Searching for dark sectors with Kaon factories

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Webinar

Elusives-InvisiblesPlus Virtual Institute

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Outline

- Intro
- Kaon factories, emphasis on KOTO
- Complementarity & independency, from exp. to theory.
- Conclusions.

Intro

- As you know we are quite puzzled

- On the one hand we know there is new physics (NP)

  on the other hand the safest bets that we had (LHC, WIMP,…), came empty

- This motivates us to look for new paradigms and/or new search strategies

- If you are a tabletopper, you can change exp' every other year

- In accelerators, need to work with what you have, or be lucky as we are now

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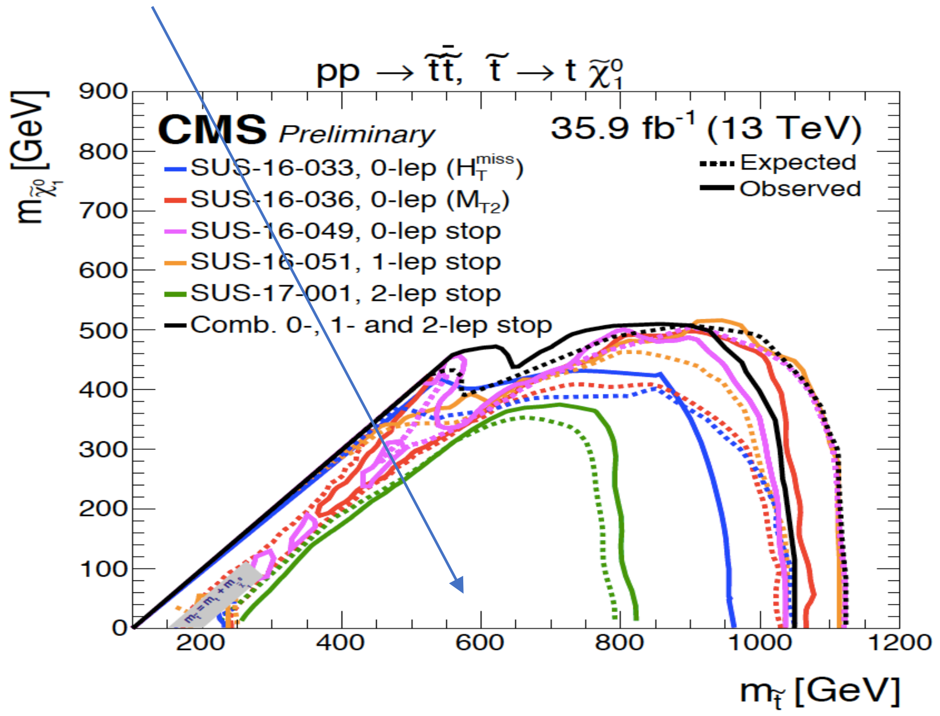
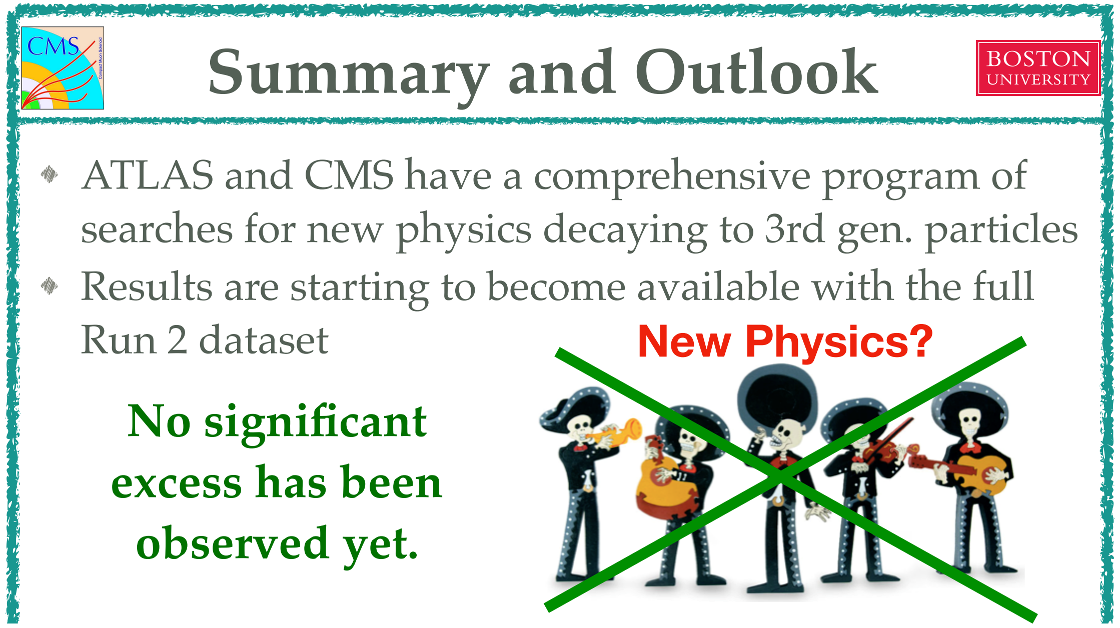
New paradigms, log crisis/opportunity

- For > 40 yrs Higgs served us as anchor to determine the new phys. (NP) scale.

