Sweeping the pion chimney for axion-like particles with KOTO

2507.01947 & 2508.08402

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BERKELEY LAB

Motivation

axion-like particles (ALPs) are well motivated and naturally arise in many extension of the SM:

- QCD axion/strong CP problem
- dark matter
- portal to dark sector
- ‘axiverse’
- composite models
- supersymmetry

Motivation

Flavor Probes of ALPs

e.g. Bauer et al. 2110.10698
Camalich et al. 2002.04623

- flavor and CP violation are suppressed in the SM
- flavor violating & CP violating observables are very sensitive to small BSM contributions
- charged kaon decays place strong bounds on axions

$$K^+ \to \pi^+ a(inv) \;\to\; f_a/c_{sd} > 10^9 \text{ GeV}$$

NA62 2103.15389

Motivation

Flavor & CP Probes of ALPs

- **neutral kaon decays** are unique probes of CP-violation (CPV) in BSM sector
- for ALP couplings, CPV and FV are **related**

SM Yukawa's only source of FV (minimal flavor violation - MFV)	$\rightarrow$	no additional CP violation in ALP couplings
additional sources of FV	$\rightarrow$	additional CP violating phases

Motivation

Flavor & CP Probes of ALPs

- **goal:** study 3-body decays of neutral kaons:

$$K_L \to \pi^0\pi^0 a \qquad\qquad K_L \to \pi^+\pi^- a$$

$$\frac{\Gamma\left(K_L \to \pi^0\pi^0 a\right)}{\Gamma\left(K_L \to \pi^0 a\right)} = ?$$

SM:

$$\frac{\Gamma\left(K_L \to \pi^0\pi^0\pi^0\right)}{\Gamma\left(K_L \to \pi^0\pi^0\right)} = 200$$

Plan

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

I. Theory: focus on FV and EW contributions

(R. Balkin, S. Gori, CS: 2507.01947)

II. Application using KOTO calibration data

(R. Balkin, S. Gori, D. Robinson, CS: 2508.08402)

Flavor violating ALP couplings - from UV to IR

$$\mathcal{L}_a(\Lambda) = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2\, a^2 + \frac{\partial_\mu a}{f} \sum_F \bar{F}\, \boldsymbol{c}_F\, \gamma_\mu F$$
$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W^i_{\mu\nu} \tilde{W}^{i,\mu\nu} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

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in MFV:

$$\kappa_U = c_0^Q \mathbb{1} + \epsilon c_1^Q (\mathbf{Y}_t)^2 + \mathcal{O}(\epsilon^2)$$
$$\kappa_D = c_0^Q \mathbb{1} + \epsilon c_1^Q \mathbf{V}^\dagger (\mathbf{Y}_t)^2 \mathbf{V} + \mathcal{O}(\epsilon^2)$$
$$\kappa_u = c_0^u \mathbb{1} + \epsilon c_1^u (\mathbf{Y}_t)^2 + \mathcal{O}(\epsilon^2)$$
$$\kappa_d = c_0^d \mathbb{1}$$

real coefficients!

Flavor violating ALP couplings - from UV to IR

above the QCD scale:

$$\mathcal{L}_a(\mu) \supset \frac{\partial_\mu a}{f}(\kappa_R \bar{d}_R \gamma_\mu s_R + \kappa_L \bar{d}_L \gamma_\mu s_L + \text{h.c})$$

with

$$\kappa_R = [\mathbf{c}_{d_R}(\Lambda)]_{12}$$

$$\kappa_L = [\hat{c}_{Q_L}(\Lambda)]_{12} + \Delta\kappa_L$$

mass basis

matching contribution

Flavor violating ALP couplings - from UV to IR

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$$\kappa_R = [\mathbf{c}_{d_R}(\Lambda)]_{12}$$

$$\kappa_L = \boxed{[\hat{c}_{Q_L}(\Lambda)]_{12}} + \Delta\kappa_L$$

mass basis

matching contribution

$$[\hat{c}_{Q_L}(\Lambda)]_{12} = [\mathbf{V}^\dagger \mathbf{c}_{Q_L} \mathbf{V}]$$
$$= [\mathbf{c}_{Q_L}]_{12} + V_{cd}^* V_{cs}\left([\mathbf{c}_{Q_L}]_{22} - [\mathbf{c}_{Q_L}]_{11}\right)$$
$$+ V_{td}^* V_{ts}\left([\mathbf{c}_{Q_L}]_{33} - [\mathbf{c}_{Q_L}]_{11}\right) + \ldots$$

in MFV: $\mathbf{c}_{Q_L} \approx \text{diag}(0, 0, y_t^2)$

Flavor violating ALP couplings - from UV to IR

above the QCD scale:

$$\mathcal{L}_a(\mu) \supset \frac{\partial_\mu a}{f}\left(\kappa_R \bar{d}_R \gamma_\mu s_R + \kappa_L \bar{d}_L \gamma_\mu s_L + \mathrm{h.c}\right)$$

RGE evolution

with

$$\kappa_R = [\mathbf{c}_{d_R}(\Lambda)]_{12}$$

$$\kappa_L = [\hat{c}_{Q_L}(\Lambda)]_{12} + \boxed{\Delta\kappa_L}$$

mass basis

matching contribution

$$\Delta\kappa_L = \boxed{n_t} c_{tt}(\Lambda) + \boxed{n_G} \tilde{c}_{GG}(\Lambda) + \boxed{n_W} \tilde{c}_{WW}(\Lambda) + \boxed{n_B} \tilde{c}_{BB}(\Lambda)$$

$$c_{tt} = [\mathbf{c}_{u_r}]_{33} - [\mathbf{c}_{Q_L}]_{33}$$

$$\tilde{c}_{GG} = c_{GG} + \frac{1}{2}\mathrm{Tr}\left[\mathbf{c}_{u_R} + \mathbf{c}_{d_R} - 2\mathbf{c}_{Q_L}\right]$$

$$\tilde{c}_{WW} = c_{WW} - \frac{1}{2}\mathrm{Tr}\left[3\mathbf{c}_{Q_L} + \mathbf{c}_{L_L}\right]$$

$$\tilde{c}_{BB} = c_{BB} + \mathrm{Tr}\left[\frac{4}{3}\mathbf{c}_{u_R} + \frac{1}{3}\mathbf{c}_{d_R} - \frac{1}{6}\mathbf{c}_{Q_L} - \frac{1}{2}\mathbf{c}_{L_L} + \mathbf{c}_{e_R}\right]$$

Flavor violating ALP coulings - from UV to IR

below confinement scale: chiral Lagrangian

$$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu a)^2 + \frac{f_\pi^2}{8}\mathrm{Tr}\left[D^\mu\Sigma(D_\mu\Sigma^\dagger)\right]$$

$$\mathcal{L}_m = \frac{f_\pi^2}{4}B_0\mathrm{Tr}\left[\hat{\mathbf{m}}_q\Sigma^\dagger + h.c.\right] - \frac{1}{2}m_{a,0}^2a^2$$

$$\mathcal{L}_{weak} = \frac{4N_8}{f_\pi^2}[L_\mu L^\mu]^{32} + h.c.$$

$$\Sigma = \exp\left[i\Pi/f_\pi\right]$$

$$D_\mu\Sigma = \partial_\mu\Sigma - i\frac{\partial_\mu a}{f}\left(\hat{\mathbf{k}}_Q\Sigma - \Sigma\hat{\mathbf{k}}_q\right)$$

$$\hat{\mathbf{m}}_q = \exp\left[-2i\kappa_q c_{GG}\frac{a(x)}{f}\right]\mathbf{m}_q$$

