Constraints on MeV Axions from Kaon Decays

ArXiv:2602.15117

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MeV mass range Axion

- **QCD axion is a dynamical solution of strong CP problem**
- **Axion mass**

$$m_a^2 \approx \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

f_a: axion decay constant

f_π: pion decay constant

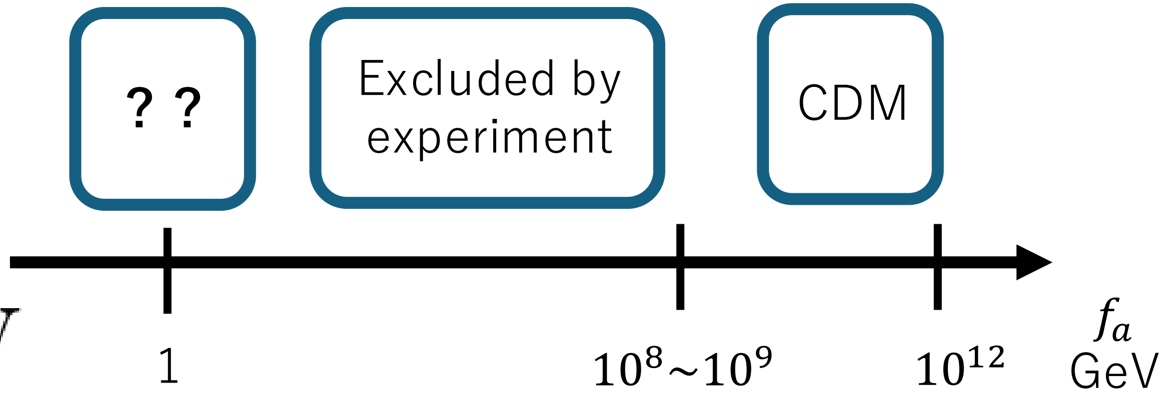
Many studies

$$10^9\,\mathrm{GeV} \le f_a \le 10^{12}\,\mathrm{GeV}$$

Recently

$$f_a \sim 1\mathrm{GeV} \quad m_a \sim 10\,\mathrm{MeV}$$

D. S. M. Alves et.al. JHEP 07, 092 (2018)



MeV axion model

MeV Axion Model

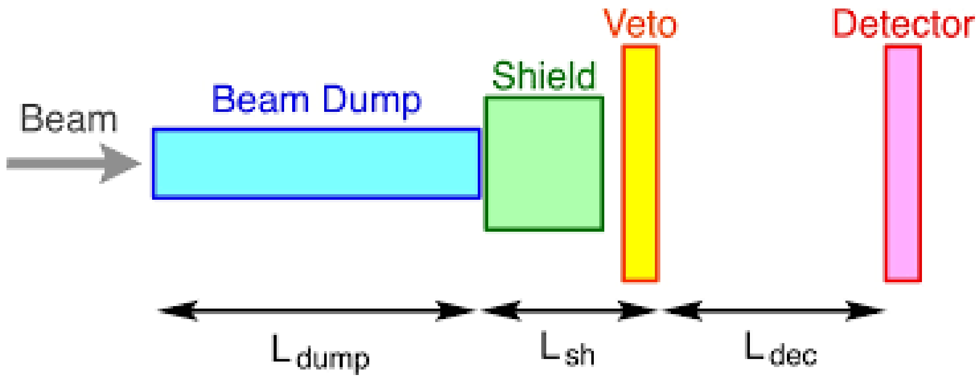
Kaon experiment

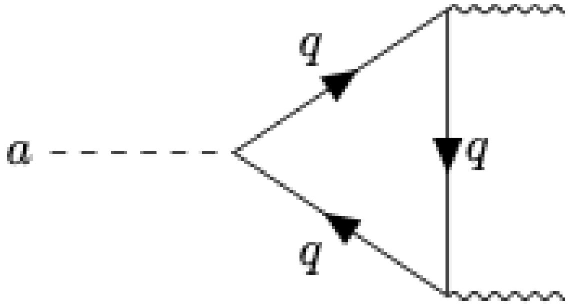
$$\mathrm{Br}(K^+ \to \pi^+(a \to \text{invisible})) \lesssim 4.5 \times 10^{-11}$$

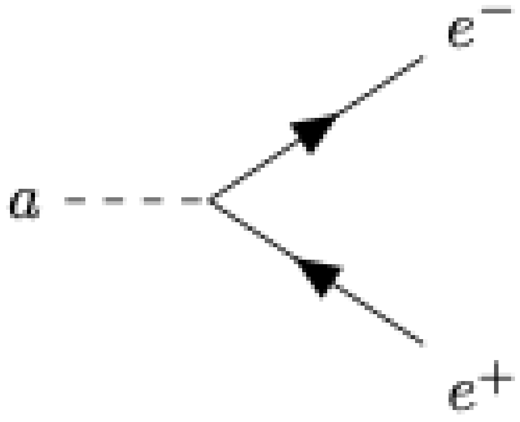
(E787 Collaboration)

MeV axion model

$$\mathrm{Br}(K^+ \to \pi^+ a) \sim 10^{-4} \times \left(\frac{f_a}{1\ \mathrm{GeV}}\right)^{-1}$$







Axion couples to e^-

MeV Axion Model

Quarkonia Decay

Muon $g-2$

→ **Axion couples to only first generation fermions**

The rare decay process $\pi^+ \to e^+ \nu_e a$

$$\theta_{a\pi} \lesssim (0.5 - 0.7) \times 10^{-4}$$ SINDRUM collaboration

$$\theta_{a\pi} \sim -\left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d}\right)\frac{f_\pi}{f_a}$$

MeV Axion Model

Quarkonia Decay

Muon $g-2$

→ Axion couples to only first generation fermions

The rare decay process

$$\mathcal{O}(10^{-2}) \times \left(\frac{Q_u}{Q_d} - \frac{m_d}{m_u}\right)$$

$$\theta_{a\pi} \sim -\left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d}\right)\frac{f_\pi}{f_a}$$

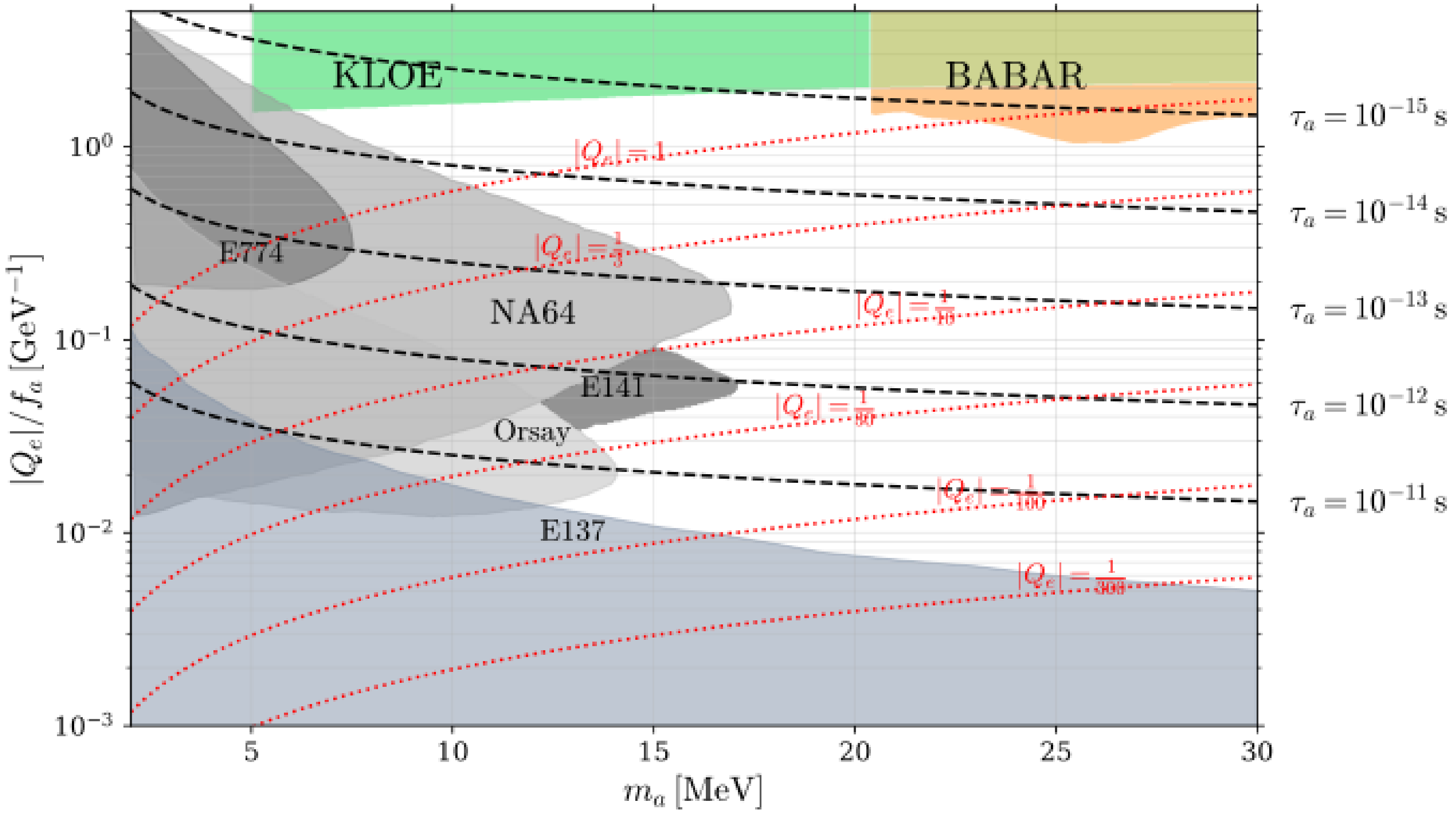
$$\theta_{a\pi} \lesssim (0.5 - 0.7) \times 10^{-4}$$

