Properties of strange mesons in dense resonance matter
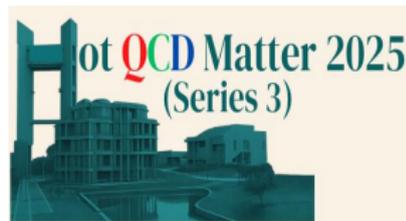
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Hot QCD Matter 2025 (Series 3)
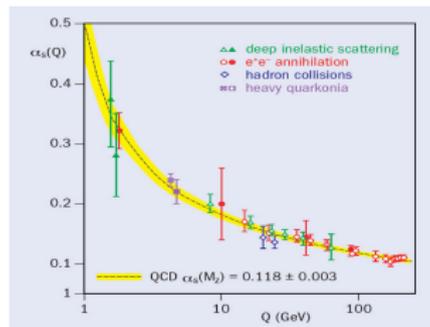September 4-6, 2025
IIT Bhilai

Outline

Introduction

- The theory of strong interactions : QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_{f=u,d,s,c,b,t} \bar{q}_f \left(i\gamma^\mu D_\mu - m_f \right) q_f - \frac{1}{4} G^{(a)}_{\mu\nu} G^{(a)\,\mu\nu}$$

- Asymptotic freedom and low energy confinement

- Current quark mass for u and d $4 - 5$ MeV ; Nucleon mass : 939 MeV

- Hadron masses: Chiral symmetry and related properties play significant role

Introduction

- For light quarks $m_f \approx 0$: QCD Lagrangian has chiral symmetry

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$$\mathcal{L}_0 = i\bar{q}\gamma^\mu \partial_\mu q = i\bar{q}_L \gamma^\mu \partial_\mu q_L + i\bar{q}_R \gamma^\mu \partial_\mu q_R$$

$$q_R = \frac{1}{2}\left(1 + \gamma_5\right)q, \qquad q_L = \frac{1}{2}\left(1 - \gamma_5\right)q$$

- Invariance under

$$q_R \rightarrow exp\left(i\frac{\theta_R^a \tau^a}{2}\right)q_R, \qquad q_L \rightarrow exp\left(i\frac{\theta_L^a \tau^a}{2}\right)q_L$$

lead to $SU(2)_L \times SU(2)_R$

- Conserved vector and axial-vector current

Introduction

-
$$[Q^a, H_{QCD}] = [Q_5^a, H_{QCD}] = 0$$

- Degenerate spectrum of hadrons with same spin and opposite parity expected but not observed in nature

meson
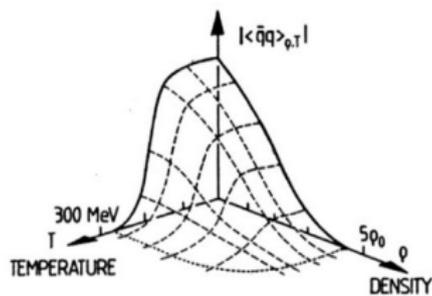- $m_\pi = 139$ MeV (0^-)
- $m_\sigma = 600$ MeV (0^+)

Baryon
- *Nucleon* = 939 MeV $(\frac{1}{2}^+)$
- $N(1535) = 1535$ MeV $(\frac{1}{2}^-)$

- Chiral symmetry is not the symmetry of ground state and breaks spontaneously
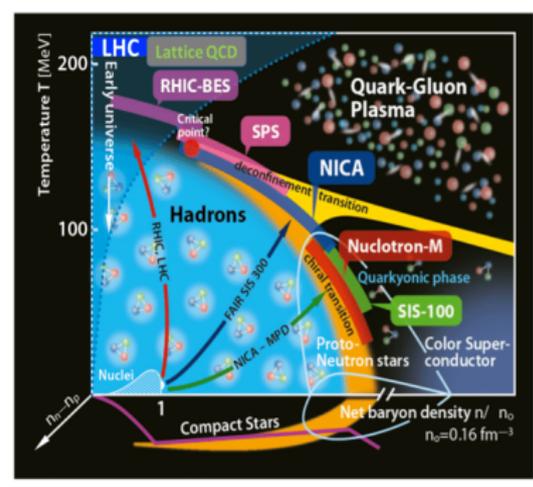- QCD vacuum populates with $q\bar{q}$ pairs

$$< 0|q\bar{q}|0 > \neq 0$$

Why in-medium properties of hadrons?

