ALPs at Future Lepton Colliders

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with Martin Bauer, Mathias Heiles and Matthias Neubert

based on arXiv: 1704.08207, 1708.00443, 1808.10323

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CEPC Workshop

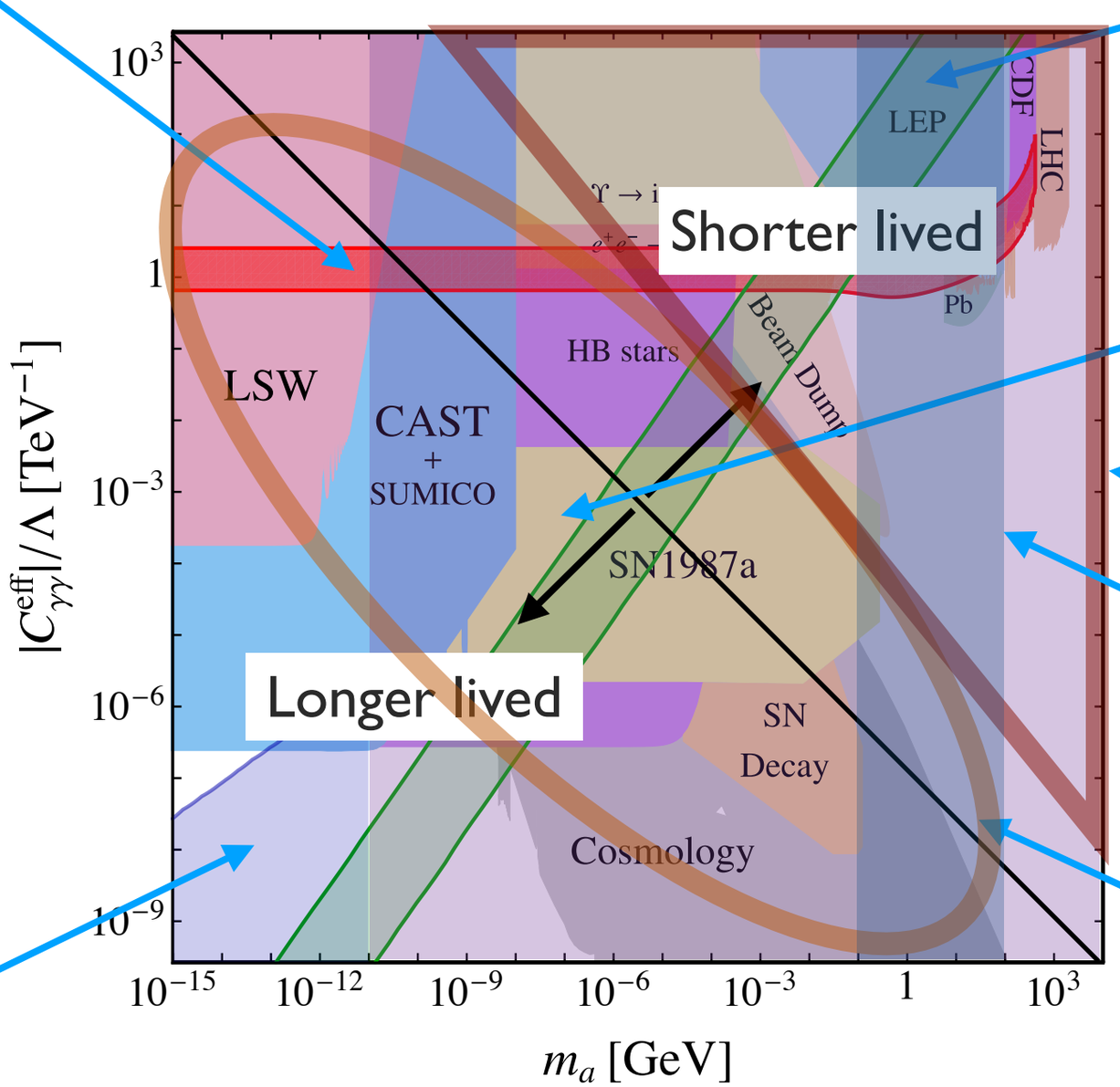
Outline

- Background on ALPs
- ALPs at future lepton colliders
  - Production in association with a photon, Z, H
  - Production in exotic H decays
  - Electroweak precision constraints

Theory Motivation

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

Solves the strong CP problem



ALPs from sun and stars

ALPs decay within collider

pNGB from Composite Models

DM candidate

Mediator to the dark sector

Effective Lagrangian

- Interactions at dimension-5

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

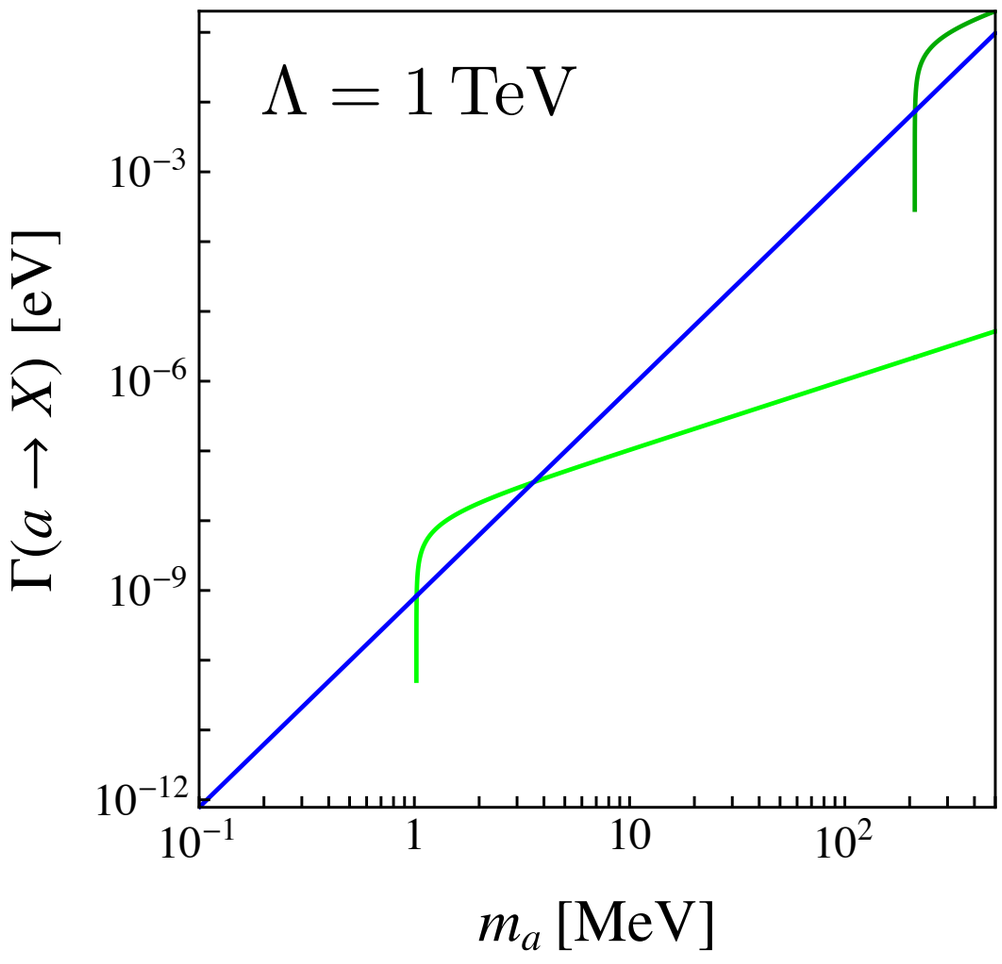
$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f + g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G^A_{\mu\nu}\,\tilde{G}^{\mu\nu,A}$$

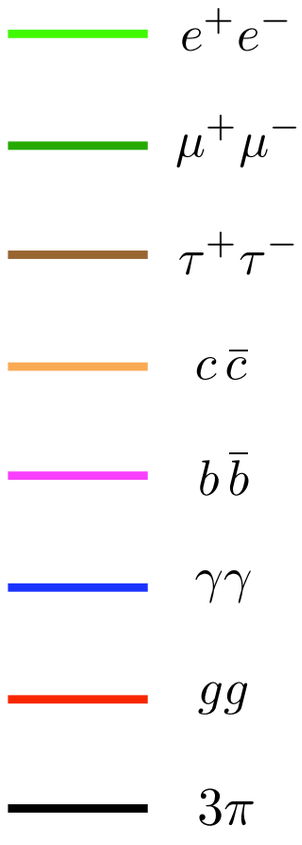
$$+ e^2\,C_{\gamma\gamma}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\,C_{\gamma Z}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\,C_{ZZ}\,\frac{a}{\Lambda}\,Z_{\mu\nu}\,\tilde{Z}^{\mu\nu}$$

- Decay into photons, leptons, hadrons

ALP decays

- Assuming effective Wilson coefficients to be 1





Effective Lagrangian

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- Decay into photons, leptons, hadrons
- 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: 1607.01016]

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Production at lepton colliders

- Resonant production
- Vector boson fusion

[Buttazzo, Redigolo, Sala, Tesi: 1807.04743]

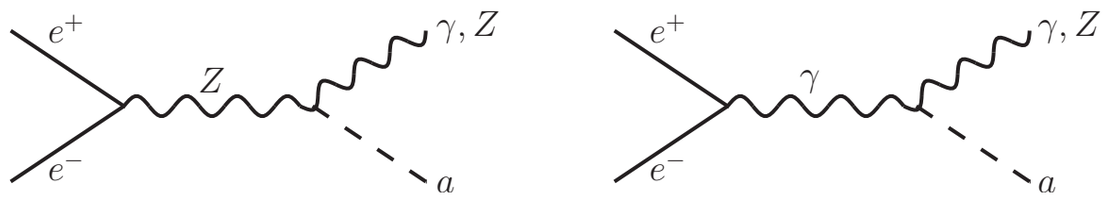
- ALP associated production

[Bauer, Heiles, Neubert, Thamm: 1808.10323]

- ALP production through exotic decay of H or Z

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

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

Detecting ALPs

- 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

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

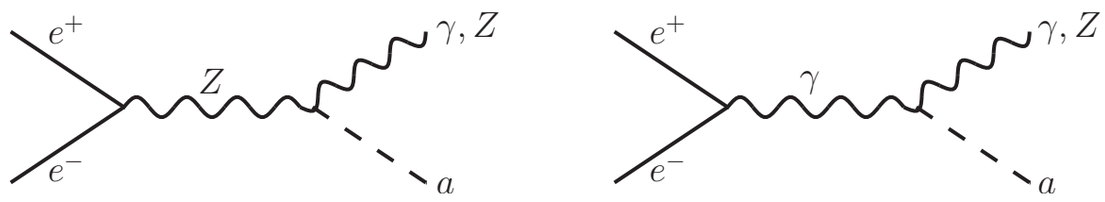
Detecting ALPs

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

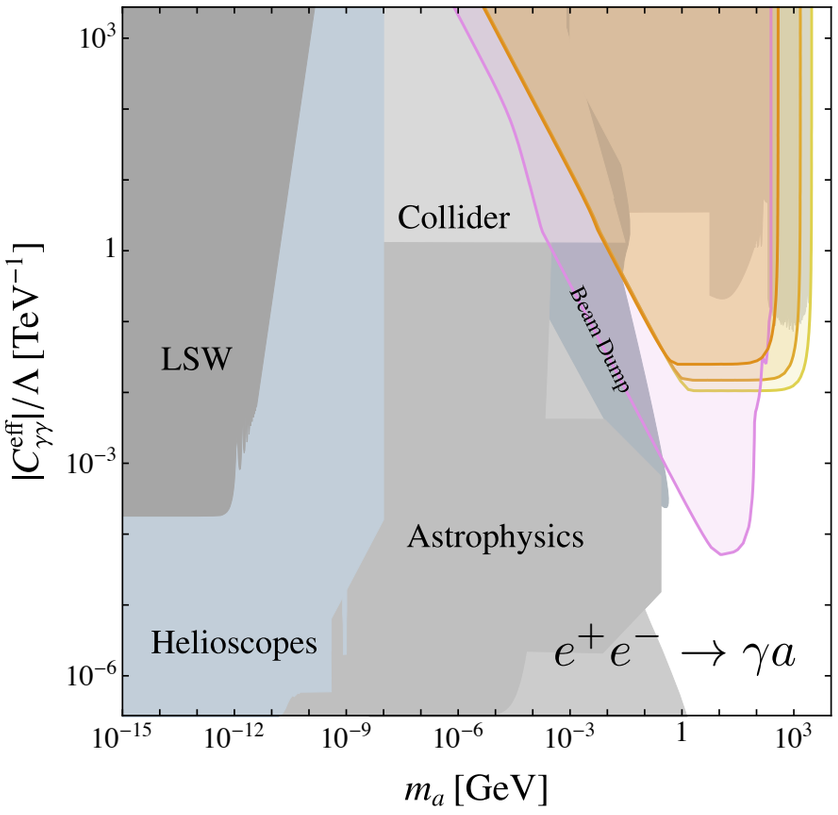
- Only estimates - also need full analysis!

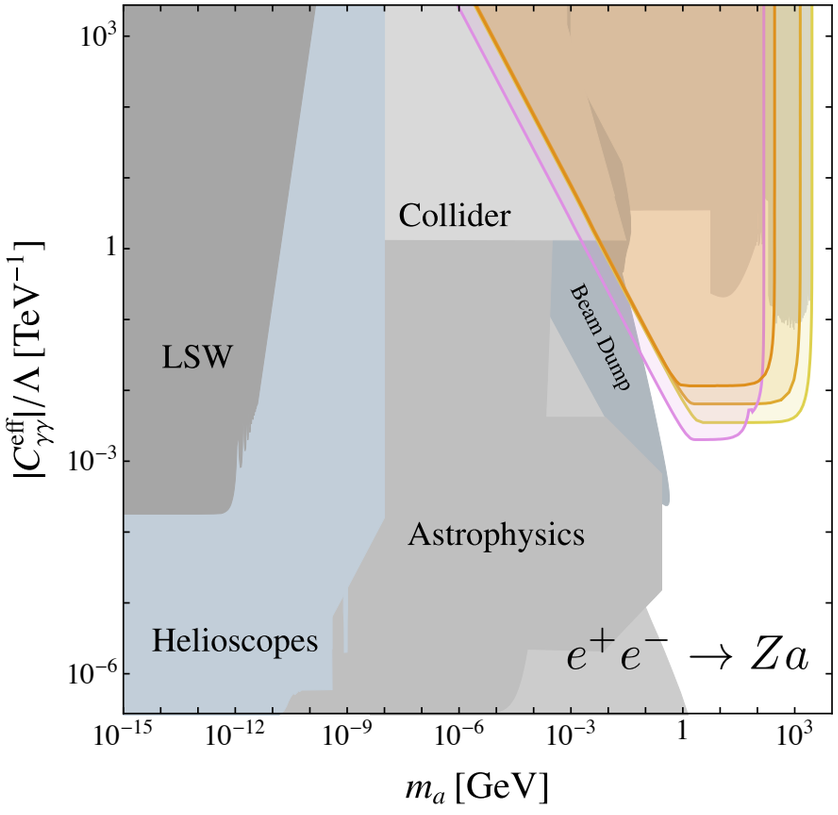
Associated production

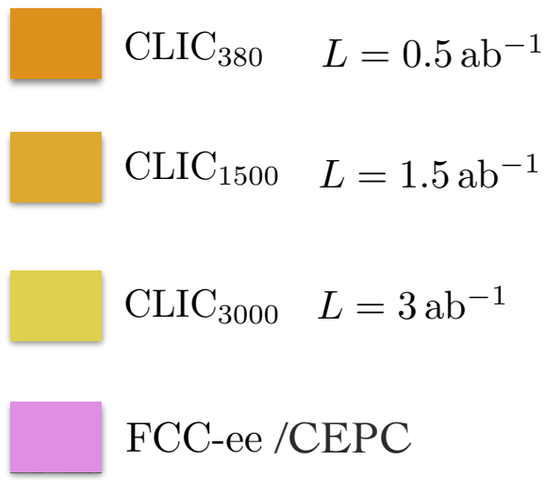
- ALP associated production with a photon or Z