Sym' based solution to Naturalness <=> TeV NP

- NP searches according to leading paradigm, driven by E-frontier on linear scale:





LHCP19: Suarez on behalf of the ATLAS & CMS

Higgs @ 21st century => crisis & opportunity

- New ideas & null LHC results cast tiny doubt on this paradigm.

  eg: "Cosmic attractors", "dynamical relaxation", "N-naturalness", "relating the weak-scale to the CC" & "inflating the Weak scale".

- Are they all anthropic solution for the weak scale ? Is it satisfying for the weak scale?

  Giudice, Kehagias & Riotto; Kaloper & Westphal; Dvali (19);
  Agrawal, Barr, Donoghue & Seckel (98) Harnik, Kribs & GP (06);
  Gedalia, Jenkins & GP (11)

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- New scalar common to several of above: concretely let us consider the relaxion:

  Graham, Kaplan & Rajendran (15)

  under some assumption allows for a concrete QFT realisation.

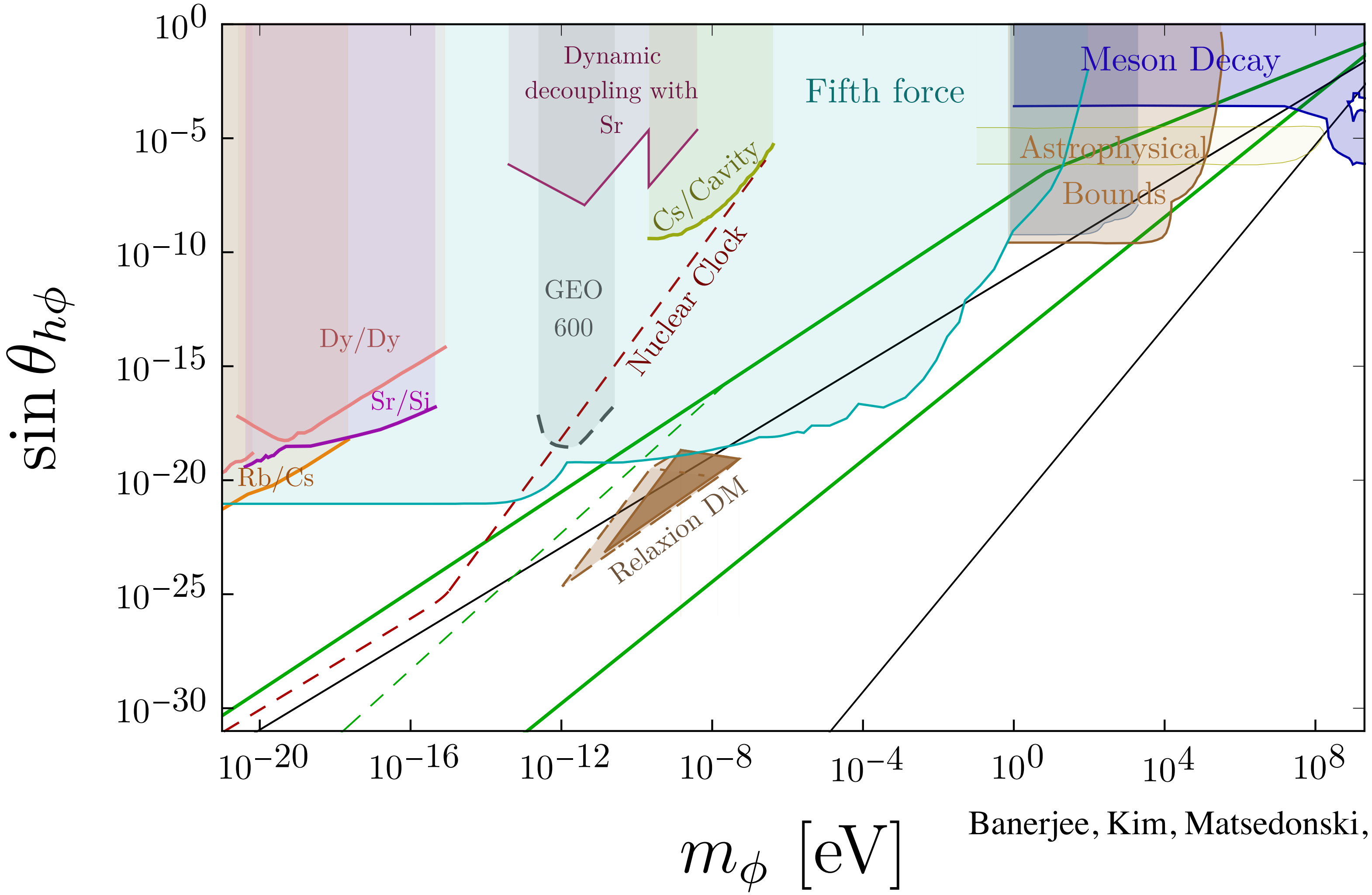
- Bottomline here: relaxion is ALP-DM that (due to CP violation) can be described as scalar mixes \w the Higgs.

  Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)
  Banerjee, Kim & GP (18)

- However, searching the relaxion => *log crisis* as follows:

The relaxion (Higgs portal) parameter space & the *log crisis*

Overview plot: the relaxion 30-decade-open parameter space



Banerjee, Kim, Matsedonski, GP, Safranova (20)

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The era of Kaon factories

CERN

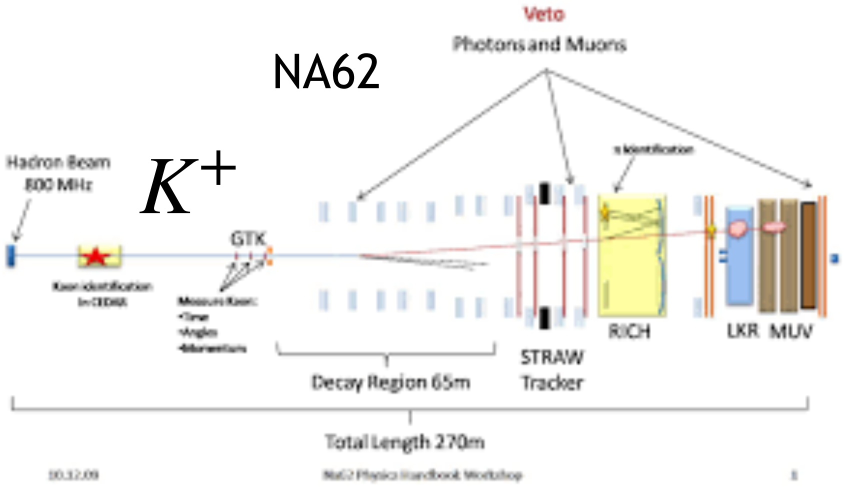
J-PARC

The Kaon factories:

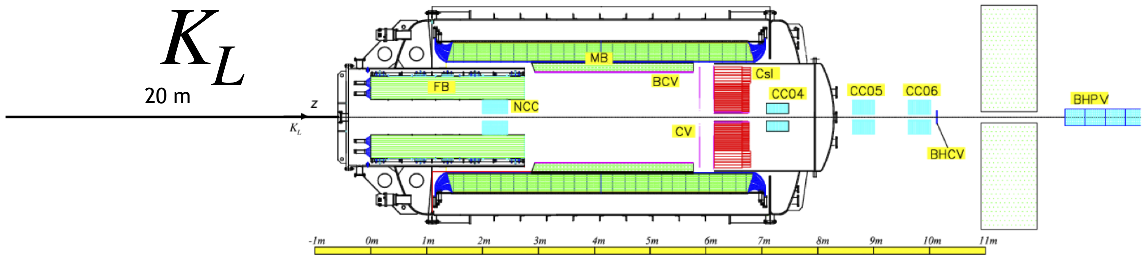
# of Kaon of $O(10^{13})$ & aiming for BR of $O(10^{-11})$ in a few years !

Brief look: NA62 & KOTO

NA62



KOTO



	NA62	KOTO
POT	10^{19} (400 GeV)	$10^{19\text{-}20}$ (30 GeV)
# Kaons	10^{13}	10^{13}
K-Energy	40 GeV	1.5 GeV
Length	300 m	30 m
Decay region	150 m	3-4 m

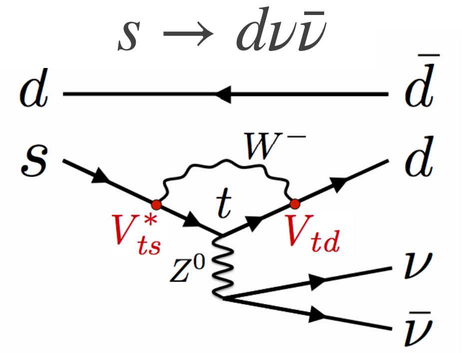
(Charm~ 10^{18})

Before data: NA62 & KOTO, the SM story

★ Both are searching to super-rare events:

$$\text{NA62}: \quad K^+ \to \pi^+ \nu\bar{\nu} \qquad \text{KOTO}: \quad K_L \to \pi^0 \nu\bar{\nu}$$

★ Suppression result of Loop (+GIM) + CKM:



$$\text{SM}: \text{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.4 \pm 1.0) \times 10^{-11}, \quad \text{BR}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.4 \pm 0.6) \times 10^{-11}$$

$K^+ \to \pi^+ \nu \bar{\nu}$ vs. $K_L \to \pi^0 \nu \bar{\nu}$ SM & Beyond

★ The Grossman-Nir (GN) bound (97):

In the SM, $K_L \to \pi^0 \nu\nu$ and $K^+ \to \pi^+ \nu\nu$ decays go through the same operator, $(s \to d\nu\nu)$.

