ϕ meson properties in nuclear matter from QCD sum rules with chirally separated four-quark condensate

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Outline

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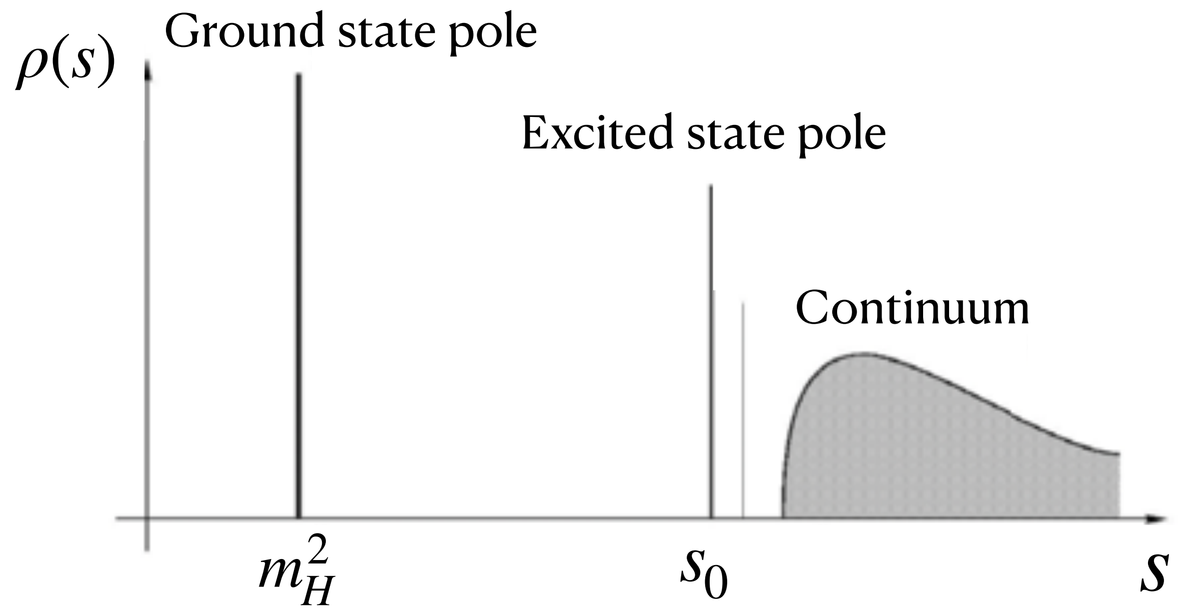
QCD sum rules

An interpolating current $\eta(x)$ reflects the quantum #s of the hadron of interest.



$$\Pi(q) = i\int d^4x\, e^{iqx}\langle 0|T\{\eta(x)\bar{\eta}(0)\}|0\rangle$$

Wilson's Operator Product Expansion

$$\widehat{\Pi}^{\text{phen.}}(M^2) = \int_0^\infty ds\, e^{-s/M^2}(\rho^{\text{pole}}(s) + \rho^{\text{cont}}(s))$$

$$\widehat{\Pi}^{\text{OPE}}(M^2) = \sum_d C_d(M^2)\langle O^d\rangle$$

M	: Borel mass
d	: Mass dimension
C_d	: Wilson coefficient
$\langle O^d\rangle_{vac}$	: Vacuum condensates

Phenomenological (Hadronic) Side = OPE (Quark-Gluon) Side

$$\rho^{\text{pole}}(s) = \frac{1}{\pi}\frac{f\Gamma_H\sqrt{s}}{(s-m_H^2)^2 + s\Gamma_H^2}$$

Introduction

- We've investigated ϕ meson in nuclear matter, using QCD sum rules method.

$$\widehat{\Pi}_H^{OPE} = C_0(M^2) + C_4(M^2)\langle\frac{\alpha_s}{\pi}G_{\mu\nu}G^{\mu\nu}\rangle + C_4'(M^2)\langle m_u\bar{u}u\rangle + C_6(M^2)\boxed{\langle(\bar{u}\Gamma^\alpha\lambda^a u)(\bar{u}\Gamma_\alpha\lambda_a u)\rangle} + \cdots \quad (1)$$

- The values of four-quark condensates both in vacuum are barely known.

- It is also barely known how they change in nuclear matter.