SINDRUM collaboration

$$\frac{m_u}{m_d} = 0.462 \pm 0.020$$ (PDG 2024)

if $\frac{Q_u}{Q_d} = 2$ → $\theta_{a\pi} \sim 0$

Previous Experimental Bound



Beam dump Experiments

$$8\,\mathrm{MeV} \lesssim m_a \lesssim 30\,\mathrm{MeV}$$

B Meson Decays

S. Nakagawa et.al.(2024)
JHEP 10, 153 (2024)

$K_L \to \pi^0 \pi^0 e^+ e^-$ at KTeV

Branch of $K_L \to \pi^0\pi^0(a \to e^+e^-)$

$$\mathrm{Br}(K_L \to \pi^0\pi^0 e^+e^-) \lesssim 6.6 \times 10^{-9}$$

KTeV Collaboration

Surprisingly, despite the stringent KTeV bound, this constraint has been overlooked!!

$$\mathrm{Br}(K_L \to \pi^0\pi^0 a) \simeq 0.75\left(\theta_{a\eta_{ud}} + \sqrt{2}\,\theta_{a\eta_s}\right)^2$$

D. S. M. Alves
Phys. Rev. D **103**, 055018

Leading order estimation

$$\mathrm{Br}(K_L \to \pi^0\pi^0(a \to e^+e^-)) \simeq 6 \times 10^{-6} \times \left(\frac{m_a}{10\,\mathrm{MeV}}\right)^2$$

Branch of $K_L \to \pi^0\pi^0 a$

$$\mathrm{Br}(K_L \to \pi^0\pi^0 e^+ e^-) \lesssim 6.6 \times 10^{-9}$$

KTeV Collaboration

This constraint cannot be applied directly

Information Obtained from the Experiment → Upper Limit on the Total Number of Events

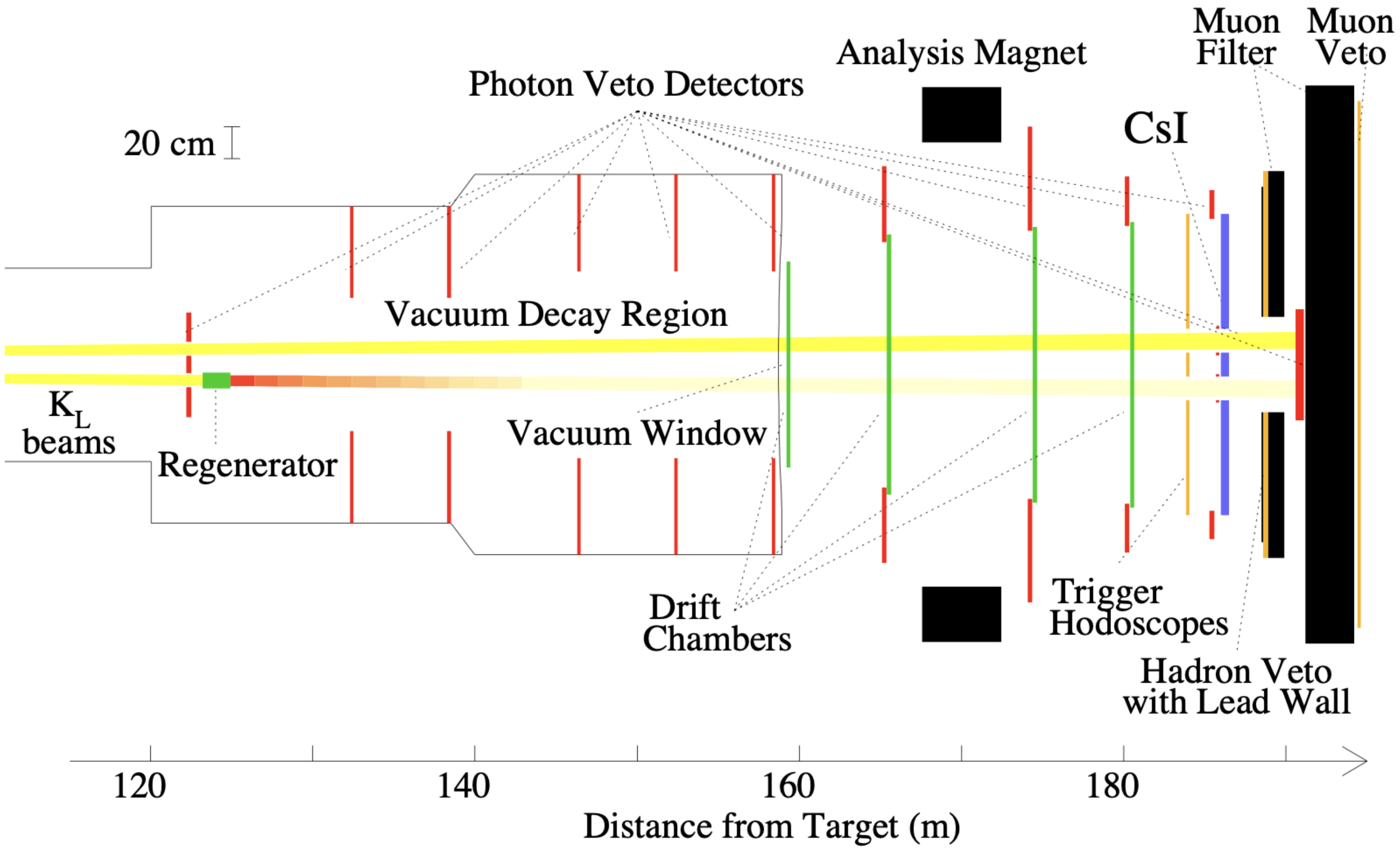
Number of incoming K_L × Branching ratio × **Efficiency**

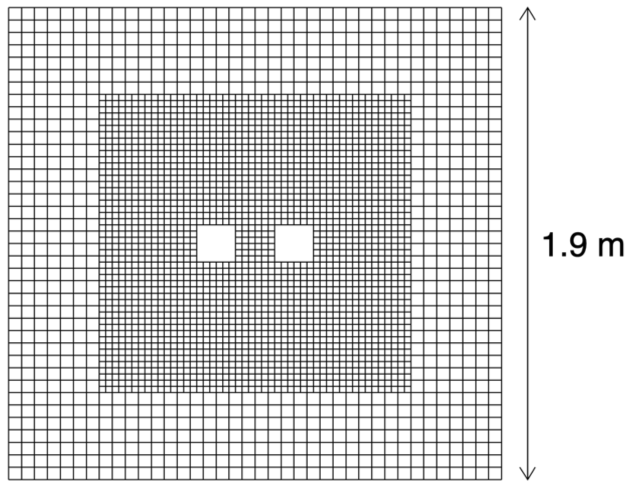
= Total Number of Events

Efficiency SM $\approx 0.2\%$ MeV Axion Model ???

→ Let's determine the efficiency in the MeV Axion Model using a Monte Carlo simulation!

