Density dependence of the heavy light meson distribution amplitude

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In collaboration with:

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PRD **107**, 114010 (2023)

14th APCTP-BLTP JINR Joint Workshop-Memorial Workshop in Honor of Prof. Yongseok Oh: Modern problems in nuclear and elementary particle physics, 9-14 July 2023, PIC-APCTP, Pohang

My memoriam with Prof. Yongseok Oh

- I joined the **Asia Pacific Center for Theoretical Physics** (APCTP) as **APEC-YST Postdoctoral**
- In my contract letter, it was obviously mentioned that I must work with Prof. Yongseok Oh (50%) and with APCTP (50%)
- During working with Prof. Yongseok Oh, we published 5 papers

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Parada T. P. Hutauruk, Yongseok Oh, and K. Tsushima
Phys. Rev. D **98**, 013009 – Published 30 July 2018

JPS Conf. Proc. 26, 031031 (2019) [4 pages]
Proceedings of the 8th International Conference on Quarks and Nuclear Physics (

Pion Structure in a Nuclear Medium

Abstract References
Full text: PDF (eReader) / PDF (Download) (356 kB)
Parada T. P. Hutauruk[1], Yongseok Oh[1,2], and Kazuo Tsushima[1,3]

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Phys. Rev. D **100**, 094011 – Published 13 November 2019

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Parada T. P. Hutauruk, Yongseok Oh, and K. Tsushima
Phys. Rev. C **99**, 015202 – Published 10 January 2019

JPS Conf. Proc. 26, 024031 (2019) [4 pages]
Proceedings of the 8th International Conference on Quarks and Nuclear Physics (QNP2018)
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Effects of Medium Modifications of Nucleon Form Factors on Neutrino Scattering in Dense Matter

Abstract References
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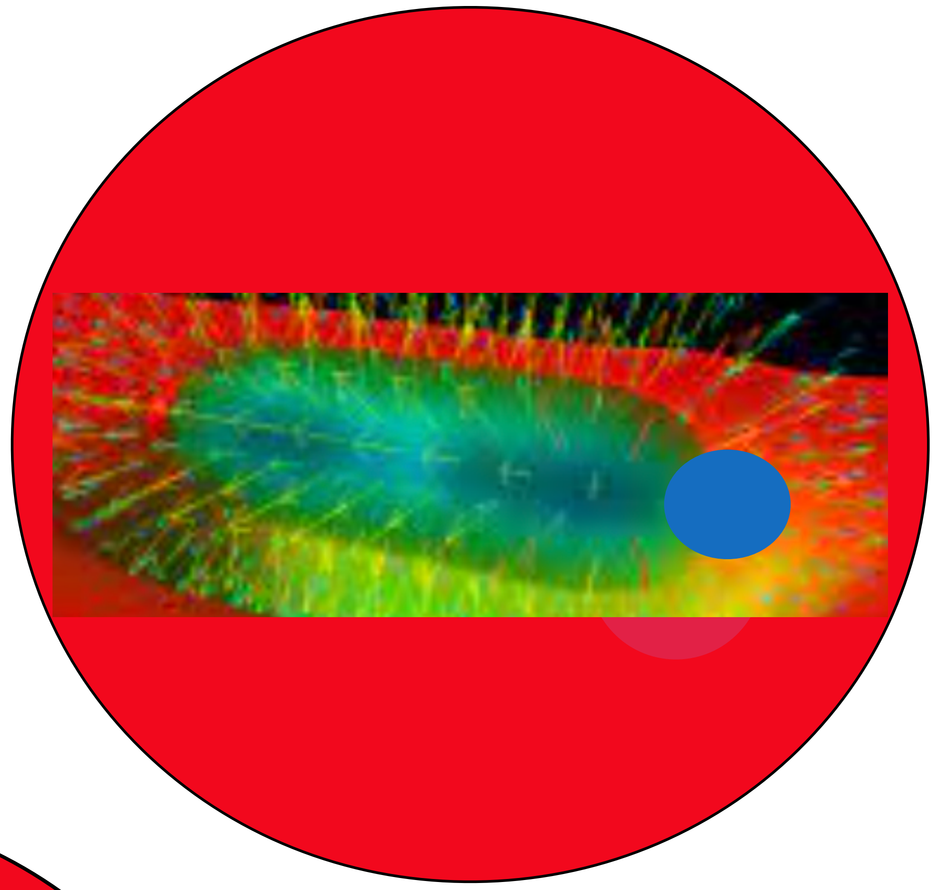
Parada T. P. Hutauruk[1], Yongseok Oh[1,2], and Kazuo Tsushima[1,3]

Outline

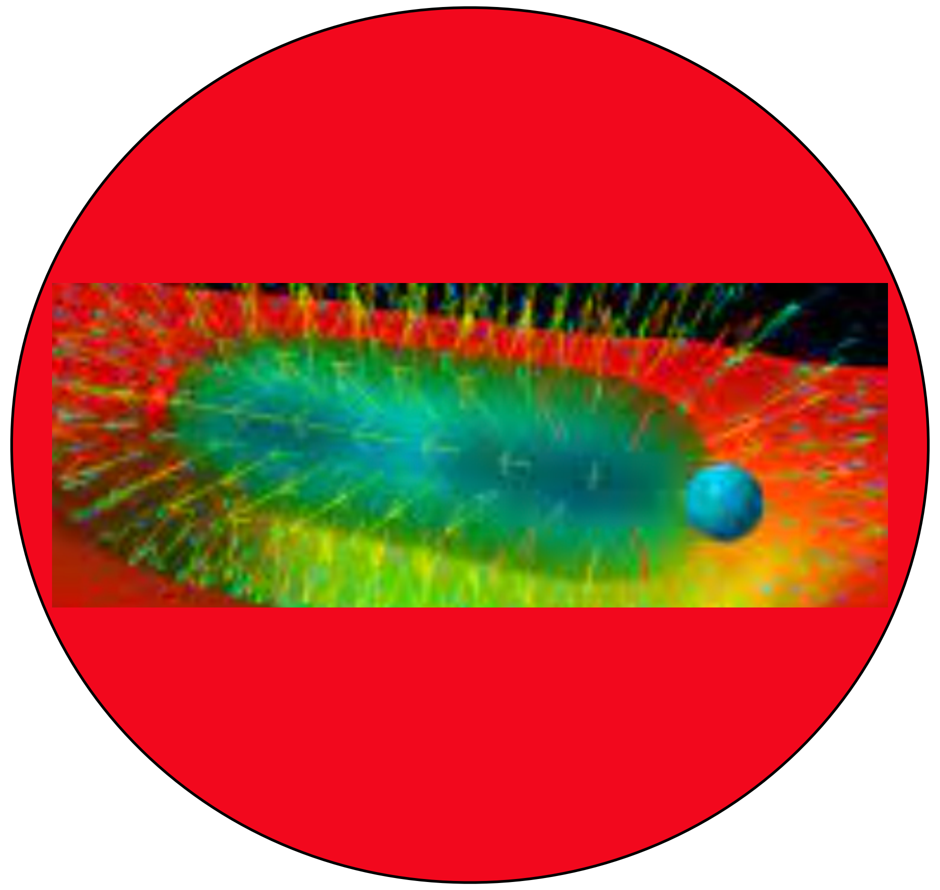
- **Light Front Quark Model (LFQM)**
  - Weak decay constants
  - Distribution amplitudes (DAs)
- **A nuclear medium effect from the quark meson coupling (QMC) model**
  - Effective Lagrangian of the QMC model
  - Quark masses in a nuclear medium
- **DAs in a nuclear medium**
- **Summary and outlook**

