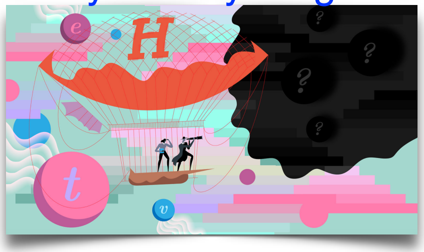
Axion-like-particles @ light meson experiments

Stefania Gori
UC Santa Cruz

Light dark world 2020
December 15, 2020

Outline

from symmetry magazine



1. Introduction

2. Light meson experiments: status and prospects

- Status of the measurement of very rare meson decays ($K \to \pi \nu \nu$, $\pi^+ \to l \nu$, $\pi^+ \to \pi^0 l \nu$)
- Anomalies?

3. Testing axion-like-particles (ALPs) at light meson experiments

- Testing the ALP-pion mixing at pion experiments
- ALP production at Kaon experiments
- New proposed ALP searches for the KOTO and NA62 experiments ($K \to \pi \gamma \gamma$)
- Complementarity with other experiments

Main references for this talk

W. Altmannshofer, SG, D. Robinson, 1909.00005

SG, G. Perez, K. Tobioka, 2005.05170

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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1.

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 scale (and above) axion-like-particles (ALPs)

The precision frontier @ flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
B-factories		
Kaon-factories		
Pion-factories		

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)	?

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!

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

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

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

Theoretical uncertainty
a factor of ~2 smaller

Precision Kaon experiments

Several (past and present) small-scale experiments built to measure <u>Kaon rare decays</u>

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

NA62 @ CERN:

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

17 events observed

stat.

(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

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

For the SM prediction, see: Brod, Gorbahn, Stamou 1009.0947;
Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

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

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

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

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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:

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

$$X = \underbrace{\frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \frac{\mathrm{Re}(V_{cs}^* V_{cd})}{\lambda} P_{c,u}}_{\text{SM contribution}} + \frac{1}{\lambda^5}(c_1 + c_2)$$

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

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

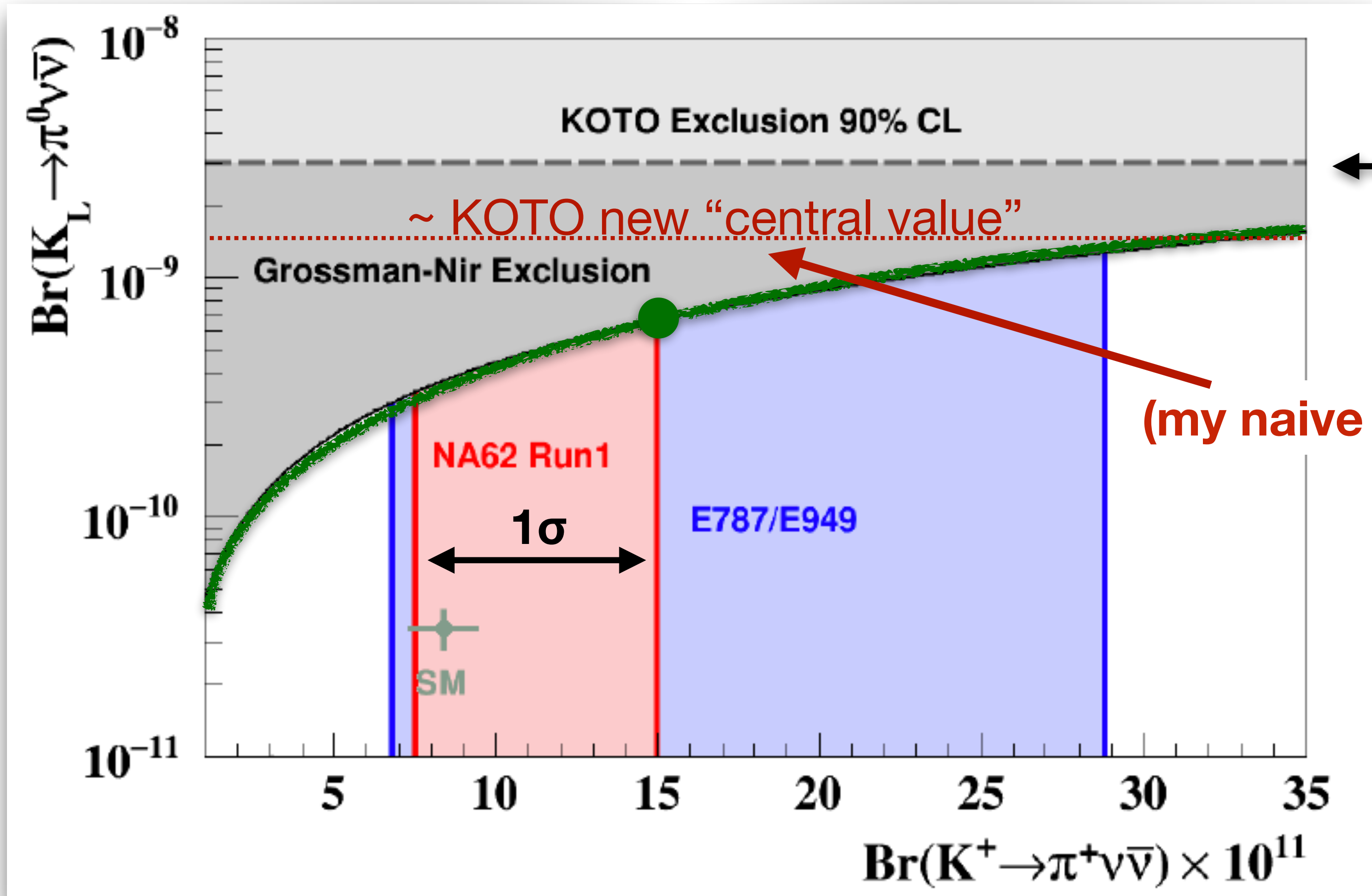
because of the isospin symmetry, the form factors: $F_0 \sim F_+$

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

How do the NA62 & KOTO results compare?



2015 data

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

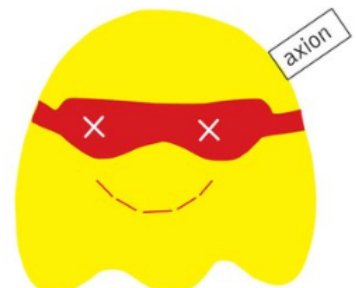
(my naive estimate!)

Marchevski talk @ ICHEP

Light (< m_K) new physics
would be required
if this will turn out to be
a "real" anomaly

It cannot be
described by a EFT

How to test ALPs at these experiments



For concreteness,

we will consider two benchmark scenarios:

1. ALP-pion mixed scenario → pion experiments $a - \pi^0$

2. ALP-GG coupled scenario → kaon experiments $aG_{\mu\nu}\tilde{G}^{\mu\nu}$

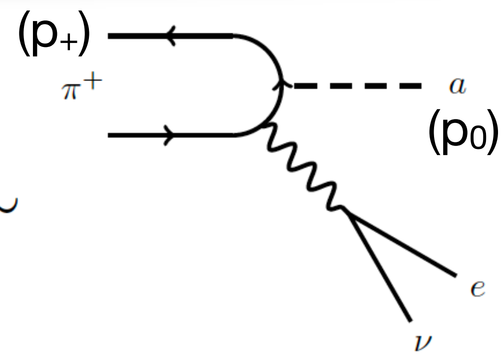
(+ comment on the KOTO anomaly)

1. Pion-ALP mixed scenario & pion decays

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

Not helicity suppression, nor phase space suppression!

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

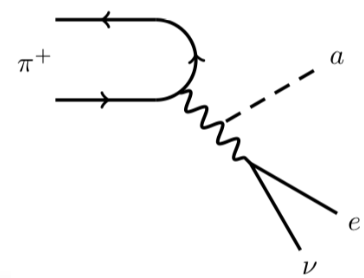


$$\mathcal{A}^\mu \simeq \langle a|\pi^{*0}\rangle\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle$$
$$\equiv \sin\vartheta\langle\pi^{*0}|\bar{d}\gamma^\mu u|\pi^+\rangle$$

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

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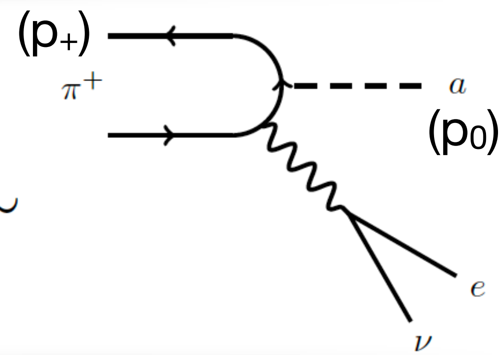


$$\mathcal{A}^\mu \simeq \langle a | \pi^{*0} \rangle \langle \pi^{*0} | \bar{d} \gamma^\mu u | \pi^+ \rangle$$
$$\equiv \underbrace{\sin\vartheta}_{\text{mixing angle}} \langle \pi^{*0} | \bar{d} \gamma^\mu u | \pi^+ \rangle$$

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 ➡ $m_0 >\sim 10$ MeV

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

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

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

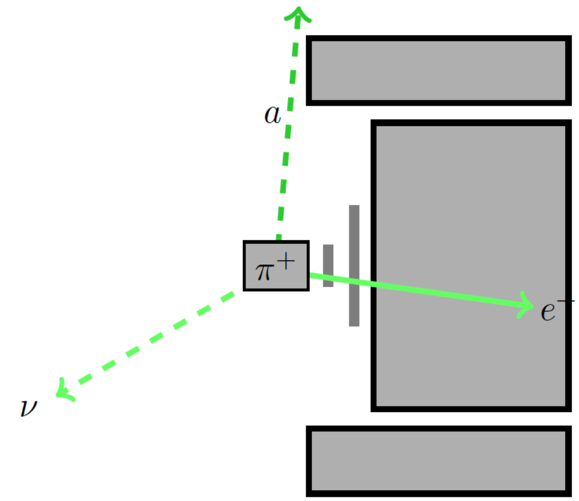
W. Altmannshofer, SG, D. Robinson, 1909.00005

ALPs at PIENU

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

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

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



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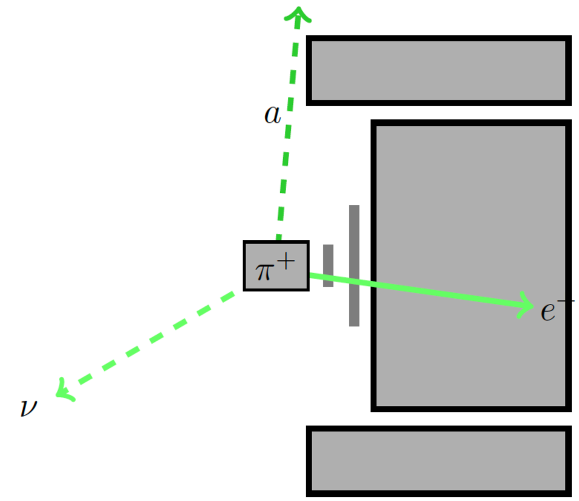
1. <u>Invisible regime:</u> the energy spectrum of the positron depends on the ALP mass.



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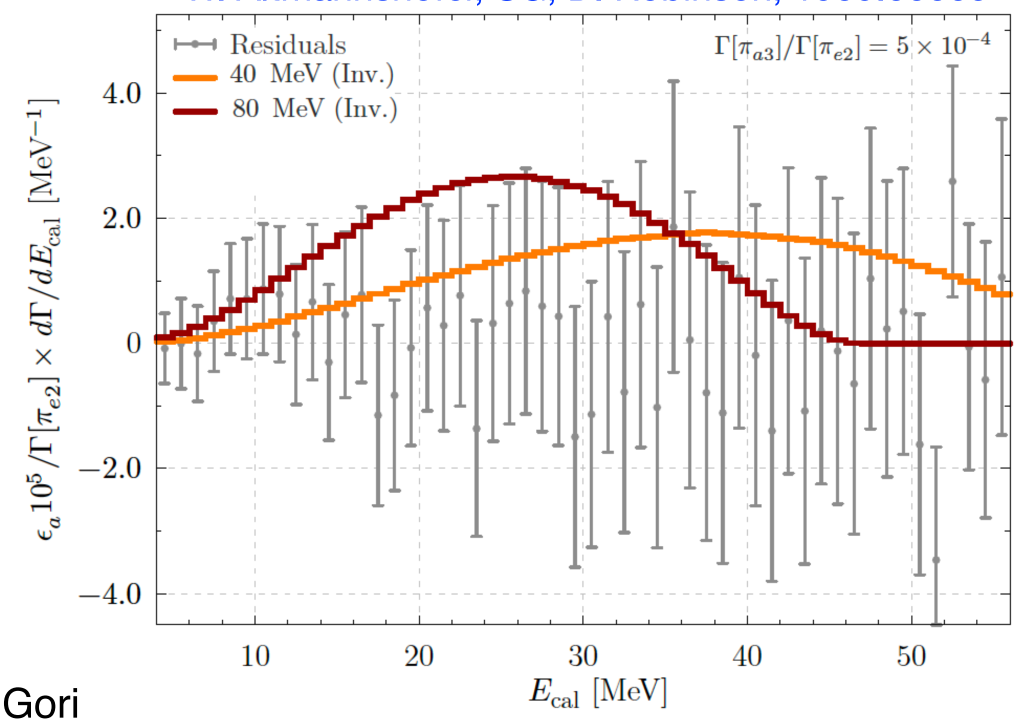
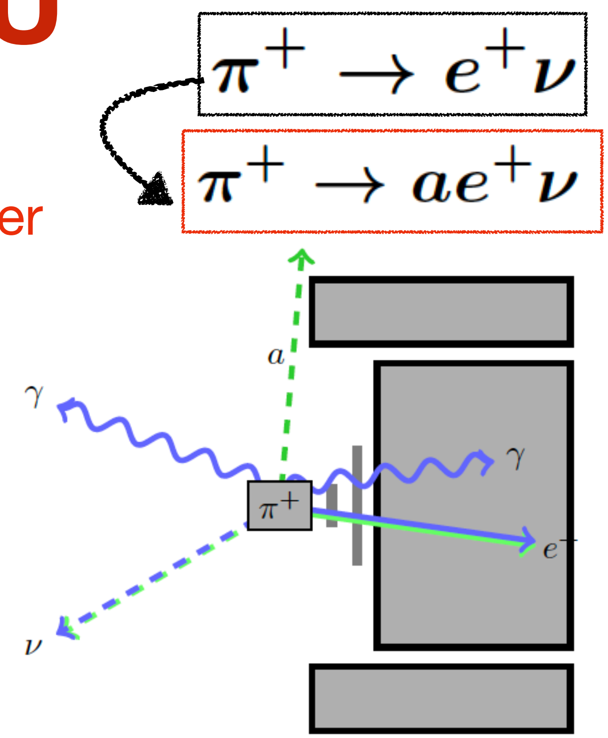


