Axion-like-particles @ Kaon experiments

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UC Santa Cruz

High Energy / Nuclear Theory / RIKEN seminars,
BNL
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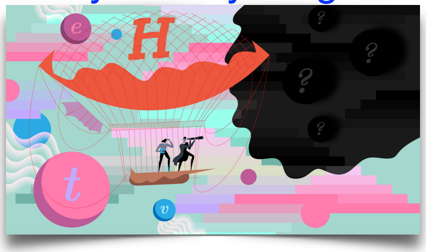
Outline

from symmetry magazine



1. Introduction

2. Kaon experiments: status and prospects

- Measurement of the very rare $K \to \pi \nu \nu$ decays
- KOTO (K_L) anomaly
- How to address the anomaly

3. Testing ALPs at Kaon experiments

- New proposed searches for the KOTO and NA62 experiments ($K \to \pi \gamma \gamma$)
- Interpretation in terms of ALP simplified models (aGG, aWW)
- Complementarity with other experiments (highlight: precision pion experiments)

Main references for this seminar

SG, G. Perez, K. Tobioka, 2005.05170

(W. Altmannshofer, SG, D. Robinson, 1909.00005)

Focus:
ALPs with masses
above the MeV scale

High intensity experiments & dark sectors

1. Several flavor experiments are coming online/will collect very large datasets in the coming years.
2. Several fixed target experiments are proposed for the near future.

All of these facilities can be used to search for light dark sector particles

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Many Standard Model (SM) flavor violating processes will be measured for the first time in the coming years:

For example:
$K \to \pi \nu \nu$ (KOTO and NA62)
$B \to K^{(*)} \nu \nu$ (Belle-II)
$B_d \to \mu\mu$ (LHCb)

As we will demonstrate, (some of) these decays can be easily affected by the presence of MeV and above axion-like-particles (ALPs)

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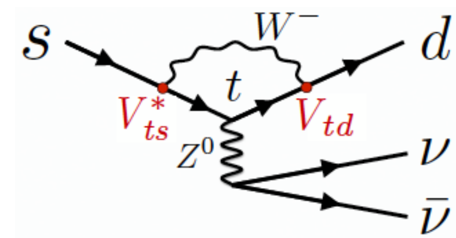
Kaon rare decays in the SM: K → π ν ν

$$\mathcal{H}_{\rm SM} = g_{\rm SM}^2 \sum_{\ell=e,\mu,\tau} \left[V_{cs}^* V_{cd} X(x_c) + V_{ts}^* V_{td} X(x_t) \right] \underbrace{(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\ell \gamma^\mu \nu_\ell)}_{\text{Only operator in the SM}}$$



+ box diagrams

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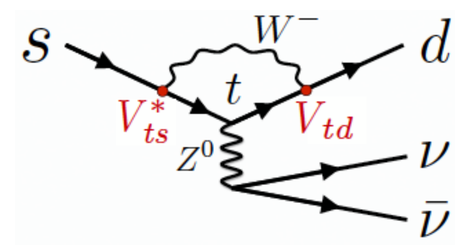


Very clean decays (mainly short distance contribution)

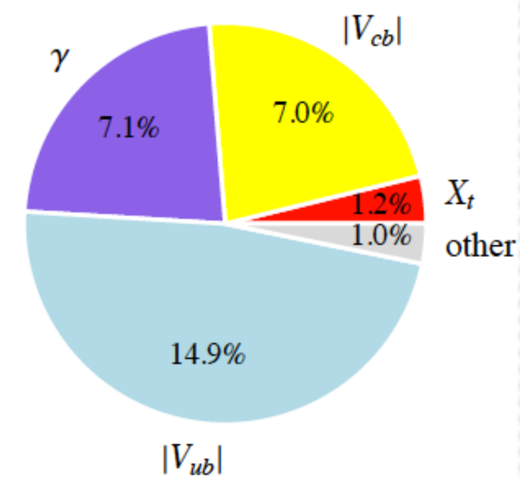
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq \kappa_+ \left| \frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \frac{V_{cs}^* V_{cd}}{\lambda} \left(\frac{X(x_c)}{\lambda^4} + \delta P \right) \right|^2$$

CP-conserving

Long-distance contributions

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \simeq \kappa_L \, \mathrm{Im} \left(\frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) \right)^2$$

CP-violating



$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) &= (9.11 \pm 0.72) \times 10^{-11} \\ \mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) &= (3.4 \pm 0.6) \times 10^{-11} \end{aligned}$$

Very rare!
→ Access to NP

Brod, Gorbahn, Stamou 1009.0947;
Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

The Grossman-Nir (GN) bound

Beyond the Standard model theories can easily induce a New Physics (NP) effect in these very rare Kaon decays.

Generically, the NP effects in the K^+ and in the K_L decay are highly correlated.

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From an EFT perspective:

$$\mathcal{H}_{\text{eff}} = \frac{c_1}{\Lambda^2}(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\ell \gamma^\mu \nu_\ell) + \frac{c_2}{\Lambda^2}(\bar{s}_R \gamma_\mu d_R)(\bar{\nu}_\ell \gamma^\mu \nu_\ell)$$

SM operator

$$X = \frac{\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}(\lambda_c)}{\lambda} P_{c,u} + \frac{1}{\lambda^5}(c_1 + c_2)$$

$$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) \propto F_0 (\mathrm{Im} X)^2$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) \propto F_+ |X|^2$$

because of the isospin symmetry, the form factors: $F_0 \sim F_+$

Grossman-Nir bound (model independent):

$$\frac{\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})} < 4.3$$

hep-ph/9701313

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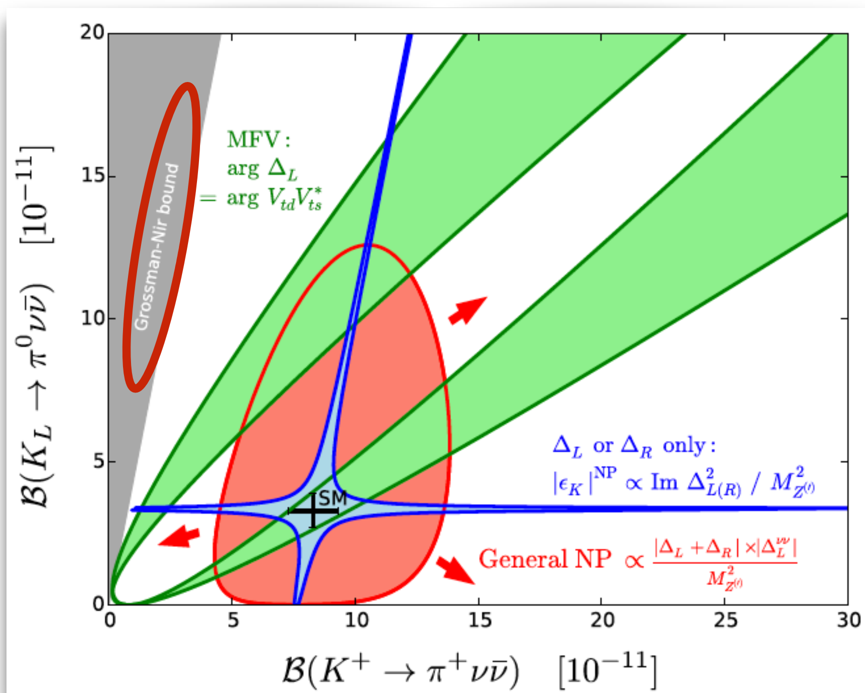

Buras, Buttazzo, Knegjens, 1507.08672

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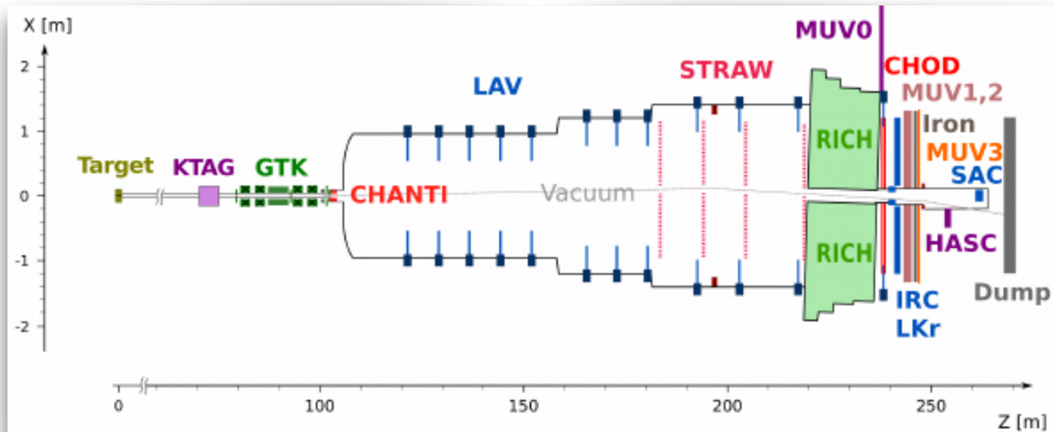
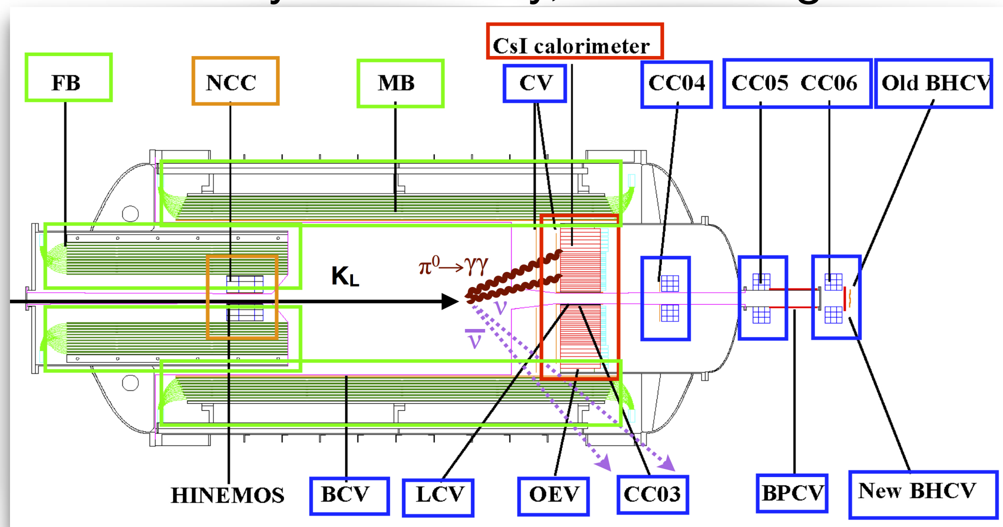
Brief look: NA62 & KOTO

Only calorimetry, no tracking



NA62



KOTO

future goals

	NA62	KOTO
POT	10^{19} (400 GeV)	10^{21} (30 GeV)
# Kaons	10^{13}	10^{13}
K-Energy	75 GeV	1.5 GeV
Length	300 m	10 m
Decay region	150 m	3-4 m

In comparison,
CHARM
(beam dump experiment):
~10^{18} POT

Status of the NA62 experiment (K^+)

- E949 experiment: 0903.0030

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

- Analysis of the full 2016 data

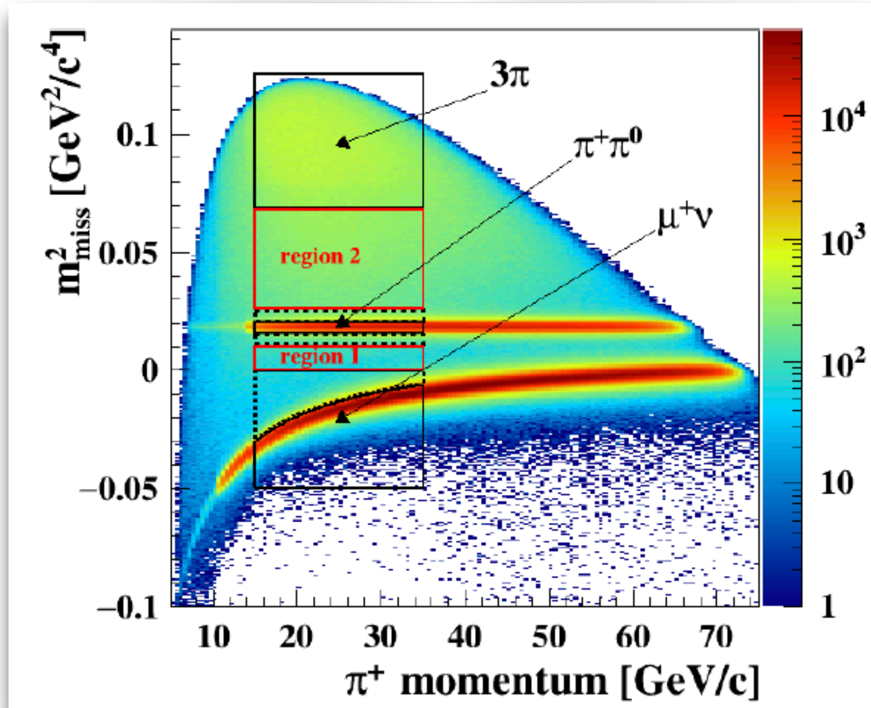
Optimized to suppress backgrounds from leading Kaon decay modes

$$15 < P_{\pi^+} < 35 \text{ GeV/c}$$

$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

1 event seen! (0.3 expected)

Published analysis, 1811.08508



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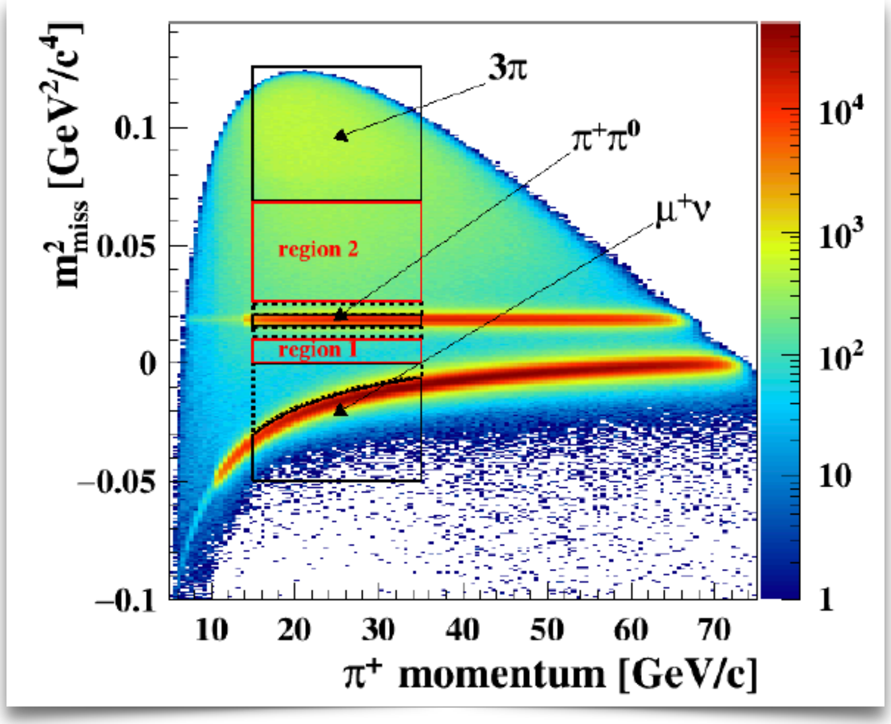

- Analysis of the 2016-2017 data (preliminary)

3 event observed

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$$ 90% C.L.