Meson contents

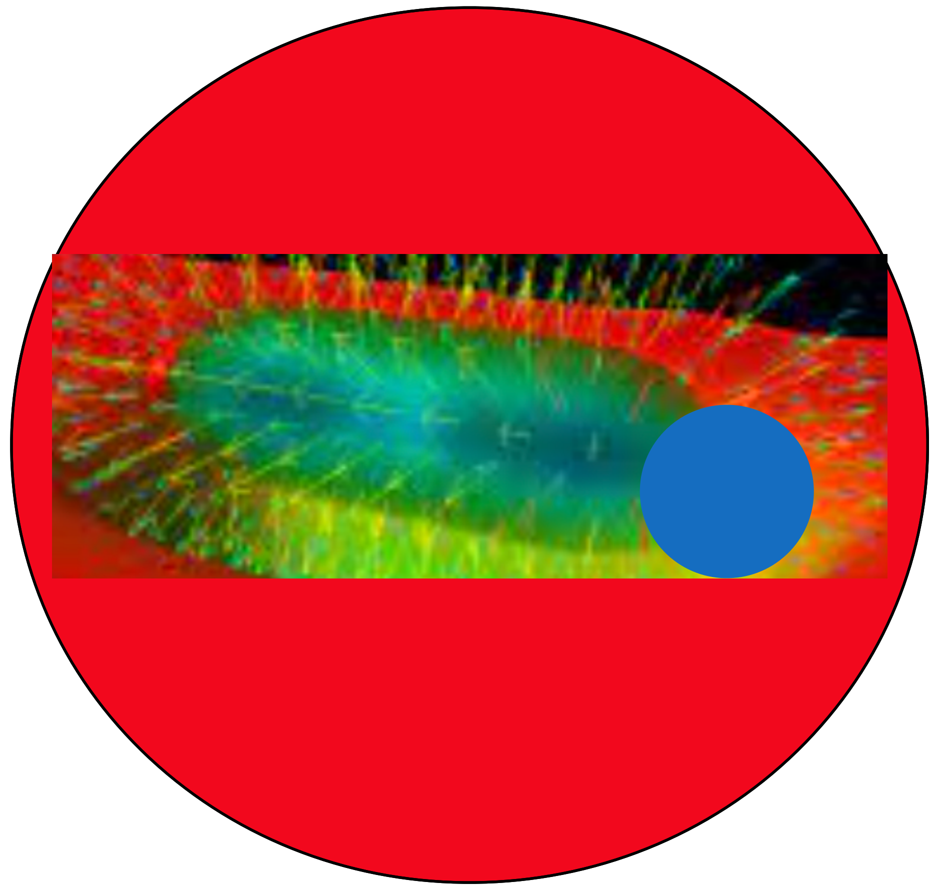
- **L**ight-**L**ight and **H**eavy-**l**ight **m**esons quark contents:
- **P**seudoscalar **m**esons: π^+ ($\mathbf{u}\bar{d}$), K^+($\mathbf{u}\bar{s}$), D^+($c\bar{d}$), and B^+($\mathbf{u}\bar{b}$)
- **V**ector **m**esons: ρ^+($\mathbf{u}\bar{d}$), K^{*+}($\mathbf{u}\bar{s}$), B^{*+}($\mathbf{u}\bar{b}$), and D^{*+}($c\bar{d}$)



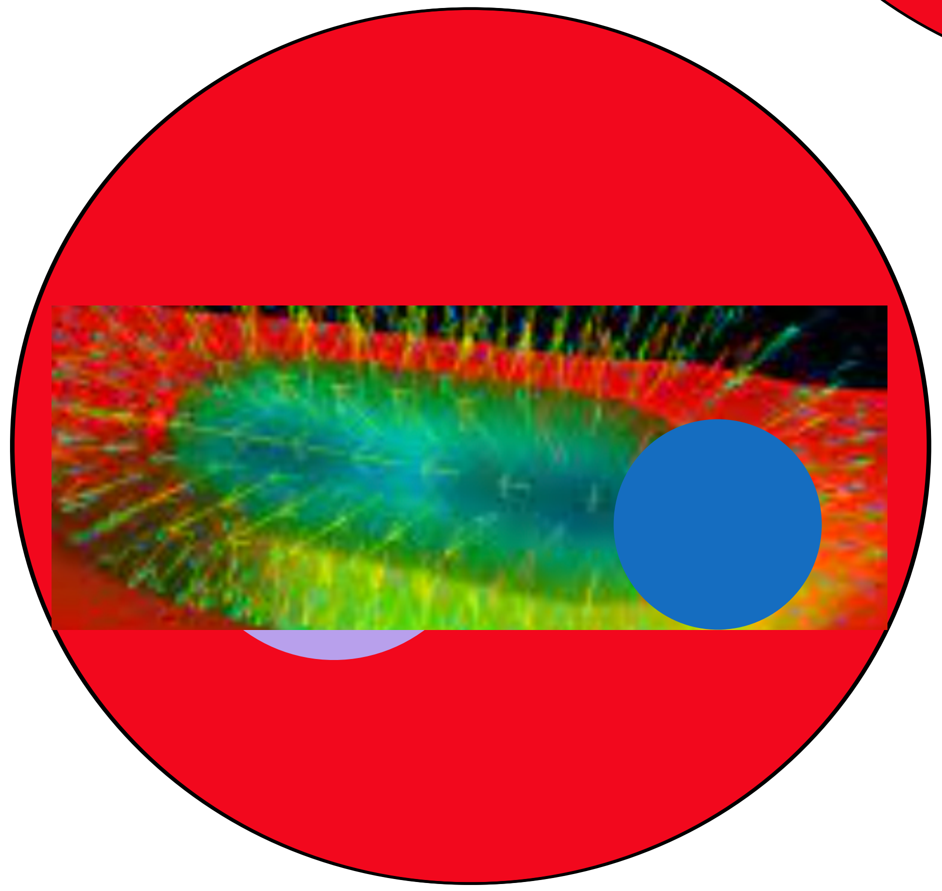
Kaon (K)



Pion (π)



D meson



B meson

Light Front Quark Model (LFQM)

- In the LFQM, the meson state——**bound state of the constituent quark and antiquark pair in the noninteracting representation**—-Bakamjian Thomas (BT) Construction—-the interaction is included in the meson mass operator—-satisfy the Poincare group structure [Bakamjian and Thomas, PR 92 (1953) 1300]
- Interaction encoded in the mass eigenfunctions—-**applying the variational principle**—-to deal with the mass eigenvalues problem—-trial wave function in the Gaussian basis [Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003 and References therein]
- The LFWF of the ground state meson in momentum space is given

