Spectral function of the η' meson in nuclear medium

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Reference: S. Sakai, DJ, in preparation

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Introduction

partial restoration of chiral symmetry

η' meson in nuclear medium

Introduction

- spontaneously broken chiral symmetry may be restored in nuclear medium with reduction of chiral condensate

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).

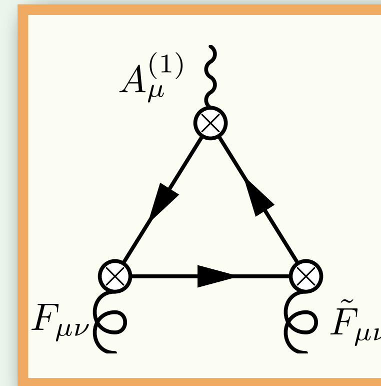
- such phenomenon can be observed by hadrons in nuclei
- natural that hadron properties are modified in nuclear medium due to the strong interaction between hadrons
- significant to identify the origin of the in-medium modification
- observe how much hadrons are modified

η' meson

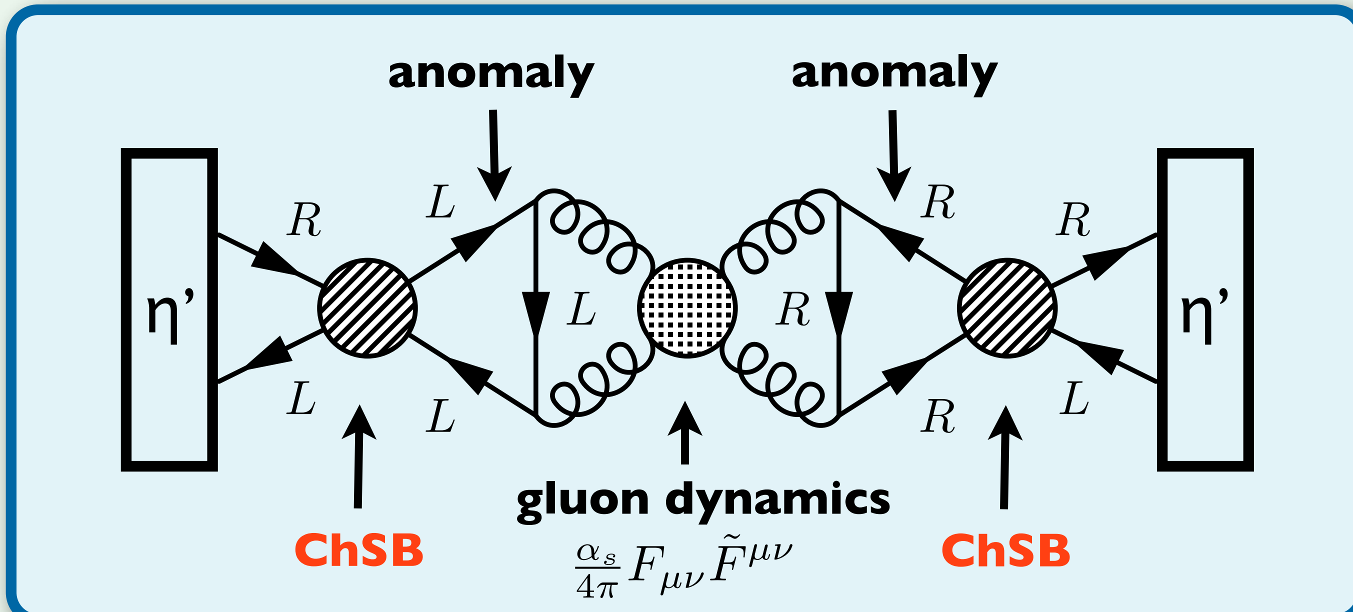
- degraded from NG boson due to $U_A(1)$ anomaly

flavor singlet **(small) PCAC** **anomaly**

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



- $U_A(1)$ anomaly contributes to η' mass only through chiral symmetry breaking



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

- expects 80 MeV mass reduction at normal density

S. Sakai, DJ, Phys. Rev. C88, 064906 (13)

- mass reduction should be observed as an attractive potential in nucleus

Preliminaries

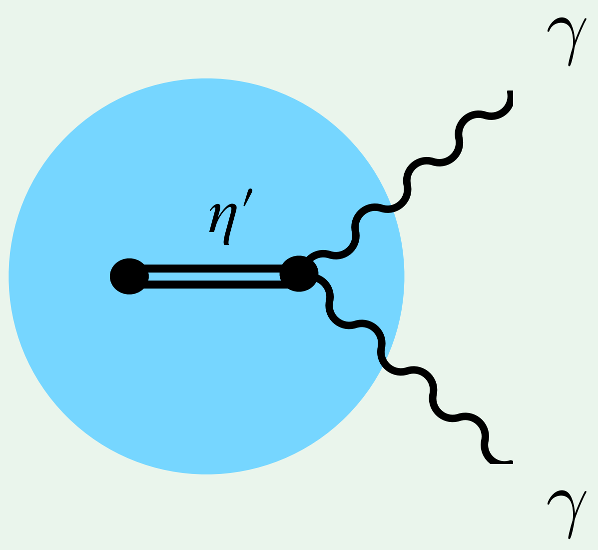
spectral function

in-medium mass

$T\rho$ approximation

Spectral function

- η' meson decays into two gamma
  when observing invariant mass spectrum of two gamma,
  essence is given by η' spectral function