KTeV Experiment





KTeV Collaboration

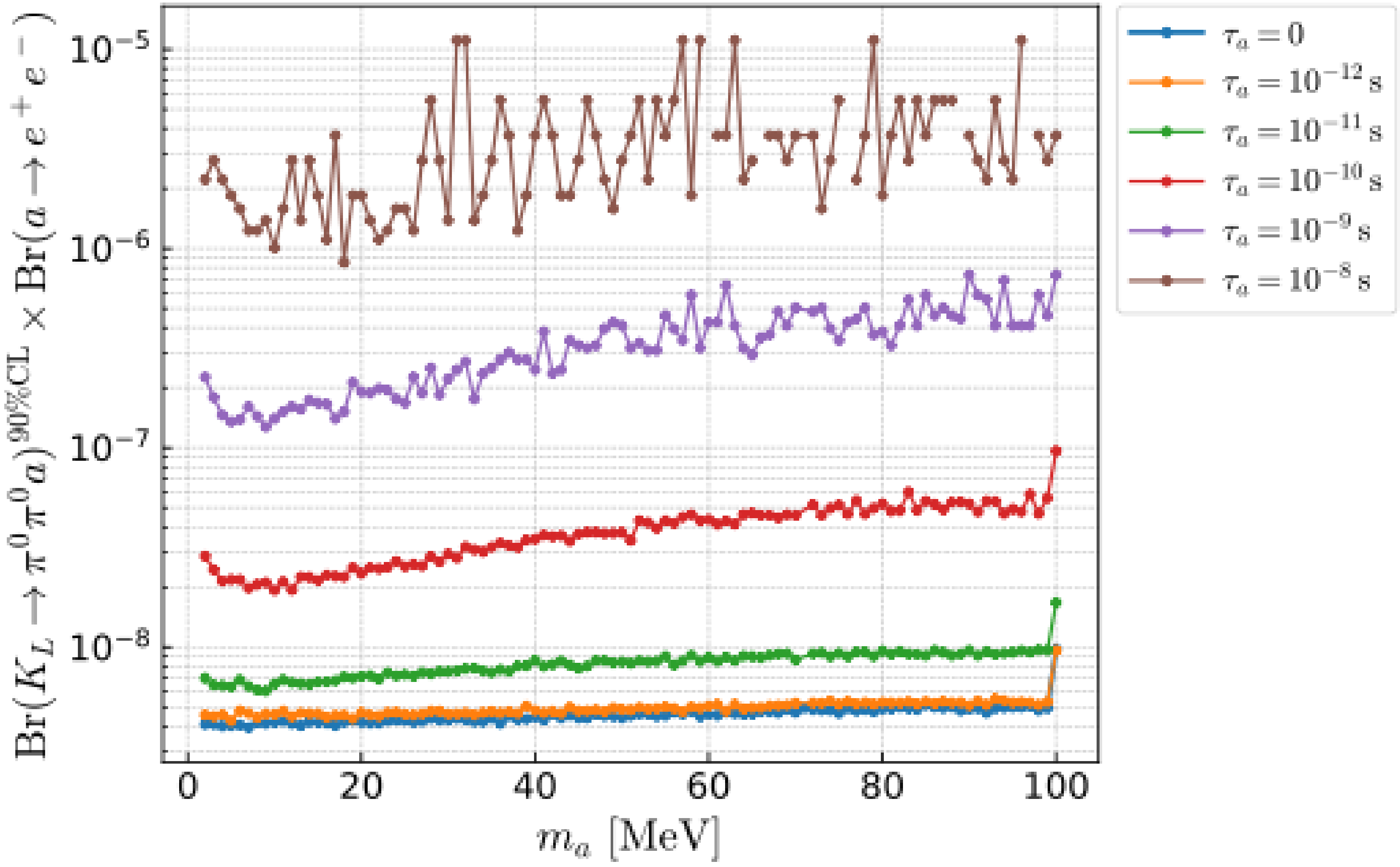
Monte Carlo Simulation

Step	Selection / Processing	Event count
1	Total number of incident K_L	1,000,000
2	Number of hit events	5,812
3	After applying cuts: $0.493 \le M_{\pi^0\pi^0e^+e^-} \le 0.501, \quad p_x^2 + p_y^2 \le 1.5 \times 10^{-4}$	5,561
4	Removal of $K_L \to \pi^0\pi^0(\pi^0 \to e^+e^-e^+e^-)$ background	
	Apply cut $M_{ee} > 0.10$ GeV/c^2	5,561
5	Removal of $K_L \to \pi^0\pi^0(\pi^0 \to e^+e^-\gamma)$ background	
	Apply cut $M_{ee} > 0.045$ GeV/c^2	3,119
6	Removal of $K_L \to \pi^0\pi^0(\pi^0 \to \gamma(\gamma \to e^+e^-))$ background	
	Apply cut on $M_{e\gamma}$ within 0.115–0.145 GeV/c^2, and require remaining $\gamma\gamma$ to satisfy $m_{\pi^0} \pm 3$ MeV/c^2	2,648
—	**Final number of events**	**2,648**

