Exotic meson decays and polarization asymmetry in hadron environment with a chiral imbalance

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in collaboration with
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Outline

Motivation and aims

After heavy ion collision, the fireball cools down to hadron gas, where pions predominate

Due to a local violation of CP-symmetry, the pions in the fireball can change and acquire new properties

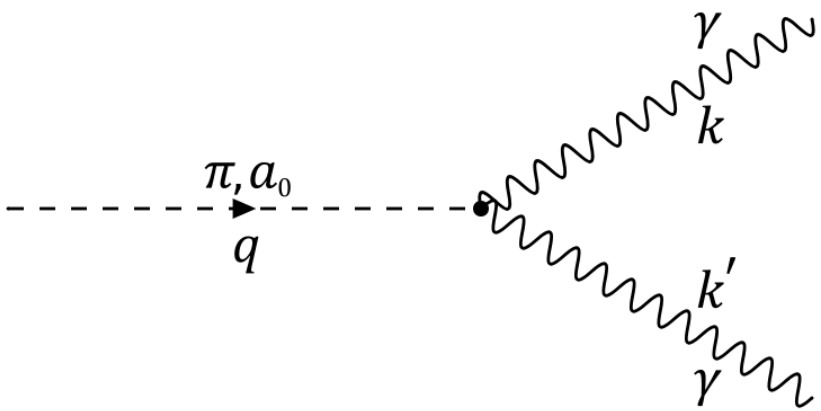
- New vertices of meson decay
- Decay widths dependence on energy and chiral chemical potential
- An additional way of a pion-photon scattering
- Polarizations asymmetry in a pion-photon scattering

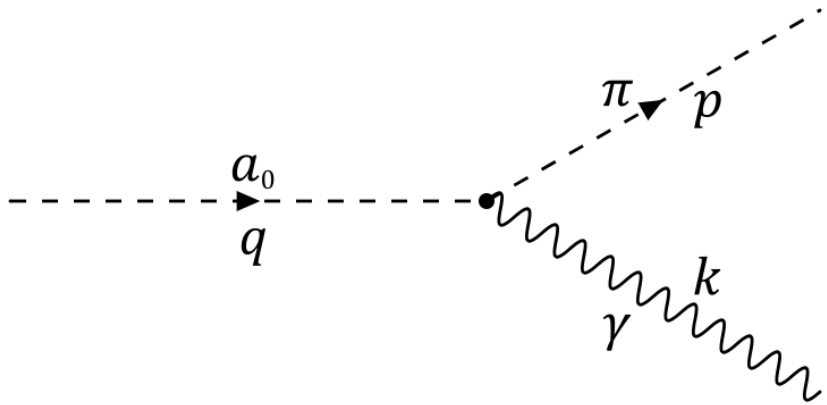
Wess-Zumino-Witten action

Describing of anomalous decay of strong interaction $\pi \longrightarrow \gamma\gamma$ and other interaction: $\gamma\pi^- \longrightarrow \pi^0\pi^-$ and $\gamma \longrightarrow \pi\pi\pi$

$$-\frac{e^2 N_c}{24\pi^2 f_\pi}\epsilon^{\nu\sigma\lambda\rho}\partial_\sigma A_\lambda \partial_\nu A_\rho \pi^0 \quad (1)$$

$$-\frac{ie\mu_5 N_c}{6\pi^2 f_\pi^2}\epsilon_0^{\sigma\lambda\rho} A_\rho \partial_\sigma \pi^+ \partial_\lambda \pi^- \quad (2)$$





$\pi^0 \longrightarrow \gamma\gamma, \quad a_0^0 \longrightarrow \gamma\gamma$

$a_0^\pm \longrightarrow \pi^\pm\gamma$

$\pi^0 \to \gamma\gamma$ decay

$$\frac{d\Gamma}{d\Omega} = \left(\frac{e^2 N_c}{24\pi^2 f_\pi}\right)^2 \cdot \tag{3}$$

$$\cdot \frac{C_+^2(q_0)|\mathbf{k}|^3\sqrt{|\mathbf{k}|^2+|\mathbf{q}|^2-2|\mathbf{k}||\mathbf{q}|\cos\theta}}{\pi^2 f_-(q_0)\left|1+\frac{|\mathbf{k}|-|\mathbf{q}|\cos\theta}{\sqrt{|\mathbf{k}|^2+|\mathbf{q}|^2-2|\mathbf{k}||\mathbf{q}|\cos\theta}}\right|} \cdot \left(1+\frac{|\mathbf{k}|-|\mathbf{q}|\cos\theta}{\sqrt{|\mathbf{k}|^2+|\mathbf{q}|^2-2|\mathbf{k}||\mathbf{q}|\cos\theta}}\right)^2$$