- spectral function

$$S_{\eta'} = -\frac{1}{\pi}\mathrm{Im}\, D_{\eta'}$$

- in-medium propagator

$$D_{\eta'}(\omega, \boldsymbol{p}; \rho) = \frac{1}{\omega^2 - \boldsymbol{p}^2 - m_{\eta'}^2 - \Pi_{\eta'}(\omega, \boldsymbol{p}; \rho) + i\epsilon}$$

  η' self-energy $\Pi_{\eta'}(\omega, \boldsymbol{p}; \rho)$

  function of energy ω, momentum $\boldsymbol{p}$, density ρ

- obtain properties of self-energy

In-medium mass

- describes interaction between η' meson to nuclear medium $\Pi_{\eta'}(\omega, \boldsymbol{p}; \rho)$

- in-medium mass is given by pole position for eta' at rest

$$D_{\eta'}^{-1}(\omega_P, \mathbf{0}; \rho) = \omega_P^2 - m_{\eta'}^2 - \Pi_{\eta'}(\omega_P, \mathbf{0}; \rho) = 0$$

parametrize as $\omega_P^2 = m_*^2 - i m_* \Gamma_*$ (mass: m_*, width: Γ_*)

$$m_*^2 = m_{\eta'}^2 + \mathrm{Re}\left(\Pi_{\eta'}(\omega_P, \mathbf{0}; \rho)\right),$$

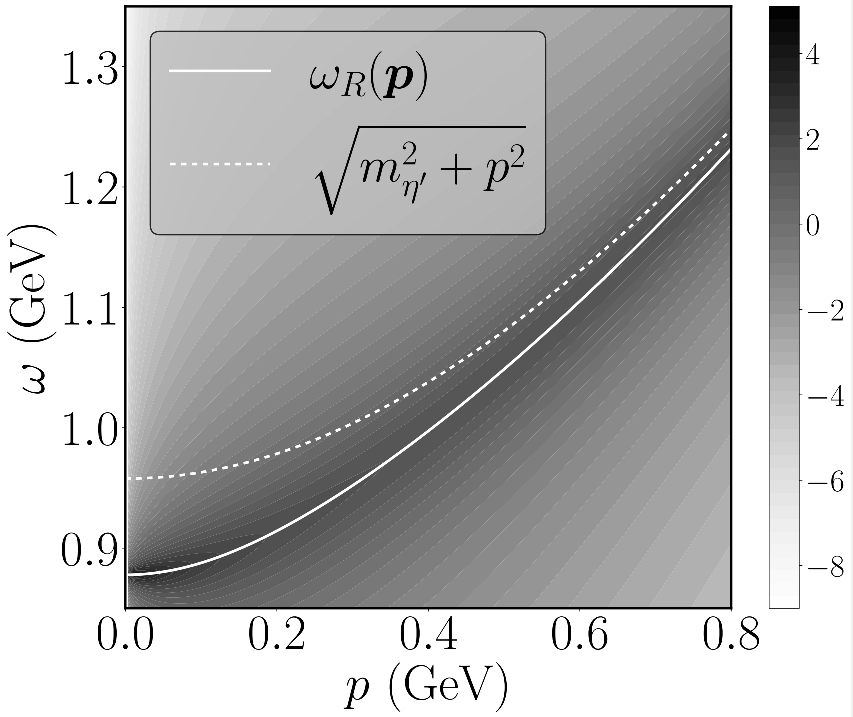
$$\Gamma_* = -\frac{1}{m_*}\mathrm{Im}\left(\Pi_{\eta'}(\omega_P, \mathbf{0}; \rho)\right)$$

$$\omega_P = m_* - i\frac{\Gamma_*}{2}$$

Self-energy with finite momentum

- spectral function depends on spatial momentum

$$S_{\eta'}(\omega, \boldsymbol{p}; \rho) = -\frac{1}{\pi}\mathrm{Im}\, D_{\eta'}(\omega, \boldsymbol{p}; \rho)$$



- pole position depends on the momentum
  - $\rightarrow$ dispersion relation

$$\omega_P^2(\boldsymbol{p}) - \boldsymbol{p}^2 - m_{\eta'}^2 - \Pi_{\eta'}(\omega_P(\boldsymbol{p}), \boldsymbol{p}; \rho) = 0$$

- invariant mass $p_{\eta'}^2 = \omega^2 - \boldsymbol{p}^2$ at pole position $\omega^2 = \omega_P^2$

$$p_{\eta'}^2 = m_{\eta'}^2 + \Pi_{\eta'}(\omega_P(\boldsymbol{p}), \boldsymbol{p}; \rho) = m_*^2 - i m_* \Gamma_* + \Big(\Pi_{\eta'}(\omega_P(\boldsymbol{p}), \boldsymbol{p}; \rho) - \Pi_{\eta'}(\omega_P(\boldsymbol{0}), \boldsymbol{0}; \rho)\Big)$$

depends on spatial momentum

not necessarily at in-medium mass squared

T ρ approximation

- η'-nucleus interaction is not well-known yet

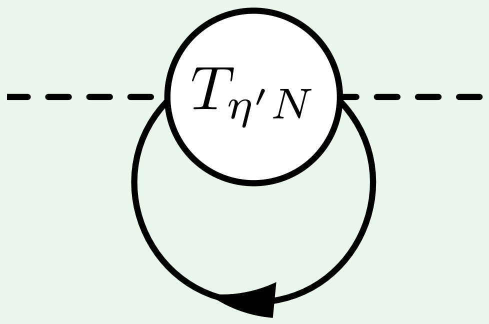
  $\eta' N$ interaction is relatively better known