- ALP decay into photons

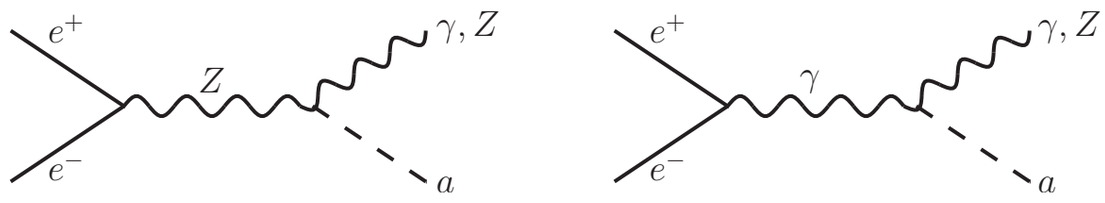






Associated production

- ALP associated production with a photon or Z

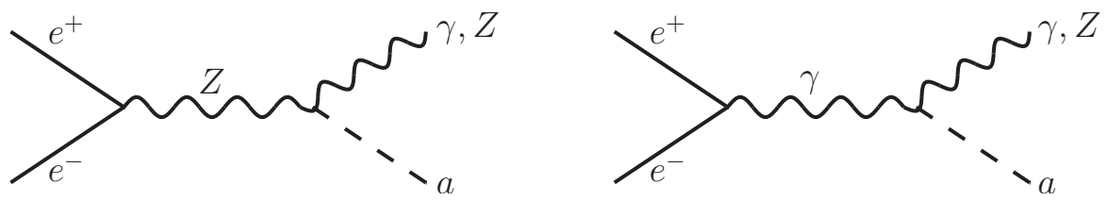


- Includes exotic Z decays at the Z pole
- ALP coupling via lepton loop
- ALP decay into leptons

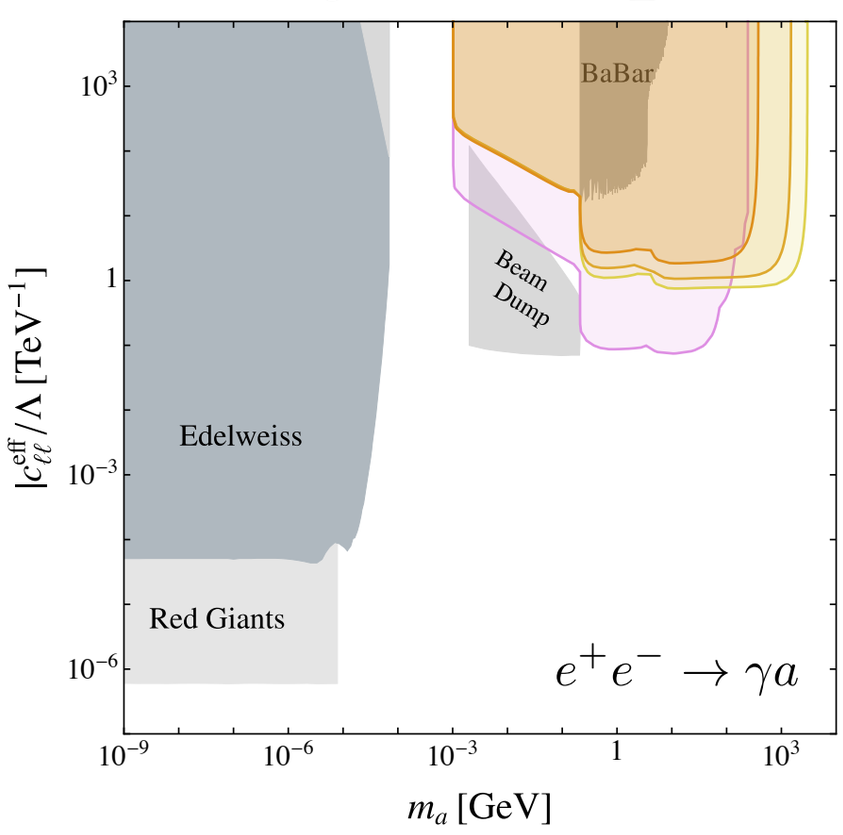
→ Process depends on only one coupling

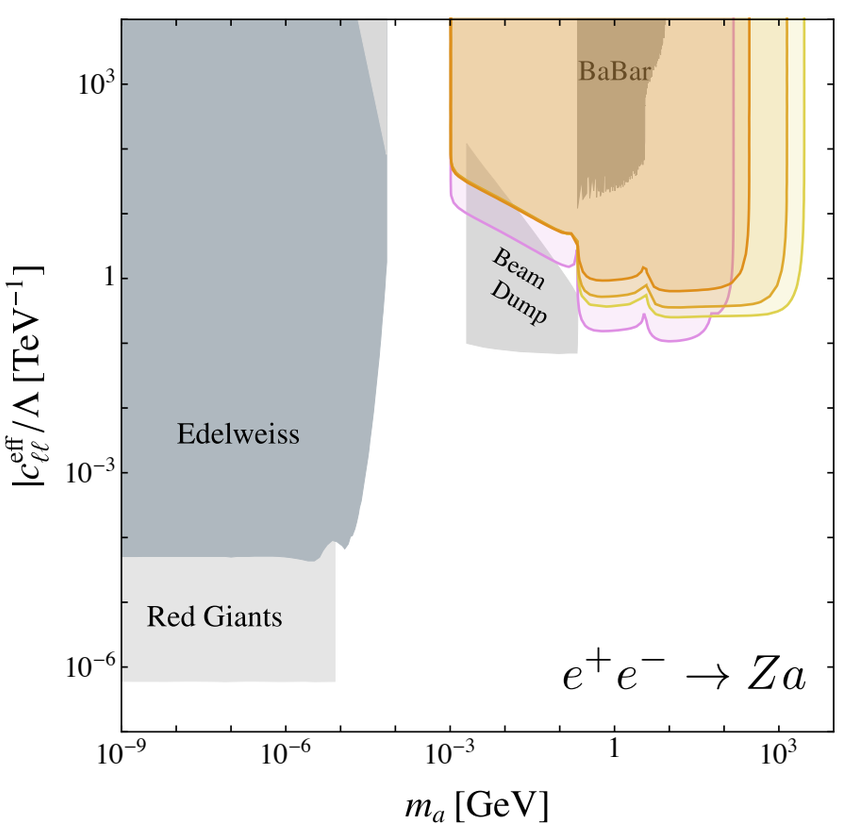
Associated production

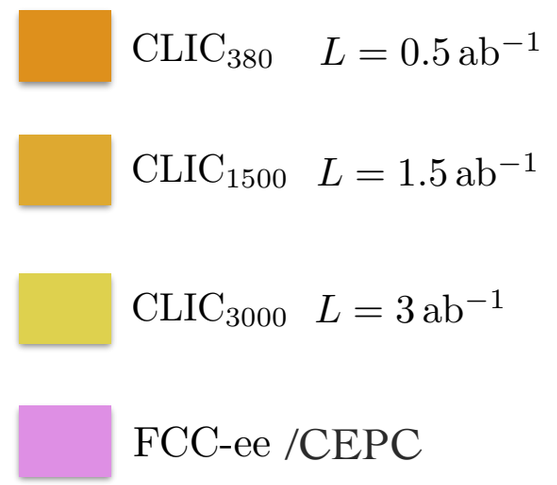
- ALP associated production with a photon or Z



