ALPs at Future Colliders

Andrea Thamm
CERN

with Martin Bauer, Mathias Heiles and Matthias Neubert

based on arXiv:1610.00009, 1704.08207, 1708.00443, 1808.10323

01 October 2018

The future of particle physics,
A quest for guiding principles
Karlsruhe

Outline

- Background on ALPs
- ALPs at future colliders
  - Future lepton colliders
  - Future hadron colliders
  - Experiments searching for macroscopic lifetimes

Motivation

- Pseudo-scalars in many extensions of the SM
  - QCD axion - solution to strong CP-problem
  - Nambu-Goldstone bosons of a broken symmetry
  - mediators to the dark sector
  - explanations of various anomalies
- Good reason to study them!
- Large regions of parameter space already probed by many different experiments
- We add a region that can be probed through exotic Higgs decays in run 2 of LHC and at future colliders

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
- 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]

$h \to Za$

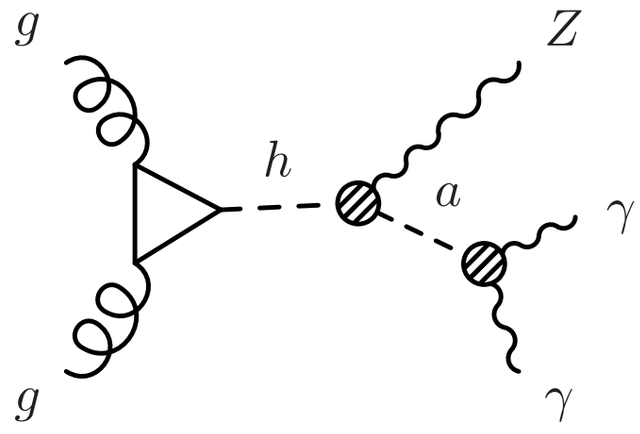
[Bauer, Neubert, Thamm: 1607.01016]

Production at colliders

- Drell-Yan production
- Vector boson fusion

[Buttazzo, Redigolo, Sala, Tesi: 1807.04743]