- focus on one-nucleon process

  self-energy is evaluated by

  T ρ approximation: $\Pi_{\eta'}(\omega, \boldsymbol{p}; \rho) = T_{\eta' N}(\sqrt{s})\, \rho$

  (low density)



- the $\eta' N$ scattering amplitude determines η' self-energy

- consider spin-isospin symmetric uniform nuclear matter

Simple exercise

a minimal scattering amplitude

Simple exercise

- scattering length + elastic unitarity

$$T_{\eta' N}(W) = -\frac{8\pi W}{2m_N}\frac{1}{1/a_{\eta' N} - ip},$$

$\eta' N$ scattering length $a_{\eta' N}$

- three examples of scattering length

(positive sign corresponds to attractive self-energy)

- 【theory】 linear sigma model (80 MeV mass reduction)

$$a_{\eta' N} = 0.87 \text{ fm}$$

S. Sakai, DJ, Phys. Rev. C88, 064906 (13)

- 【experiment】 low-energy $pp \to pp\eta'$ data

E. Czerwinski et al., Phys. Rev. Lett.113, 062004 (14)

$$a_{\eta' N} = (0^{+0.43}_{-0.43} + i0.37^{+0.40}_{-0.16}) \text{ fm}$$

→ obtained by N* dominance model

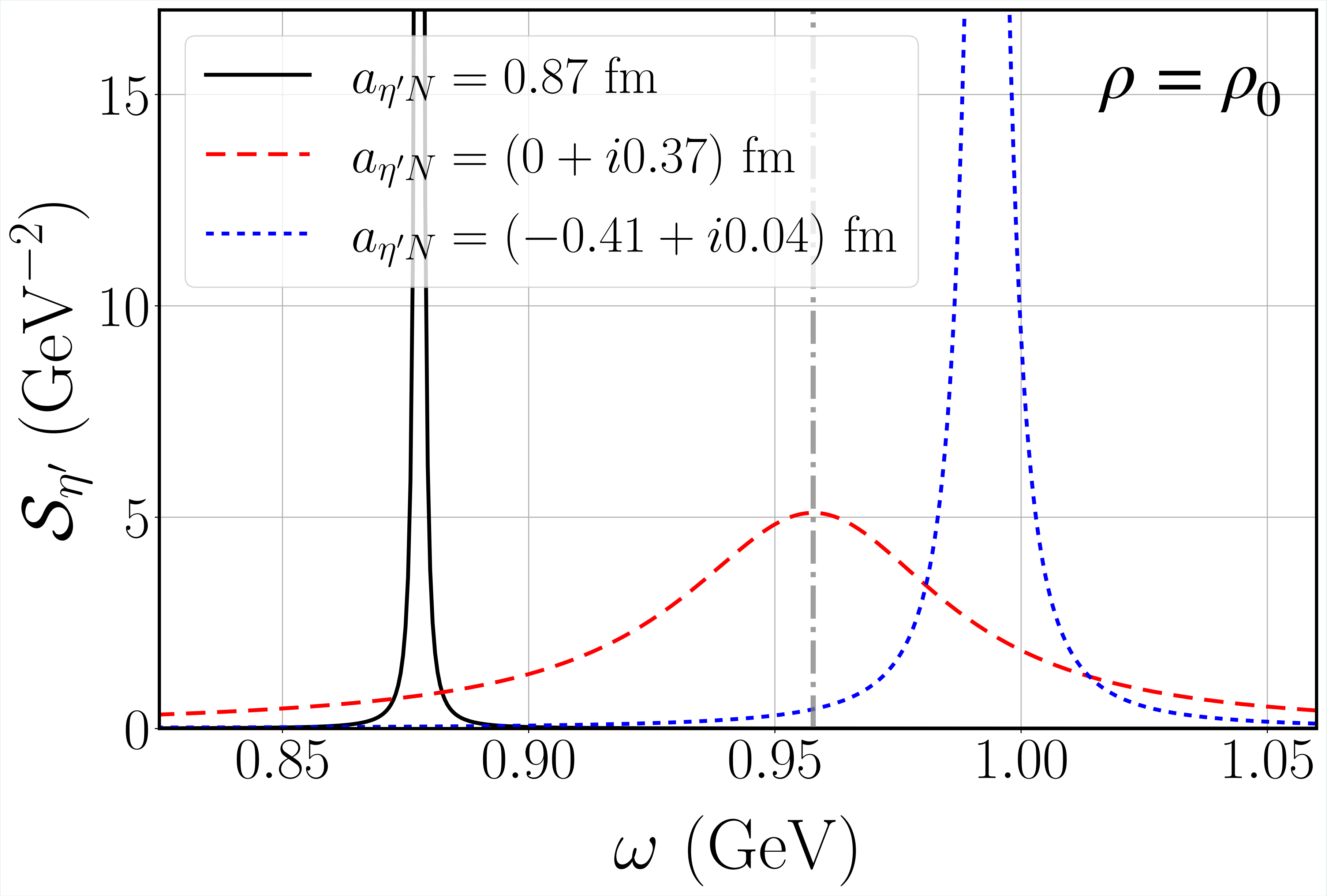
- 【phenomenology】 coupled channels model

