# ALPs at the FCC-ee

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based on arXiv: 1704.08207, 1708.00443, 1808.10323


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FCC workshop 2024

# Outline

1. ALP Motivation
2. ALPs at the FCC-ee
    - ALP associated production
    - Exotic Higgs decays
    - Electroweak precision tests
3. Conclusions

# ALP Motivation

Axion-like particles are pseudo-Nambu Goldstone bosons

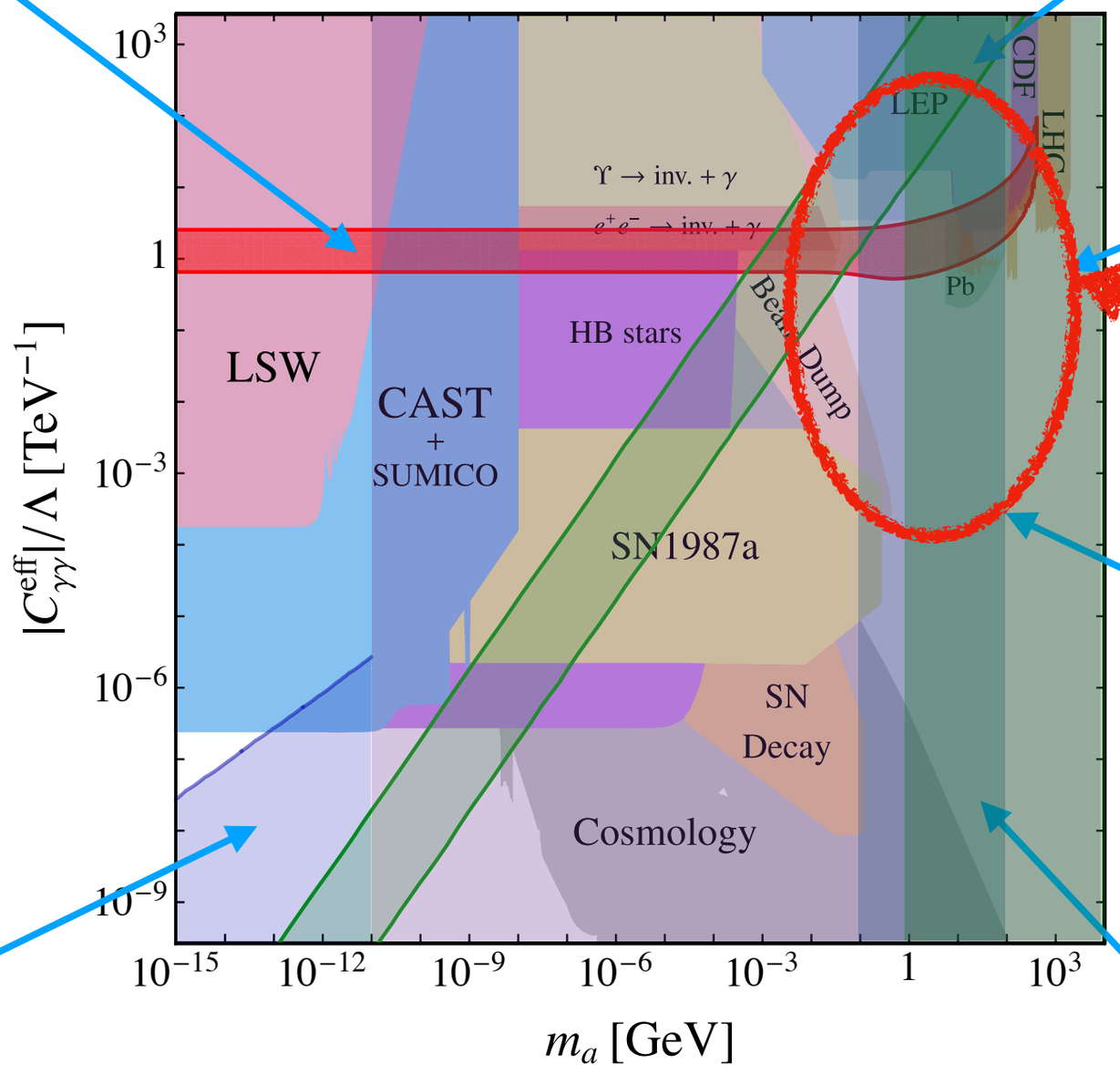
Solves $(g-2)_\mu$ anomaly

1708.00443, 1908.00008

QCD axion

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Heavy axion




Really interesting but untested region!

pNGB in supersymmetric or composite models

0902.1483, 1312.5330, 1702.02152, 2104.11064

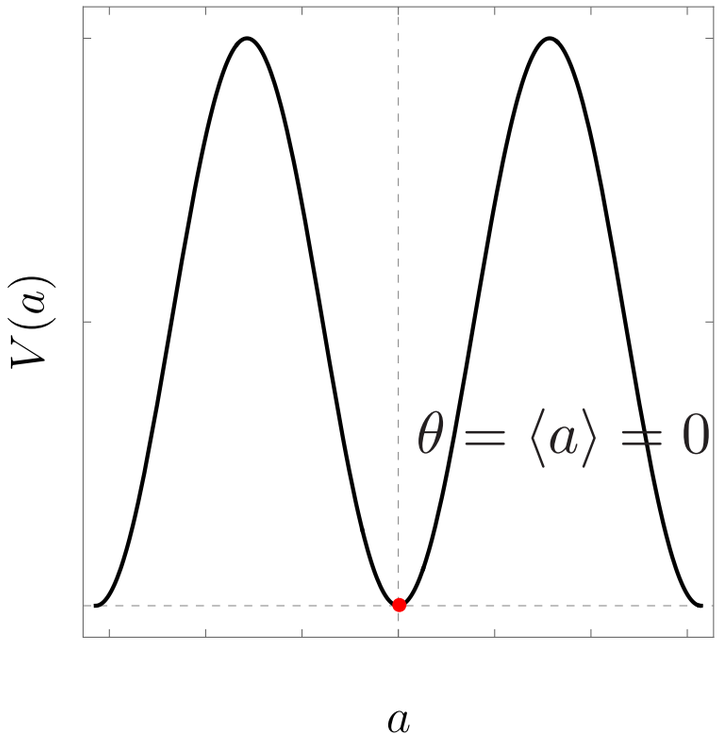
DM candidate

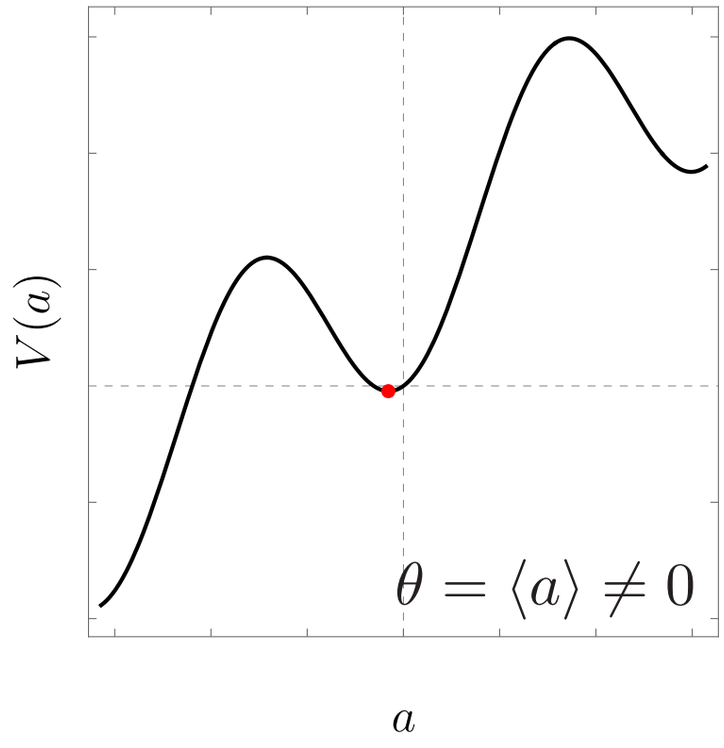
Mediator to the dark sector

# ALP Motivation

Axion quality problem

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



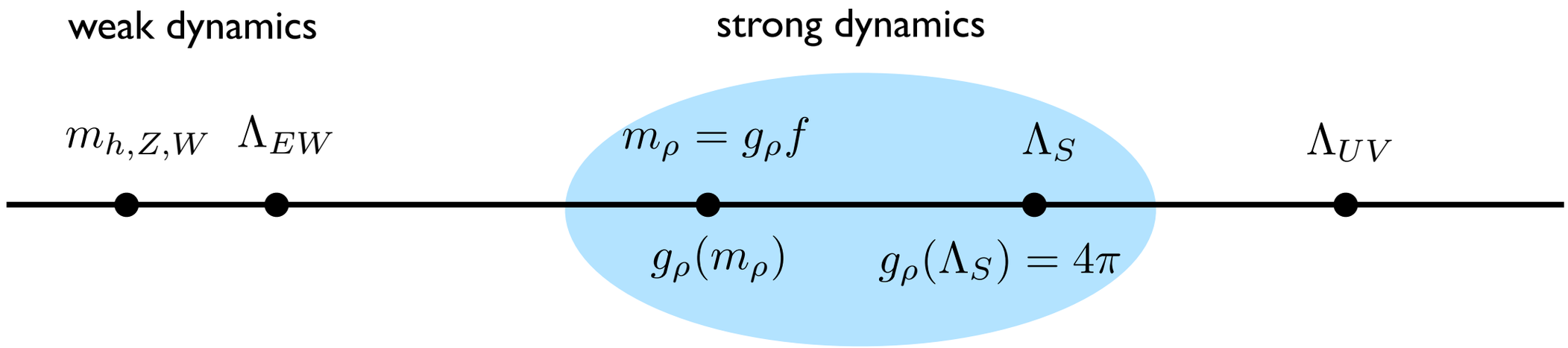

New sector contributes to potential and mass

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

# ALP Motivation

Strongly coupled heavy sector at scale $m_\rho$

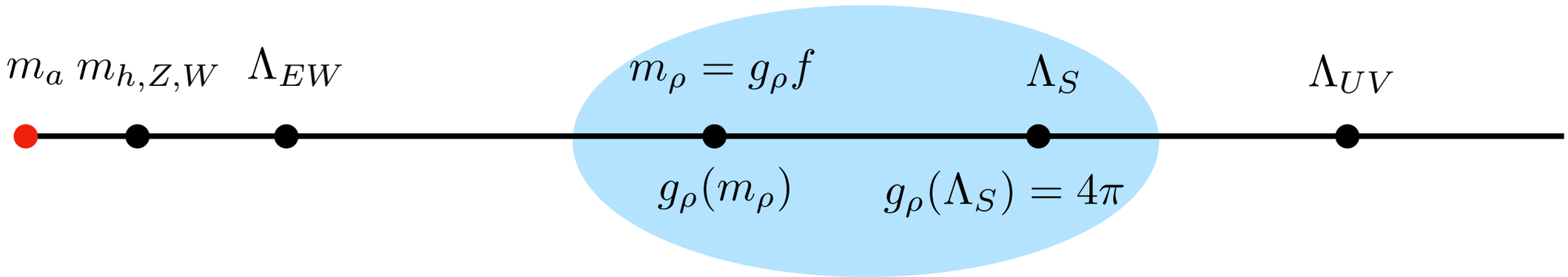
[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164 ]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]




