Hadron properties in nuclear medium: perspectives from QCD sum rules

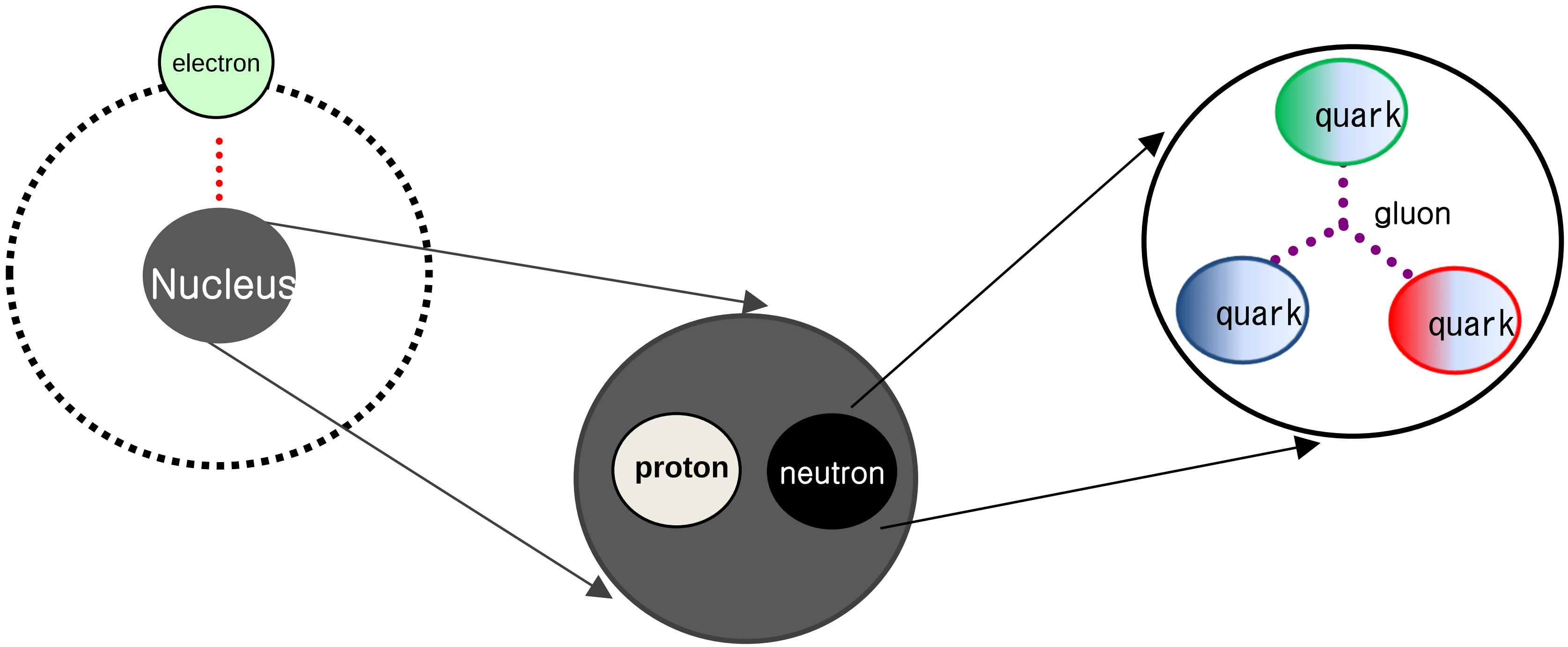
Su Houng Lee

YONSEI UNIVERSITY

Previous works +

- Su Houng Lee, PRC57 (1998) 927
- T. Song, T. Hatsuda, Su Houng Lee, PLB792 (2019) 160
- Jisu Kim and Su Houng Lee, PRD103(21) L051501,PRD105 (2022)014014
- Jisu Kim, Philipp Gubler, Su Houng Lee PRD105(2022)114053

Understanding the mass of a Hadron



Mass of an Atom

Nucleon: 99.95 %

electron: 0.05 %

EM binding< 0.00001 %

Nucleus

Nucleons: 99%

Nuclear binding < 1 %

Nucleon

Quark < 5 %

The rest ??

QCD → { Confinement / $U_A(1)$ breaking / χ-sym breaking }

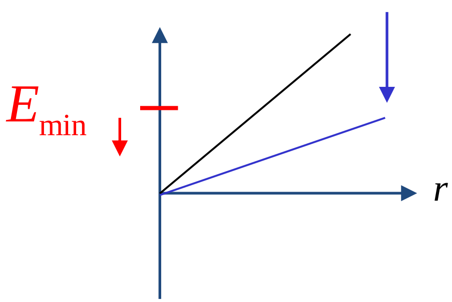
Is Chiral symmetry breaking the origin of the hadron mass ?

☞ Consider a meson in a quark model

$$H = 2m_q + \frac{p^2}{2m_q} + \sigma\, r$$

Deconfinement

$\sigma \rightarrow$ decrease

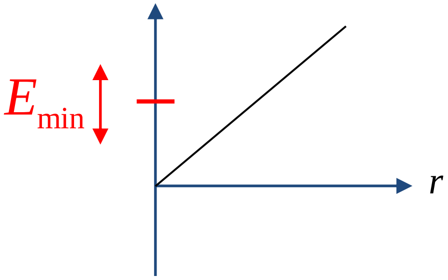


χ –symmetry ?
Confinement ?

