Hadron in Nucleus 2025 (HIN25)

Mesic-Nuclei Bound States

Arpita Mondal*, Amruta Mishra

Indian Institute of Technology, Delhi, India

based on..

- AM and Amruta Mishra, Phys. Rev. C 109, 025201 (2024);Phys. Rev. C 110, 055201 (2024);arXiv:2502.08320

Hadron in Nucleus 2025 (HIN25)

Mesic-Nuclei Bound States

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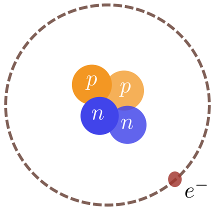
proceed with..

- Overview
- Theoretical Background
- Results & Discussions

Overview

Overview



Atom

Overview

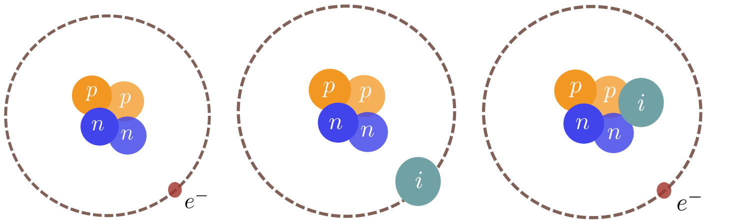
Mesons

Atomic nuclei

☆ *substantial attraction*

Mesic-nuclei bound states

Signatures of the Meson-N interactions



Atom **Mesic-Atom** **Mesic-Nucleus**

Schematic Idea

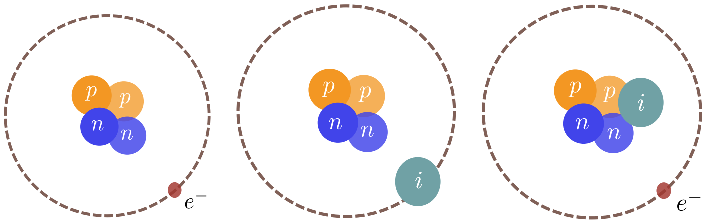
Overview

Mesons

Atomic nuclei ☆ *substantial attraction*

Mesic-nuclei bound states

Signatures of the Meson-N interactions



Atom **Mesic-Atom** **Mesic-Nucleus**

Schematic Idea

☑

1950s (Pionic Atoms): Stearns et al., Phys. Rev. 105, 1573 (1957)

1988 (η-Mesic): BNL : Chrien et al., Phys. Rev. Lett. 60, 2595 (1988)

1996 (Deeply Bound Pionic States): GSI : Yamazaki et al., Z. Phys. A 355, 219 (1996)

2005 (Kaonic nuclei): KEK, FINUDA : Agnello et al., Phys. Rev. Lett. 94, 212303 (2005); Suzuki et al., Nucl. Phys. A 754, 375c (2005)

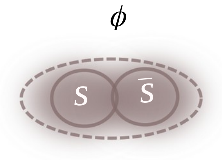
2013–14 (η-Mesic): COSY : Smyrski et al., Phys. Rev. C 87, 015201 (2013); Adlarson et al., Phys. Rev. Lett. 112, 202301 (2014)

2020s: (Kaonic nuclei) : J-PARC E15 : Prog. Theor. Exp. Phys. 2021, 051J01 (2021);

: (η’-Mesic) : MAMI : Metag et al., Eur. Phys. J. A 59, 183 (2023)

Upcominng: J-PARC, JLab, and FAIR

What's in our mind?



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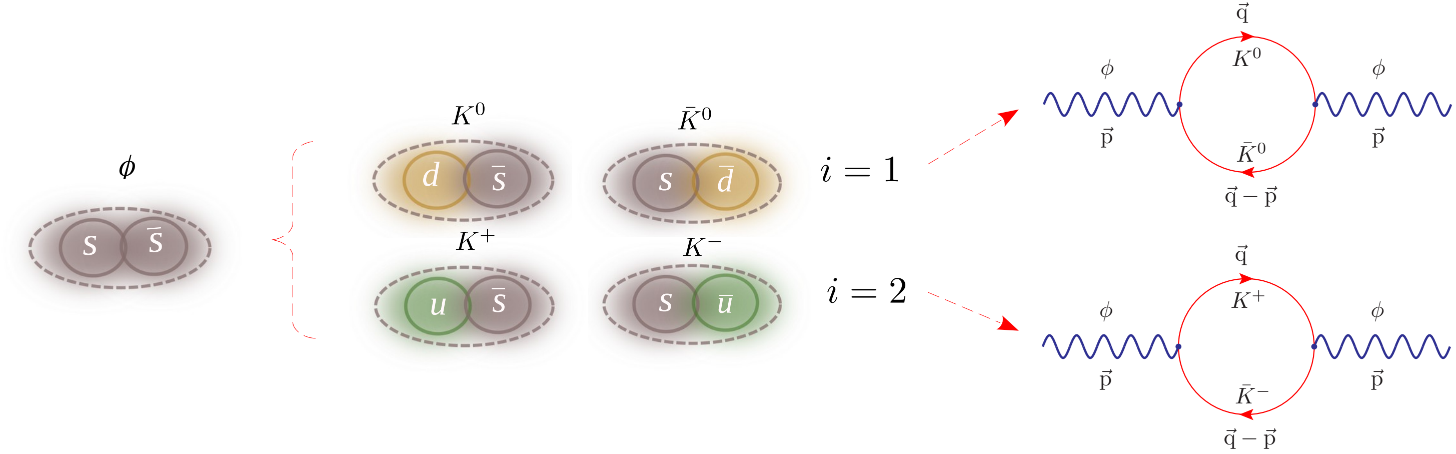
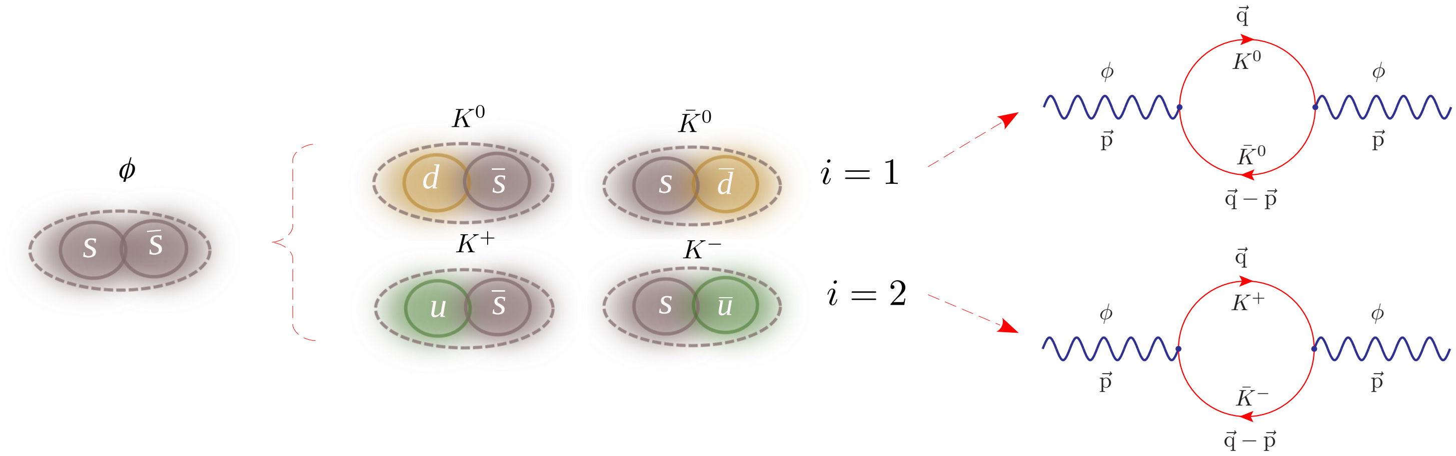
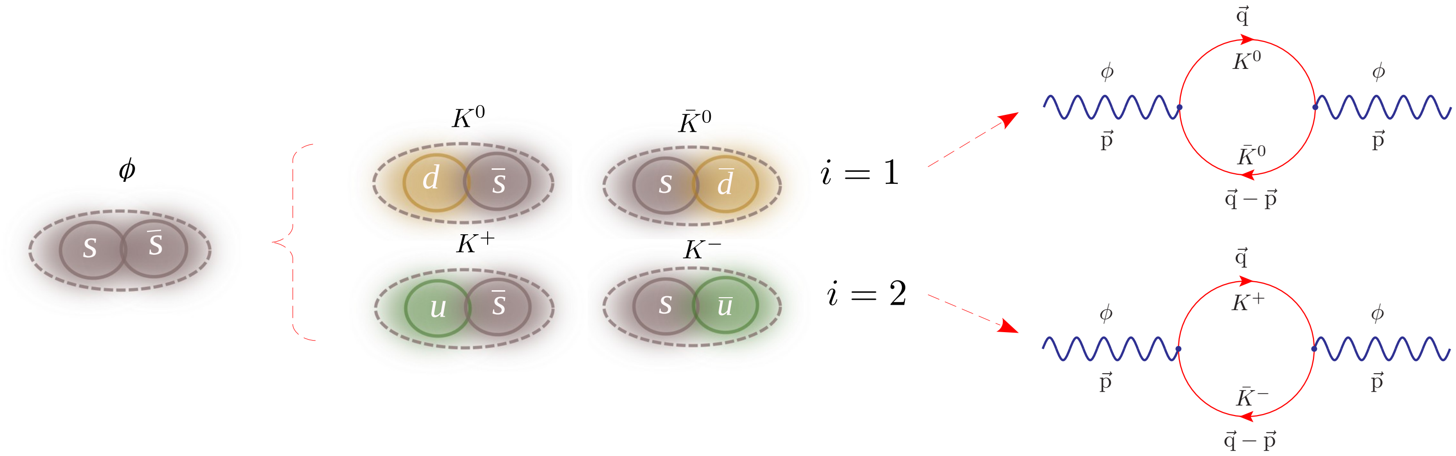


What's in our mind?