- ALP associated production
- ALP production through exotic decay of H or Z



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

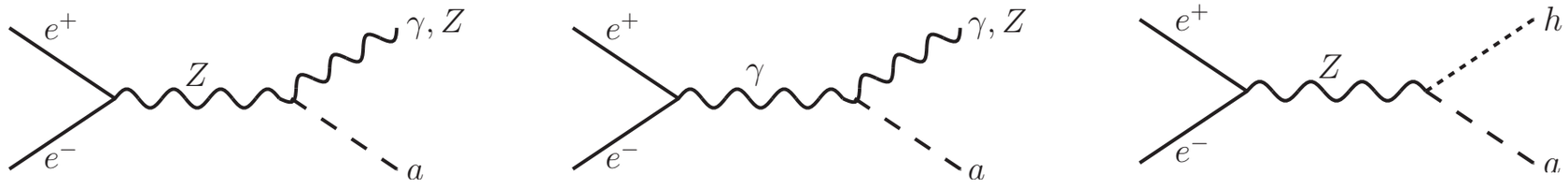
$L_{\mathrm{det}} = 2\,\mathrm{cm}$

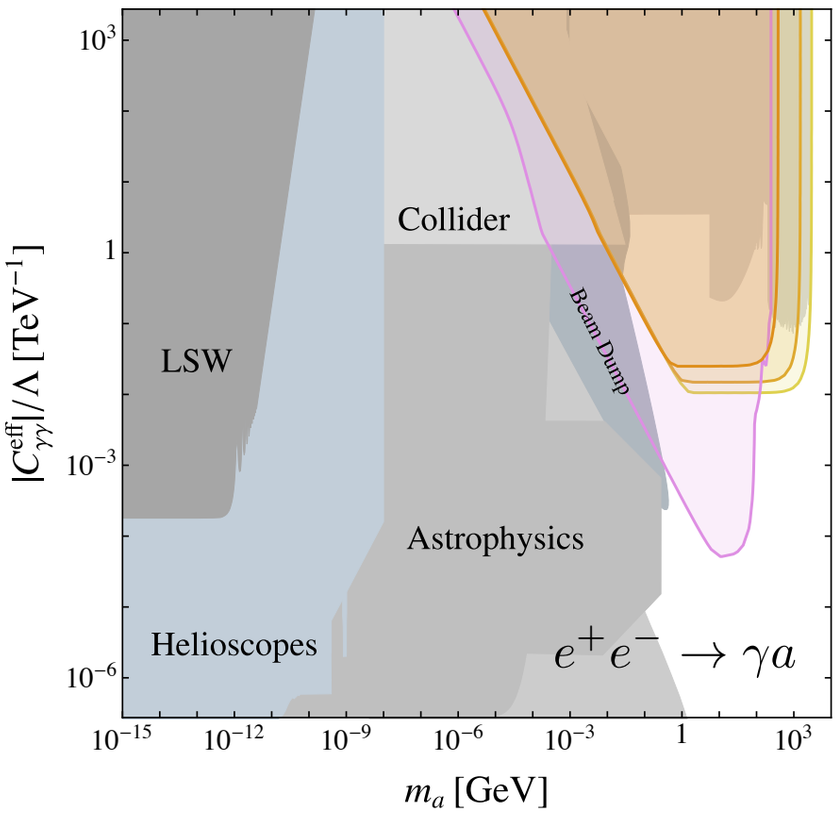
- Effective branching ratios

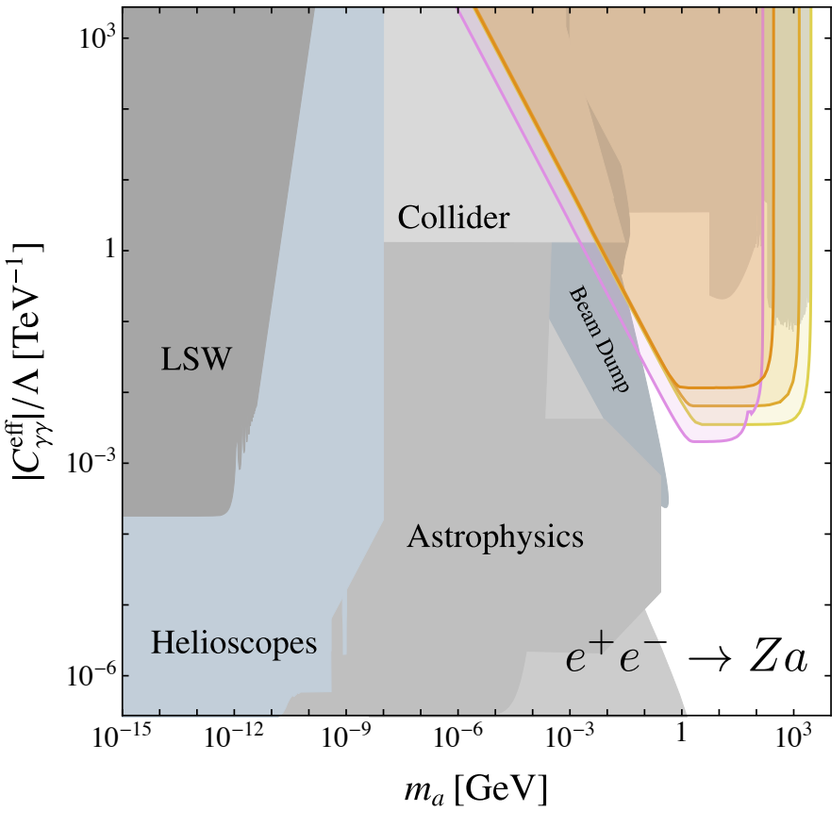
$$\mathrm{Br}(h\to Za\to \ell^+\ell^- X\bar{X})\big|_{\mathrm{eff}} = \mathrm{Br}(h\to Za)\times\mathrm{Br}(a\to X\bar{X})\,f_{\mathrm{dec}}\,\mathrm{Br}(Z\to\ell^+\ell^-)$$