$$|\mathbf{k}| = \frac{m_{eff+}^2\left(\sqrt{|\mathbf{q}|^2+m_{\text{eff+}}^2}+|\mathbf{q}|\cos\theta\right)}{2\left(m_{\text{eff+}}^2+|\mathbf{q}|^2\sin^2\theta\right)} \tag{4}$$

$$f_-(q_0) = 2q_0 + \frac{32\, q_0\mu_5^2}{\sqrt{(m_a^2-m_\pi^2)^2+(8\, q_0\mu_5)^2}} \tag{5}$$

$\pi^0 \to \gamma\gamma$ decay

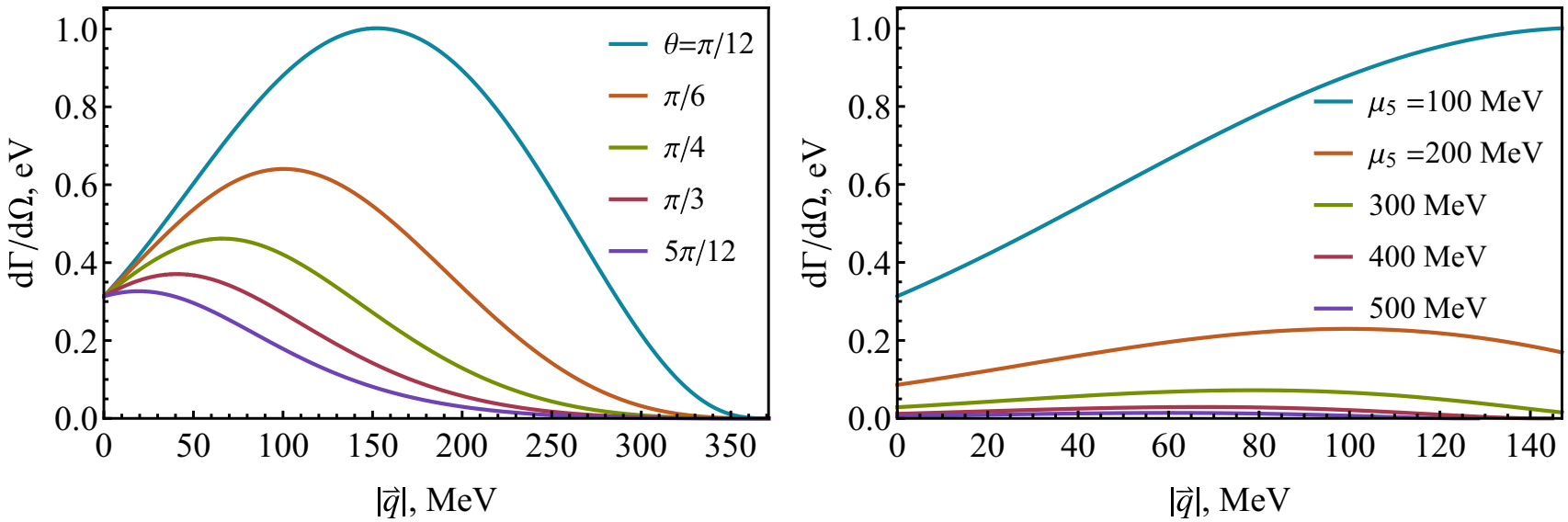


Figure 1: Differential decay width at $\mu_5 = 100$ MeV (a), and $\theta = \pi/12$ (b)

