Probing axion-like-particle effective couplings at Kaon (and other light meson) experiments

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All things EFT seminar
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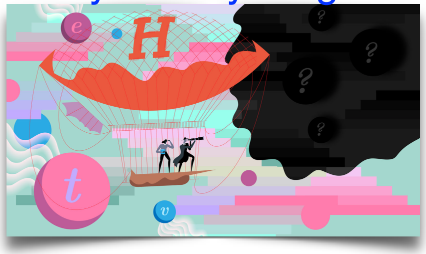
from symmetry magazine



Outline

1. Introduction:

Axion like particles & dimension 5 ALP-SM operators

2. The experimental landscape: light meson experiments

- Pion experiments (Pienu, Pibeta)
- Kaon experiments (NA62, KOTO)
- New proposed search

3. Probing the ALP parameter space at pion & Kaon experiments

- Bound on aWW effective coupling
- Bound on aGG effective coupling

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

Intro

- What particles do we want to test? Axion-like particles (ALPs)
- What effective theory? Dimension 5 ALP-SM couplings

The QCD axion & axion-like-particles (ALPs)

Strong CP problem:
why is the QCD θ parameter so small? $\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$

QCD axion: elegant way to address this problem.
Dynamical solution to achieve: $\bar{\theta} \lesssim 10^{-10}$ in agreement with EDM constraints

The QCD axion mass is set by its decay constant, f_a: $m_a f_a$ = const
The generic expectation is that it couples ~$1/f_a$

<u>At the same time</u>, the QCD axion can be a **DM candidate**!
The axion window:

$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

➡ $10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-2}\,\mathrm{eV}$ (if the confining group is QCD)

$$m_a f_a \sim m_\pi f_\pi$$

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Several proposed models to go beyond the axion window.
Solving the strong CP problem with **heavy axion-like-particles with a smaller decay constant, f_a.**

Additional motivations for massive ALPs

Beyond the strong CP problem…

ALPs are pretty generic new physics particles!
Pseudo Nambu Goldstone boson in models with a spontaneously broken global symmetry

Couplings with the Standard Model (SM) particles determined by the particular UV theory

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Couplings with the Standard Model (SM) particles determined by the particular UV theory

- Models to address the gauge hierarchy problem (relaxion)
- SUSY extended models (NMSSM with an approximate PQ symmetry)
- Generic feature of string compactification
- Models addressing anomalies in data
  ($(g-2)_\mu$, galactic center excess for Dark Matter, …)
- General (low dimensional) portal to the dark sector

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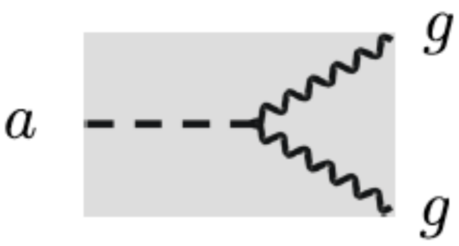
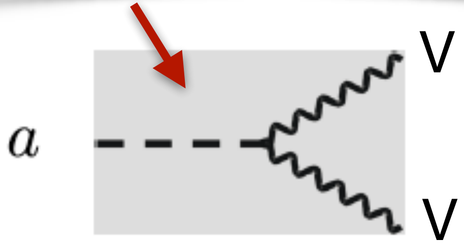
How to discover these particles in our laboratories?

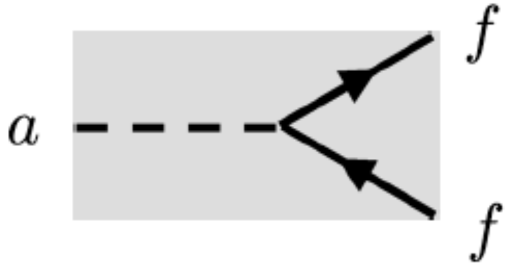
Effective ALP couplings to the SM

Strong case for looking everywhere for a EFT of a spin 0 CP-odd particle. At **dimension 5**:

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \underbrace{- \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu}} + i g_{af} (\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$







Effective ALP couplings to the SM

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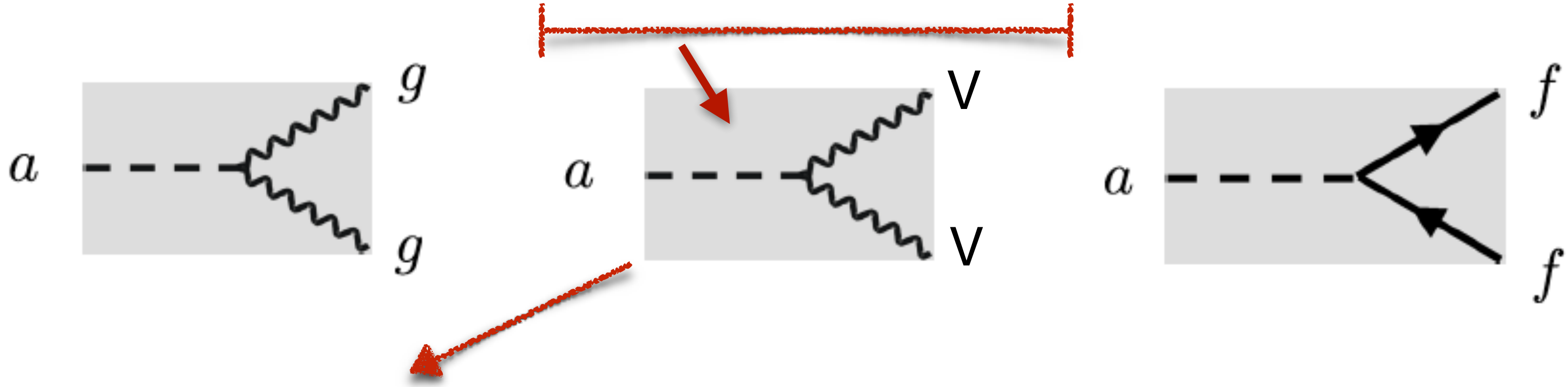

In particular, a ALP-photon coupling is generated in the broken phase

$$g_{aB}\cos^2\theta + g_{aW}\sin^2\theta$$

This is the **main coupling that has been considered** for phenomenological studies.

From a phenomenological perspective, the a-ZZ, a-Zgamma, a-WW, and a-gg couplings have been largely disregarded up to very recently

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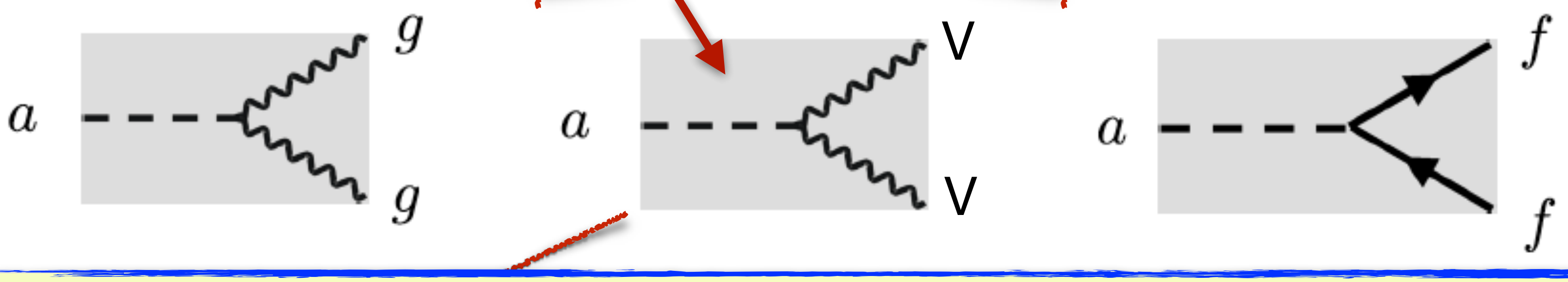


Generically, we expect $g_{ag} \sim g_{aW} \sim g_{aB} \sim g_{af} \sim O(1/f_a)$

However, **it is important to study all these dim 5 operators separately**. What's the scale that can be probed at present and future experiments?

Focus of this talk: g_{aW} and g_{ag}

From a phenomenological perspective, the a-ZZ, a-Zgamma, a-WW, and a-gg couplings have been largely disregarded up to very recently

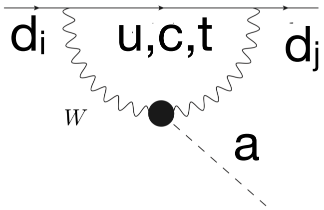
The WW and GG effective couplings

Effective coupling:

$$\frac{g_{aW}}{4}\, a\, W^{a}_{\mu\nu} \tilde{W}^{a\mu\nu} \qquad \frac{g_{ag}}{4}\, a\, G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

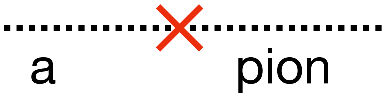
Main phenomenological consequences:

- Coupling with SM EW gauge bosons
- Loop-induced couplings to SM fermions (including flavor violating)



- Coupling with SM gluons
- Mixing with SM mesons

e.g.



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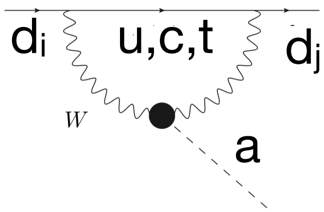

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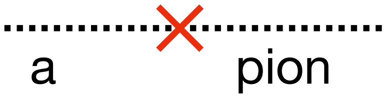

Note on the ALP-pion mixing:

ALPs generically mix with the SM pions.
The mixing is generated by several operators:

$$\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \hookrightarrow \sin\theta_{a\pi} \simeq \frac{m_a^2}{m_\pi^2 - m_a^2} \frac{f_\pi}{f_a}$$

$$i g_{af} (\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f) \hookrightarrow \sin\theta_{a\pi} \simeq \frac{f_\pi^2}{m_\pi^2 - m_a^2} \frac{v}{f_a}$$

Some measurements are more easily interpreted in terms of a bound on the mixing angle. Then one can re-interpret this bound as a bound on the several operators.

ALP EFTs at light meson experiments

Pion experiments

Production of the ALP:

Depends directly on
the ALP-pion mixing angle:

$$|a^{\text{phys}}\rangle = (\cos\vartheta + \ldots)|a_0\rangle + \sin\vartheta\,|\pi^0\rangle$$

$$\begin{tikzcd} \pi^+ \to \pi^0 e^+ \nu \quad \text{(SM)} \arrow[d, bend right] \\ \pi^+ \to a e^+ \nu \quad \text{(ALP)} \end{tikzcd}$$

Decay of the ALP:

More model dependent

a →γγ, a →e^+e^-, a →invisible, …

ALP EFTs at light meson experiments

Pion experiments

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$$\pi^+ \to \pi^0 e^+ \nu \quad \text{(SM)}$$

$$\pi^+ \to a e^+ \nu \quad \text{(ALP)}$$

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Kaon experiments

Production of the ALP:

Different production mechanisms depending on the ALP-EFT

K→ π a

Penguin diagram

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

Mixing effect

$$\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Decay of the ALP:

Model dependent

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Experimental landscape

- Pion experiments: Pienu ($\pi^+ \to e^+ \nu$), Pibeta ($\pi^+ \to \pi^0 e^+ \nu$)
- Kaon experiments: NA62 ($K^+ \to \pi^+ \nu \nu$), KOTO ($K_L \to \pi^0 \nu \nu$)

Proposed new search: $K_L \to \pi^0 \gamma \gamma$

Precision pion experiments

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

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Among the most interesting:

u→de+v

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

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

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!

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

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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$$\pi^+ \to a e^+ \nu$$

a → **invisible**

$$\pi^+ \to a e^+ \nu$$

$a \to \gamma\gamma$

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s→dνν

$$\boxed{K^+ \to \pi^+ \nu \bar{\nu}}$$

NA62 @ CERN:

$$\mathrm{BR}_{\mathrm{exp}} = (11.0^{+4.0}_{-3.5} \pm 0.3) \times 10^{-11}$$

stat.

17 events observed

(expected: 5.3 background events
+ 7.6 SM signal events)

(combination of the 2016, 2017, 2018 runs)

3.5σ evidence

Loop and GIM suppressed decays

$$\mathrm{BR}_{\mathrm{SM}} = (9.11 \pm 0.72) \times 10^{-11}$$

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$$\boxed{K_L \to \pi^0 \nu \bar{\nu}}$$

KOTO @ J-PARC:

$$\mathrm{BR}^{\mathrm{naive}}_{\mathrm{exp}} = (1.4 \pm 1.0) \times 10^{-9}$$

3 events observed
(expected: 1.05±0.28 background events)

$$\mathrm{BR}_{\mathrm{SM}} \ = \ (3.4 \pm 0.6) \times 10^{-11}$$

Loop and GIM suppressed decays

The two decay modes are related by the so-called Grossman-Nir bound:

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

Precision Kaon experiments

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$K^+ \to \pi^+ a$ **→ invisible**

$K_L \to \pi^0 a$ **→ invisible**

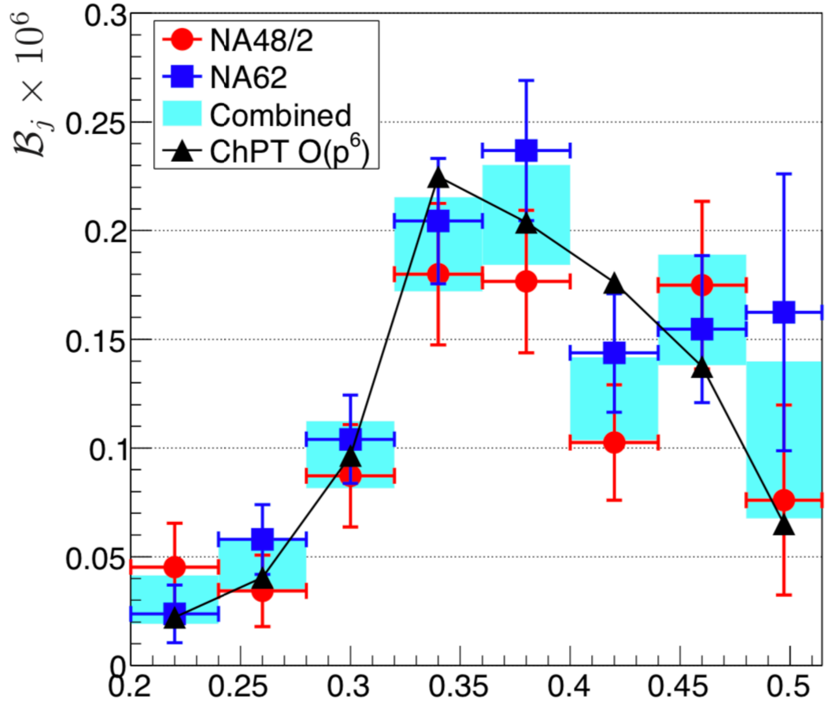
What about a →γγ?

K → π γ γ (charged mode)

K⁺ → π⁺ γ γ has been searched for at past experiments:

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

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



NA62 did not perform the search (yet).

