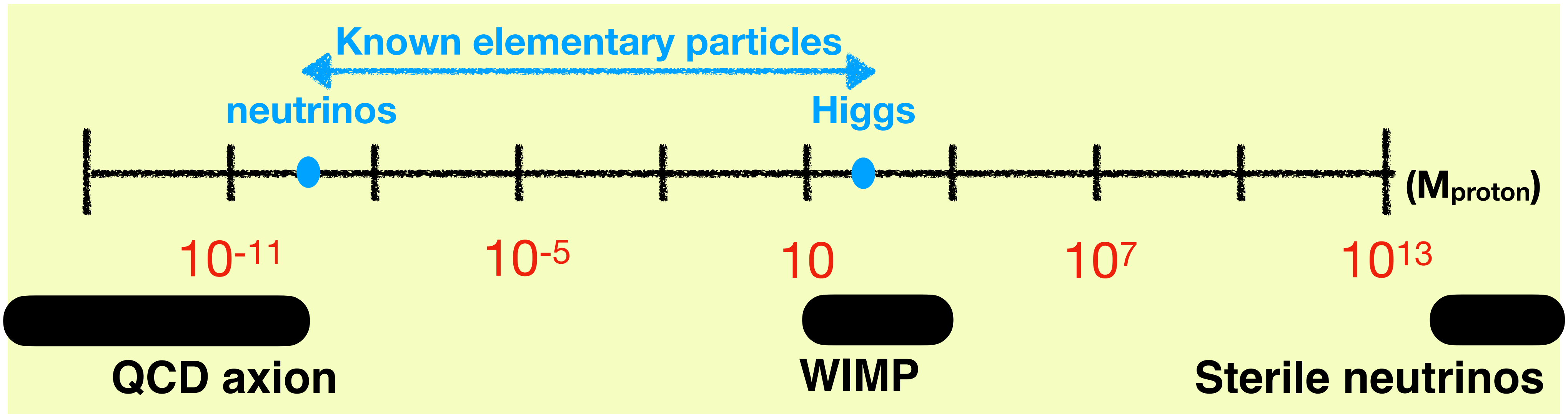
ALP searches with fixed target experiments

Stefania Gori
UC Santa Cruz

The Axion Quest, 20th Rencontres du Vietnam

August 6, 2024

MeV-GeV New Physics (NP)?



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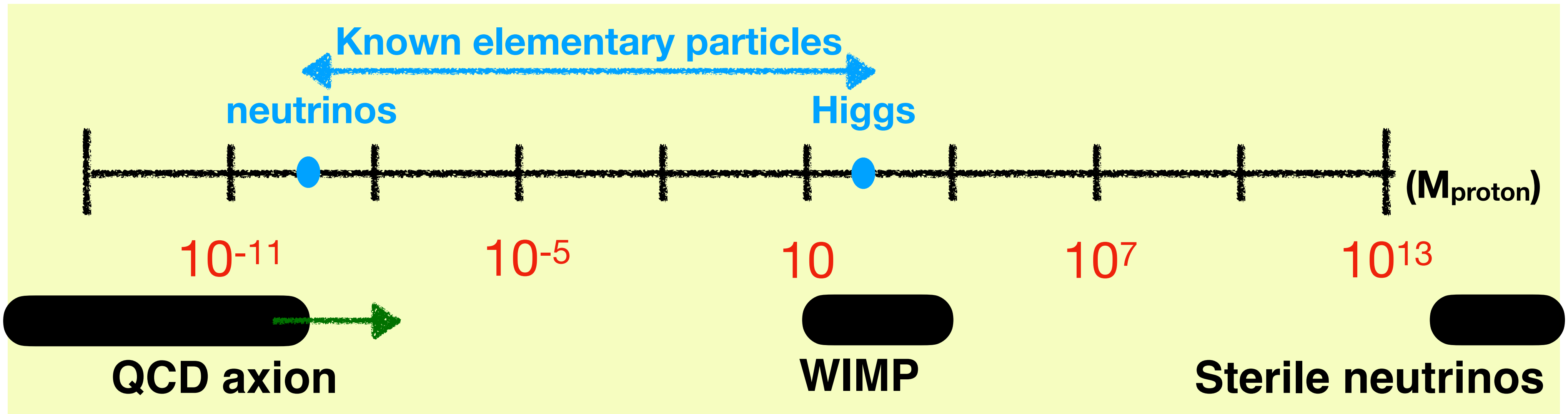
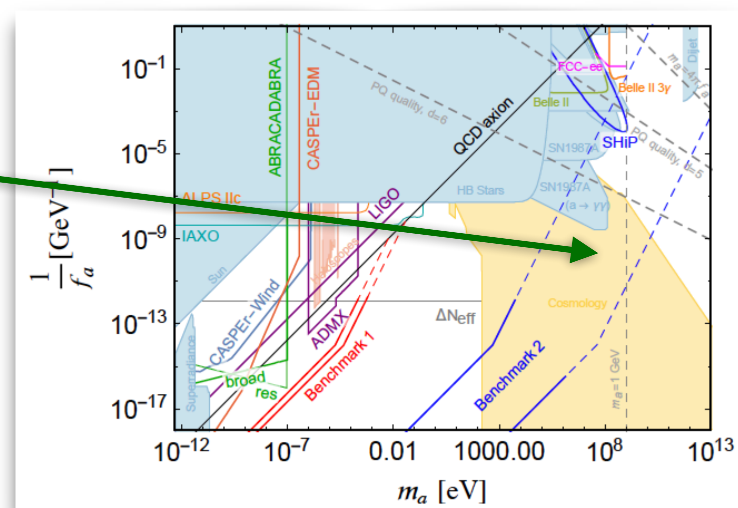


Can the strong CP problem be addressed by **heavier axions** (or axion-like-particles, ALPs)?

YES!



Extended QCD sectors can do that. (Easier to address the <u>axion quality problem</u> with heavier axions and lower f_a.)

(e.g., Agrawal, Howe, 1710.04213;
Foster, Kumar, Safdi, Soreq, 2208.10504, …)

+ Several additional motivations for MeV-GeV NP: freeze-out dark matter, inverse or linear seesaw models, …

Additional motivations for sub-GeV 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

- 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 DM, …)
- General (low dimensional) portal to the dark sector

How do ALPs couple?

At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

Georgi, Kaplan, Randall 1986

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

+ possible couplings to BSM particles, e.g., DM: $i g_\chi(\partial_\mu a)(\bar{\chi}\gamma^\mu\gamma_5\chi)$

$$g_i \propto \frac{1}{f_a}$$

At dimension 5, also the operator $i g_{aH}(\partial_\mu a)(H^\dagger D_\mu H + \mathrm{h.c.})$ exists.

However, it can be reabsorbed in the definition of the fermion coupling. In fact, if we redefine

Redundant operator

$$H \to e^{i g_{aH} a} H, \quad f \to e^{-i\beta_f g_{aH} a} f$$

$$\beta_u - \beta_Q = -1, \quad \beta_d - \beta_Q = 1, \quad \beta_e - \beta_L = 1, \quad 3\beta_Q + \beta_L = 0$$

the Higgs operator disappears

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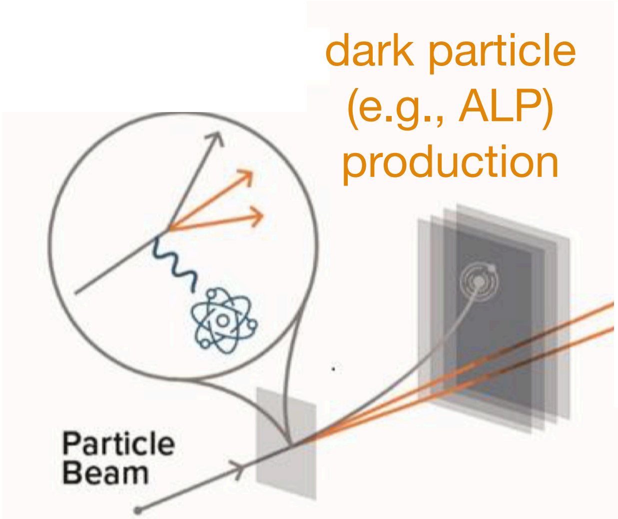
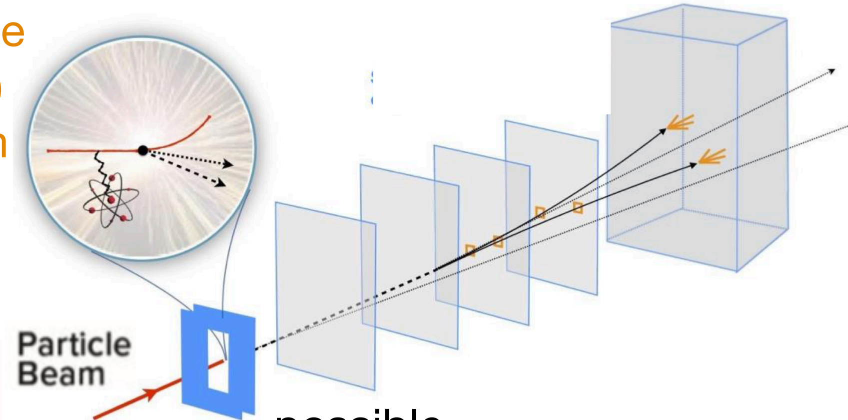
How to probe all these possible couplings?

- **Fixed target experiments,**
- Meson factories,
- Colliders,
- Precision flavor experiment, …

Fixed target (beam dump) experiments





Missing energy/momentum measurement

Invisible ALPs

Search for **visible decay** products

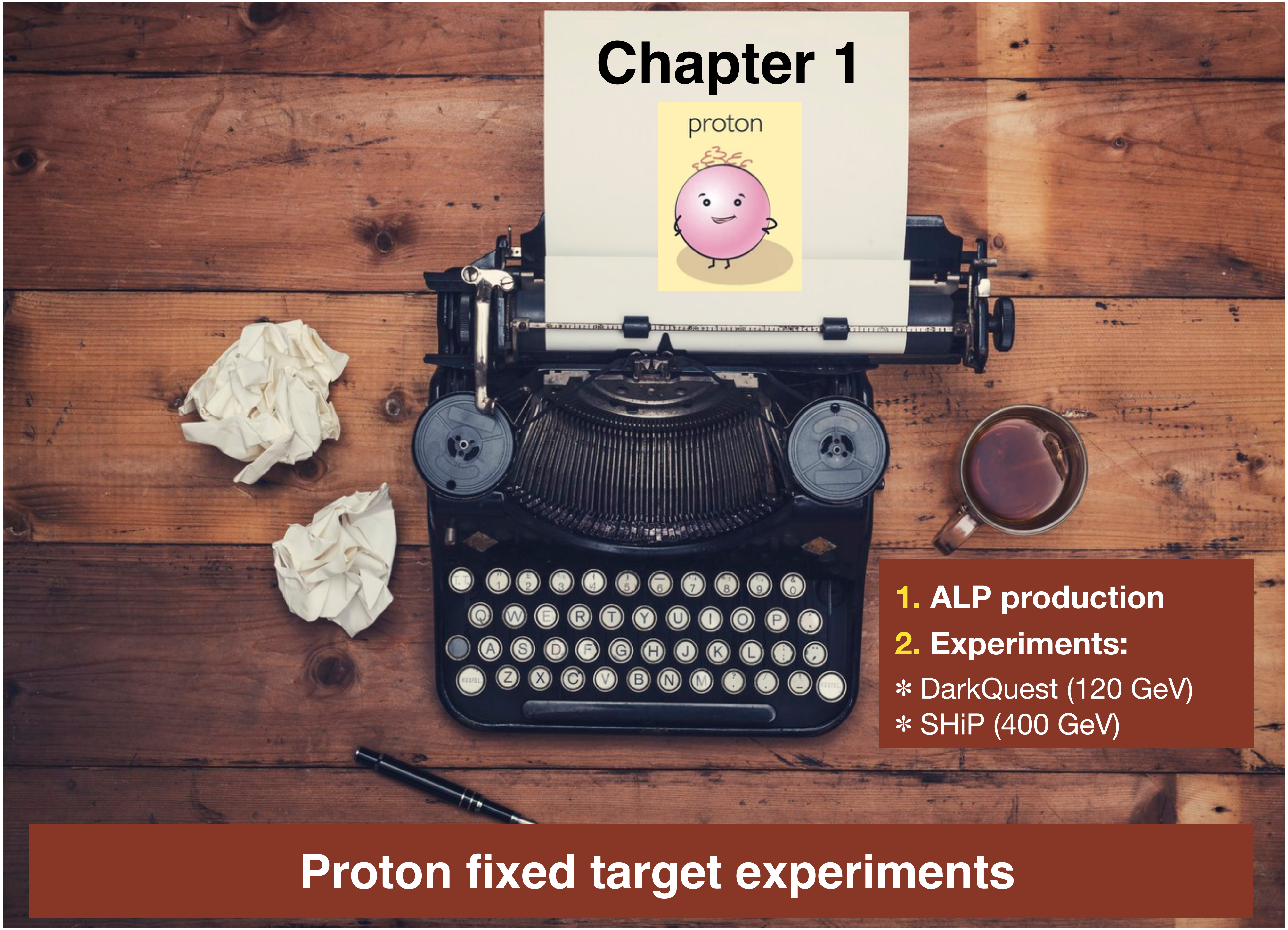
Visible ALPs

ALP production mechanisms:

Chapter 1 ✱ Proton beam: meson decays, radiation from secondary beams (electron, muons, photons), photon fusion.

Jerhot et al., 2201.05170

Chapter 2 ✱ Electron beam: bremsstrahlung, radiation from secondary beams (photons), photon fusion.



Chapter 1

1. **ALP production**
2. **Experiments:**
   - ✻ DarkQuest (120 GeV)
   - ✻ SHiP (400 GeV)

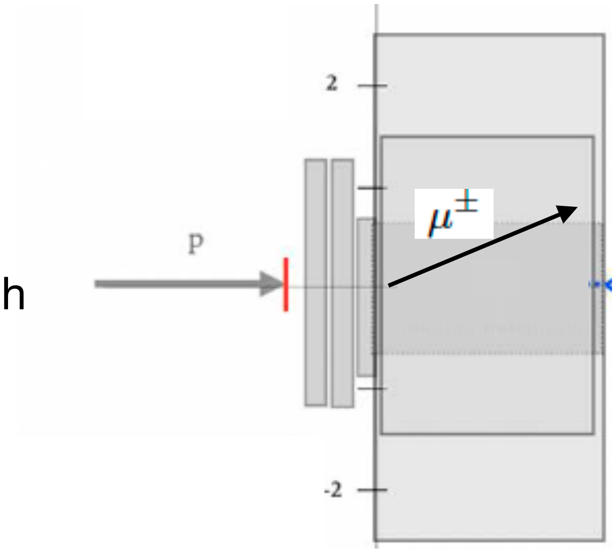
Proton fixed target experiments

A huge particle production at proton fixed target

For example, for a 120 GeV proton beam and 10^{18} POT:

$\mu^{\pm}$	γ	prompt $\pi^{\pm}$ dec.	prompt $K^{\pm}$ dec.
1.0×10^{16}	3.8×10^{18}	8.6×10^{15}	1.9×10^{15}

decaying in the 1st interaction length



ALPs can be emitted by this secondary muon beam
Connection to $(g-2)_\mu$?

ALPs can be emitted by this secondary photon beam

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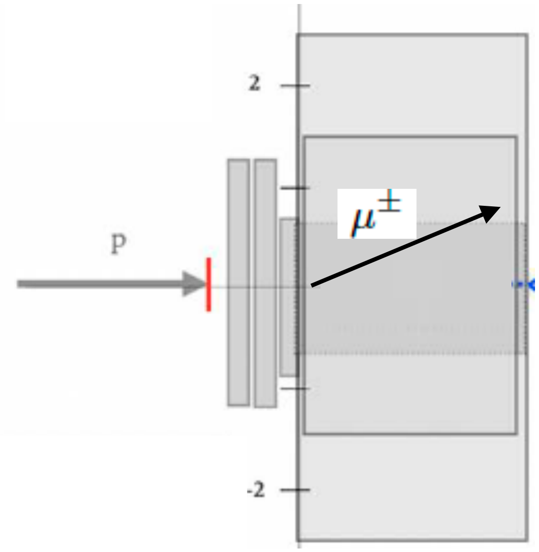

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Huge sample of light mesons.