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (4.7^{+7.2}_{-4.7}) \times 10^{-11}$$

see e.g. talk by Volpe, pheno 2020

Final NA62 goal:
measurement of the SM BR with ~10% uncertainty

Status of the KOTO experiment (K_L)

Experimental challenges associated to the signature (2 photons+nothing)

- Initial physics data taken in 2013

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 5.1 \times 10^{-8}$$

(1609.03637)

- 2015 run: ~ 20 times more data

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$$

(1810.09655)

- Indirect bound:

(using Grossman-Nir)

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{GN}} < 7.96 \times 10^{-10}$$

Final KOTO goal (~100 times more data)
measurement of/evidence for
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$$\mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) = (3.4 \pm 0.6) \times 10^{-11}$$

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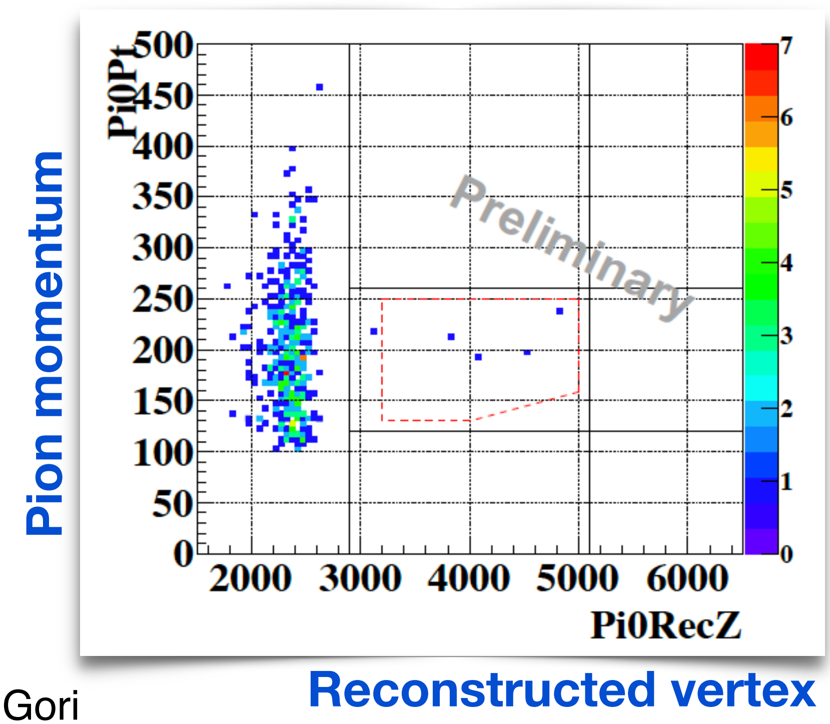
(1810.09655)

* 2016-2018 run: ~ 50% more data



* Indirect bound:
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$$BR(K_L \to \pi^0 \nu \bar{\nu})_{GN} < 7.96 \times 10^{-10}$$

4-events in the signal region!
Expected number of events: 0.05±0.02

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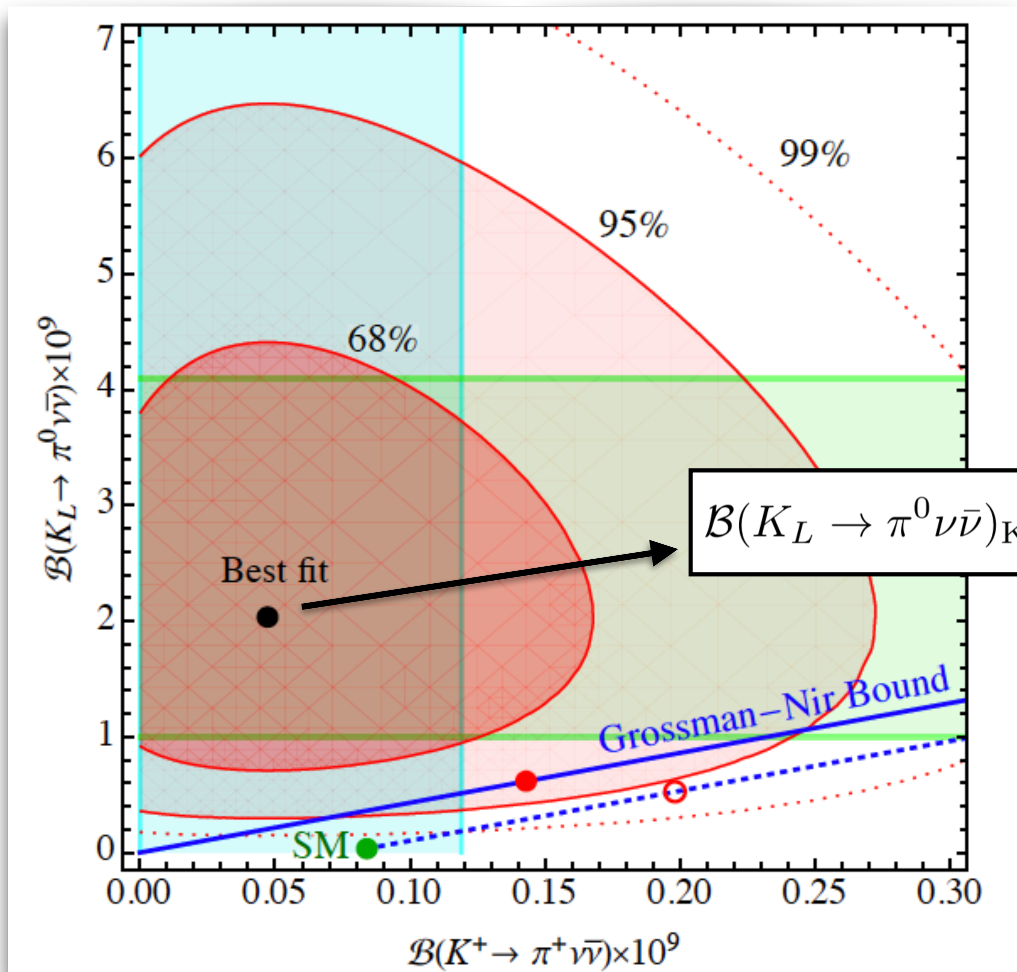
Compatibility NA62/KOTO?



Kitahara et al.,1909.11111

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

(theory interpretation)

~2σ tension (interference with the SM)

~3σ tension (no interference with the SM)

Class of models addressing the anomaly

- Heavy New Physics described by a EFT framework ✗

- Light New Physics (X) that satisfies the GN bound: $\boxed{K \to \pi X}$

- X is "long-lived enough" for KOTO, but not for NA62
K → π (X →invisible) for KOTO, but NOT for NA62
Preferred lifetime: O(0.1-0.01)ns

(based on the observation that NA62 is effectively larger than KOTO: $L_{\mathrm{NA62}}/p_{\mathrm{NA62}} > L_{\mathrm{KOTO}}/p_{\mathrm{KOTO}}$)

- X has a mass in (100-160) MeV (close to the pion mass)
NA62 has large $K^+ \to \pi^+ \pi^0$ in this region. (Fuyuto et al, 1412.4397)

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- Light New Physics (X) that breaks the GN bound: (see next slide)

- Exotics:
  e.g. New particle, ϕ, produced at the target and that decays $\phi \to \gamma\gamma$ inside the KOTO fiducial

An incomplete list of pheno interpretations:
Kitahara et al. 1909.11111; Egana-Ugrinovic et al. 1911.10203; Dev et al. 1911.12334
Jho et al. 2001.06572; Liu et al. 2001.06522; He et al. 2002.05467; Ziegler et al. 2005.00451 Liao et al. 2005.00753; Hostert et al. 2005.07102; Datta et al. 2005.08920; Altmannshofer et al. 2006.05064

(Strongly) Breaking the GN bound

One can avoid the Grossman-Nir bound in models with **only neutral New Physics particles.**

Based on an idea by M. Pospelov

Let us suppose to have a new decay:

$$K_L \to \sigma\chi, \quad \chi = \mathrm{Im}(\phi), \ \sigma = \mathrm{Re}(\phi)$$

This would dominate the 3-body final states of the charged Kaon:

$$K^+ \to \pi^+\chi\chi, \quad K^+ \to \pi^+\sigma\sigma$$

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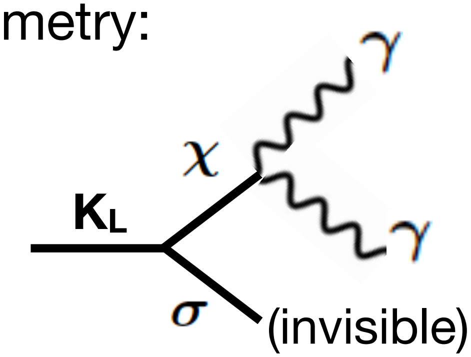
A working model based on an approximate strange flavor symmetry:

$$\begin{cases} y_1 H\bar{Q}_1 s\phi^2/\Lambda^2 \;\; \text{and/or} \;\; y_2 H\bar{Q}_2 d\phi^2/\Lambda^2 + h.c. \\ \mathcal{L}_\chi \supset \dfrac{\chi}{\Lambda_\chi} F_{\mu\nu}\tilde{F}^{\mu\nu} \end{cases}$$

SG, Perez, Tobioka, 2005.05170



$$\Gamma(K_L \to \chi\sigma) \sim M_K \left|\frac{y_{1,2} v}{\Lambda^2}\right|^2 \times F_\pi^2$$

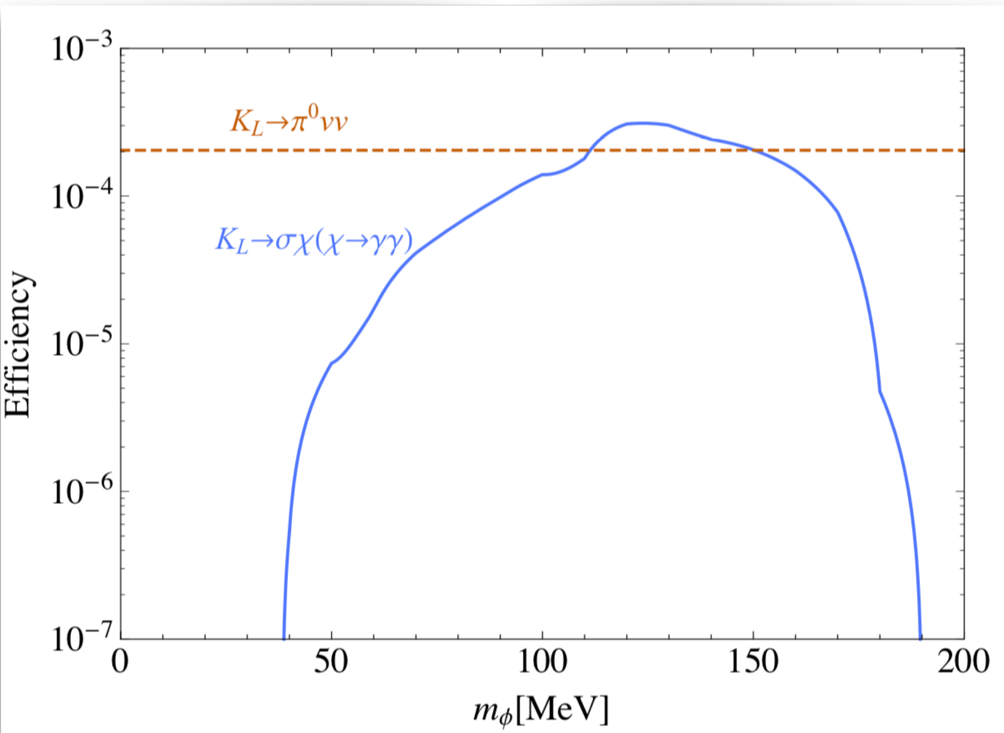
Depending on the ϕ mass, this decay can fall into the KOTO signal region

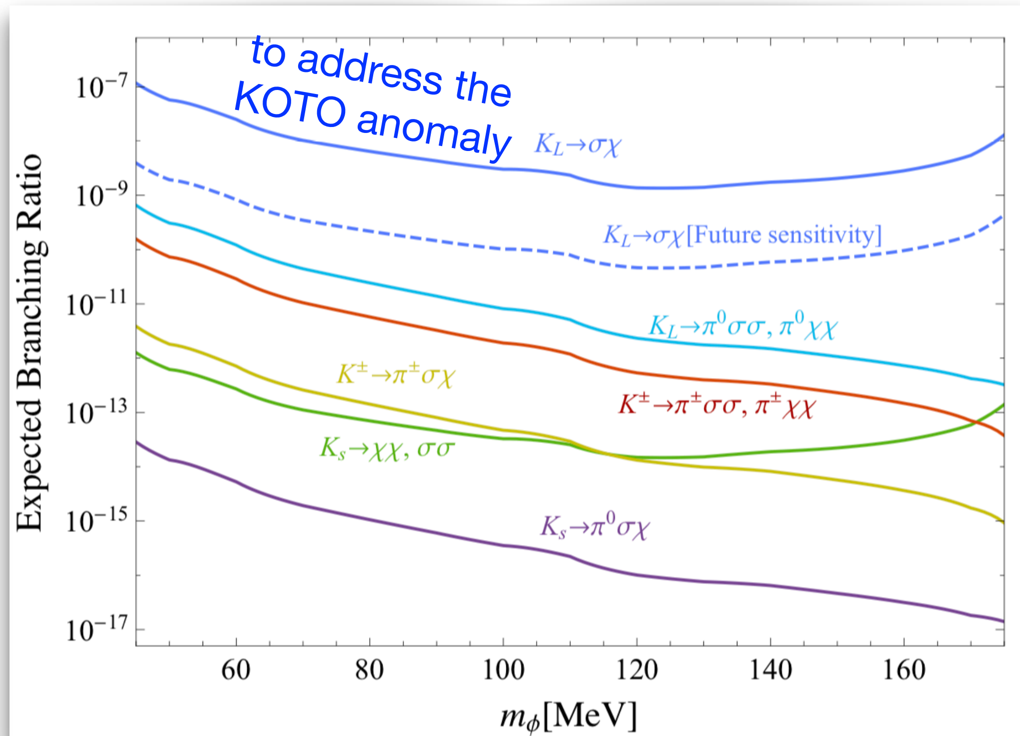
See also Hostert et al. 2005.07102; Altmannshofer et al. 2006.05064

Predictions for Kaon experiments

$$\boxed{\frac{v}{\Lambda^2_{\rm GNV}}\phi^2\frac{F_\pi^2 B_0}{2}{\rm Tr}[y_1\lambda_{sd}\Sigma] + \frac{v}{\Lambda^2_{\rm GNV}}\phi^2\frac{F_\pi^2 B_0}{2}{\rm Tr}[y_2\lambda_{sd}^\dagger\Sigma] + h.c.}$$

$$\Sigma \equiv \exp[2i\Pi/F_\pi] \qquad \Pi \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -2\frac{\eta_8}{\sqrt{6}} \end{pmatrix}, \quad \lambda_{sd} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$





SG, Perez, Tobioka, 2005.05170

Other New Physics searches we can do at these two Kaon experiments?

