



Kaon Decays – New Physics Perspectives

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$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}$$

Why Kaons?

- ▶ Very strong GIM suppression of top contribution:
 - ▶ $\lambda^5 \sim 0.0005$ (kaons) vs. $\lambda^3 \sim 0.01$ (B mesons)
- ▶ Generically large QCD enhancements (M.E., running)
- ▶ ⇒ Sensitivity to high-scale (non-MFV) dynamics

Why Kaons?

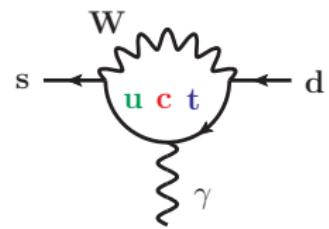
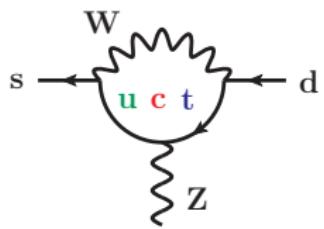
$$\Gamma_K \propto \frac{M_K^5}{M_W^4}$$

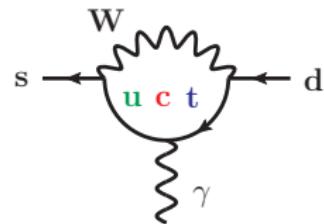
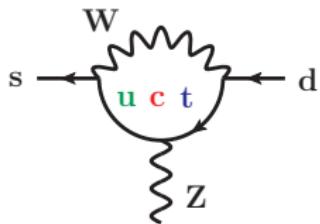
vs.

$$\Gamma_{D,B} \propto \frac{M_{D,B}^5}{M_W^4}$$

- ▶ E.g., for dim.-4 couplings we have
 - ▶ $\text{Br}(K \rightarrow \pi X) \propto (M_W/M_K)^4$ vs.
 $\text{Br}(B \rightarrow \pi X) \propto (M_W/M_B)^4$
- ▶ Axions couple with dim.-5 couplings, so
 - ▶ $\text{Br}(K \rightarrow \pi a) \propto (M_W/f_a M_K)^2$ vs.
 $\text{Br}(B \rightarrow \pi a) \propto (M_W/f_a M_B)^2$
- ▶ ⇒ High sensitivity to light NP

Observables





$$\text{Re}(\lambda_u) \sim \lambda$$

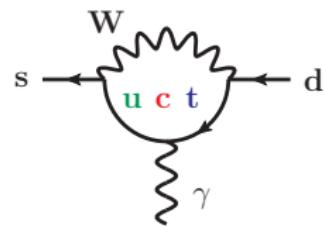
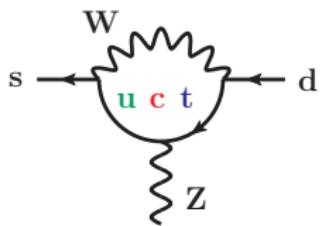
$$\text{Im}(\lambda_u) = 0$$

$$\text{Re}(\lambda_c) \sim \lambda$$

$$\text{Im}(\lambda_c) \sim \lambda^5$$

$$\text{Re}(\lambda_t) \sim \lambda^5$$

$$\text{Im}(\lambda_t) \sim \lambda^5$$



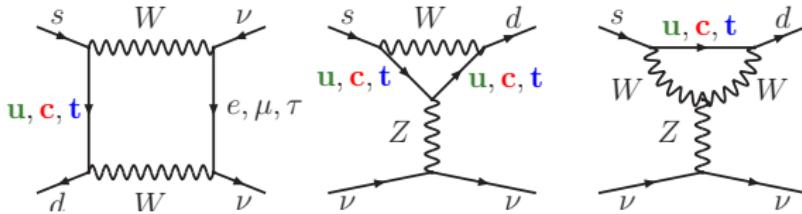
$$X_0(x) \xrightarrow{x \rightarrow \infty} x$$

$$X_0(x) \xrightarrow{x \rightarrow 0} x \log x$$

$$D_0(x) \xrightarrow{x \rightarrow \infty} \log x$$

$$D_0(x) \xrightarrow{x \rightarrow 0} \log x$$

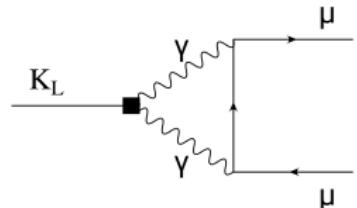
Top-dominated: $K_L \rightarrow \pi^0 \nu \bar{\nu}$