Spin-orbit wave function

$$\Psi^{JJ_z}_{\lambda_q\lambda_{\bar{q}}}(x,\mathbf{k}_\perp) = \Phi(x,\mathbf{k}_\perp)\mathcal{R}^{JJ_z}_{\lambda_q\lambda_{\bar{q}}}(x,\mathbf{k}_\perp),$$

Radial wave function

Light Front Quark Model (LFQM)

- The spin-orbit wave functions are defined by

M—-Pseudo-scalar or vector mesons

$$\mathcal{R}^{JJ_z}_{\lambda_q\lambda_{\bar{q}}} = \frac{1}{\sqrt{2}\tilde{M}_0}\bar{u}_{\lambda_q}(p_q)\Gamma_{\rm M} v_{\lambda_{\bar{q}}}(p_{\bar{q}}),$$

$$\tilde{M}_0 \equiv \sqrt{M_0^2 - (m_q - m_{\bar{q}})^2},$$

- The invariant meson mass is defined [Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003 and References therein]

$$M_0^2 = \frac{\mathbf{k}_\perp^2 + m_q^2}{x} + \frac{\mathbf{k}_\perp^2 + m_{\bar{q}}^2}{1-x}.$$

- The vertices for the pseudoscalar and vector mesons

$$\Gamma_{\rm P} = \gamma_5, \qquad \Gamma_{\rm V} = -\not{\epsilon}(J_z) + \frac{\epsilon\cdot(p_q - p_{\bar{q}})}{M_0 + m_q + m_{\bar{q}}},$$

Light Front Quark Model (LFQM)

- The trial radial wave function in the Gaussian basis [Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003]

$$\Phi_{1S}(x,\mathbf{k}_\perp) = \frac{4\pi^{3/4}}{\beta^{3/2}}\sqrt{\frac{\partial k_z}{\partial x}}e^{-\mathbf{k}^2/2\beta^2},$$

$$\frac{\partial k_z}{\partial x} = \frac{M_0}{4x(1-x)}\left[1-\frac{(m_q^2-m_{\bar{q}}^2)^2}{M_0^4}\right],$$

- The LFWF is normalized

$$\int \frac{dx d^2\mathbf{k}_\perp}{2(2\pi)^3}|\Psi(x,\mathbf{k}_\perp)|^2 = 1.$$

- Computing the eigenvalue—-BT construction—-using the meson mass operator

$$(H_0+V_{q\bar{q}})|\Psi_{q\bar{q}}\rangle = M_{q\bar{q}}|\Psi_{q\bar{q}}\rangle,$$

$$H_0 = \sqrt{m_q^2+\mathbf{p}_q^2}+\sqrt{m_{\bar{q}}^2+\mathbf{p}_{\bar{q}}^2},$$

Light Front Quark Model (LFQM)

- The quark-antiquark potentials

$$V_{q\bar{q}} = V_{\text{Conf}} + V_{\text{Coul}} + V_{\text{Hyp}},$$

$$V_{\text{Conf}} = a + br, \qquad V_{\text{Hyp}} = \frac{32\pi\alpha_s \langle \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \rangle}{9 m_q m_{\bar{q}}} \delta^3(r),$$

$$V_{\text{Coul}} = -\frac{4\alpha_s}{3r},$$

- The LFWF and mass of the meson ground state—variational analysis

[Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003]

$$M_{q\bar{q}} = \langle \Psi_{q\bar{q}} | H_{q\bar{q}} | \Psi_{q\bar{q}} \rangle = \langle \phi_{1S} | H_{q\bar{q}} | \phi_{1S} \rangle,$$

- Analytic mass formula

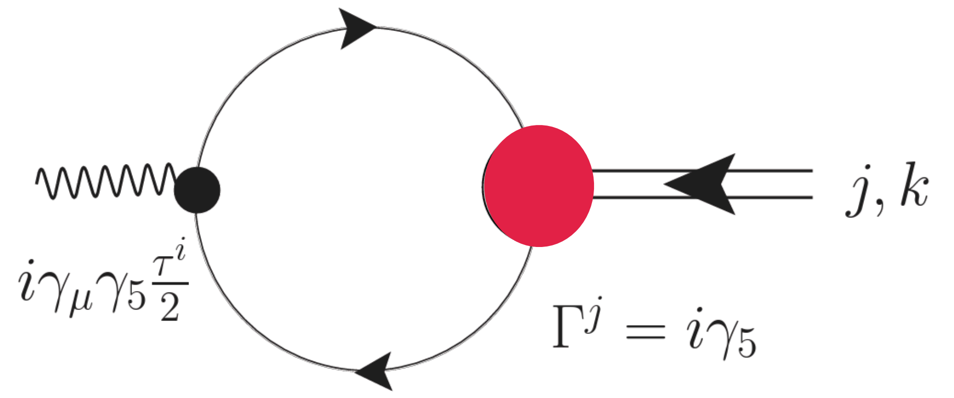
$$M_{q\bar{q}} = \frac{\beta}{\sqrt{\pi}} \sum_{i=q,\bar{q}} z_i e^{z_i/2} K_1\left(\frac{z_i}{2}\right) + a + \frac{2b}{\beta\sqrt{\pi}} - \frac{8\alpha_s \beta}{3\sqrt{\pi}} + \frac{32\alpha_s \beta^3 \langle \mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} \rangle}{9\sqrt{\pi} m_q m_{\bar{q}}},$$

Light Front Quark Model (LFQM)

- The weak decay constant for the **pseudoscalar** and **vector mesons**

[Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003

$$\langle 0|\bar{q}\gamma^{\mu}\gamma_5 q|\mathrm{P}(P)\rangle = i f_{\mathrm{P}} P^{\mu},$$
$$\langle 0|\bar{q}\gamma^{\mu} q|\mathrm{V}(P,J_z)\rangle = f_{\mathrm{V}} M_{\mathrm{V}} \epsilon^{\mu}(J_z),$$



- The weak decay constant expressions in the LFQM

$$f_{\mathrm{M}} = 2\sqrt{6}\int_0^1 \mathrm{d}x \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{2(2\pi)^3}\frac{\Phi(x,\mathbf{k}_\perp)}{\sqrt{\mathcal{A}^2+\mathbf{k}_\perp^2}}\mathcal{O}_{\mathrm{M}},$$

$$\mathcal{O}_{\mathrm{P}} = \mathcal{A}, \qquad \mathcal{O}_{\mathrm{V}} = \mathcal{A} + \frac{2\mathbf{k}_\perp^2}{D_0},$$

$$\mathcal{A} = (1-x)m_q + x m_{\bar{q}} \qquad D_0 = M_0 + m_q + m_{\bar{q}}.$$

- The leading twist DAs for the **pseudoscalar** and **vector mesons**—-plus component currents

$$A_P^+ = \langle 0|\bar{q}(z)\gamma^+\gamma_5 q(-z)|\mathrm{P}(P)\rangle,$$
$$= i f_{\mathrm{P}} P^+ \int_0^1 \mathrm{d}x e^{i\zeta P\cdot z}\phi_{\mathrm{P}}(x)|_{z^+=z_\perp=0},$$

$$A_V^+ = \langle 0|\bar{q}(z)\gamma^+ q(-z)|\mathrm{V}(P,0)\rangle,$$
$$= f_{\mathrm{V}} M_{\mathrm{V}} \epsilon^+(0)\int_0^1 \mathrm{d}x e^{i\zeta P\cdot z}\phi_{\mathrm{V}}(x)|_{z^+=z_\perp=0},$$