Flavor violating ALP coulings - from UV to IR

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Kinetic term:

- FV interactions proportional to off-diagonal ALP couplings
- kinetic mixing

Flavor violating ALP coulings - from UV to IR

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Kinetic term:

- FV interactions proportional to off-diagonal ALP couplings
- kinetic mixing

Mass term:

- mass mixing
- flavor preserving interactions

Flavor violating ALP coulings - from UV to IR

below confinement scale: chiral Lagrangian

$$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu a)^2 + \boxed{\frac{f_\pi^2}{8}\mathrm{Tr}\left[D^\mu\Sigma(D_\mu\Sigma^\dagger)\right]}$$

$$\mathcal{L}_m = \boxed{\frac{f_\pi^2}{4}B_0\mathrm{Tr}\left[\hat{\mathbf{m}}_q\Sigma^\dagger + h.c.\right]} - \frac{1}{2}m_{a,0}^2a^2$$

$$\mathcal{L}_{weak} = \boxed{\frac{4N_8}{f_\pi^2}[L_\mu L^\mu]^{32}} + h.c.$$

$$\Sigma = \exp\left[i\Pi/f_\pi\right]$$

$$D_\mu\Sigma = \partial_\mu\Sigma - i\frac{\partial_\mu a}{f}\left(\hat{\mathbf{k}}_Q\Sigma - \Sigma\hat{\mathbf{k}}_q\right)$$

$$\hat{\mathbf{m}}_q = \exp\left[-2i\kappa_q c_{GG}\frac{a(x)}{f}\right]\mathbf{m}_q \qquad L_\mu^{ji} = -\frac{if_\pi^2}{4}e^{i(\phi_{q_i}^- - \phi_{q_j}^-)a(x)/f}[\Sigma(D_\mu\Sigma)^\dagger]^{ji}$$

Kinetic term:

- FV interactions proportional to off-diagonal ALP couplings
- kinetic mixing

Mass term:

- mass mixing
- flavor preserving interactions

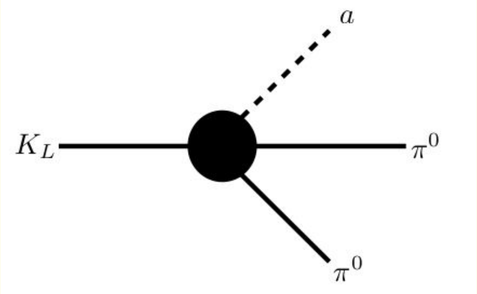
Weak-mediated term:

- flavor violating interactions proportional to diagonal ALP couplings
- kinetic mixing (neutral and charged meson, neutral and ALP mixing)

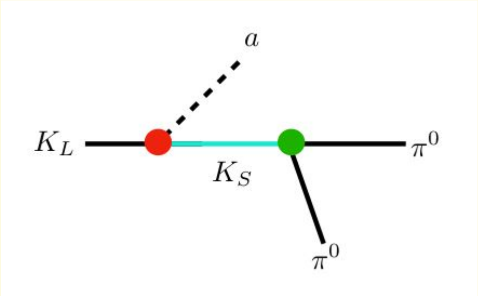
Kaon decay amplitudes

1) move to physical basis (remove all mixings)

2) sum up all relevant 4-point contact terms



3) sum up all relevant factorizable contributions



Kaon decay amplitudes

$$s_{\pi^0} = (p_{\pi_1^0} + p_{\pi_2^0})^2$$

calculated for the first time!

$$\mathcal{M}(K_L \to a\,\pi^0\,\pi^0) = \frac{m_K^2}{2\sqrt{2}f_\pi f}\left(\mathrm{Re}\,\mathcal{M}_0 + i\varepsilon\mathrm{Im}\,\mathcal{M}_0\right)$$

$$\mathcal{M}(K_S \to a\,\pi^0\,\pi^0) = \frac{m_K^2}{2\sqrt{2}f_\pi f}\left(\mathrm{Im}\,\mathcal{M}_0 - i\varepsilon\mathrm{Re}\,\mathcal{M}_0\right)$$

$$\mathcal{M}_0 \equiv \kappa_A\left(\frac{s_{\pi^0}}{m_K^2 - m_a^2} - 1\right) + N_8\left(\mathcal{C}_2 + \mathcal{C}_3\frac{s_{\pi^0}}{m_K^2}\right)$$

"direct" "indirect"

$$\mathcal{C}_1 = -2c_{GG}(\Lambda) - 2[\boldsymbol{c}_d]_{11} + [\boldsymbol{c}_Q]_{11} + [\boldsymbol{c}_Q]_{22} + \mathcal{O}\left(\frac{m_\pi^2}{m_K^2}, \frac{m_a^2}{m_K^2}\right)$$

$$\mathcal{C}_2 = -2c_{GG}(\Lambda) - 2[\boldsymbol{c}_d]_{11} + [\boldsymbol{c}_Q]_{11} + [\boldsymbol{c}_Q]_{22} + \mathcal{O}\left(\frac{m_\pi^2}{m_K^2}, \frac{m_a^2}{m_K^2}\right)$$

$$\mathcal{C}_3 = -3[\boldsymbol{c}_Q]_{11} + 2[\boldsymbol{c}_d]_{22} + [\boldsymbol{c}_Q]_{22} + \mathcal{O}\left(\frac{m_\pi^2}{m_K^2}, \frac{m_a^2}{m_K^2}\right)$$

$$\mathcal{M}(K_L \to \pi^0 a) = \frac{(m_K^2 - m_\pi^2)}{2f}\left(\mathrm{Im}\,\widetilde{\mathcal{M}} - i\varepsilon\mathrm{Re}\,\widetilde{\mathcal{M}}\right)$$

$$\widetilde{\mathcal{M}} \equiv \kappa_V + N_8\mathcal{C}_1$$

FV and CPV - some numbers

$$\varepsilon = 2.228(11) \times 10^{-3} e^{i\theta_\varepsilon}$$

$$\theta_\varepsilon \approx 0.76$$

$$|N_8| \approx 1.53 \times 10^{-7}$$

$$\delta_8 \approx \mathrm{Im}\left[-\frac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*}\right] \approx -6 \times 10^{-4}$$

contributes to ε'