- $$D_i(\omega_i, |\vec{p}| \to 0, \rho) = \frac{1}{{\omega_i}^2 - {m^0_{\phi_i}}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$$
- $$\Pi^*_i(p) = i\frac{8}{3}g_i^2 \int \frac{d^4q}{(2\pi)^4}\vec{q}^{\,2}\frac{1}{(q^2 - m^{*2}_{K_i} + i\epsilon)}\frac{1}{((q-p)^2 - m^{*2}_{\bar{K}_i} + i\epsilon)}$$

What's in our mind?



$$m_{\phi_i}^{*2} - (m_{\phi_i}^0)^2 - \mathrm{Re}\Pi_i^*(m_{\phi_i}^{*2}) = 0$$

$$\Gamma_{\phi_i}^* = -\frac{1}{m_{\phi_i}^*}\mathrm{Im}\Pi_i^*$$

- $$D_i(\omega_i, |\vec{p}| \to 0, \rho) = \frac{1}{{\omega_i}^2 - {m_{\phi_i}^0}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$$
- $$\Pi_i^*(p) = i\frac{8}{3}g_i^2 \int \frac{d^4q}{(2\pi)^4}\vec{q}^{\,2}\frac{1}{(q^2 - m_{K_i}^{*2} + i\epsilon)}\frac{1}{((q-p)^2 - m_{\bar{K}_i}^{*2} + i\epsilon)}$$

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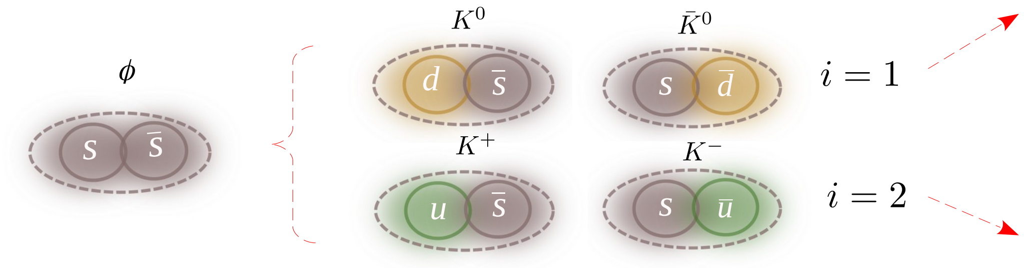
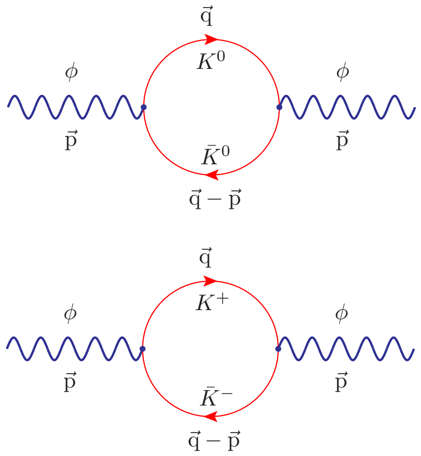
Quark Meson Coupling Model

P. A. M. Guichon, Phys. Lett. B 200, 235 (1988)





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$$m^{*2}_{\phi_i} - (m^0_{\phi_i})^2 - \mathrm{Re}\Pi^*_i(m^{*2}_{\phi_i}) = 0$$

$$\Gamma^*_{\phi_i} = -\frac{1}{m^*_{\phi_i}}\mathrm{Im}\Pi^*_i$$

- $D_i(\omega_i, |\vec{p}| \to 0, \rho) = \dfrac{1}{{\omega_i}^2 - {m^0_{\phi_i}}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$
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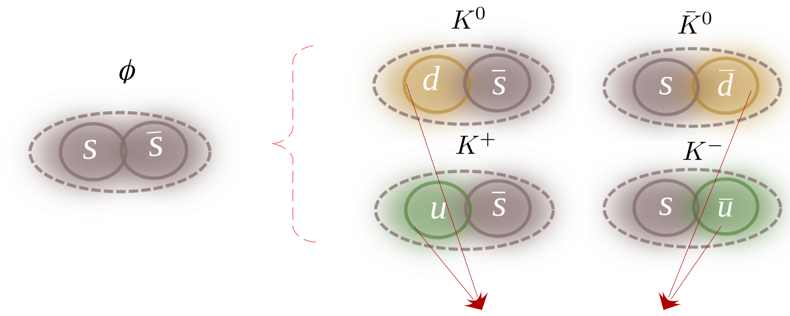

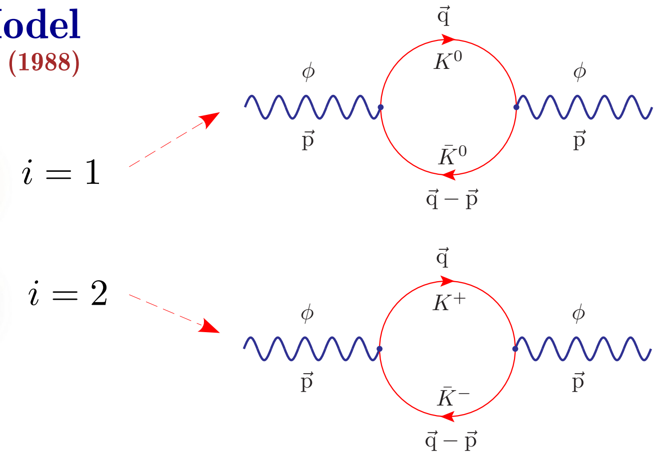

Nuclear Environment

$\sigma, \omega, \rho, \delta$

fields

- $$m^{*\,2}_{\phi_i} - \left(m^0_{\phi_i}\right)^2 - \mathrm{Re}\Pi^*_i(m^{*\,2}_{\phi_i}) = 0$$
  $$\Gamma^*_{\phi_i} = -\frac{1}{m^*_{\phi_i}} \mathrm{Im}\Pi^*_i$$

- $$D_i(\omega_i, |\vec{p}| \to 0, \rho) = \frac{1}{{\omega_i}^2 - {m^0_{\phi_i}}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$$

- $$\Pi^*_i(p) = i\frac{8}{3}g_i^2 \int \frac{d^4q}{(2\pi)^4} \vec{q}^{\,2} \frac{1}{(q^2 - m^{*\,2}_{K_i} + i\epsilon)} \frac{1}{((q-p)^2 - m^{*\,2}_{\bar{K}_i} + i\epsilon)}$$

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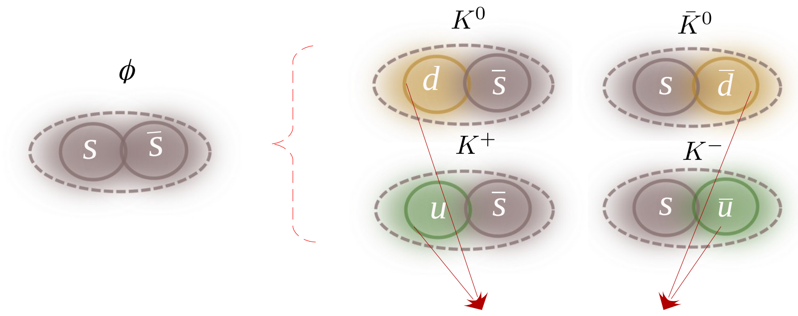
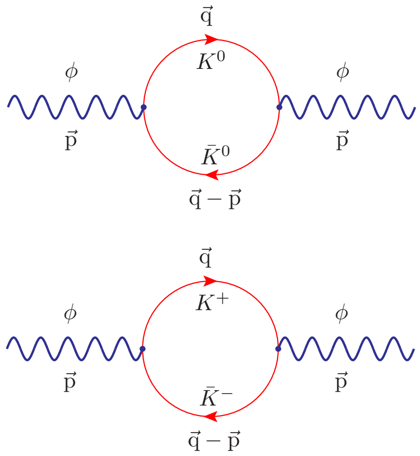


$i = 1$

$i = 2$



$$m^{*2}_{\phi_i} - \left(m^0_{\phi_i}\right)^2 - \mathrm{Re}\Pi^*_i(m^{*2}_{\phi_i}) = 0$$

$$\Gamma^*_{\phi_i} = -\frac{1}{m^*_{\phi_i}}\mathrm{Im}\Pi^*_i$$

Nuclear Environment

$\sigma, \omega, \rho, \delta$

fields

- $$\begin{aligned} m^\star_u &= m_u - g^q_\sigma \sigma - \frac{1}{2} g^q_\delta \delta_3, \\ m^\star_{\bar{u}} &= m_{\bar{u}} - g^q_\sigma \sigma + \frac{1}{2} g^q_\delta \delta_3, \\ m^\star_d &= m_d - g^q_\sigma \sigma + \frac{1}{2} g^q_\delta \delta_3, \\ m^\star_{\bar{d}} &= m_{\bar{d}} - g^q_\sigma \sigma - \frac{1}{2} g^q_\delta \delta_3 \end{aligned}$$

- $$D_i(\omega_i, |\vec{p}| \to 0, \rho) = \frac{1}{{\omega_i}^2 - {m^0_{\phi_i}}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$$

- $$\Pi^*_i(p) = i\frac{8}{3} g^2_i \int \frac{d^4 q}{(2\pi)^4} \vec{q}^{\,2} \frac{1}{(q^2 - m^{*2}_{K_i} + i\epsilon)} \frac{1}{((q-p)^2 - m^{*2}_{\bar{K}_i} + i\epsilon)}$$

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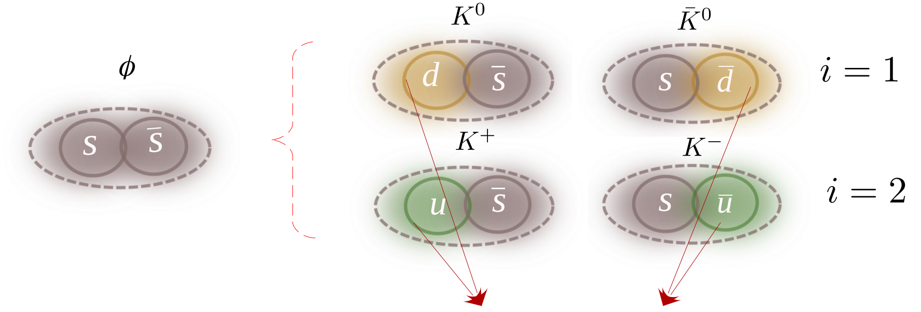

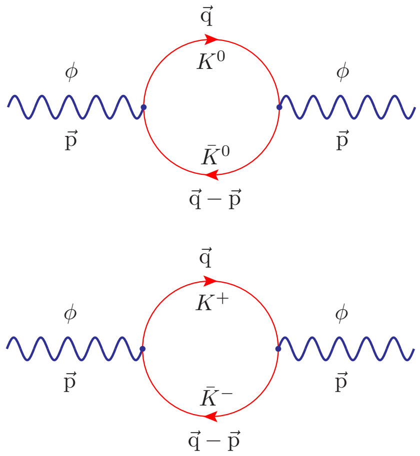

Nuclear Environment

$\sigma, \omega, \rho, \delta$

fields

- $$m^{*2}_{\phi_i} - (m^0_{\phi_i})^2 - \mathrm{Re}\Pi^*_i(m^{*2}_{\phi_i}) = 0$$
$$\Gamma^*_{\phi_i} = -\frac{1}{m^*_{\phi_i}}\mathrm{Im}\Pi^*_i$$

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$$m^\star_h(\sigma,\delta) = \frac{\sum_f n_{fh}\Omega^\star_{fh} - Z_h}{R^\star_h} + \frac{4}{3}\pi R^{\star 3}_h B,\ \Omega^\star_{fh} = \sqrt{x^{\star 2}_{fh} + (R^\star_h m^\star_{fh})^2}$$

What's in our mind?