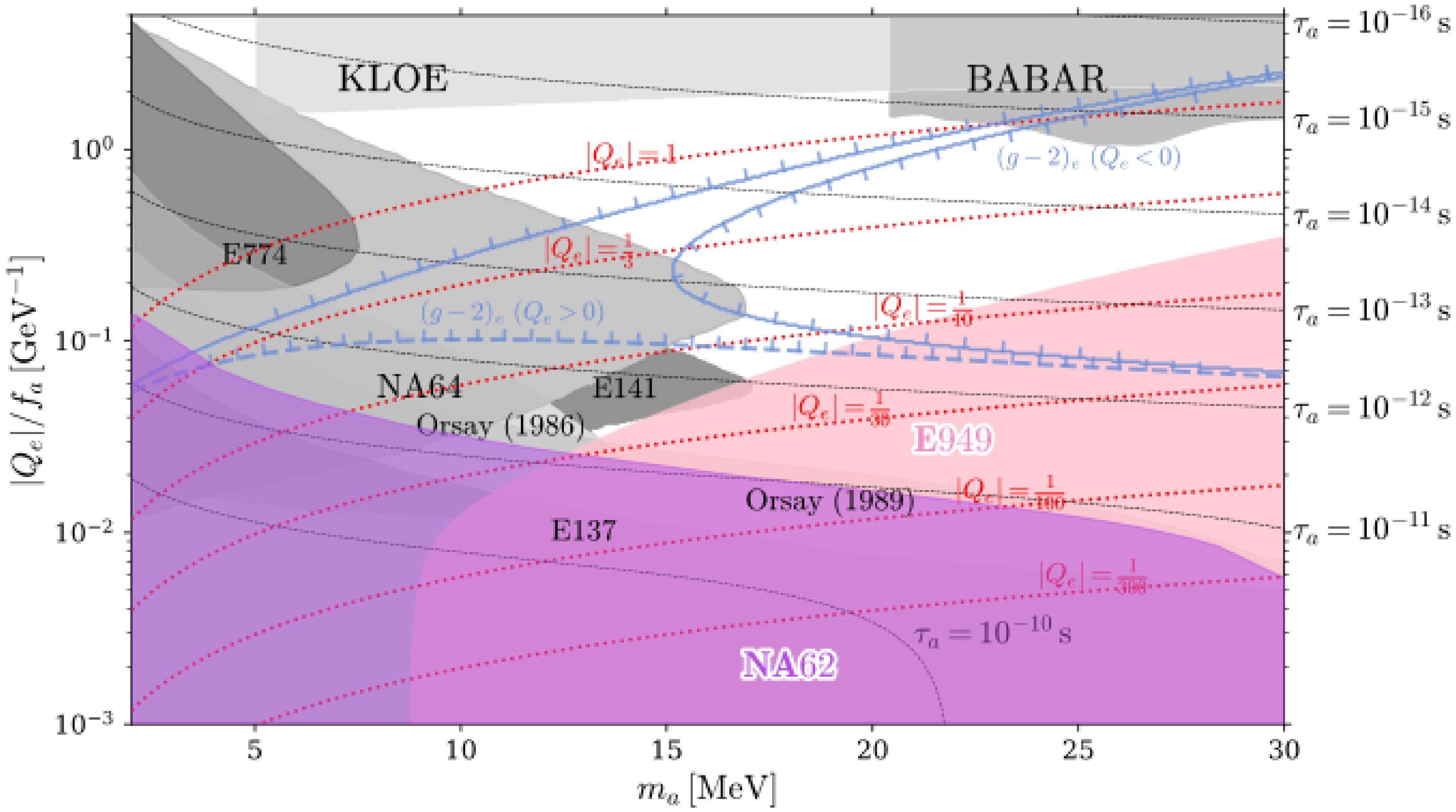
➡ **Efficiency(MeV Axion) ≈ 0.26%**

Efficiency(SM) ≈ 0.18%

Upper bound for Branching ratio



Result



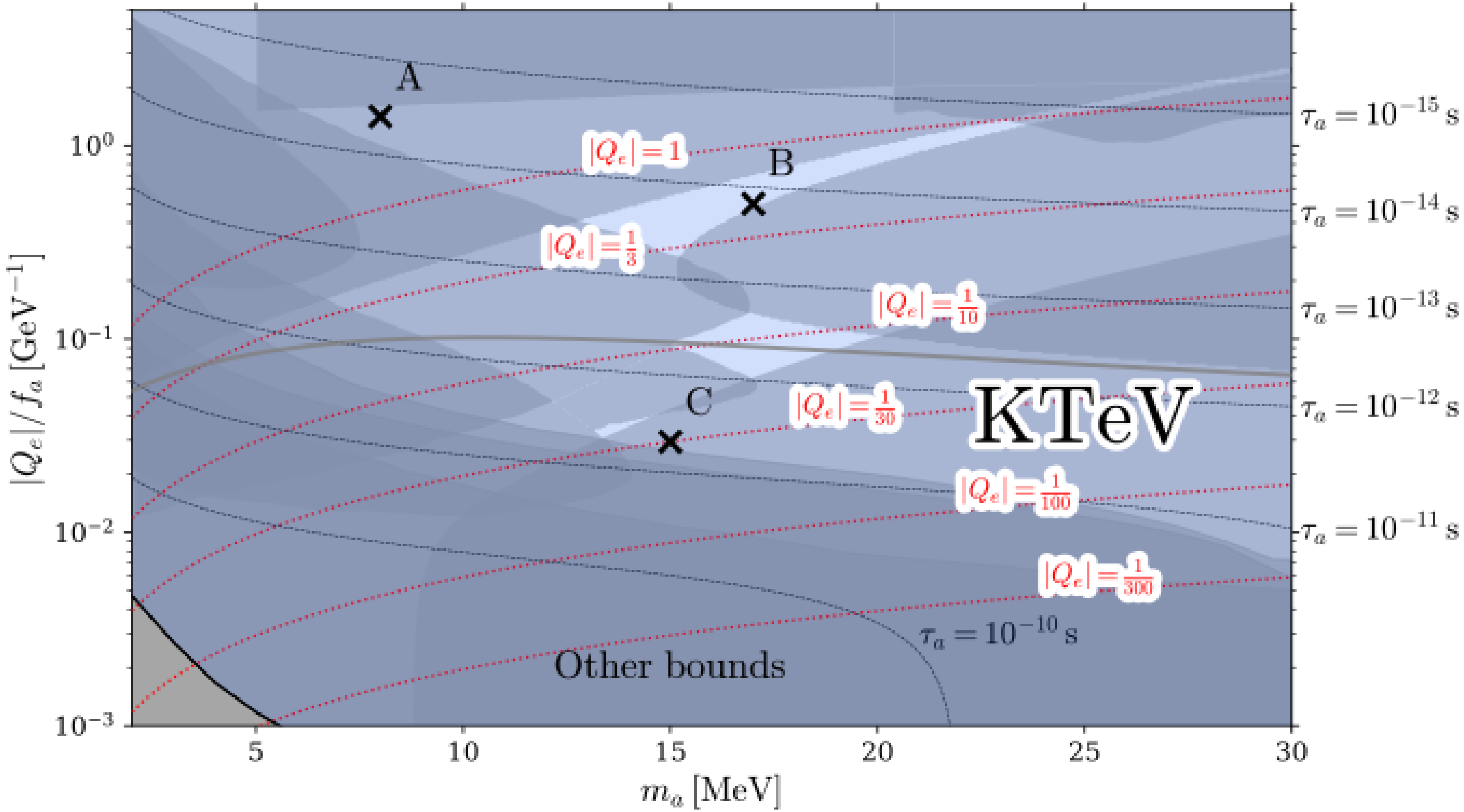
Blue lines
Electron g-2

NA62
$K^+ \to \pi^+ X_{inv}$