The $K_L \to \pi^0 \nu\nu$ and $K^+ \to \pi^+ \nu\nu$ matrix elements related through isospin -

$$\mathrm{BR}\left(K_L \to \pi^0 \nu \bar{\nu}\right) \leq 4.3\,\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) .$$

★ The relation may hold in cases NP, say in 2 body, or heavy particles:

$$\Gamma\left(K_L \to \pi^0 a\right) \leq \Gamma\left(K_S \to \pi^0 a\right) . \quad [a = \text{axion like particle (ALP)}]$$

Leutwyler and M. A. Shifman (90)

NA62 & KOTO, data

$\left\{\text{SM} : \text{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (8.4 \pm 1.0) \times 10^{-11},\ \text{BR}\left(K_L \to \pi^0 \nu \bar{\nu}\right) = (3.4 \pm 0.6) \times 10^{-11}\right\}$

★ NA62 (2019) prelim' result is consistent \w expectation:

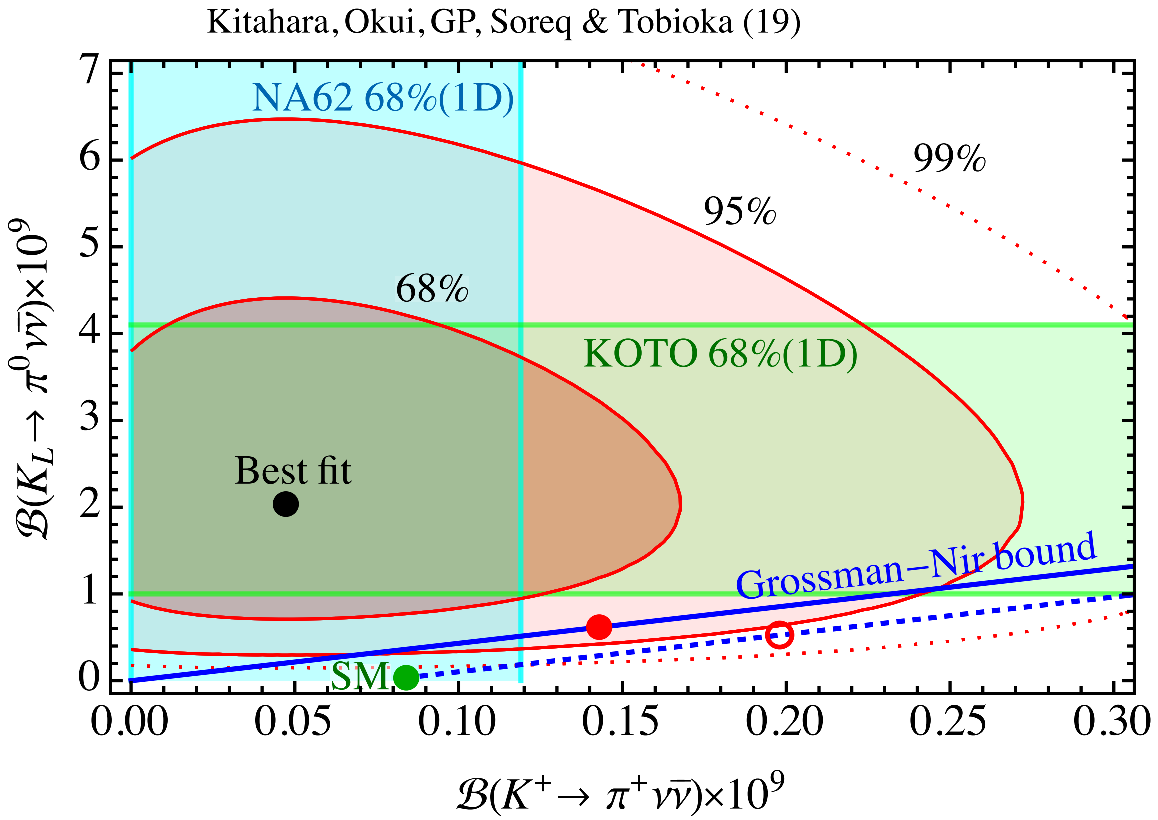
$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})_{\rm NA62} = 0.47^{+0.72}_{-0.47} (< 2.44) \times 10^{-10} \,,$$

★ KOTO (2019) prelim' analysis reveals 2-3 events \w BG << 0.5

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})_{\rm KOTO} = 2.1^{+2.0\,(+4.1)}_{-1.1\,(-1.7)} \times 10^{-9} \,,$$

KOTO is currently intensely investigating their BG estimation.

Are the two results compatible @ face value (v1)?



- ★ GN: $\sim 2\sigma$ with SM interference; $\sim 3\sigma$ without interference.
- ★ Can easily accommodated \w EFT:

Are the two results compatible @ face value (v1)?