Four-quark cond. in vacuum

$$\mathscr{M}^{\phi} = -\pi\alpha_s\langle(\bar{s}\gamma_\mu\gamma_5\lambda^a s)^2 - \frac{2\pi\alpha_s}{9}\langle(\bar{s}\gamma_\mu\lambda^a s)(\sum_{q=u,d,s}\bar{q}\gamma_\mu\lambda^a q)\rangle \quad (2)$$

Total four-quark condensate value $\mathscr{M}^{\phi}$ can be evaluated by comparing the mass and decay width from experiments.

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Banks-Casher relation :

$$\langle\bar{u}u\rangle = -\pi\langle\rho(\lambda = 0)\rangle \quad (3)$$

The chiral order parameter is proportional to the density of zero mode.

T. Banks, A. Casher, NPB(1980)

Every four-quark condensates can be separated into terms proportional to the chiral order parameter and chirally invariant part.

J. Kim and S. H. Lee, PRD(2021)

Four-quark cond. in vacuum

Every four-quark condensates can be separated into the chiral order parameter and chirally invariant part.
J. Kim and S. H. Lee, PRD(2021)

$$\rho : \mathscr{M}^{\rho} = -2\pi\alpha_s\langle(\bar{q}\gamma_\mu\gamma_5\lambda^a\tau^3 q)^2\rangle - \frac{4\pi\alpha_s}{9}\langle(\bar{q}\gamma_\mu\lambda^a q)(\sum_{f=u,d,s}\bar{q}_f\gamma_\mu\lambda^a q_f)\rangle = -\frac{28\pi\alpha_s}{9}\langle B_{uu}\rangle_B + \pi\alpha_s\langle S_{\rho-a_1}\rangle_S \quad (4)$$

$$a_1 : \mathscr{M}^{a_1} = -2\pi\alpha_s\langle(\bar{q}\gamma_\mu\lambda^a\tau^3 q)^2\rangle - \frac{4\pi\alpha_s}{9}\langle(\bar{q}\gamma_\mu\lambda^a q)(\sum_{f=u,d,s}\bar{q}_f\gamma_\mu\lambda^a q_f)\rangle = \frac{44\pi\alpha_s}{9}\langle B_{uu}\rangle_B + \pi\alpha_s\langle S_{\rho-a_1}\rangle_S \quad (5)$$

Furthermore, we can evaluate the values of each $\langle B_{uu}\rangle_B$ and $\langle S_{\rho-a_1}\rangle_S$ by comparing the two $\mathscr{M}$s.

Similarly,

$$\phi : \mathscr{M}^{\phi} = -\pi\alpha_s\langle(\bar{s}\gamma_\mu\gamma_5\lambda^a s)^2 - \frac{2\pi\alpha_s}{9}\langle(\bar{s}\gamma_\mu\lambda^a s)(\sum_{q=u,d,s}\bar{q}\gamma_\mu\lambda^a q)\rangle = -\frac{7\pi\alpha_s}{9}\langle B_{ss}\rangle_B + \pi\alpha_s\langle S_\phi\rangle_S \quad (6)$$

ϕ meson in nuclear matter

In linear density approximation, condensates in nuclear matter

T. Hatsuda and S. H. Lee PRC(1992), T. D. Cohen, R. J. Furnstahl and D. K. Griegel PRC(1992)

$$\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_\rho = \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_0 - \frac{8}{9}(M_N - \sigma_{\pi N} - \sigma_{sN})\rho \qquad (7)$$

$$\langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \frac{\sigma_{sN}}{m_s}\rho \qquad (8)$$

The quark condensates changes due to the partial restoration of chiral symmetry breaking.

$$\phi : \mathscr{M}^\phi = -\frac{7\pi\alpha_s}{9}\langle B_{ss}\rangle_B + \pi\alpha_s\langle S_\phi\rangle_S \qquad (9)$$

When the partial restoration occurs,

$\langle B_{ss}\rangle_B$ will change like $(\langle \bar{s}s \rangle_\rho)^2$.

$\langle S_\phi\rangle_S$ will be invariant.