For comparison:
future pion factory (PIONEER): ~**10^{12} pions**
Kaon factories (NA62, KOTO): **10^{13} - 10^{14} Kaons**

B mesons need high energy beams:
10^8 @ 120 GeV; 10^{13} @ 400 GeV
(10^{18} POT)
For comparison:
HL-LHCb: ~**10^{14}** b quarks,
Belle II: ~**10^{11}** B mesons

Mesons can decay to ALPs.
(some of these decay modes have not been investigated yet..see later)

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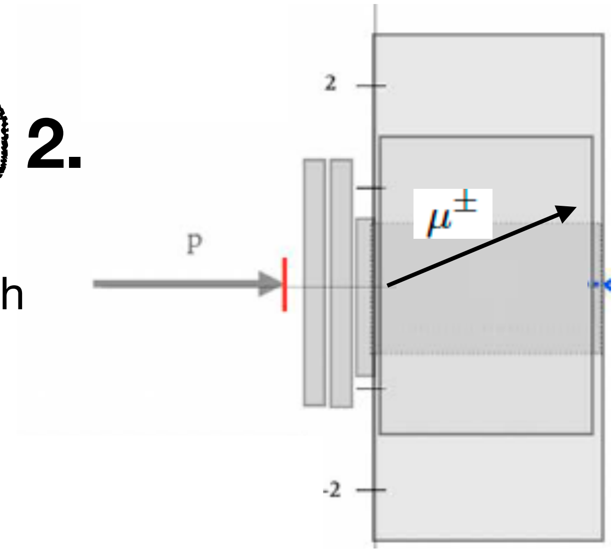
2.

decaying in the 1st interaction length



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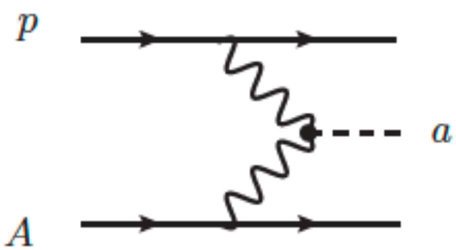
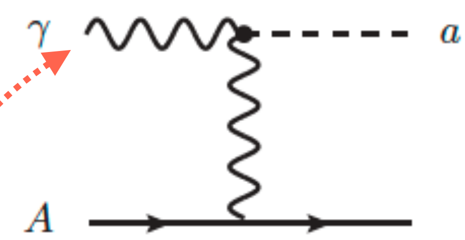
1. ALPs from photons

a. Photon fusion

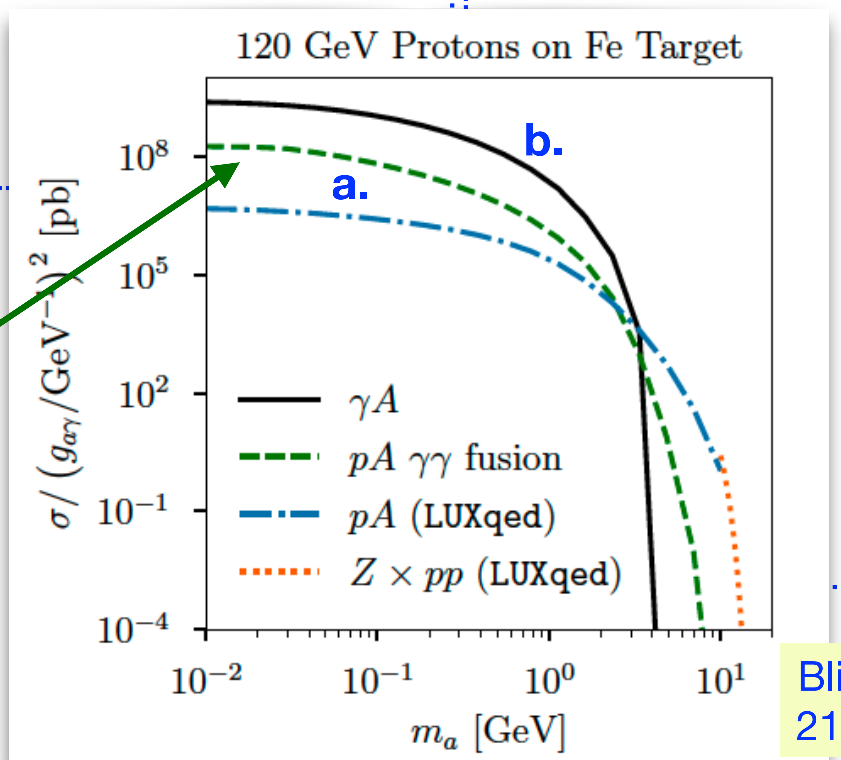


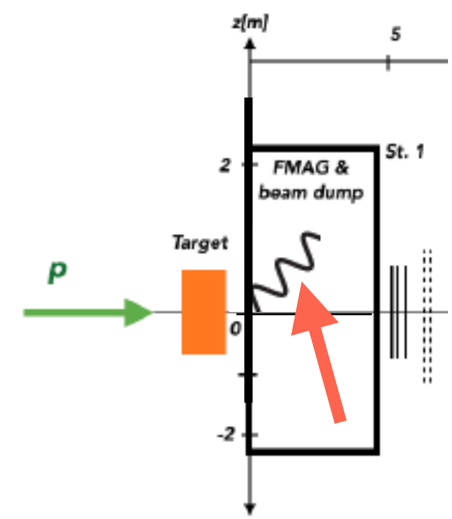
This was the main channel studied for proton beam dump experiments

b. Radiation (Primakoff)



Secondary photon beam from meson decays at the beginning of the dump





More boosted ALPs both channels are important

Blinov et al, 2112.09814

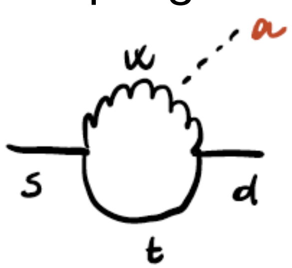
2. ALPs from meson decays

Flavor changing neutral current

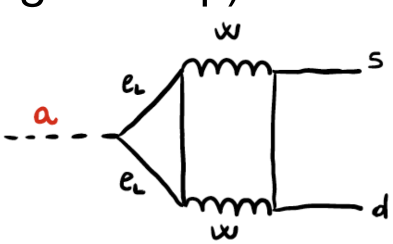
They arise in models with

* ALPs mixed with SM neutral pions (e.g. $K^+ \to \pi^+ \pi^0 \;\Rightarrow\; K^+ \to \pi^+ a$)

* ALPs coupling to W or tops



* ALPs coupling to leptons (higher loop)



* Flavor violating ALPs

$$K_L \to \pi^0 a$$
$$K^+ \to \pi^+ a$$
$$B \to K a$$

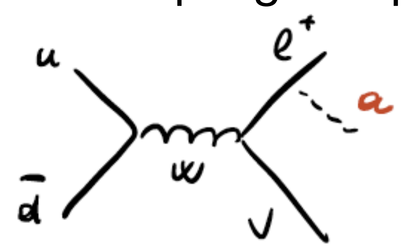
Most studied (both th. and exp.)

Charged current

They arise in models with

- ALPs mixed with SM neutral pions (e.g. $\pi^+ \to \ell^+ \nu \pi^0 \;\Rightarrow\; \pi^+ \to \ell^+ \nu a$)

- ALP coupling to leptons or quarks



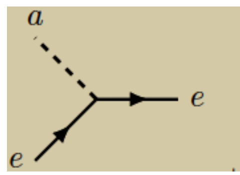
$$\pi^+ \to a \ell^+ \nu$$
$$K^+ \to a \ell^+ \nu$$
$$B^+ \to a \ell^+ \nu$$

Example scenario: Lepton-coupled ALPs

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

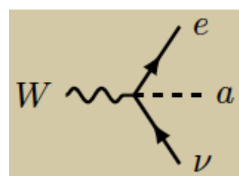
$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

"Standard" vertex



$$\partial_\mu j^\mu_{\rm PQ}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$
$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

Weak vertex



(only present for **SU(2) weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

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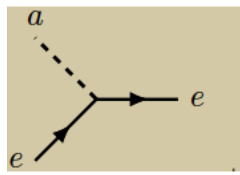

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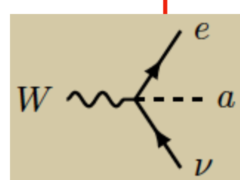


(only present for **SU(2) weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

Enhancement of the charged-current decays:

$$\Gamma_{\pi^+\to e^+\nu a}\propto g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ "standard" vertex

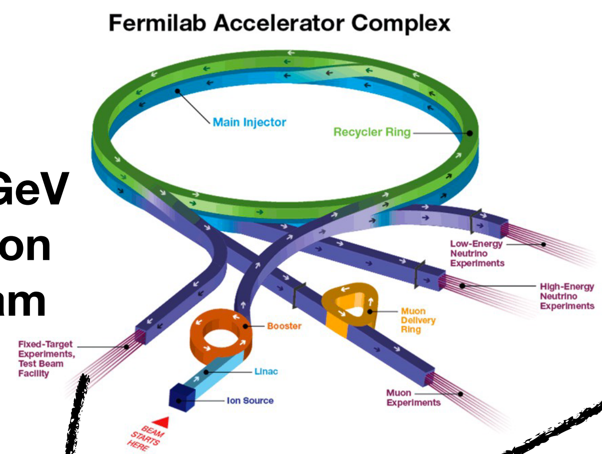
$$\Gamma_{\pi^+\to e^+\nu a}\propto \frac{m_\pi^2}{m_e^2}g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ weak vertex

Altmannshofer, Dror, SG, 2209.00665

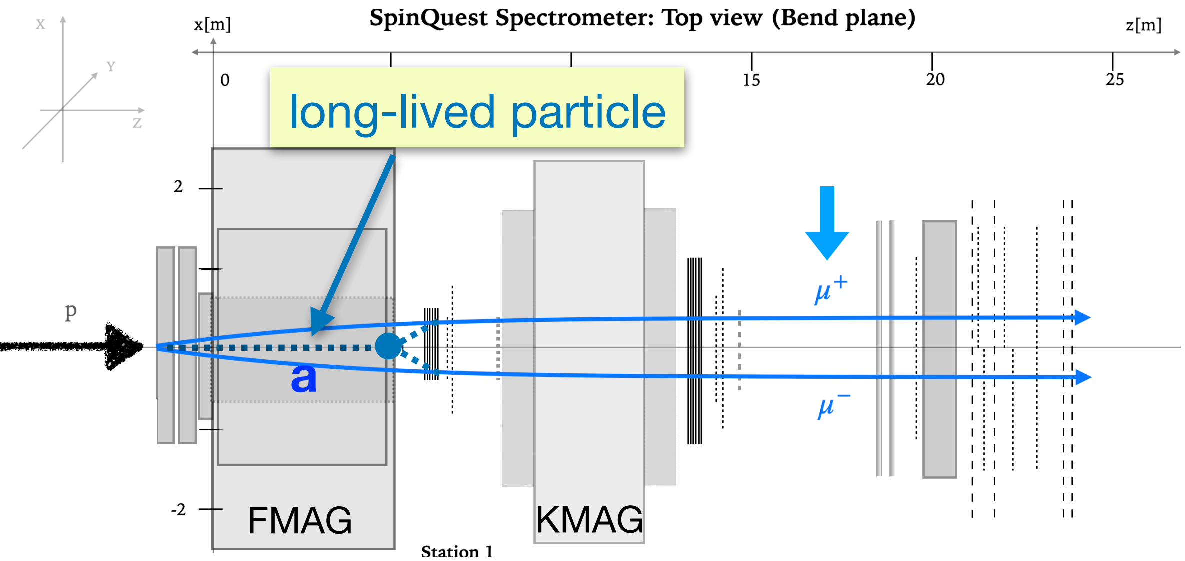
The SpinQuest experiment

Compact geometry.
Unique aspect of the experiment

120 GeV proton beam



Fermilab accelerator complex



Dump

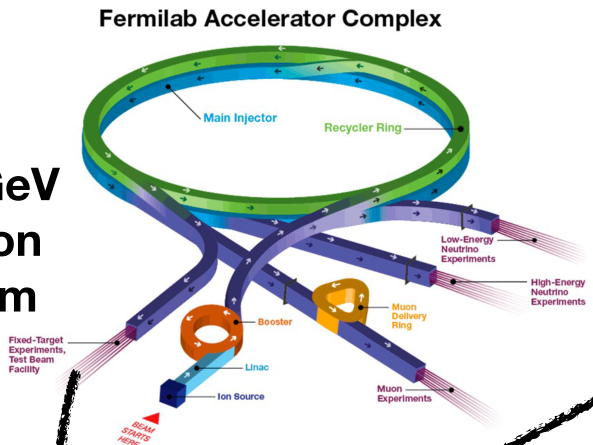
SeaQuest → SpinQuest
1706.09990
polarized target
+ displaced trigger
muon signatures

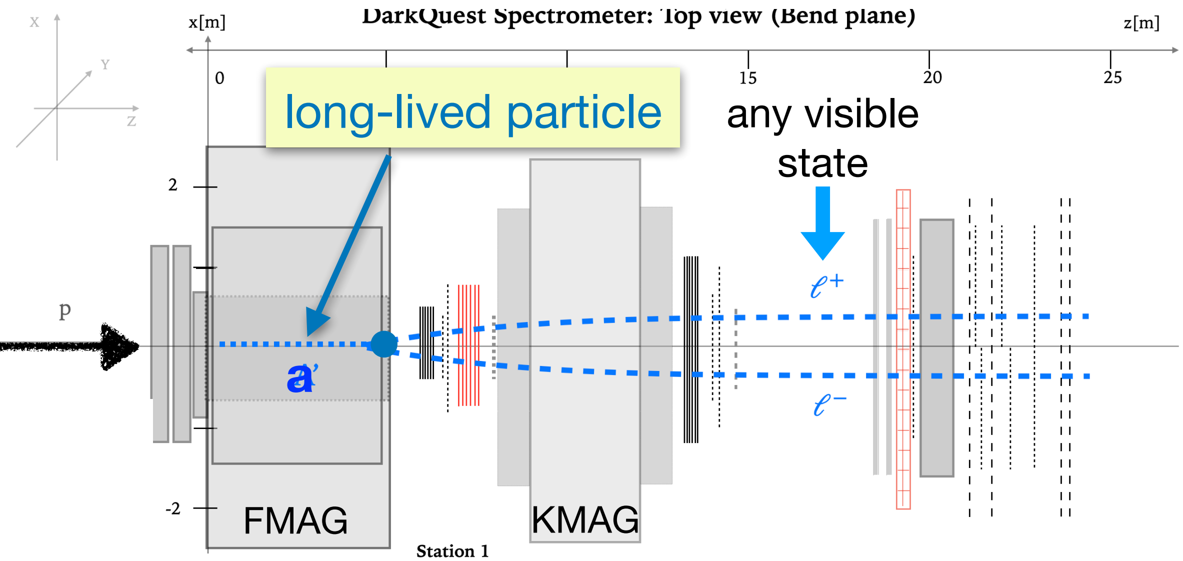
Took first data in May-July, 2024! ~6*10^{14} POT

The DarkQuest upgrade

Compact geometry.
Unique aspect of the experiment

120 GeV proton beam





Dump

Fermilab accelerator complex

SeaQuest
1706.09990

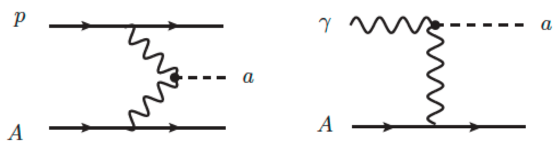
→ **SpinQuest**
polarized target
+ displaced trigger
muon signatures

