What's going on at the weak scale? — CERN-CKC Workshop, Jeju Island, 2 June 2017

LHC as an Axion Factory:

Probing an Axion-Based Explanation of $(g\text{-}2)_\mu$ with Exotic Higgs Decays

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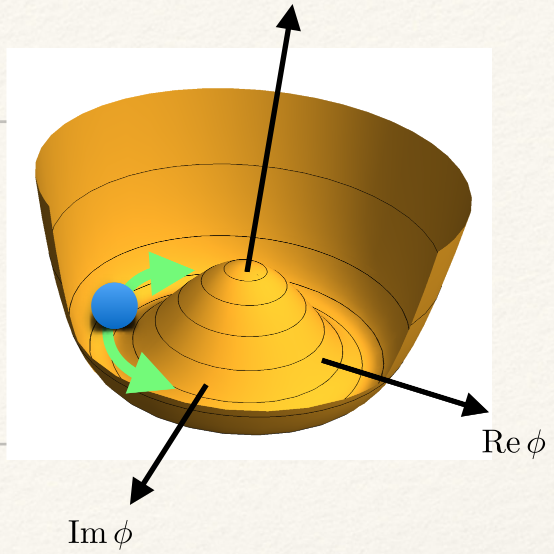
based on work with Andrea Thamm and Martin Bauer: 1704.08207 & in progress

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 particles could explain various low-energy anomalies, such as the muon $(g-2)_\mu$ 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]

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

- The only other dimension-5 operator:

$$\frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right)$$

can be reduced to the fermion operators above by the equations of motion, hence no tree-level couplings to the Higgs arise!

Effective Lagrangian

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$$+ g_s^2\, C_{GG}\, \frac{a}{\Lambda}\, G_{\mu\nu}^A\, \tilde G^{\mu\nu,A} + g^2\, C_{WW}\, \frac{a}{\Lambda}\, W_{\mu\nu}^A\, \tilde W^{\mu\nu,A} + g'^2\, C_{BB}\, \frac{a}{\Lambda}\, B_{\mu\nu}\, \tilde B^{\mu\nu}$$

- At dimension-6 order and higher additional interactions arise; those relevant to our discussion are:

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

- We are interested in probing 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:

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

with:

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

- 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:

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

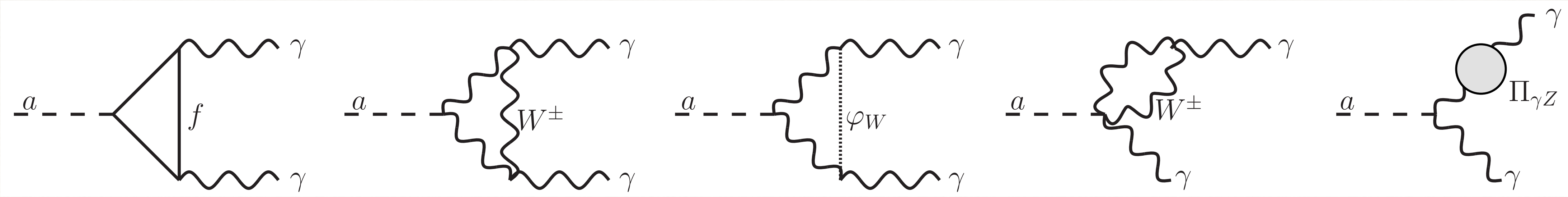
ALP decay into photons

- Including the complete set of one-loop corrections, we obtain from the effective Lagrangian:

$$\Gamma(a\to\gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2}\left| C_{\gamma\gamma} + \sum_f \frac{N_c^f Q_f^2}{16\pi^2}\, c_{ff}\, B_1(\tau_f) + \frac{2\alpha}{\pi}\,\frac{C_{WW}}{s_w^2}\, B_2(\tau_W)\right|^2 \equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2}\left|C_{\gamma\gamma}^{\rm eff}\right|^2$$

where $\tau_i \equiv 4m_i^2/m_a^2$ and:

$$B_1(\tau) = 1 - \tau\, f^2(\tau)\,, \qquad B_2(\tau) = 1 - (\tau-1)\, f^2(\tau)\,, \qquad \text{with} \quad f(\tau) = \begin{cases} \arcsin\frac{1}{\sqrt{\tau}}\,; & \tau \ge 1 \\ \frac{\pi}{2} + \frac{i}{2}\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\,; & \tau < 1 \end{cases}$$



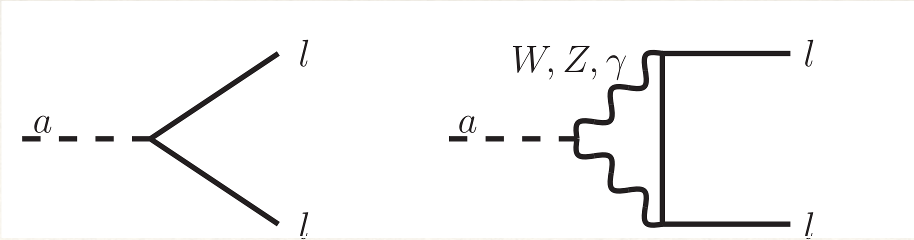
ALP decay into lepton pairs

- Including the complete set of one-loop corrections, we obtain from the effective Lagrangian:

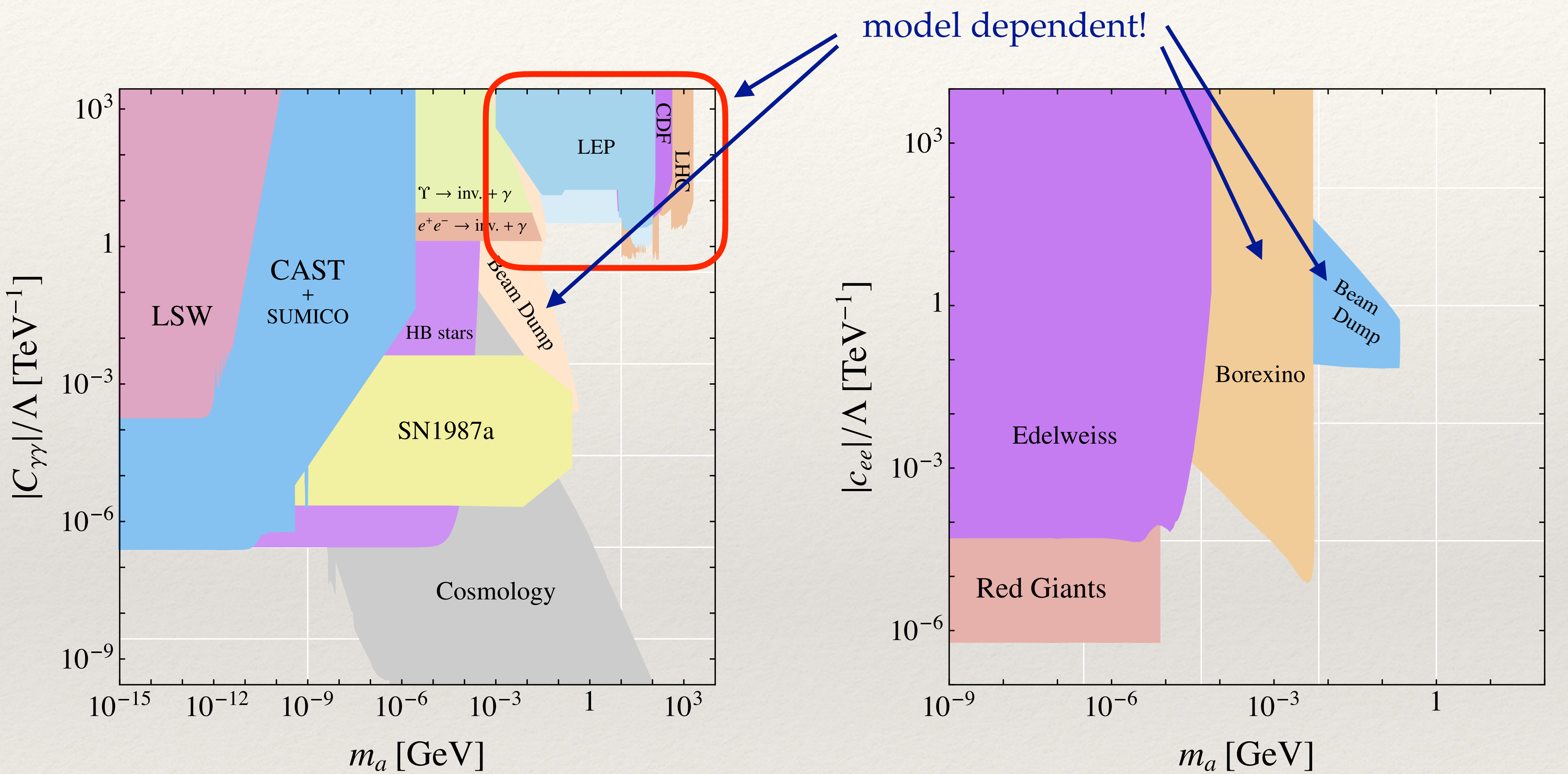
$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2} \left| c_{\ell\ell}^{\rm eff} \right|^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$$

where:

$$\begin{aligned} c_{\ell\ell}^{\rm eff} &= c_{\ell\ell}(\mu) \left[1 + \mathcal{O}(\alpha)\right] - 12 Q_\ell^2\, \alpha^2 C_{\gamma\gamma} \left[\ln \frac{\mu^2}{m_\ell^2} + \delta_1 + g(\tau_\ell) \right] \\ &\quad - \frac{3\alpha^2}{s_w^4} C_{WW} \left(\ln \frac{\mu^2}{m_W^2} + \delta_1 + \frac{1}{2} \right) - \frac{12\alpha^2}{s_w^2 c_w^2} C_{\gamma Z}\, Q_\ell \left(T_3^\ell - 2Q_\ell s_w^2 \right) \left(\ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{3}{2} \right) \\ &\quad - \frac{12\alpha^2}{s_w^4 c_w^4} C_{ZZ} \left(Q_\ell^2 s_w^4 - T_3^\ell Q_\ell s_w^2 + \frac{1}{8} \right) \left(\ln \frac{\mu^2}{m_Z^2} + \delta_1 + \frac{1}{2} \right) \end{aligned}$$



