η’-nucleon interaction in chiral dynamics and η' meson in nuclear madium

D. Jido
(Tokyo Metropolitan University)

collaboration with
H. Nagahiro, S. Hirenzaki (Nara WU)
S. Sakai (Kyoto)

References

DJ, H. Nagahiro, S. Hirenzaki, Phys.Rev. C85 (2012) 032201
S. Sakai, DJ, Phys.Rev. C88 (2013) 064906; in preparation
see also
H. Nagahiro, DJ, S. Hirenzaki, H. Fujioka, K. Itahashi, Phys.Rev. C87 (2013) 045201

Related contributions to η' physics in this conference

Sakai, Nagahiro, Fujioka, Tanaka, Metag, Moskal, Bass, ...

首都大学東京
TOKYO METROPOLITAN UNIVERSITY

科研費
KAKENHI

η'-nucleon system

keywords in this talk

1. exotic hadron

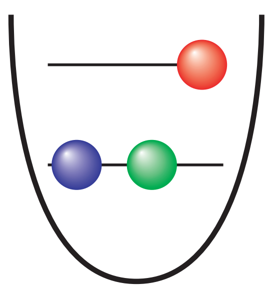
2. chiral symmetry

Introduction

I. exotic hadrons hadrons which do not fit quark model systematics

hadrons have been classified based on quark model

various excitation modes are possible, but only quark excitation in quark model



quark excitation

conventional picture

hadronic excitation

Λ(1405)

hadron composite state

strong interaction is as complicated as we expect

dual nature of strong force

colorful "constituent" force and **colorless "interaction" force**

inside confinement range — **~ 0.5 fm**

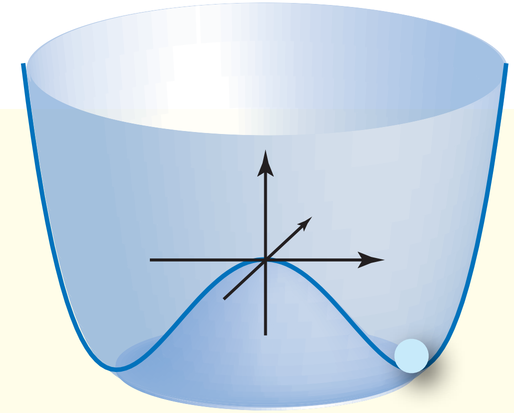
larger than hadron size — **> 1.0 fm**

we show that

η'-nucleon system has **attraction in isoscalar-scalar channel** and
it forms **a bound state N*** with several MeV binging energy and a small width

Introduction

2. chiral symmetry



- chiral symmetry, ChS, is a fundamental symmetry in QCD
- ChS is spontaneously broken by physical states
- ChSB is a **phase transition phenomenon** and provides **vacuum property**
- most of light hadron properties is determined by ChSB light pion mass, mass generation etc.

we show that, also for the η' meson mass

chiral symmetry plays an important role on the η' mass

partial (incomplete) restoration of ChS in nuclear medium

quark condensate does decrease in nuclear medium

- phenomenological proof by analysis of pionic atom and low energy pi-A scattering
- 30-40 % reduction at saturation density, if believe linear extrapolation

K. Suzuki et al. PRL92, 072302, (04); Friedman et al., PRL93, 122302 (04); DJ, Hatsuda, Kunihiro, PLB 670, 109 (08).

combining the role of ChS in the η' mass and PRChS in nuclear medium,

we discuss the η' mass in nuclear medium

Contents

1. introduction
   - exotic hadron
   - chiral symmetry
   - partial restoration of chiral symmetry in nuclear medium
2. **η' meson and chiral symmetry**
   - $U_A(1)$ anomaly
   - significant role of chiral symmetry breaking
   - **η' mass is reduced under PRχS**
3. **η'-N interaction in linear sigma model**
   - estimate η'-N interaction
   - **strong attraction in scalar channel**
   - linear σ model as a model of chiral restoration
4. **summary**

η' meson
and
chiral symmetry

References

DJ, H. Nagahiro, S. Hirenzaki, Phys.Rev. C85 (2012) 032201

η' meson and chiral symmetry

η' is a PS meson having 1 GeV mass.

1 GeV is a **typical mass scale** of hadrons

looks **nothing special**

$\eta'(958)$ $I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 957.78 \pm 0.06$ MeV

Full width $\Gamma = 0.198 \pm 0.009$ MeV

special mesons are π, K, η

light mass because they are Nambu-Goldstone bosons associated with ChSB

η' meson and chiral symmetry

η' is a PS meson having 1 GeV mass.

1 GeV is a **typical mass scale** of hadrons

looks **nothing special**

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

special mesons are π, K, η

light mass because they are Nambu-Goldstone bosons associated with ChSB

chiral symmetry in QCD

octet axial currents are (almost) conserved

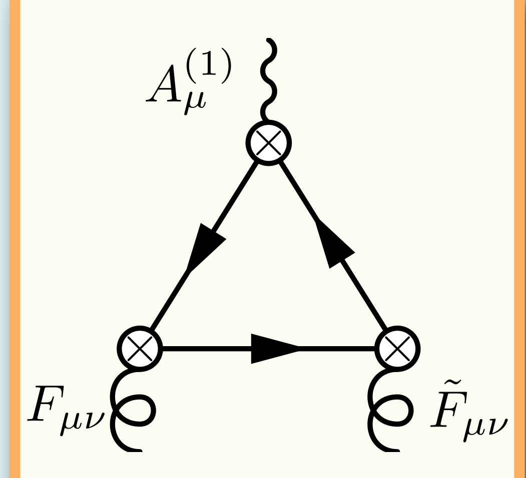
$$\partial^\mu A_\mu^{(8)} = \frac{i}{\sqrt{3}}(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d - 2m_s \bar{s}\gamma_5 s)$$ **(small) PCAC**

octet chiral symmetry is spontaneously broken $\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \to \mathrm{SU}(3)_V$

singlet axial current is NOT conserved due to quantum anomaly

$$\partial^\mu A_\mu^{(0)} = 2i(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d + m_s \bar{s}\gamma_5 s) + \boxed{\frac{3\alpha_s}{8\pi} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a}$$