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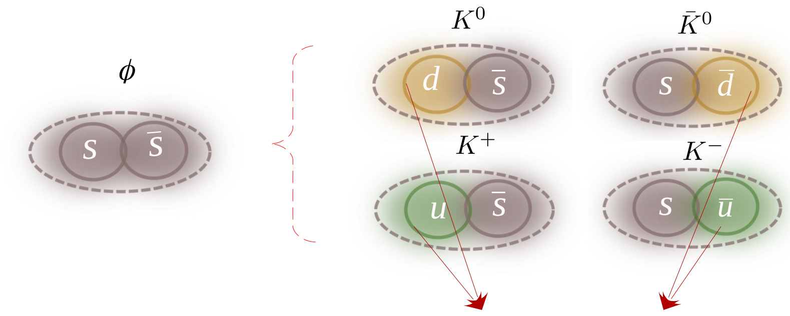

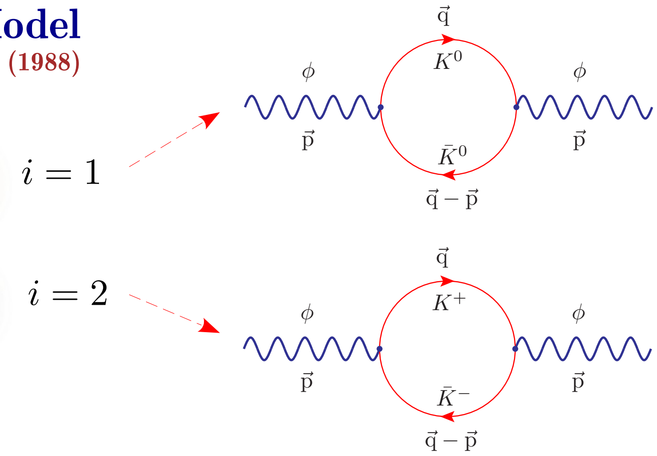

Nuclear Environment

$\sigma, \omega, \rho, \delta$ *fields*

- $$m^*_{\phi_i}{}^2 - (m^0_{\phi_i})^2 - \mathrm{Re}\Pi^*_i(m^*_{\phi_i}{}^2) = 0$$
$$\Gamma^*_{\phi_i} = -\frac{1}{m^*_{\phi_i}} \mathrm{Im}\Pi^*_i$$

- $$D_i(\omega_i, |\vec{p}| \to 0, \rho) = \frac{1}{\omega_i{}^2 - m^0_{\phi_i}{}^2 - \Pi_i(\omega_i, |\vec{p}| \to 0, \rho)}$$

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$$m^\star_h(\sigma, \delta) = \frac{\sum_f n_{fh} \Omega^\star_{fh} - Z_h}{R^\star_h} + \frac{4}{3}\pi R^{\star 3}_h B, \; \Omega^\star_{fh} = \sqrt{x^{\star 2}_{fh} + (R^\star_h m^\star_{fh})^2}$$

Framework: QMC Model

$$\mathcal{L} = \bar{\psi}\Big[i\gamma.\partial - \Big(m_N - \tilde{g}_\sigma(\sigma)\sigma - \tilde{g}_\delta(\delta)\frac{\tau^a}{2}\delta^a\Big) - \gamma^\mu\Big(g_\omega\omega_\mu + g_\rho\frac{\tau^a}{2}\rho^a_\mu\Big)\Big]\psi$$
$$+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) + \frac{1}{2}(\partial_\mu\delta^a\partial^\mu\delta^a - m_\delta^2\delta^a\delta^a) - \Big[\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\Big]$$
$$- (\frac{1}{4}\rho^a_{\mu\nu}\rho^{\mu\nu,a} - \frac{1}{2}m_\rho^2\rho^a_\mu\rho^{\mu,a})$$

- $$\tilde{g}_{\sigma,\delta}(\sigma,\delta) = g^q_{\sigma,\delta}\sum_q n_{qN}S_{qN}(\sigma,\delta)$$

$$S_{qN}(\sigma) = \mathcal{I}^s_N, \quad S_{qN}(\delta^3) = \frac{\tau^3_q}{2}\mathcal{I}^s_N,$$

$$\mathcal{I}^s_N = \frac{\Omega_{qN}/2 + m^\star_{qN}R^\star_N(\Omega_{qN}-1)}{\Omega_{qN}(\Omega_{qN}-1) + m^*_{qN}R^\star_N/2}$$

$$g_\omega = g^q_\omega\sum_q n_{qN}, \; g_\rho = g^q_\rho$$

Nuclear Matter

(i) $$\phi = \frac{1}{m_\phi^2}\sum_{N=p,n}\Big(-\frac{\partial m^*_N(\phi)}{\partial\phi}\Big)\rho^s_N, \quad \text{where, } \phi = \sigma, \delta^3,$$

(ii) $$\omega_0 = \sum_{N=p,n}\frac{g_\omega}{m_\omega^2}\rho_N = \frac{g_\omega}{m_\omega^2}\rho_B,$$

(iii) $$\rho^3_0 = \sum_{N=p,n}\frac{g_\rho}{m_\rho^2}\frac{(\tau^3\rho)_N}{2} = -\frac{g_\rho}{m_\rho^2}\eta\rho_B,$$

Scalar densities and number densities:

$$\rho^s_N = \frac{2}{(2\pi)^3}\int d^3\vec{k}\,\Theta(k_{FN} - |\vec{k}|)\frac{m^*_N(\sigma,\delta^3)}{\sqrt{m^{*2}_N(\sigma,\delta^3) + |\vec{k}|^2}},$$

$$\rho_N = \frac{2}{(2\pi)^3}\int d^3\vec{k}\,\Theta(k_{FN} - |\vec{k}|) = \frac{k^3_{FN}}{3\pi^2}$$

$$\eta = (\rho_n - \rho_p)/(2\rho_B)$$ Asymmtery Parameter

Framework: QMC Model

$$\mathcal{L} = \bar{\psi}\Big[i\gamma.\partial - \Big(m_N - \tilde{g}_\sigma(\sigma)\sigma - \tilde{g}_\delta(\delta)\frac{\tau^a}{2}\delta^a\Big) - \gamma^\mu\Big(g_\omega\omega_\mu + g_\rho\frac{\tau^a}{2}\rho^a_\mu\Big)\Big]\psi$$
$$+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) + \frac{1}{2}(\partial_\mu\delta^a\partial^\mu\delta^a - m_\delta^2\delta^a\delta^a) - \Big[\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\Big]$$
$$- (\frac{1}{4}\rho^a_{\mu\nu}\rho^{\mu\nu,a} - \frac{1}{2}m_\rho^2\rho^a_\mu\rho^{\mu,a}) - \frac{e}{2}\psi\gamma^\mu(1+\tau^a)A_\mu - \frac{1}{4}A_{\mu\nu}A^{\mu\nu}$$

- $\tilde{g}_{\sigma,\delta}(\sigma,\delta) = g^q_{\sigma,\delta}\sum_q n_{qN}S_{qN}(\sigma,\delta)$

$$S_{qN}(\sigma) = \mathcal{I}^s_N, \quad S_{qN}(\delta^3) = \frac{\tau^3_q}{2}\mathcal{I}^s_N,$$
$$\mathcal{I}^s_N = \frac{\Omega_{qN}/2 + m^\star_{qN}R^\star_N(\Omega_{qN}-1)}{\Omega_{qN}(\Omega_{qN}-1) + m^*_{qN}R^\star_N/2}$$
$$g_\omega = g^q_\omega\sum_q n_{qN}, \; g_\rho = g^q_\rho$$