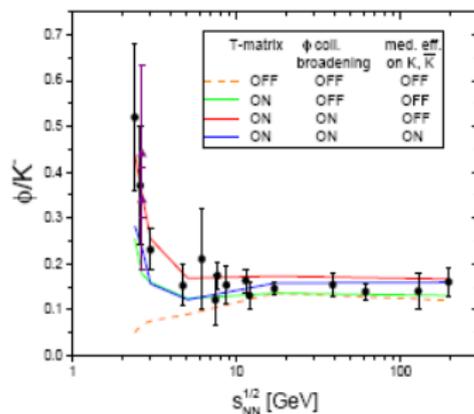- Understanding of QCD phase structure and restoration of chiral symmetry
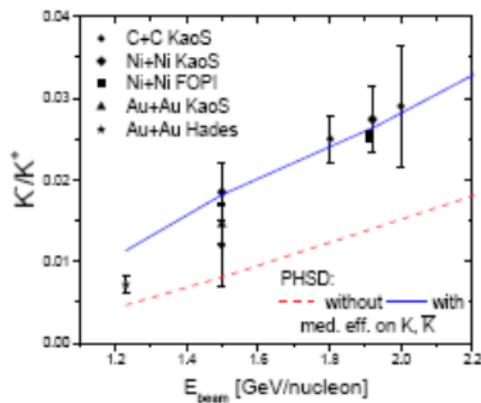

- Lattice QCD: reduction of $q\bar{q}$ at high T

- Study of deeply bound pionic atoms in Sn nuclei: reduction of $q\bar{q}$ at finite ρ_B
  Ref.: T. Nishi et. al., Nature Physics 19, 788 (2023)
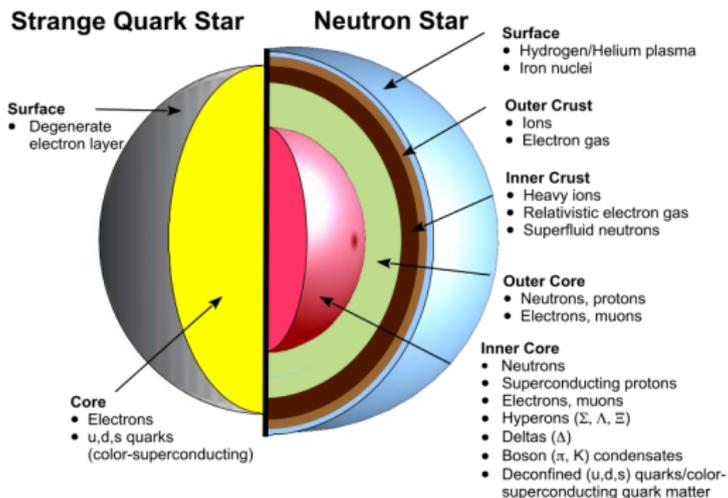
Why in-medium properties of hadrons?

Impact on experimental observables

Ref. T. Song et. al., Phys. Rev. C 106 (2022) 024903.

Why in-medium properties of hadrons?

- Dense matter in compact stars

Theoretical framework (Non-perturbative methods)

- Lattice QCD: For finite T and near zero ρ_B

- Other approaches (for finite baryon density)
    - MIT Bag model and Quark meson coupling model
    - Quark mean field model
    - Chiral SU(3) hadronic model
    - QCD sum rules
    - Coupled channel approach
    - Functional renormalization approach (Beyond mean field)
    - NJL and PNJL
    - QM and PQM
    - ...

Chiral SU(3) model

- Calculations of in-medium masses of K and $\bar{K}$ involve two steps

Step 1

- Consider dense medium consisting of baryons
  - spin$-\frac{1}{2}$ octet ($p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}$)
  - spin$-\frac{3}{2}$ decuplet ($\Delta^{++,+,0,-}, \Sigma^{*\pm,0}, \Xi^{*0,-}, \Omega^-$

- Scalar fields σ, ζ and δ

- Vector fields ω, ρ and ϕ

- Minimize thermodynamic potential and obtain the density and temperature dependent Scalar and vector fields

Chiral SU(3) model

Step 2

- Interaction Lagrangian density for K and $\bar{K}$ with baryons of medium

- Solve dispersion relation to obtain in-medium masses

Chiral SU(3) model

- Thermodynamic potential

$$\frac{\Omega}{V} = -\frac{\gamma_i\, T}{(2\pi)^3} \sum_i \int d^3k \left\{ \ln\left(1 + e^{-\beta\left[E_i^*(k) - \mu_i^*\right]} \right) \right.$$

$$\left. + \ln\left(1 + e^{-\beta\left[E_i^*(k) + \mu_i^*\right]} \right) \right\} - \mathcal{L}_{vec} - \mathcal{L}_0 - \mathcal{L}_{SB} - V_{vac}$$