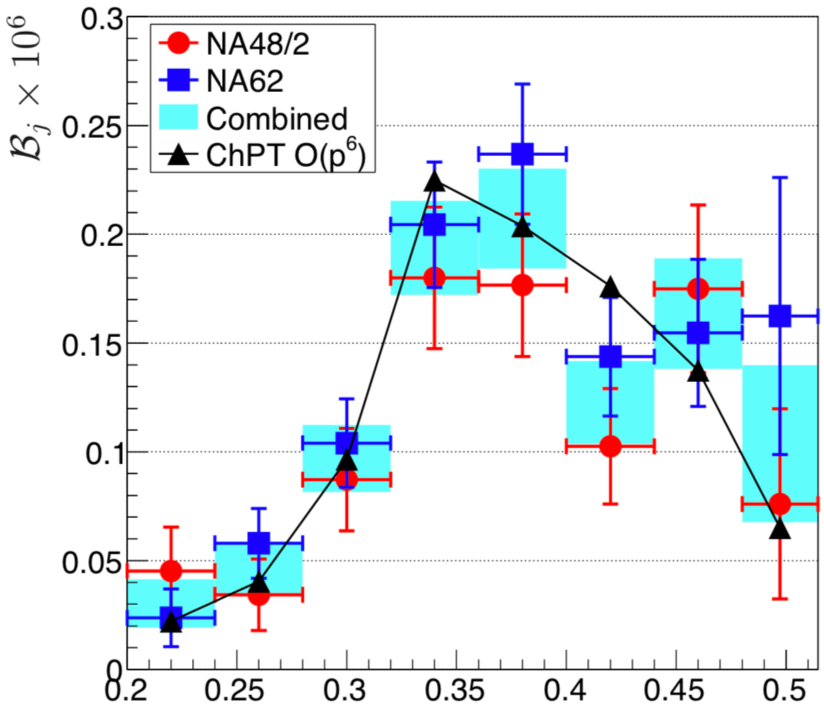
$K \to \pi X$ with a visible X

K → π γ γ (charged mode)

K⁺ → π⁺ γ γ has been searched for at:

- **E949** with the requirements (hep-ex/0505069)
  - Photons originate within 80 cm of the stopped Kaon
  - $p_{\pi^+} > 213$ MeV

- at the **NA62/48** experiment (1402.4334)



NA62 did not perform the search (yet). In the following, we will rescale the NA48/62 bound with $\sqrt{L}$ considering a downscaling trigger factor of 400.

$$220 \text{ MeV} \lesssim m_{\gamma\gamma} \lesssim 350 \text{ MeV}$$

z $= (m_{\gamma\gamma}/m_K)^2$

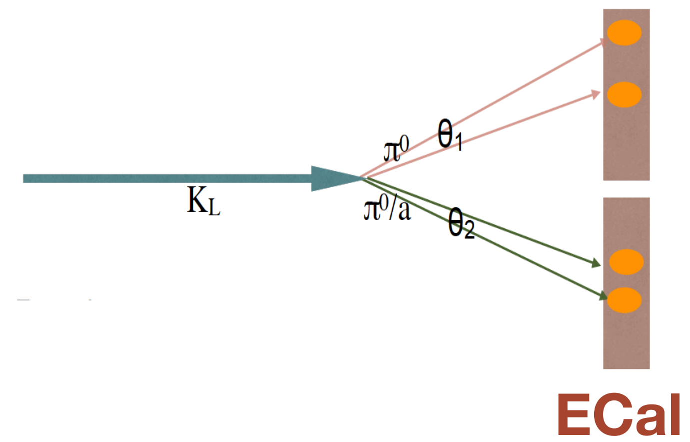
~10^9 K⁺ in the fiducial region

K → π γ γ (neutral mode)

$\boxed{K_L \to \pi^0 a \to 4\gamma}$ **Our new proposed search**

Challenges of the search:

- the decay point is unknown (only ECal, no tracker)
- combinatorics of γγ pairs



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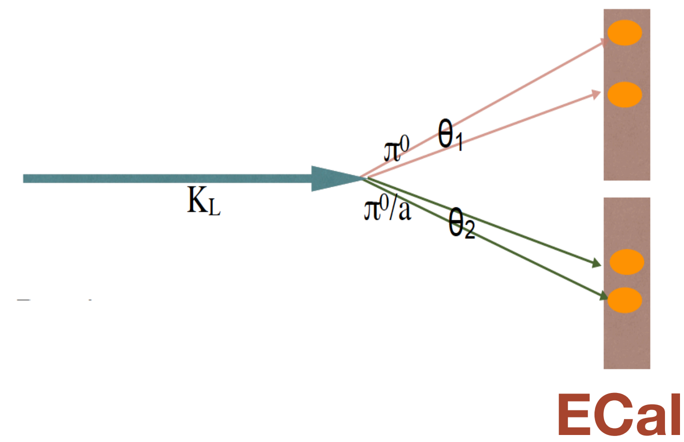
Main ingredients :

1. We derive the K_L decay vertex location of the 6 possible di-photon pair combinations, assuming
$$m^2_{\gamma_i\gamma_j} = m^2_{\pi^0}$$
2. Require $m_{4\gamma} \simeq m_{K_L}$ to find a correct pair



Importance of a good <u>vertex resolution</u>! (~5cm) and small <u>energy smearing</u> (~2%)

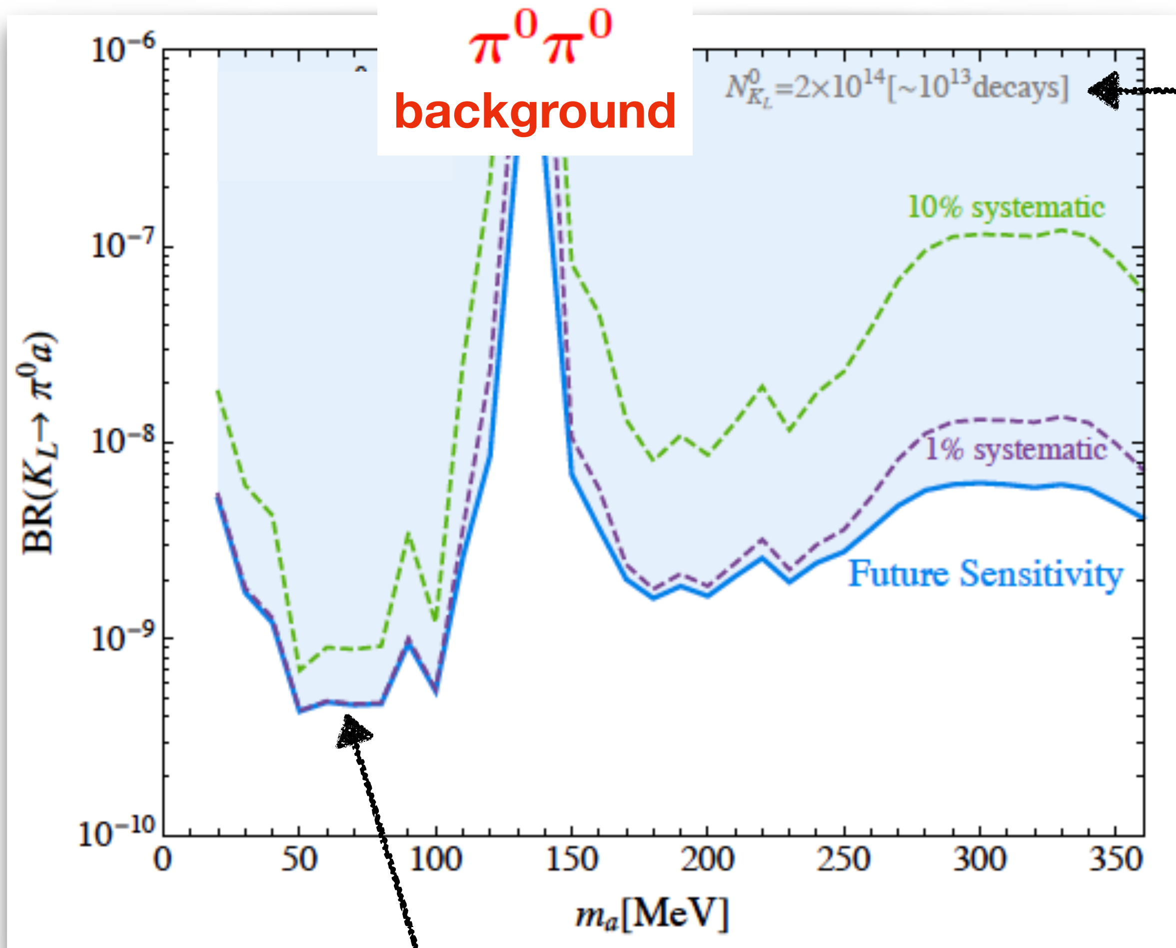
We simulate the main sources of background:

$$K_L \to \pi^0\pi^0,\ K_L \to \pi^0\gamma\gamma$$

mainly for $m_a \sim m_{pion}$

The KOTO reach

$$\boxed{K_L \to \pi^0 a \to 4\gamma}$$



Ultimate KOTO luminosity goal

Branching ratios as small as **few 10^{-10}** can be tested!

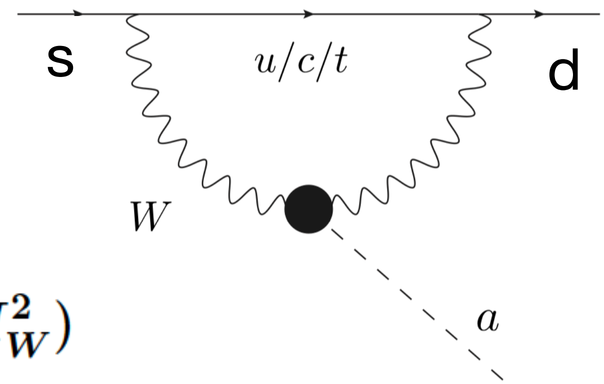
Interpretation in terms of New Physics models

1. $$\frac{g_{aW}}{4}\, a\, W^{a}_{\mu\nu}\tilde{W}^{a\mu\nu}$$ (SU(2) gauge bosons)

2. $$\frac{\alpha_s}{8\pi F_a}\, a\, G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu}$$ (gluons)

1. WW coupled ALP simplified model

$$\frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$



$$g_{ads} \equiv -\frac{3\sqrt{2}G_F M_W^2 g_{aW}}{16\pi^2}\sum_{\alpha\in c,t} V_{\alpha d}V^*_{\alpha s} f(M_\alpha^2/M_W^2)$$

$$\Gamma(K_L \to \pi^0 a) = \frac{M_{K_L}^3}{64\pi}\left(1-\frac{M^2_{\pi^0}}{M^2_{K_L}}\right)^2 \mathrm{Im}(g_{asd})^2\, \lambda^{1/2}_{\pi^0 a}$$

This coupling will induce the decay of the ALP into two photons:

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad g_{a\gamma} = g_{aW}\sin^2\theta$$

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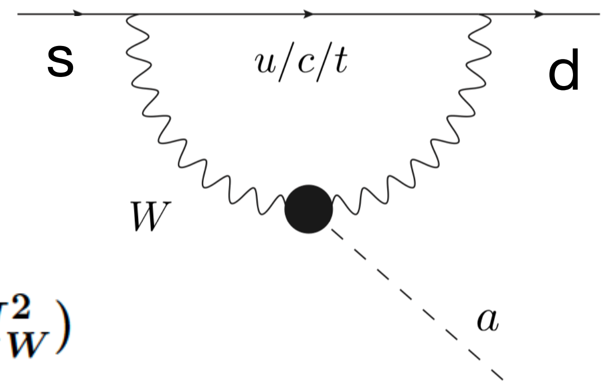

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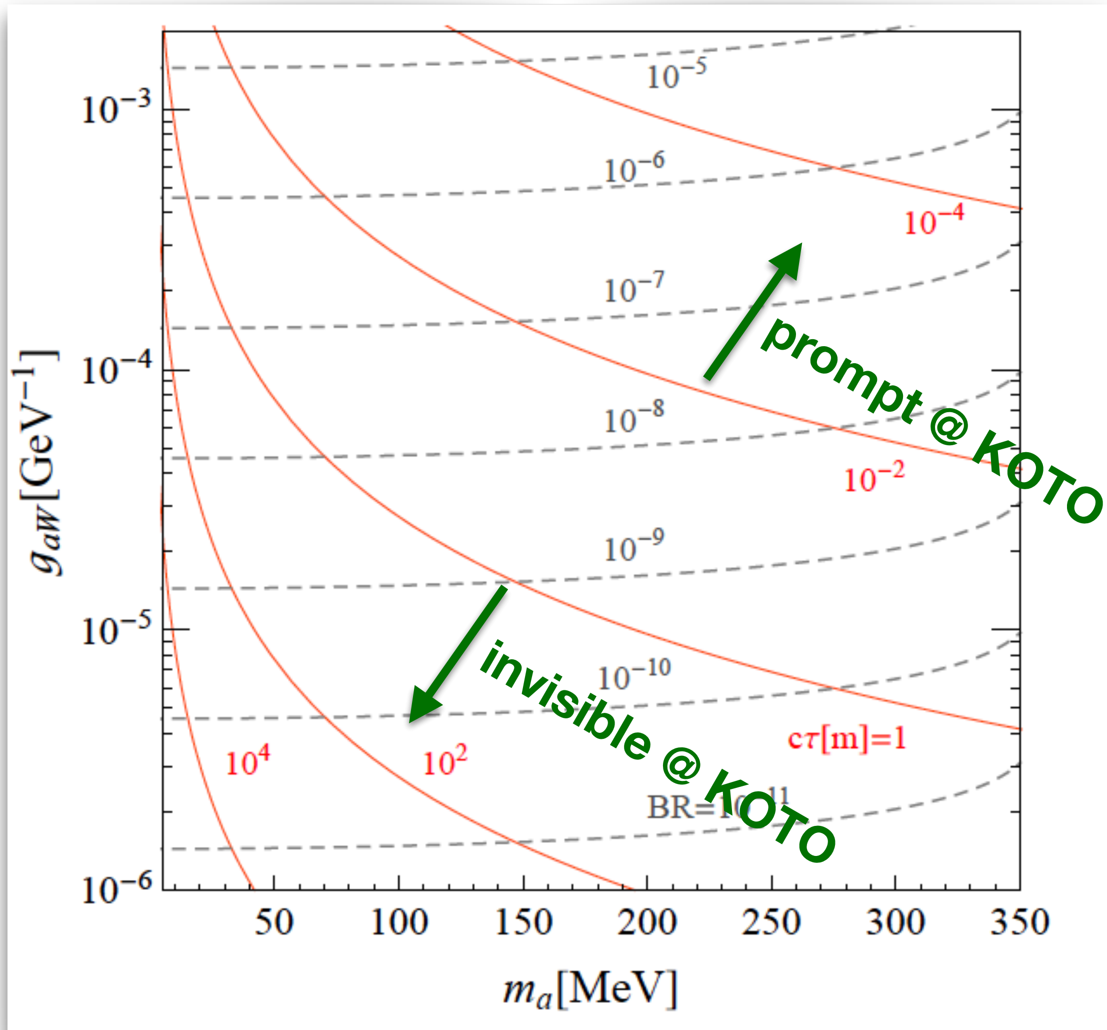
According to the Grossman-Nir bound, we expect an effect also in the K^+ decay. Indeed:

$$\Gamma(K^+ \to \pi^+ a) \;=\; \frac{M^3_{K^+}}{64\pi}\left(1-\frac{M^2_{\pi^+}}{M^2_{K^+}}\right)^2 |g_{asd}|^2\,\lambda^{1/2}_{\pi^+ a}$$