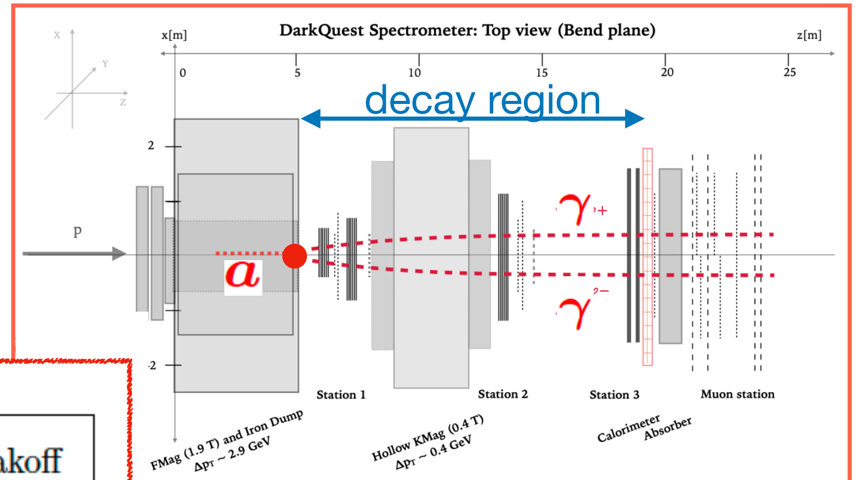
→ **DarkQuest**
proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)
all visible signatures

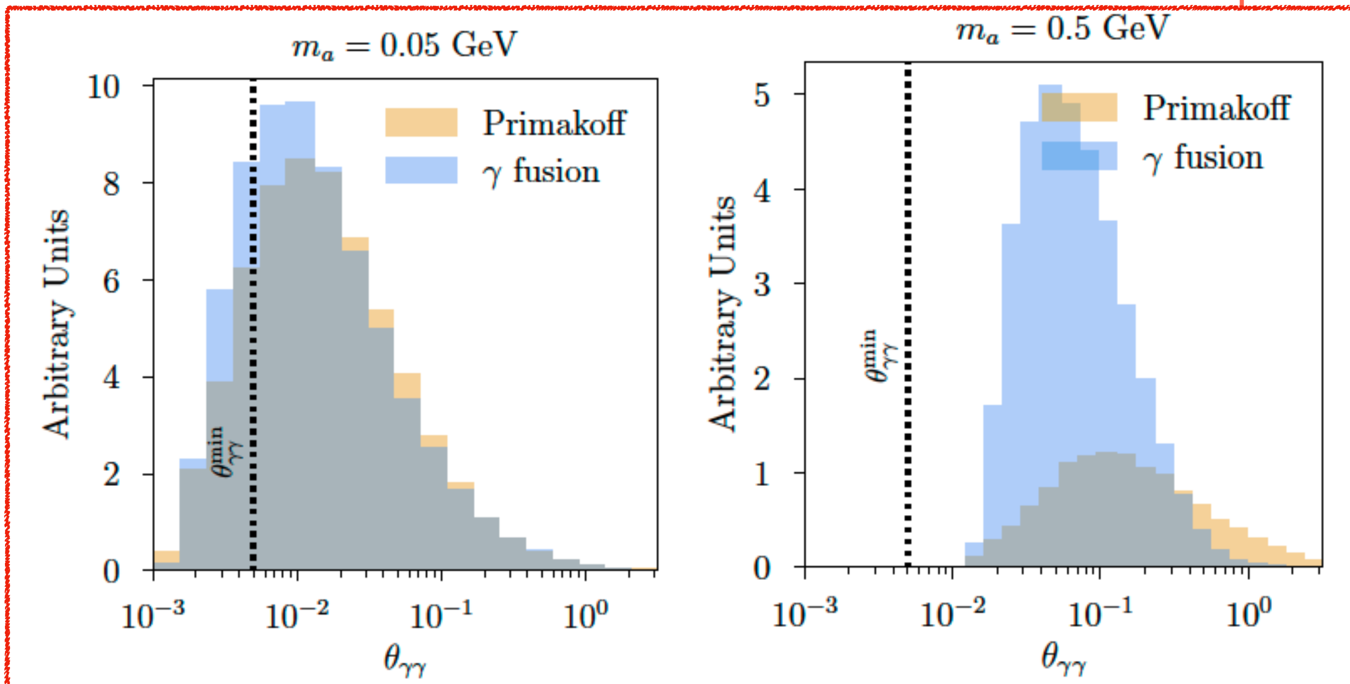
Initial proposal: Berlin, SG, Schuster, Toro, 1804.00661
Snowmass white paper: 2203.08322

ALPs at DarkQuest

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

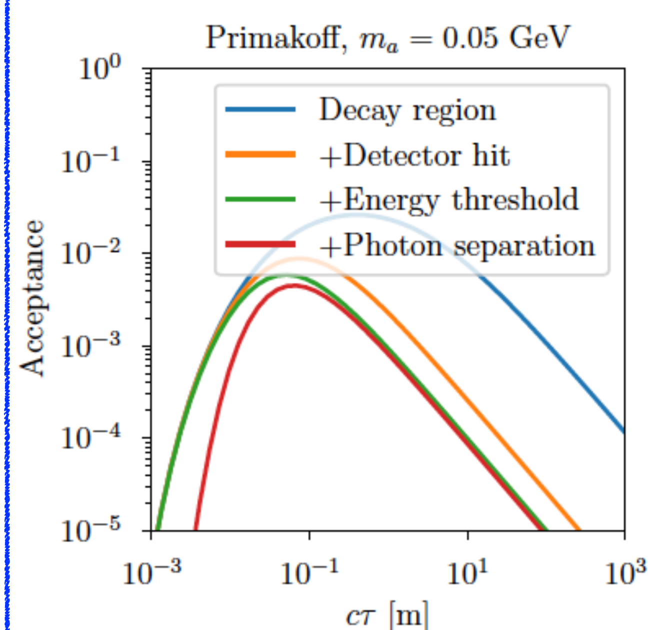






for > 5.5 cm separation

very high acceptance



Blinov et al, 2112.09814

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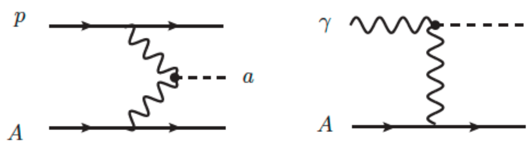

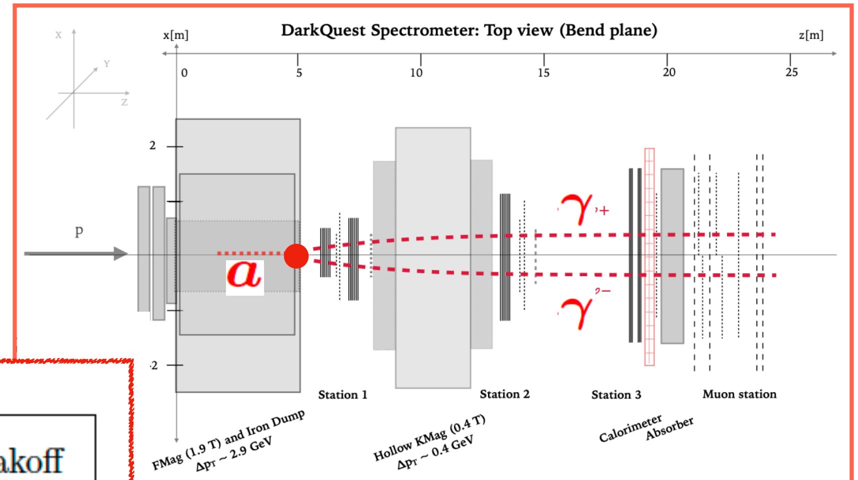

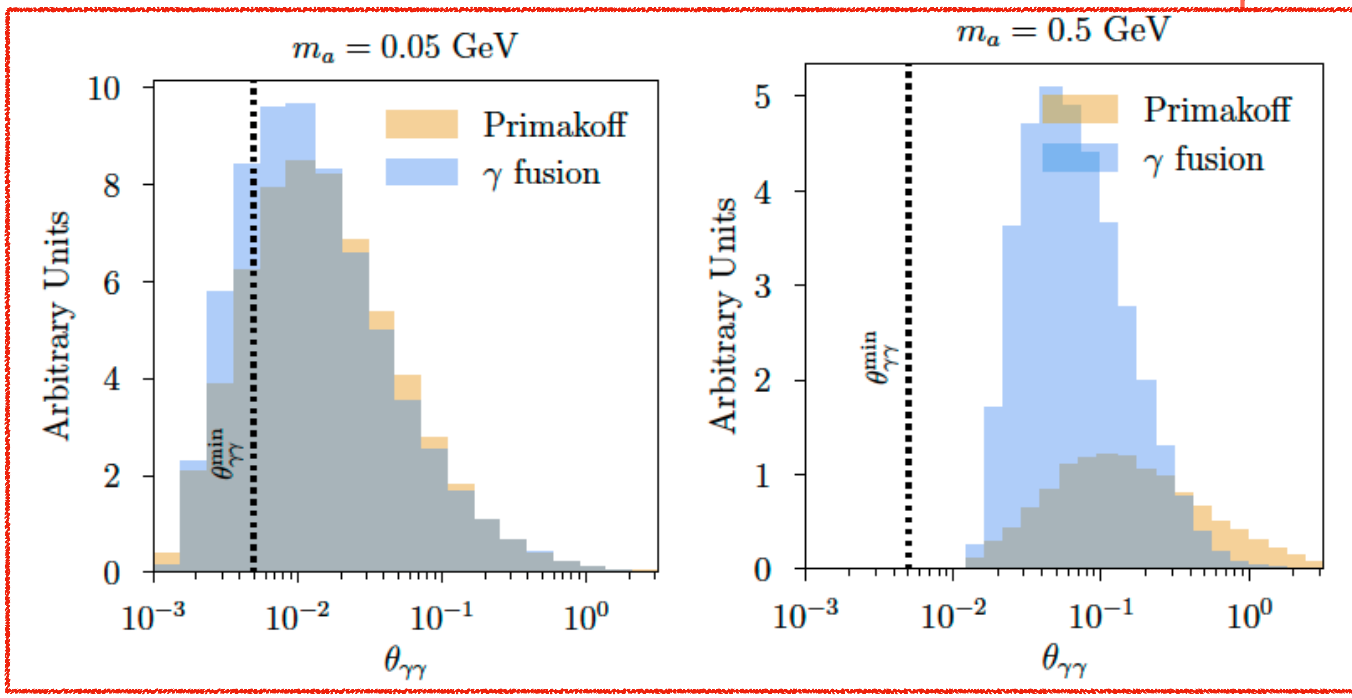

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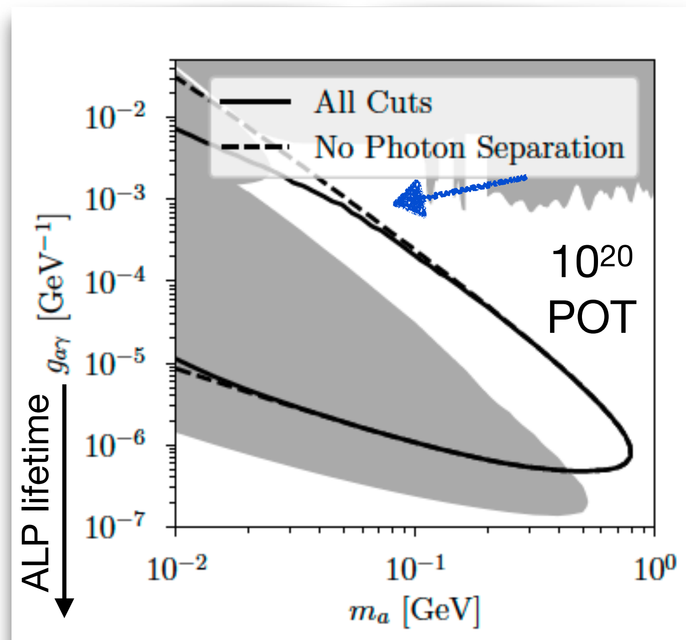


Blinov et al, 2112.09814

S.Gori

photons with E > 1GeV

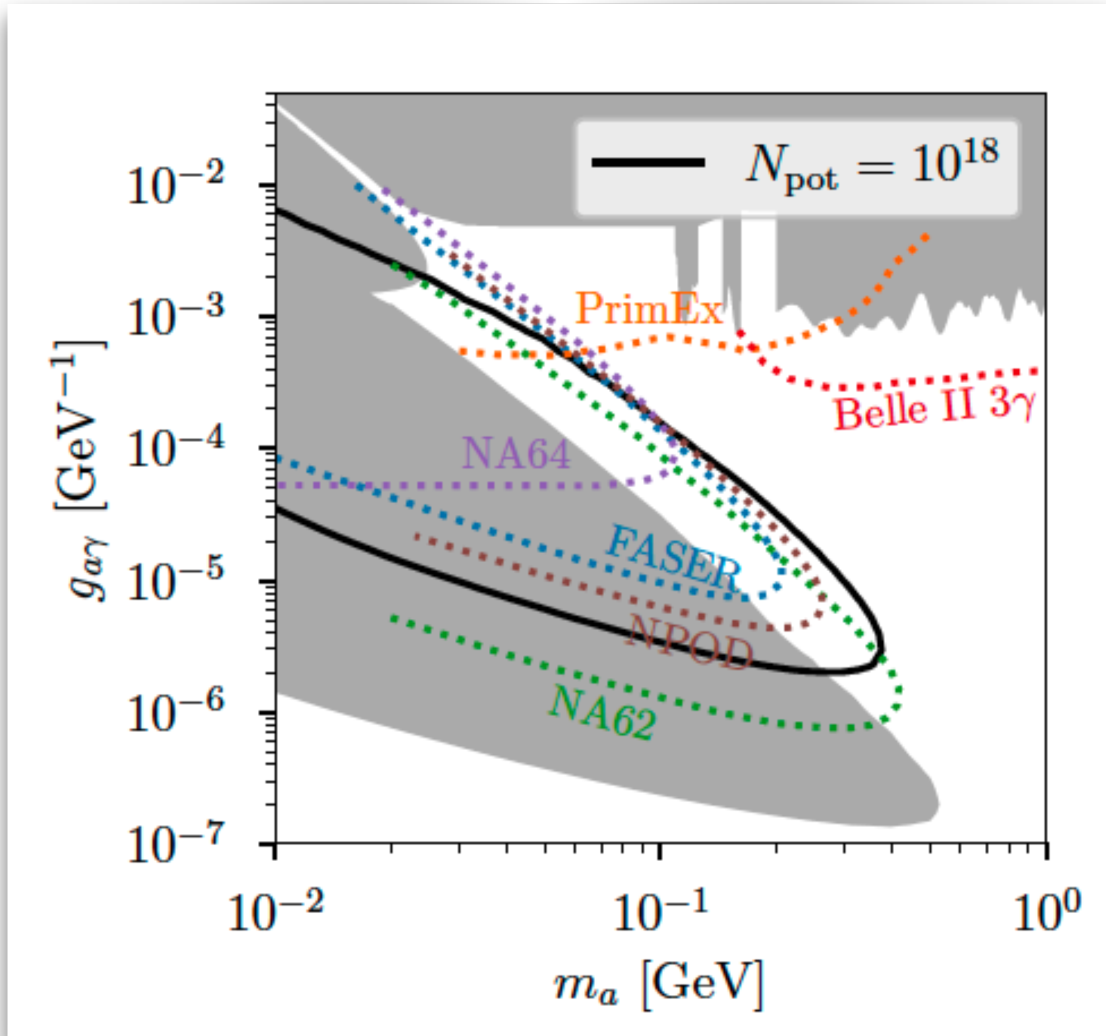
DarkQuest reach on photon-coupled ALPs

NA64,
γN→Na, a→γγ
5 x 10^{12} EOT

Dusaev et al,
2004.04469
(see later in this talk)

FASER,
300/fb

Feng et al,
1806.02348



Blinov et al, 2112.09814

LUXE, phase 0,
Bai et al, 2107.13554

NA62
dump-mode
10^{18} POT

Dobrich et al,
1904.02091

Photon backgrounds

The reach is obtained asking for **10 signal events**. This reach is obtainable only if backgrounds are pretty small. This is the typical assumption for this type of experiments.