- Effective baryon mass

$$m_i^* = -\left(g_{\sigma i}\sigma + g_{\zeta i}\zeta + g_{\delta i} I_{3i}\delta \right) + m_{i0}$$

- Effective chemical potential

$$\mu_i^* = \mu_i - g_{\omega i}\omega - g_{\rho i} I_{3i}\rho - g_{\phi i}\phi$$

Chiral SU(3) model

- For scalar mesons

$$\mathcal{L}_0 = -\frac{1}{2} k_0 \chi^2 \left(\sigma^2 + \delta^2 + \zeta^2\right) + k_1 \left(\sigma^2 + \delta^2 + \zeta^2\right)^2$$

$$+ k_2 \left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2\delta^2 + \zeta^4\right) + k_3 \chi\zeta \left(\sigma^2 - \delta^2\right)$$

$$- k_4 \chi^4 - \frac{1}{4}\chi^4 \ln\frac{\chi^4}{\chi_0^4} + \frac{d}{3}\chi^4 \ln\left(\left(\frac{\left(\sigma^2 - \delta^2\right)\zeta}{\sigma_0^2\zeta_0}\right)\left(\frac{\chi}{\chi_0}\right)^3\right)$$

- For vector mesons

$$\mathcal{L}_{\text{vec}} = \frac{1}{2}\left(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2\right)\frac{\chi^2}{\chi_0^2} + g_4\left(\omega^4 + 6\omega^2\rho^2 + \rho^4 + 2\phi^4\right)$$

Chiral SU(3) model

- Explicit symmetry breaking

$$\mathcal{L}_{SB} = -\frac{1}{2} Tr A_p \left(uXu + u^\dagger X u^\dagger \right),$$

where

$$A_p = \frac{1}{\sqrt{2}} \, \mathrm{diag}(m_\pi^2 f_\pi, m_\pi^2 f_\pi, 2m_K^2 f_K - m_\pi^2 f_\pi)$$

-

$$u = exp\left(iP/\sqrt{2}\sigma_0 \right) = 1 + iP/\sqrt{2}\sigma_0$$

$$\mathcal{L}_{SB} = -\left(\frac{\chi}{\chi_0} \right)^2 \left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2}m_K^2 f_K - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi \right) \zeta \right]$$

Chiral SU(3) model

- General interaction Lagrangian

$$\frac{\partial \Omega}{\partial \sigma} = \frac{\partial \Omega}{\partial \zeta} = \frac{\partial \Omega}{\partial \delta} = \frac{\partial \Omega}{\partial \chi} = \frac{\partial \Omega}{\partial \omega} = \frac{\partial \Omega}{\partial \rho} = \frac{\partial \Omega}{\partial \phi} = 0.$$
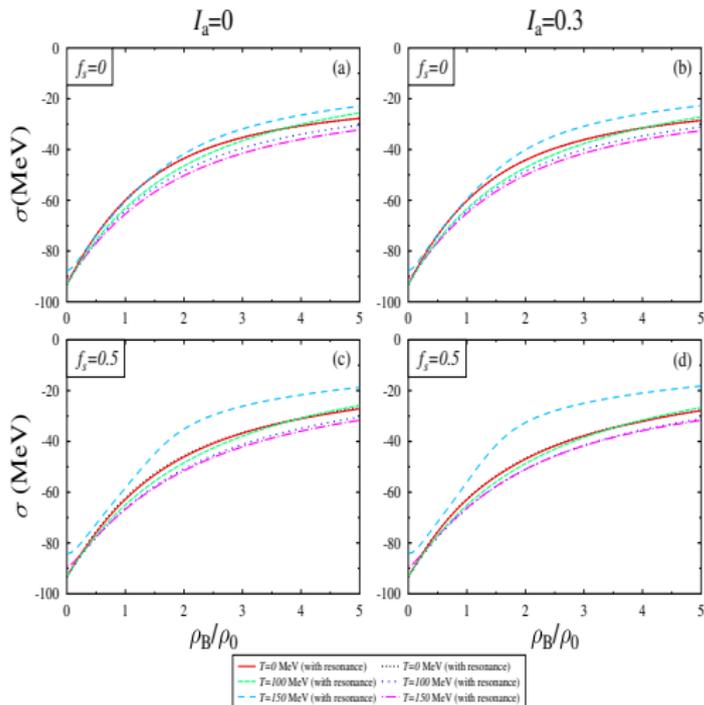
- Baryon number density

$$\rho_i^v = \gamma_i \int \frac{d^3 k}{(2\pi)^3} \left(f_i(k) - \bar{f}_i(k) \right),$$

$$f_i(k) = \frac{1}{1 + \exp\left[\beta(E_i^*(k) - \mu_i^*)\right]}, \qquad \bar{f}_i(k) = \frac{1}{1 + \exp\left[\beta(E_i^*(k) + \mu_i^*)\right]}$$