- ALP decay into leptons

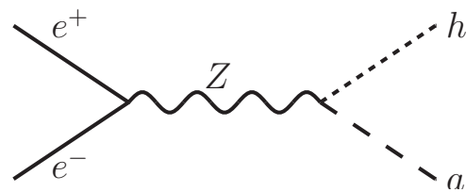




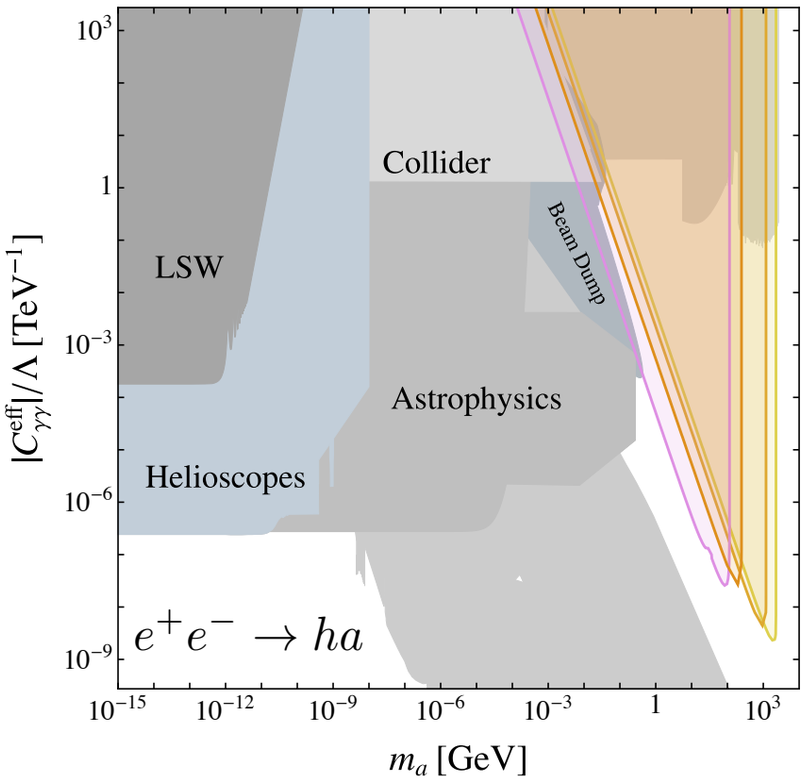


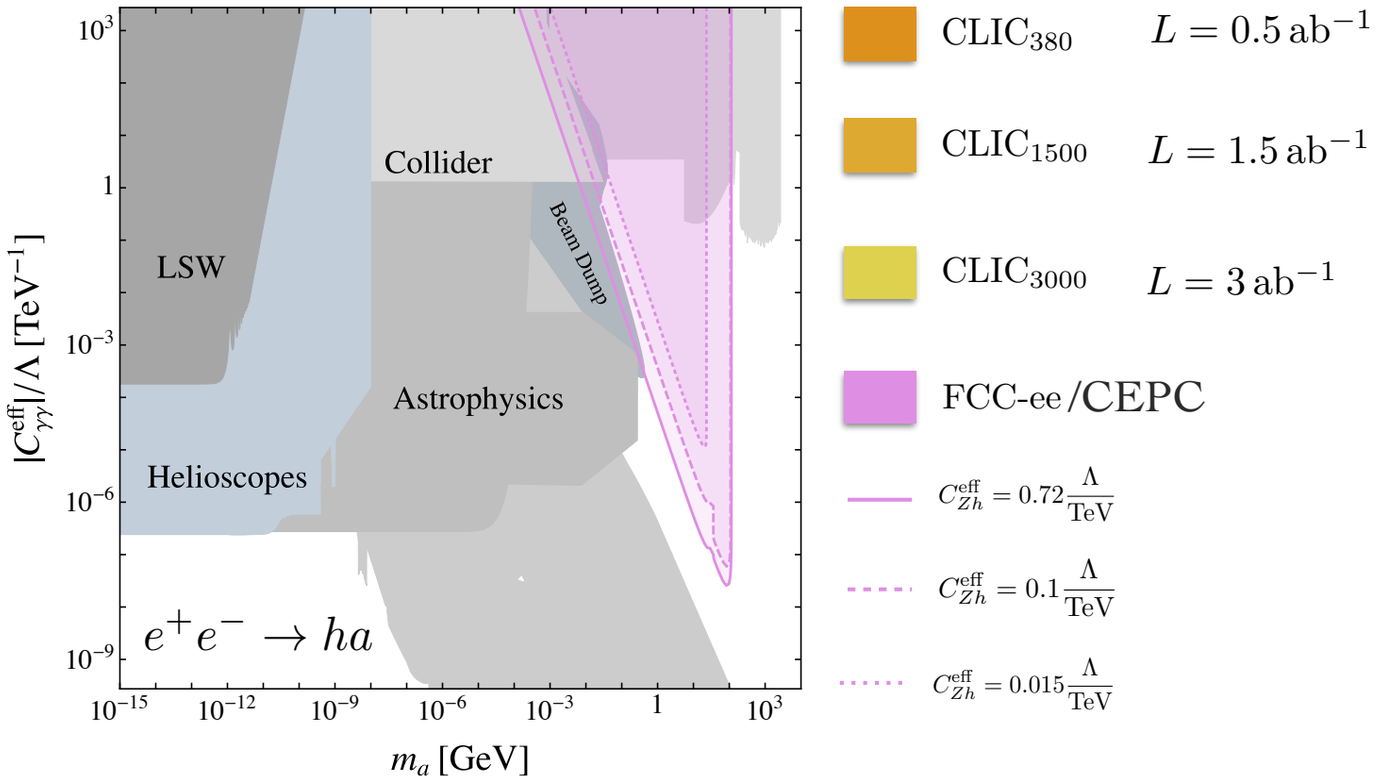
Associated production

- ALP associated production with a H



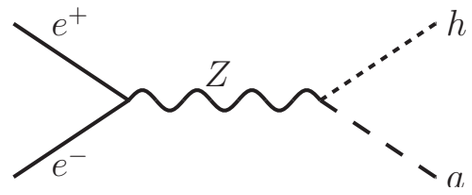
- ALP decay into photons



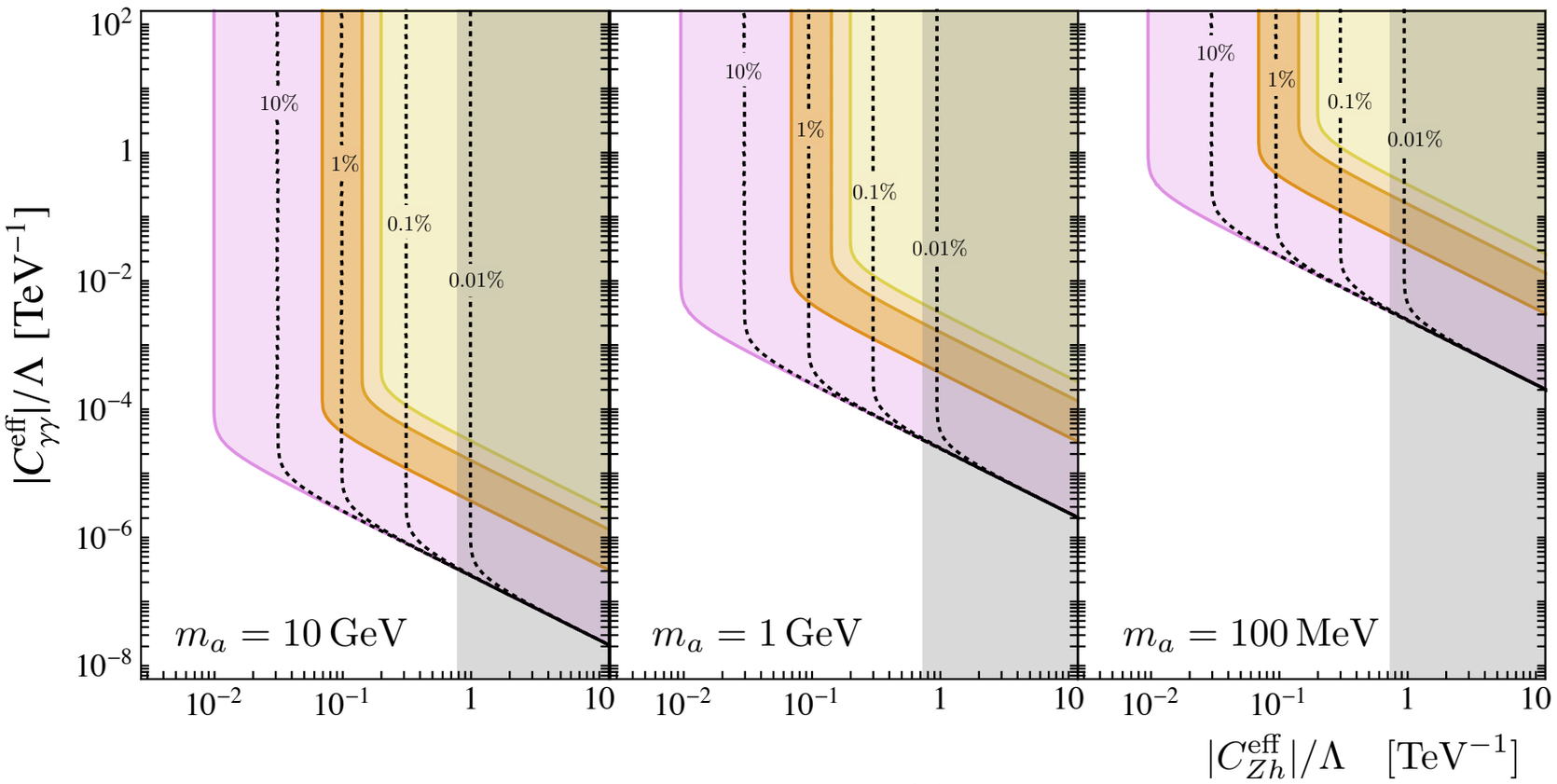


Associated production

- ALP associated production with a H



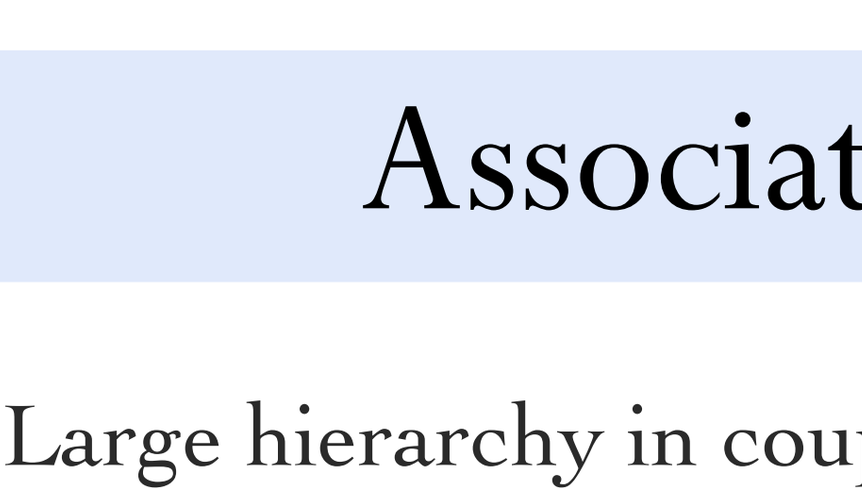
- ALP decay into photons

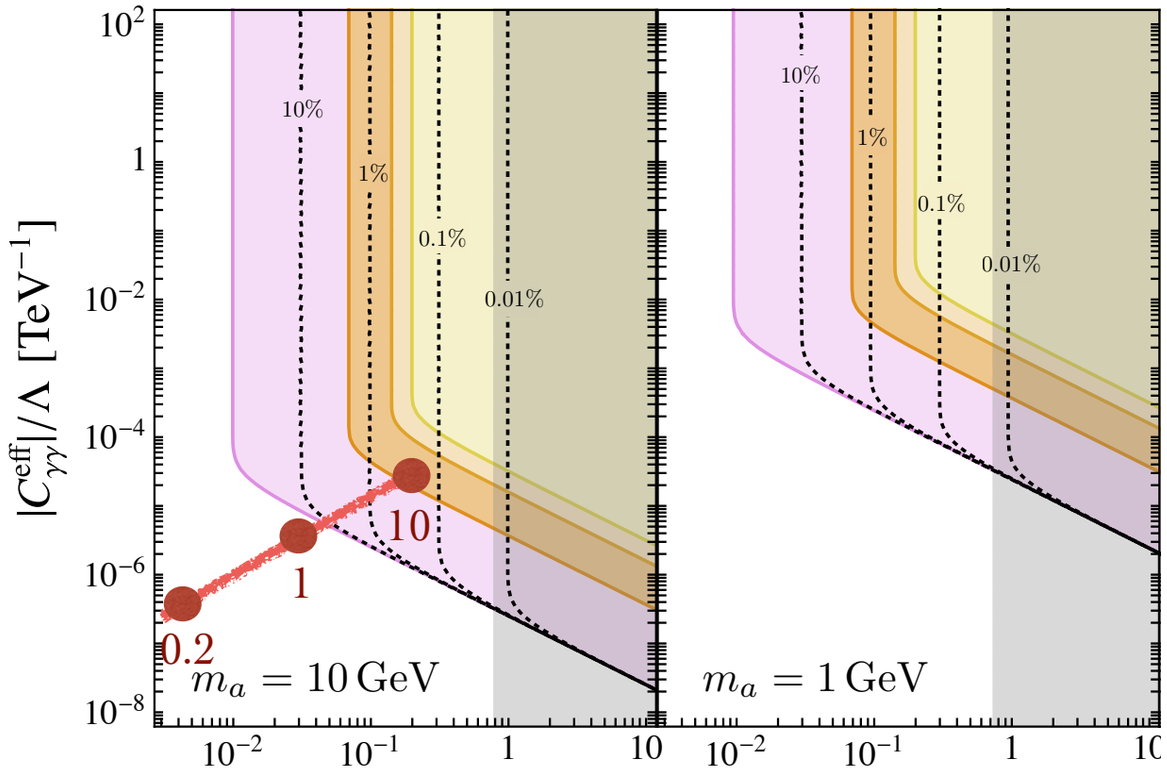


Cross-section ~ 1/s

Associated production