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

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

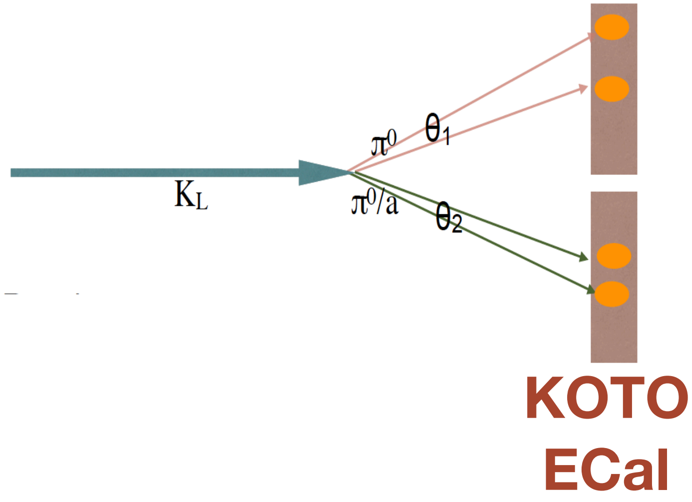
~10^9 K⁺ in the fiducial region

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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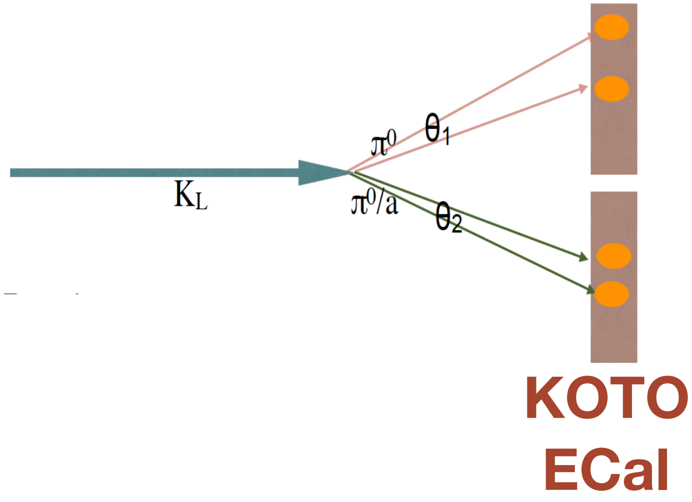
Main ingredients :

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%)

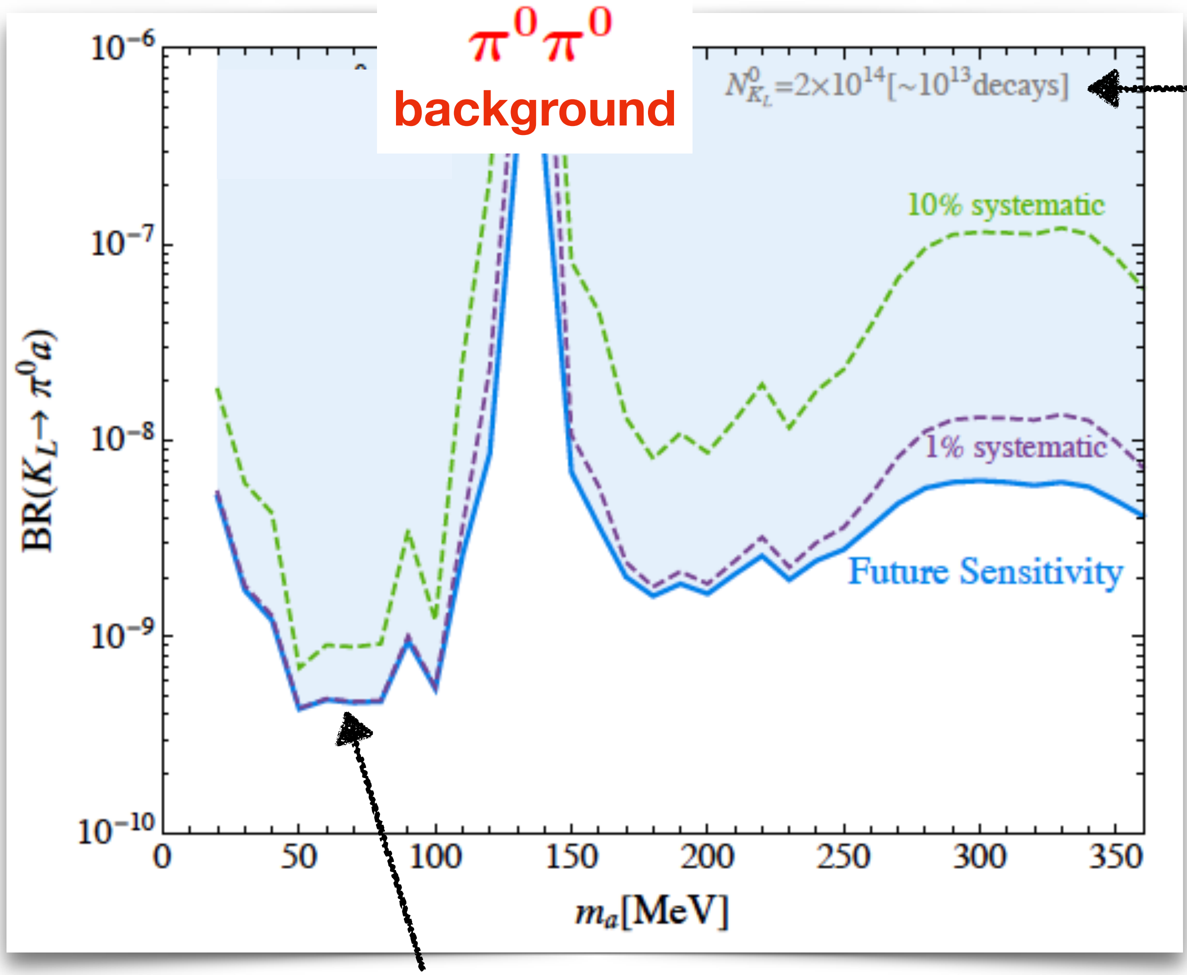
We simulate the main sources of background:

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

mainly for $m_a \sim m_{pion}$

The KOTO reach

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



$\pi^0\pi^0$
background

Ultimate KOTO luminosity goal

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

SG, Perez, Tobioka, 2005.05170

S.Gori

1. $\frac{g_{aW}}{4}\, a\, W^{a}_{\mu\nu}\tilde{W}^{a\mu\nu}$

2. $\frac{g_{ag}}{4}\, a\, G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu}$

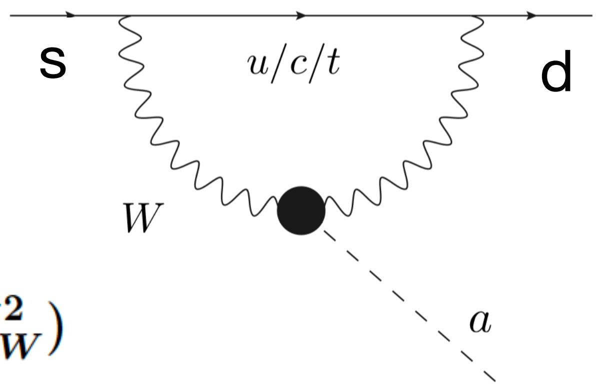
Bounds on the ALP EFT

- Recasting pion & Kaon past measurements to set bounds on the ALP-SM effective couplings
- What are the future prospects? What scale can be probed?

1.

ALP-WW effective coupling

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



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

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

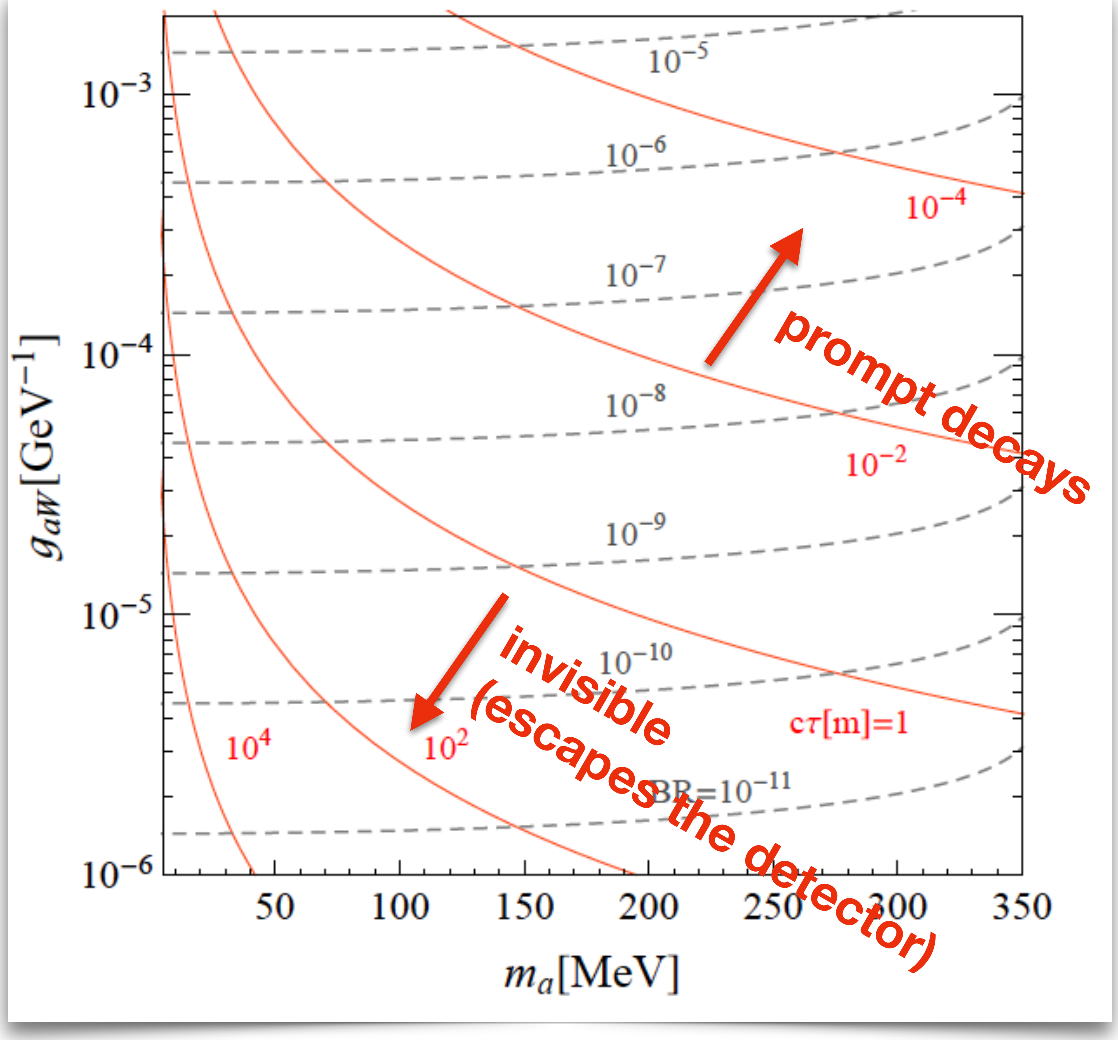
This coupling will induce the decay of the ALP into two photons:

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

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



prompt decays

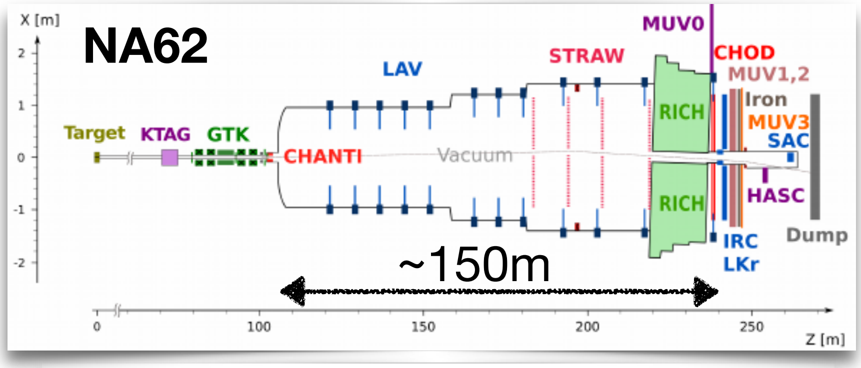
invisible (escapes the detector)

SG, Perez, Tobioka, 2005.05170

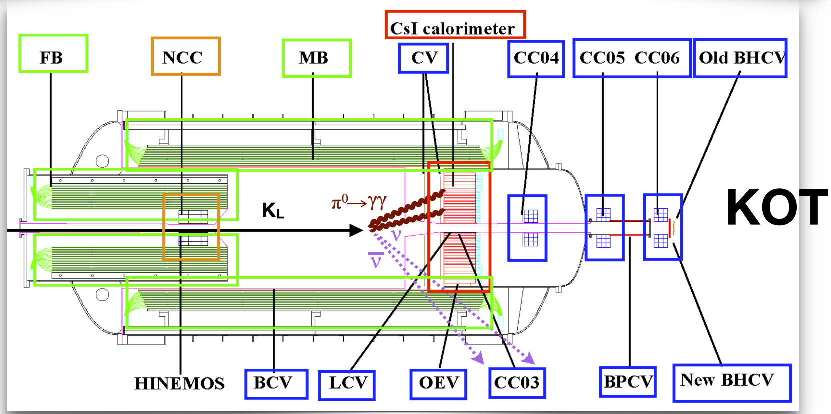
ALP lifetime (in meters)