Electron signatures, indeed, have very low backgrounds.

What about signatures with photons? There are interesting background sources…

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1. Backgrounds from **primary interactions**:

$K_L \to 3\pi^0 \to 6\gamma$, $O(10^5$ events)

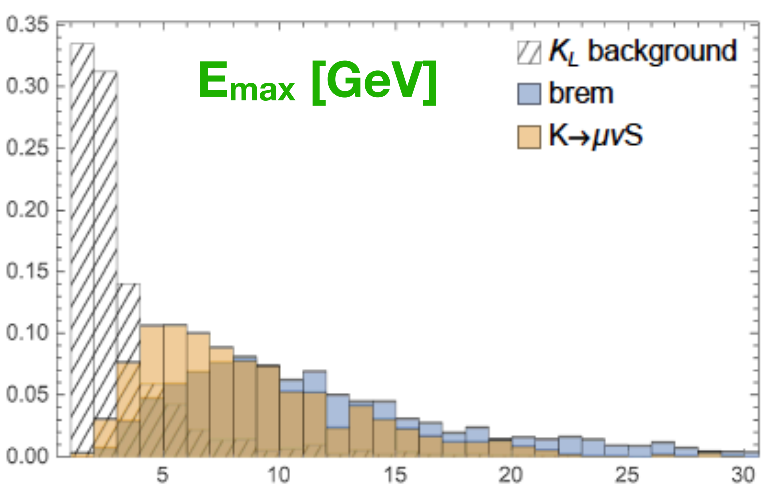
(Life time $K_L \sim 15$m)

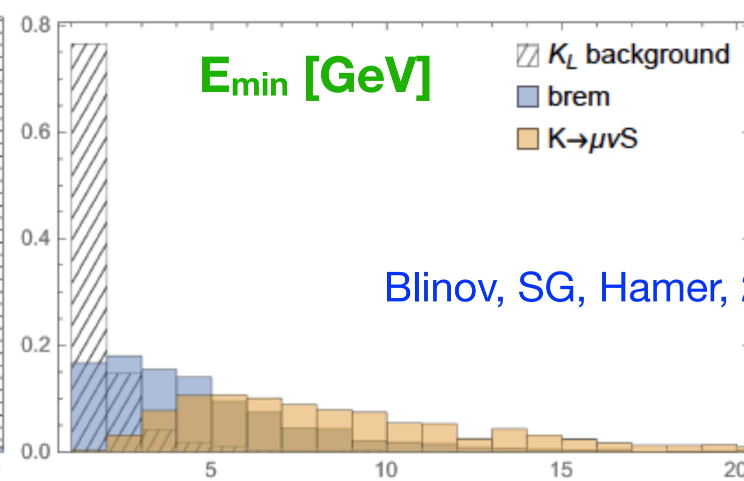
$$e^{-z_{\rm shield}/\lambda_{K\ {\rm int}}}$$

suppression of Kaons through the dump

Strategies to suppress it:

- O(100) if we ask only 2 photons to be in geometric acceptance
- O(10-100) with cuts on energy, p_T of the two photons
- Another possibility is to add more shielding: +1.5m → $O(10^4)$





Blinov, SG, Hamer, 2405.17651

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2. Backgrounds from **secondary interactions**:

$\pi^0 \to \gamma\gamma$ produced from attenuated proton beam at the end of the dump,

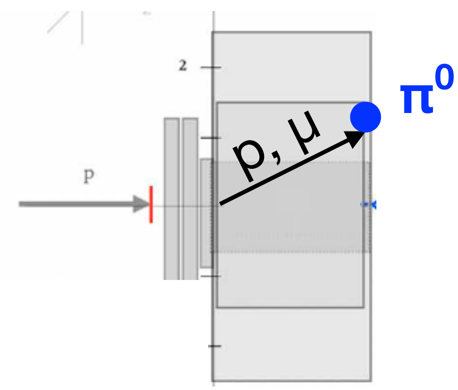
O(10^4 events)

$$e^{-z_{\rm shield}/\lambda_{p\ \rm int}}$$

suppression of protons through the dump

Strategies to suppress it:

- O(few) with di-photon invariant mass requirement (we computed it: ~30%).
- Another possibility is to add more shielding: +1m → O(10^3)



$\pi^0 \to \gamma\gamma$ produced from attenuated muon beam at the end of the dump,

O(10^6 events)

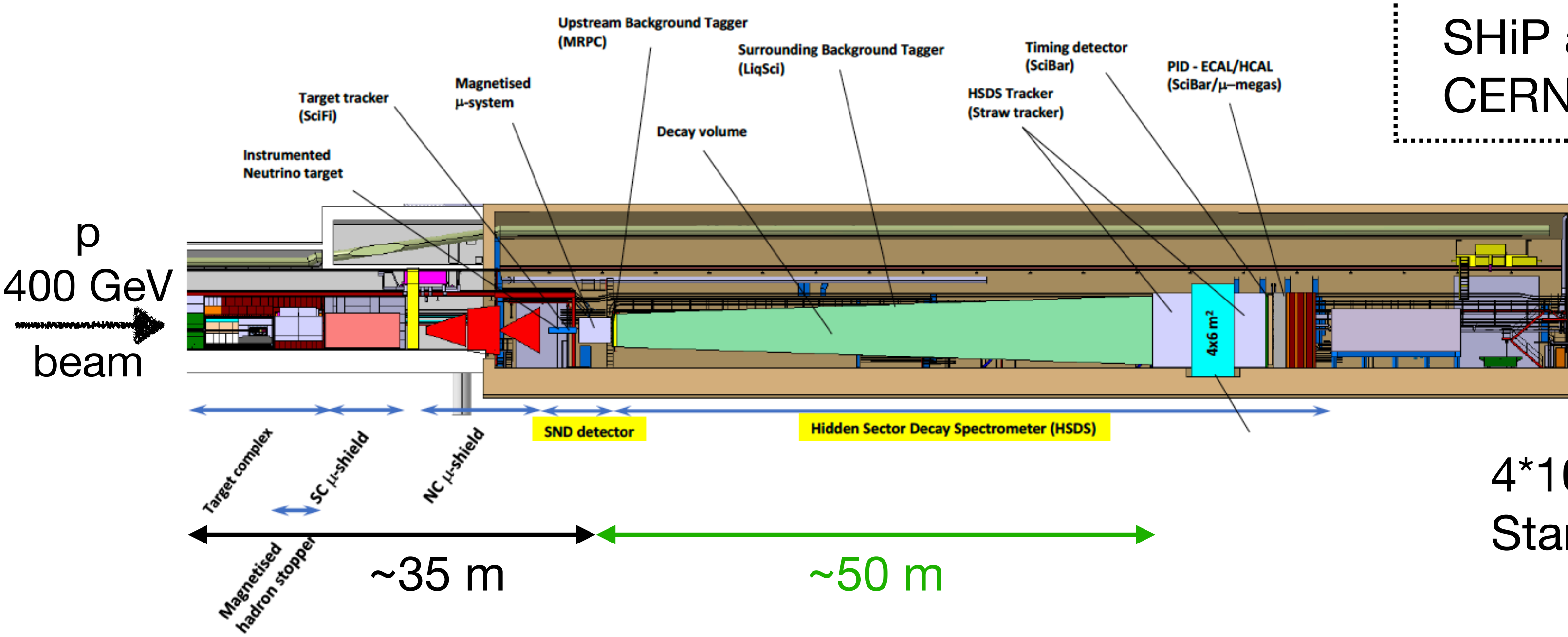
Possible to reduce the background to O(few) with 10^{18} POT

Strategies to suppress it:

- O(few) with di-photon invariant mass requirement.
- O(10^3) with the requirement of photon separation and minimum energy
- veto on the muon

Blinov, SG, Hamer, 2405.17651

The SHiP reach on ALP models



SHiP approved by CERN in March 2024

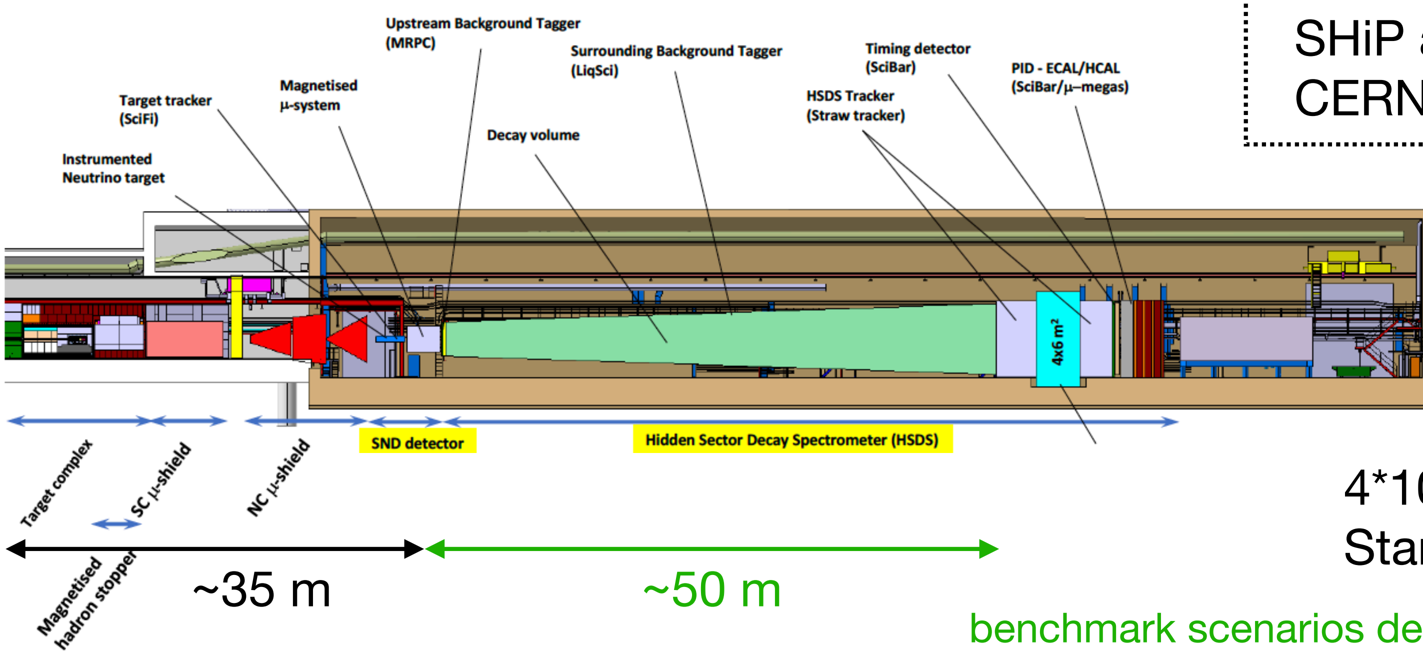
CERN-SPSC-2023-033

4*10^{19} POT/year
Starting early 2030s

The SHiP reach on ALP models

SHiP approved by CERN in March 2024

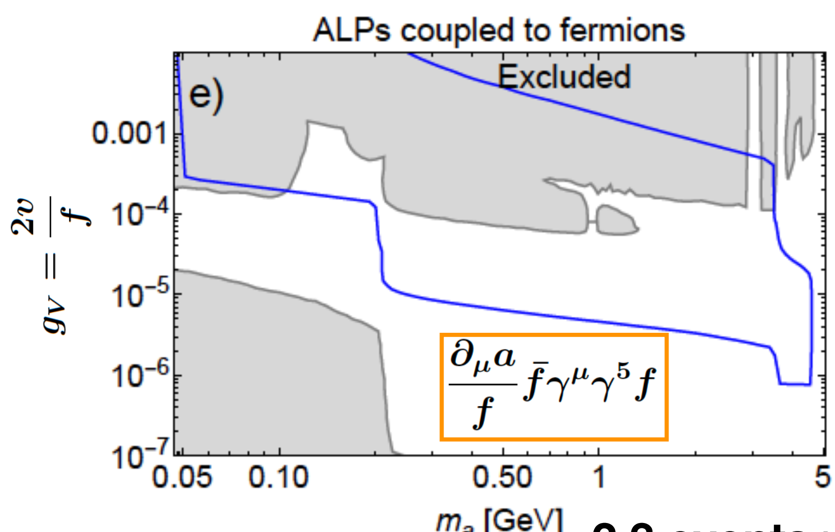
p
400 GeV
beam

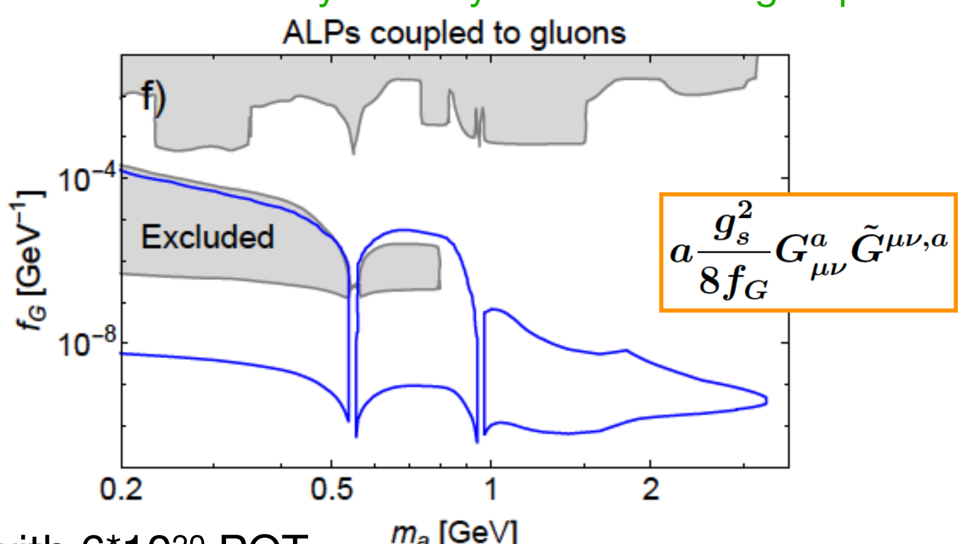


CERN-SPSC-2023-033

$4 \cdot 10^{19}$ POT/year
Starting early 2030s

benchmark scenarios defined by the "Physics beyond colliders" group at CERN





2.3 events with $6 \cdot 10^{20}$ POT

A note on the electron coupling

We already saw that if

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

and

$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$ (SU(2) weak violating)

$$\Gamma_{\pi^+\to e^+\nu a}\propto\frac{m_\pi^2}{m_e^2}g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$

These decays are typically not studied for fixed target experiments

$$\pi^+\to ae^+\nu,\ K^+\to ae^+\nu,\ D^+\to ae^+\nu,\ B^+\to ae^+\nu$$

A note on the electron coupling

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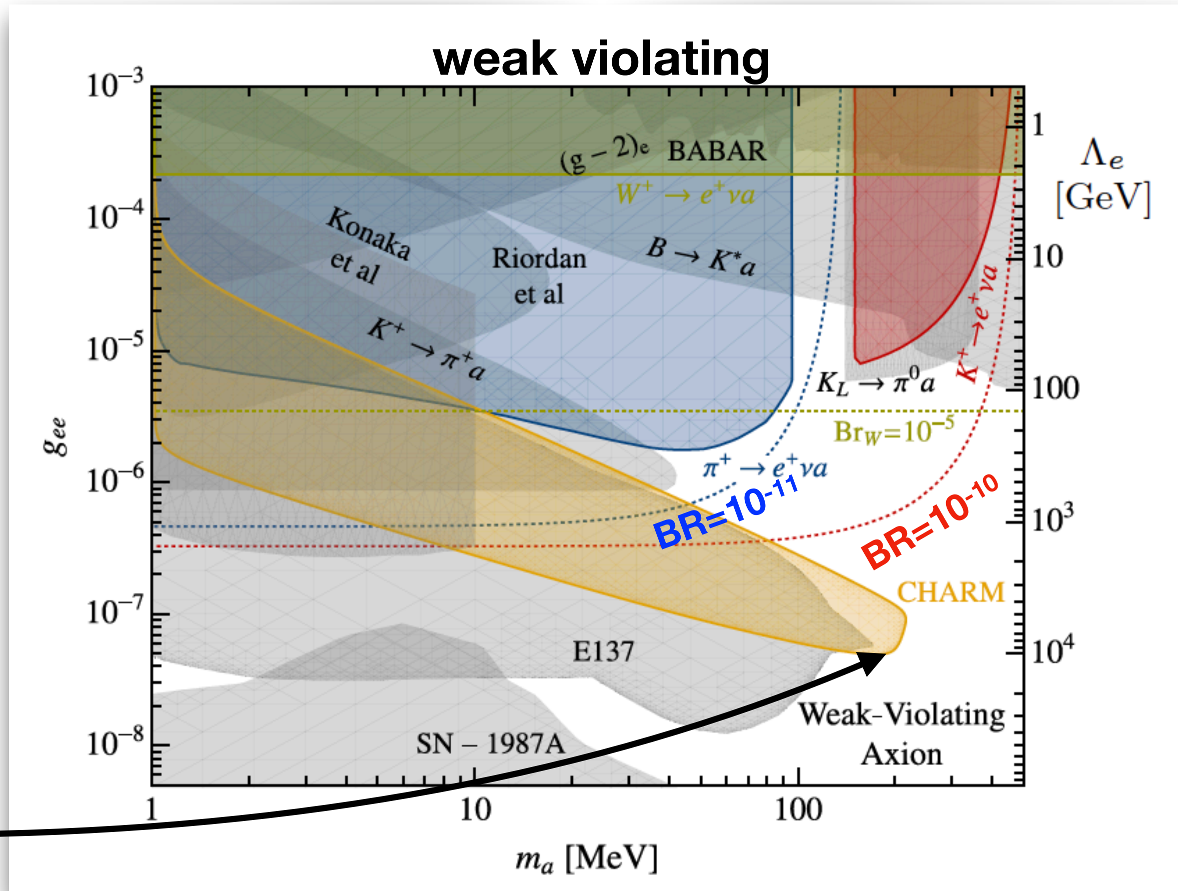


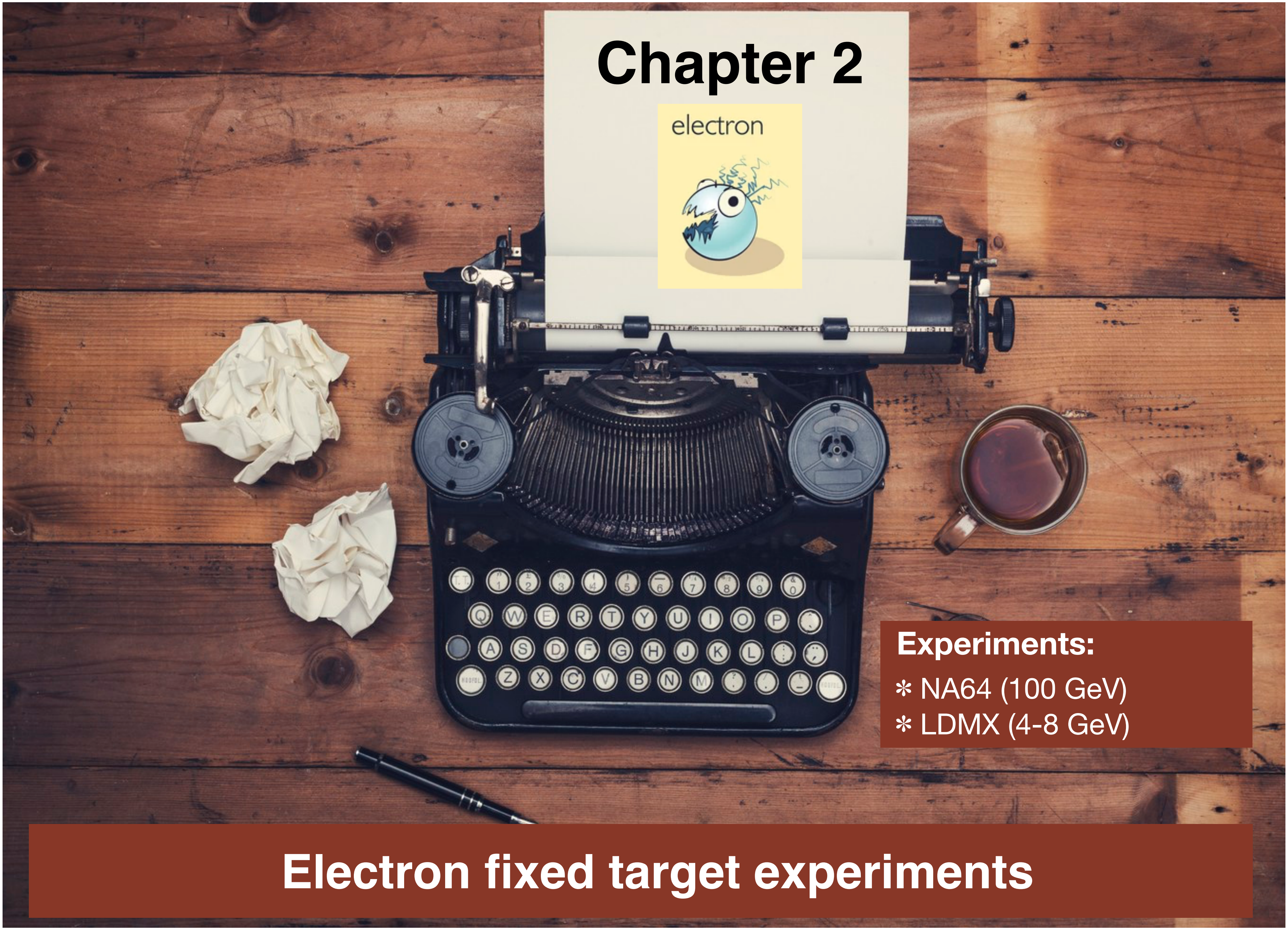
The reach of proton fixed target experiments can be extended!

Altmannshofer, Dror, SG, 2209.00665

Red: K → eν**a**→eν(ee)

Green: W→ eν**a**→eν(ee) **exotic W boson decay**

} Additional searches can also be done at meson factories + LHC

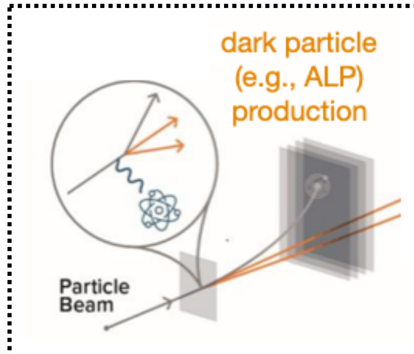


Chapter 2

Experiments:
- NA64 (100 GeV)
- LDMX (4-8 GeV)

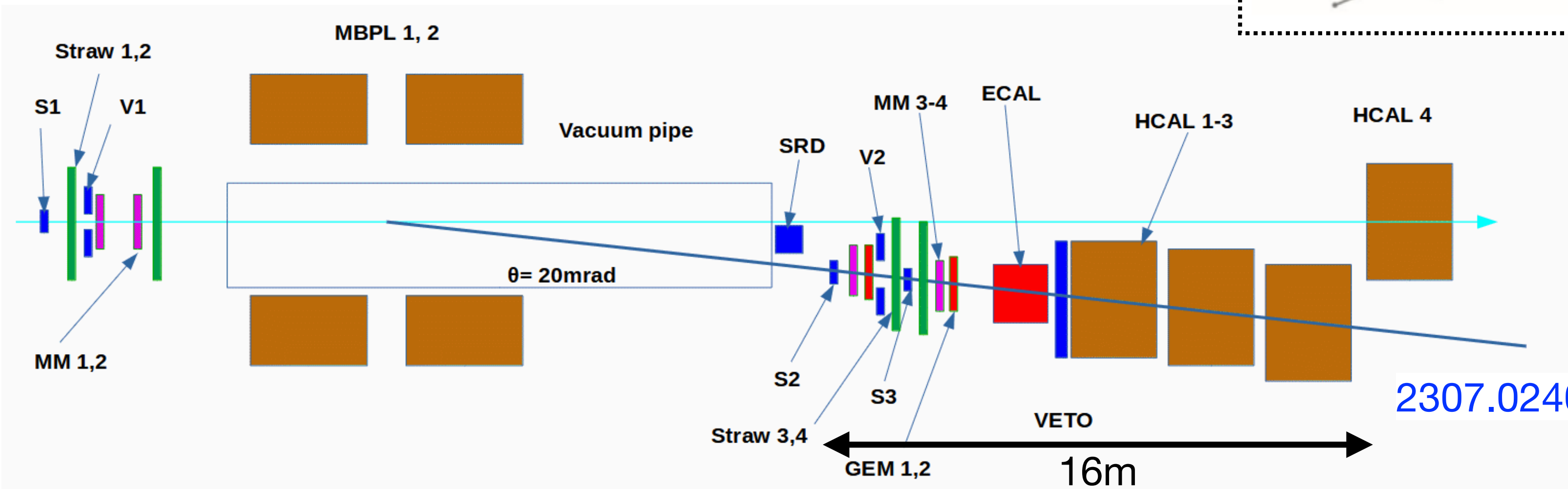
Electron fixed target experiments

The NA64 experiment



Initiated by the CERN 400 GeV SPS protons:

e⁻
100, 150 GeV
beam

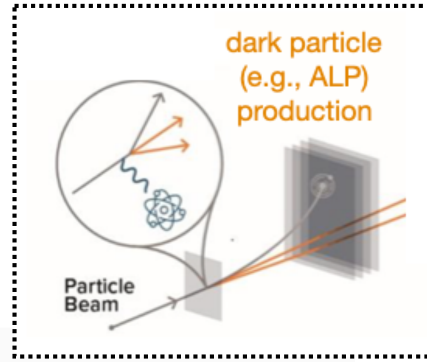


2307.02404

~1.5*10[12] EOT collected in 2016-2023
Plan to collect a factor of a few more data

Beam time structure: particles impinge on the detector "one at time", to be individually resolved

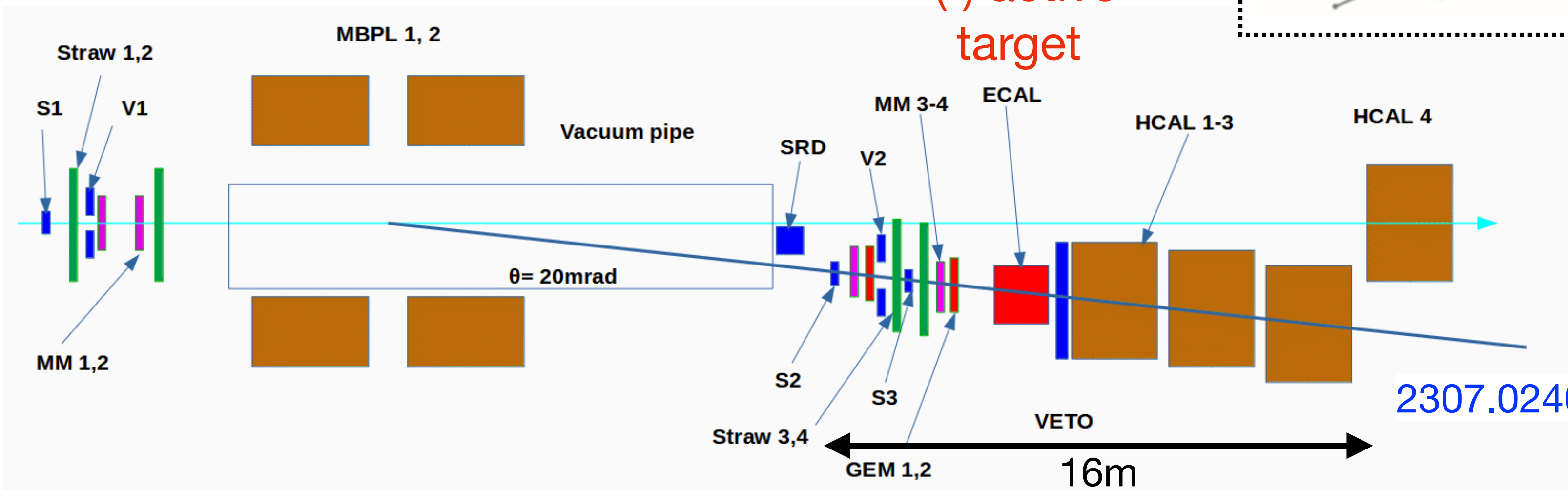
The NA64 experiment



Initiated by the CERN 400 GeV SPS protons:

e⁻
100, 150 GeV
beam

(*) active target



2307.02404

~1.5*10^{12} EOT collected in 2016-2023
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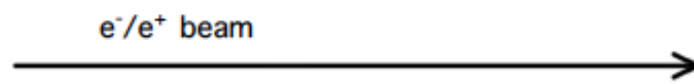
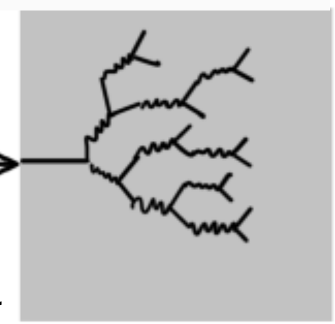




1. Missing energy technique

It looks the data in the form of a hermeticity plot, showing the energy deposited in the ECAL and HCAL

(*) target = detector

2. Searches for visible signatures using ECAL+HCAL

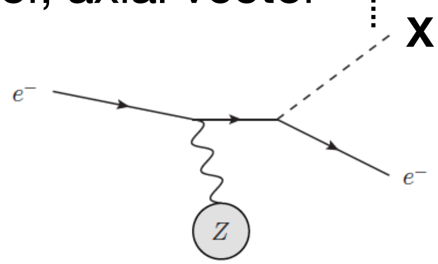
Future **muon** (160 GeV, ~2*10^{10} MOT, 2401.01708), hadron (50 GeV, ~2.9*10^{9} pionsOT, 2406.01990) **positron** (100 GeV, 10^{10} EOT, 2308.15612) runs

↖ for enhancing the resonant e^+e^- annihilation

Invisible ALPs at NA64

2102.01885

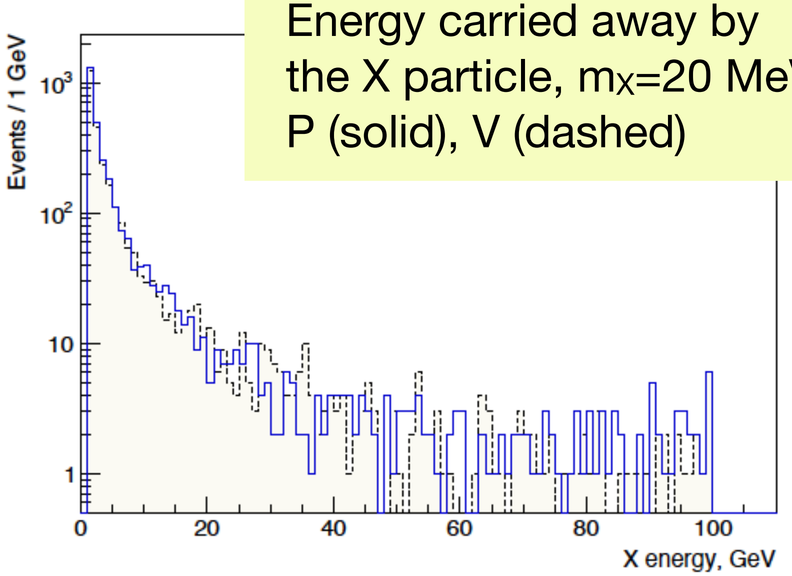
X= S, V, A = scalar, vector, axial vector coupled to electrons



X = P = pseudo scalar:

$$ie\epsilon_X a(\bar{e}\gamma_5 e) \equiv \frac{\partial_\mu a}{f_a}(\bar{e}\gamma^\mu\gamma_5 e)$$

Energy carried away by the X particle, m_X=20 MeV
P (solid), V (dashed)



Signal window:

E_{ECAL} < 50 GeV, $E_{HCAL}[1+2+3]$ < 1 GeV

Invisible ALPs at NA64

X= S, V, A = scalar, vector, axial vector coupled to electrons

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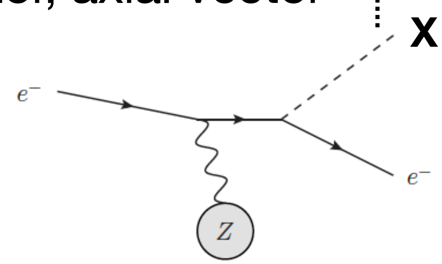

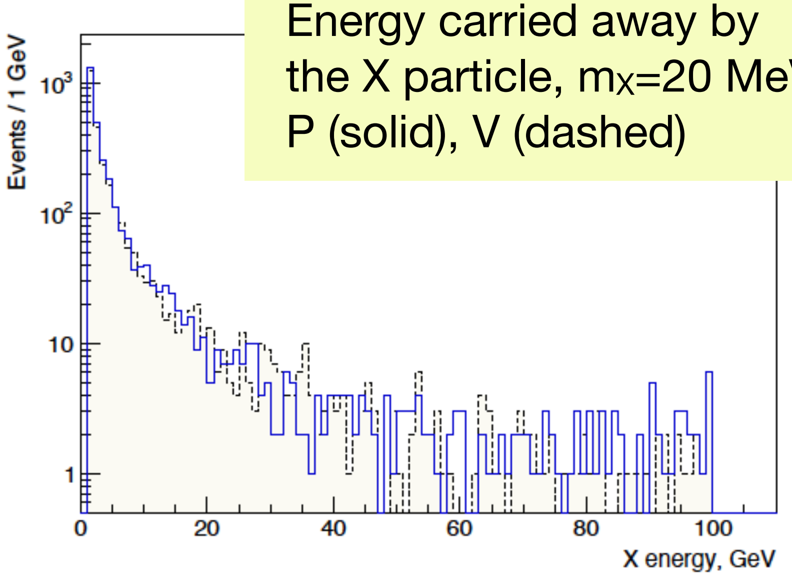

Energy carried away by the X particle, m_X=20 MeV P (solid), V (dashed)

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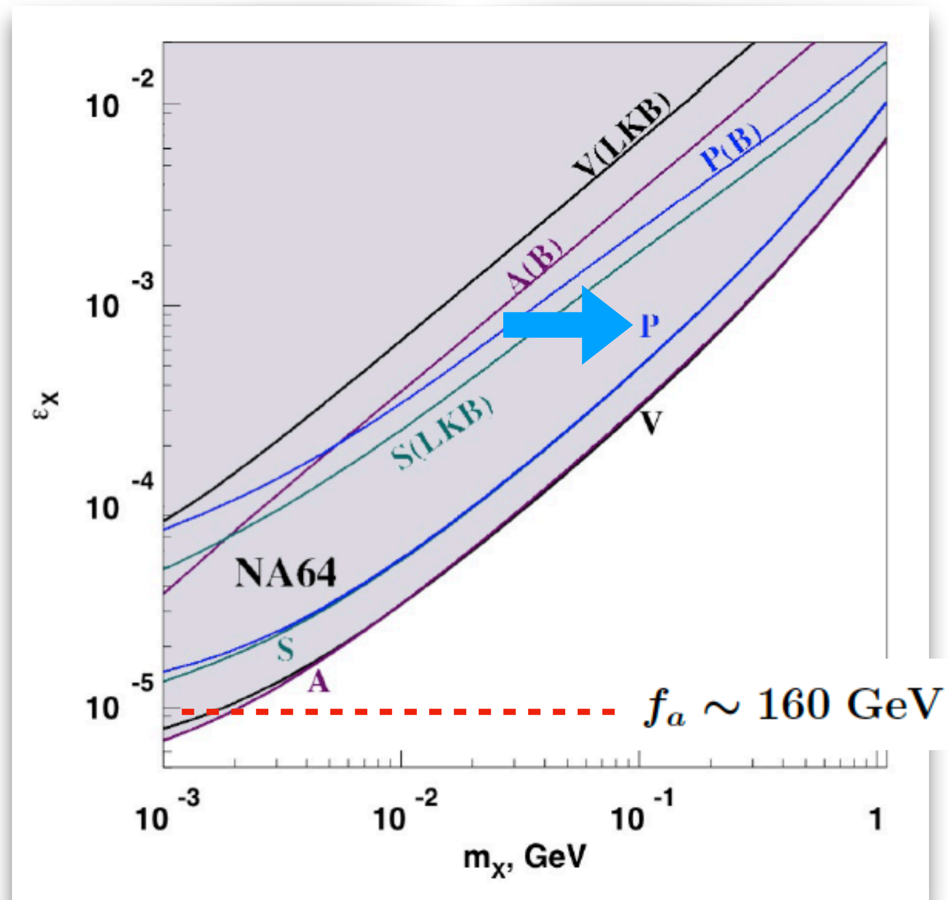
2102.01885

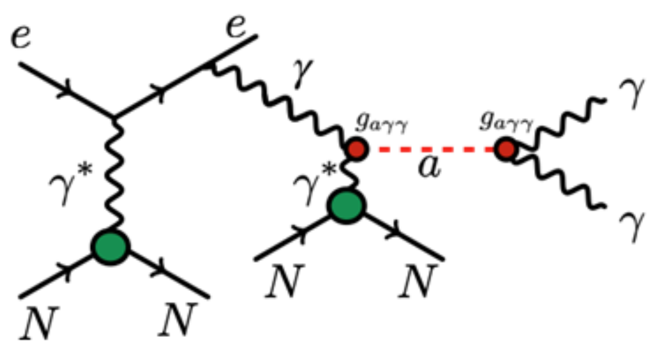


2.84*10^{11} EOT collected in 2016-2018

0 events observed, 0.53±0.17 expected background events

Sensitivity proportional to coupling^2

Visible / invisible ALPs at NA64



$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

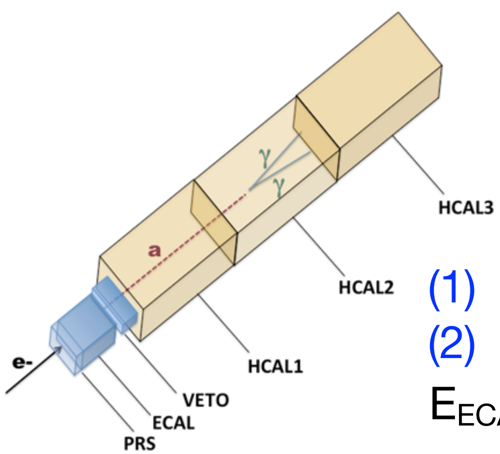
2005.02710

See also 2104.13342 for electron coupling

Two possible searches of this ALP:

(1) photons in $H_{CAL2,3}$ (visible);

(2) photons downstream of H_{CAL} (invisible)

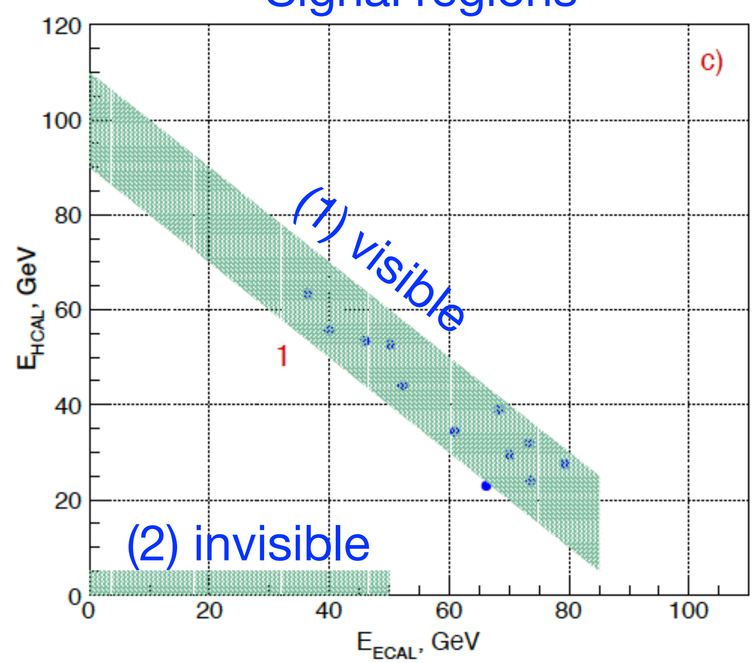


(1) $E_{ECAL} < 85$ GeV

(2) $E_{ECAL} < 50$ GeV

$E_{ECAL} + E_{HCAL} \sim 100$ GeV

Signal regions

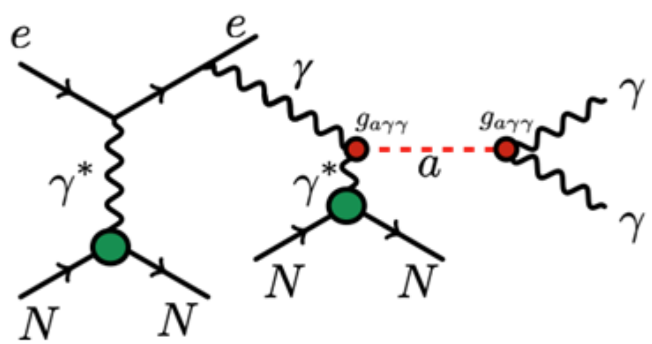


(1) Collimated photons. Single EM shower
No shower in H_{CAL1}

(1) visible background: 0.19±0.07 events

(2) invisible background: 0.53±0.17 events

Visible / invisible ALPs at NA64



$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

2005.02710

See also 2104.13342 for electron coupling

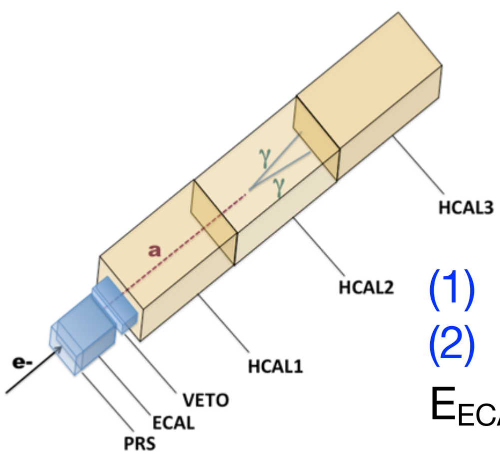
$$g_{a\gamma\gamma} = \left(0.203\frac{E}{N} - 0.39\right)\frac{m_a}{\mathrm{GeV}^2}$$

DFSZ: E/N=8/3; KSVZ: E/N=0

Two possible searches of this ALP:

(1) photons in $H_{CAL2,3}$ (visible);

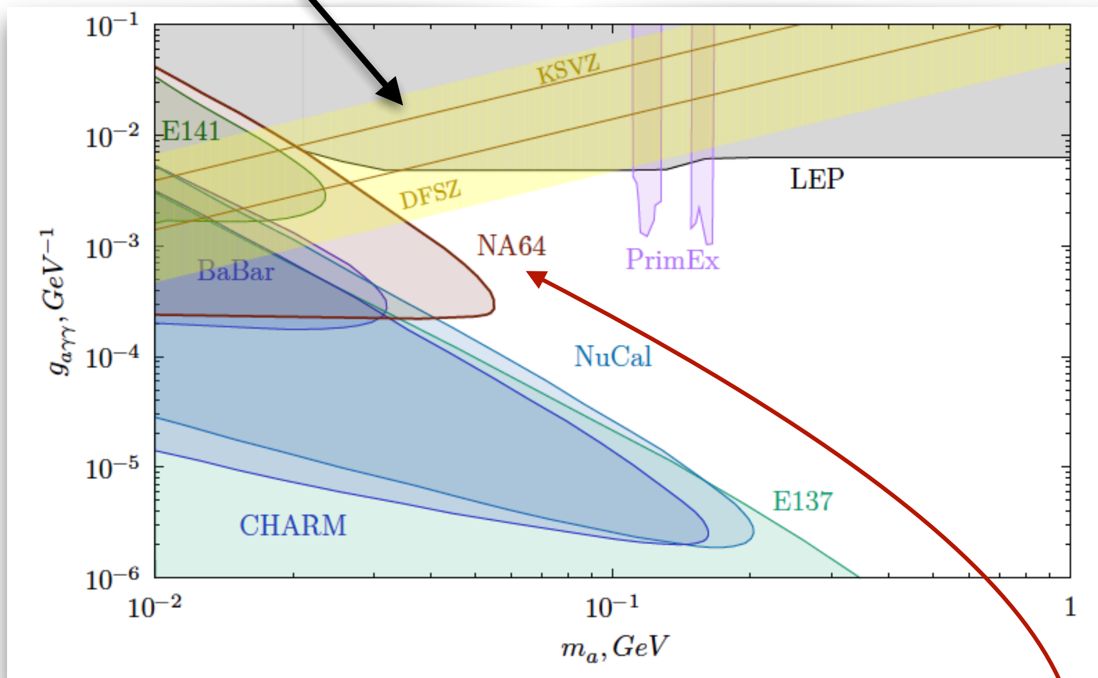
(2) photons downstream of H_{CAL} (invisible)



(1) E_{ECAL} < 85 GeV

(2) E_{ECAL} < 50 GeV

$E_{ECAL} + E_{HCAL}$ ~ 100 GeV



2.84*10^{11} EOT collected in 2016-2018

(1) Collimated photons. Single EM shower

No shower in H_{CAL1}

Couplings in the intermediate range are challenging at beam dump experiments

(1) visible background: 0.19±0.07 events

(2) invisible background: 0.53±0.17 events

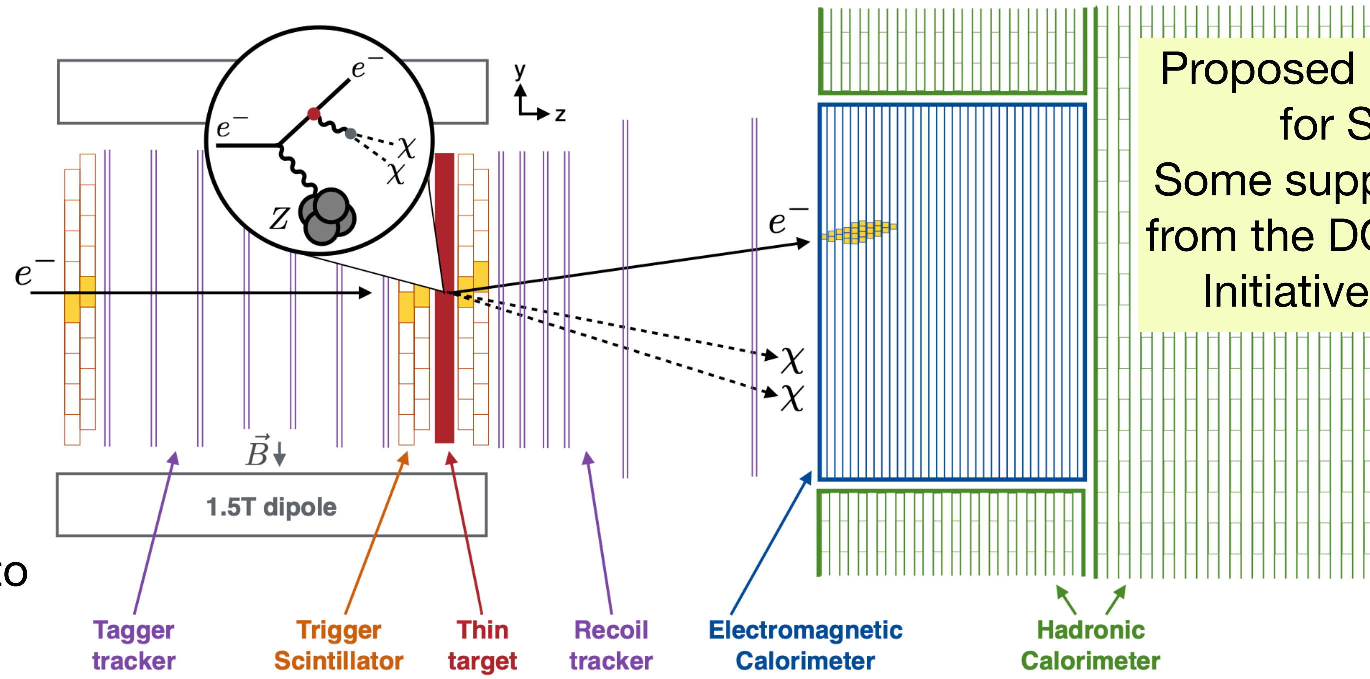
The LDMX experiment

Main goal:

Perform missing momentum searches for light dark matter (or invisible dark sectors)

High intensity electron beam (4 and 8 GeV)

The SLAC LCLS-II currently delivers 4 GeV e^-, but an accelerator upgrade to 8 GeV is imminent.