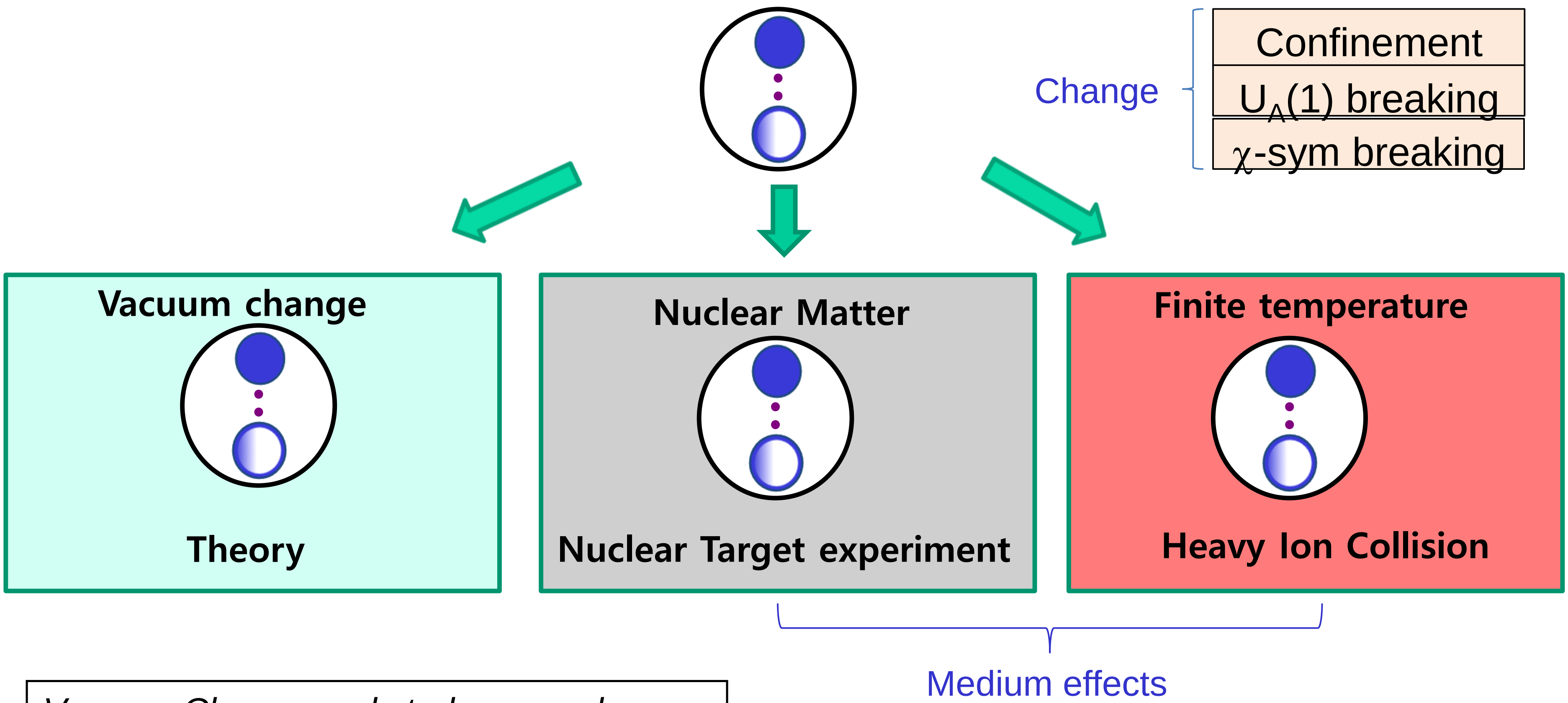
Is such a separation possible?

Chiral symmetry restoration

$m_q \rightarrow$ decrease



To understand the origin of Hadron mass



Vacuum Change and study mass change

1. Chiral symmetry restoration: $\langle \bar{q}q \rangle$, $\left[\left\langle \left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 - \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2 \right\rangle\right]$,.....

2. Changes in other Non-perturbative effects: $\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle$, ...

Additional effects in nuclear matter and/or finite temperature

1. Changes in Chiral symmetric operators: $\left[\left\langle \left(\bar{q}\gamma_\mu \gamma^5 \lambda^a \tau^3 q \right)^2 + \left(\bar{q}\gamma_\mu \lambda^a \tau^3 q \right)^2 \right\rangle \right]$,.....

$\Rightarrow$ Mass changes in medium from effects other than chiral symmetry restoration

2. Appearance of Tensor operators due to denisty and energy ect. :

$$\left\langle \bar{q}\gamma_0 q \right\rangle,\ \left\langle \bar{q}\gamma_\mu D_\nu q \right\rangle,\ \left\langle E^2 + B^2 \right\rangle \ \ ......$$

$\Rightarrow$ Momentum dependent masses; Transverse and Longitudinal Masses

But in all cases,

1. Mass difference between Chiral partners are proportional to chiral symmetry breaking:

$$m_{a_1} - m_\rho,\ m_{K_1} - m_{K^*} \ \propto \ \left\langle \bar{q}q \right\rangle, \quad \left[\left\langle \left(\bar{q}\gamma_\mu \gamma^5 \lambda^a \tau^3 q \right)^2 - \left(\bar{q}\gamma_\mu \lambda^a \tau^3 q \right)^2 \right\rangle \right],.....$$

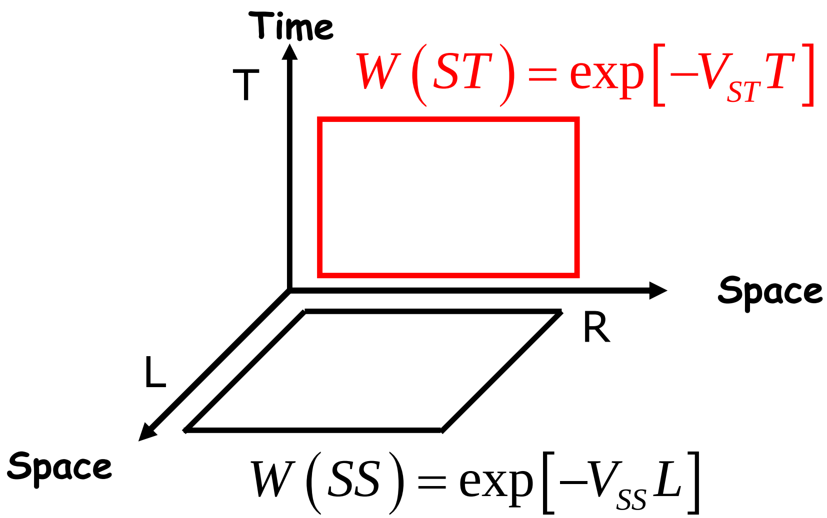
2. Effects of Tensor operators can be isolated by looking at