(small) PCAC **anomaly**



singlet chiral symmetry is **always broken by anomaly explicitly**

η’ cannot be a NG boson, nor necessarily massless,
when ChSB takes place

η' meson in chiral symmetry

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

chiral symmetry plays an important role in η' mass as well as anomaly

in fact, π, η and η' are in the **same multiplet** of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

no matter how $U_A(1)$ symmetry is broken by quantum anomaly

because all the particle belonging to the same multiplet should get degenerate,
when the system has the symmetry,

π, η and η' get degenerate when chiral symmetry is restored.

η' meson in chiral symmetry

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

chiral symmetry plays an important role in η' mass as well as anomaly

in fact, π, η and η' are in the **same multiplet** of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

no matter how $U_A(1)$ symmetry is broken by quantum anomaly

because all the particle belonging to the same multiplet should get degenerate, when the system has the symmetry,

π, η and η' get degenerate when chiral symmetry is restored.

- symmetry property of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$ **without** $U_A(1)$ **symmetry**

Scalar and Pseudoscalar mesons in $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

$$(\bar{\mathbf{3}}, \mathbf{3}) \oplus (\mathbf{3}, \bar{\mathbf{3}}) \qquad \bar{q}_i^L q_j^R \pm \bar{q}_i^R q_j^L$$

contains both octet and singlet

8+1 scalar and 8+1 pseudoscalar

$\bar{q}_i q_j$ $\qquad$ $\bar{q}_i \gamma_5 q_j$

σ_0 scalar singlet	a_0, κ, σ_8 scalar octet
η_0 pseudoscalar singlet	π, K, η_8 pseudoscalar octet

these 18 mesons including η and η' get degenerate if chiral symmetry is not broken.

$U_A(1)$ is broken so that singlet axial current is not conserved, but π, η, η'... do get degenerate in case of no chiral symmetry breaking.

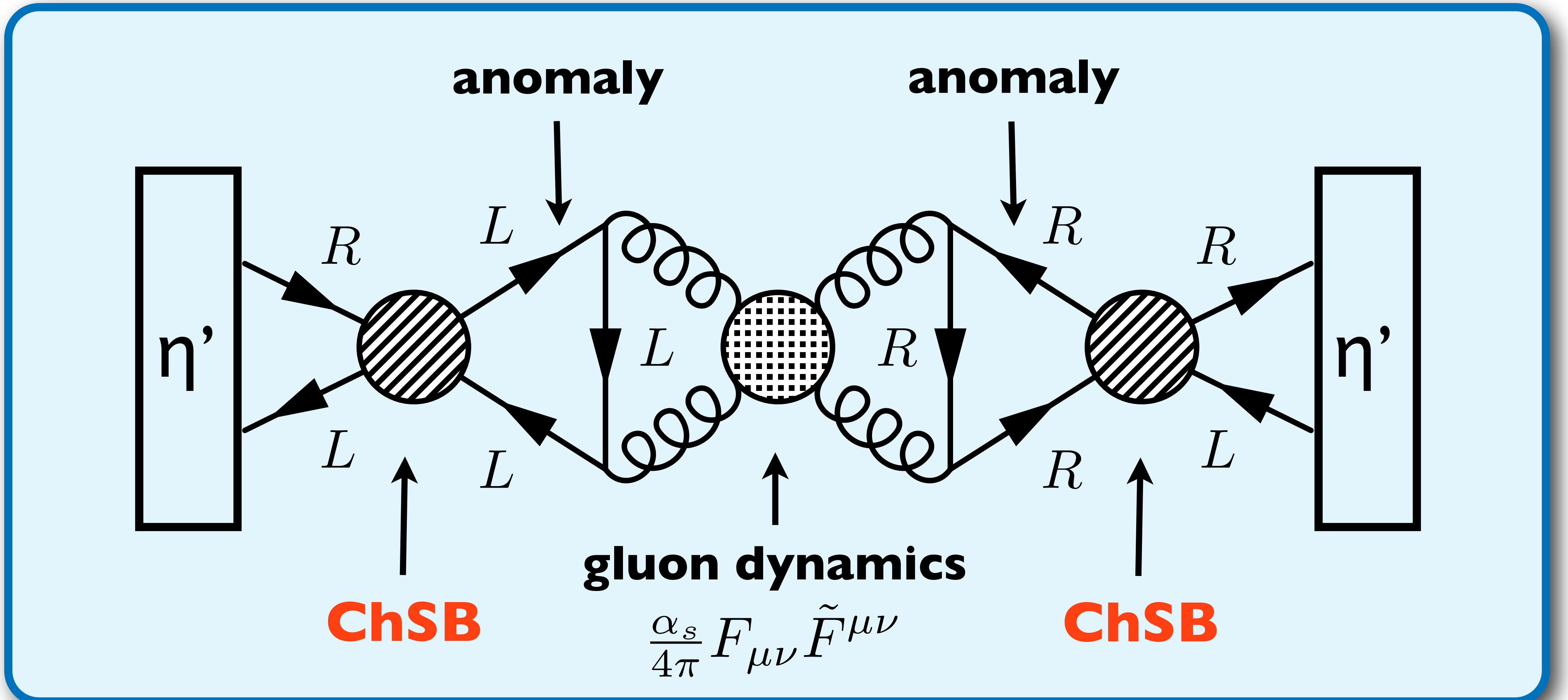
dynamical argument is given by Lee and Hatsuda

Lee, Hatsuda, PRD54, 1871 (1996)