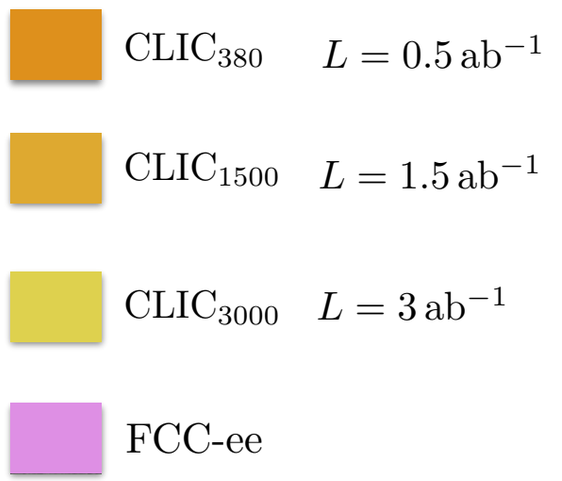
Future lepton colliders

- ALP associated production



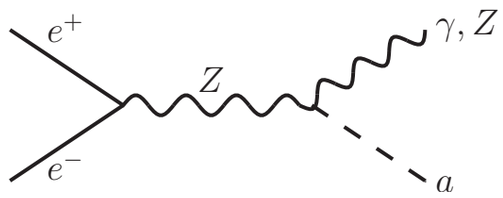


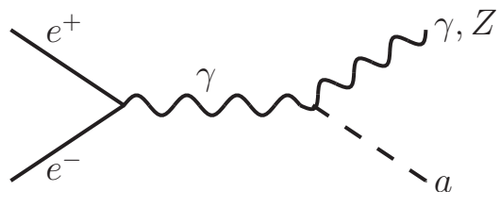


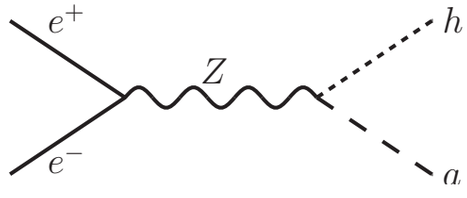


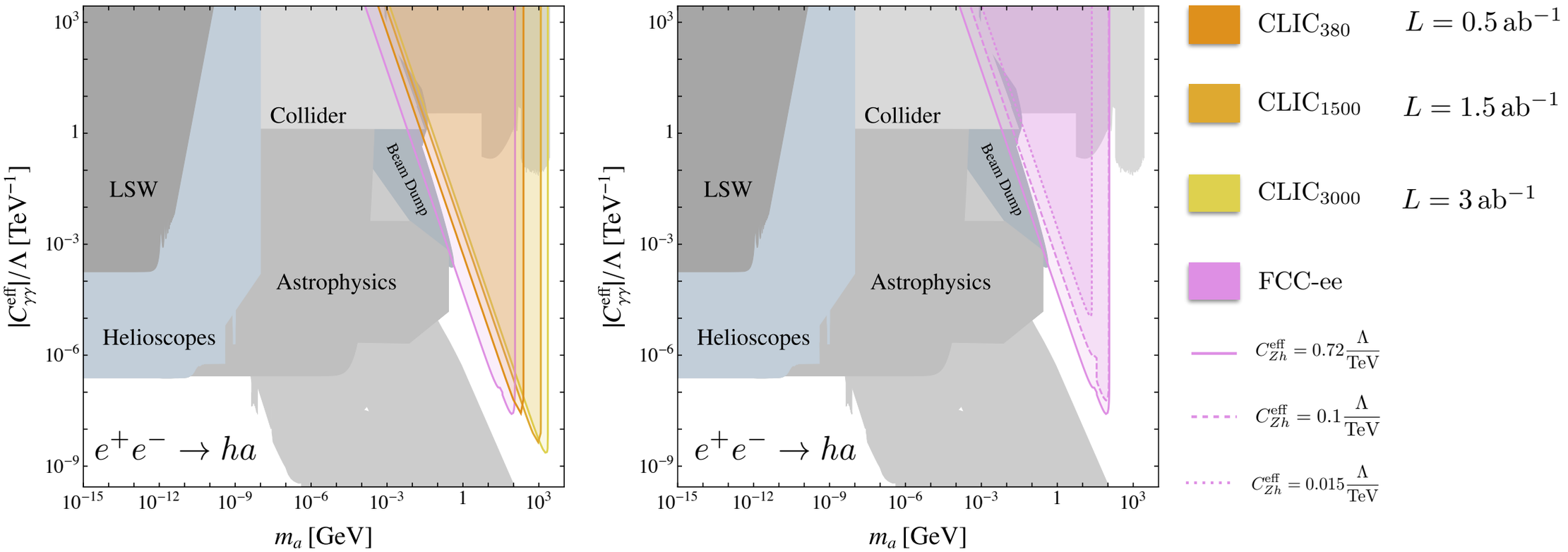
Future lepton colliders

- ALP associated production



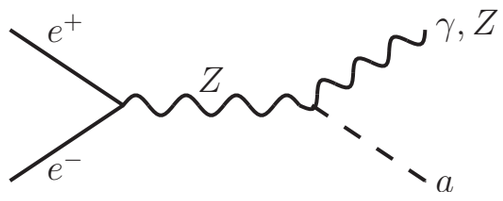


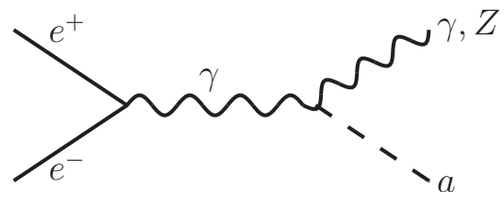


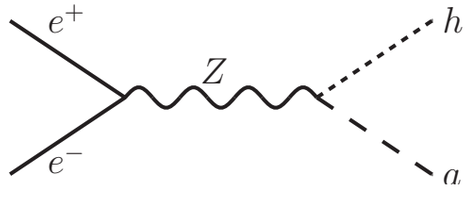


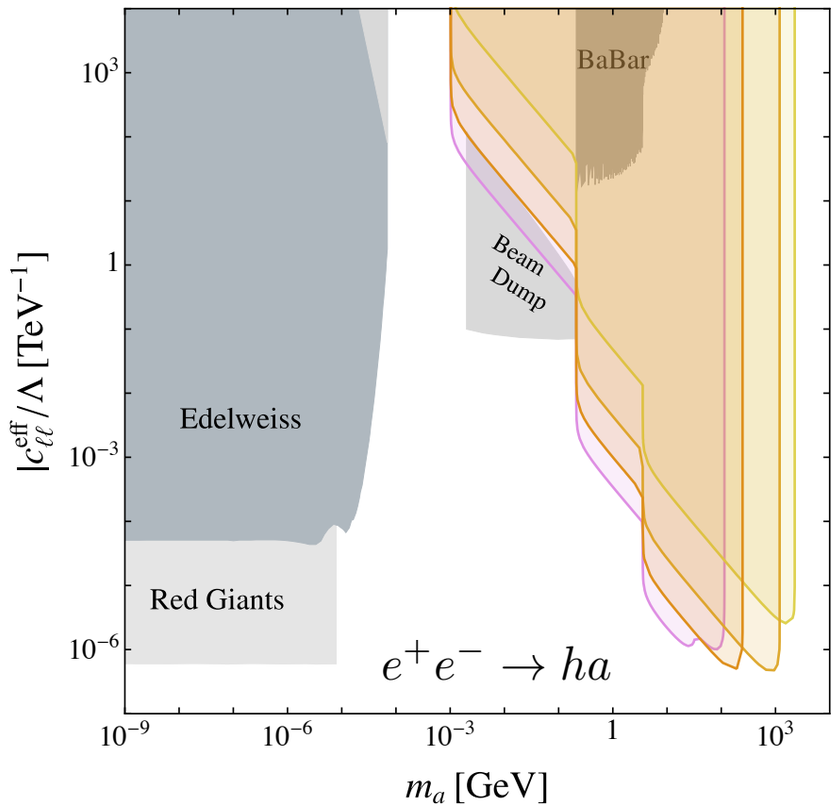
Future lepton colliders

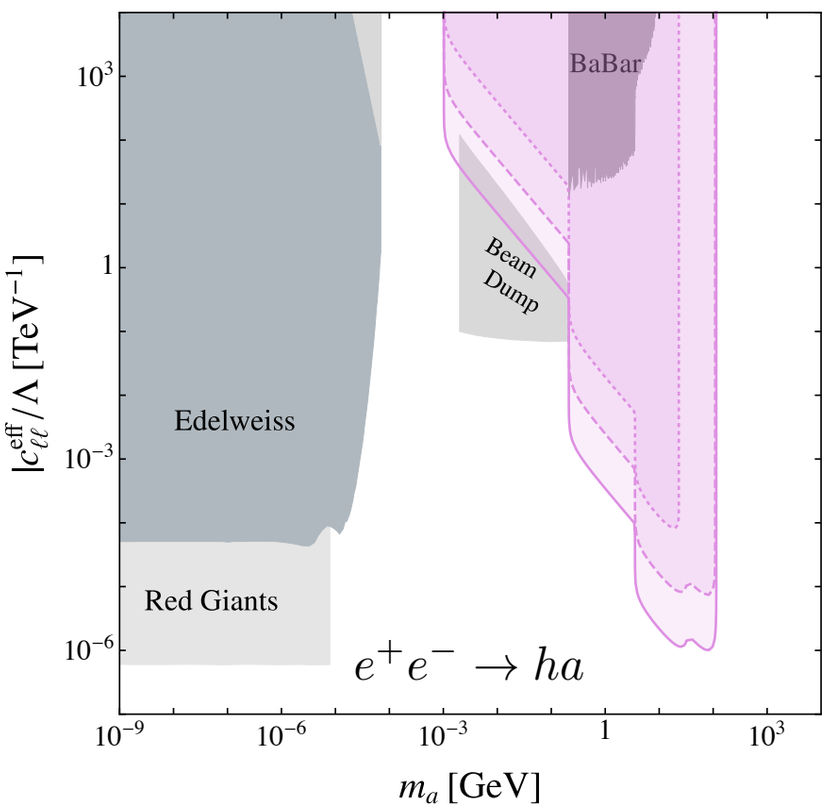