Transverse and Longitudional components of vector mesons

Confinement and heavy quark system

Confinement and gluon condensates

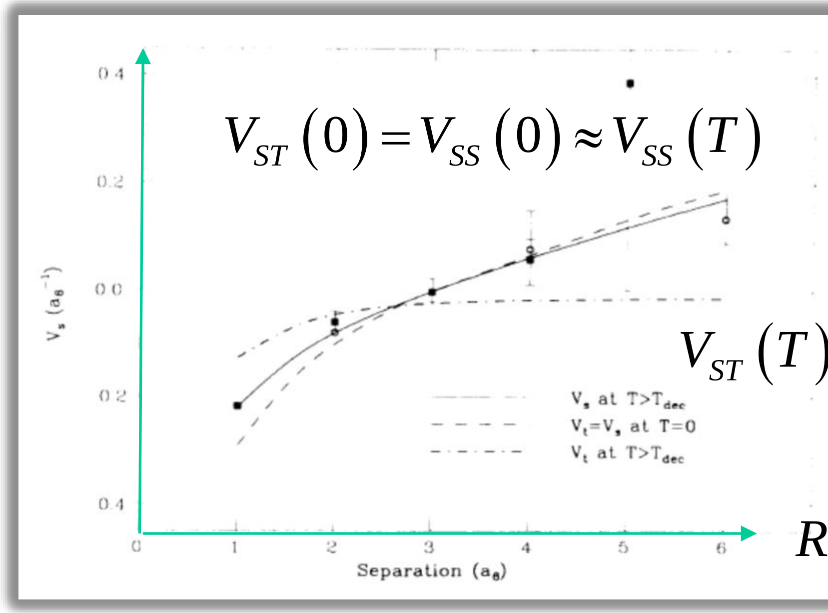
☞ Wilson Loops and potential



$$W(ST) = \exp[-V_{ST}T]$$

$$W(SS) = \exp[-V_{SS}L]$$

Manousakis, Polonyi PRL 1987



$$V_{ST}(0) = V_{SS}(0) \approx V_{SS}(T)$$

☞ Local operators

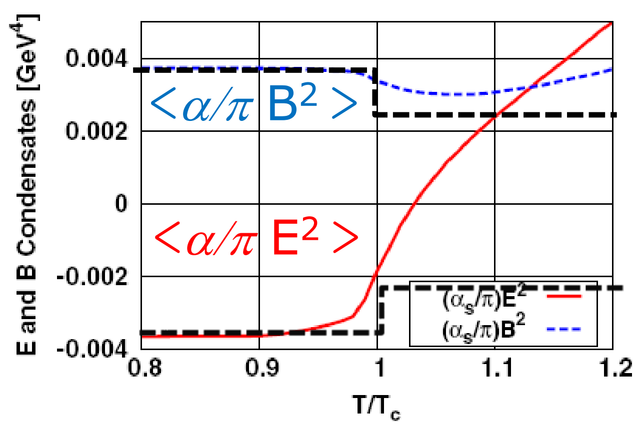
OPE for Wilson lines: Shifman NPB73 (80)
Dosch, Simonov PLB339 (88)

W(S-T) = 1- ⟨α/π E²⟩ (ST)² +…

W(S-S) = 1- ⟨α/π B²⟩ (SS)² +…

SHLee PRD40 (89): ------------
Non-perturbative Gluon condensate above Tc

Morita, SHLee, PRL 2008, PRD 2009



☞ Condensate change in nuclear matter around 5%

$$\Delta\left\langle \frac{\alpha}{\pi} E^2 \right\rangle = \frac{1}{4}\Delta\left\langle \frac{\alpha}{\pi} G^2 \right\rangle + \frac{1}{2}\Delta\left\langle \frac{\alpha}{\pi}\left(E^2+B^2\right)\right\rangle = +M_0 + \frac{\alpha}{\pi}M_2 \;\rightarrow \text{larger change}$$

$$\Delta\left\langle \frac{\alpha}{\pi} B^2 \right\rangle = -\frac{1}{4}\Delta\left\langle \frac{\alpha}{\pi} G^2 \right\rangle + \frac{1}{2}\Delta\left\langle \frac{\alpha}{\pi}\left(E^2+B^2\right)\right\rangle = -M_0 + \frac{\alpha}{\pi}M_2 \;\rightarrow \text{smaller change}$$

$$M_0 = \frac{2}{11} m_N^0 \times \rho$$

$$M_2 = \frac{3}{2} m_N \int dx x G(x) \times \rho$$

☞ Expected Mass shift in nuclear matter (Lee, Ko, PRC67 (03)038202)

	Quantum numbers	QCD 2nd Stark eff.	Potential model	QCD sum rules	Effects of DD loop
η_c	0^{-+}	**−8 MeV**		**−5 MeV** (Klingl, SHL ,Weise, Morita)	No effect
J/ψ	1^{--}	**−8 MeV** (Peskin, Luke)	**-10 MeV** (Brodsky et al).	**−7 MeV** (Klingl, SHL ,Weise, Morita)	<2 MeV (SHL, Ko)
χ_c	$0,1,2^{++}$	**-20 MeV**		**-15 MeV** (Morita, Lee)	No effect on χ_{c1}
$\psi(3686)$	1^{--}	**-100 MeV**			< 30 MeV
$\psi(3770)$	1^{--}	**-140 MeV**			< 30 MeV

→ Heavy quark system can probe confinement physics

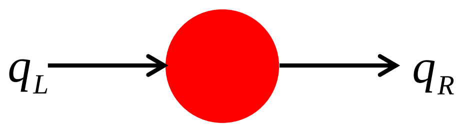
→ Could be searched at PANDA or future JPARC (G. Wolf)

Chiral symmetry breaking and chiral partners

Chiral symmetry breaking (m→0) : $\mathrm{SU}(N_F)_L \times \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)_V$

- *Chiral order parameter: Quark condensate*

☞ $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle = -\lim_{x\to 0} \langle \mathrm{Tr}[S(x,0)] \rangle = -\lim_{x\to 0} \left\langle \frac{1}{2} \mathrm{Tr}\left[S(x,0) - i\gamma^5 S(x,0) i\gamma^5 \right] \right\rangle$