- ▶ Proceeds almost purely via interference-type CP violation
- ▶ Small $\sim 1\%$ CP-conserving component
- ▶ “Short-distance” theory uncertainty $\mathcal{O}(2\%)$
[Brod, Gorbahn, Stamou, 2105.02868]

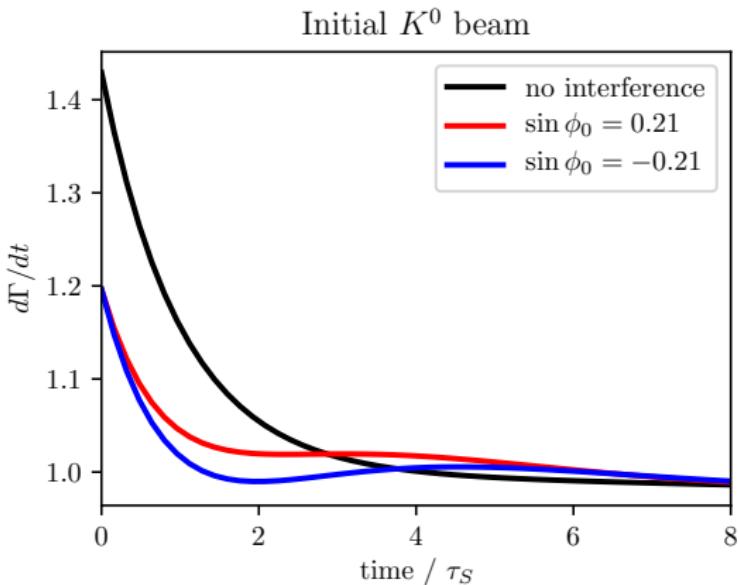
Top-dominated: $K_S \rightarrow (\mu^+ \mu^-)_{\ell=0}$

- $\text{Br}(K_L \rightarrow \mu^+ \mu^-) = 6.84(11) \times 10^{-9}$
- $\text{Br}(K_S \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$



	$(\mu^+ \mu^-)_{\ell=0}$	$(\mu^+ \mu^-)_{\ell=1}$
K_L	CP conserving	(CP violating)
K_S	CP violating	CP conserving

Experiment cannot distinguish $\ell = 0$ and $\ell = 1$



Interference terms
sensitive to
short-distance
component!

[D'Ambrosio, Kitahara
1707.06999]

$$\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = \text{Br}(K_L \rightarrow \mu^+ \mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\text{int}}}{C_L} \right)^2$$

[Dery et al. 2104.06427]

Top-dominated: $K_S \rightarrow (\mu^+ \mu^-)_{\ell=0}$

- ▶ “Short-distance” theory uncertainty $\mathcal{O}(1\%)$
- ▶ Sizeable $\mathcal{O}(3\%)$ CP-conserving component due to ϵ_K
[Brod, Stamou, 2209.07445]
 - ▶ Hard to calculate;
estimate from $K_{L/S} \rightarrow \mu^+ \mu^-$, $K_L \rightarrow \gamma\gamma$

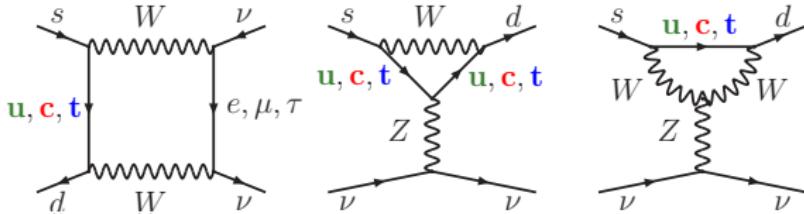
Ratios as SM tests

$$R_S = \frac{\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0}}{\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})} \approx 1.55 \times 10^{-2} \times \frac{Y(x_t)}{X(x_t)}$$

Essentially CKM-parameter free (up to $\mathcal{O}(3\%)$ correction)