P. C. Bruns, A. Cieply, Nucl. Phys. A992, 121630 (19)

$$a_{\eta' N} = (-0.41 + i0.04) \text{ fm}$$

Simple exercise

- spectral function of η' at rest in normal nuclear medium $(p = 0)$

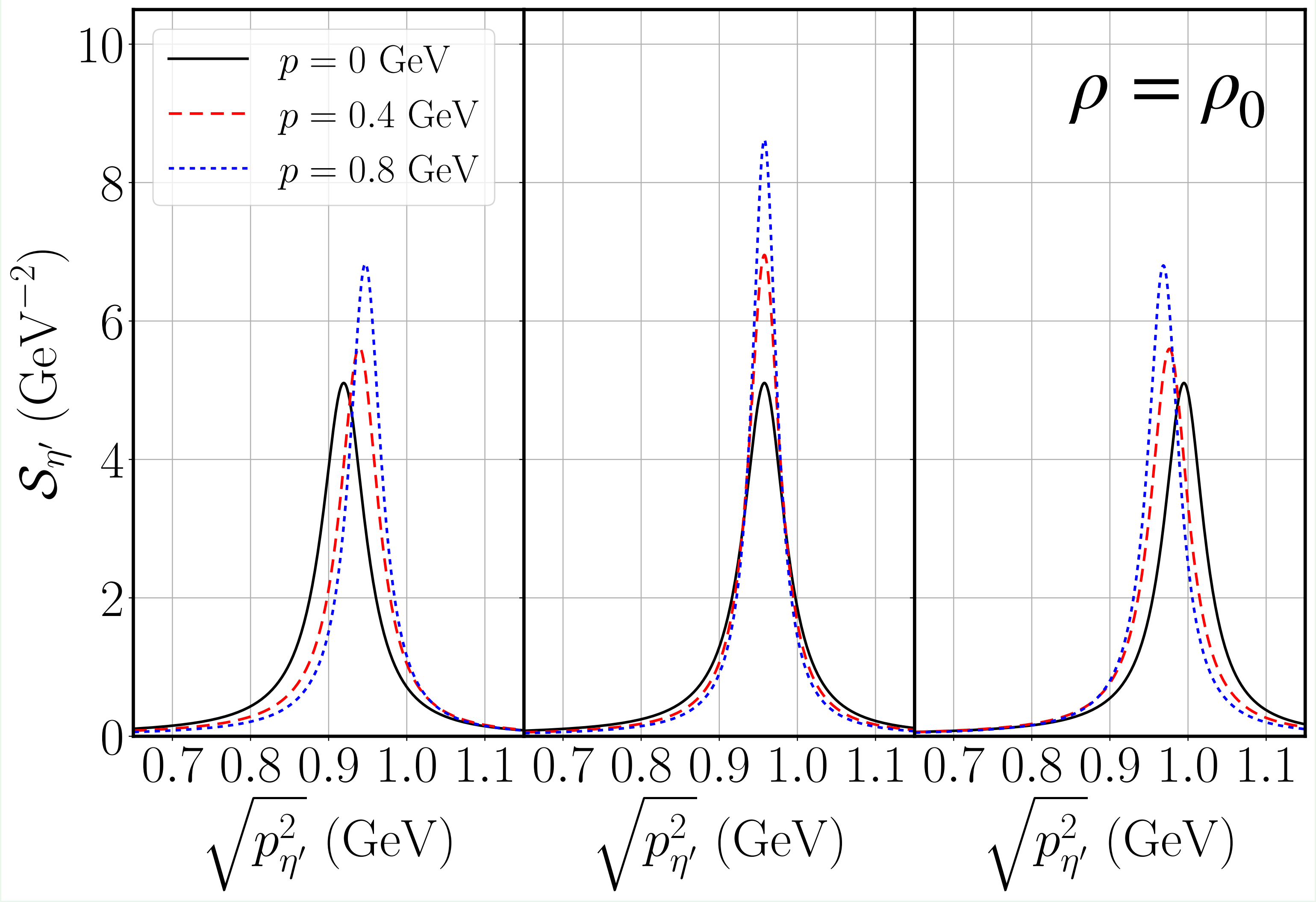


Simple exercise

- spectral function of η' with finite momentum at $\rho = \rho_0$

  low-energy $pp \to pp\eta'$ data: $a_{\eta' N} = (0^{+0.43}_{-0.43} + i0.37^{+0.40}_{-0.16})$ fm

$a_{\eta' N} = (+0.43 + i0.37)$ fm $\quad (0 + i0.37)$ fm $\quad (-0.43 + i0.37)$ fm



$$T_{\eta' N}(W) = -\frac{8\pi W}{2m_N} \frac{1}{1/a_{\eta' N} - ip}$$

medium effect on mass gets less noticeable for finite momentum

N* dominance model

two phenomenological models

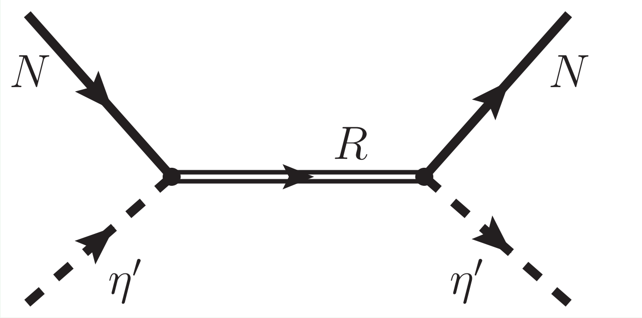
- N* dominance model

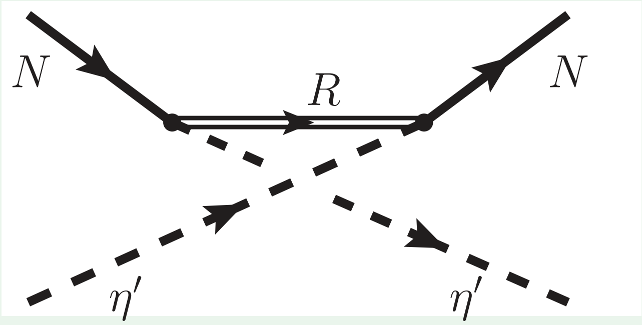
  N(1895) is located just below the $\eta' N$ threshold