- Baryon scalar density

$$\rho_i^s = \gamma_i \int \frac{d^3 k}{(2\pi)^3} \frac{m_i^*}{E_i^*(k)} \left(f_i(k) + \bar{f}_i(k) \right).$$

Scalar field σ

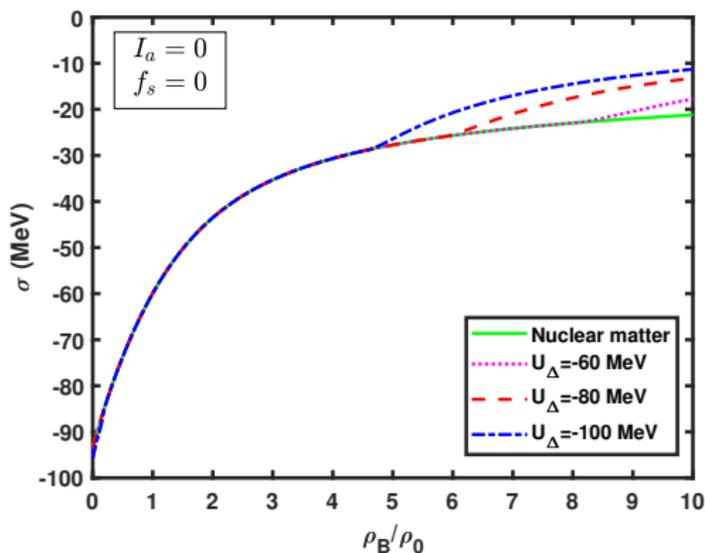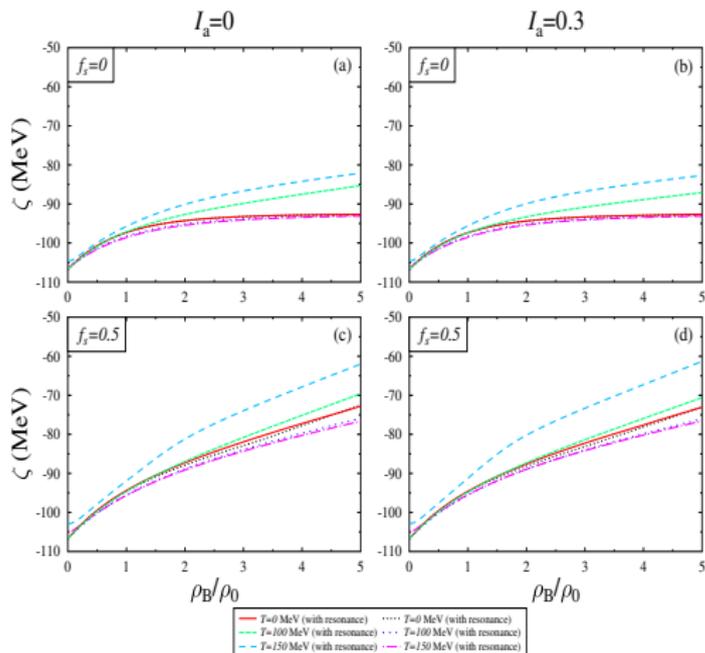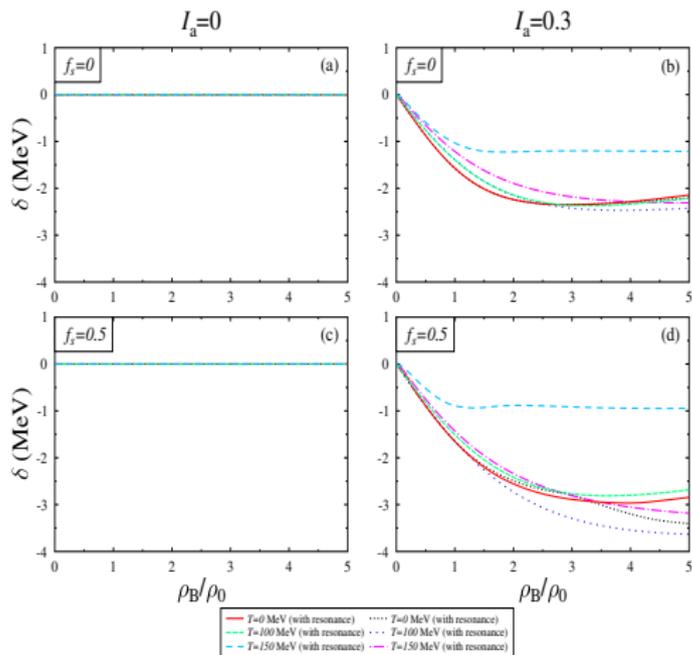Manpreet Kaur and Arvind Kumar, Phys. Rev. D 110, 114054 (2024)

Scalar field σ

Figure: The σ field at various values of Δ baryon potentials for symmetric resonance matter.