ALPs at PIENU

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

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

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



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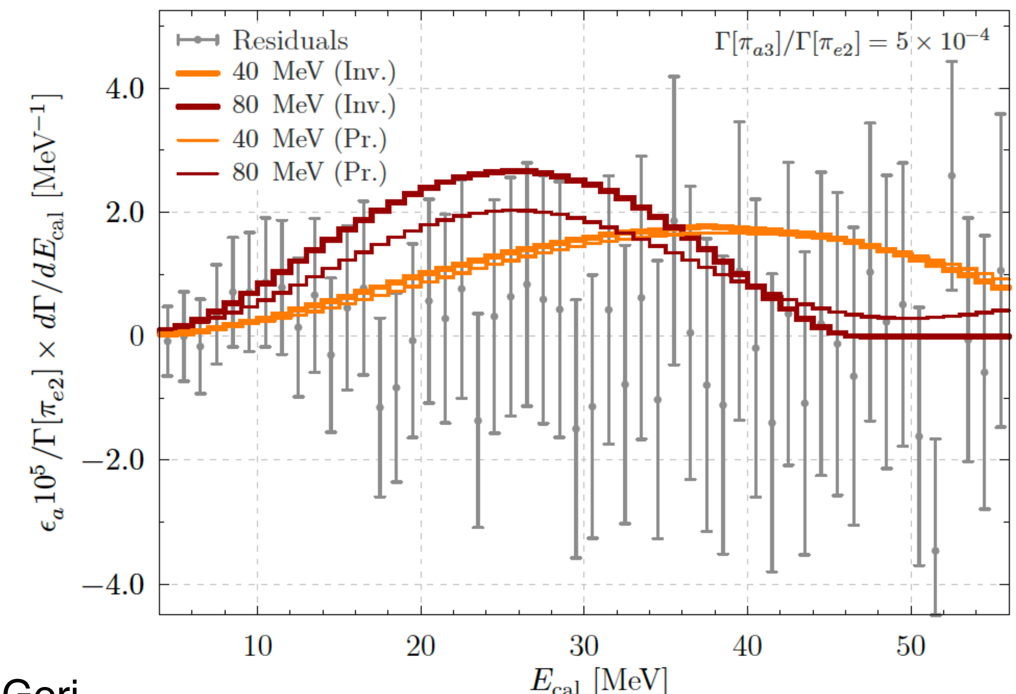

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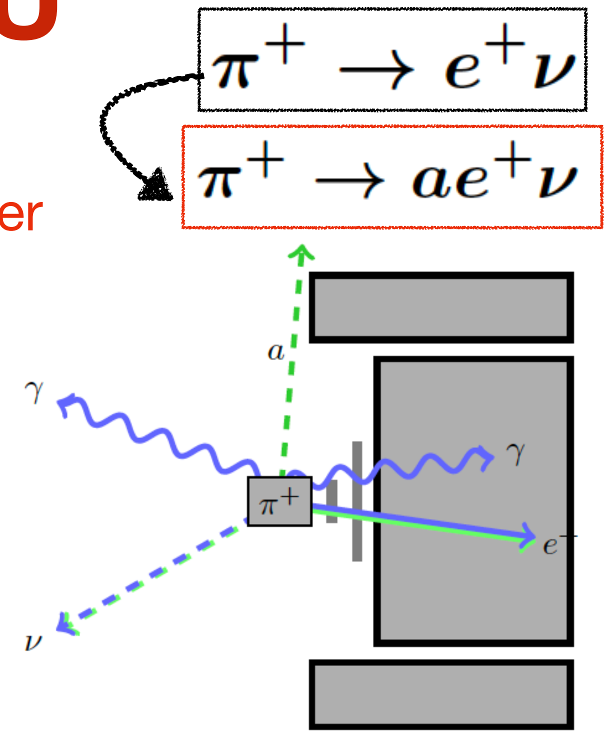

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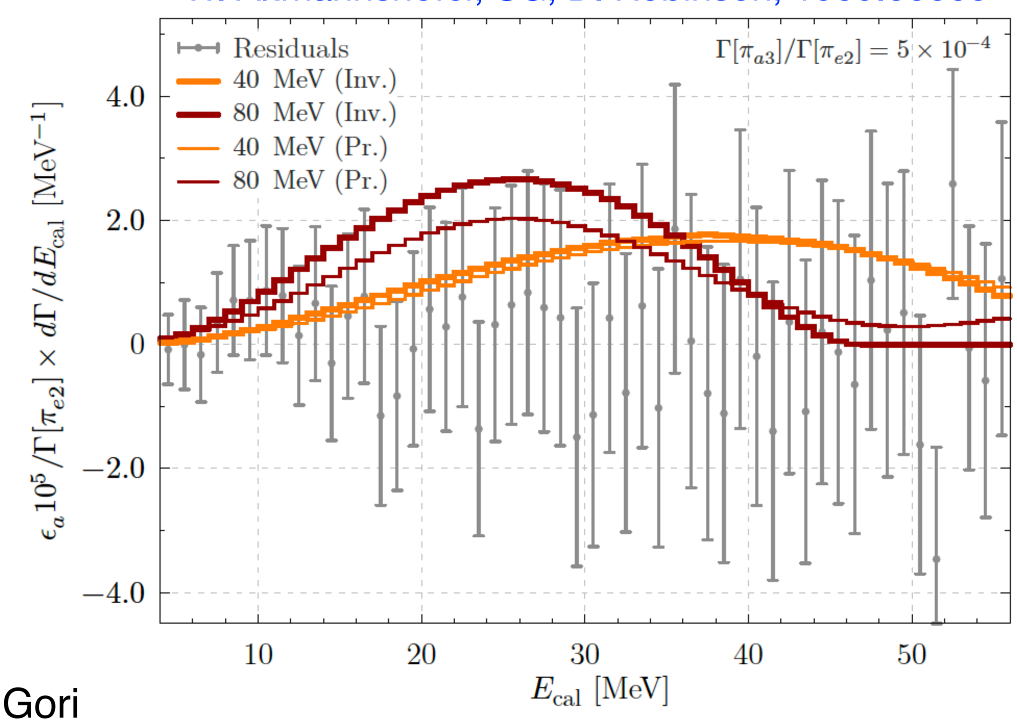
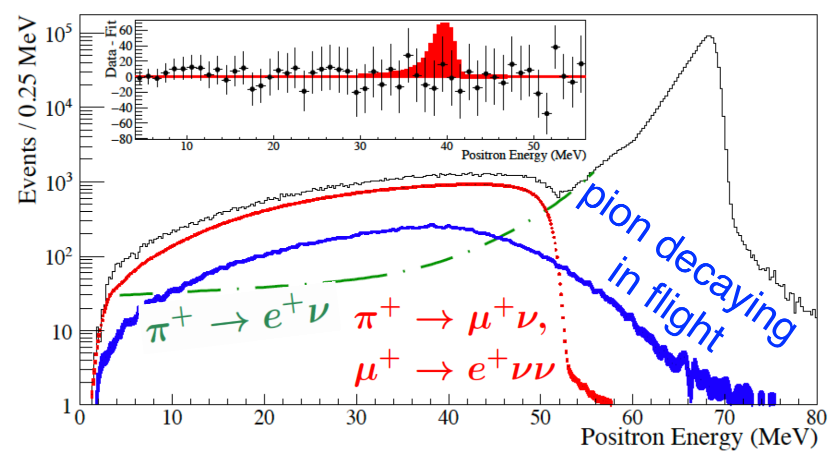


We can compare these distributions with the PIENU residuals:



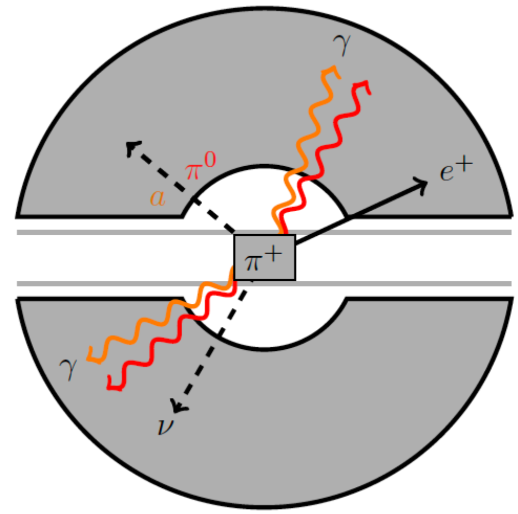
ALPs at PIBETA

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



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

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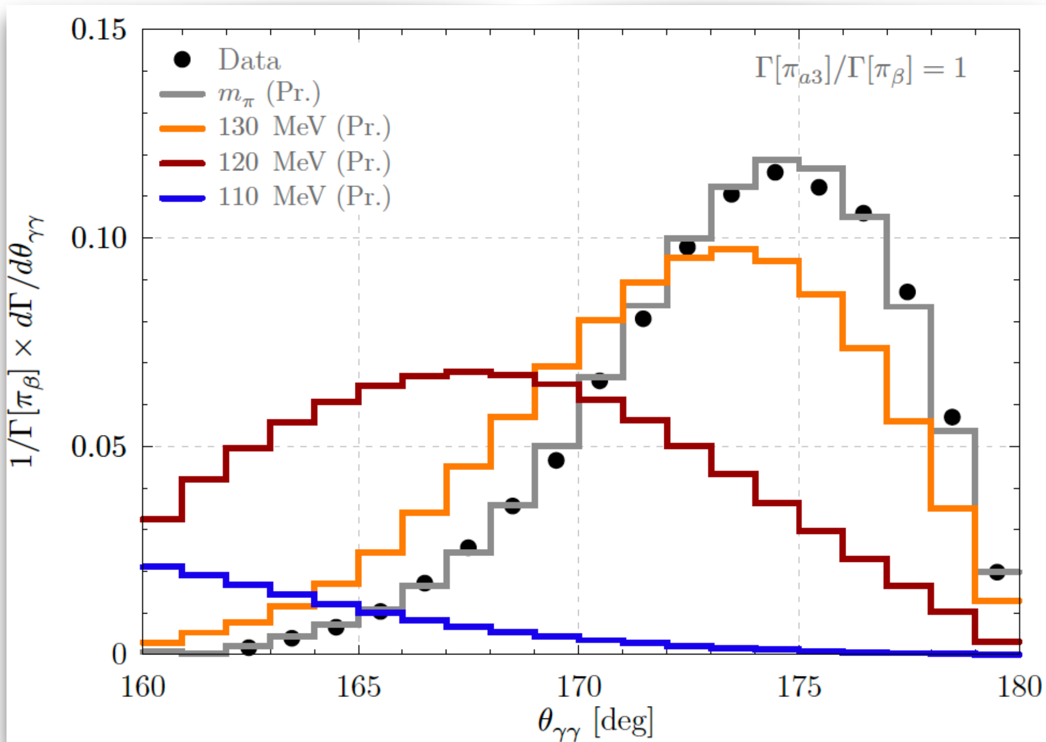
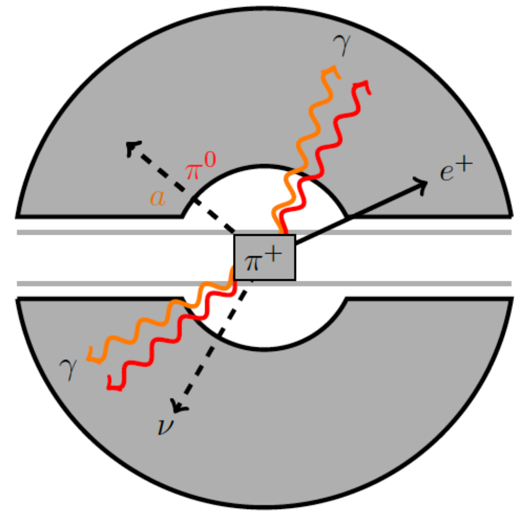