Chiral rotation $q \to \exp\left(i\gamma^5 \tau^a \alpha^a\right) q$

☞ Casher Banks formula: nontrivial zero mode (λ =0) contribution

$$\langle \bar{q}q \rangle = -\left\langle \mathrm{Tr}\left[\left(0 \,|\, \frac{1}{\not{D} + m} \,|\, 0 \right) \right] \right\rangle = -\frac{1}{2} \left\langle \sum_\lambda \psi_\lambda^+ \left(\frac{1}{i\lambda + m} + \frac{1}{-i\lambda + m} \right) \psi_\lambda \right\rangle = -\frac{1}{2} \left\langle \sum_\lambda \psi_\lambda^+ \left(\frac{2m}{\lambda^2 + m^2} \right) \psi_\lambda \right\rangle$$

$$\xrightarrow{m=0} \langle \pi \rho(\lambda = 0) \rangle$$

where $i\not{D}\psi_\lambda = \lambda \psi_\lambda$

cf. $\left\langle \frac{\alpha}{\pi} G^2 \right\rangle = 12 \left\langle \sum_\lambda \rho(\lambda) \right\rangle$

(SHL, S.Cho, arXiv:1302.0642)

- *Chiral order parameter: $\rho\rho - a_1 a_1$ correlator*

☞ $$\Pi^{\rho\rho} - \Pi^{a_1 a_1} = \frac{1}{V}\int d^4x \left[\left\langle \bar{q}\gamma^{\mu}\tau^{a}q(x), \bar{q}\gamma^{\mu}\tau^{a}q(0)\right\rangle - \left\langle \bar{q}\tau^{a}i\gamma^{5}\gamma^{\mu}q(x), \bar{q}\tau^{a}i\gamma^{5}\gamma^{\mu}q(0)\right\rangle \right]$$

$$= -\frac{1}{2}\mathrm{Tr}\left[\gamma^{\mu}\left(S(x,0) - i\gamma^{5}S(x,0)i\gamma^{5}\right)\gamma^{\mu}\left(S(0,x) - i\gamma^{5}S(0,x)i\gamma^{5}\right)\right] \propto \left\langle \rho^{2}(\lambda = 0)\right\rangle$$

Always proportional to chiral order parameter

whether in nuclear matter or finite temperature

☞ Weinberg sum rule

$$\left.\begin{cases} f_{\rho}^{2}m_{\rho}^{2} - f_{a_1}^{2}m_{a_1}^{2} = f_{\pi}^{2} \\ f_{\rho}^{2}m_{\rho}^{4} - f_{a_1}^{2}m_{a_1}^{4} = 0 \end{cases}\right\} \quad f_{\rho}^{2}m_{\rho}^{2}\left(1 - \frac{m_{\rho}^{2}}{m_{a_1}^{2}}\right) = f_{\pi}^{2}$$

$m_{\rho} = m_{a_1} = m_{\mathrm{sym}}$ when chiral symmetry is restored.

What about m_{sym} ? $\rightarrow$ Can be calculated in QCD sum rules

Vector meson mass in the chiral symmetry restored vacuum

- QCD sum rule for ρ and a_1 meson

Jisu Kim, SHL: arXiv2012.06463 (PRD21)

Jisu Kim, SHL: arXiv2109.12791 (PRD22)

☞

$$\Pi^{\rho\rho} = \dots \frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\Pi^{a_1 a_1} = \dots \frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle = \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 + \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_S + \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 - \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_B$$

$$\left\langle\left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle = \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 + \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_S - \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 - \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_B$$

$$\propto \left(S(0) + i\gamma^5 S(0) i\gamma^5\right) \quad \pm \quad \left(S(0) - i\gamma^5 S(0) i\gamma^5\right) \propto \langle\bar{q}q\rangle^2$$

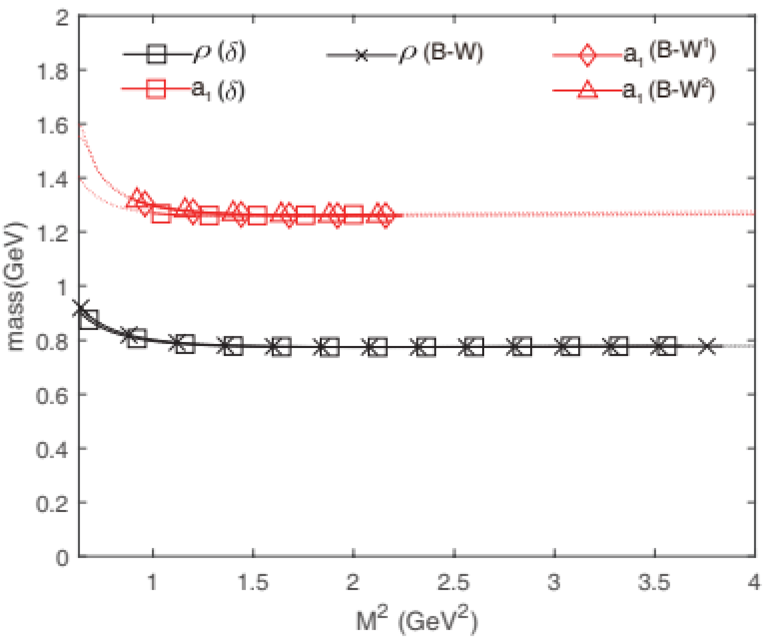
Chiral symmetric operator $\pm$ Chiral symmetry breaking operator

☞ $$\Pi^{\rho\rho} = ...\frac{1}{Q^6}\left[\frac{14}{9}\langle B\rangle + \langle S\rangle\right], \qquad \Pi^{a_1 a_1} = ...\frac{1}{Q^6}\left[-\frac{22}{9}\langle B\rangle + \langle S\rangle\right]$$

$$\langle B\rangle = -\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle_B$$ Chiral symmetry order parameter

$$\langle S\rangle = -\frac{22\pi\alpha}{9}\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle_S$$ No relation to chiral symmetry breaking

☞ $\langle B\rangle$ and $\langle S\rangle$ can be determined separately from ρ and a_1 sum rules



Pole	$B\,(\mathrm{GeV}^6)$	$S\,(\mathrm{GeV}^6)$
δ	7.42×10^{-4}	5.65×10^{-4}
B-W[1]	6.42×10^{-4}	6.05×10^{-4}
B-W[2]	5.75×10^{-4}	7.11×10^{-4}

