Constrains on MeV Axions from Kaon Decays

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MeV mass range Axion

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

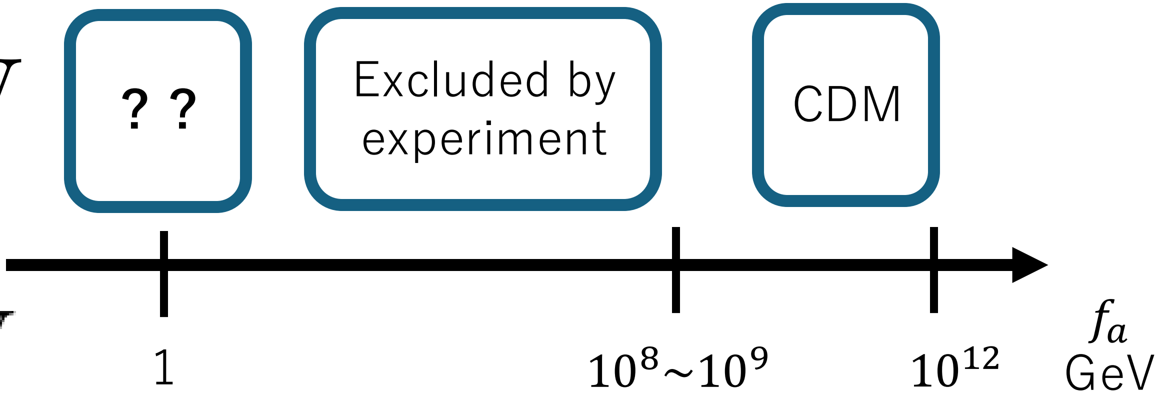
$$m_a^2 \approx \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

f_a:axion decay constant

f_π:pion decay constant

Many studies

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



Recently

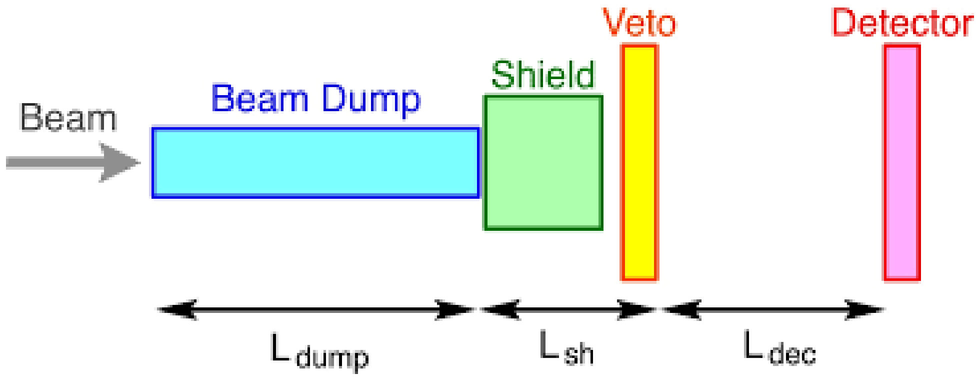
$$f_a \sim 1\mathrm{GeV} \quad m_a \sim 10\,\mathrm{MeV}$$

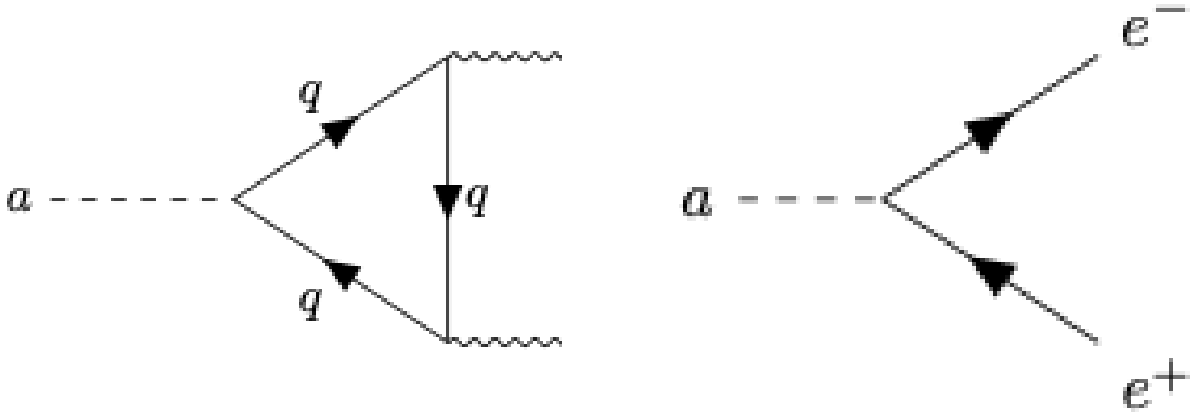
D. S. M. Alves et.al. JHEP 07, 092 (2018)