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

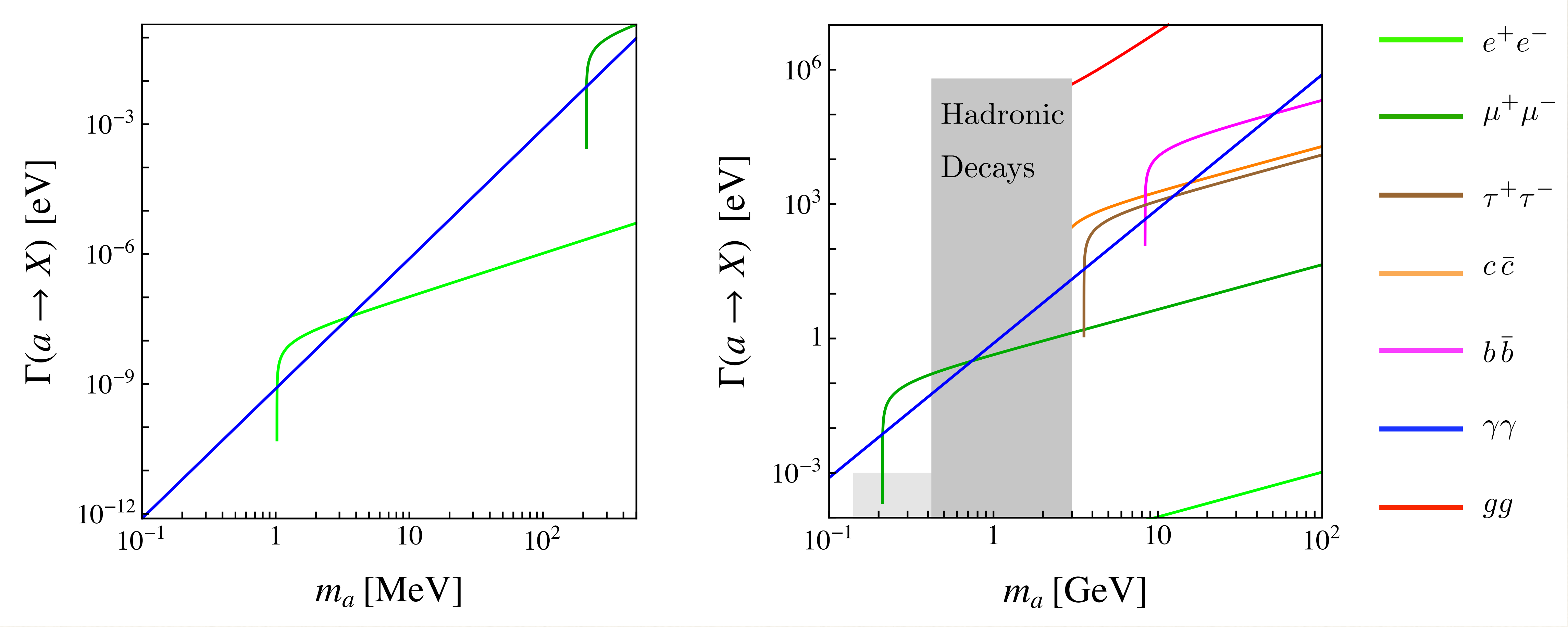


[Armengaud et al. 2013; Jaeckel, Spannovsky 2015; many others …]

- ALPs with masses below ~1 MeV are **incompatible** with couplings $C_i/\Lambda \sim (0.01 - 1)\,\text{TeV}^{-1}$

Pattern of decay rates

- Assuming that the relevant Wilson coefficients are equal to 1, one finds the following pattern of decay rates:



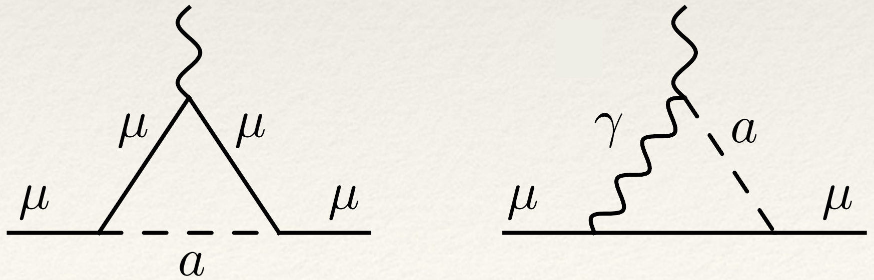
$(g\text{-}2)_\mu$ anomaly

- Persistent deviation of the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu/2$, from its SM value provides one of the most compelling hints for new physics:

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$

- In our model we find two one-loop contributions of potentially different sign (with $x = m_a^2/m_\mu^2$):

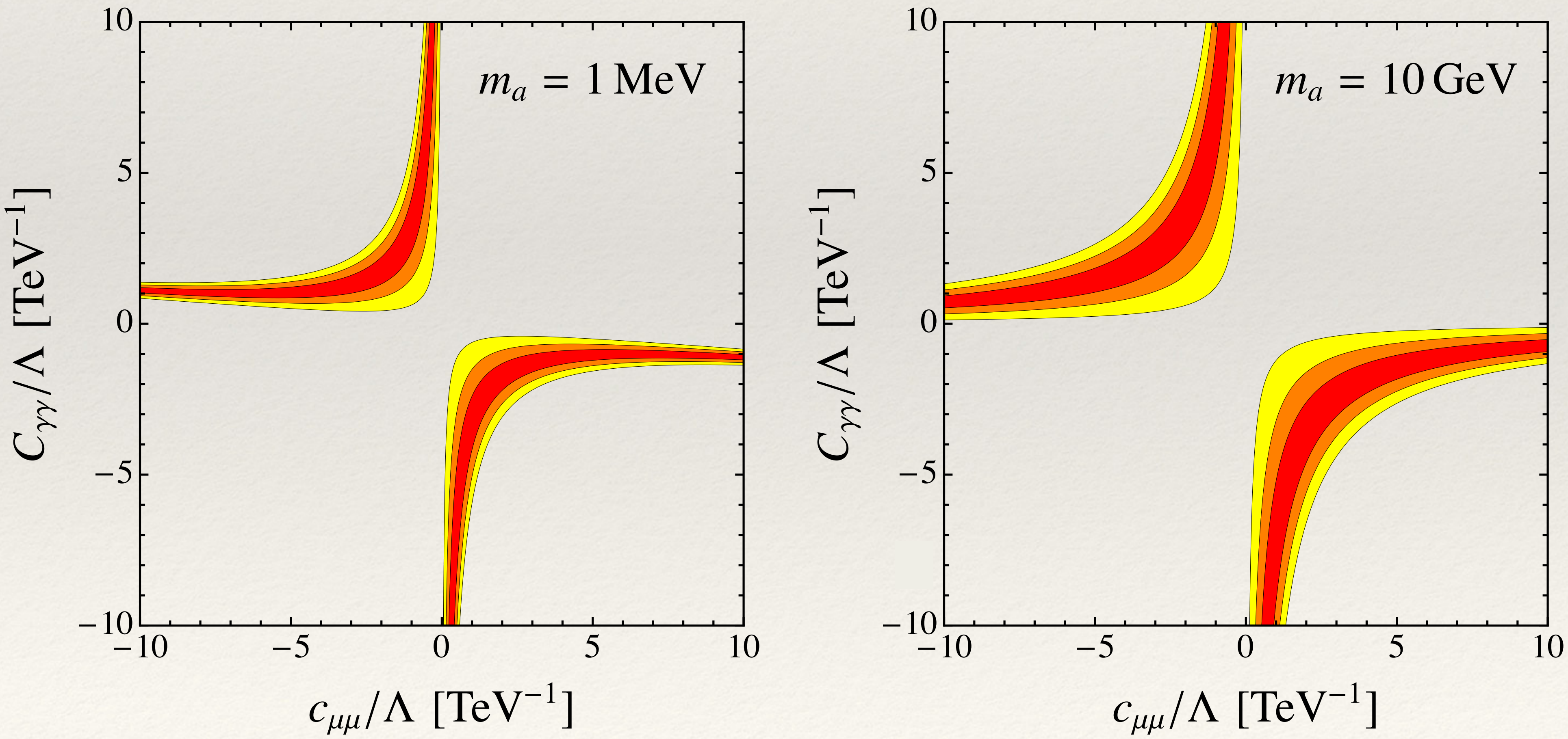
$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2} \left\{ -\frac{c_{\mu\mu}^2}{16\pi^2}\, h_1(x) - \frac{2\alpha}{\pi}\, c_{\mu\mu} C_{\gamma\gamma} \left[\ln\frac{\Lambda^2}{m_\mu^2} - h_2(x) \right] \right\}$$



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

$(g\text{-}2)_\mu$ anomaly

- Assuming the ALP-induced contributions are the dominant new-physics effect, the anomaly can be explained for natural values of Wilson coefficients:



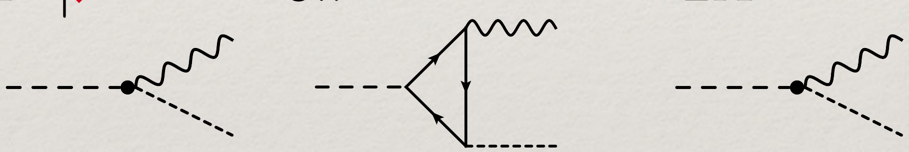
Higgs decays into ALPs

- 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

Operator analysis of the decay h→Za

- The effective Lagrangian does not contain any D=5 operator giving a tree-level contribution to this decay
- Including one-loop corrections, we find:

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left| \cancel{C_{Zh}^{(5)}} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \right|^2 \lambda^{3/2}\!\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2} \right)$$



