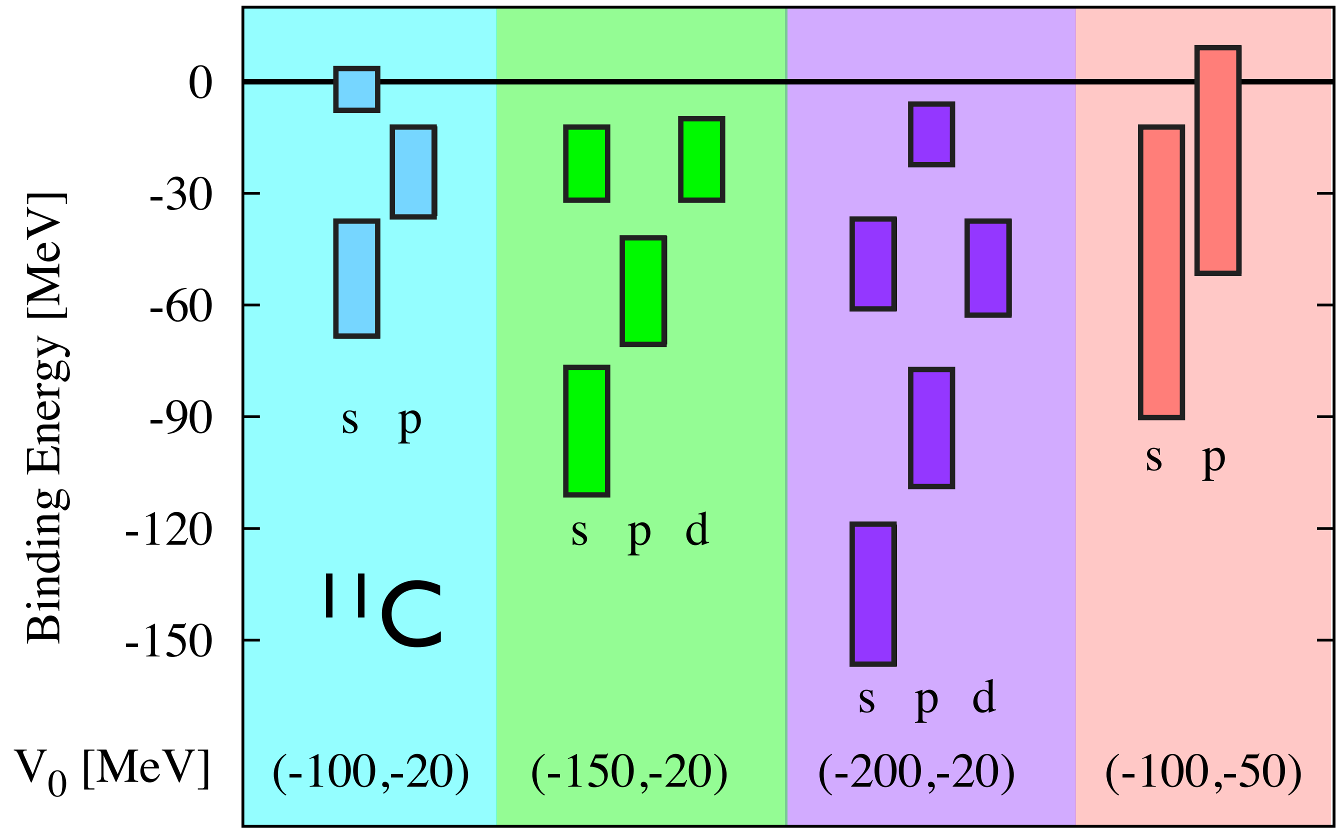
mass reduction in nuclear matter provides a scalar potential in finite nucleus

a simple η' optical potential (Woods-Saxon type)