Real time identification of electrons

Missing energy in the E_{Cal} is a trigger condition.

Proposed experiment for SLAC. Some support already from the DOE DM New Initiative program

Akesson et al., 2203.08192

No fundamentally irreducible backgrounds, that do not have veto handles at relevant rates.
Neutrino production has a $\sim 10^{-16}$ rate
Zero-background has been established for a sample of 2×10^{14} EOT, 4 GeV beam.

The LDMX experiment

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Perform missing momentum searches for light dark matter (or invisible dark sectors)

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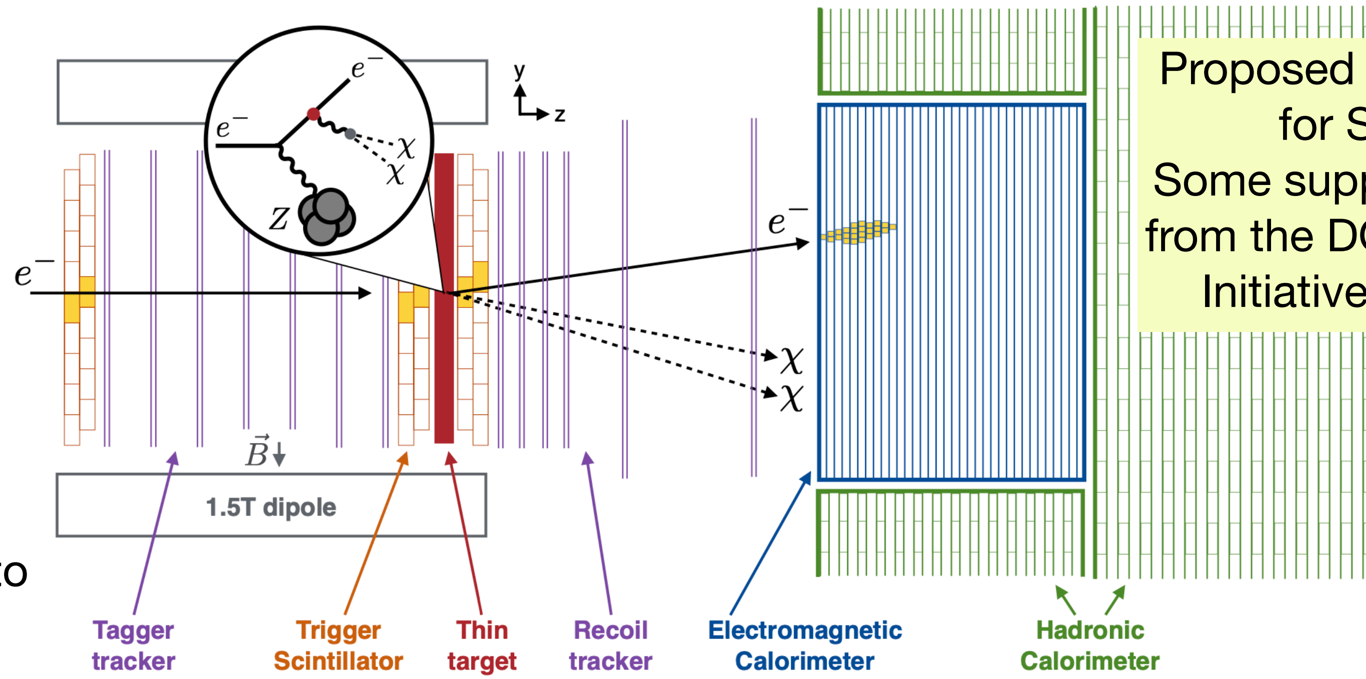


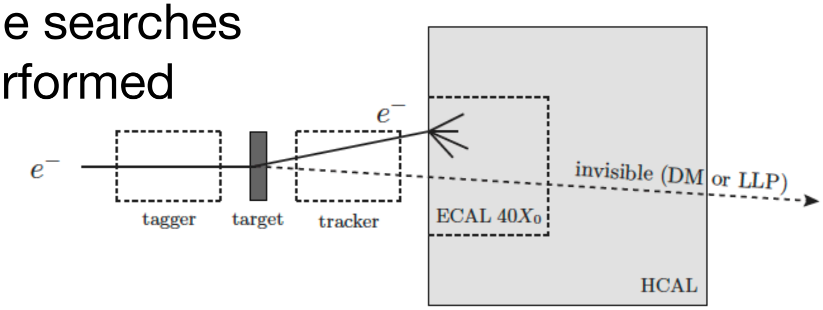
Proposed experiment for SLAC.
Some support already from the DOE DM New Initiative program

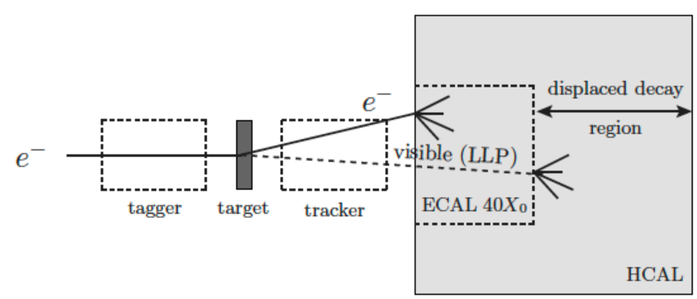
Real time identification of electrons

Missing energy in the ECal is a trigger condition.

Akesson et al., 2203.08192

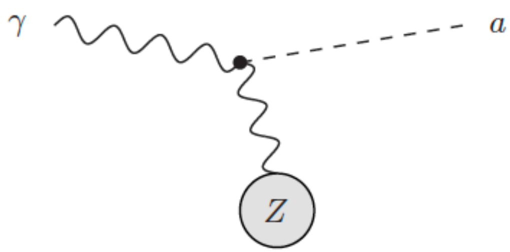
Also visible searches can be performed

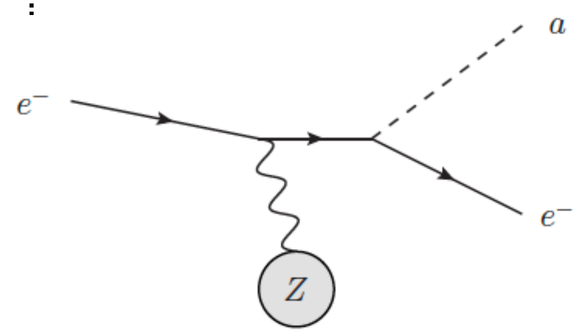


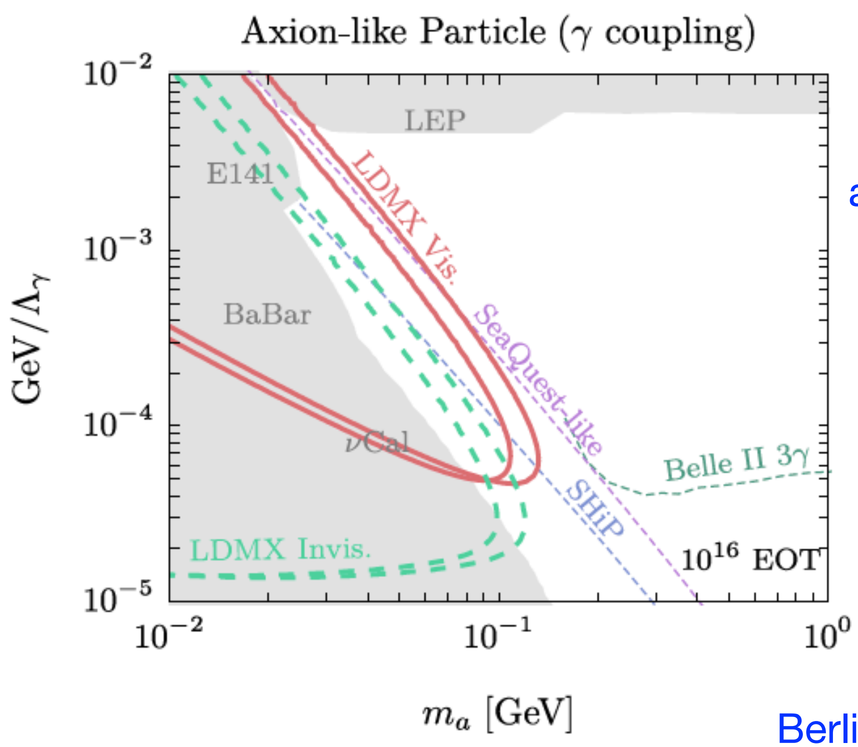


Visible / invisible ALPs at LDMX

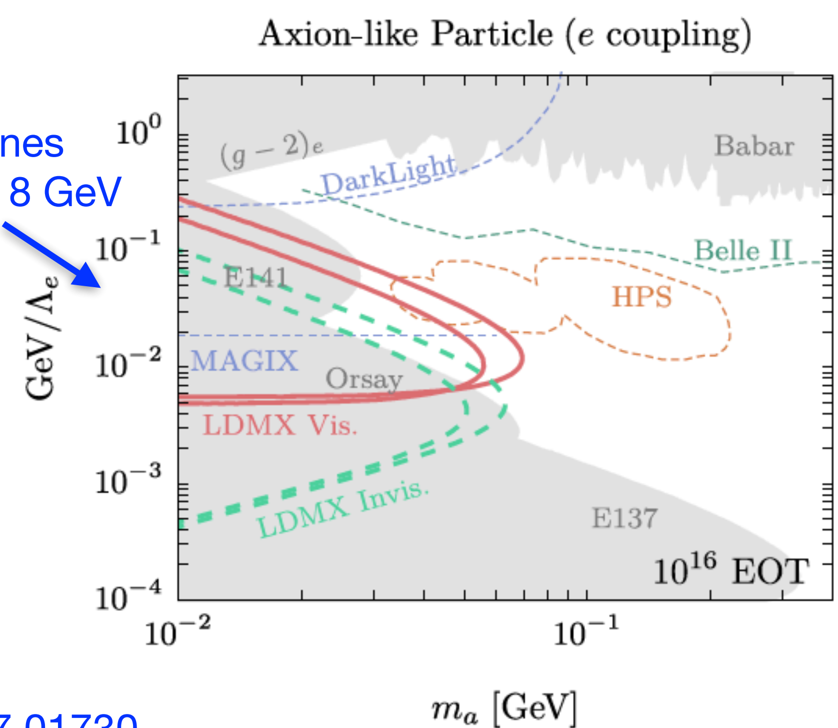
$$\frac{1}{4\Lambda_\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu a}{\Lambda_e}(\bar{e}\gamma^\mu\gamma_5 e)$$







The two lines are for 4 and 8 GeV



Berlin et al., 1807.01730

z_{min} = 43 cm and z_{max} = 315 cm

Conclusions & Outlook

Sub-GeV “heavy” axion-like-particles (ALPs) arise in numerous New Physics theories.

Plenty of opportunities to test ALPs at fixed target experiments.

Complementarity of visible and invisible searches.

Proton (DarkQuest, SHiP) and electron (NA64, LDMX) fixed target experiments will have access to currently unprobed ALP parameter space.

New theoretical aspects (e.g. weak violating effects in charged current meson decays).

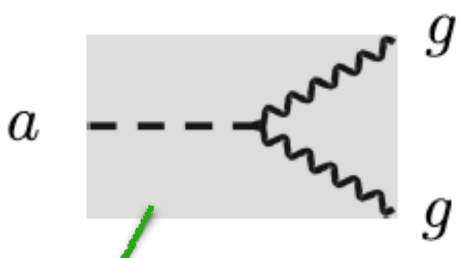
Many new searches to be done in the coming years!

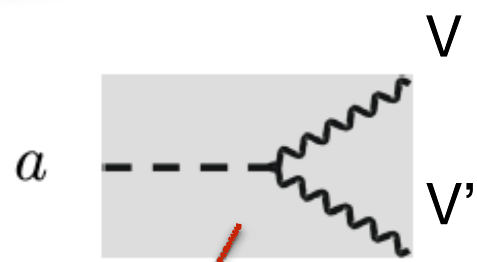
EFTs for ALPs

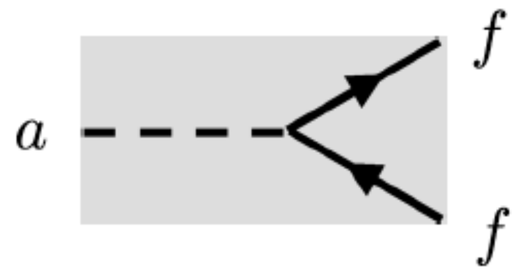
At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

Georgi, Kaplan, Randall 1986

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







Minimal coupling expected if connection to the strong CP problem.

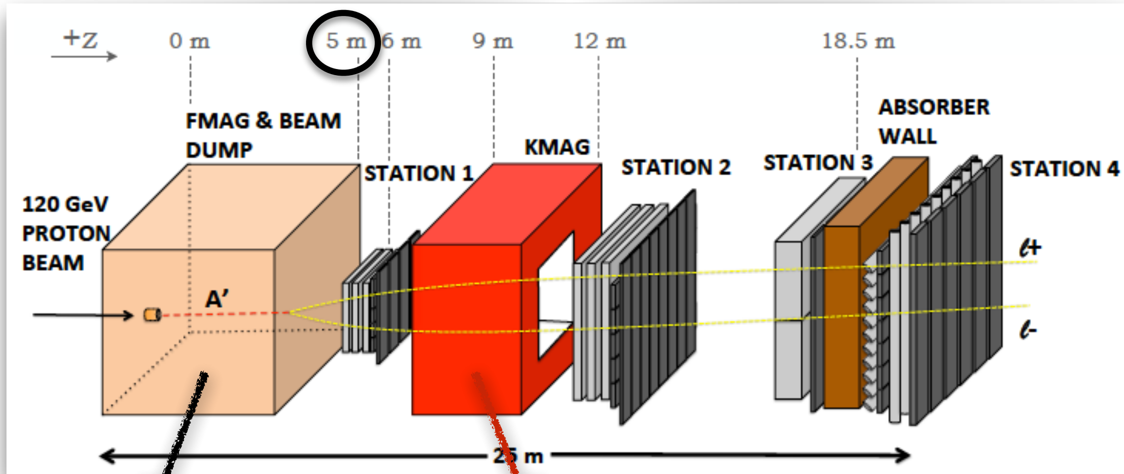
A ALP-photon coupling is generated in the broken phase

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

This is the main coupling that has been considered for phenomenological studies of ALPs in the sub-GeV scale.