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





Associated production

- Large hierarchy in couplings can be plausible
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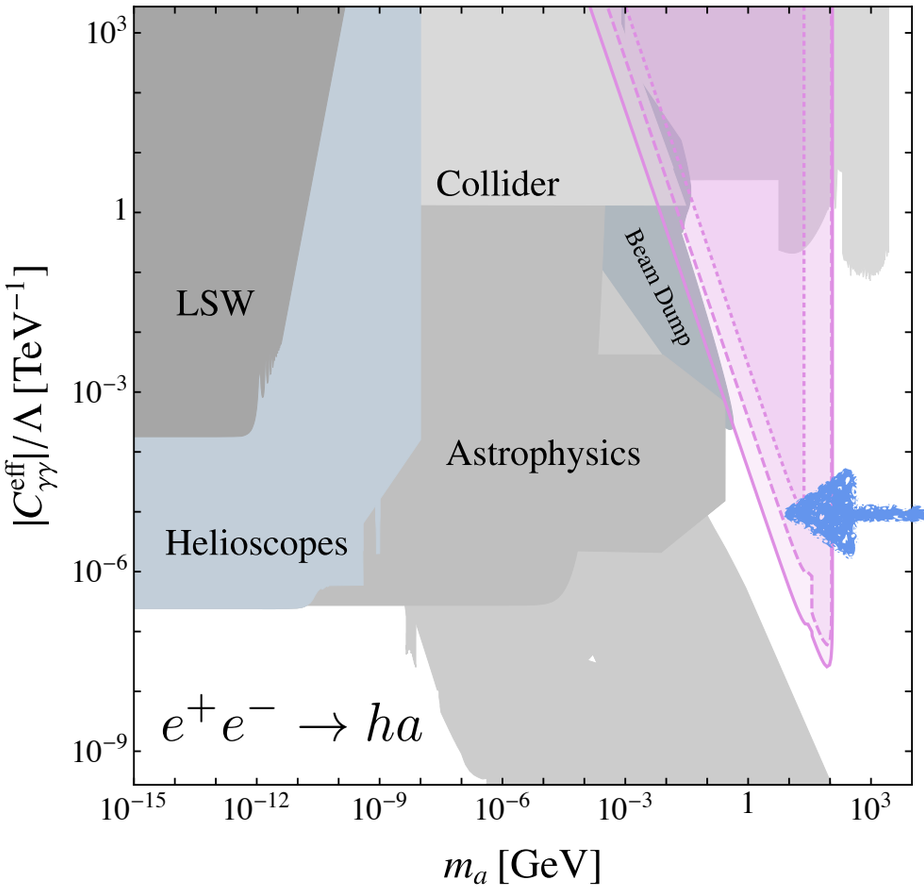
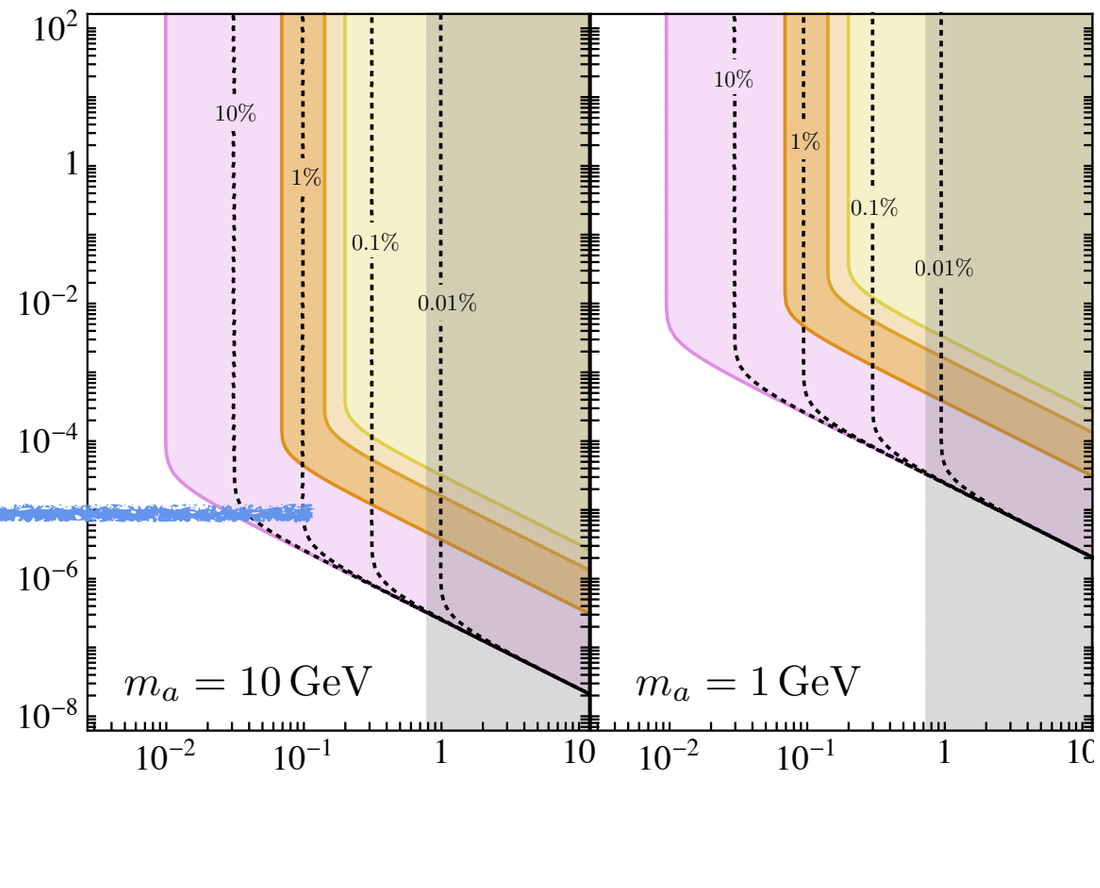
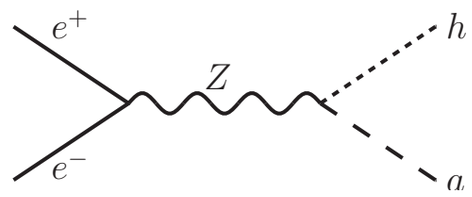