☞ $\Pi^{VV} = \ldots \frac{1}{Q^6}\left[\frac{14}{9}\langle B\rangle + \langle S\rangle\right]$, $\Pi^{AA} = \ldots \frac{1}{Q^6}\left[-\frac{22}{9}\langle B\rangle + \langle S\rangle\right]$

☞ When only chiral symmetry is restored : $\langle S\rangle \to$ fixed but $\langle B\rangle \to 0$

QCD sum rule analysis gives

$\mathrm{m}_\rho = \mathrm{m}_{a_1} = \mathrm{m}_{\mathrm{sym}} \sim 550 \pm 50$ MeV in the chiral symmetry restored vacuum

☞ QSR: masses of other hadrons when chiral symmetry is restored

Particle	$\bar{m}_{\mathrm{sym}}$(MeV)
ρ, a_1	572.5 ± 27.5
ω	655 ± 15
f_1	1060 ± 30
K^*, K_1	545 ∓ 5

Particle	$\bar{m}_{\mathrm{sym}}$(MeV)
N	525
Δ	600

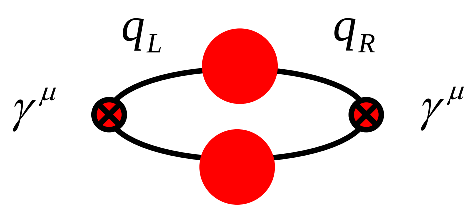
Scalar nucleon mass in nuclear matter

$m_{\mathrm{sym}} \sim M + (S)$ where $S = -400$ MeV

- *Not* a Chiral order parameter: $\omega\omega - f_1^{\bar{q}q} f_1^{\bar{q}q}$ correlator

☞ $$\Pi^{\omega\omega} - \Pi^{f_1 f_1} = \frac{1}{V}\int d^4x \left[\langle \bar{q}\gamma^\mu q(x), \bar{q}\gamma^\mu q(0) \rangle - \langle \bar{q} i\gamma^5\gamma^\mu q(x), \bar{q} i\gamma^5\gamma^\mu q(0) \rangle \right]$$

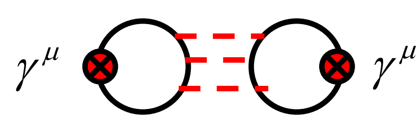
$$= -\frac{1}{2}\mathrm{Tr}\left[\gamma^\mu \left(S(x,0) - i\gamma^5 S(x,0) i\gamma^5 \right) \gamma^\mu \left(S(0,x) - i\gamma^5 S(0,x) i\gamma^5 \right) \right]$$



$$\propto \langle \rho^2(\lambda = 0) \rangle \propto \langle \bar{q}q \rangle^n$$

$$+ \frac{1}{4}\mathrm{Tr}\left[\gamma^\mu \left(S(x) + i\gamma^5 S(x) i\gamma^5 \right) \right] \mathrm{Tr}\left[\gamma^\mu \left(S(0) + i\gamma^5 S(0) i\gamma^5 \right) \right] + \left(\gamma^\mu \to \gamma^\mu \gamma^5 \right)$$

Invariant under Chiral rotation $q \to \exp\left(i\gamma^5 \tau^a \alpha^a \right) q$



$$\propto \langle \rho^2(\lambda \neq 0) \rangle$$

ω has no chiral partner

☞ Origin of hadron masses in the chiral symmetry restored vacuum

In QCD sum rules

$$\left[\left\langle \left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 + \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2 \right\rangle\right]_S \propto \left(S(0) + i\gamma^5 S(0) i\gamma^5\right)$$

$$\left\langle \frac{\alpha}{\pi} G^2 \right\rangle = 12 \left\langle \sum_\lambda \rho(\lambda) \right\rangle$$

$$cf.\quad \langle \bar{q}q \rangle = \xrightarrow{m=0} \langle \pi\rho(\lambda=0) \rangle$$

Light vector mesons – chiral partners ?

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ $(\bar{q}\gamma_\mu \tau q)$	770	150.	a_1 $(\bar{q}\gamma_\mu \gamma^5 \tau q)$	1260	250-600
ω $(\bar{q}\gamma_\mu q)$	782	8.49	f_1 $(\bar{q}\gamma_\mu \gamma^5 q)$	1285	24.2
ϕ $(\bar{s}\gamma_\mu s)$	1020	4.266	f_1 $(\bar{s}\gamma_\mu \gamma^5 s)$	1420	54.9
K* $(\bar{s}\gamma_\mu q)$	892	50.3	K_1 $(\bar{s}\gamma_\mu \gamma^5 q)$	1270	90

Are chiral partners

Are NOT chiral partners

Masses of chiral partners become identidal when chiral symmetry is restored.
But the restored value m_{sym} depends on the properties of the medium

Studying individual masses are nevertheless important because

Experimentally feasible → JPARC E-16 (P. Gulber, K. Aoki)

Theory can link to chiral symmetry breaking to mass shift

Other effects of the medium

1. Effects of medium $n^{\mu} = \left(1, 0, 0, 0\right)$

2. Effects of non-zero energy and Tensor operators

$$\left\langle E^2 + B^2 \right\rangle, \quad \left\langle \bar{q}\left(\gamma_\mu D_\nu\right) q \right\rangle, ...$$

- *Scalar Particle*

☞ in Vacuum $q^2 - m^2 = 0 \quad \rightarrow \quad q^2 = \omega^2 - \vec{q}^{\,2} = m^2$

☞ in medium characterized by $n^\mu = (1,0,0,0)$

$$q^2 - m^2 = a\omega^2 - b\vec{q}^{\,2} + S \quad \rightarrow \quad (1-a)\omega^2 - (1-b)\vec{q}^{\,2} = m^2 + S$$

$$\rightarrow \begin{cases} \vec{q} = 0, \quad \omega^2 = \dfrac{m^2 + S}{(1-a)} = m^2_{medium} \\ \omega = 0, \quad -\vec{q}^{\,2} = \dfrac{m^2 + S}{(1-b)} = m^2_{screening} \end{cases}$$

• *Spinor Particle*

☞ in Vacuum $\omega\gamma^0 - \vec{\gamma}\vec{p} - M = 0$

☞ in medium characterized by $n^\mu = (1,0,0,0)$

$$\omega\gamma^0 - \vec{\gamma}\vec{p} - M = 0 \xrightarrow{\vec{p}=0} \omega\gamma^0 - M = S + \gamma^0 V$$

