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Axion-Like Particles at the LHC and Future Colliders

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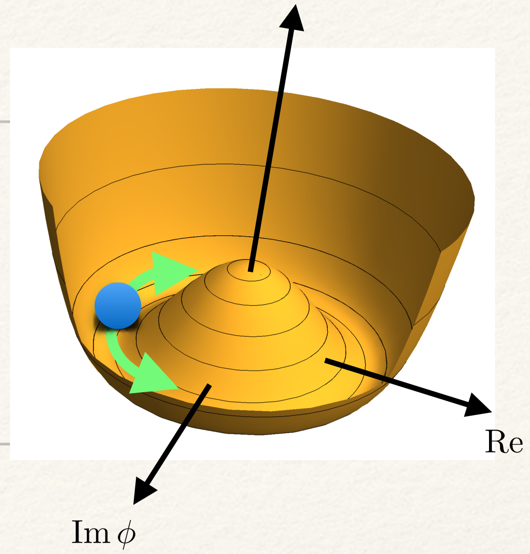
based on work with Martin Bauer and Andrea Thamm: 1704.08207 (PRL), 1708.00443 (JHEP) & in preparation

Motivation



- New pseudoscalar particles appear in many extensions of the SM and are well motivated theoretically: strong CP problem, mediators to a hidden sector, pNGB of a spontaneously broken global symmetry
- Assume the existence of a new pseudoscalar resonance a, which is a SM gauge singlet and whose mass is kept much lighter than the electroweak scale by a shift symmetry $a \to a + c$
- Such a particle could explain the muon's anomalous magnetic moment or the recently observed excess in Beryllium decays

[Chang, Chang, Chou, Keung 2000; Marciano, Masiero, Paradisi, Passera 2016]
[Feng et al. 2016; Ellwanger, Moretti 2016]

Effective Lagrangian

- The couplings of an axion-like particle (ALP) *a* to the SM start at dimension 5 and are described by the effective Lagrangian (with Λ a new-physics scale): [Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$
$$+ g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde G^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + g'^{\,2}\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde B^{\mu\nu}$$

- At dimension-6 order and higher additional interactions arise:

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

- Our goal is to probe scales **Λ~1-100 TeV** at the LHC

Effective Lagrangian

- After electroweak symmetry breaking the effective Lagrangian contains couplings to photons and Z-bosons given by:

$$\mathcal{L}_{\rm eff}^{D\le 5} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

with:

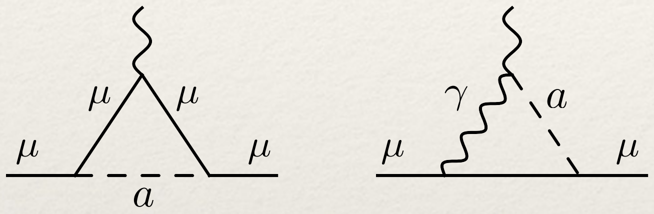
$$C_{\gamma\gamma} = C_{WW} + C_{BB}\,, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB} \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

- In the mass basis, the couplings to fermions contain both flavor diagonal and flavor off-diagonal contributions, but the latter must be strongly suppressed; the diagonal couplings can be written as:

$$\mathcal{L}_{\rm eff}^{D\le 5} \ni \sum_f \frac{c_{ff}}{2}\, \frac{\partial^\mu a}{\Lambda}\, \bar{f}\, \gamma_\mu \gamma_5\, f$$

Resolving the (g-2)$_\mu$ anomaly

- The anomalous magnetic moment of the muon can be explained by virtual ALP exchange:

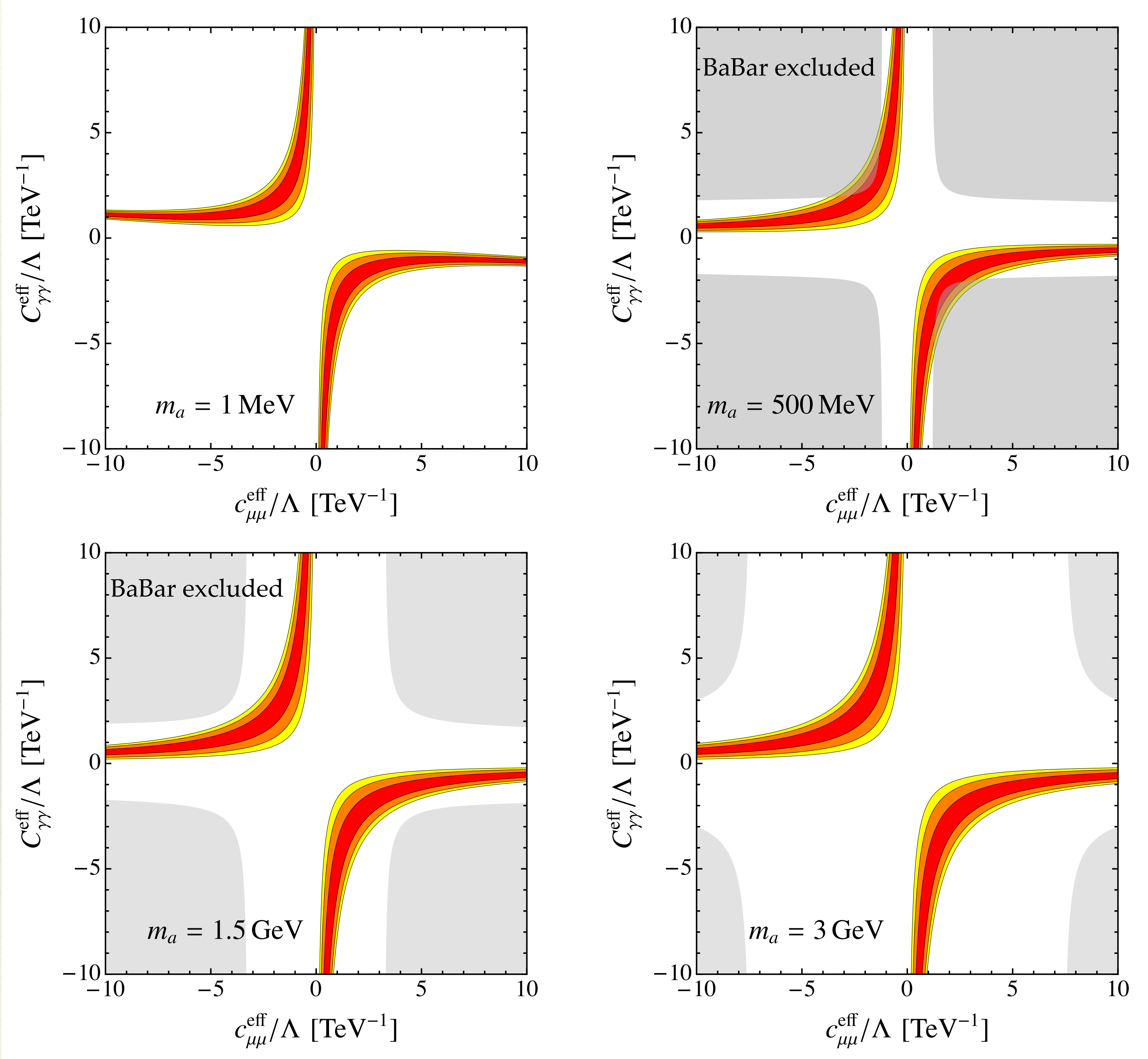


[see also: Marciano, Masiero, Paradisi, Passera 2016]

- Anomaly $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49) \cdot 10^{-11}$ can be explained for O(1) Wilson coefficients $C_{\gamma\gamma}$ and $c_{\mu\mu}$