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

# ALP Motivation

Composite Higgs models




Light pseudo-scalar particles = axion-like particles [Ferretti 1604.06467]

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# ALP Motivation

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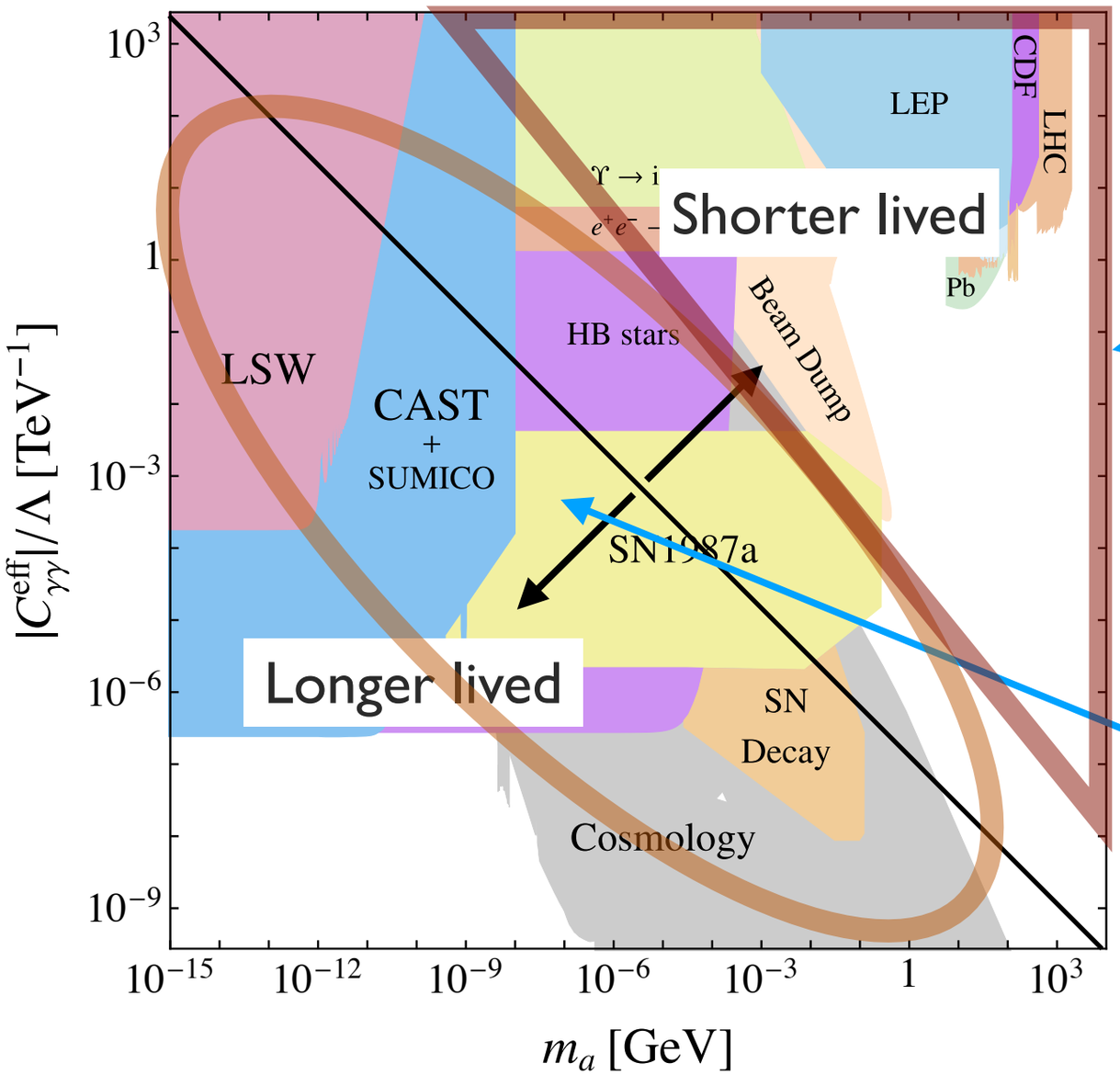



ALPs decay within collider

ALPs from sun and stars

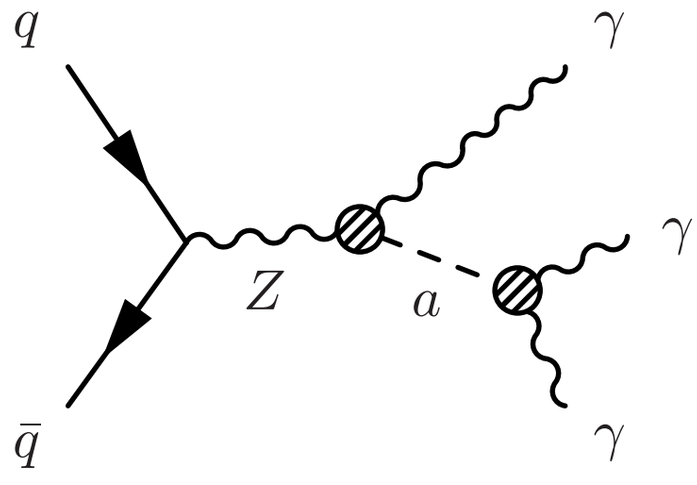
# ALPs at Colliders

Interactions at dimension-5

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

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

Exotic Z-decays



# ALPs at Colliders

Higgs interactions at dimension-6 and 7

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

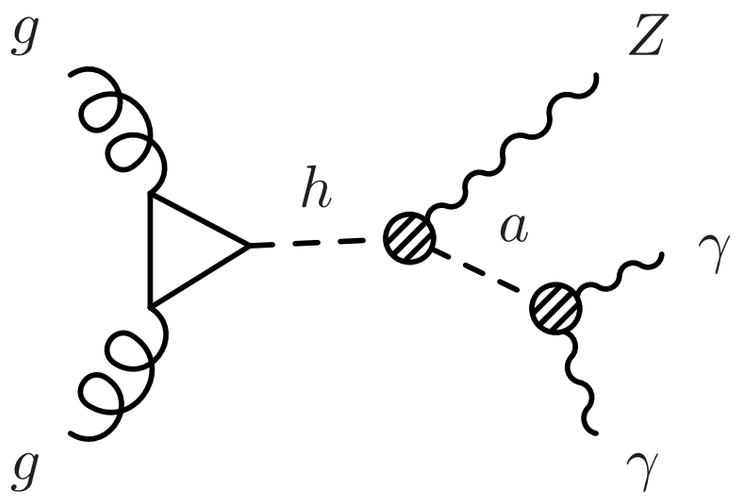
$h \to aa$

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

$h \to Za$

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

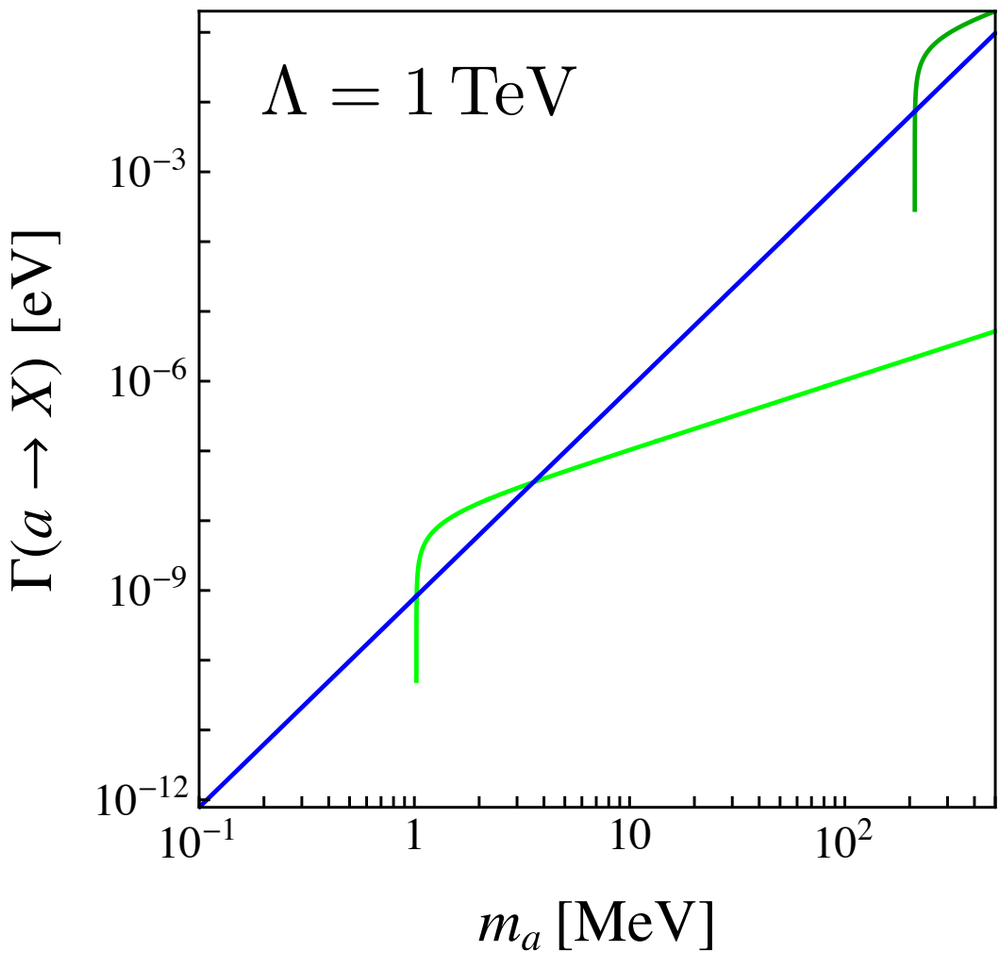
Exotic Higgs decays

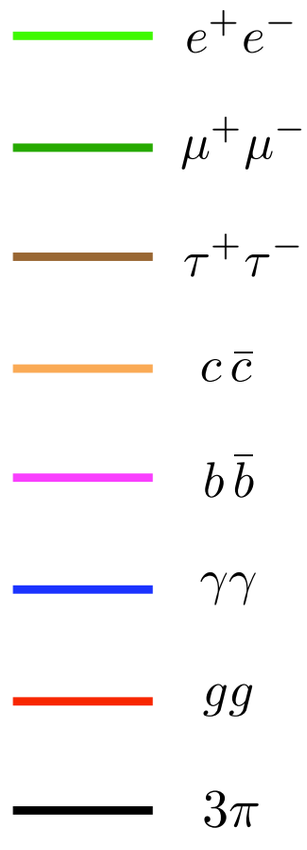


# ALPs at Colliders

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

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



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# Production at lepton colliders

- Resonant production
- Vector boson fusion

[Buttazzo, Redigolo, Sala, Tesi: 1807.04743]
[Teles, d'Genterria, Goncalves, Martins 2310.17270]

- ALP associated production

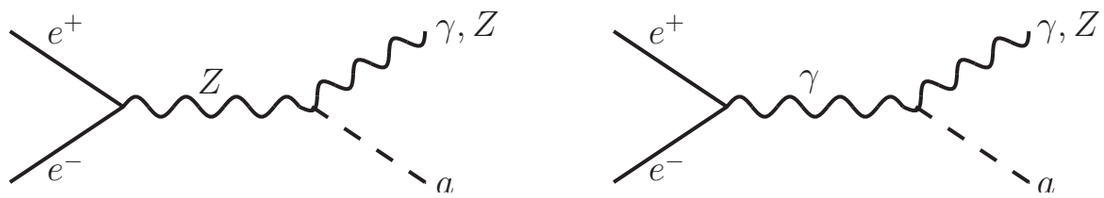
[Bauer, Heiles, Neubert, Thamm: 1808.10323]

- ALP production through exotic decay of H or Z

[Bauer, Heiles, Neubert, Thamm: 1808.10323]

# ALP associated production

- ALP associated production with a photon or Z




- Includes exotic Z decays at the Z pole

- ALP decay into photons

→ Process depends on only one coupling

$$C_{\gamma\gamma} = C_{WW} + C_{BB}\,, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB} \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

# ALP associated production

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

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

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

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

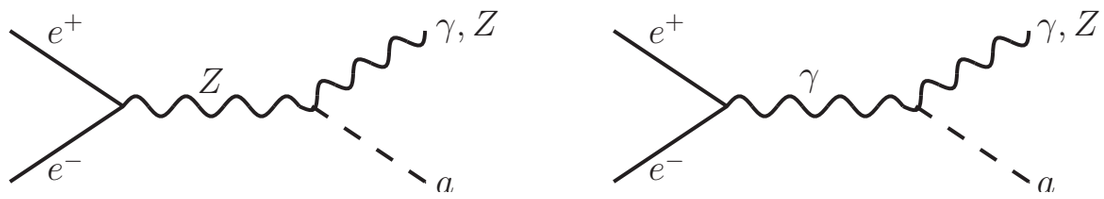
# ALP associated production

- Number of required events:
  - 100 for LHC estimates
  - 4 for lepton collider estimates

- Only estimates - also need full analysis!