D=5 **D=5** **D=7**

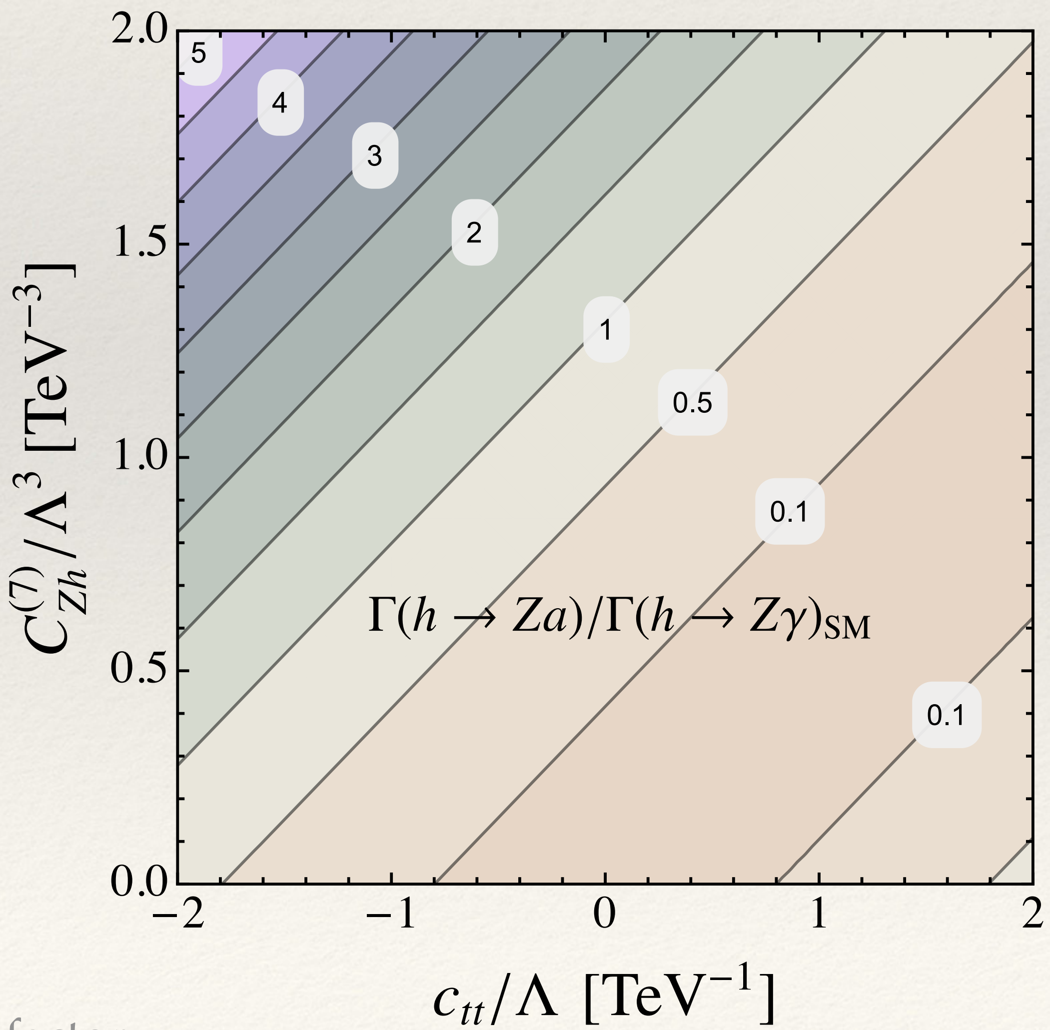
[Bauer, MN, Thamm 2016]

where $C_{Zh}^{(5)} = 0$ and:

$$F = \int_0^1 d[xyz]\, \frac{2m_t^2 - x m_h^2 - z m_Z^2}{m_t^2 - xy m_h^2 - yz m_Z^2 - xz m_a^2} \approx 0.930 + 2.64 \cdot 10^{-6}\, \frac{m_a^2}{\mathrm{GeV}^2}$$

Operator analysis of the decay h→Za

- The resulting rates can naturally be of the same order as the $h \to Z\gamma$ rate in the SM, which makes them a realistic target for discovery at the high-luminosity LHC run:



Operator analysis of the decay h→Za

- The argument for the absence of a tree-level D=5 operator can be avoided in BSM models containing new heavy particles receiving their mass from EWSB!

[see e.g.: Pierce, Thaler, Wang 2006]

- In such models the unique, non-polynomial D=5 operator:

$$\mathcal{L}_{\text{eff}}^{\text{non-pol}} \ni \frac{C_{Zh}^{(5)}}{\Lambda} (\partial^\mu a) \left(\phi^\dagger iD_\mu \phi + \text{h.c.}\right) \ln \frac{\phi^\dagger \phi}{\mu^2}$$

[Bauer, MN, Thamm 2016]

can arise, which contributes to the rate at tree level

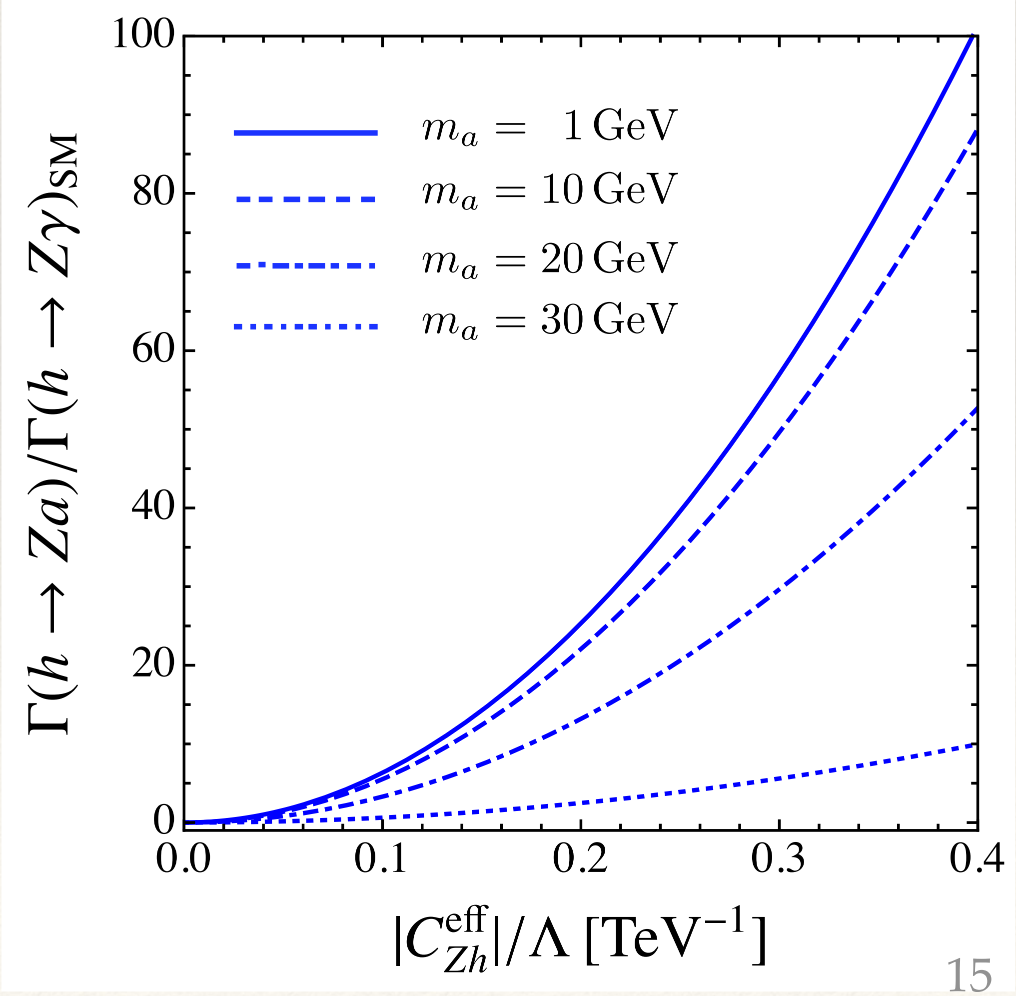
Operator analysis of the decay h→Za

- One then obtains:

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left| C_{Zh}^{(5)} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \right|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$

with non-zero $C_{Zh}^{(5)}$, allowing for much enhanced rates!

- For example, a 10% branching ratio (huge!) is obtained for $|C_{Zh}^{\rm eff}| \approx 0.34\,(\Lambda/\mathrm{TeV})$



Operator analysis of the decay h→Za

- Depending on the decay modes of the ALP, several interesting final-state signatures can arise:
  - $h \to Za \to Z\gamma\gamma$, where the two photons are either resolved (for $m_a >$ ~100 MeV) or appear as a single photon in the calorimeter
  - $h \to Za \to Zl^+l^-$ with $l = e, \mu, \tau$
  - $h \to Za \to Z + 2\,jets$, including heavy-quark jets
  - $h \to Za \to Z + invisible$
- All of these decay modes (perhaps even the invisible ones) can be reconstructed in Run-2 at the LHC!