η' meson in chiral symmetry

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

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

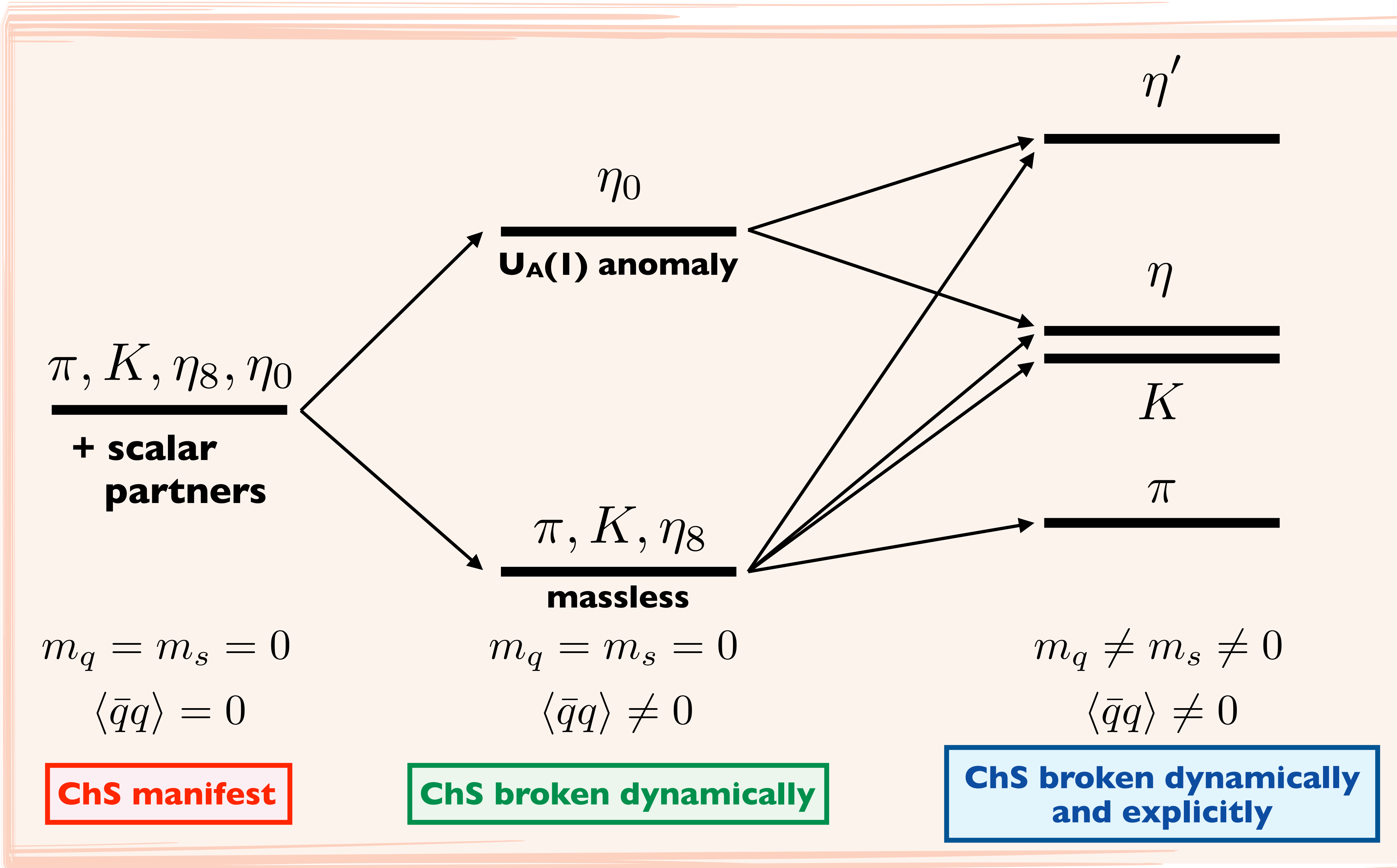


nonchiral gluon field cannot couple to chiral pseudoscalar states without chiral symmetry breaking.

η' meson in chiral symmetry

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

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



the mass gap of η' and η is generated by chiral symmetry breaking through $U_A(1)$ anomaly

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

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 @ $\rho = \rho_0$

assume linear dependence of quark condensate on η’-η mass difference

$$m_{\eta'}^2 - m_\eta^2 = B(2\langle \bar{q}q \rangle + \langle \bar{s}s \rangle)$$

consistent with linear σ model

assume no change of η mass and $\langle \bar{s}s \rangle$ in nuclear medium

$$m_{\eta'}^2 - m_{\eta'}^{*2} = 2B(\langle \bar{q}q \rangle - \langle \bar{q}q \rangle^*)$$

using low density theorem

$$\Delta m_\eta' = \frac{2}{3} \frac{m_{\eta'}^2 - m_\eta^2}{2m_{\eta'}} \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2} \rho$$

low density theorem

$$\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2} \rho\right) \langle \bar{q}q \rangle$$

$$B = \frac{m_{\eta'}^2 - m_\eta^2}{3\langle \bar{q}q \rangle} \text{ @ SU(3)}$$

we expect strong η’ mass reduction

$\Delta m_{\eta'} \sim 80 - 100$ MeV @ $\rho = \rho_0$ for $\sigma_{\pi N} = 45\sim60$ MeV