E949
$K^+ \to \pi^+ \gamma\gamma$

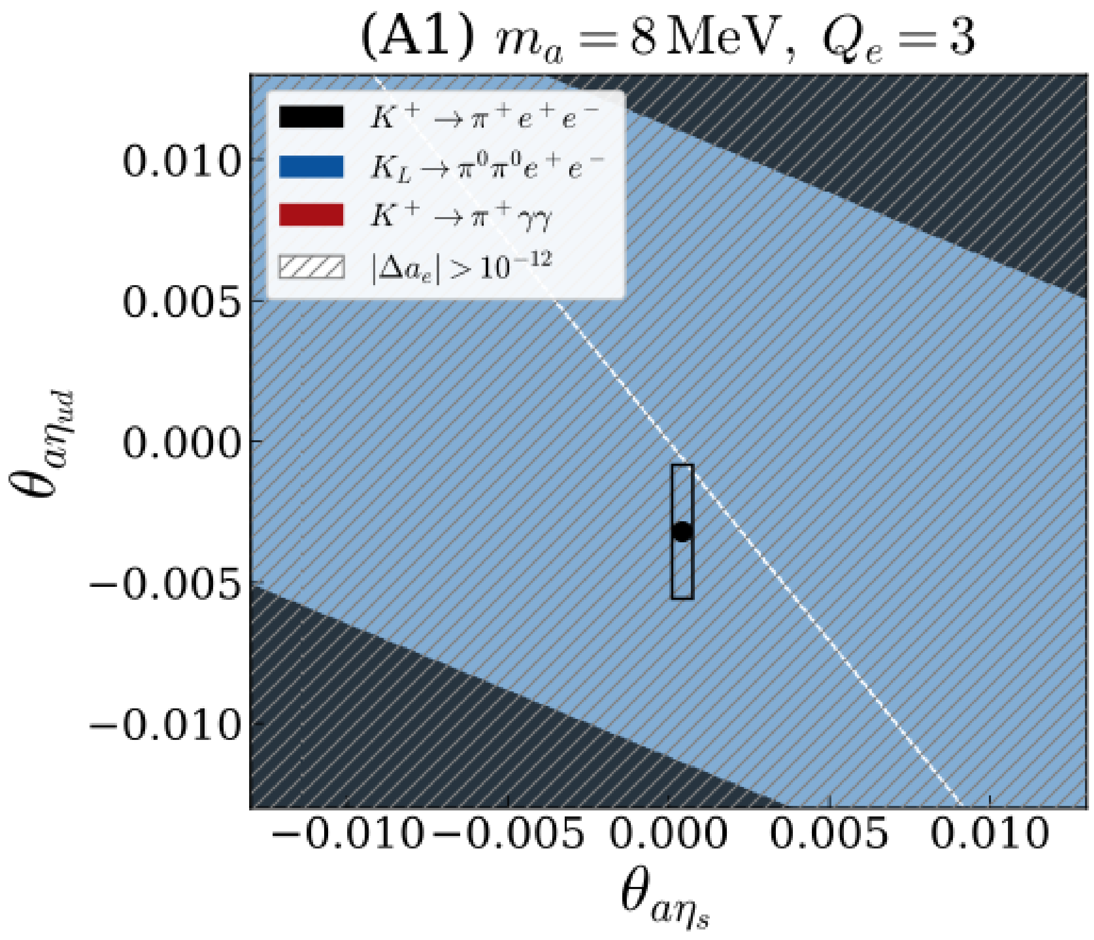
Result

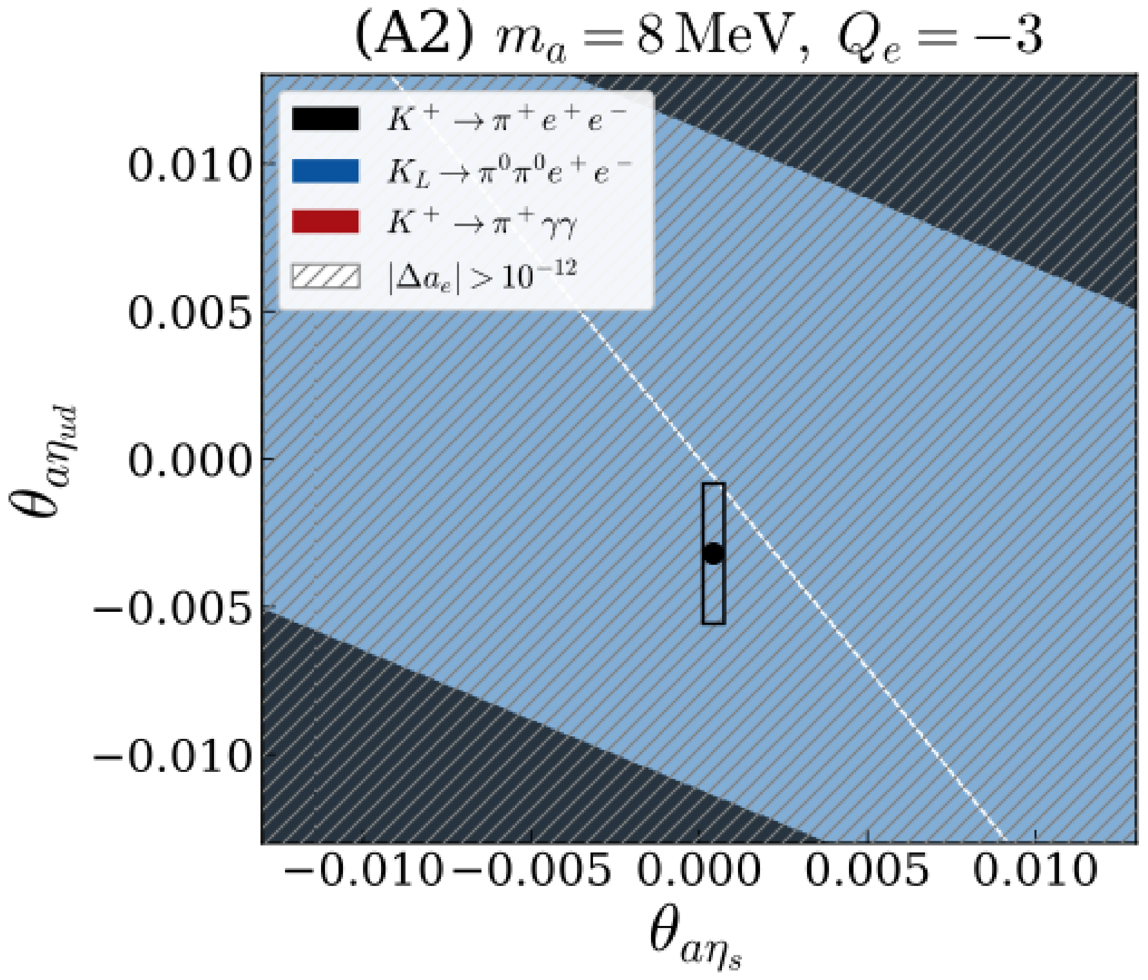
Leading order estimation



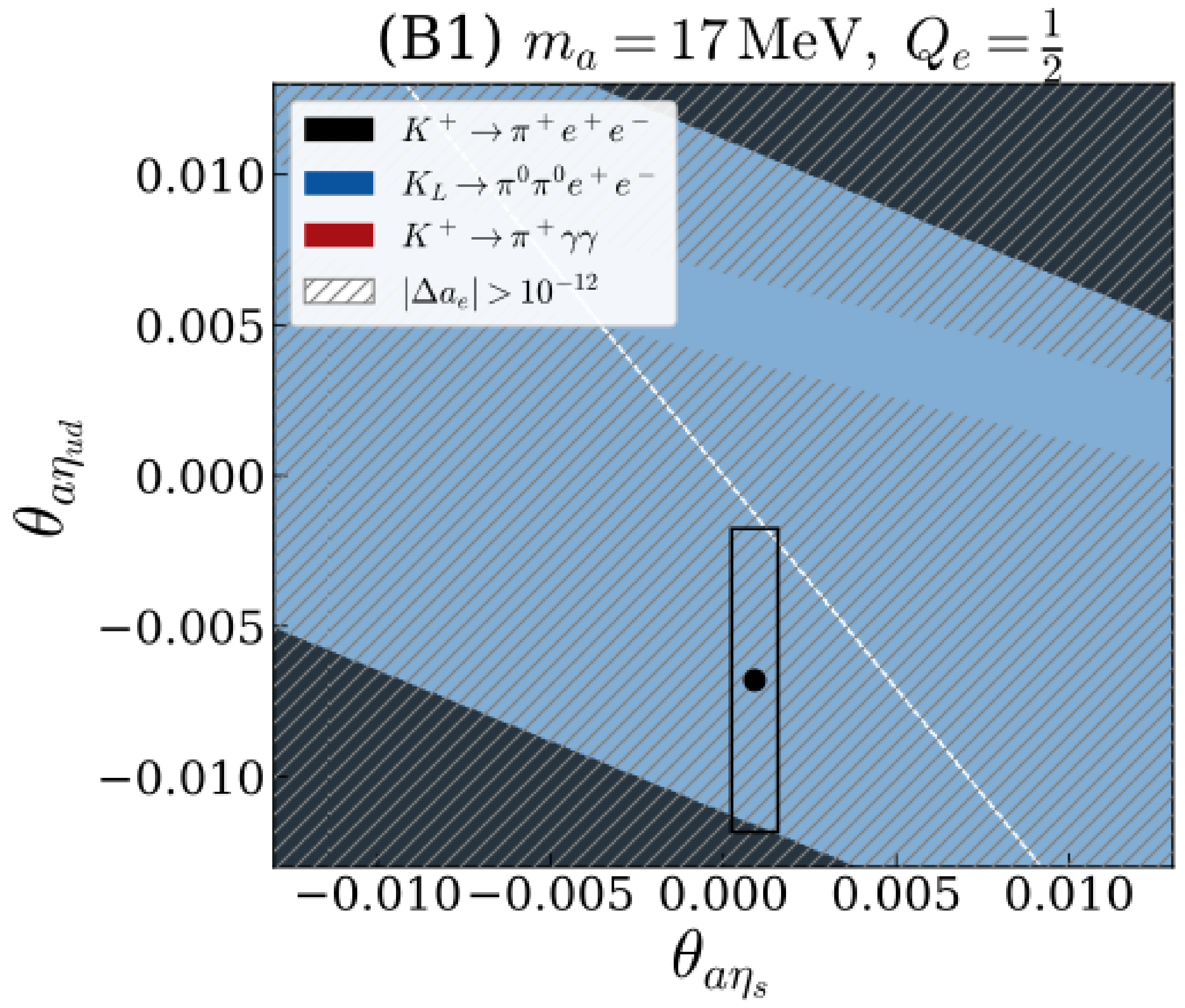
All region is excluded!