MeV Axion Model

Beam dump experiment

$$\mathrm{Br}(K^+ \to \pi^+(a \to \mathrm{invisible})) \lesssim 4.5 \times 10^{-11}$$ (E787 Collaboration)





Axion couples to e^-

MeV Axion Model

Quarkonia Decay

(F. Wilczek, Phys. Rev. Lett. 39 (1977) 1304)

$$\Gamma(J/\psi \to \gamma a) = \Gamma(J/\psi \to \mu^+\mu^-)\frac{Q_c^2\lambda_c^2}{2\pi\alpha}C_{J/\psi} \quad \lambda_c \sim O\left(\frac{m_c}{f_a}\right) \quad \lambda_b \sim O\left(\frac{m_b}{f_a}\right)$$

$$\Gamma(\Upsilon \to \gamma a) = \Gamma(\Upsilon \to \mu^+\mu^-)\frac{Q_b^2\lambda_b^2}{2\pi\alpha}C_{\Upsilon} \quad \Rightarrow \quad Q_c = Q_b = Q_t = 0$$

The rare decay process

$$\Gamma(\pi^+ \to e^+\nu_e a) = \frac{\cos\theta_c{}^2}{384\pi^3}G_F^2 m_\pi^5 \theta_{a\pi}^2$$

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

SINDRUM collaboration,
Phys. Lett. B 175 (1986) 101

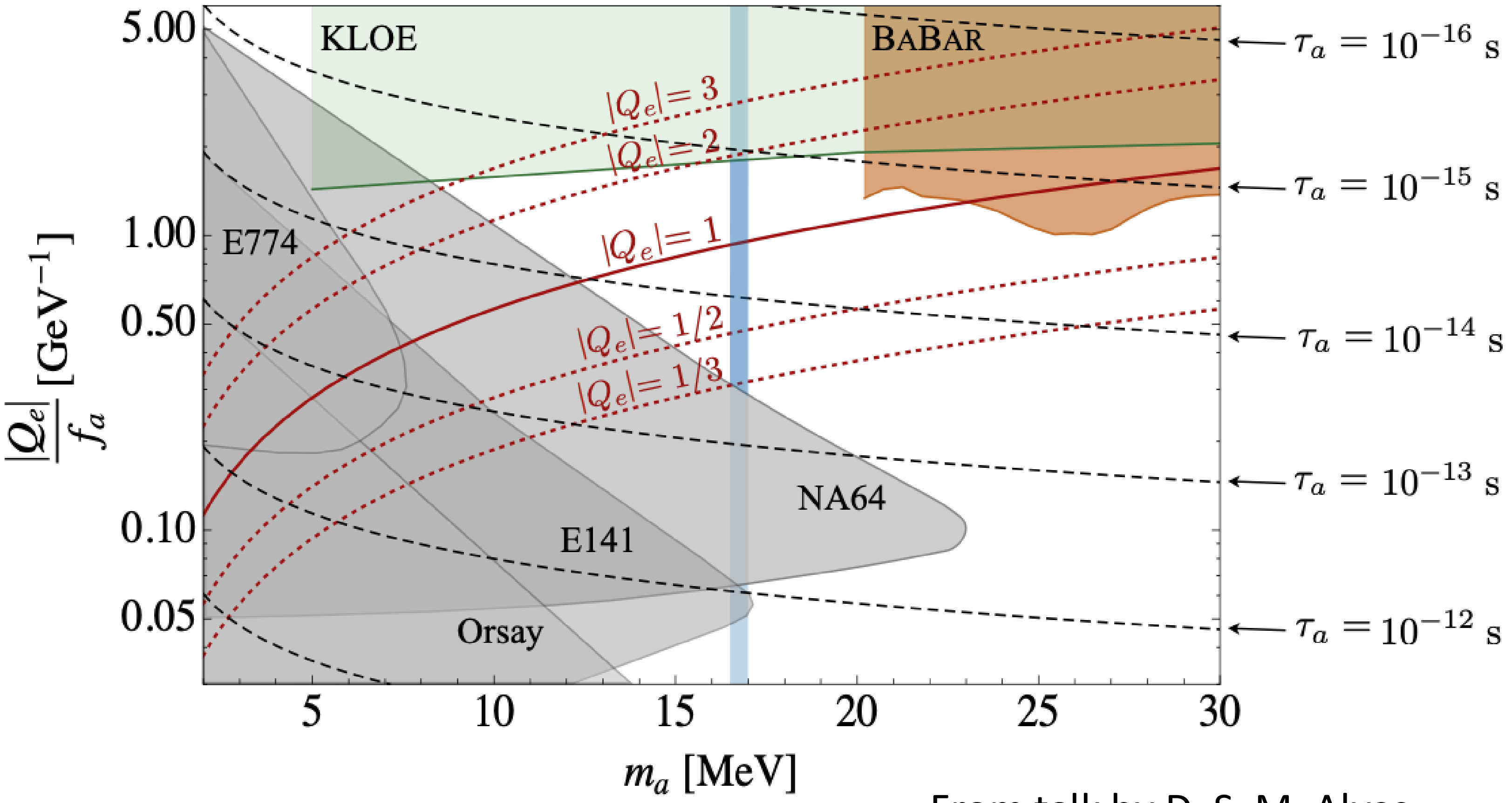
$$\mathcal{O}\left(\frac{f_\pi}{f_a}\right) \sim (0.5 - 10) \times 10^{-2}$$