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

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 @ $\rho = \rho_0$

we assume that η’ is purely **flavor singlet**

$$m_{\eta'}^2 - m_\eta^2 = B(2\langle\bar{q}q\rangle + \langle\bar{s}s\rangle)$$

strange component of η' can be different

here we discuss the mass gap of η' and η and assume **no change of η mass**

the η mass can be changed in nuclear matter, see S. Bass's talk

here we consider only the **scalar part** of the η' self-energy in nuclear matter

the (Lorentz) vector part of the self-energy could be repulsive

Nanova et al. PLB727 (13) 417

energy dependence of self-energy is also important

~ -40 MeV [CBELSA/TAPS] from η' production

η′ meson in nuclear matter

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

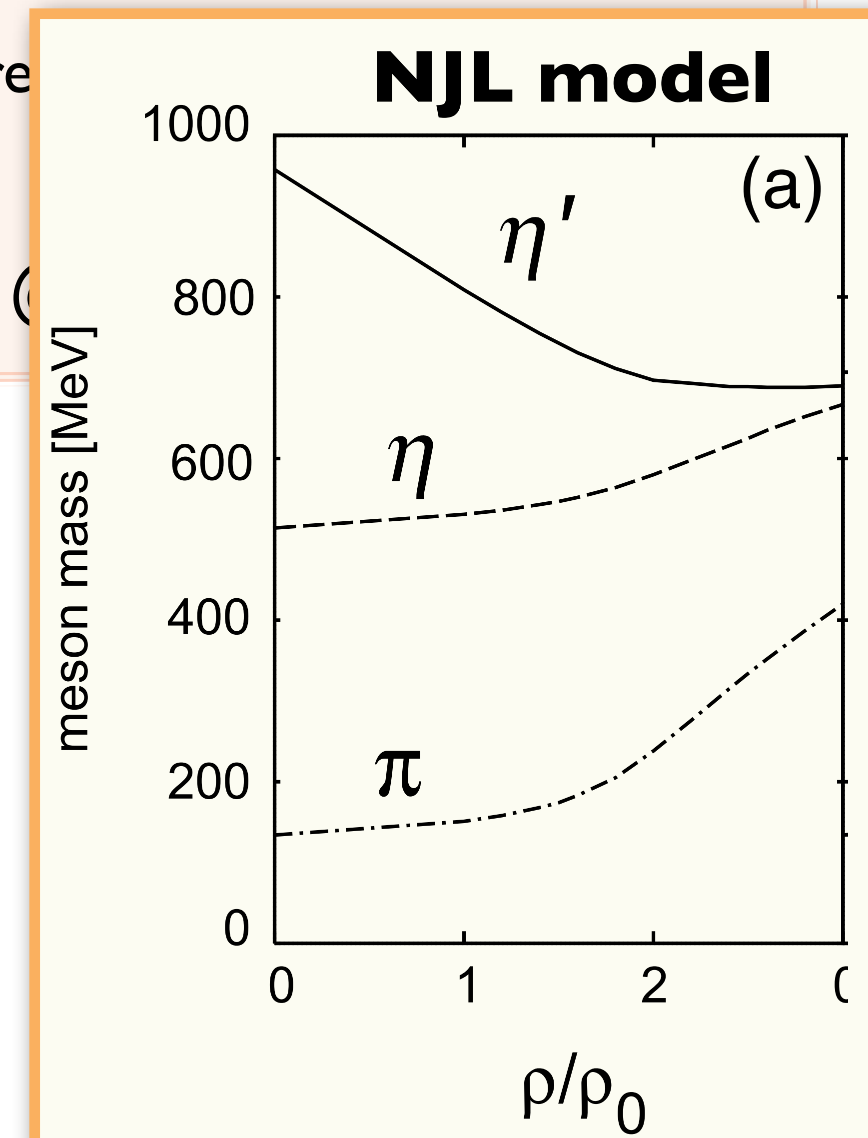
the mass gap of η' and η is generated by chiral symmetry breaking

a simple order estimation

linear dependence of quark condensate on η’-η mass differe

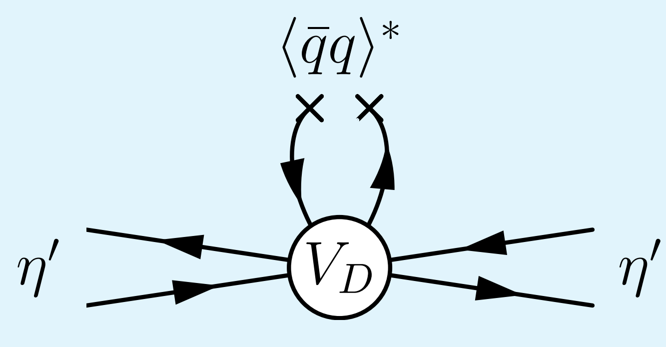
partial restoration of ChS takes place with 35% at ρ_0

we expect strong η’ mass reduction $\Delta m_{\eta'} \sim 100$ MeV @



‘t Hooft - Kobayashi - Maskawa interaction

$U_A(1)$ anomaly contributes η’ mass through ChSB



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

Nagahiro, Takizawa, Hirenzaki PRC74,045203 (2006)

See also, P. Costa, M. C. Ruivo, and Y. L. Kalinovsky, Phys. Lett. B560, 171 (2003).

η'-N interaction in SU(3) linear σ model

References

S. Sakai, DJ, Phys.Rev. C88 (2013) 064906; in preparation

see the talk (Wed.) by S. Sakai for the details

SU(3) linear sigma model

Schechter, Ueda, PRD3, 2874 (71)
Papazoglou et al., PRC57, 2576 (98)

has mechanism of spontaneous chiral symmetry breaking

Lagrangian $M = \Sigma + i\Pi$ quark mass $\chi = \mathrm{diag}(m_q, m_q, m_s)$

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2}\mathrm{Tr}[MM^\dagger] - \frac{\lambda}{4}\mathrm{Tr}[(MM^\dagger)^2] - \frac{\lambda'}{4}\left(\mathrm{Tr}[MM^\dagger]\right)^2$$

$$- A\mathrm{Tr}[\chi M^\dagger + \chi^\dagger M] + \sqrt{3}B(\det M + \det M^\dagger)$$