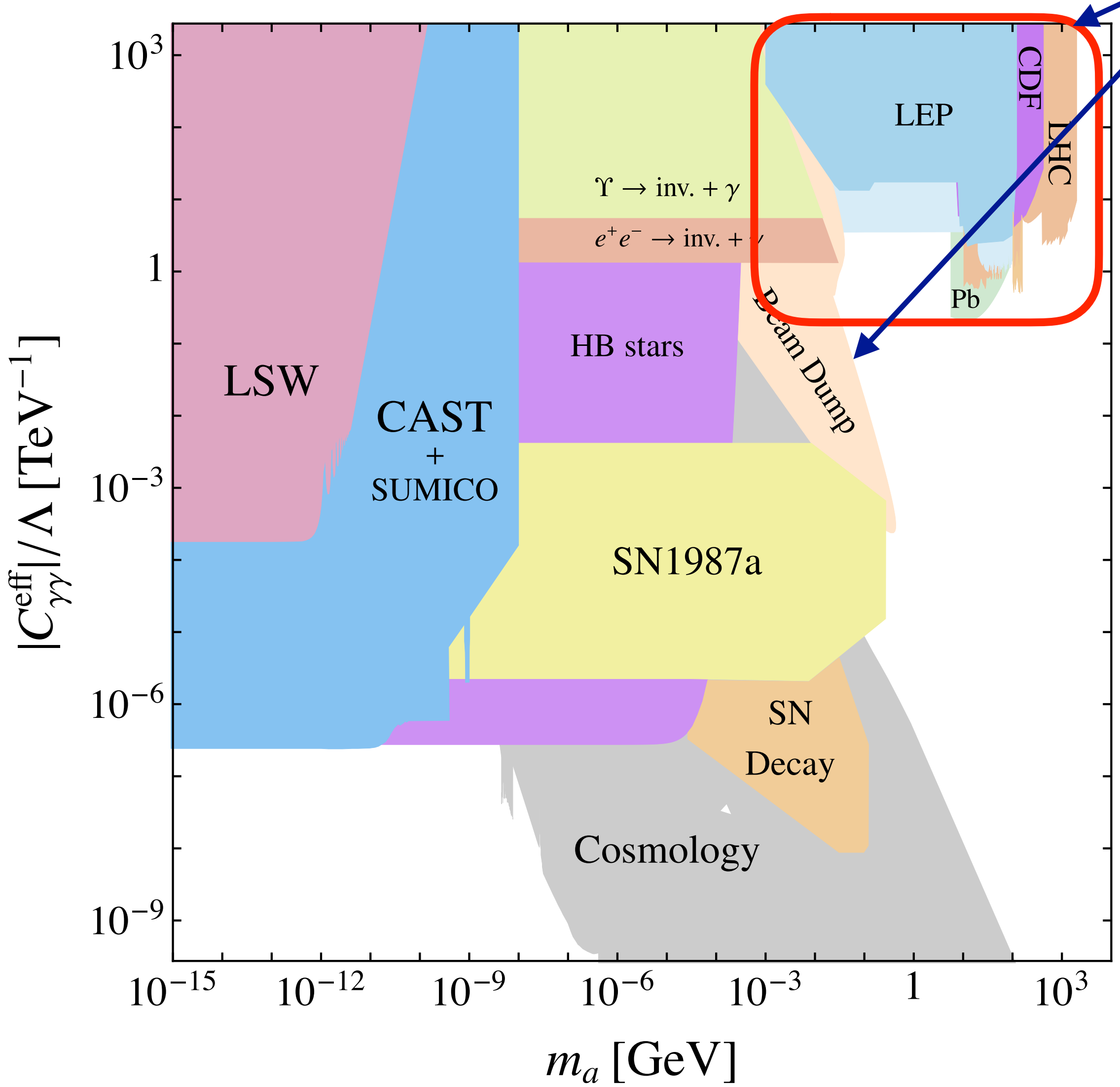
- BaBar search for [BaBar: 1606.03501] $e^+e^- \to \mu^+\mu^- + Z' \to \mu^+\mu^- + \mu^+\mu^-$ significantly constrains the allowed parameter space

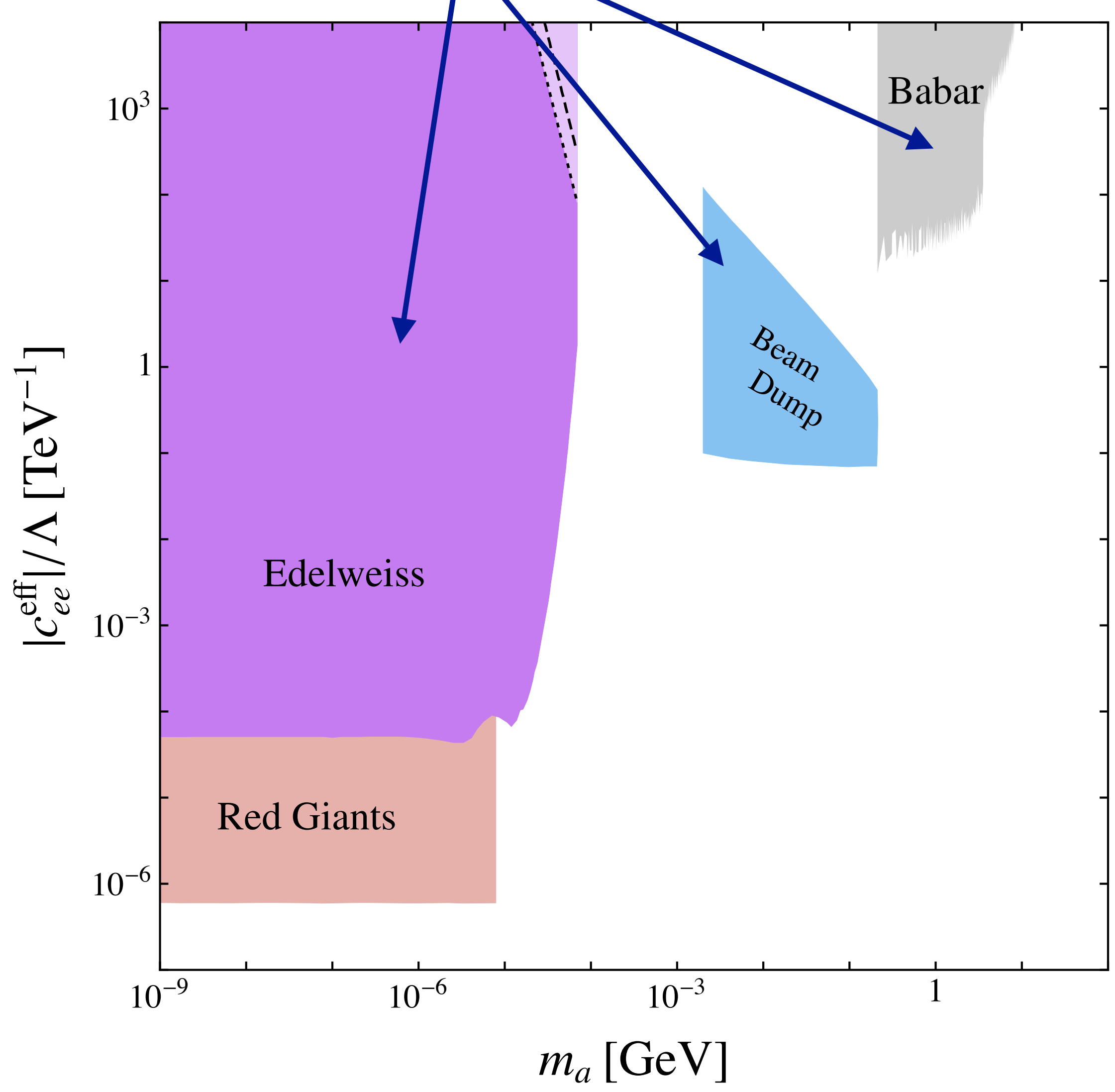
- Much tighter constraints expected from Belle II



Constraints on $C_{\gamma\gamma}^{\rm eff}$ and $c_{ee}^{\rm eff}$

model dependent!