Result(ϕ meson at rest, $T = 0$ and $\rho = \rho_0$)

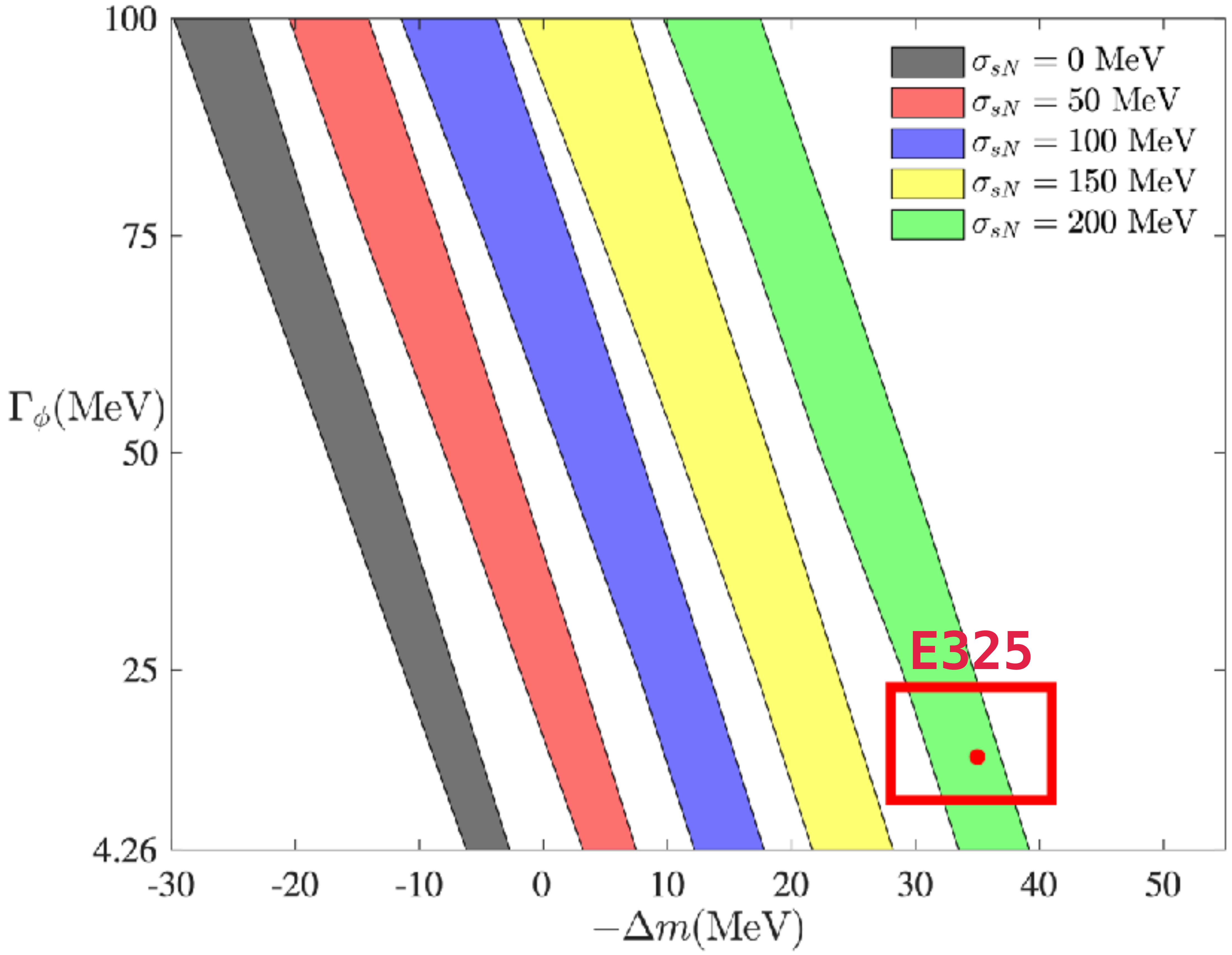

Figure 1. Negative mass shift versus decay width at normal nuclear matter

The peak position is quite affected by the broadening.

$$\rho^{\text{pole}}(s) = \frac{1}{\pi}\frac{f\Gamma_\phi\sqrt{s}}{(s - m_\phi^2)^2 + s\Gamma_\phi^2}$$

Changes in OPE gives constraint on Γ_ϕ and m_ϕ

Fitting them as linear functions,

$$\Gamma_\phi = a(\Delta m_\phi) + b \qquad (10)$$

a is 4.2 and b is a linear function of σ_{sN}.

Summary

- ϕ meson properties are investigated using QCD sum rules
- Four-quark condensates can be separated into chiral symmetric and breaking parts.
- Each of separate four-quark condensates also can be evaluated.
- Under the partial restoration of chiral symmetry restoration, only the breaking part will change.
- If the broadening effect in nuclear matter is sufficiently large, the change in peak position due to this should be taken into account.