Light Front Quark Model (LFQM)

- **I**n the LFQM model, the final expression for the LFWF

$$\phi_{\mathrm{M}}(x) = \frac{2\sqrt{6}}{f_{\mathrm{M}}} \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\Phi(x, \mathbf{k}_\perp)}{\sqrt{\mathcal{A}^2 + \mathbf{k}_\perp^2}} \mathcal{O}_{\mathrm{M}}.$$

- **D**As must satisfy the normalization

$$\int_0^1 \phi_{\mathrm{M}}(x)\mathrm{d}x = 1.$$

[Arifi, HM Choi, and C-R.Ji, PRD 107 (2023) 053003] [HM Choi, and C-R.Ji, PRD 59 (1999) 074015]

Quark-Meson Coupling (QMC) Model

[PAM Guichon, PLB 200 (1988) 235-240]

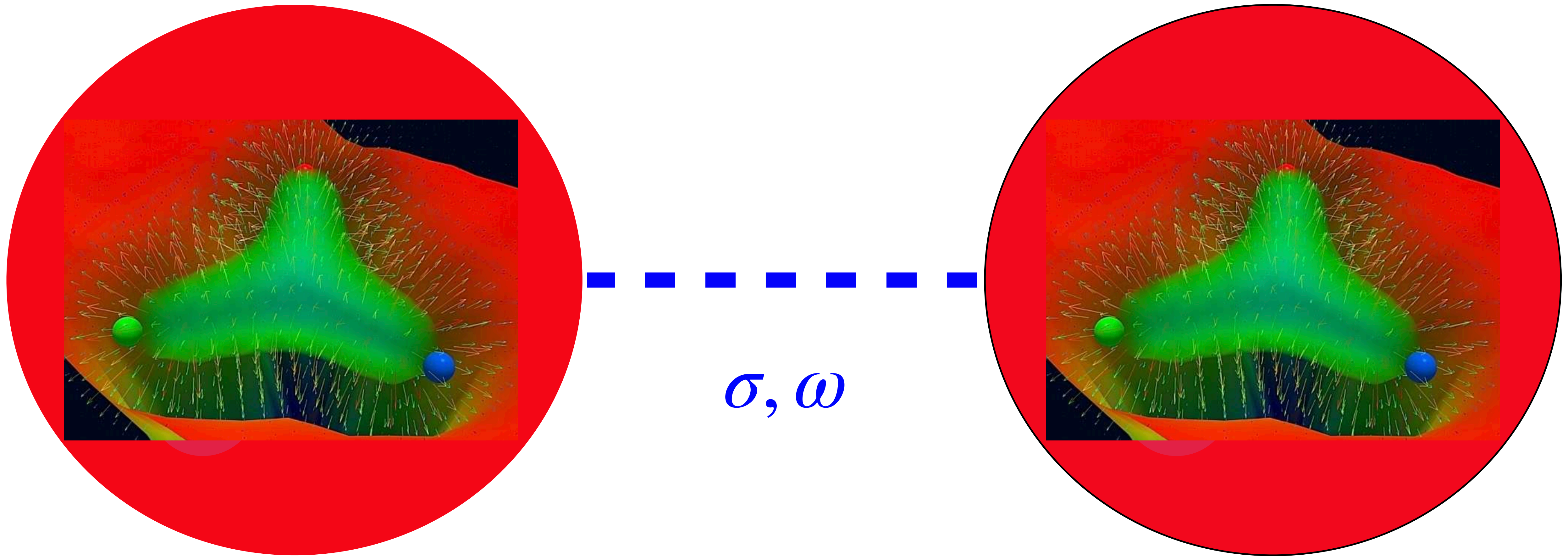
- **E**ffective **L**agrangian of the QMC model for the **s**ymmetric **n**uclear **m**atter (SNM)

$$\mathcal{L}_{\rm QMC} = \bar{\psi}_N [i\gamma\cdot\partial - M_N^*(\sigma) - g_\omega \omega^\mu \gamma_\mu]\psi_N + \mathcal{L}_{\rm meson},$$

$$M_N^*(\sigma) = M_N - g_\sigma(\sigma)\sigma.$$

$$\mathcal{L}_{\rm meson} = \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{2}\partial_\mu\omega_\nu(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu) + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu.$$

[PAM Guichon, Koichi Saito, Rodionov, A. William, NPA 601 (1996) 349-379]



Nonoverlapping baryon

Quark-Meson Coupling (QMC) Model

[PAM Guichon, JR Stone, AW Thomas, PPNP 100 (2018) 262-297]

- In the mean-field approach, the nucleon Fermi momentum is related to the baryon density and scalar density

$$\rho_B = \frac{\gamma}{(2\pi)^3}\int d\boldsymbol{k}\Theta(k_F - |\boldsymbol{k}|) = \frac{\gamma k_F^3}{3\pi^2},$$

$$\rho_s = \frac{\gamma}{(2\pi)^3}\int d\boldsymbol{k}\Theta(k_F - |\boldsymbol{k}|)\frac{M_N^*(\sigma)}{\sqrt{M_N^{*2}(\sigma)+\boldsymbol{k}^2}},$$

- In the QMC model, the nuclear matter is described as a collection of non-overlapping MIT bags of nucleon [PAM Guichon, JR Stone, AW Thomas, PPNP 100 (2018) 262-297]
- The Dirac equations for the quark and antiquarks in the bag

$$\left[i\gamma\cdot\partial_x - (m_l - V_\sigma^q) \mp \gamma^0\left(V_\omega^q + \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0, \quad \left[i\gamma\cdot\partial_x - (m_l - V_\sigma^q) \mp \gamma^0\left(V_\omega^q - \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0, \quad [i\gamma\cdot\partial_x - m_s]\begin{pmatrix}\psi_s(x)\\ \psi_{\bar{s}}(x)\end{pmatrix} = 0,$$

Quark-Meson Coupling (QMC) Model

- The effective in-medium quark masses **[PAM Guichon, JR Stone, AW Thomas, PPNP 100 (2018) 262-297]**

$$m_l^* \equiv m_l - V_\sigma^q,$$

- For the strange, charm, and bottom quarks, the effective mass in the medium is equal to that in the vacuum—-decoupled from the scalar and vector potential in nuclear matter
- The scalar and vector mean-field potentials felt by the light quarks in SNM

$$V_\sigma^q \equiv g_\sigma^q \sigma = g_\sigma^q \langle \sigma \rangle,$$
$$V_\omega^q \equiv g_\omega^q \omega = g_\omega^q \delta^{\mu,0} \langle \omega^\mu \rangle,$$

- The effective mass of the hadron in the nuclear medium

$$m_h^* = \sum_{j=l,\bar{l},s,\bar{s}} \frac{n_j \Omega_j^* - z_h}{R_h^*} + \frac{4}{3}\pi R_h^{*3} B,$$