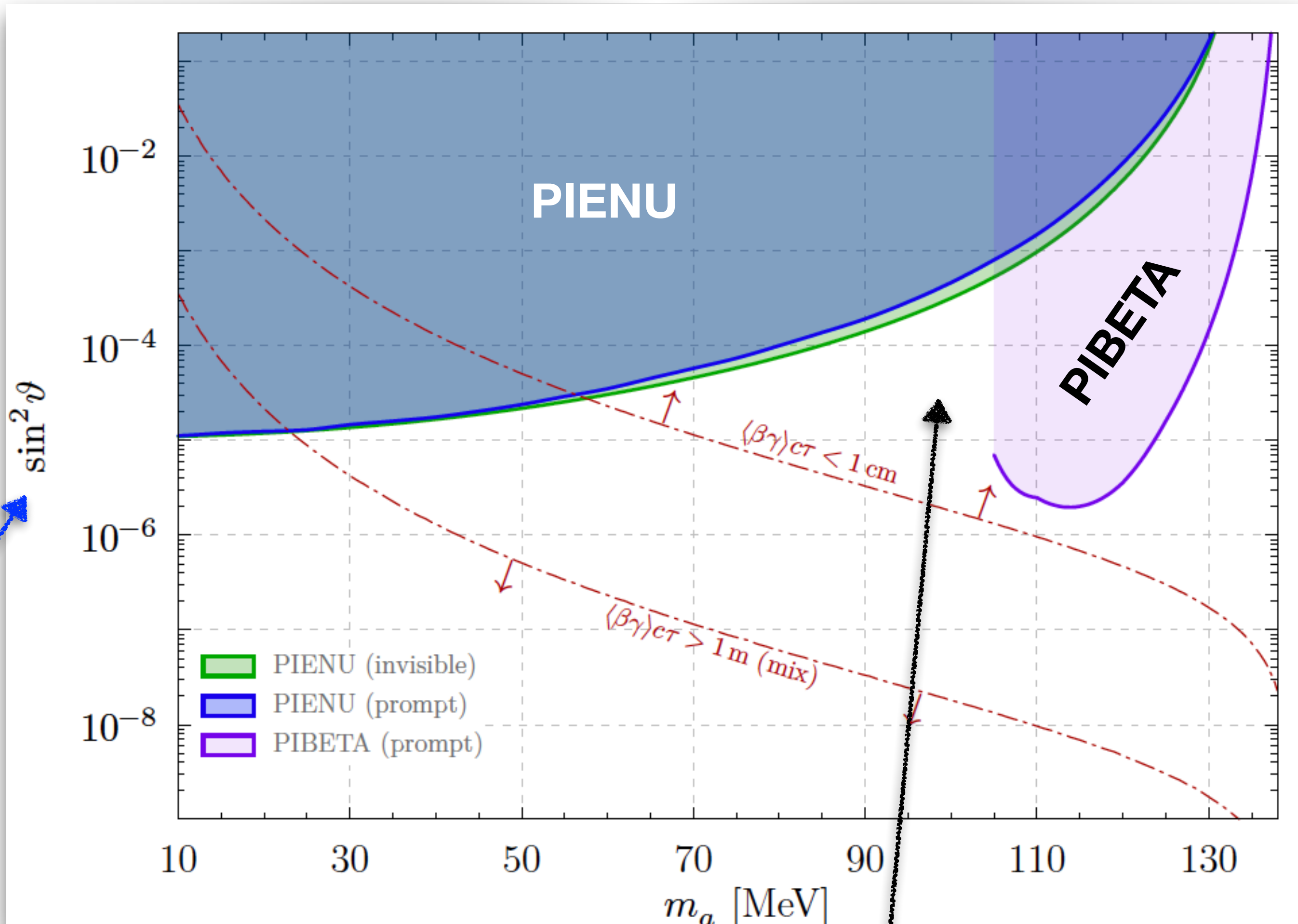


$$-1 \leq \cos\theta_{\gamma\gamma} \leq -1 + 2\left(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\right)^2$$

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

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

2. GG-coupled ALP simplified model

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

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

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

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

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

Theory prediction for K → π a

The ALP-pion and ALP-eta mixing will induce

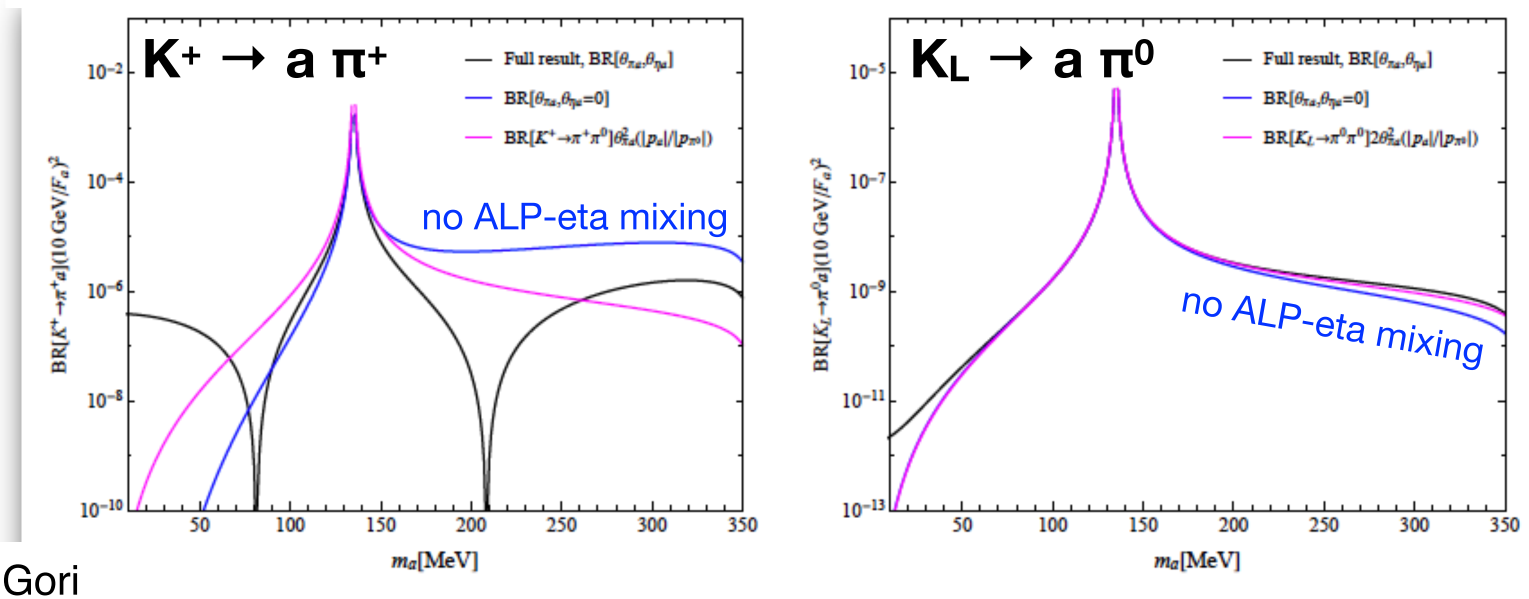
- an effective K-π-ALP coupling (K → aπ)
- an ALP coupling to photons (a → γγ)

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

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

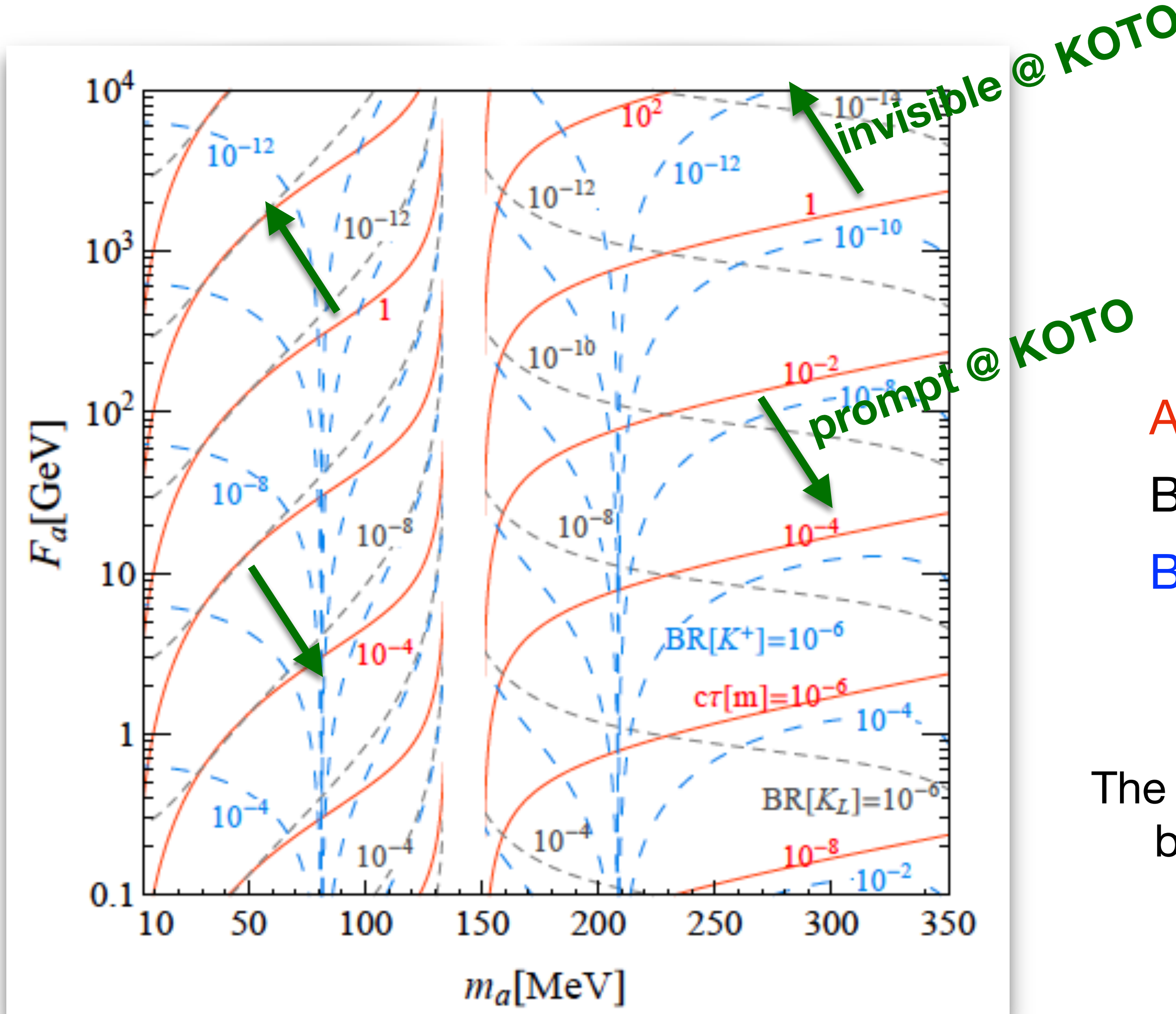
$$\begin{aligned} \pi^0 &\rightarrow \pi^0_{\rm phy} + \theta_{\pi a} a_{\rm phy} \\ \eta &\rightarrow \eta_{\rm phy} + \theta_{\eta a} a_{\rm phy} \end{aligned}$$

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



Note:
possible additional UV contributions

GG-coupled ALP pheno



ALP lifetime (in meters)

BR($K_L \to \pi$ a)

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

The charged BR is typically larger but there are regions where

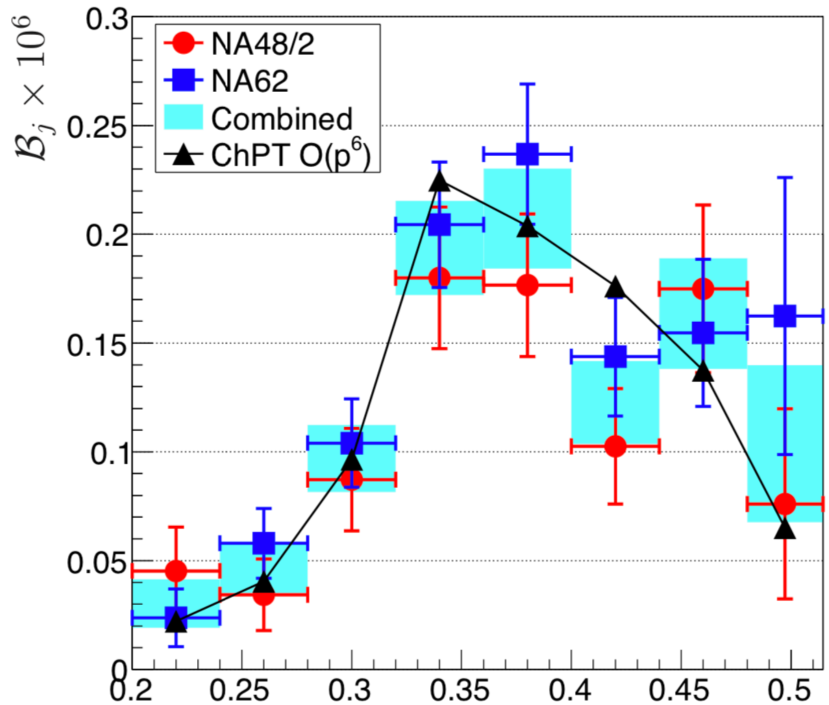
$$\frac{\mathrm{BR}(\mathrm{K_L} \to \pi^0 \mathrm{a})}{\mathrm{BR}(\mathrm{K}^+ \to \pi^+ \mathrm{a})} \gg 1$$

K → π X , X → γ γ (charged mode)

K⁺ → π⁺ γ γ has been searched for at:

- at the **E949** experiment 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)



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

~10^9 K⁺ in the fiducial region

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.