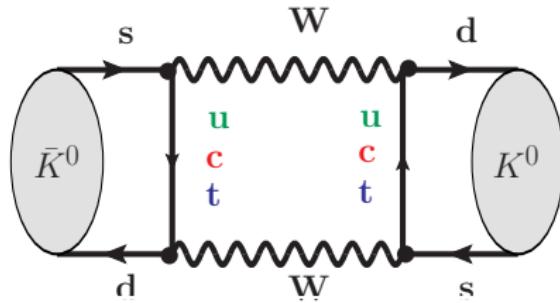
[Buras, Venturini, 2109.11032]

Charm under control: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



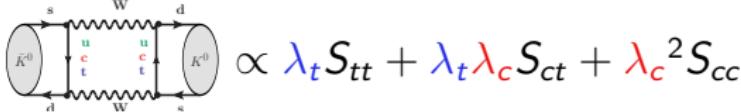
- ▶ CP-conserving decay
- ▶ “Short-distance” theory uncertainty $\mathcal{O}(2\%)$
[Brod, Gorbahn, Stamou, 2105.02868]
- ▶ $\mathcal{O}(3\%)$ “long-distance” uncertainty

Charm under control: ϵ_K



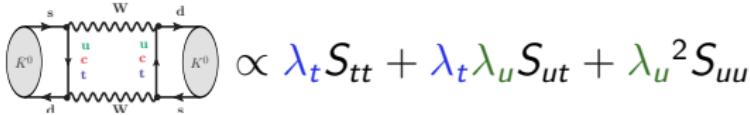
Charm under control: ϵ_K

- ▶ Traditionally, use $\lambda_u = -\lambda_c - \lambda_t$ to write:



- ▶ LARGE $\mathcal{O}(50\%)$ perturbative uncertainty in charm sector

- ▶ Better: use $\lambda_c = -\lambda_u - \lambda_t$ to write:



- ▶ SMALL $\mathcal{O}(1\%)$ perturbative uncertainty in charm sector
[Brod et al. 1911.06822]

Other kaon observables

- ▶ FCNC:
 - ▶ ϵ'_K (lattice)
 - ▶ $K_L \rightarrow \pi^0 \ell^+ \ell^-$
(tensor operators; see [Mescia, Smith, Trine, hep-ph/0606081])
- ▶ Non-FCNC:
 - ▶ CKM unitarity (see talk by Marc Knecht)
 - ▶ “Auxiliary” modes: $K_L \rightarrow \gamma\gamma$, $K_S \rightarrow \pi^0 \ell^+ \ell^-$, ...

Heavy NP

Heavy NP – bounds from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

$$\mathcal{H}_{\text{eff}} = \left[\frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_w} C^{\text{SM}} + \frac{1(i)}{\Lambda_+^2} \right] (\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L) + \text{h.c.}$$

90% CL	current	10% ("100 evts")	3% ("1000 evts")
K^+ , Re	$\Lambda_+ \gtrsim 236 \text{ TeV}$	$\Lambda_+ \gtrsim 510 \text{ TeV}$	$\Lambda_+ \gtrsim 803 \text{ TeV}$
K^+ , Im	$\Lambda_+ \gtrsim 145 \text{ TeV}$	$\Lambda_+ \gtrsim 193 \text{ TeV}$	$\Lambda_+ \gtrsim 213 \text{ TeV}$

- ▶ Exp: $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6_{-3.4}^{+4.0} |_{\text{stat}} \pm 0.9 |_{\text{syst}}) \times 10^{-11}$ [NA62 2103.15389]
- ▶ SM: $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 7.73(16)(25)(54) \times 10^{-11}$ [BGS, 2105.02868]
- ▶ SM uncertainty scaled by 0.5 for 3% bound
- ▶ Note that semileptonic decays test vector current only
- ▶ Note that SM corresponds to $\Lambda_+ = 182 \text{ TeV}$ (re) and $\Lambda_+ = 337 \text{ TeV}$ (im)

Heavy NP – bounds from $K_L \rightarrow \pi^0 \nu \bar{\nu}$

$$\mathcal{H}_{\text{eff}} = \left[\frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_w} C^{\text{SM}} + \frac{1(i)}{\Lambda_L^2} \right] (\bar{s}_L \gamma^\mu d_L) (\bar{\nu}_L \gamma_\mu \nu_L) + \text{h.c.}$$

90% CL	current	10% (“100 evts”)	3% (“1000 evts”)
K_L , Re	no bound	no bound	no bound
K_L , Im	$\Lambda_L \gtrsim 96 \text{ TeV}$	$\Lambda_L \gtrsim 907 \text{ TeV}$	$\Lambda_L \gtrsim 1364 \text{ TeV}$