proportional to nuclear density

$$V_{\eta'}(r) = V_0 \frac{\rho(r)}{\rho_0}$$

Δm = 150 MeV
Γ/2 = 20 MeV



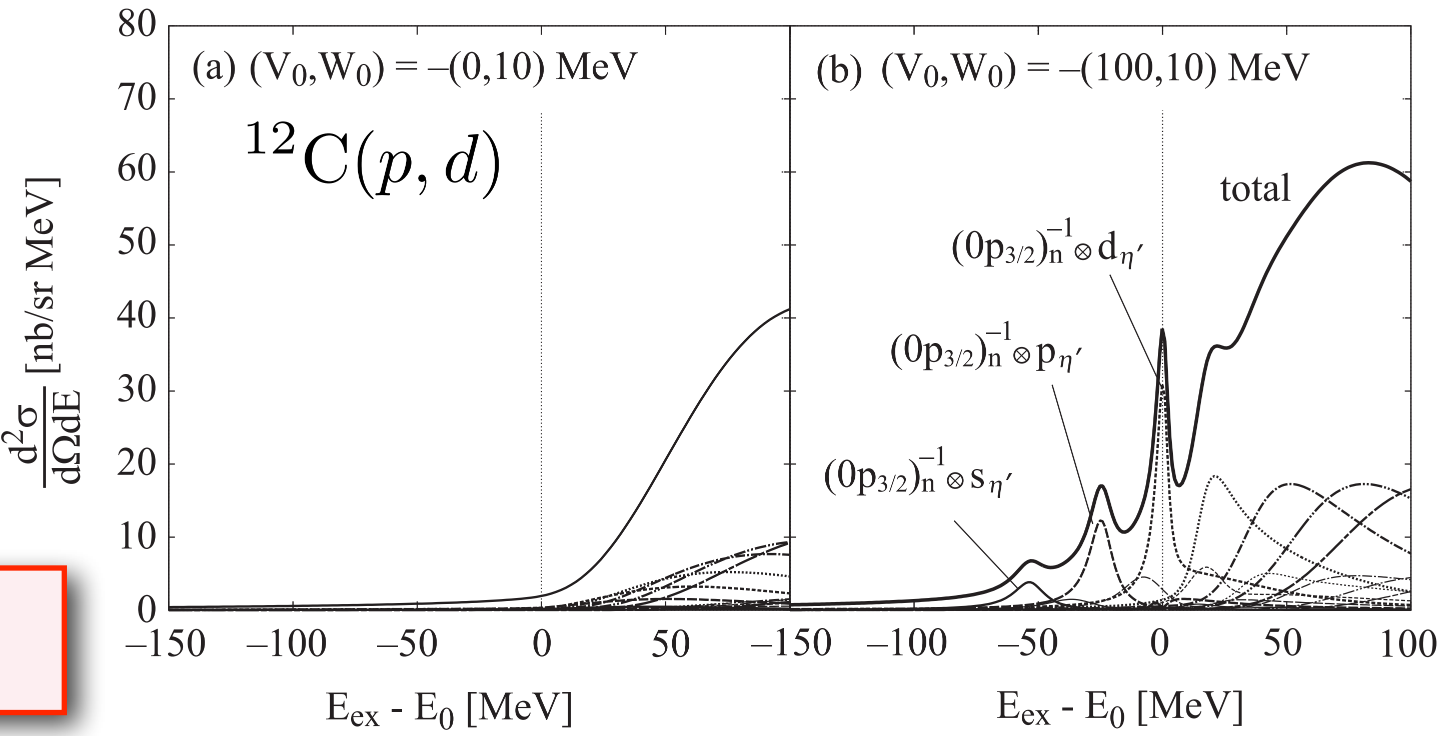
Re: theoretical expectation

Im: phenomenological observation

well-separated bound states

for realistic calculation

core polarization effect could be important



Nagahiro, DJ, Fujioka, Itahashi, Hirenzaki, PRC87 (12) 045201

η'-N interaction

Sakai, DJ, PRC88 (13) 064906;
in preparation

in linear sigma model

nucleon mass is generated also by spontaneous breaking of ChS

$$m_N = g\langle\sigma_0\rangle$$

→ presence of strong coupling σNN

this is the origin of the scalar attraction in NN interaction

in the same way

chiral symmetry breaking generates a part of eta' meson with help of anomaly

$$m_{\eta_0}^2 - m_{\eta_8}^2 = 6B\langle\sigma_0\rangle$$

→ presence of strong coupling ση'η'

B term : anomaly effect

we expect strong attraction in η'-N in scalar-isoscalar exchange

with this attraction

two body η'N bound state is expected with several MeV binding energy

two-body bound state ~ 6 MeV

coupled channel effect (η'N, ηN) BE = 12 - 3i [MeV]

calculated in the same way as Λ(1405) of $K^{bar}N$ bound state

Summary

we have discussed mesons in nuclear medium under the situation that chiral symmetry is partially (30%) restored in nuclear medium

expectations in partial restoration of chiral symmetry

- reduction of mass difference of chiral partners

the reduction of N-N* mass difference could be seen in eta mesonic nuclei

- substantial effect from wave function renormalization of NG bosons

self-energy of NG boson has energy dependence (low energy theorem)

$$Z = \left(1 - \frac{\partial \Sigma}{\partial p_0^2}\right)^{-1}$$

enhancement of K^+A scattering is explained by K^+ wave function renorm.

large enhancement of $\pi^0 \to \gamma\gamma$ in medium is expected

- reduction of hadron mass

a part of eta’ meson mass is generated by chiral symmetry breaking

100 MeV reduction of eta’ mass is expected in nuclear density

strong attraction of eta’-N int. from isoscalar-scalar σ exchange