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

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



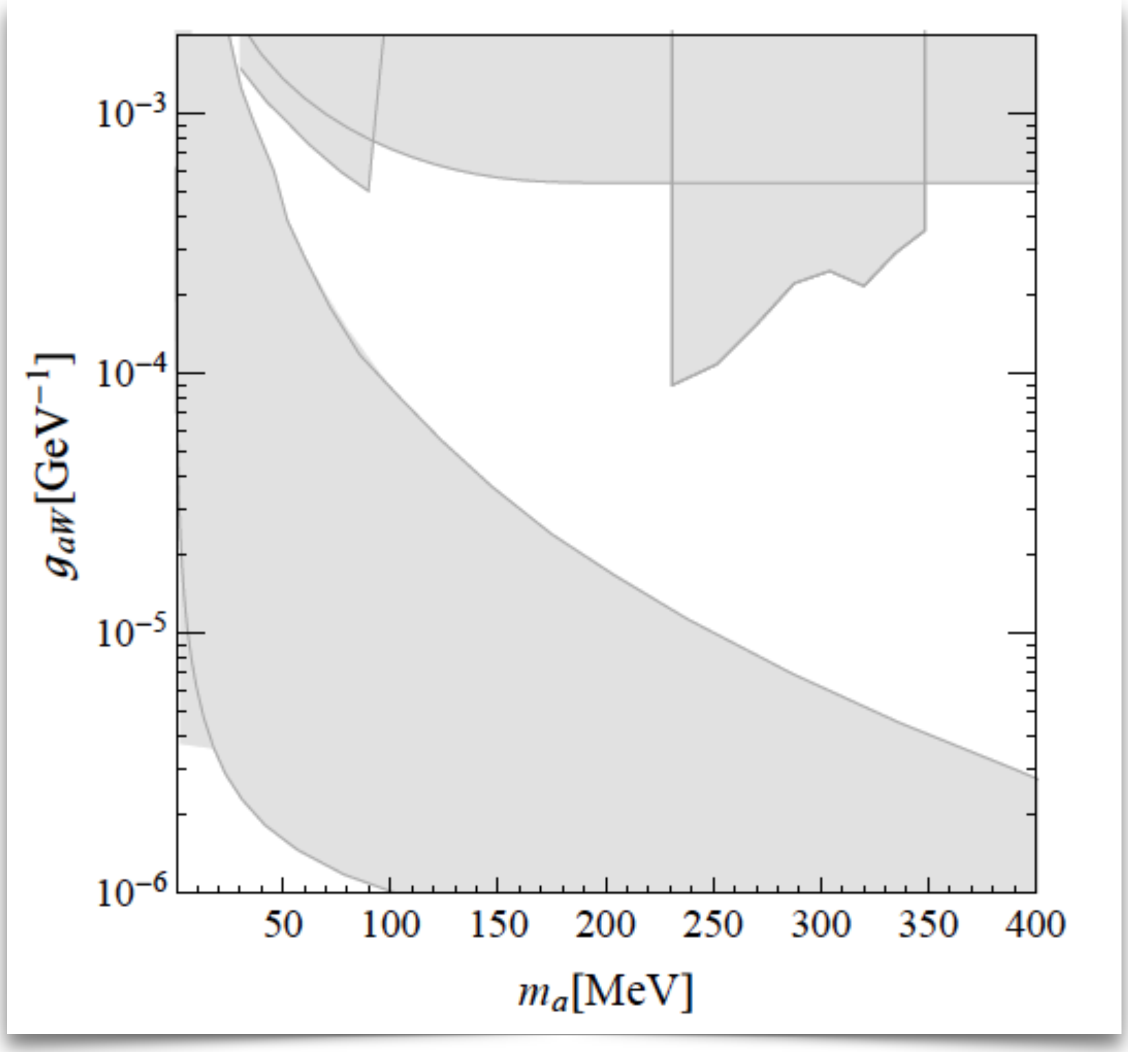
~150m



KOTO

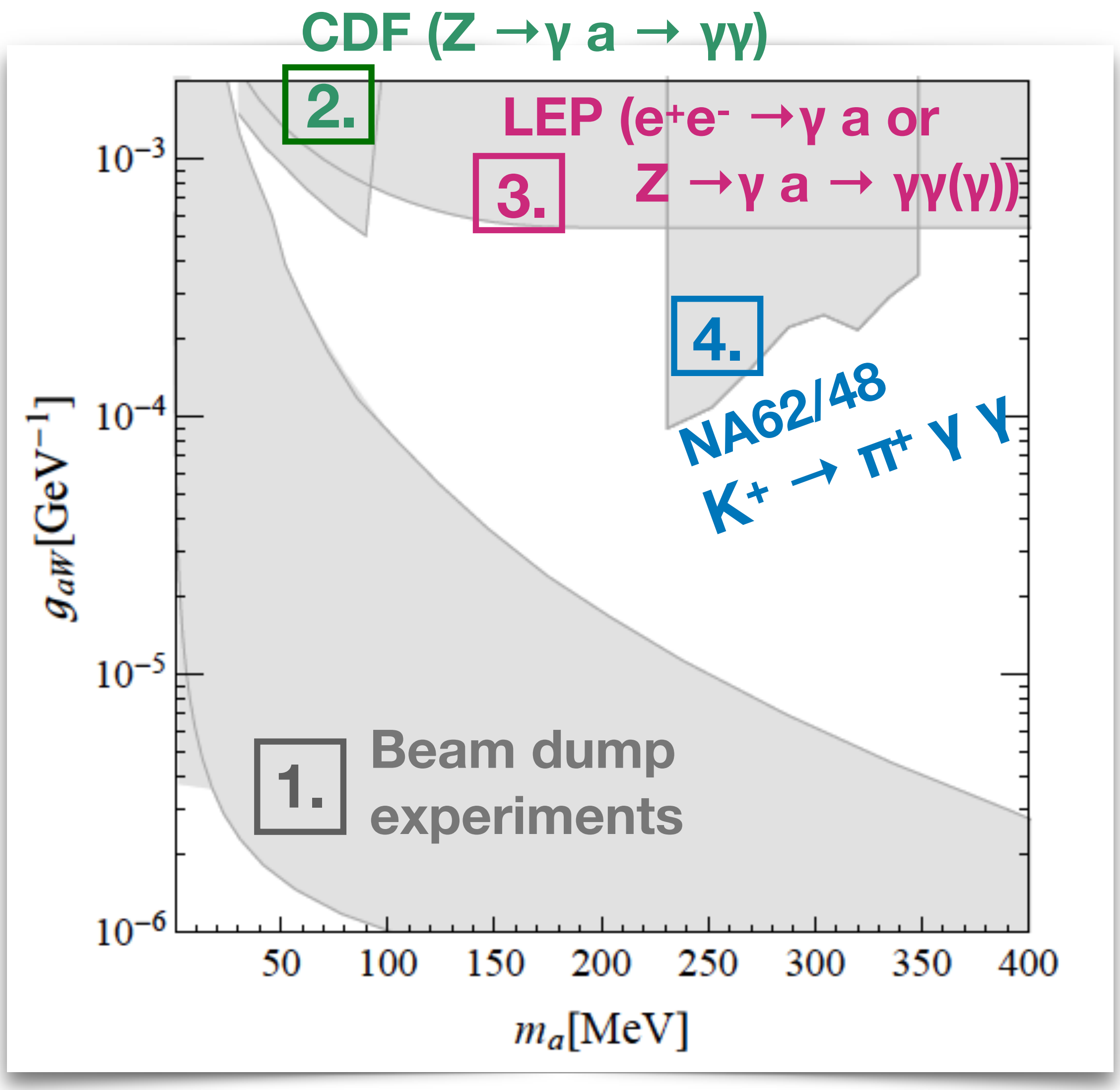
~3m

$aW\tilde{W}$ at past experiments



SG, Perez, Tobioka, 2005.05170

$aW\tilde{W}$ at past experiments

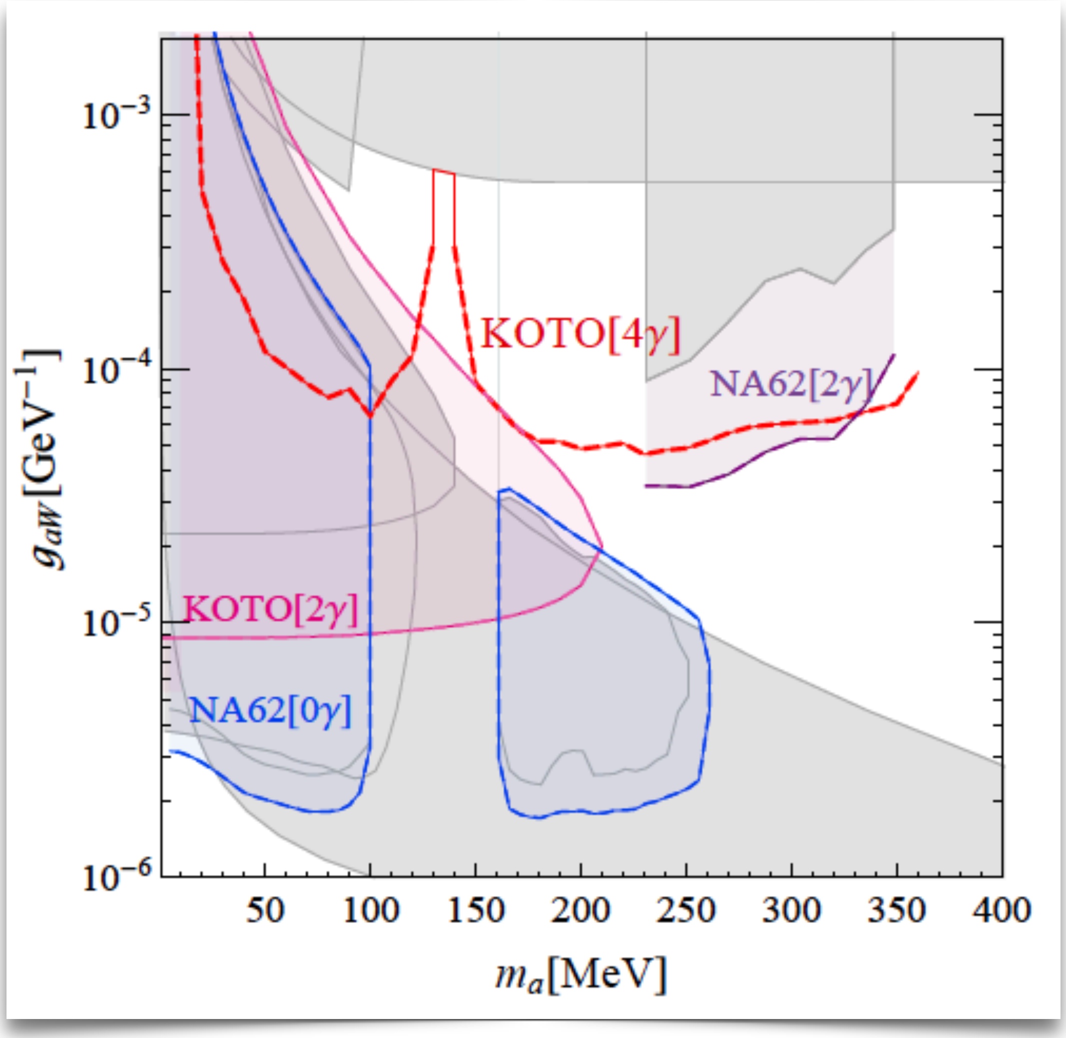


SG, Perez, Tobioka, 2005.05170

$aW\tilde{W}$ prospects @ KOTO and NA62

KOTO[2γ]:
$K_L \to \pi^0 a$,
$a \to$ inv.
(re-interpretation)

NA62[0γ]:
$K^+ \to \pi^+ a$,
$a \to$ inv.
(re-interpretation)



SG, Perez, Tobioka, 2005.05170

KOTO[4γ]:
$K_L \to \pi^0 a$,
$a \to \gamma\gamma$.
(proposed search)

NA62[2γ]:
$K^+ \to \pi^+ a$,
$a \to \gamma\gamma$.
(re-scaling of NA62/48)

2.

ALP-GG effective coupling

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

We can match onto the chiral Lagrangian

ALP interactions with SM mesons:

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

Kinetic mixing

Mass mixing

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

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

SM (light) mesons

2.

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$$\theta_{\pi a} \simeq \frac{F_\pi}{2F_a}(\kappa_u - \kappa_d)\frac{m_a^2}{m_a^2 - m_{\pi^0}^2}$$

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

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

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

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

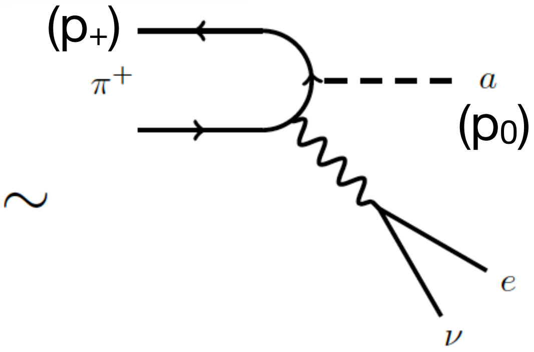
2a.

Pion-ALP mixing & pion decays

$$\boxed{\pi^+ \to \pi^0 e^+ \nu} \xrightarrow{\text{mix}} \boxed{\pi^+ \to a e^+ \nu}$$

Not helicity suppression, nor phase space suppression!

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

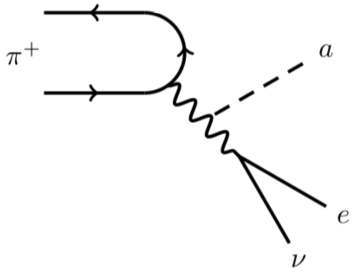


$$\begin{aligned} \mathcal{A}^\mu &\simeq \langle a|\pi^{*0}\rangle\langle\pi^{*0}|\bar d\gamma^\mu u|\pi^+\rangle \\ &\equiv \sin\vartheta\langle\pi^{*0}|\bar d\gamma^\mu u|\pi^+\rangle \end{aligned}$$

π-a mixing angle

Other contributions are generically suppressed:

$$\sum_{M^+}\langle 0|\bar d\gamma^\mu u|M^+\rangle\langle M^+ a|\bar q \not{p}_a \gamma^5 q|\pi^+\rangle \quad \sim m_a^2/m_\rho^2$$



electroweak suppressed

W. Altmannshofer, SG, D. Robinson, 1909.00005

2a.

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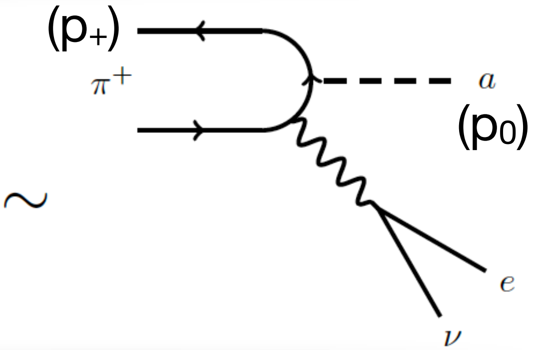


$$\begin{aligned} \mathcal{A}^\mu &\simeq \langle a | \pi^{*0} \rangle \langle \pi^{*0} | \bar{d} \gamma^\mu u | \pi^+ \rangle \\ &\equiv \sin\vartheta \langle \pi^{*0} | \bar{d} \gamma^\mu u | \pi^+ \rangle \end{aligned}$$

π-a mixing angle

ALP mass

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

form factors

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

Theory: better understanding of form factors is needed to probe lighter ALPs!