Operator analysis of the decay h→aa

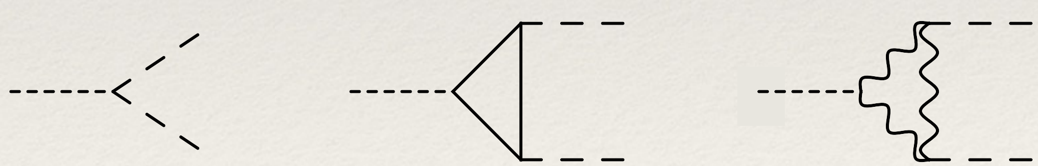
- The Higgs portal interaction and other loop-mediated processes allow for ALP pair production in Higgs decay starting at D=6 order; we find:

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

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 $|C_{ah}^{\rm eff}| \approx 0.62\,(\Lambda/\text{TeV})^2$

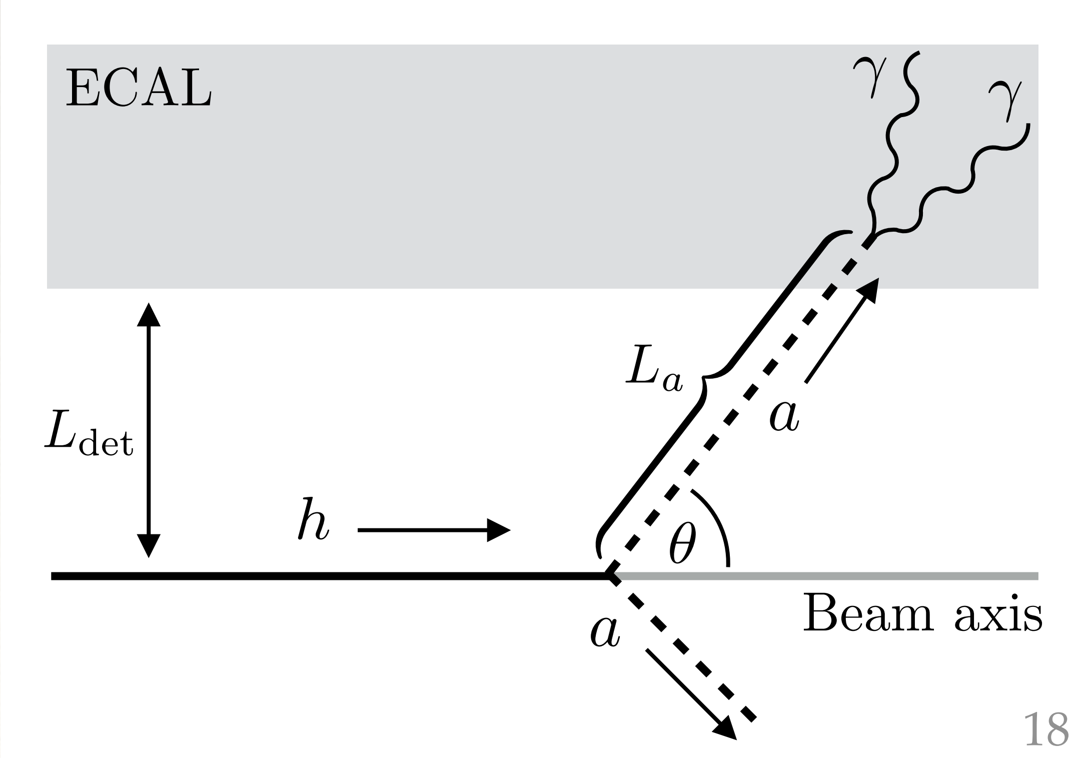
Decay-length effect

- Light ALPs with weak couplings can have macroscopic decay length, and hence only a fraction of them decays inside the detector
- If the ALP is detected in the decay mode a→XX, its average transverse decay length can be written as:

$$L_a^\perp(\theta) = \sin\theta\,\beta_a\gamma_a/\Gamma_a$$

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

$$\equiv L_a\sin\theta$$



Decay-length effect

- Fraction of events with ALPs decaying in the detector:

$$f_{\rm dec}^{Za} = \int_0^{\pi/2} d\theta \sin\theta \left(1 - e^{-L_{\rm det}/L_a^\perp(\theta)}\right) \xrightarrow{L_a \gg L_{\rm det}} \frac{\pi}{2}\,\frac{L_{\rm det}}{L_a}$$

$$f_{\rm dec}^{aa} = \int_0^{\pi/2} d\theta \sin\theta \left(1 - e^{-L_{\rm det}/L_a^\perp(\theta)}\right)^2 \xrightarrow{L_a \gg L_{\rm det}} \left(\frac{L_{\rm det}}{L_a}\right)^2 \ln\frac{1.258 L_a}{L_{\rm det}}$$

- We can then define effective branching ratios:

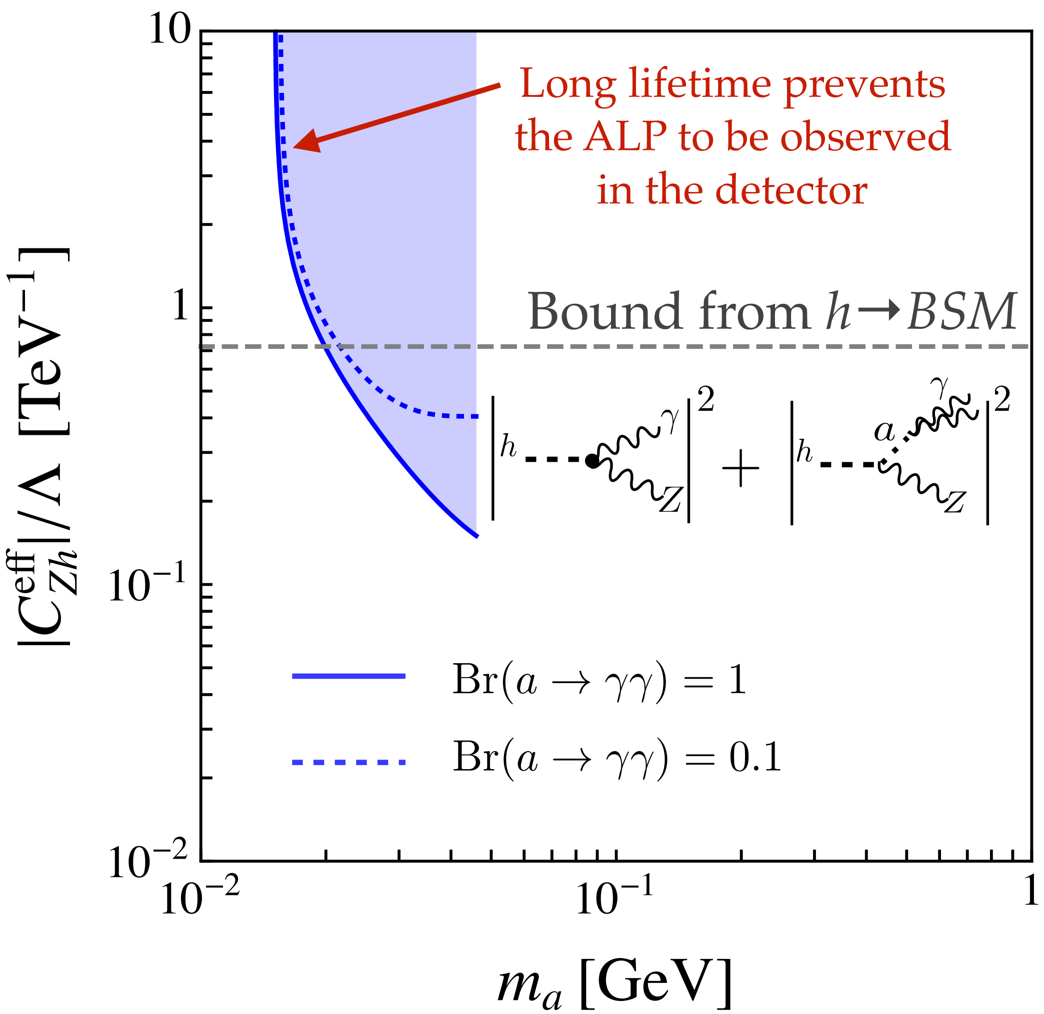
$$\text{Br}(h \to Za \to \ell^+\ell^- XX)\big|_{\rm eff} = \text{Br}(h \to Za) \times \text{Br}(a \to XX)\, f_{\rm dec}\, \text{Br}(Z \to \ell^+\ell^-)$$

$$\text{Br}(h \to aa \to 4X)\big|_{\rm eff} = \text{Br}(h \to aa)\, \text{Br}(a \to XX)^2\, f_{\rm dec}^2$$

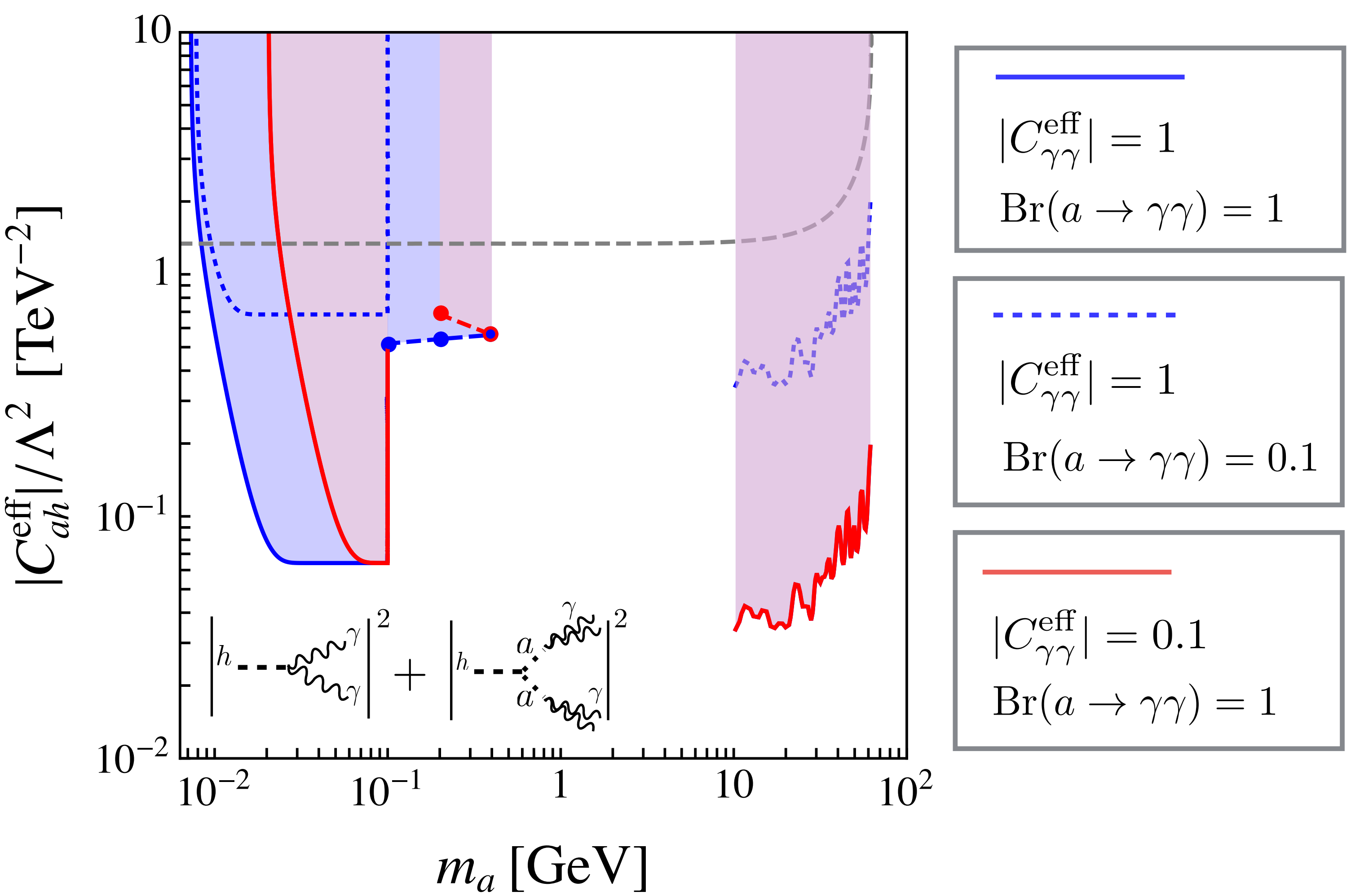
- For $L_a >> L_{\rm det}$, these become independent of $\text{Br}(a \to XX)$