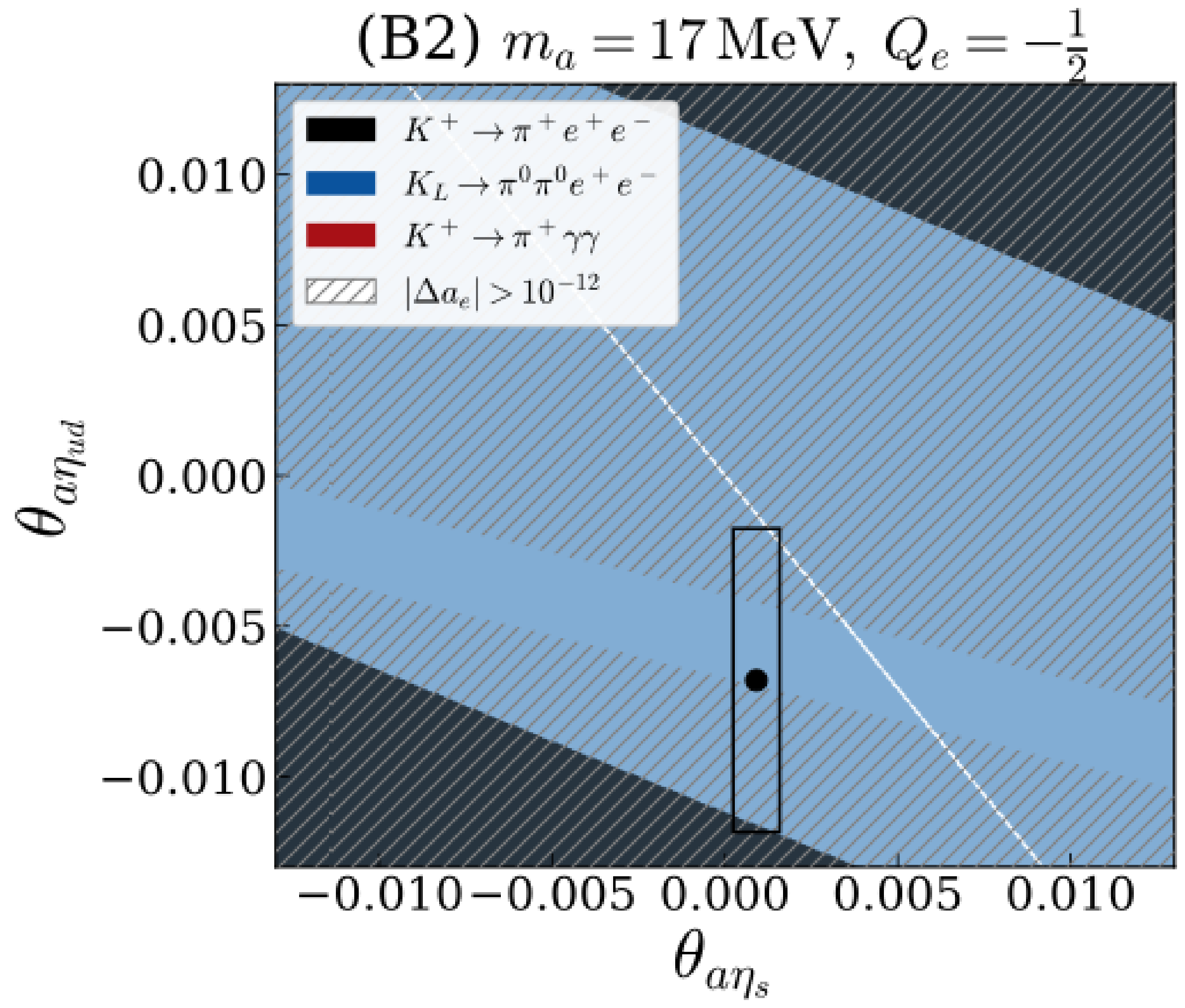
Result


(A1) $m_a = 8\,\mathrm{MeV},\ Q_e = 3$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to \pi^0 \pi^0 e^+ e^-$
$K^+ \to \pi^+ \gamma\gamma$
$|\Delta a_e| > 10^{-12}$
0.010
0.005
0.000
−0.005
−0.010
$\theta_{a\eta_{ud}}$
−0.010
−0.005
0.000
0.005
0.010
$\theta_{a\eta_s}$

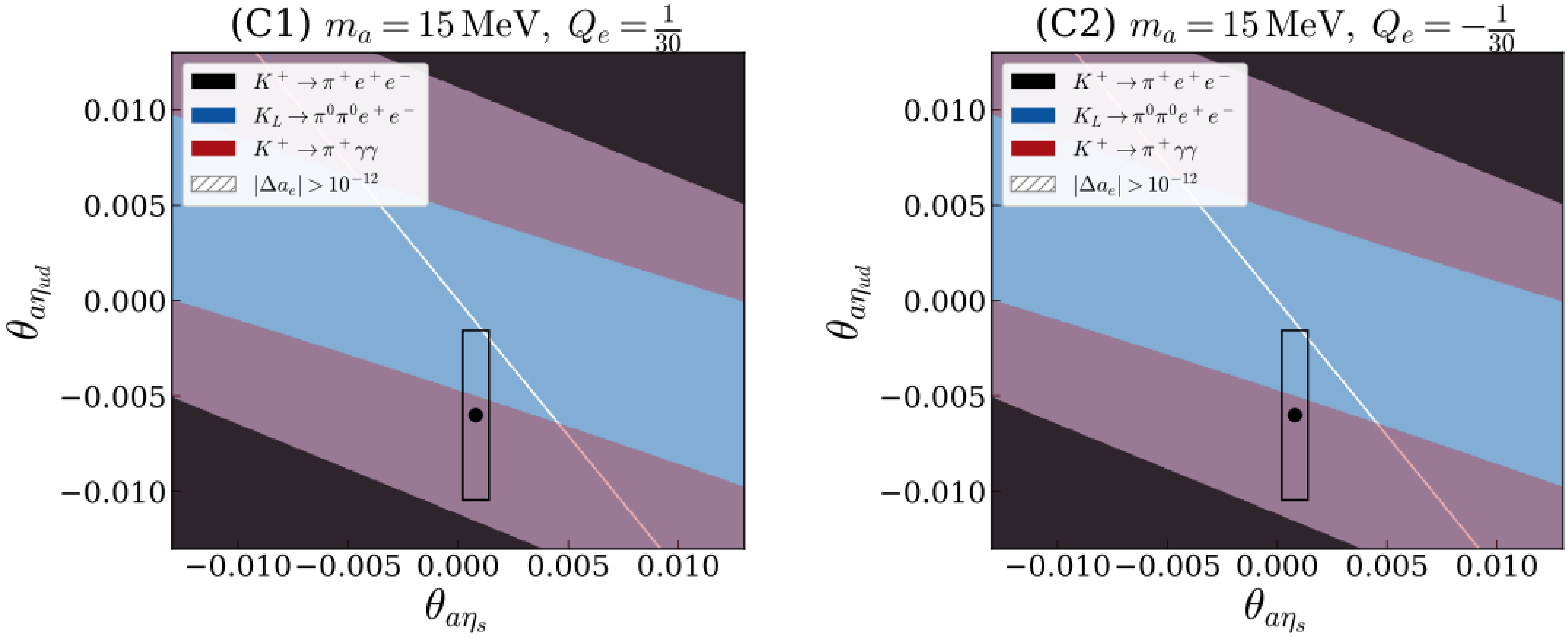

(A2) $m_a = 8\,\mathrm{MeV},\ Q_e = -3$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to \pi^0 \pi^0 e^+ e^-$
$K^+ \to \pi^+ \gamma\gamma$
$|\Delta a_e| > 10^{-12}$
0.010
0.005
0.000
−0.005
−0.010
$\theta_{a\eta_{ud}}$
−0.010
−0.005
0.000
0.005
0.010
$\theta_{a\eta_s}$

Result


(B1) $m_a = 17\,\mathrm{MeV},\ Q_e = \frac{1}{2}$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to \pi^0 \pi^0 e^+ e^-$
$K^+ \to \pi^+ \gamma\gamma$
$|\Delta a_e| > 10^{-12}$
$\theta_{a\eta_{ud}}$
$\theta_{a\eta_s}$
0.010
0.005
0.000
−0.005
−0.010


(B2) $m_a = 17\,\mathrm{MeV},\ Q_e = -\frac{1}{2}$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to \pi^0 \pi^0 e^+ e^-$
$K^+ \to \pi^+ \gamma\gamma$
$|\Delta a_e| > 10^{-12}$
$\theta_{a\eta_{ud}}$
$\theta_{a\eta_s}$
0.010
0.005
0.000
−0.005
−0.010

