Probing the Dark Sector at Kaon Factories

Snowmass RF townhall meeting
[RF6 topical group]
Friday Oct 2, 2020

Kohsaku Tobioka
Florida State University

Joint effort with

Evgueni Goudzovski, Diego Redigolo and Jure Zupan

Letter of Interest: Probing the Dark Sector at Kaon Factories

Evgueni Goudzovski[1], Diego Redigolo[2], Kohsaku Tobioka[3,4], and Jure Zupan[5]

[1]School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom
[2]CERN, Theory Division, CH-1211 Geneva 23, Switzerland
[3]Department of Physics, Florida State University, Tallahassee, FL 32306, USA
[4]High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[5]Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA

3 Theorists (BSM) + 1 Experimentalist (NA62)

<u>bottomline</u>

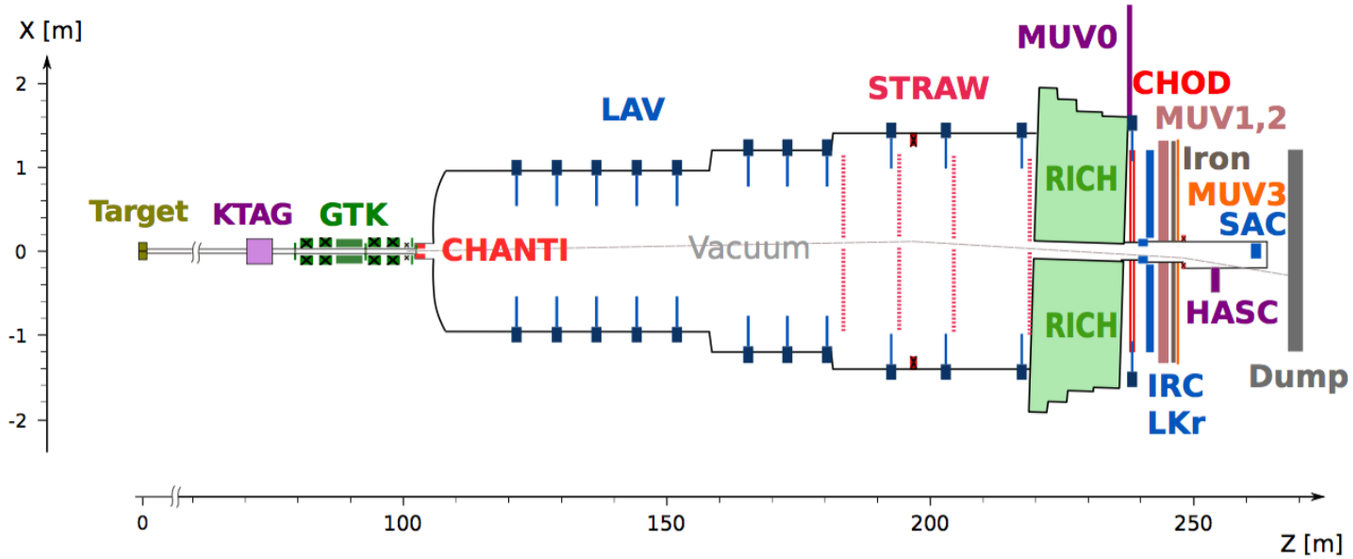
- Study the potential of Kaon factories as discovery machine
- Encourage more people to join the study