  has spin $1/2^-$, s-wave coupling to $\eta' N$

$\eta' N$ threshold at 1896 MeV

N^* at 1894 MeV





$$T_{\eta' N}(\sqrt{s}) = \frac{g^2_{\eta' N}}{\sqrt{s} - E_{N^*} + i\Gamma_{N^*}/2} + \frac{g^2_{\eta' N}}{-E'_{\eta'} + E_N - E_{N^*} + i\Gamma_{N^*}/2}$$

use isobar model parameters

L. Tiator, et al. (EtaMAID2018), Eur. Phys. J. A54, 210 (18)

$$m_{N^*} = 1894.4 \text{ MeV}, \quad \Gamma_{N^*} = 70.7 \text{ MeV}, \quad g_{\eta' N} = 1.4$$

provides $a_{\eta' N} = (-0.02 + i0.43)$ fm

assume no medium effects on N*

N* dominance model for η meson

H.C. Chiang, E. Oset, L.C. Liu, Phys. Rev. C44, 738 (91).

D.J., H. Nagahiro, S. Hirenzaki, Phys. Rev. C66, 045202 (02),
D.J., E.E. Kolomeitsev, H. Nagahiro, S. Hirenzaki, Nucl. Phys. A811, 158 (08)

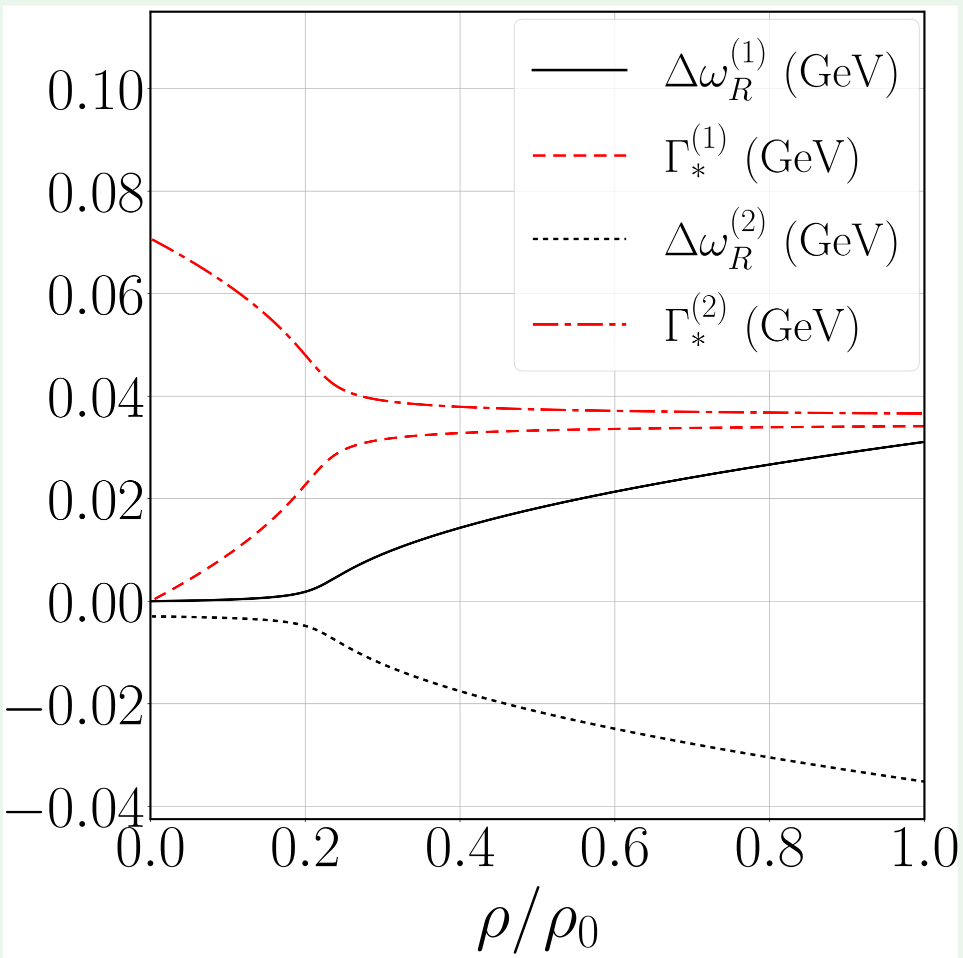
N* dominance model

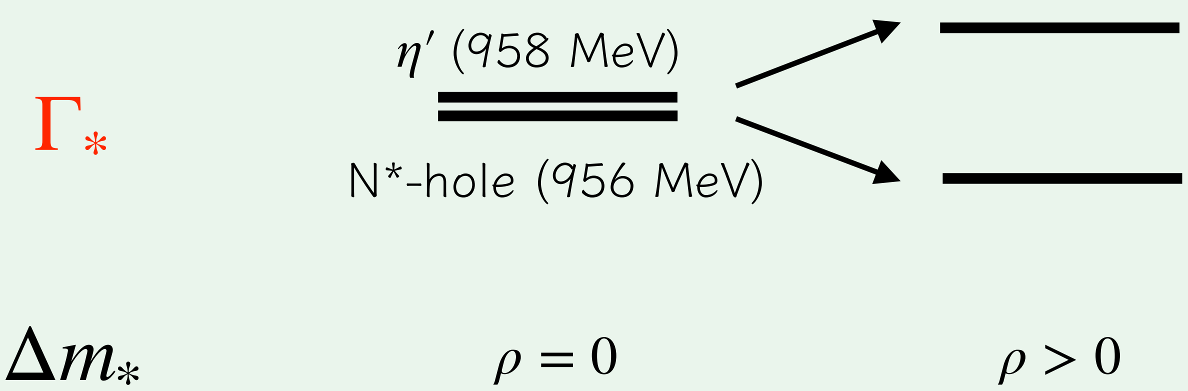
S. Sakai, DJ, in preparation

- there are two poles in in-medium propagator

  one comes from η' mode, the other comes from N*-hole mode

- in-medium masses and widths of two modes



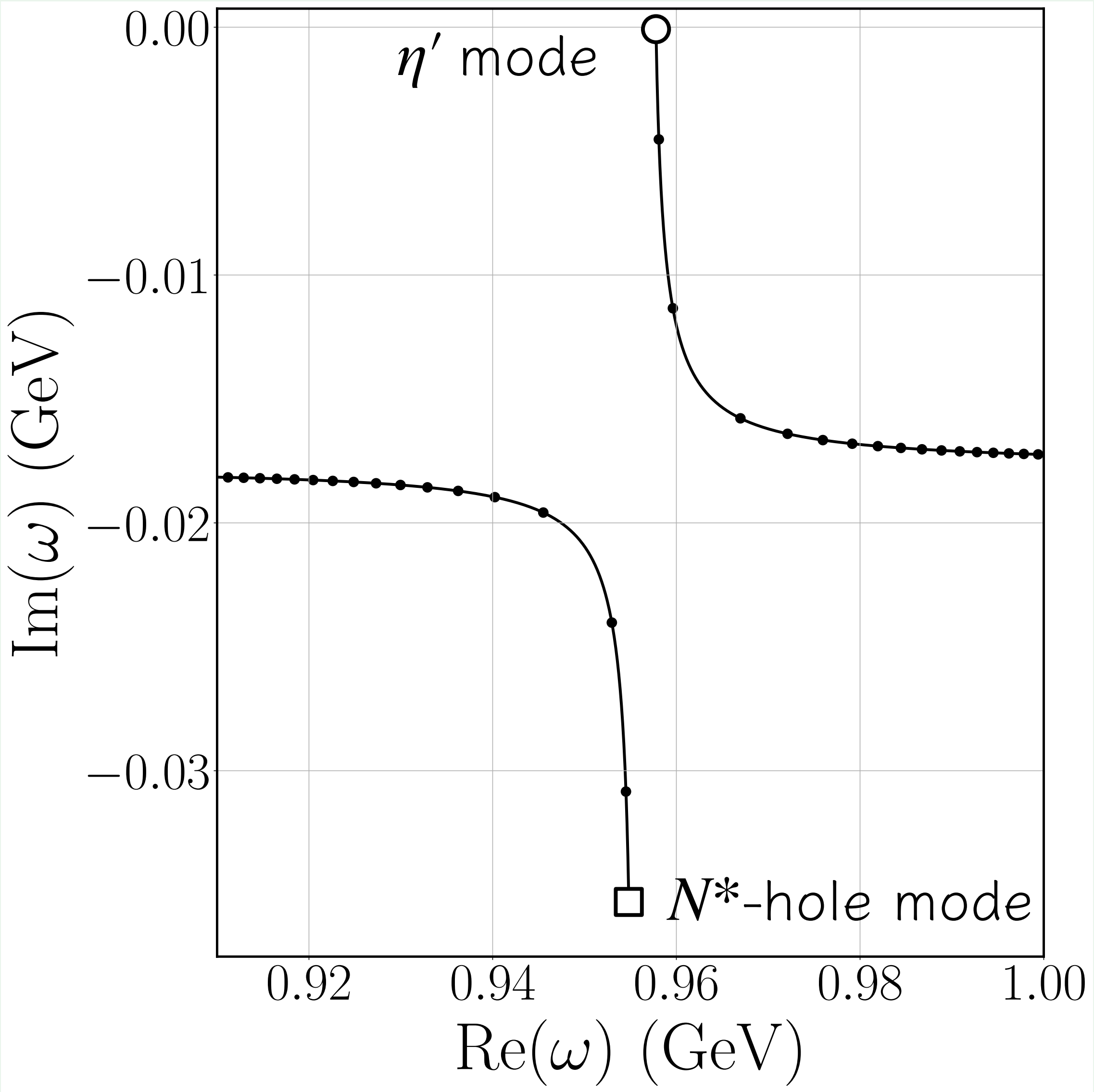


in-medium masses are around $m_{\eta'} \pm 30$ MeV at $\rho = \rho_0$

N* dominance model

S. Sakai, DJ, in preparation

- pole trajectory against nuclear density



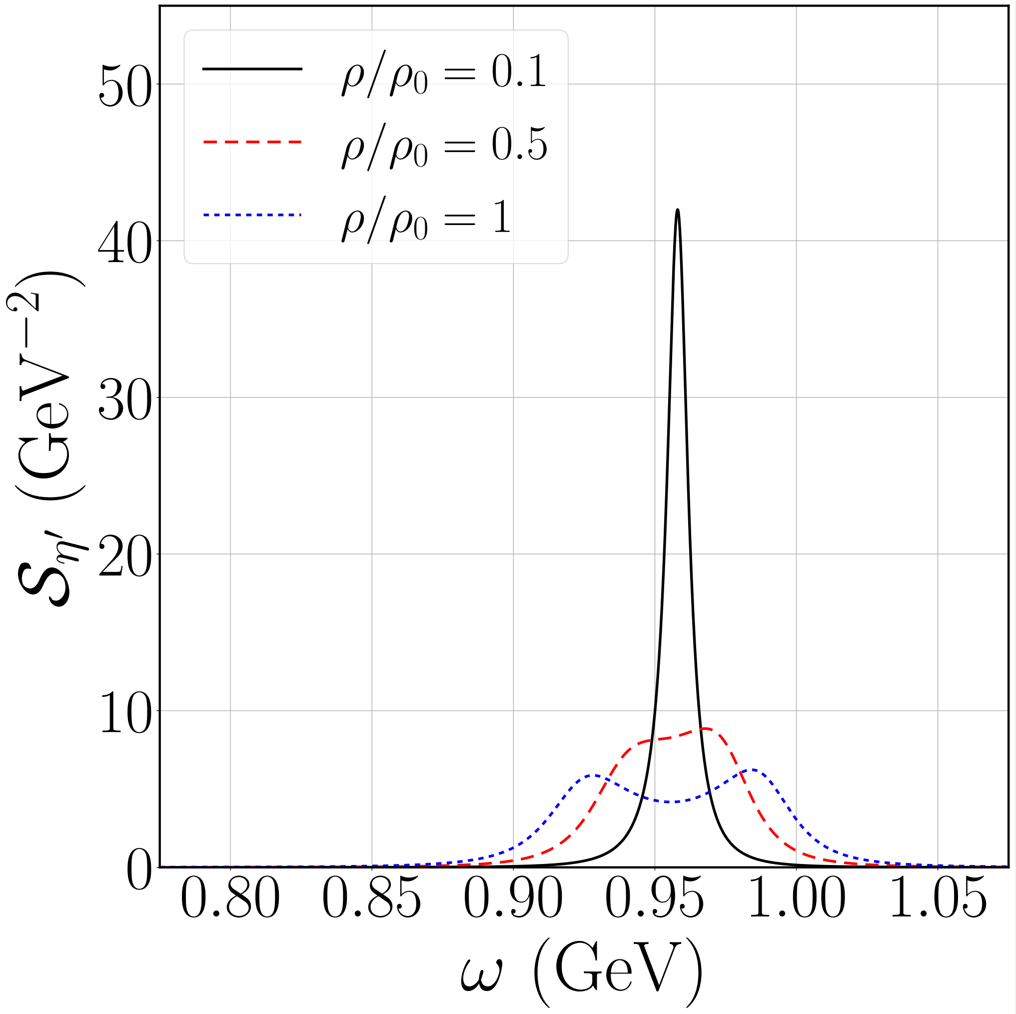
dots are plotted at every $0.1\rho_0$