$a_0^0 \to \gamma\gamma$ decay

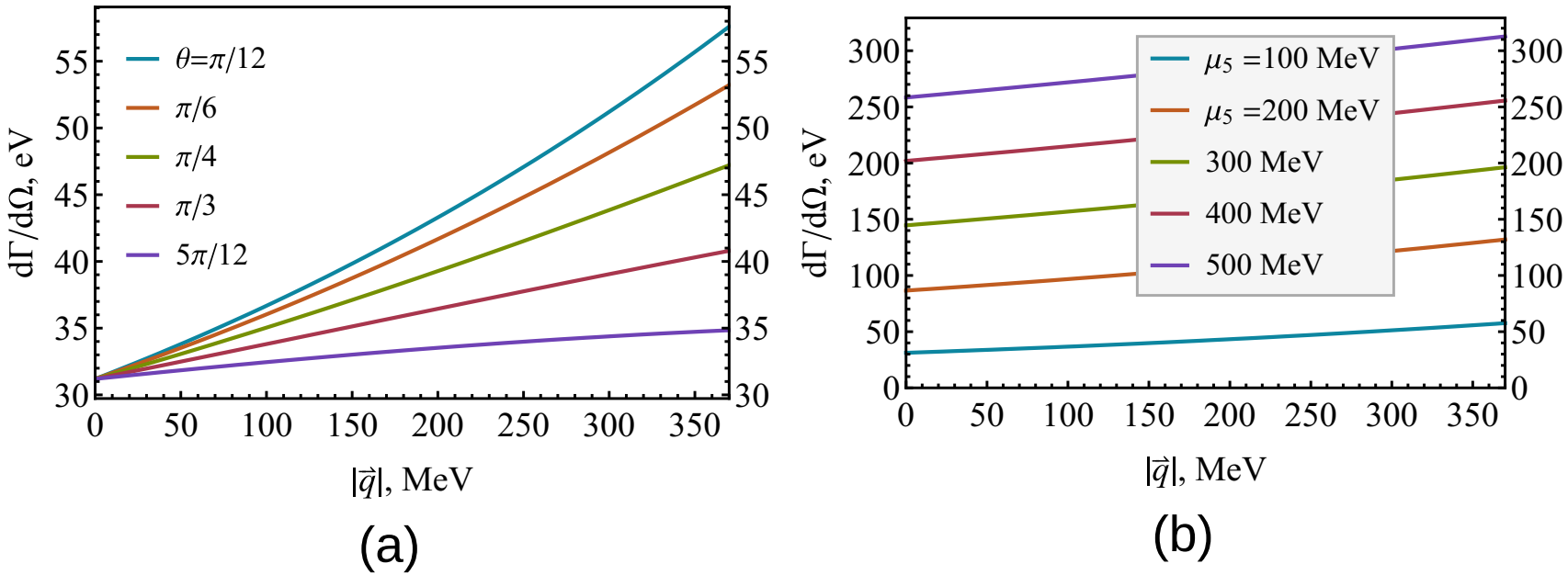


Figure 2: Differential decay width at $\mu_5 = 100$ MeV (a), and $\theta = \pi/12$ (b)

$a_0^{\pm} \to \pi^{\pm}\gamma$ decays

$$\frac{d\Gamma}{d\Omega} = \left(\frac{e\mu_5 N_c}{6\,\pi^2 f_\pi^2}\right)^2 \frac{C_-^2(q_0)C_+^2(k_0)\,|\mathbf{p}|^2|\mathbf{q}|^2\sin^2\theta}{(2\pi)^2 n\, f_+(q_0) f_-(k_0) 2\sqrt{|\mathbf{p}|^2+|\mathbf{q}|^2-2|\mathbf{p}||\mathbf{q}|\cos\theta}} \tag{6}$$

$$n = \left| \frac{|\mathbf{p}|-|\mathbf{q}|\cos\theta}{\sqrt{|\mathbf{p}|^2+|\mathbf{q}|^2-2|\mathbf{p}||\mathbf{q}|\cos\theta}} + \right. \tag{7}$$

$$\left. + \frac{|\mathbf{p}|}{\sqrt{|\mathbf{p}|^2+m^2_{\text{eff-}}}} \left(1 - \frac{16\,\mu_5^2}{\sqrt{(m_a^2+m_\pi^2+16\,\mu_5^2)^2 - 4m_a^2 m_\pi^2 + 64\mu_5^2|\mathbf{p}|^2}}\right)\right|$$

$$\sqrt{|\mathbf{p}|^2+m^2_{\text{eff-}}} + \sqrt{|\mathbf{p}|^2+|\mathbf{q}|^2-2|\mathbf{p}||\mathbf{q}|\cos\theta} - \sqrt{|\mathbf{q}|^2+m^2_{\text{eff+}}} = 0 \tag{8}$$