1107.6001
hep-ph/0309172
hep-ph/0005189

$$V_{td}^* V_{ts}$$

$$= (0.33 + 0.13i) \times 10^{-3}$$

Kaon decay amplitudes

$$\mathcal{M}(K_L \to a\,\pi^0\,\pi^0) = \frac{m_K^2}{2\sqrt{2}f_\pi f}\left(\mathrm{Re}\,\mathcal{M}_0 + i\varepsilon\mathrm{Im}\,\mathcal{M}_0\right)$$

axial

CP-preserving

$$\mathcal{M}(K_S \to a\,\pi^0\,\pi^0) = \frac{m_K^2}{2\sqrt{2}f_\pi f}\left(\mathrm{Im}\,\mathcal{M}_0 - i\varepsilon\mathrm{Re}\,\mathcal{M}_0\right)$$

axial

CP-violating

$$\mathcal{M}(K_L \to \pi^0 a) = \frac{(m_K^2 - m_\pi^2)}{2f}\left(\mathrm{Im}\,\widetilde{\mathcal{M}} - i\varepsilon\mathrm{Re}\,\widetilde{\mathcal{M}}\right)$$

vector

Ratio of rates

$$R_0 = \frac{\mathrm{Br}(K_L \to \pi^0\pi^0 a)}{\mathrm{Br}(K_L \to \pi^0 a)} \qquad R_\pm = \frac{\mathrm{Br}(K_L \to \pi^+\pi^- a)}{\mathrm{Br}(K_L \to \pi^0 a)}$$

$$R_0, R_\pm \sim \left| \frac{\text{largest CP-conserving coupling}}{\text{largest CP-violating coupling}} \right|^2 \cdot I$$

phase space ratio $I \sim \mathcal{O}(10^{-3} - 10^{-2})$

Scenarios

1. maximal flavor violation $\kappa_L \gg V_{td}^* V_{ts}$

2. minimal flavor violation $\kappa_L = c_{MFV} V_{td}^* V_{ts}$

   "directly mediated" $N_8 \ll c_{MFV} V_{td}^* V_{ts}$ $R_0 \sim \mathcal{O}(10^{-2})$

   "mix" $\epsilon N_8 \ll c_{MFV} V_{td}^* V_{ts} \ll N_8$ $R_0 \sim \mathcal{O}(10^{-1} - 10)$

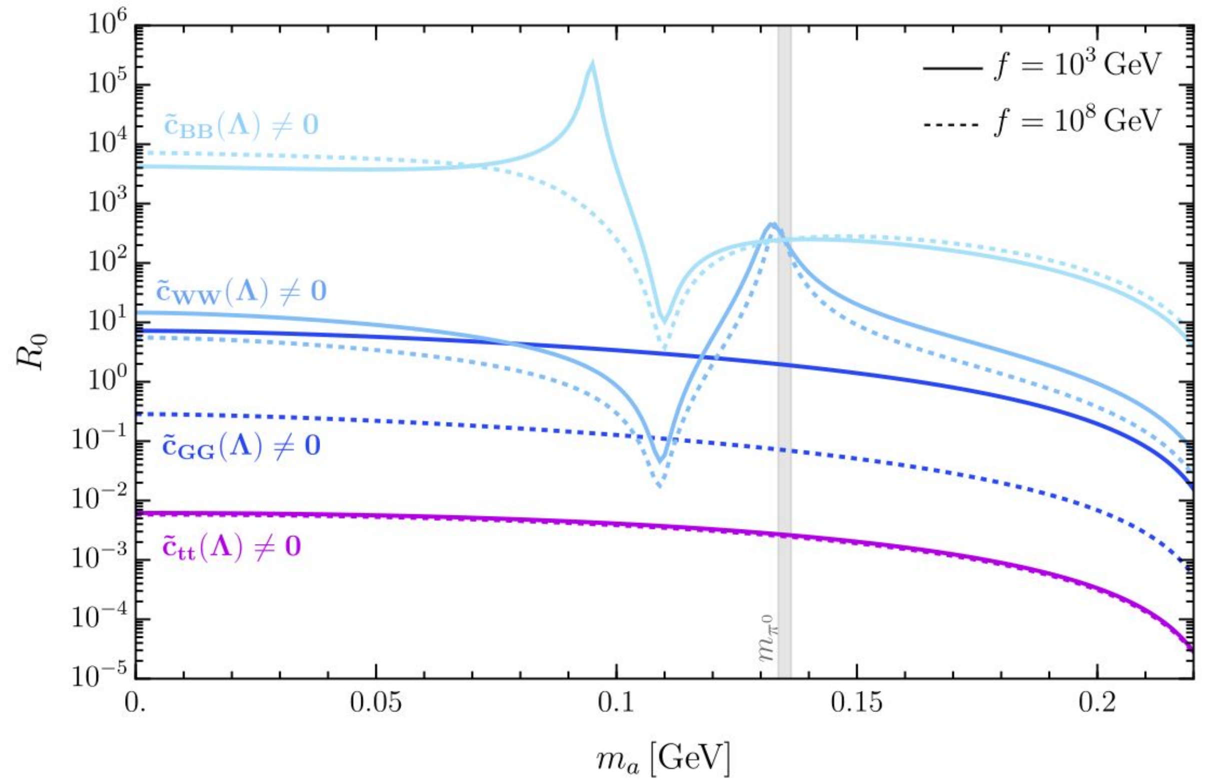
   "indirectly mediated" $c_{MFV} V_{td}^* V_{ts} \ll \epsilon N_8$ $R_0 \sim \mathcal{O}(10^2 - 10^3)$

Minimal flavor violation - neutral

$$c_{MFV} V_{td}^* V_{ts} \ll \epsilon N_8$$
"directly mediated"

$$\epsilon N_8 \ll c_{MFV} V_{td}^* V_{ts} \ll N_8$$
"mix"

$$N_8 \ll c_{MFV} V_{td}^* V_{ts}$$
"indirectly mediated"



Minimal flavor violation - neutral

$N_8 \ll c_{MFV} V_{td}^* V_{t}$

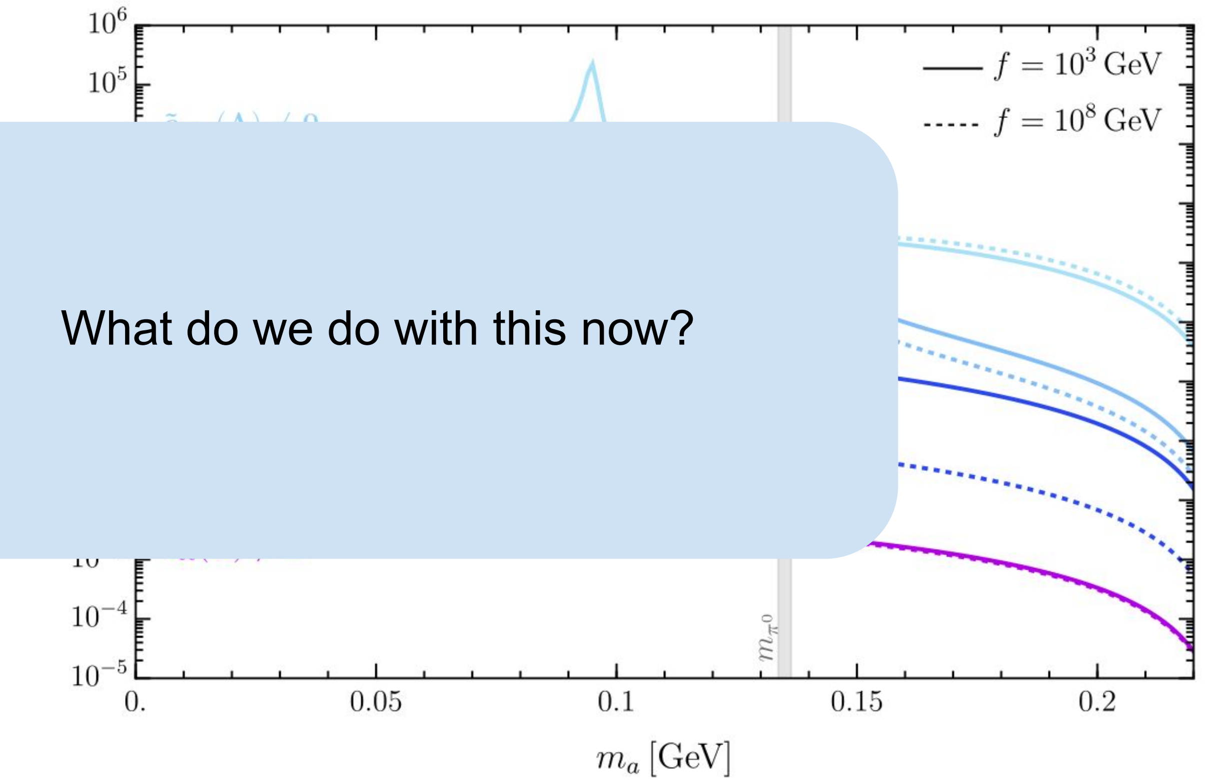
"directly mediated

$\epsilon N_8 \ll c_{MFV} V_{td}^* V_{ts} <$

"mix"

$N_8 \ll c_{MFV} V_{td}^* V_{ts}$

"indirectly mediated"



What do we do with this now?

Minimal flavor violation - neutral

$N_8 \ll c_{MFV} V_{td}^* V_{t...}$

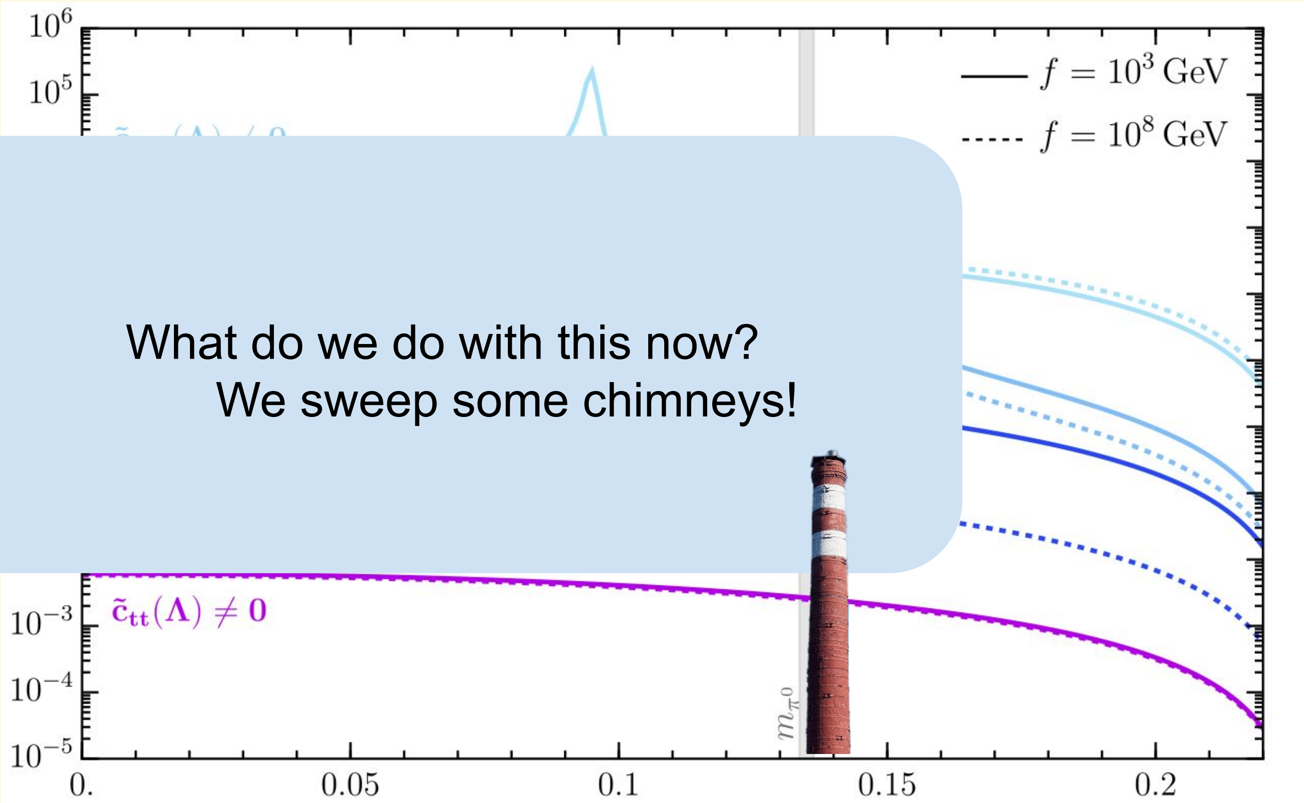
“directly mediated...

$\epsilon N_8 \ll c_{MFV} V_{td}^* V_{ts} <...$

“mix”

$N_8 \ll c_{MFV} V_{td}^* V_{ts}$

“indirectly mediated”

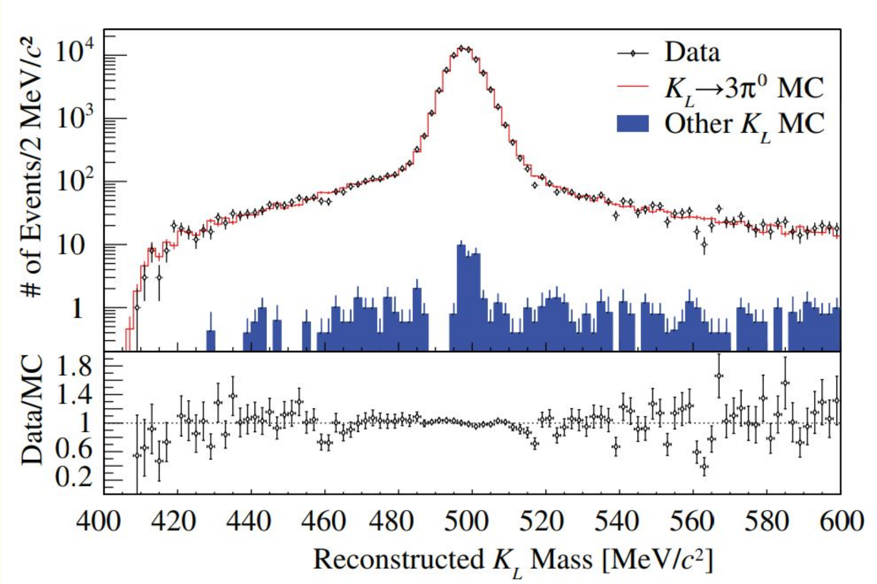


What do we do with this now?
We sweep some chimneys!

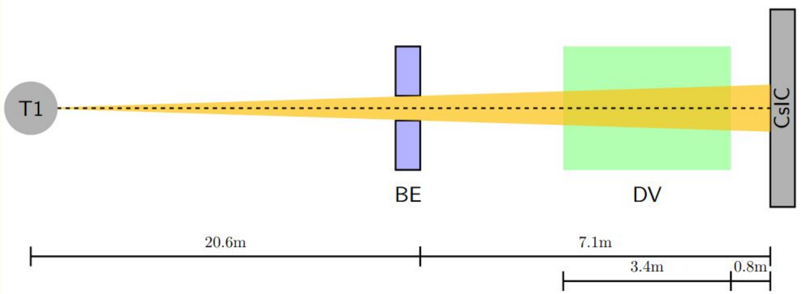
Look at some data!

Long-lived neutral-kaon flux measurement for the KOTO experiment

T. Masuda[1,16,*], J. K. Ahn[2], S. Banno[3,17], M. Campbell[4], J. Comfort[5], Y. T. Duh[6], T. Hineno[1,18], Y. B. Hsiung[6], T. Inagaki[7], E. Iwai[3,19], N. Kawasaki[1], E. J. Kim[8], Y. J. Kim[9], J. W. Ko[9], T. K. Komatsubara[7], A. S. Kurilin[10,†], G. H. Lee[8], J. W. Lee[3,20], S. K. Lee[8], G. Y. Lim[7], J. Ma[11,21], D. MacFarland[5], Y. Maeda[1,22], T. Matsumura[12], R. Murayama[3], D. Naito[1], Y. Nakaya[3,†], H. Nanjo[1], T. Nomura[7], Y. Odani[13,23], H. Okuno[7], Y. D. Ri[3,24], N. Sasao[14], K. Sato[3,25], T. Sato[7], S. Seki[1], T. Shimogawa[13,19], T. Shinkawa[12], K. Shiomi[3,19], J. S. Son[8], Y. Sugiyama[3], S. Suzuki[13], Y. Tajima[15], G. Takahashi[1], Y. Takashima[3,26], M. Tecchio[4], M. Togawa[3], T. Toyoda[3,27], Y. C. Tung[6,28], Y. W. Wah[11], H. Watanabe[7], J. K. Woo[9], J. Xu[4,31], T. Yamanaka[3], Y. Yanagida[3,29], H. Y. Yoshida[15], and H. Yoshimoto[3,30]



KOTO

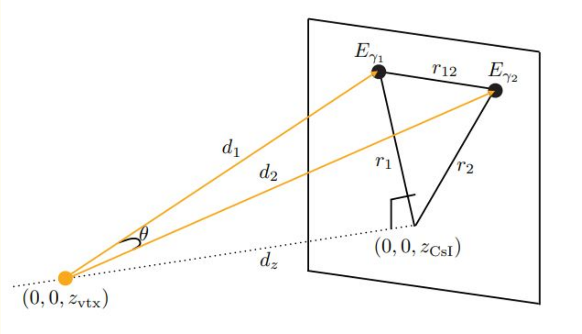


KOTO measures photon energies and positions

to reconstruct kaon mass:

1. use opening angle between any pair of photons to find potential kaon decay vertex
2. choose photon pairing combination that minimizes

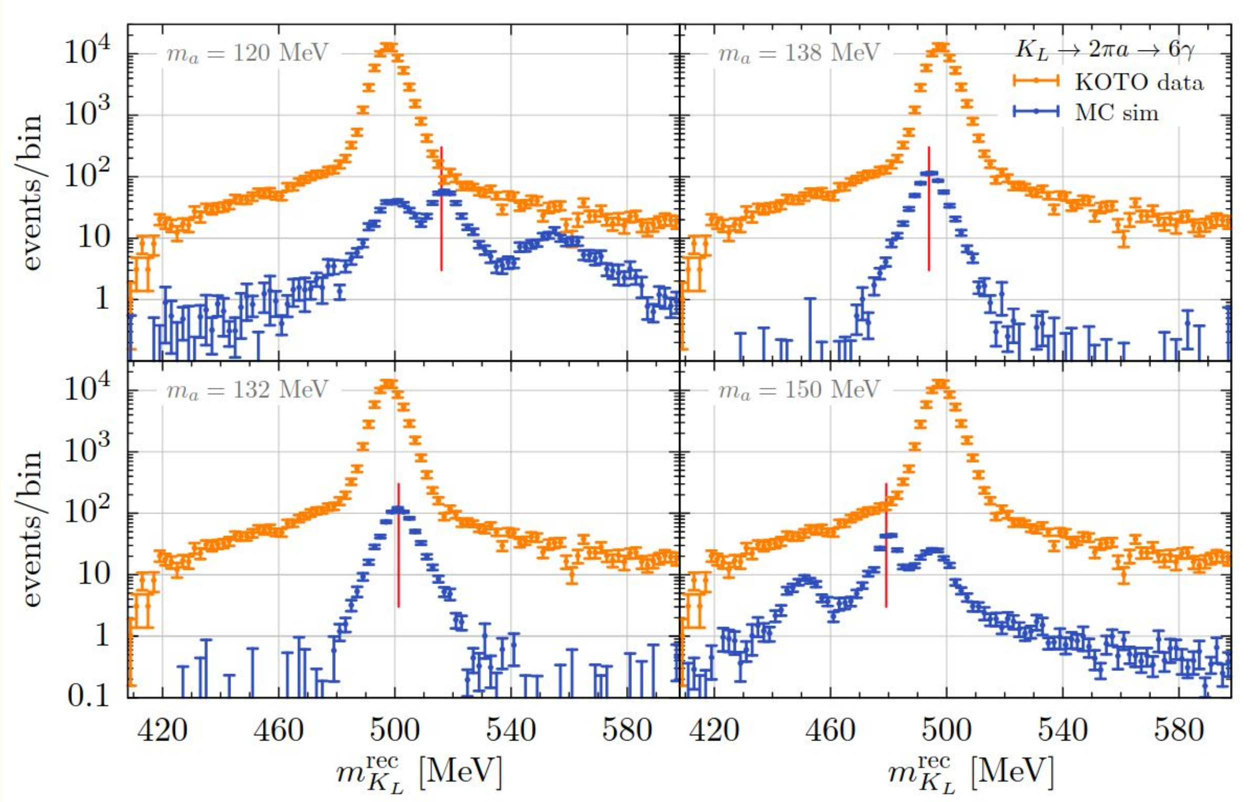
$$m_{\pi^0}^2 = 2E_1E_2(1-\cos\theta)$$



$$\chi_Z^2 = \sum_{i=1}^{15} \frac{(Z_i - \bar{Z})^2}{\sigma_{zi}^2} \quad \text{with} \quad \bar{Z} = \frac{\sum_{n=1}^{15} Z_i/\sigma_{zi}^2}{\sum_{n=1}^{15} 1/\sigma_{zi}}$$

3. reconstruct photon momenta and pion and kaon mass
4. choose events with $\Delta m_{\pi^0} \leq 10\ \mathrm{MeV}$

How would that look for ALPs?



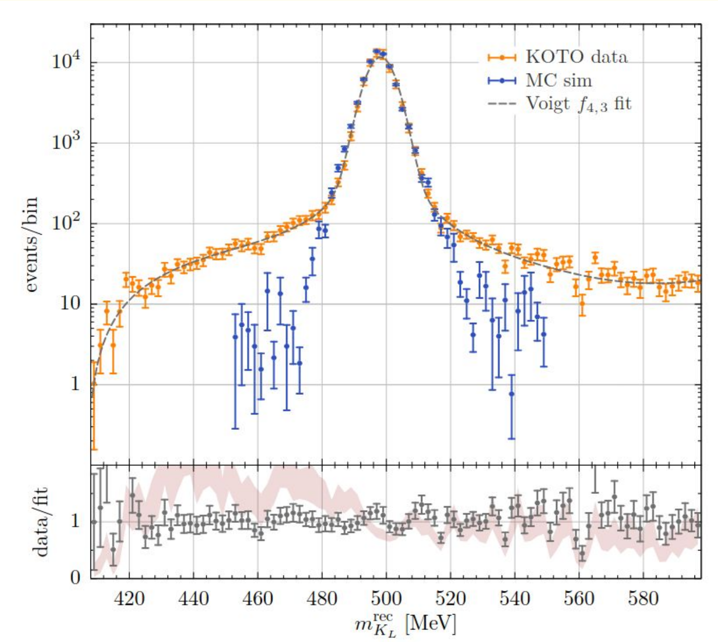
one photon pair originates from an ALP

ALP mass must be close to pion mass to be selected

$$\delta m_{K_L}^{rec} \simeq -\left[m_{K_L}/3m_{\pi^0}\right]\delta m \simeq -1.2\,\delta m$$

Fits and limits

KOTO signal contains detector backgrounds that we can't simulate!

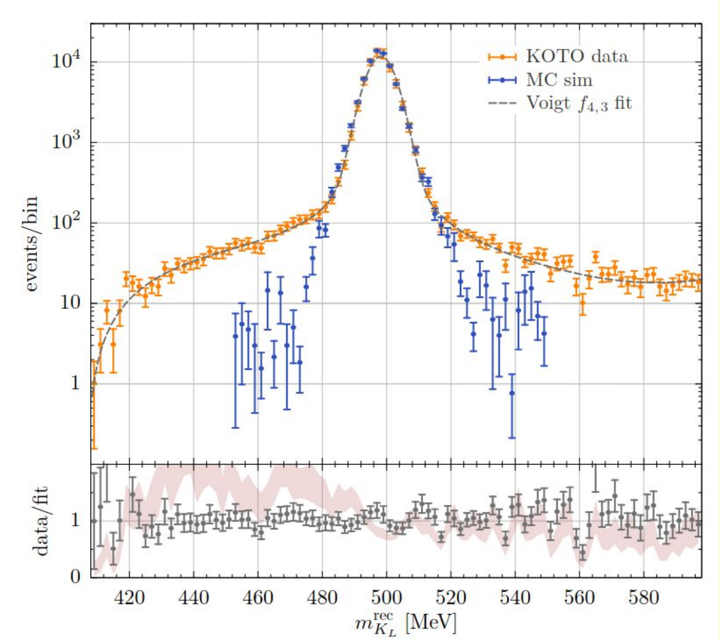


Fits and limits

KOTO signal contains detector backgrounds that we can't simulate!

use lineshape fit instead

$$f_{2n_a,n_b}(\mu) = \sqrt{\mu^2 - 9m_{\pi^0}^2}\left\{\sum_{k=1}^{n_a} a_{2k}\frac{\left[\mu^2 - 9m_{\pi^0}^2\right]^{2k-2}}{\mu^{2k}} + \left[\sum_{k=0}^{n_b} b_k \frac{\left[\mu^2 - 9m_{\pi^0}^2\right]^k}{\mu^k}\right] V_{\delta,\sigma}(\mu - m_{K_L} + \delta m)\right\}$$



construct likelihood ratio

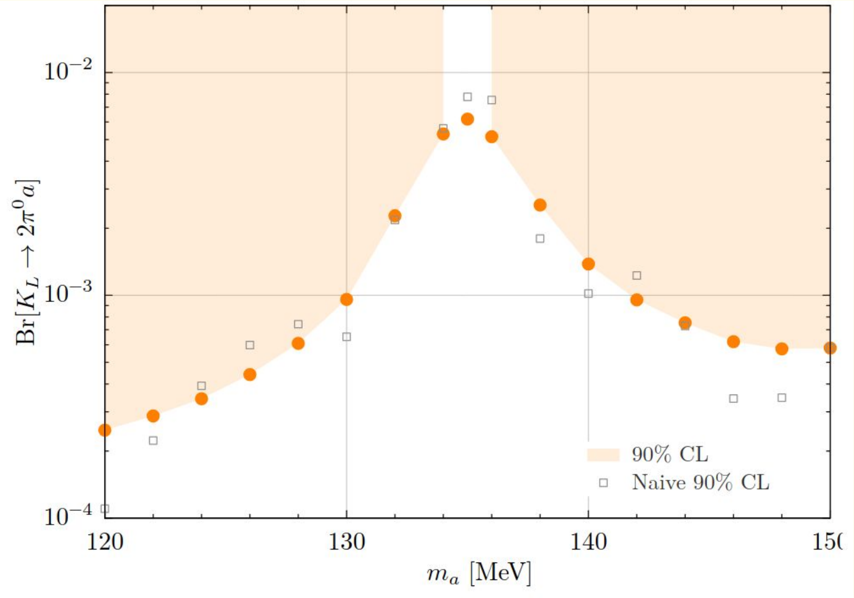
$$\delta\chi^2(m_a,\rho) = \chi^2_{\rm sub}(m_a,\rho) - \chi^2_0$$

fit residuals of re-fitted lineshape - (KOTO data + ρ ALP contribution)

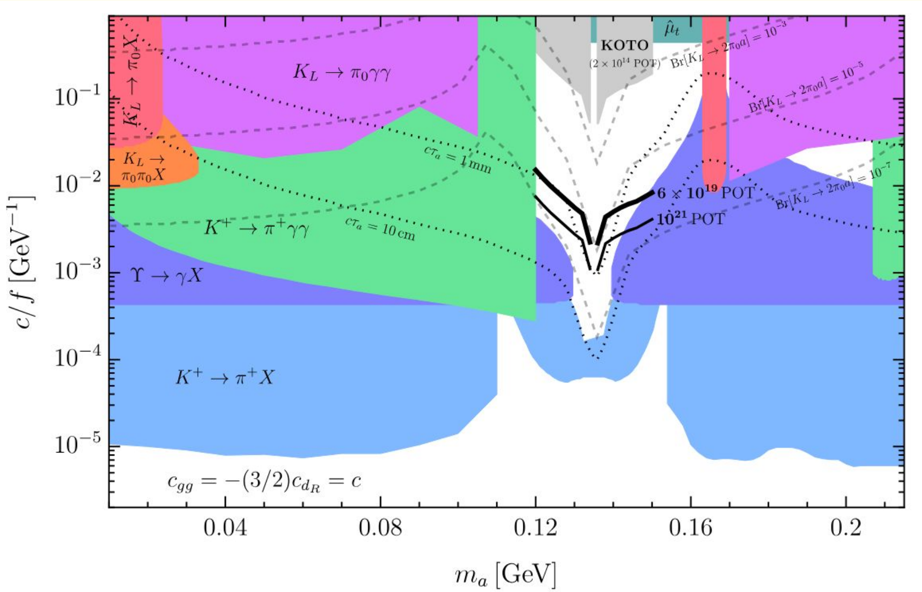
fit residuals of lineshape - KOTO data

$$\rho = {\rm Br}[K_L \to 2\pi^0 a]/{\rm Br}[K_L \to 3\pi^0] \geq 0$$

Results



10^{-2}
10^{-3}
10^{-4}
$\mathrm{Br}[K_L \to 2\pi^0 a]$
120
130
140
150
m_a [MeV]
90% CL
Naive 90% CL



$K_L \to \pi_0 X$
$K_L \to \pi_0\gamma\gamma$
$K_L \to \pi_0\pi_0 X$
$K^+ \to \pi^+\gamma\gamma$
$\Upsilon \to \gamma X$
$K^+ \to \pi^+ X$
KOTO
$(2 \times 10^{14}$ POT)
$\hat{\mu}_t$
$c\tau_a = 1\,\mathrm{mm}$
$c\tau_a = 10\,\mathrm{cm}$
6×10^{19} POT
10^{21} POT
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-3}$
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-5}$
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-7}$
$c_{gg} = -(3/2)c_{d_R} = c$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
c/f [GeV^{-1}]
0.04
0.08
0.12
0.16
0.2
m_a [GeV]

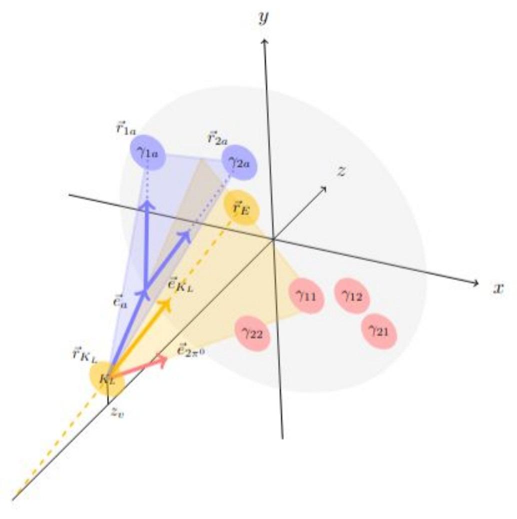
Beyond the chimney

for small ALP masses, ALPs become long-lived

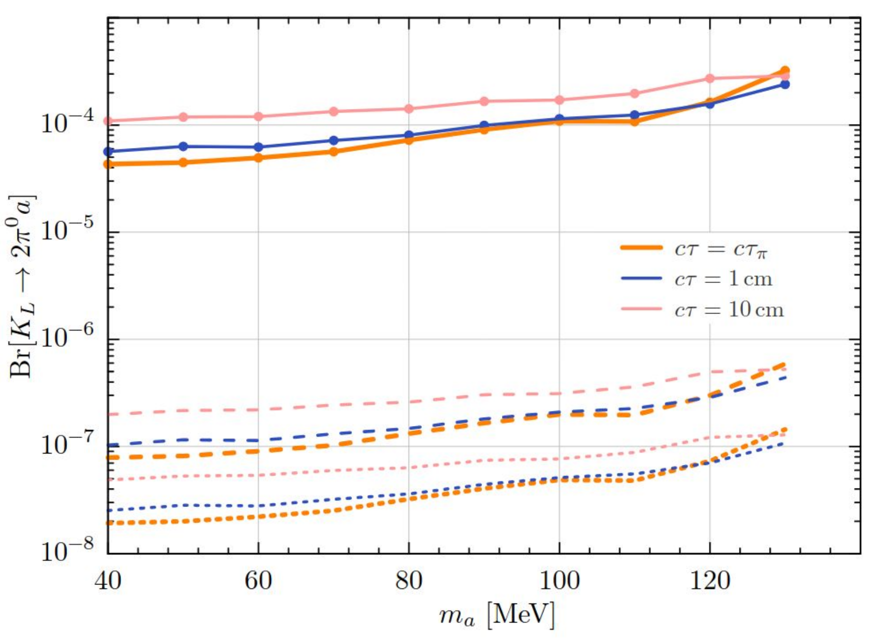
alternative selection:

- only require two photon pairs to reconstruct kaon vertex (now 45 possible combinations of photon pairs)
- ALP momentum coplanar to kaon-two-pion momentum plane and plane of kaon vertex and last two photons
- introduce displacement parameter in ALP momentum, so that

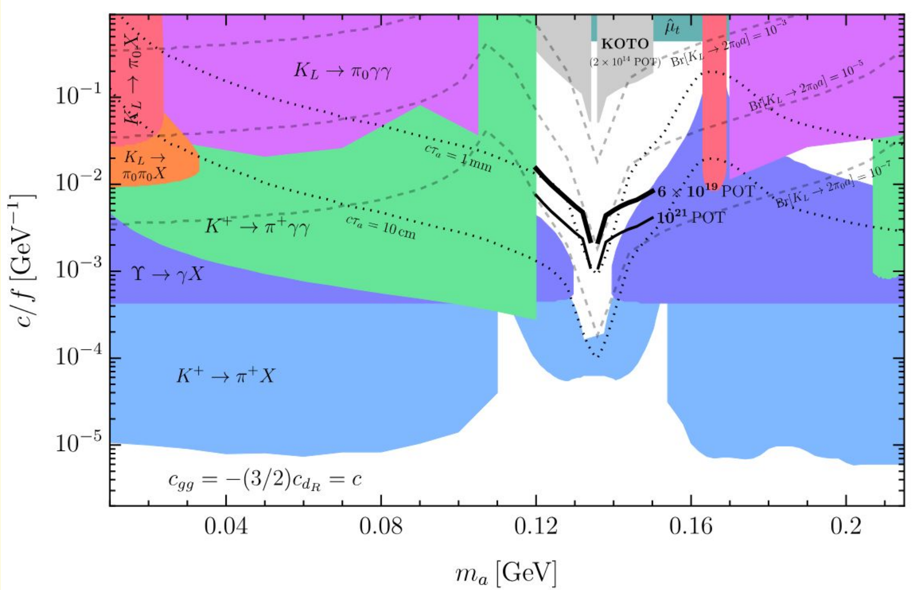
$$\sqrt{\left[p_{2\pi^0} + k_{1a}(\lambda_{K_L}) + k_{2a}(\lambda_{K_L})\right]^2} = m_{K_L}$$



Results



$\mathrm{Br}[K_L \to 2\pi^0 a]$
m_a [MeV]
$c\tau = c\tau_\pi$
$c\tau = 1\,\mathrm{cm}$
$c\tau = 10\,\mathrm{cm}$



c/f [GeV^{-1}]
m_a [GeV]
$K_L \to \pi_0 X$
$K_L \to \pi_0\gamma\gamma$
$K_L \to \pi_0\pi_0 X$
$K^+ \to \pi^+\gamma\gamma$
$\Upsilon \to \gamma X$
$K^+ \to \pi^+ X$
KOTO
$(2\times10^{14}$ POT)
$\hat{\mu}_t$
$c\tau_a = 1\,\mathrm{mm}$
$c\tau_a = 10\,\mathrm{cm}$
$\mathbf{6\times10^{19}}$ POT
$\mathbf{10^{21}}$ POT
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-3}$
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-5}$
$\mathrm{Br}[K_L \to 2\pi_0 a] = 10^{-7}$
$c_{gg} = -(3/2)c_{d_R} = c$

Summary

- first calculation of ALPs in 3-body neutral kaon decays, probing the CP properties of ALP couplings
- in some scenarios, 3-body decays are the **dominant** channel for neutral kaon decays
- can potentially provide the strongest probe in some part of the parameter space, e.g. in the pion chimney using

  KOTO $K_L \to 3\pi^0 \to 6\gamma$ data

Backup

Starting point : $N_f = 3$ QCD

$$\mathcal{L}_a(\mu_{\rm QCD}) \supset c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G\tilde{G} + \frac{\partial^\mu a}{f}(\bar{q}_L \mathbf{k}_Q \gamma_\mu q_L + \bar{q}_R \mathbf{k}_q \gamma_\mu q_R)\,,$$

Field redefinition:

$$q(x) \to \exp\left[-i(\boldsymbol{\delta}_q + \boldsymbol{\kappa}_q\gamma_5)c_{GG}\frac{a(x)}{f}\right]q(x)$$

1

$$\mathbf{k}_Q \to \hat{\mathbf{k}}_Q(a) = U_-(\mathbf{k}_Q + \phi_q^-)U_-^\dagger\,,$$

$$\mathbf{k}_q \to \hat{\mathbf{k}}_q(a) = U_+(\mathbf{k}_q + \phi_q^+)U_+^\dagger\,,$$

2

$$\mathbf{m}_q \to \hat{\mathbf{m}}_q = \exp\left[-2i\boldsymbol{\kappa}_q c_{GG}\frac{a(x)}{f}\right]\mathbf{m}_q$$

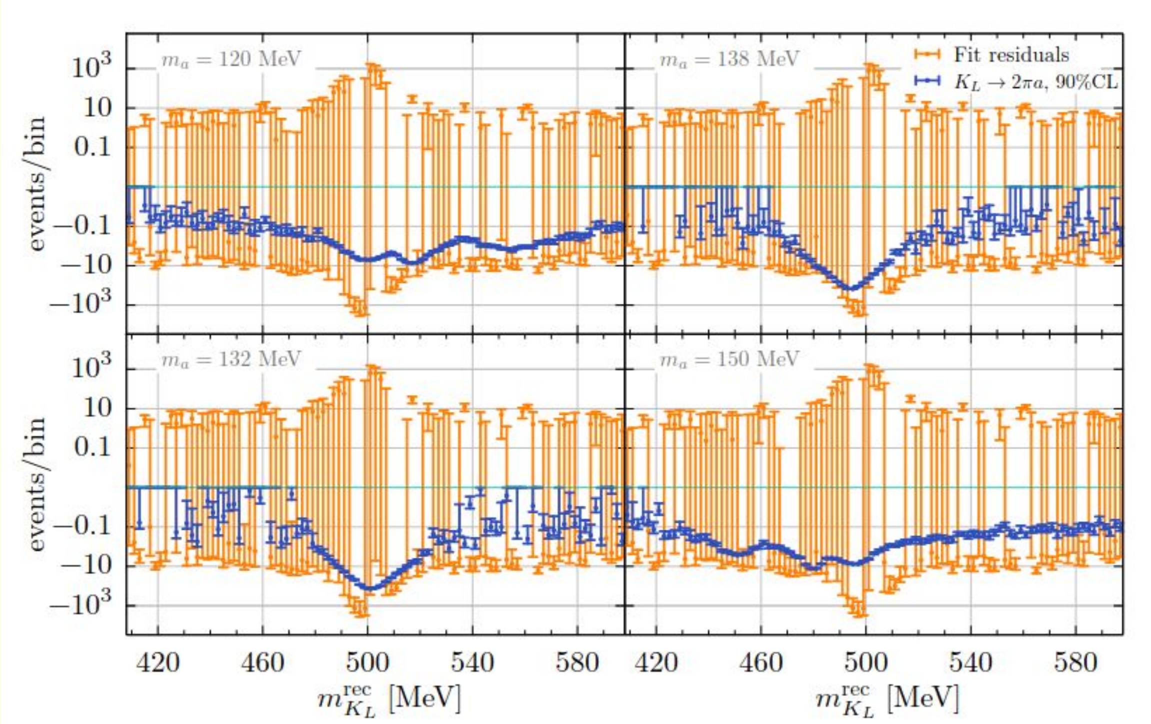
3

$\mathrm{Tr}[\kappa_q] = 1 \quad \to \quad$ removes $G\tilde{G}$ term

Classification of decay amplitudes in terms of CP and P

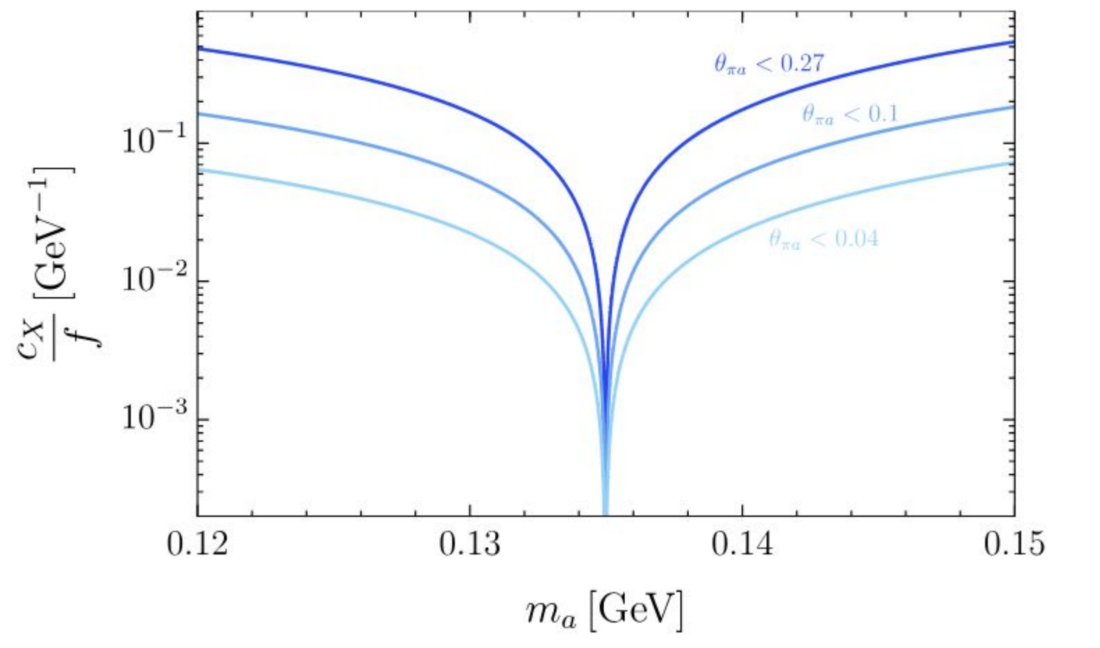
	$P = -1$ (κ_V, N_8)	$P = +1$ (κ_A, N_8)
$CP = +1$ $(\text{Re}[c], \varepsilon \cdot \text{Im}[c])$	$K_S \to \pi^0 a$	$K_L \to \pi^0\pi^0 a$ or $\pi^+\pi^- a$
$CP = -1$ $(\text{Im}[c], \varepsilon \cdot \text{Re}[c])$	$K_L \to \pi^0 a$	$K_S \to \pi^0\pi^0 a$ or $\pi^+\pi^- a$

Residuals



$m_a = 120$ MeV
$m_a = 138$ MeV
$m_a = 132$ MeV
$m_a = 150$ MeV
Fit residuals
$K_L \to 2\pi a$, 90%CL
events/bin
10^3
10
0.1
−0.1
−10
-10^3
420
460
500
540
580
$m_{K_L}^{rec}$ [MeV]

Validity of ChPT



$$\theta_{\pi a} \sim f_\pi / f \times c_X / |\delta_{m_a}| \ll 1$$

Modified reconstruction