$$\frac{m_u}{m_d} = 0.462 \pm 0.020$$

(PDG 2024)

$$\theta_{a\pi} \sim -\left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d} + \frac{Q_s}{2}\frac{m_u - m_d}{m_u + m_d}\right)\frac{f_\pi}{f_a} \quad \Rightarrow \quad \frac{Q_u}{Q_d} = 2 \quad Q_s = 0$$

Current Experimental Bound



From talk by D. S. M. Alves (2020)

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)

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

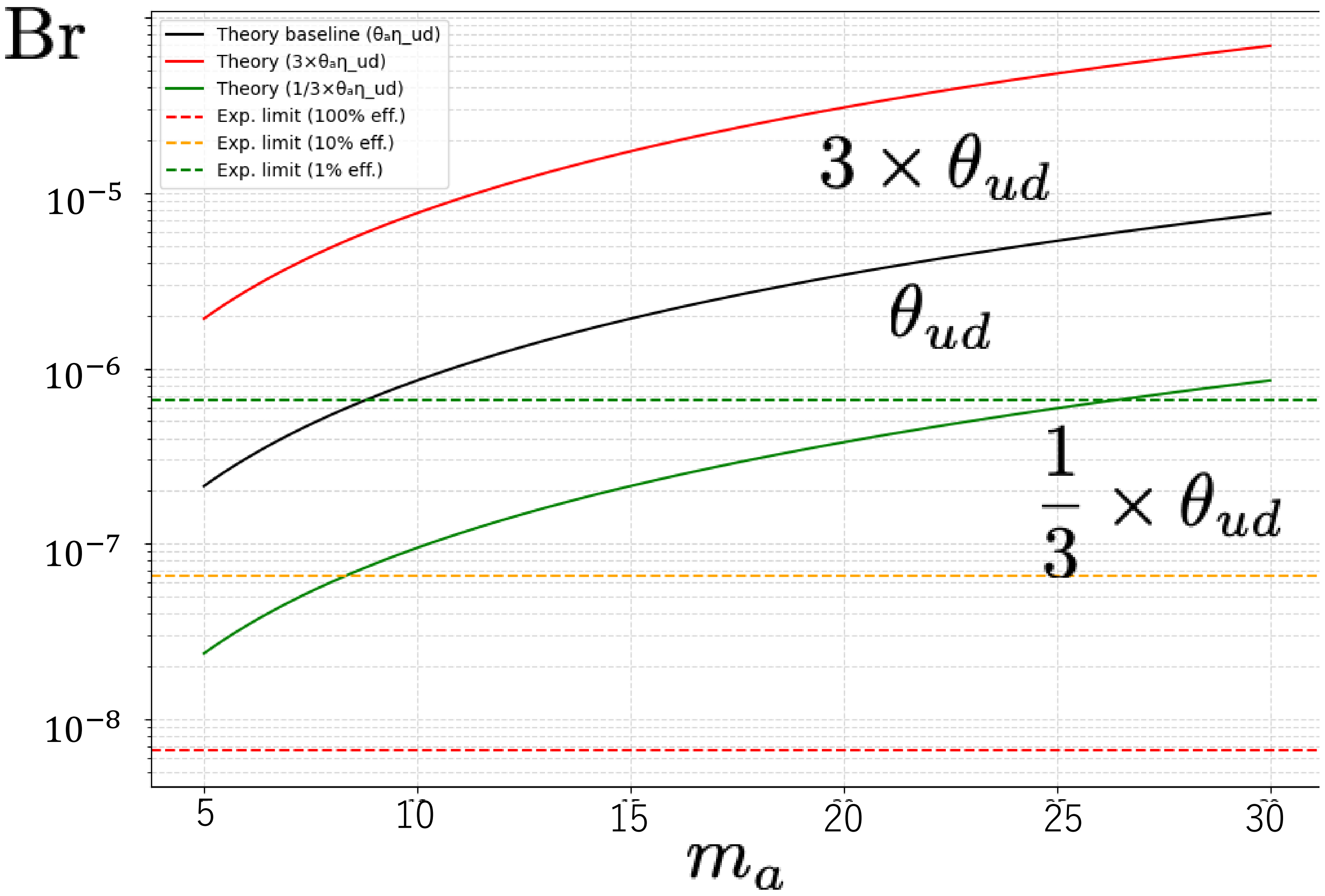
$$\mathcal{L}_\chi^{\Delta S=1}\Big|_{O(p^4)} \supset -\frac{4g_8' B}{f_\pi^2\Lambda^2} m_s K_L(-\pi^0 + \eta_{ud} + \sqrt{2}\eta_s)\partial_\mu\pi^0\partial^\mu\pi^0$$