$a_0^{\pm} \to \pi^{\pm}\gamma$ decays

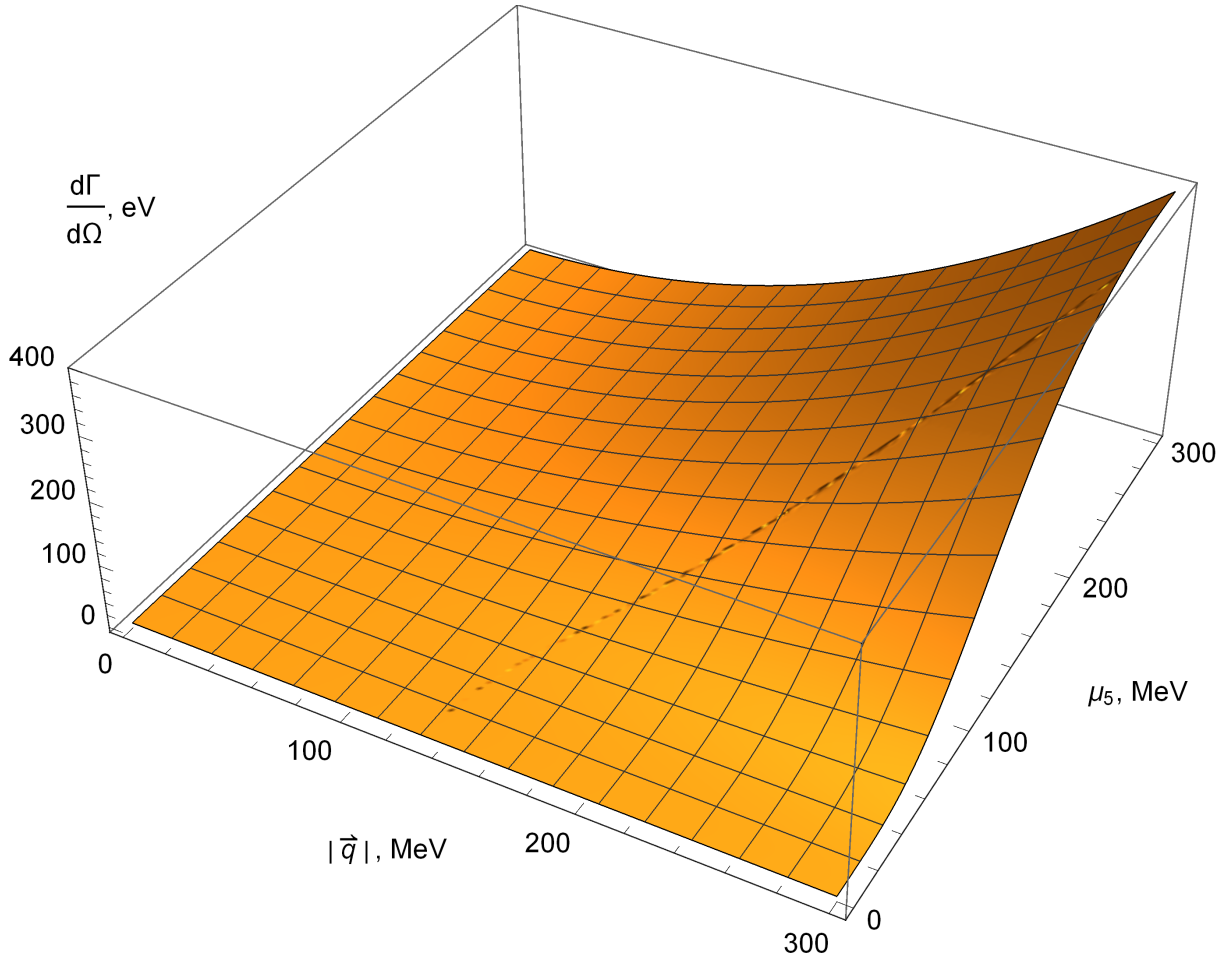


Figure 3: Differential decay width, the angle between the momenta of $a_0^{\pm}$, $\pi^{\pm}$ is equal to $5\,\pi/12$