Which is determined by satisfying the stability condition

$$\left.\frac{dm_h^*}{dR_h}\right|_{R_h=R_h^*} = 0,$$

Quark-Meson Coupling (QMC) Model

- The scalar and vector meson mean fields at the hadron level are related to baryon and scalar densities

$$\sigma = \frac{4 g_\sigma^N C_N(\sigma)}{(2\pi)^3 m_\sigma^2} \int d\boldsymbol{k} \Theta(k_F - |\boldsymbol{k}|) \frac{M_N^*(\sigma)}{\sqrt{M_N^{*2}(\sigma) + \boldsymbol{k}^2}}, \qquad \omega = \frac{g_\omega \rho_B}{m_\omega^2}, \qquad C_N(\sigma) = \frac{-1}{g_\sigma^N}\left[\frac{\partial M_N^*(\sigma)}{\partial \sigma}\right],$$

$$= \frac{4 g_\sigma^N C_N(\sigma)}{(2\pi)^3 m_\sigma^2} \rho_s,$$

- $C_N(\sigma) = 1$ for the point-like nucleon—-the QMC model is similar to the QHD (Walecka) model
- The energy total per nucleon

$$E^{\mathrm{tot}}/A = \frac{4}{(2\pi)^3 \rho_B} \int d\boldsymbol{k} \Theta(k_F - |\boldsymbol{k}|) \sqrt{M_N^{*2}(\sigma) + \boldsymbol{k}^2} + \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2 m_\omega^2}.$$

Quark-Meson Coupling (QMC) Model

[PAM Guichon, JR Stone, AW Thomas, PPNP 100 (2018) 262-297]

- The total energy per nucleon

$$E^{\text{tot}}/A = \frac{4}{(2\pi)^3 \rho_B} \int d\boldsymbol{k} \Theta(k_F - |\boldsymbol{k}|) \sqrt{M_N^{*2}(\sigma) + \boldsymbol{k}^2} + \frac{m_\sigma^2 \sigma^2}{2\rho_B} + \frac{g_\omega^2 \rho_B}{2m_\omega^2}.$$

- The coupling constants are taken by fitting to energy at saturation density

m_q [MeV]	$(g_\sigma^N)^2/4\pi$	$(g_\omega^N)^2/4\pi$	m_N^* [MeV]	K [MeV]
5	5.39	5.30	755	279
220	6.40	7.57	699	321

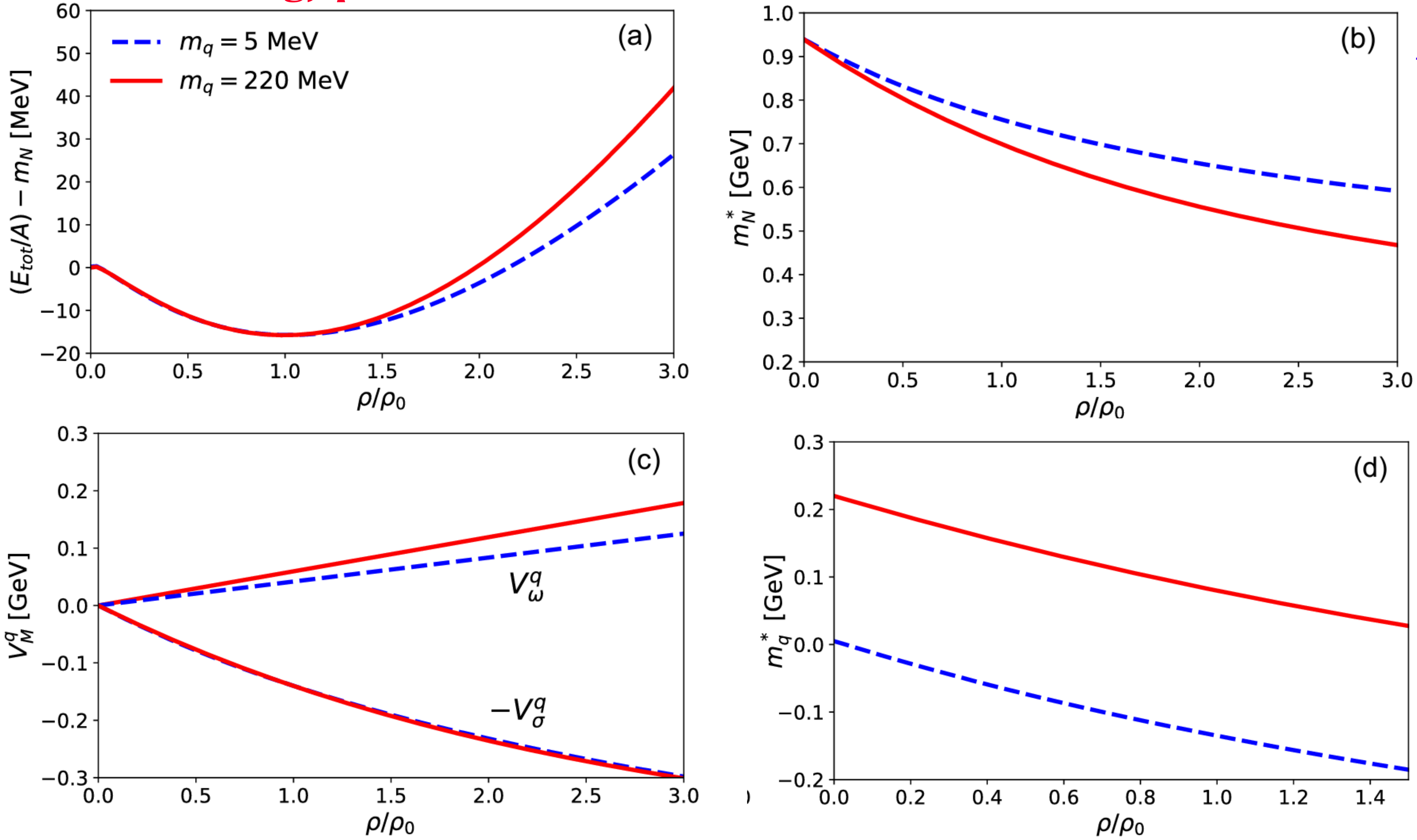
Quark-Meson Coupling (QMC) Model

- Numerical results for the QMC model

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

Energy per nucleon **Effective nucleon mass**

Potentials **Quark masses**



——The energy total per nucleon for different quark masses produces the binding energy at saturation density

——Effective nucleon mass decreases as density increases—- consistent with other models