[Armengaud et al. 2013; Jaeckel, Spannovsky 2015; many others …]

Higgs decays into ALPs

- The effective Lagrangian allows for the decays $h \to Za$ and $h \to aa$ at rates likely to be accessible in the high-luminosity run of the LHC (already with 300 fb^{-1})
- The subsequent ALP decays can readily be reconstructed, largely irrespective of how the ALP decays
- Higgs physics thus provides a powerful observatory for ALPs in the mass range between 1 MeV and 60 GeV, which is otherwise not easily accessible to experimental searches

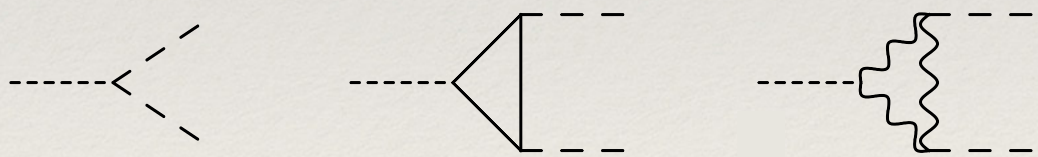
Higgs decays into ALPs

- We compute the relevant production and decay rates of the ALP at one-loop order, e.g.:

$$\Gamma(h \to aa) = \frac{\left|C_{ah}^{\rm eff}\right|^2}{32\pi}\,\frac{v^2 m_h^3}{\Lambda^4}\left(1-\frac{2m_a^2}{m_h^2}\right)\sqrt{1-\frac{4m_a^2}{m_h^2}}$$

with:

$$C_{ah}^{\rm eff} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln\frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] - \frac{3\alpha}{2\pi s_w^2}\left(g^2 C_{WW}\right)^2 \left[\ln\frac{\mu^2}{m_W^2} + \delta_2 - g_2(\tau_{W/h})\right]$$
$$- \frac{3\alpha}{4\pi s_w^2 c_w^2}\left(\frac{g^2}{c_w^2}\, C_{ZZ}\right)^2 \left[\ln\frac{\mu^2}{m_Z^2} + \delta_2 - g_2(\tau_{Z/h})\right]$$



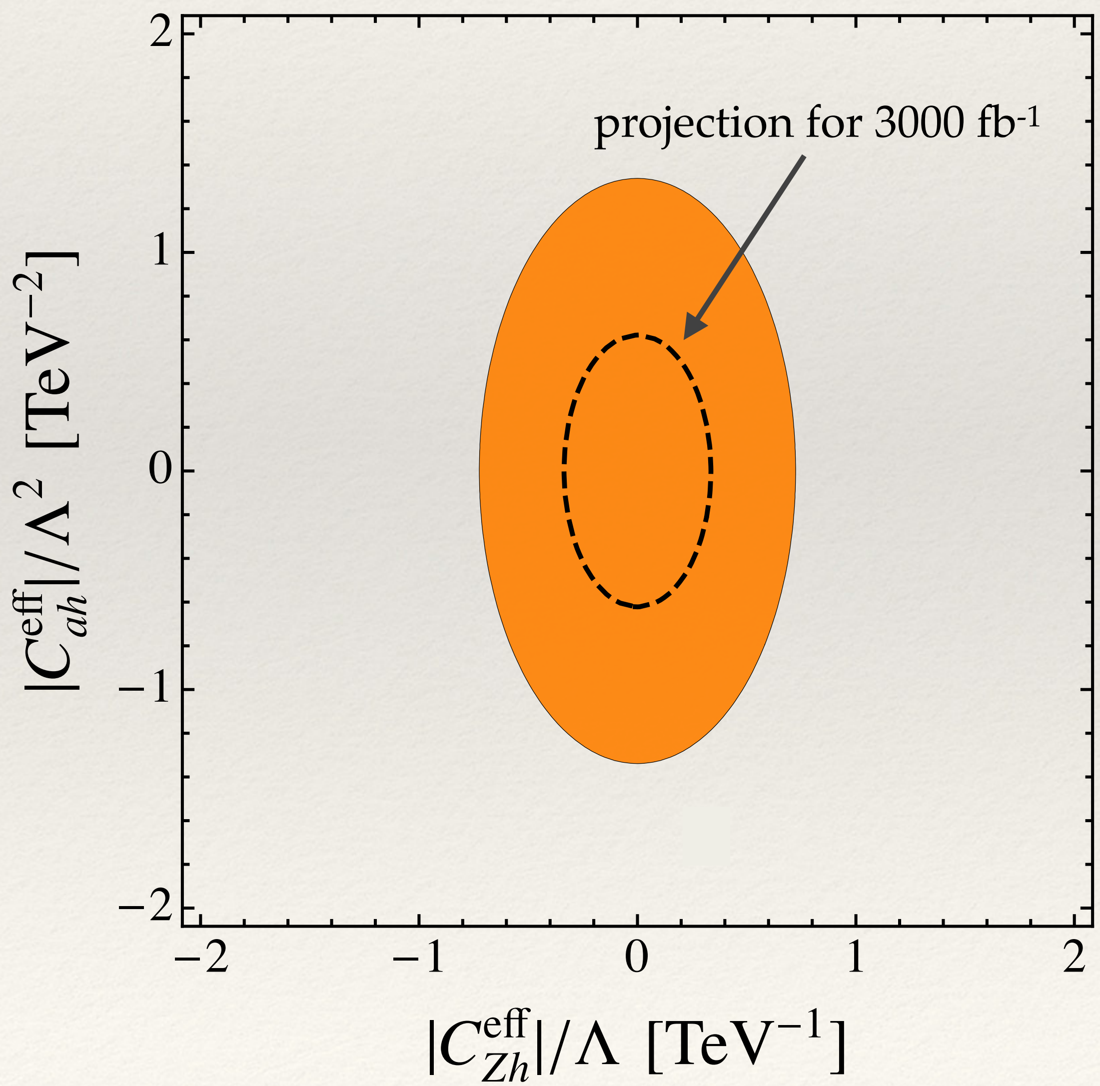
$$\approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\left(C_{WW}^2 + C_{ZZ}^2\right)$$

- A 10% branching ratio is obtained for $|C_{ah}^{\rm eff}| \approx 0.62\,(\Lambda/\text{TeV})^2$

Higgs decays into ALPs

- Current bounds (at 95% CL) on the relevant (effective) ALP-Higgs couplings from Br($h \to$BSM) < 0.34:

[ATLAS & CMS: 1606.02266]



Higgs decays into ALPs

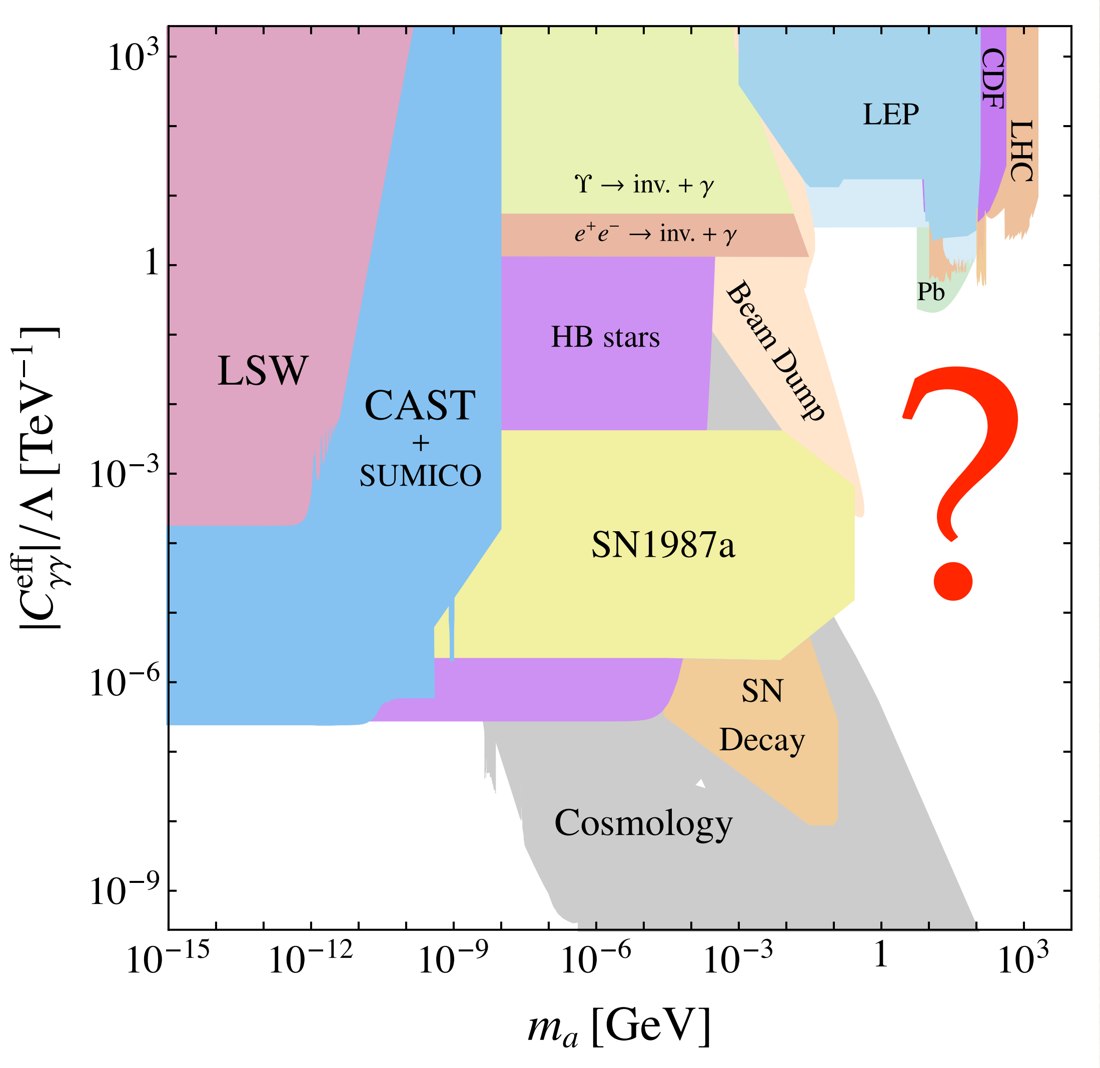
- The effect of the ALP decay length must be carefully taken into account (important for small ALP mass or couplings)
- We require 100 signal events in 300 fb^{-1} of LHC data (Run 2)
- Always probe a pair of ALP couplings, those relevant for the production and decay process; here we focus on $h \to aa$ and $a \to \gamma\gamma$, $l^+ l^-$