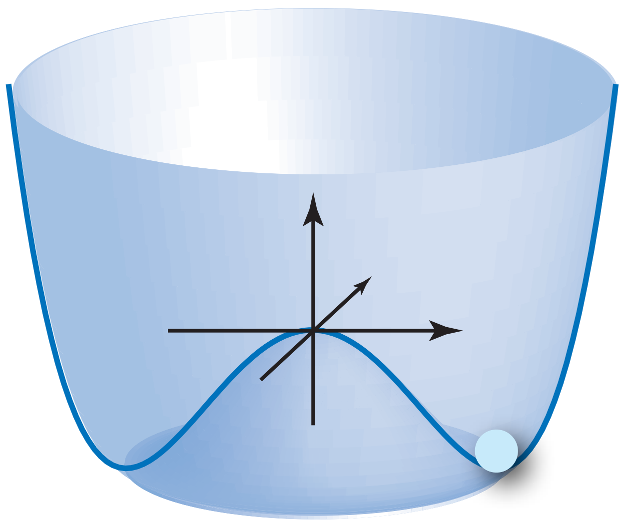
explicit ChS breaking
flavor symmetry breaking

anomaly term
breaks $U_A(1)$ symmetry

vacuum is determined so as to realize spontaneous breaking of ChS

finite sigma condensates $\langle\sigma_0\rangle, \ \langle\sigma_8\rangle$

massless PS boson obtained with the vacuum condition



η' meson mass

at chiral limit

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

SU(3) linear sigma model

Sakai, DJ, PRC88 (13) 064906

has mechanism of spontaneous chiral symmetry breaking

Lagrangian $M = \Sigma + i\Pi$ quark mass $\chi = \mathrm{diag}(m_q, m_q, m_s)$

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}[\partial_\mu M \partial^\mu M^\dagger] - \frac{\mu^2}{2}\mathrm{Tr}[MM^\dagger] - \frac{\lambda}{4}\mathrm{Tr}[(MM^\dagger)^2] - \frac{\lambda'}{4}\left(\mathrm{Tr}[MM^\dagger]\right)^2$$

$$- A\mathrm{Tr}[\chi M^\dagger + \chi^\dagger M] + \sqrt{3}B(\det M + \det M^\dagger)$$

explicit ChS breaking
flavor symmetry breaking

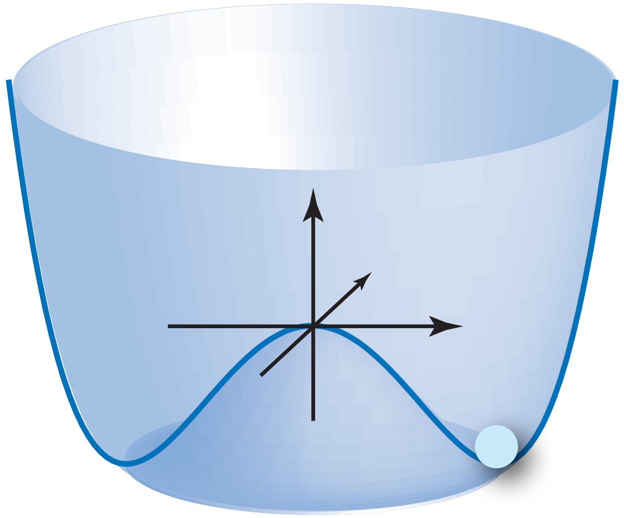
anomaly term
breaks $U_A(1)$ symmetry

$$\mathcal{L}_N = \bar\psi(i\partial\!\!\!/ - m_N)\psi - g\bar\psi\left(\frac{1}{\sqrt{3}}\tilde\sigma_0 + \frac{1}{\sqrt{6}}\tilde\sigma_8\right)\psi$$

σN interaction

$$- g\bar\psi i\gamma_5\left(\frac{1}{\sqrt{2}}\vec\pi\cdot\vec\tau + \frac{1}{\sqrt{3}}\eta_0 + \frac{1}{\sqrt{6}}\eta_8\right)\psi$$

Yukawa coupling



meson and baryon fields transform linearly under the SU(3)xSU(3) chiral symmetry

partial restoration of chiral symmetry in nuclear medium

parameter g is determined so as to restore chiral symmetry in order of 35% in mean field approximation