WW coupled ALP pheno

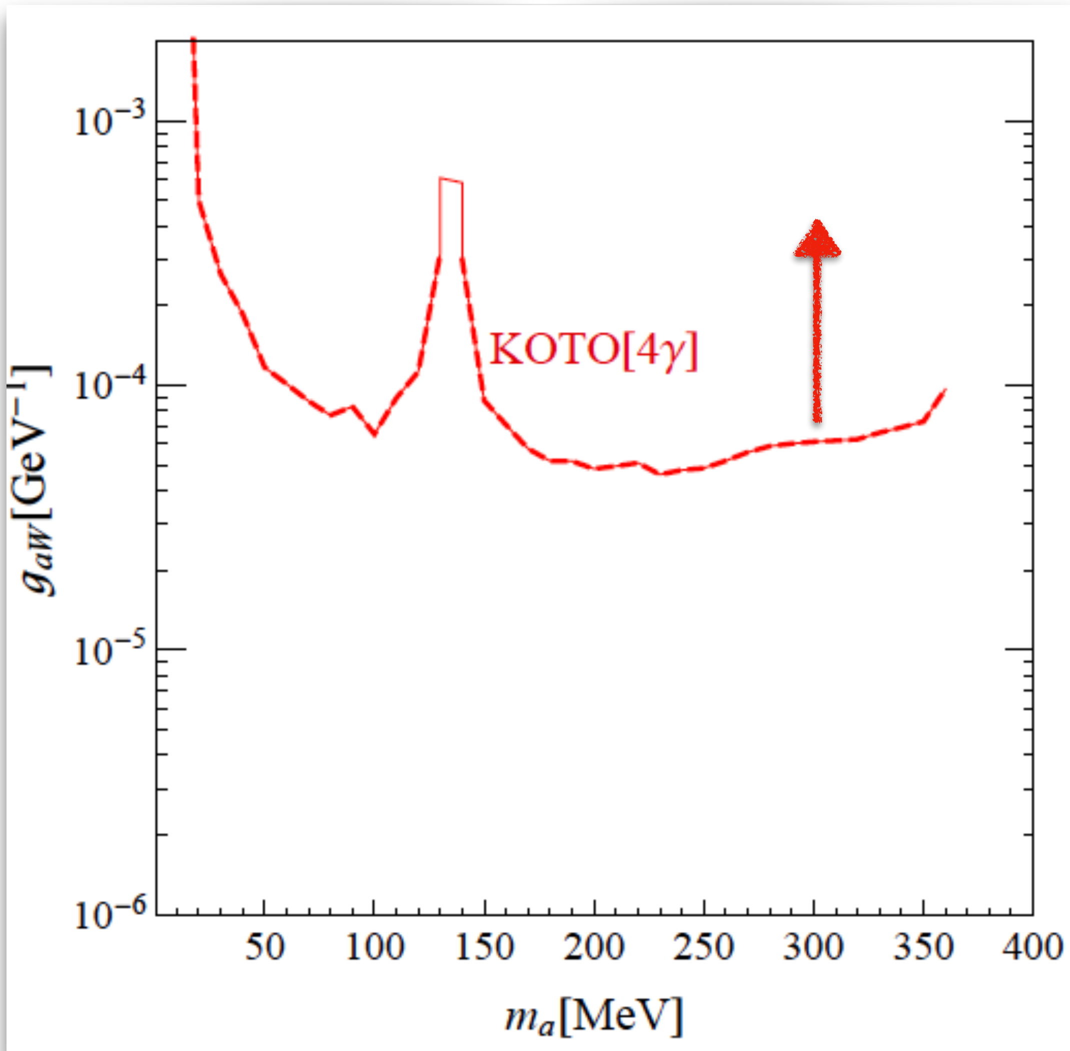


ALP lifetime (in meters)

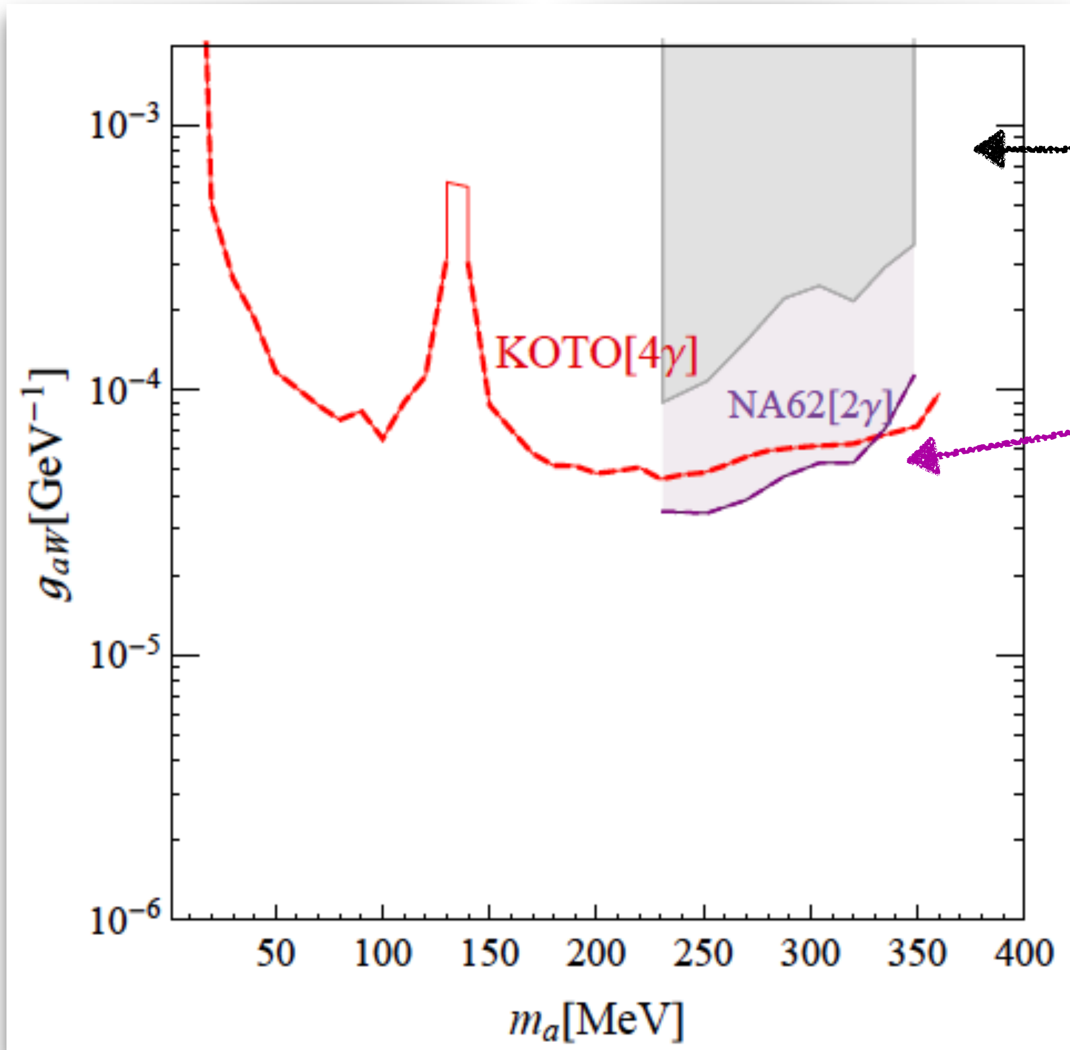
BR($K_L \to \pi\, a$)

BR($K^+ \to \pi^+ a$) ~ 1.8 BR($K_L \to \pi\, a$)

$aW\tilde{W}$ at KOTO



$aW\tilde{W}$ at KOTO and NA62 (visible)



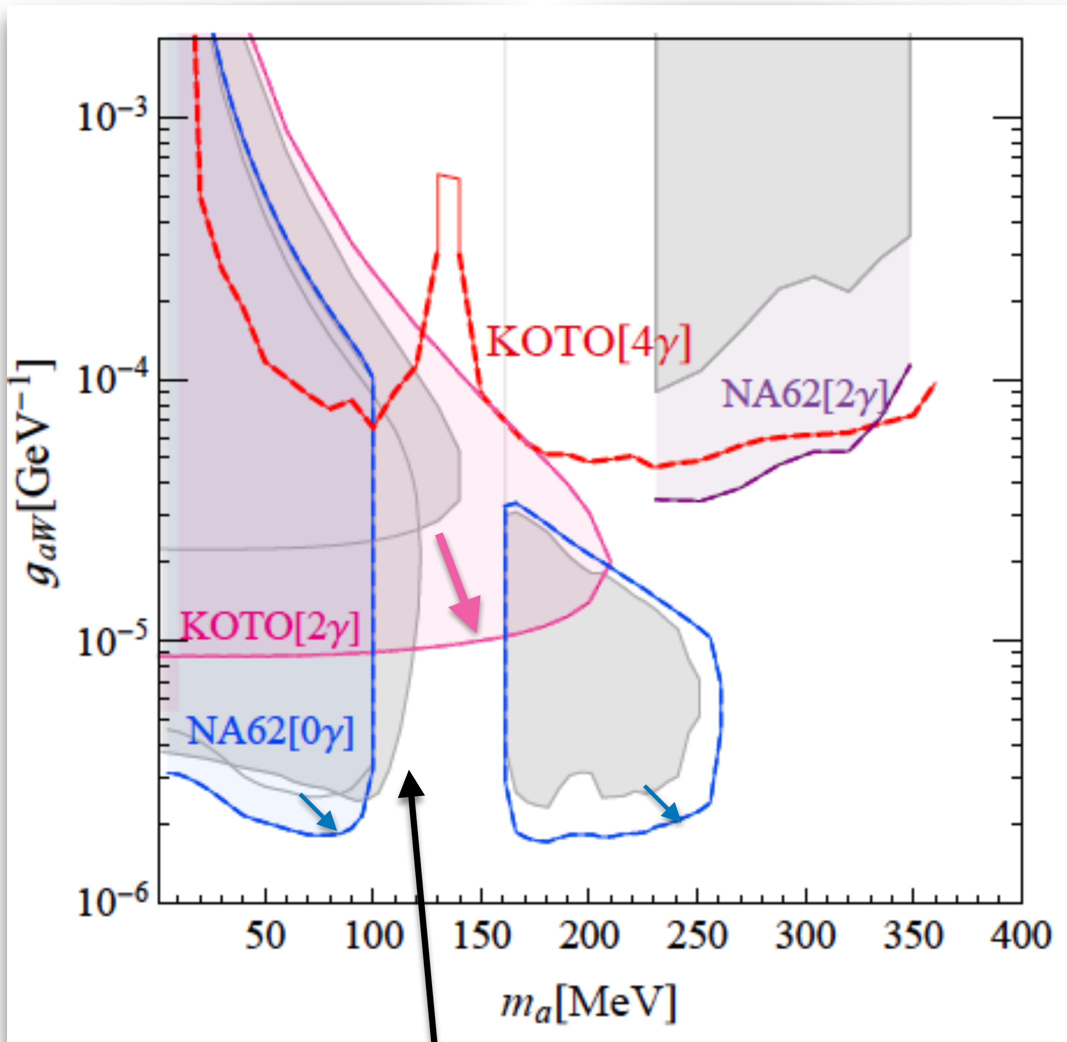
NA48/62 search for

$K^+ \to \pi^+ a, \;\; a \to \gamma\gamma$

Izaguirre, Lin, Shuve, 1611.09355

projection with
the full NA62 luminosity

$aW\tilde{W}$ at KOTO and NA62



E949 invisible

Longer life-time

Both NA62 and KOTO can search for

$$K \to \pi + \text{invisible}$$

(the ALP is long lived enough to decay after the detector)

Complementarity with other experiments

This specific model ($aW\tilde{W}$) also predicts a coupling of the ALP with photons

→ Several other experiments can probe the parameter space

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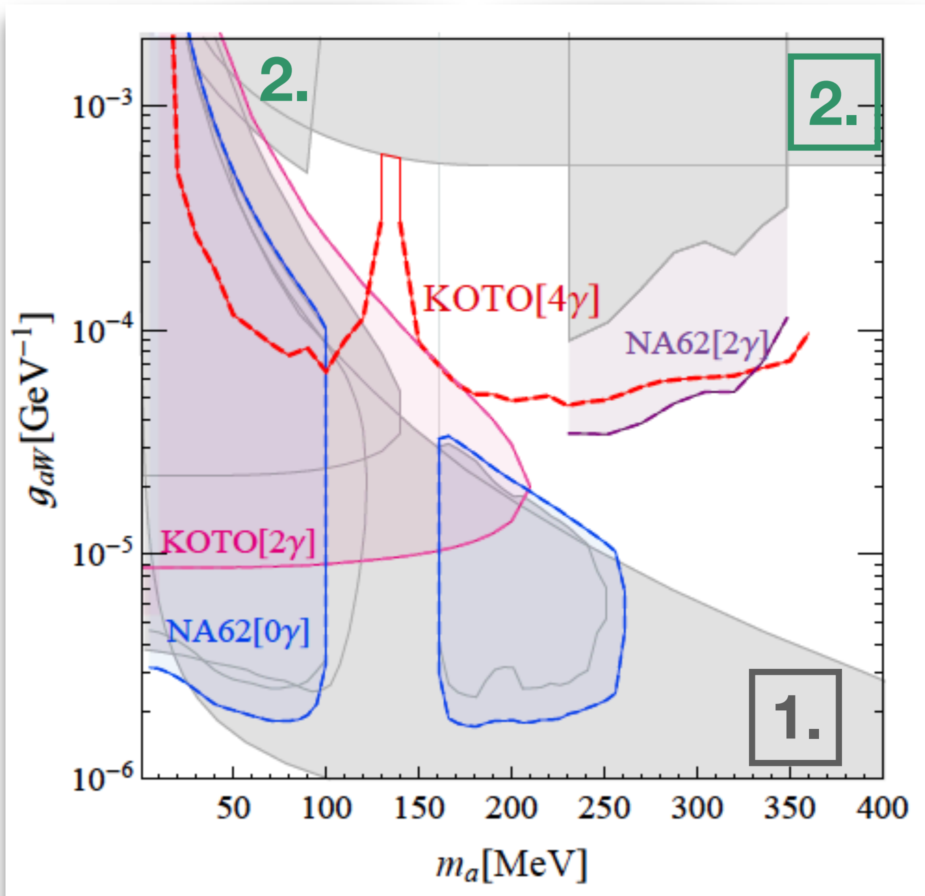


1. Beam dump experiments
2. LEP ($e^+e^- \to \gamma$ a or Z $\to \gamma$ a $\to \gamma\gamma(\gamma)$) + CDF (Z $\to \gamma$ a $\to \gamma\gamma$)

Additional opportunities at B-factories? (Belle-II) Izaguirre, Lin, Shuve, 1611.09355

Note, however, that NA62 and KOTO will have **~ 3 orders of magnitude more** Kaons than the number of B-mesons at Belle-II!