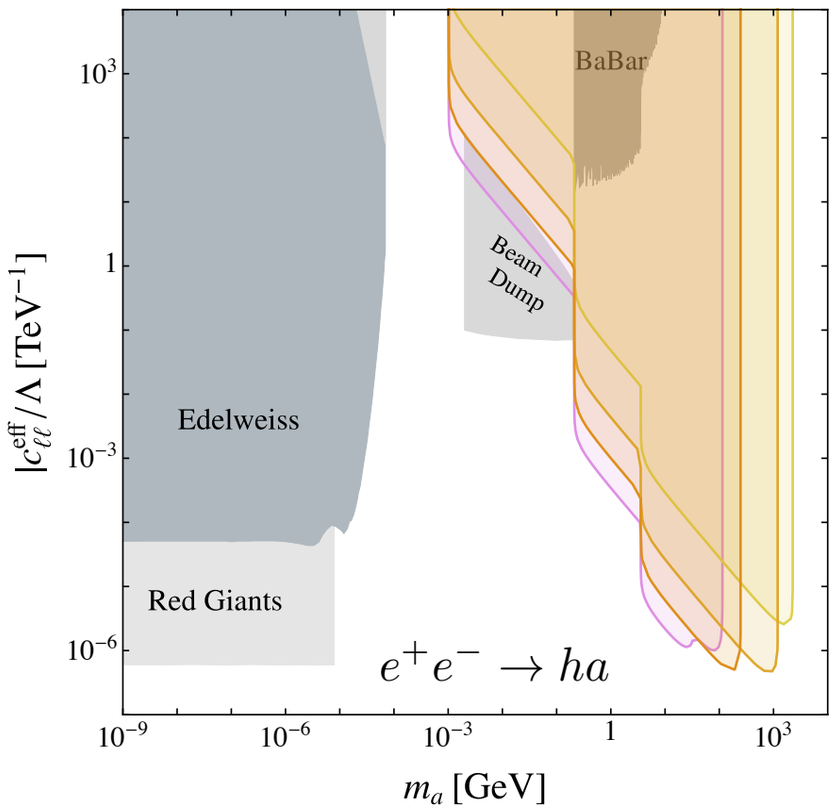


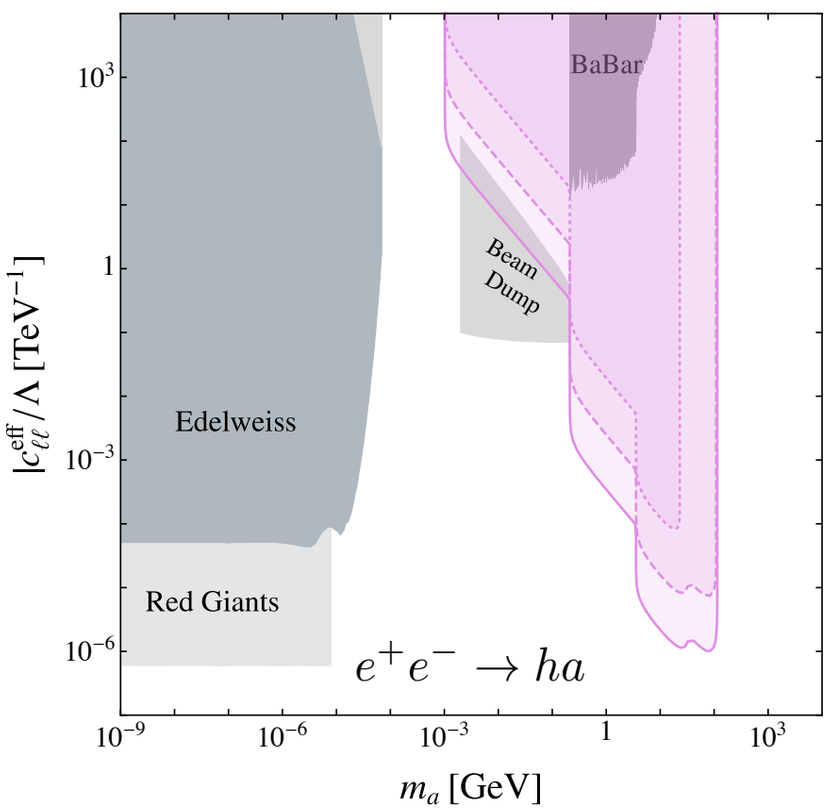
Associated production

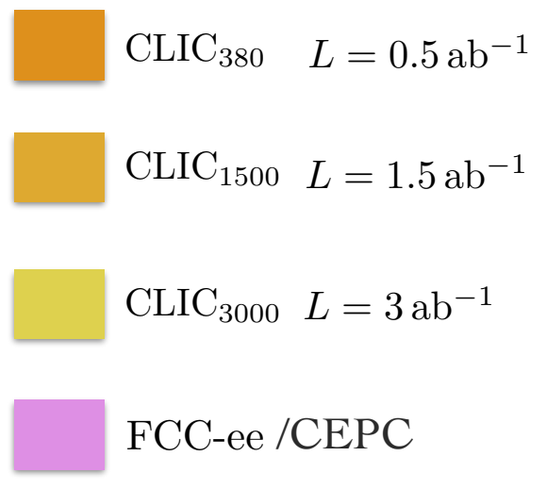
- ALP associated production with a H



- ALP decay into leptons







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- Background on ALPs
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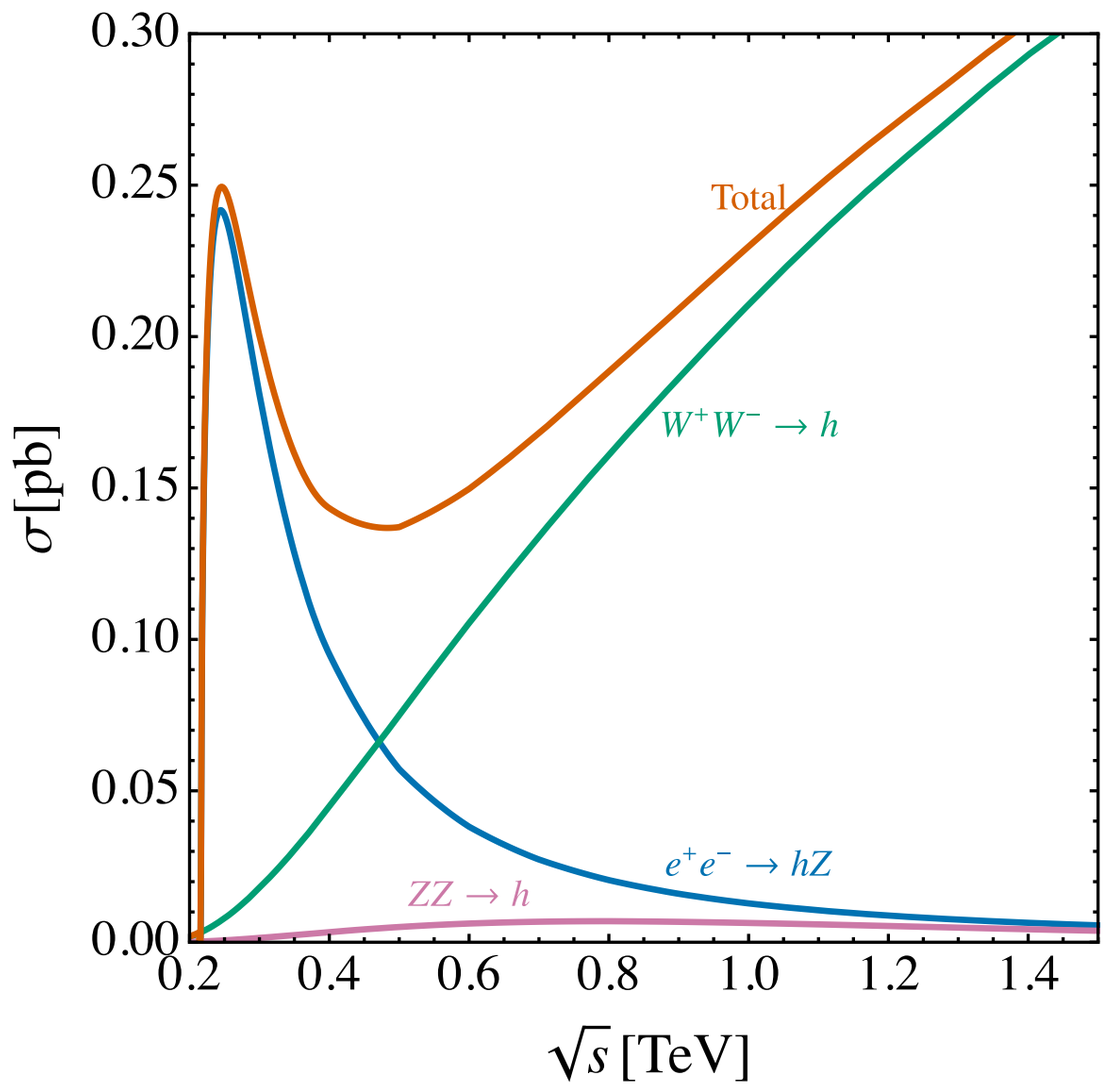
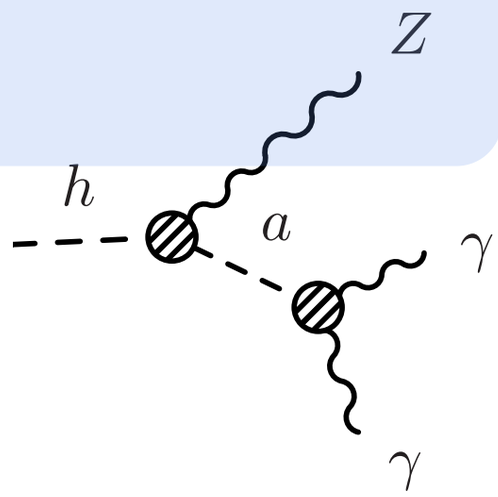
Exotic Higgs decays