in-medium condensates

Sakai, DJ, PRC88 (13) 064906

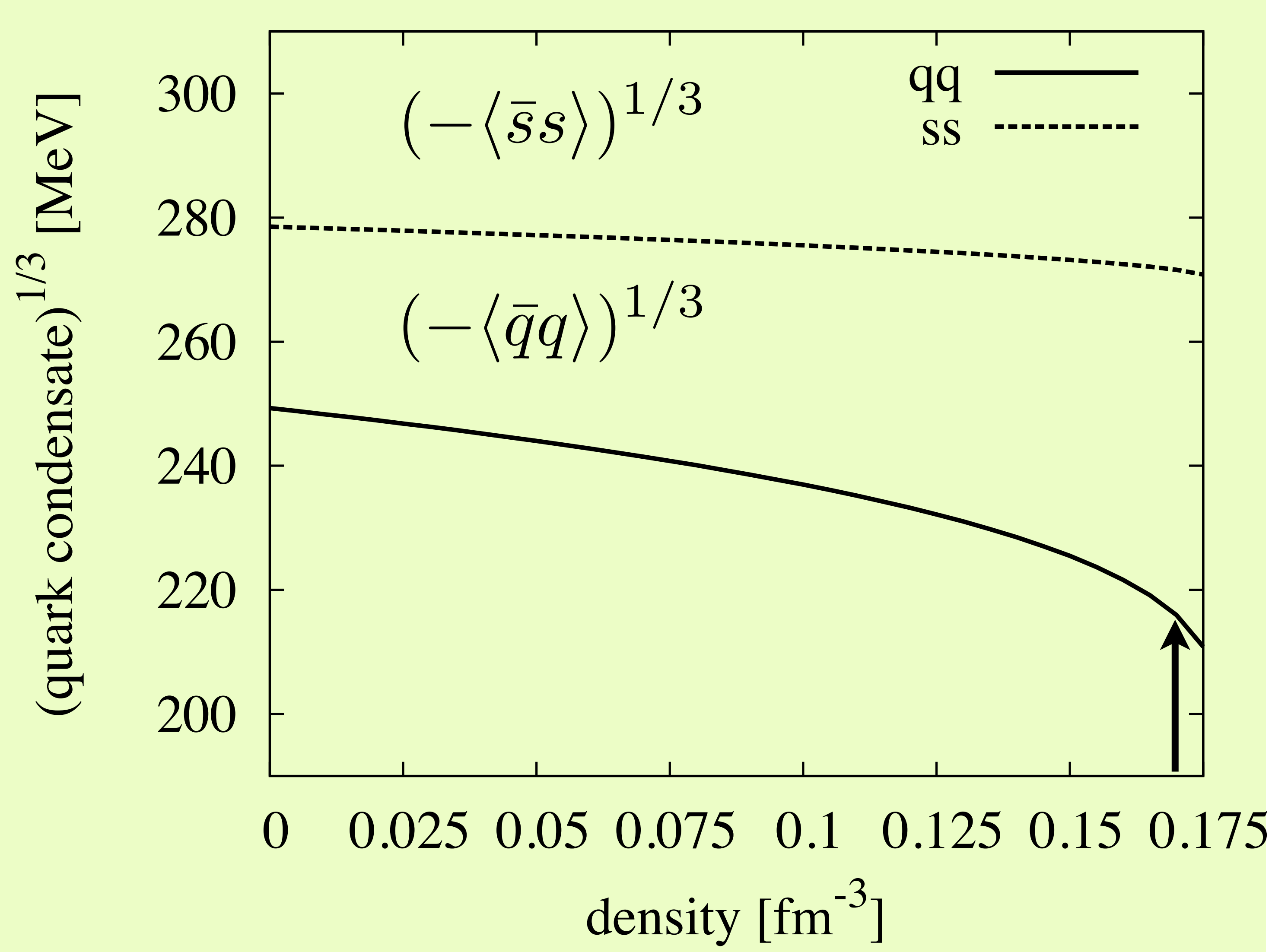
determine values of in-medium condensates from effective potential $V(\sigma_0, \sigma_8, \rho)$

$$\left.\frac{\delta V}{\delta \sigma_0}\right|_{\sigma_i=\langle\sigma_i\rangle^*} = 0, \qquad \left.\frac{\delta V}{\delta \sigma_8}\right|_{\sigma_i=\langle\sigma_i\rangle^*} = 0,$$

in-medium condensates $\langle\sigma_0\rangle^*, \ \langle\sigma_8\rangle^*$

quark condensate

$$\langle\bar{q}q\rangle^* = A(2\langle\sigma_0\rangle^* + \sqrt{2}\langle\sigma_8\rangle^*) \qquad \langle\bar{s}s\rangle^* = 2A(\langle\sigma_0\rangle^* - \sqrt{2}\langle\sigma_8\rangle^*)$$



not change so much

input : 35% reduction at ρ_0

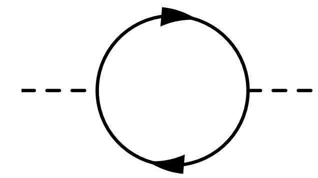
in-medium masses

Sakai, DJ, PRC88 (13) 064906

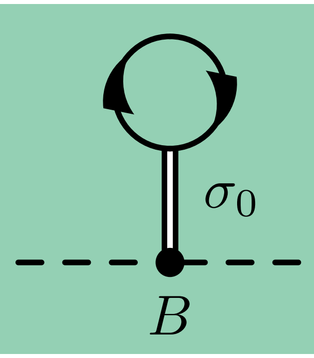
meson mass

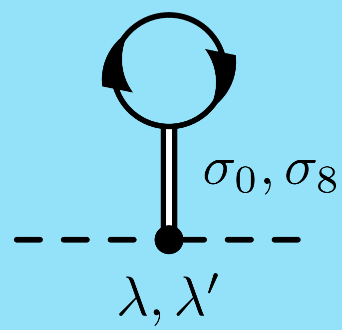
in vacuum $m^2 = m^2(\langle\sigma_0\rangle, \langle\sigma_8\rangle)$

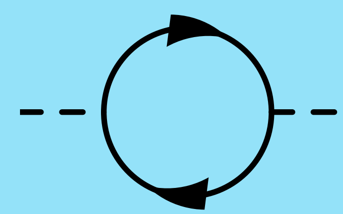
in medium $m^{*2} = m^2(\langle\sigma_0\rangle^*, \langle\sigma_8\rangle^*) + \Sigma_{ph}$



medium effect on η’ mass

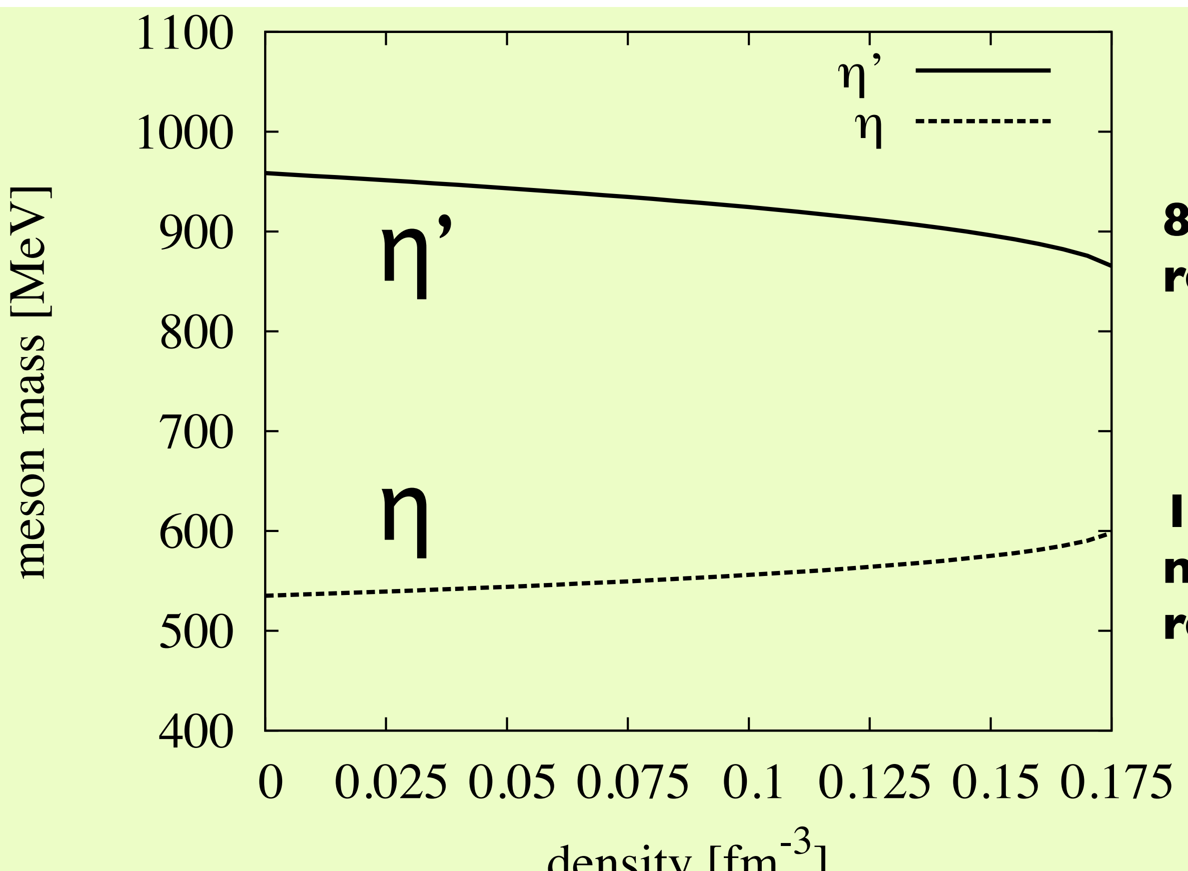






+ crossed

cancelled in chiral limit



83 MeV η’ mass reduction

135 MeV η-η’ mass diff. reduction

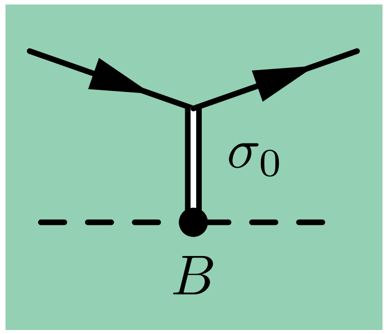
This model reproduces η’ mass reduction associated with PRChS

In-medium η mass is a consequence of cancellation of several terms. For qualitative discussion, we have to fix model parameters more precisely.

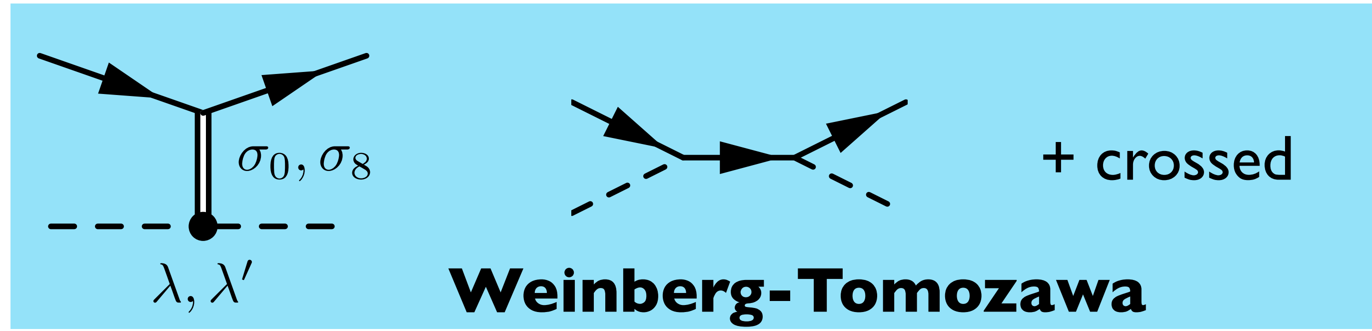
η′-N interaction

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

η'-nucleon interaction in LσM



B term : anomaly effect



cancel each other at chiral limit thanks to ChS

interaction strength (symmetric limit)

$$V_{\eta' N} = 6B \cdot \frac{g/\sqrt{3}}{-m_{\sigma_0}^2} \simeq -0.053 \text{ [MeV^-1]}$$

cf. - 0.086 MeV^{-1} WT term of K^{bar}N (I=0)

→ 10-15 MeV binding of K^{bar}N

two-body bound state

~ 6 MeV

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

coupled channel effect (η'N, ηN)

BE = 12 - 3i [MeV]

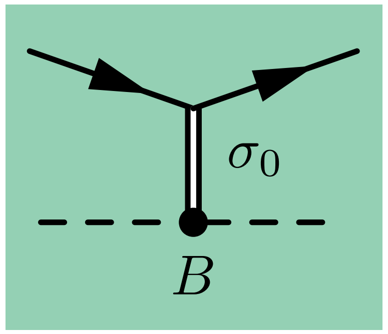
scattering length = -1.9 + 0.2i [fm]