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

$$\Rightarrow \quad \mathrm{Br}(K_L \to \pi^0\pi^0 a) = \frac{1}{2} \times 1.49(\theta_{a\pi} - \theta_{a\eta_{ud}} - \sqrt{2}\theta_{a\eta_s})^2$$

$$\mathrm{Br}(K_L \to \pi^0\pi^0(a \to e^+e^-)) \simeq \frac{1}{2} \times 1.49\,\theta_{a\eta_{ud}}^2$$

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



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

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!

Simulation Flow

1. Simulate 3-body decay of K_L in rest frame

2. Inject K_L with given energy spectrum and simulate decay

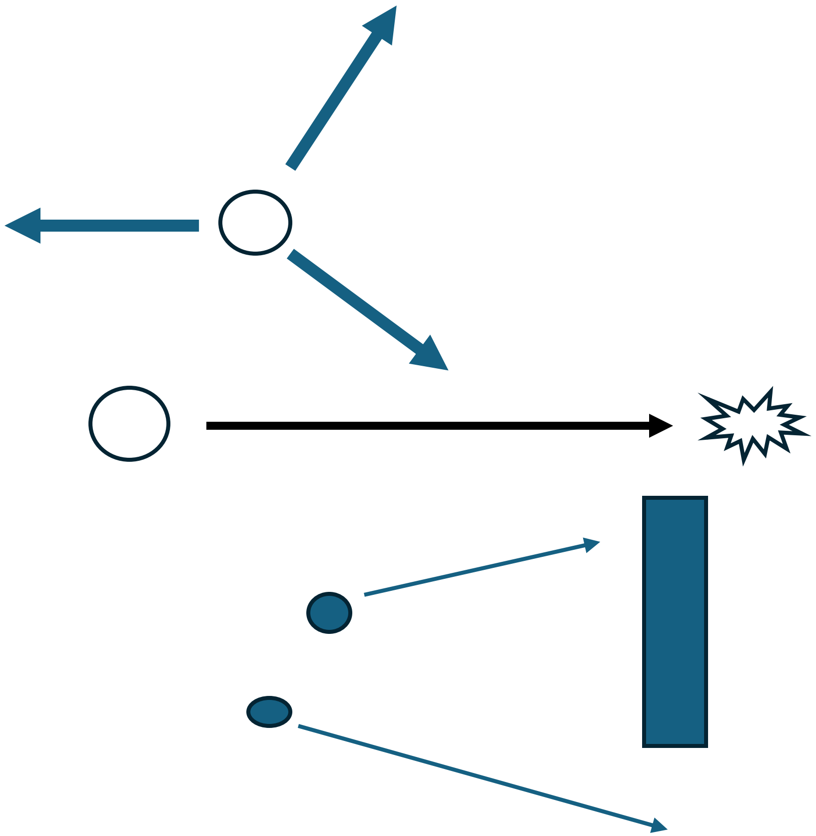
3. Boost simulated decay products to lab frame