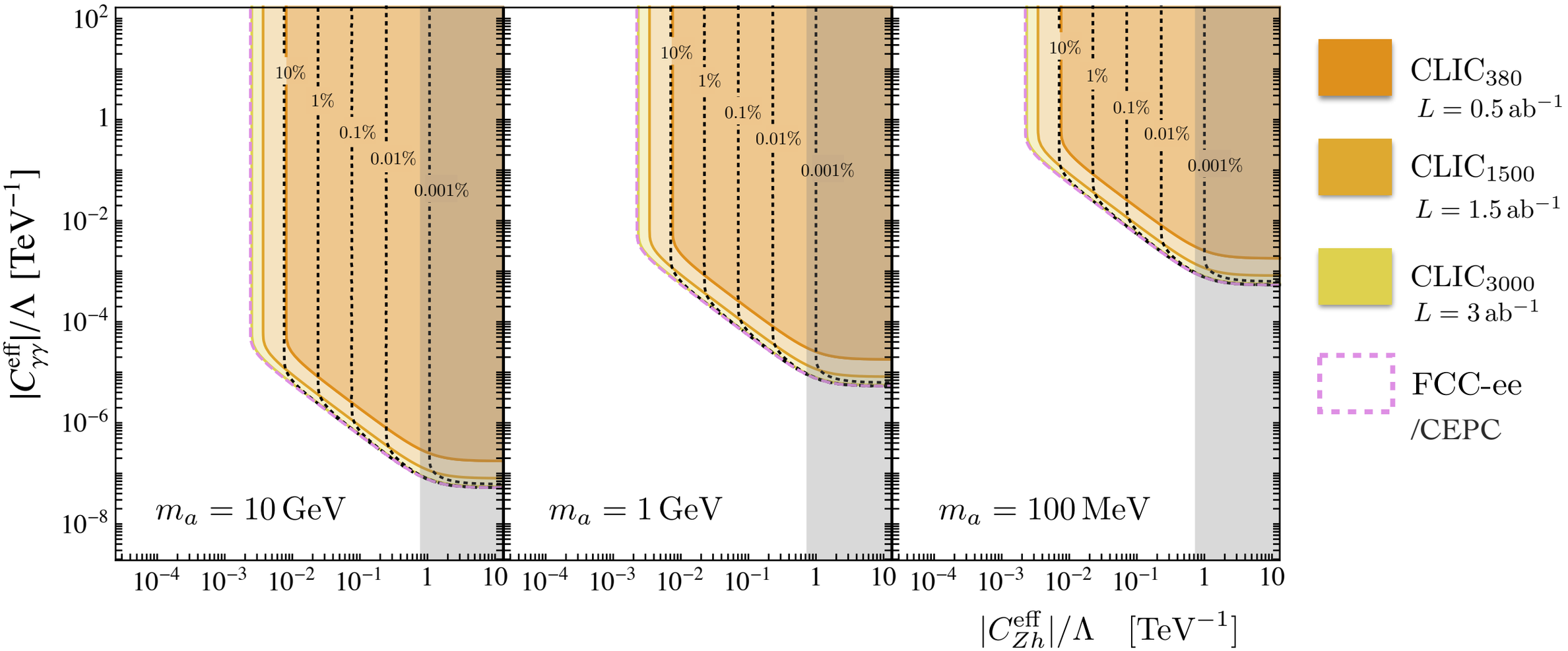
- Exotic Higgs decay: number of Higgses



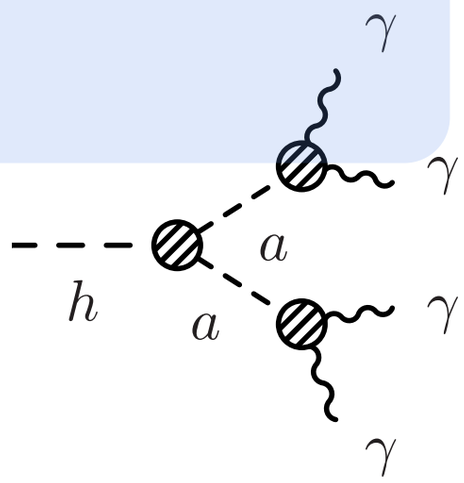
Exotic Higgs decays



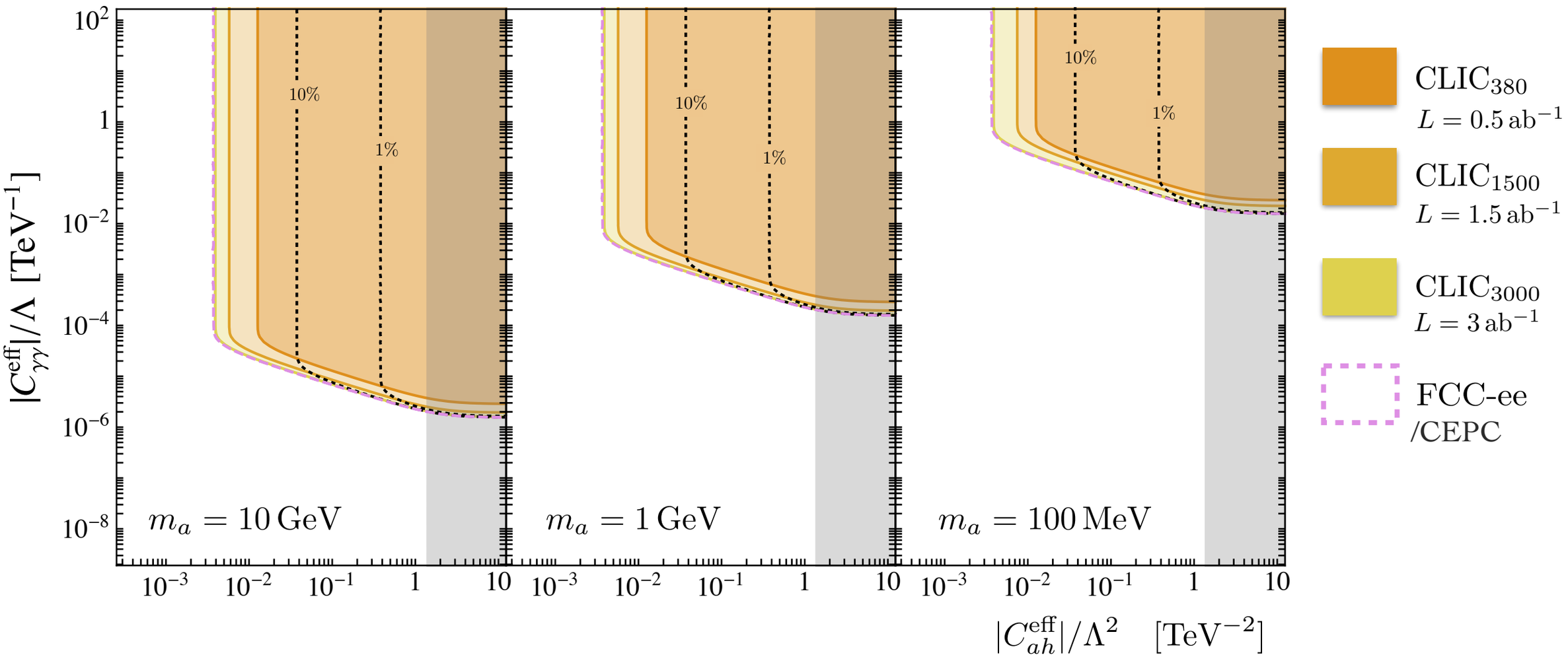
- Exotic Higgs decay: $h \to Za$



Exotic Higgs decays



- Exotic Higgs decay: $h \to aa$



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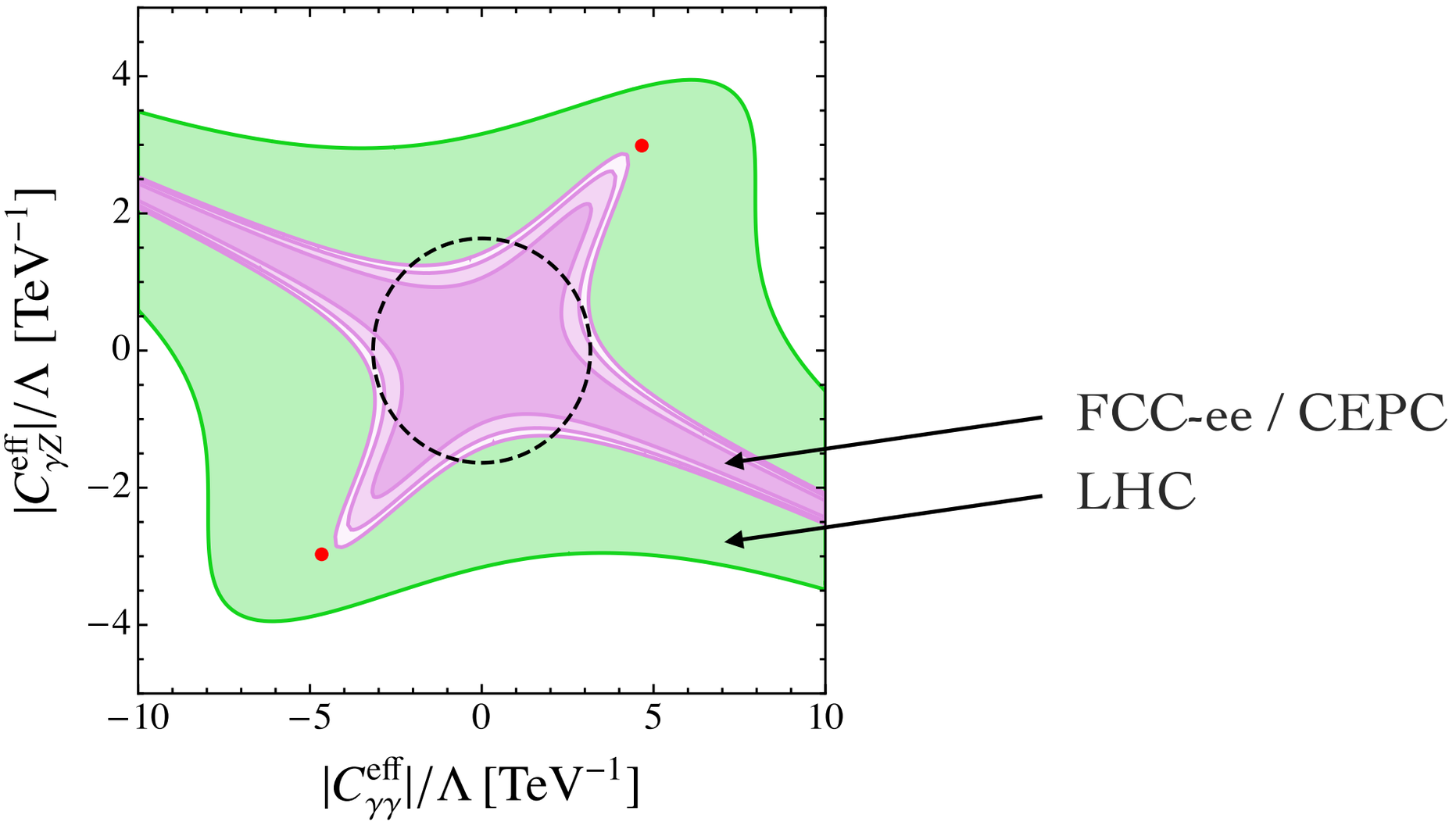
Electroweak precision tests

- Unprecedented precision of electroweak observables



Conclusions

- Lepton colliders can probe well motivated parameter space
- Exotic Z decays are particularly powerful
- Can probe individual couplings