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

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

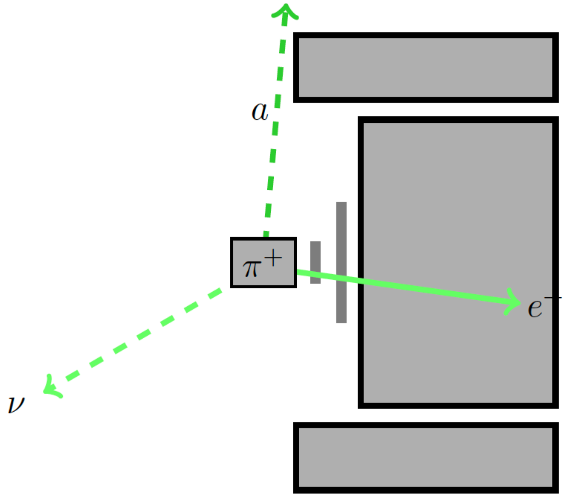
W. Altmannshofer, SG, D. Robinson, 1909.00005

ALPs at PIENU

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

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

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



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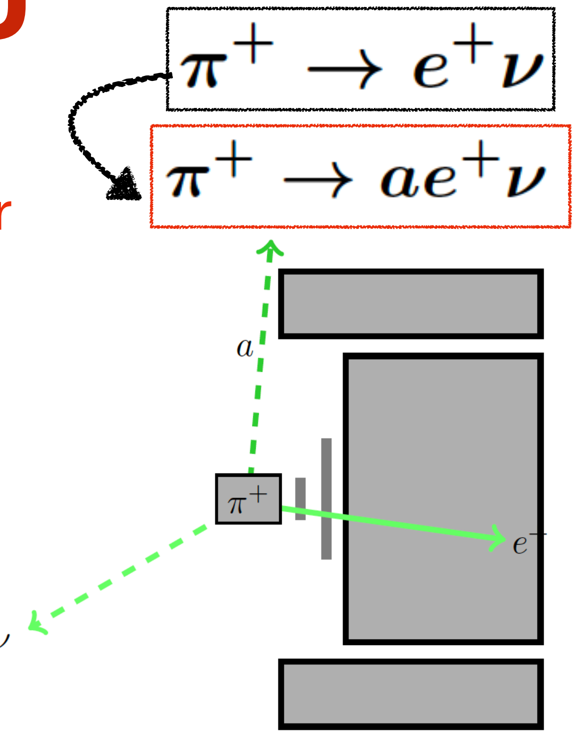
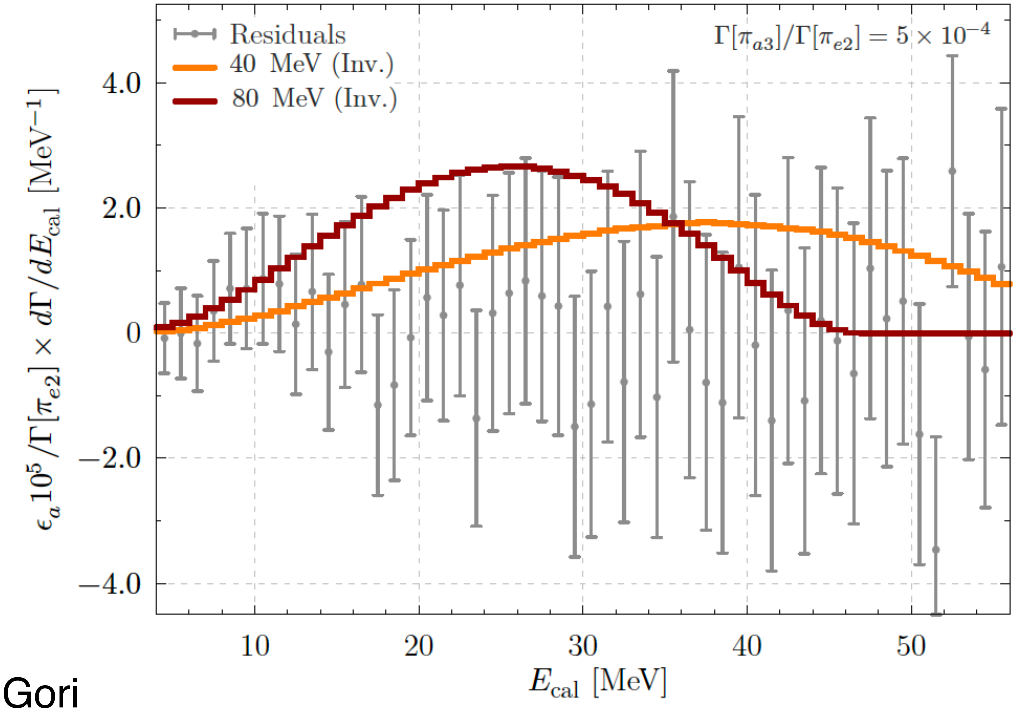
1. Invisible regime: the energy spectrum of the positron depends on the ALP mass.



$\pi^+ \to e^+ \nu$

$\pi^+ \to a e^+ \nu$



W. Altmannshofer, SG, D. Robinson, 1909.00005

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$$\pi^+ \to e^+\nu$$

$$\pi^+ \to a e^+\nu$$

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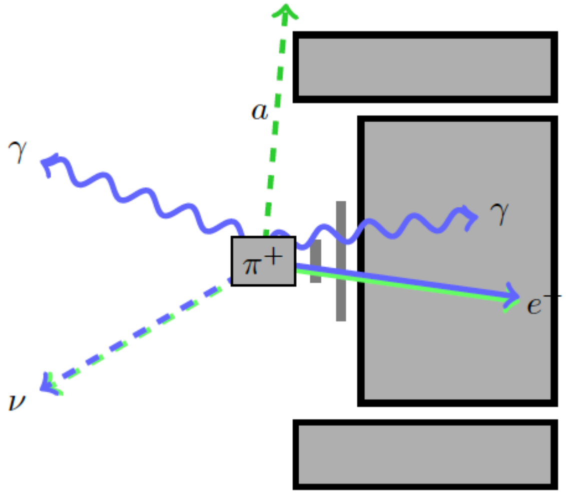
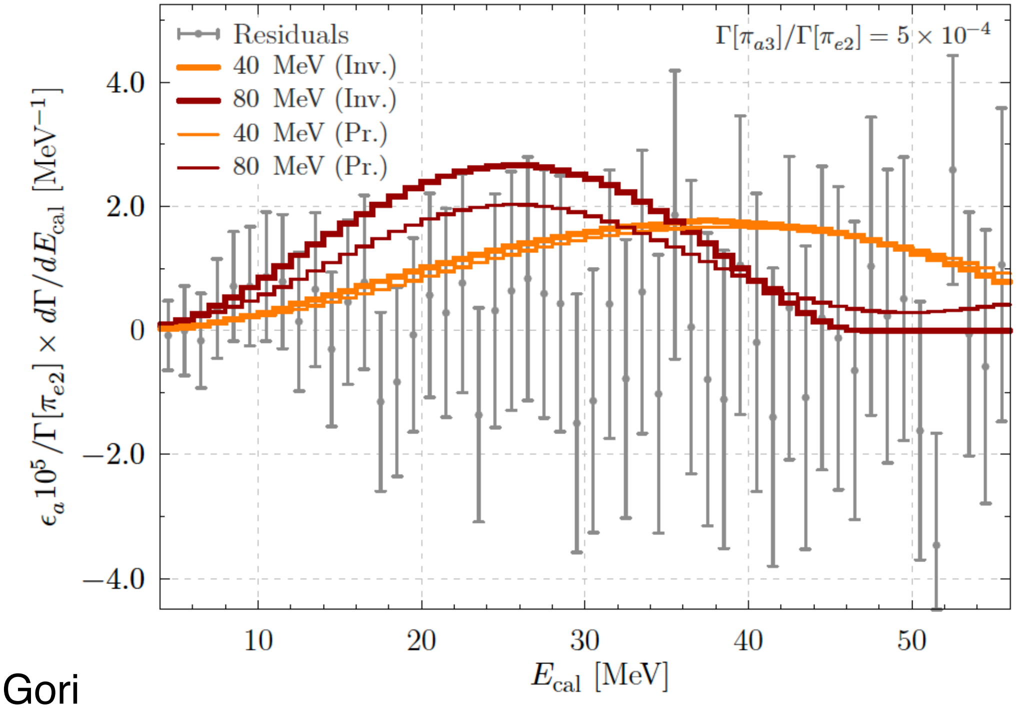
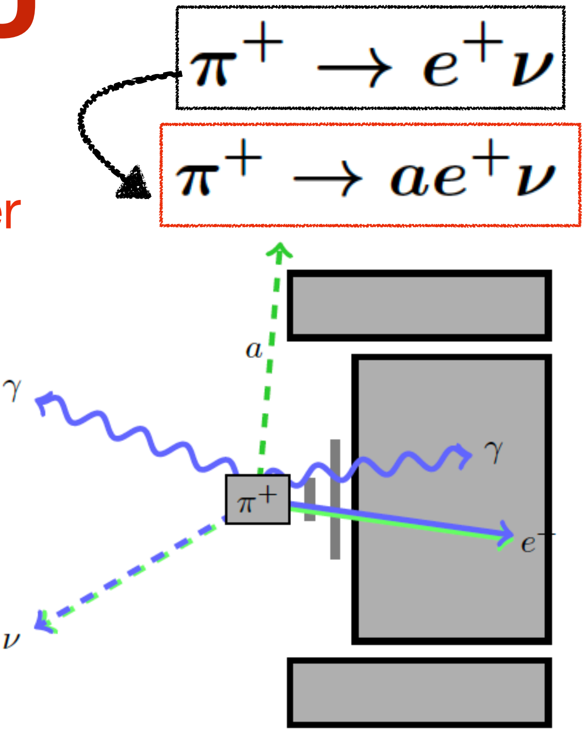
2. Prompt regime: the energy measured by the calorimeter can get a contribution from the photons produced from the ALP decay.



W. Altmannshofer, SG, D. Robinson, 1909.00005



ALPs at PIENU



$\pi^+ \to e^+\nu$

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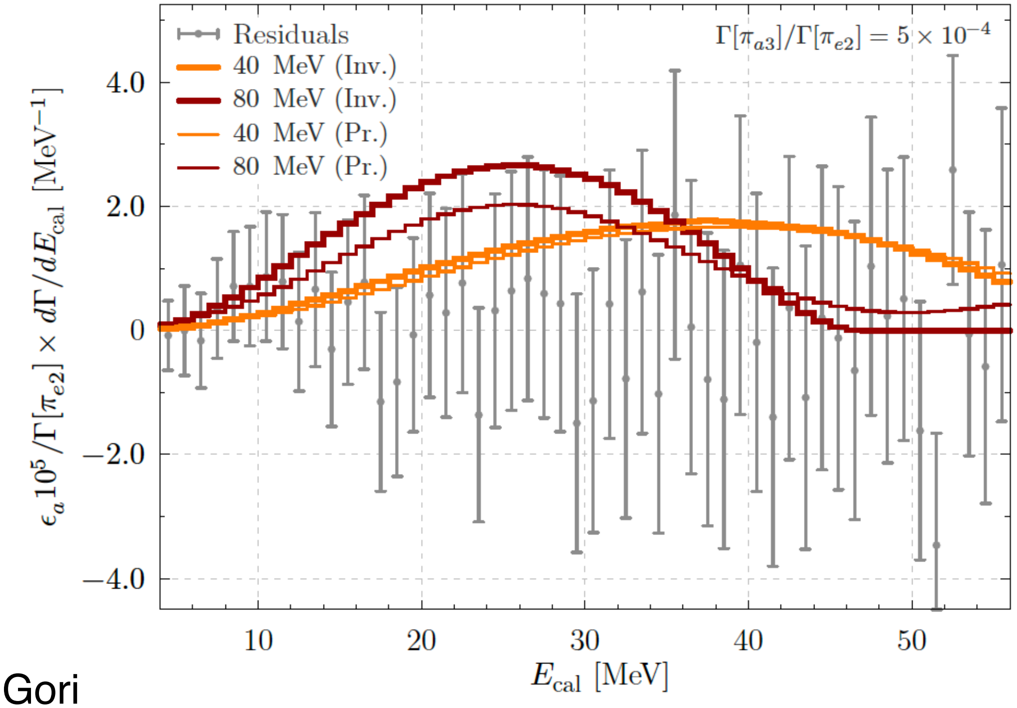
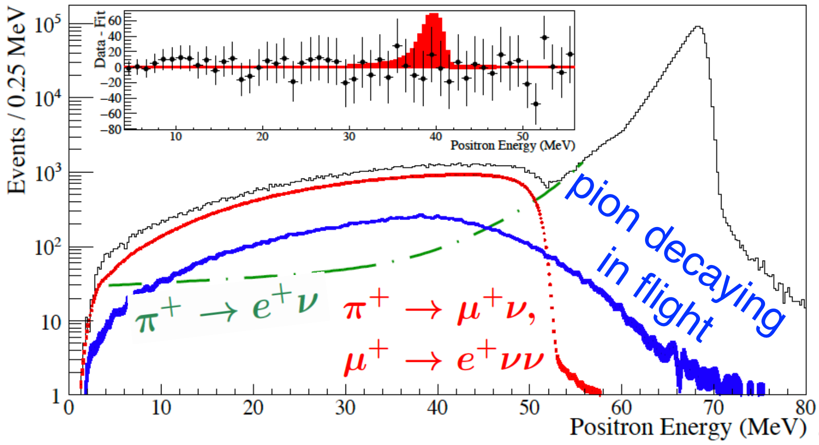
W. Altmannshofer, SG, D. Robinson, 1909.00005



We can compare these distributions with the PIENU residuals:



ALPs at PIBETA

The production of the ALP will affect the photon spectrum measured by PIBETA

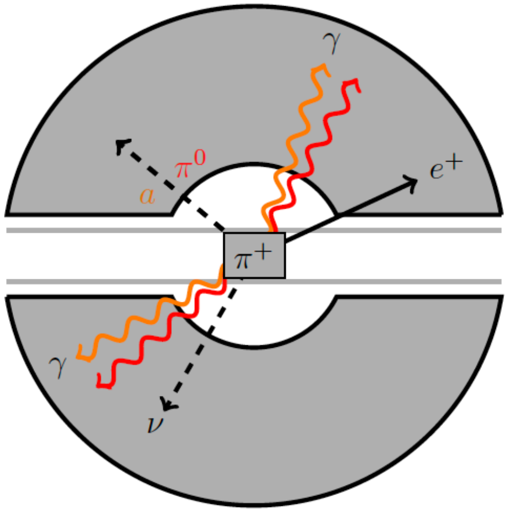
$\boxed{\pi^+ \to \pi^0 e^+ \nu}$ vs. $\boxed{\pi^+ \to a e^+ \nu}$