4. Simulate secondary decays: $\pi^0 \to \gamma\gamma, \quad a \to e^+e^-$

5. Simulate detector hits of decay products

K_L 1000000

Hit Events ???



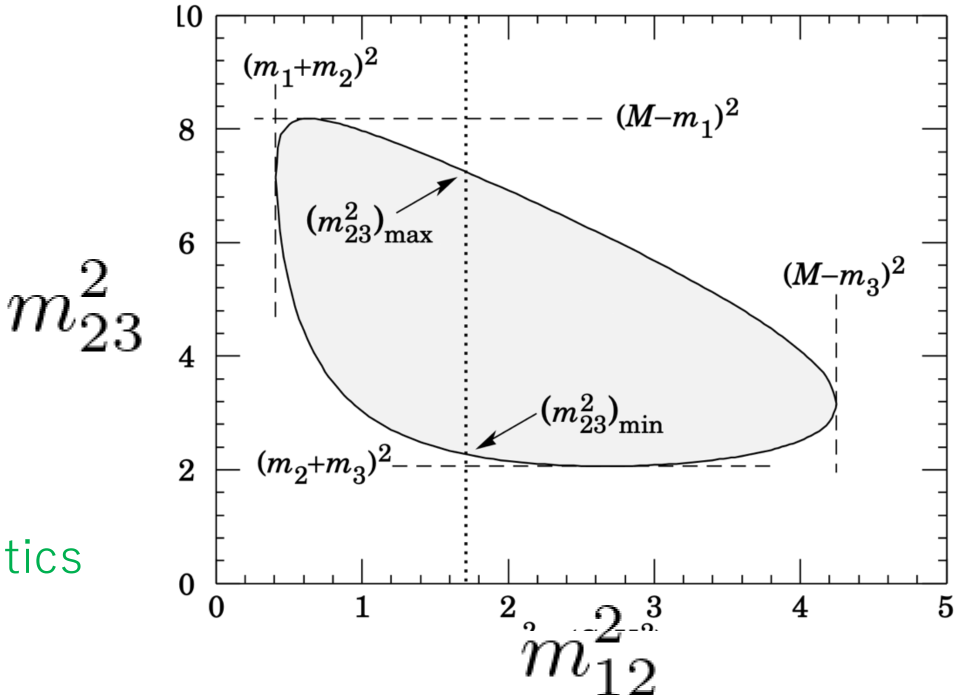
3 body Decays

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