see https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-034.pdf

(Future) Kaon Experiments

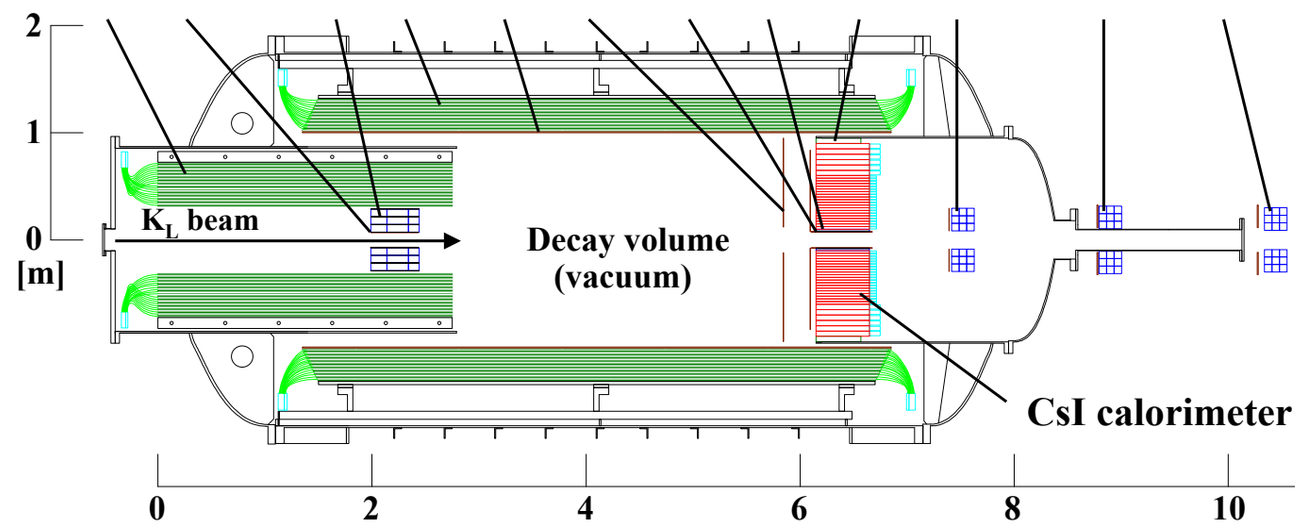
NA62 [K+]

- operating
- tracker+ECAL
- π^+,μ^+,e^+,γ, inv



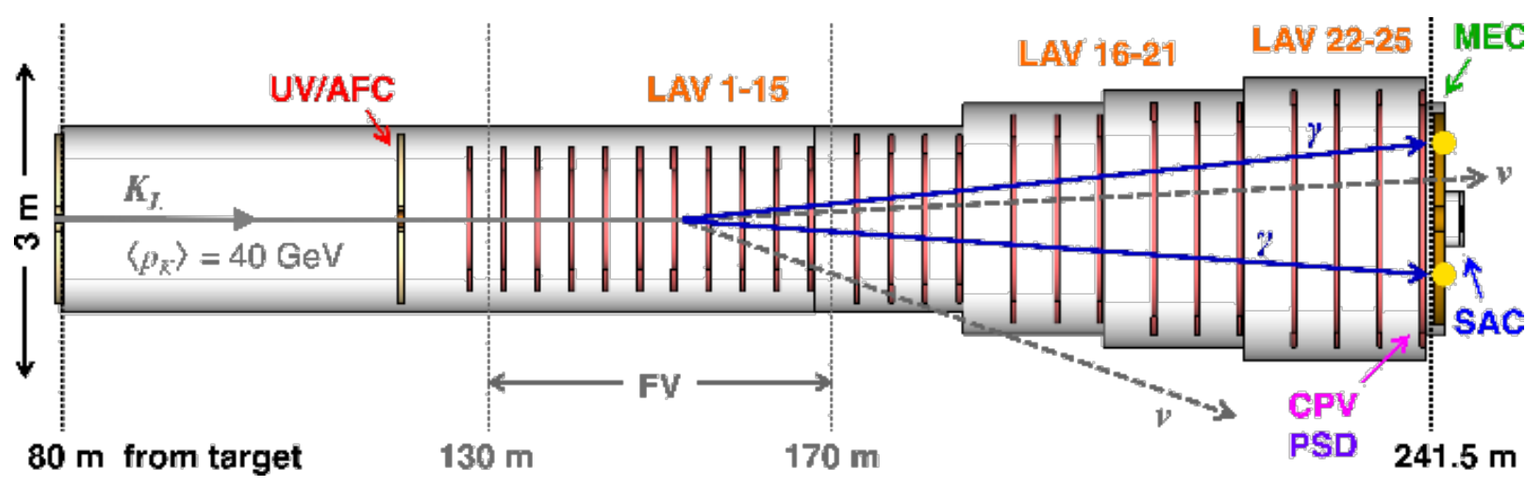
KOTO [K_L]