Scalar field ζ

Scalar field δ

Kaons and antikaons interactions

- Interaction Lagrangian density

$$\mathcal{L}_{KB} = \mathcal{L}_{OW} + \mathcal{L}_{DW} + \mathcal{L}_{mass} + \mathcal{L}_{kin}^{P} + + \mathcal{L}_{d_1}^{BM} + \mathcal{L}_{d_2}^{BM},$$

- Octet baryons

$$\mathcal{L}_{OW} = i \, \text{Tr} \, \bar{B} \gamma_\mu D^\mu B$$

$D_\mu B = \partial_\mu B + i \left[\Gamma_\mu, B \right]$
$\Gamma_\mu = -\frac{i}{4} \left[u^\dagger \partial_\mu u - \partial_\mu u^\dagger u + u \partial_\mu u^\dagger - \partial_\mu u u^\dagger \right], u = exp\left(iP/\sqrt{2}\sigma_0 \right).$

- Decuplet baryons

$$\mathcal{L}_{DW} = -i \, \bar{T}^\mu \slashed{D} T_\mu$$

$$\mathcal{D}^\nu T_{abc}^\mu = \partial^\nu T_{abc}^\mu + i \left(\Gamma^\nu \right)_a^d T_{dbc}^\mu + i \left(\Gamma^\nu \right)_b^d T_{adc}^\mu + i \left(\Gamma^\nu \right)_c^d T_{abd}^\mu$$

Kaons and antikaons interactions

- Symmetry breaking term

$$\mathcal{L}_{SB} = -\frac{1}{2} Tr A_p \left(uXu + u^\dagger X u^\dagger \right),$$

where $A_p = \frac{1}{\sqrt{2}} \, \mathrm{diag}(m_\pi^2 f_\pi, m_\pi^2 f_\pi, 2m_K^2 f_K - m_\pi^2 f_\pi)$.

$$\mathcal{L}_{mass} = \frac{m_K^2}{2f_K} \left[\left(\sigma + \sqrt{2}\zeta + \delta \right) K^+ K^- + \left(\sigma + \sqrt{2}\zeta - \delta \right) K^0 \bar{K}^0 \right]$$

- Kinetic term for pseudoscalar mesons

$$\mathcal{L}_{kin}^P = Tr \left(u_\mu X u^\mu X + X u_\mu u^\mu X \right)$$

$$\mathcal{L}_{kin}^P = -\frac{1}{f_K} \left[\left(\sigma + \sqrt{2}\zeta + \delta \right) (\partial_\mu K^+)(\partial^\mu K^-) \right.$$
$$\left. + \left(\sigma + \sqrt{2}\zeta - \delta \right) (\partial_\mu K^0)(\partial^\mu \bar{K}^0) \right]$$

Kaons and antikaons interactions

- Meson-baryon interaction at next-to-leading order

$$\mathcal{L}_{d_1}^{BM} = \frac{d_1}{2} Tr(u_\mu u^\mu) \Big[Tr(\bar{B}B) + Tr(\bar{T}T) \Big],$$

and

$$\mathcal{L}_{d_2}^{BM} = d_2 \Big[Tr(\bar{B}u_\mu u^\mu B) + Tr(\bar{T}u_\mu u^\mu T) \Big].$$
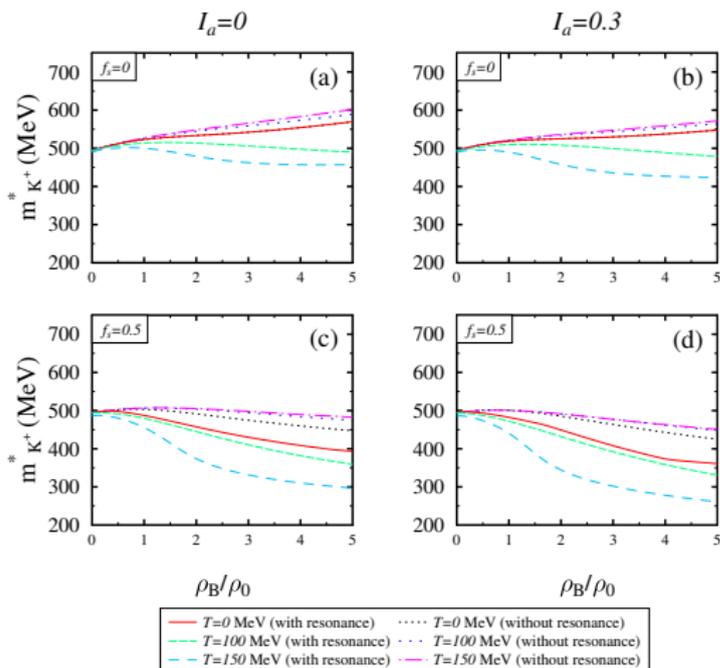
$$d_1 = \frac{2.56}{m_K}, \qquad d_2 = \frac{0.73}{m_K}$$