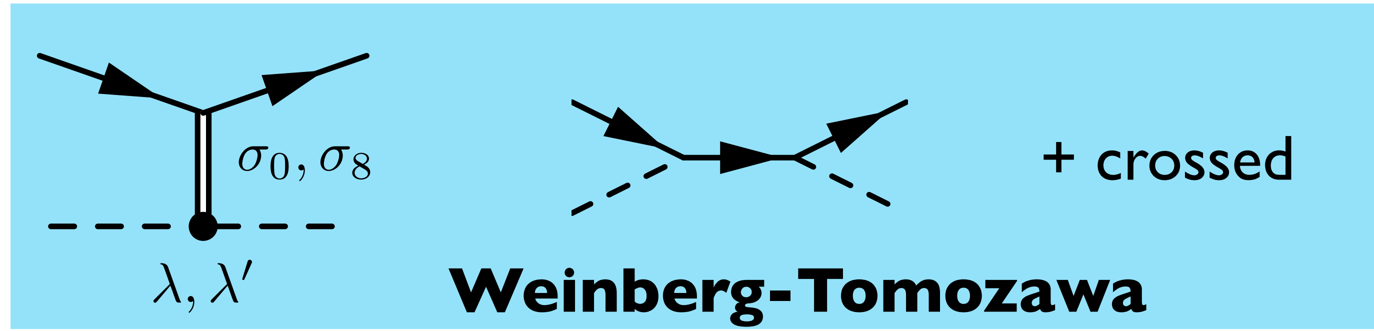
the details numbers are sensitive to the parameters of symmetry breaking

η′-N interaction

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

η’-nucleon interaction in LσM





B term : anomaly effect

cancel each other at chiral limit thanks to ChS

attraction in scalar channel is related to mass generation mechanism

a part of η' mass (400 MeV) is generated by spontaneous breaking of ChS

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

→ presence of strong coupling ση'η'

nucleon mass is generated also by spontaneous breaking of ChS

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

→ presence of strong coupling σNN

strong attraction in η’-nucleon channel with scalar-isoscalar exchange

this mechanism is same as scalar attraction in NN interaction

η'N interaction mediated by $\frac{\alpha_s}{4\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}$ was studied by S. Bass

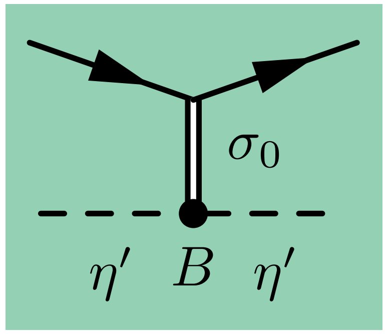
Bass, PLB463 (99) 286

Narrow width ??

Sakai, DJ, in preparation

inelastic channel η' N → η N

attraction coming from sigma exchange with anomaly

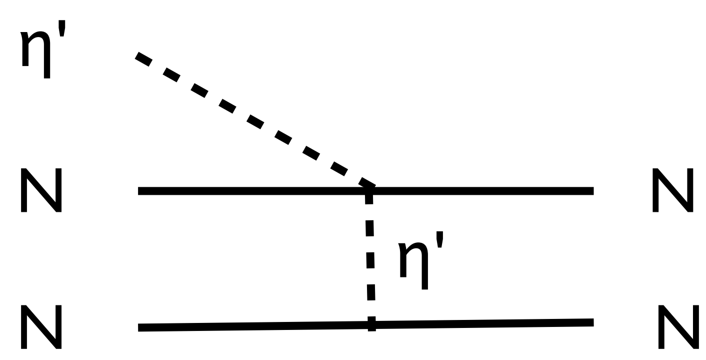


anomaly effect selectively affects η' channel

large **elastic channel** η' N → η' N

small **inelastic channel** η' N → η N η' N → π N

two-body absorption ?? η' NN → NN



depending on size of Yukawa coup. of η'NN

calculation result coming soon.

Conclusion

η' mass : interplay of chiral symmetry breaking and $U_A(1)$ anomaly

$U_A(1)$ anomaly can affect η' mass only through chiral symmetry breaking

reduction of η' mass due to partial restoration of chiral symmetry

in order of 100 MeV at saturation density

strong attraction of η'-N interaction in scalar channel

same mechanism as NN attraction in isoscalar-scalar channel

mass generation by sigma condensate and sigma exchange

strength is comparable with $K^{bar}N$ Weinberg-Tomozawa interaction

enough strength to form η'-N bound state

if no bound state, we need repulsive interaction in other channels

no Weinberg-Tomozawa (vector exchange) interaction

Partial restoration of chiral symmetry

effective reduction of quark condensate $\langle \bar{q}q \rangle^* / \langle \bar{q}q \rangle < 1$

low density theorem

Drukarev, Levin,
Prog. Part. Nucl. Phys. 27, 77 (1991)

model-independent theoretical relation

$$\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho\right) \langle \bar{q}q \rangle + \mathcal{O}(\rho^{n>1})$$

$\sigma_{\pi N}$: πN sigma term, $O(m_q)$,
obtained from $T_{\pi N}$ at soft limit

quark condensate does decrease in nuclear medium

phenomenological proof by analysis of pionic atom and low energy pi-A scattering

30-40 % reduction at saturation density, if believe linear extrapolation

K. Suzuki et al.
PRL92, 072302, (04);
Friedman et al.,
PRL93, 122302 (04);
DJ, Hatsuda, Kunihiro,
PLB 670, 109 (08).

since QCD is fundamental theory of strong interaction

all hadron quantities have their substantial quark-gluon description

once one knows in-medium change of fundamental quantities, such as quark condensate, one can expect modification of hadron quantities

this does NOT contradict conventional nuclear physics

"quark-hadron duality"

hadronic quantities $\rightleftarrows$ quark-gluon description (substantial)