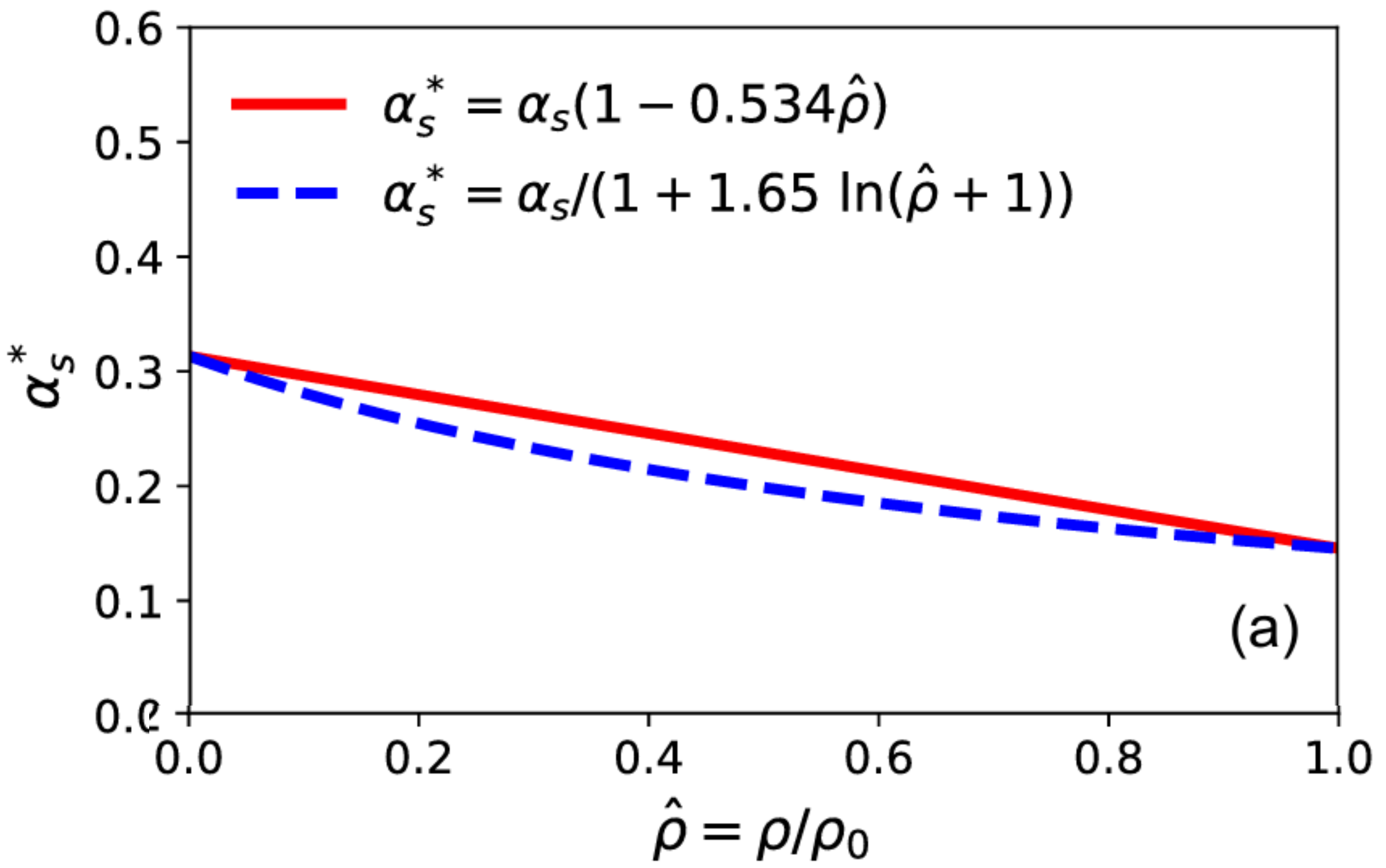
——Quark mass decreases as the density increases

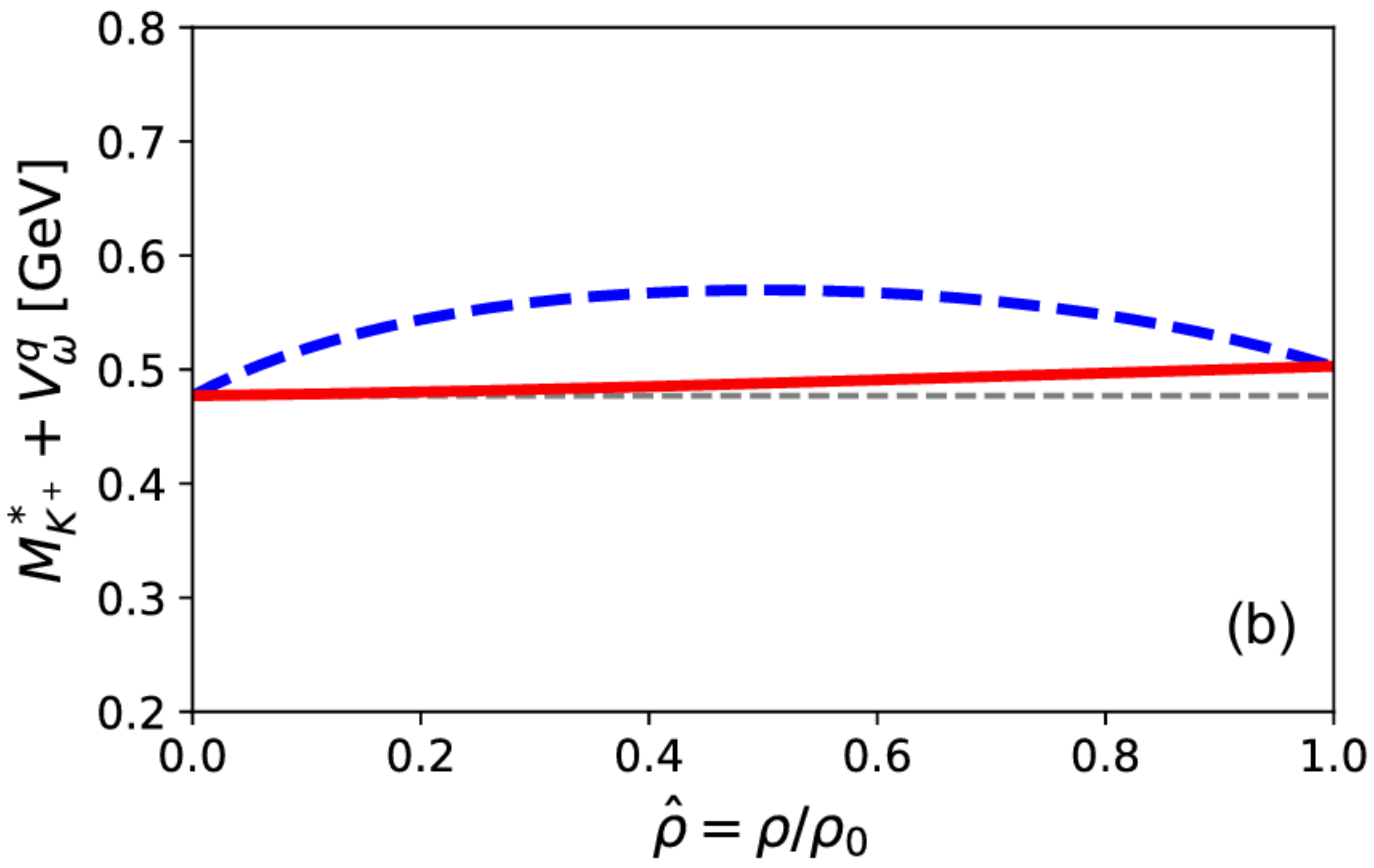
Medium Modifications in the LFQM+QMC model