Kitahara, Okui, GP, Soreq & Tobioka (19)

- Can easily accommodated \w EFT: $\mathcal{L}_{\rm eff} = \sum_{i=S,A,D} C_i^{\nu\nu} \mathcal{O}_i^{\nu\nu}$

$$\mathcal{O}_D^{\nu\nu} = \left(\bar{d}^2 d^1\right)_{V+A} \left(\bar{L}L\right)_{V-A}$$

$$\mathcal{O}_{S,A}^{\nu\nu} = \left[\bar{Q}^2 \left(\mathbf{1}_2, \sigma^i\right) Q^1\right]_{V-A} \left[\bar{L} \left(\mathbf{1}_2, \sigma^i\right) L\right]_{V-A}$$

where Q/L is a quark/lepton doublet, d is the down-type quark singlet.

$$C_{S,D}^{\nu\nu} - C_A^{\nu\nu} \approx \begin{cases} \mathrm{i}/(110\,\mathrm{TeV})^2, & \mathrm{KOTO} \\ \mathrm{e}^{-\mathrm{i}\frac{3}{4}\pi}/(150\,\mathrm{TeV})^2, & \mathrm{KOTO}\,\&\,\mathrm{NA62} \end{cases}$$

The two results compatible "experimentally" (v2)

Kitahara, Okui, GP, Soreq & Tobioka (19)

- Koto & NA62: different parameters & structure => account for significant differences:

(i) consider 2 body decay $K \to \pi X$, \w X stable => can't accommodate results:

With $m_X < m_{\pi^0}$, $K_L \to \pi^0 X$ & $K_L \to \pi^0 \nu\nu$ have same KOTO acceptance => BR~ 10^{-9} explain the data.

However this is in conflict with the generalised GN bound: $\mathcal{B}(K_L \to \pi^0 X) \lesssim 4.3\, \mathcal{B}(K^+ \to \pi^+ X)\,.$

Leutwyler and M. A. Shifman (90)

As seen above, in 3 sigma tension & BTW prefers that X would be a scalar.

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- Koto & NA62: different parameters & structure => account for significant differences:

(i) consider 2 body decay $K \to \pi X$, \w X stable => can’t accommodate results.

(ii) If $K \to \pi X(\gamma\gamma)$, \w X being long lived (~ 1-10% ns) => accommodate results, why?

The dependence of X-lifetime of $K_L \to \pi^0 X$ differs from $K^+ \to \pi^+ X$ due to boost and size:

$$\mathcal{B}(K \to \pi X; \text{detector}) = \mathcal{B}(K \to \pi X) e^{-\frac{L}{p}\frac{m_X}{c\tau_X}},$$

with $\left(\frac{L}{E}\right)_{\text{KOTO}} \sim 2 \;<\; \left(\frac{L}{E}\right)_{\text{NA62}} \sim 4$ & 2-photon searches @ NA62 suffer from BGs…

The two results compatible “experimentally” (v2)

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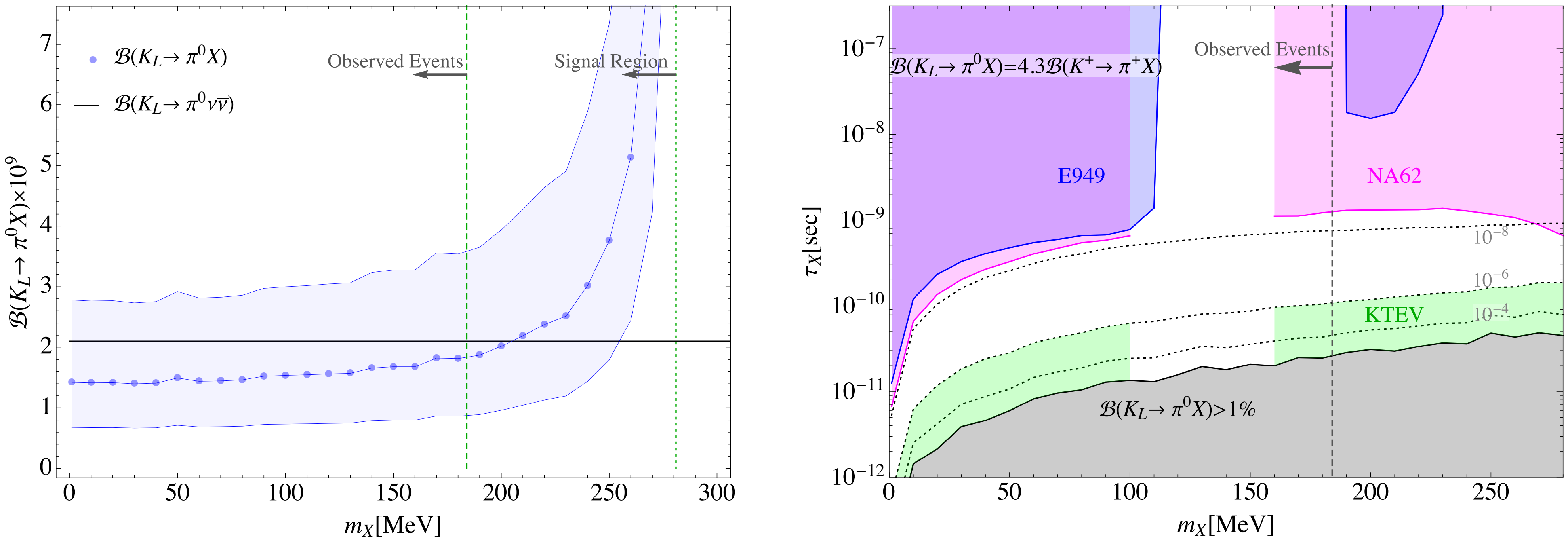