Finite Nucleus

$$(-\frac{d^2}{dr^2} - \frac{2}{r}\frac{d}{dr} + m_M^2)M(r) = \mathcal{J}_M(r)$$

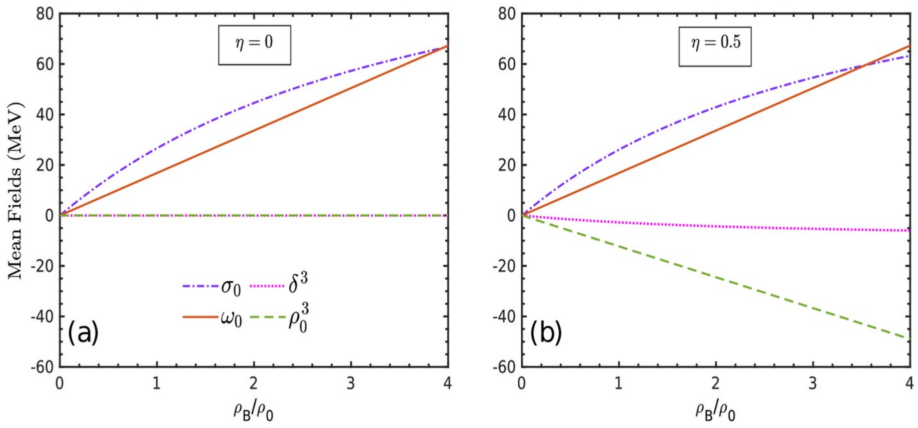
$$\begin{cases} g_\sigma\Big[\rho^s_p(r)\Big(-\frac{\partial m^*_p(r)}{\partial\sigma}\Big) + \rho^s_n(r)\Big(-\frac{\partial m^*_n(r)}{\partial\sigma}\Big)\Big] & \text{for } \sigma \text{ field} \\ \frac{g_\delta}{2}\Big[\rho^s_p(r)\Big(-\frac{\partial m^*_p(r)}{\partial\delta^3}\Big) + \rho^s_n(r)\Big(-\frac{\partial m^*_n(r)}{\partial\delta^3}\Big)\Big] & \text{for } \delta^3 \text{ field} \\ g_\omega\Big[\rho_p(r) + \rho_n(r)\Big] & \text{for } \omega_0 \text{ field} \\ \frac{g_\rho}{2}\Big[\rho_p(r) - \rho_n(r)\Big] & \text{for } \rho^3_0 \text{ field} \\ e\rho_p(r) & \text{for Coulomb field} \end{cases}$$

Scalar densities and number densities:

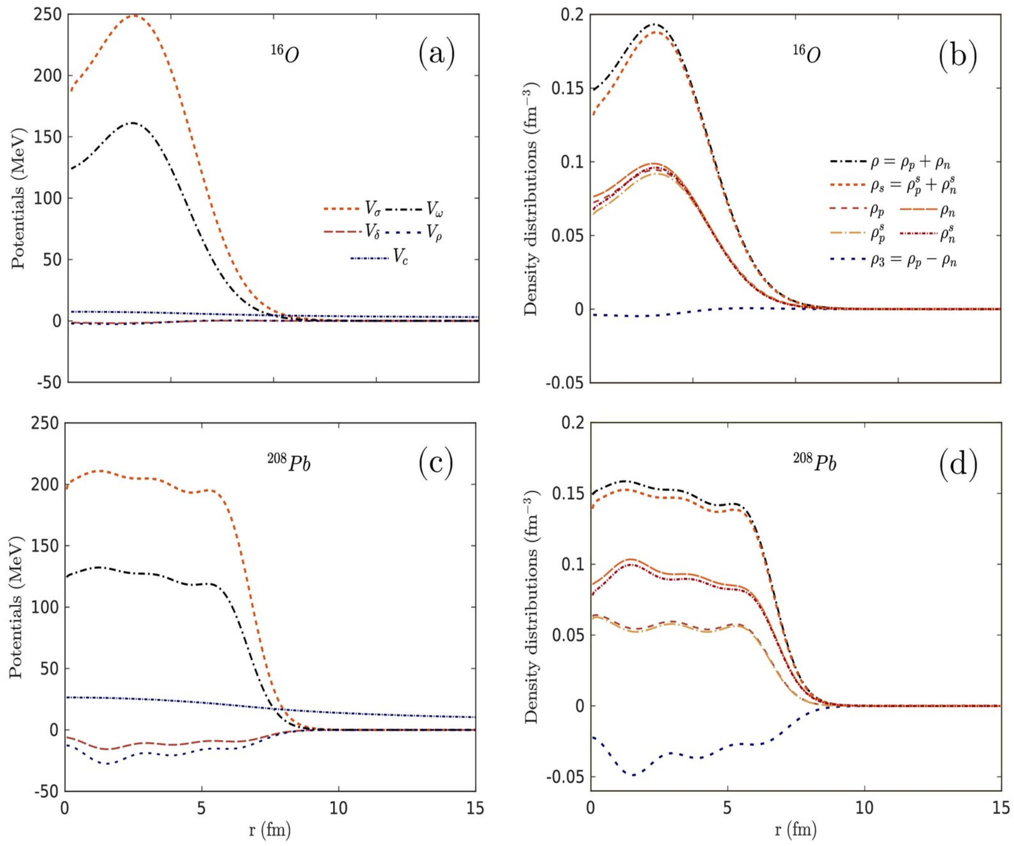
$$\rho^s_p(r) = \sum_p^Z \frac{(2j_p+1)}{4\pi r^2}(|G_p(r)|^2 - |F_p(r)|^2),$$
$$\rho^s_n(r) = \sum_n^N \frac{(2j_n+1)}{4\pi r^2}(|G_n(r)|^2 - |F_n(r)|^2),$$
$$\rho_p(r) = \sum_p^Z \frac{(2j_p+1)}{4\pi r^2}(|G_p(r)|^2 + |F_p(r)|^2),$$
$$\rho_n(r) = \sum_n^N \frac{(2j_p+1)}{4\pi r^2}(|G_n(r)|^2 + |F_n(r)|^2),$$

Potentials in different nuclear environment

Nuclear Matter

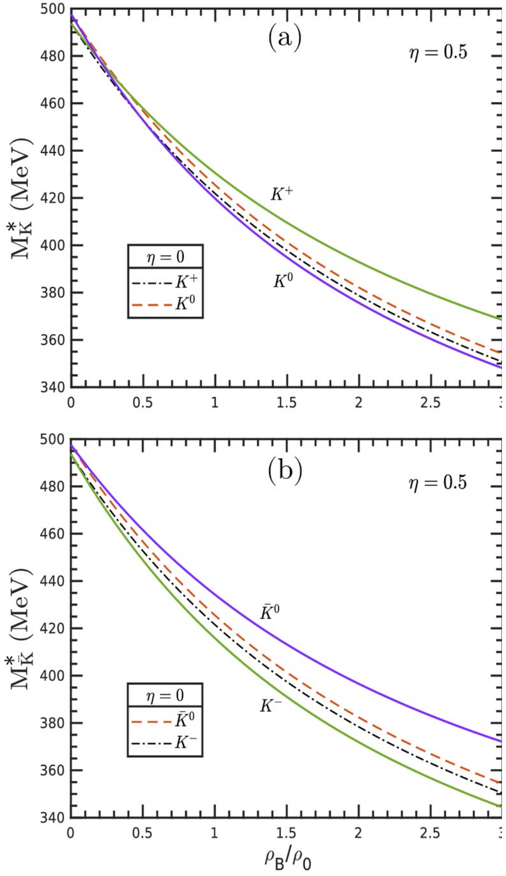


Finite Nucleus

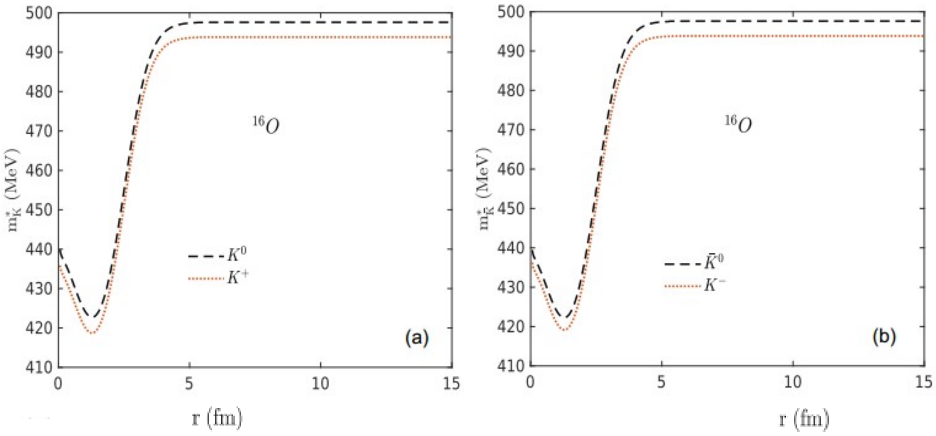


AM and Amruta Mishra, Phys. Rev. C 109, 025201 (2024); Phys. Rev. C 110, 055201 (2024)

Masses of K mesons



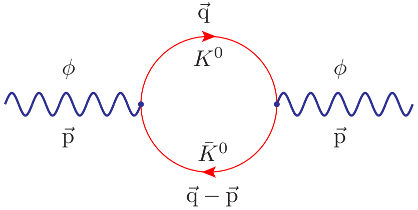
Mass Splittings



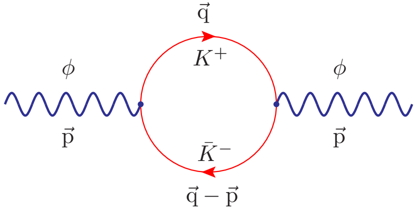
AM and Amruta Mishra, Phys. Rev. C 109, 025201 (2024); Phys. Rev. C 110, 055201 (2024)

Phi in nuclear environment

- ϕ meson ← - - - kaons



$i = 1$



$i = 2$

- $$\Pi_i^*(p) = i\frac{8}{3}g_i^2 \int \frac{d^4q}{(2\pi)^4}\vec{q}^{\,2}\frac{1}{(q^2 - m_{K_i}^{*2} + i\epsilon)}\frac{1}{((q-p)^2 - m_{\bar{K}_i}^{*2} + i\epsilon)}$$

$$\mathrm{Re}\Pi_i^* = -\frac{4}{3}g_i^2\,\mathcal{P}\int_0^{\Lambda_K}\left[\frac{d^3q}{(2\pi)^3}q^2\left(\frac{\Lambda_K^2 + m_{\phi_i}^{*2}}{\Lambda_K^2 + 4E_{K_i}^{*2}}\right)^2\left(\frac{\Lambda_K^2 + m_{\phi_i}^{*2}}{\Lambda_K^2 + 4E_{\bar{K}_i}^{*2}}\right)^2\frac{(E_{K_i}^* + E_{\bar{K}_i}^*)}{E_{K_i}^*E_{\bar{K}_i}^*((E_{K_i}^* + E_{\bar{K}_i}^*)^2 - m_{\phi_i}^{*2})}\right], E_{K(\bar{K})_i}^* = (q^{\,2} + m_{K(\bar{K})_i}^{*2})^{1/2}$$

$$\mathrm{Im}\Pi_i^* = \frac{2}{3\pi}g_i^2|\vec{q}_i|^3 \qquad |\vec{q}_i| = \frac{1}{2m_\phi^*}\left((m_{\phi_i}^{*2} - (m_{K_i}^* + m_{\bar{K}_i}^*)^2)(m_{\phi_i}^{*2} - (m_{K_i}^* - m_{\bar{K}_i}^*)^2)\right)^{1/2}$$

i	$\phi \to K_L^0 K_S^0$	$\phi \to K^+K^-$
$\Gamma_{\phi_i}/\Gamma_\phi^{tot}$	33.9 %	49.1 %
Γ_{ϕ_i} (MeV)	1.440	2.086
g_i	3.3212	3.2281