2. GG coupled ALP simplified model

$$\frac{\alpha_s}{8\pi F_a}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\boxed{\mathcal{L}_{eff} = \frac{iF_\pi^2}{4}\frac{\partial_\mu a}{F_a}\mathrm{Tr}[\tilde{\kappa}_q(\Sigma^\dagger D^\mu\Sigma - \Sigma D^\mu \Sigma^\dagger)] + \frac{F_\pi^2}{2}B_0\mathrm{Tr}[\Sigma m^\dagger + m^\dagger \Sigma^\dagger]}$$

Kinetic mixing — Mass mixing

$$m = \exp\left(i\kappa_q \frac{a}{2F_a}\gamma_5\right)\cdot m_q \cdot \exp\left(i\kappa_q \frac{a}{2F_a}\gamma_5\right) \quad \tilde{\kappa}_q = \mathrm{diag}(\kappa_q), \quad \kappa_q = \frac{1}{m_q}/\sum_{q'}\left(\frac{1}{m_{q'}}\right)$$

$$\begin{cases} \theta_{\pi a} \simeq \dfrac{F_\pi}{2F_a}(\kappa_u - \kappa_d)\dfrac{m_a^2}{m_a^2 - m_{\pi^0}^2} \\ \theta_{\eta a} \simeq \dfrac{F_\pi}{F_a}\dfrac{\sqrt{2}m_a^2[\kappa_u+\kappa_d-2\kappa_s]\cos\theta_{\eta\eta'} - 2\left(m_a^2[\kappa_u+\kappa_d+\kappa_s] - 6\Delta m_{\pi^0}^2\right)\sin\theta_{\eta\eta'}}{2\sqrt{6}(m_a^2 - m_\eta^2)} \end{cases}$$

Kinetic mixing with the **pion** of the SM

Kinetic mixing and mass mixing with the **eta** of the SM

(mass mixing is due to the eta-eta' mixing, $\theta_{\eta\eta'}$)

Christ et al., 1002.2999

Theory prediction for $K \to \pi\, a$

The ALP-pion and ALP-eta mixing will induce

- an effective K-π-ALP coupling $(K \to a\pi)$
- a ALP coupling to photons $(a \to \gamma\gamma)$

Theory prediction for K → π a

The ALP-pion and ALP-eta mixing will induce

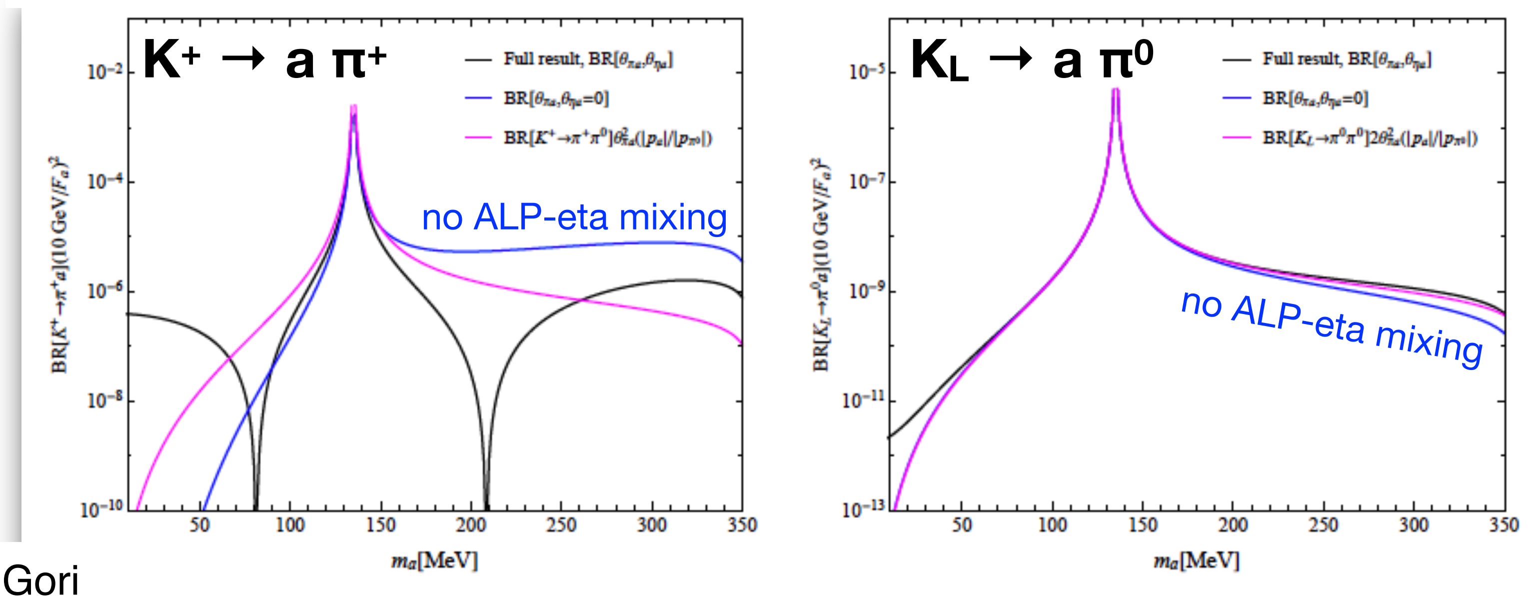
- an effective K-π-ALP coupling (K → aπ)
- a ALP coupling to photons (a → γγ)

At low energy, the two operators responsible for ΔS = 1 transitions are

$$\mathcal{L}_{\Delta S=1} = G_8 F_\pi^4 \mathrm{Tr}[\lambda_{sd} D^\mu \Sigma^\dagger D_\mu \Sigma] + G_{27} F_\pi^4 \left(L_{\mu 23} L^\mu_{11} + \frac{2}{3} L_{\mu 21} L^\mu_{13} \right) + h.c.$$

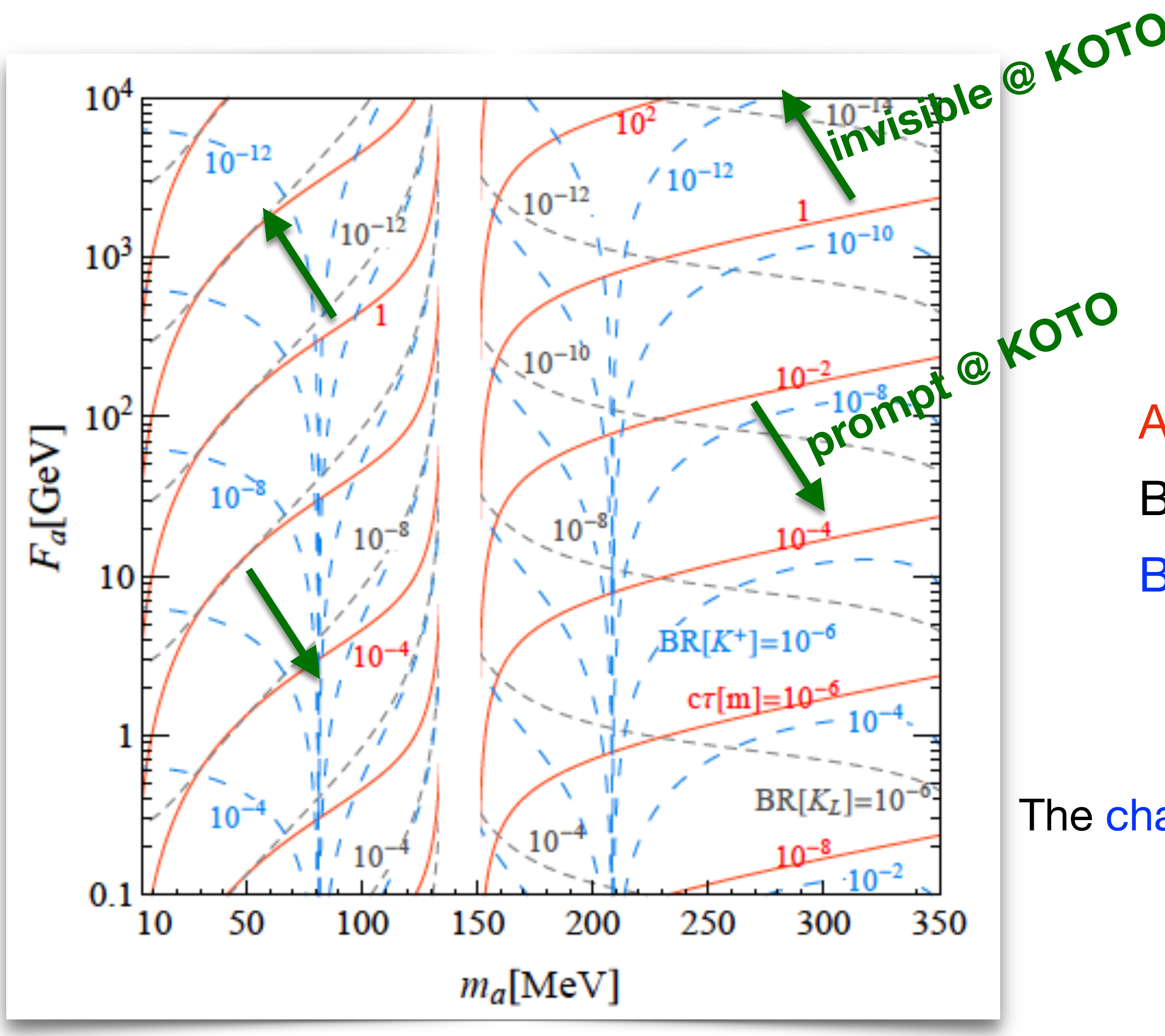
$$\begin{aligned} \pi^0 &\to \pi^0_{\mathrm{phy}} + \theta_{\pi a} a_{\mathrm{phy}} \\ \eta &\to \eta_{\mathrm{phy}} + \theta_{\eta a} a_{\mathrm{phy}} \end{aligned}$$

$$L_\mu \equiv i \Sigma^\dagger D_\mu \Sigma, \quad \lambda_{sd} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$



Note:
possible additional
UV contributions

GG coupled ALP pheno



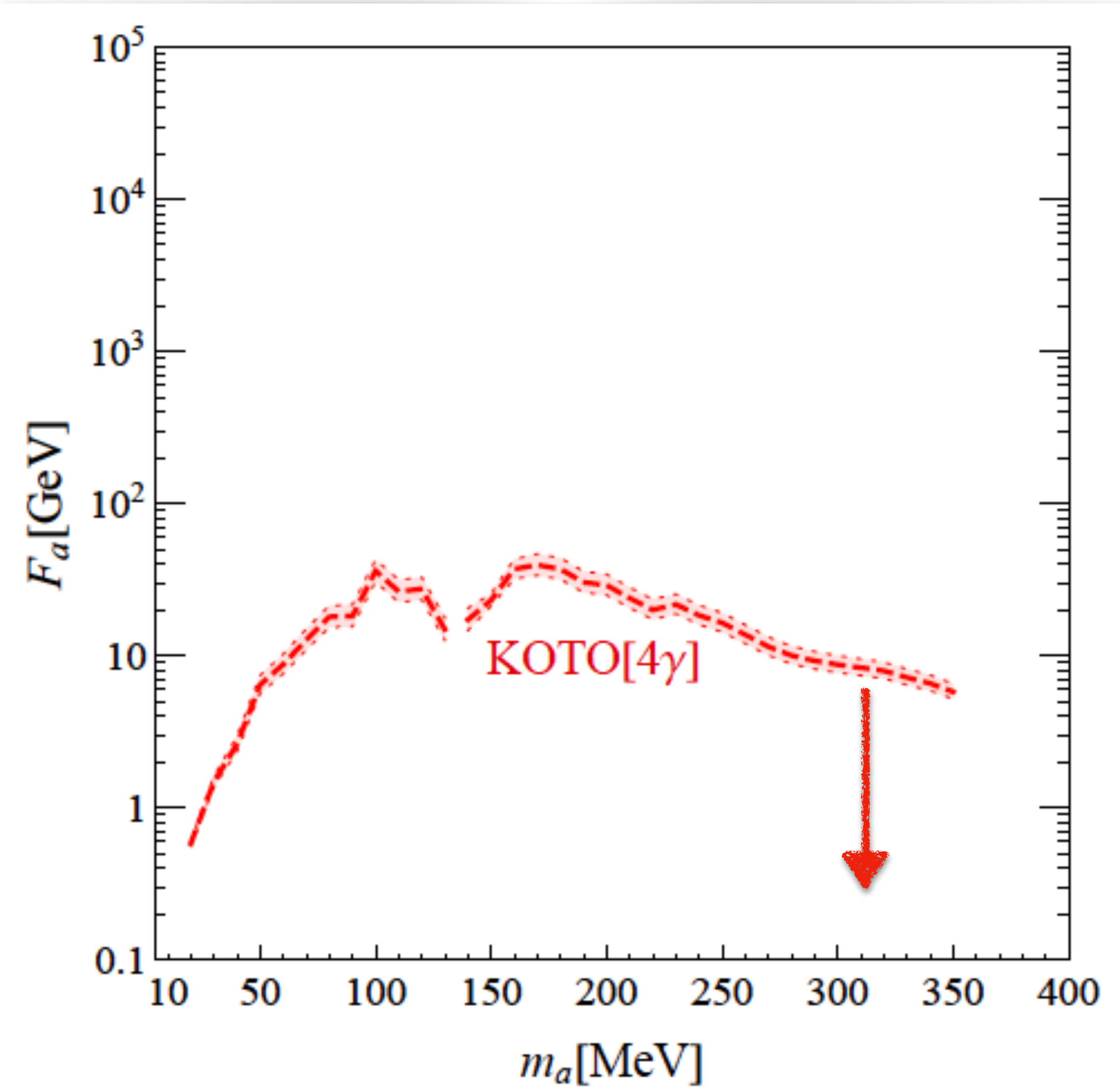
ALP lifetime (in meters)

BR($K_L \rightarrow \pi$ a)

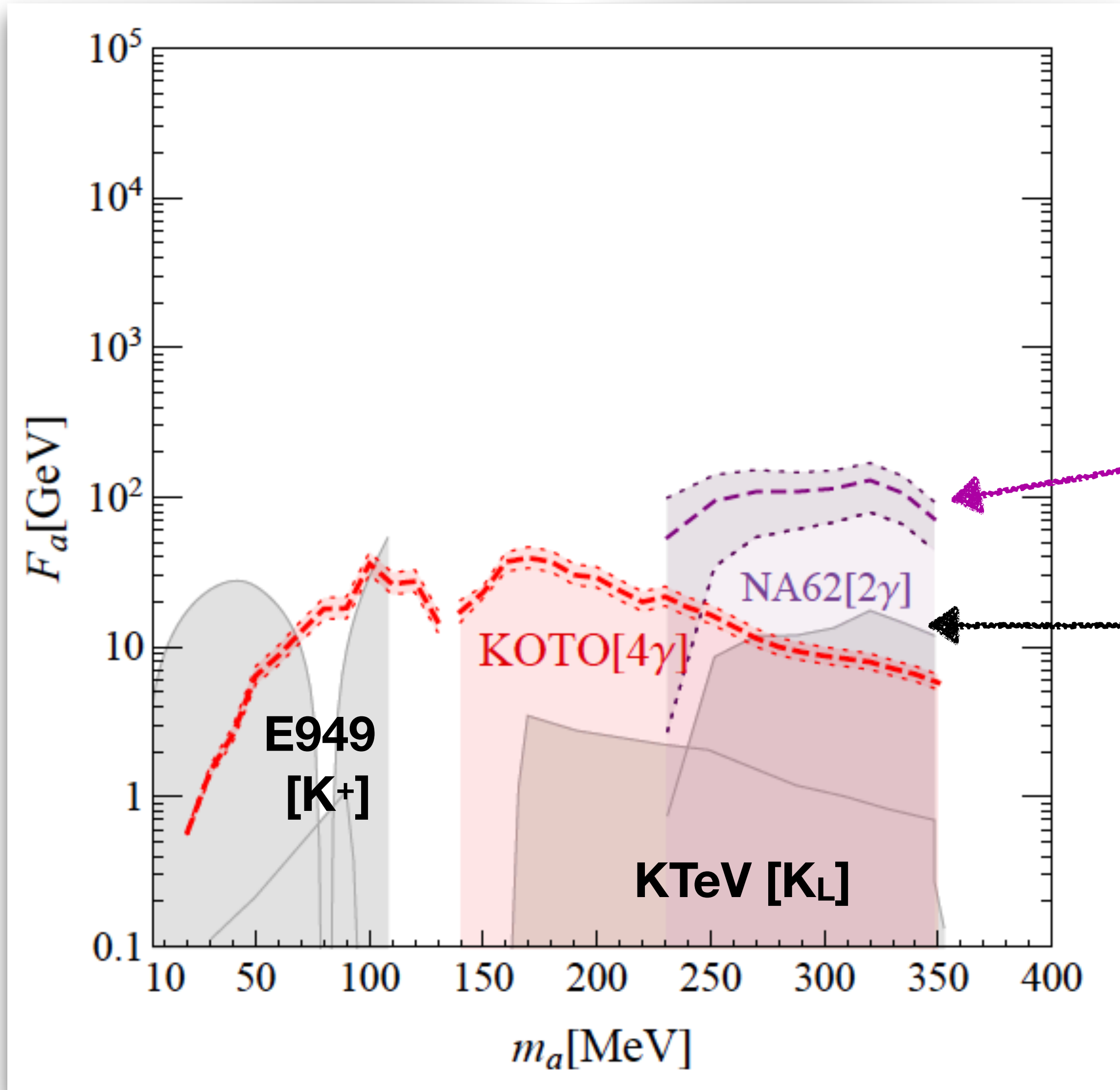
BR($K^+ \rightarrow \pi^+$ a)

