ALPs from light meson decays

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UC Santa Cruz

Summiting the Unknown:
New Physics, New Opportunities, New Voices

University of Washington

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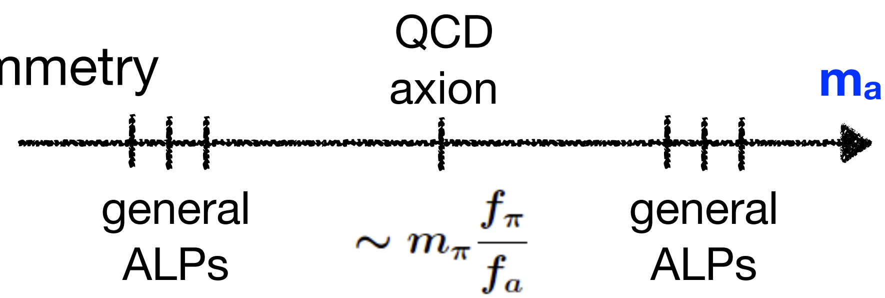
Axion-like-particles (ALPs)

Scalar with an approximate shift symmetry

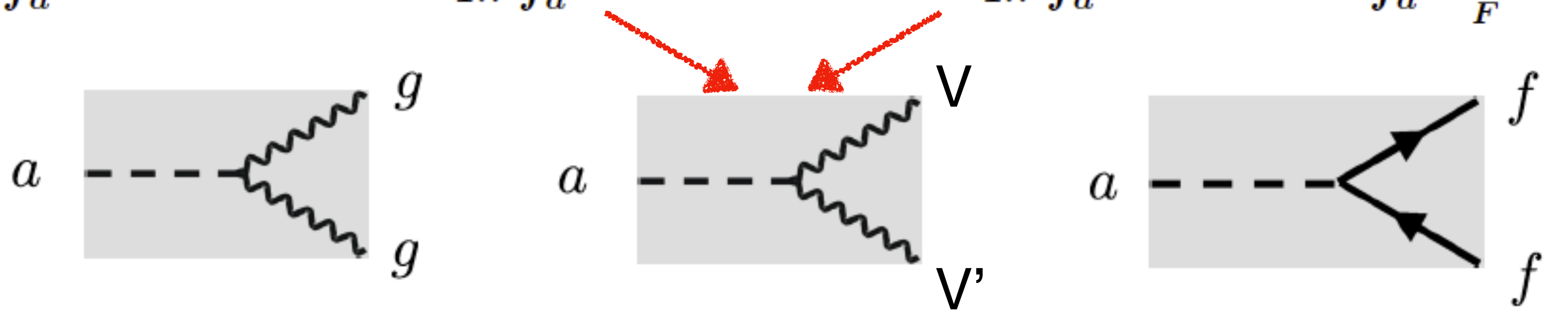
(Possibly) connected to the Strong CP problem:
why is the QCD θ parameter so small?

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Mass can be protected by a Peccei-Quinn symmetry
→ ALPs below the EW scale?



$$\mathcal{L} \supset c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_F \bar{\psi}_F C_F \gamma_\mu \psi_F$$



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

by far the most studied

How to discover this particle in our laboratories?

The precision frontier @ flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
Pion-factories	**PIENU experiment** at TRIUMF: ~10^{11} pi^+	**PIONEER experiment** at PSI (phase 1 approved. Data in ~2028(?)): ~10^{12} pi^+
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
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	**LHCb:** ~40 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced.

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Focus of this talk

Precision pion experiments

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

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

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

Helicity suppressed decay

* Most precise measurement: PIENU experiment @ TRIUMF

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

Mainly stat. uncertainty

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* PIONEER future measurement: ~20 times more accurate

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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

- PIONEER future measurement: ~10 times more accurate

The PIONEER collaboration

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[7] Tsinghua University
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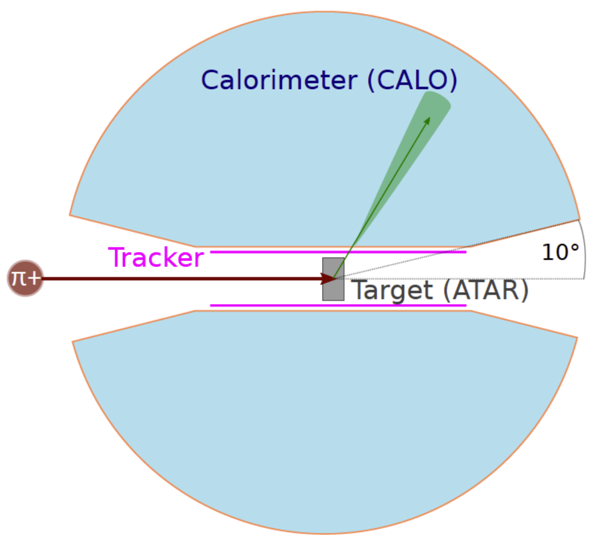
[9] Argonne National Laboratory
[10] University of Zurich
[11] CERN
[12] Tec de Monterrey
[13] Brookhaven National Laboratory
[14] PRISMA+ Cluster of Excellence, University of Mainz
[15] Fermilab
[16] Cornell University
[17] University of Virginia
[18] ETH Zurich
[19] University of Kentucky
[20] University of Bern
[21] KEK
[22] University of Tokyo
[23] University of Mainz
[24] Stony Brook University
[25] University of Victoria
[26] Inst. Div, BNL

Proposal in 2203.01981



Producing ALPs in pion decays

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

The helicity and/or phase space suppression can be lifted

Producing ALPs in pion decays

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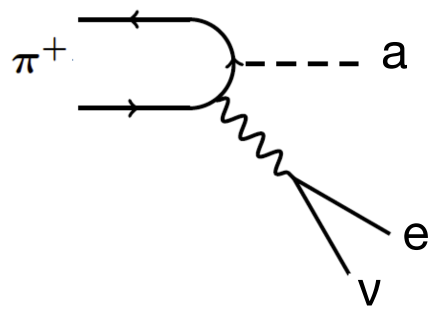
Models can generate a ALP-π^0 mixing

$$-\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \Rightarrow \frac{f_\pi}{\alpha_s} g_{ag} \frac{m_d - m_u}{m_d + m_u}$$

$$i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f) \Rightarrow f_\pi(g_{au} - g_{ad})$$

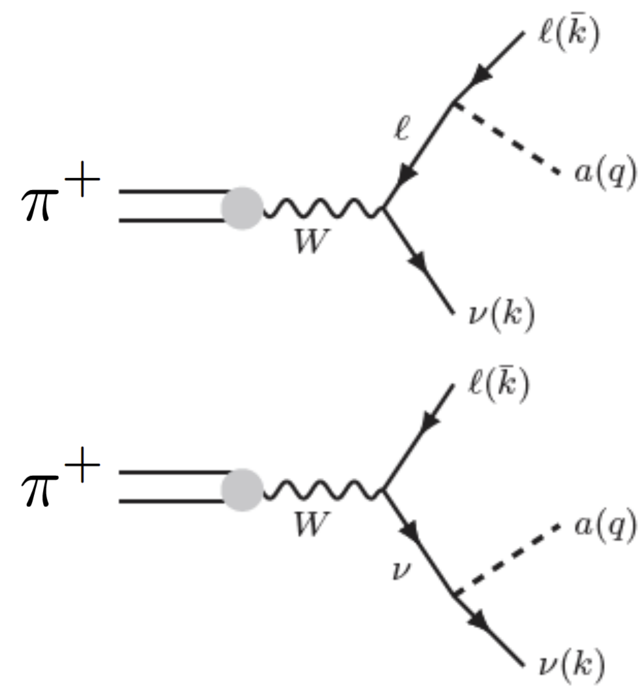
$\mathcal{A}[\pi^+ \to a e \nu] \sim$



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

Chapter 1. Altmannshofer, SG, Robinson, 1909.00005

ALPs can couple to leptons



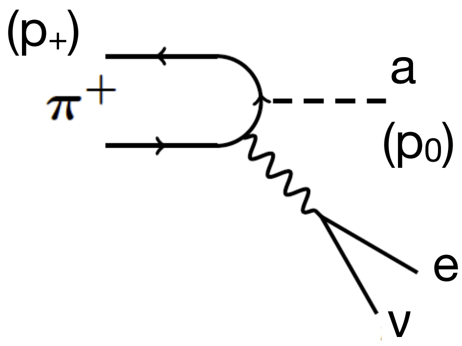
Chapter 2. Altmannshofer, Dror, SG, 2208.xxxxx

Altmannshofer, SG, Robinson,

"Constraining axion-like particles from rare pion decays"

1909.00005

ALP-pion mixing scenario



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

ALP mass

form factors

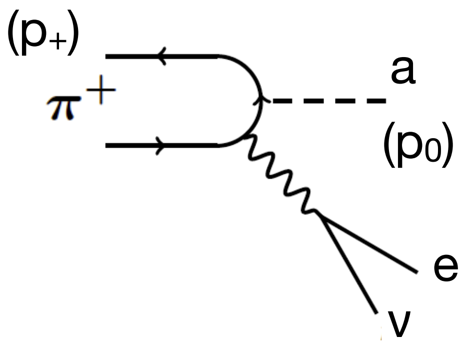
$f_+(q^2) \simeq 1$ as long as q^2 is small ⇨ m_0>~10 MeV

Theory: more understanding of form factors would be needed to get precision constraints for lighter ALPs

$$\frac{\mathrm{BR}[\pi^+\to a e^+\nu]}{\mathrm{BR}[\pi^+\to e^+\nu]} \sim \frac{m_0^4\sin^2\vartheta}{f_\pi^2 m_e^2(1-m_e^2/m_+^2)^2} \times \int_1^{\frac{(m_0^2+m_+^2)}{2m_0m_+}}(w^2-1)^{3/2}dw$$

no helicity suppression

ALP-pion mixing scenario



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no helicity suppression

Once produced, the ALP can

- decay to photons: $g_{a\gamma}^{\mathrm{eff}} = \sin^2\vartheta \frac{\sqrt{2}\alpha}{8\pi f_\pi} + g_{a\gamma}$
- be invisible to our detectors

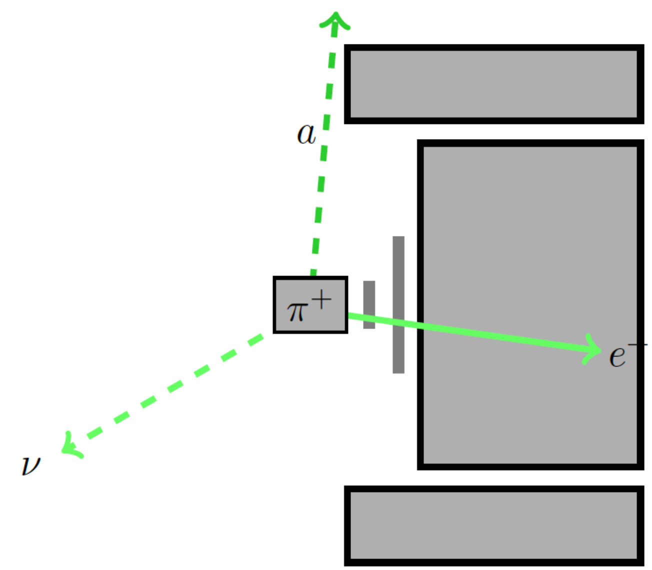
Possible UV contribution

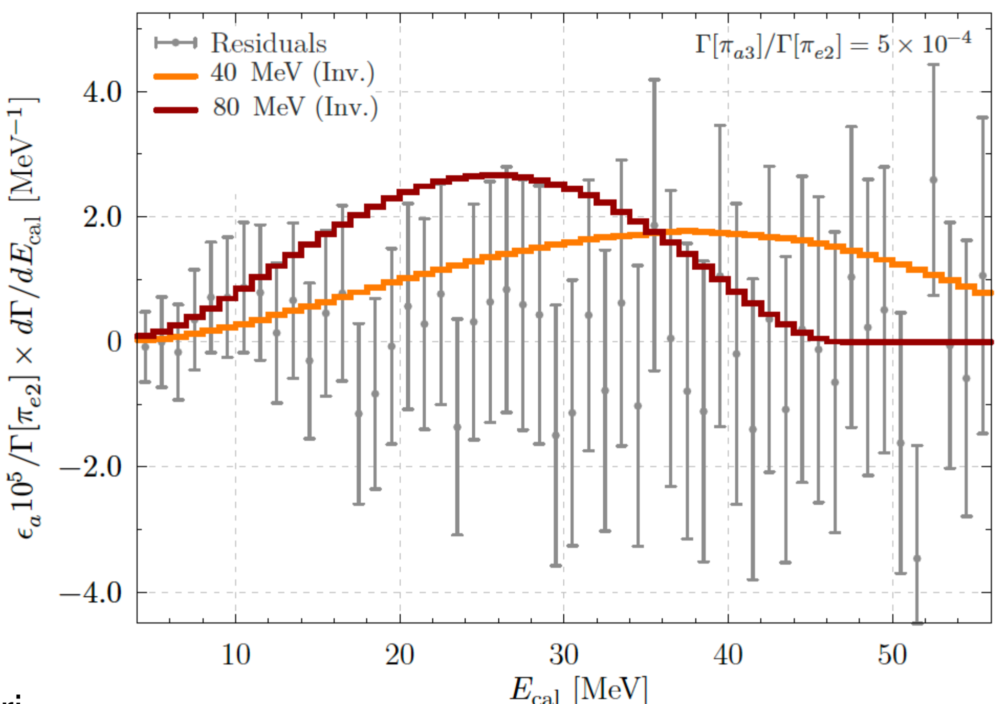
ALPs at PIENU

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

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

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





PIENU residue from the measurement of $\pi^+ \to e^+ \nu$

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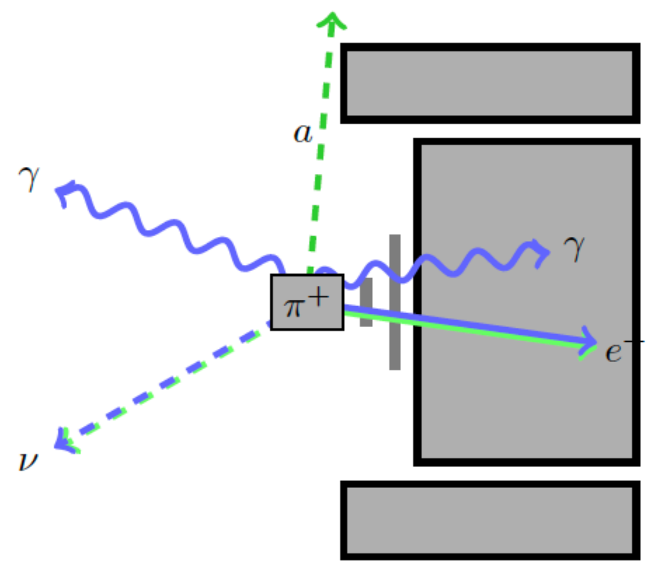
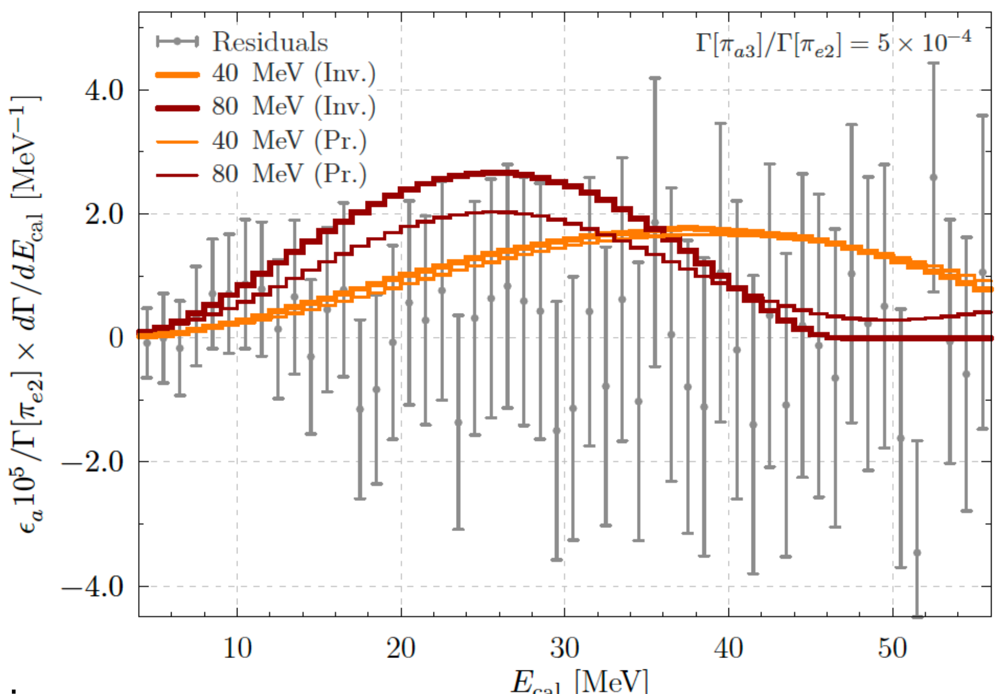


1. <u>Invisible regime:</u> the energy spectrum of the positron depends on the ALP mass.

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



PIENU residue
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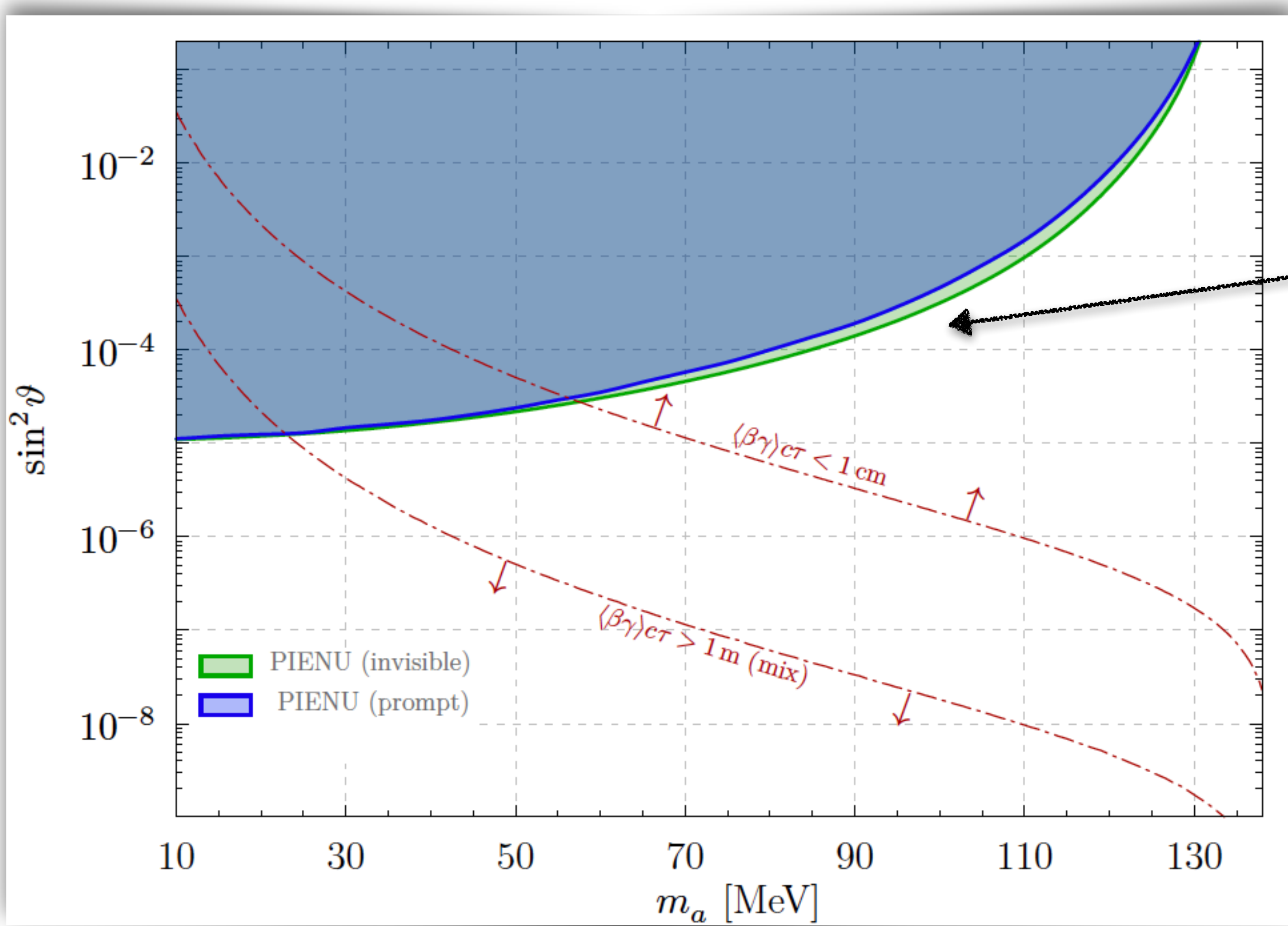
ALP bound from PIENU

Fitting the residuals…



This bound corresponds to $\mathrm{BR}(\pi^+ \to a e^+ \nu) \sim \mathcal{O}(10^{-8})$

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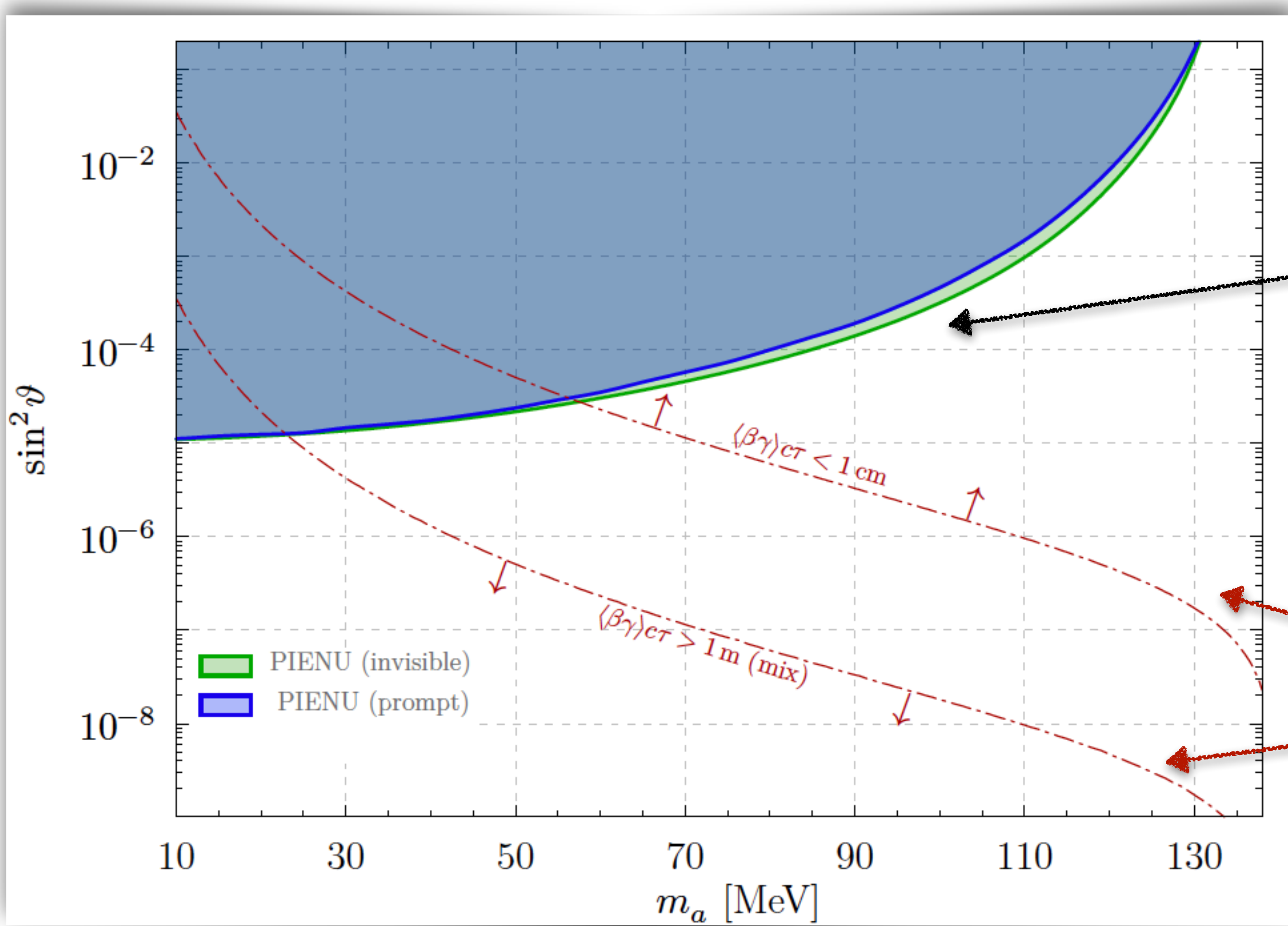

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Life time in the mixing scenario

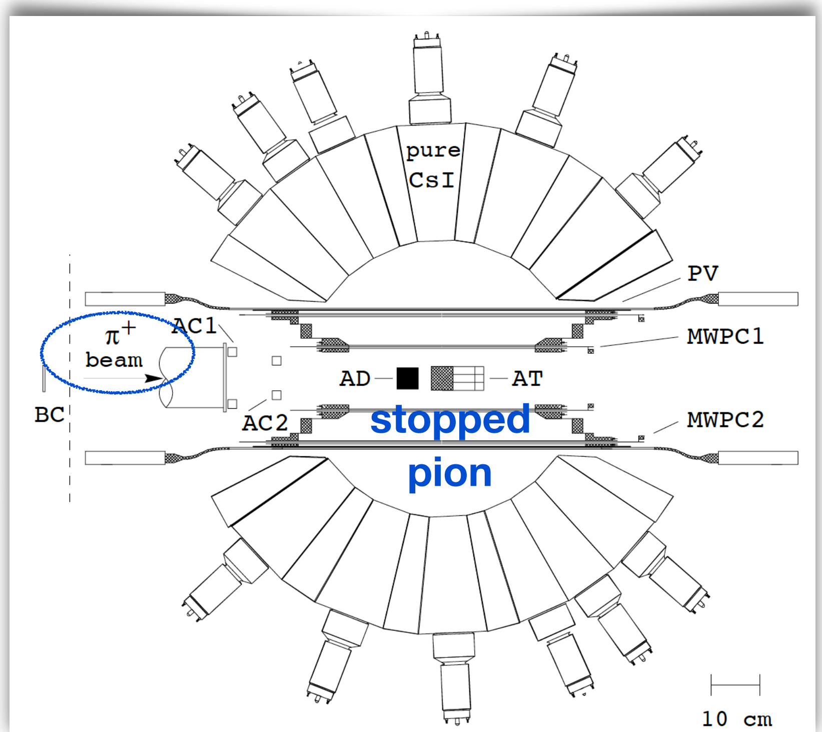
$$g_{a\gamma}^{\text{eff}} = \sin\vartheta \, \frac{\sqrt{2}\alpha}{8\pi f_\pi}$$

What about targeting photons?
The Pibeta experiment

$$\pi^+ \to \pi^0 e^+ \nu$$

π^0 is produced (almost) at rest

$\gamma\gamma$ will be produced ~ back to back



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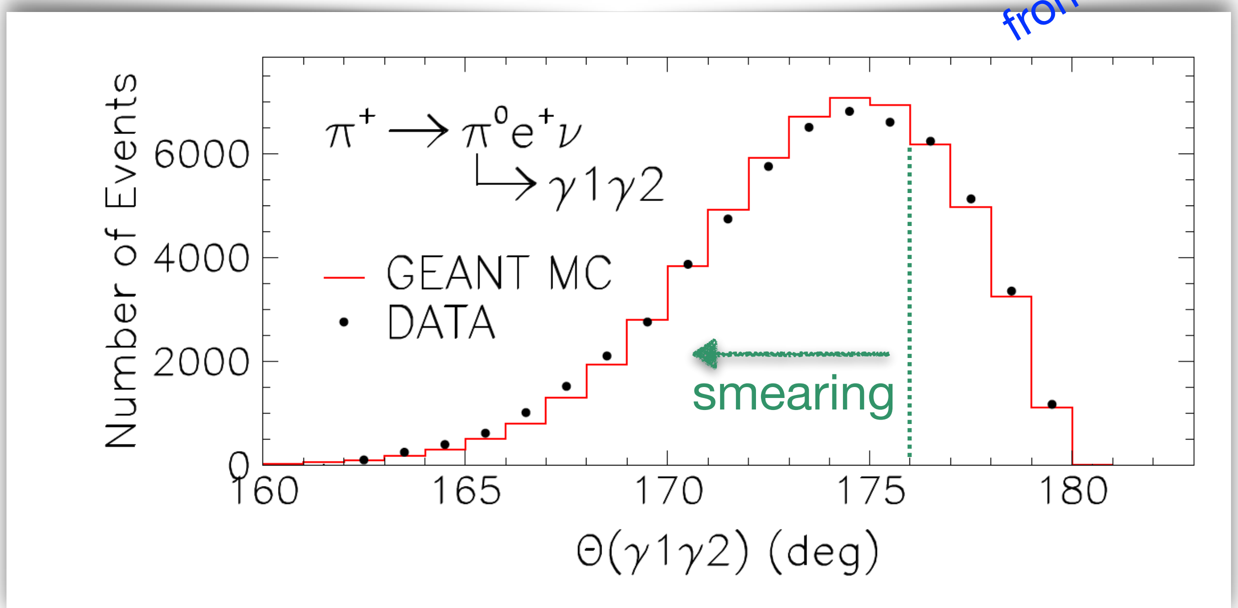
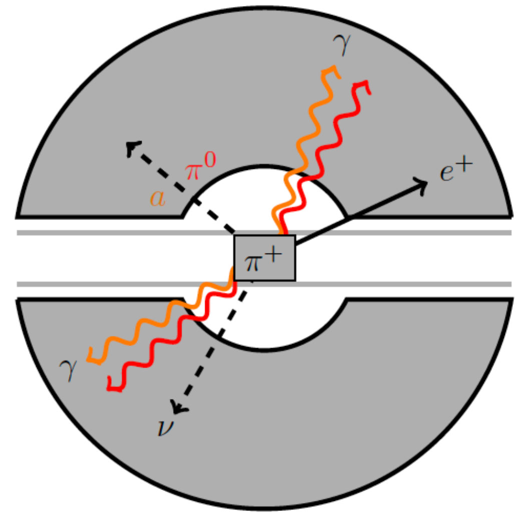


ALPs at PIBETA

$\pi^+ \to a e^+ \nu$ The spectrum of the photons will change:



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

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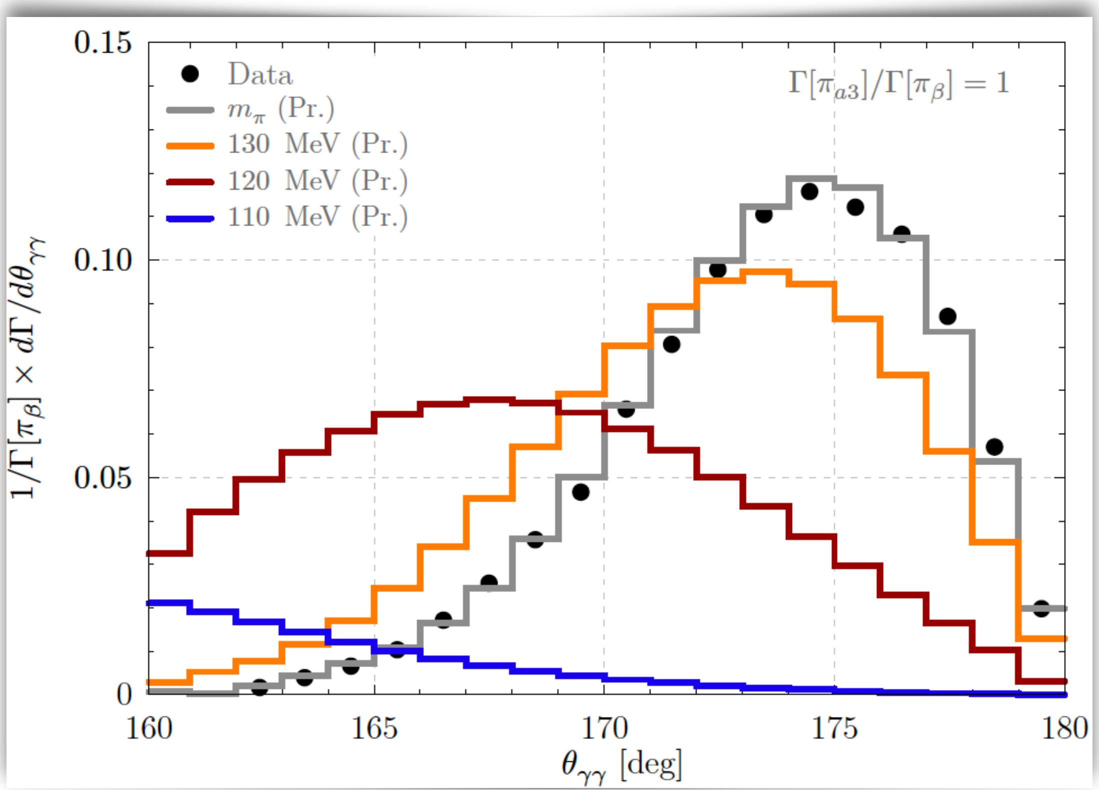

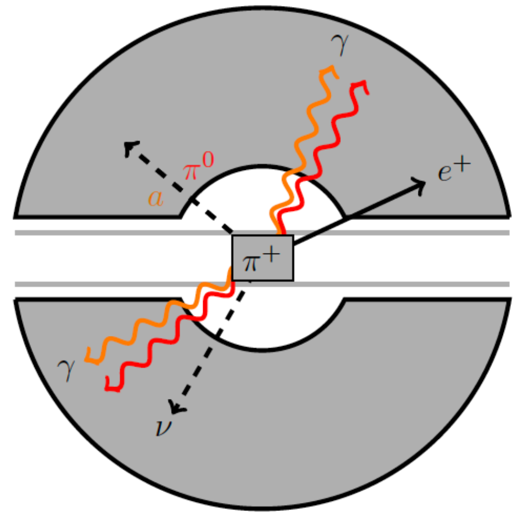

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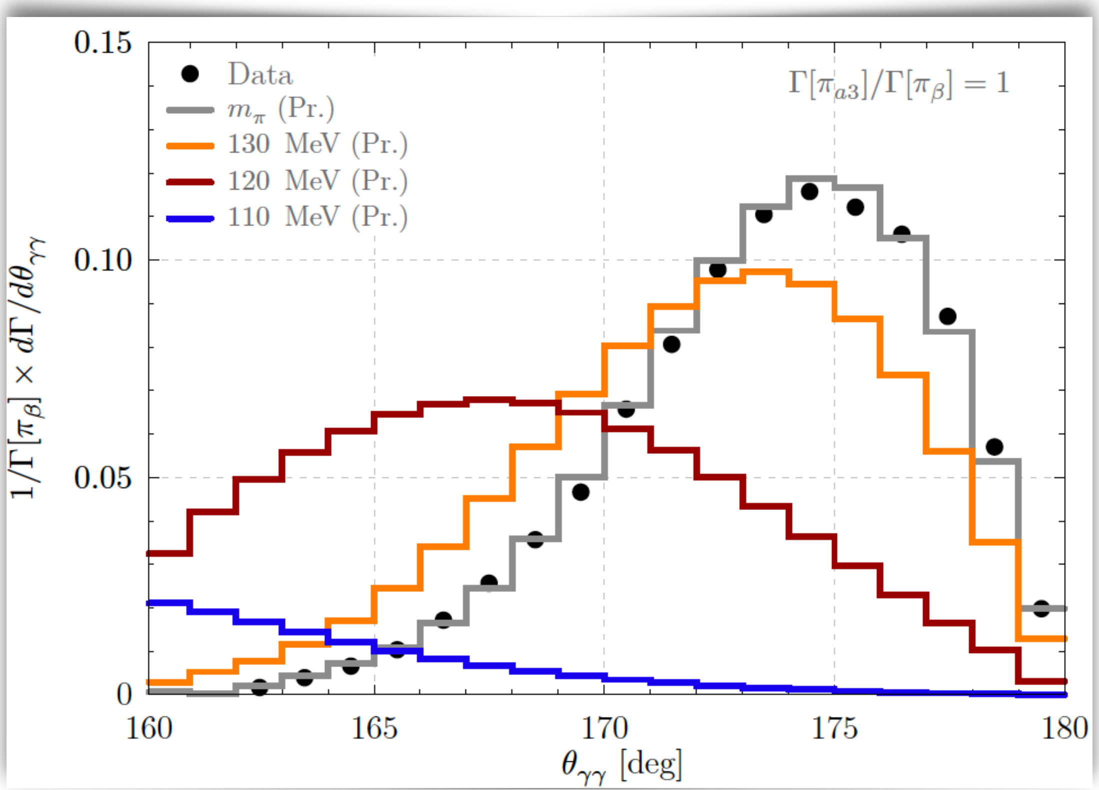
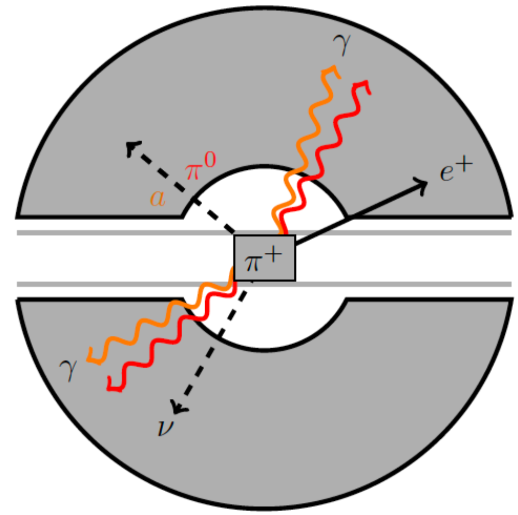


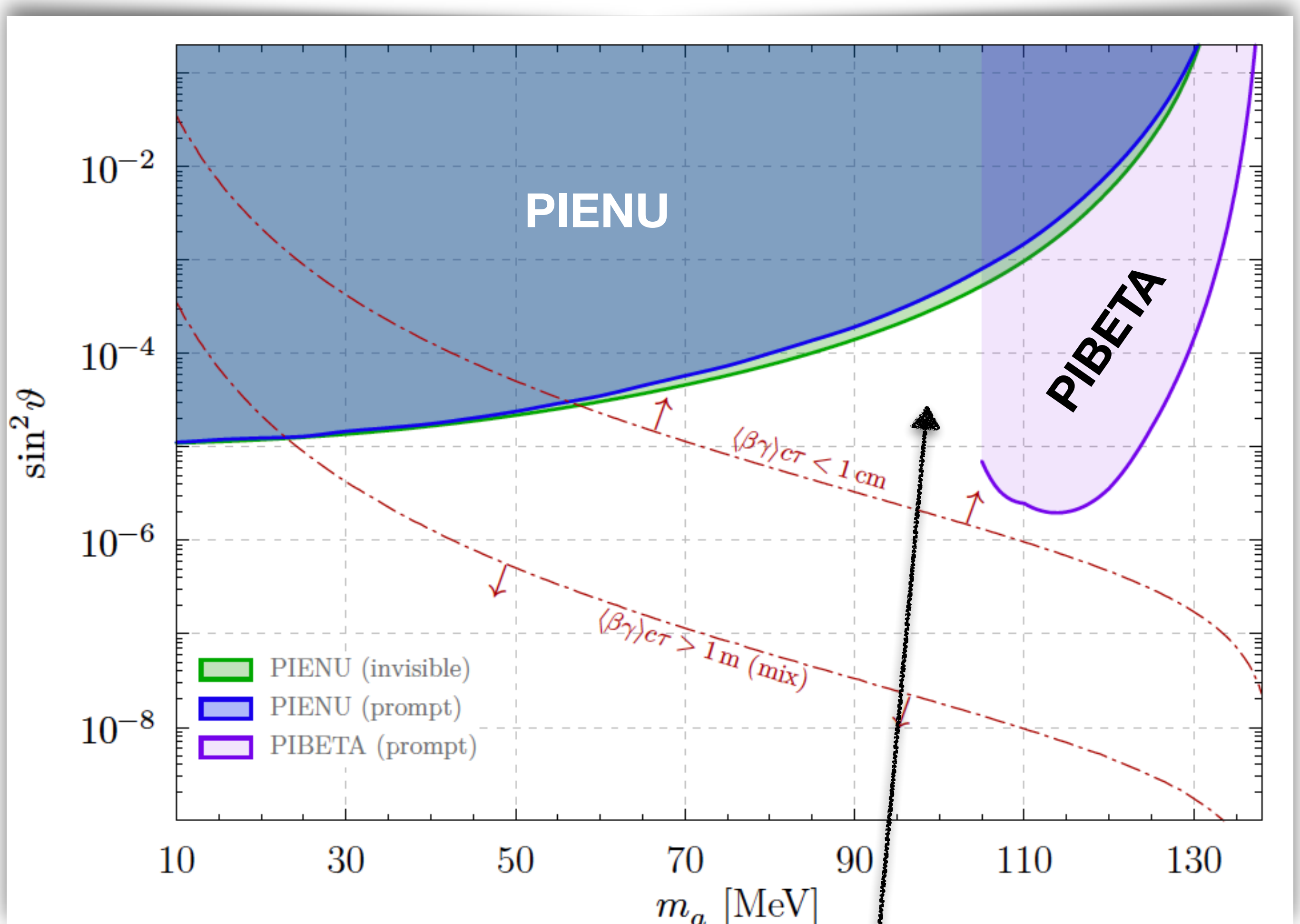


$$-1 \leq \cos\theta_{\gamma\gamma} \leq -1 + 2\left(\frac{m_{\pi^+}^2 - m_a^2}{m_{\pi^+}^2 + m_a^2}\right)^2$$

Unfortunately the PIBETA collaboration does not report residuals.

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

ALP bound from PIBETA



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

Reach at PIONEER?

Phase I: ~2 x 10^{12} pions

Phase II/III: ~7 x 10^{13} pions

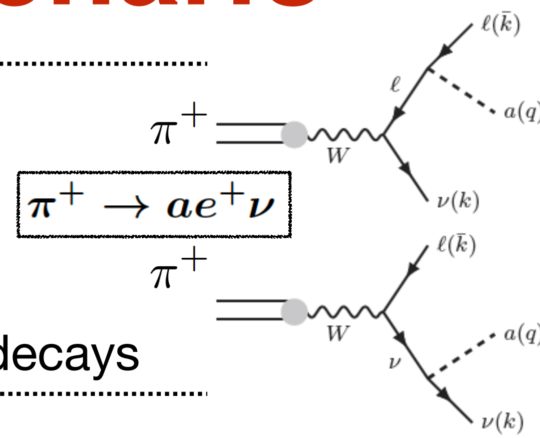
Altmannshofer, Dror, SG, 2208.xxxxx

Leptonically coupled ALPs

Lepton-coupled ALP scenario

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

Because of the conservation of lepton number,
one combination of couplings does not contribute at LO to pion decays



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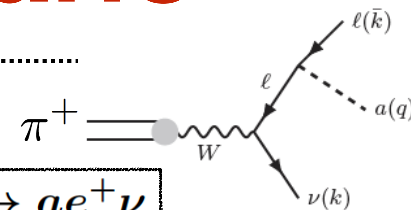

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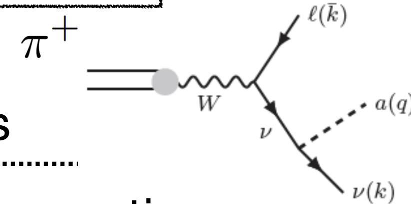

0 if SU(2) conservation

$$\mathrm{BR}(\pi^+\to e^+ a\nu) = \frac{1}{384\pi^2}\frac{m_\pi^4}{m_e^2 m_\mu^2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^{-2}\left[\underbrace{(g_{ee}-\bar{g}_{ee}+g_\nu)^2}f_0\left(\frac{m_a^2}{m_\pi^2}\right)\right.$$

$$+\frac{4m_e^2}{m_\pi^2}\left(3(g_{ee})^2 f_3\left(\frac{m_a^2}{m_\pi^2}\right)+3(\bar{g}_{ee}-g_\nu)^2 f_4\left(\frac{m_a^2}{m_\pi^2}\right)\right.$$

$$\left.\left.+2g_{ee}(\bar{g}_{ee}-g_\nu)f_5\left(\frac{m_a^2}{m_\pi^2}\right)\right)+\mathcal{O}\left(\frac{m_e^3}{m_\pi^3}\right)\right]$$

Helicity suppression is lifted only
in the case of SU(2) violation

Lepton-coupled ALP scenario

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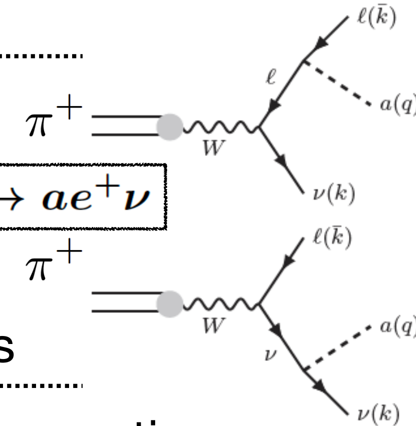

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SU(2) violating: $g_{ee}\frac{(\partial_\mu a)}{m_e}\bar{e}\gamma^\mu\gamma_5 e$ ➡ $\mathrm{BR}(\pi^+\to a e^+\nu)\simeq 2\times 10^{-4}\left(\frac{g_{ee}}{10^{-3}}\right)^2$

SU(2) preserving (e.g. P_R): $2g_{ee}\frac{(\partial_\mu a)}{m_e}\bar{e}\gamma^\mu P_R e$ ➡ $\mathrm{BR}(\pi^+\to a e^+\nu)\simeq 4\times 10^{-8}\left(\frac{g_{ee}}{10^{-3}}\right)^2$

Lepton-coupled ALP scenario

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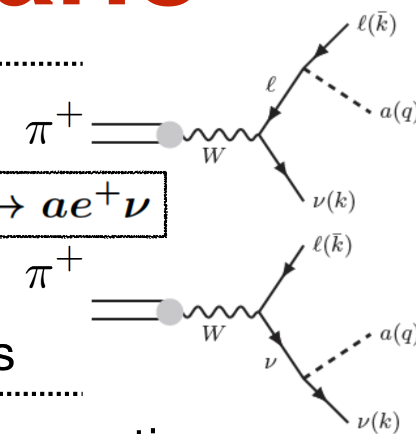


0 if SU(2) conservation

$$\mathrm{BR}(\pi^+\to e^+a\nu) = \frac{1}{384\pi^2}\frac{m_\pi^4}{m_e^2 m_\mu^2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^{-2}\left[\overbrace{(g_{ee}-\bar{g}_{ee}+g_\nu)}^{}{}^2 f_0\left(\frac{m_a^2}{m_\pi^2}\right)\right.$$
$$+\frac{4m_e^2}{m_\pi^2}\left(3(g_{ee})^2 f_3\left(\frac{m_a^2}{m_\pi^2}\right)+3(\bar{g}_{ee}-g_\nu)^2 f_4\left(\frac{m_a^2}{m_\pi^2}\right)\right.$$
$$\left.\left.+2g_{ee}(\bar{g}_{ee}-g_\nu)f_5\left(\frac{m_a^2}{m_\pi^2}\right)\right)+\mathcal{O}\left(\frac{m_e^3}{m_\pi^3}\right)\right]$$

Helicity suppression is lifted only
in the case of SU(2) violation

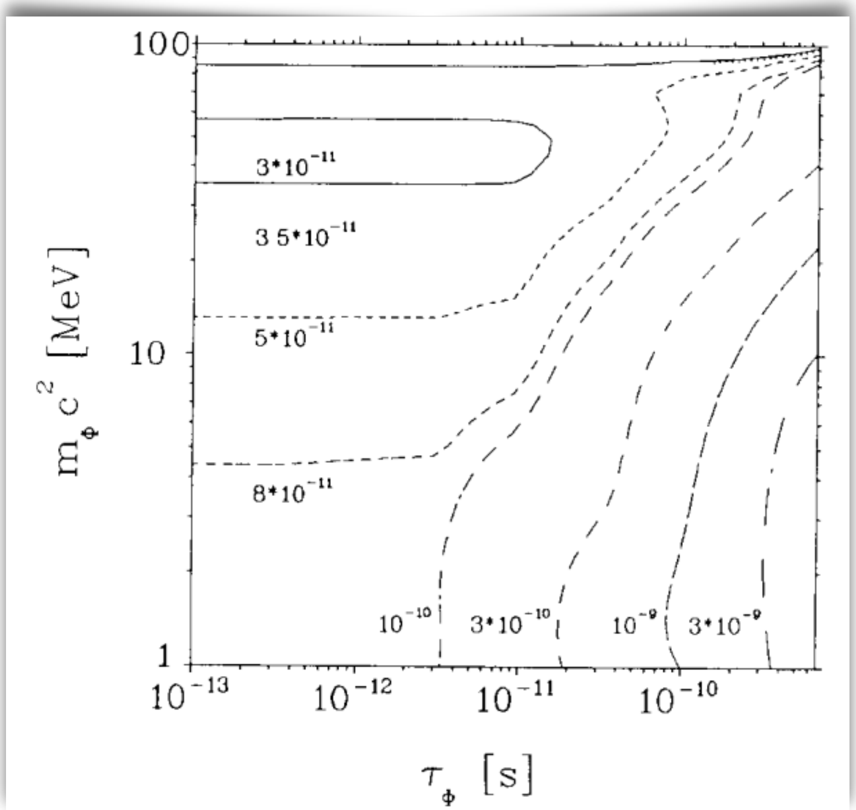
Once produced, the ALP will

- decay to electrons $\pi^+\to e^+\nu(a\to e^+e^-)$
- be invisible in our detectors (if too long-lived)

The past search for $\pi^+ \to e^+\nu(a \to e^+e^-)$

In the late ‘80s,
the SINDRUM experiment at CERN:

Almost background free search



Eichler et al. Physics Letters B 175 (1986), no. 1 101–104

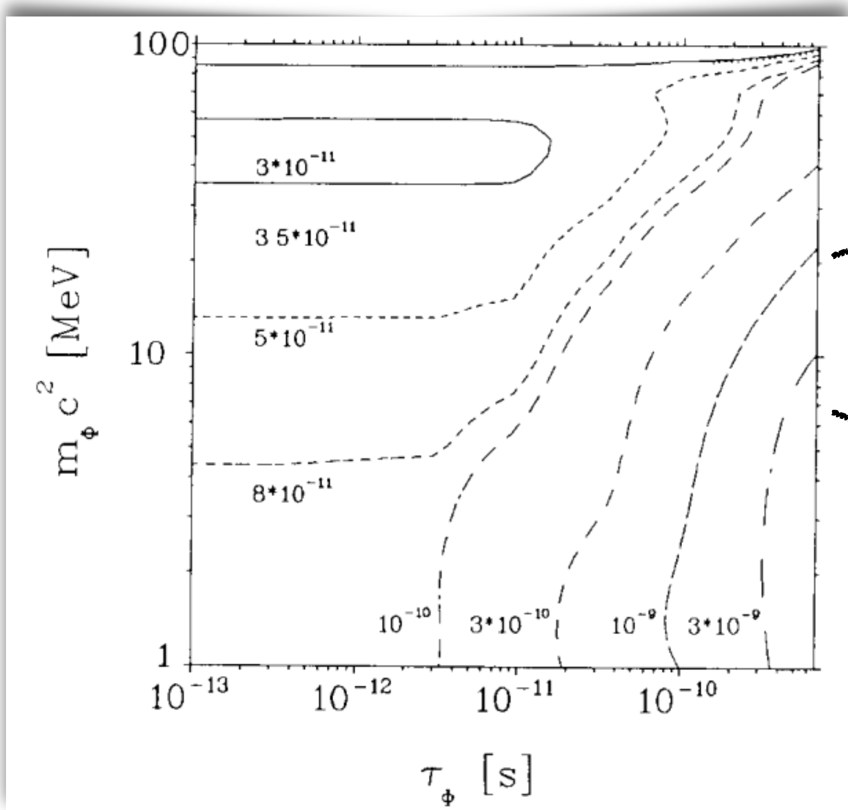
Decay length below the vertex resolution of the SINDRUM detector

Mass resolution: 3-8 MeV

The past search for $\pi^+ \to e^+ \nu(a \to e^+ e^-)$

In the late '80s,
the SINDRUM experiment at CERN:

Almost background free search

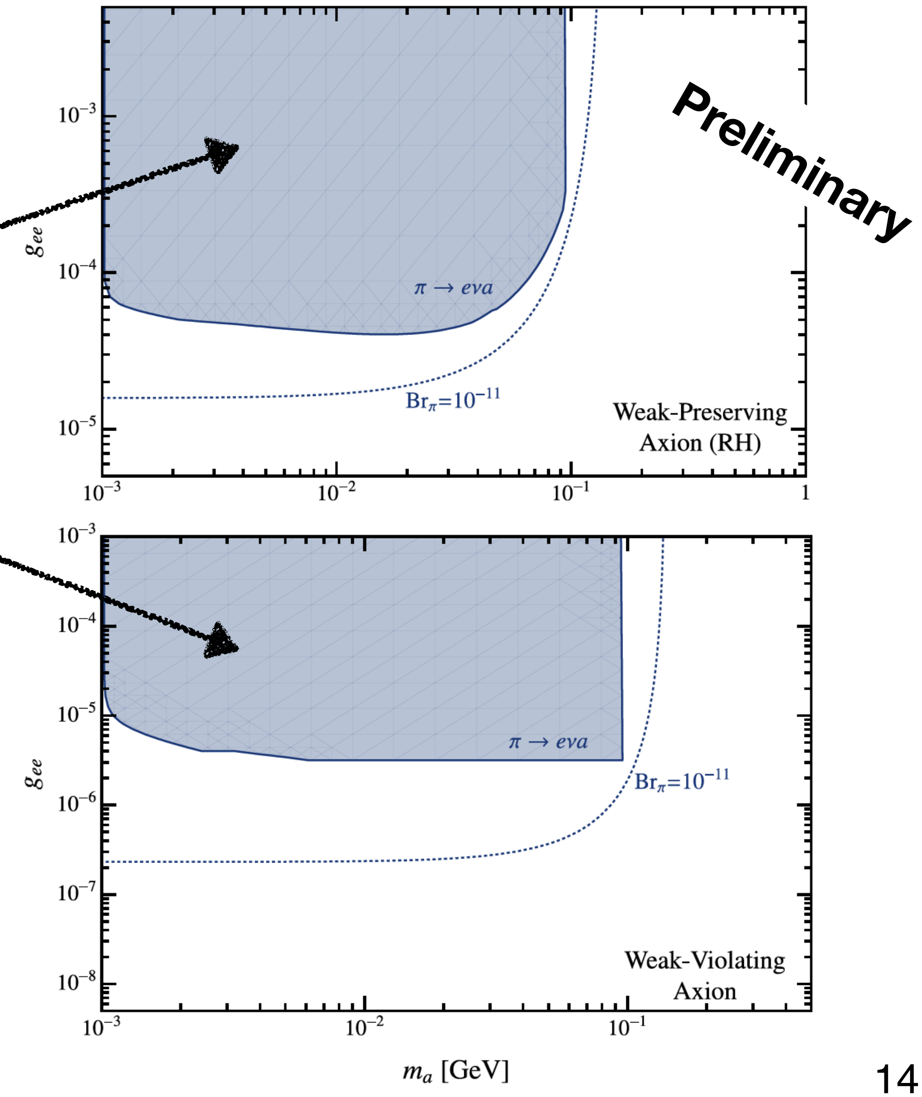


Eichler et al. Physics Letters B 175 (1986), no. 1 101–104

Reach at PIONEER?

Phase I: ~2 x 10^{12} pions

Phase II/III: ~7 x 10^{13} pions

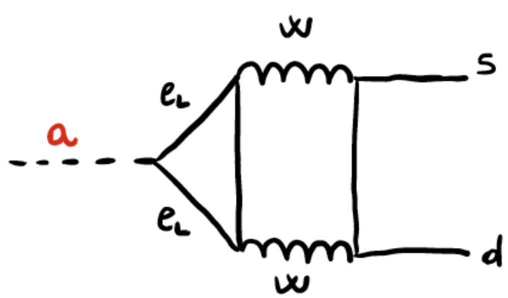


Complementarity with Kaon decays

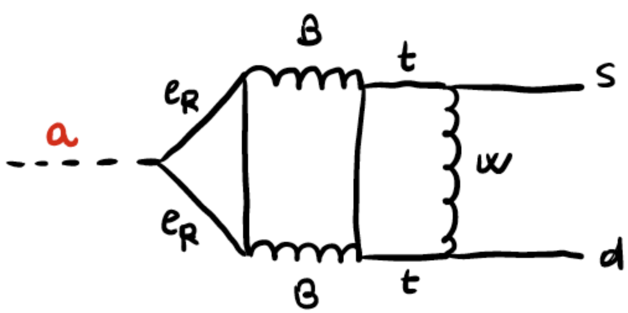
1. Neutral current Kaon decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$

ALP with LH coupling



ALP with RH coupling



Main bounds:

NA62, 2103.15389: $K^+ \to \pi^+ + (a \to \text{ invisible})$

KTeV, 0309072: $K_L \to \pi^0(a \to e^+e^-)$

777 @ BNL, Phys. Rev. Lett. 59 (1987) 2832–2835 : $K^+ \to \pi^+(a \to e^+e^-)$

see also Alves, Weiner, 1710.03764

2. Charged current Kaon decays

Similarly to the pion decays:

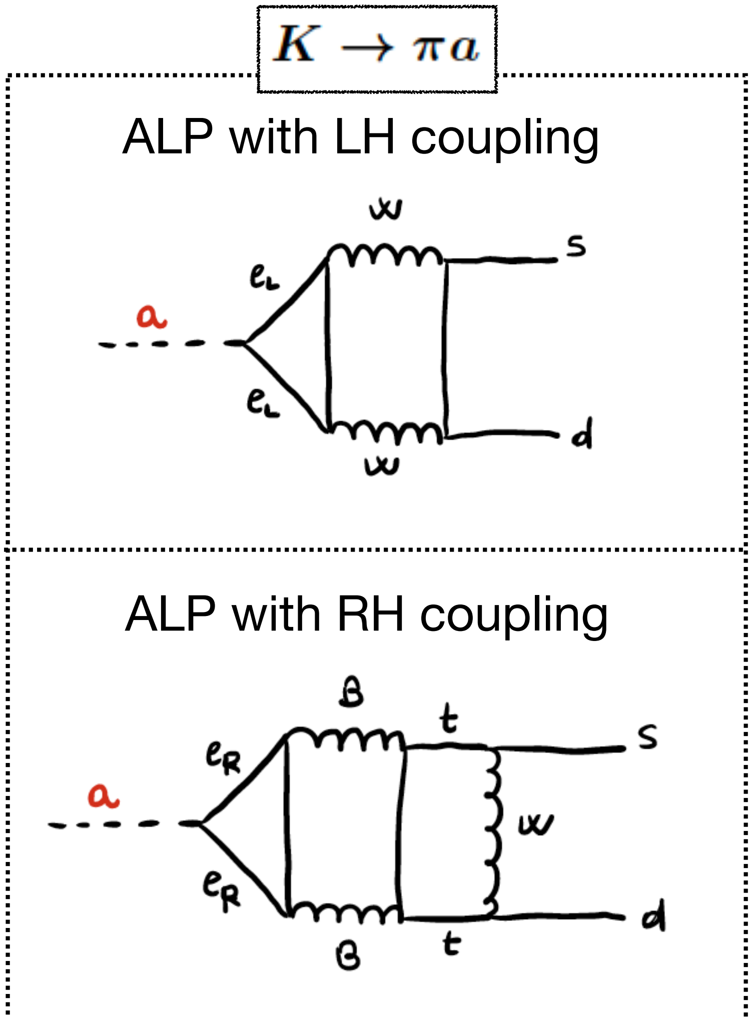
$K^+ \to e^+\nu(a \to e^+e^-)$

The 865 experiment at Brookhaven, 0204006

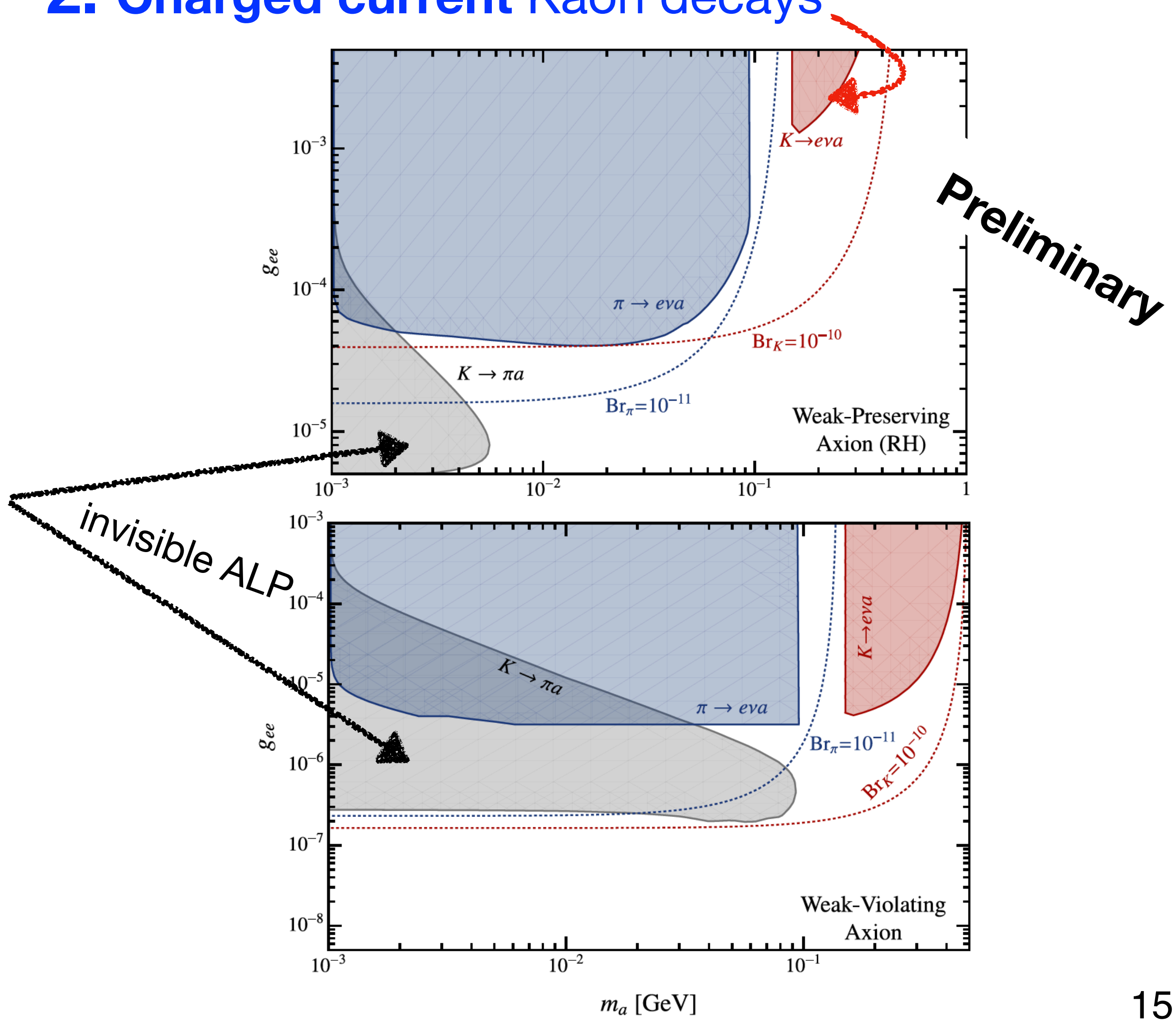
measured the differential BR for $K^+ \to e^+\nu e^+e^-$

Complementarity with Kaon decays

1. Neutral current Kaon decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

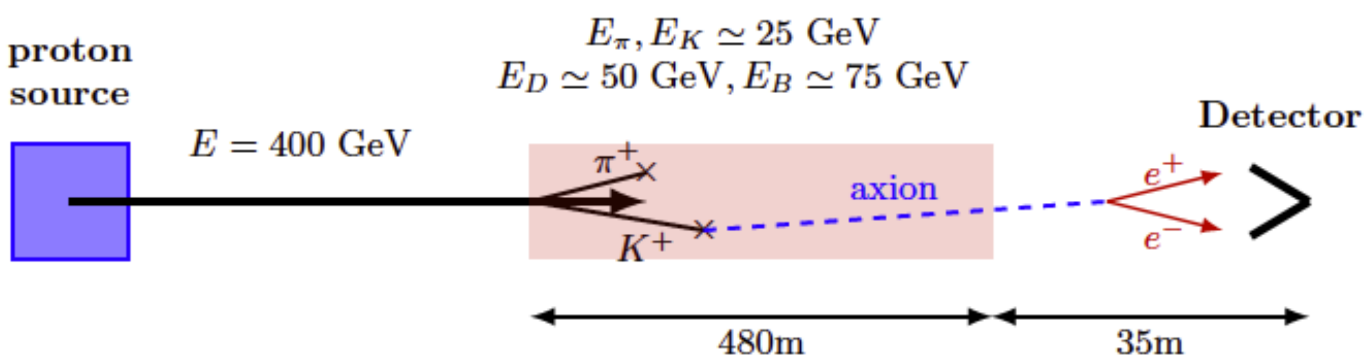


2. Charged current Kaon decays



B-factories & beam dump experiments

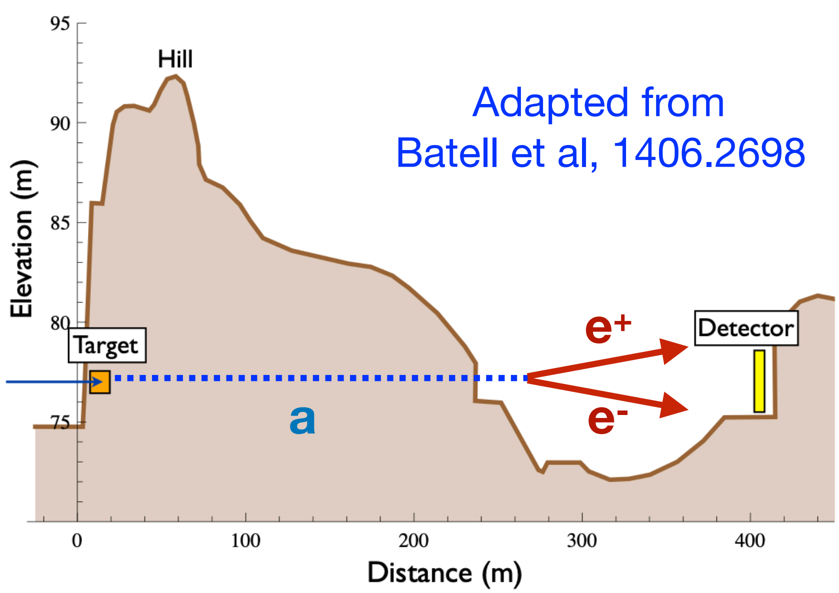
CHARM experiment (late 80s at CERN)



E137 experiment (late 80s at SLAC)

Bjorken et al., Phys. Rev. D 38 (1988) 3375

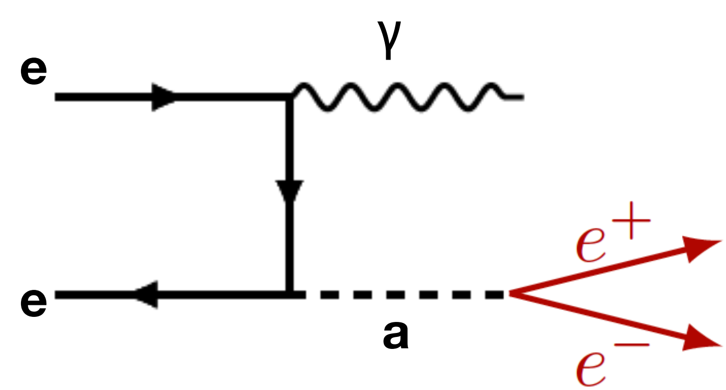
electron
(E=20GeV)



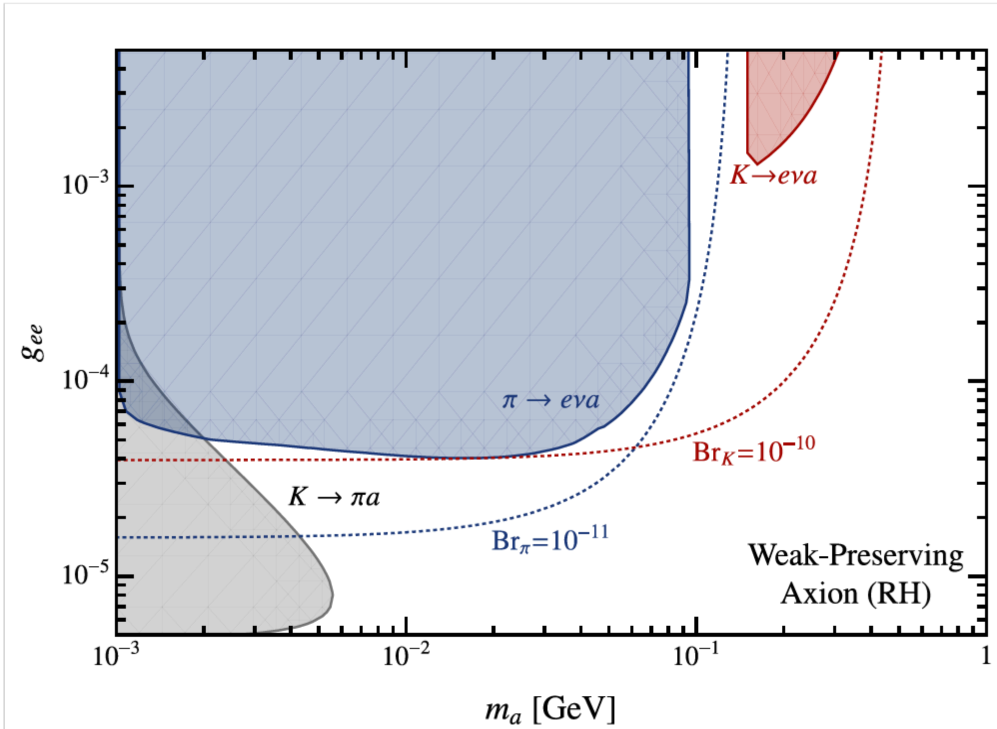
Adapted from
Batell et al, 1406.2698

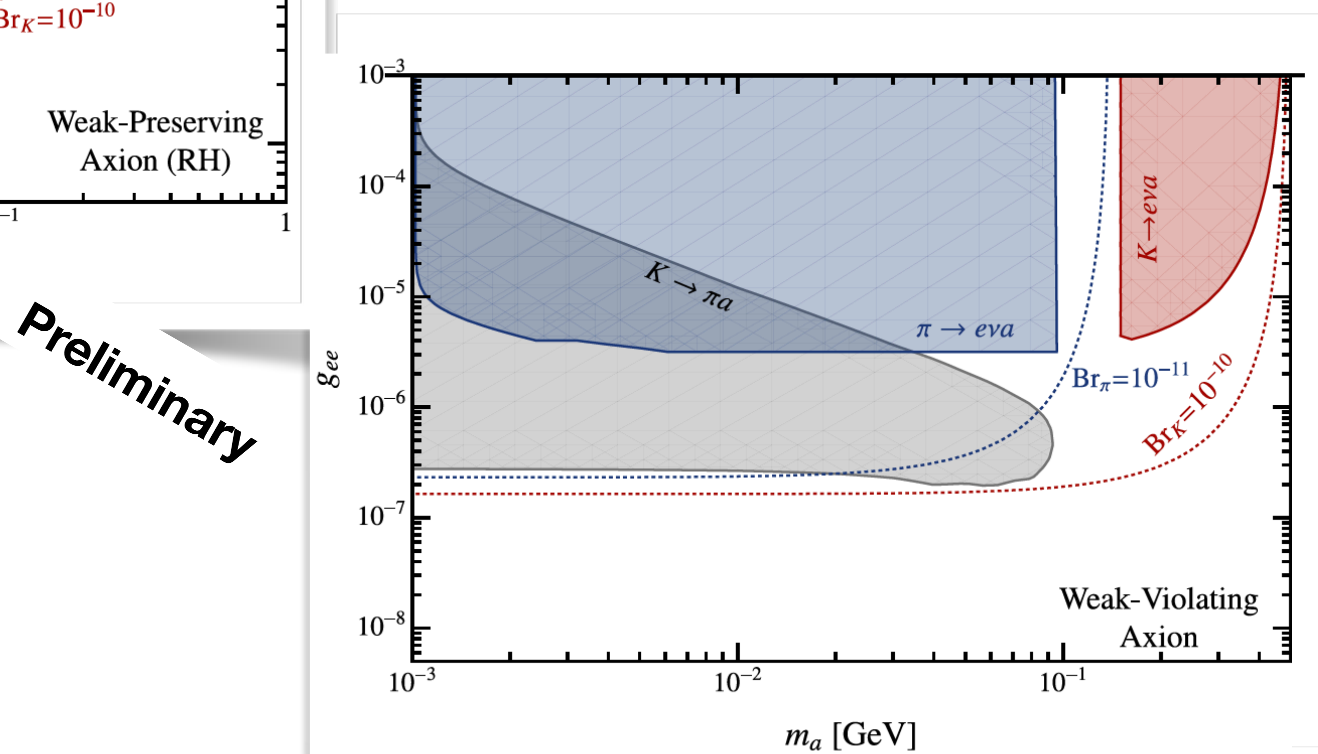
Babar

Re-interpretation of
the dark photon search, 1406.2980

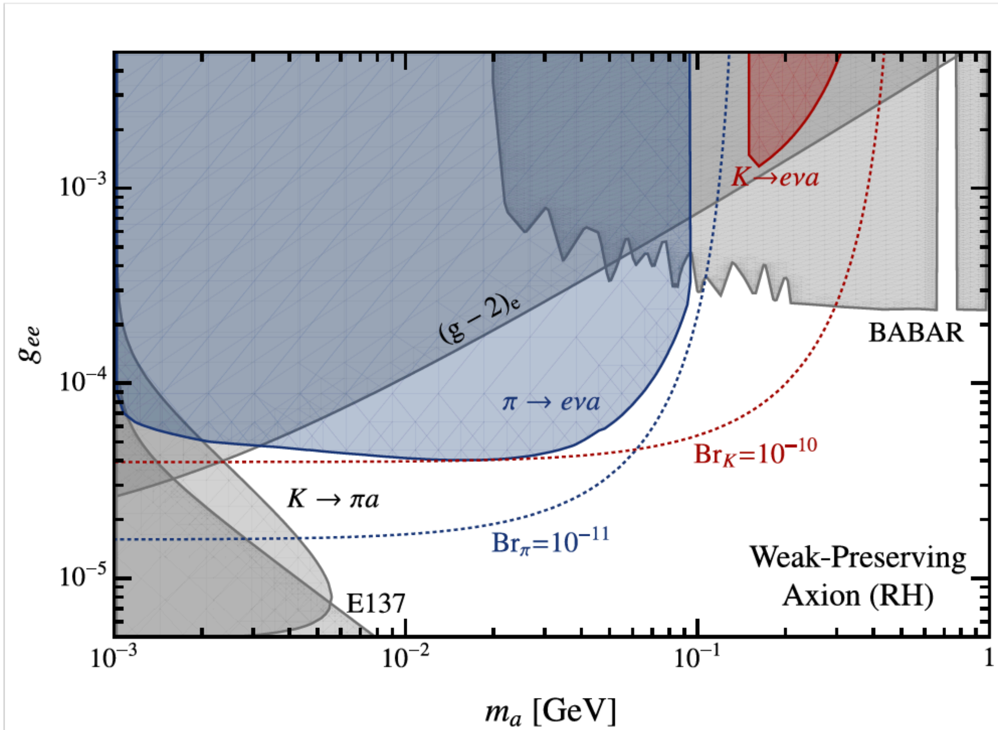


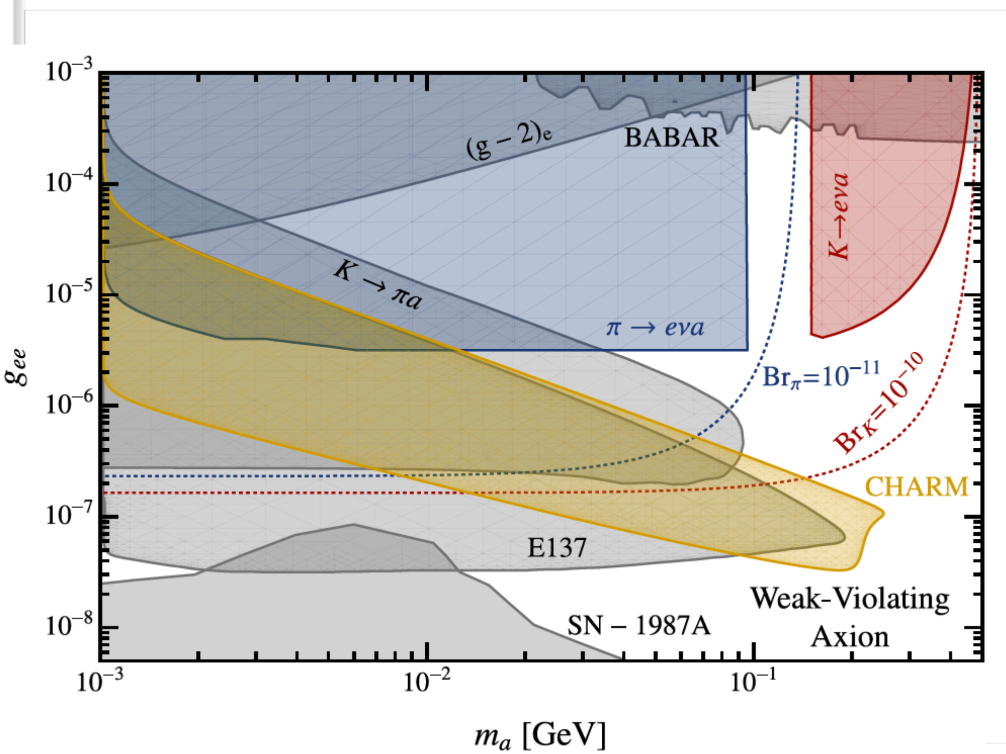
Putting everything together





Putting everything together





Preliminary

Conclusions & Outlook

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

Plenty of opportunities to test dark sectors at these experiments

For this talk:
testing ALPs at pion experiments
(New approved experiment: PIONEER)

Direct searches for $\pi \rightarrow a\, e\, \nu$ can probe un-explored ALP parameter space

- recast of past measurements (PIENU, PIBETA, SINDRUM)
- New direct searches (PIONEER)

Complementarity with Kaon experiments, B-factories, and beam dump experiments

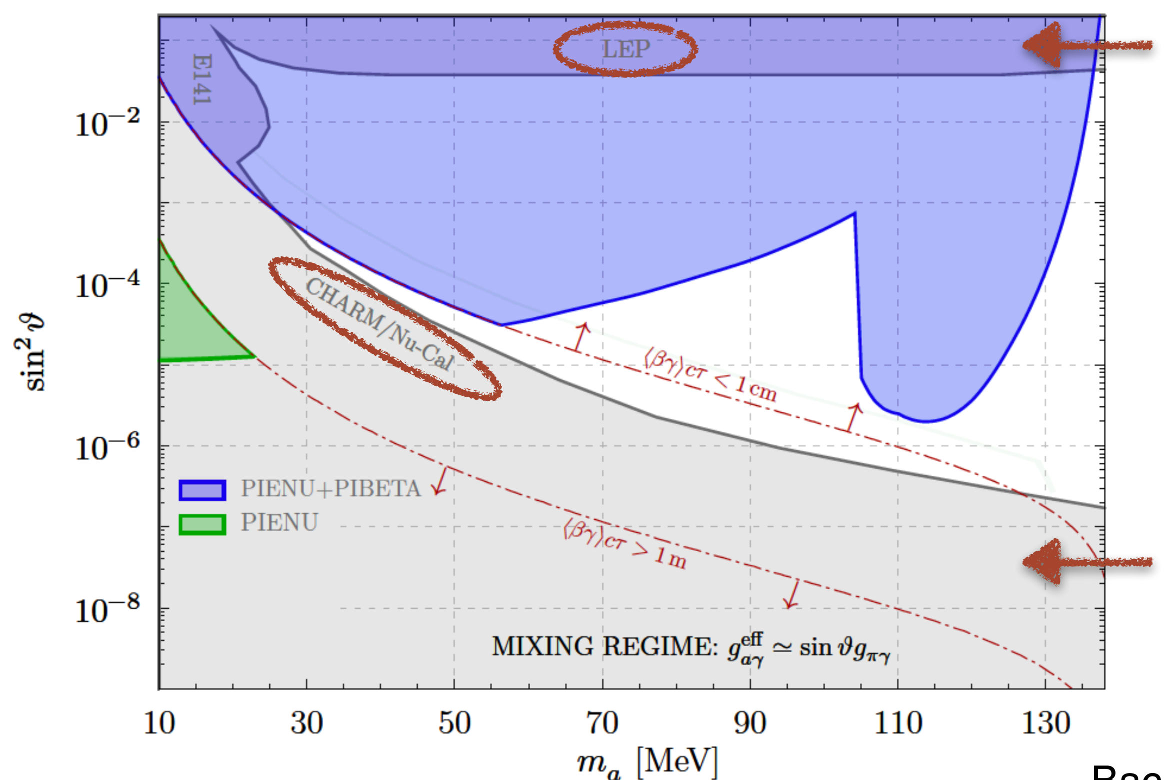
Connection with other accelerator experiments

- The bounds shown until now are ~model independent.

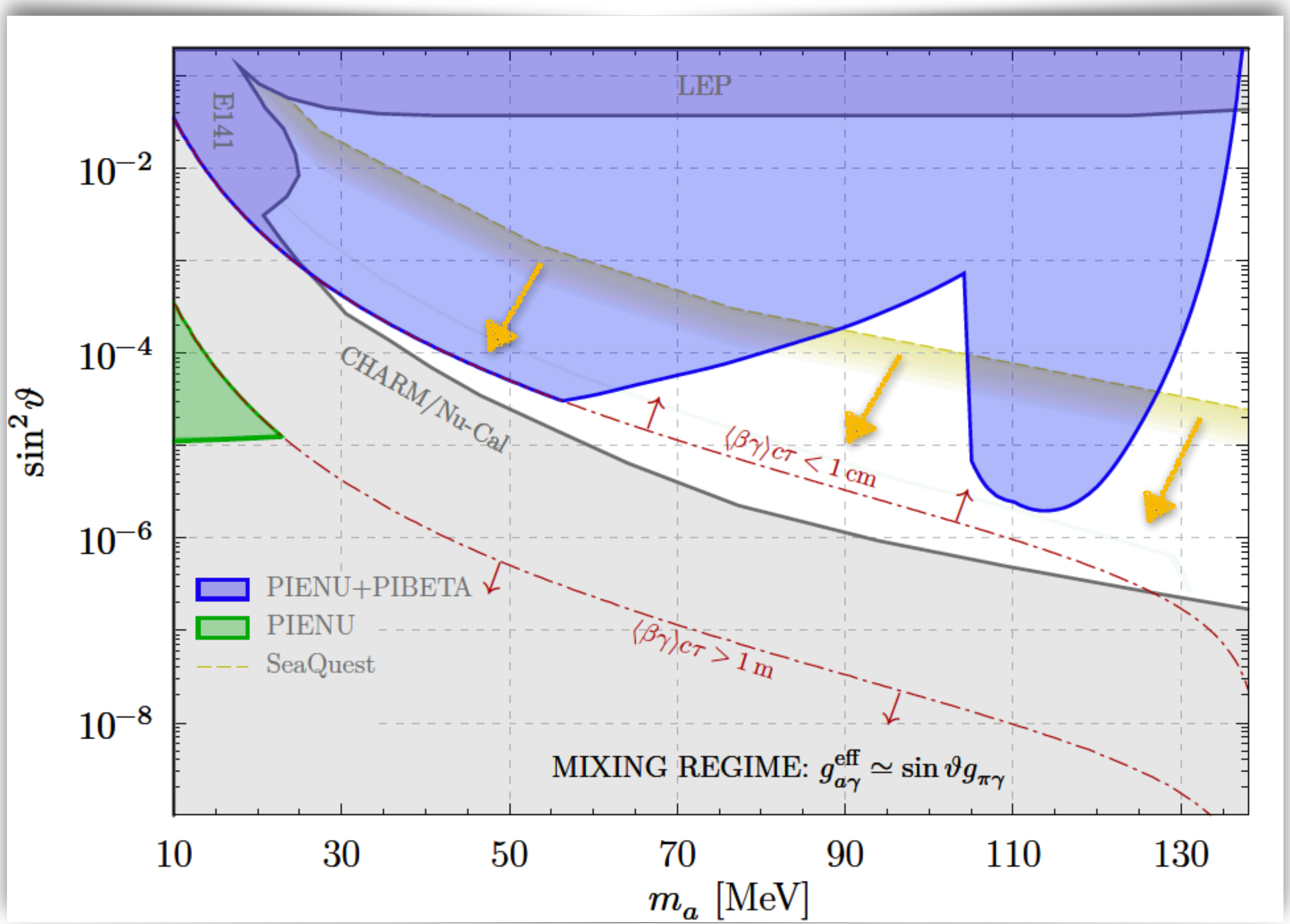
- If we assume a theory with no extra contribution to the diphoton coupling (mixing regime) then $\Gamma_{a\gamma\gamma} = \sin^2\vartheta \frac{\alpha^2 m_a^3}{32\pi^3 f_\pi^2}$

(decay & production of the ALP depend only on the mixing angle and on its mass)

- We can directly compare the PIENU, PIBETA bounds with LEP and old fixed target experiments:



What about future beam dumps?

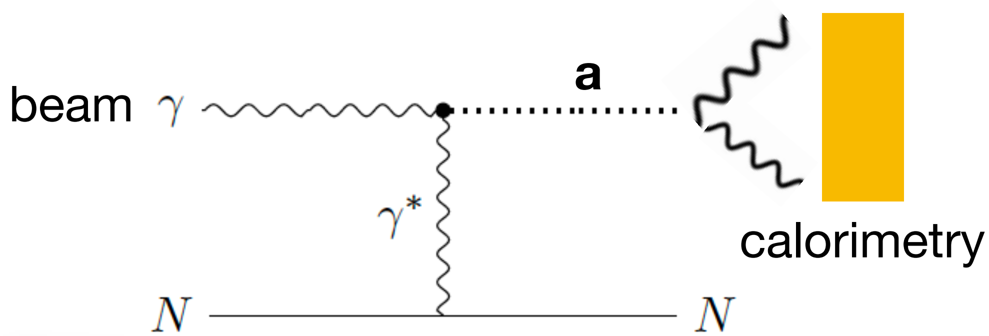


DarkQuest reach below the line

(from A.Berlin, SG, P.Schuster, N.Toro, 1804.00661)

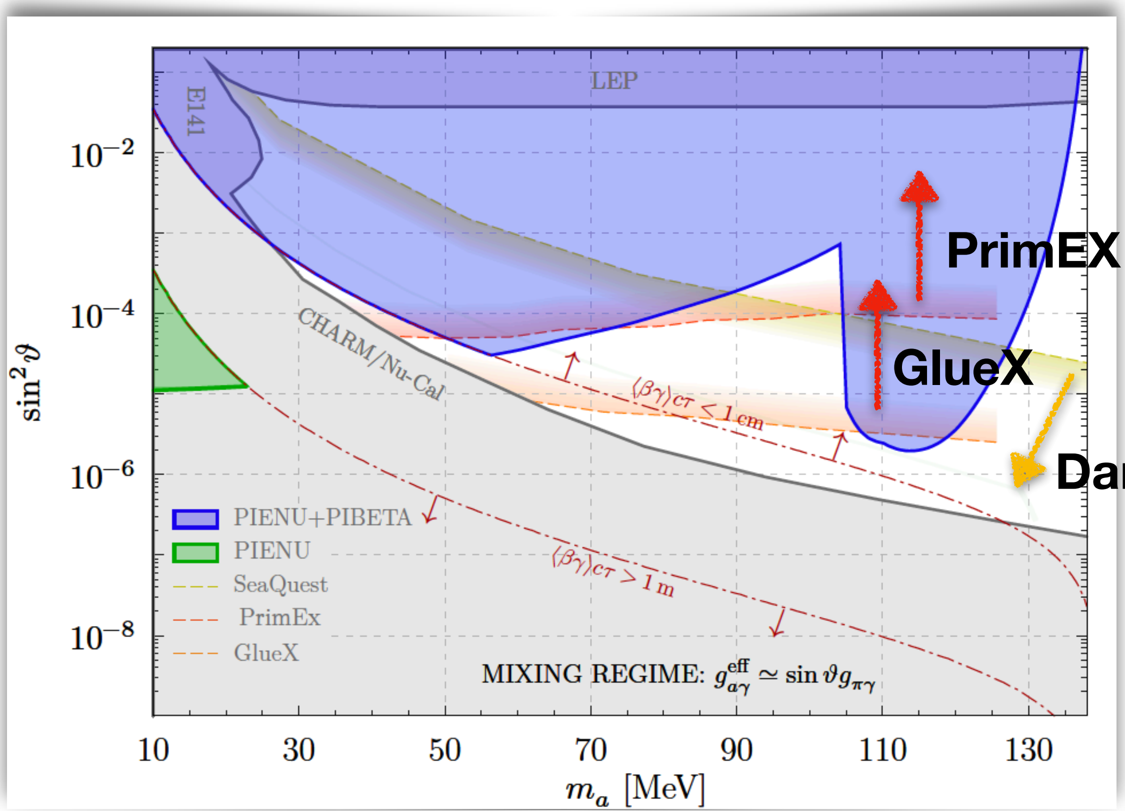
DarkQuest + pion experiments can almost completely probe ALPs with a mass below the pion mass (and above ~MeV).

More new measurements coming up? PrimEX, GlueX



Proposed upgrades for the PrimEX and GlueX experiments at JLAB

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

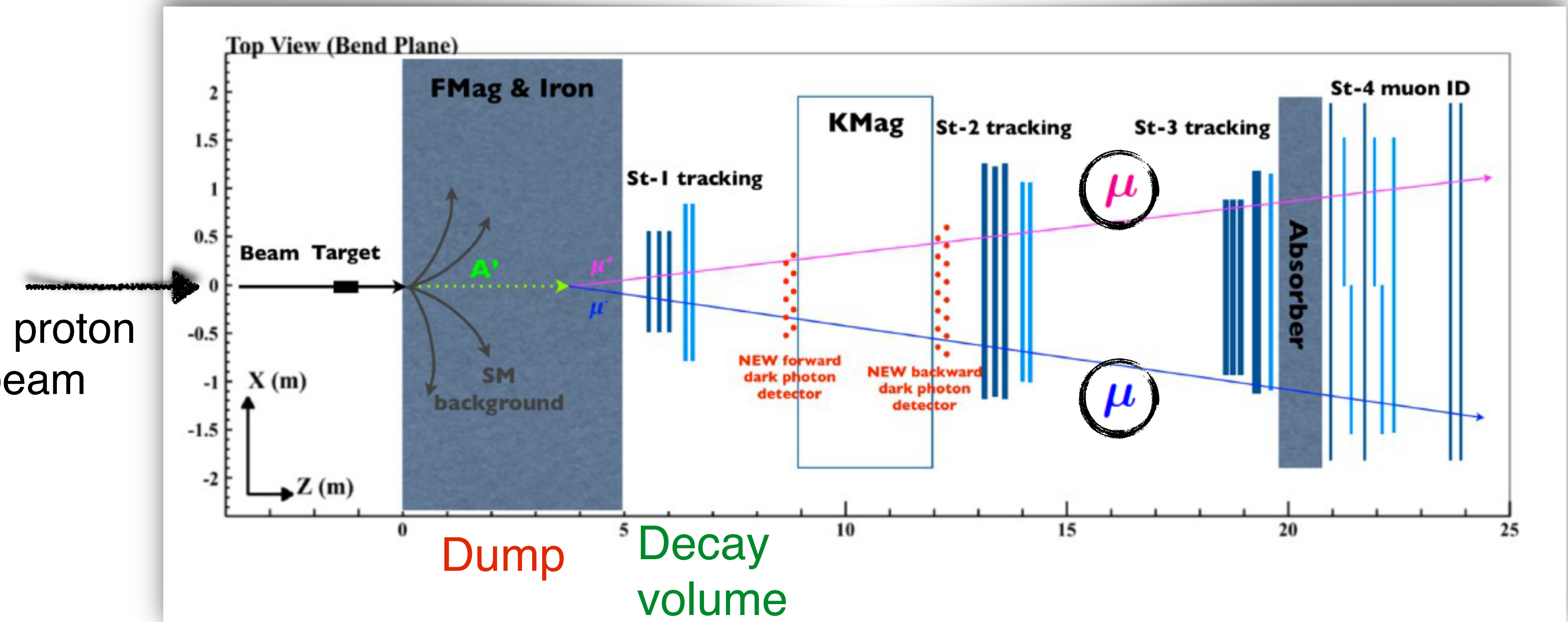


The parameter space for ALPs with mass below the pion mass (and above a few MeV) could be fully covered!

Aloni et al., 1903.03586

More new measurements coming up? SeaQuest

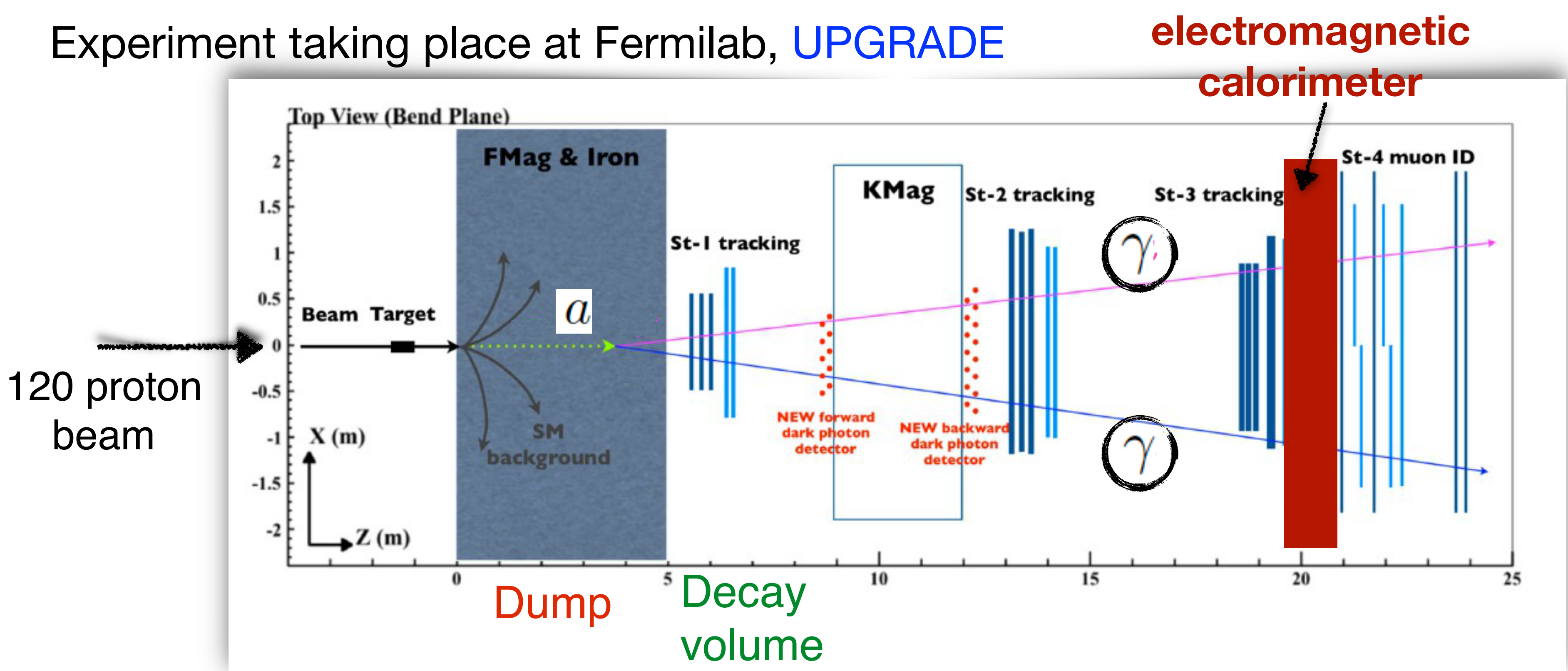
Experiment taking place at Fermilab



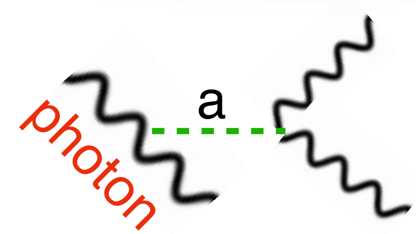
Approved running in <u>2019 - 2021</u>. ~10^{18} protons on target.
Displaced muon signatures

More new measurements coming up? DarkQuest

Experiment taking place at Fermilab, UPGRADE



Proposed running after 2021. ~10^{20} protons on target.
Displaced electromagnetic objects (including photons)

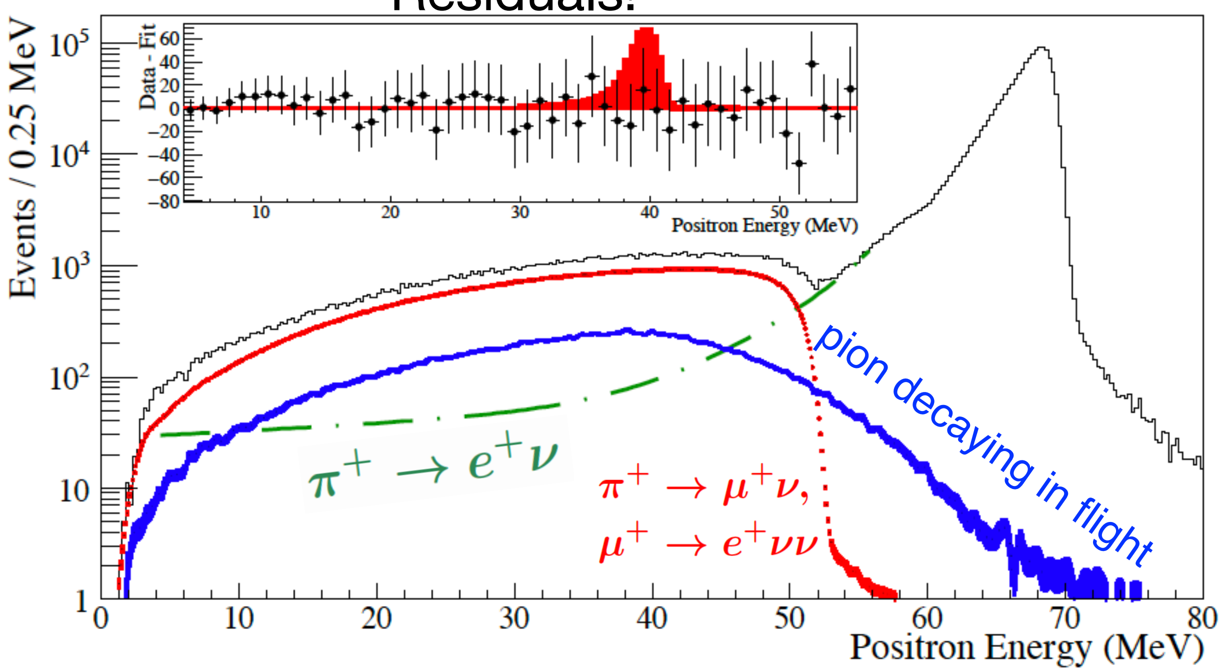


axions radiated from secondary photons produced in the collisions

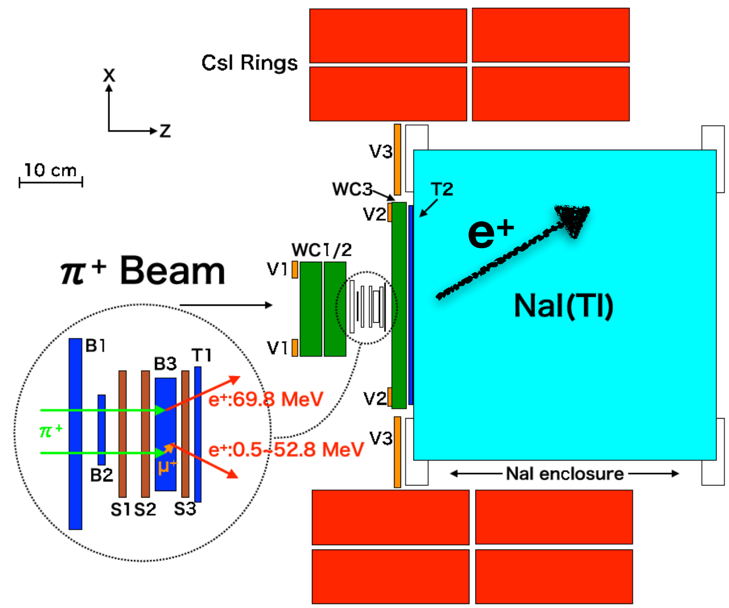
Back to the PIENU experiment…

Effectively they test lepton flavor universality:
$$R_{e,\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$

Residuals!



PIENU collaboration, 1712.03275



Courtesy of D.Bryman

Multi-component fit with floating normalizations

Lepton-coupled ALP lifetime