$\pi^0 \to \gamma\gamma$

will be produced
~ back to back

$a \to \gamma\gamma$

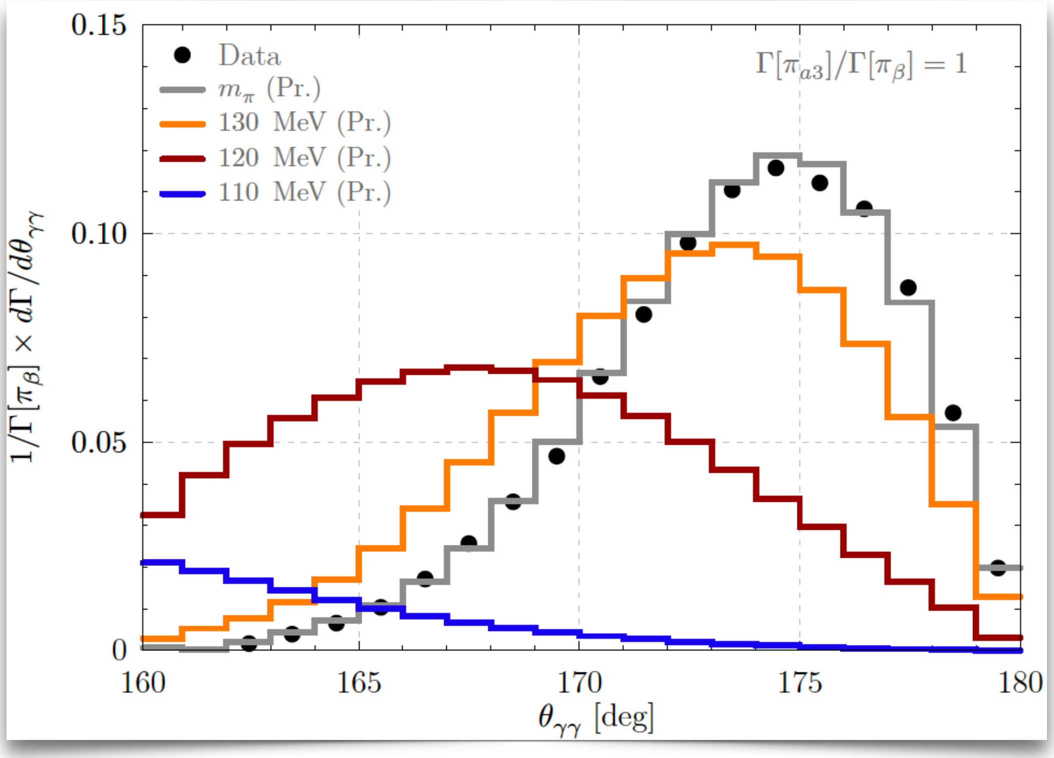
will have a smaller
opening angle

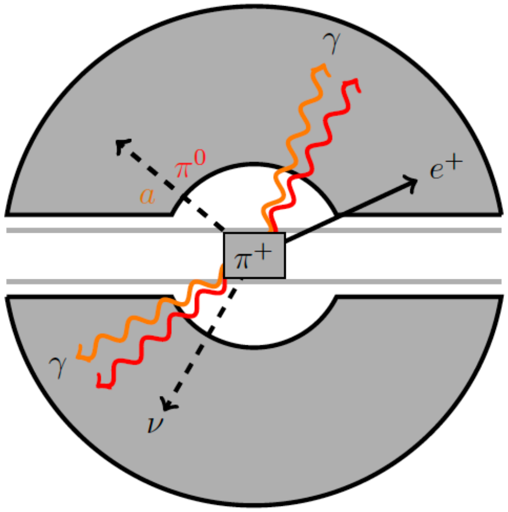


$$-1 \leq \cos\theta_{\gamma\gamma} \leq -1 + 2\Big(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\Big)^2$$

ALPs at PIBETA

The production of the ALP will affect
the photon spectrum measured by PIBETA



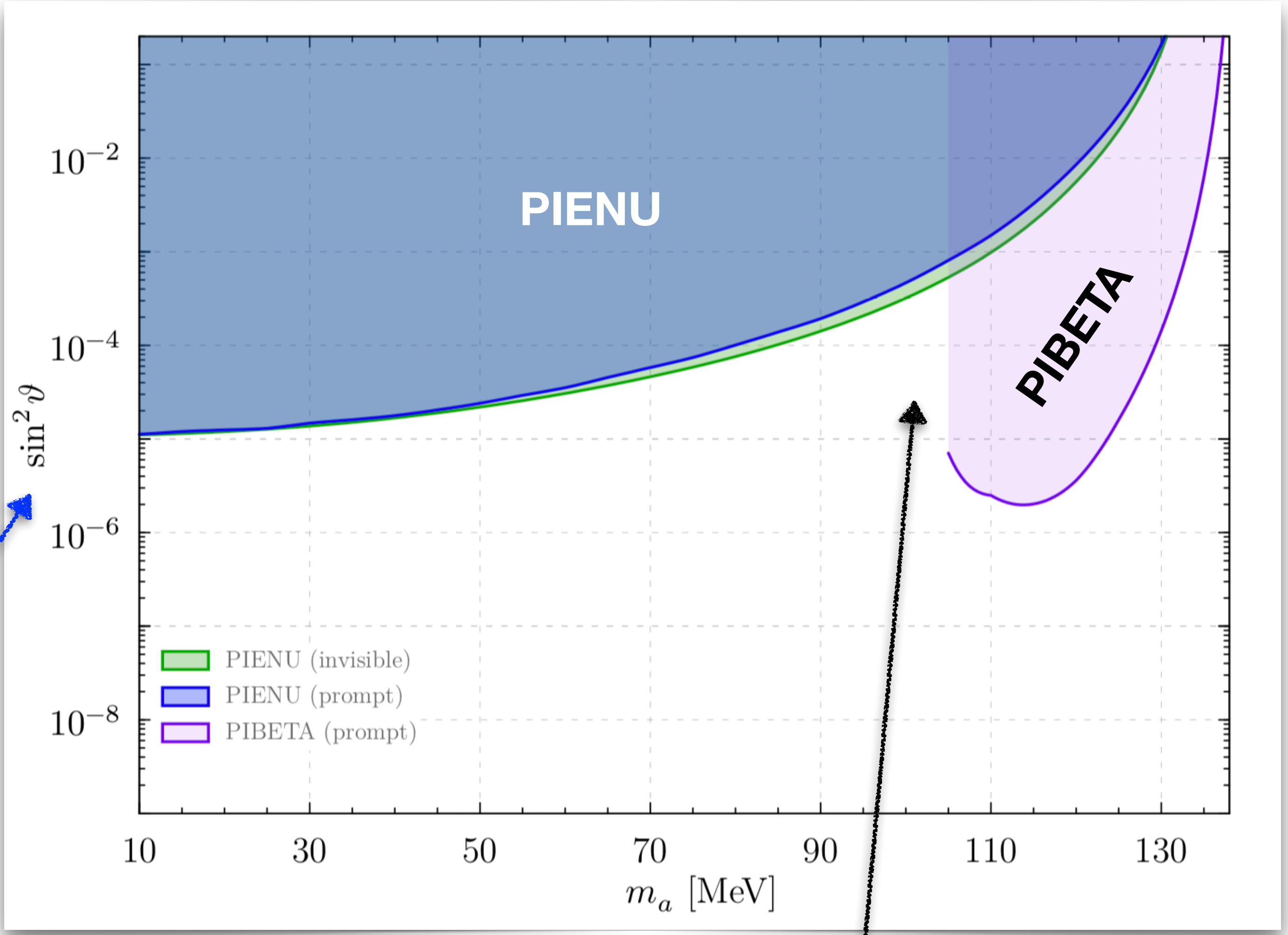


$$-1 \le \cos\theta_{\gamma\gamma} \le -1 + 2\left(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\right)^2$$

Unfortunately the PIBETA collaboration does not report residuals.

We require that the integrated contribution in (160-180) deg
is smaller than the experimental uncertainty in the $\mathrm{BR}(\pi^+ \to \pi^0 e^+ \nu)$

ALP bounds at pion experiments



pion-ALP mixing

W. Altmannshofer, SG,
D. Robinson, 1909.00005

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

2b.

SM meson-ALP mixing & Kaon decays

The ALP-pion and ALP-eta mixing will induce

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

2b.

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- an ALP coupling to photons (a → γγ)

At low energy, the two operators responsible for s → d transitions are

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

measured

$$\pi^0 \rightarrow \pi^0_{\mathrm{phy}} + \theta_{\pi a} a_{\mathrm{phy}}$$

$$\eta \rightarrow \eta_{\mathrm{phy}} + \theta_{\eta a} a_{\mathrm{phy}}$$

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

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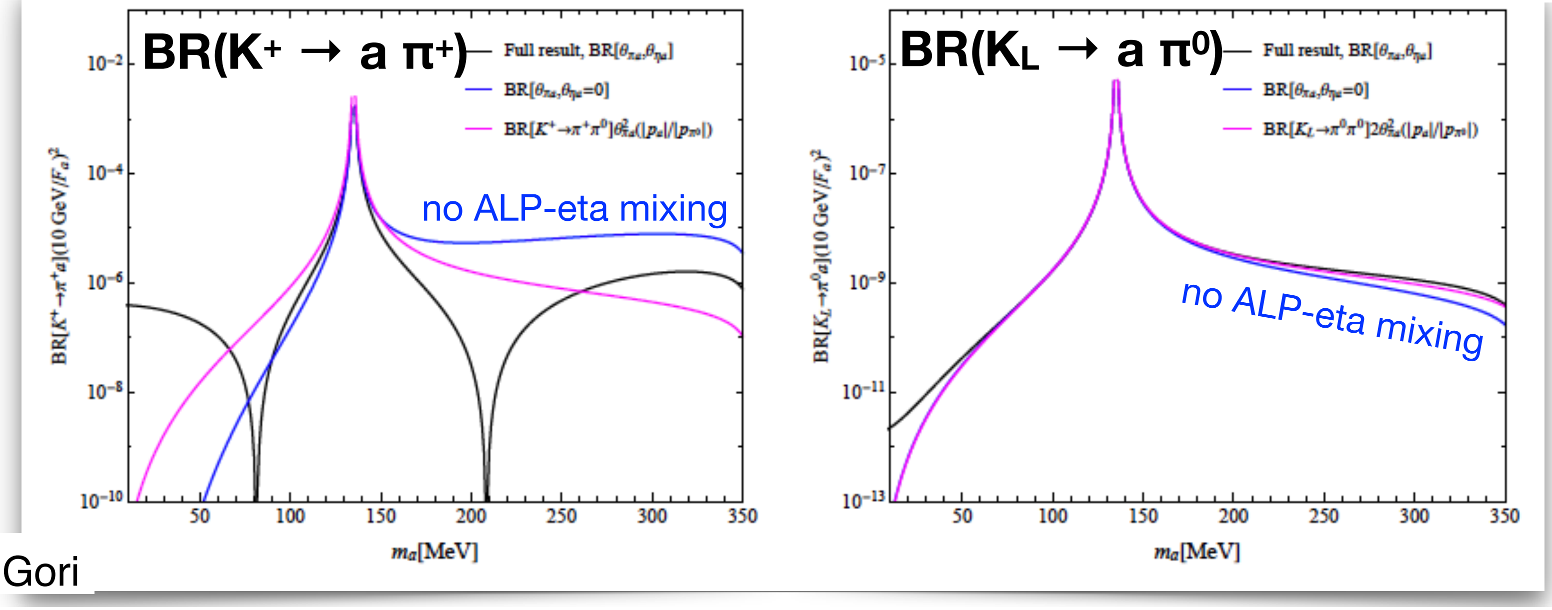


BR($K^+ \rightarrow a\,\pi^+$)

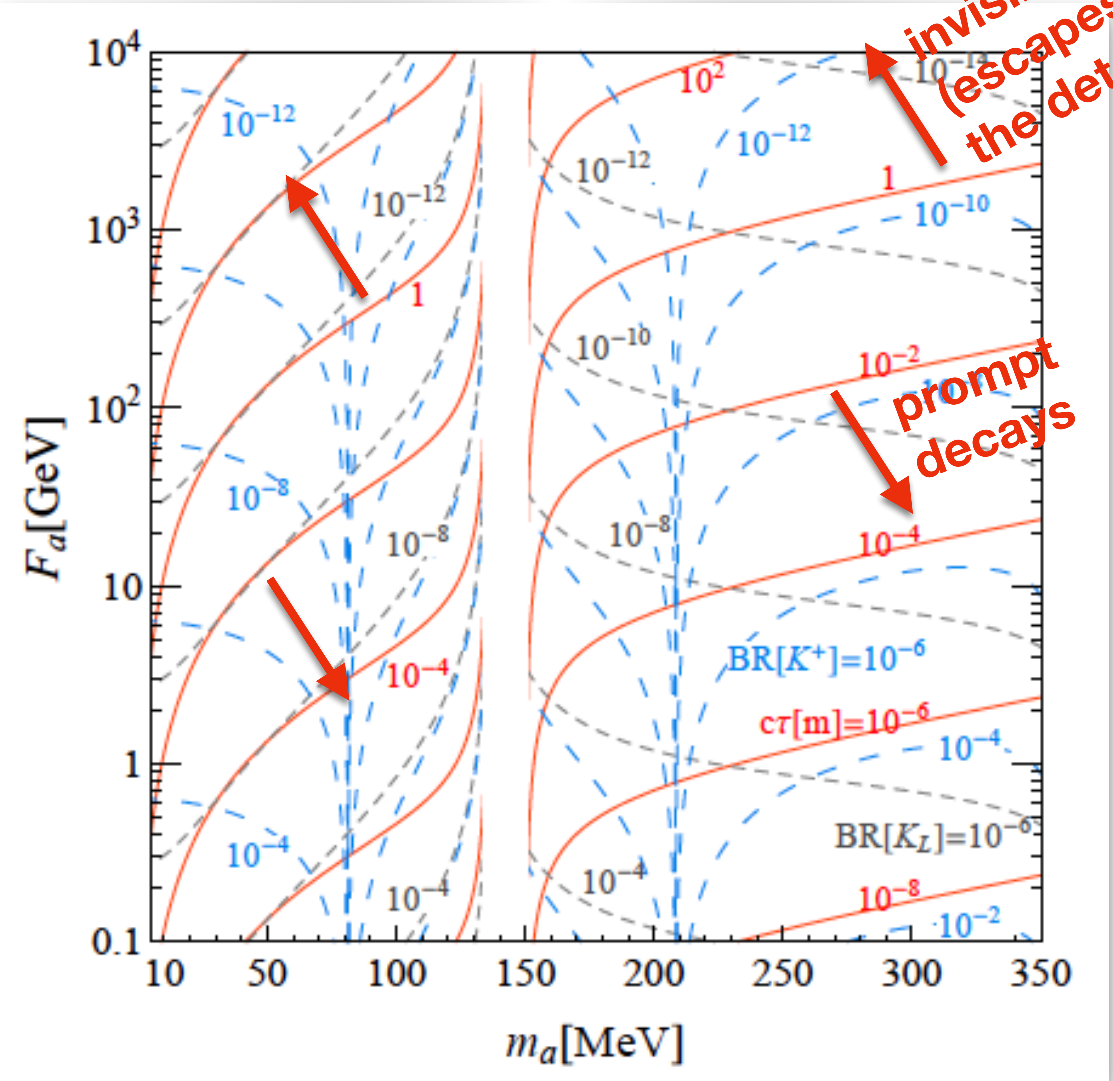
no ALP-eta mixing

BR($K_L \rightarrow a\,\pi^0$)

no ALP-eta mixing

Note:
possible additional
UV contributions

GG-coupled ALP pheno



invisible (escapes the detector)

prompt decays

ALP lifetime (in meters)

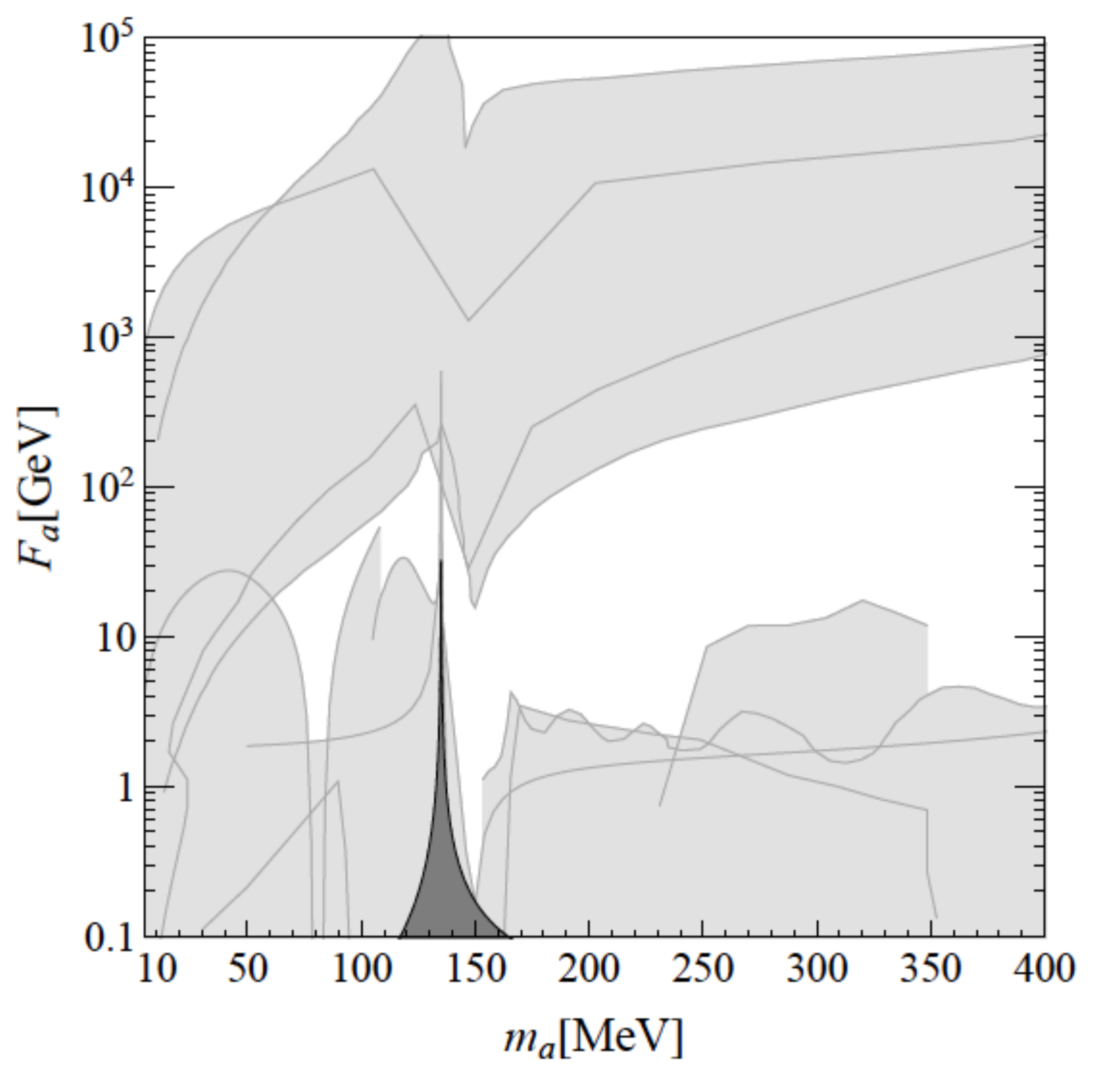
BR($K_L \to \pi$ a)

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

The charged BR is typically larger but there are regions where

$$\frac{\mathrm{BR}(\mathrm{K_L} \to \pi^0 \mathrm{a})}{\mathrm{BR}(\mathrm{K}^+ \to \pi^+ \mathrm{a})} \gg 1$$

$aG\tilde{G}$ at past experiments



SG, Perez, Tobioka, 2005.05170

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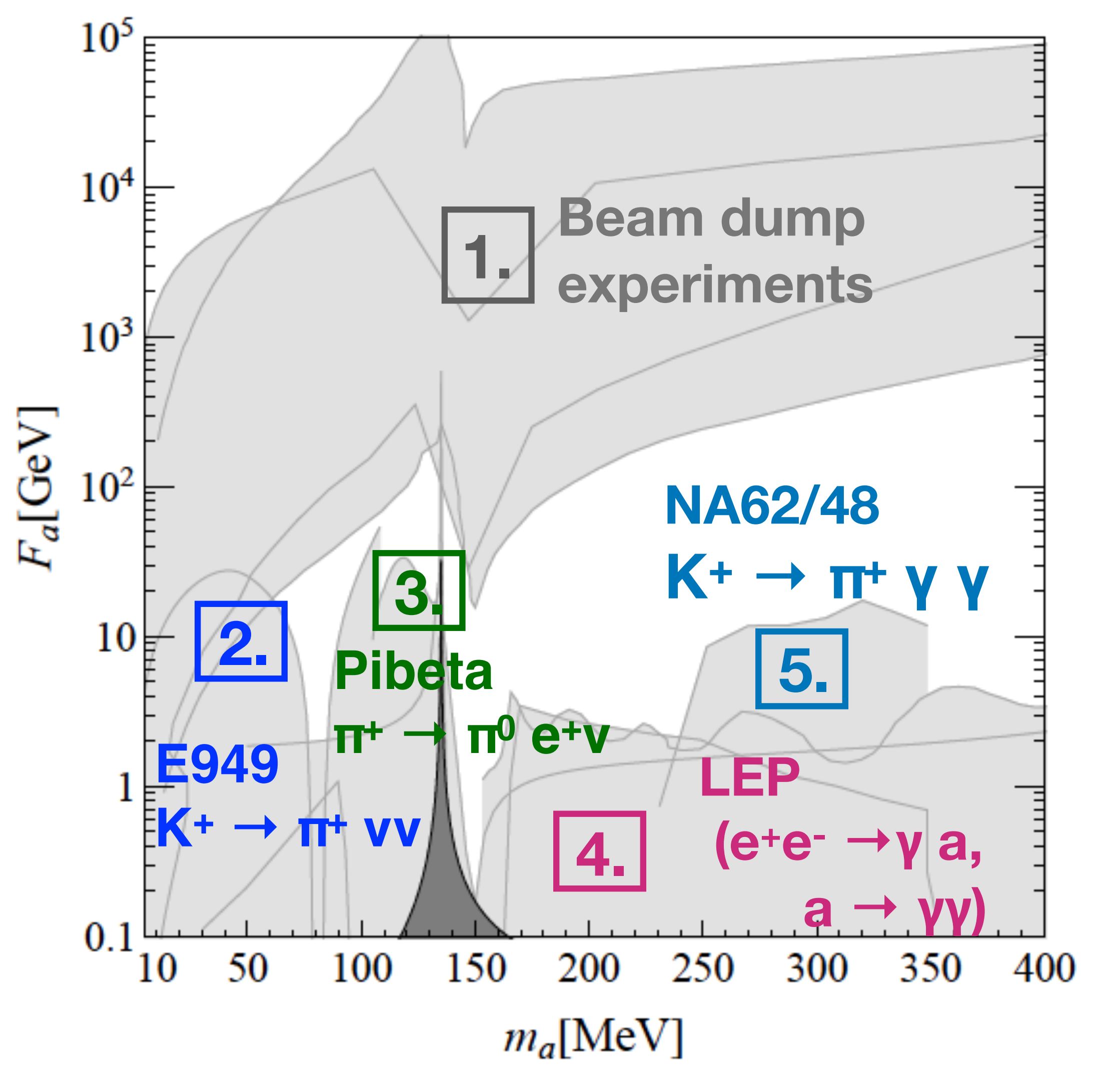
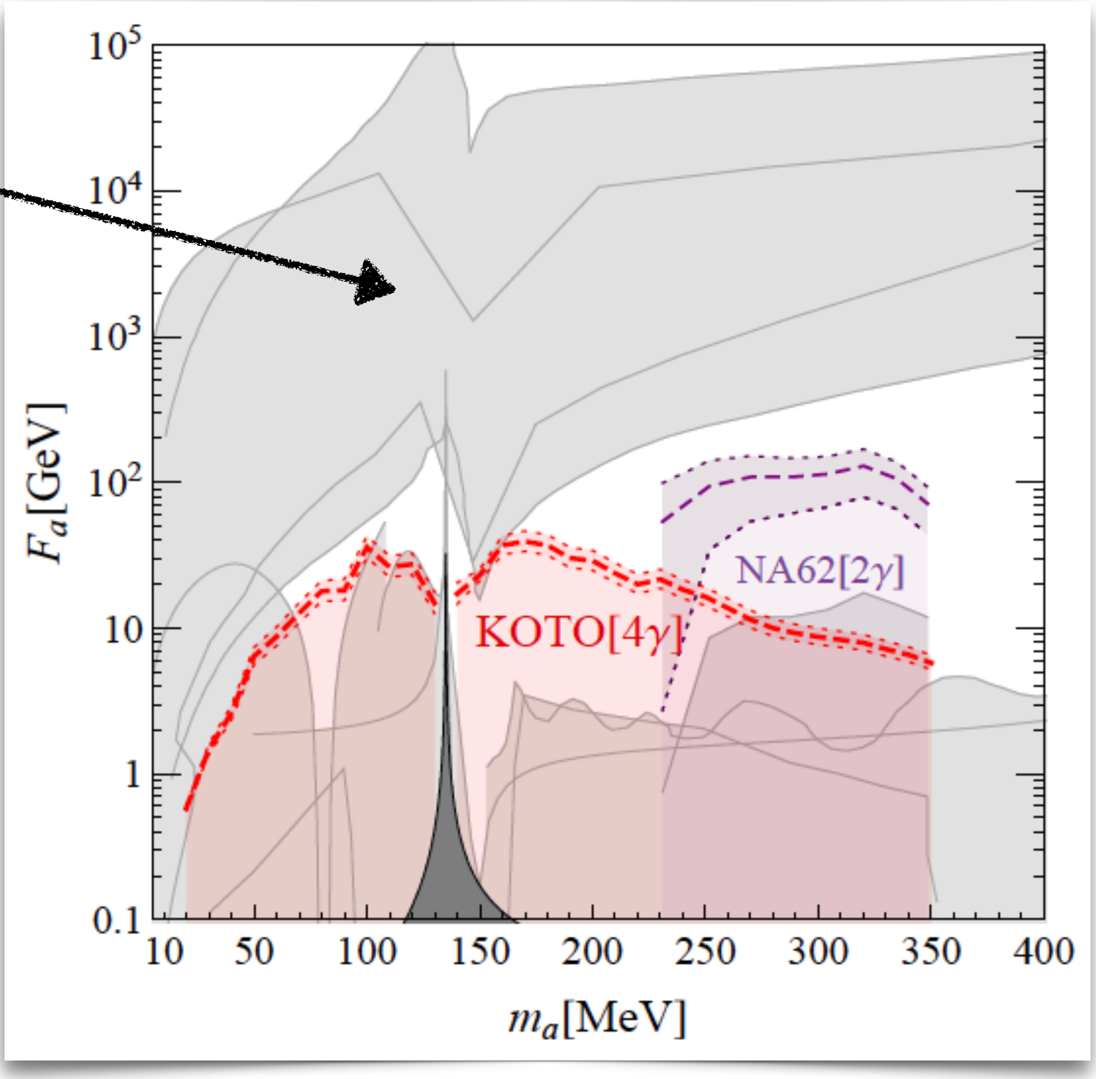


SG, Perez, Tobioka, 2005.05170

$aG\tilde{G}$ prospects @ KOTO and NA62

$K_L \to \pi^0\, a,$
$a \to \text{inv.}$
$K^+ \to \pi^+\, a,$
$a \to \text{inv.}$
aren't powerful (below the beam-dump)



SG, Perez, Tobioka, 2005.05170

NA62[2γ]:
$K^+ \to \pi^+\, a,$
$a \to \gamma\gamma.$
(re-scaling of NA62/48)

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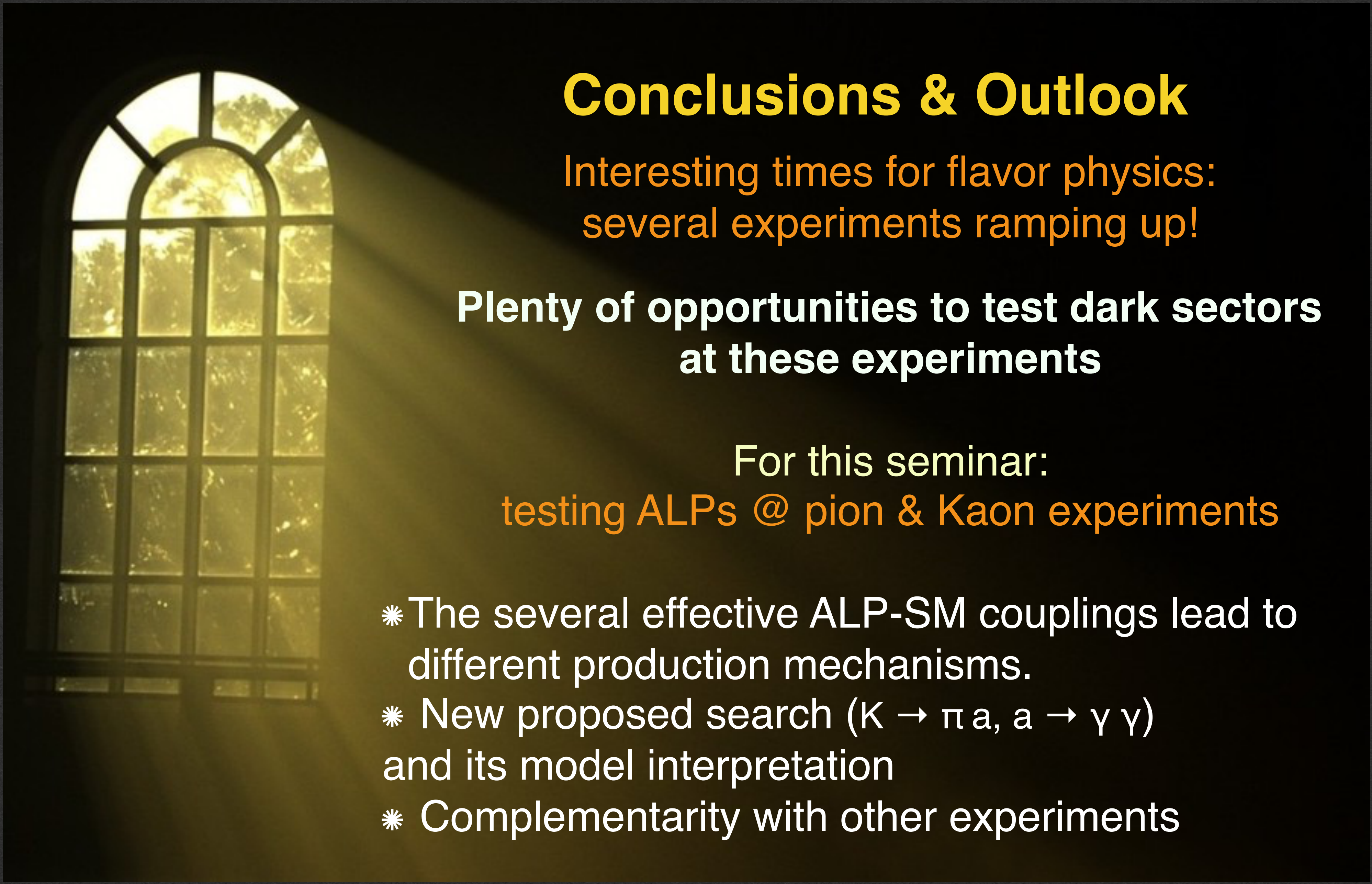


Conclusions & Outlook

Interesting times for flavor physics:
several experiments ramping up!