- Dispersion relation from Euler Lagrange equation of motion and its Fourier transformation

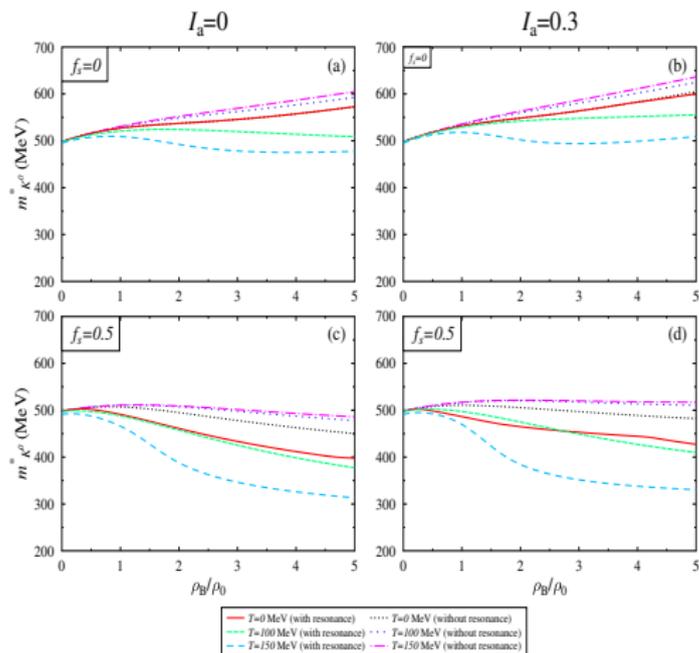$$-\omega^2 + \vec{k}^2 + m_{K(\bar{K})}^2 - \Pi^*(\omega, |\vec{k}|) = 0,$$
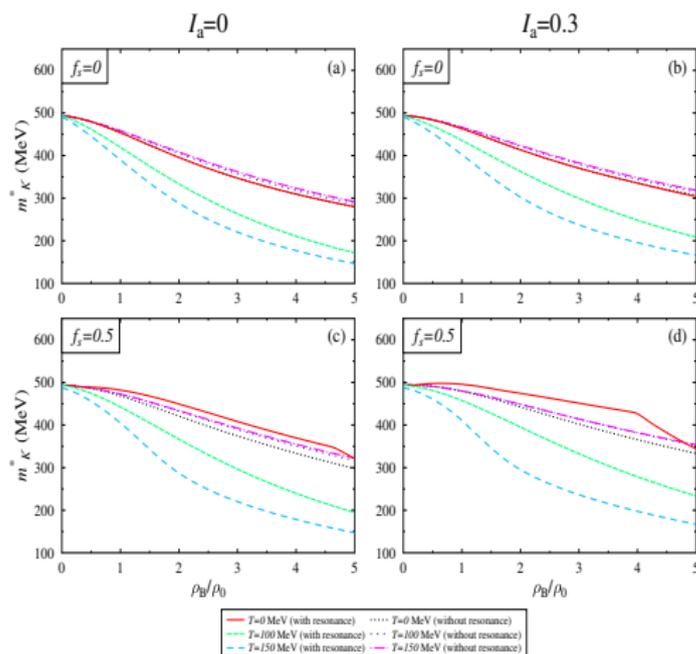
Kaons and antikaons interactions

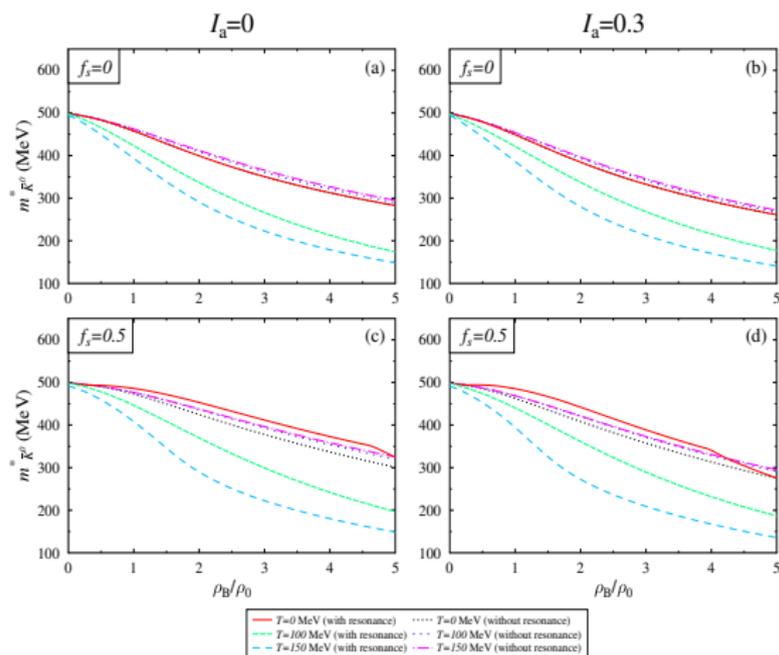- For K^+

Kaons and antikaons interactions

- For K^0

Kaons and antikaons interactions

- For K^-

Kaons and antikaons interactions

- For $\bar{K}^0$

φ mesons interactions

Experimental efforts

- LEPS collaboration Spring-8 : γA induced reaction

- KEK E325 : $p - A$ reaction (12 GeV proton beam)

- CLAS collab. at Jefferson Lab: γA induced reaction

- ANKE-COSY: $p - A$ reaction (2.83 GeV proton beam)

- HADES: $\pi^- A$ reaction

- ALICE: pp collisions

- J-PARC: : $p - A$ reaction (30 GeV proton beam)

Different observations on mass-shift and width broadening in nuclear medium

ϕ mesons interactions

- Interaction Lagrangian density

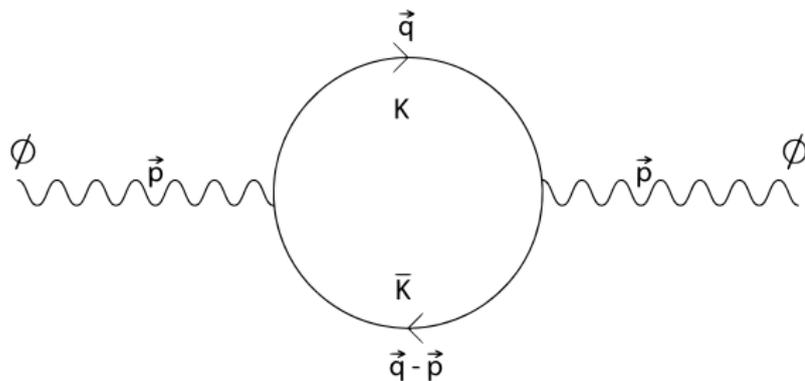$$\mathcal{L}_{\phi K \bar{K}} = ig_\phi \phi^\mu \left[\bar{K}(\partial_\mu K) - (\partial_\mu \bar{K})K \right].$$

Figure: $\phi K \bar{K}$ interaction at one loop level.

J.J. Cobos-Martínez et. al, Phys. Lett. B 771 (2017) 113

ϕ mesons interactions

- Self energy

$$i\Pi^*_\phi(p) = -\frac{8}{3}g^2_\phi \int \frac{d^4q}{(2\pi)^4}\,\vec{q}^{\,2}D_K(q)D_{\bar{K}}(q-p)\,.$$
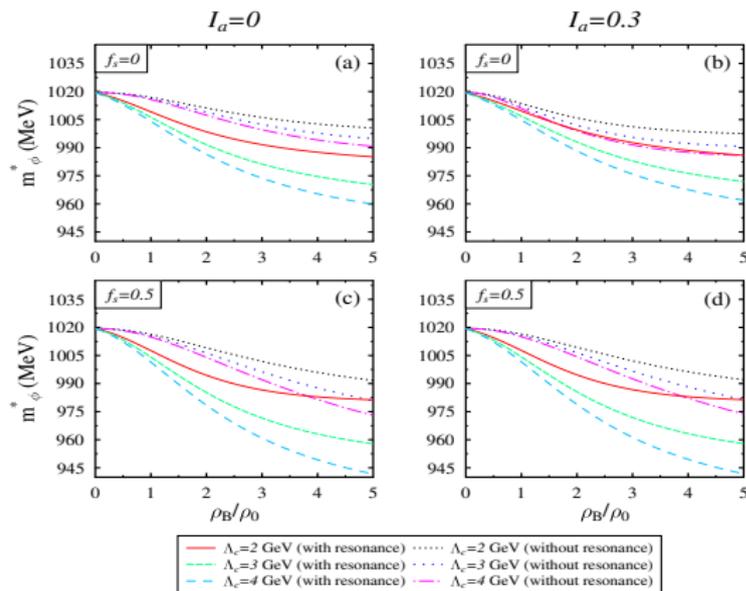
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$$m^{*\,2}_\phi = \left(m^0_\phi\right)^2 + \mathrm{Re}\Pi^*_\phi(m^{*\,2}_\phi),$$