$a_0^{\pm} \to \pi^{\pm}\gamma$ decays

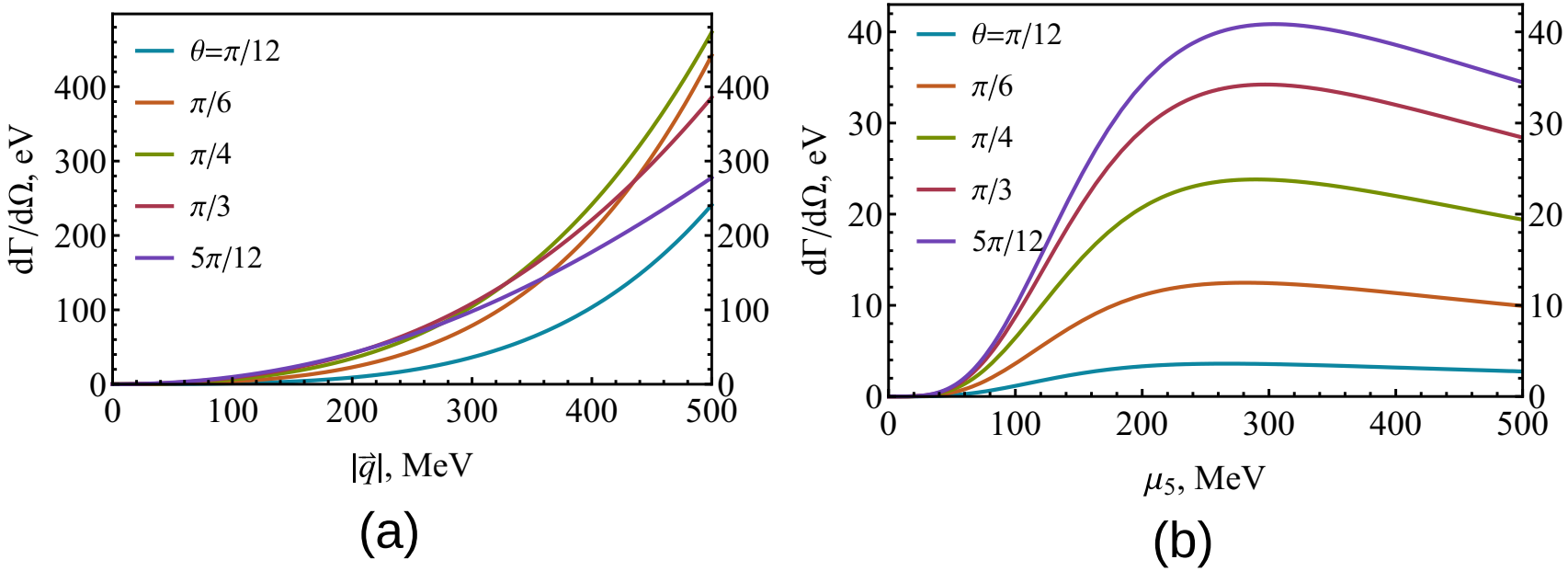


Figure 4: Differential decay width at $\mu_5 = 100$ MeV (a), and $|\mathbf{q}| = 100$ MeV (b)

Pion-photon scattering

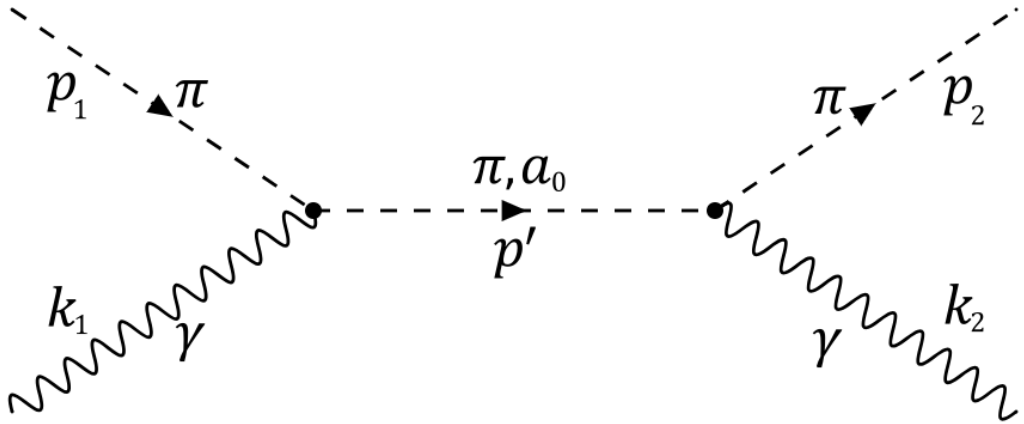


Figure 5: The Feynman graph illustrating $\pi^+\gamma \to \pi^+\gamma$ scattering

$$\pi^{\pm}(\vec{p}_1) + \gamma(\vec{k}_1) \to \pi^{\pm}(\vec{p}_2) + \gamma_+(\vec{k}_2)$$
$$\pi^{\pm}(-\vec{p}_1) + \gamma(-\vec{k}_1) \to \pi^{\pm}(-\vec{p}_2) + \gamma_-(-\vec{k}_2) \quad (9)$$