Result

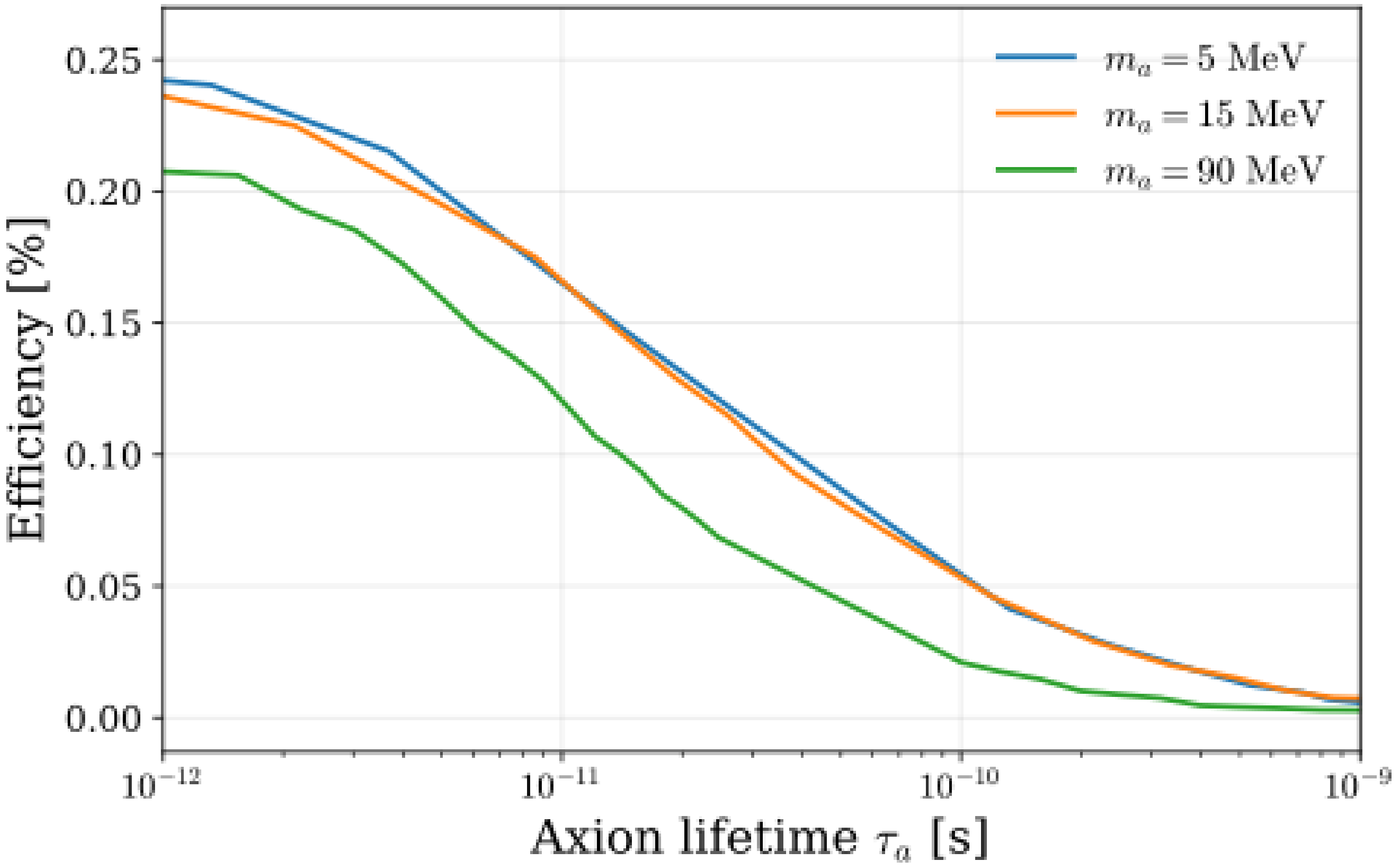

(C1) $m_a = 15\,\mathrm{MeV},\ Q_e = \frac{1}{30}$
(C2) $m_a = 15\,\mathrm{MeV},\ Q_e = -\frac{1}{30}$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to \pi^0 \pi^0 e^+ e^-$
$K^+ \to \pi^+ \gamma\gamma$
$|\Delta a_e| > 10^{-12}$
$\theta_{a\eta_{ud}}$
$\theta_{a\eta_s}$
0.010
0.005
0.000
−0.005
−0.010

Summary

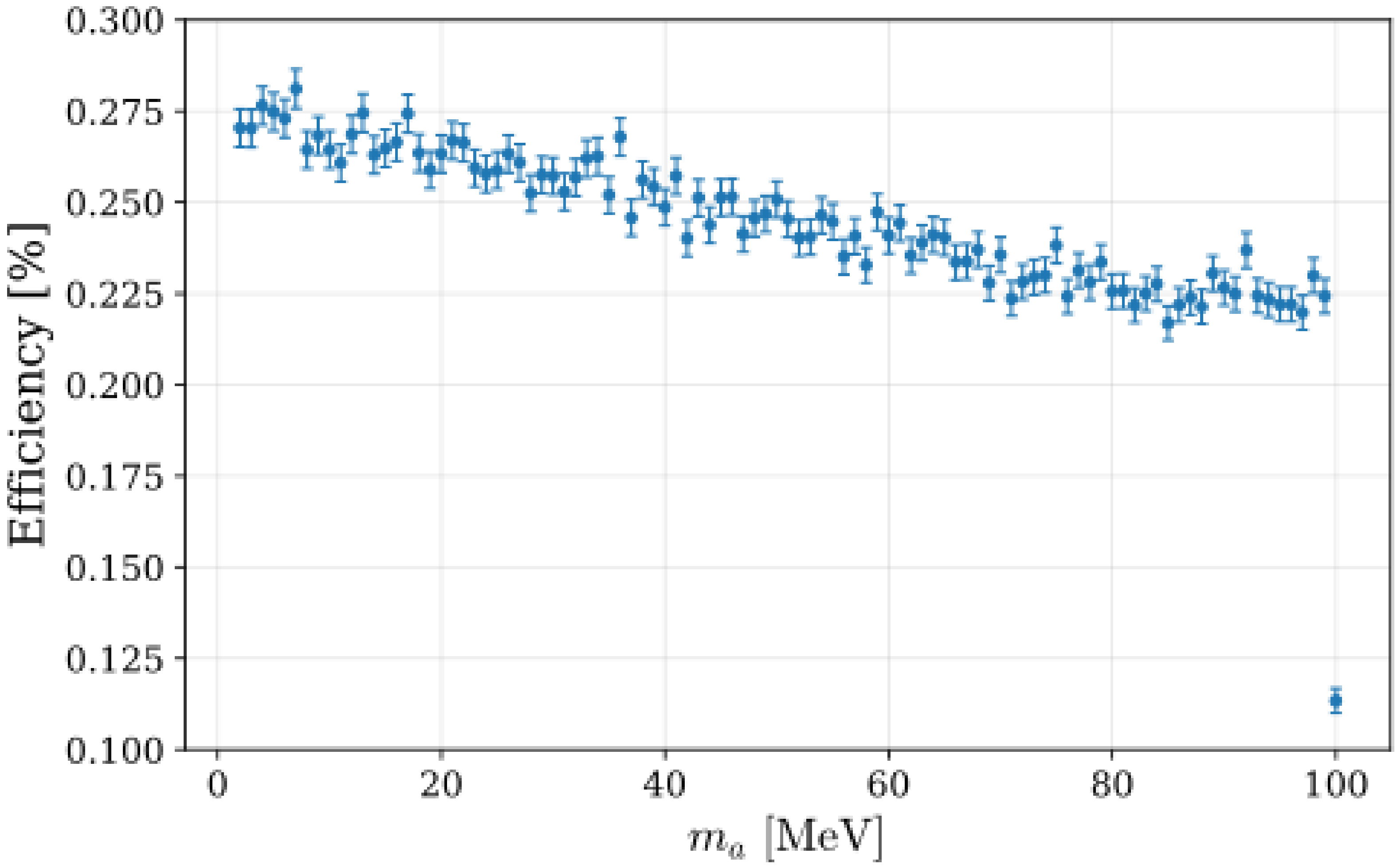
- The KTeV experiment places strong constraint on MeV axion model
- In LO estimation, we obtained the efficiency sufficient to exclude the MeV axion model.
- Even after taking into account the uncertainties of χPT, an extreme tuning is required.