Phenomenological constraints

- Assuming the ALP decays into photons with a significant BR, current LHC data imply interesting bounds:



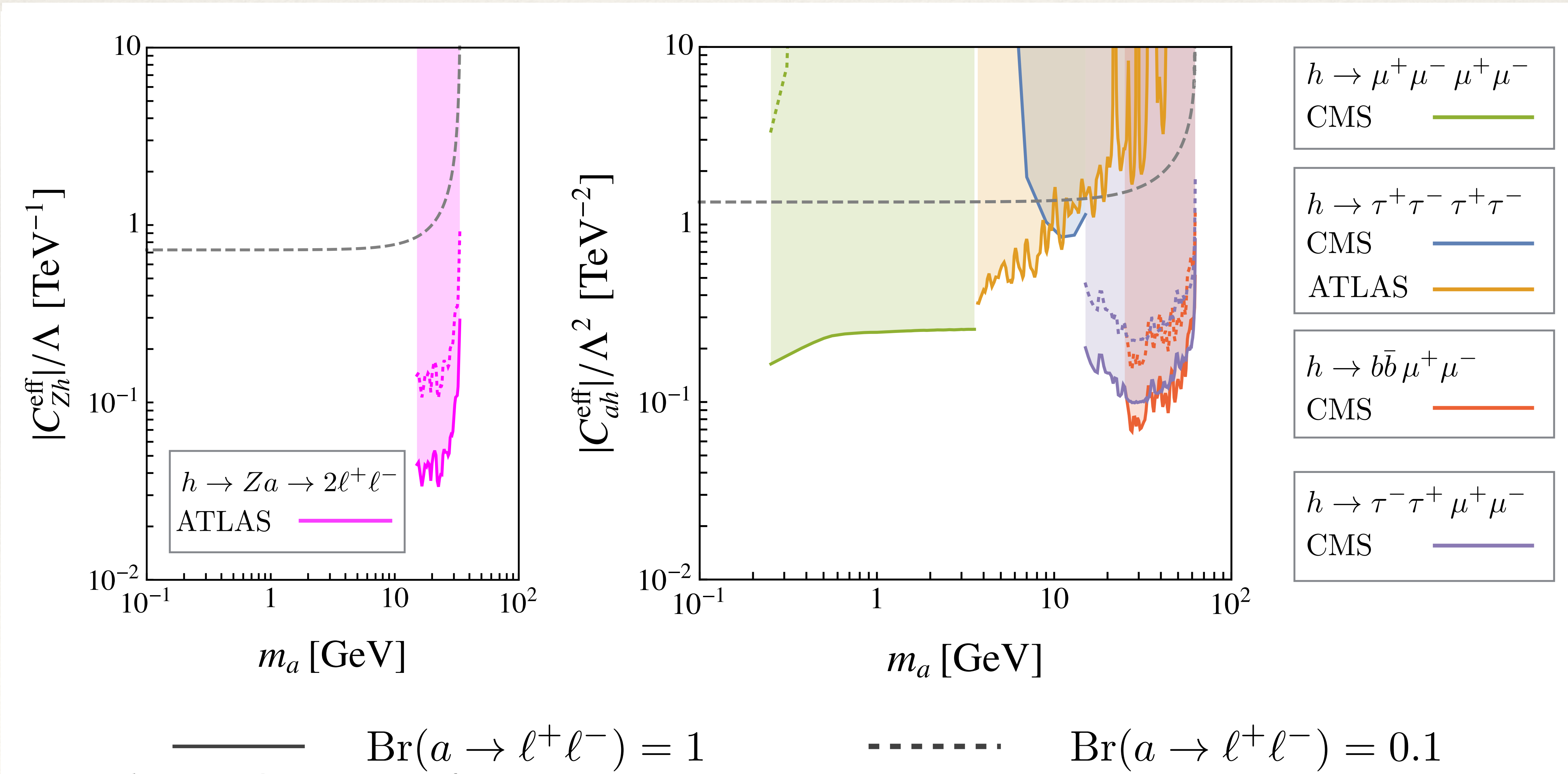
Upper bound derived from non-observation of $h \to Z\gamma$ decay at ATLAS/CMS



Upper bounds derived from $h \to \gamma\gamma$ data (left) and ATLAS $h \to \gamma\gamma\gamma\gamma$ searches (right)

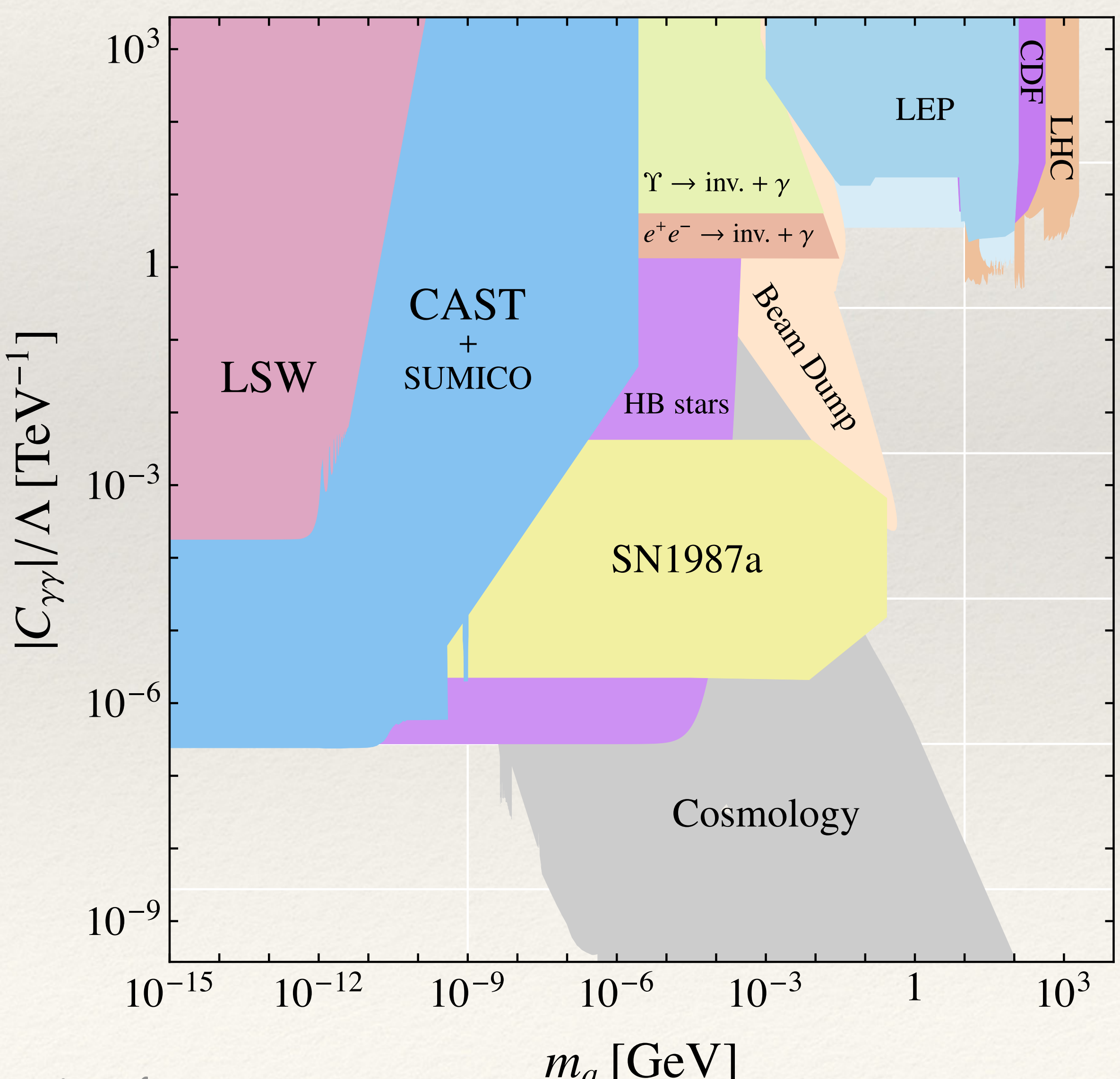
Phenomenological constraints

- Assuming the ALP decays into leptons with a significant BR, current LHC data imply interesting bounds:



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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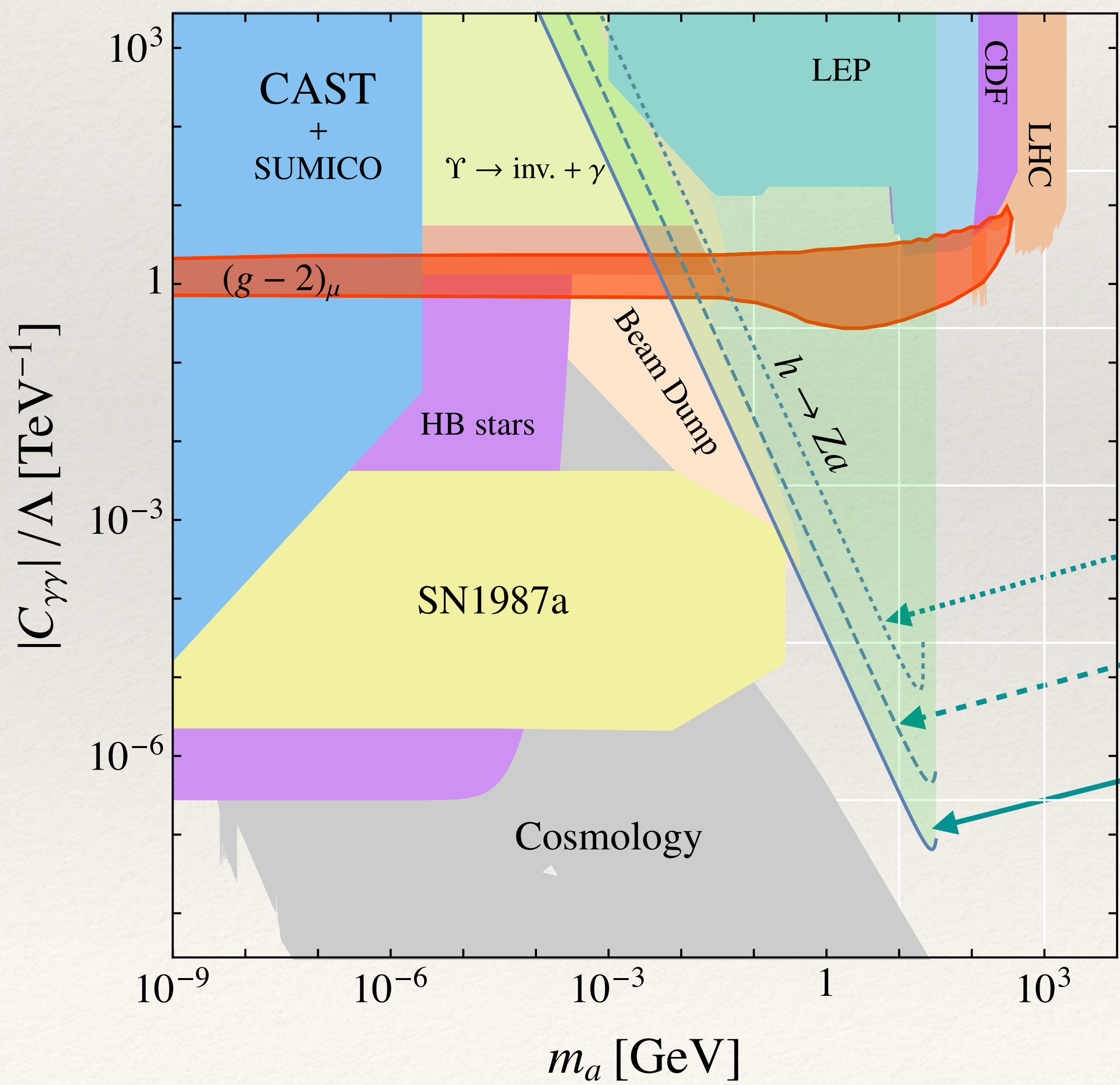

- The ALP-photon coupling can be probed even if the ALP decays predominantly to other particles!
- Region preferred by (g-2)$_\mu$ almost completely covered!

$|C_{Zh}^{\text{eff}}| = 0.015\,,\ \text{Br}(a \to \gamma\gamma) > 0.46$

$|C_{Zh}^{\text{eff}}| = 0.1\,,\ \text{Br}(a \to \gamma\gamma) > 0.011$

$|C_{Zh}^{\text{eff}}| = 0.72\,,\ \text{Br}(a \to \gamma\gamma) > 3 \cdot 10^{-4}$

(for $\Lambda = 1$ TeV)

Probing the ALP-photon coupling

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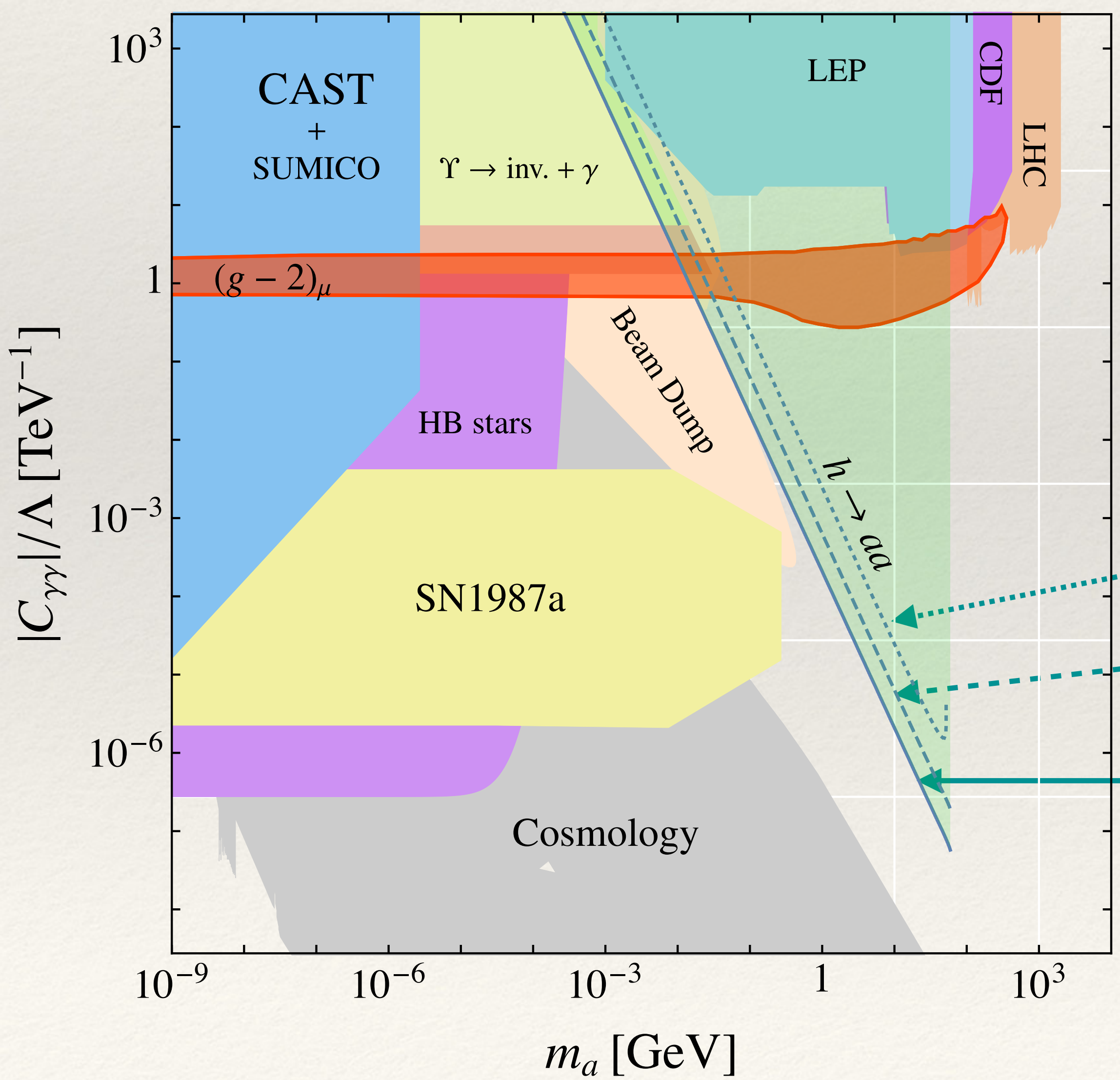

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$|C_{ah}^{\rm eff}| = 0.01,\ {\rm Br}(a \to \gamma\gamma) > 0.49$