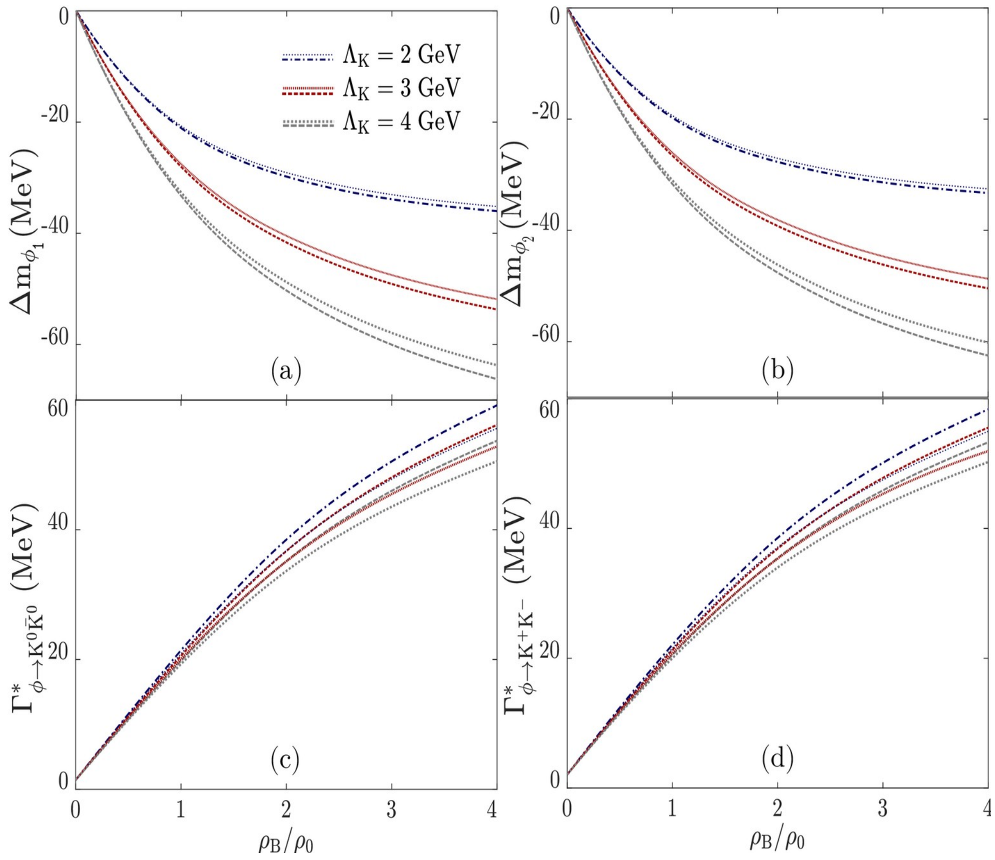
- $$\begin{cases} m_{\phi_i}^{*2} - \left(m_{\phi_i}^0\right)^2 - \mathrm{Re}\Pi_i^*(m_{\phi_i}^{*2}) = 0 \\ \Gamma_{\phi_i}^* = -\dfrac{1}{m_{\phi_i}^*}\mathrm{Im}\Pi_i^* \end{cases}$$

Λ_K	$m_{\phi_i}^0$ (MeV)	
(GeV)	$(i = 1)$	$(i = 2)$
2	1074.0	1073.2
3	1133.6	1130.7
4	1215.2	1209.4

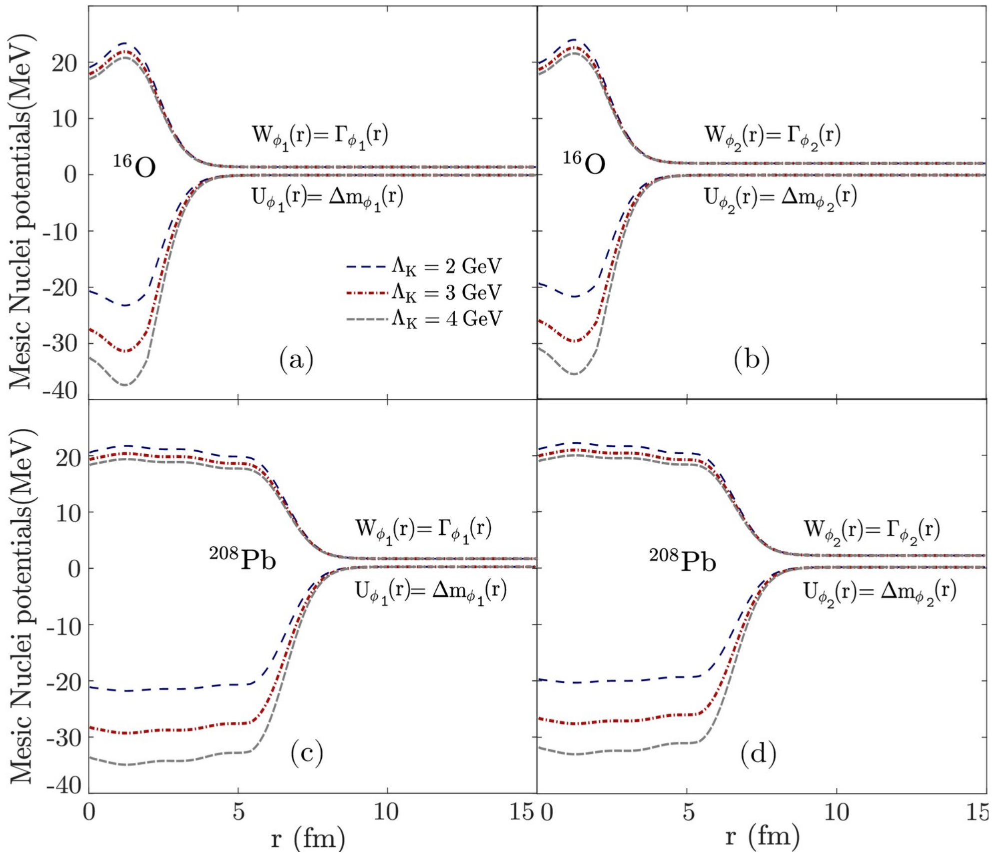
G. Krein, A. W. Thomas, and K. Tsushima, Phys. Lett. B 697, 136 (2011), AM and Amruta Mishra, arXiv:2502.08320

