Alps 2017 — An Alpine LHC Physics Summit (Obergurgl, Austria, 17-22 April 2017)

Opening Talk

Matthias Neubert

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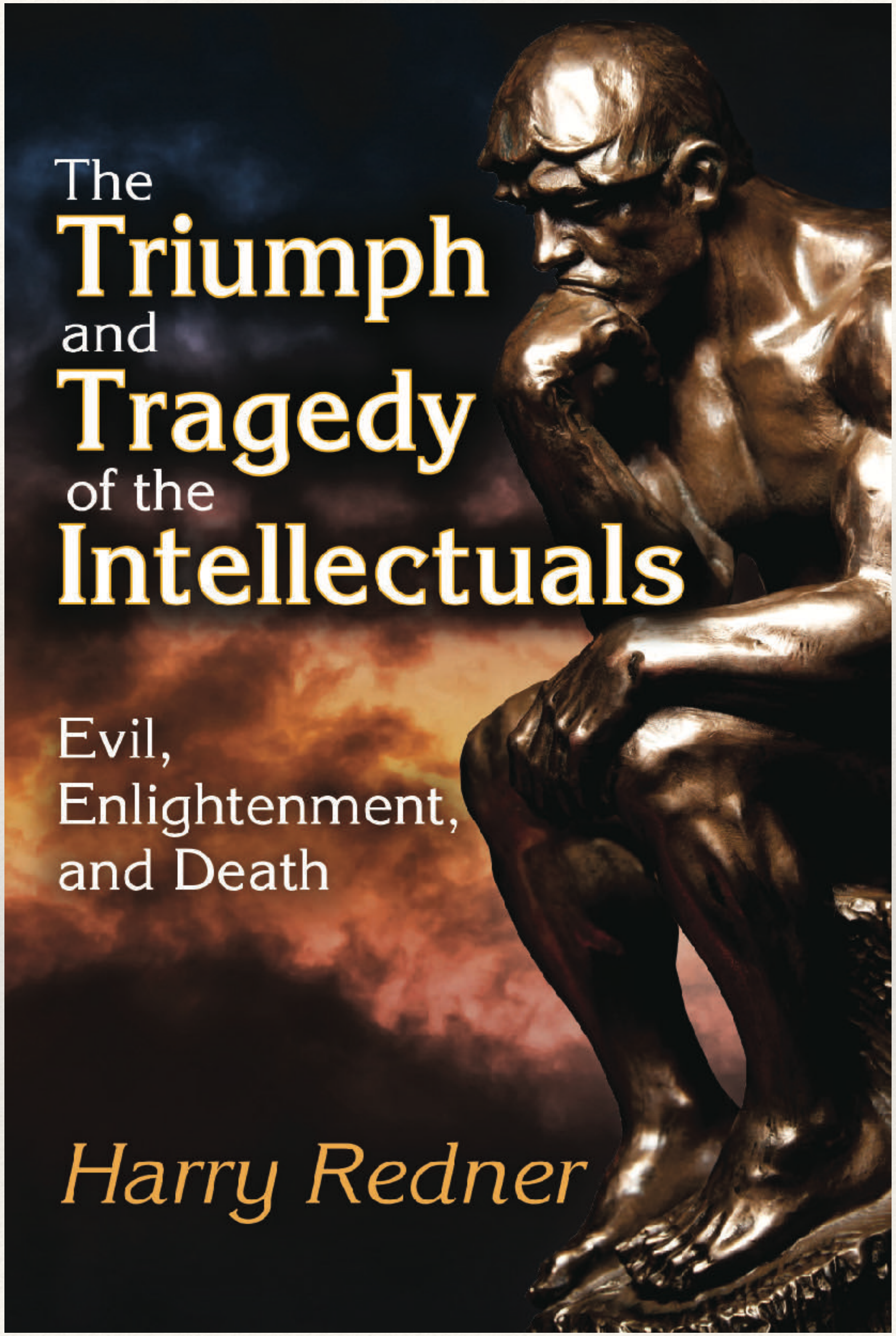
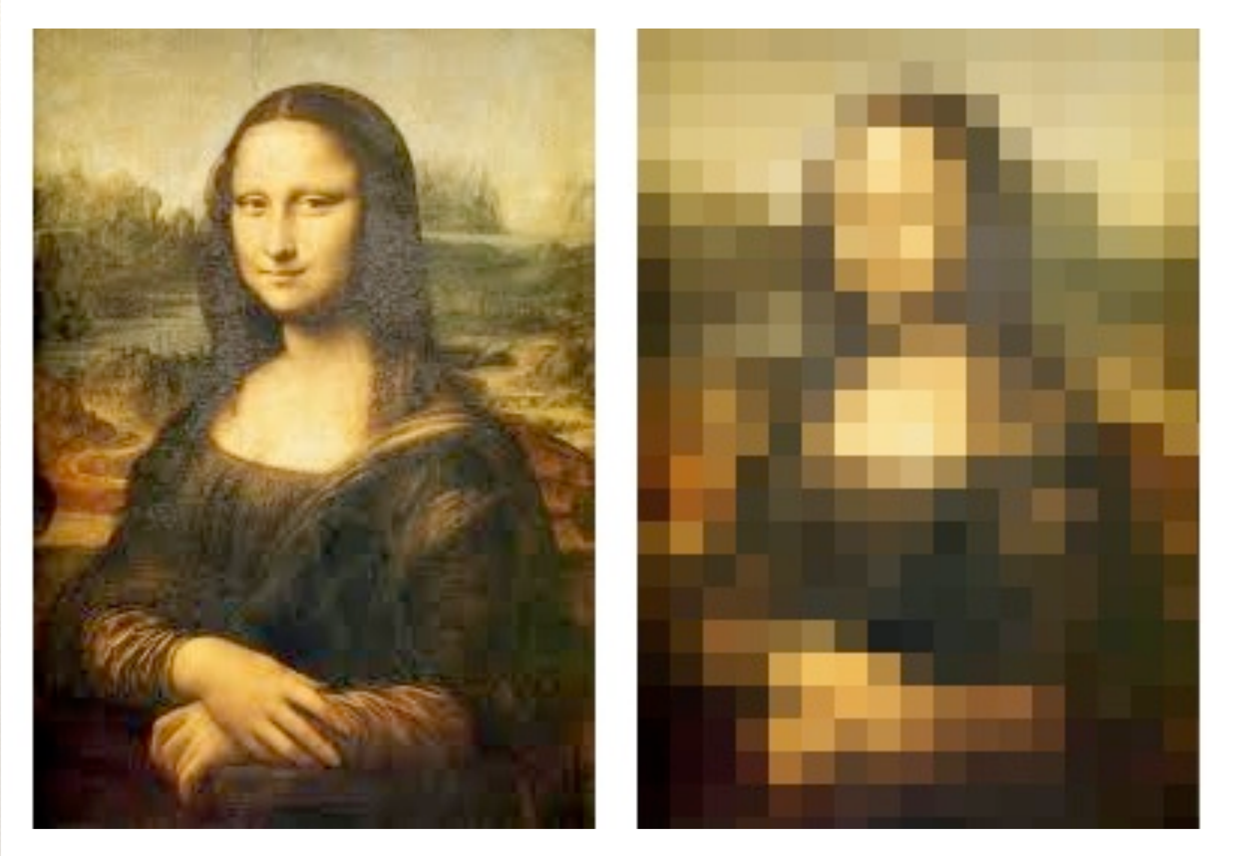
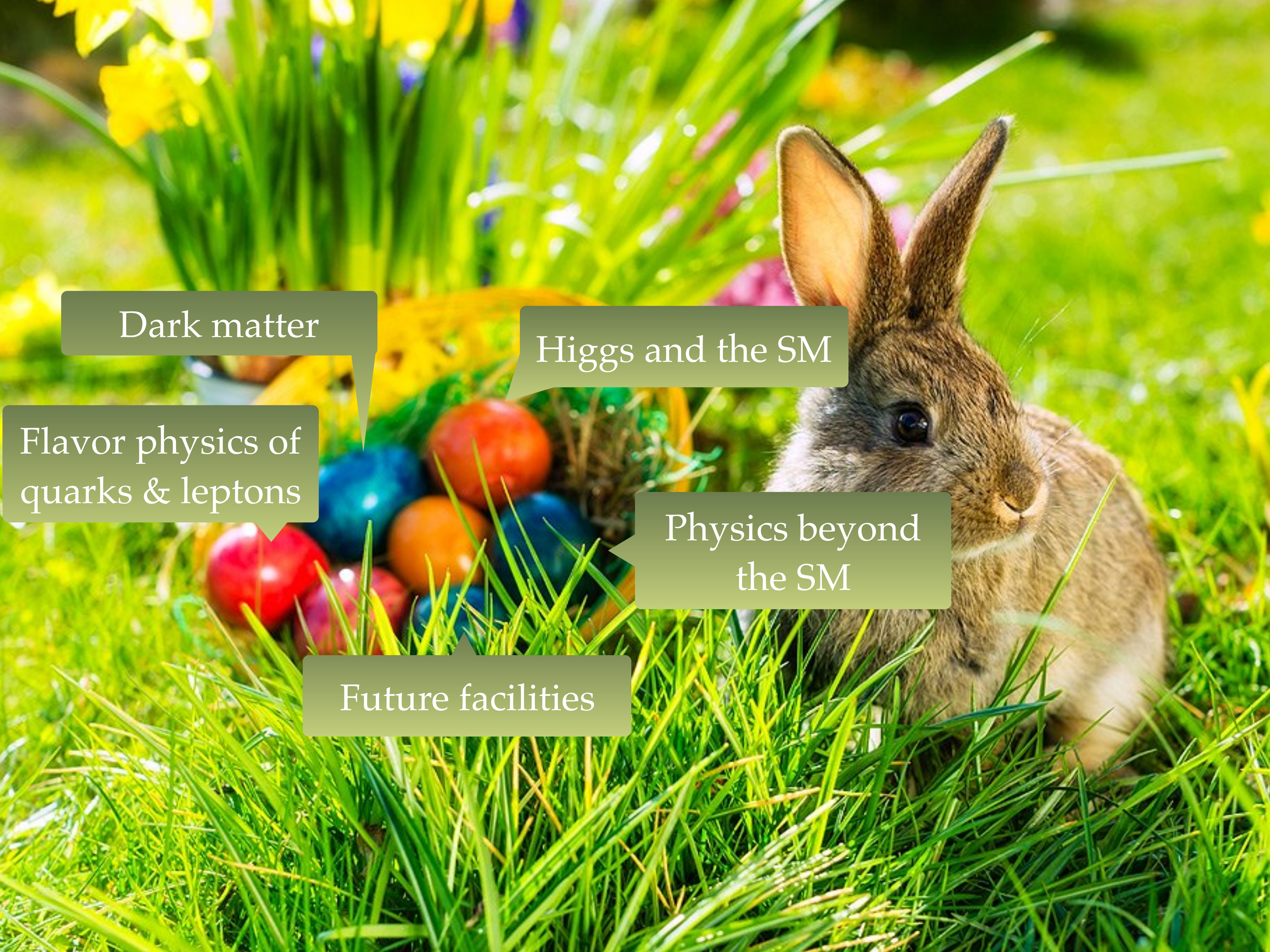
Triumph & Tragedy



Beyond the SM

Searching on all Fronts




Dark matter
Higgs and the SM
Flavor physics of quarks & leptons
Physics beyond the SM
Future facilities

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LHC Probes of Axion-Like Particles

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(based on work in collaboration with Andrea Thamm and Martin Bauer)

Motivation

- New pseudoscalar particles with masses below the weak scale 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, …
- In the absence of hints for new physics at the energy frontier, searches for weakly-coupled light particles are becoming a high-priority target for the HEP community
- 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]

Motivation

- Assume the existence of a new spin-0 resonance a, which is a gauge singlet under the SM and whose mass is much lighter than the electroweak scale
- A natural way to get such a light particle is to impose a shift symmetry under $a \to a+c$
- We assume that the UV theory is CP invariant, and that CP is broken only by the SM Yukawa interactions
- The boson a is assumed to be a CP-odd pseudoscalar, i.e. an axion-like particle (ALP)

Effective Lagrangian

- The couplings of *a* to SM particles start at dimension-5 order and are described by the effective Lagrangian (with Λ a new-physics scale):

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

- The only other dimension-5 operator:

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

can be reduced to the fermionic operators above by the equations of motion

Effective Lagrangian

- The couplings of *a* to SM particles start at dimension-5 order and are described by the effective Lagrangian (with Λ a new-physics scale):

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \frac{\partial^\mu a}{\Lambda} \sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$

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

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

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

Effective Lagrangian

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

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

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:

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

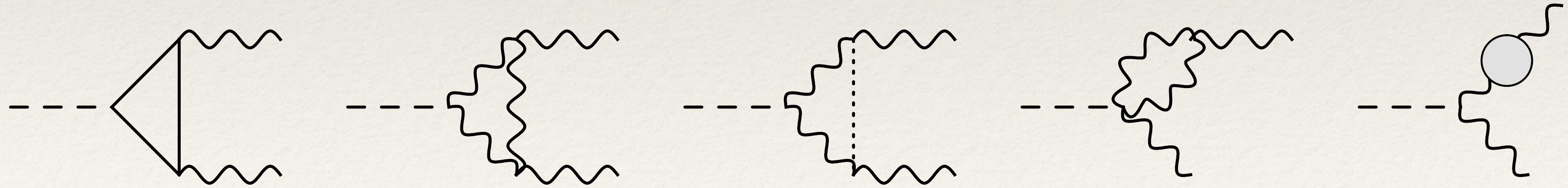
ALP decay into photons

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

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

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

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



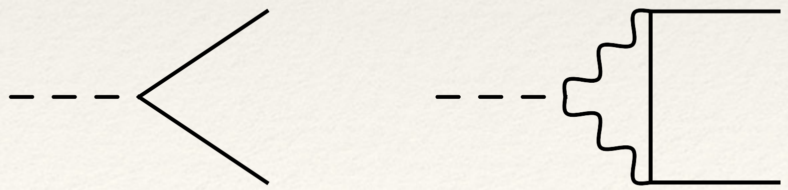
ALP decay into lepton pairs

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

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

where:

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



Hadronic decays of ALPs

- At the parton level, *a* can decay into gluons and quarks
- In the real world, these decays are allowed only if m_a is larger than (twice) the pion mass
- The corresponding decay rates can only be calculated reliably if $m_a \gg \Lambda_{\rm QCD}$ is in the perturbative regime:

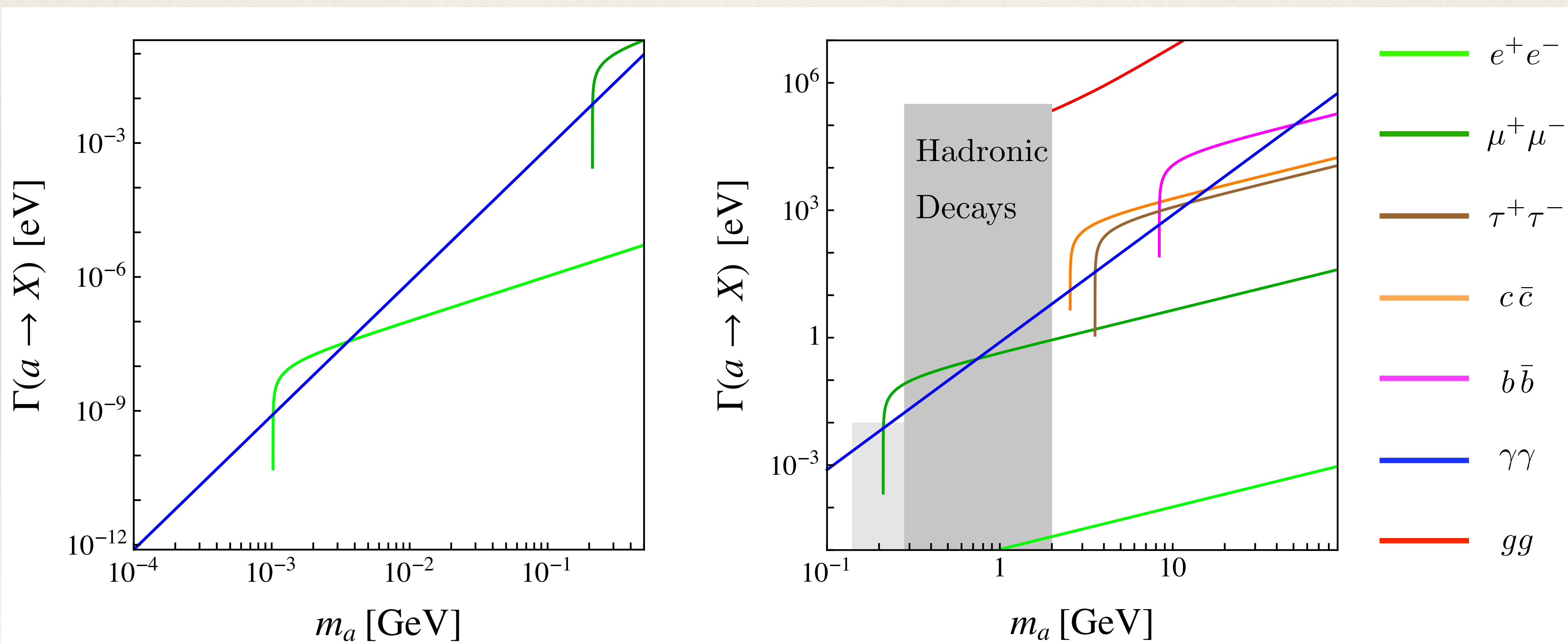
$$\Gamma(a \to \text{hadrons}) = \frac{32\pi\, \alpha_s^2(m_a)\, m_a^3}{\Lambda^2} \left[1 + \left(\frac{97}{4} - \frac{7n_q}{6} \right) \frac{\alpha_s(m_a)}{\pi} \right] \left| C_{GG} + \sum_{q=1}^{n_q} \frac{c_{qq}}{32\pi^2} \right|^2$$

$$\Gamma(a \to Q\bar{Q}) = \frac{3m_a\, \overline{m}_Q^2(m_a)}{8\pi\Lambda^2} \left| c_{QQ}^{\rm eff} \right|^2 \sqrt{1 - \frac{4m_Q^2}{m_a^2}}$$

[Spira, Djouadi, Graudenz, Zerwas 1995]

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:

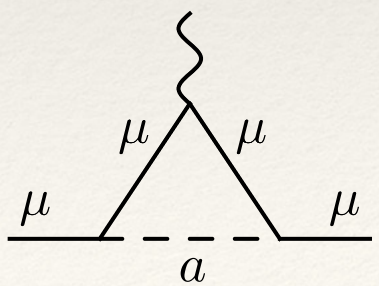
$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49)\cdot 10^{-11}$$

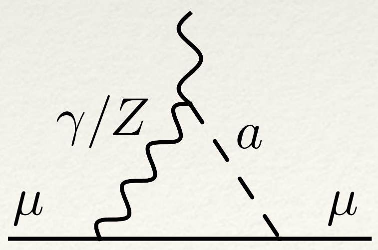
- In our model we find two one-loop contributions of potentially different sign:

$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} + \delta_2 + 2 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right]\right.$$
$$\left. - \frac{\alpha}{2\pi}\,\frac{1-4s_w^2}{s_w c_w}\,c_{\mu\mu}\,C_{\gamma Z}\left(\ln\frac{\mu^2}{m_Z^2} + \delta_2 + \frac{3}{2}\right)\right\}$$

from D=6 SMEFT

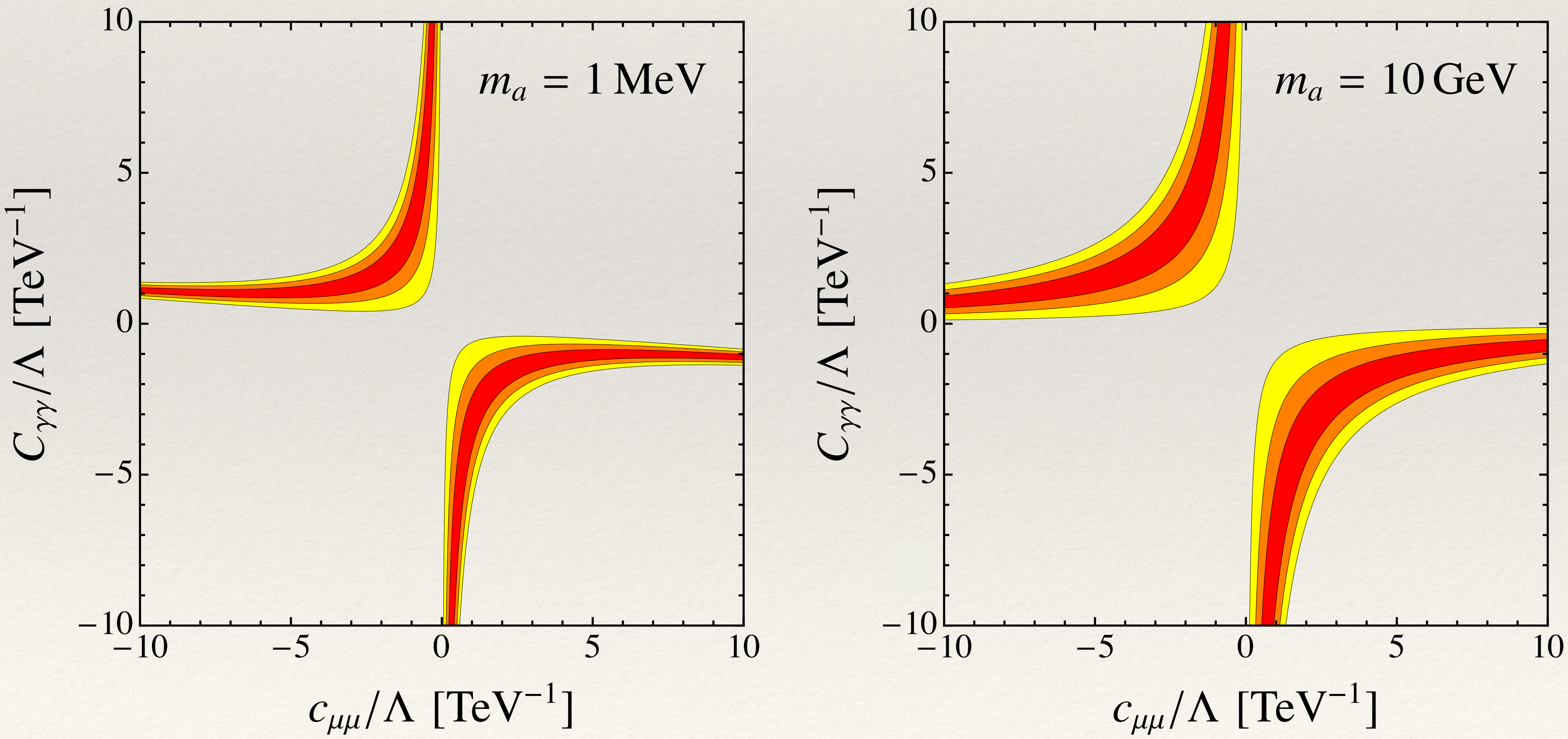
[see also: Marciano, Masiero, Paradisi, Passera 2016]





$(g-2)_\mu$ anomaly

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



Rare Higgs decays as an ALP laboratory

Higgs decays into ALPs

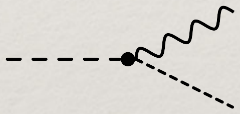
- The effective Lagrangian allows for the decays $h \to Za$ and $h \to aa$ at rates likely to be easily accessible in the high-luminosity phase of the LHC [Bauer, MN, Thamm (to appear)]
- The subsequent ALP decays can readily be reconstructed, largely irrespective of how the ALP decays
- Higgs physics thus provides a powerful observatory for ALPs in the mass range between 30 MeV and 60 GeV, which is otherwise not easily accessible to experimental searches (except for some rather loose bounds, see below)

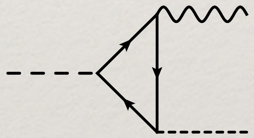
Operator analysis of the decay h→Za

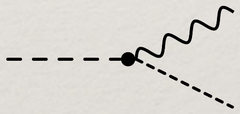
- The effective Lagrangian does not contain any D=5 operator giving a tree-level contribution to this decay

- 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

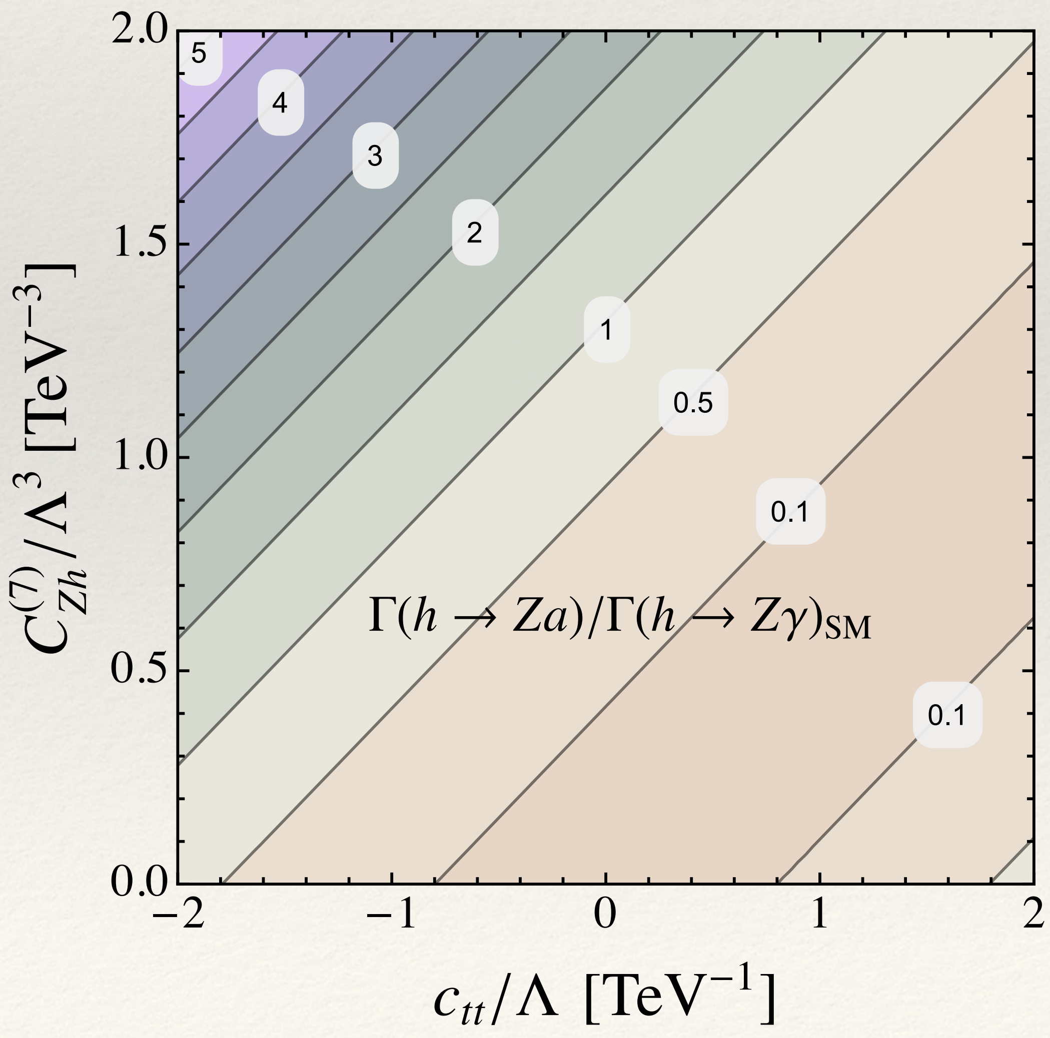
[Bauer, MN, Thamm 2016]

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 $h \to Za$

- The argument for the absence of a D=5 operator giving a tree-level contribution to the rate can be avoided in the class of 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:

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

can arise, which does give a tree-level contribution to the rate [Bauer, MN, Thamm 2016]

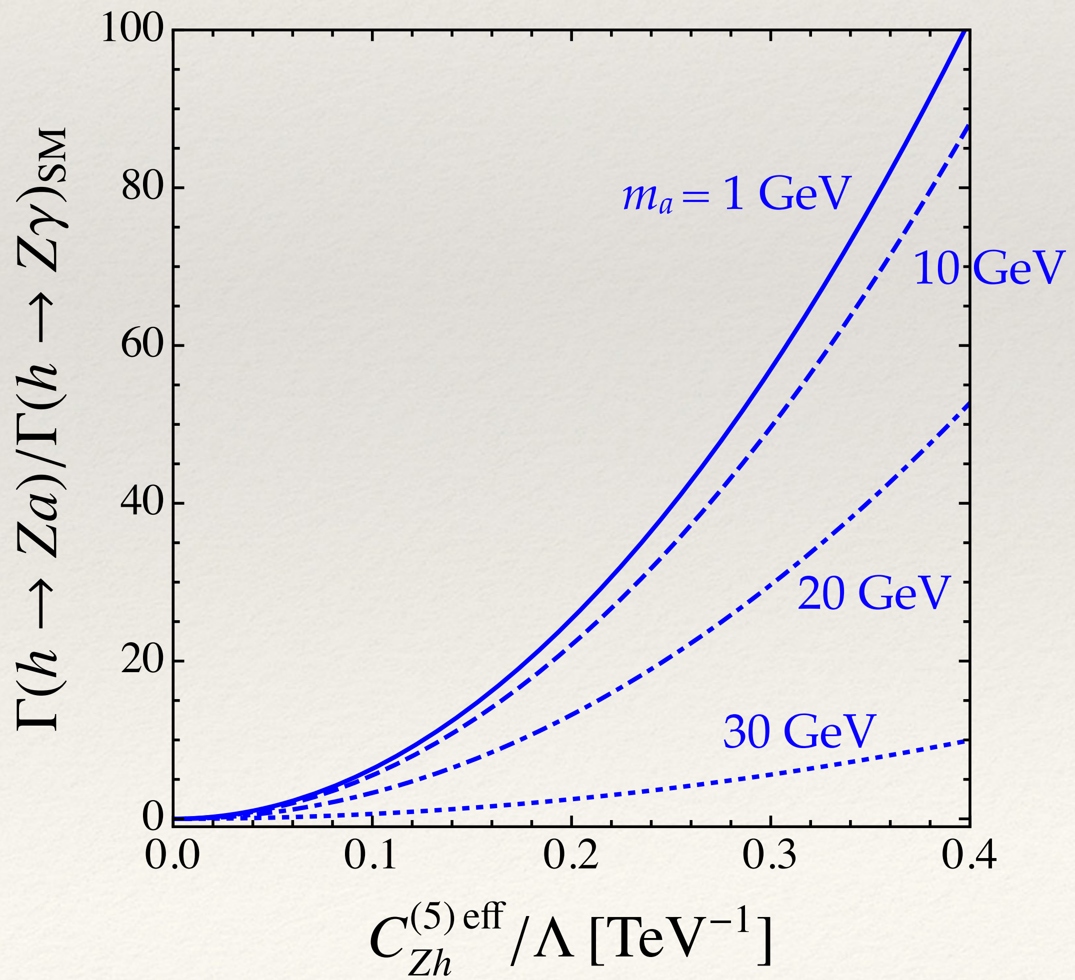
Operator analysis of the decay h→Za

- 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 $h \to Za$

- 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 $l = e, \mu, \tau$
  - $h \to Za \to Z + 2jets$, 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!

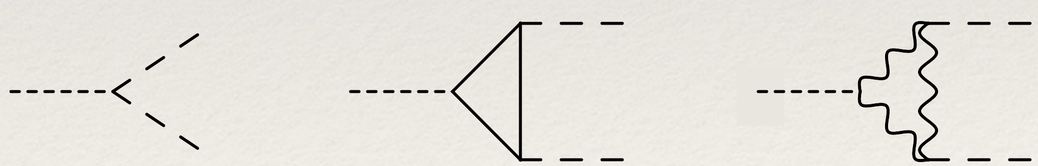
Operator analysis of the decay h→aa

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

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

with:

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



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

Operator analysis of the decay $h \to aa$

- 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 four photons are either resolved (for $m_a > \sim 100$ MeV) or appear as two photons in the calorimeter
  - $h \to aa \to l^+ l^- l^+ l^-$ with $l = e, \mu, \tau$
  - $h \to aa \to 4 jets$, including heavy-quark jets
  - $h \to aa \to invisible$
- All of these decay modes (perhaps even the invisible ones) can be reconstructed in Run-2 at the LHC!

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 decay length can be written as:

$$L_a = \frac{\beta_a \gamma_a}{\Gamma_a} = \sqrt{\gamma_a^2 - 1}\,\frac{\mathrm{Br}(a \to XX)}{\Gamma(a \to XX)}$$

- Fraction of events with ALPs decaying in the detector:

$$f_{\rm dec} = 1 - e^{-L_{\rm det}/L_a}$$

Decay-length effect

- We can then define effective branching ratios:

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

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

- For $L_a >> L_{\mathrm{det}}$, the fraction of events scales like:

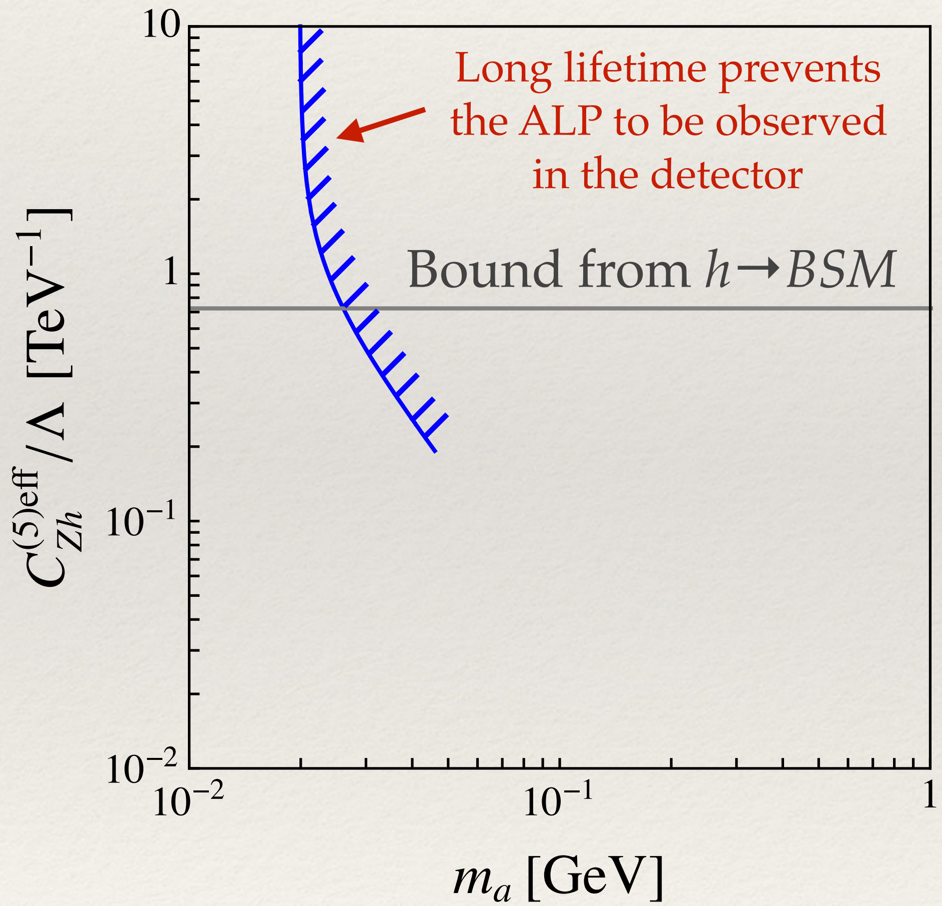
$$f_{\mathrm{dec}} \approx L_{\mathrm{det}}/L_a \propto \Gamma(a \to XX)/\mathrm{Br}(a \to XX)$$

and hence the effective branching ratios become independent of $\mathrm{Br}(a \to XX)$

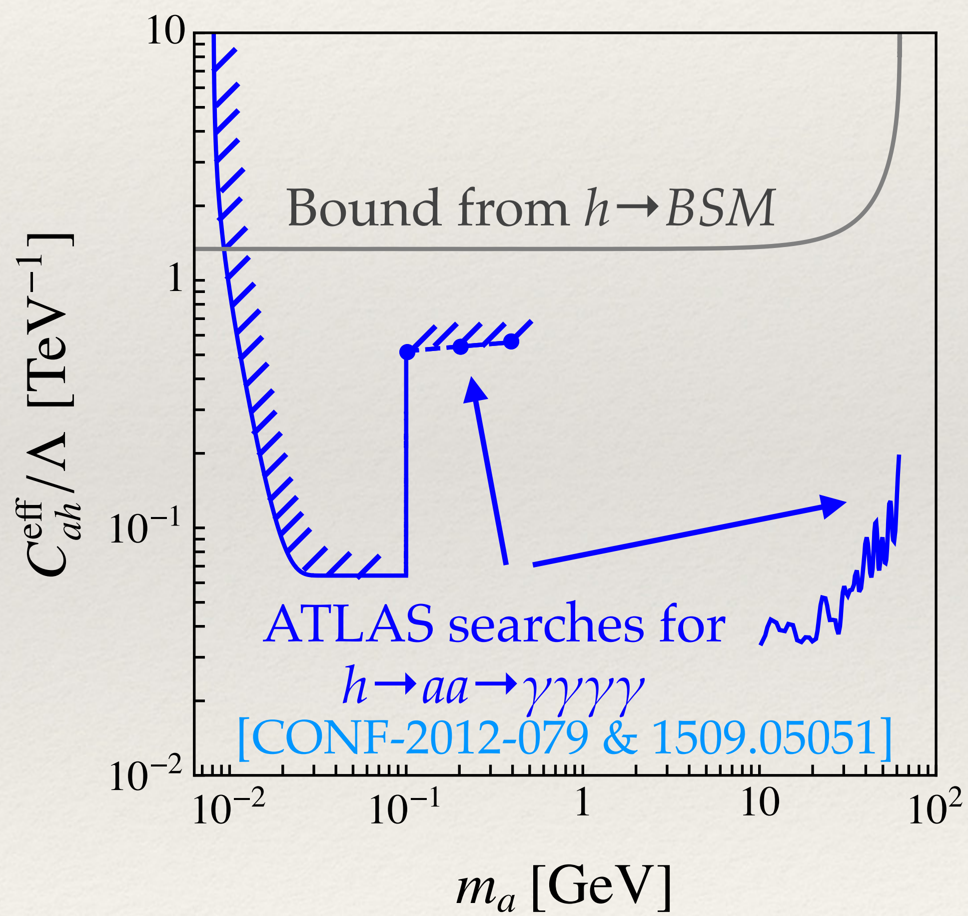
Probing the ALP–photon coupling

Phenomenological constraints

- Under the **assumption that the ALP decays into photons**, current LHC data imply interesting bounds:



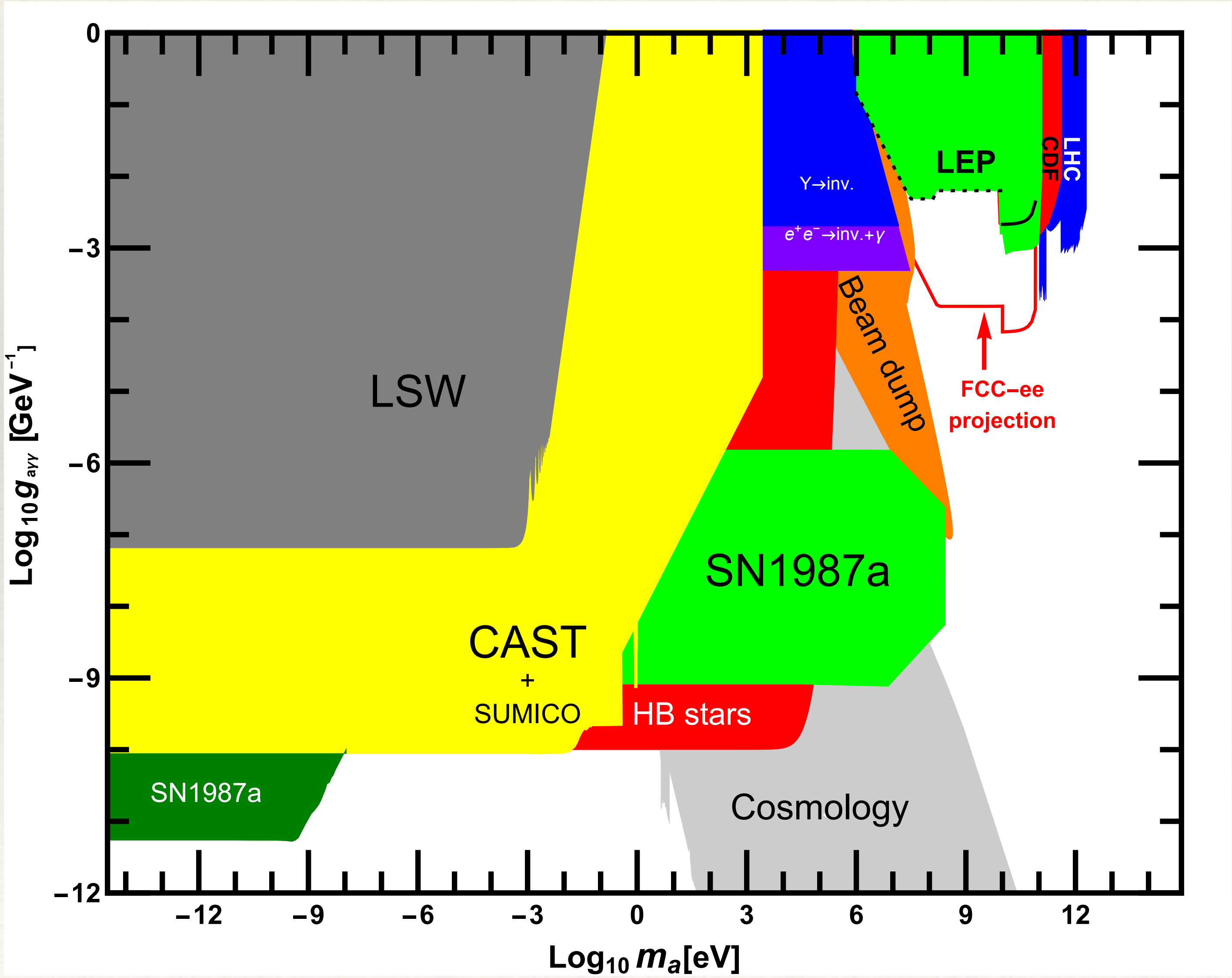
Upper bound derived from the non-observation of $h \to Z\gamma$ decay at ATLAS/CMS



Upper bound derived from the measurements of $h \to \gamma\gamma$ decay at ATLAS/CMS

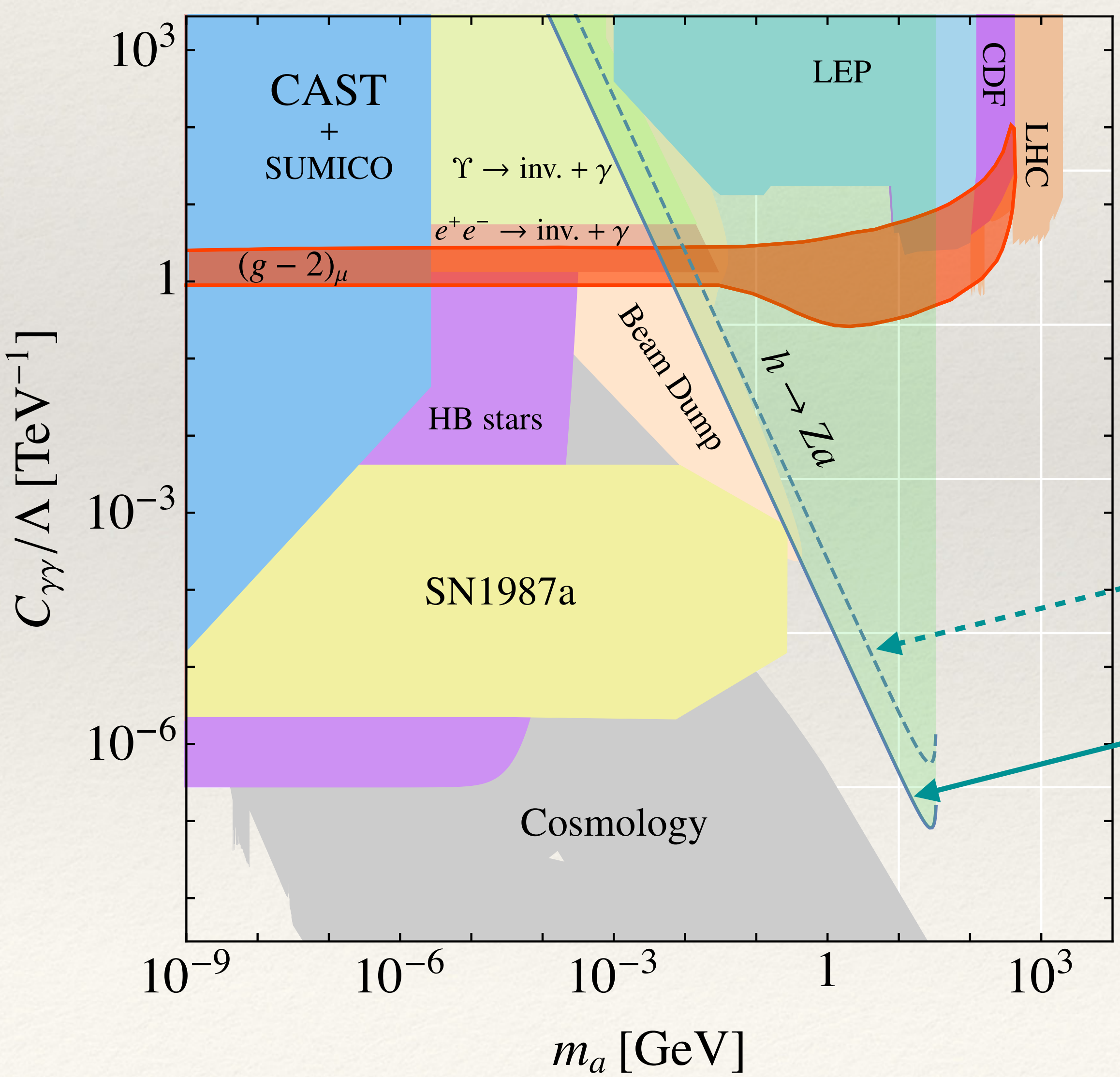
Region accessible to LHC searches

- At present, limits on photophilic ALPs with masses above 30 MeV are rather weak: [Jaeckel, Spannovsky 2015]



Region accessible to LHC searches

- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore a much larger 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!

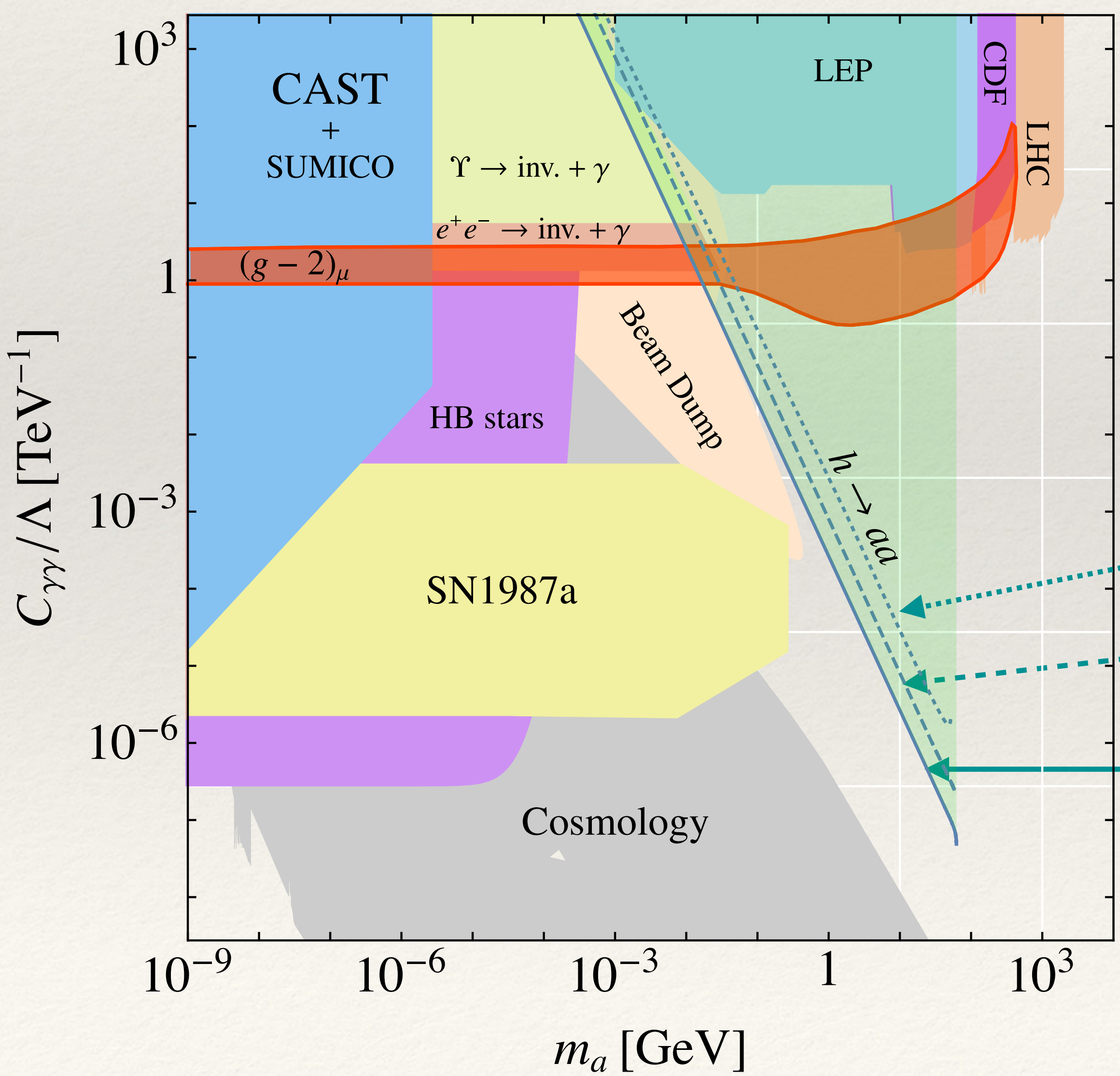
$|C_{Zh}^{\text{eff}}| = 0.1,\ \text{Br}(a \to \gamma\gamma) > 0.011$

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

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

Region accessible to LHC searches

- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore a much larger 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!

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

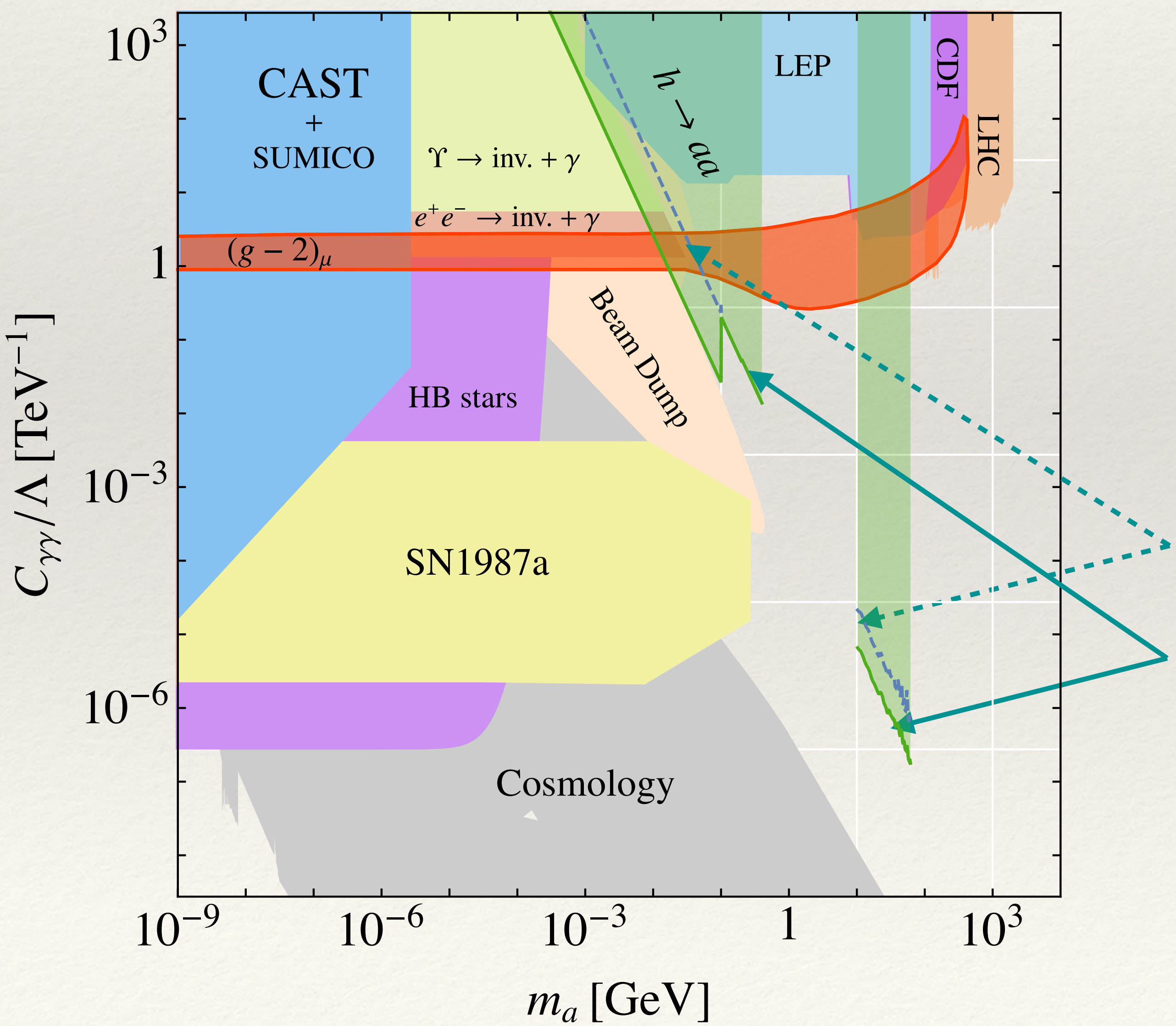
$|C_{ah}^{\mathrm{eff}}| = 0.1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.049$

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

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

Region accessible to LHC searches

- 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!

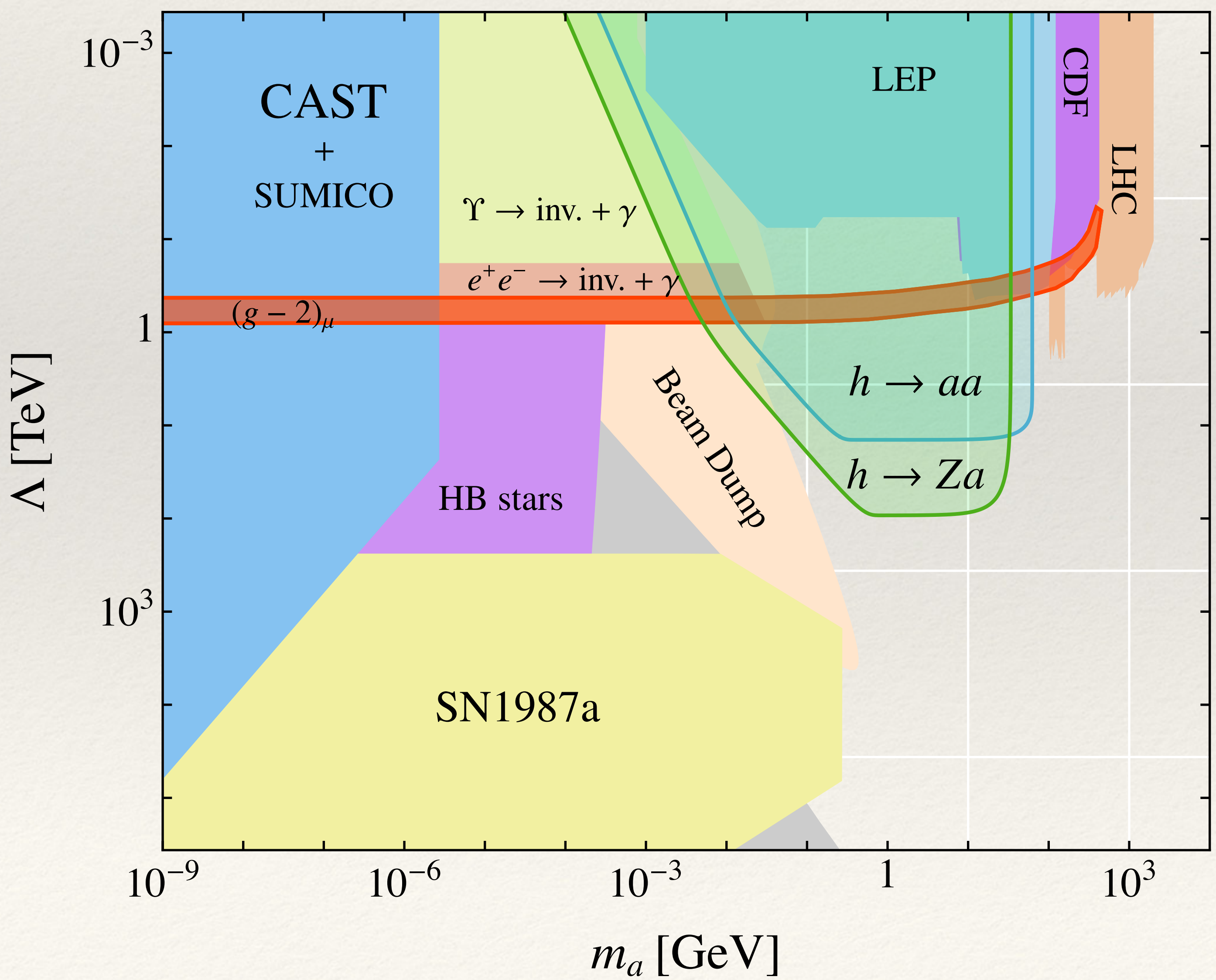
$|C_{ah}^{\rm eff}| = 0.1, \ \mathrm{Br}(a \to \gamma\gamma) > 0.049$

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

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

Region accessible to LHC searches

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



- 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!

Conclusions

- Rare decays of the Higgs boson provide multiple new ways to probe for the existence of ALPs in the mass range between 30 MeV and 60 GeV and with couplings suppressed by the 1-100 TeV scale
- 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

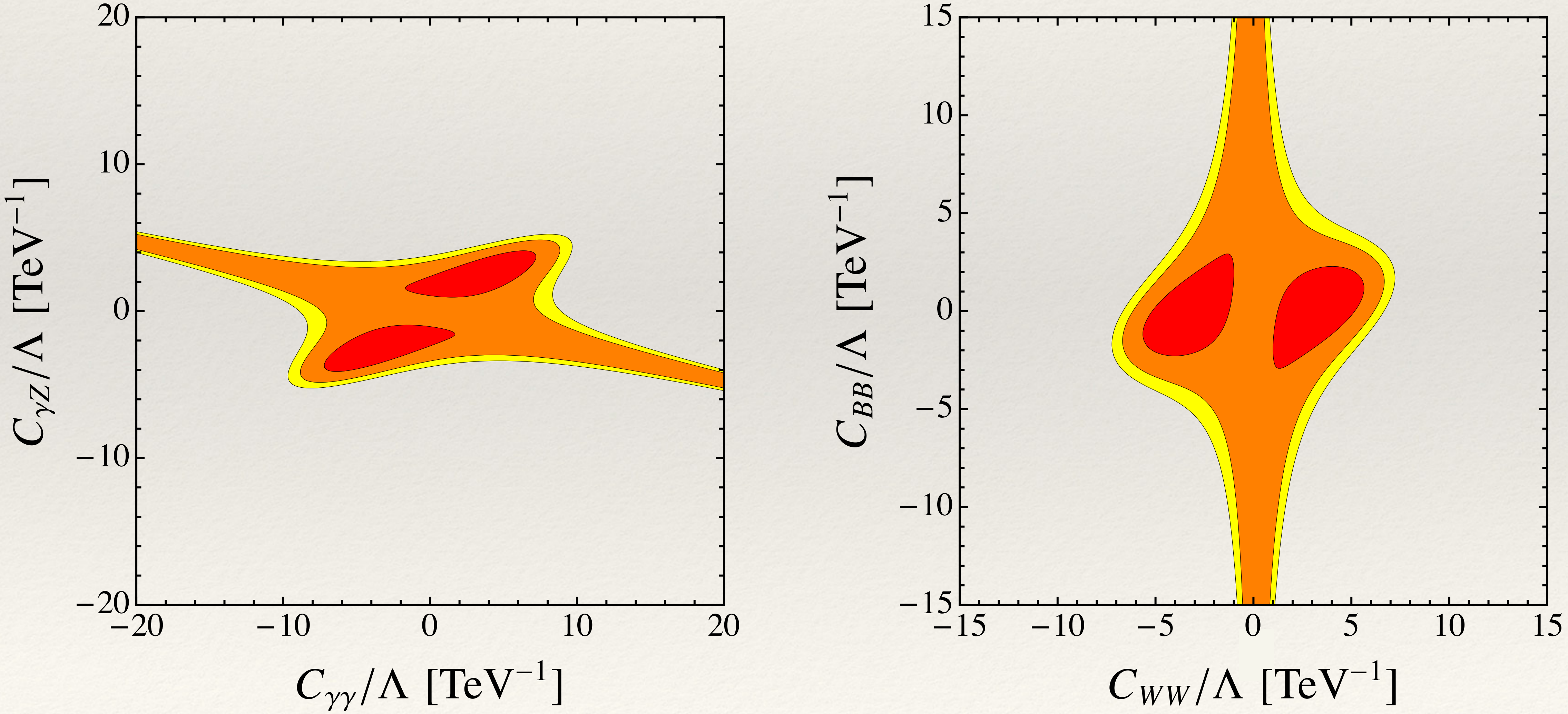
- Since we consider light new particles, loop corrections to electroweak precision observables can, in general, not be described in terms of oblique corrections
- Still, in our model the one-loop corrections to different definitions of the weak mixing angle and of the ϱ parameter can be recast in terms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

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

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

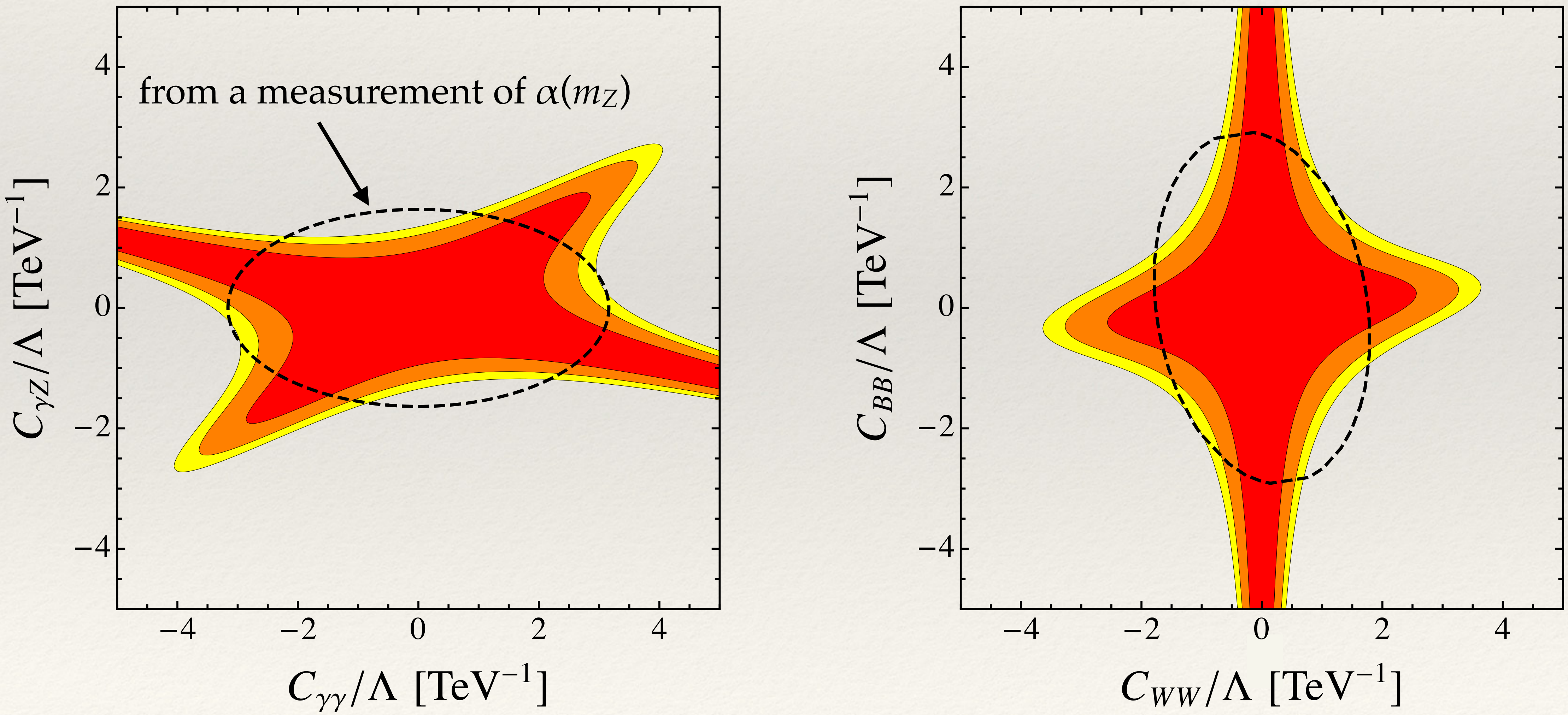
Electroweak precision tests

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



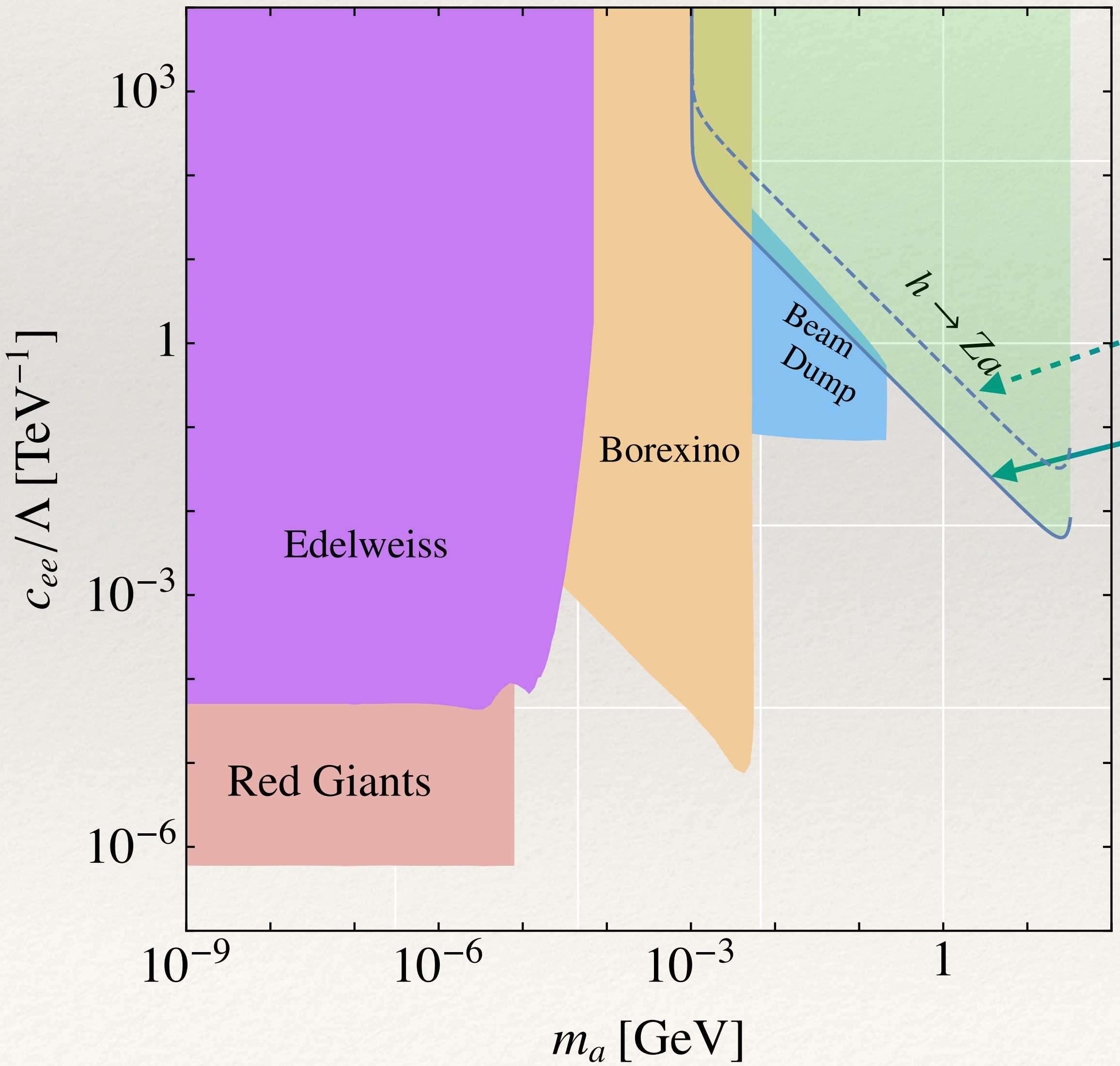
Electroweak precision tests

- Projections for a future FCC-ee lepton collider:



Probing the ALP-electron coupling

- Higgs analyses at the LHC will allow exploring a much larger region of parameter space than previous searches:



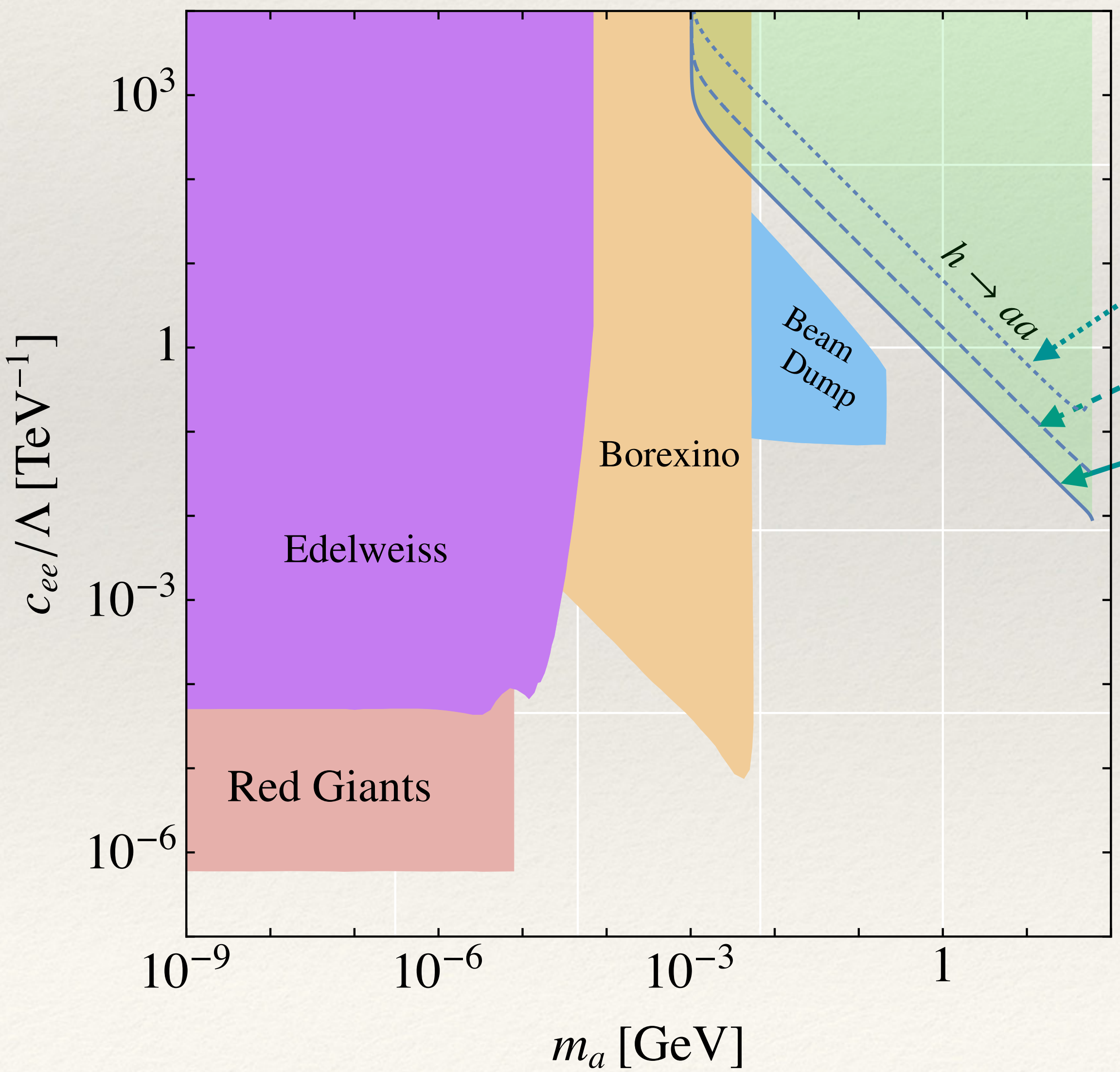
$|C_{Zh}^{\mathrm{eff}}| = 0.1,\ \mathrm{Br}(a \to e^+e^-) > 0.08$

$|C_{Zh}^{\mathrm{eff}}| = 0.72,\ \mathrm{Br}(a \to e^+e^-) > 0.002$

(for $\Lambda = 1$ TeV)

Probing the ALP-electron coupling

- Higgs analyses at the LHC will allow exploring a much larger region of parameter space than previous searches:



$|C_{ah}^{\mathrm{eff}}| = 0.01,\ \mathrm{Br}(a \to e^+e^-) > 0.8$

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

$|C_{ah}^{\mathrm{eff}}| = 1,\ \mathrm{Br}(a \to e^+e^-) > 0.02$

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