- exceptional point: $\rho_{\mathrm{EX}} = (0.22 - i0.03)\rho_0$

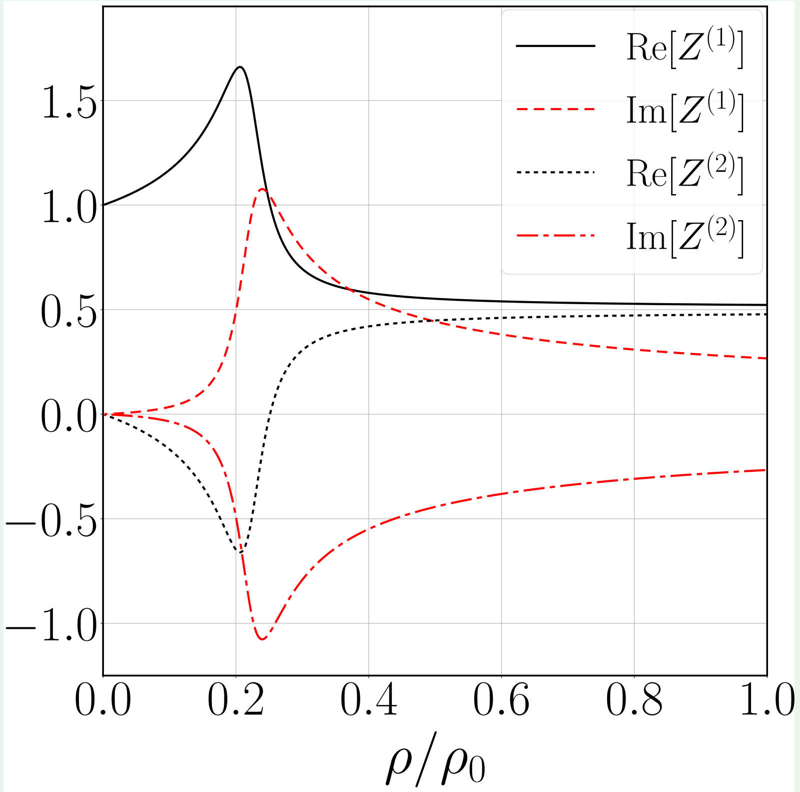
N* dominance model

S. Sakai, DJ, in preparation

- spectral function of η' at rest, $\rho = 0.1\rho_0,\ 0.5\rho_0,\ \rho_0$



wave function renormalization



two peaks appear at higher density

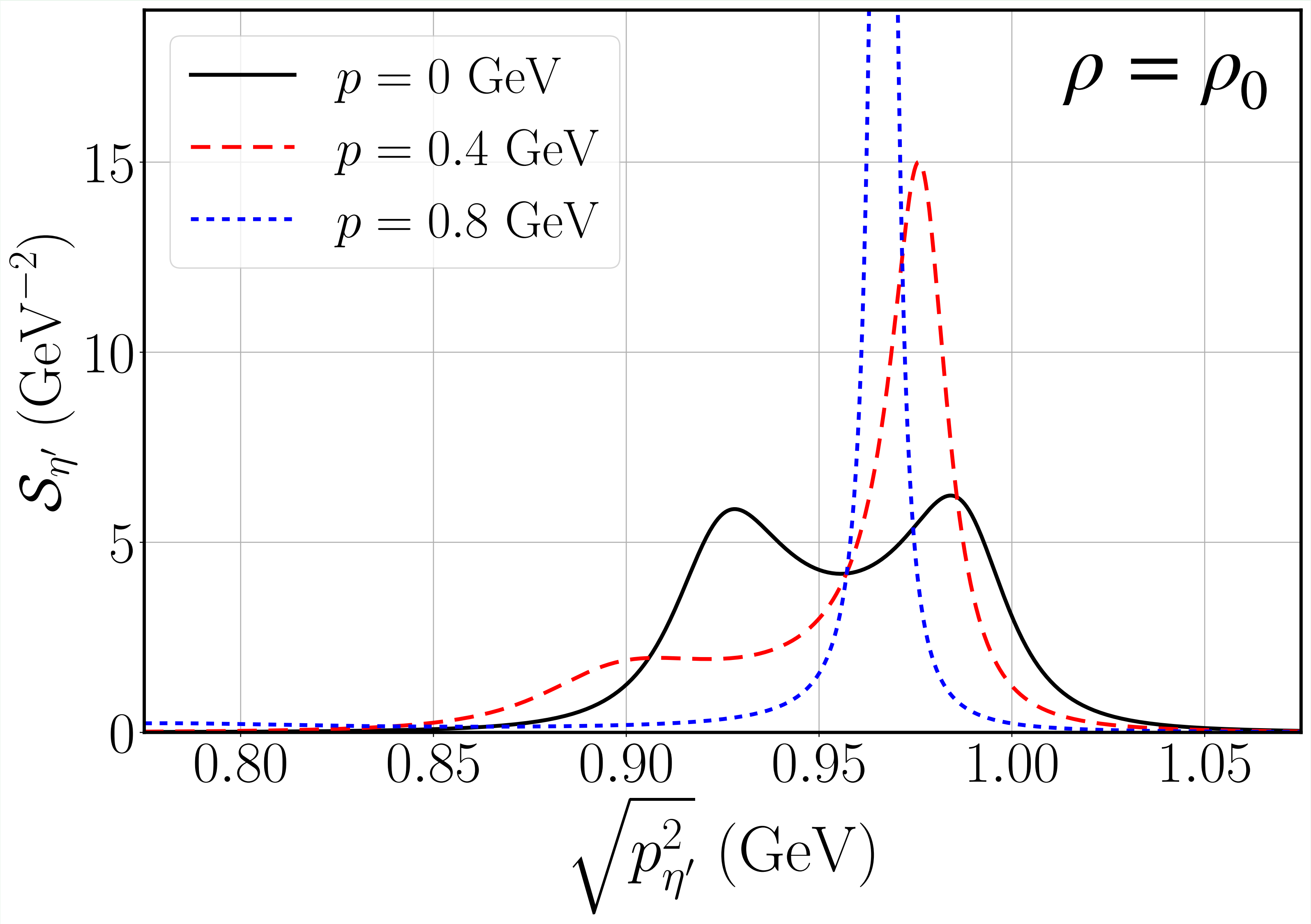
peak positions are around $m_{\eta'} \pm 30$ MeV at $\rho = \rho_0$

Re[$Z^{(1)}$] and Re[$Z^{(2)}$] approach to 0.5 for $\rho > 0.4\rho_0$

N* dominance model

S. Sakai, DJ, in preparation

- spectral function with finite momentum at $\rho = \rho_0$



higher peak goes down, and lower peak gets less distinct

Summary

- investigate spectral function of in-medium η' meson in $T\rho$ approximation

  $\eta' N$ scattering amplitude determines in-medium behavior of η' meson

- for attractive (repulsive) scattering length, peak of spectral function goes down (up) for $p = 0$ as one expects

- peak position in finite density approaches to one in vacuum with increase of spatial momentum

  medium effect on mass gets less noticeable for finite momentum

- momentum dependence of spectral function is important for better understanding

- if N* strongly couples to $\eta' N$, two peaks may appear in spectral function

- clarification of interaction mechanism of η' and nucleon is an important piece to understand in-medium properties of η' meson