Ideas and Motivation For a Feebly Interacting Sector

Andrea Thamm
The University of Melbourne

THE UNIVERSITY OF MELBOURNE

17 May 2022
LHCP2022

Outline

1. Motivation for feebly interacting particles
2. ALPs as feebly interacting particles
3. ALPs at a Collider
4. Conclusions

Motivation for FIPs

Feebly interacting particles - very weak couplings

Generic feature - long lift time

$$\tau = \frac{1}{\Gamma}$$

$$d\Gamma \sim \frac{1}{M} |\mathcal{M}|^2 d\Phi_n$$

Various features can imply a long life time

- Suppressed phase space
- Small matrix element
    - Approximate symmetry
    - Small couplings to lighter states

Motivation for FIPs

Long life time = long decay lengths $\lambda = c\tau$

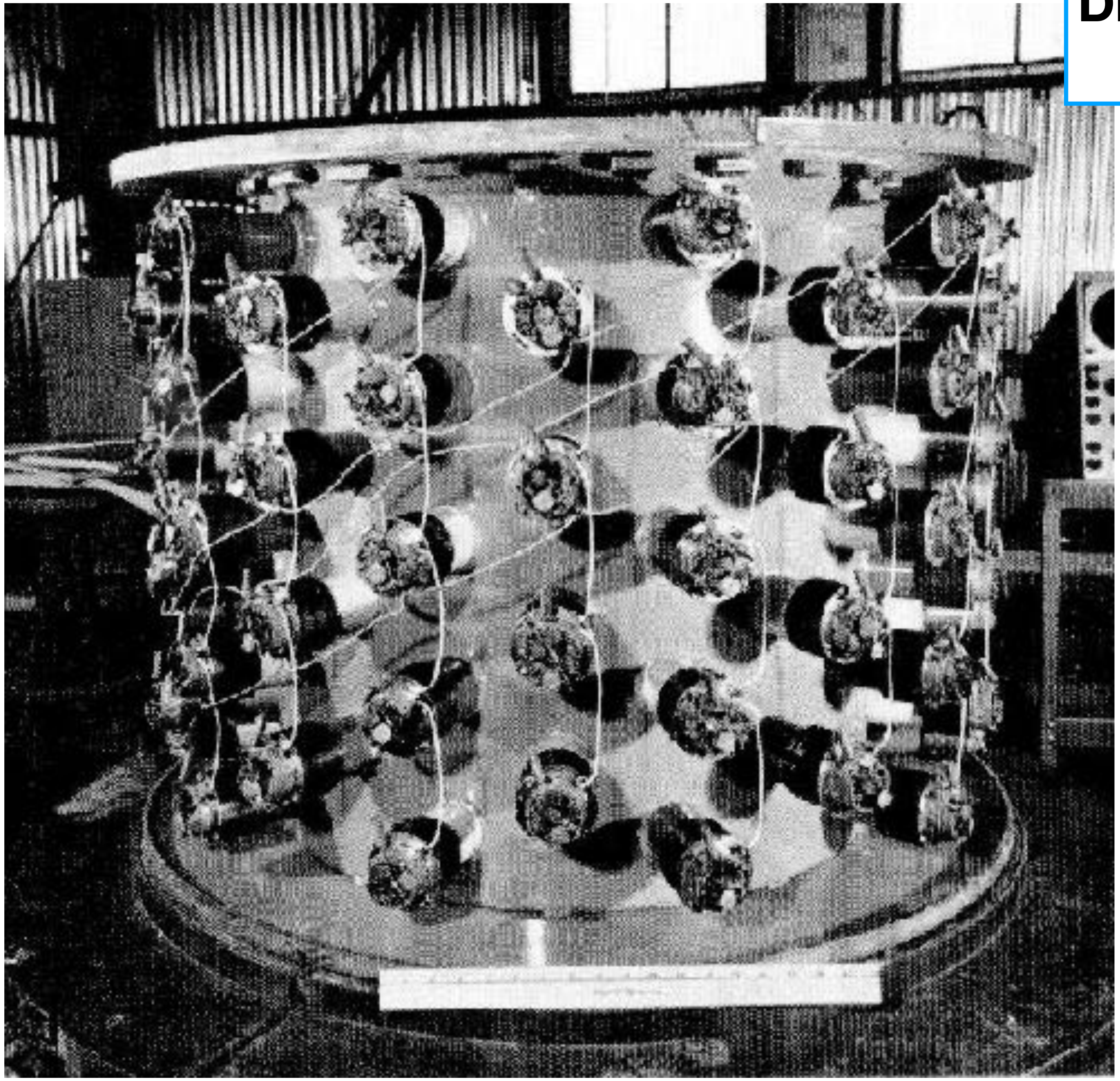
Light or heavy wrt to the electroweak scale

Can couple and decay to quarks, leptons or gauge bosons

Motivation for FIPs

In the SM - neutrino

1956
Discovery of neutrino



Motivation for FIPs

Theoretical models that include feebly interacting particles

Models motivated by the hierarchy problem

Extra dimensional models - KK towers of the scalar graviton (FIPs below the EW scale)

Neutral naturalness - FIPs in the mirror sector

Coupling via Higgs portal

$$(H^\dagger H) \times m_H^2 \rightarrow (H^\dagger H) \times (m_H^2 + c_1 S + c_2 S^2)$$

Motivation for FIPs

Theoretical models that include feebly interacting particles

Models motivated by the strong CP problem

$$\theta_{QCD}\tilde{G}_{\mu\nu}G_{\mu\nu} \rightarrow (\theta_{QCD} + \frac{a}{f_a})\,\tilde{G}_{\mu\nu}G_{\mu\nu}$$

QCD axion or generalisation to ALP

Motivation for FIPs

Theoretical models that include feebly interacting particles

Models motivated by extended gauge groups

$$SU(3)_{QCD} \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_{QCD} \times SU(2)_L \times U(1)_Y \times U(1)_X$$

New gauge boson as FIP

Motivation for FIPs

Theoretical models that include feebly interacting particles

Models motivated by neutrino masses

$$m_{\nu,D}\bar{\nu}\nu \to y_\nu \bar{N}\nu H + \text{h.c.}$$

Dirac neutrino as a FIP

Majorana neutrino used in leptogenesis with light HNL as a FIP

Motivation for FIPs

Theoretical models that include feebly interacting particles

Models motivated Dark Matter

WIMP with a FIP coannihilation partner

Freeze in Dark Matter

Motivation for FIPs

Powerful bottom-up characterisation via portals

Taken from 2011.02157

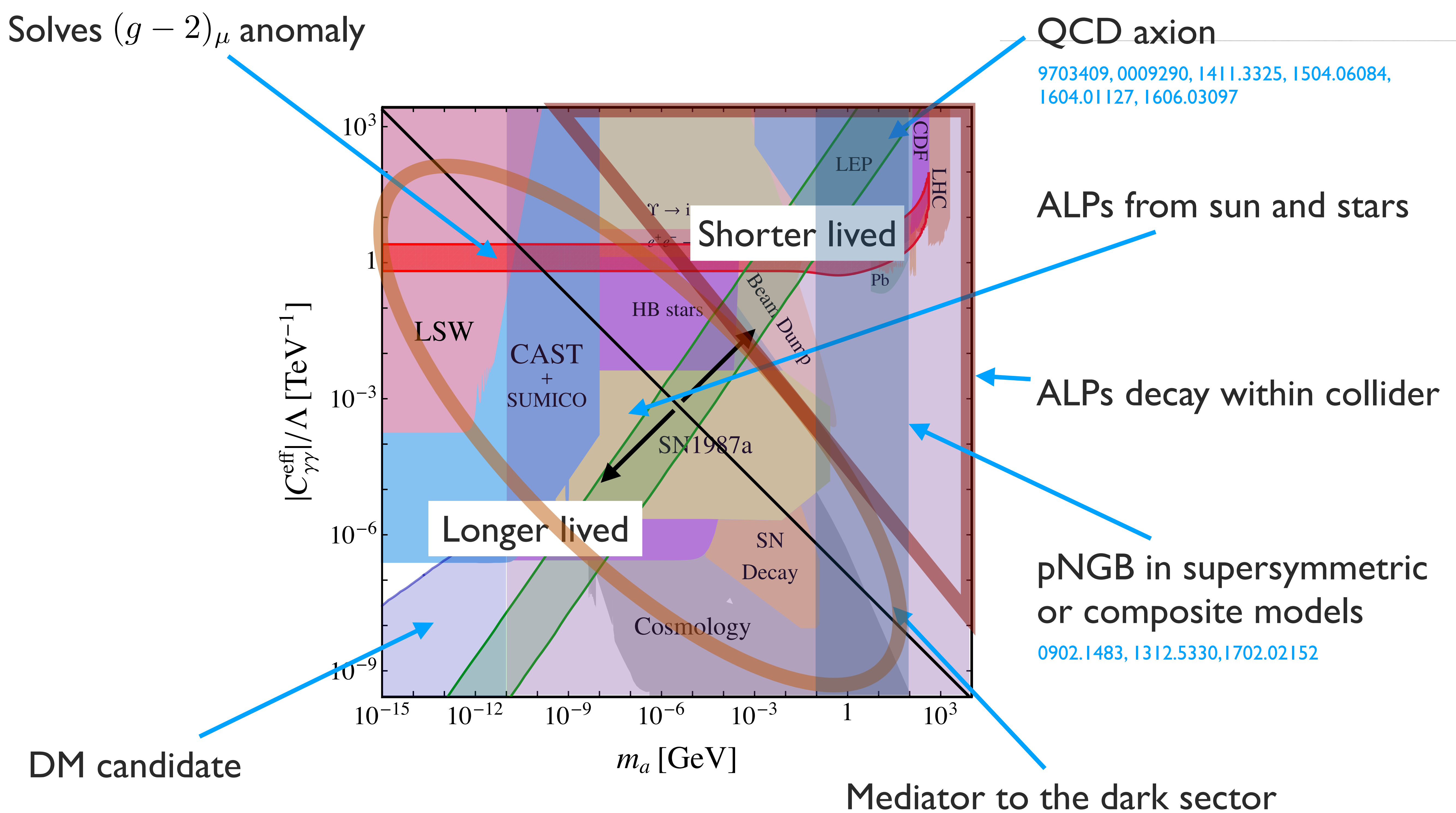
Portal	Coupling
Vector: Dark Photon, A'	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar: Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
Fermion: Heavy Neutral Lepton, N	$y_N LHN$
Pseudo-scalar: Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$