Higgs decays into ALPs

- Depending on the decay modes of the ALP, several interesting final-state signatures can arise:
  - $h \to aa \to \gamma\gamma + \gamma\gamma$, where the two photons in each pair are either resolved (for $m_a > \sim 100$ MeV) or appear as a single photon in the calorimeter (adds to $h \to \gamma\gamma$ signal)
  - $h \to aa \to l^+l^- + l^+l^-$ with $l = e, \mu, \tau$
  - $h \to aa \to 4jets$, including heavy-quark jets, …
- Most of these decays can be reconstructed in LHC Run-2

Probing the ALP-photon coupling

- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore a large region of uncovered parameter space:



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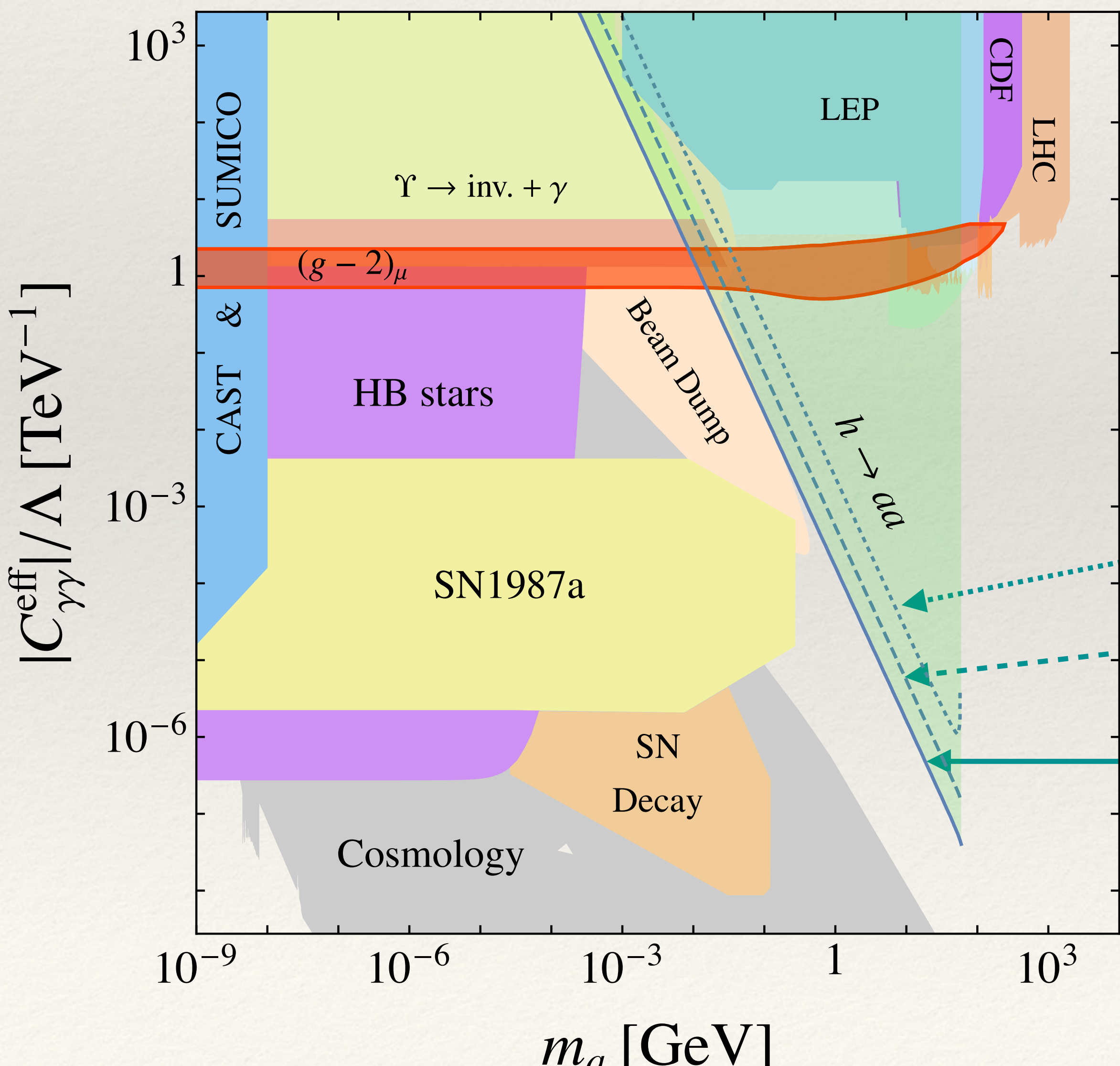


- The ALP-photon coupling can be probed even if the ALP decays predominantly to other particles!
- Region preferred by $(g-2)_\mu$ can be covered completely!

$|C_{ah}^{\rm eff}| = 0.01,\ \mathrm{Br}(a \to \gamma\gamma) > 0.49$

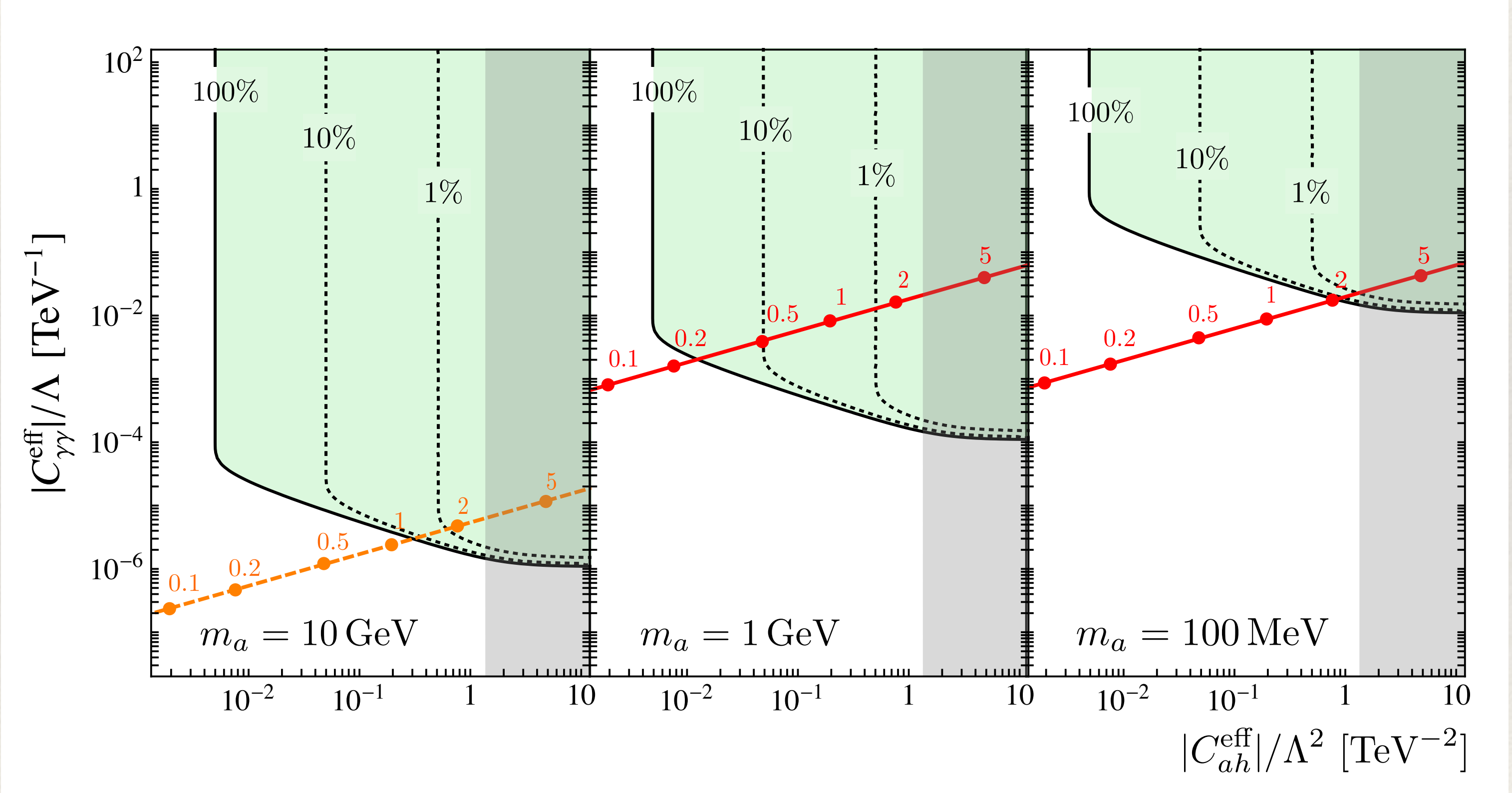
$|C_{ah}^{\rm eff}| = 0.1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.049$