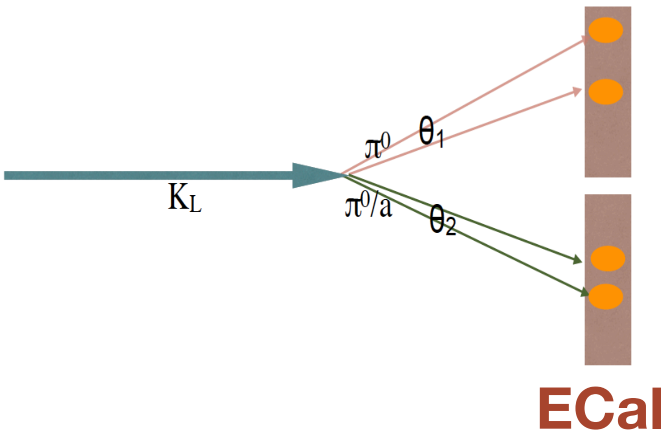
$$220 \text{ MeV} \lesssim m_{\gamma\gamma} \lesssim 350 \text{ MeV}$$

$K \to \pi\, X$, $X \to \gamma\,\gamma$ (neutral mode)

- KTeV analysis for $K_L \to \pi^0 \gamma\gamma$
- Our new proposed search for KOTO: $K_L \to \pi^0 X \to 4\gamma$

Challenges of the search:

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



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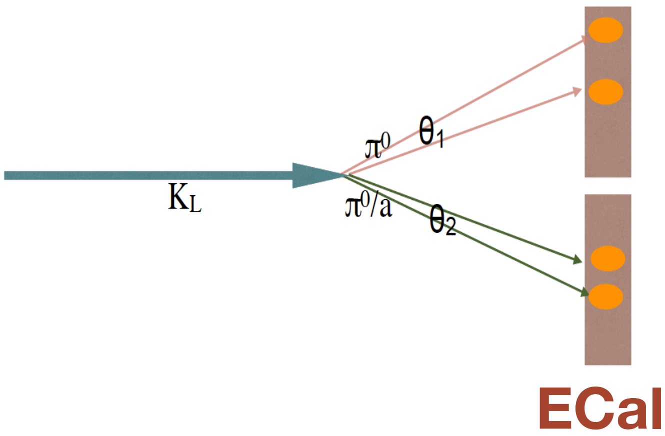
- combinatorics of γγ pairs

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 vertex resolution! (~5cm) and small energy smearing (~2%)

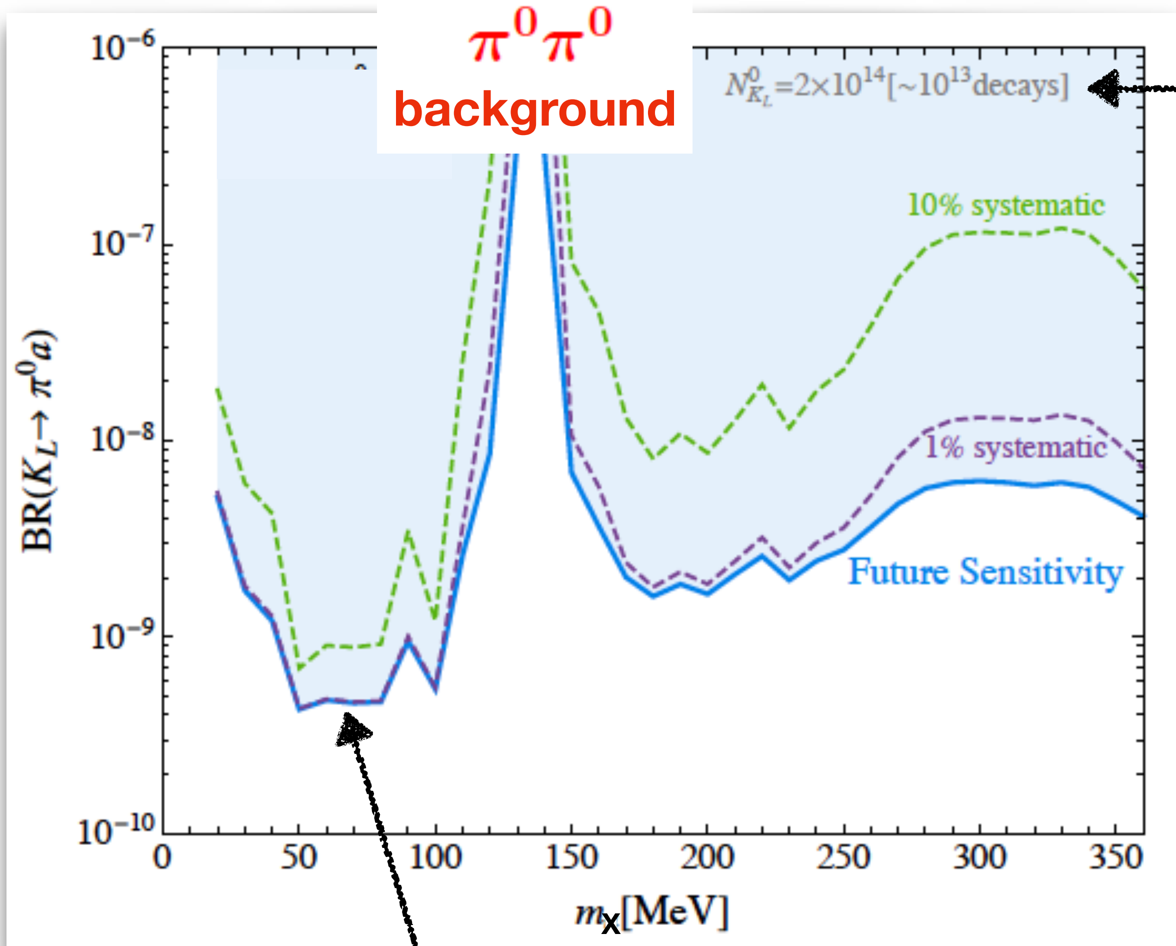
We simulate the main sources of background:

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

mainly for $m_a \sim m_{pion}$

The KOTO reach

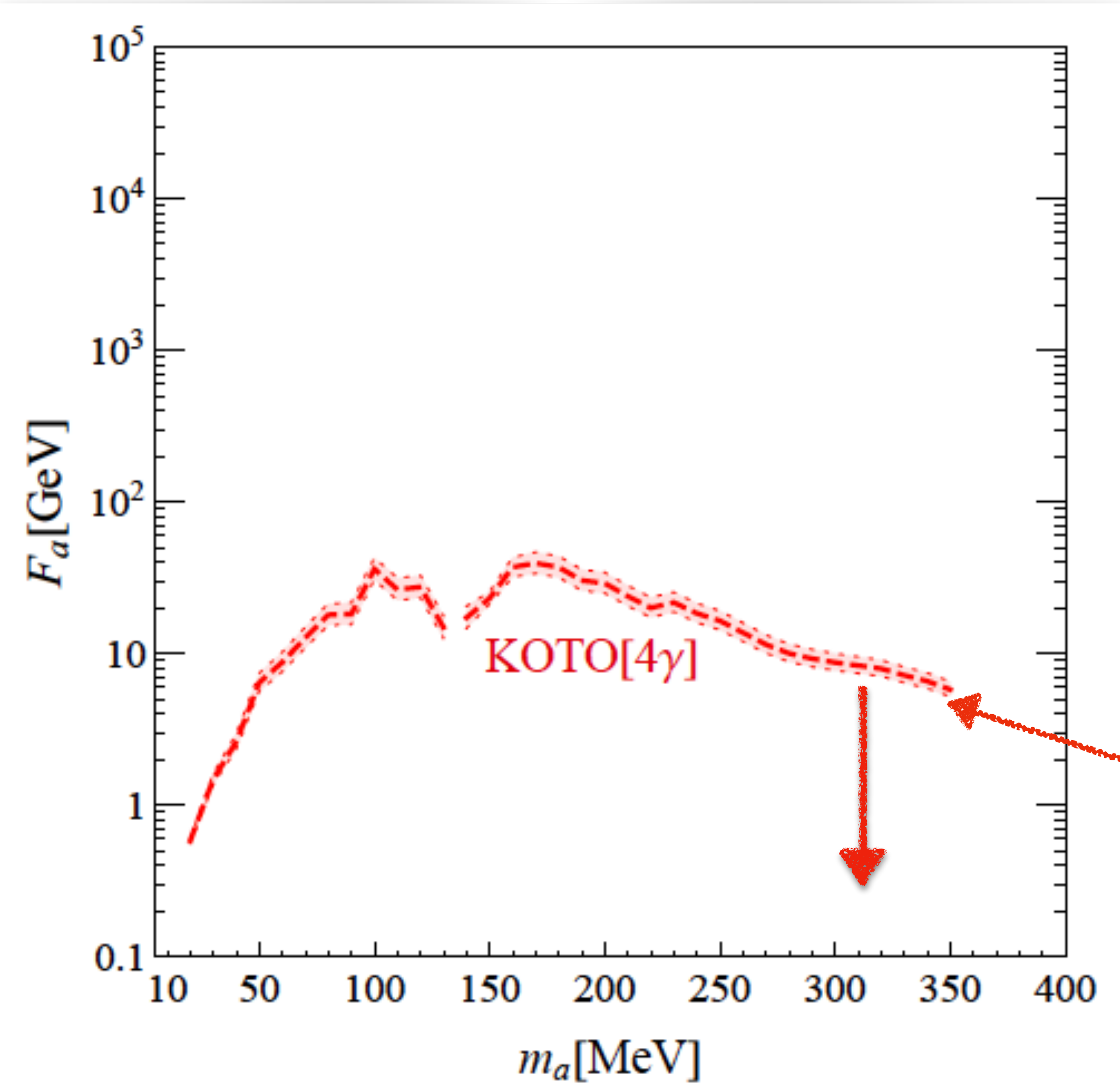
$$\boxed{K_L \to \pi^0 X \to 4\gamma}$$



Ultimate KOTO luminosity goal

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

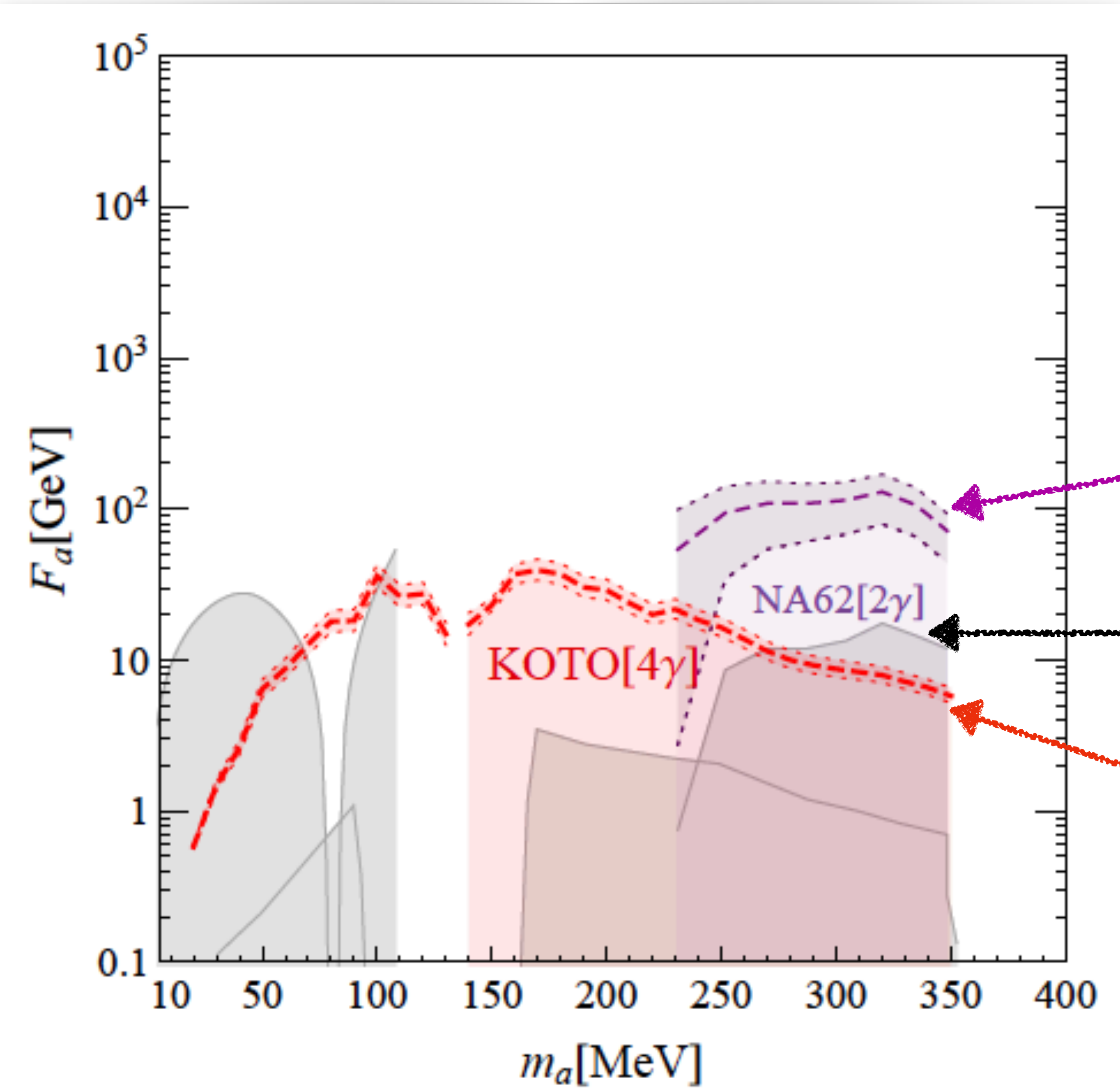
$aG\tilde{G}$ at KOTO



KOTO (proposed) search for

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

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

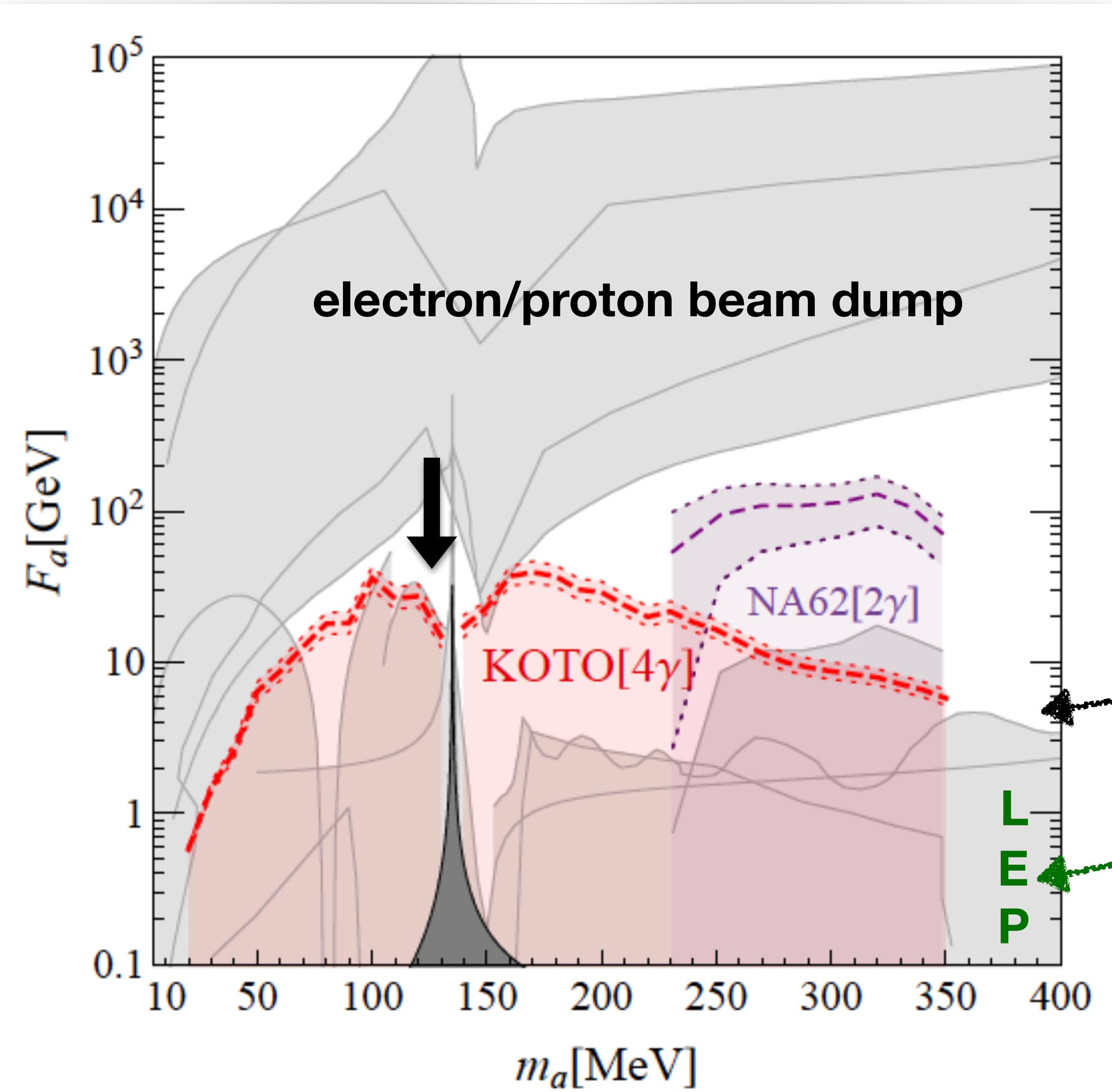


projection with
the full NA62 luminosity
$K^+ \to \pi^+ a, \; a \to \gamma\gamma$

NA48/62 search for
$K^+ \to \pi^+ a, \; a \to \gamma\gamma$

KOTO (proposed) search for
$K_L \to \pi^0 a, \; a \to \gamma\gamma$

Complementarity with other experiments



In gray,
we show all present constraints

This bound comes from precision pion experiments

(new interpretation of existing PIBETA data for $\pi^+ \to \pi^0 (\to \gamma\gamma) e^+ \nu$)

W. Altmannshofer, SG, D. Robinson, 1909.00005

GlueX,
Aloni et al., 1903.03586

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

3. Class of models for the KOTO anomaly

1. 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

$K \to \pi$ ($X \to$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 $K^+ \to \pi^+ \pi^0$ background in this region.

(Fuyuto et al, 1412.4397)

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(Fuyuto et al, 1412.4397)

2. Light New Physics (X) that **breaks** the GN bound (produced from Kaon decays)

(e.g. SG, G. Perez, K. Tobioka, 2005.05170)

3. Exotics:

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

An (incomplete) list of pheno interpretations:

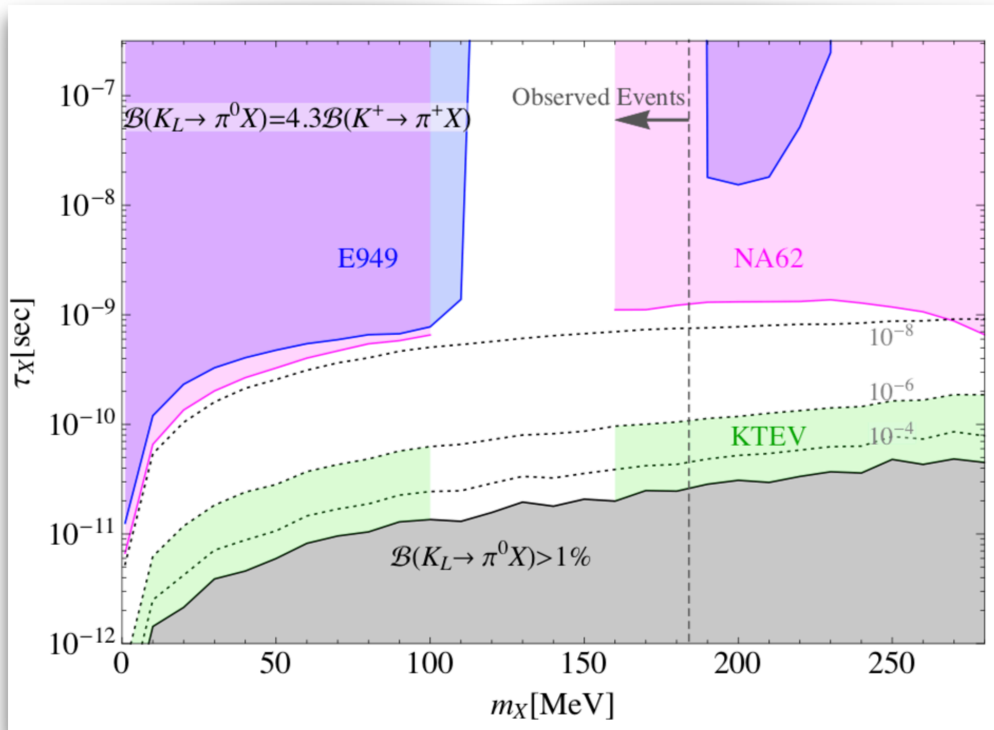
Kitahara et al. 1909.11111; Egana-Ugrinovic et al. 1911.10203; Dev et al. 1911.12334
Jho et al. 2001.06572; Liu et al. 2001.06522; He et al. 2002.05467; Ziegler et al. 2005.00451; Liao et al. 2005.00753; Hostert et al. 2005.07102; Datta et al. 2005.08920; Altmannshofer et al. 2006.05064; …

Models addressing the KOTO anomaly

(light new physics satisfying the GN bound)

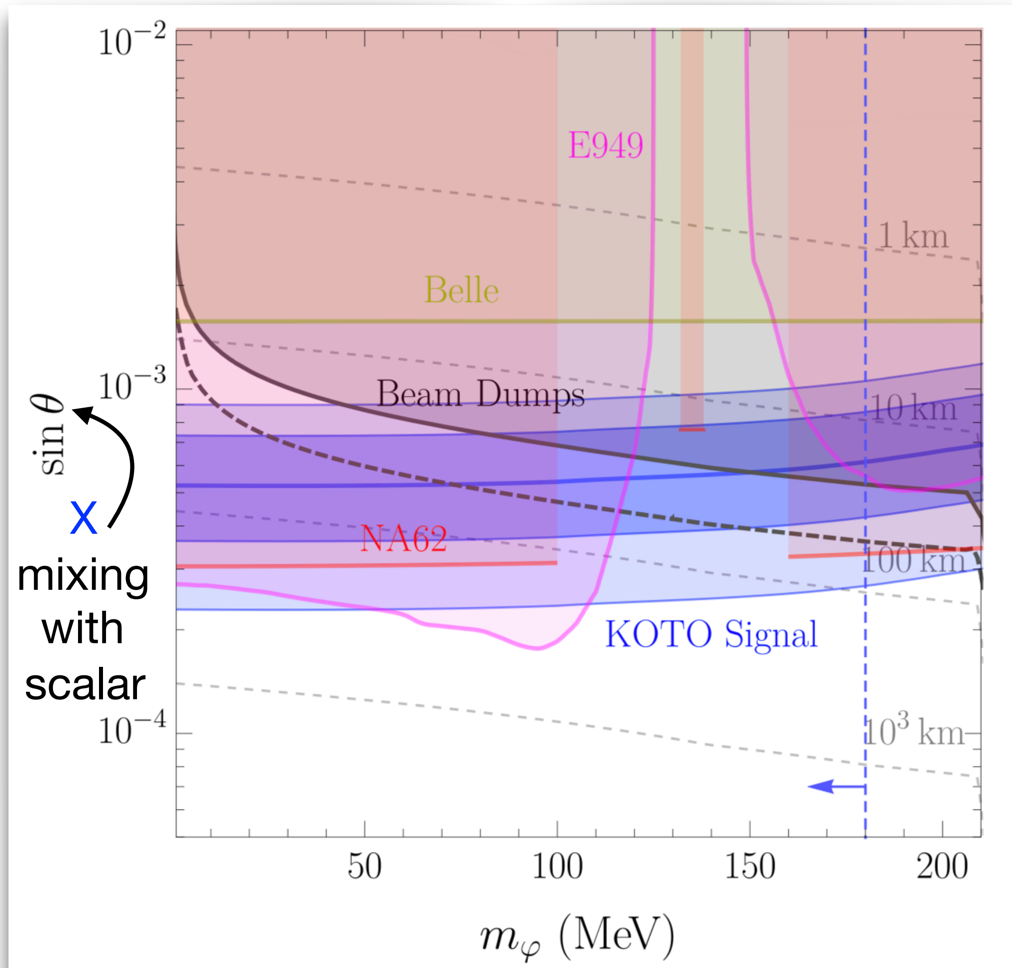
$K \to \pi$ X

Life-time



Kitahara et al.,1909.11111

Mass



Egana-Ugrinovic et al, 1911.10203

(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:

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

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

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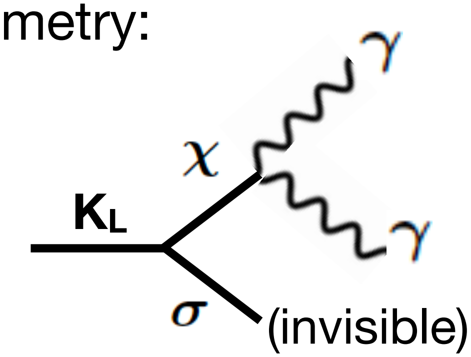
A working model based on an approximate strange flavor symmetry:

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

SG, Perez, Tobioka, 2005.05170



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

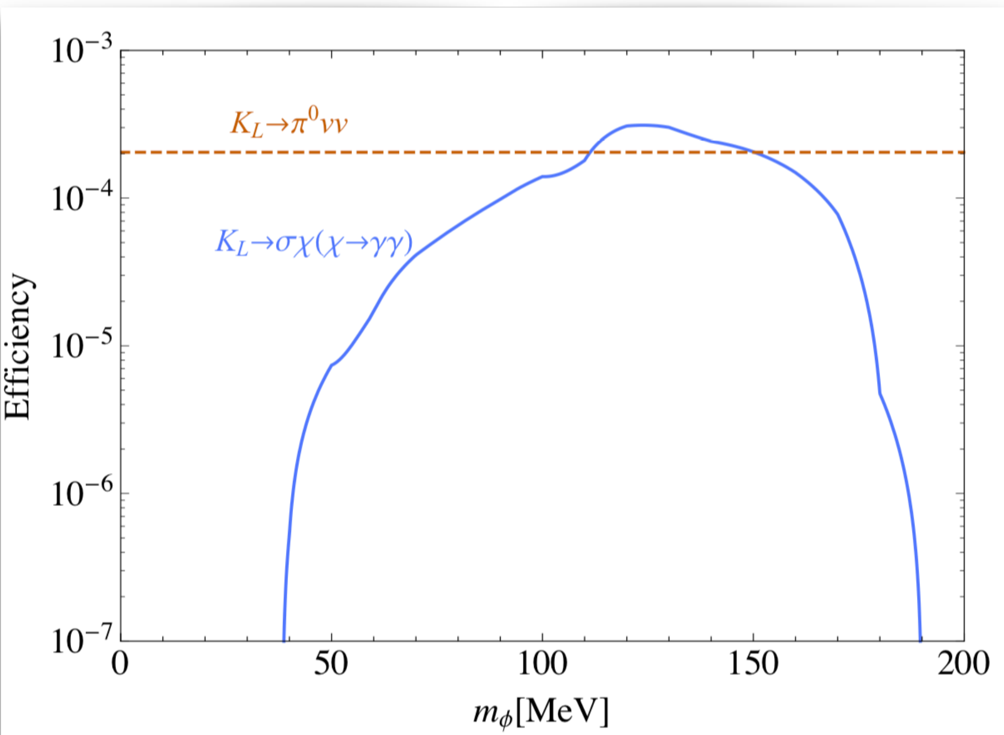
Depending on the ϕ mass, this decay can fall into the KOTO signal region