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

- The strong coupling constant is modified in nuclear medium

$$\alpha_s^* \equiv \begin{cases} \alpha_{s(1)}^*(\rho) = \alpha_s(1 - b_1\hat{\rho}), \\ \alpha_{s(2)}^*(\rho) = \frac{\alpha_s}{1+b_2\ln(\hat{\rho}+1)}, \end{cases}$$





Medium Modifications in the LFQM+QMC model

- The light quark and antiquark energies are modified in a nuclear medium by the vector potential

$$p_i^{*0} = \begin{cases} E_q^* + V_\omega^q, & \text{for light quark,} \\ E_{\bar{q}}^* - V_\omega^q, & \text{for light antiquark,} \end{cases}$$

- The total meson energies

$$P^{*0} = \begin{cases} E_M^*, & \text{for } (q\bar{q}), \\ E_M^* + V_\omega^q, & \text{for } (q\bar{Q}), \\ E_M^* - V_\omega^q, & \text{for } (Q\bar{q}), \end{cases}$$

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

Medium Modifications in the LFQM+QMC model

- The Brjorken variable x——defined by the plus-component ratio of the quark to the meson momenta in free space

$$x = \frac{p_q^+}{P^+} = \frac{p_q^0 + p_q^3}{P^0 + P^3} = \frac{E_q + p_q^3}{E_M + P^3}, \quad \Rightarrow \quad x^* \equiv \frac{p_q^{*+}}{P^{*+}},$$

- For the quark-antiquark mesons $\quad p_q^{*+} = p_{\bar{q}}^{*+} \equiv E_q^* + p_q^{*3}, \qquad P^{*+} \equiv E_M^* + P^{*3},$
- In a nuclear medium, the Bjorken variable has a new definition

$$x \to \tilde{x}^* = \frac{p_q^{*+} + V_\omega^q}{P^{*+}} = x^* + \frac{V_\omega^q}{P^{*+}},$$

- By applying a change variable definition——to shift the integral limit of the Bjorken variable in **calculating the weak decay constant for the light mesons**

Medium Modifications in the LFQM+QMC model

- The weak-decay constant for the light meson in a nuclear medium is given by

$$f_{\mathrm{M}}^{*}=2\sqrt{6}\int_{-\frac{V_{\omega}^{q}}{P^{*+}}}^{1-\frac{V_{\omega}^{q}}{P^{*+}}}\mathrm{d}x^{*}\int\frac{\mathrm{d}^{2}\mathbf{k}_{\perp}}{2(2\pi)^{3}}\frac{\Phi(\tilde{x}^{*},\mathbf{k}_{\perp})}{\sqrt{\mathcal{A}(\tilde{x}^{*})^{2}+\mathbf{k}_{\perp}^{2}}}\mathcal{O}_{\mathrm{M}}(\tilde{x}^{*},\mathbf{k}_{\perp}).$$

- A final expression of the weak decay constant for the light meson in a nuclear medium

$$f_{\mathrm{M}}^{*}=2\sqrt{6}\int_{0}^{1}\mathrm{d}\tilde{x}^{*}\int\frac{\mathrm{d}^{2}\mathbf{k}_{\perp}}{2(2\pi)^{3}}\frac{\Phi(\tilde{x}^{*},\mathbf{k}_{\perp})}{\sqrt{\mathcal{A}(\tilde{x}^{*})^{2}+\mathbf{k}_{\perp}^{2}}}\mathcal{O}_{\mathrm{M}}(\tilde{x}^{*},\mathbf{k}_{\perp}).$$

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

Medium Modifications in the LFQM+QMC model

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

- For the light-heavy meson—-$q\bar{Q}$ or $\bar{q}Q$ contents—-Both scalar and vector potential contribute to the weak decay constant and DAs in a nuclear medium

- The longitudinal momentum for the quark and antiquark in a nuclear medium are given

$$x \to \begin{cases} \tilde{x}^* = \frac{p_q^{*+}+V_\omega^q}{P^{*+}+V_\omega^q} = \frac{x^*+V_\omega^q/P^{*+}}{(1+V_\omega^q/P^{*+})}, & \text{for } (q\bar{Q}), \\ \tilde{x}^* = \frac{p_q^{*+}-V_\omega^q}{P^{*+}-V_\omega^q} = \frac{x^*-V_\omega^q/P^{*+}}{(1-V_\omega^q/P^{*+})}, & \text{for } (Q\bar{q}). \end{cases}$$

$$\mathrm{d}x^* = (1 \pm V_\omega^q/P^{*+})\mathrm{d}\tilde{x}^*,$$

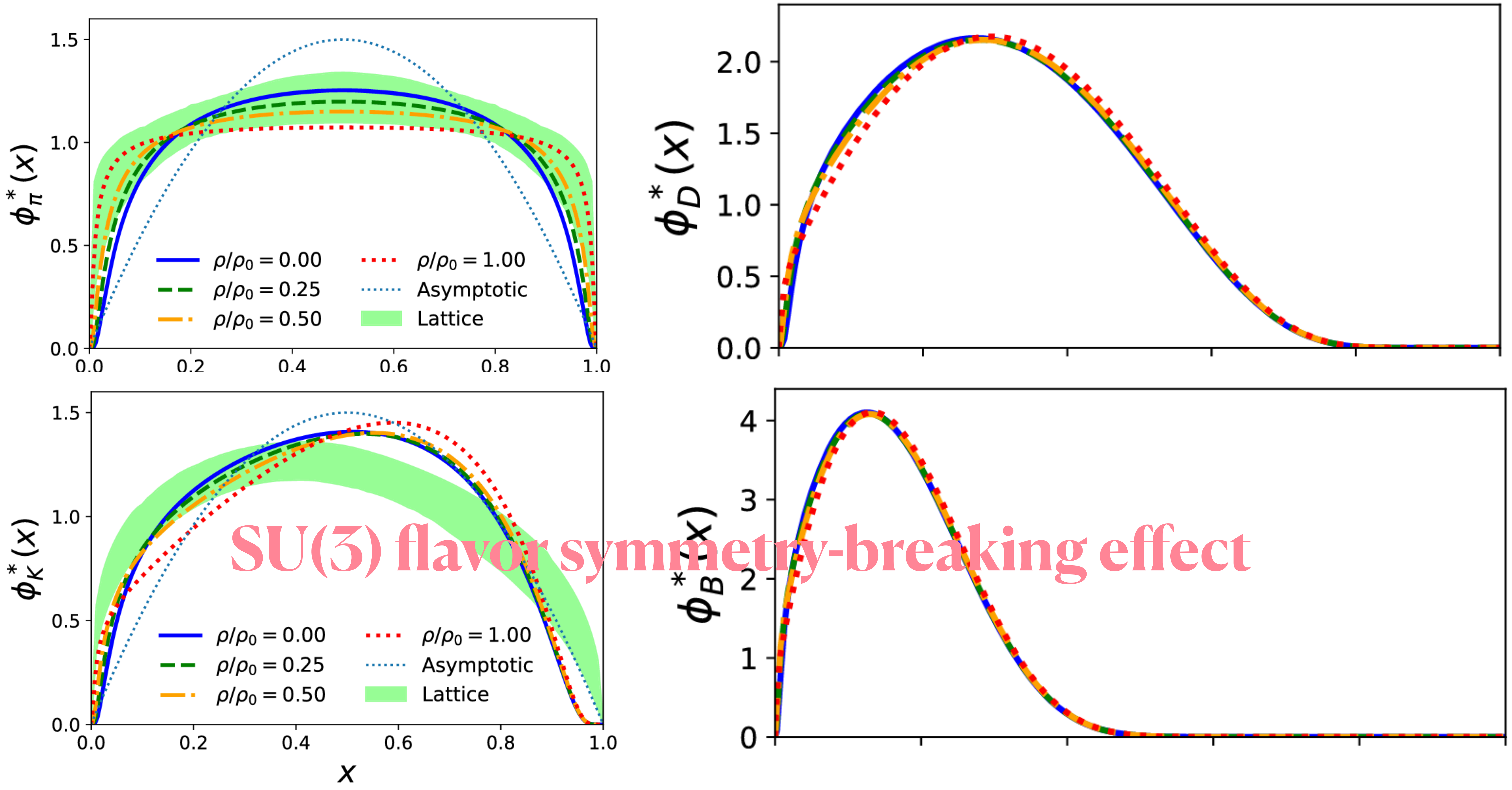
- A final expression for the light-heavy meson decay weak constant in a nuclear medium