$|C_{ah}^{\rm eff}| = 1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.006$

(for $\Lambda = 1\,\mathrm{TeV}$)

Probing the ALP-photon coupling

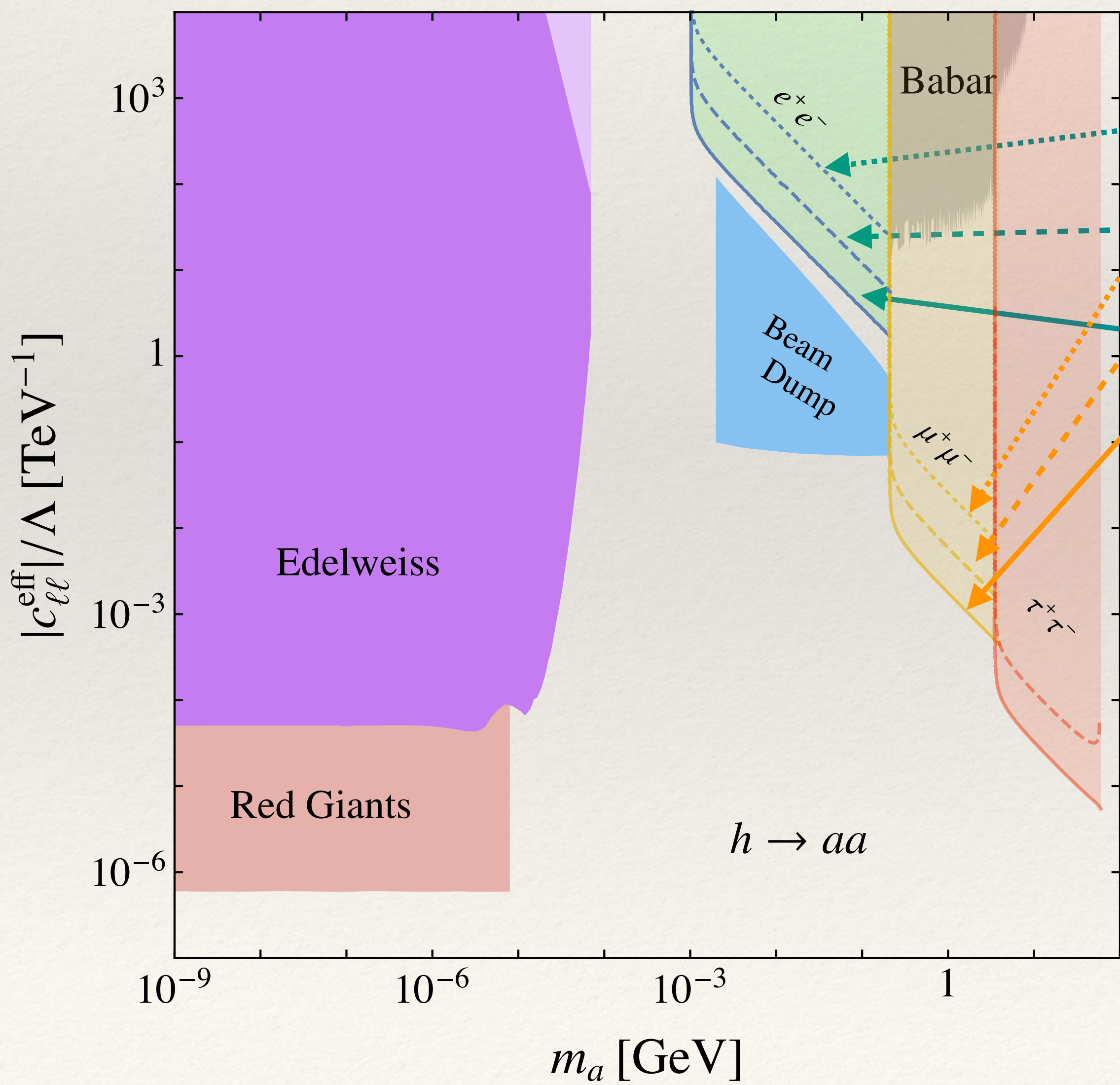
- Alternative representation of the parameter space in the ALP-Higgs and ALP-photon coupling plane
- Accessible region depends on the ALP mass and $a \to \gamma\gamma$ branching ratio (dashed contours)
- Lines show predictions for the coefficients in two scenarios with couplings induced by loops of SM fermions



$$h \to aa \to \gamma\gamma + \gamma\gamma$$

Probing the ALP-lepton couplings

- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore a large region of uncovered parameter space:



$|C_{ah}^{\rm eff}| = 0.01\,,\ \mathrm{Br}(a \to e^+e^-) > 0.49$

$|C_{ah}^{\rm eff}| = 0.1\,,\ \mathrm{Br}(a \to e^+e^-) > 0.049$

$|C_{ah}^{\rm eff}| = 1\,,\ \mathrm{Br}(a \to e^+e^-) > 0.006$

(for $\Lambda = 1\,\mathrm{TeV}$)