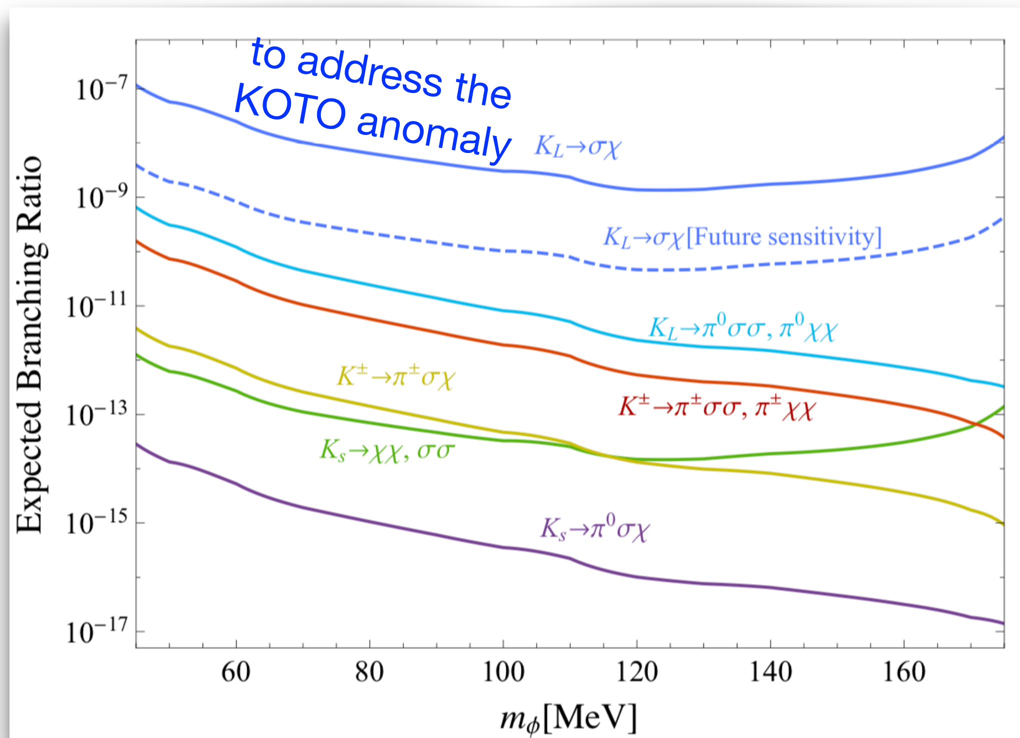
See also Hostert et al. 2005.07102; Altmannshofer et al. 2006.05064

Predictions for Kaon experiments

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

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





SG, Perez, Tobioka, 2005.05170

Conclusions & Outlook

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

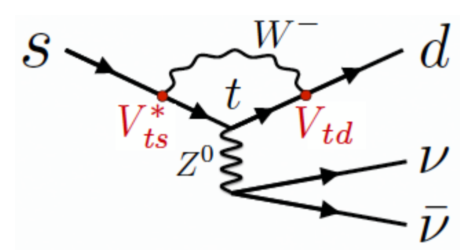
Plenty of opportunities to test dark sectors at these experiments

For this seminar:
testing ALPs at pion & kaon experiments

- New proposed searches & model interpretations.
- Complementarity with other experiments.

Kaon rare decays in the SM: K → π ν ν

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



Very clean decays (mainly short distance contribution)

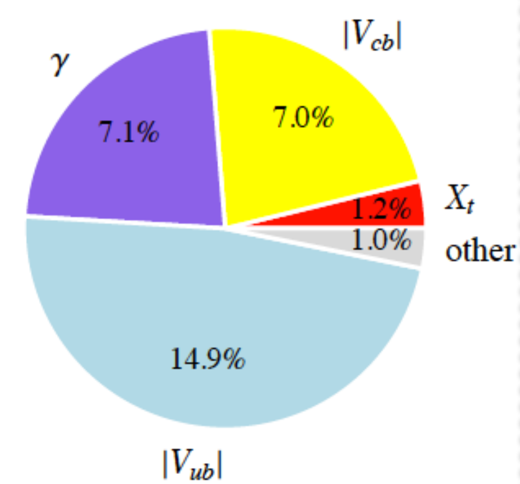
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq \kappa_+ \left| \frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \frac{V_{cs}^* V_{cd}}{\lambda} \left(\frac{X(x_c)}{\lambda^4} + \delta P \right) \right|^2$$

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



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

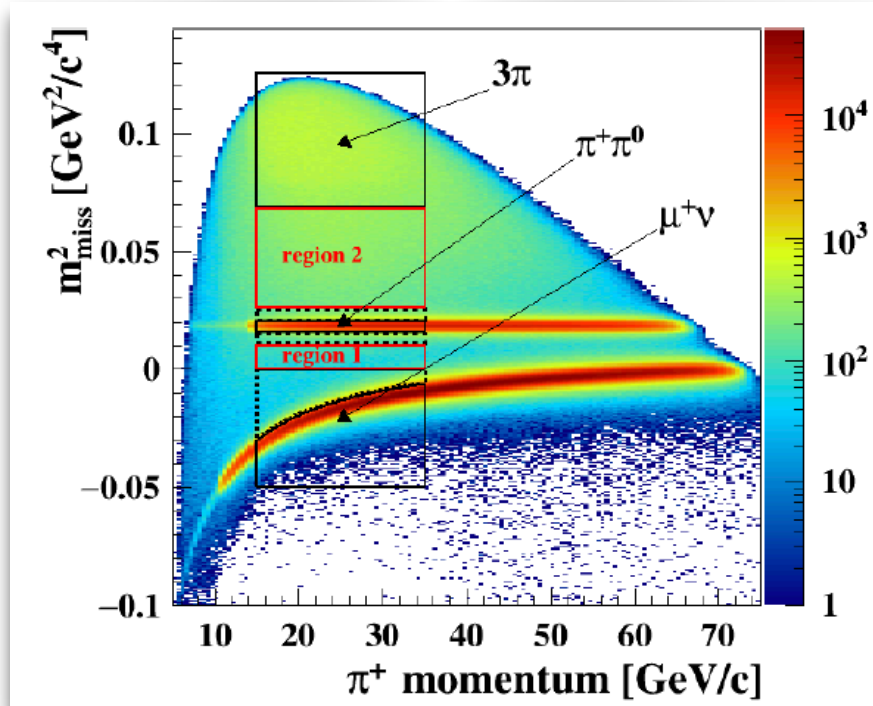
Very rare!
→ Access to NP

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

Status of the NA62 experiment (K^+)

- E949 (past) experiment: 0903.0030

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



- Analysis of the 2016-2017 data

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

3 events observed

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10}$$ (90% C.L.)

2007.08218

- Analysis of the 2018 data

other 17 events observed

NEW

$$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) = (11.0^{+4.0}_{-3.5\ \mathrm{stat.}} \pm 0.3_{\mathrm{syst.}}) \times 10^{-11}$$

3.5σ evidence

Marchevski talk @ ICHEP

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

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

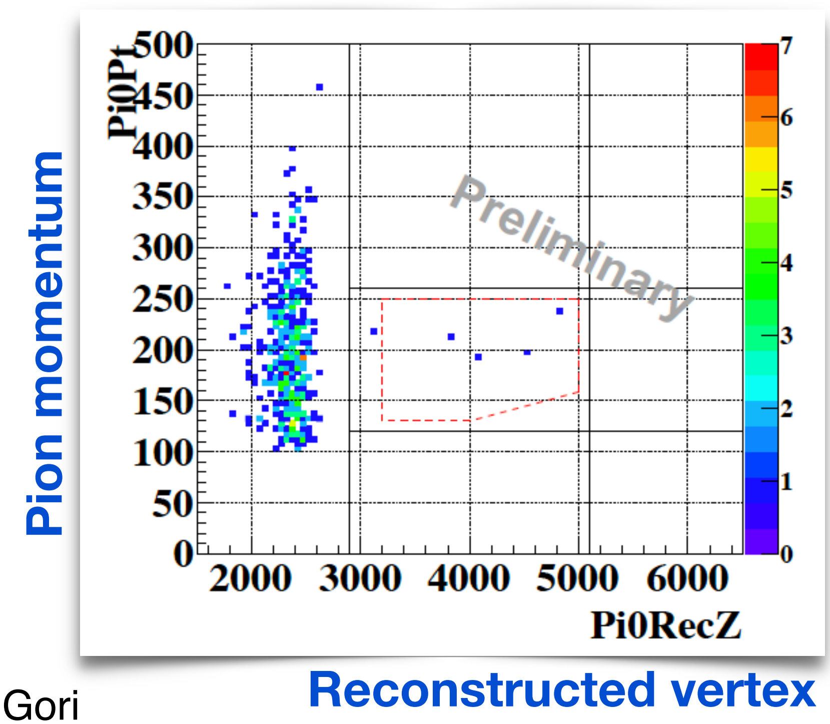
(1609.03637)

* 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



3 events in the signal region! NEW

Expected number of events:

0.05±0.02 → 1.05±0.28 $(K^\pm \to \pi^0 e^\pm \nu)$

(pre → post-ICHEP)

talk by Shimizu @ ICHEP

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

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

The Grossman-Nir (GN) bound

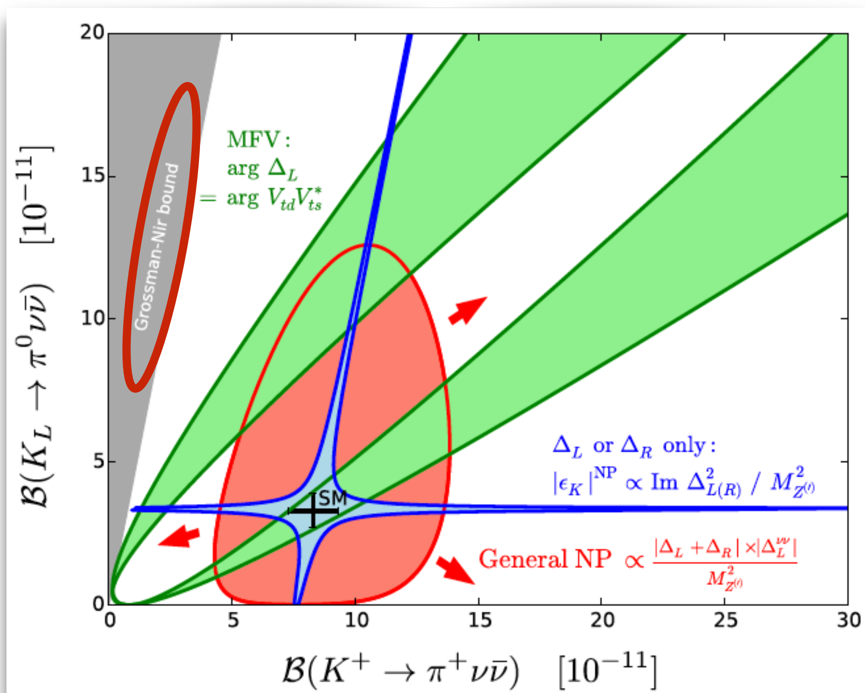
Beyond the Standard model theories can easily induce a New Physics (NP) effect in these very rare Kaon decays.

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

From an EFT perspective:

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

SM operator



Grossman-Nir bound (model independent):

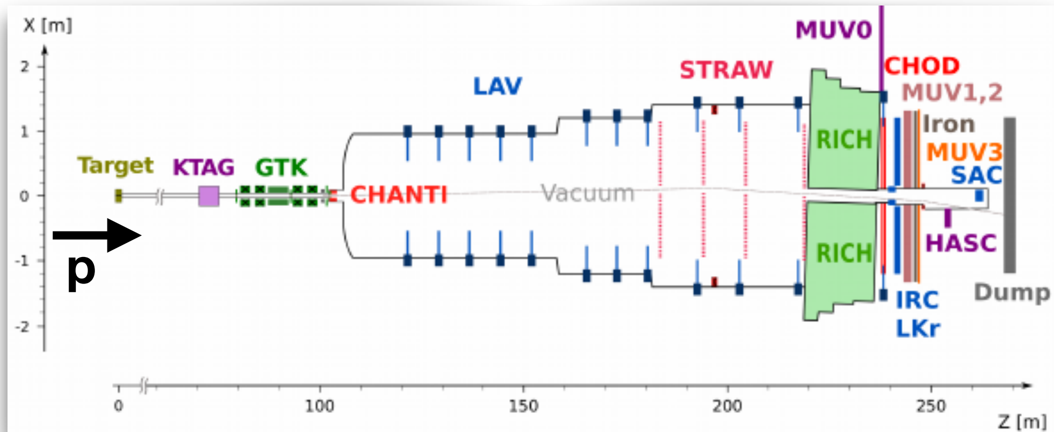
$$\frac{\text{BR}(K_L\to\pi^0\nu\bar{\nu})}{\text{BR}(K^+\to\pi^+\nu\bar{\nu})} < 4.3$$

hep-ph/9701313

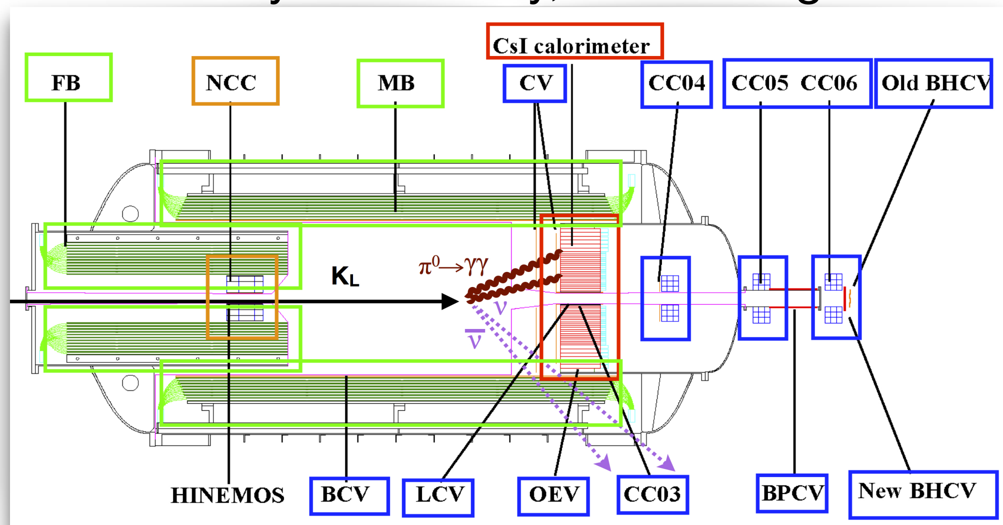
Buras, Buttazzo, Knegjens, 1507.08672

Brief look: NA62 & KOTO

Only calorimetry, no tracking



NA62



KOTO

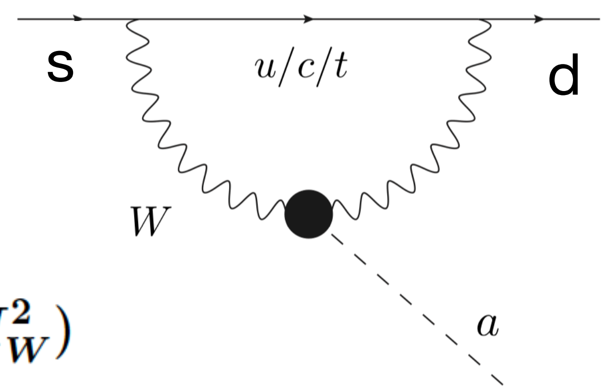
future goals

	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 (past beam dump experiment): $\sim 10^{18}$ POT

WW coupled ALP simplified model

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



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

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

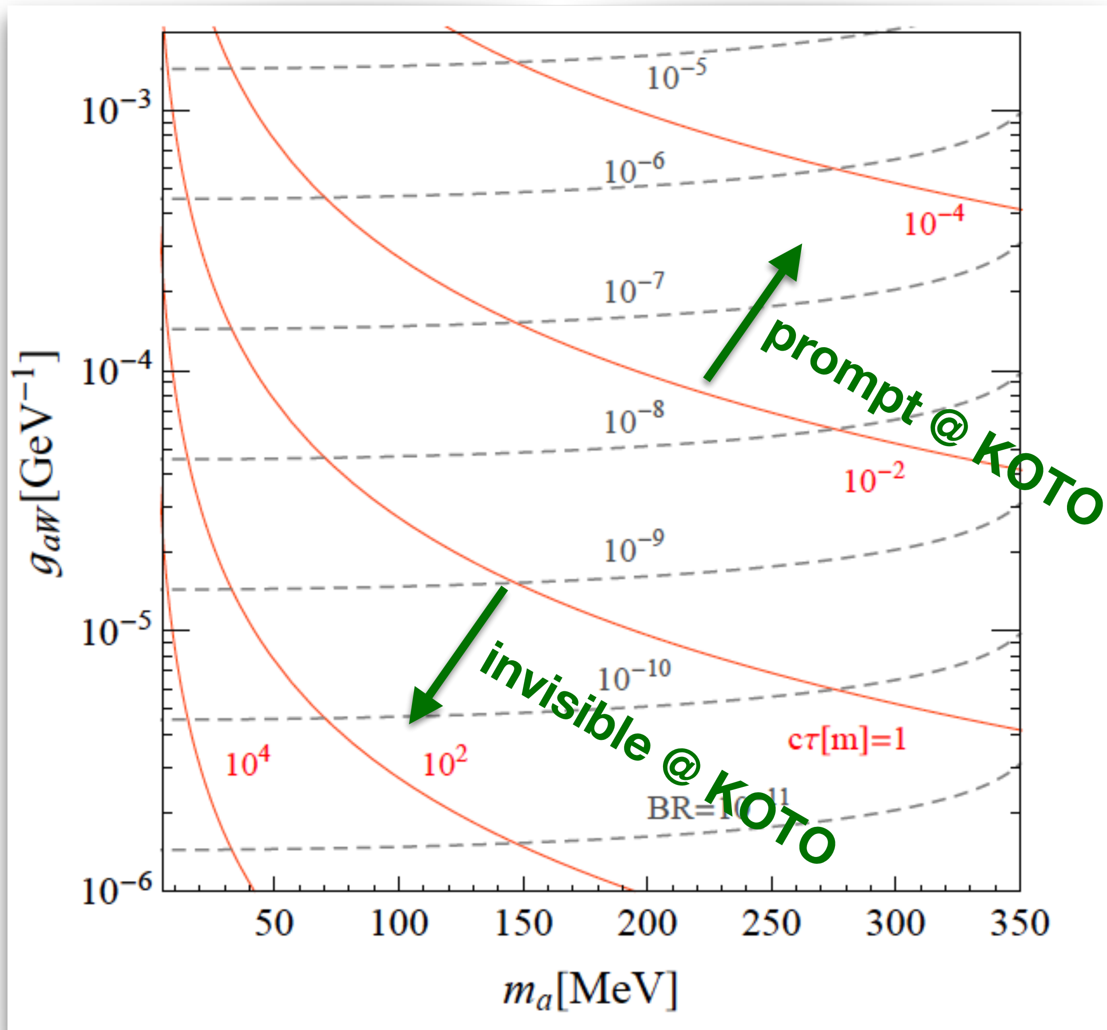
This coupling will induce the decay of the ALP into two photons:

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

Due to isospin, 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

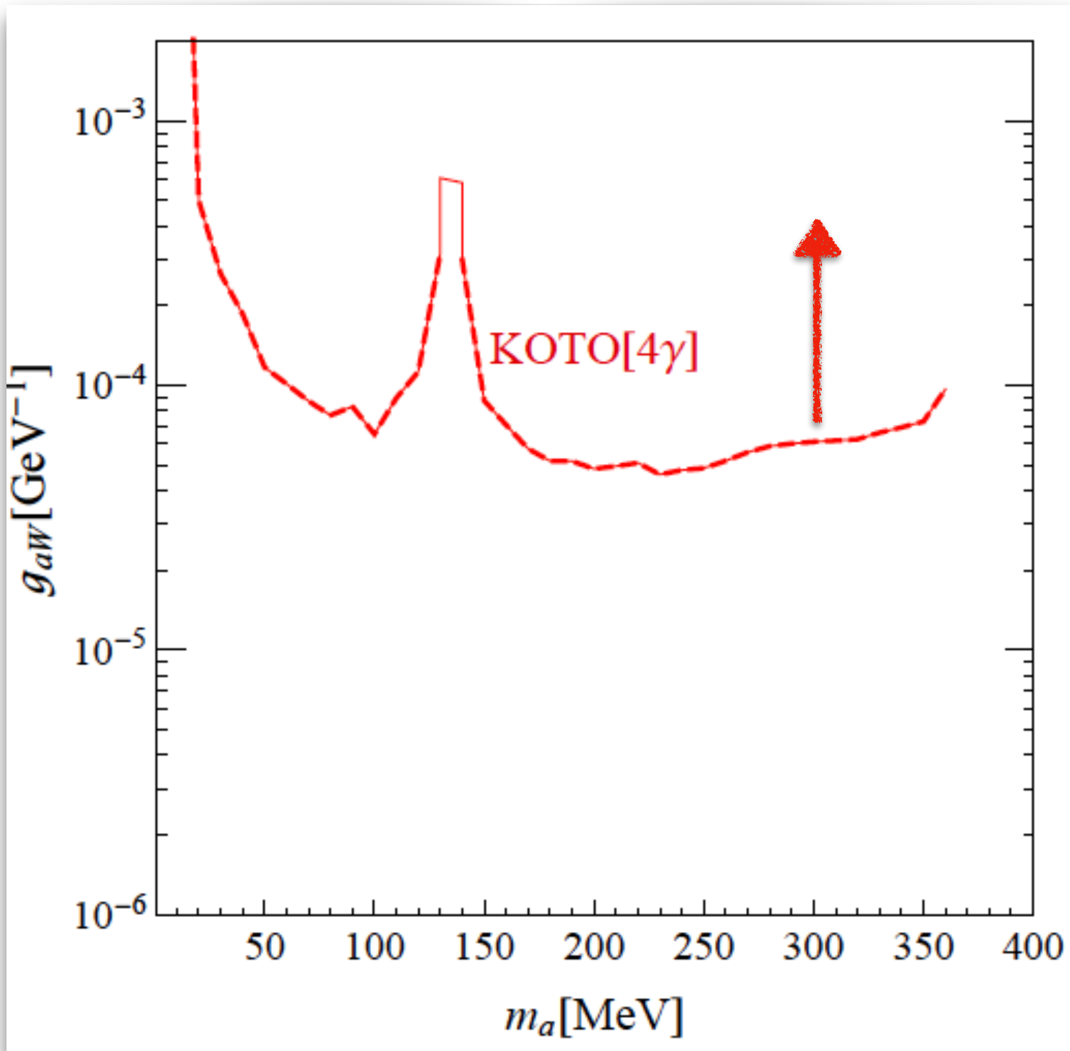


ALP lifetime (in meters)