Left, BR to accommodate KOTO: dotted blue (solid gray) line correspond to the central value of $K_L \to \pi^0 X$ ($\pi^0 \nu\bar{\nu}$) interpretation, with blue shaded band (dashed horizontal lines) for two-sided 68% confidence interval. An uncertainty of Monte Carlo statistics is less than 10% thus omitted here. The dashed (dotted) vertical line corresponds to m_X = 180(280)MeV, and its left-hand side is compatible with the observed events (the signal region). Right: the new particle has finite lifetime considering the GN bound and $K^+ \to \pi^+ \nu\bar{\nu}$ search, and the allowed parameter space for two body decay $K_L \to \pi^0 X$ in mass and lifetime of X is shown. The $K^+ \to \pi^+ X$ bound is translated to K_L bound assuming a saturation of the GN bound. The purple(blue) shaded region is constrained by NA62 at 95% CL(E949 at 90% CL). Too short lifetime leads to $B(K_L \to \pi^0 X) > 1\%$, which is inconsistent with untagged K_L branching ratio. The $B(K_L \to \pi^0 X) = 10^{-4}$, 10^{-6} and 10^{-8} are indicated on the plot. The green shaded region is constrained from KTEV search for $K_L \to \pi^0\gamma\gamma$ assuming $B(X \to \gamma\gamma) = 1$.

The two results compatible theoretically (v3)

Gori, GP & Tobioka (20); inspired by a talk of Pospelov.

R. Ziegler, J. Zupan, and R. Zwicky; Y. Liao, H.-L. Wang, C.-Y. Yao, and J. Zhang, M. Hostert, K. Kaneta, M Pospelov (20)

- ★ Koto & NA62 differ by isospin, KOTO's initial state is neutral:

  Suppose 2-body neutral final state $K_L \to \sigma\chi, [\chi = Im(\phi), \sigma = Re(\phi)]$ is allowed by a model;

  it would then dominates the charged 3-body final state $K^+ \to \pi^+\phi^2$ decay mode.

- ★ A working model based on approx' strange flavor sym.:

  Add a light scalar, ϕ, it carries a half strange (or 2nd gen. doublet) flavor charge (in mass basis):

$$y_1 H\bar{Q}_1 s\phi^2/\Lambda^2 \ \text{ and/or } \ y_2 H\bar{Q}_2 d\phi^2/\Lambda^2 + h.c.\,, \quad \& \quad \frac{\chi}{\Lambda_\chi} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \text{(for the decay)}$$

Leading to: $\Gamma(K_L \to \chi\sigma) \sim M_K \left|\frac{y_{1,2} v}{\Lambda^2}\right|^2 \times F_\pi^2$ followed by: $\chi \to \gamma\gamma$, σ being stable.