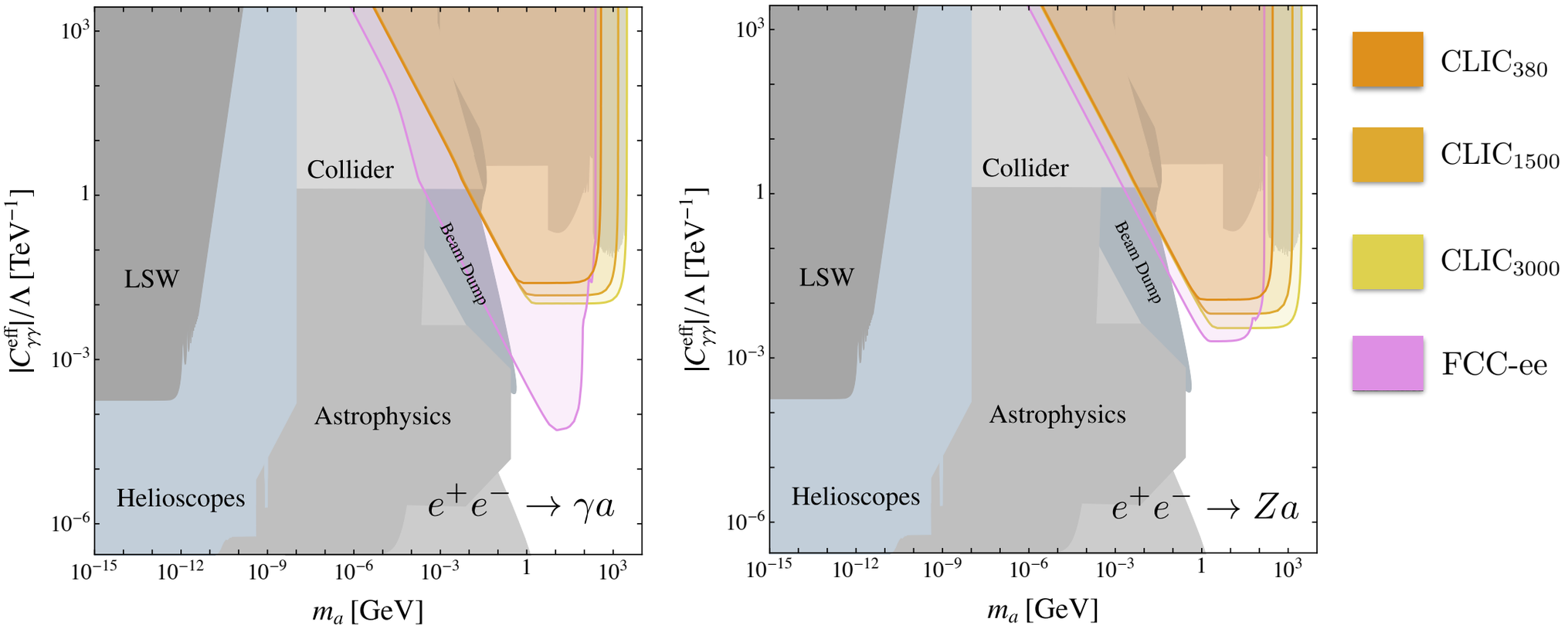
# ALP associated production

- ALP associated production with a photon or Z




- ALP decay into photons

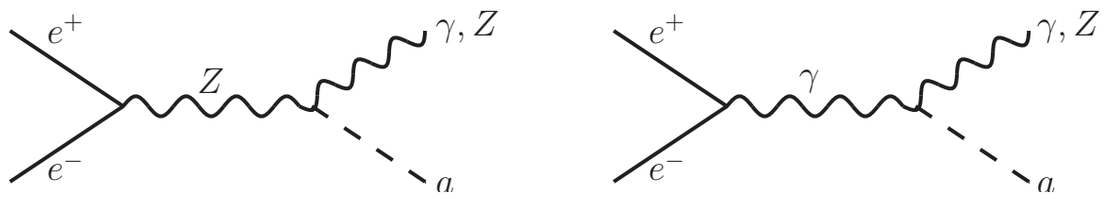
[Bauer, Heiles, Neubert, Thamm: 1808.10323]




[see also Tian, Wang, Wang: 2201.08960]

# ALP associated production

- ALP associated production with a photon or Z

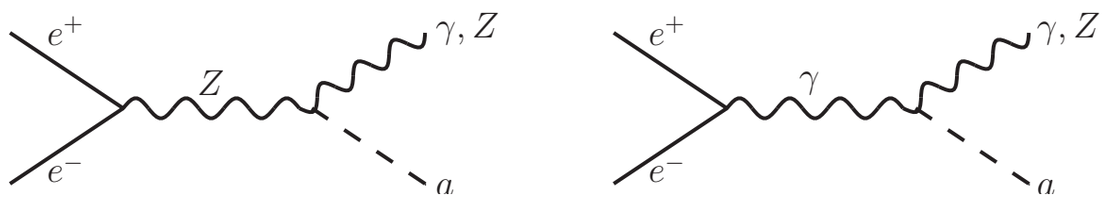



- Includes exotic Z decays at the Z pole
- ALP coupling via lepton loop
- ALP decay into leptons

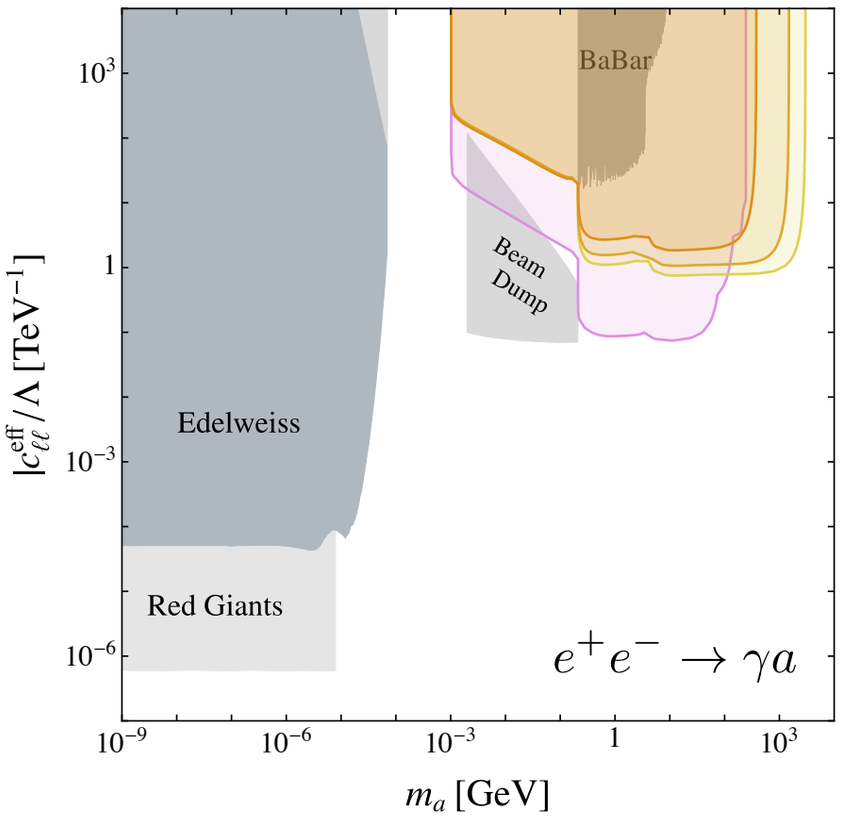
→ Process depends on only one coupling

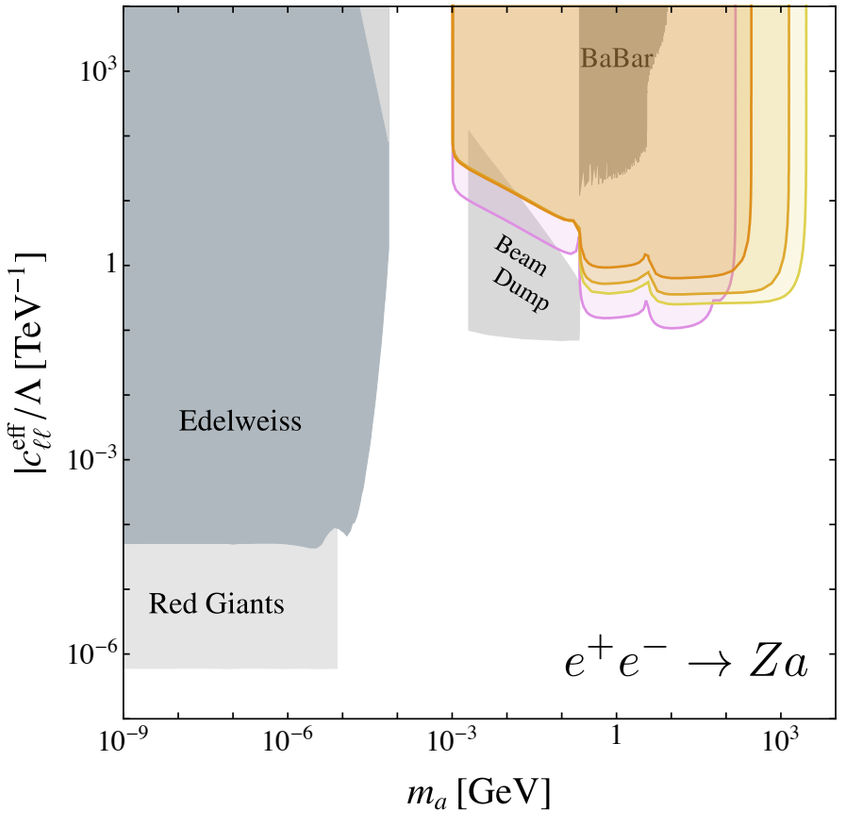
# ALP associated production

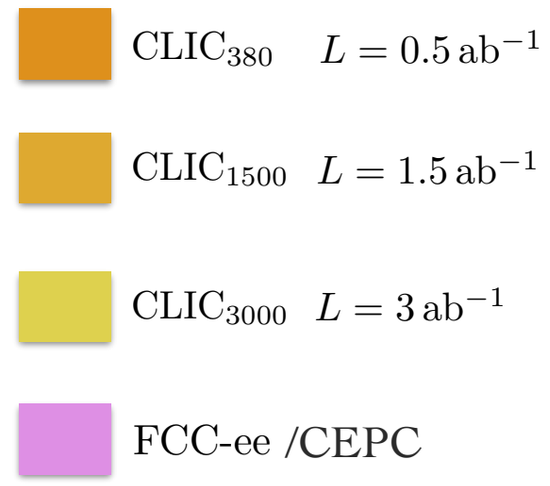
- ALP associated production with a photon or Z