Asymmetry in photon polarizations

$\pi^+\gamma \to \pi^+\gamma$

$$\mathcal{A} = \left| \frac{M_+^2 - \mathcal{P}[M_+]^2}{\sum_{m=\pm}\left(M_m^2 + \mathcal{P}[M_m]^2\right)} \right| \tag{10}$$

$$\mathcal{A}^{\text{s-channel}} = \frac{\mu_5 N_c}{12\pi^2 f_\pi^2} \frac{E_\gamma \left(E_\pi^2 - m_\pi^2\right) \sin^2\theta}{m_\pi^2 + E_\gamma E_\pi \left(1 - \sqrt{1 - \frac{m_\pi^2}{E_\pi^2}} \cos\theta\right)} \tag{11}$$

Kawaguchi M., Harada M., Matsuzaki S., Ouyang R. Charged pions tagged with polarized photons probing strong C P violation in a chiral-imbalance medium. Phys. Rev. C 95, 065204 (2017)

$$E \gg m,\ \theta \to 0,\ E = 1\text{GeV},\ \mu_5 = 200\text{MeV}$$

$$\mathcal{A}^{\text{s-channel}}|_{\text{max}} \simeq 0,2 \tag{12}$$

Ward identity

$$M = M_{\text{even-even}} + M_{\text{even-odd}} + M_{\text{odd-even}} + M_{\text{odd-odd}} \tag{13}$$

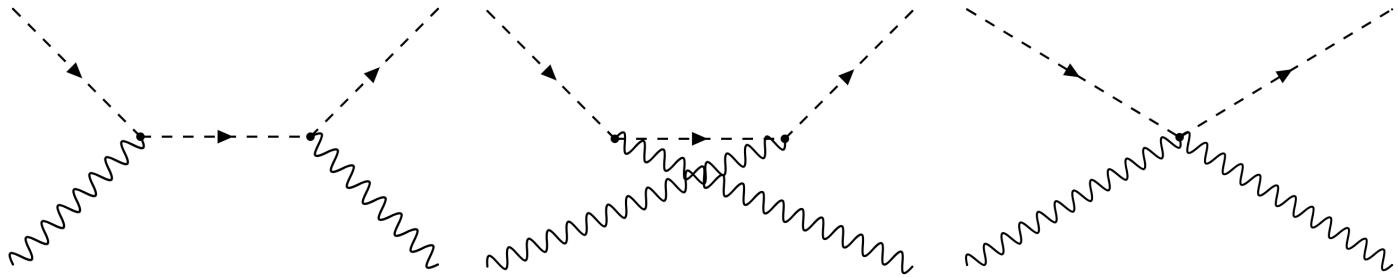


Figure 6: The Feynman graphs illustrating $\pi^+\gamma \to \pi^+\gamma$ scattering

$$a_0,\ \pi \ \to \ \tilde{a}_0,\ \tilde{\pi}$$

$$a_0 = C_{aa}\,\tilde{a}_0 + C_{a\pi}\tilde{\pi}, \qquad \pi = C_{\pi a}\,\tilde{a}_0 + C_{\pi\pi}\tilde{\pi} \tag{14}$$

$$k_\mu M^\mu_{\text{even-even}} \neq 0 \tag{15}$$

Polarization sum

$$\sum_m e_\mu^{(m)} e_\nu^{(m)} = -g_{\mu\nu} + \frac{\eta \cdot k}{D} \left(\eta_\mu k_\nu + k_\mu \eta_\nu \right) - \frac{k^2}{D} \eta_\mu \eta_\nu - \frac{\eta^2}{D} k_\mu k_\nu \quad (16)$$

$$D = (\eta \cdot k)^2 - \eta^2 k^2, \quad \eta_\mu = (\mu_5, 0, 0, 0) \quad (17)$$

$$A_0 = 0 \quad (18)$$

$$\sum_m e_\mu^{(m)} e_\nu^{(m)} = -g_{\mu\nu} - \frac{\eta^2}{D} k_\mu k_\nu \quad (19)$$