Positive energy solution $E = M + (S + V) \approx M + (-400 + 300)\,\mathrm{MeV}$

↑

Related to chiral symmetry breaking

- *Vector particle*

☞ in Vacuum $P_{\mu\nu}\left(q^2-m^2\right)A_\nu=0$ where $P_{\mu\nu}=\left(\frac{q_\mu q_\nu}{q^2}-g_{\mu\nu}\right)$

☞ in medium characterized by $n^\mu=\left(1,0,0,0\right)$

$$P_{\mu\nu}\left(q^2-m^2\right)=P^T_{\mu\nu}\Pi^T\left(\omega,\vec{q}\right)+P^L_{\mu\nu}\Pi^L\left(\omega,\vec{q}\right)$$

$$\text{where}\quad P^T_{ij}=\left(\delta_{ij}-\frac{\vec{q}_i\vec{q}_j}{\vec{q}^2}\right),\quad P^L_{\mu\nu}=\left(\frac{q_\mu q_\nu}{q^2}-g_{\mu\nu}-P^T_{\mu\nu}\right)$$

$$\text{when}\ \ \vec{q}=0\ \text{then}\ \ \Pi^T=\Pi^L\ \ \rightarrow\ \ P_{\mu\nu}\left(q^2-m^2\right)=P_{\mu\nu}\Pi\left(\omega,0\right)$$

$$\rightarrow\ \ \left(\omega^2-m^2\right)=\Pi\left(\omega,0\right)$$

$$\text{when}\ \ \vec{q}\neq 0\ \text{then}\ \ \Pi^T\neq\Pi^L\ \ \rightarrow\ \ \left(P^T_{\mu\nu}+P^L_{\mu\nu}\right)\left(q^2-m^2\right)=P^T_{\mu\nu}\Pi^T\left(\omega,\vec{q}\right)+P^L_{\mu\nu}\Pi^L\left(\omega,\vec{q}\right)$$

$$\rightarrow\ \begin{cases}\text{Transverse} & \left(q^2-m^2\right)=\Pi^T\left(\omega,\vec{q}\right)\\ \text{Longitudinal} & \left(q^2-m^2\right)=\Pi^L\left(\omega,\vec{q}\right)\end{cases}$$

- *Where is the effect of chiral symmetry in vector mesons*

☞ in medium characterized by $n^{\mu} = (1,0,0,0)$

when $\vec{q} = 0$ then $\Pi^T = \Pi^L \quad \rightarrow \quad P_{\mu\nu}(q^2 - m^2) = P_{\mu\nu}\Pi(\omega, 0)$

$$\rightarrow \quad (\omega^2 - m^2) = \Pi(\omega, 0)$$

when $\vec{q} \neq 0$ then $\Pi^T \neq \Pi^L \quad \rightarrow \quad (P^T_{\mu\nu} + P^L_{\mu\nu})(q^2 - m^2) = P^T_{\mu\nu}\Pi^T(\omega, \vec{q}) + P^L_{\mu\nu}\Pi^L(\omega, \vec{q})$

$$\rightarrow \begin{cases} \text{Transverse} \quad (q^2 - m^2) = \Pi^T(\omega, \vec{q}) \\ \text{Longitudinal} \quad (q^2 - m^2) = \Pi^L(\omega, \vec{q}) \end{cases}$$

What is the relation between chiral symmetry restoration and

$$\omega^2 = m^2 + \Pi(\omega, 0) \quad \rightarrow \quad m^2_{medium} = m^2_{breaking} + m^2_{symmetric}$$

$$\Pi^T(\omega, \vec{q}) - \Pi^L(\omega, \vec{q}) = \Delta\Pi_{breaing} + \Delta\Pi_{symmetric}$$

Vector meson mass in the chiral symmetry restored vacuum

1. *Su Houng Lee, "Vector mesons in-medium with finite three momentum", PRC 57 (1998) 927:*

   Studied $\Pi^T(\omega,\vec{q}),\ \Pi^L(\omega,\vec{q})$ for ρ,ω,ϕ

2. *B. Friman, Su Houng Lee, H-C Kim, "Constraints on vector mesons with finite three momentum in nuclear medium", NPA 653 (1999) 91*

   Compared OPE of $\Pi^T(\omega,\vec{q}),\ \Pi^L(\omega,\vec{q})$ to that of phenomenological model

   found model overestimate effect due to incorrect use of form factor

3. *HyungJoo Kim, Philipp Gubler, "The phi meson with finite momentum in dense medium" PLB 805 (2020) 135412.*

   Detailed study of $\Pi^T(\omega,\vec{q}),\ \Pi^L(\omega,\vec{q})$ for ϕ

4. *Su Houng Lee, AAPPS Bulletin (2021) 31.3*

   study of $\Pi^T - \Pi^L = \Delta\Pi = \Delta\Pi_{breaking} + \Delta\Pi_{symmetric}$ for Vector mesons

   Conclusion is $\Delta\Pi_{breaking} \ll \Delta\Pi_{symmetric}$

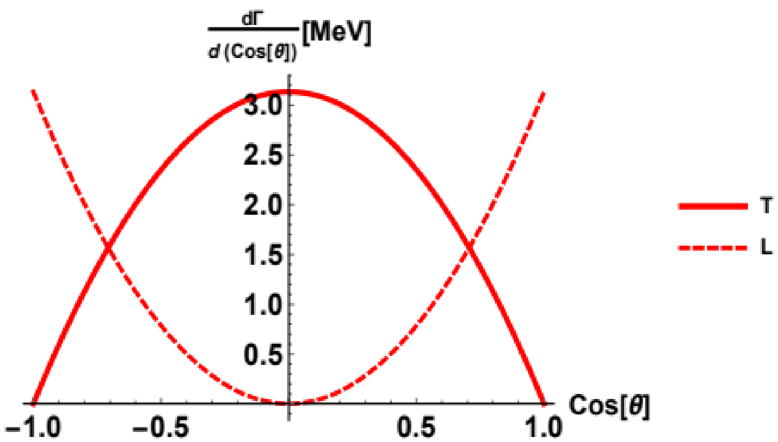
JPARC will disentangle the T and L component