$$f_{\mathrm{M}}^* = 2\sqrt{6}\int_0^1 \mathrm{d}\tilde{x}^* \int \frac{\mathrm{d}^2\mathbf{k}_\perp}{2(2\pi)^3}\left(1 \pm \frac{V_\omega^q}{P^{*+}}\right) \times \frac{\Phi(\tilde{x}^*, \mathbf{k}_\perp)}{\sqrt{\mathcal{A}(\tilde{x}^*)^2 + \mathbf{k}_\perp^2}}\mathcal{O}_{\mathrm{M}}(\tilde{x}^*, \mathbf{k}_\perp).$$

DAs in Nuclear Medium

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

- Numerical results for DAs for the pseudoscalar mesons



SU(3) flavor symmetry-breaking effect

[Lattice Parton Collaboration, PRL 129 (2022) 132001]

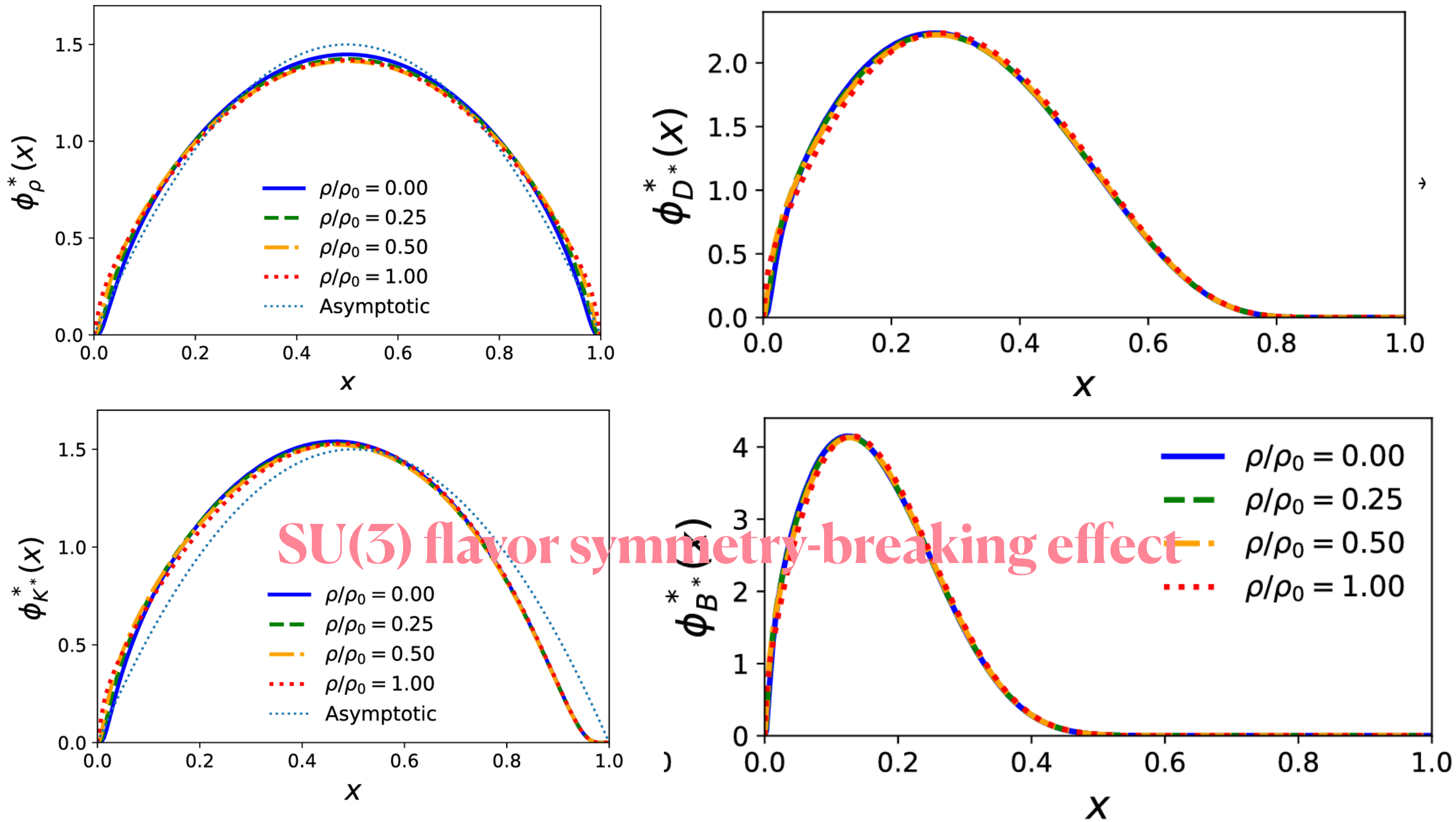
—-Pion DA is consistent with the lattice QCD results in free space

—-Kaon DA is consistent with the lattice QCD results in free space at low -x but at x>0.45 is rather different

DAs in Nuclear Medium

[Ahmad Jafar Arifi, PTPH, Kazuo Tsushima, PRD 107 (2023) 114010]

- Numerical results for DAs for the vector mesons



SU(3) flavor symmetry-breaking effect

Summary and Outlook

- We have demonstrated the DAs for the light-light and heavy-light mesons in free space and nuclear medium——**Pion and Kaon DAs (low-x) results are consistent with the lattice QCD data**——Unfortunately no (exp+lattice) data available for the heavy-light mesons
- Results for this calculation look promising——-**we are going to extend our investigation/studying on the medium effects on the heavy-light meson form factors**——Heavy-light meson is a very interesting object/system because they have different quark contents—-light and heavy quarks ——different symmetries
- Other indirect observables could be possible to observe heavy-light mesons——**to observe the sensitiveness of the structure and properties of meson to the nuclear medium effects**—-PDF, GPD, etc

Thank you very much for your attention

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