We will see how we can generalize this coupling.

More details on the DarkQuest experiment



FMAG sweeps away soft SM radiation

1. Compact geometry

Sensitivity to (slightly) displaced dark particles with **d > 5m**

2. KMAG separating even very forward charged particles ($\Delta p_T \sim 0.4$ GeV)

Identification of very light dark particles/squeezed spectra

Experiment	Proton energy	POT	Dump	Decay volume
DarkQuest	120GeV	10^{18}	5 m	10 m
CHARM	400GeV	2.4×10^{18}	480 m	35 m
LSND	800MeV	10^{22}	30 m	10 m
NA62-dump	400 GeV	5×10^{19}	100 m	250 m
SHiP	400 GeV	2×10^{20}	35 m	100 m

Past: CHARM, LSND

Future: NA62-dump, SHiP

+ SHADOWS (off-axis)

+ neutrino experiments

Status of pion factories

PIONEER experiment

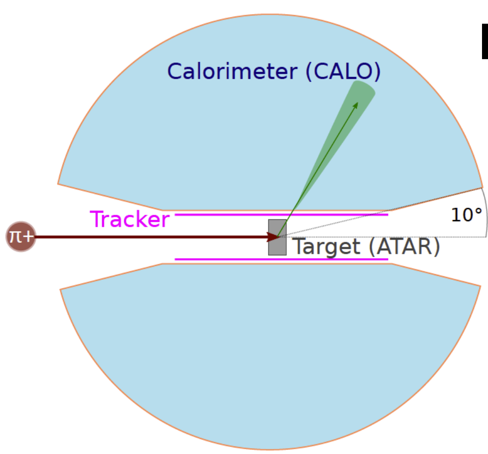
W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6]
S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12]
A. DiCanto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17]
M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2]
M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16]
J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5]
T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15]
D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2]
A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13]
A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

Main goals:

world-leading measurements for the branching ratios of the SM rare decays

* $\pi^+ \rightarrow e^+\nu$
* $\pi^+ \rightarrow \pi^0 e^+\nu$

Proposal in 2203.01981



Pion-decaying-at-rest experiment

Previous experiments:

* PIENU @ TRIUMF
* PIBETA @ PSI

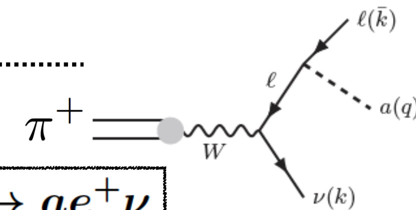
+ searches for light new particles produced from pion decays

Experiment approved in the summer of '22 for PSI

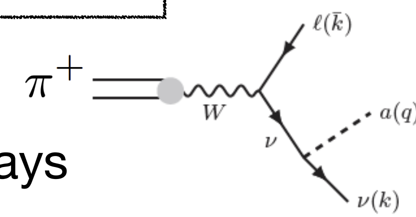
Phase I: ~2 x 10^{12} pions
Phase II/III: ~7 x 10^{13} pions

ALP coupling to leptons

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



$\pi^+\to ae^+\nu$



- Because of the conservation of lepton number at the classical level, one combination of couplings does not contribute at LO to pion decays
- It is not true that the vector coupling, $\bar{g}_{ee}$, is "unphysical"

$\neq 0$ only if weak SU(2) violation

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

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

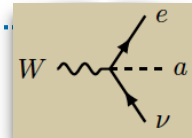
SU(2) (or weak) violation:
$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$

SU(2) violation can be generated

- by operators like $\partial^\mu a(HL)^\dagger\gamma_\mu(HL)$
- Running effects below the EW scale, but they are very suppressed

New searches for ALP coupled to leptons

Kaon decays



$$\frac{\mathrm{BR}(K^+ \to e^+ \nu a)}{10^{-10}} \simeq \begin{cases} \left(\frac{g_{ee}}{3.3 \cdot 10^{-7}}\right)^2 & \text{weak violating} \\ \left(\frac{g_{ee}}{7.9 \cdot 10^{-5}}\right)^2 & \text{weak preserving} \end{cases}$$

hep-ex/0204006, E865 at BNL:

BR measured for $m_{ee} > 150$ MeV

No dedicated search

W boson decays

$$\frac{\mathrm{BR}(W^+ \to \ell^+ \nu_\ell a)}{\mathrm{BR}(W^+ \to e^+ \nu)} = \frac{3}{1024\pi^2} \frac{m_W^2}{m_\ell^2} (g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})^2$$

$$\mathrm{BR}(W^+ \to e^+ \nu_e a) \simeq \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

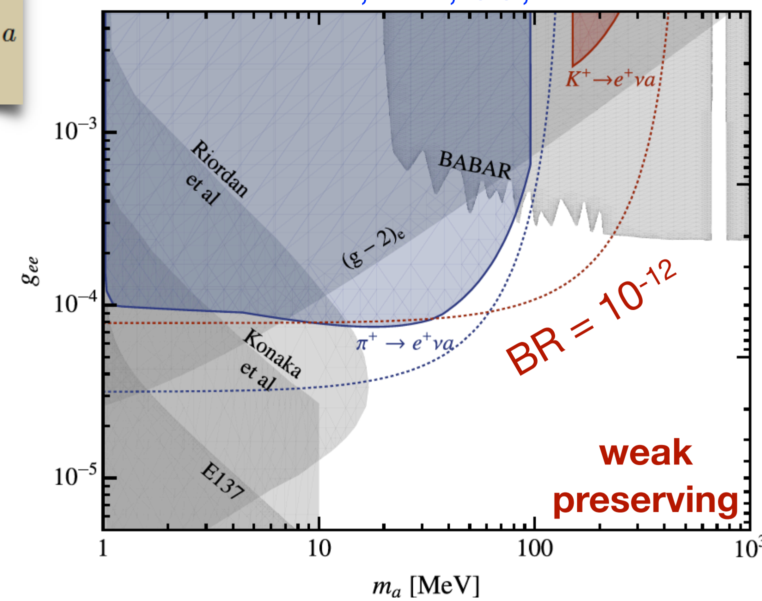
(only for weak violating)

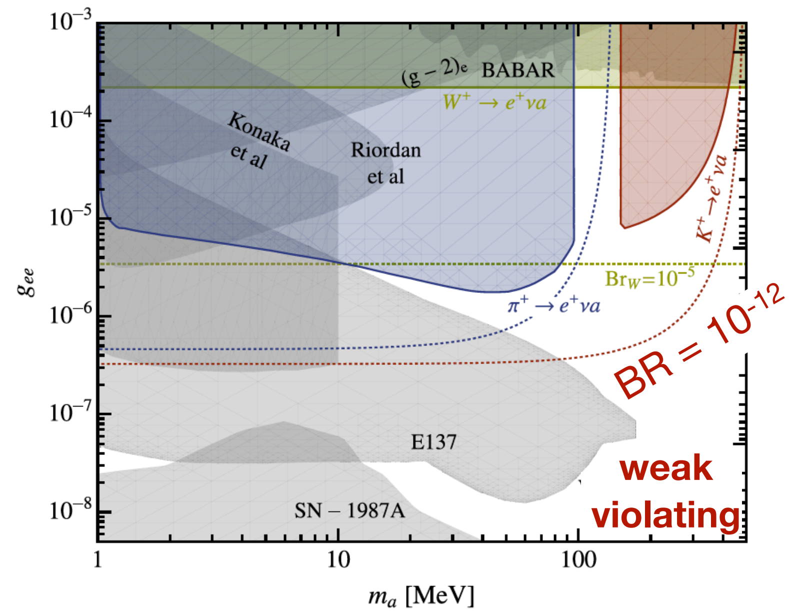
No dedicated search

We impose:

the new width < exp uncertainty on W width

Altmannshofer, Dror, SG, 2209.00665





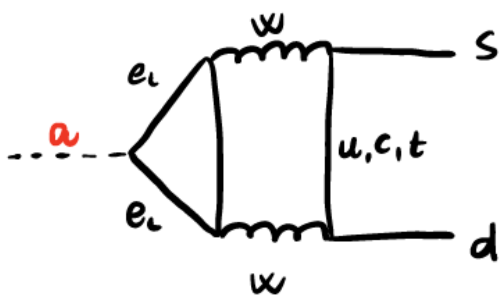
Reach at LHC?

Complementarity with neutral current decays

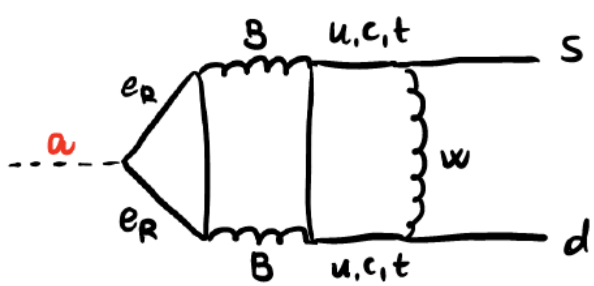
Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$

1. ALP with LH coupling



2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)}a$

They arise from the anomaly terms induced at loop level

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

1. The sum of these diagrams is finite

$$\mathcal{L} \supset \frac{\partial_\mu a}{m_\ell} g_{d_i d_j} (\bar{d}_i \gamma^\mu P_L d_j) \; + \; \text{h.c.}$$

$$g_{d_i d_j} \simeq -\frac{g^2}{16\pi^2} V^*_{ti} V_{tj} \Big[\frac{g^2}{16\pi^2} \frac{3}{8} \underbrace{(g_{ee} - \bar{g}_{ee} - g_{\nu_e}) F(x_t)}_{1.} + \underbrace{\frac{g'^4}{(16\pi^2)^2} \frac{17}{96} (g_{ee} + \bar{g}_{ee}) \frac{m_t^2}{m_W^2} \log^2\left(\frac{\Lambda^2}{m_t^2}\right)}_{2.} \Big]$$

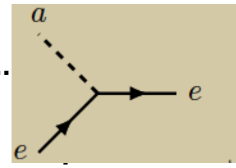
2. Log divergent

$$\Gamma(K^+ \to \pi^+ a) \;\propto\; |g_{asd}|^2$$
$$\Gamma(K_L \to \pi^0 a) \;\propto\; \text{Im}(g_{asd})^2$$

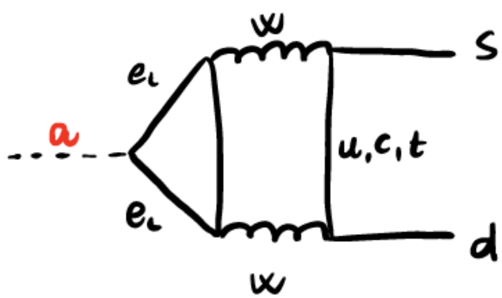
Complementarity with neutral current decays

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

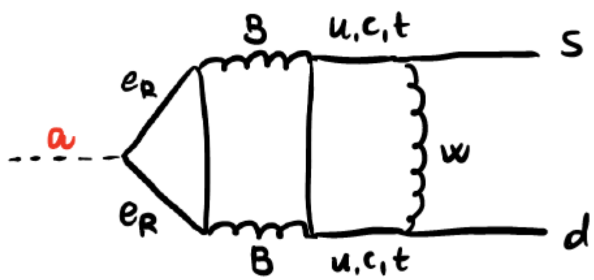
$K \to \pi a$



1. ALP with LH coupling



2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)} a$

Main bounds: reinterpreting past data

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

KTeV, 0309072: $K_L \to \pi^0 (a \to e^+ e^-)$
m_{ee} in (140, 363) MeV

777 @ BNL, Phys. Rev. Lett. 59 (1987) 2832–2835:
$K^+ \to \pi^+ (a \to e^+ e^-)$ m_a < 100 MeV

see also Alves, Weiner, 1710.03764

LHCb, 1501.03038: $B^0 \to K^{(*)0} (a \to e^+ e^-)$

Many new searches can be done in the future!

Only a few ALP searches have been performed. Many are missing.

For example:

$$
\begin{aligned}
\pi^+ &\to e^+\nu a \to e^+\nu\gamma\gamma && \text{PIONEER}\\
K_L &\to \pi^0 a \to \pi^0\gamma\gamma && \text{KOTO + HIKE}\\
K_L &\to \pi^0 a \to \pi^0 e^+e^- && \text{KOTO + HIKE}\\
K^+ &\to \pi^+ a \to \pi^+ e^+e^- && \text{NA62 + HIKE}\\
K^+ &\to e^+\nu a \to e^+\nu\gamma\gamma && \text{NA62 + HIKE}\\
B &\to K^{(*)} a \to K^{(*)} e^+e^- && \text{LHCb + Belle II}
\end{aligned}
$$

Combination of prompt and long-lived ALP searches.

Also final states involving muons, charged pions, …

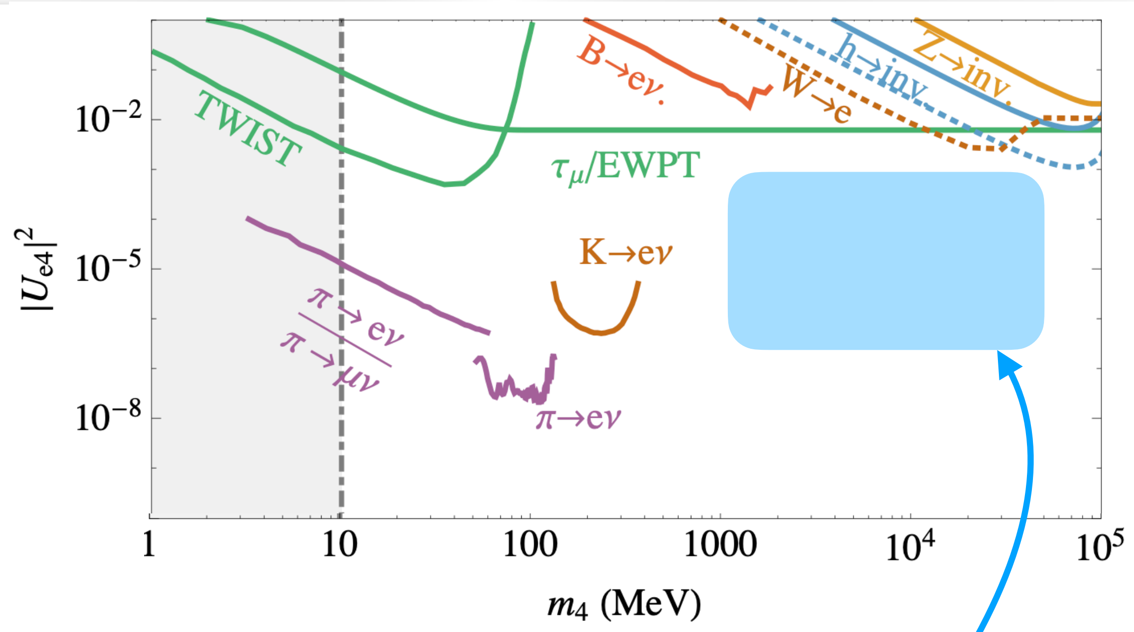
SU(2) violating models

$$\mathcal{L} \supset -yHLN^c - Me^{ia/f_a}NN^c + \text{h.c.}$$

$$\Rightarrow \mathcal{L} \supset \frac{\theta^2}{f_a}\partial_\mu a(\bar{\nu}_e \gamma^\mu P_L \nu_e) \Rightarrow \begin{cases} g_\nu = \dfrac{2\theta^2 m_e}{f_a} = 1.0 \times 10^{-5} \left(\dfrac{\theta}{0.1}\right)^2 \left(\dfrac{\text{GeV}}{f_a}\right) \\ g_{ee} = \bar{g}_{ee} = 0 \end{cases}$$

Batell, et al, 1709.07001

$\theta^2 =$



additional constraints from visibly decaying HNL (less robust)

Charged current heavy meson decays