☞ *Talk by P. Gubler and K. Aoki*

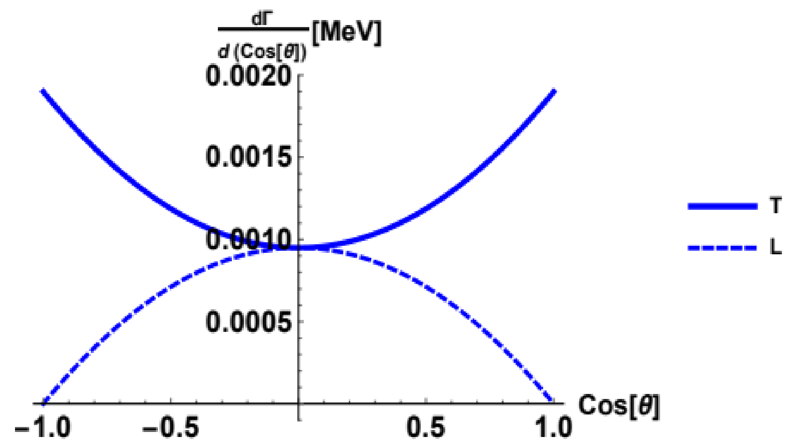
Disentangling longitudinal and transverse modes of the ϕ meson through dilepton and kaon decays

In Woo Park,[1,*] Hiroyuki Sako,[2] Kazuya Aoki,[3,4] Philipp Gubler,[2] and Su Houng Lee[1,†]

[1] *Department of Physics and Institute of Physics and Applied Physics, Yonsei University, Seoul 03722, Korea*
[2] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 319-1195, Japan*
[3] *KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[4] *RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan*



(a) $\frac{d\Gamma}{d\cos\theta}$ of kaonic decay in the CM frame



(b) $\frac{d\Gamma}{d\cos\theta}$ of leptonic decay in the CM frame

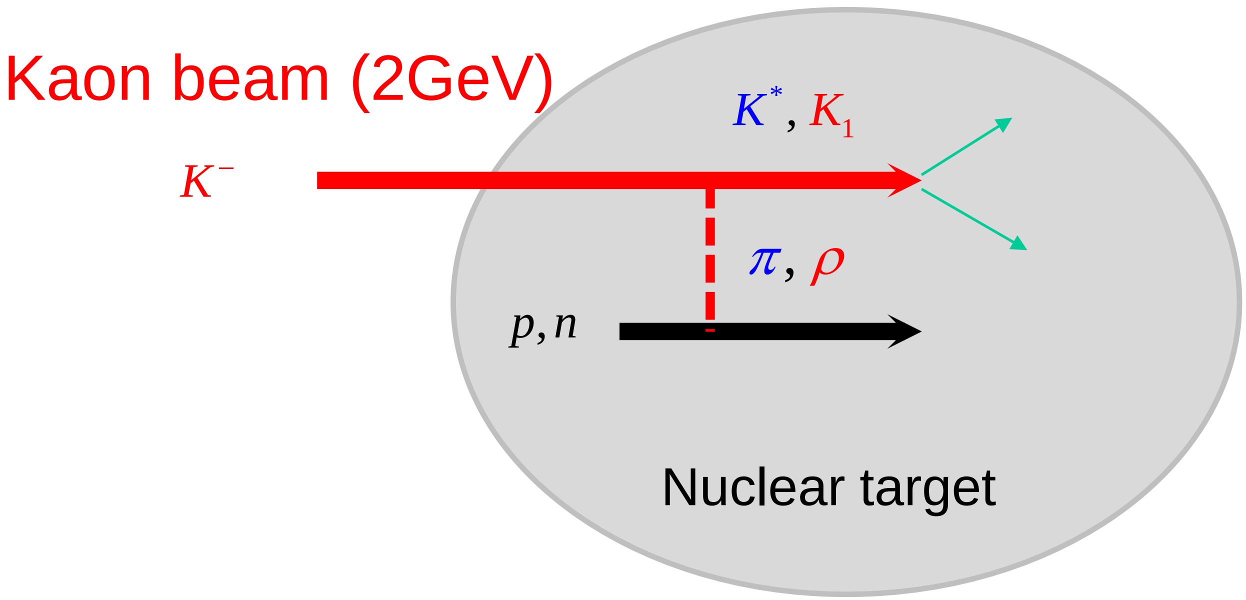
FIG. 3: Angular distribution of decay rate of $\phi \rightarrow K^+ + K^-$ and $\phi \rightarrow e^+ + e^-$ in the CM frame for each polarization. T stands for transverse polarization and L stands for longitudinal polarization.

- *Possible future experiment to measure masses of chiral partners*

→ K_1 excitation energy measurement at JPARC

Decay mode of K_1 (Γ=90MeV)

Decay mode	Fraction
K1(1270)→ K ρ	42 %
K1(1270)→ K* π	16 %



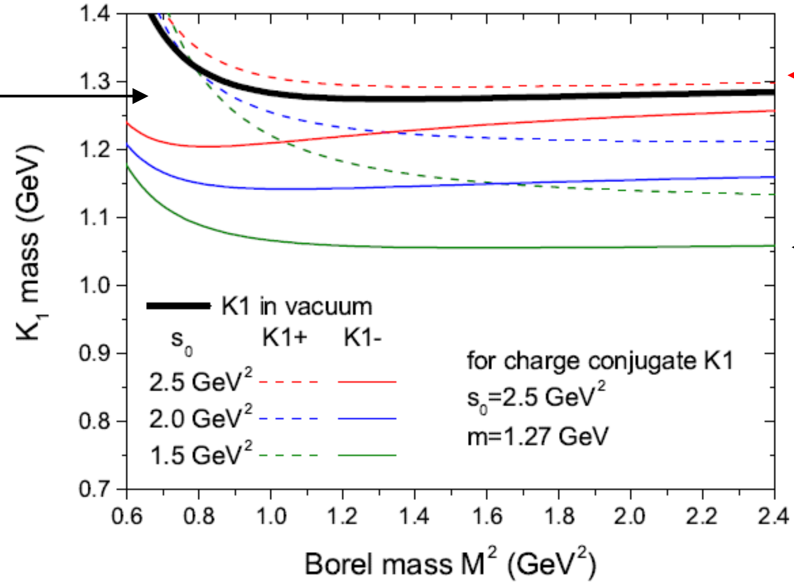
$$K_1^- \to \begin{pmatrix} \rho^0 K^- \\ \rho^- \bar{K}^0 \end{pmatrix} \quad \begin{pmatrix} \pi^0 K^{*-} \\ \pi^- \bar{K}^{*0} \end{pmatrix}$$

$$\bar{K}_1^0 \to \begin{pmatrix} \rho^+ K^- \\ \rho^0 \bar{K}^0 \end{pmatrix} \quad \begin{pmatrix} \pi^+ K^{*-} \\ \pi^0 \bar{K}^{*0} \end{pmatrix}$$