Plenty of opportunities to test dark sectors at these experiments

For this seminar:
testing ALPs @ pion & Kaon experiments

- The several effective ALP-SM couplings lead to different production mechanisms.
- New proposed search ($K \rightarrow \pi a$, $a \rightarrow \gamma\gamma$) and its model interpretation
- Complementarity with other experiments

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

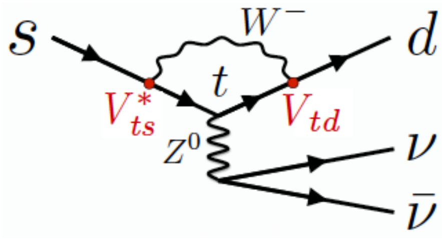
Many Standard Model (SM) flavor violating processes will be measured for the first time in the coming years:

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)

Kaon rare decays in the SM: K → π ν ν

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



\+ box diagrams

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

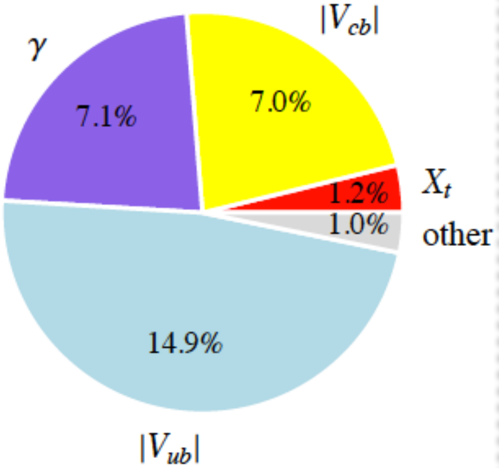
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \simeq \kappa_L \, {\rm Im} \left(\frac{V^*_{ts} V_{td}}{\lambda^5} X(x_t) \right)^2$$

CP-violating

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

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.

From an EFT perspective:

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

SM operator

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

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

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

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

Grossman-Nir bound (model independent):

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

hep-ph/9701313

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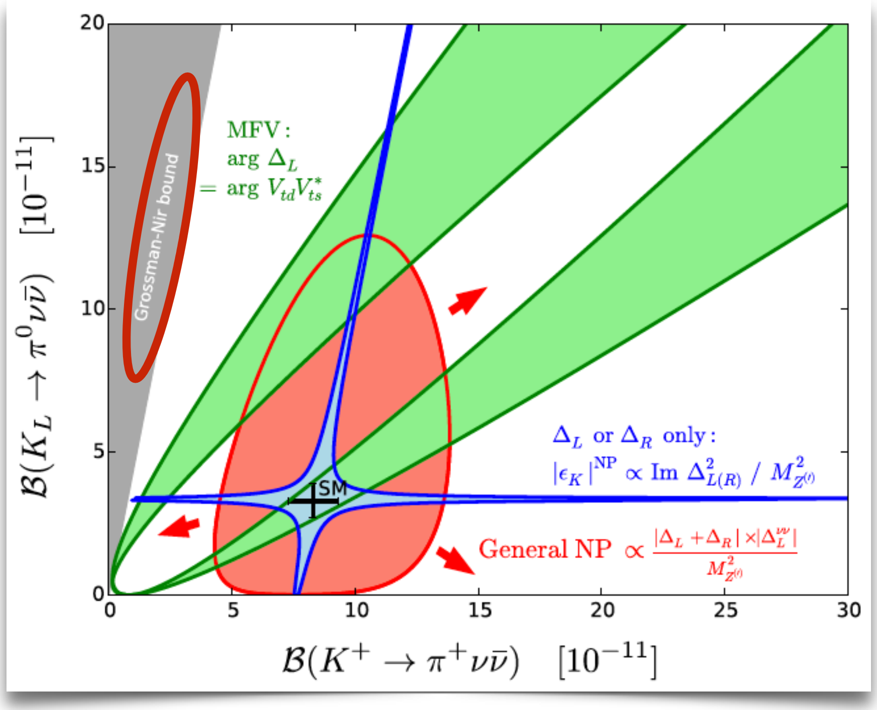
SM operator



Buras, Buttazzo, Knegjens, 1507.08672

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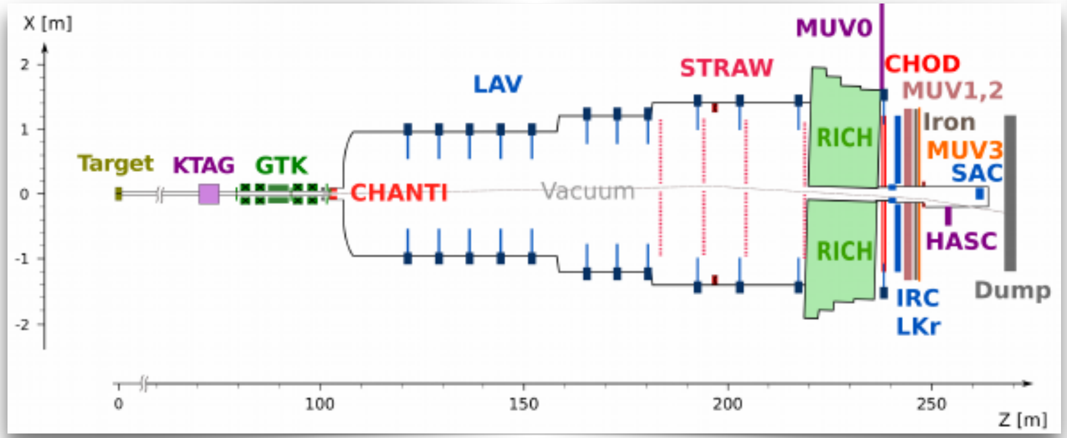
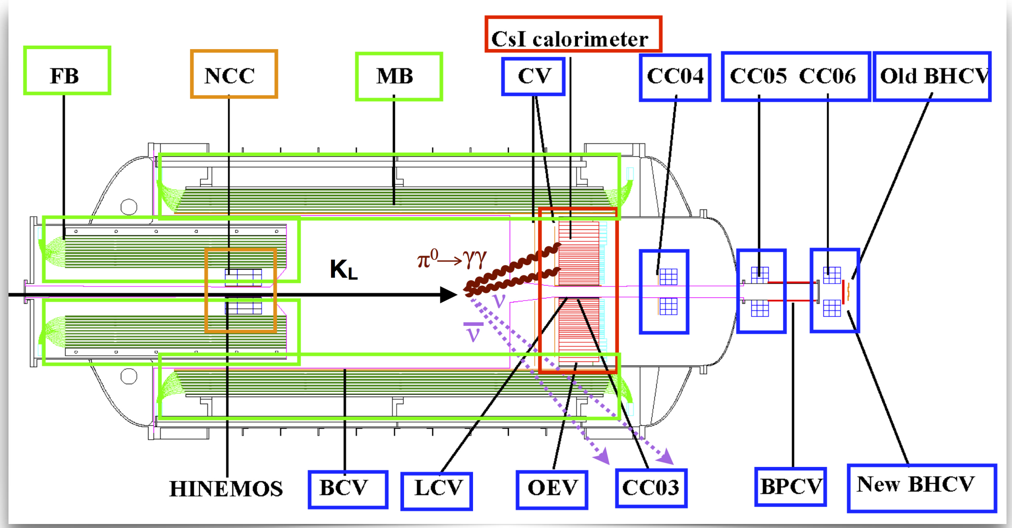
hep-ph/9701313

Brief look: NA62 & KOTO



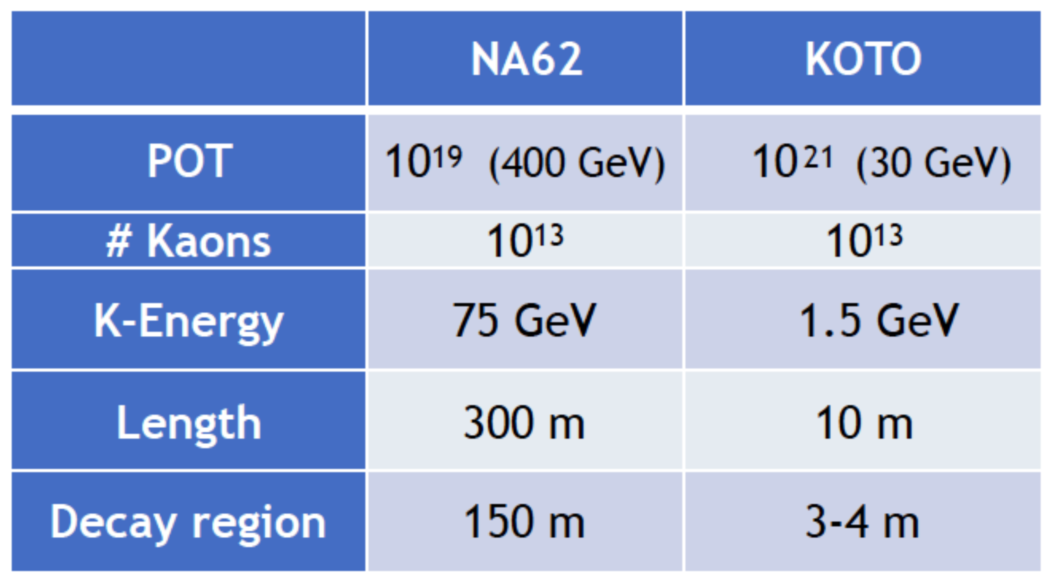
NA62

Only calorimetry, no tracking



KOTO

future goals



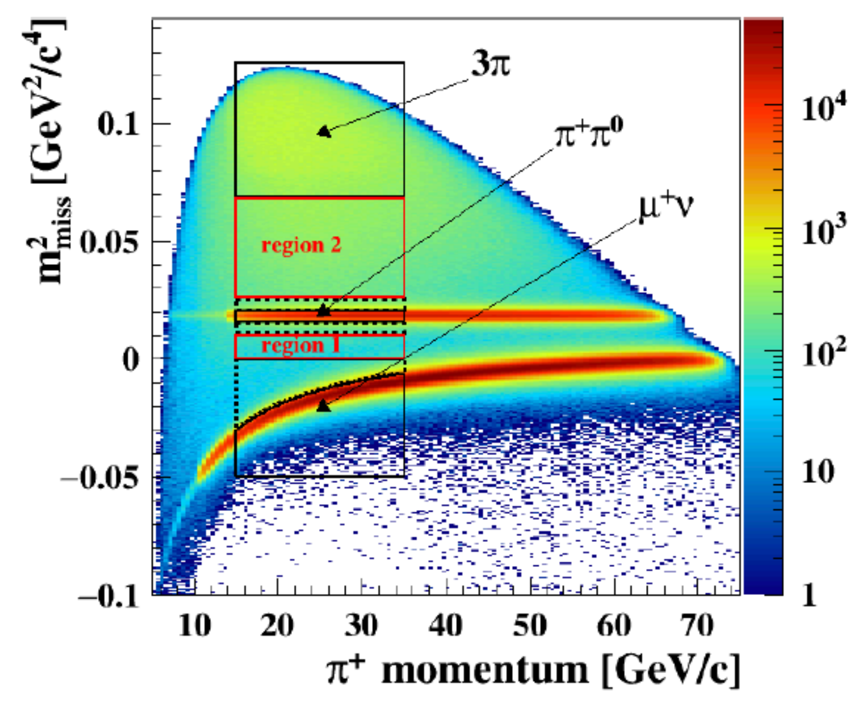
	NA62	KOTO
POT	10^{19} (400 GeV)	10^{21} (30 GeV)
# Kaons	10^{13}	10^{13}
K-Energy	75 GeV	1.5 GeV
Length	300 m	10 m
Decay region	150 m	3-4 m

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

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

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

1 event seen! (0.3 expected)

Published analysis, 1811.08508

- 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

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

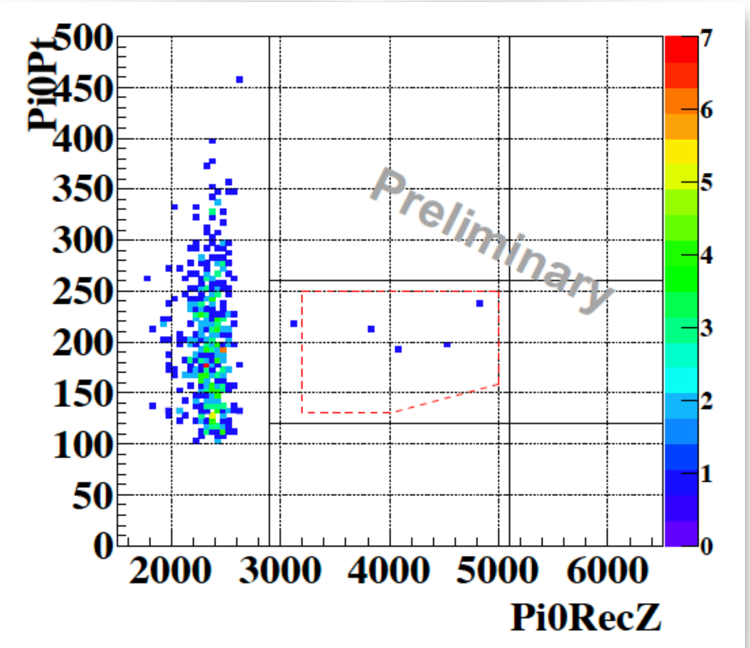
(1609.03637)

- 2015 run: ~ 20 times more data

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

(1810.09655)

- 2016-2018 run: ~ 50% more data



Pion momentum

Reconstructed vertex

- Indirect bound:

(using Grossman-Nir)