- operating
- ECAL
- π^0,γ, inv



KLEVER [K_L]

- future
- ECAL+tracker?
- π^+,μ^+,e^+,γ, inv?



New light particles from Kaon decays

Listed BSM possibilities that can be probed **[a-i]**.

- *Heavy axion, ALP*
- *Higgs portal scalar*
- *Muonic force*
- *Heavy neutral leptons*
- *Dark photon*
- *many exotics*
- *...*

a Production of a dark scalar (such as a Higgs portal scalar) or a QCD axion/axion-like particle (ALP), in $K^+ \to \pi^+ X, \pi^+\pi^0 X$ and $K_L \to \pi^0 X, \pi^0\pi^0 X$ decays. The BSM particles can either escape the detector, or decay invisibly (Higgs portal, ALPs), or decay to the SM final states as $X \to e^+e^-, \gamma\gamma$ (ALPs). The decay vertex can be displaced for ALPs [7–11]. The final state with e^+e^- can currently only be tested at NA62.

b Production of a dark scalar or a dark vector, such as leptonic force mediators, in the $K^+ \to \mu^+\nu X$ decay, where X is either invisible, or decays promptly via $X \to \mu^+\mu^-$, $X \to e^+e^-$ or $X \to \gamma\gamma$ [12–14]. These channels are particularly important to probe light muonic force carrier as a solution to the muon $g-2$ anomaly. The $K^+ \to e^+\nu X$ decay is another possibility, even though the NA62 reach in this channel will compete with direct production from electron/positron beams.

c Production of long-lived heavy neutral leptons in $K^+ \to (\pi^0)e^+N$ and $K^+ \to \mu^+N$ decays [15, 16].

d Production and decay of short-lived heavy neutral leptons, e.g., $K^+ \to \ell_\alpha N$, followed by the $N \to \ell_\beta^- \ell_\beta^+ \nu$ decay [17].

e Production of an invisible dark photon (γ') in $K^+ \to \pi^+\pi^0\gamma'$ decays [11, 18] or through $\pi^0 \to \gamma\gamma'$ where the π^0 is produced in $K^+ \to \pi^+\pi^0(\pi^0)$ or $K_L \to 3\pi^0$ decays.

f Processes violating the Grossmann-Nir bound: $K_L \to \gamma\gamma X_1, \gamma\gamma X_1 X_1$ and $K^+ \to \pi^+ X_1 X_1$. The $\gamma\gamma$ is emitted directly from K_L, or is from a decay of an intermediate particle, either π^0 or a new particle X_2, while X_1 is a massive stable particle [8, 19, 20]. Effective violation of the GN bound expects $K \to \pi X$ where a fraction of X decays to $\gamma\gamma$ [21].

g Similar processes violating the Grossmann-Nir bound but with $\ell^+\ell^-$ in the final state: $K_L \to \ell^+\ell^-\pi^0, \ell^+\ell^-(X_{\rm NP} \to \gamma\gamma), \ldots$, with K^+ decays suppressed.

h Production of two dark sector particles, $K \to \pi XX$. This is realized if a heavier scalar S is a portal to the dark sector (SXX) with a flavor violating coupling of $S\bar{s}d$. This scenario predicts an addition process, $K_L \to XX$, but it would not be detectable.

i Other more exotic scenarios can also be considered. For instance, lepton flavor violating decays such as $K^+ \to \pi^-\ell_1^+\ell_2^+$ are already being searched for [22]. A more exotic, yet still viable possibility, are showers in the dark sector with final states decaying back to the SM, leading to prompt signals or displaced vertices (emergent jets).