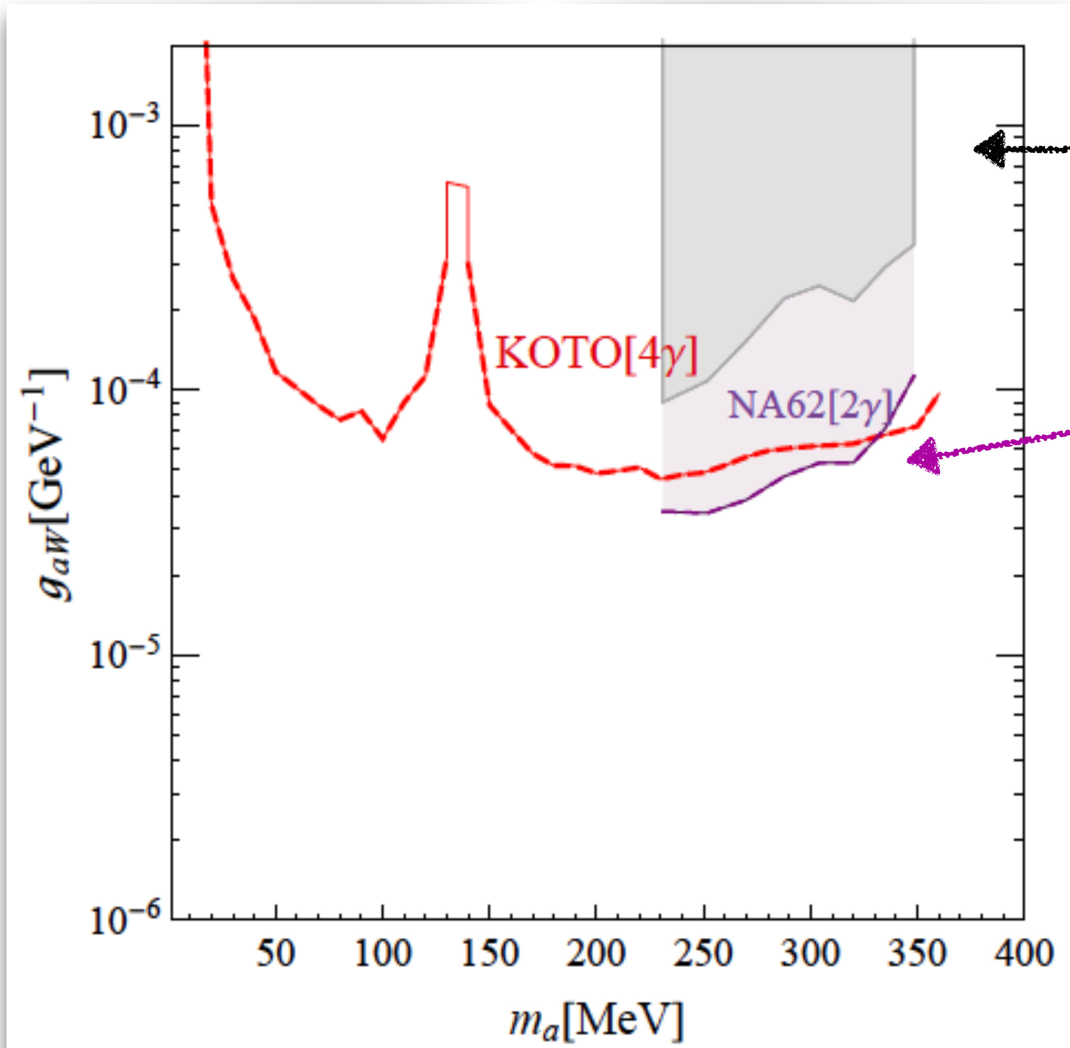
$BR(K_L \to \pi a)$

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

$aW\tilde{W}$ at KOTO



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



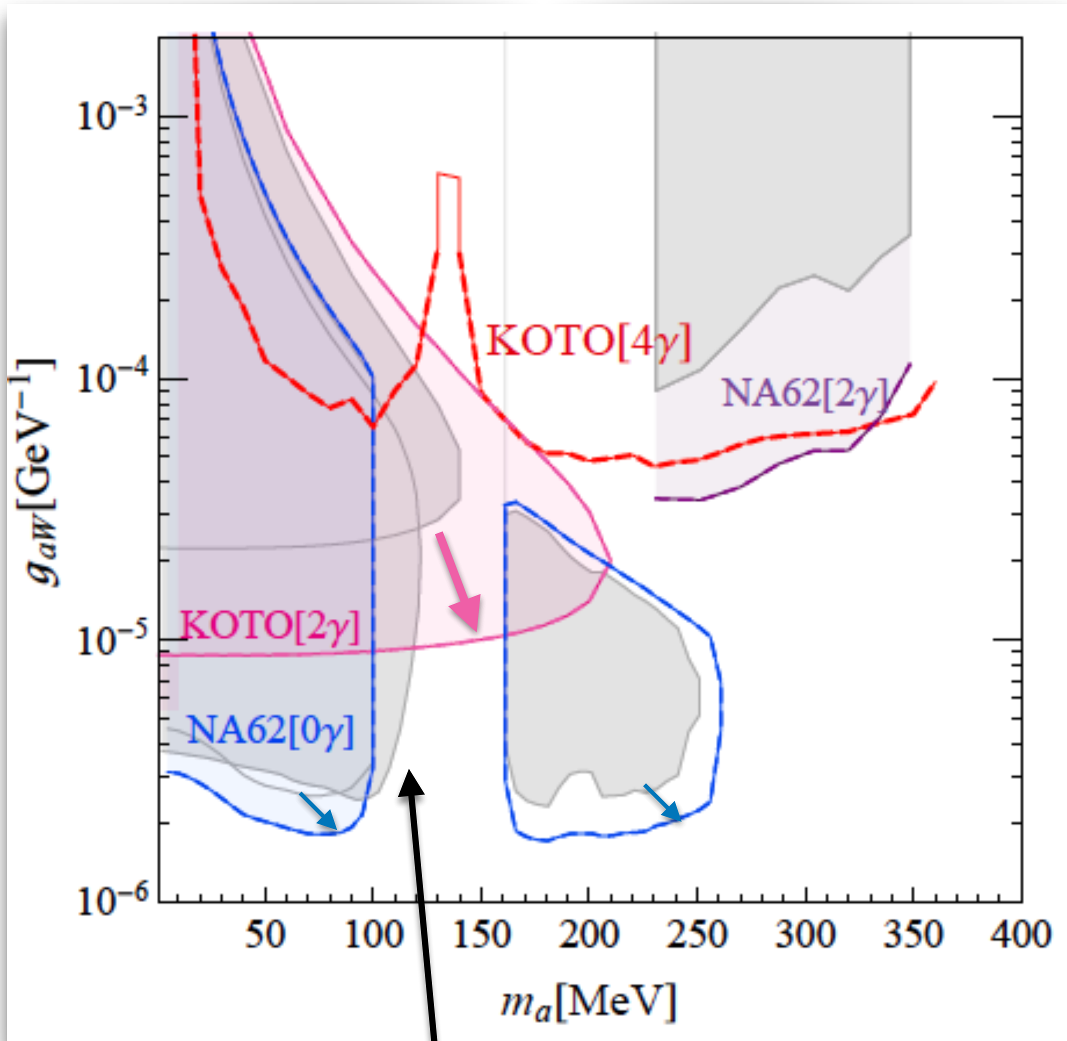
NA48/62 search for

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

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

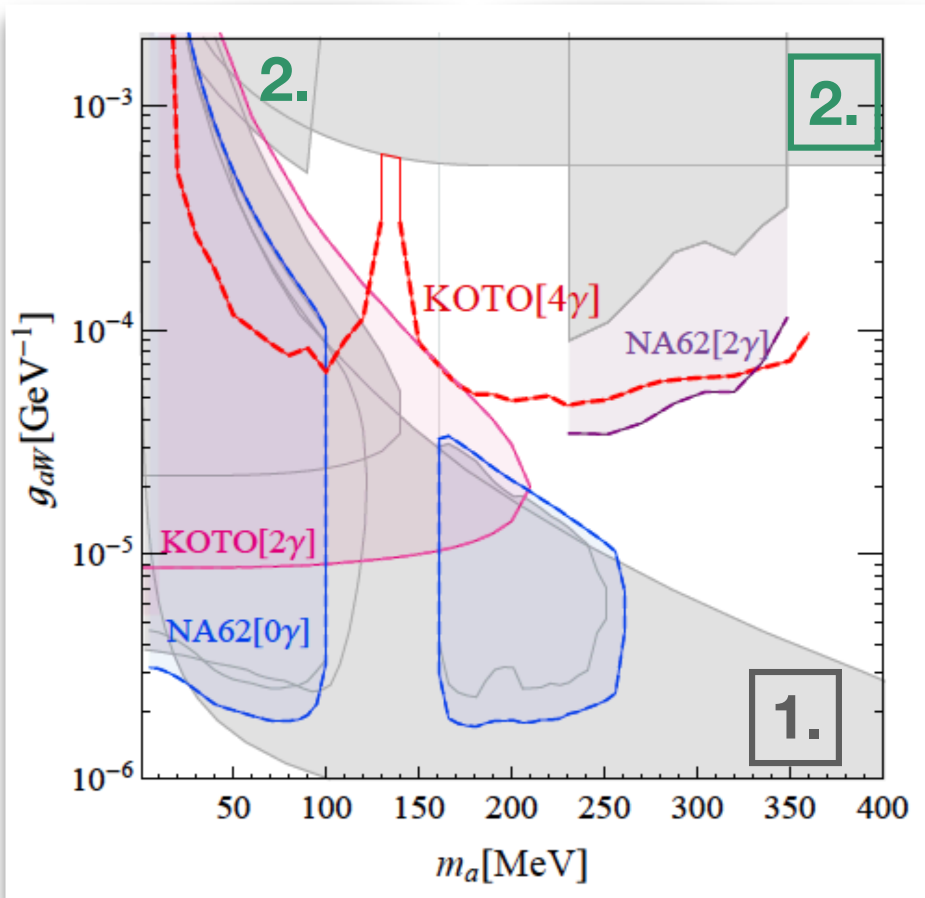
$$K \to \pi + \text{invisible}$$

(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



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!

ALP-pion & ALP-eta mixing

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

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

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

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

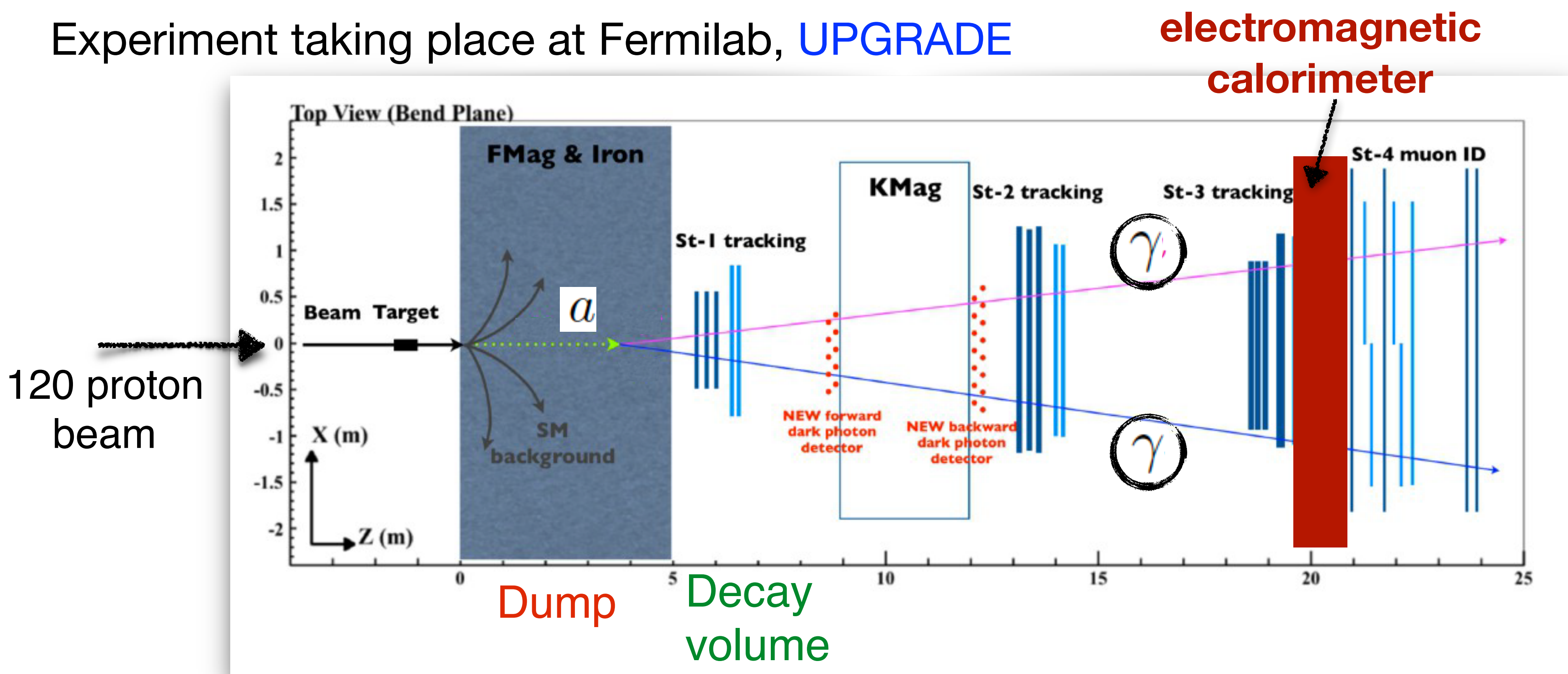
$\theta_{\eta\eta'} \subset -(10-20)^\circ$

Large uncertainties

this is decoupled

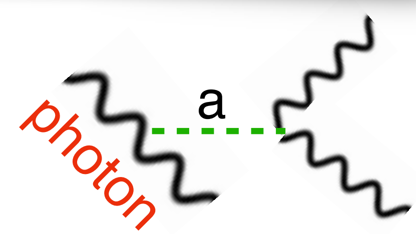
More new measurements coming up? DarkQuest

Experiment taking place at Fermilab, UPGRADE



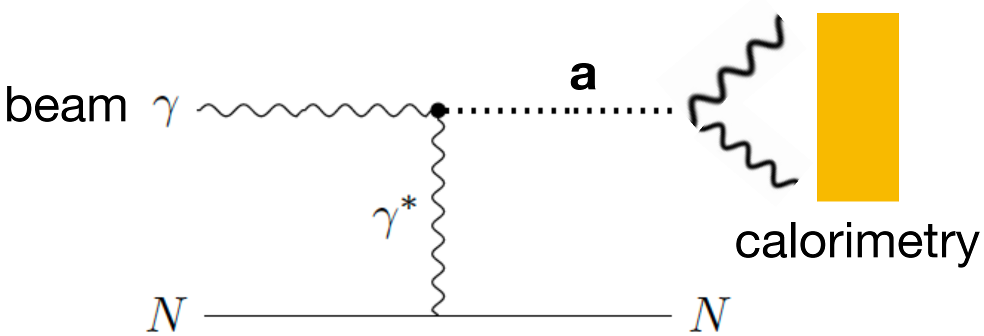
Proposed running after 2022. ~10^{20} protons on target.

Displaced electromagnetic objects (including photons)



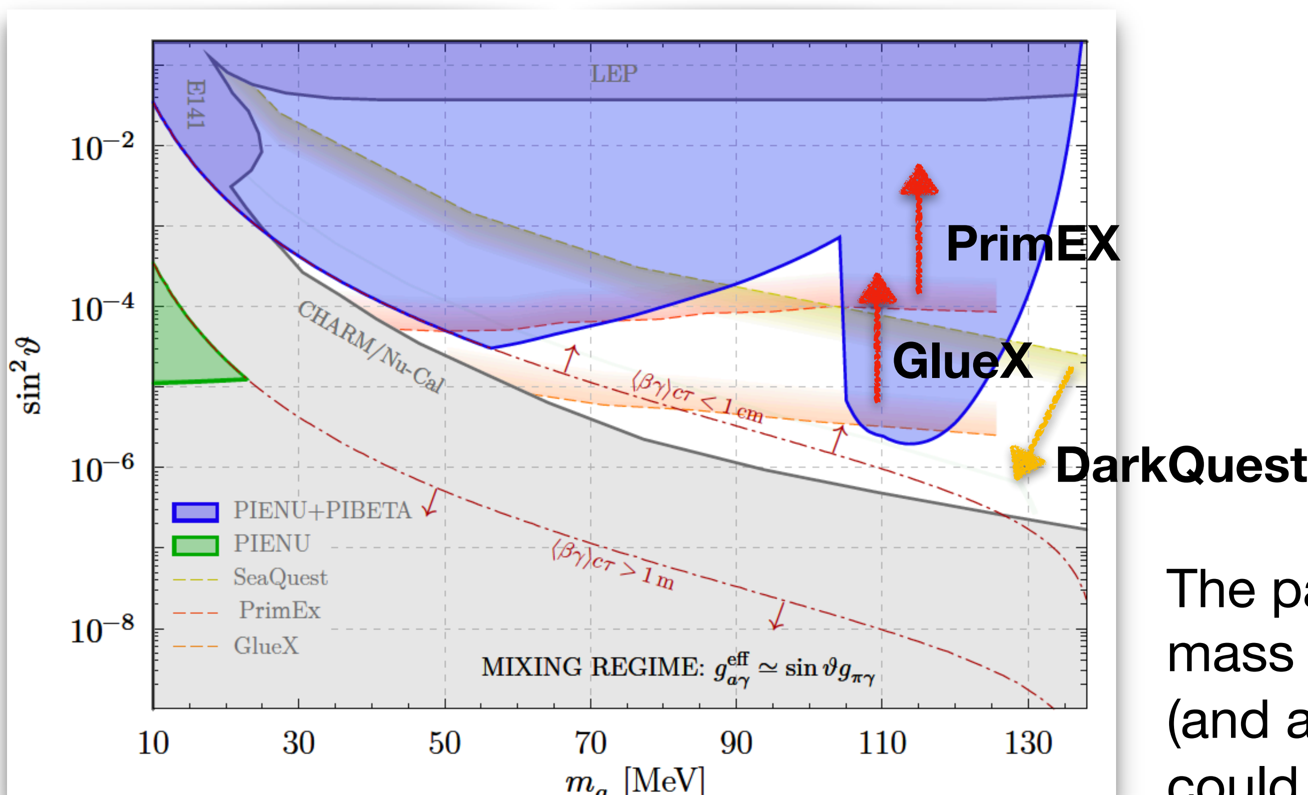
axions radiated from secondary photons produced in the collisions

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