- ALP associated production

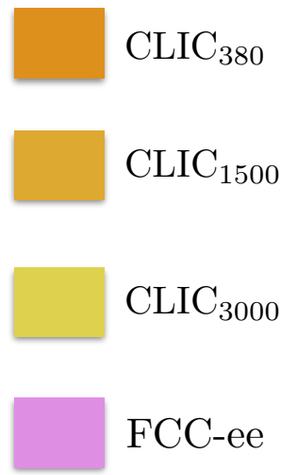












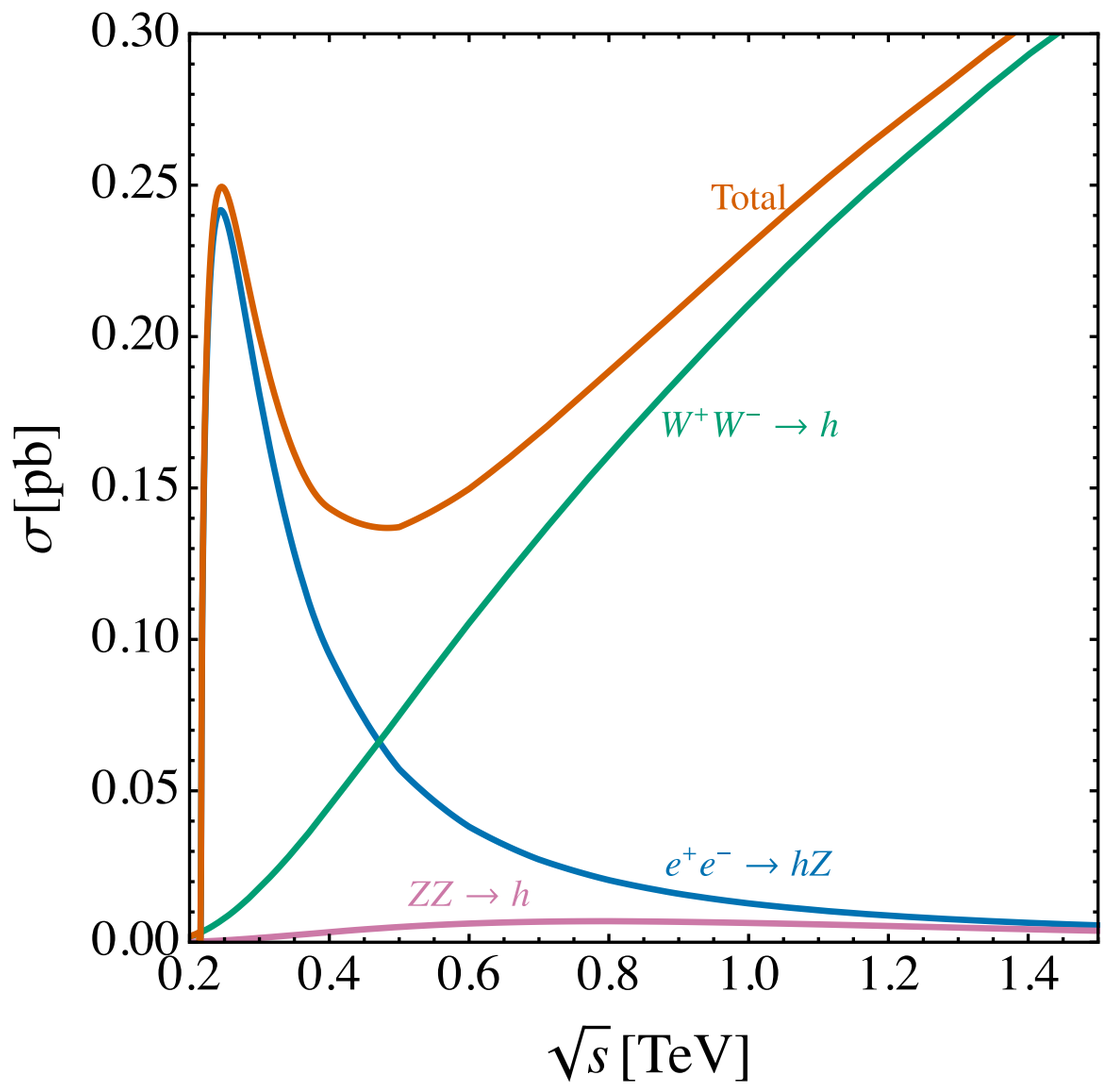
$L = 0.5\,\mathrm{ab}^{-1}$

$L = 1.5\,\mathrm{ab}^{-1}$

$L = 3\,\mathrm{ab}^{-1}$

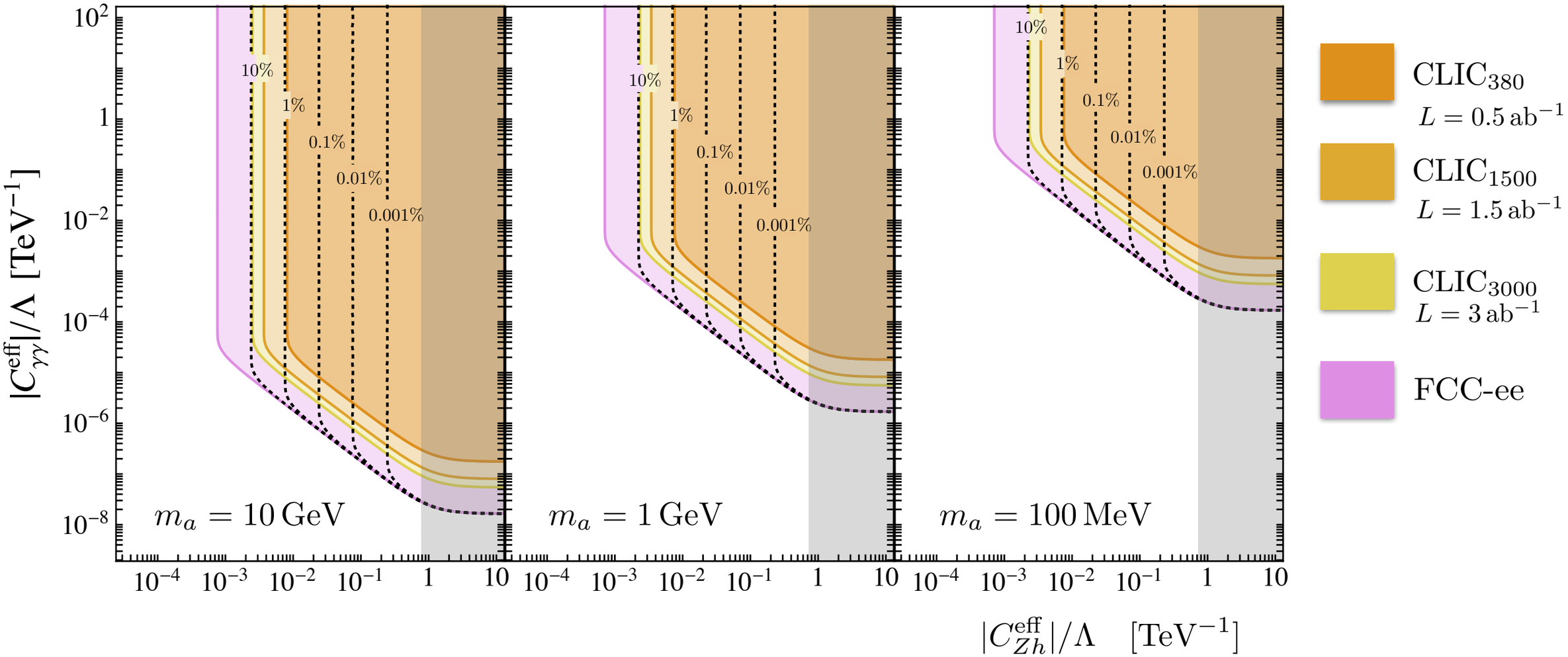
Future lepton colliders

- Exotic Higgs decay: number of Higgses



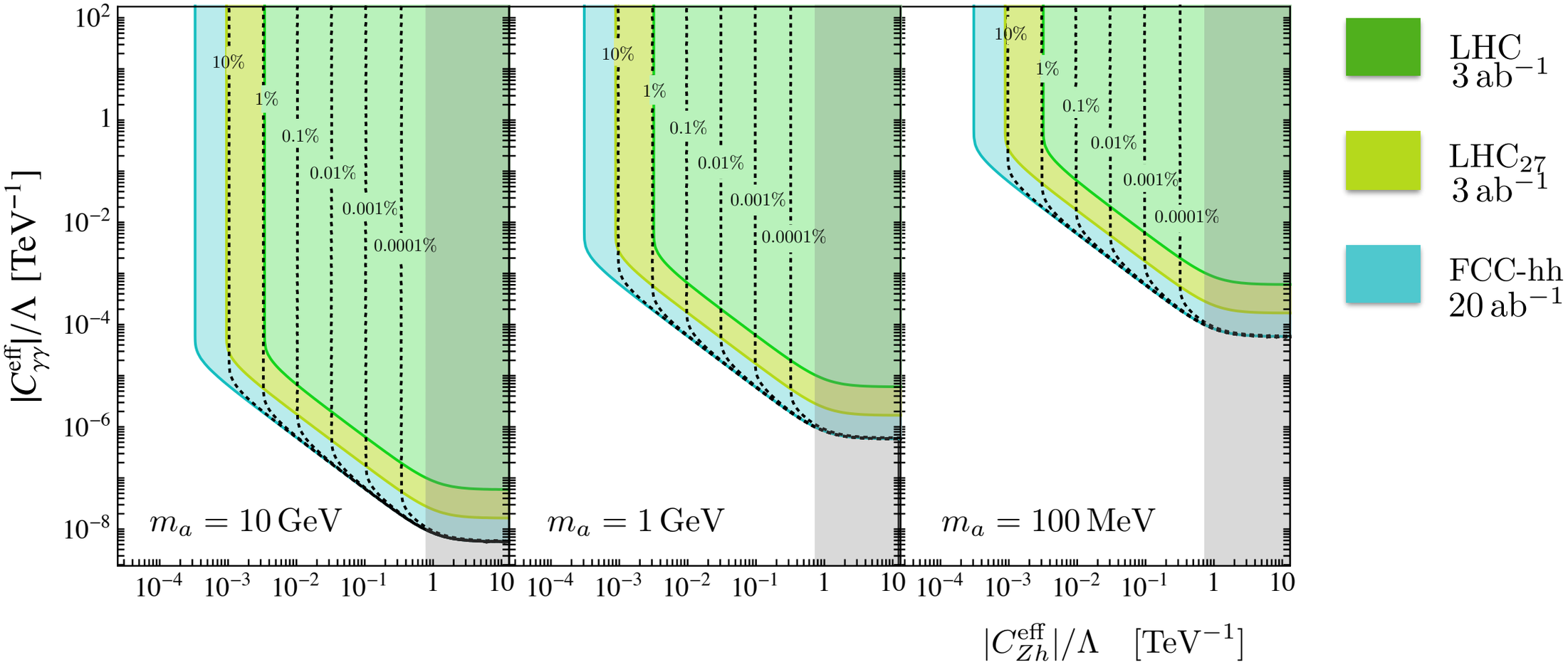
Future lepton colliders

- Exotic Higgs decay



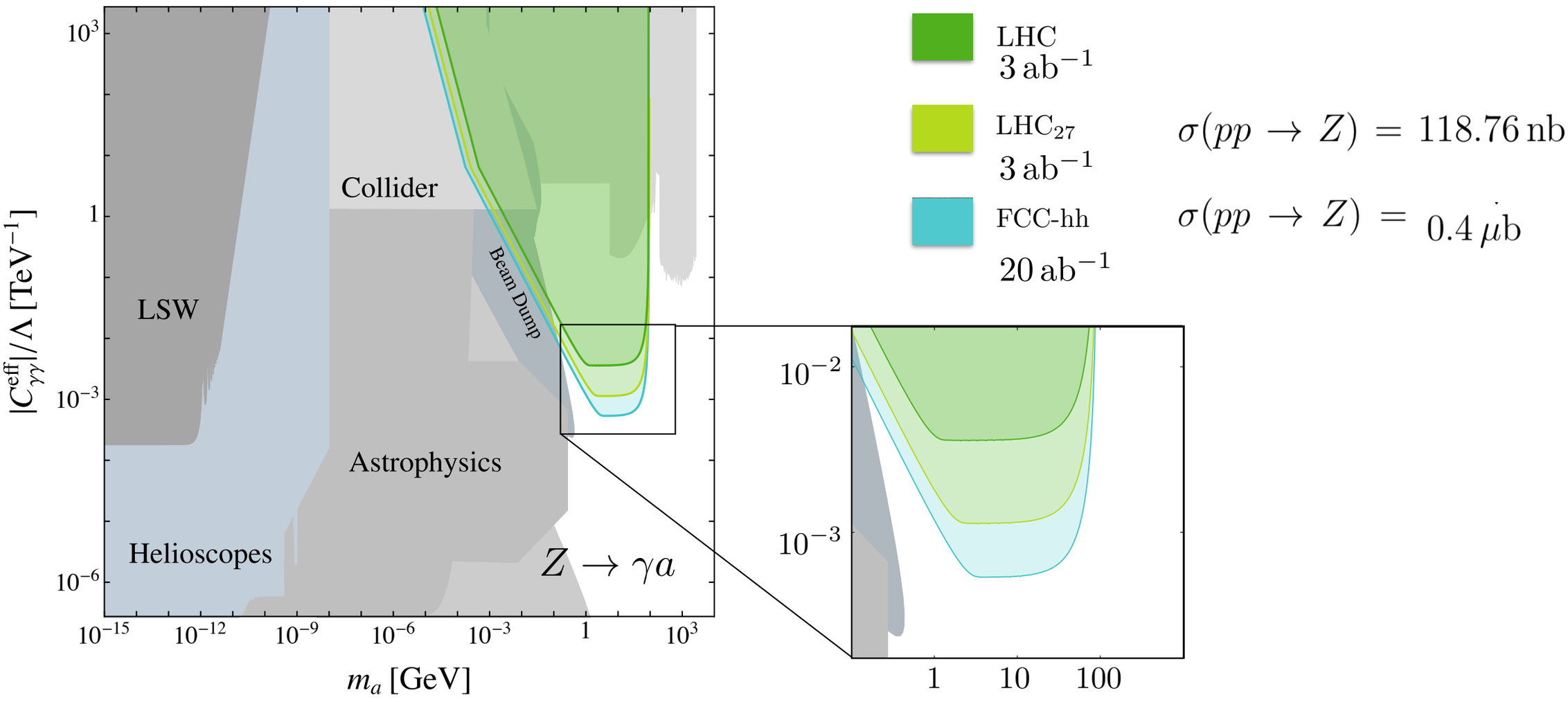
Future hadron colliders

- Exotic Z and Higgs bosons



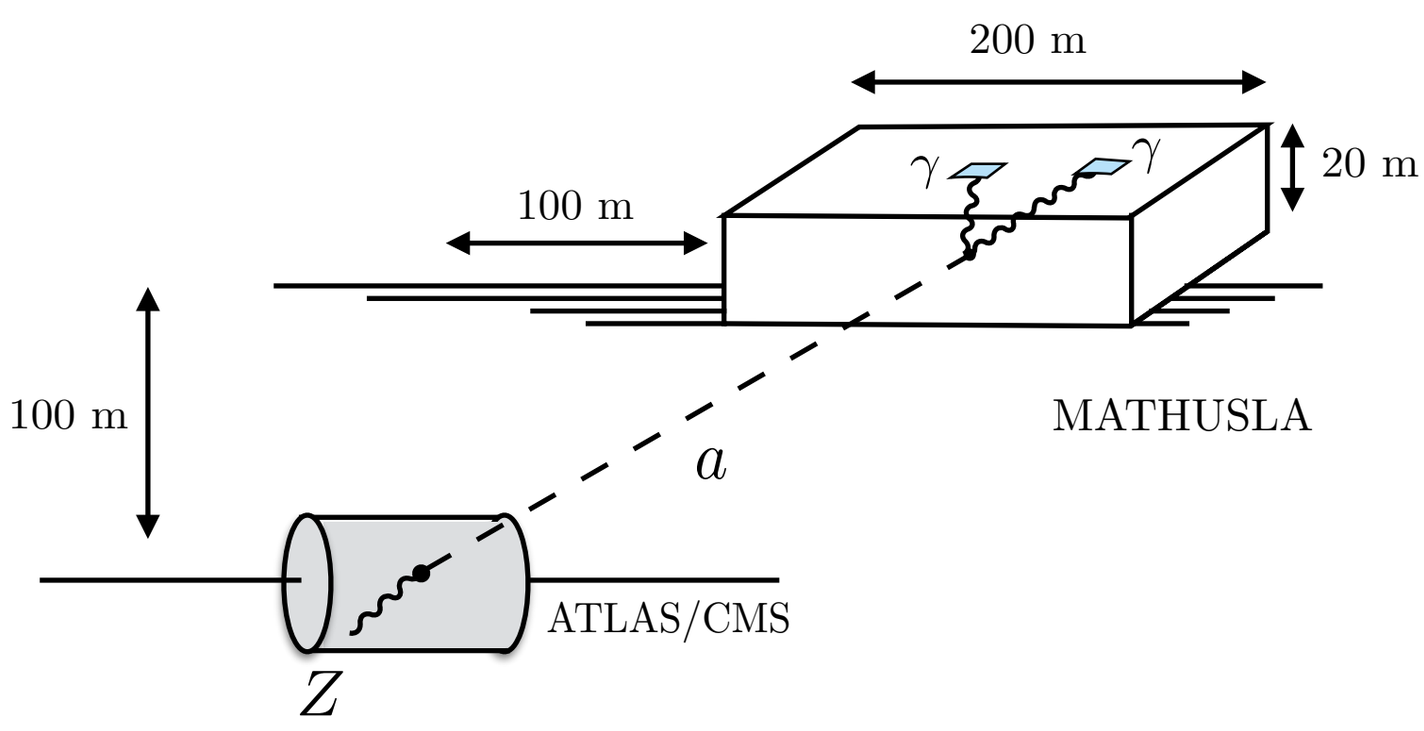
Future hadron colliders

- Current bounds on $Z \to \gamma a$
- Improvement by factor 1.5



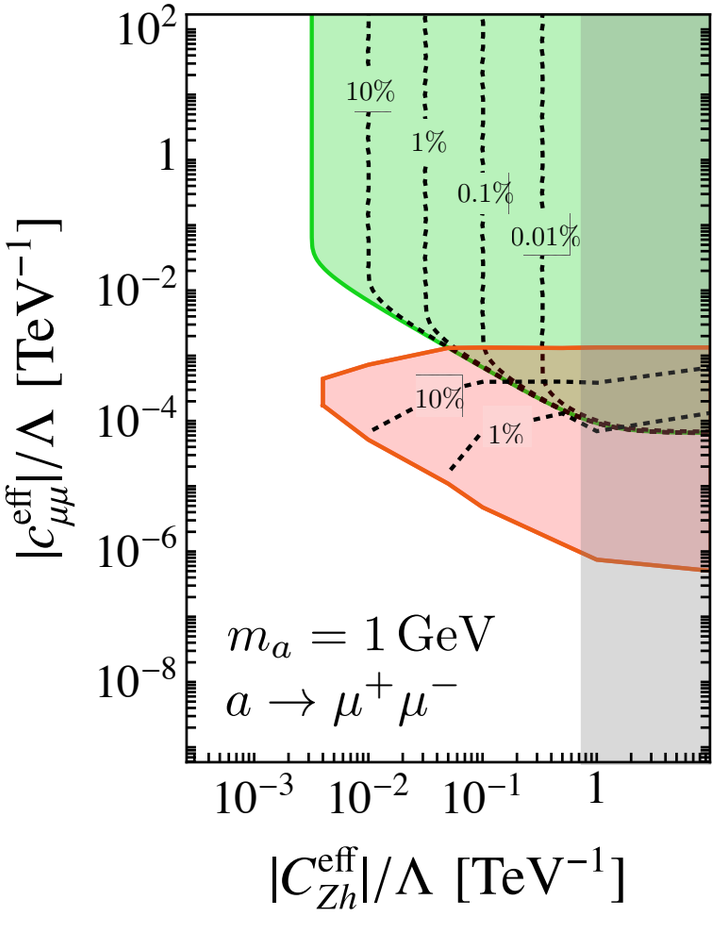
Mathusla

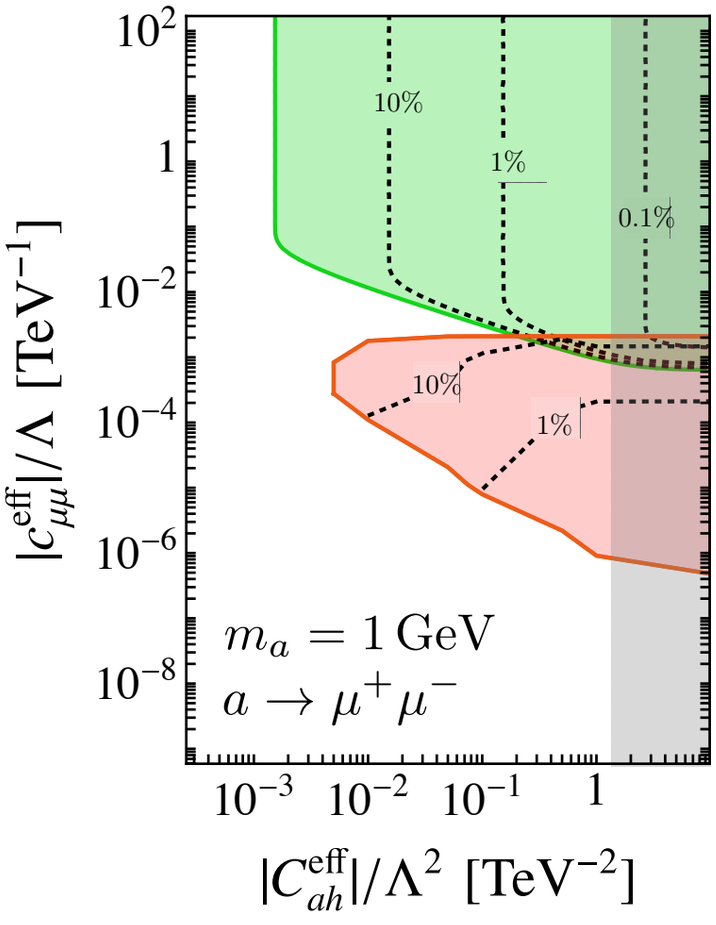
- Experimental setup

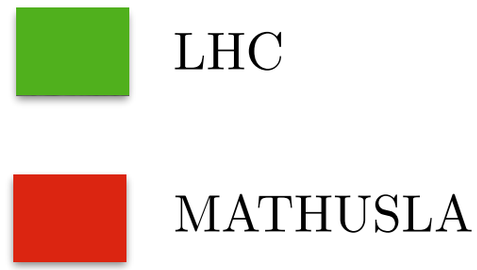


Mathusla

- Exotic Higgs decays

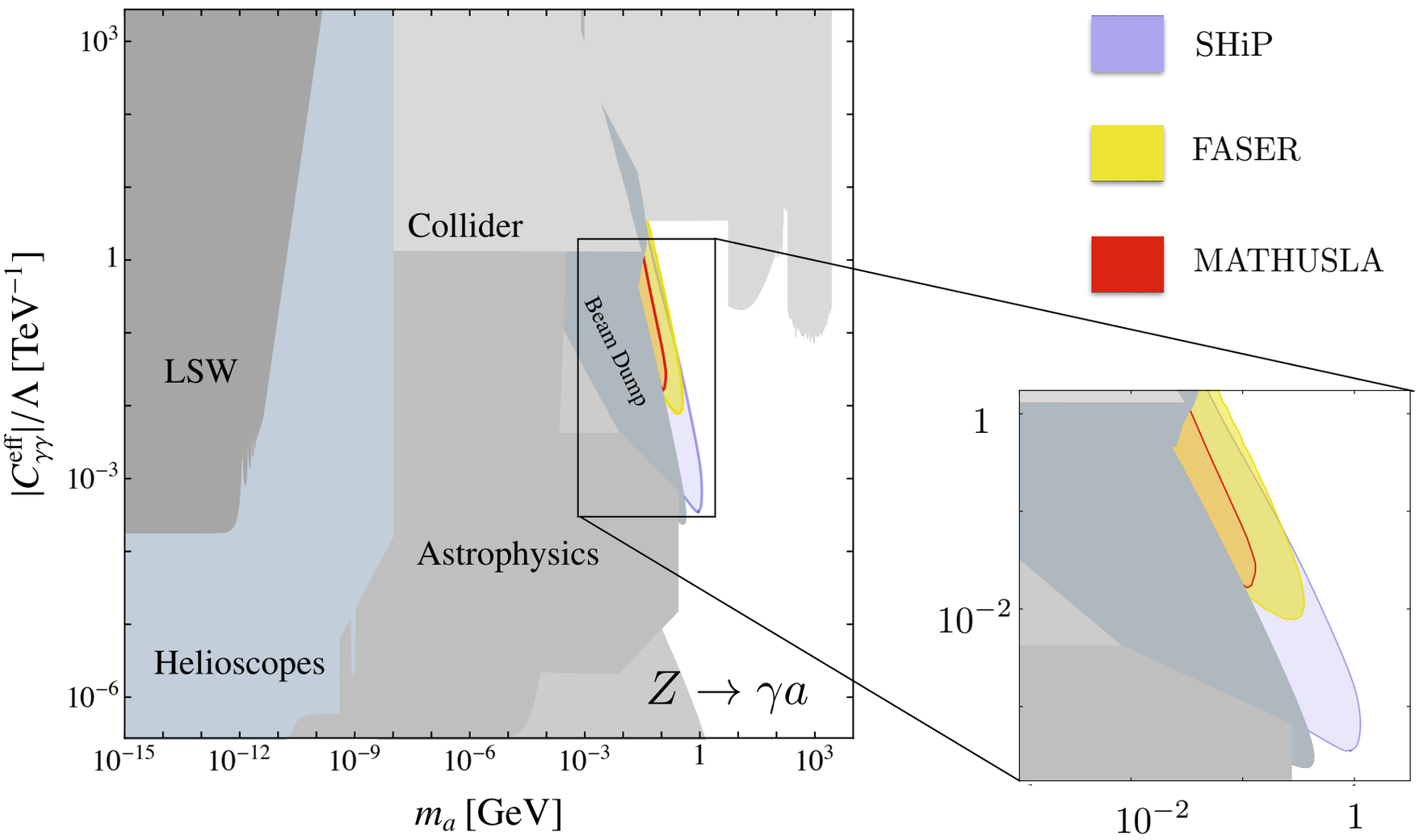






Mathusla

- Exotic Higgs decays



Conclusions

- Lepton colliders:
  associated ALP production very promising
- Hadron colliders:
  gluon fusion and exotic decays improve sensitivity
- Mathusla
  sensitivity to smaller couplings