Phi in nuclear environment

Nuclear Matter



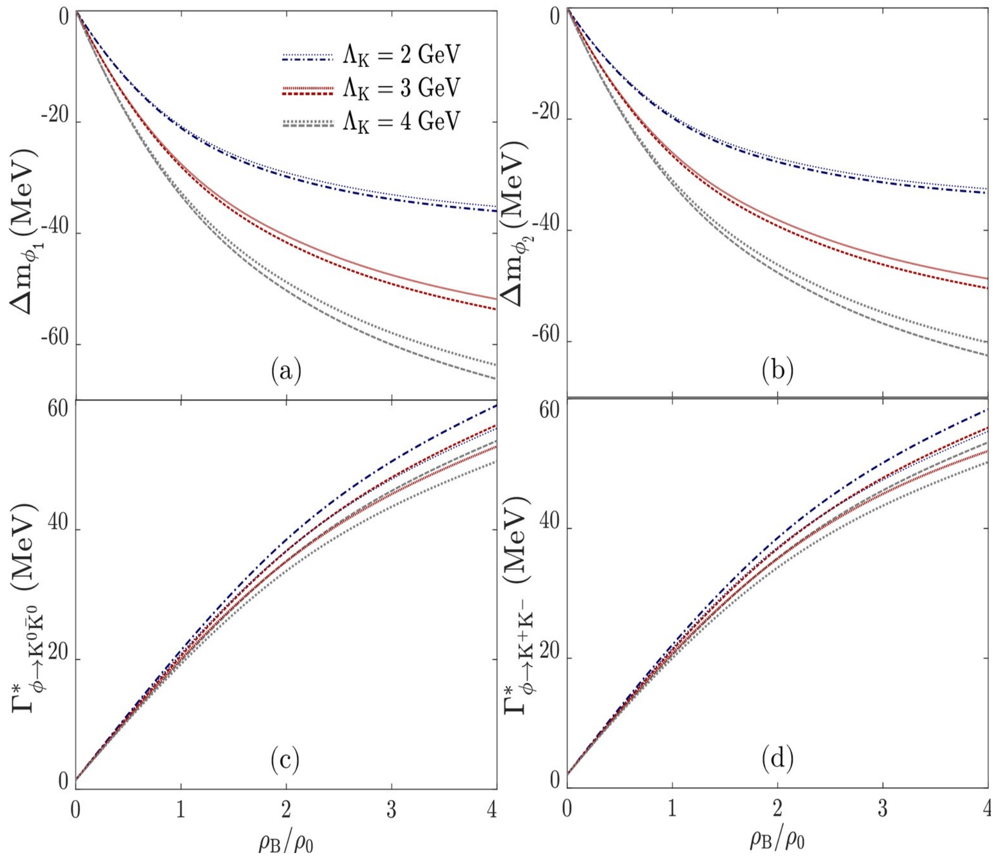
Finite Nuclei



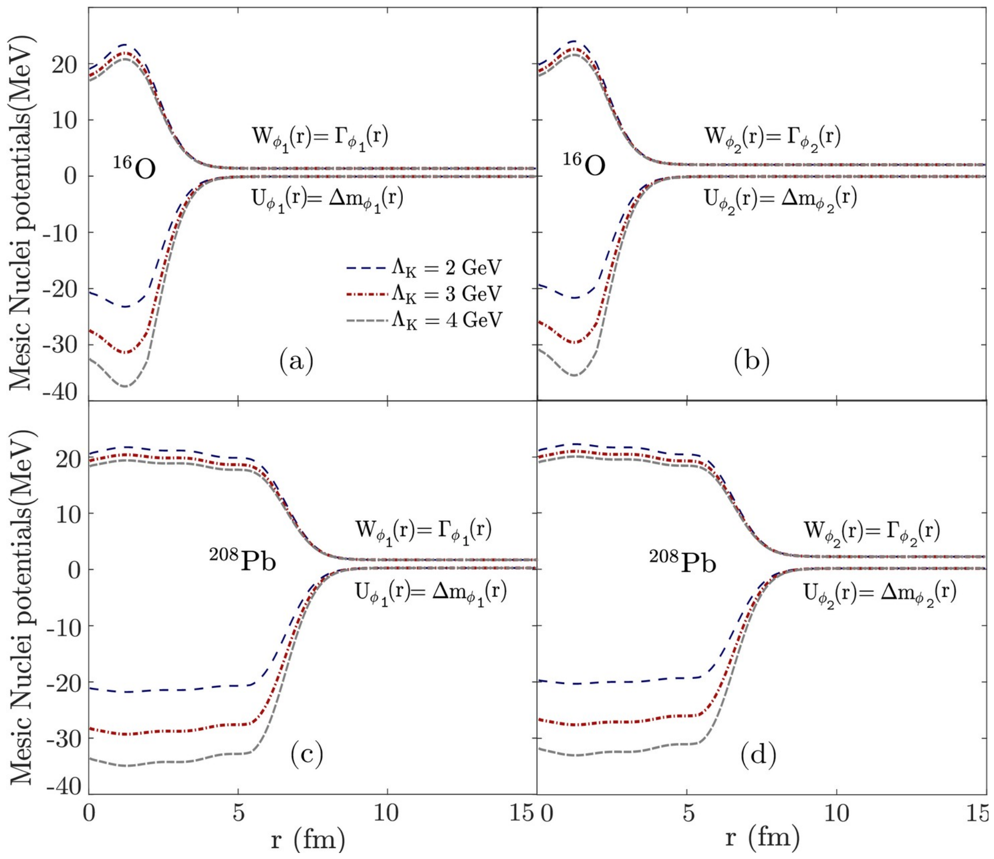
AM and Amruta Mishra, arXiv:2502.08320

Phi in nuclear environment

Nuclear Matter



Finite Nuclei

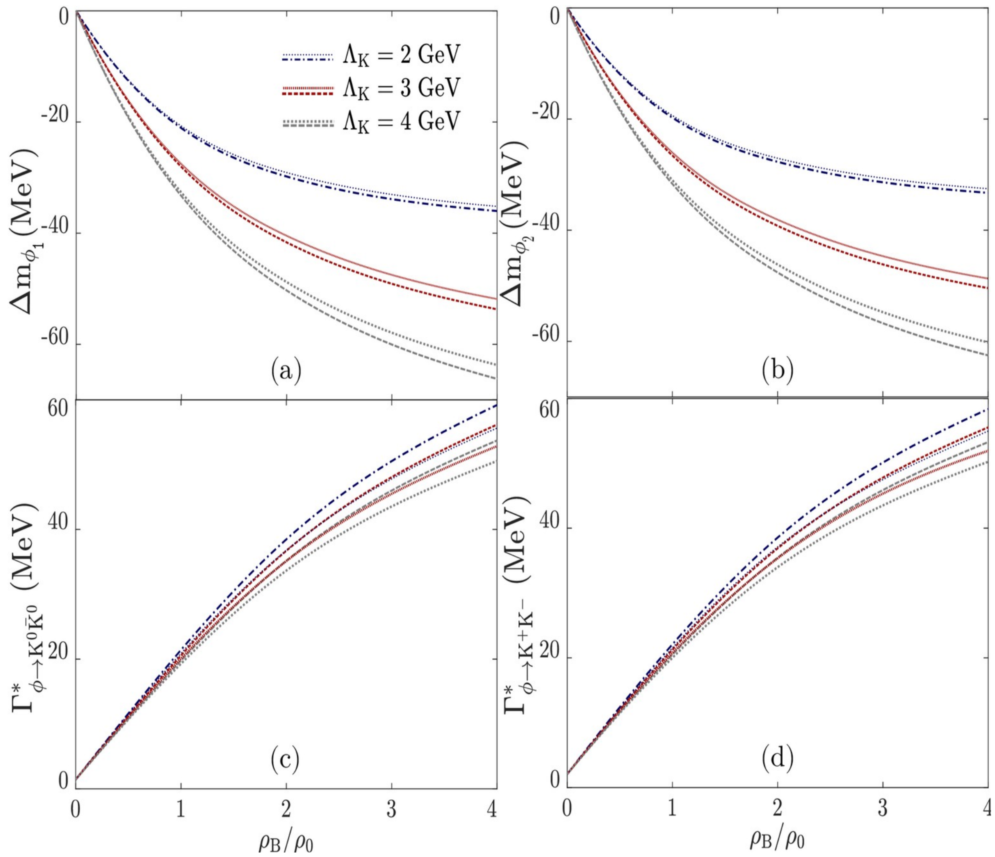


AM and Amruta Mishra, arXiv:2502.08320

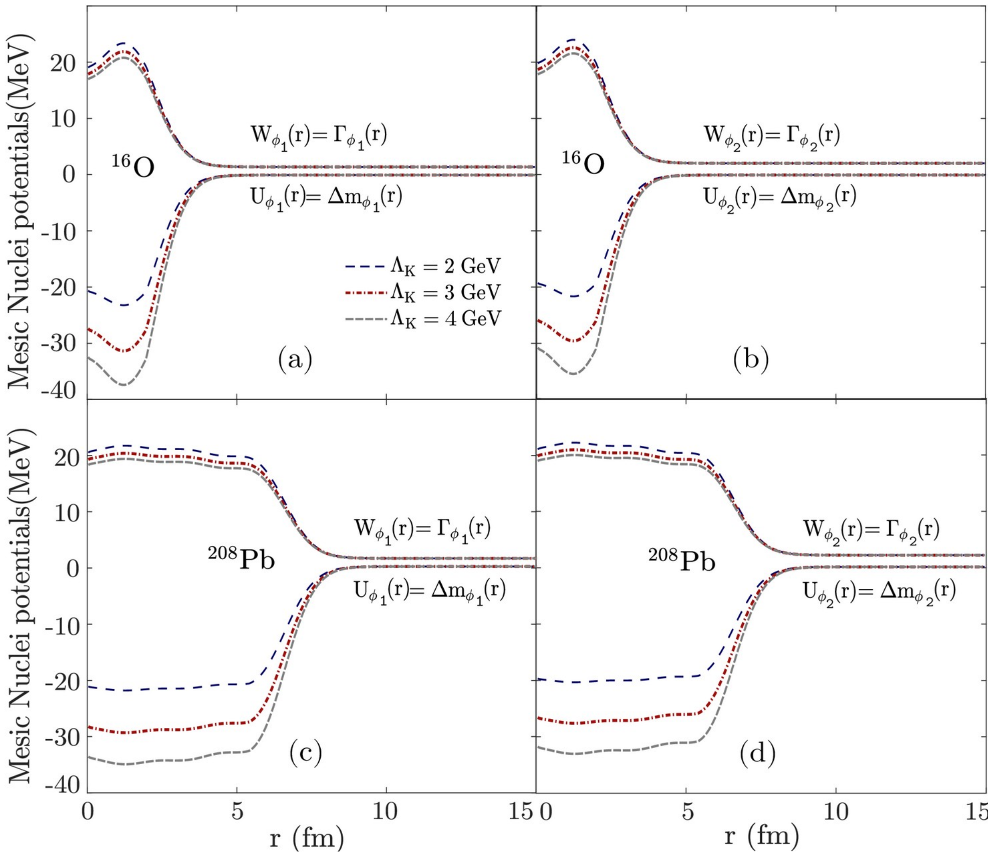
Phi in nuclear environment

HIN25

Nuclear Matter



Finite Nuclei



✓ $V_{\phi_i}(r) = U_{\phi_i}(r) - \frac{i}{2} W_{\phi_i}(r)$

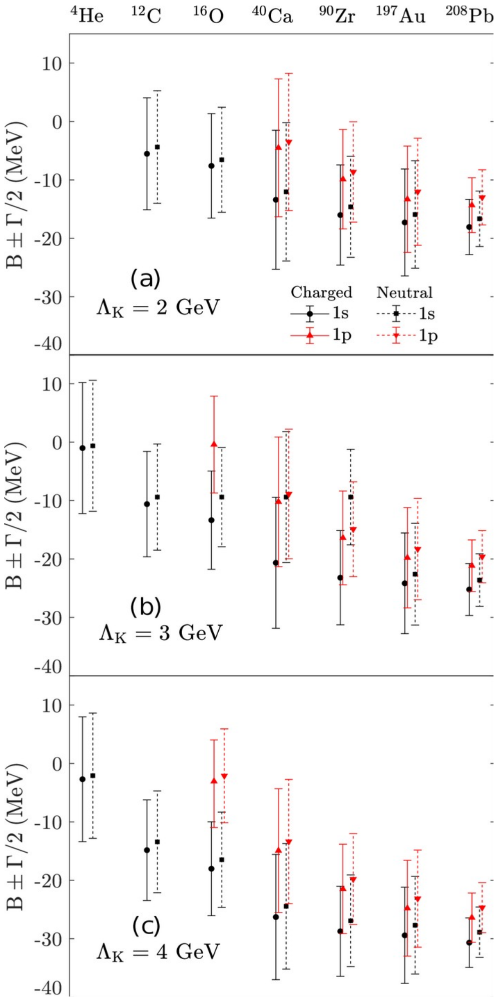
AM and Amruta Mishra, arXiv:2502.08320

Formation of Meson-Nucleus bound states

$$\Big(-\nabla^2 + (\mu + V_{\phi_i}(r))^2 \Big)\Phi_i(r) = \epsilon_i^2 \Phi_i(r)$$

$$\mathrm{B}_i = \mathrm{Re}(\epsilon_i) - \mu \qquad\qquad \Gamma_i = -2\mathrm{Im}(\epsilon_i)$$