- ▶ Exp: $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 300 \times 10^{-11}$ @90%CL [KOTO 1810.09655]
- ▶ SM: $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 2.59(6)(2)(28) \times 10^{-11}$ [BGS, 2105.02868]
- ▶ SM uncertainty scaled by 0.5 for 3% bound
- ▶ Note that semileptonic decays test vector current only
- ▶ Note that SM corresponds to $\Lambda_L = 337 \text{ TeV}$

Heavy NP – bounds from $K_S \rightarrow (\mu^+ \mu^-)_{\ell=0}$

$$\mathcal{H}_{\text{eff}} = \left[\frac{2G_F^2 M_W^2}{\pi^2} C^{\text{SM}} + \frac{1(i)}{\Lambda_S^2} \right] (\bar{s}_L \gamma^\mu d_L)(\bar{\mu}_L \gamma_\mu \mu_L) + \text{h.c.}$$

90% CL	current	10% (“100 evts”)	3% (“1000 evts”)
K_S, Re	no bound	no bound	no bound
K_S, Im	no bound	$\Lambda_S \gtrsim 566 \text{ TeV}$	$\Lambda_S \gtrsim 855 \text{ TeV}$

- ▶ No current experimental bound
- ▶ SM: $\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = 1.70(2)(1)(19) \times 10^{-13}$ [Brod, Stamou, 2209.07445]
- ▶ SM uncertainty scaled by 0.5 for 3% bound
- ▶ Note that leptonic decays test axialvector current only
- ▶ Note that SM corresponds to $\Lambda_L = 210 \text{ TeV}$

- ▶ Models
 - ▶ Renormalizable (if complete)
 - ▶ Which parameters are independent?
 - ▶ *Proliferation of models*
- ▶ EFT (SMEFT, HEFT, ...)
 - ▶ Nonrenormalizable (intrinsic cutoff)
 - ▶ *Proliferation of operators*
- ▶ Generic loop functions [Brod, Gorbahn 1903.05116; Bishara et al. 2104.10930]
 - ▶ Explicit results – no need to calculate
 - ▶ Minimal number of parameters

“Unitarity Sum Rule”



$$\sum_{v_3} g_{v_3 \bar{f}_1 f_2}^{L/R} g_{v_1 v_2 \bar{v}_3} = \sum_{f_3} (g_{v_1 \bar{f}_1 f_3}^{L/R} g_{v_2 \bar{f}_3 f_2}^{L/R} - g_{v_2 \bar{f}_1 f_3}^{L/R} g_{v_1 \bar{f}_3 f_2}^{L/R})$$

Generalized GIM

- ▶ General rule (from Slavnov-Taylor identities):

$$\sum_{v_3} g_{v_3 \bar{f}_1 f_2}^{L/R} g_{v_1 v_2 \bar{v}_3} = \sum_{f_3} (g_{v_1 \bar{f}_1 f_3}^{L/R} g_{v_2 \bar{f}_3 f_2}^{L/R} - g_{v_2 \bar{f}_1 f_3}^{L/R} g_{v_1 \bar{f}_3 f_2}^{L/R})$$

- ▶ In the SM:

$$0 = \sum_{f_3} g_{W_2^- \bar{s} f_3}^{L/R} g_{W_1^+ \bar{f}_3 d}^{L/R}$$

- ▶ Unitarity of “generalized CKM matrix” follows from universality and diagonality of neutral gauge boson couplings

Generalized Penguin-Box Functions

- ▶ Write general dimension-four Lagrangian
- ▶ Implement sum rules
- ▶ Generalize penguin and box functions
 - ▶ Gauge independent and finite
 - ▶ Minimal number of couplings
- ▶ Public `mathematica` code `WellPut`

Light NP

Occam's razor



VS.