The charged BR is typically larger

$aG\tilde{G}$ at KOTO



$aG\tilde{G}$ at KOTO and NA62 (visible)



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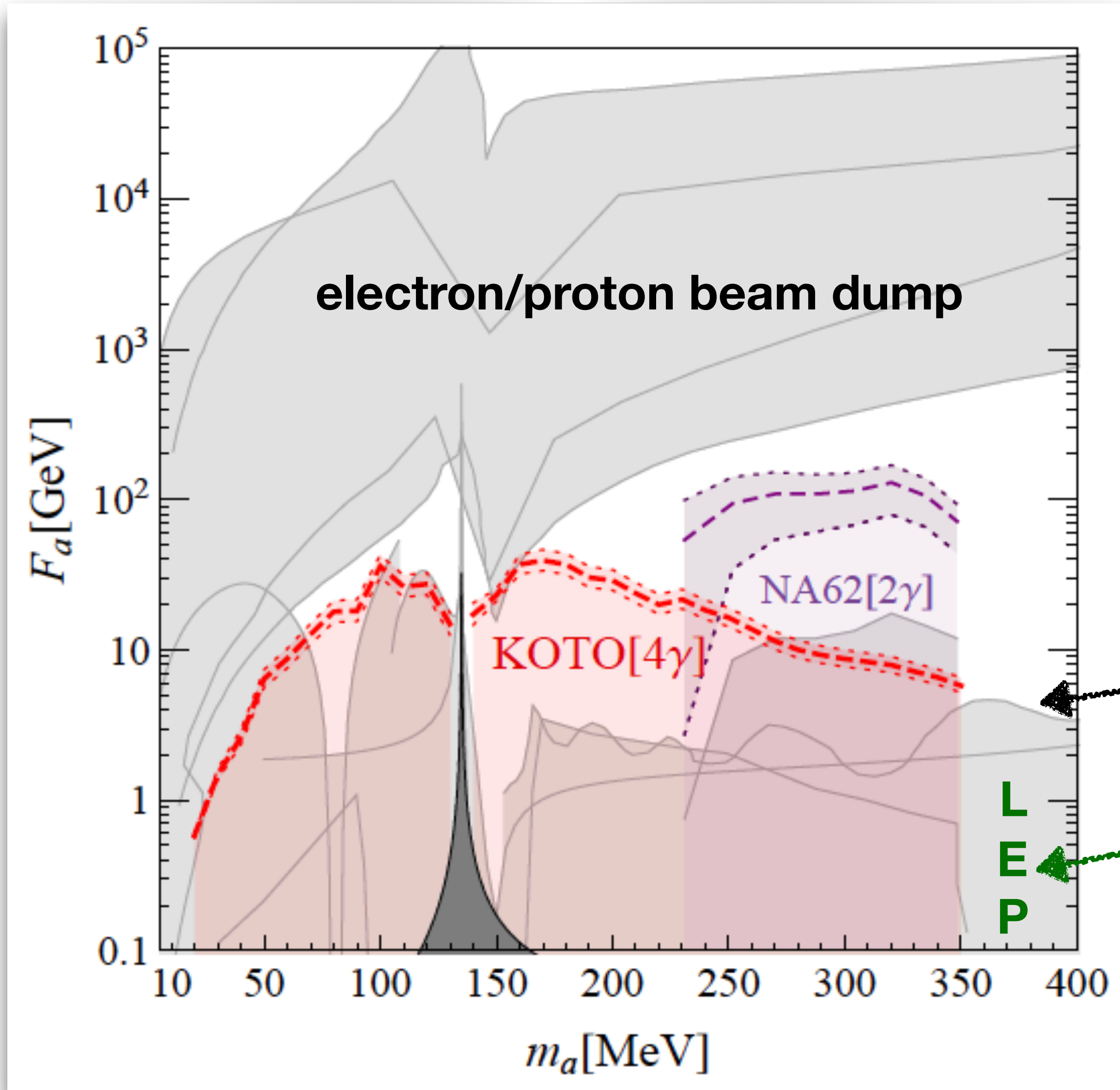
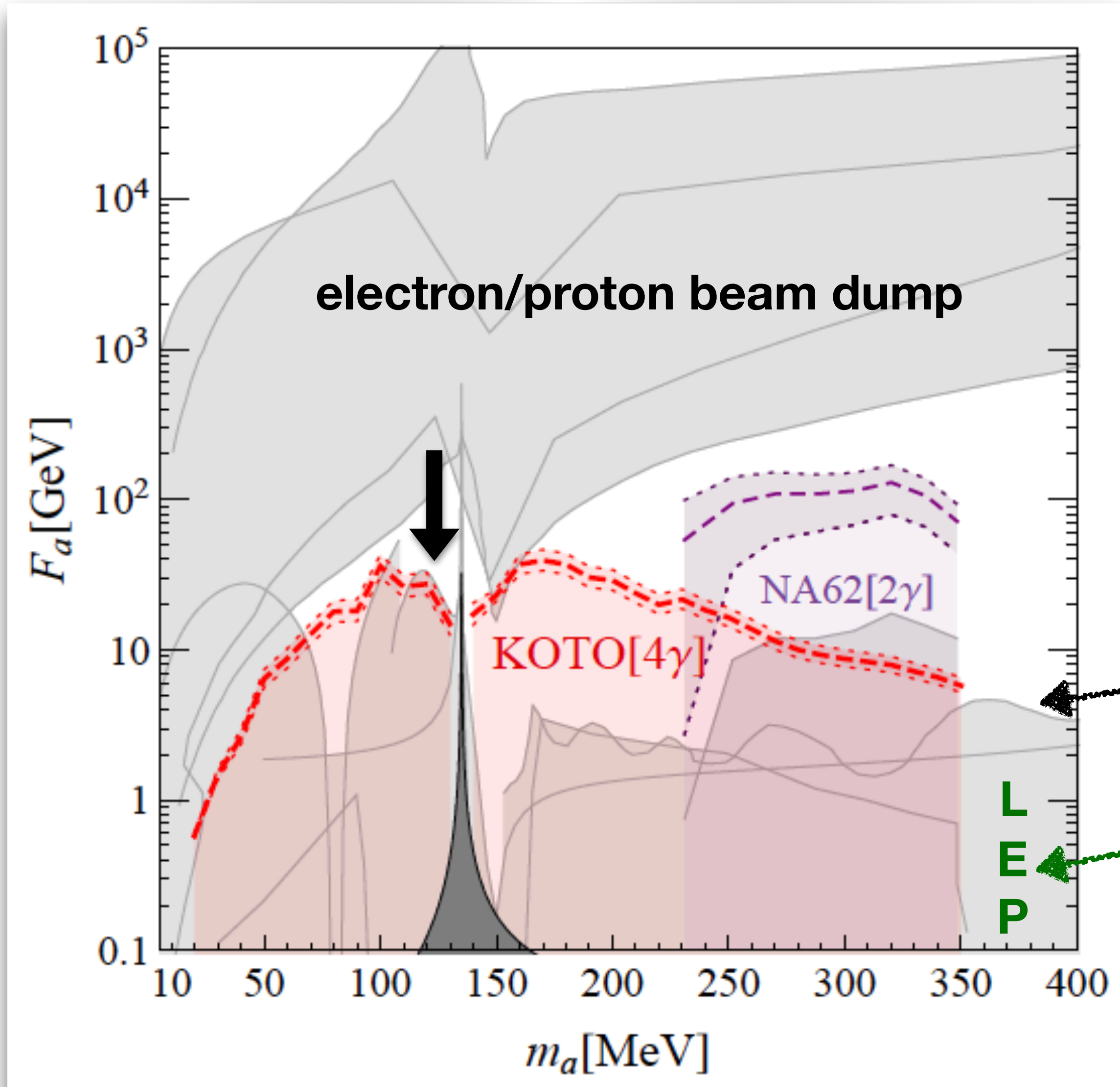


In gray,
we show all present constraints

GlueX,
Aloni et al., 1903.03586

$e^+e^- \to \gamma\, a,\ a \to \gamma\gamma$
(collimated)

Complementarity with other experiments



In gray,
we show all present constraints

This bound comes from precision pion experiments
W. Altmannshofer, SG, D. Robinson, 1909.00005

GlueX,
Aloni et al., 1903.03586

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Precision pion experiments

Several (past and present) small-scale experiments built to measure π^+ rare decays

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Among the most interesting:

$$\boxed{\pi^+ \to e^+ \nu}$$

$$\mathrm{BR} \sim \frac{m_e^2}{m_\mu^2} \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2}$$

Helicity suppressed decay

Most precise measurement:
PIENU experiment @ TRIUMF

$$\mathrm{BR}^{\mathrm{exp}} = (1.234 \pm 0.004) \times 10^{-4}$$

Mainly stat. uncertainty

Theoretical uncertainty
~1 order of magnitude smaller!

$$\boxed{\pi^+ \to \pi^0 e^+ \nu}$$

$$\mathrm{BR} \sim \frac{(m_{\pi^\pm} - m_{\pi^0})^5 \, m_{\pi^\pm}^3}{f_\pi^2 m_\mu^2 (m_{\pi^\pm}^2 - m_\mu^2)^2}$$

Phase space suppressed decay

Most precise measurement:
PIBETA experiment @ PSI

$$\mathrm{BR}^{\mathrm{exp}} = (1.036 \pm 0.006) \times 10^{-8}$$

Comparable stat. and sys. uncertainties

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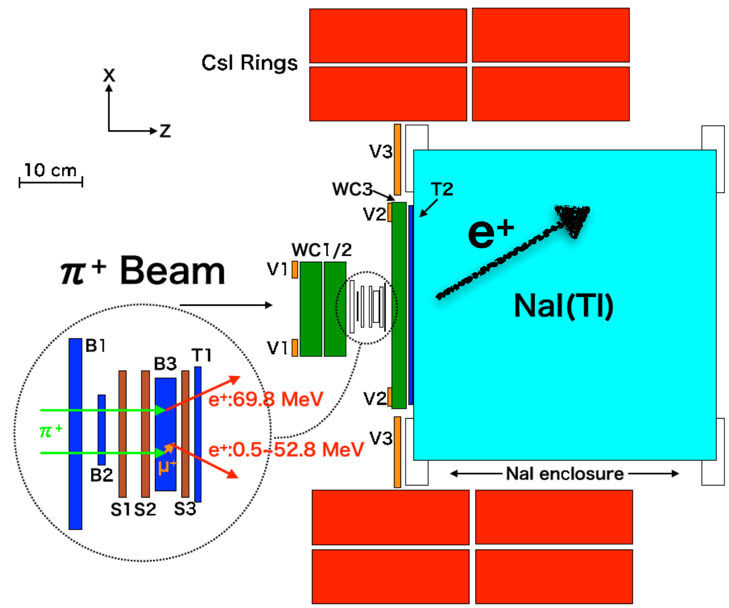
a factor of ~2 smaller

$\pi^+ \to a e^+ \nu$ is not suppressed!

ALPs @ PIENU

The production of the ALP will affect
the energy spectrum measured by the calorimeter

$$\boxed{\pi^+ \to a e^+ \nu}$$



Courtesy of D.Bryman

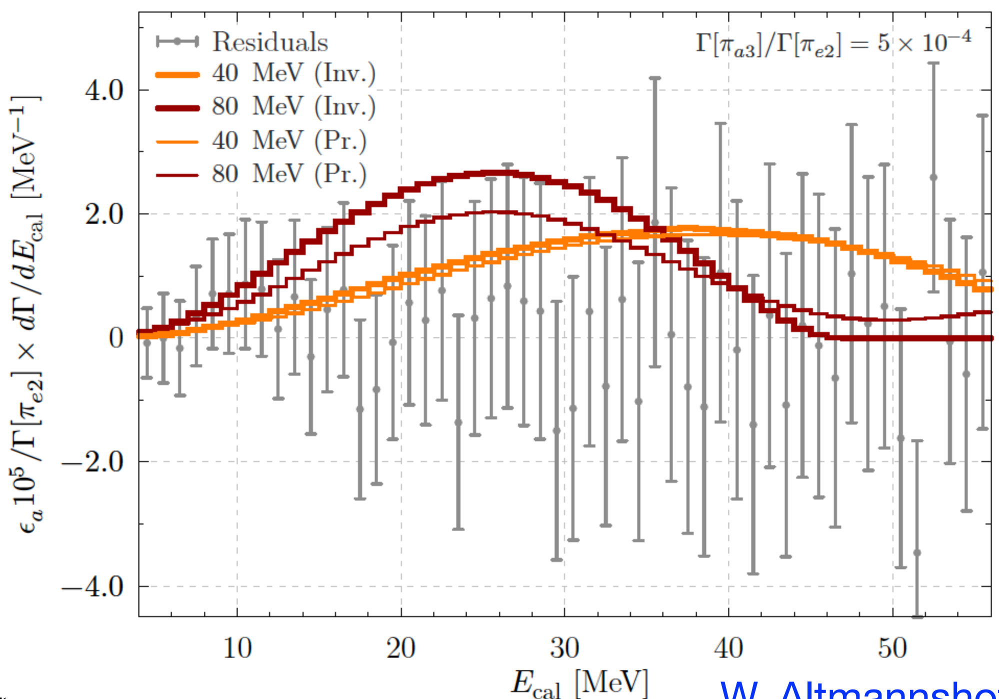
ALPs @ PIENU

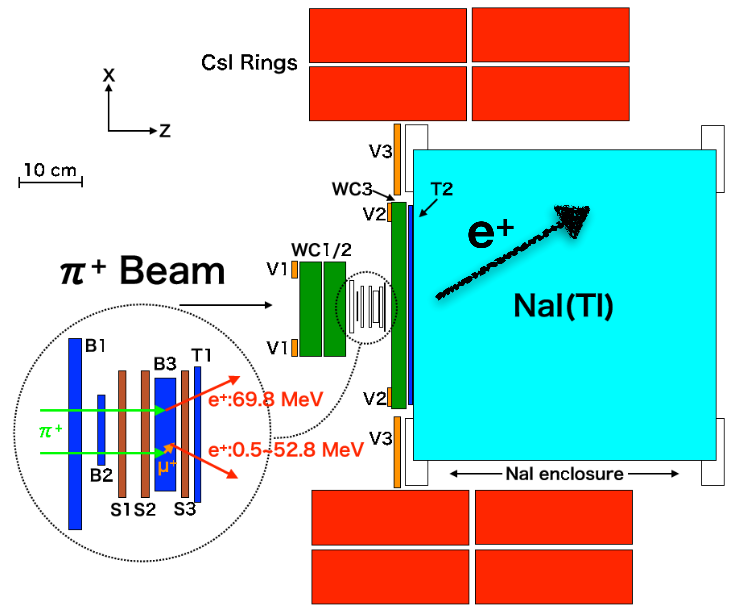
$$\boxed{\pi^+ \to a e^+ \nu}$$

The production of the ALP will affect the energy spectrum measured by the calorimeter

2. Invisible regime: the energy spectrum of the positron depends on the ALP mass.

1. Prompt regime: the energy measured by the calorimeter can get a contribution from the photons produced from the ALP decay (a → γγ).





Courtesy of D.Bryman

W. Altmannshofer, SG, D. Robinson, 1909.00005

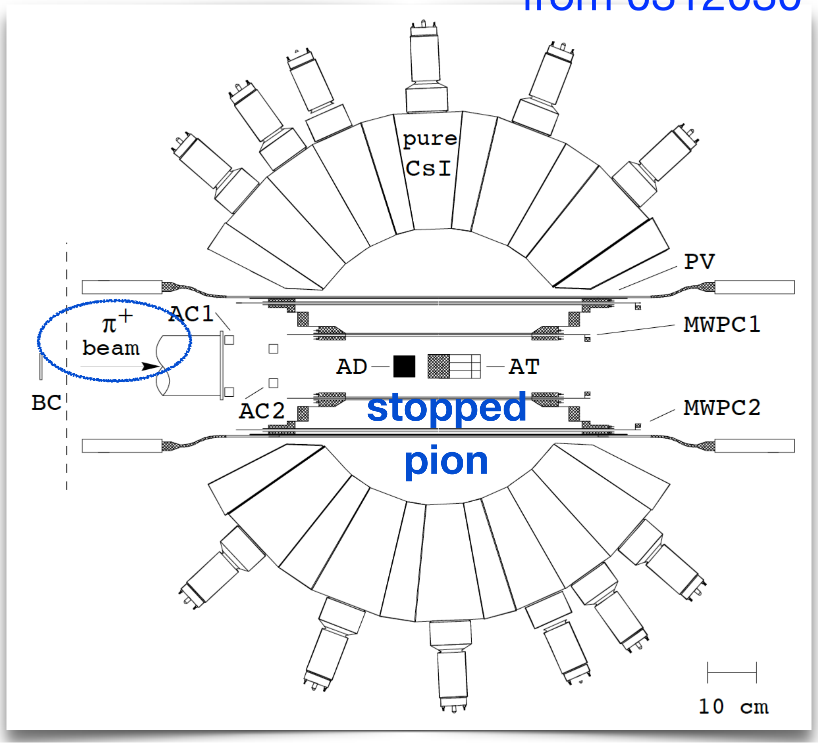
ALPs @ PiBeta

$\boxed{\pi^+ \to \pi^0 e^+ \nu}$ vs. $\boxed{\pi^+ \to a e^+ \nu}$

$\pi^0 \to \gamma\gamma$ will be produced ~ back to back

$a \to \gamma\gamma$ will have a smaller opening angle

from 0312030



$$-1 \le \cos\theta_{\gamma\gamma} \le -1 + 2\left(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\right)^2$$

ALPs @ PiBeta

$\boxed{\pi^+ \to \pi^0 e^+ \nu}$ vs. $\boxed{\pi^+ \to a e^+ \nu}$

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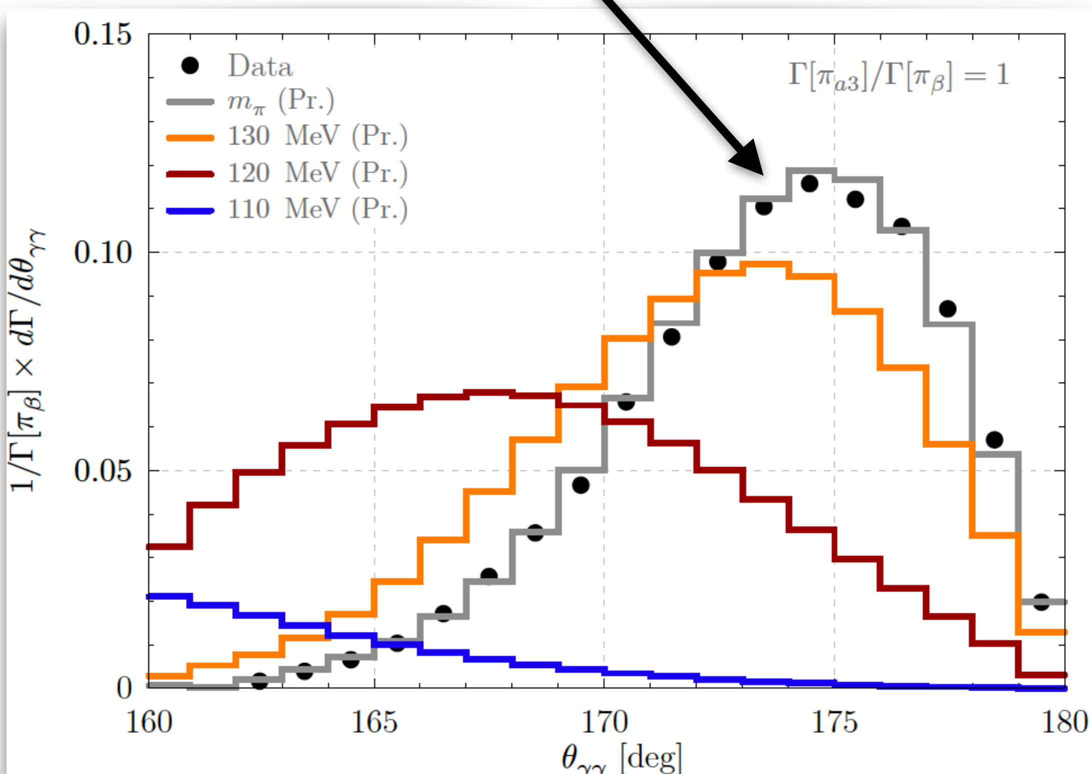

W. Altmannshofer, SG, D. Robinson, 1909.00005

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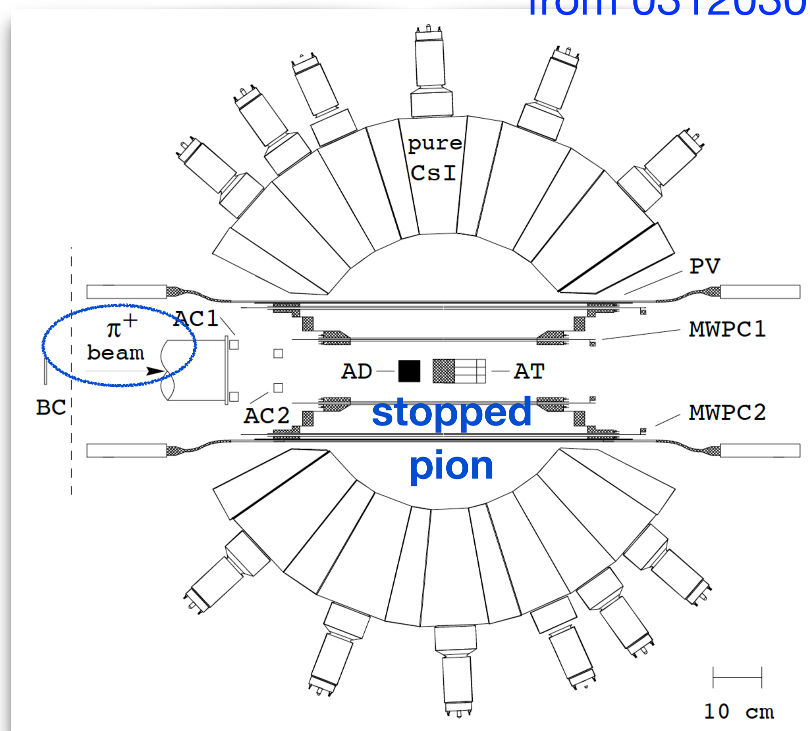
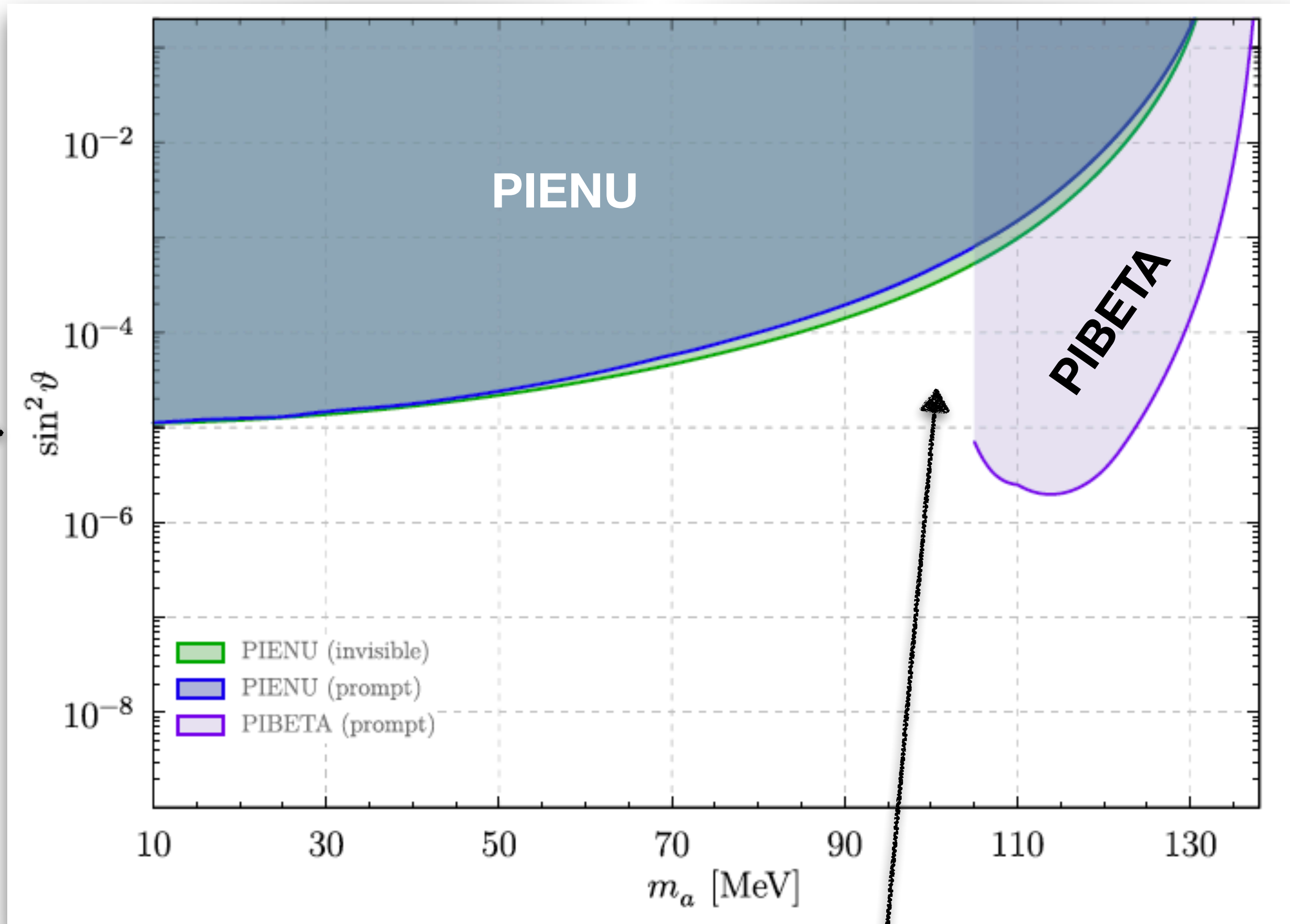


$$-1 \leq \cos\theta_{\gamma\gamma} \leq -1 + 2\left(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\right)^2$$

ALP bounds from PIENU and PiBeta

W. Altmannshofer, SG, D. Robinson, 1909.00005

ALP-pion mixing angle



Possibility to go to lower masses at future experiments (data at smaller angles!)

Conclusions & Outlook

Interesting times for flavor physics:
anomalies + several experiments ramping up

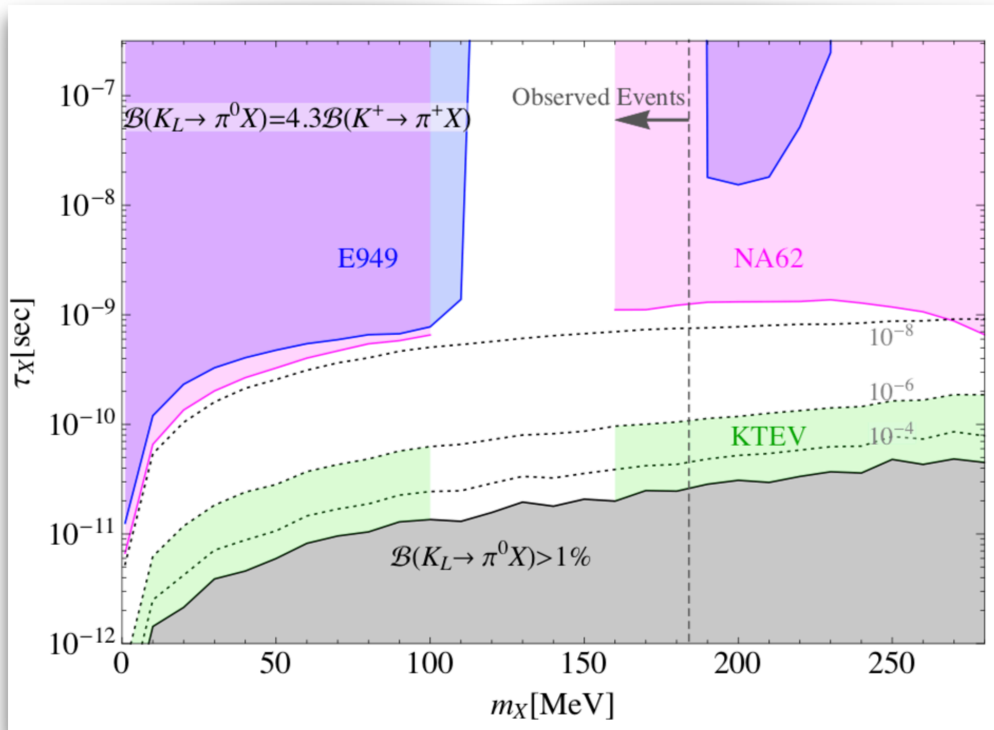
Plenty of opportunities to test dark sectors at these experiments