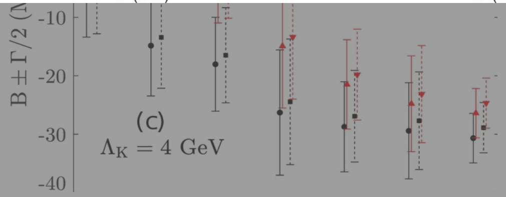
Phi in atomic nucleus

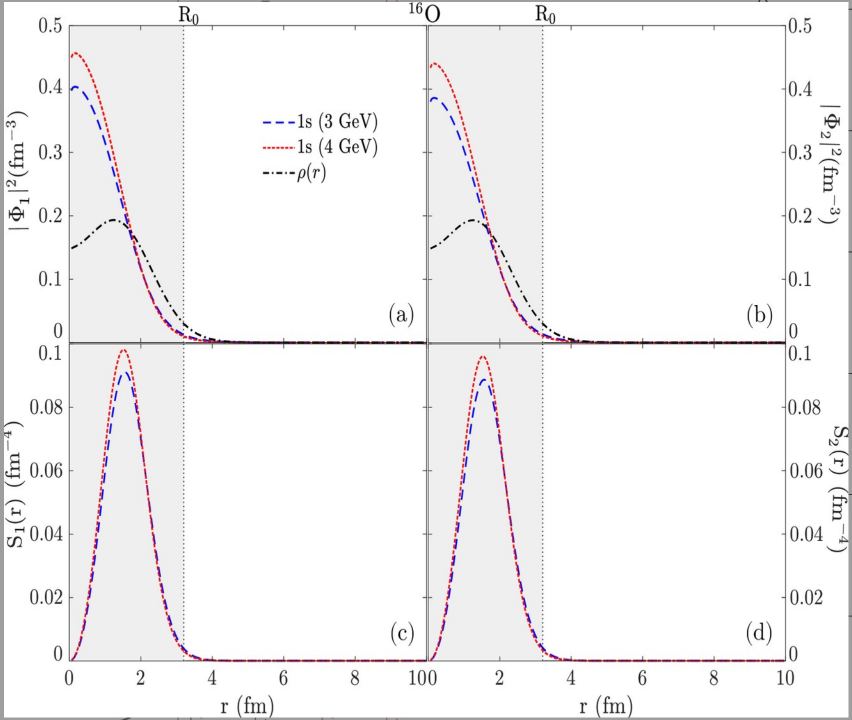


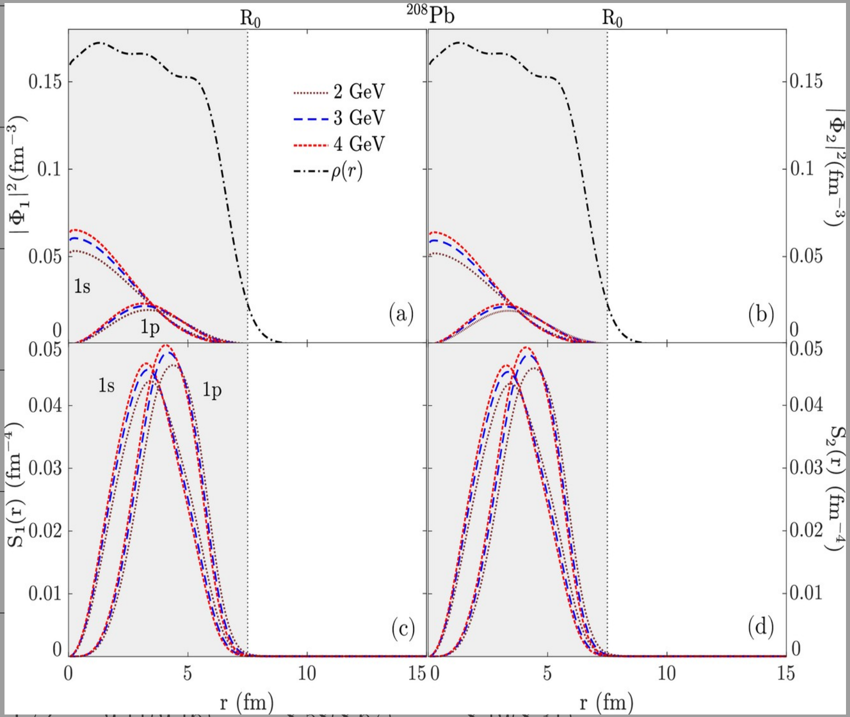
Λ_K			2 GeV	3 GeV	4 GeV
^{4}He	1s	B	×(×)	-1.02(-0.64)	-2.70(-2.09)
		Γ/2	×(×)	11.21(11.21)	10.68(10.72)
	1p	B	× (×)	×(×)	×(×)
		Γ/2	×(×)	×(×)	×(×)
^{12}C	1s	B	-5.53(-4.63)	-10.61(-9.41)	-14.84(-13.42)
		Γ/2	9.59(9.63)	9.02(9.09)	10.68(10.72)
	1p	B	× (×)	×(×)	×(×)
		Γ/2	×(×)	×(×)	×(×)
^{16}O	1s	B	-7.60(-6.55)	-13.36(-12.02)	-18.02(-16.48)
		Γ/2	8.94(8.99)	8.41(8.50)	8.03(8.15)
	1p	B	× (×)	-0.42(×)	-3.06(-2.11)
		Γ/2	×(×)	8.30(×)	7.90(8.03)
^{40}Ca	1s	B	-13.40(-12.04)	-20.66(-19.03)	-26.29(-24.45)
		Γ/2	11.90(11.84)	11.21(11.21)	10.72(10.75)
	1p	B	-4.51(-3.49)	-10.22(-8.88)	-14.92(-13.36)
		Γ/2	11.79(11.74)	11.09(11.09)	10.59(10.63)
^{90}Zr	1s	B	-16.01(-14.61)	-23.21(-21.59)	-28.73(-26.92)
		Γ/2	8.57(8.64)	8.07(8.18)	7.71(7.84)
	1p	B	-9.88(-8.64)	-16.39(-14.90)	-21.48(-19.80)
		Γ/2	8.51(8.59)	8.02(8.12)	7.65(7.78)
^{197}Au	1s	B	-17.28(-15.92)	-24.17(-22.61)	-29.42(-27.69)
		Γ/2	9.15(9.20)	8.62(8.71)	8.23(8.35)
	1p	B	-13.31(-12.03)	-19.79(-18.31)	-24.78(-23.13)
		Γ/2	9.11(9.16)	8.58(8.67)	8.19(8.31)
^{208}Pb	1s	B	-18.06(-16.65)	-25.23(-23.61)	-30.67(-28.88)
		Γ/2	9.44(9.48)	8.89(8.97)	8.49(8.60)
	1p	B	-14.33(-12.99)	-21.16(-19.61)	-26.39(-24.67)
		Γ/2	9.40(9.44)	8.85(8.94)	8.45(8.57)

AM and Amruta Mishra, arXiv:2502.08320

Phi in atomic nucleus







Λ_K			2 GeV	3 GeV	4 GeV
		Γ/2	9.11(9.16)	8.58(8.67)	8.19(8.31)
^{208}Pb	1*s*	B	-18.06(-16.65)	-25.23(-23.61)	-30.67(-28.88)
		Γ/2	9.44(9.48)	8.89(8.97)	8.49(8.60)
	1*p*	B	-14.33(-12.99)	-21.16(-19.61)	-26.39(-24.67)
		Γ/2	9.40(9.44)	8.85(8.94)	8.45(8.57)

AM and Amruta Mishra, arXiv:2502.08320

Summary

- We study the probable interactions of ϕ meson in different nuclear environment.

- ϕ meson-nucleus bound states are studied with the mass modification of ϕ meson using the charged as well as neutral kaon loops with the modified masses of K and $\bar{K}$ mesons as calculated within the QMC model.

Thank you for your attention

Back Ups

Bag Parameters

M_p (MeV)	R_p (fm)	$B^{1/4}$ (MeV)$^{1/4}$	Z_p	M_n (MeV)	R_n (fm)	Z_n
938.272	0.6	211.238	4.0015	939.565	0.6003	4.0012

A.M. and Amruta Mishra, Phys. Rev. C 109 025201(2024)

Coupling Constants

g_σ^q	g_δ^q	g_ω^q	g_ρ^q
5.98	12.60	2.98	12.59

in MeV

$m_u=2.16$ $m_d=4.67$	$m_s=93.4$ $m_c=1270$ $m_b=4180$

[A. M. Santos et al., Phys. Rev. C 79, 045805 (2009)]

For the vacuum masses and constant B

	M(MeV) (I)	R (fm)	Z
K^0 ($\bar{K}^0$)	497.611	0.4824	3.2860
K^+ (K^-)	493.677	0.4811	3.2924
D^0 ($\bar{D}^0$)	1864.84	0.5798	1.8423
D^+ (D^-)	1869.66	0.5808	1.8319
B^0 ($\bar{B}^0$)	5279.66	0.6508	-0.2609
B^+ (B^-)	5279.34	0.6507	-0.2638

$$M_i^\star(\sigma,\delta^3)=\frac{\sum_f n_{fi}\Omega_{fi}^\star - Z_i}{R_i^\star}+\frac{4}{3}\pi R_i^{\star 3}B$$

R. Brockmann,
Phys Rev. C 18,
3 (1978)

Initial Guess :

$$\left(\frac{d}{dr}+\frac{\kappa}{r}\right)G_\alpha(r)-\left[\epsilon_\alpha-V(r)+m_N-S(r)\right]F_\alpha(r)=0$$
$$\left(\frac{d}{dr}-\frac{\kappa}{r}\right)F_\alpha(r)+\left[\epsilon_\alpha-V(r)-m_N+S(r)\right]G_\alpha(r)=0$$

$$\psi_{\alpha,k,m}=\begin{pmatrix} i\dfrac{G^k_\alpha(r)}{r}Y^l_{jm}(\theta,\phi,s)\\ -\dfrac{F^k_\alpha(r)}{r}Y^{\tilde{l}}_{jm}(\theta,\phi,s)\end{pmatrix}\chi_{t_\alpha}(t)$$