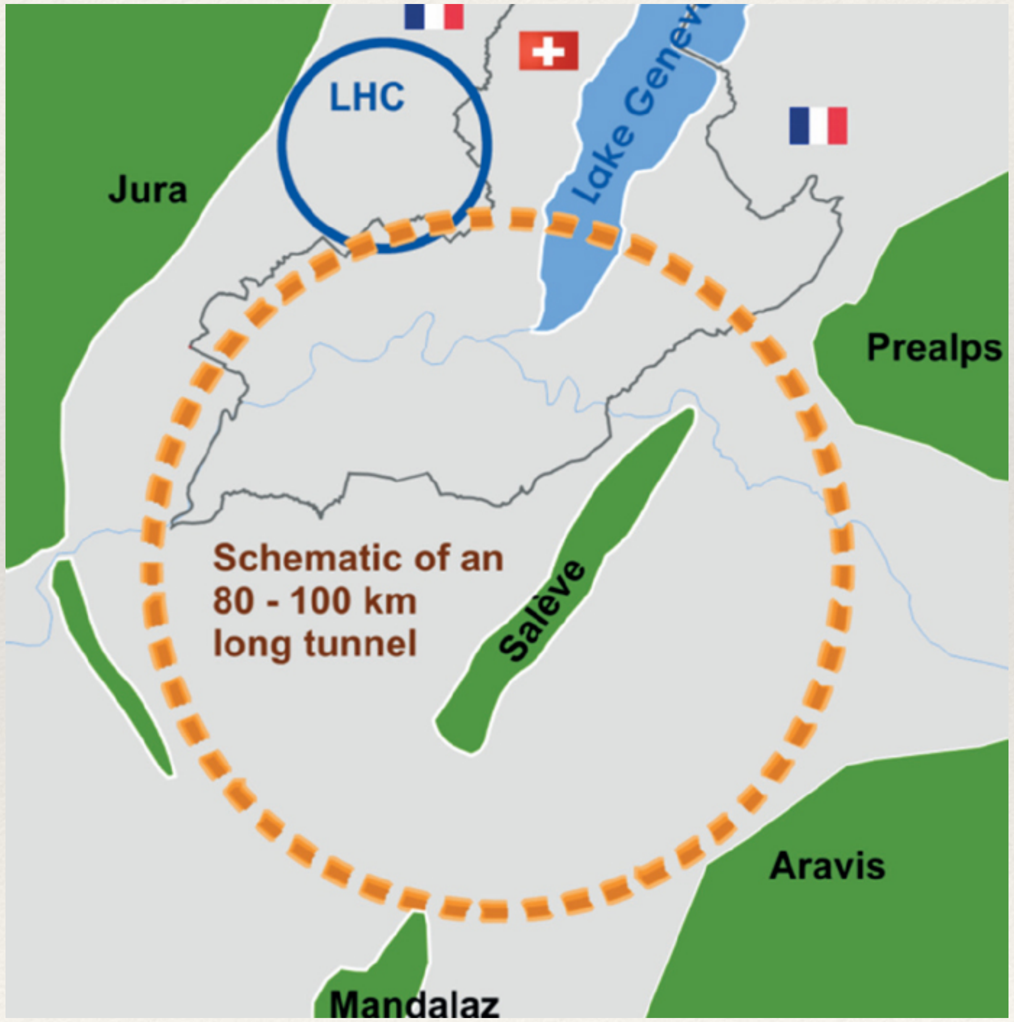
Conclusions

- Exotic Higgs decays provide multiple new ways to probe for ALPs in the mass range between 1 MeV and 60 GeV, with couplings suppressed by Λ~1-100 TeV and beyond
- In some regions of parameter space, the ALP signal would enhance the measured rates for $h\to\gamma\gamma$ and $h\to Z\gamma$
- In other regions, new searches for final states such as $h\to l^+l^-\gamma\gamma$, $h\to 4\gamma$, $h\to l_1^+l_1^-l_2^+l_2^-$ or final states with jets need to be devised
- Accessible parameter space can be enlarged significantly with planned future lepton and hadron colliders

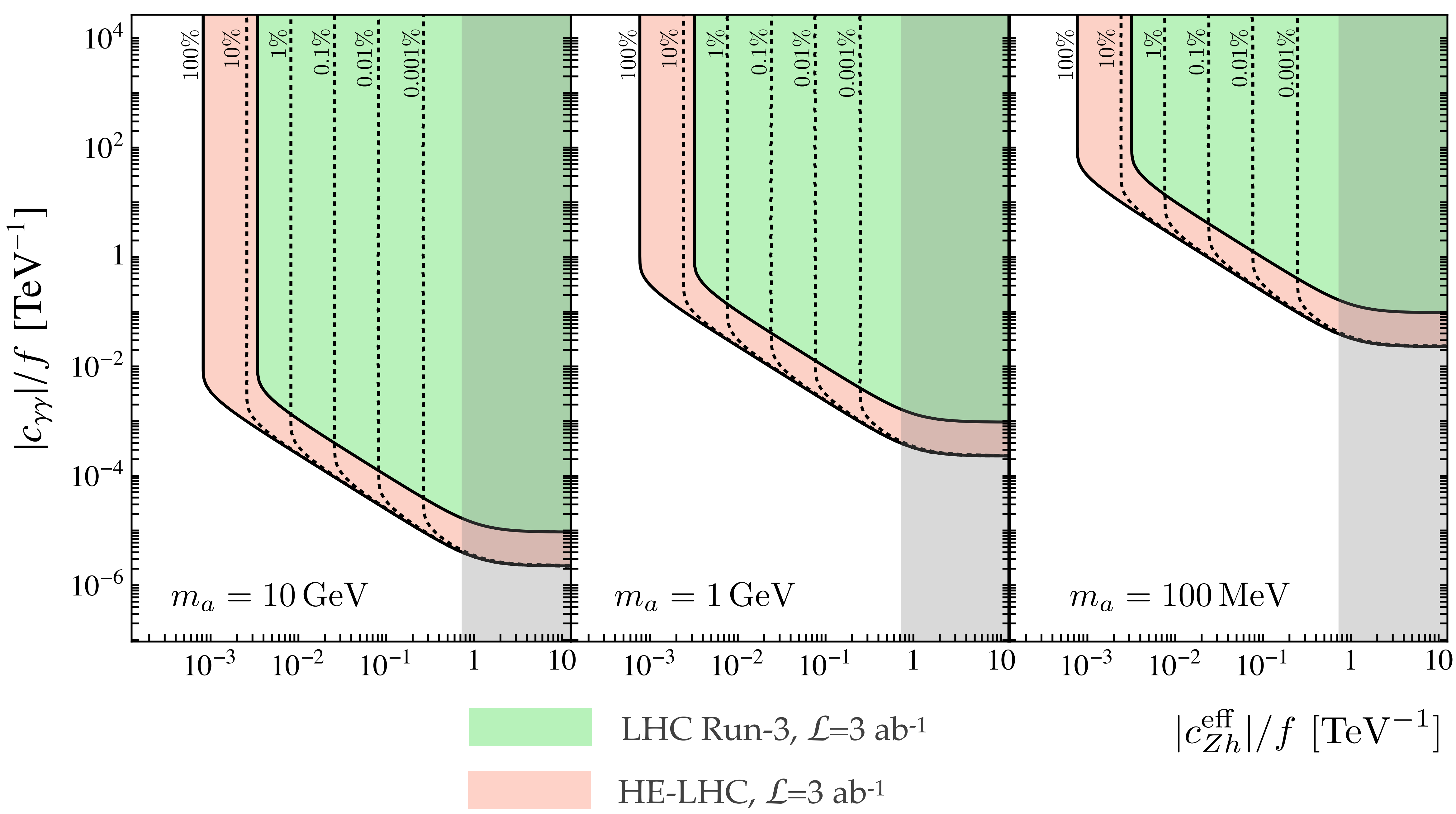
Backup Slides

Probing ALPs at Future Colliders

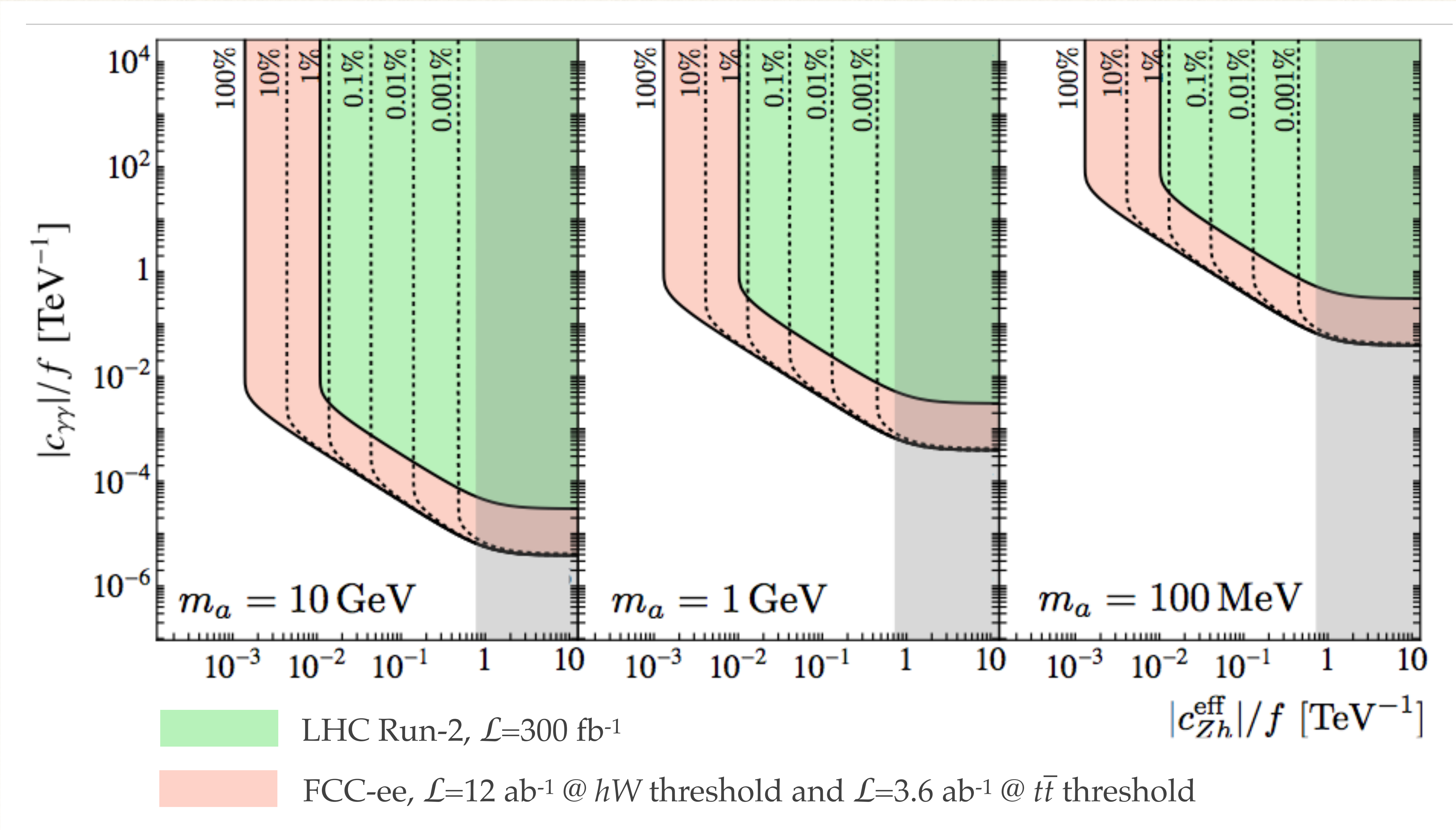
- We focus on the decay chains $pp\to h\to Za\to l^+l^-+\gamma\gamma$ and $pp\to h\to Za\to l^+l^-+l^+l^-$, but similar results hold for the ALP production channels $h\to aa$ and $Z\to\gamma a$