see https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-034.pdf

Theories to Signatures

Listed relevant signatures in kaon decays

Signature	$s \to dX_{\rm NP}$	$s \to dX_{\rm NP}X_{\rm NP}$	$\pi^0 \to \gamma X_{\rm NP}$
$K \to \pi + \text{inv}$	$s \to d(a/\gamma')$ [a,e]	$s \to d(aa/\gamma'\gamma'/\bar{N}N)$ [h]	–
$K \to 2\pi$+inv	$K \to 2\pi(a/\gamma')$ [a,e]	–	–
$K \to \pi\gamma + \text{inv}$	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to \pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to 2\pi\gamma$+inv	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to 2\pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to \pi\gamma\gamma$	$s \to d(a \to \gamma\gamma)$ [a,f]	–	–
$K \to \pi\ell^+_\alpha\ell^-_\alpha$	$s \to d(a/\gamma' \to \ell^+_\alpha\ell^-_\alpha)$ [a,e]	–	–
$K_L \to \gamma\gamma + \text{inv}$	$K_L \to \pi^0 a, \gamma\gamma a$ [f]	$K_L \to \pi^0(aa/\bar{N}N)$ [f]	–
		$K_L \to \gamma\gamma(aa/\bar{N}N)$ [f]	–
$K_L \to \ell^+\ell^-$+ inv	$K_L \to \ell^+\ell^-(a/\gamma')$ [g]	–	–
$K_L \to \ell^+\ell^-\gamma\gamma$	$K_L \to \ell^+\ell^-(a \to \gamma\gamma)$ [g]	–	–
$K^+ \to \ell^+_\alpha$+inv	$K^+ \to \ell^+_\alpha N, \ell^+_\alpha\nu(a/\gamma')$ [b,c]	–	–
$K^+ \to \ell^+_\alpha\ell^-_\beta\ell^+_\beta$	$K^+ \to \ell^+_\alpha\nu(a/\gamma' \to \ell^+_\beta\ell^-_\beta)$ [b,e]	–	–
+inv	$K^+ \to \ell^+_\alpha(N \to \ell^+_\beta\ell^-_\beta\nu)$ [d]		
$K^+ \to \ell^+_\alpha\gamma\gamma$+inv	$K^+ \to \ell^+_\alpha\nu(a \to \gamma\gamma)$ [b]	–	–
	$K^+ \to \pi^0\ell^+_\alpha N$ [c]		
$K^+ \to \pi^-\ell^+_\alpha\ell^+_\beta$	$u\bar{s} \to \ell^+_\alpha(N^* \to d\bar{u}\ell^+_\beta)$ [i]	–	–

see https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0-034.pdf

Toward Contributed Paper

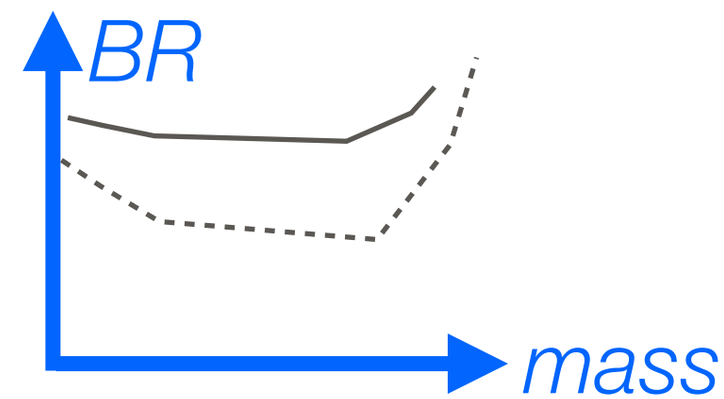
letter of interest → Snowmass → arXiv / Journal

Theoretical possibilities + Experimental signatures

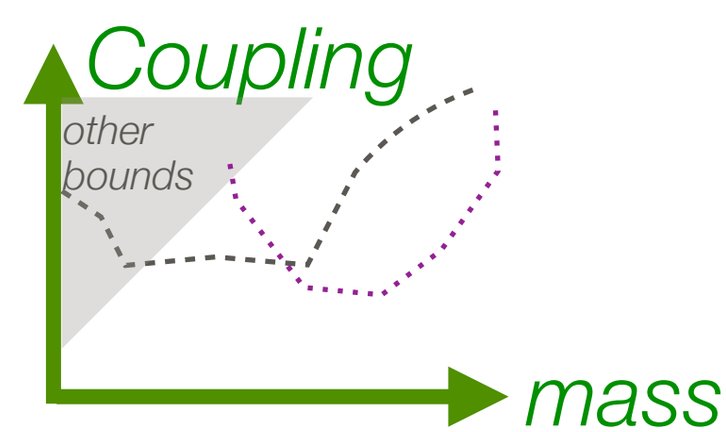
Projections (table→plots)

Signature	$s \to dX_{\rm NP}$	$s \to dX_{\rm NP}X_{\rm NP}$	$\pi^0 \to \gamma X_{\rm NP}$
$K \to \pi + \text{inv}$	$s \to d(a/\gamma')$ [a,e]	$s \to d(aa/\gamma'\gamma'/NN)$ [h]	–
$K \to 2\pi + \text{inv}$	$K \to 2\pi(a/\gamma')$ [a,e]	–	–
$K \to \pi\gamma + \text{inv}$	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to \pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to 2\pi\gamma + \text{inv}$	$s \to d(a \to \gamma\gamma')$ [i]	–	$K \to 2\pi(\pi^0 \to \gamma\gamma')$ [e]
$K \to \pi\gamma\gamma$	$s \to d(a \to \gamma\gamma)$ [a,f]	–	–
$K \to \pi\ell^+_\alpha\ell^-_\alpha$	$s \to d(a/\gamma' \to \ell^+_\alpha\ell^-_\alpha)$ [a,e]	–	–
$K_L \to \gamma\gamma + \text{inv}$	$K_L \to \pi^0 a, \gamma\gamma a$ [f]	$K_L \to \pi^0(aa/\bar{N}N)$ [f]	–
		$K_L \to \gamma\gamma(aa/\bar{N}N)$ [f]	–
$K_L \to \ell^+\ell^- + \text{inv}$	$K_L \to \ell^+\ell^-(a/\gamma')$ [g]	–	–
$K_L \to \ell^+\ell^-\gamma\gamma$	$K_L \to \ell^+\ell^-(a \to \gamma\gamma)$ [g]	–	–
$K^+ \to \ell^+_\alpha + \text{inv}$	$K^+ \to \ell^+_\alpha N, \ell^+_\alpha\nu(a/\gamma')$ [b,c]	–	–
$K^+ \to \ell^+_\alpha\ell^-_\beta\ell^+_\beta$	$K^+ \to \ell^+_\alpha\nu(a/\gamma' \to \ell^+_\beta\ell^-_\beta)$ [b,e]	–	–
$+\text{inv}$	$K^+ \to \ell^+_\alpha(N \to \ell^+_\beta\ell^-_\beta\nu)$ [d]		
$K^+ \to \ell^+_\alpha\gamma\gamma + \text{inv}$	$K^+ \to \ell^+_\alpha\nu(a \to \gamma\gamma)$ [b]	–	–
	$K^+ \to \pi^0\ell^+_\alpha N$ [c]		
$K^+ \to \pi^-\ell^+_\alpha\ell^+_\beta$	$u\bar{s} \to \ell^+_\alpha(N^* \to d\bar{u}\ell^+_\beta)$ [i]	–	–

Ex reach



Th interpretation

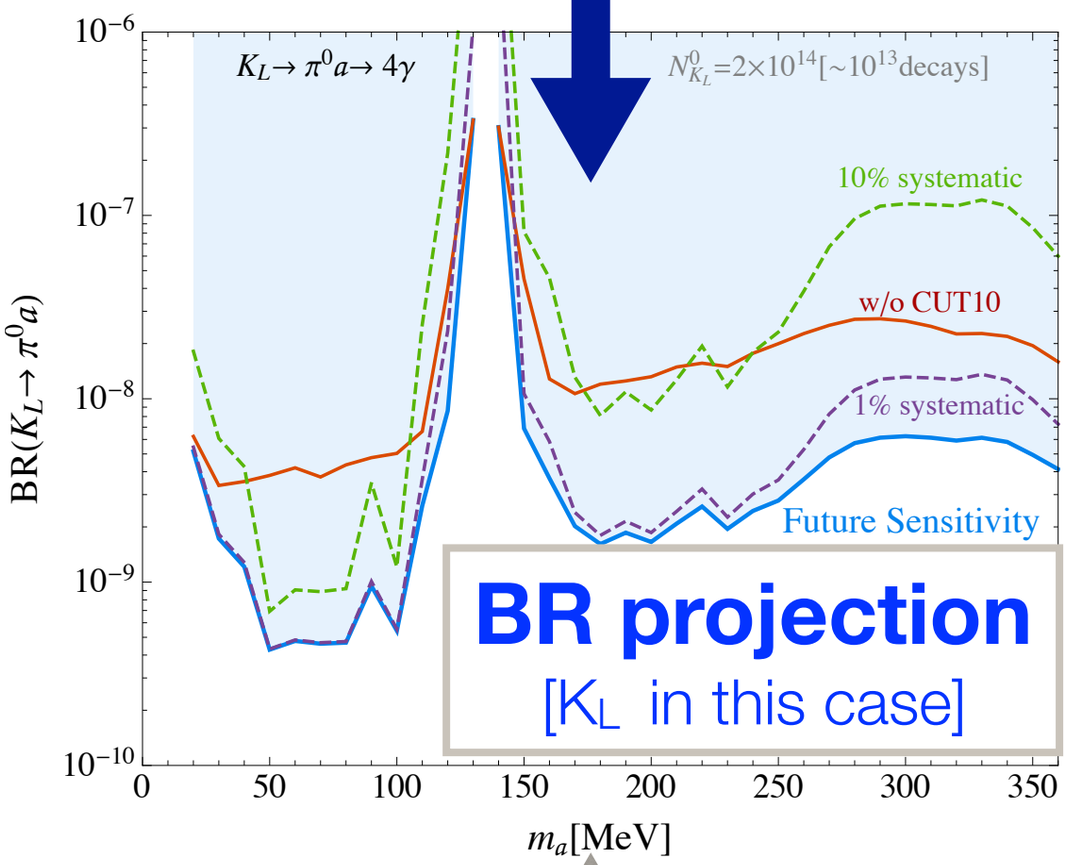


Need more people:
experimentalists, theorists, and young people!
More people→more channels.

Example: K→π a(→γγ)

Physics case:
100MeV ALP with decay

[arXiv:2005.05170] JHEP **08** (2020) 110
S. Gori, G. Perez, K. Tobioka

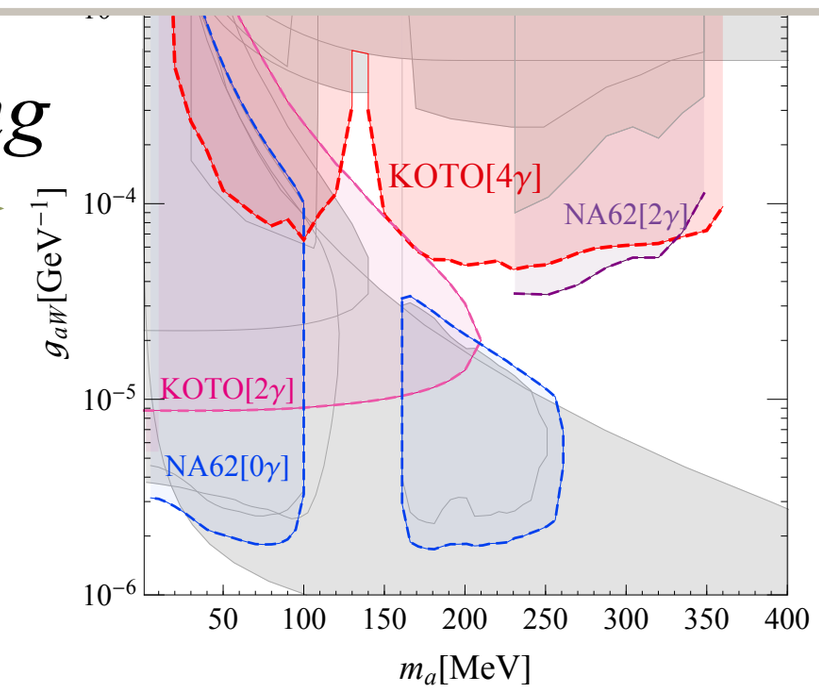


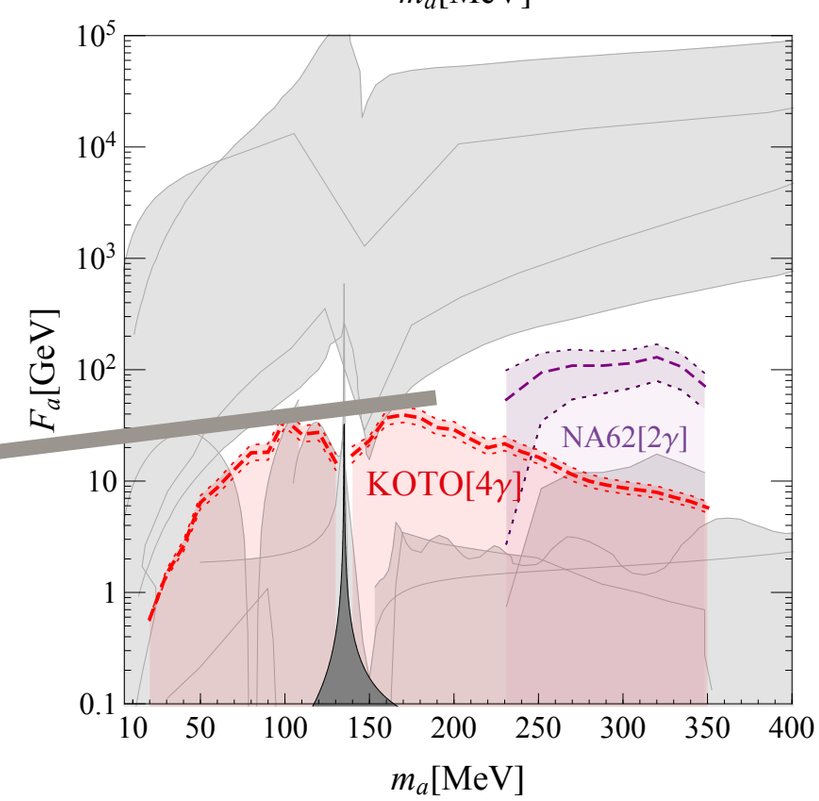
BR projection
[K_L in this case]

W-coupling

Gluon-coupling

Theory Interpretations
[two models]





May notice
a loophole/new channel
[K+ in this case]

Prospects

✓ Physics cases →Ex signatures (LoI)

- Collect the existing projections
- Prioritize physics cases and signatures
- Study the projections
  - Experimental reach
  - Theoretical interpretations

Need more people, please contact us!

ktobioka@fsu.edu