Outline

1. Motivation for feebly interacting particles
2. ALPs as feebly interacting particles
3. ALPs at a Collider
4. Conclusions

ALPs as FIPs

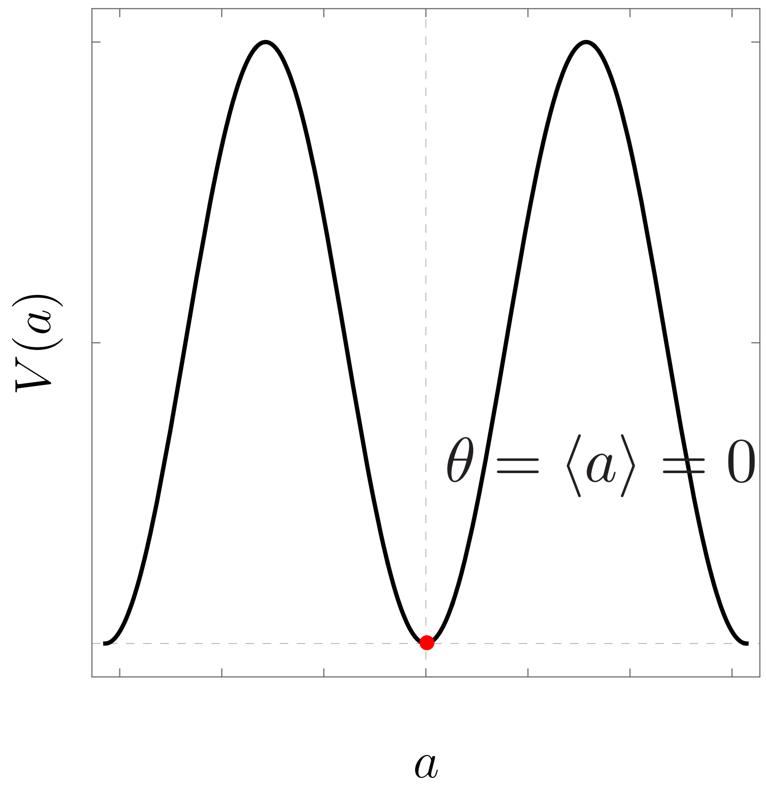
Axion-like particles are pseudo-Nambu Goldstone bosons

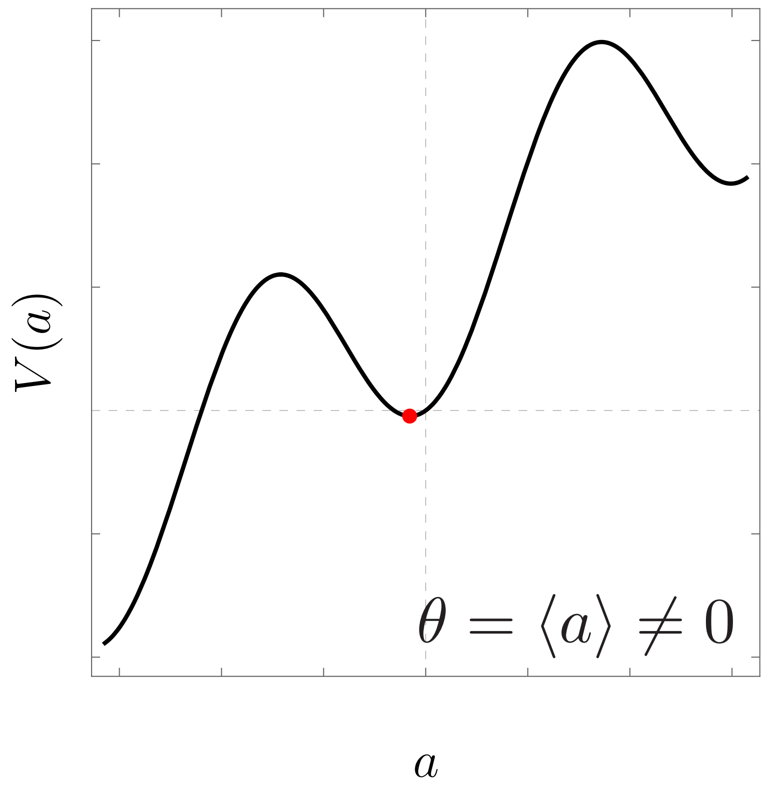


ALPs as FIPs

Axion quality problem

$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right] \qquad + a\,\frac{f_a^{\Delta-1}}{M_{pl}^{\Delta-4}}$$





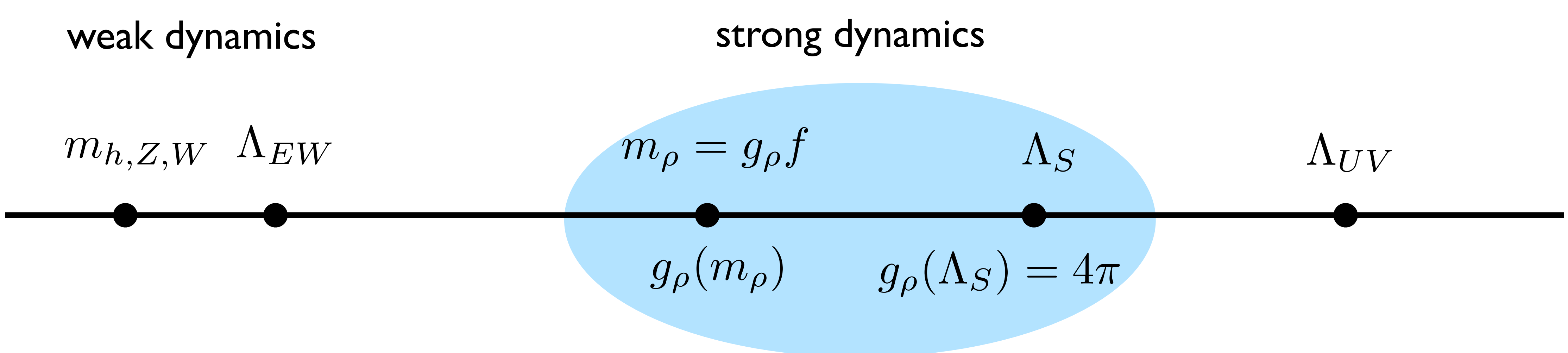
New sector contributes to potential and mass

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

ALPs as FIPs

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]