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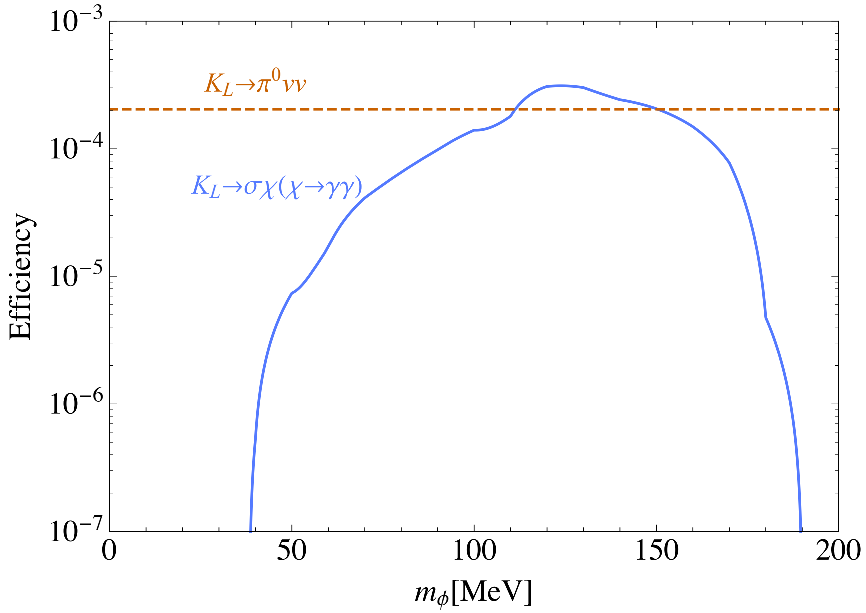
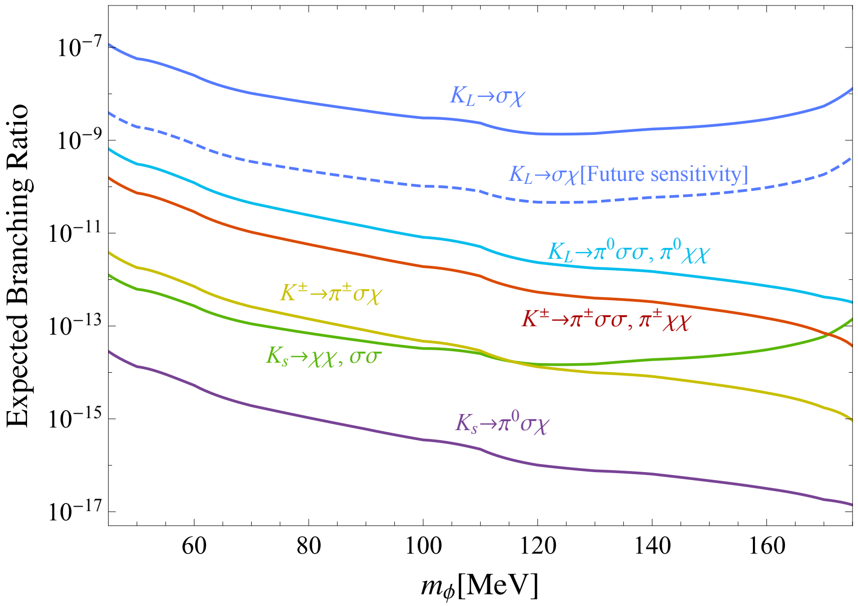
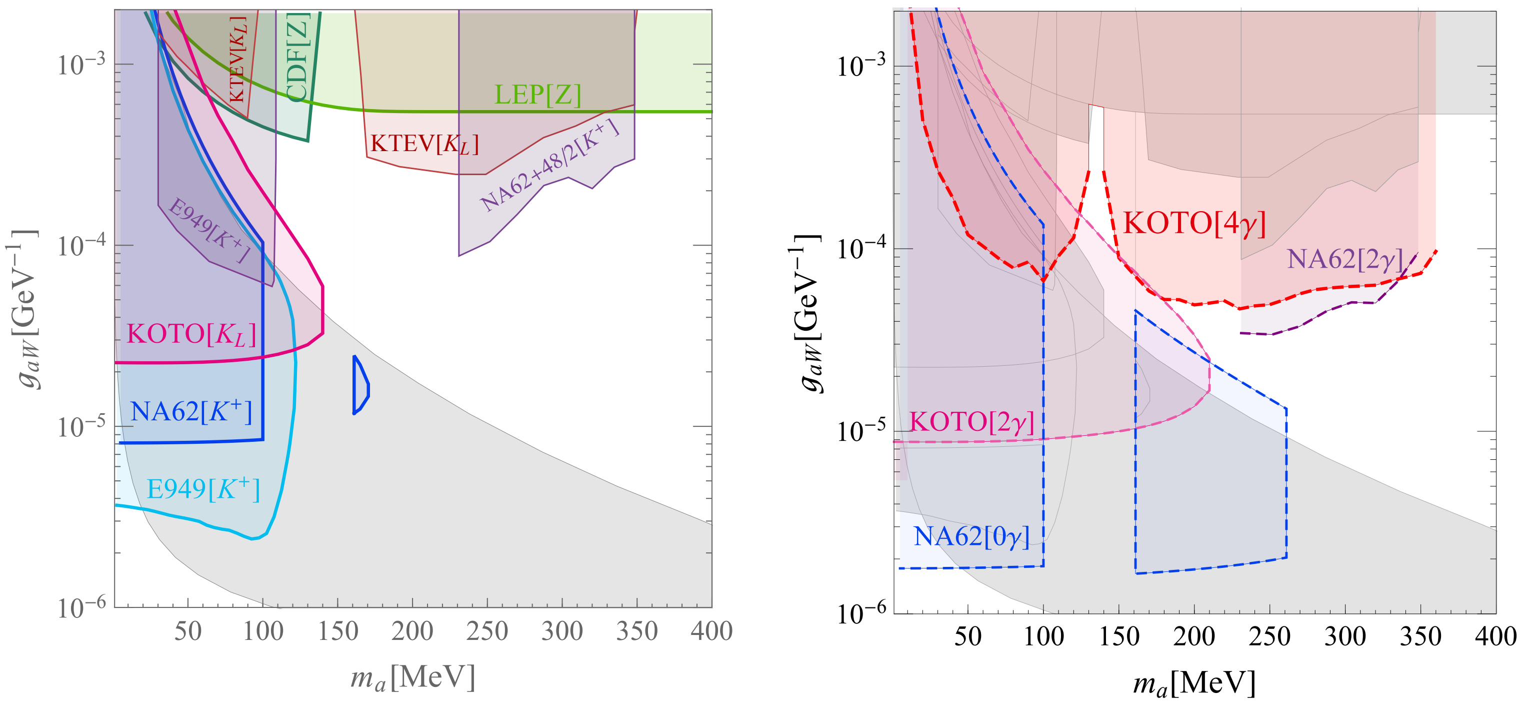




Gori, GP & Tobioka (20)

(different than NA62) KOTO has good sensitivity to $\pi^0(\gamma\gamma)X(\gamma\gamma)$