Back up

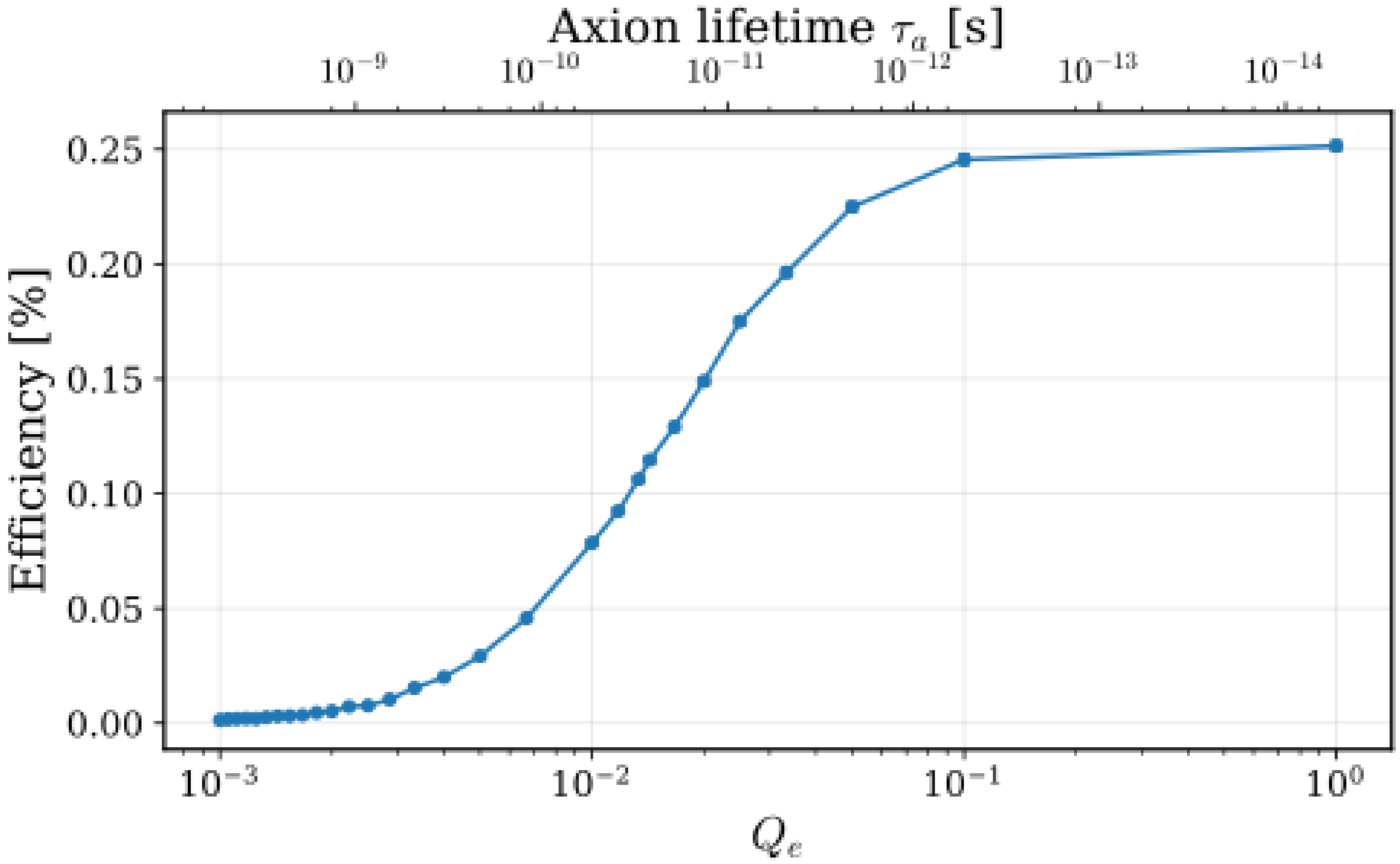
Efficiency plot



Efficiency plot



Efficiency plot

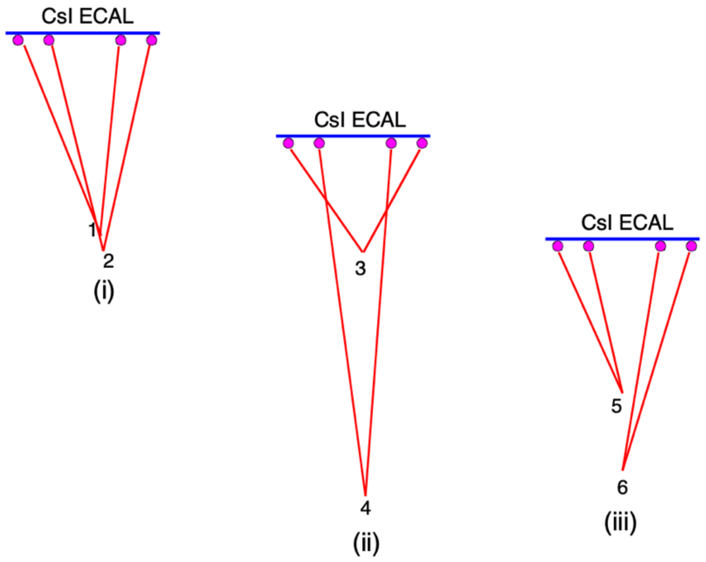


Events reconstruction

$$\chi^2 = \chi^2_{trac} + \chi^2_{cal}$$

$$\chi^2_{trac} = \sum_{i=1,2}\sum_{DC=1,2}\left(\frac{[x^i_{DC} - s^i_x(z^i_{DC} - z_v)]^2}{\sigma^2_x} + \frac{[y^i_{DC} - s^i_y(z^i_{DC} - z_v)]^2}{\sigma^2_y}\right)$$

$$\chi^2_{cal} = \frac{(z_A - z_v)^2}{\sigma^2_A} + \frac{(z_B - z_v)^2}{\sigma^2_B}$$



Monte Carlo Simulation

$$K_L \to \pi^0 \pi^0 a$$

$$d\Phi_3 = \frac{1}{(2\pi)^9} \prod_{i=1}^{3} \frac{d^3 p_i}{2E_i} \delta^4(P - p_1 - p_2 - p_3)$$

$$d\Phi_3 = (2\pi)^3 \int ds_{12} d\Phi_2(P \to q, p_3) d\Phi_2(q \to p_1, p_2)$$

Chiral Lagrangian

$$\mathcal{L}_a^{\text{eff}} = m_u e^{iQ_u^{PQ} a/f_a} u u^c + m_d e^{iQ_d^{PQ} a/f_a} d d^c + m_e e^{iQ_e^{PQ} a/f_a} e e^c$$

Chiral Lagrangian

$$\mathcal{L}_\chi^{(0)} = \frac{f_\pi^2}{4} \mathrm{Tr}\left[2BM_q(a)U + h.c.\right] - \frac{1}{2} M_0^2 \eta_0^2$$

$$M_q(a) \equiv \begin{pmatrix} m_u e^{iQ_u^{PQ} a/f_a} & & \\ & m_d e^{iQ_d^{PQ} a/f_a} & \\ & & m_s \end{pmatrix}$$

$$U \equiv exp\left(i \frac{\sqrt{2}}{f_\pi} \Sigma\right)$$

$$\Sigma \equiv \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^+ & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & K^0 \\ K^- & \overline{K^0} & -\frac{\eta_8}{\sqrt{3/2}} + \frac{\eta_0}{\sqrt{3}} \end{pmatrix}$$

Constraint of decays of Kaon

Existing bound

$$\mathrm{Br}(K^+ \to \pi^+ a \to \pi^+ e^+ e^-) \leq 10^{-6} - 10^{-5}$$

D. S. M. Alves et.al. JHEP 07, 092 (2018)

$$\mathrm{Br}(K^+ \to \pi^+ a)|_{a-\pi\, mixing} = \theta^2{}_{a\pi}\mathrm{Br}(K^+ \to \pi^+ \pi^0) \approx 10^{-9}$$

Pion Phobia

➡ **$a - \eta_{8,0}$ mixing is main contribution**

$$\mathcal{M}(K^+ \to \pi^+ a)\Big|_{a-\eta_{8,0} mixing} = \theta_{a\eta_8}\mathcal{M}(K^+ \to \pi^+ \eta_8) + \theta_{a\eta_0}\mathcal{M}(K^+ \to \pi^+ \eta_0)$$

Octet enhancement

$$\mathcal{L}_\chi^{\Delta S=1}\Big|_{O(p^2)} = g_8 f_\pi^2 \mathrm{Tr}\left[\lambda_{ds}\partial_\mu U \partial^\mu U^\dagger\right] + g_{27} f_\pi^2 C_{ab} \mathrm{Tr}\left[\lambda_a \partial_\mu U U^\dagger \lambda_b \partial^\mu U U^\dagger\right] + h.c.$$

$$\frac{\Gamma(K_s^0 \to \pi\pi)}{\Gamma(K^+ \to \pi^+\pi^0)} \approx 668 \qquad \frac{g_8}{g_{27}} \cong 31.2$$

$$\left|\theta_{a\eta_{ud}}\right|_{octet\ enh.} \leq (1.7 - 5.3) \times 10^{-4}$$

If we consider $\boldsymbol{O(p^4)}$ expansion

$$\mathcal{L}_\chi^{\Delta S=1}\Big|_{O(p^4)} \supset g'_8 \frac{f_\pi^2}{\Lambda^2} \mathrm{Tr}\left[\lambda_{ds} M_q U\right] \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] + h.c.$$

$$\frac{g_8}{g_{27}} \sim O(1) \qquad \frac{g'_8}{g_{27}} \sim O(100)$$

$$\left|\theta_{a\eta_{ud}}\right|_{not\ octet\ enh.} \leq (0.5 - 1.6) \times 10^{-2}$$