Asymmetry in photon polarizations

$\pi^+\gamma \to a_0^{+*} \to \pi^+\gamma$

$$\mathcal{A}^{\text{s-channel}} = \frac{1}{2} E_{\gamma 2} \left(E_{\pi 2}^2 - m_{\text{eff-}}^2\right) \sin^2\theta_2 \cdot \tag{20}$$

$$\cdot \left[C_{n1} \frac{\mu_5 N_c}{6\pi^2 f_\pi^2} 4(E_{\pi 1}^2 - m_{\text{eff-}}^2) \sin^2\theta_1 + C_{n2} \left(\frac{\mu_5 N_c}{6\pi^2 f_\pi^2}\right)^3 (E_{\pi 1}^2 - m_{\text{eff-}}^2) E_{\gamma 1}^2 \sin^2\theta_1 \right] \cdot$$

$$\cdot \Big[C_{d1} 16 \left(E_{\pi 1}^2 - m_{\text{eff-}}^2\right) \sin^2\theta_1 (E_{\pi 2}^2 - m_{\text{eff-}}^2) \sin^2\theta_2 +$$

$$+ C_{d2} \left(\frac{\mu_5 N_c}{6\pi^2 f_\pi^2}\right)^2 4(E_{\pi 1}^2 - m_{\text{eff-}}^2) E_{\gamma 1}^2 \sin^2\theta_1 (E_{\pi 2}^2 - m_{\text{eff-}}^2) \sin^2\theta_2 +$$

$$+ C_{d3} \left(\frac{\mu_5 N_c}{6\pi^2 f_\pi^2}\right)^2 4(E_{\pi 1}^2 - m_{\text{eff-}}^2) \sin^2\theta_1 (E_{\pi 2}^2 - m_{\text{eff-}}^2) E_{\gamma 2}^2 \sin^2\theta_2 +$$

$$+ C_{d4} \left(\frac{\mu_5 N_c}{6\pi^2 f_\pi^2}\right)^4 (E_{\pi 1}^2 - m_{\text{eff-}}^2) E_{\gamma 1}^2 \sin^2\theta_1 (E_{\pi 2}^2 - m_{\text{eff-}}^2) E_{\gamma 2}^2 \sin^2\theta_2 \Big]^{-1}$$

Asymmetry in photon polarizations

$\pi^+\gamma \to a_0^{+*} \to \pi^+\gamma$

$$C_{n1} = \frac{4p_0'^2/f_-'^2}{(p'^2 - m^2_{\text{eff-}}(p_0'))^2} \cdot C_+(p_0')C_+(E_{\pi 2}) \cdot \tag{21}$$

$$\cdot (C_+(E_{\pi 1})C_+(p_0') + C_-(E_{\pi 1})C_-(p_0'))^2 (C_+(E_{\pi 2})C_+(p_0') + C_-(E_{\pi 2})C_-(p_0')) +$$

$$+ \frac{4p_0'^2/f_+'^2}{(p'^2 - m^2_{\text{eff+}}(p_0'))^2 + m^2_{\text{eff+}}(p_0')\Gamma_a^2} \cdot C_-(p_0')C_+(E_{\pi 2}) \cdot$$

$$\cdot (C_+(E_{\pi 1})C_-(p_0') - C_-(E_{\pi 1})C_+(p_0'))^2 (C_+(E_{\pi 2})C_-(p_0') - C_-(E_{\pi 2})C_+(p_0')) +$$

$$+ \frac{(p'^2 - m^2_{\text{eff+}}(p_0'))\, 4p_0'^2/f_-'f_+'}{(p'^2 - m^2_{\text{eff-}}(p_0'))((p'^2 - m^2_{\text{eff+}}(p_0'))^2 + m^2_{\text{eff+}}(p_0')\Gamma_a^2)} \cdot$$

$$\cdot ((C_+(E_{\pi 1})C_+(p_0') + C_-(E_{\pi 1})C_-(p_0'))(C_+(E_{\pi 2})C_+(p_0') + C_-(E_{\pi 2})C_-(p_0')) \cdot$$

$$\cdot (C_+(E_{\pi 1})C_-(p_0') - C_-(E_{\pi 1})C_+(p_0'))C_-(p_0')C_+(E_{\pi 2}) +$$

$$+ (C_+(E_{\pi 1})C_-(p_0') - C_-(E_{\pi 1})C_+(p_0'))(C_+(E_{\pi 2})C_-(p_0') - C_-(E_{\pi 2})C_+(p_0')) \cdot$$

$$\cdot (C_+(E_{\pi 1})C_+(p_0') + C_-(E_{\pi 1})C_-(p_0'))C_+(p_0')C_+(p_0')C_+(E_{\pi 2}))$$