- ALP decay into leptons

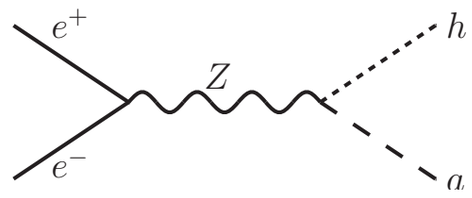


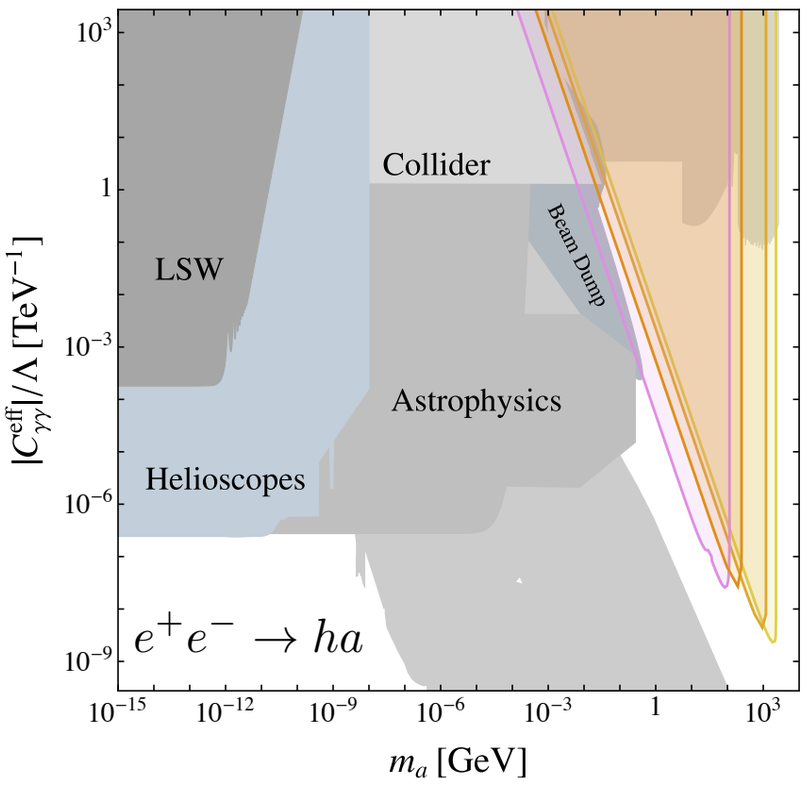



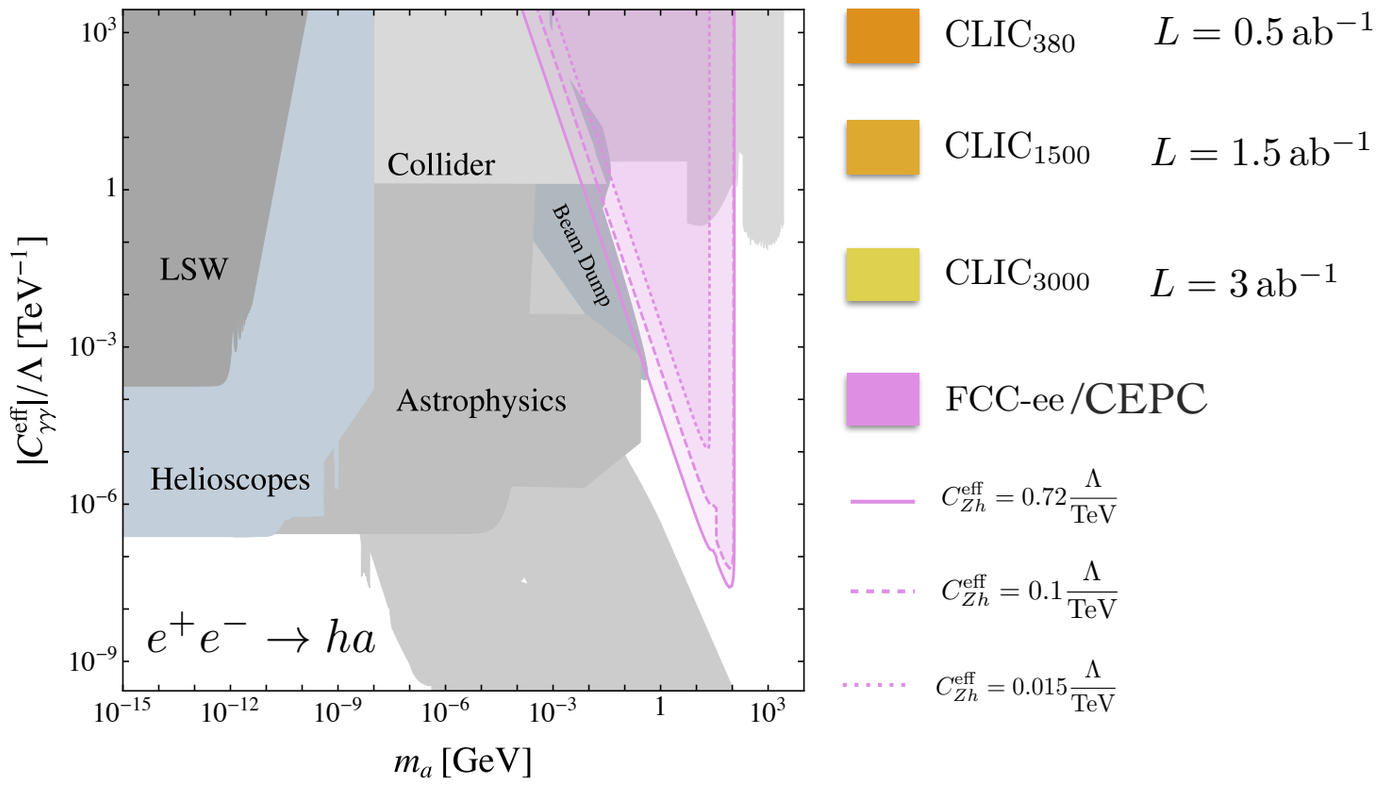
# ALP associated production

- ALP associated production with a H




- ALP decay into photons



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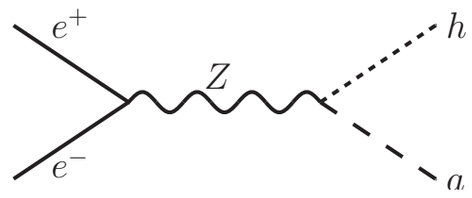
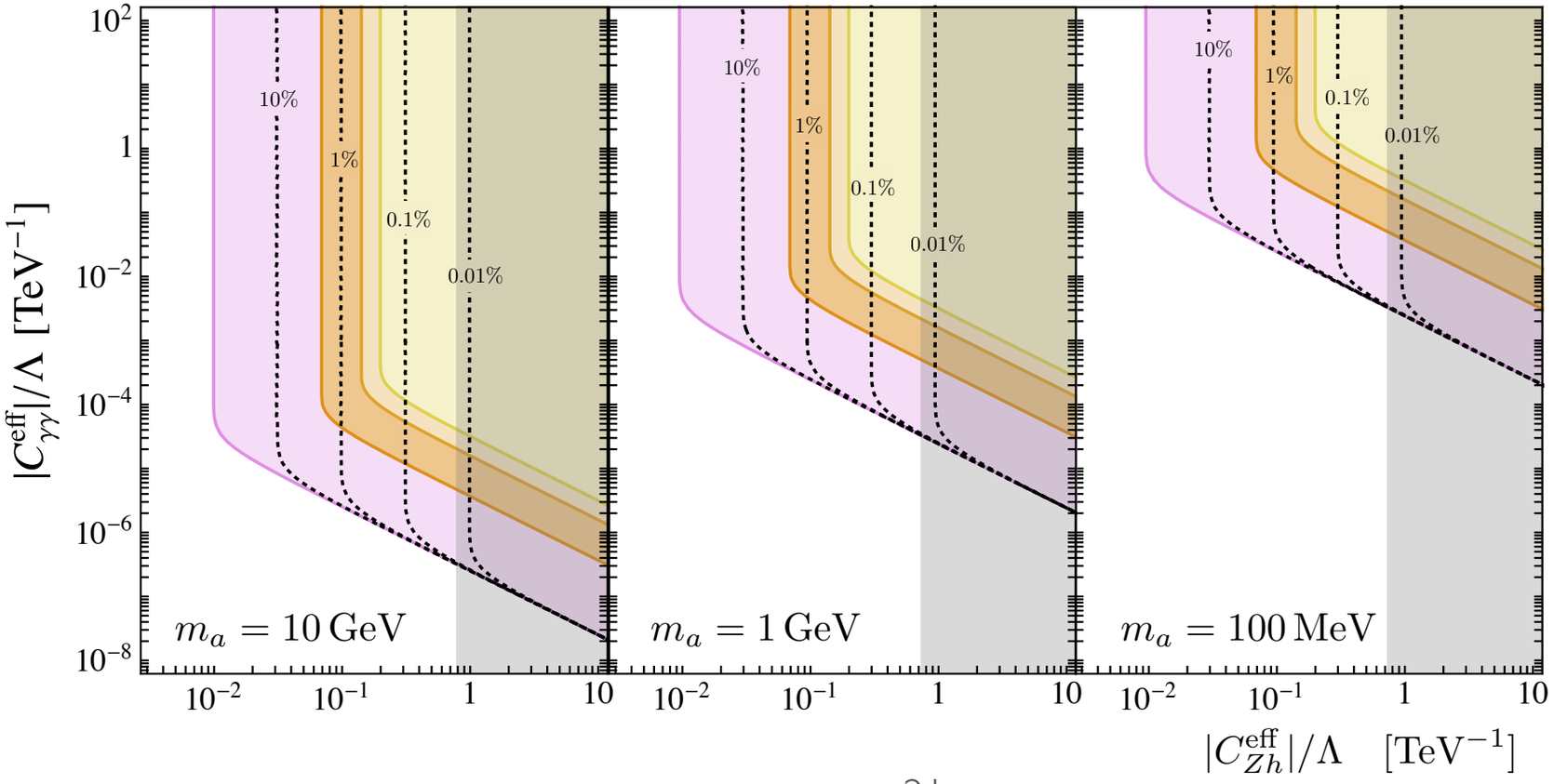