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

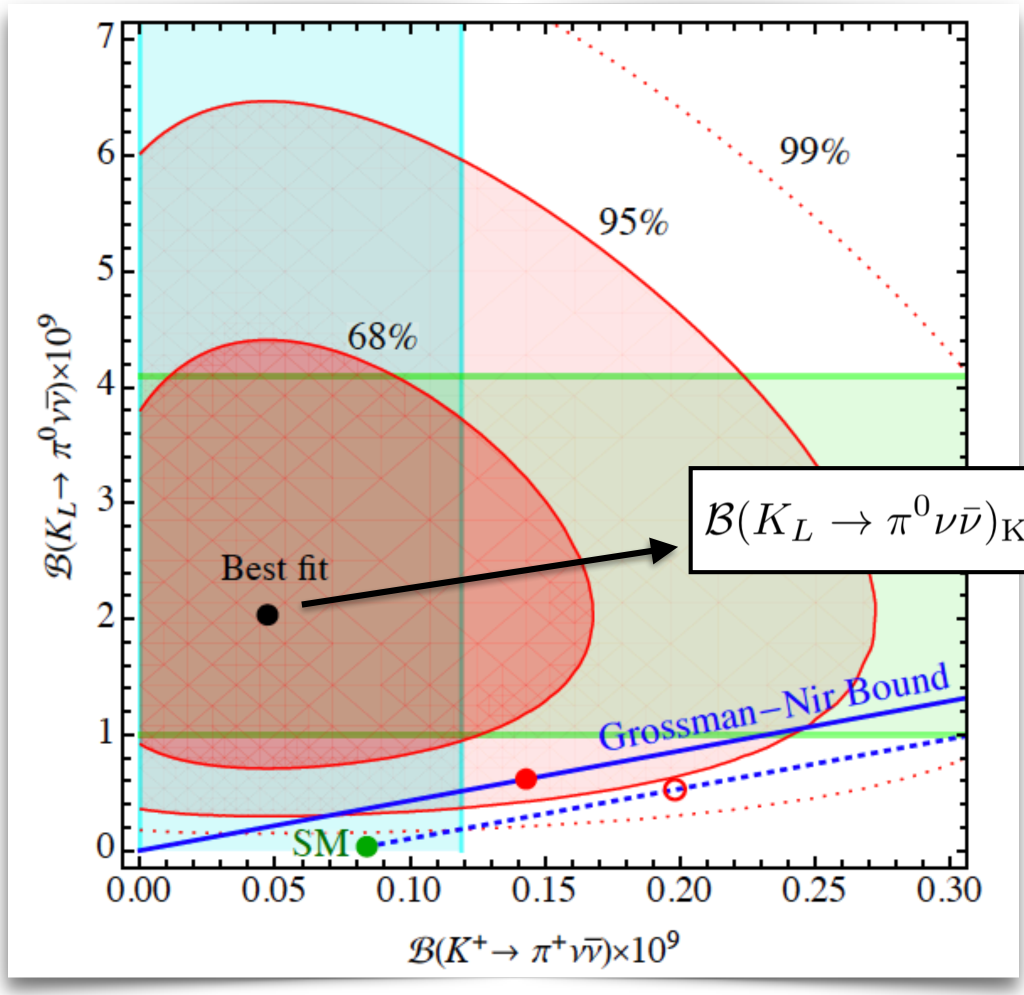
4-events in the signal region!

Expected number of events: 0.05±0.02

Final KOTO goal (~100 times more data) measurement of/evidence for the SM BR with ~?% uncertainty

$$\mathrm{BR}(K_L \to \pi^0 \bar{\nu} \nu) = (3.4 \pm 0.6) \times 10^{-11}$$

Compatibility NA62/KOTO?



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

(theory
interpretation)

~2σ tension (interference with the SM)

~3σ tension (no interference with the SM)

Kitahara et al.,1909.11111

Class of models addressing the anomaly

- Heavy New Physics described by a EFT framework ✗

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

\- 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)

- 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 ϕ →γγ 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:

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

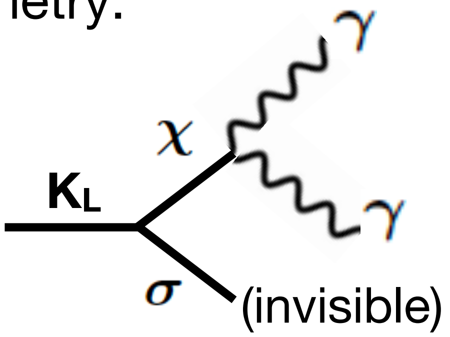
This would dominate the 3-body final states of the charged Kaon:

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

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



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

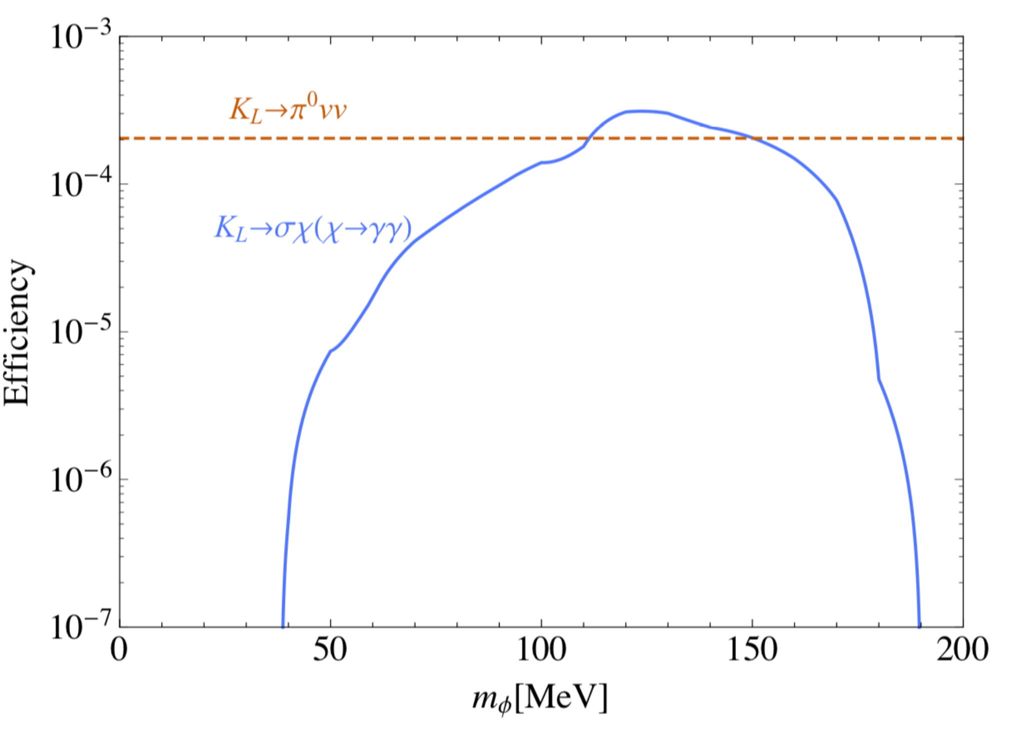
Depending on the ϕ mass, this decay can fall into the KOTO signal region

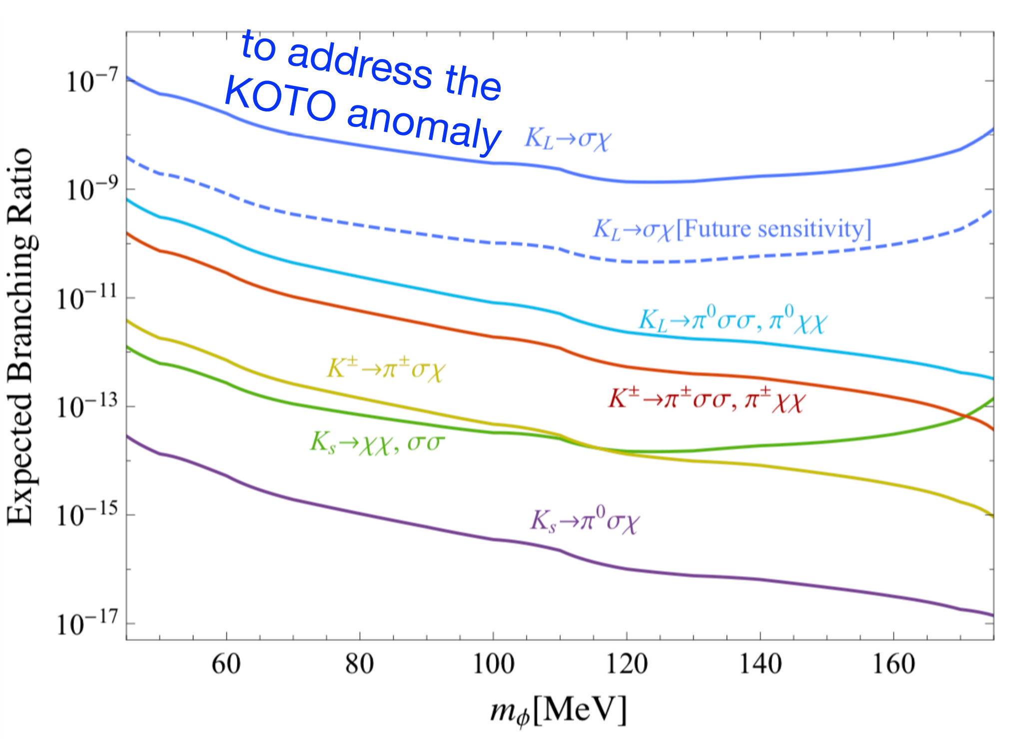
See also Hostert et al. 2005.07102; Altmannshofer et al. 2006.05064

Predictions for Kaon experiments

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

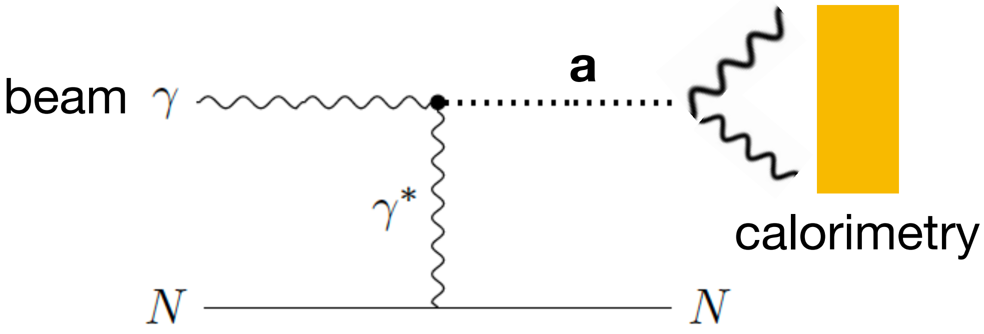
$$\Sigma\equiv\exp[2i\Pi/F_\pi]\qquad \Pi\equiv\frac{1}{\sqrt{2}}\begin{pmatrix}\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+\\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}} & K^0\\ K^- & \bar{K}^0 & -2\frac{\eta_8}{\sqrt{6}}\end{pmatrix},\qquad \lambda_{sd}=\begin{pmatrix}0&0&0\\0&0&1\\0&0&0\end{pmatrix}$$




to address the KOTO anomaly

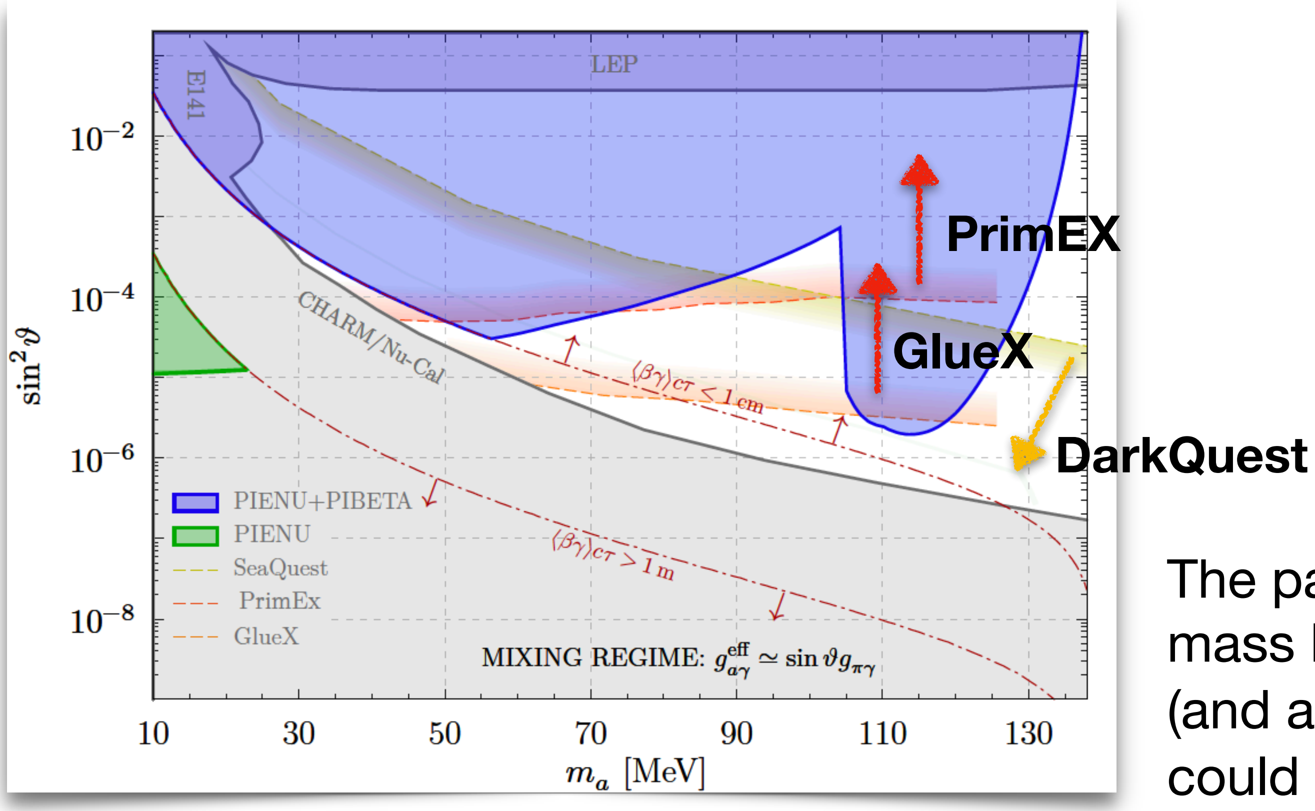
SG, Perez, Tobioka, 2005.05170

More new measurements coming up? PrimEX, GlueX



Proposed upgrades for the PrimEX and GlueX experiments at JLAB

$$\gamma N \to a N$$
$$\hookrightarrow \gamma\gamma$$



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

ALP-pion & ALP-eta mixing

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

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

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

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

this is decoupled

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

Large uncertainties

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; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	~40 times more b quarks will be produced by the end of the LHC; ~50 times more BB-pairs will be produced by **Belle-II**.
Kaon-factories	**E949** at BNL: ~10^{12} K^+ (decay at rest experiment); **E391** at KEK: ~10^{12} K_L	**NA62** at CERN: ~10^{13} K^+ by the end of its run (decay in flight experiment); **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)	?