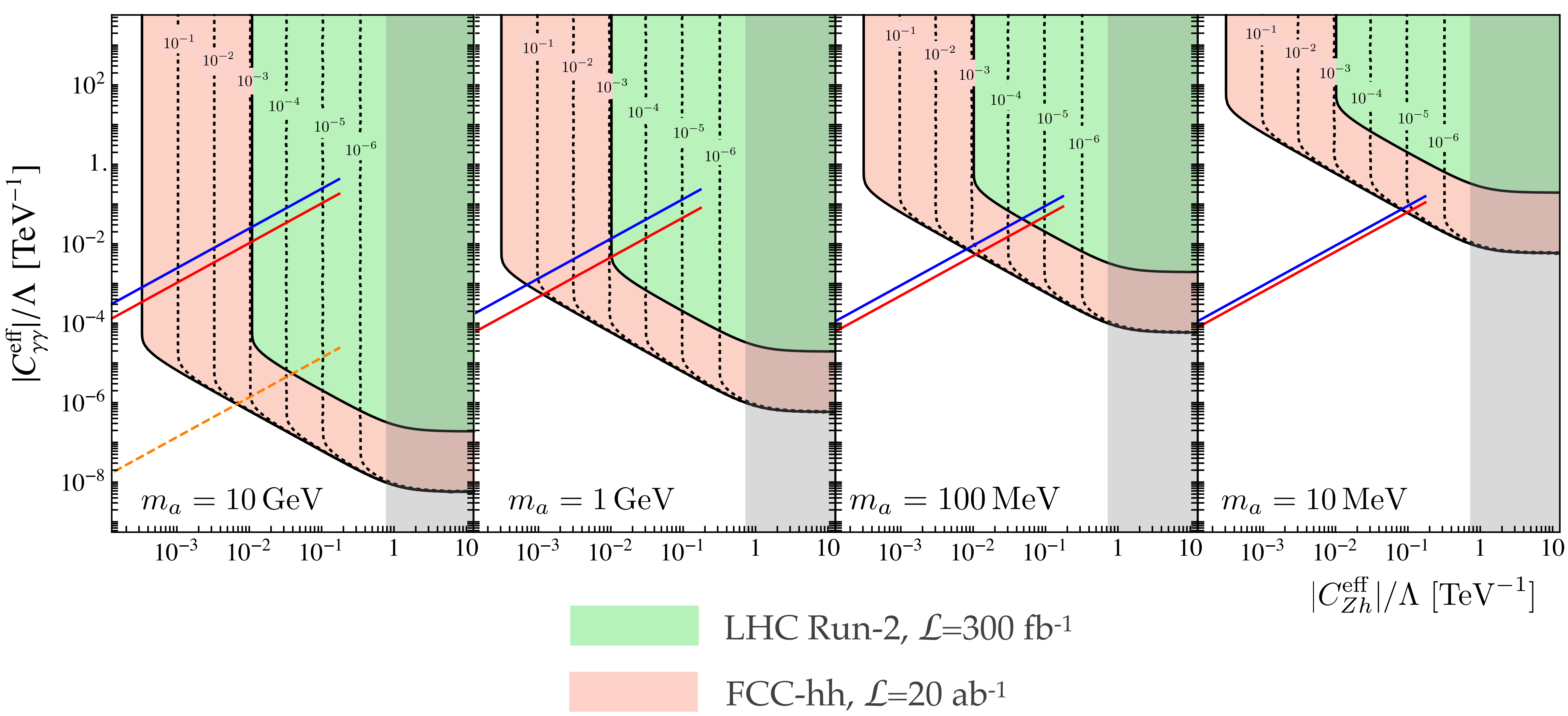
HE-LHC ($\sqrt{s}$=27 TeV, $\mathcal{L}$=3 ab^{-1})



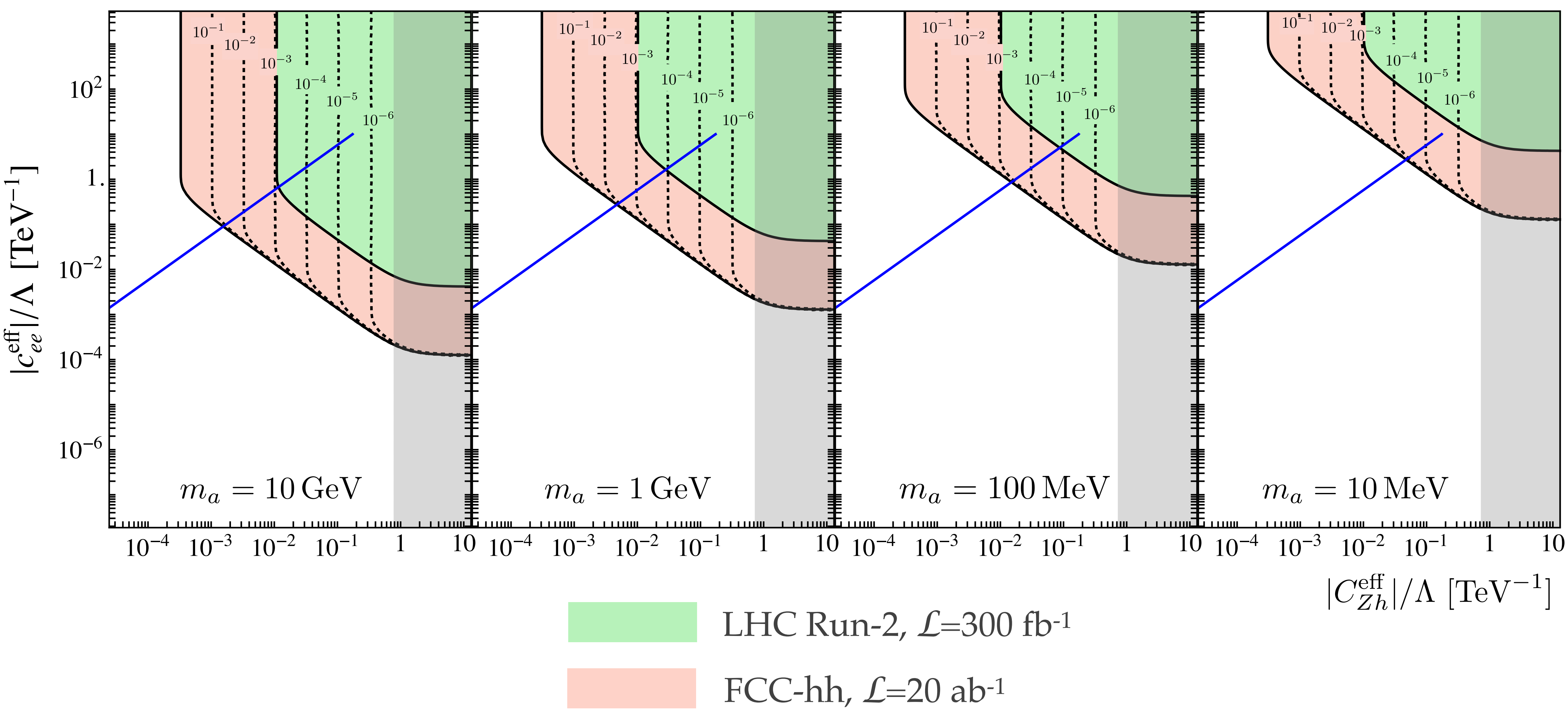
FCC-ee ($3 \cdot 10^6$ Higgses, T=10 yrs.)