- *Expected mass shift from sum rules*

☞ *current* $K_1^- \to \left(\bar{u}\gamma_\mu\gamma^5 s\right)$ $K_1^+ \to \left(\bar{s}\gamma_\mu\gamma^5 u\right)$ $K^{*-} \to \left(\bar{u}\gamma_\mu s\right)$ $K^{*+} \to \left(\bar{s}\gamma_\mu u\right)$

K_1 vacuum mass



K_1^+ medium mass

K_1^- medium mass

☞ *Hence, mass shift at nuclear matter*

$$\Delta m\left(K_1^-\right) \approx -208 \text{ MeV} \qquad \Delta m\left(K_1^+\right) \approx +32 \text{ MeV}$$

Summary

1. *Mass difference between chiral partners are directly related to chiral symmetry breaking only, (even in nuclear mater, finite temperature, ..)*

   $\rho - a_1,\ K^* - K_1$ (small width and can be measured at JPARC) $\quad m_{K_1} - m_{K*} \rightarrow 0$

2. *Still, it is important to measure individual masses. JPARC, GSI, Heavy Ion Collision*

   Theory can connect chiral symmetry breaking to masses

3. *But for vector particles, need to separately measure Transverse and Longitudinal masses.*

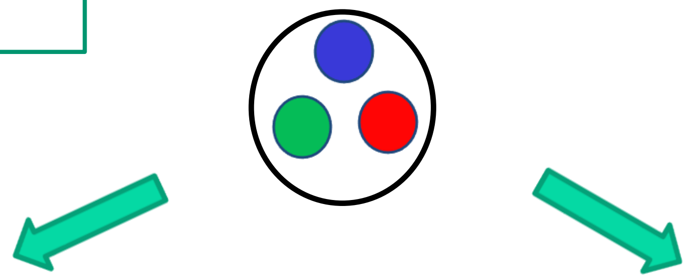
   (JPARC E-16)

   The difference has little relation to chiral symmetry breaking but otherwise can not get mass

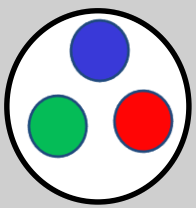
$$\omega^2 = m^2 + \Pi(\omega, 0) \quad \rightarrow \quad m^2_{medium} = m^2_{breaking} + m^2_{symmetric}$$

$$\Pi^T(\omega, \vec{q}) - \Pi^L(\omega, \vec{q}) = \Delta\Pi_{breaing} + \Delta\Pi_{symmetric}$$

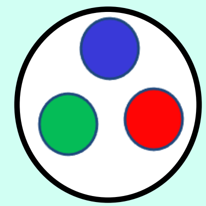
Example



Nuclear Matter



Vacuum change



$$\left[E\gamma^0 - \vec{\gamma}\,\vec{p} - M - \left(S + \gamma^0 V\right)\right]\psi = 0$$

For proton at rest inside nuclear matter

$$E = M + \left(S + V\right) \approx M + \left(-400 + 300\right)\mathrm{MeV}$$

$$\left[E\gamma^0 - \vec{\gamma}\,\vec{p} - M^*\right]\psi = 0$$

But is

$$E = M^* \xrightarrow{?} M + \left(S\right) \quad ?$$

Understanding origin of mass involves

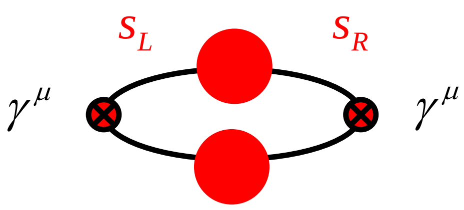
understanding relation between $M + \left(S\right)$ and M^*

- *Not a Chiral order parameter:* $\phi\phi - f_1^{\bar{s}s} f_1^{\bar{s}s}$ *correlator*

☞ $$\Pi^{\phi\phi} - \Pi^{f_1 f_1} = \frac{1}{V}\int d^4x \left[\left\langle \bar{s}\gamma^\mu s(x), \bar{s}\gamma^\mu s(0) \right\rangle - \left\langle \bar{s}i\gamma^5\gamma^\mu s(x), \bar{s}i\gamma^5\gamma^\mu s(0) \right\rangle \right]$$

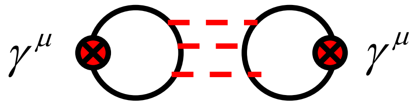
$$= -\frac{1}{2}\mathrm{Tr}\left[\gamma^\mu \left(S^s(x,0) - i\gamma^5 S^s(x,0) i\gamma^5 \right) \gamma^\mu \left(S^s(0,x) - i\gamma^5 S^s(0,x) i\gamma^5 \right) \right]$$

$$\sum_\lambda \psi_\lambda^+ \left(\frac{2m_s}{\lambda^2 + m_s^2} \right) \psi_\lambda$$



$\propto \left\langle \bar{s}s \right\rangle^n$

$$+ \frac{1}{4}\mathrm{Tr}\left[\gamma^\mu \left(S^s(x) + i\gamma^5 S^s(x) i\gamma^5 \right) \right] \mathrm{Tr}\left[\gamma^\mu \left(S^s(0) + i\gamma^5 S^s(0) i\gamma^5 \right) \right] + \left(\gamma^\mu \to \gamma^\mu\gamma^5 \right)$$



$\propto \left\langle \rho^2(\lambda \neq 0) \right\rangle$

ϕ has no chiral partner