For this seminar:
testing ALPs Kaon experiments

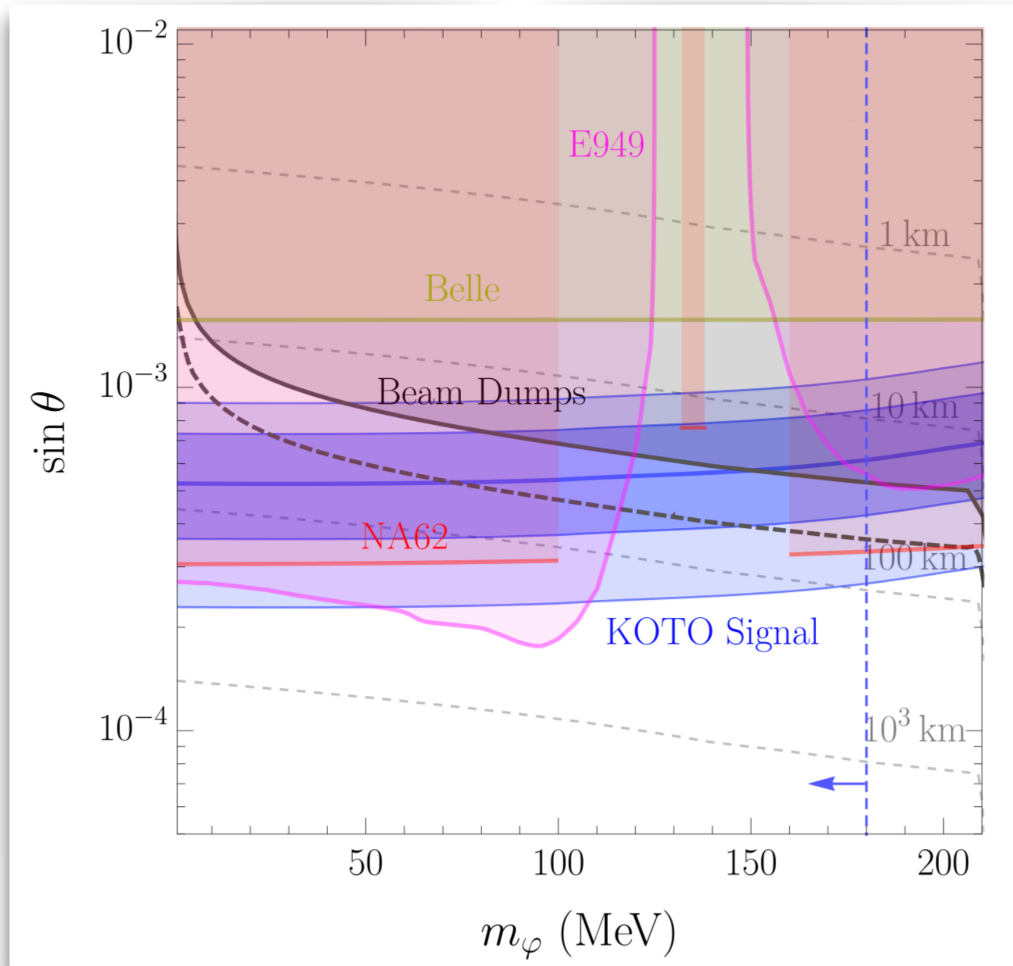
- The KOTO anomaly
- New proposed search ($K \to \pi\, a$, $a \to \gamma\,\gamma$) and its model interpretation
- Complementarity with other experiments (highlight: precision pion experiments)

Models addressing the KOTO anomaly

(light new physics satisfying the GN bound)



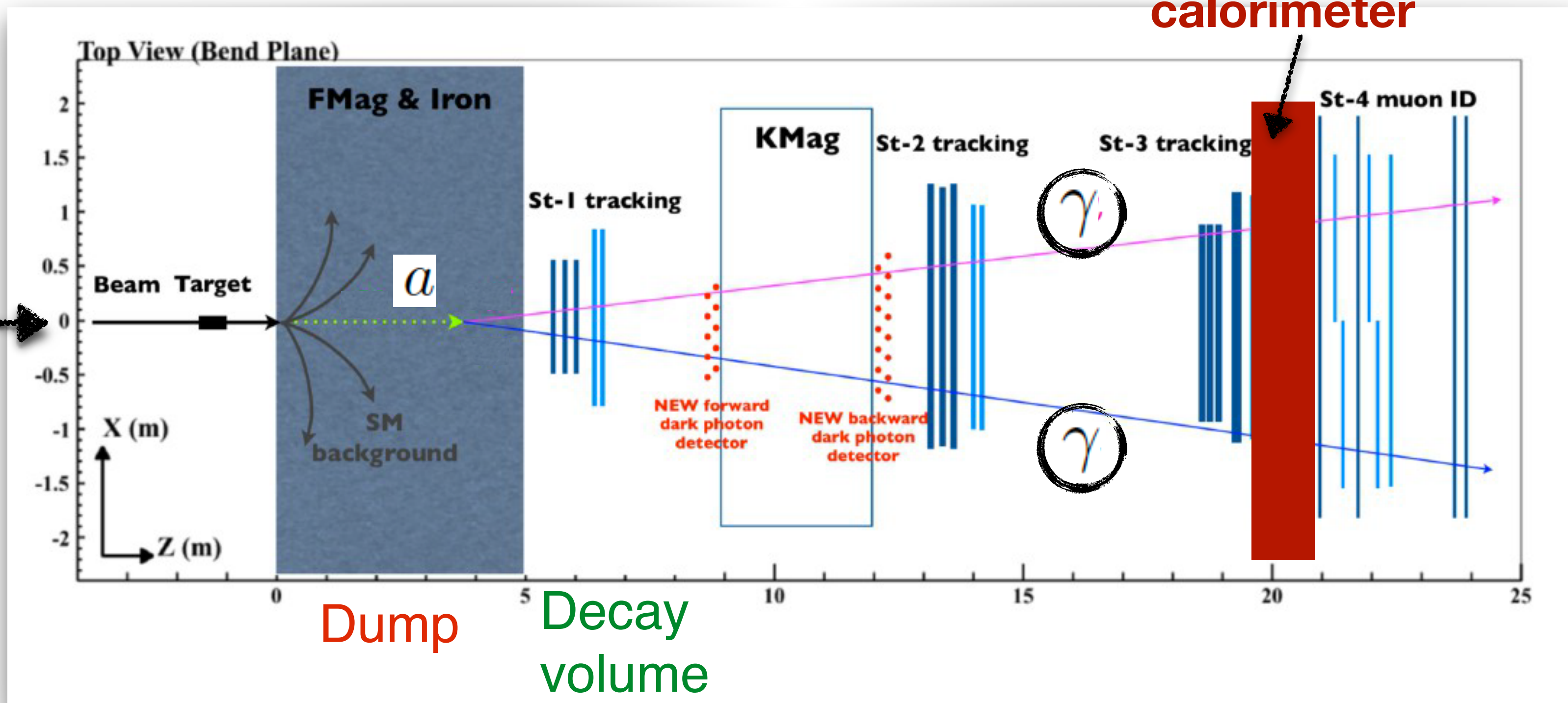
Kitahara et al.,1909.11111



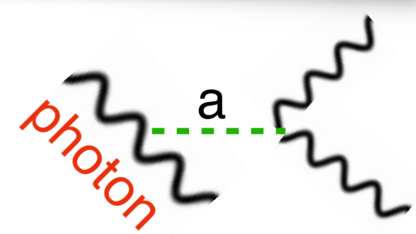
Egana-Ugrinovic et al, 1911. 10203

More new measurements coming up? DarkQuest

Experiment taking place at Fermilab, UPGRADE

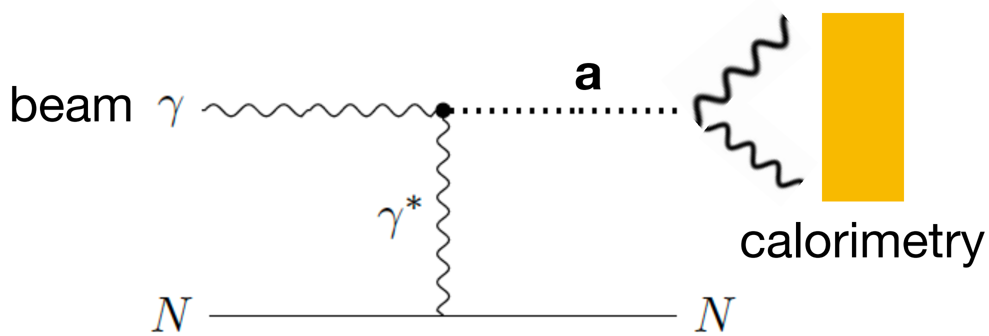


Proposed running after 2022. ~10^{20} protons on target.
Displaced electromagnetic objects (including photons)



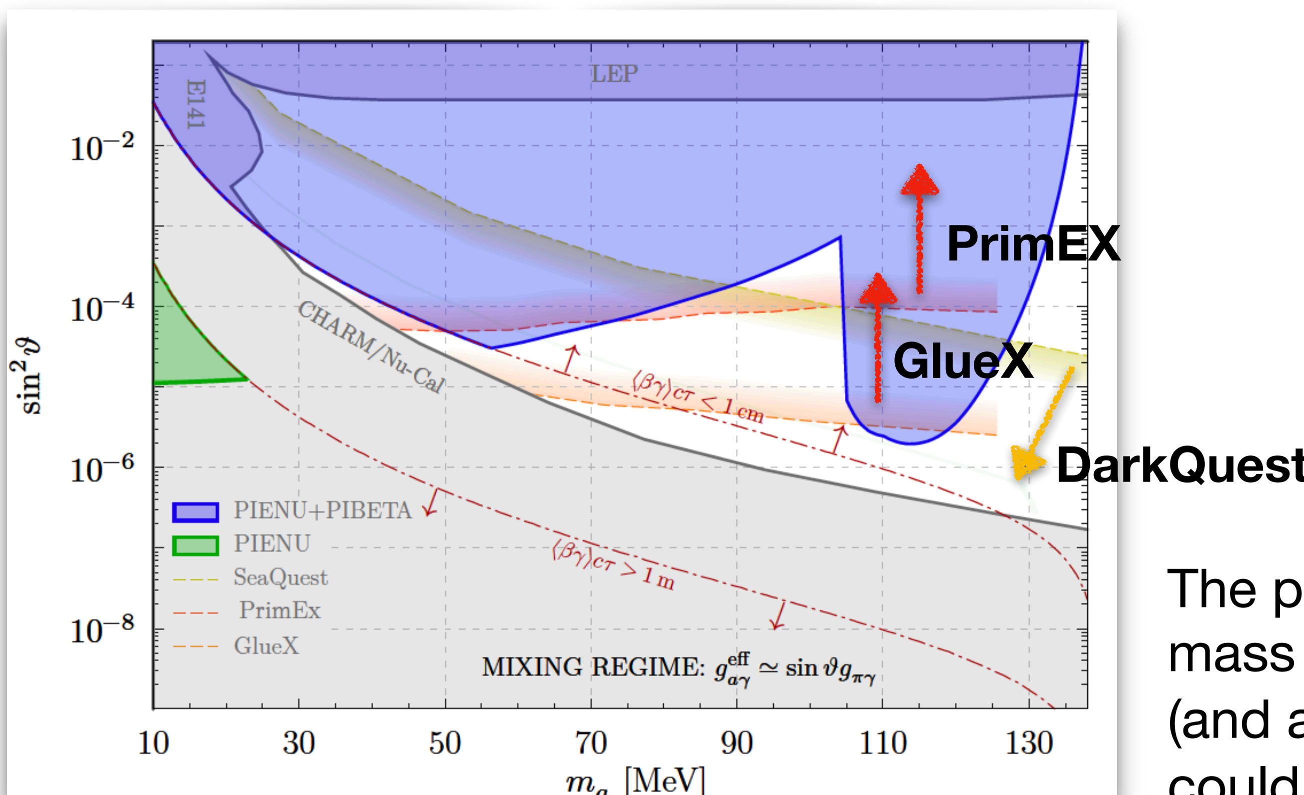
axions radiated from secondary photons produced in the collisions

More new measurements coming up? PrimEX, GlueX



Proposed upgrades for the PrimEX and GlueX experiments at JLAB

$$\gamma N \to aN, \quad a \to \gamma\gamma$$



The parameter space for ALPs with mass below the pion mass (and above a few MeV) could be fully covered!

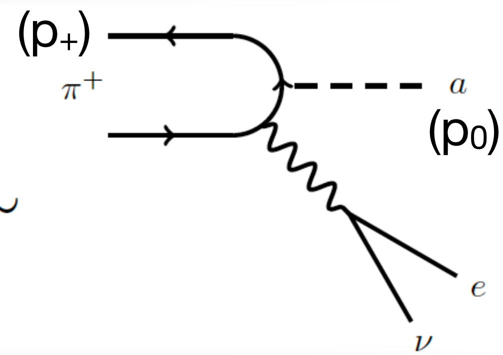
Aloni et al., 1903.03586

Producing ALPs in pion decays

$$\boxed{\pi^+ \to a e^+ \nu}$$

Not helicity suppression, nor phase space suppression!

$$\mathcal{A}[\pi^+ \to a e \nu] \sim$$



$$\begin{aligned} \mathcal{A}^\mu &\simeq \langle a|\pi^{*0}\rangle\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle \\ &\equiv \sin\vartheta\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle \end{aligned}$$

ALP mass

$$\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle = c_\pi\left[f_+(p_+^\mu + p_0^\mu) + (f_0 - f_+)\frac{m_+^2 - m_0^2}{q^2}\underbrace{(p_+^\mu - p_0^\mu)}_{q^\mu}\right]$$

form factors

$f_+(q^2) \simeq 1$ as long as q^2 is small ⇨ m_0>~10 MeV

<u>Theory:</u> better understanding of form factors is needed to probe lighter ALPs!

$$\frac{\mathrm{BR}[\pi^+ \to a e^+ \nu]}{\mathrm{BR}[\pi^+ \to e^+ \nu]} \sim \frac{m_0^4 \sin^2\vartheta}{f_\pi^2 m_\mu^2 (1 - m_e^2/m_+^2)^2} \times \int_1^{\frac{(m_0^2+m_+^2)}{2m_0 m_+}} (w^2-1)^{3/2} dw$$

$$w = \frac{m_+^2 + m_0^2 - q^2}{2m_+ m_0}$$

ALP-pion & ALP-eta mixing

$$\mathcal{L}_{eff} = \frac{iF_\pi^2}{4}\frac{\partial_\mu a}{F_a}\mathrm{Tr}[\tilde{\kappa}_q(\Sigma^\dagger D^\mu \Sigma - \Sigma D^\mu \Sigma^\dagger)] + \frac{F_\pi^2}{2} B_0 \mathrm{Tr}[\Sigma m^\dagger + m^\dagger \Sigma^\dagger]\,,$$

$$\begin{cases} m = \exp\left(i\kappa_q \frac{a}{2F_a}\gamma_5\right)\cdot m_q \cdot \exp\left(i\kappa_q \frac{a}{2F_a}\gamma_5\right) \\ \tilde{\kappa}_q = \mathrm{diag}(\kappa_q), \quad \kappa_q = \frac{1}{m_q} / \sum_{q'}\left(\frac{1}{m_{q'}}\right) \end{cases}$$

$$\Sigma \equiv \exp[2i\Pi/F_\pi], \quad \Pi \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & -2\frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} \end{pmatrix}$$

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_{\eta\eta'} & -\sin\theta_{\eta\eta'} \\ \sin\theta_{\eta\eta'} & \cos\theta_{\eta\eta'} \end{pmatrix}\begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

$\theta_{\eta\eta'} \subset -(10-20)^\circ$

Large uncertainties

this is decoupled

The precision frontier @ flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far;	~40 times more b quarks will be produced by the end of the LHC;
	Belle (running until 2010): ~10^9 BB-pairs were produced.	~50 times more BB-pairs will be produced by **Belle-II**.
Kaon-factories	**E949** at BNL: ~10^{12} K^+ (decay at rest experiment);	**NA62** at CERN: ~10^{13} K^+ by the end of its run (decay in flight experiment);
	E391 at KEK: ~10^{12} K_L	**KOTO** at JPARC: ~10^{14} K_L by the end of its run
Pion-factories	**PIENU experiment** at TRIUMF: ~10^{11} pi^+ (still analyzing data)	?