Hou [2109.02557] / Gell-Mann [Nuovo Cim. 4 (1956) S2, 848-866]:

“Everything not forbidden is compulsory”

[The original quote from Gell-Mann is “Anything that is not compulsory is forbidden” (totalitarian principle)]

Light NP

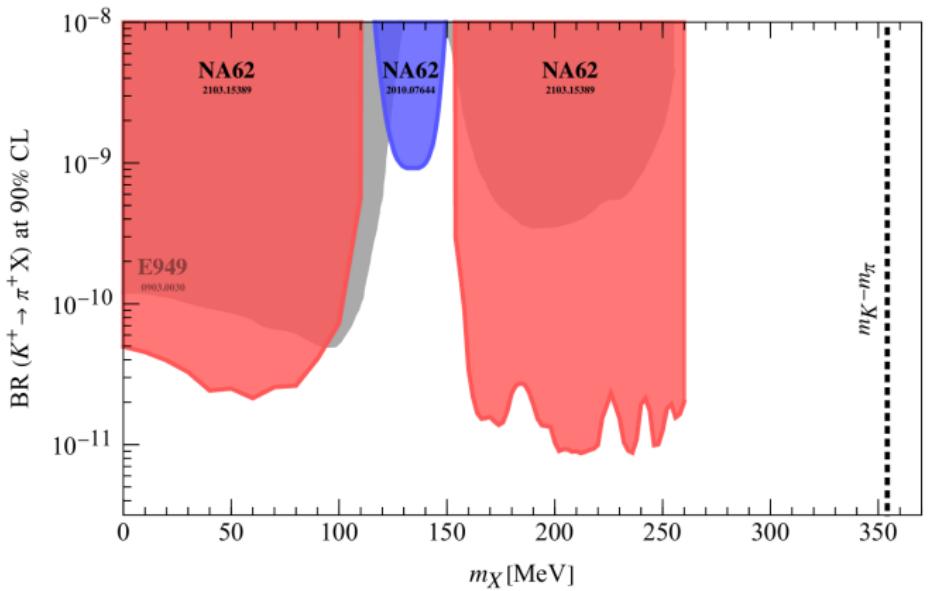
- ▶ Many models:
 - ▶ Axions
 - ▶ Light DM
 - ▶ Dark photons
 - ▶ Higgs portal scalar
 - ▶ Strongly interacting neutrinos
 - ▶ ...
- ▶ Rich phenomenology
- ▶ Recent review: [Goudzovski et al., 2201.07805]