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 dm_{12} dm_{23}$$

$$m_{12}^2 \equiv (p_{\pi_1^0} + p_{\pi_2^0})^2$$

$$m_{23}^2 \equiv (p_{\pi_2^0} + p_a)^2$$



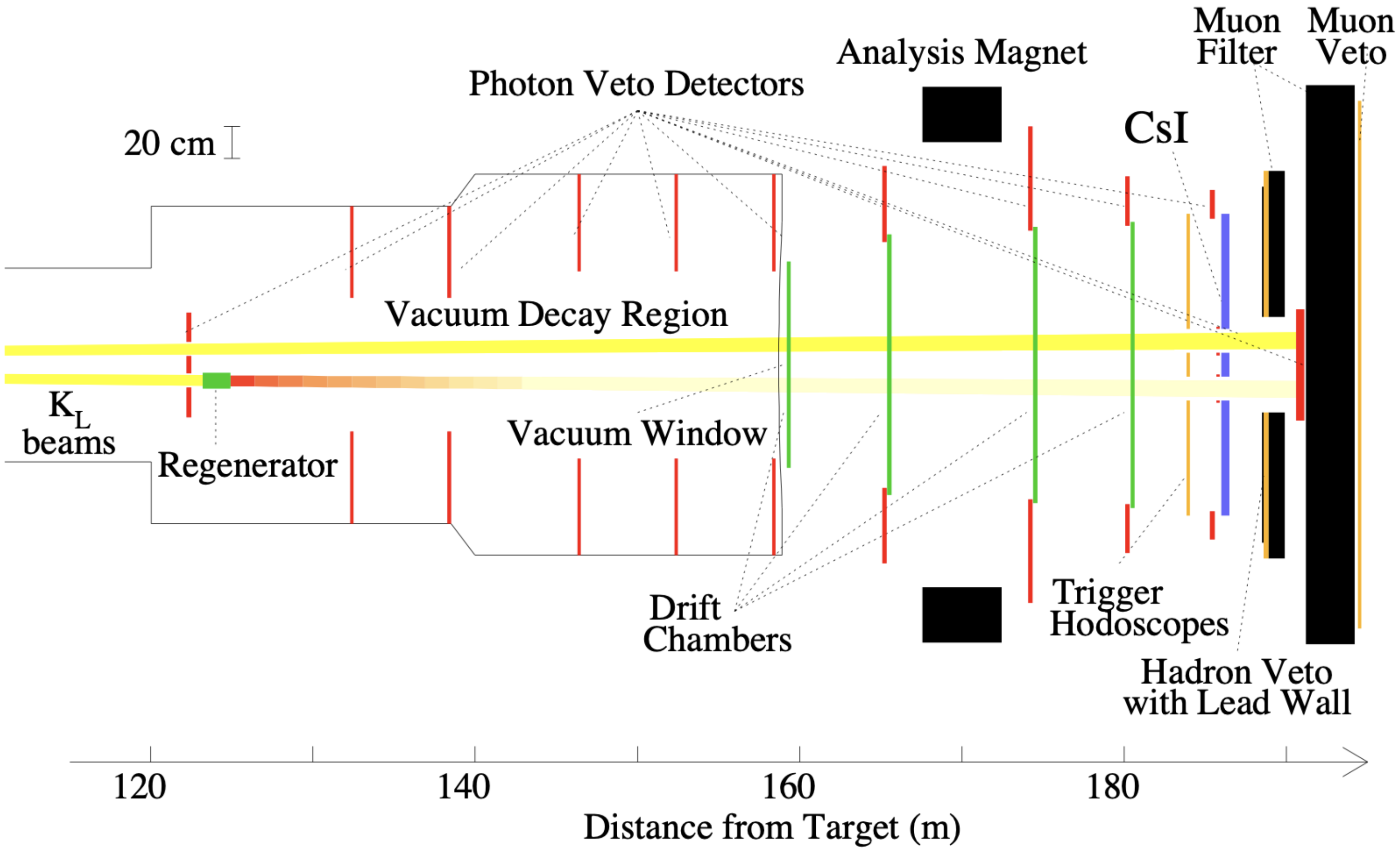
PDG kinematics

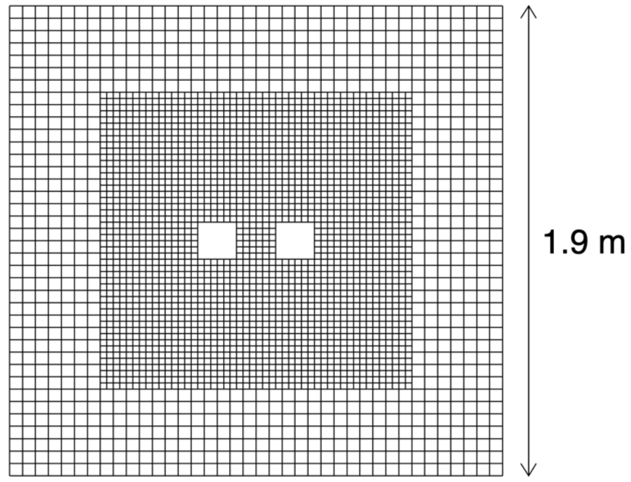
Generate random numbers in the Dalitz plot weighted by

$$\mathcal{M}(K_L \to \pi^0 \pi^0 a) \propto m_{12}^2 - 2m_\pi^2$$

+Euler angles

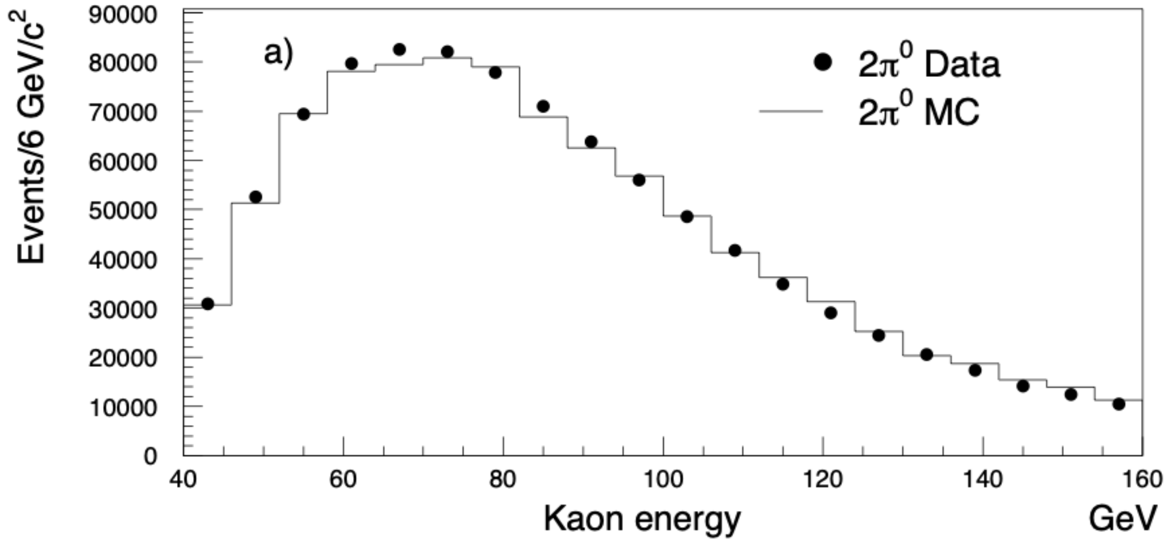
KTeV Experiment





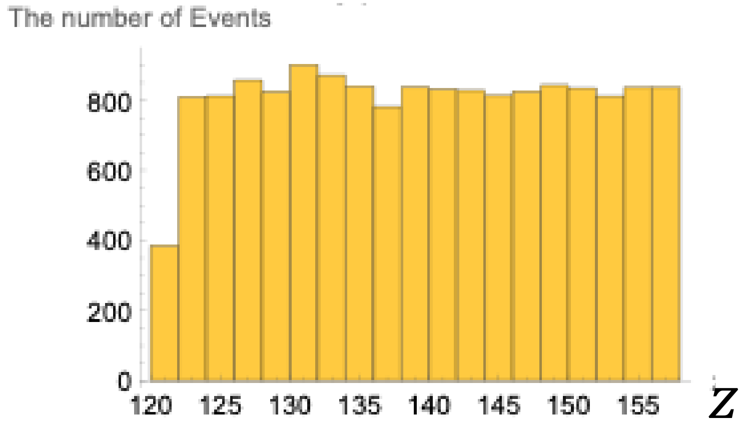
KTeV Collaboration

KTeV Experiment

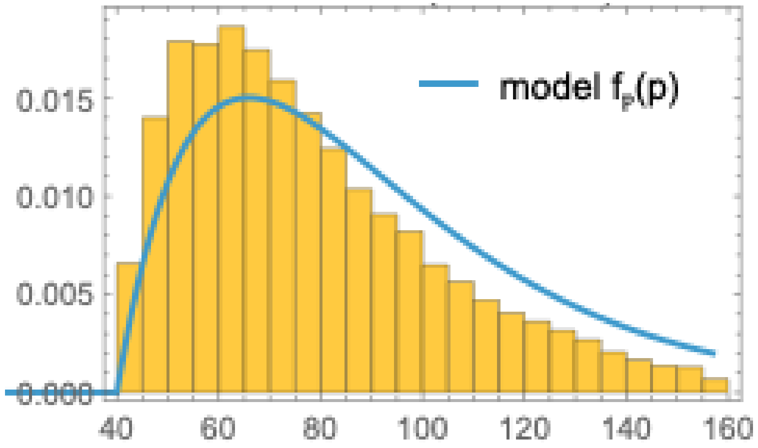


KTeV Collaboration Phys. Rev. Lett. **89**, 211801

Distribution of K_L Decay Positions



Momentum Distribution of Decayed K_L



Monte Carlo Simulation

Step	Selection / Processing	Event count
1	Number of incident K_L	1,000,000
2	Number of hit events	5,830
3	After cuts: $0.493 \leq M_{\pi^0\pi^0e^+e^-} \leq 0.501, \quad p_x^2 + p_y^2 \leq 1.5 \times 10^{-4}$	5,495
4	Removed $K_L \to \pi^0\pi^0(\pi^0 \to e^+e^-e^+e^-)$	5,495
5	Removed $K_L \to \pi^0\pi^0(\pi^0 \to e^+e^-\gamma)$	3,035
6	Removed $K_L \to \pi^0\pi^0(\pi^0 \to \gamma(\gamma \to e^+e^-))$	1,170
—	**Final number of events**	**1,170**

➡ **Efficiency(MeV Axion) $\approx \mathbf{0.1\%} \approx \frac{1}{2}$ Efficiency(SM)**

Summary

- In the MeV Axion model, there are effects arising from mixing with the η
- $\mathrm{Br}(K_L \to \pi^0\pi^0 e^+ e^-)$ is significantly larger than the Standard Model prediction.
- Efficiency(MeV Axion) $\approx \frac{1}{2}$ Efficiency(SM)
- Realizing the MeV axion model looks difficult

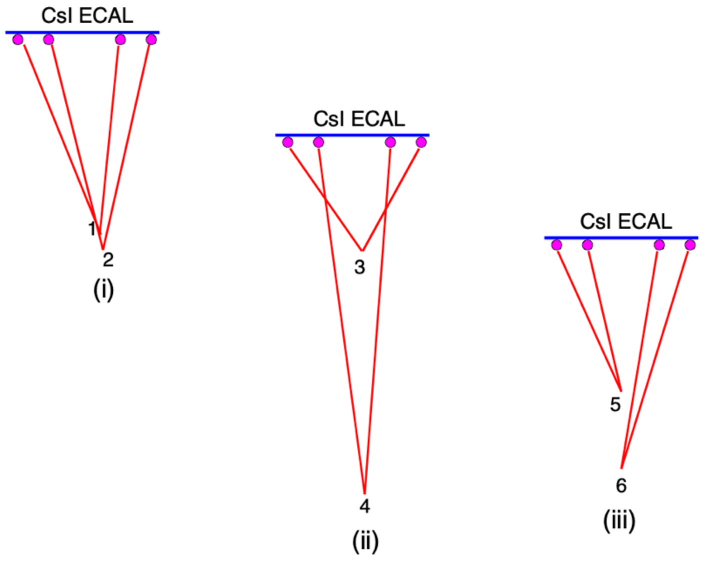
Back up

Events reconstruction

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

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

$$\chi^2_{cal} = \frac{(z_A - z_v)^2}{\sigma_A^2} + \frac{(z_B - z_v)^2}{\sigma_B^2}$$



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

$$\mathcal{L}_a^{\mathrm{eff}} = m_u e^{iQ_u^{PQ} a/f_a} uu^c + m_d e^{iQ_d^{PQ} a/f_a} dd^c + m_e e^{iQ_e^{PQ} a/f_a} ee^c$$

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

$\boldsymbol{a - \eta_{8,0}}$ 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

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

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

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

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

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

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

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