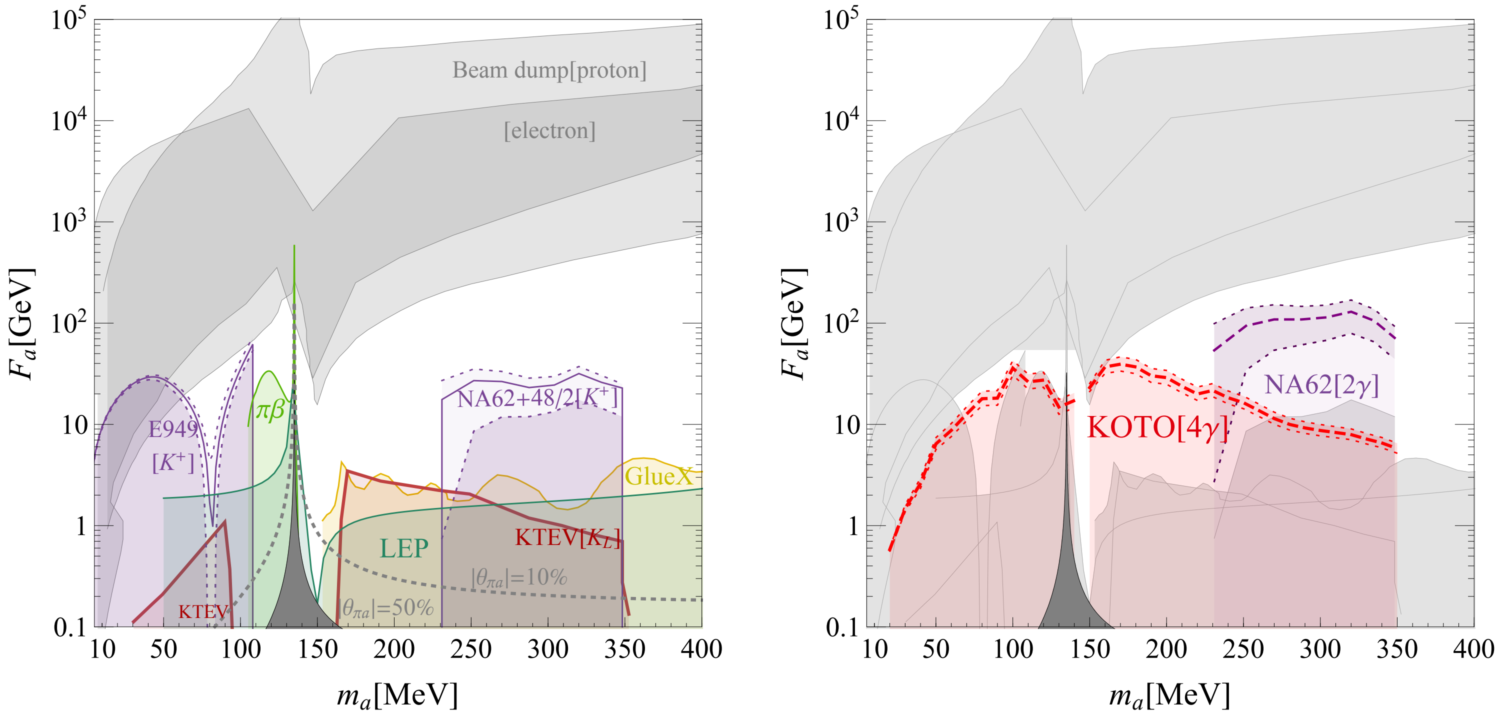
See paper for more details : Gori, GP & Tobioka (20)



Left panel: Present bounds on the parameter space of the $SU(2)$ coupled-ALPs, as a function of the ALP mass, m_a, and of its couplings with $SU(2)$ gauge bosons, g_{aW}. Right panel: Present and future bounds on the parameter space. In gray, we present the present bound (as shown in the left panel); in red and magenta, and in purple and blue, we present the future bounds at KOTO (4γ and 2γ + invisible signatures), and at NA62 ($\pi^+ + 2\gamma$ and π^+ + invisible signatures).

(different than NA62) KOTO has good sensitivity to $\pi^0(\gamma\gamma)X(\gamma\gamma)$

See paper for more details : Gori, GP & Tobioka (20)



. Left panel: Present bounds on the parameter space of the $G\tilde{G}$ coupled-ALP benchmark, as a function of the ALP mass, m_a, and of its decay constant, F_a. Right panel: Present and future bounds on the parameter space. In gray, we present the present bound (as shown in the left panel); in red and purple we present the future bounds at KOTO (4γ proposed search), and at NA62 ($\pi^+ + 2\gamma$ signature), respectively. The bands for the Kaon experiments (E949, NA62, KOTO) show the uncertainties from the quark mass values.

Conclusions

- Null-results + new theories (ex.: relaxion) => log crisis/opportunity, calls for experimental diversity.
- We have now a unique opportunity, with the 2 Kaon factories running.
- We have discussed why NA62 and KOTO are complementary.
- Keep following the development related to the recent KOTO analysis.