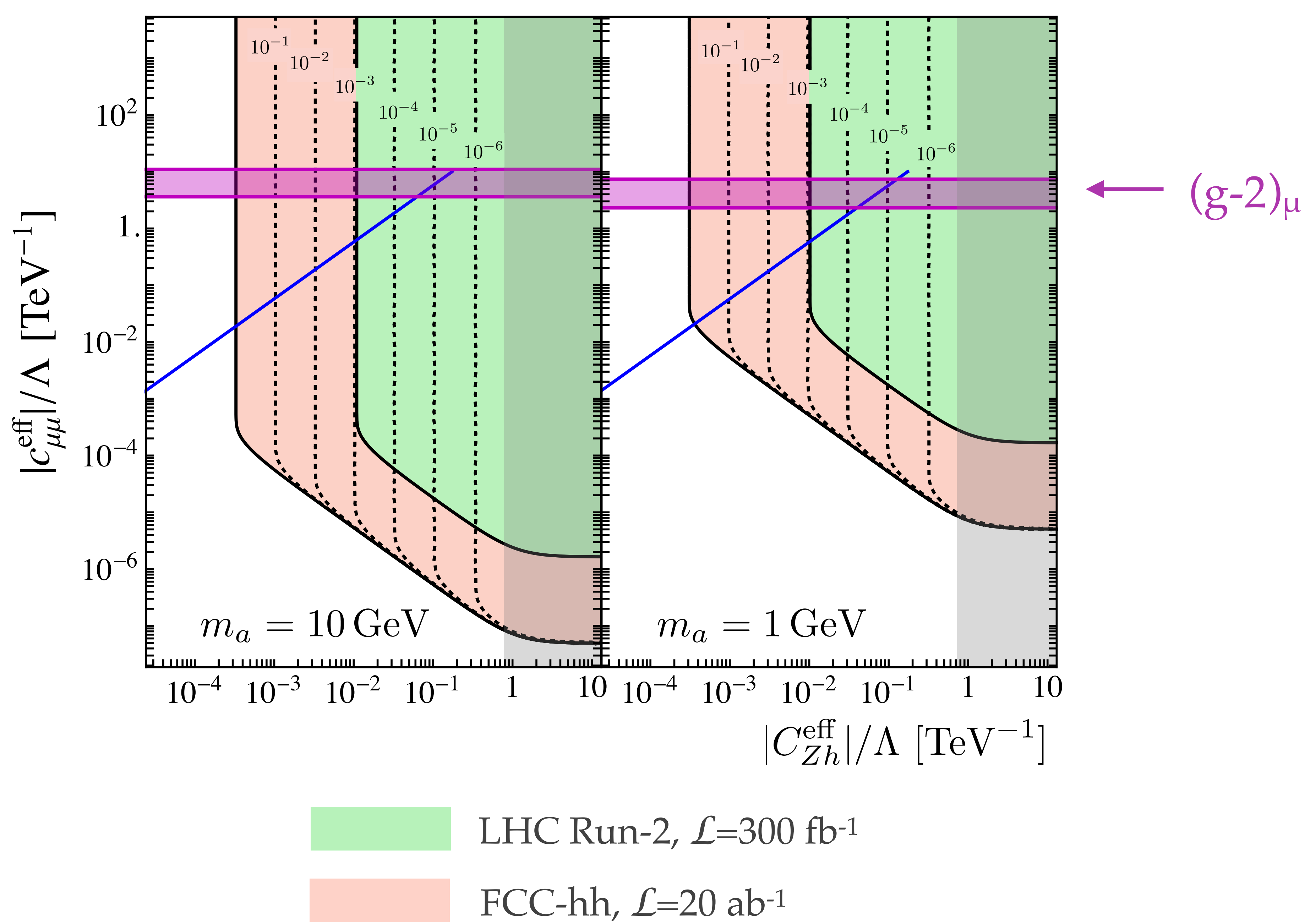
FCC-hh ($\sqrt{s}$=100 TeV, $\mathcal{L}$=20 ab^{-1})



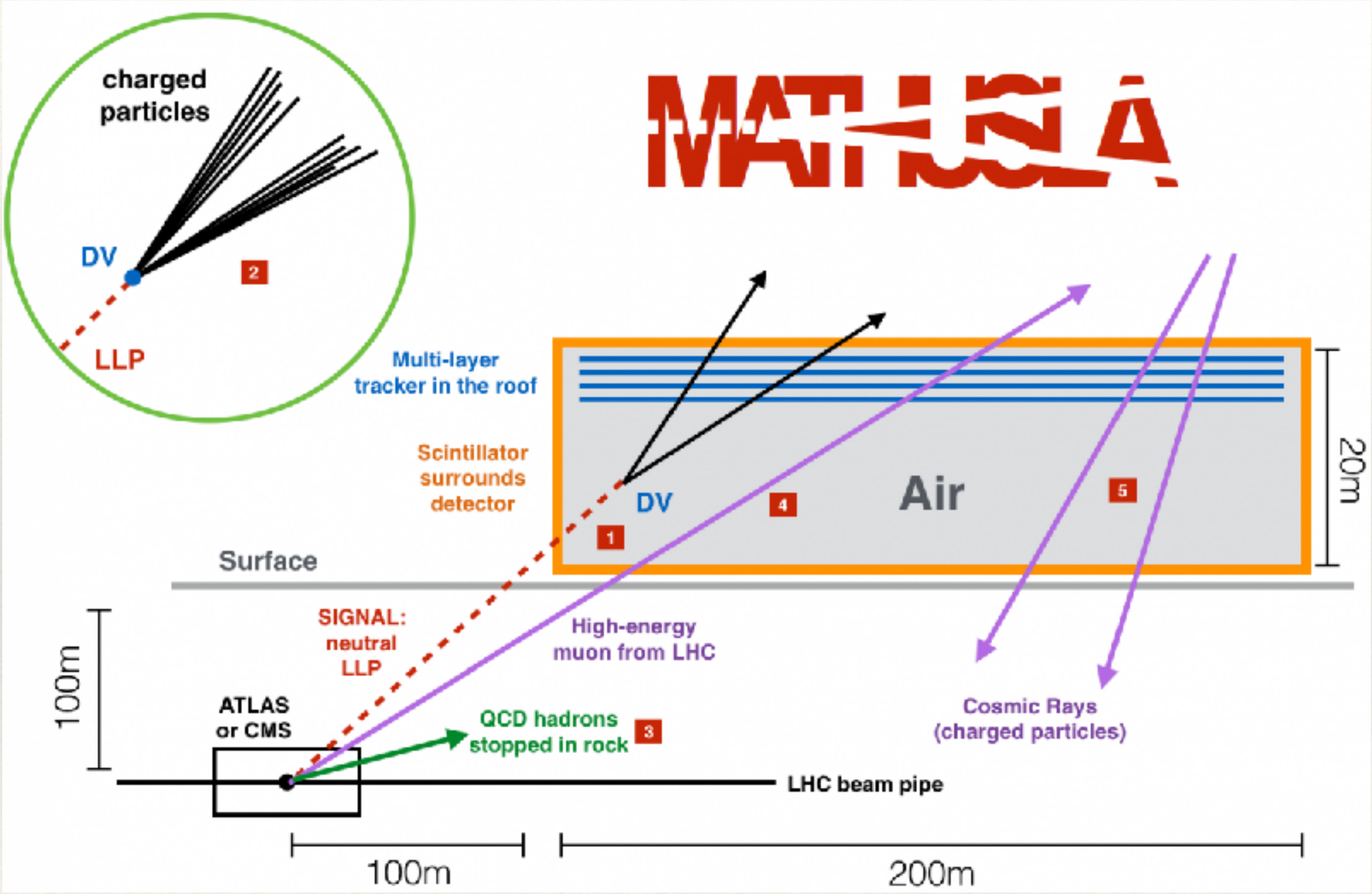
FCC-hh ($\sqrt{s}$=100 TeV, $\mathcal{L}$=20 ab^{-1})



FCC-hh ($\sqrt{s}$=100 TeV, $\mathcal{L}$=20 ab^{-1})



MATHUSLA Surface Array



A surface extension to ATLAS / CMS at LHC Run-2

[Chou, Curtin, Lubatti: 1606.06298]

MATHUSLA Surface Array