$$\mathrm{Re}\Pi^*_\phi = -\frac{4}{3}g^2_\phi\,\mathcal{P}\int_0^{\Lambda_c}\frac{d^3q}{(2\pi)^3}\vec{q}^{\,2}\left(\frac{\Lambda_c^2 + m^{*\,2}_\phi}{\Lambda_c^2 + 4E^{*\,2}_K}\right)^4$$

$$\frac{(E^*_K + E^*_{\bar{K}})}{E^*_K E^*_{\bar{K}}((E^*_K + E^*_{\bar{K}})^2 - m^{*\,2}_\phi)}\,.$$

- Decay width

$$\Gamma^*_\phi = \frac{g^2_\phi}{24\pi}\frac{1}{m^{*\,5}_\phi}\left((m^{*\,2}_\phi - (m^*_K + m^*_{\bar{K}})^2)(m^{*\,2}_\phi - (m^*_K - m^*_{\bar{K}})^2)\right)^{3/2}\,.$$

m_ϕ^* in resonance and non-resonance matter (at $T = 100$ MeV)

Manpreet Kaur and Arvind Kumar, Phys. Rev. D 112, 014030 (2025)

Γ^*_ϕ of the ϕ meson

Summary

- Impact of decuplet baryons on K and ϕ meson properties investigated

- Interaction between baryons mediated through the scalar and vector fields

- Presence of decuplet baryon causes decrease in effective masses of K mesons at finite temperature and high ρ_B

- ϕ mesons feel more attractive mass shift in resonance matter

- Decay width of ϕ mesons increases

Thank You

Kaons and antikaons interactions

- $$T^{111} = \Delta^{++}, \, T^{112} = \frac{1}{\sqrt{3}}\Delta^+, \, T^{122} = \frac{1}{\sqrt{3}}\Delta^0, \, T^{222} = \Delta^-,,$$

  $$T^{113} = \frac{1}{\sqrt{3}}\Sigma^{*+}, \, T^{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}, \, T^{223} = \frac{1}{\sqrt{3}}\Sigma^{*-}$$

  $$T^{133} = \frac{1}{\sqrt{3}}\Xi^{*0}, \, T^{233} = \frac{1}{\sqrt{3}}\Xi^{*-}, \, T^{333} = \Omega^-.$$

- $$\mathcal{L}_{\mathcal{DW}} = -\frac{3i}{4f_K^2}\Big[\Big(3\bar{\Delta}^{++}\gamma^\mu\Delta^{++} + 2\bar{\Delta}^+\gamma^\mu\Delta^+ + \bar{\Delta}^0\gamma^\mu\Delta^0 - \bar{\Sigma}^{*-}\gamma^\mu\Sigma^{*-}$$

  $$+ \bar{\Sigma}^{*+}\gamma^\mu\Sigma^{*+} - 2\bar{\Xi}^{*-}\gamma^\mu\Xi^{*-} - \bar{\Xi}^{*0}\gamma^\mu\Xi^{*0} - 3\bar{\Omega}^-\gamma^\mu\Omega^-\Big)$$

  $$\times \Big(K^-(\partial_\mu K^+) - (\partial_\mu K^-)K^+\Big)$$

  $$+ \Big(3\bar{\Delta}^-\gamma^\mu\Delta^- + \bar{\Delta}^+\gamma^\mu\Delta^+ + 2\bar{\Delta}^0\gamma^\mu\Delta^0 - \bar{\Sigma}^{*+}\gamma^\mu\Sigma^{*+} + \bar{\Sigma}^{*-}\gamma^\mu\Sigma^{*-}$$

  $$- \bar{\Xi}^{*-}\gamma^\mu\Xi^{*-} - 2\bar{\Xi}^{*0}\gamma^\mu\Xi^{*0} - 3\bar{\Omega}^-\gamma^\mu\Omega^-\Big)\Big(\bar{K}^0(\partial_\mu K^0) - (\partial_\mu \bar{K}^0)K^0\Big)\Big]$$