Asymmetry in photon polarizations

$\pi^+\gamma \to a_0^{+*} \to \pi^+\gamma$

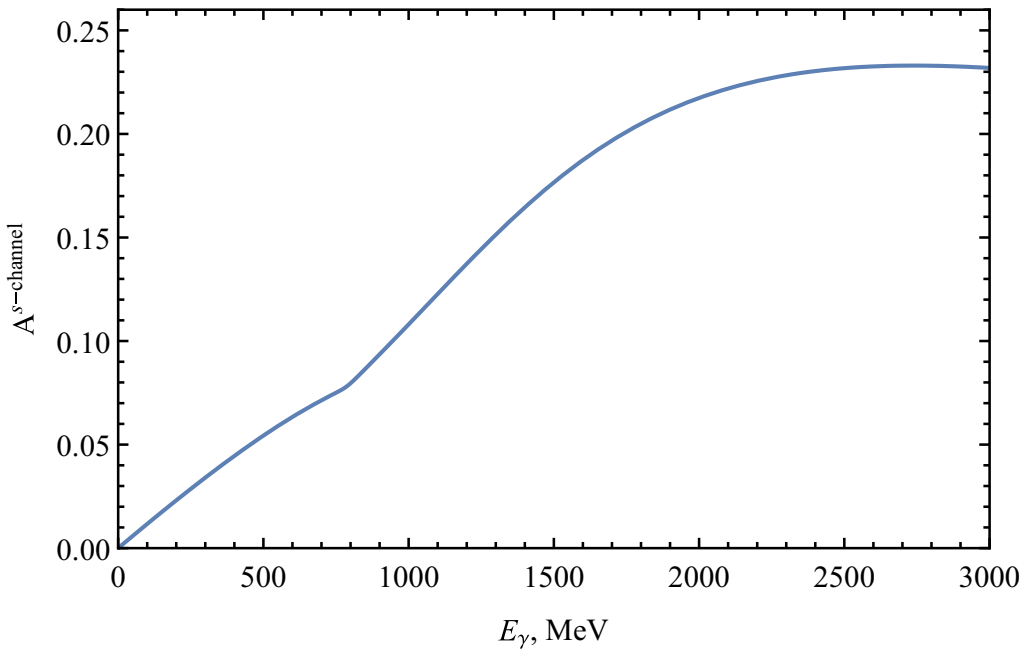


Figure 7: Asymmetry, $\mu_5 = 200$ MeV, $E_{\pi 2} = 1$ GeV

Conclusion

- Meson decay vertices in the chiral medium differ from usually known
- A new vertex of scalar meson decay $a_0^{\pm} \to \pi^{\pm}\gamma$ at $\mu_5 \neq 0$
- Decay width properties:

Process	$\lvert\mathbf{q}\rvert$	μ_5	θ
$\pi^0 \to \gamma\gamma$	has maximum	has maximum	decreases
$a_0^0 \to \gamma\gamma$	increases	increases	decreases
$a_0^{\pm} \to \pi^{\pm}\gamma$	increases	has maximum	increases

- The possibility of detecting of local parity breaking by measuring photon polarization asymmetry in the process $\pi^+\gamma \to \pi^+\gamma$ with the resonance enhancement at energies $\sim m^2_{\text{eff+}}$

Outlook

- Entering of a chiral stream to the theory instead of chiral chemical potential, interpretation of this vector, and calculation new vertices

  Andrianov A.A., Andrianov V.A., Espriu D., Putilova A.E., Iakubovich A.V. Exotic meson decays in the environment with chiral imbalance. European Physical Journal: Web of Conferences, 2017. 10 p.

- Finding the dependence of the effective theory parameters on temperature and the baryonic chemical potential

- Qualitative and quantitative explanation of the anomalous yield of dilepton pairs in the CERES, PHENIX, STAR, NA60, and ALICE experiments

  A. A. Andrianov, V. A. Andrianov, D. Espriu and X. Planells, Phys. Lett. B 710 230 (2012); Proc.Sci., QFTHEP, 025 (2013); Phys. Rev. D, 90,034024 (2014)

Thank you for attention!