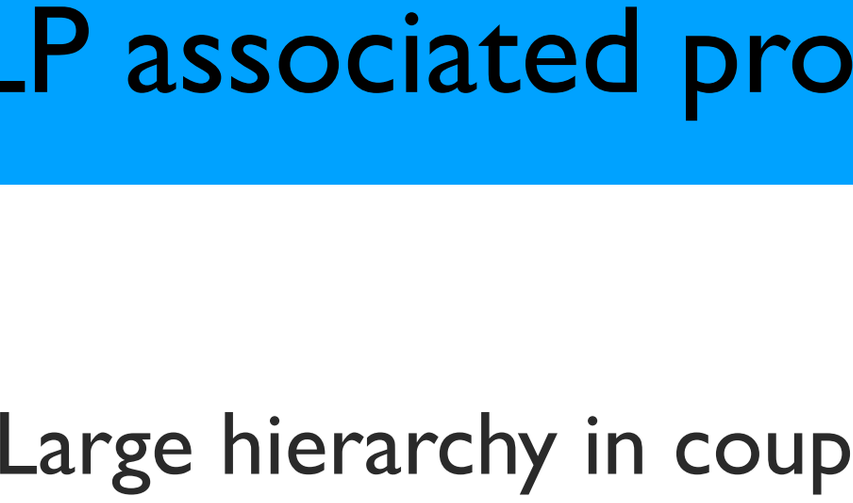

- ALP decay into photons



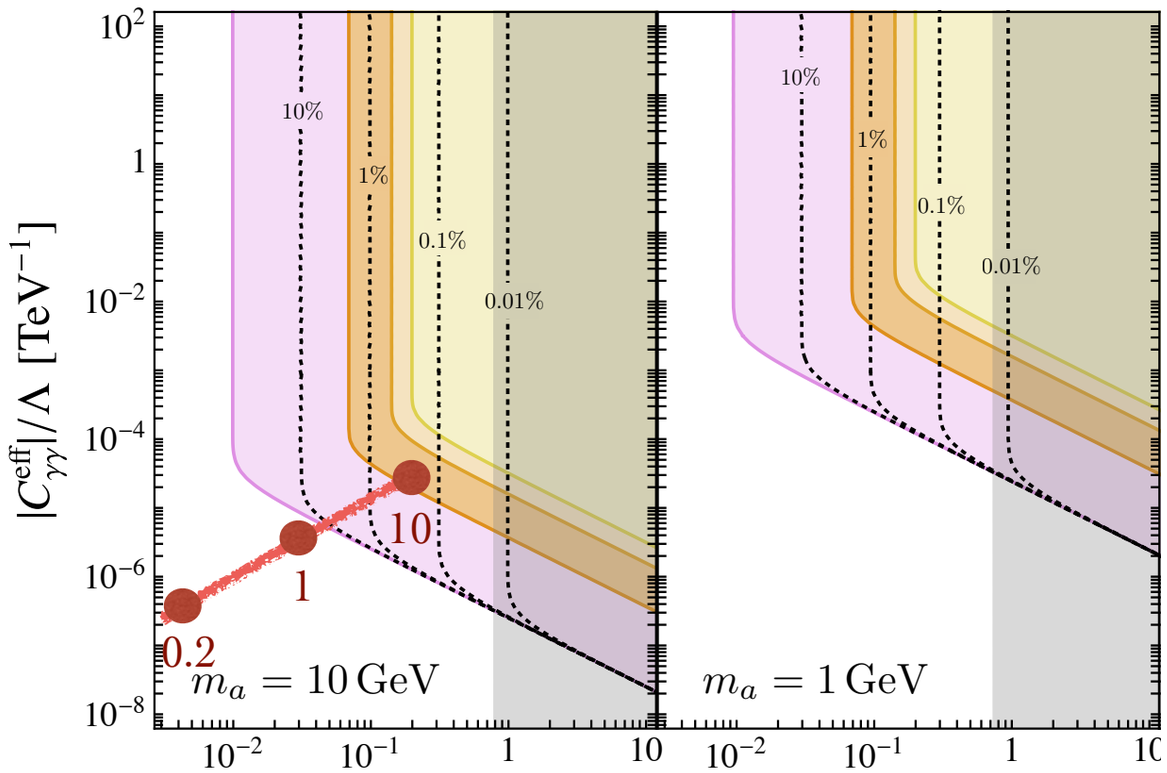

Cross-section ~ 1/s

# ALP associated production

- Large hierarchy in couplings can be plausible
- Integrating out the top




$C_{Zh}$



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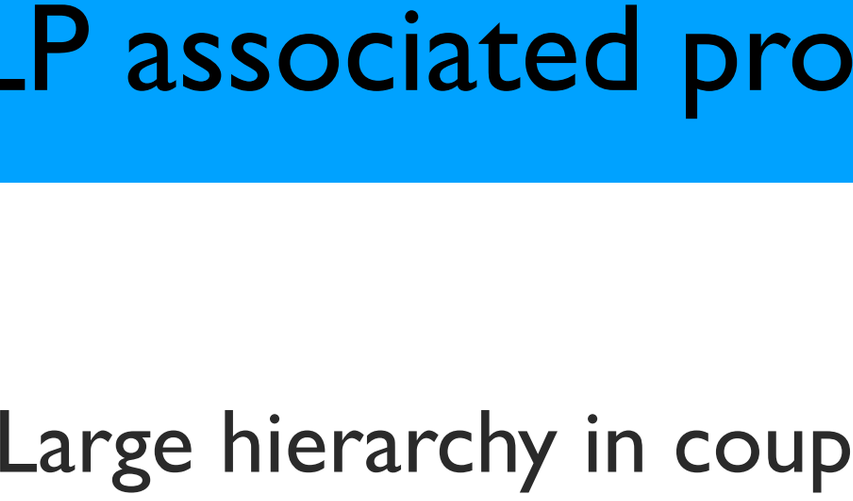


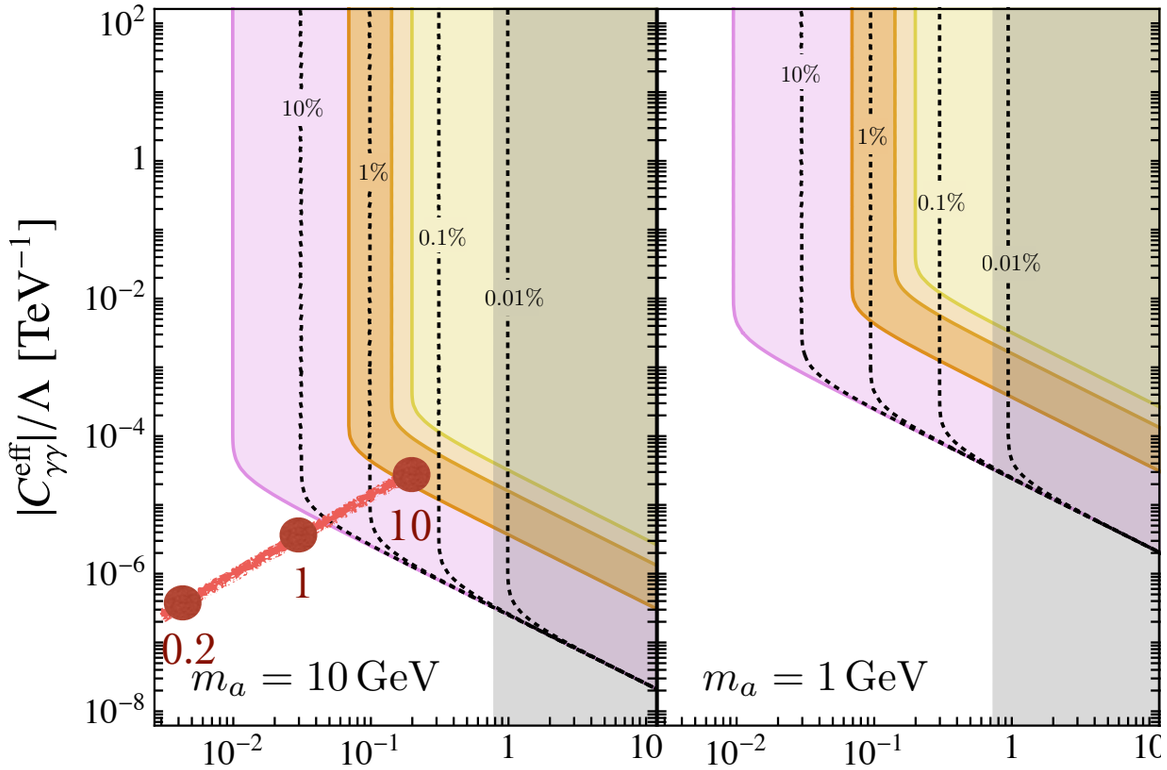

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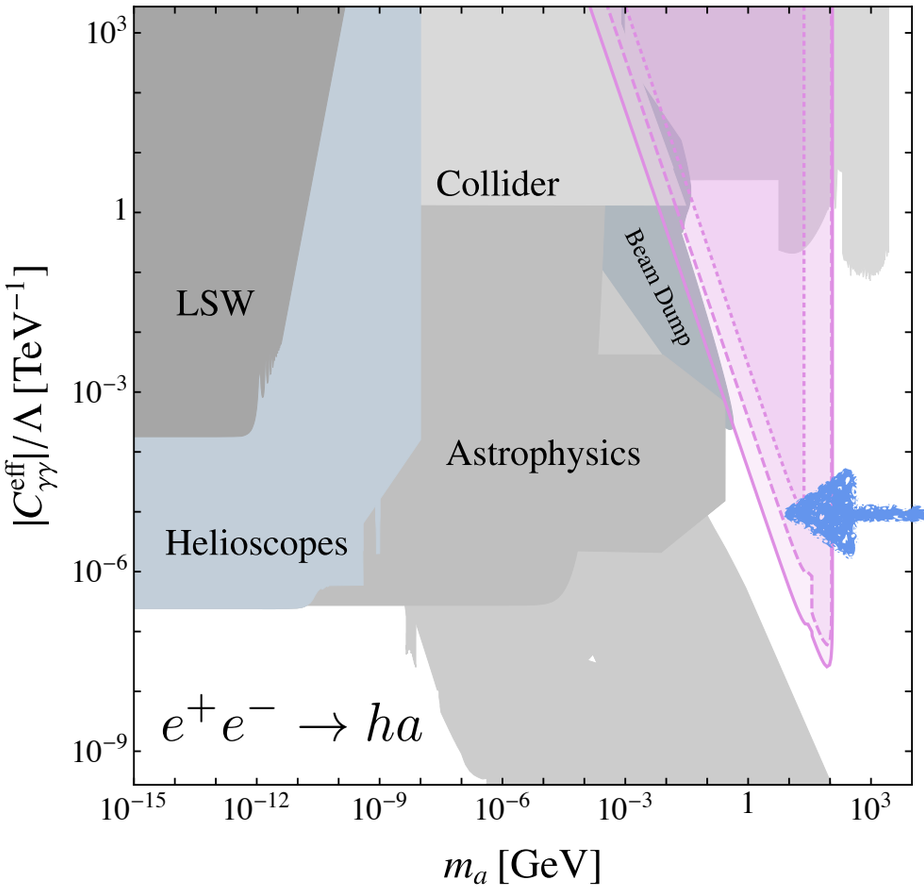
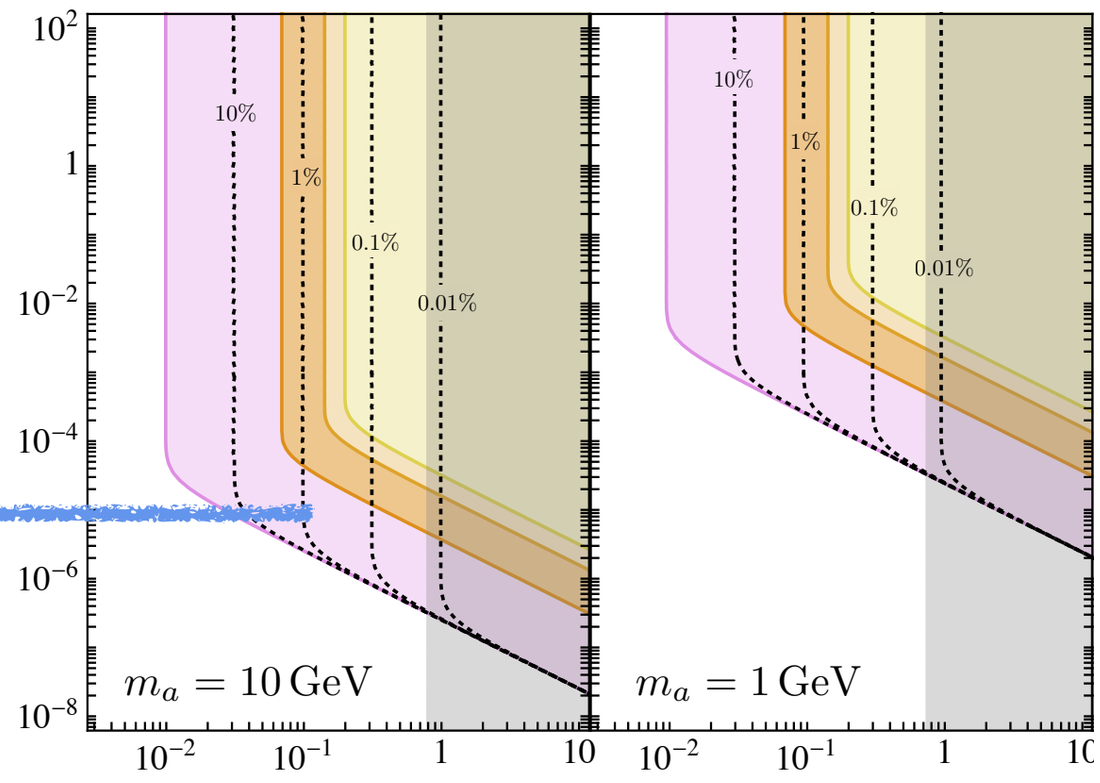
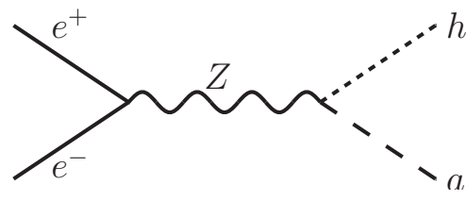


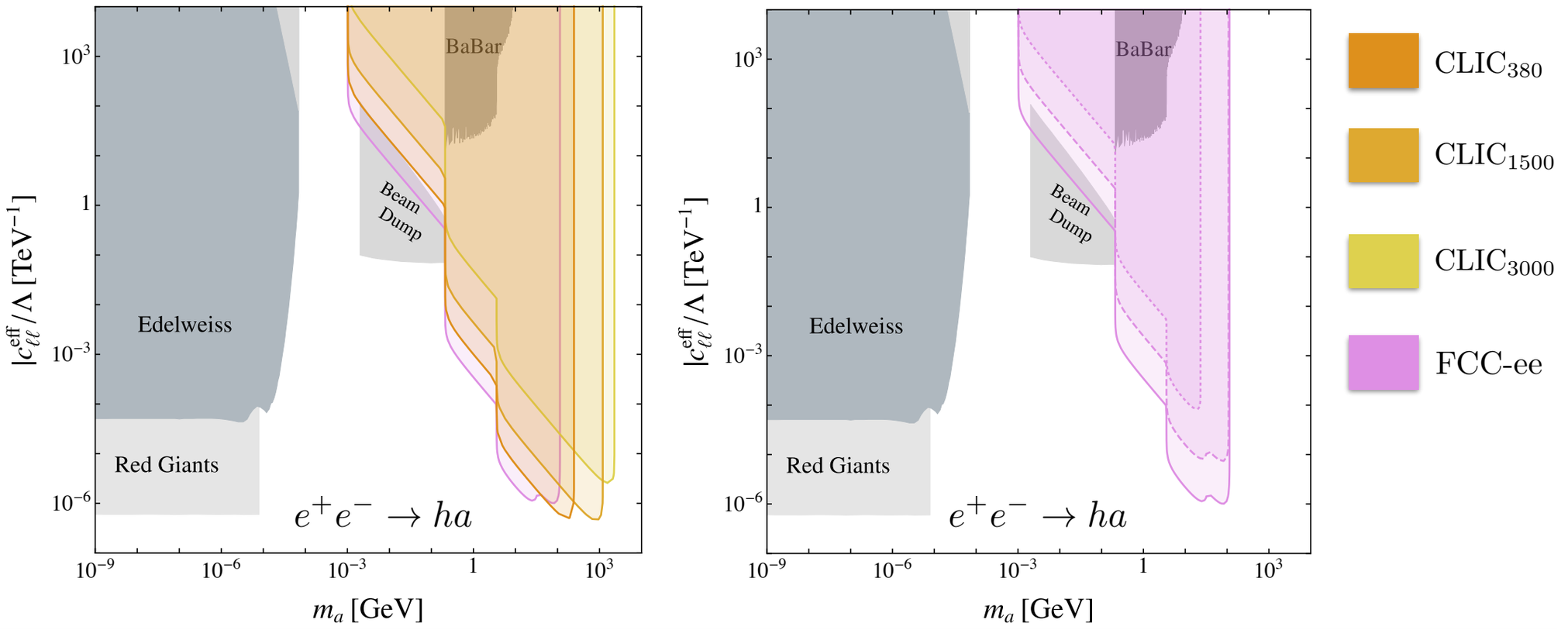



# ALP associated production

- ALP associated production with a H




- ALP decay into leptons



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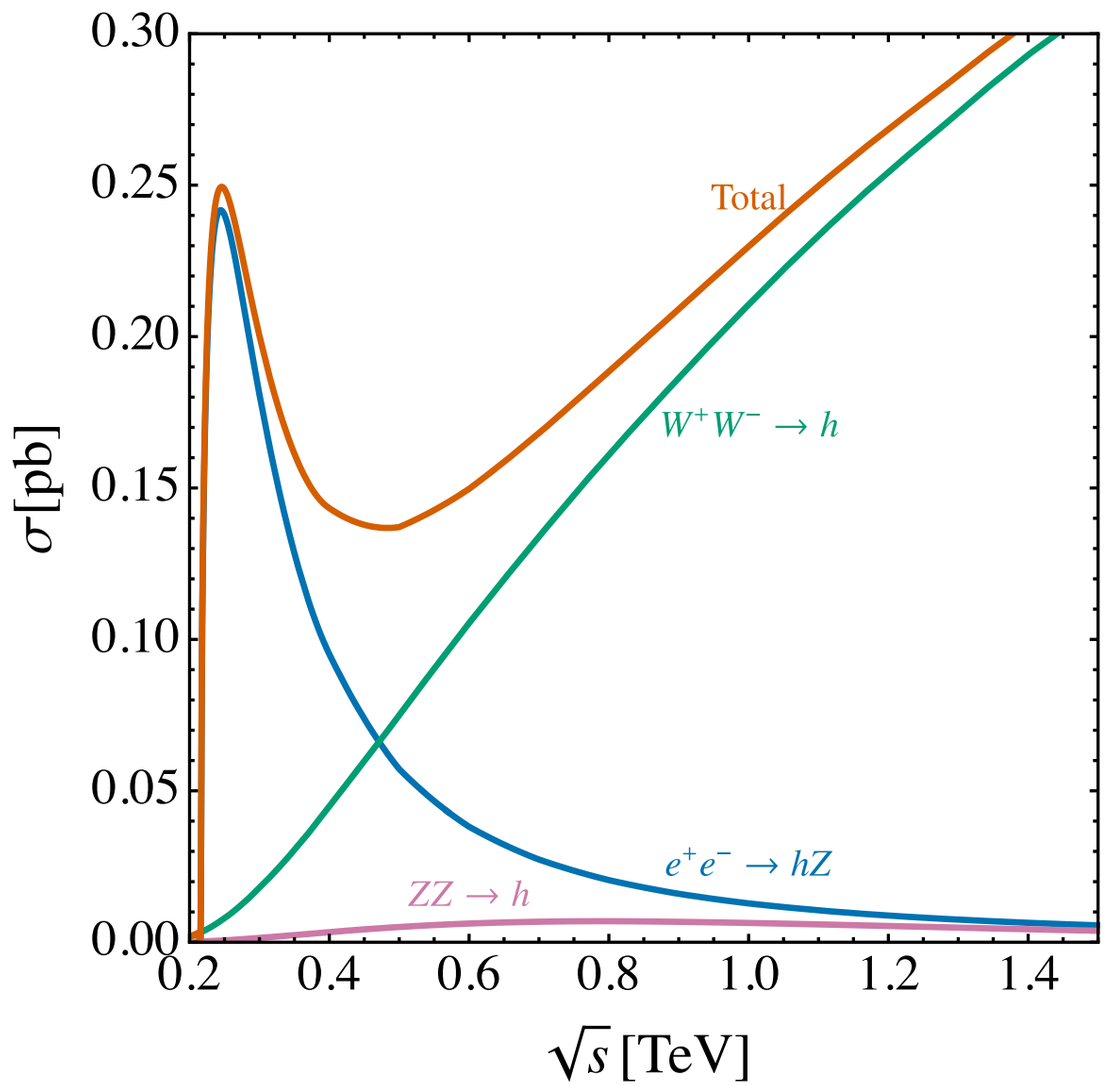
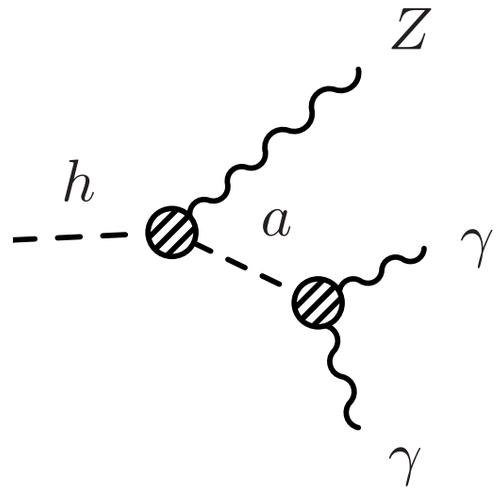
# Exotic Higgs decays

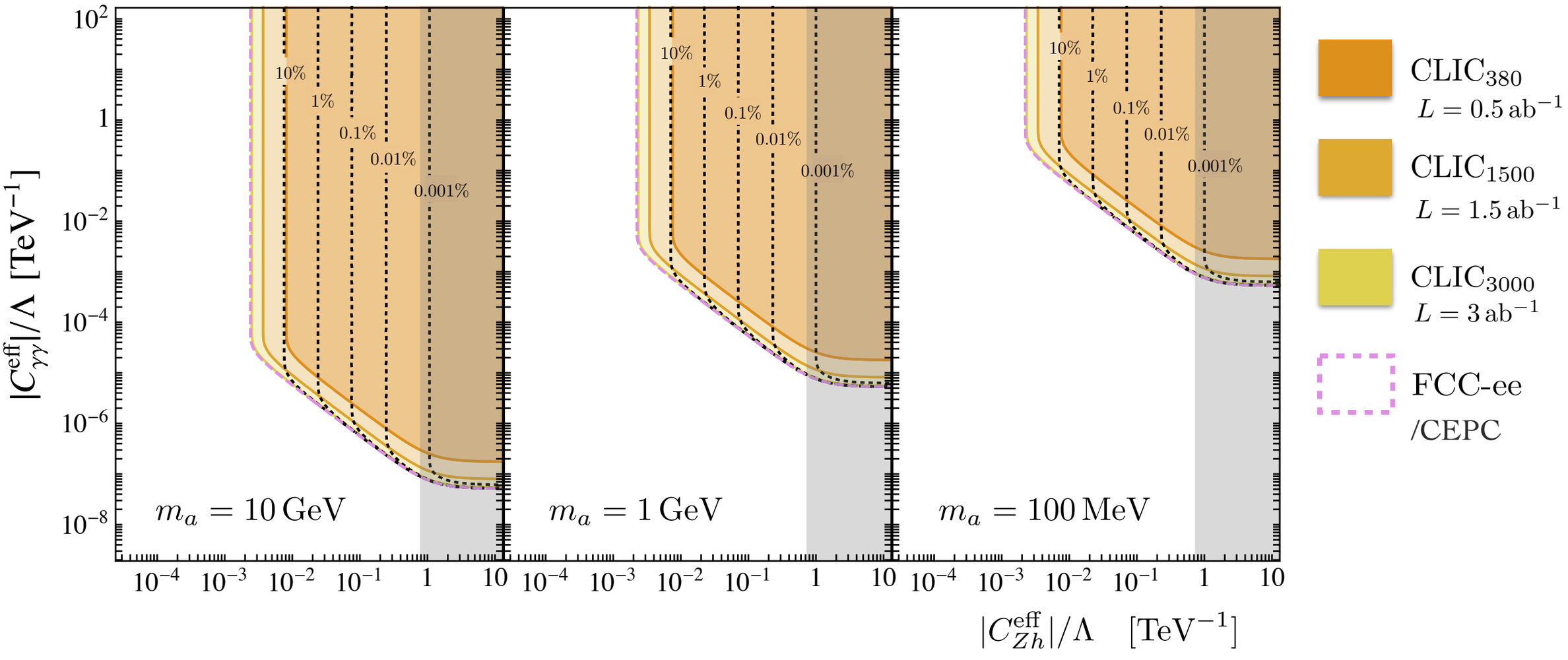
- Exotic Higgs decay: number of Higgses



# Exotic Higgs decays

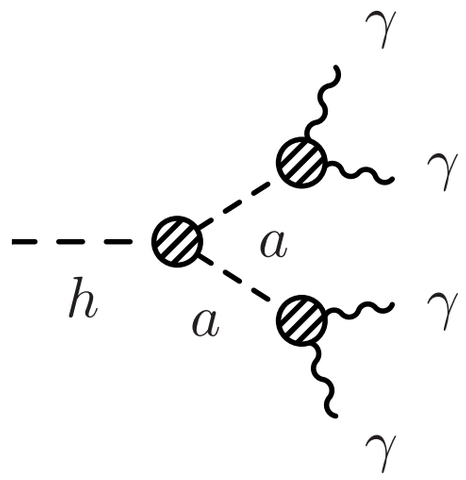


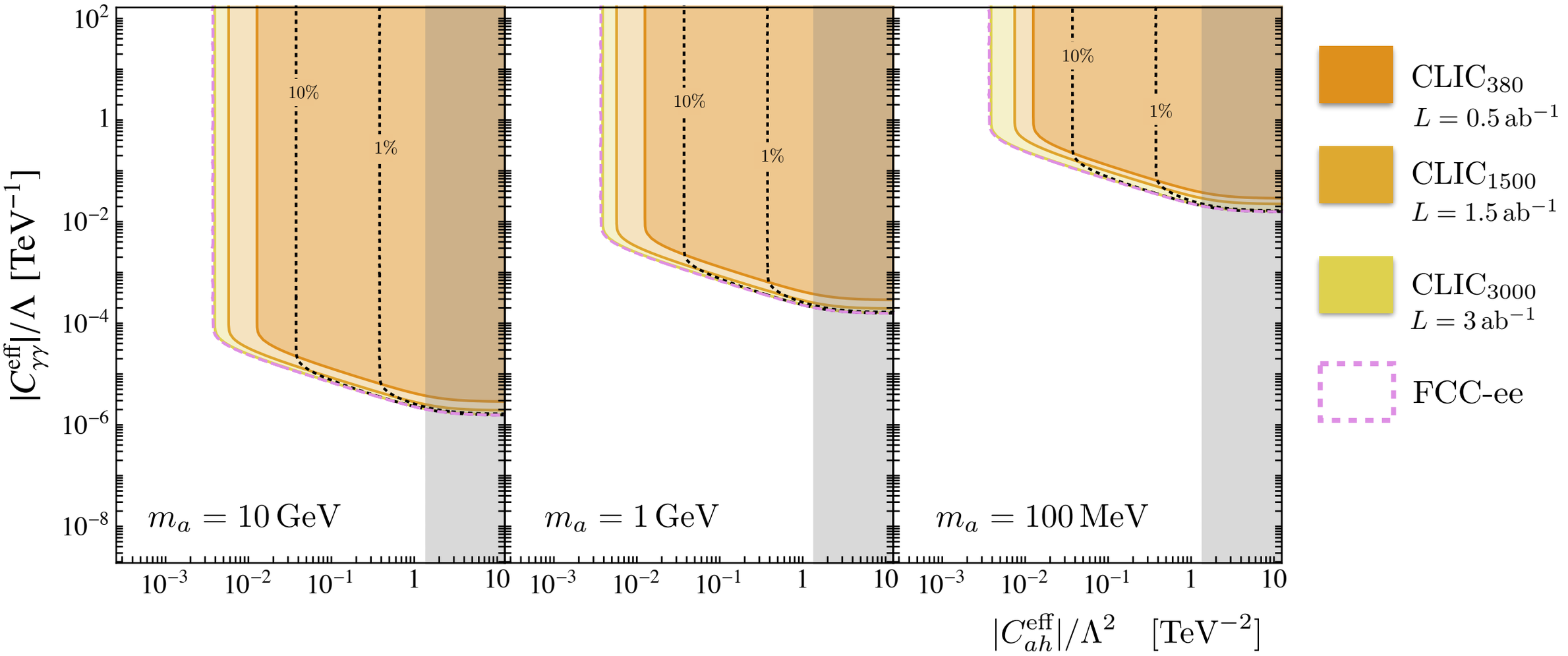

- Exotic Higgs decay: $h \to Za$



# Exotic Higgs decays

- Exotic Higgs decay: $h \to aa$



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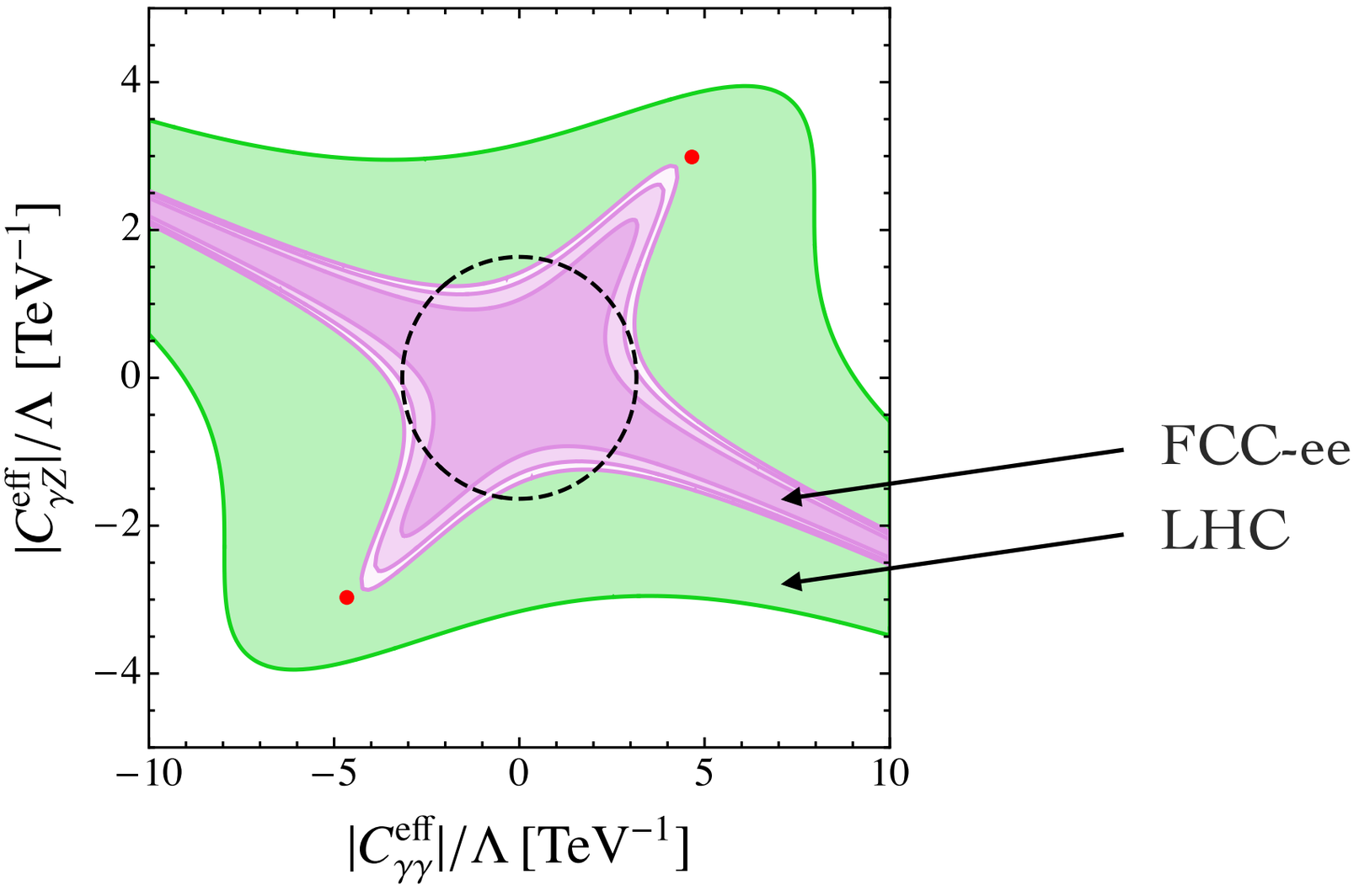
# Electroweak precision tests

- Unprecedented precision of electroweak observables

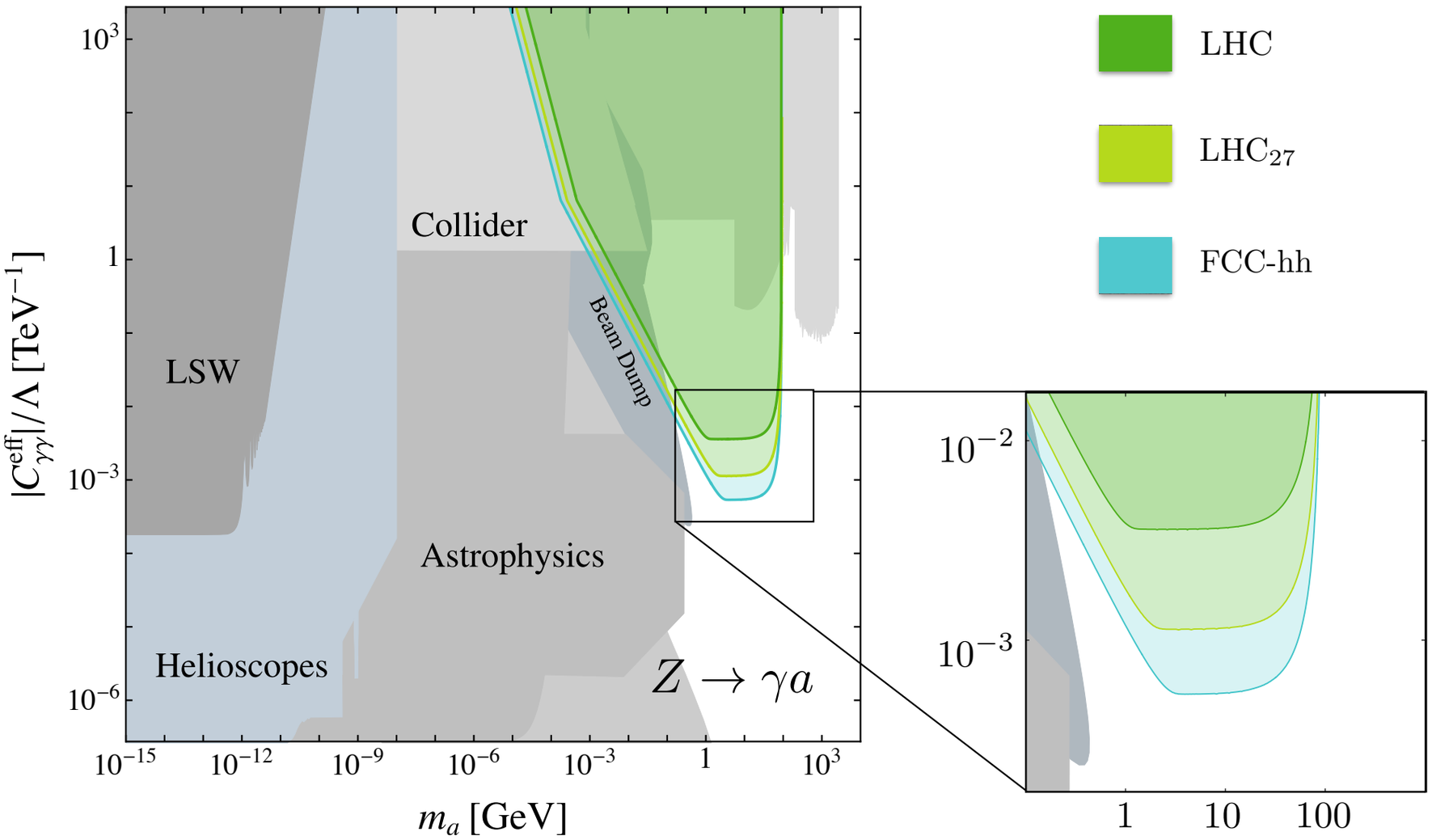


# Conclusions

- Lepton colliders can probe well motivated parameter space
- Associated production is dominant
- FCCee Z-pole run is particularly powerful

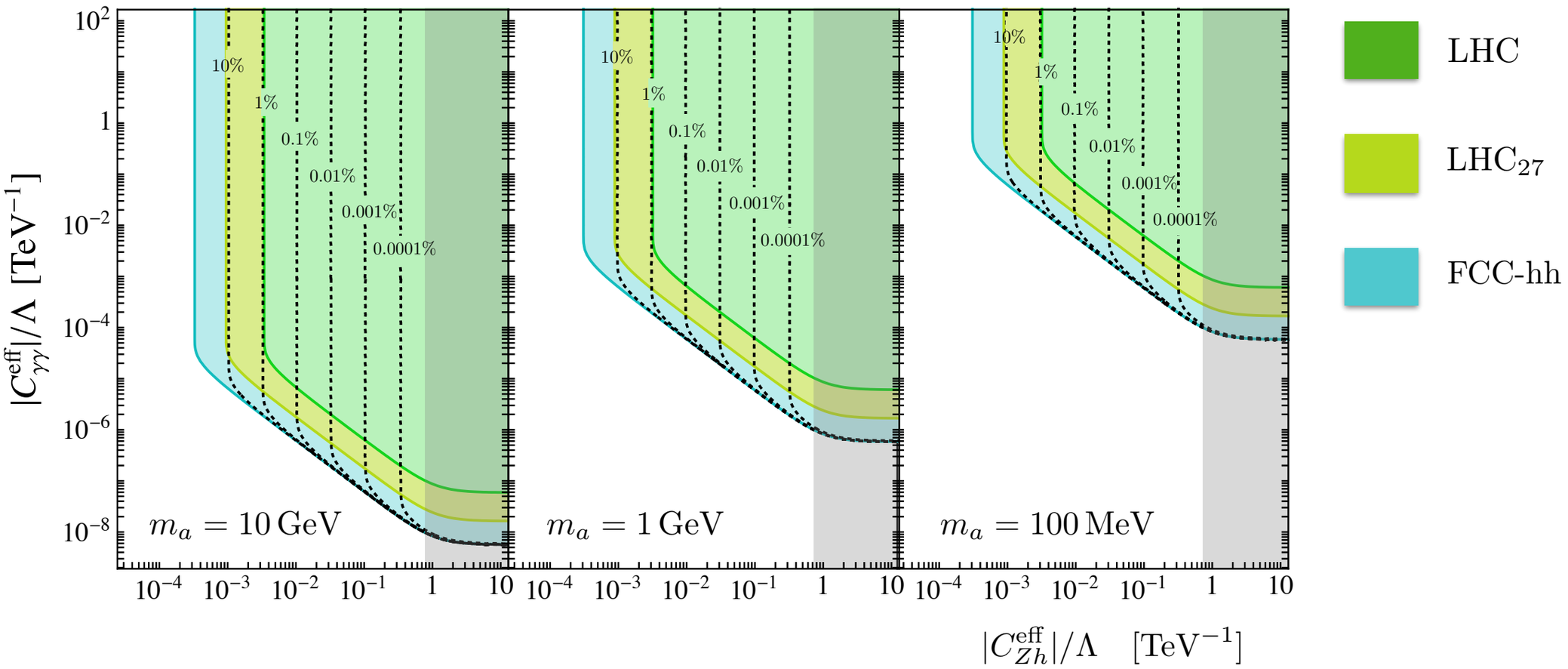
# Backup

- FCC-hh



# Backup

- FCC-hh: $h \to Za$



# Backup

See also [Zhang, Yue, Guo, Yang: 2103.05218]

- Photon-photon fusion

[Teles, d'Genterria, Goncalves, Martins 2310.17270]

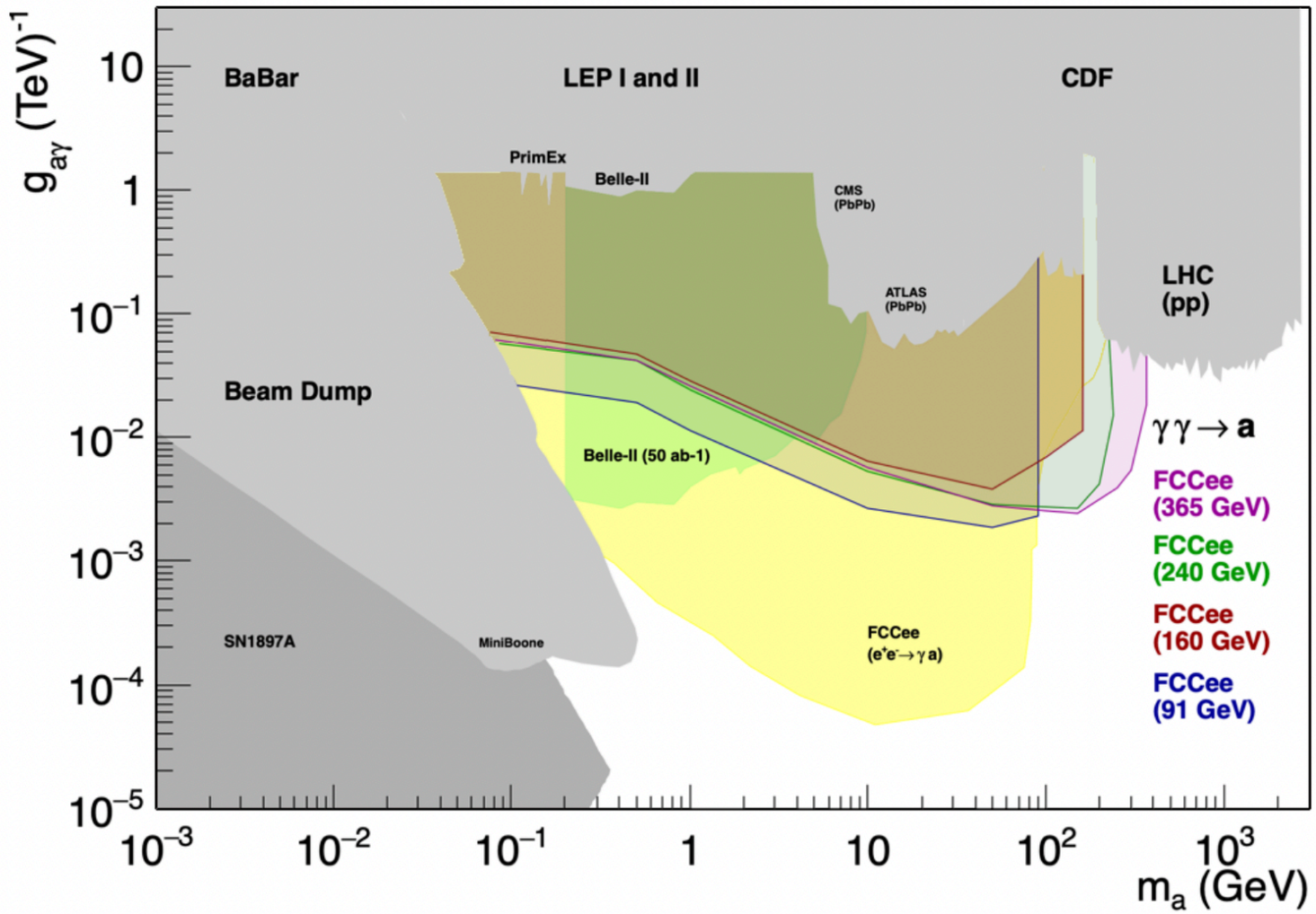



FIG. 8: Exclusion limits at 95% CL on the ALP-photon coupling as a function of the ALP mass expected from searches for $\gamma\gamma \to a \to \gamma\gamma$ in the different FCC-ee runs (Table I). The yellow area shows FCC-ee expectations based on the alternative $e^+e^- \to \gamma a$ final state [29] scaled to reflect the updated FCC-ee operation. The green area shows current Belle-II upper bounds [16, 19] scaled up to the full expected SuperKEK integrated luminosity $\mathcal{L}_{\rm int} = 50\ {\rm ab}^{-1}$.

# Backup

- ALP lepton couplings

[Calibbi, Huang, Qin, Yang, Yin 2212.02818]
[Yue, Yang, Wang, Zhang, 2204.04702]