Woods Saxon Potential

$$V_{WS}=\frac{V_0}{1+\exp\left(\frac{r-R_0}{a}\right)}$$
$$R_0=r_0A^{1/3},\ r_0=1.27\,fm,\ a=0.67\,fm$$

Adjusted with the nuclear matter results at $r \to 0$

$$\rho^s_p(r)=\sum_p^Z\frac{(2j_p+1)}{4\pi r^2}\left(|G_p(r)|^2-|F_p(r)|^2\right),$$
$$\rho^s_n(r)=\sum_n^N\frac{(2j_n+1)}{4\pi r^2}\left(|G_n(r)|^2-|F_n(r)|^2\right),$$
$$\rho_p(r)=\sum_p^Z\frac{(2j_p+1)}{4\pi r^2}\left(|G_p(r)|^2+|F_p(r)|^2\right),$$
$$\rho_n(r)=\sum_n^N\frac{(2j_p+1)}{4\pi r^2}\left(|G_n(r)|^2+|F_n(r)|^2\right),$$

$$S(r)=V_\sigma(r)+\frac{\tau^3}{2}V_\delta(r)$$
$$V(r)=V_\omega(r)+\frac{\tau^3}{2}V_\rho(r)+\frac{(1+\tau^3)}{2}V_C(r)$$

$$\left(-\frac{d^2}{dr^2}-\frac{2}{r}\frac{d}{dr}+m_M^2\right)M(r)=\mathcal{J}_M(r)$$

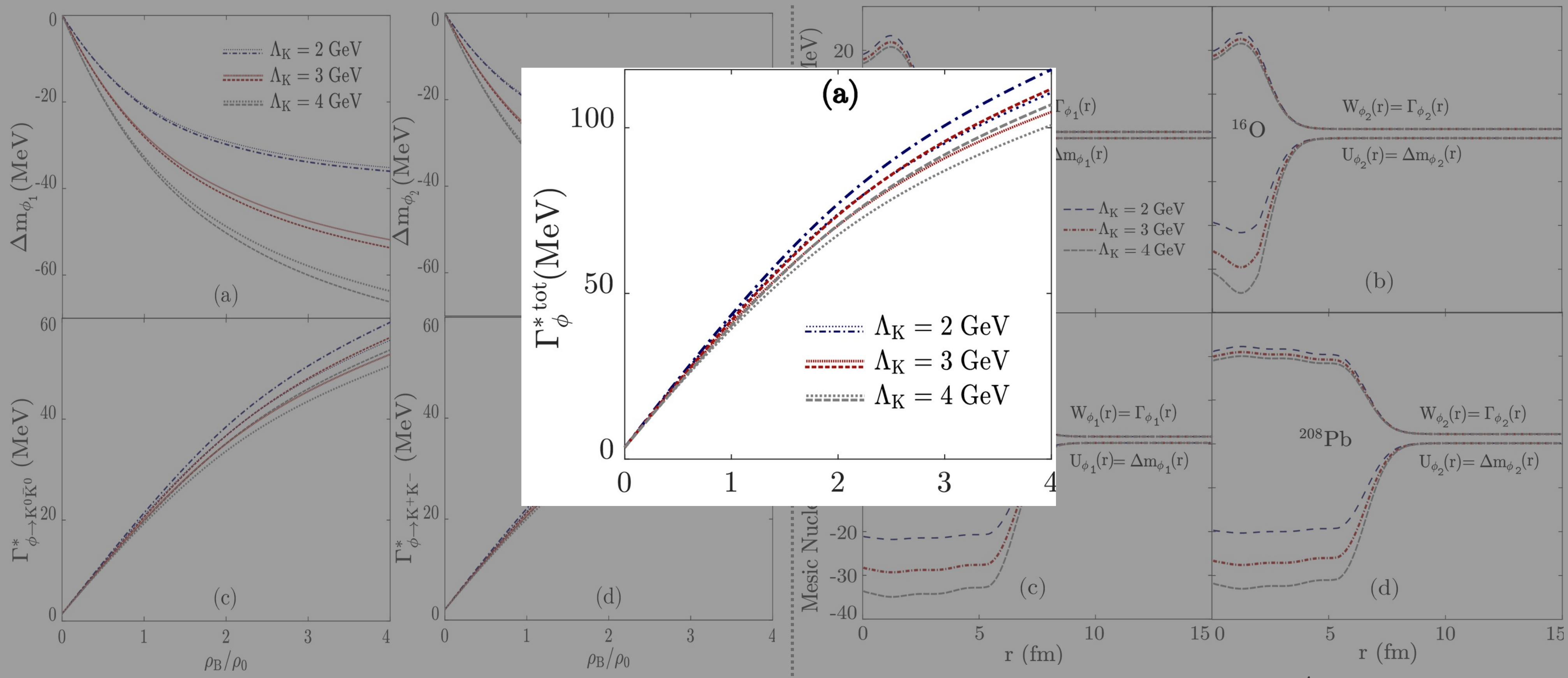
$$\mathcal{J}_M(r)=\begin{cases} g_\sigma\left[\rho^s_p(r)\left(-\frac{\partial m^*_p(r)}{\partial\sigma}\right)+\rho^s_n(r)\left(-\frac{\partial m^*_n(r)}{\partial\sigma}\right)\right] & \text{for } \sigma \text{ field}\\ \frac{g_\delta}{2}\left[\rho^s_p(r)\left(-\frac{\partial m^*_p(r)}{\partial\delta^3}\right)+\rho^s_n(r)\left(-\frac{\partial m^*_n(r)}{\partial\delta^3}\right)\right] & \text{for } \delta^3 \text{ field}\\ g_\omega\left[\rho_p(r)+\rho_n(r)\right] & \text{for } \omega_0 \text{ field}\\ \frac{g_\rho}{2}\left[\rho_p(r)-\rho_n(r)\right] & \text{for } \rho^3_0 \text{ field}\\ e\rho_p(r) & \text{for Coulomb field}\end{cases}$$

Y.K.Gambhir et.al.,
Annals of Phys, 198,
132 (1990)

How phi is introduced to nuclear environment ?

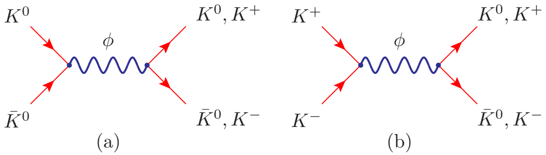
Nuclear Matter

Finite Nuclei

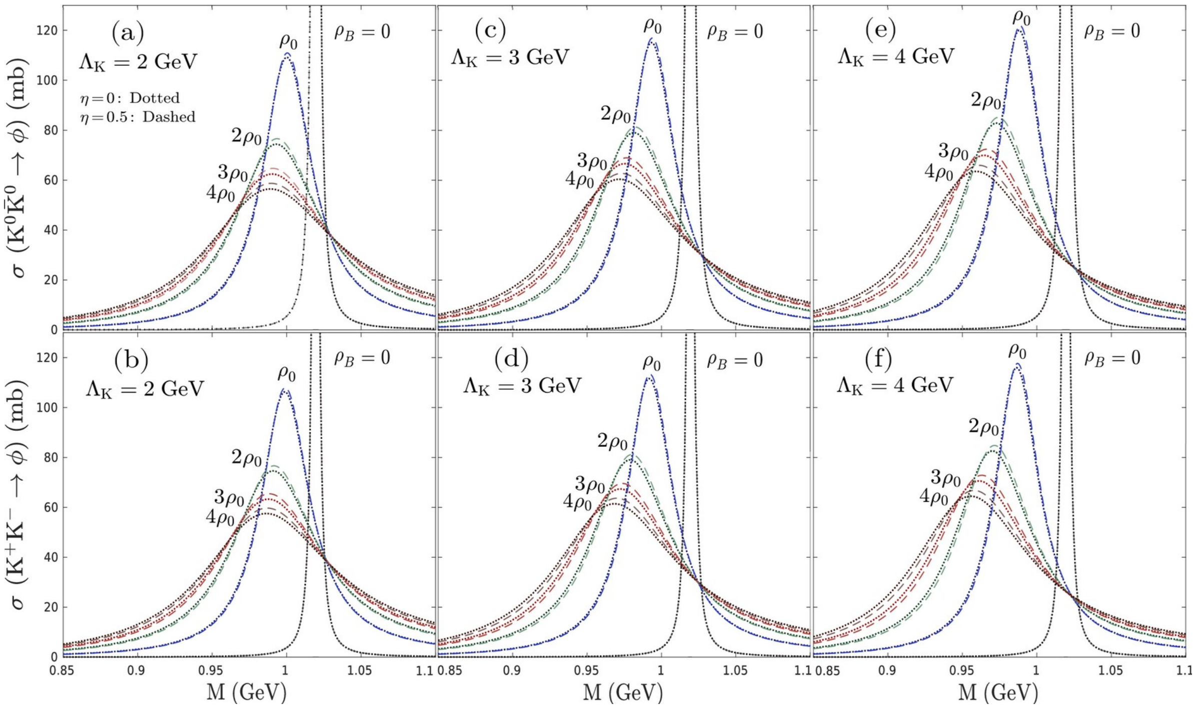


✔ $V_{\phi_i}(r) = U_{\phi_i}(r) - \frac{i}{2} W_{\phi_i}(r)$

Phi in nuclear matter



- $$\sigma_i(K\bar{K} \to \phi; M^2) = 6\pi^2 \frac{\Gamma_i^*}{|\vec{q}_i|^2} A_{\phi_i}(M^2)$$
- $$A_{\phi_i}(M^2) = C_i \frac{2}{\pi} \frac{M^2 \Gamma_\phi^{*tot}}{(M^2 - m_{\phi_i}^{*\,2})^2 (M\Gamma_\phi^{*tot})^2}$$
- $$\int_0^\infty A_{\phi_i}(M^2) dM = 1$$



AM and Amruta Mishra, arXiv:2502.08320