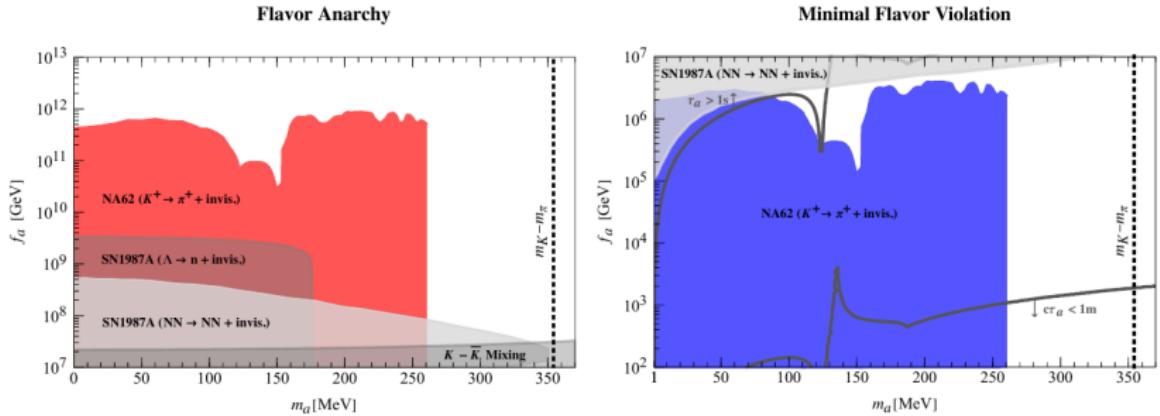
(Flavored) Axions

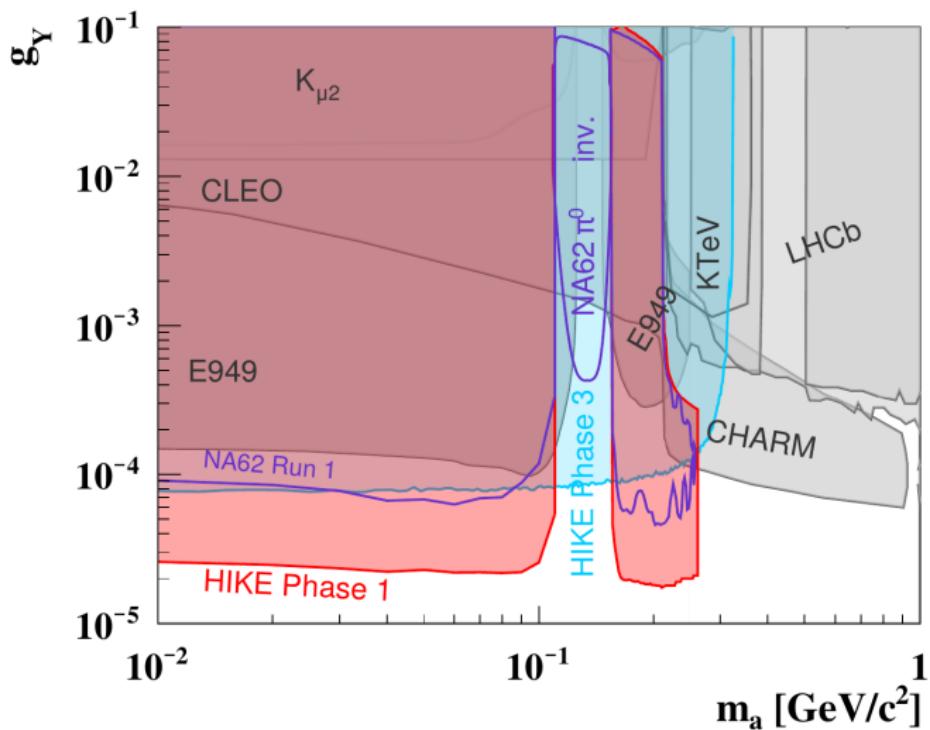
- ▶ Solution to “strong CP problem”; DM candidates
- ▶ Pseudo-Goldstone boson of broken $U_A(1)$ symmetry
 - ▶ Could be related to flavor, e.g. Frogatt-Nielsen-type

[Wilczek, PhysRevLett 49, 1549; Calibbi et al. 1612.08040; Linster et al. 1805.07341; etc.]

- ▶ $\mathcal{L} \supset C_{\text{anom.}} \times a \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} + \partial_\mu a (\bar{f}_i C_{ij}^V + C_{ij}^A \gamma_5 f_j)$
- ▶ $K^+ \rightarrow \pi^+ a$ gives strong bound on generic axion models
- ▶ Detailed predictions depend on UV model







Grossman-Nir bound

$$\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 4.3 \times \text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$

[Grossman, Nir, hep-ph/9701313]

- ▶ Essentially based on:

- ▶ Isospin relation $A(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \sqrt{2}A(K_L \rightarrow \pi^0 \nu \bar{\nu})$
- ▶ $\text{Im}(H_{\text{eff}}) \leq |H_{\text{eff}}|$
- ▶ No CPV in mixing or decay

- ▶ Under same assumptions:

$$\text{Br}(K_L \rightarrow \pi^0 X) \leq 4.3 \times \text{Br}(K^+ \rightarrow \pi^+ X)$$

- ▶ ⇒ Charged mode tends to give stronger constraints

Evading the GN bound

- ▶ CPV in decay
 - ▶ Requires light NP; no known models
- ▶ $\Delta I = 3/2$ [He et al., 1804.07449, 2005.02942]
 - ▶ Effectively requires light NP
- ▶ Charge conservation [Hostert et al., 2005.07102]
 - ▶ Dark sector couples only to neutral SM currents
 - ▶ $K_L \rightarrow X_1 X_2$, $K^+ \rightarrow \pi^+ X_1 X_2$
- ▶ Mass difference [Fabbrichesi et al., 1911.03755]
 - ▶ $354 \text{ MeV} = M_{K^+} - M_{\pi^+} < M_{K_L} - M_{\pi^0} = 363 \text{ MeV}$
- ▶ Experimental loopholes:
 - ▶ π^0 blind spot ($K^+ \rightarrow \pi^+ \pi^0$ background)
 - ▶ Lifetime gap (decay to visibles)
 - ▶ Kinematics (small effect)

Summary

- ▶ Kaons are very sensitive to **high-scale dynamics**
- ▶ Kaons are very sensitive to **light NP**
- ▶ Several kaon observables have very **precise SM predictions**
- ▶ Large (current and future) **datasets** are available
- ▶ Kaons are a major player in the study of FPCP!