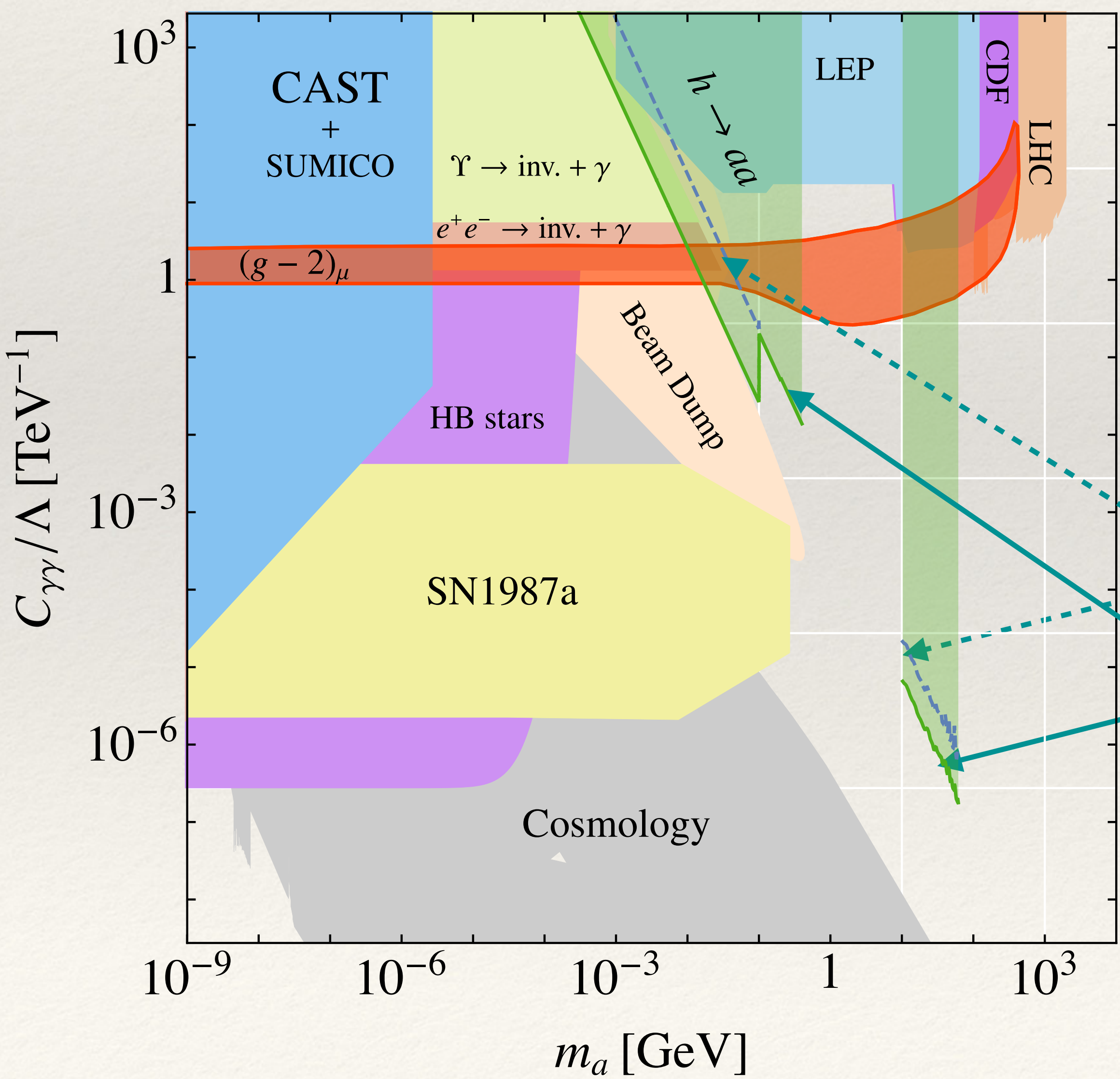
$|C_{ah}^{\rm eff}| = 0.1,\ {\rm Br}(a \to \gamma\gamma) > 0.049$

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

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

Probing the ALP-photon coupling

- Existing Higgs analyses at the LHC already probe a significant region of parameter space:



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

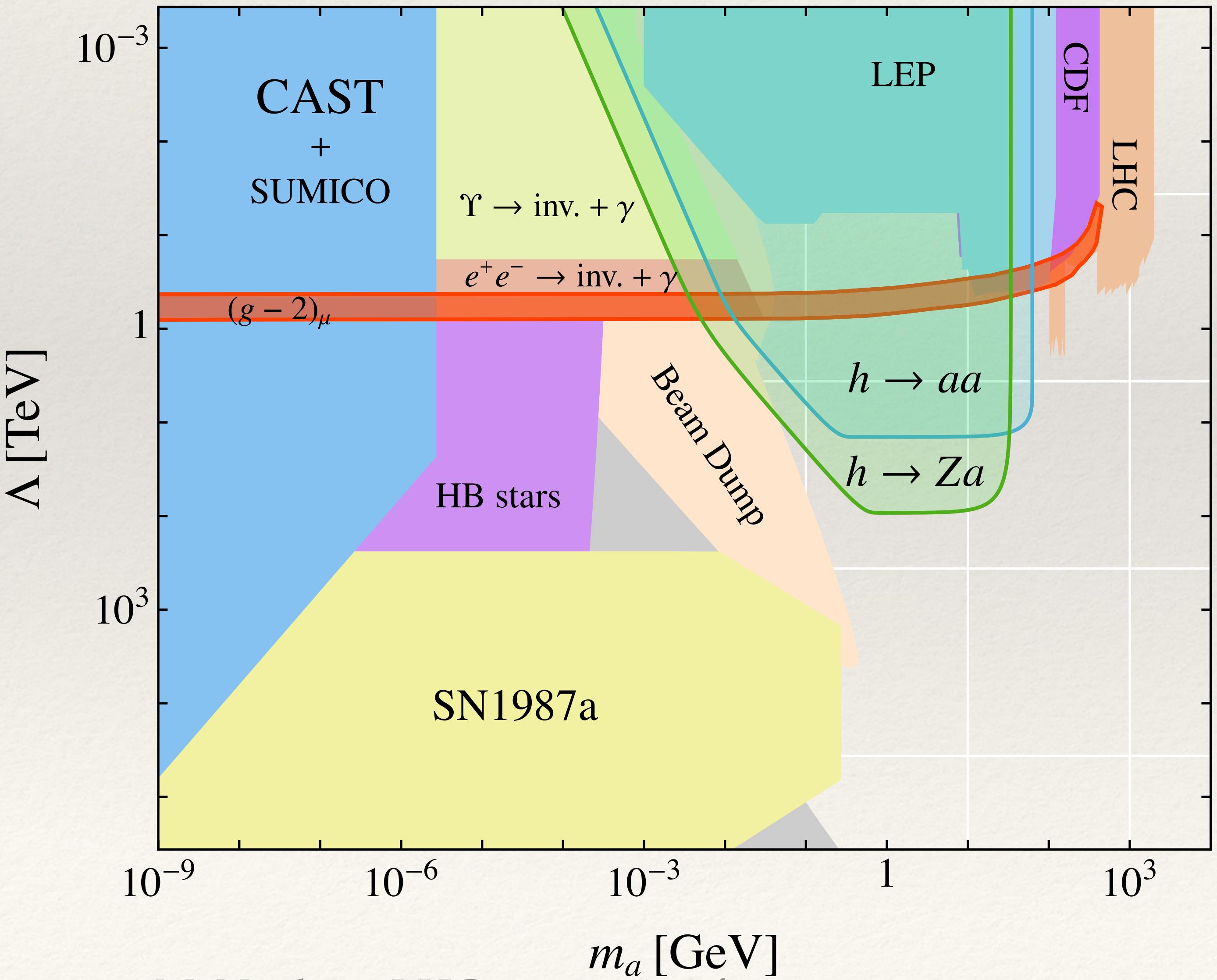
$|C_{ah}^{\text{eff}}| = 0.1, \;\; \text{Br}(a \to \gamma\gamma) > 0.049$

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

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

Probing the ALP-photon coupling

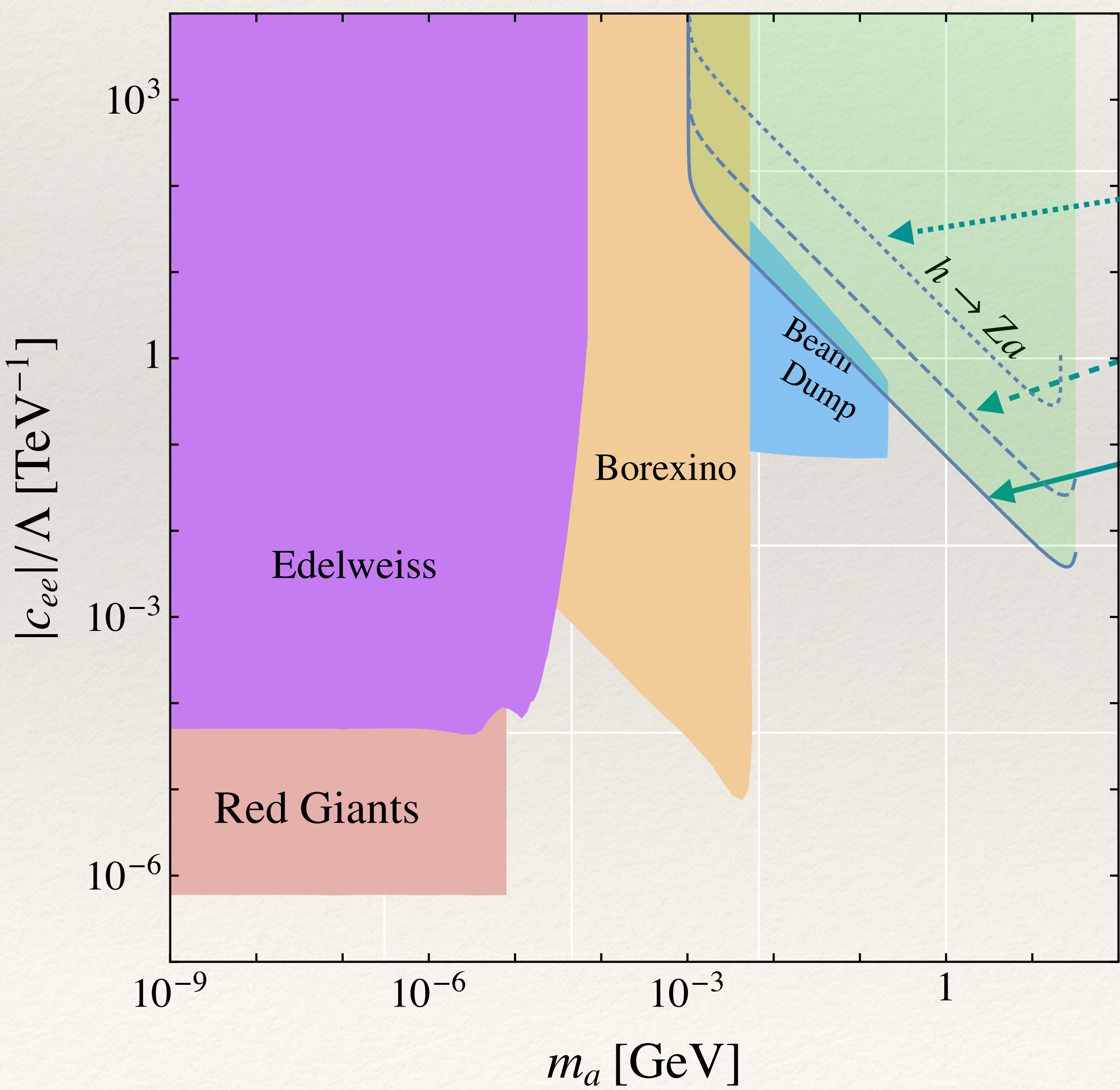
- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore new-physics scales reaching 100 TeV:



- Same as before, but with all Wilson coefficients set to 1 and varying new-physics scale Λ
- Scales up to 100 TeV can be probed in Higgs decays!