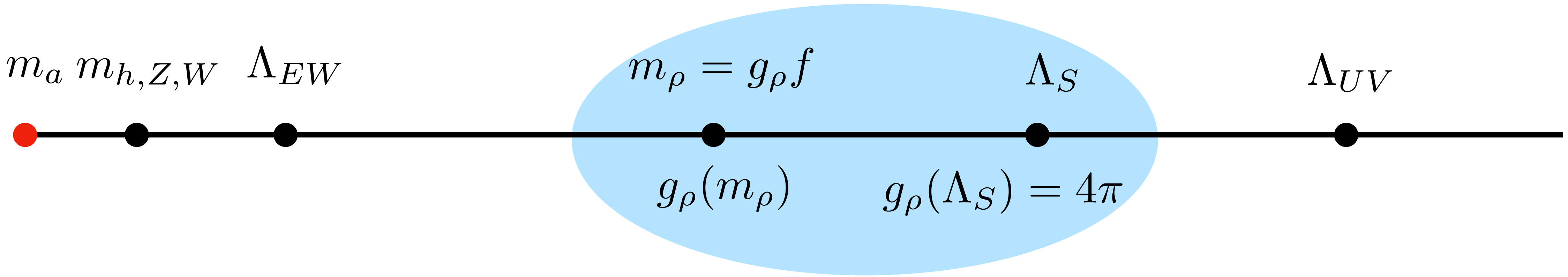
Strongly coupled heavy sector at scale m_ρ



- Spontaneous breaking of global symmetry
- Higgs arises as a pseudo-Nambu-Goldstone boson
- Above Λ_S H no longer elementary d.o.f. → solves hierarchy problem

ALPs as FIPs

Composite Higgs models



Light pseudo-scalar particles = axion-like particles

[Ferretti 1604.06467]

Outline

1. Motivation for feebly interacting particles
2. ALPs as feebly interacting particles
3. ALPs at a Collider
4. Conclusions

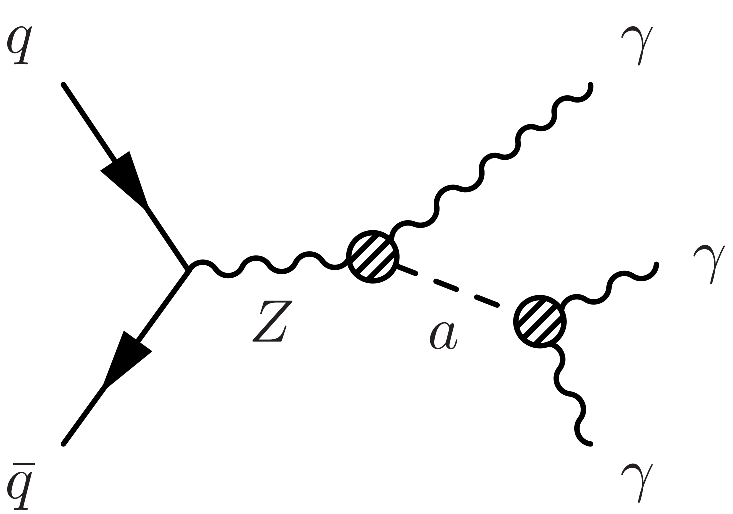
ALPs at Colliders

Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F \bar{\psi}_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F$$
$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

Exotic Z-decays



ALPs at Colliders

Higgs interactions at dimension-6 and 7

$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{\Lambda^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

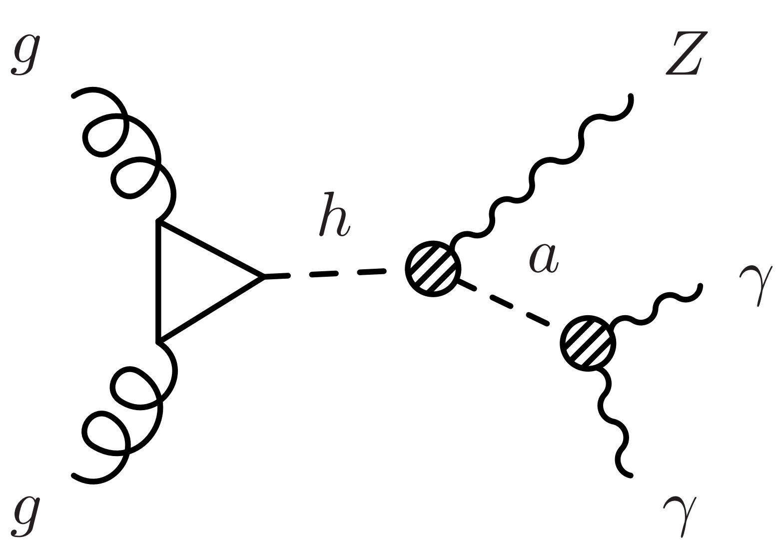
$h \to aa$

$h \to Za$

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

[Bauer, Neubert, Thamm: 1610.00009]
[Bauer, Neubert, Thamm: 1704.08207]
[Bauer, Neubert, Thamm: 1708.004433]

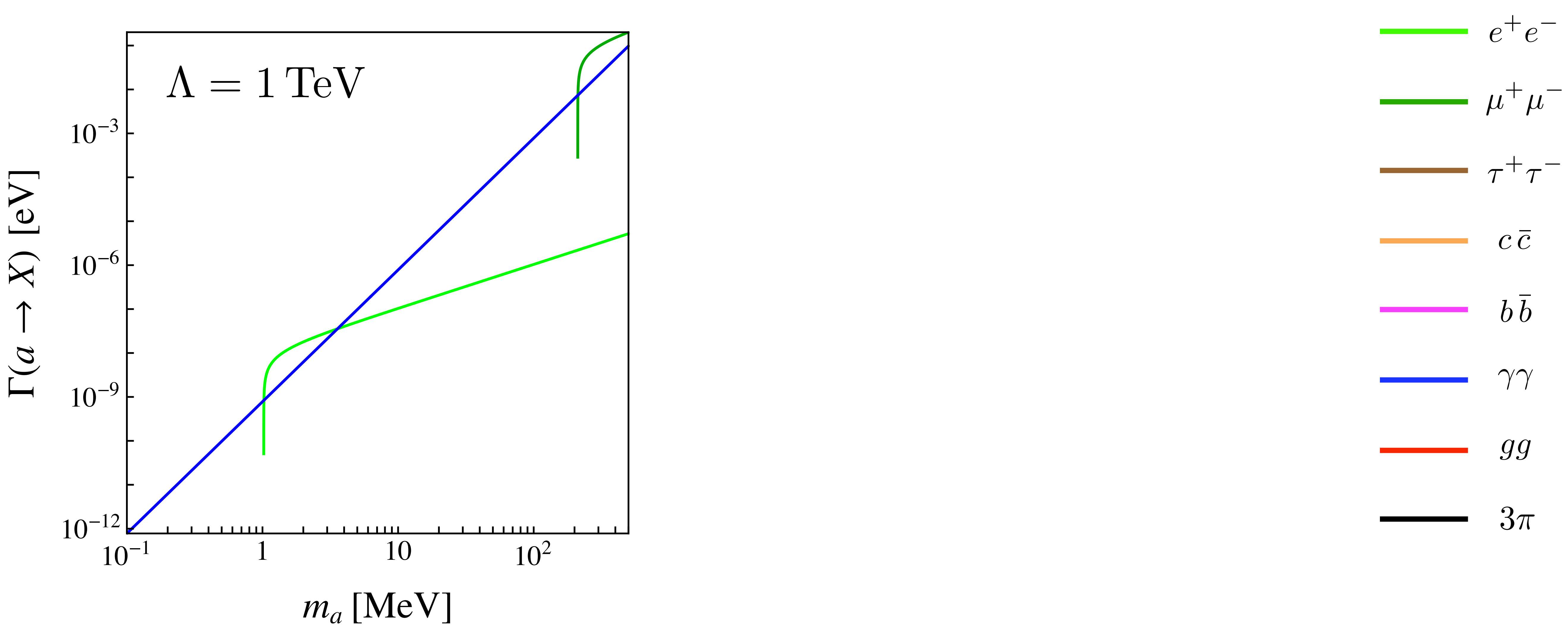
Exotic Higgs decays



ALPs at Colliders

Fermion couplings = 1, Gauge boson couplings = 1 in the plot

More motivated: gauge couplings = $1/(4\pi)^2$



ALPs at Colliders

Average decay length perpendicular to beam axis

$$L_a^\perp(\theta) = \sin\theta \, \frac{\beta_a \gamma_a}{\Gamma_a} = \sin\theta \sqrt{\gamma_a^2 - 1} \, \frac{\mathrm{Br}(a \to X\bar{X})}{\Gamma(a \to X\bar{X})}$$

Fraction of ALPs decaying before travelling a certain distance

$$f_\mathrm{det} = \int_0^{\pi/2} d\theta \, \sin\theta \Big(1 - e^{-L_\mathrm{det}/L_a^\perp(\theta)}\Big)$$

Decay into photons before EM calorimeter

$L_\mathrm{det} = 1.5\,\mathrm{m}$

Decay into electrons before inner tracker

$L_\mathrm{det} = 2\,\mathrm{cm}$

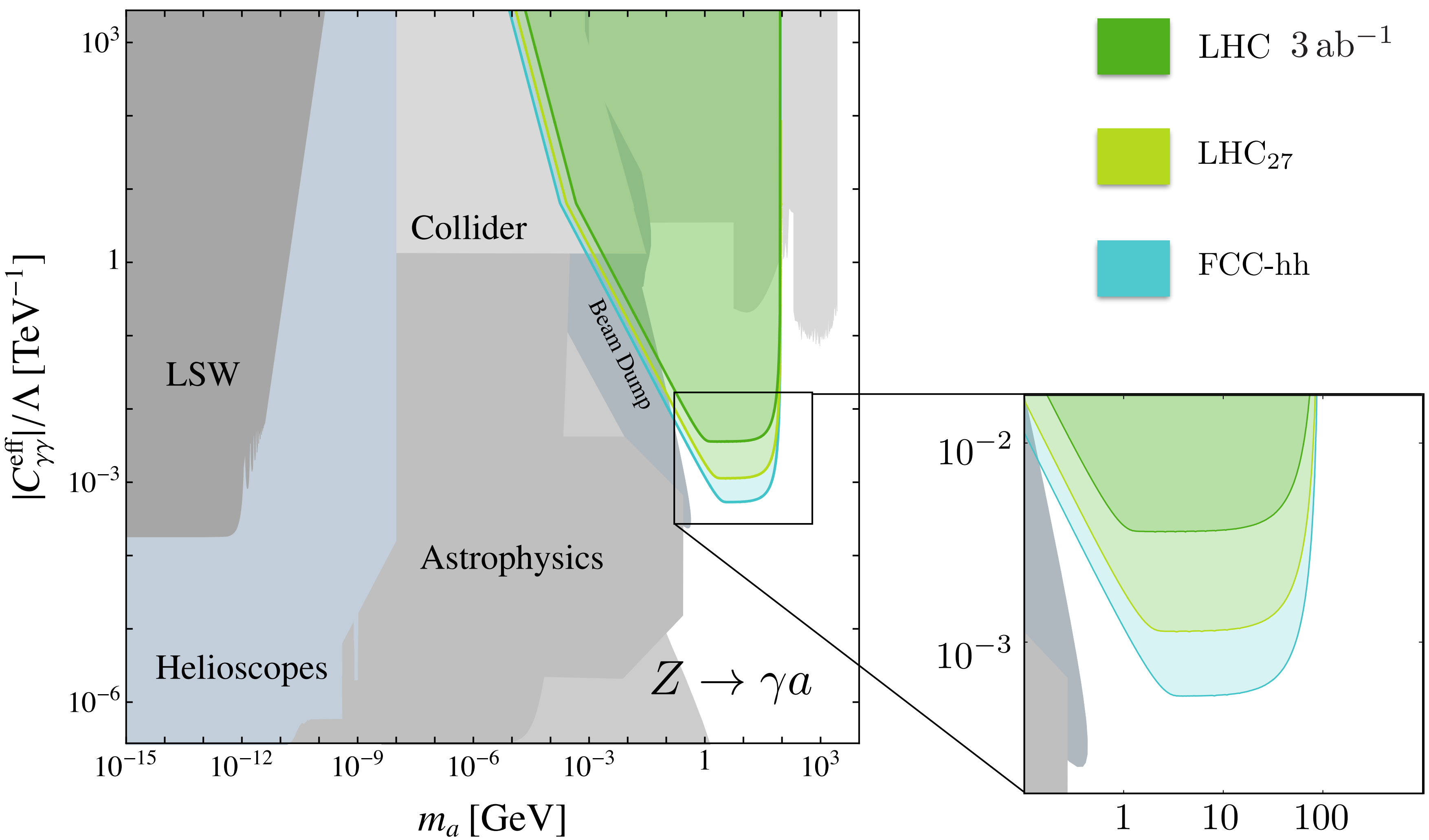
Effective branching ratios

$$\mathrm{Br}(h \to Za \to \ell^+\ell^- X\bar{X})\big|_\mathrm{eff} = \mathrm{Br}(h \to Za) \times \mathrm{Br}(a \to X\bar{X}) \, f_\mathrm{dec} \, \mathrm{Br}(Z \to \ell^+\ell^-)$$

ALPs at Colliders

Reach in $Z \to \gamma a$

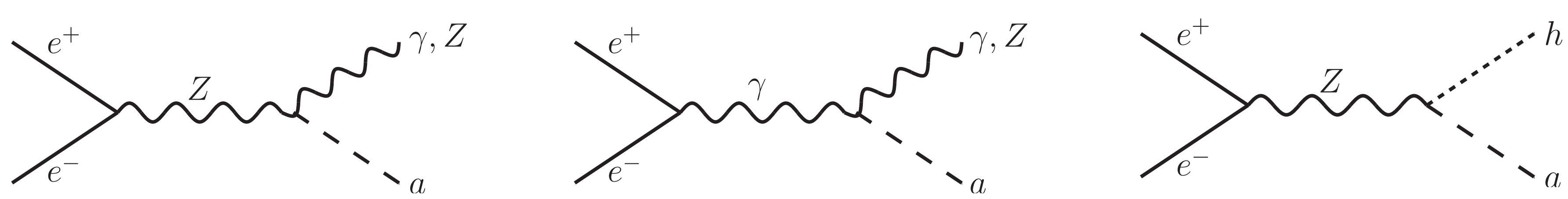
[Bauer, Heiles, Neubert, Thamm: 1808.10323]



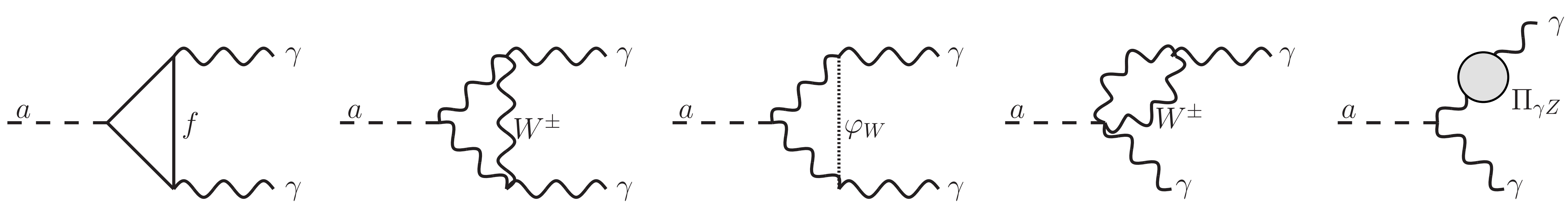
ALPs at Colliders

[Bauer, Heiles, Neubert, Thamm: 1808.10323]
[Knapen, Thamm: 2108.08949]

Dominant production mode: ALP associated production



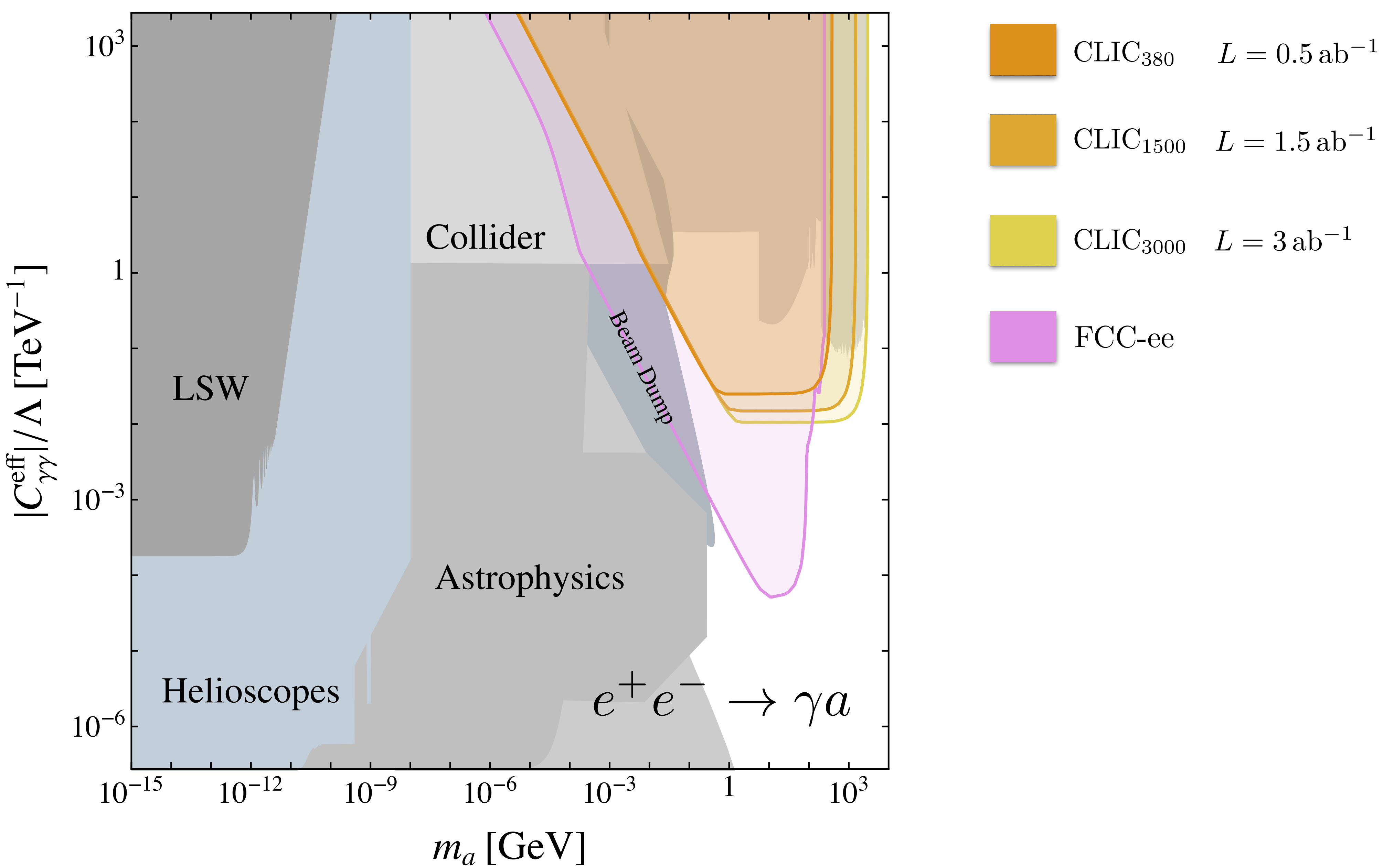
Decay mode into photons



ALPs at Colliders

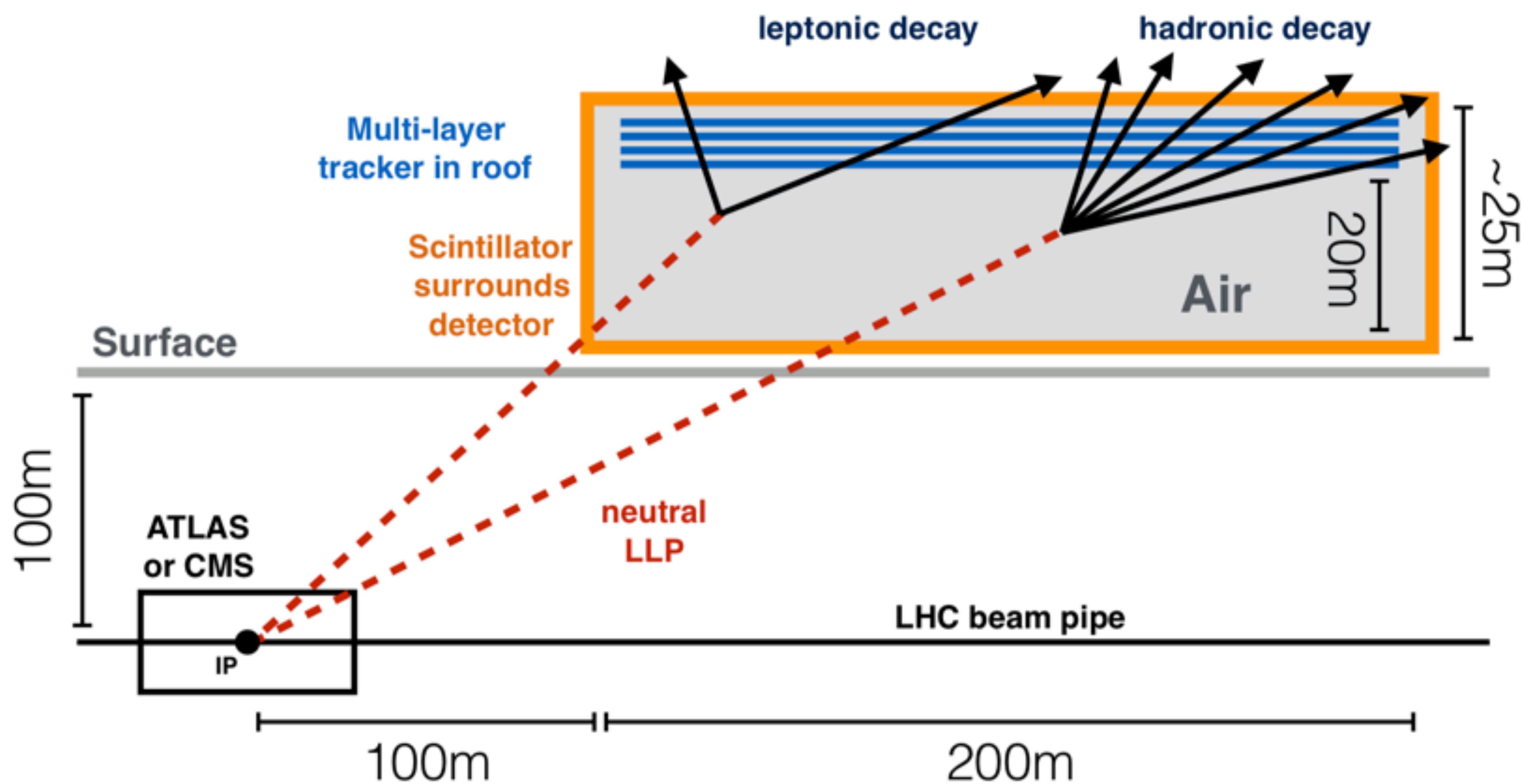
Discovery potential

[Bauer, Heiles, Neubert, Thamm: 1808.10323]



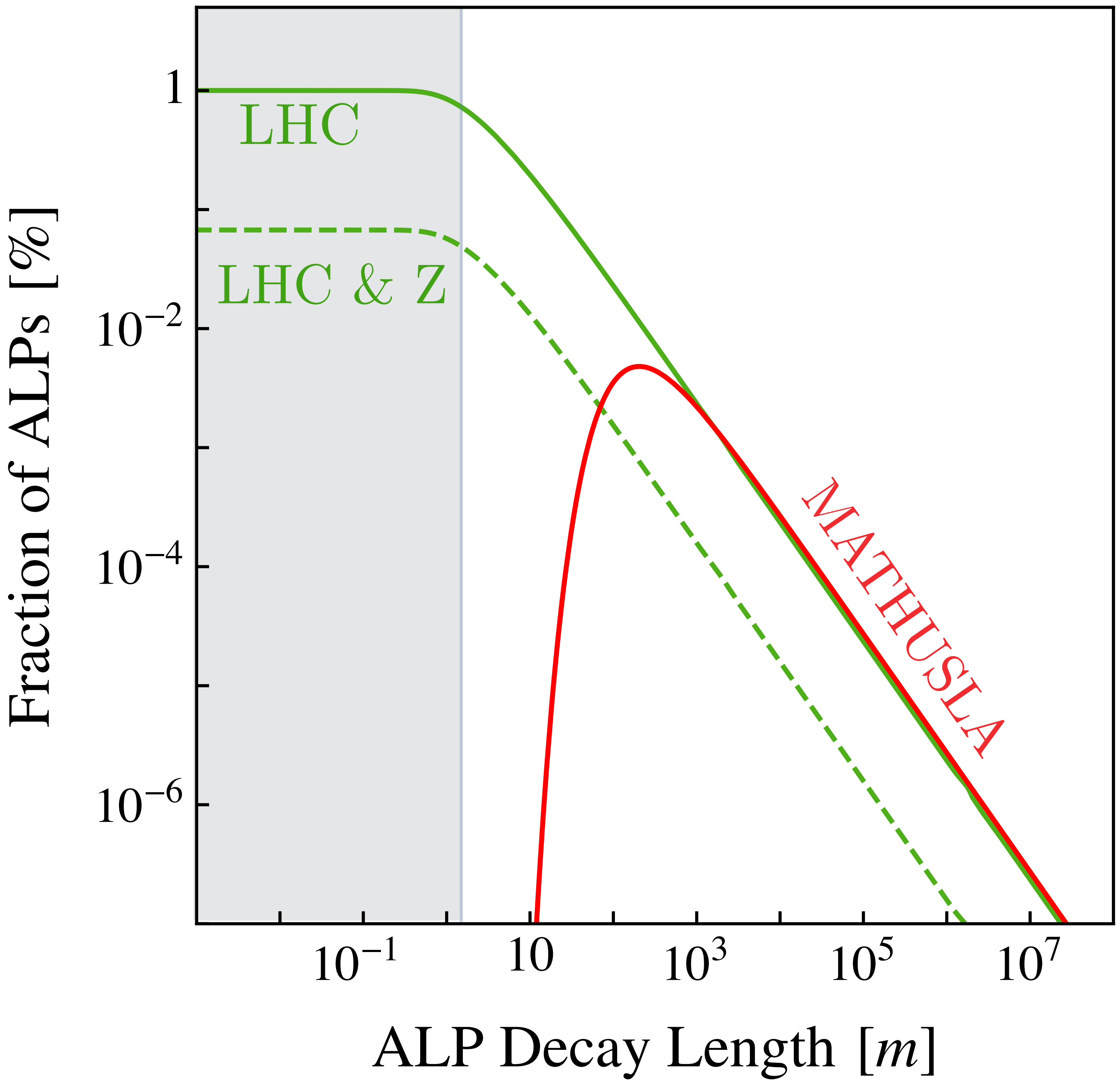
ALPs at Colliders

ALPs at Mathusla



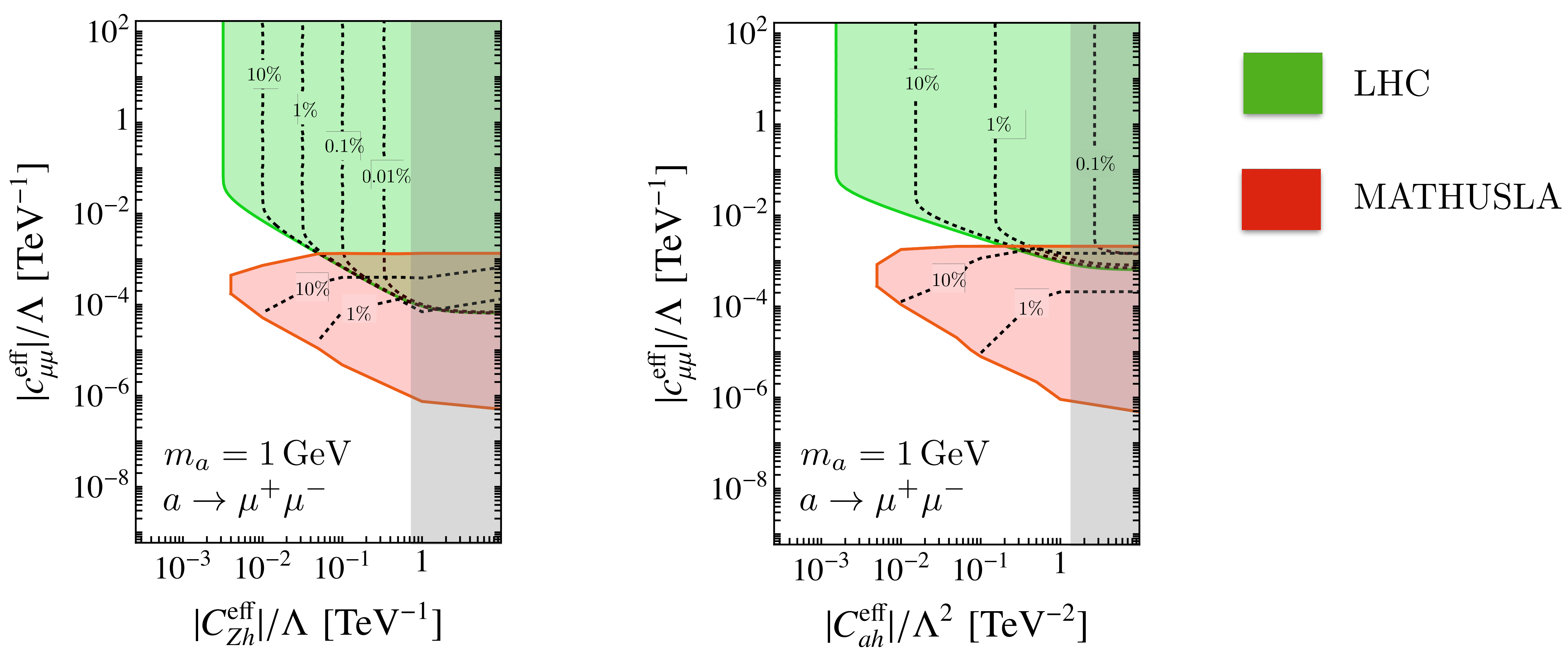
ALPs at Colliders

Decay probability



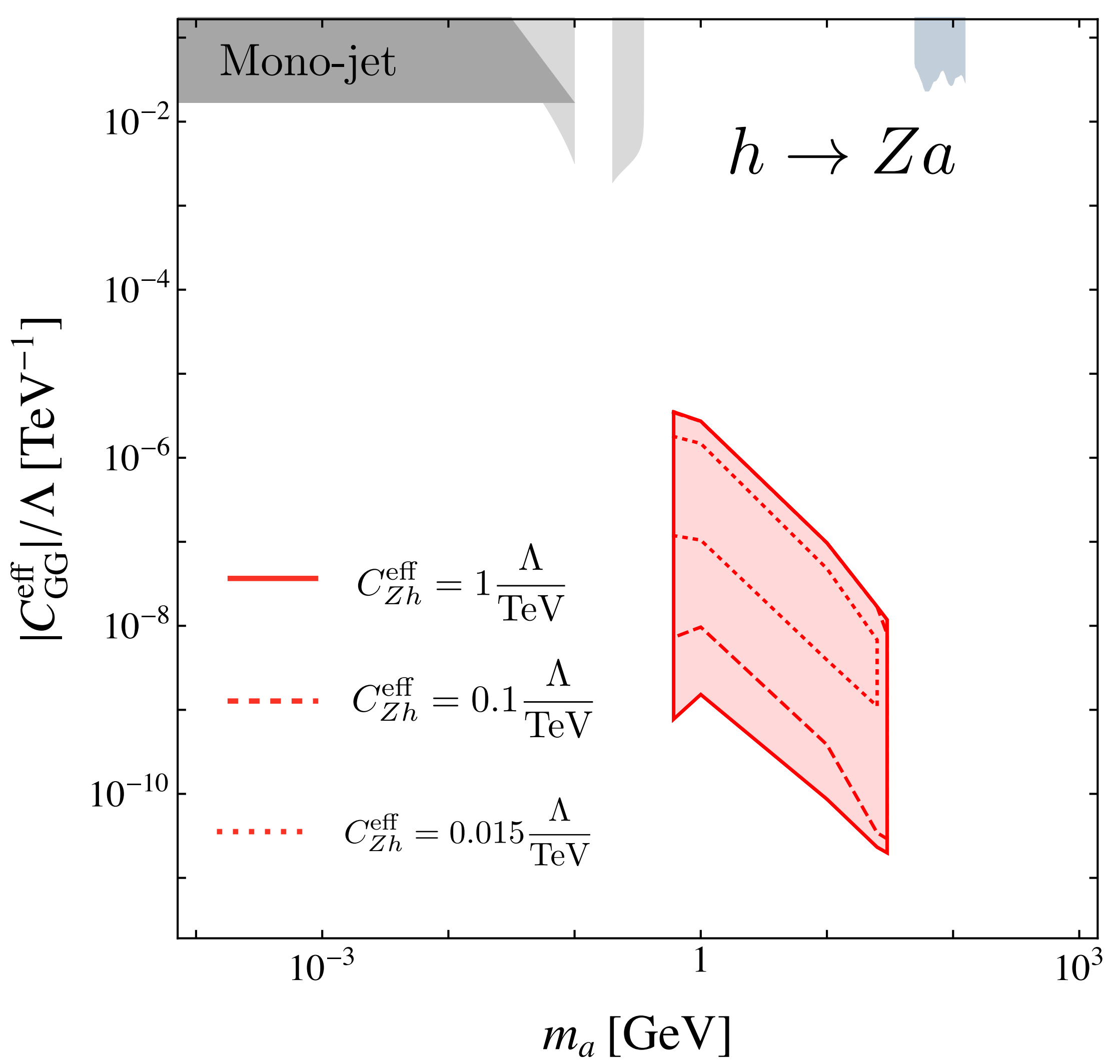
ALPs at Colliders

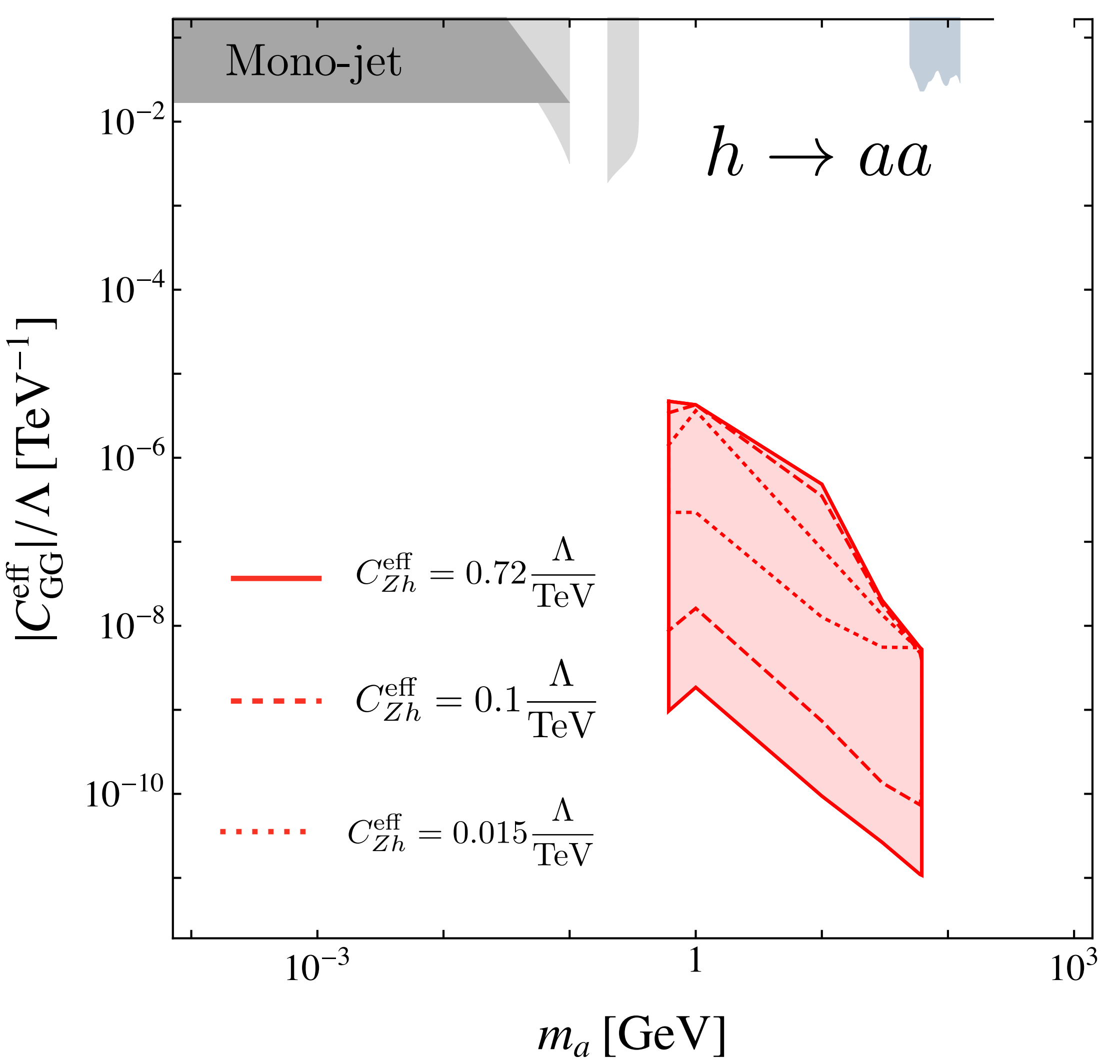
Exotic Higgs decays at Mathusla



ALPs at Colliders

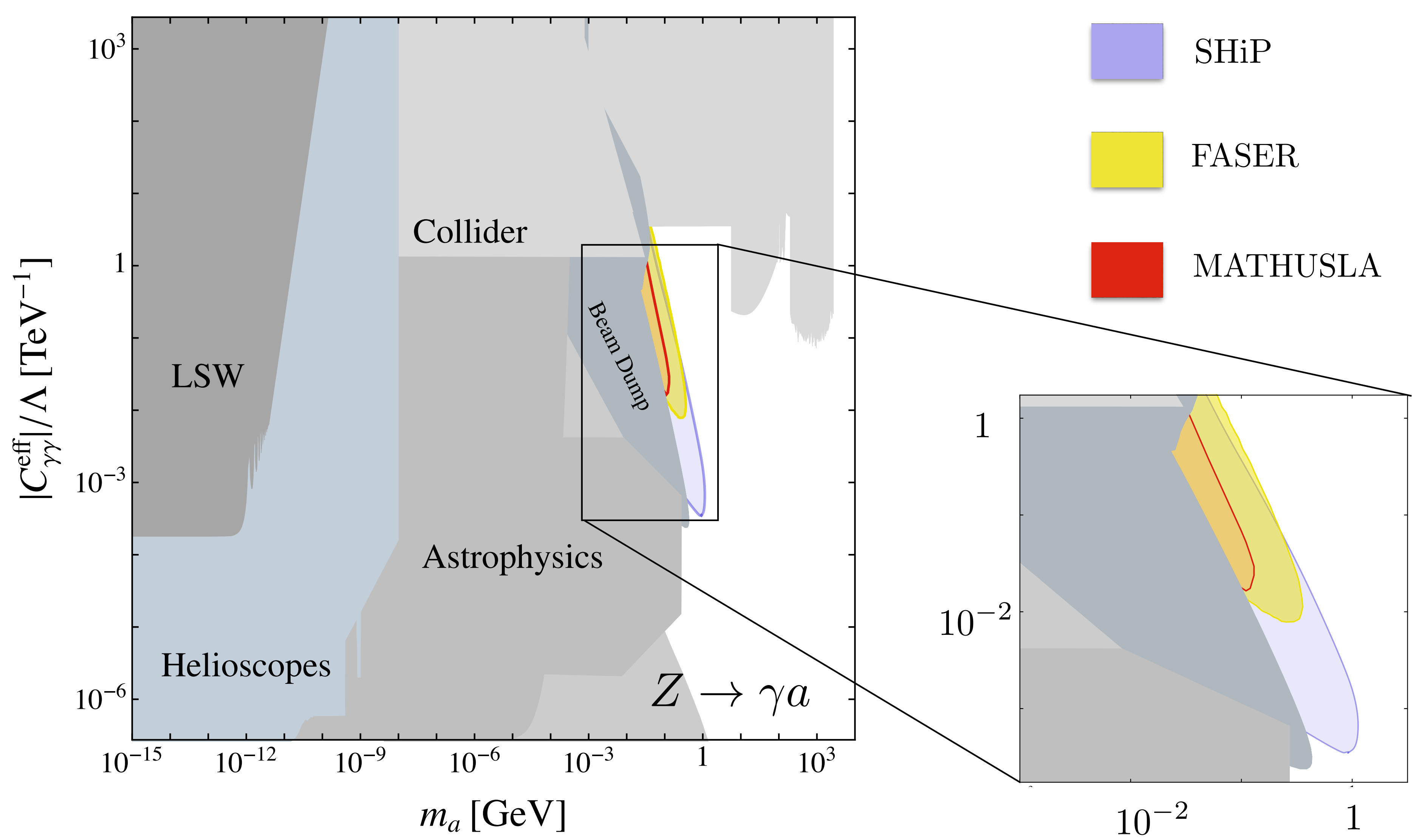
Exotic Higgs decays at Mathusla





ALPs at Colliders

Exotic Z decays at Mathusla



Outline

1. Motivation for feebly interacting particles
2. ALPs as feebly interacting particles
3. ALPs at a Collider
4. Conclusions

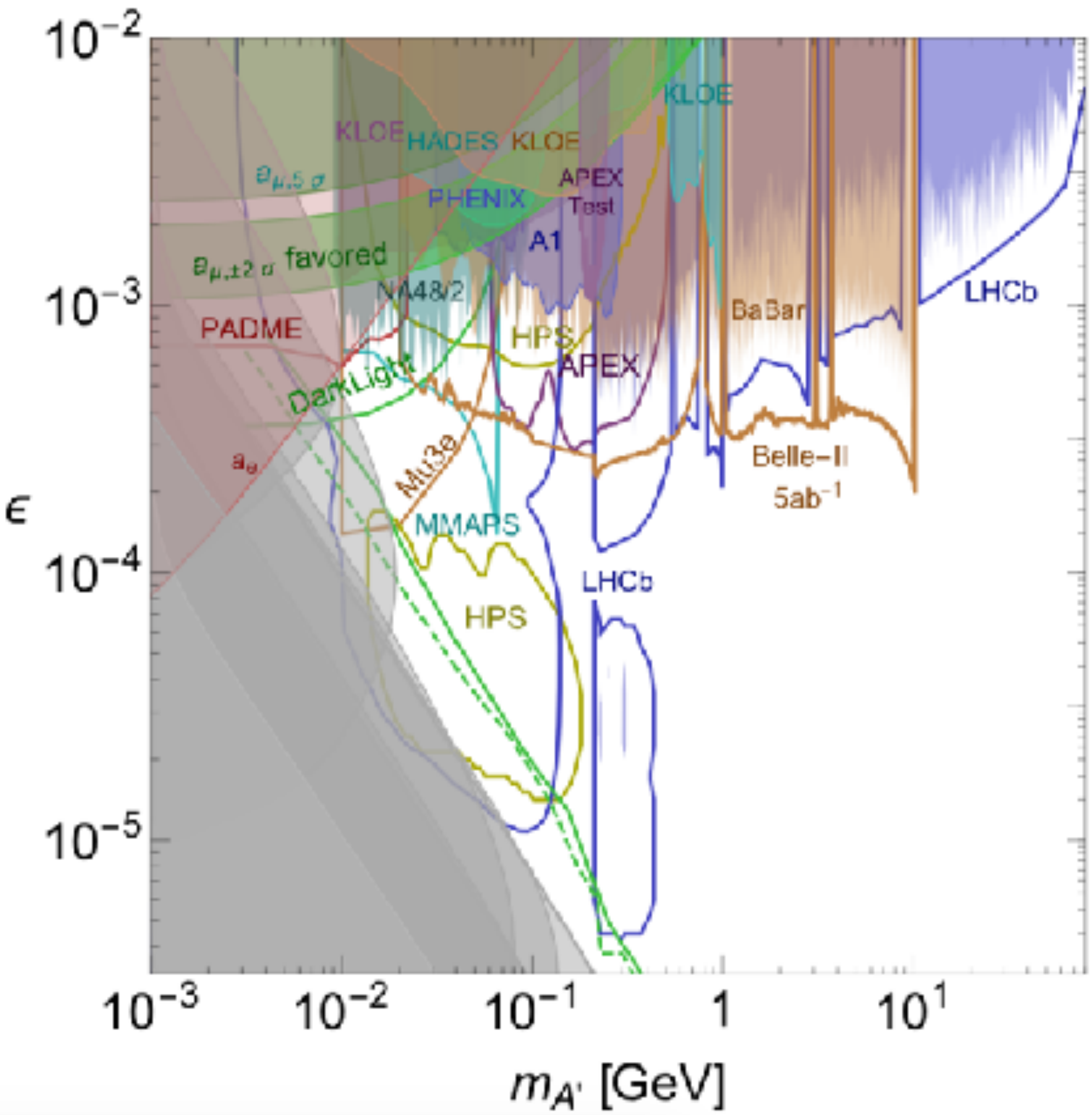
Conclusions

- Large variety of models motivate search for FIPs
- LHC can search for FIPs

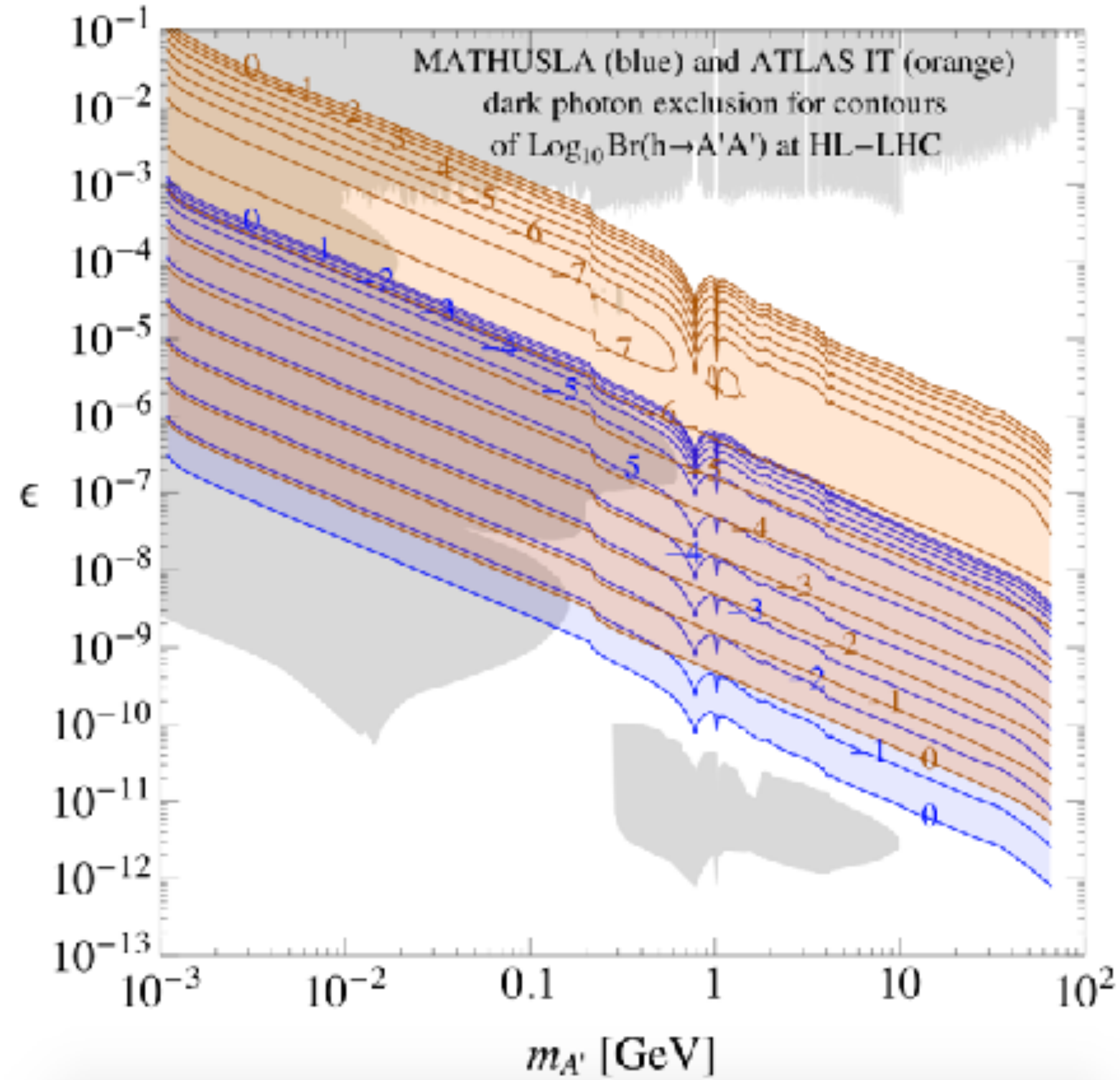
Thank you!

Backup

Dark Photon



10^{-2}
10^{-3}
10^{-4}
10^{-5}
ϵ
KLOE
HADES
KLOE
KLOE
APEX Test
PHENIX
A1
favored
NA48/2
PADME
HPS
APEX
BaBar
LHCb
DarkLight
Mu3e
Belle-II 5ab^{-1}
MMARS
LHCb
HPS
10^{-3}
10^{-2}
10^{-1}
1
10^{1}
$m_{A'}$ [GeV]



MATHUSLA (blue) and ATLAS IT (orange)
dark photon exclusion for contours
of $\text{Log}_{10}\text{Br}(h\to A'A')$ at HL−LHC
ϵ
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-3}
10^{-2}
0.1
1
10
10^{2}
$m_{A'}$ [GeV]