Probing the ALP-electron coupling

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



$|C_{Zh}^{\text{eff}}| = 0.015\,,\ \text{Br}(a \to e^+e^-) > 0.46$

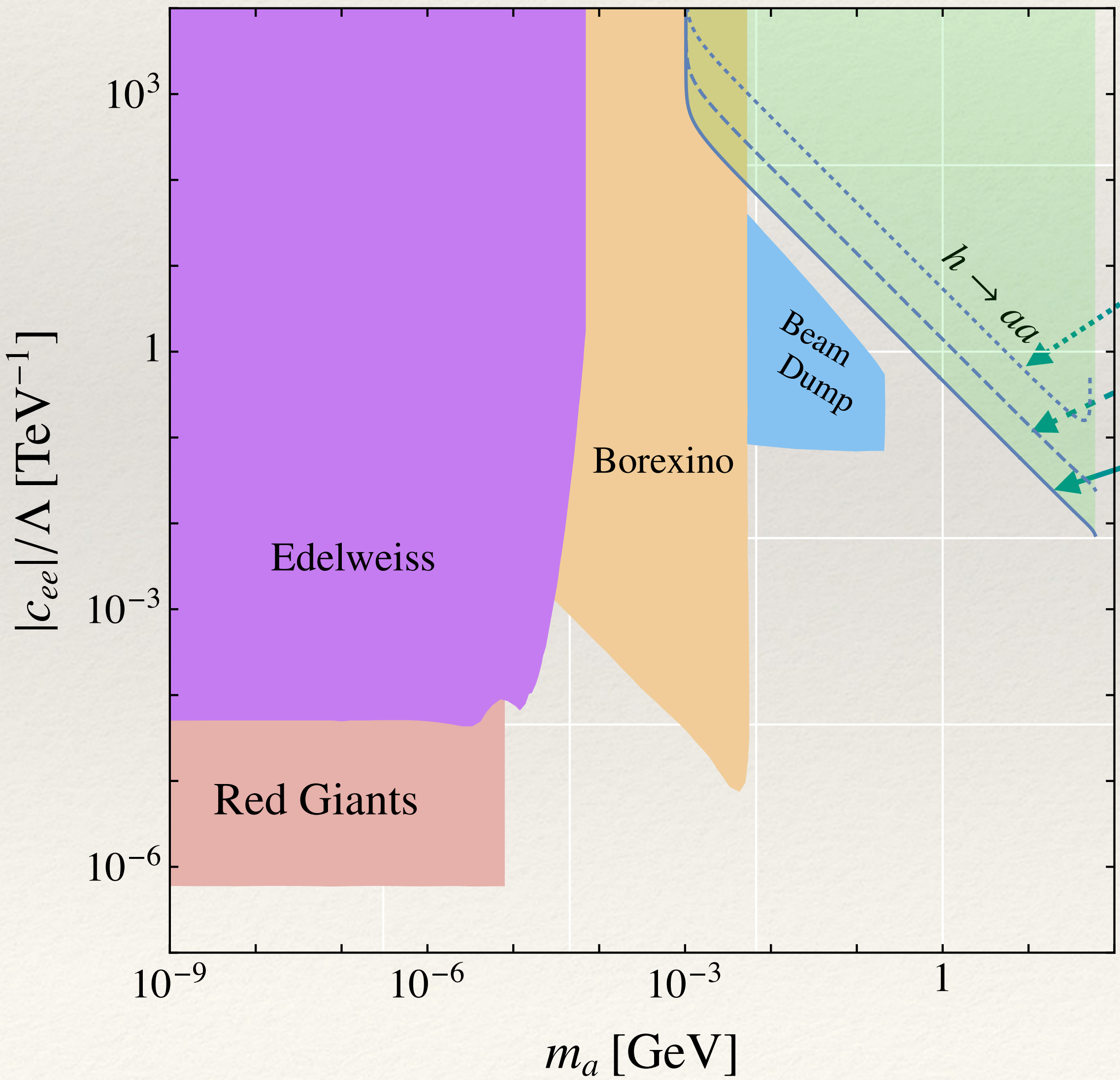
$|C_{Zh}^{\text{eff}}| = 0.1\,,\ \text{Br}(a \to e^+e^-) > 0.011$

$|C_{Zh}^{\text{eff}}| = 0.72\,,\ \text{Br}(a \to e^+e^-) > 2 \cdot 10^{-4}$

(for $\Lambda = 1$ TeV)

Probing the ALP-electron coupling

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



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

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

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

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

Conclusions

- Rare decays of the Higgs boson provide multiple new ways to probe for the existence of ALPs in the mass range between 1 MeV and 60 GeV and with couplings suppressed by scales Λ~1-100 TeV
- In some regions of parameter space, the ALP signal would enhance the measured rates for $h\to\gamma\gamma$ and $h\to Z\gamma$ (a target for the high-luminosity LHC run)
- In other regions, new searches for final states such as $h\to 4\gamma$, $h\to\mu^+\mu^-\gamma\gamma$, $h\to e^+e^-\mu^+\mu^-$ or $h\to e^+e^-+2jets$ need to be devised

Backup Slides

Electroweak precision tests

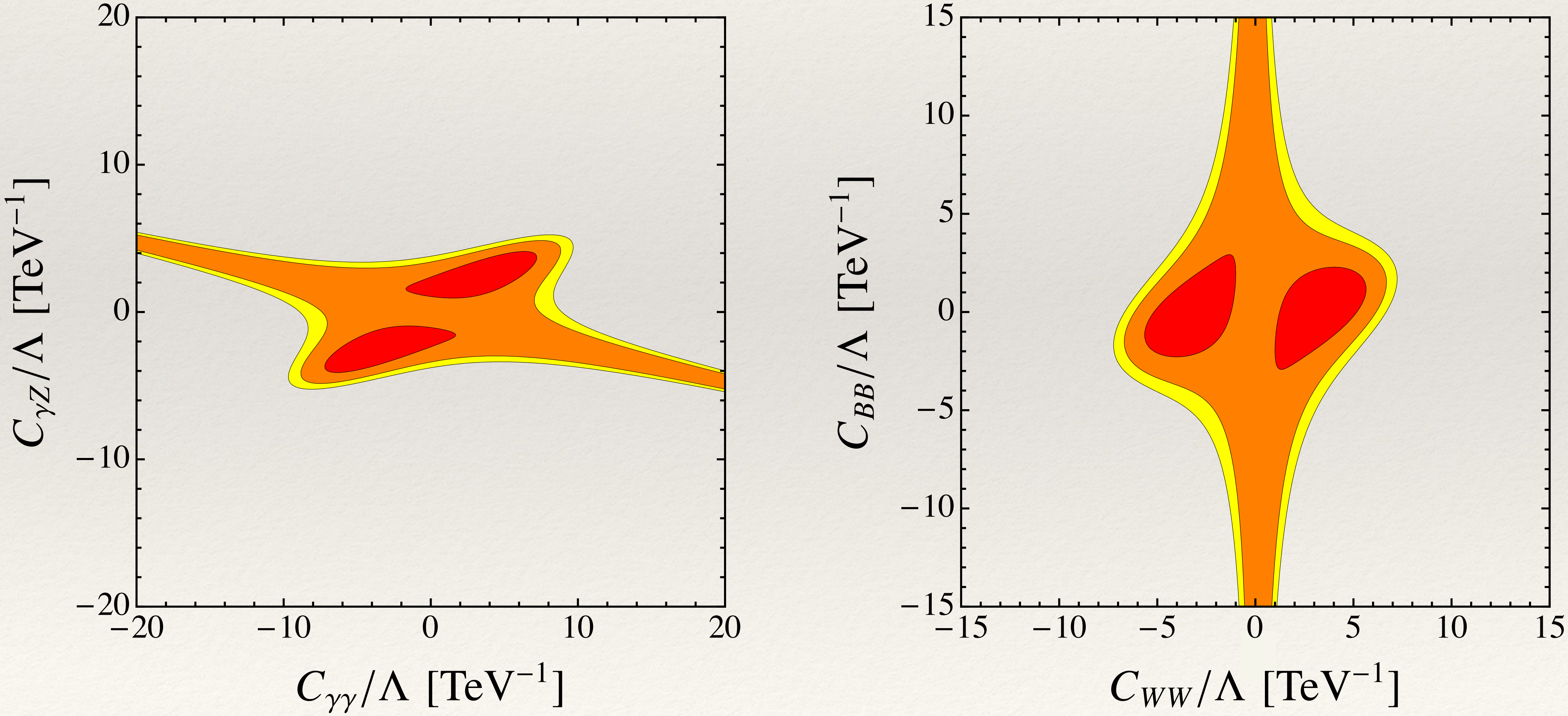
- Since we consider light new particles, loop corrections to electroweak precision observables can, in general, not be described in terms of oblique corrections
- Still, in our model the one-loop corrections to different definitions of the weak mixing angle and of the ϱ parameter can be recast in terms of *S*, *T*, *U*:

$$S = 32\alpha \frac{m_Z^2}{\Lambda^2} C_{WW}\, C_{BB} \left(\ln \frac{\Lambda^2}{m_Z^2} - 1 \right) , \qquad T = 0$$

$$U = \frac{32\alpha}{3} \frac{m_Z^2}{\Lambda^2}\, C_{WW}^2 \left(\ln \frac{\Lambda^2}{m_Z^2} - \frac{1}{3} - \frac{2c_w^2}{s_w^2} \ln c_w^2 \right)$$

Electroweak precision tests

- The resulting constraints on the Wilson coefficients derived from the global electroweak fit are rather weak:



Electroweak precision tests

- Projections for a future FCC-ee lepton collider: