
© Matthias Neubert

*Les Rencontres de Physique de la Vallée d'Aoste*
*La Thuile, Aosta Valley, 15 March 2019*

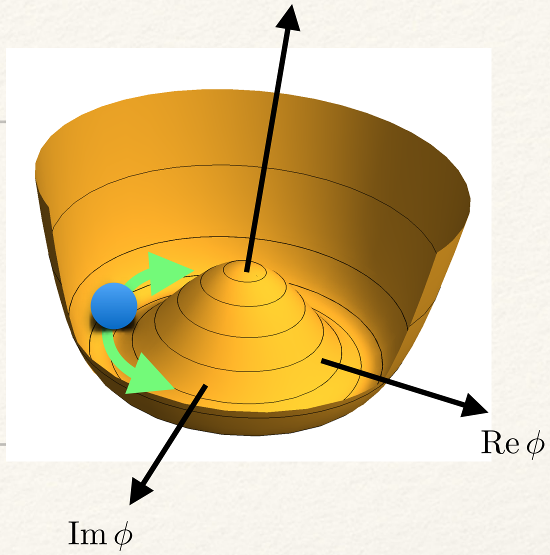
# Recent Progress on ALPs

Matthias Neubert

PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

based on work with M. Bauer, A. Thamm & M. Heiles: 1704.08207 (PRL), 1708.00443 (JHEP) & 1808.10323 (EPJC)

# Motivation



- **Axion-like particles** (ALPs) appear in many BSM scenarios and are well motivated: strong CP problem, mediator to hidden sector, pNGB of spontaneously broken global symmetry, explanation of $(g-2)_\mu$, …

- Assume the existence of a new pseudoscalar resonance *a*, which is a SM singlet and whose mass is protected by a (approximate) shift symmetry $a \to a + const.$

- How can one probe such an ALP at colliders?

[previous studies: Kim, Lee 1989; Djouadi, Zerwas, Zunft 1991; Rupak, Simmons 1995; Kleban, Ramadan 2005; Mimasu, Sanz 2014; Jäckel, Spannowsky 2015; Knapen, Lin, Lou, Melia 2016; Brivio et al. 2017; …]

# Effective Lagrangian

- The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale):

[Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$

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

# Effective Lagrangian

- The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale):

[Georgi, Kaplan, Randall 1986]

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

# Effective Lagrangian

- The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale):

[Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$

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

⇓ EWSB

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

$$(C_{\gamma\gamma} = C_{WW} + C_{BB}\ \text{etc.})$$

# Effective Lagrangian

- The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP scale):

[Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar\psi_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$

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

EWSB

EWSB

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

$(C_{\gamma\gamma} = C_{WW} + C_{BB}$ etc.)

$$\sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar f\,\gamma_\mu\gamma_5\,f \quad + \text{flavor off-diagonal terms}$$

# Effective Lagrangian

- The ALP couplings to the SM start at D=5 and are described by the effective Lagrangian (with $\Lambda = 32\pi^2 f_a |C_{GG}|$ a NP 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 D=6 order and higher, additional interactions arise:

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

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

- Include one-loop corrections in production and decay rates

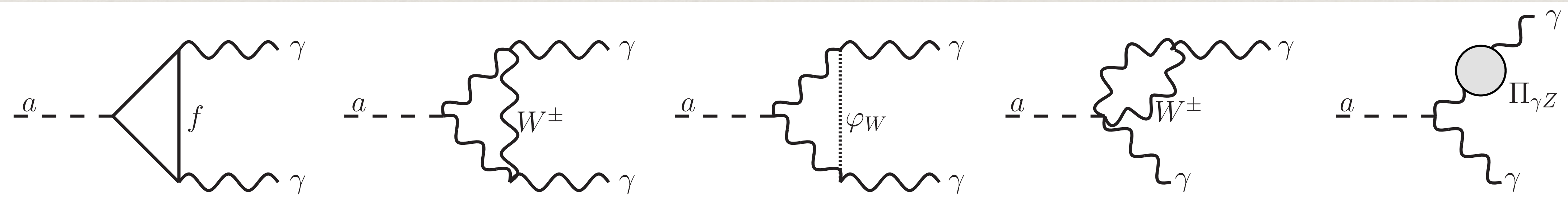
# Example: ALP decay into photons

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

$$\Gamma(a\to\gamma\gamma)\equiv\frac{4\pi\alpha^2 m_a^3}{\Lambda^2}\left|C_{\gamma\gamma}^{\text{eff}}\right|^2$$

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

$$C_{\gamma\gamma}^{\text{eff}}(m_a\gg\Lambda_{\text{QCD}})=C_{\gamma\gamma}+\sum_f\frac{N_c^f Q_f^2}{16\pi^2}\,c_{ff}\,B_1(\tau_f)+\frac{2\alpha}{\pi}\,\frac{C_{WW}}{s_w^2}\,B_2(\tau_W)$$



# Example: ALP decay into photons

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

$$\Gamma(a \to \gamma\gamma) \equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma}^{\rm eff} \right|^2$$

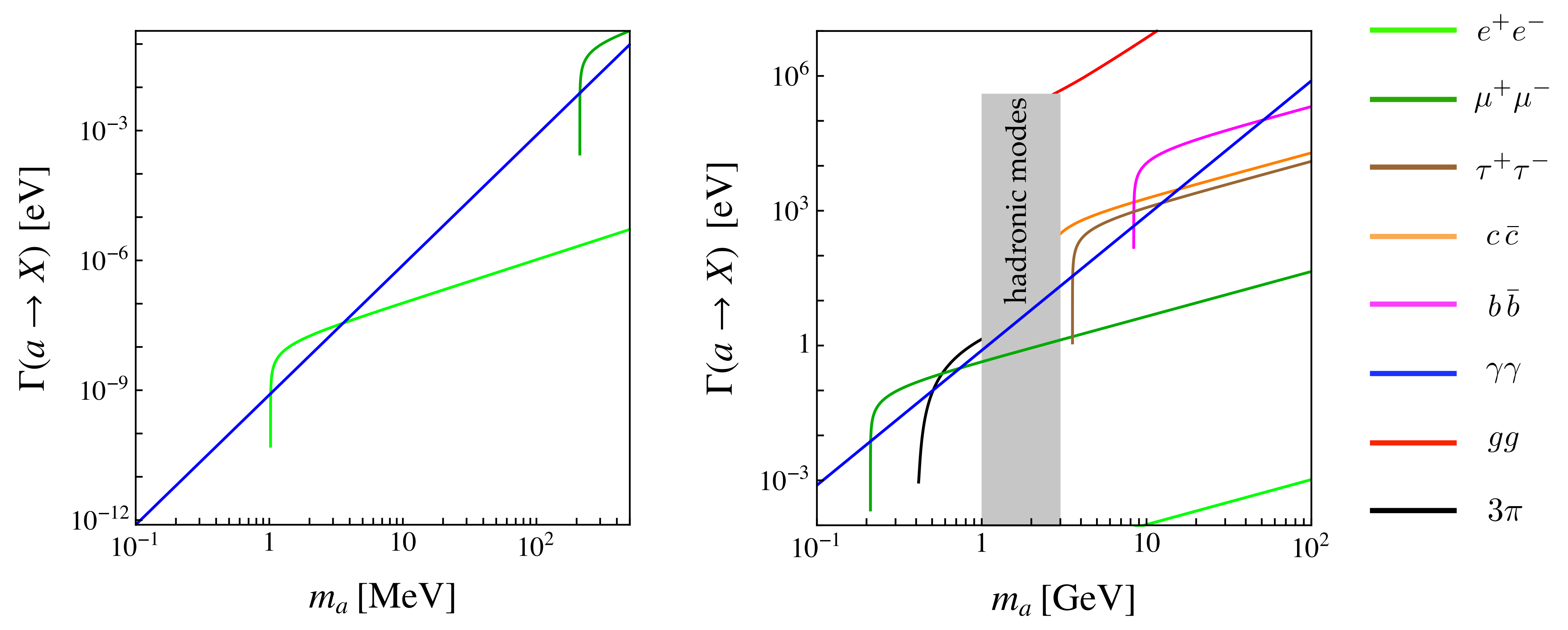
where ($\tau_i \equiv 4m_i^2/m_a^2$):

$$C_{\gamma\gamma}^{\rm eff}(m_a \gg \Lambda_{\rm QCD}) = C_{\gamma\gamma} + \sum_f \frac{N_c^f Q_f^2}{16\pi^2}\, c_{ff}\, B_1(\tau_f) + \frac{2\alpha}{\pi} \frac{C_{WW}}{s_w^2}\, B_2(\tau_W)$$

$$\begin{aligned} C_{\gamma\gamma}^{\rm eff}(m_a \lesssim 1\,\text{GeV}) &\approx C_{\gamma\gamma} - (1.92 \pm 0.04)\, C_{GG} - \frac{m_a^2}{m_\pi^2 - m_a^2} \left[ C_{GG}\, \frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32\pi^2} \right] \\ &\quad + \sum_{q=c,b,t} \frac{N_c Q_q^2}{16\pi^2}\, c_{qq}\, B_1(\tau_q) + \sum_{\ell=e,\mu,\tau} \frac{c_{\ell\ell}}{16\pi^2}\, B_1(\tau_\ell) + \frac{2\alpha}{\pi} \frac{C_{WW}}{s_w^2}\, B_2(\tau_W) \end{aligned}$$

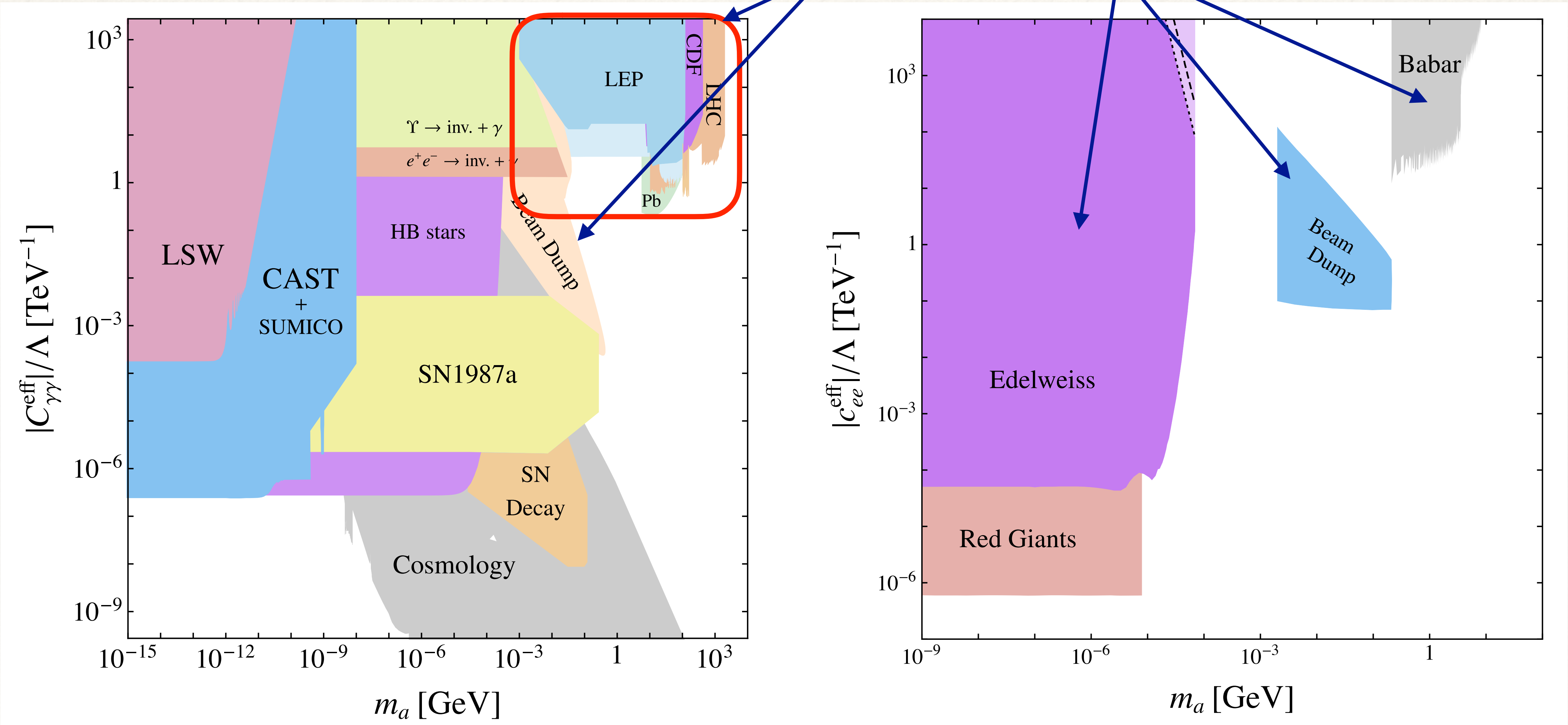
# Pattern of decay rates

- Assuming that the relevant Wilson coefficients are equal to 1/TeV, we find the following pattern of decay rates:



# Constraints on $C_{\gamma\gamma}$ and $c_{ee}$

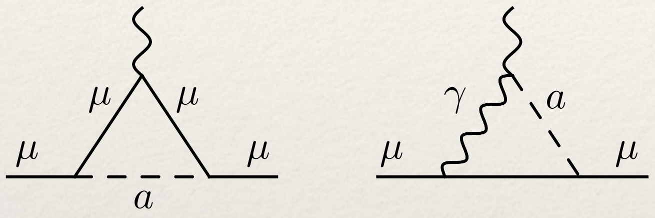
model dependent!



[Armengaud et al. 2013; Jäckel, Spannowsky 2015; many others …]

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

- Anomalous magnetic moment of the muon could be explained by virtual ALP exchange:

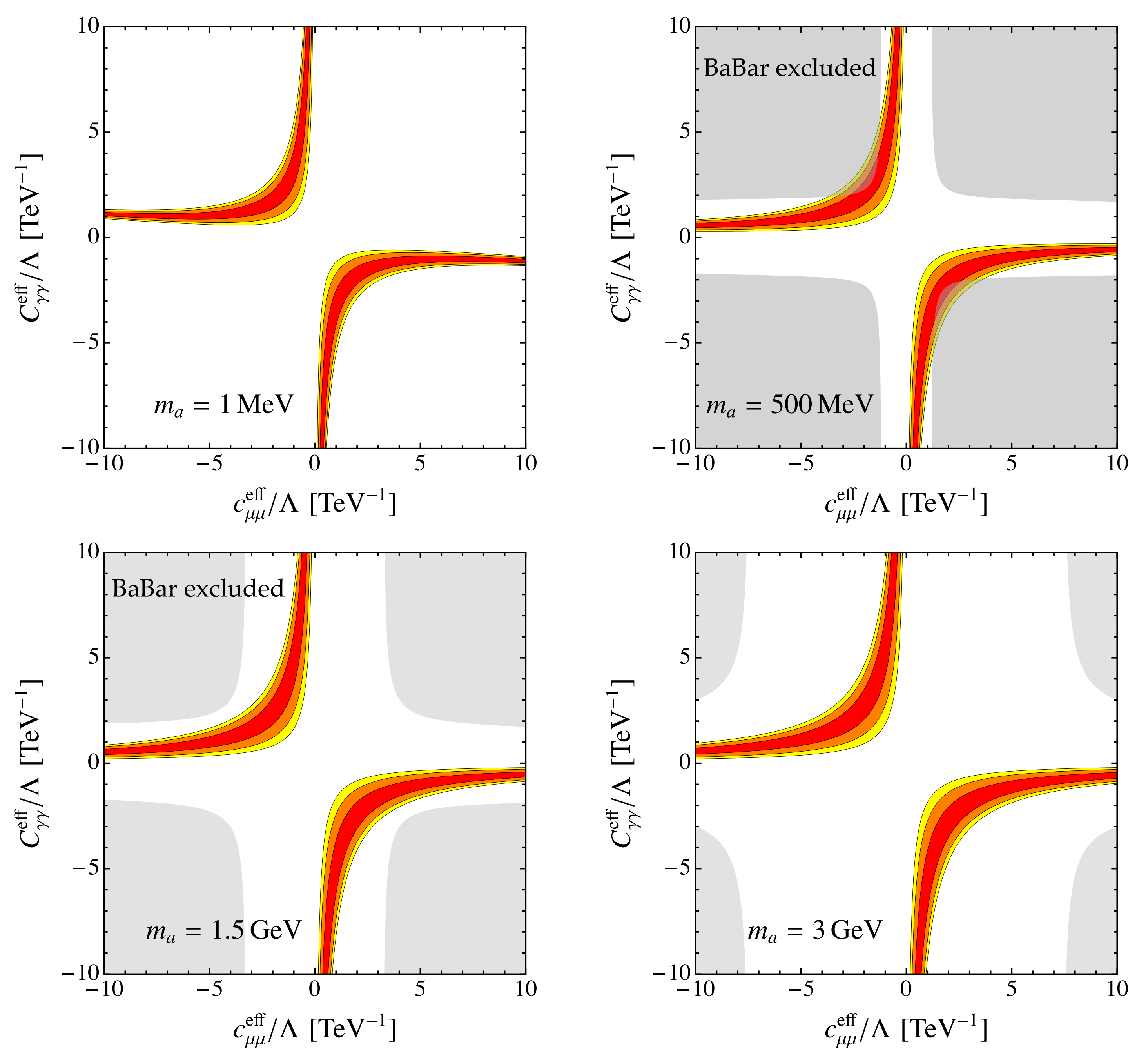


[Marciano, Masiero, Paradisi, Passera 2016]

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

- Tighter constraints expected from Belle II



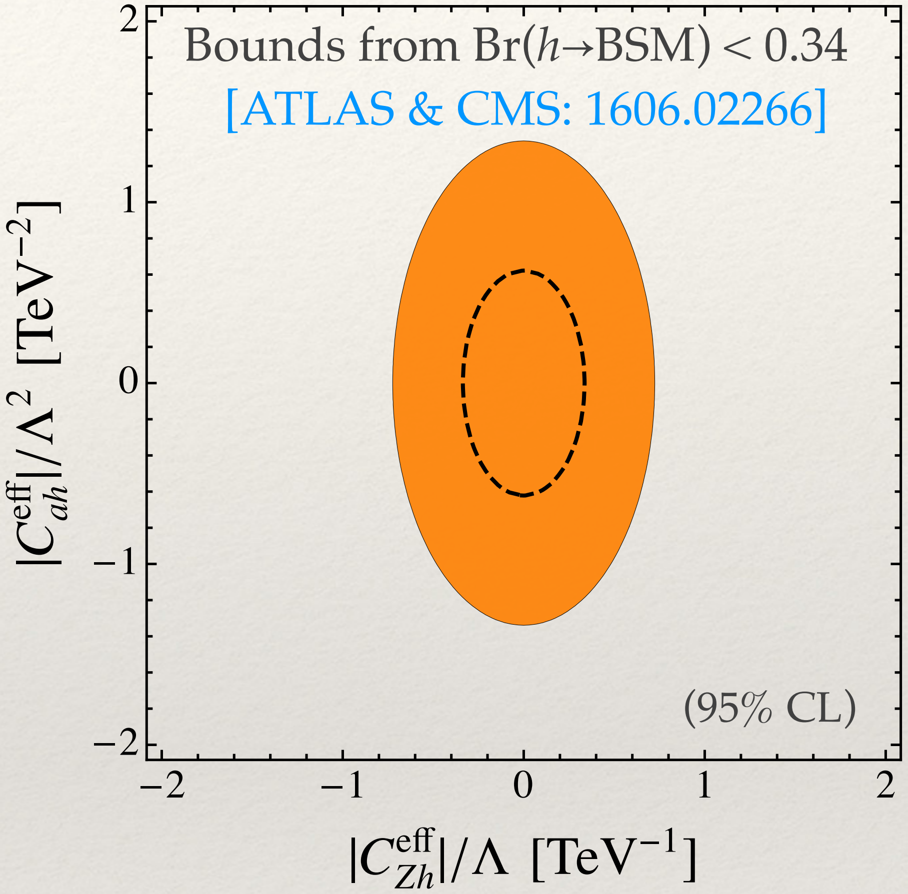
© Matthias Neubert

# Higgs Decays as an ALP Factory

[see also: Dobrescu, Landsberg, Matchev 2000; Chang, Fox, Weiner 2006; Draper, McKeen 2012; Curtin et al. 2013]

# On-shell Higgs decays into ALPs

- Effective Lagrangian allows for $h \to Za$ and $h \to aa$ decays at rates likely to be accessible in the high-luminosity run of LHC (already with 300 fb$^{-1}$)
- Branching ratios can reach 10%



- Higgs physics provides powerful observatory for ALPs in the mass range between 1 MeV and 60 GeV, which is otherwise not easily accessible to experimental searches

# Example: Exotic decay h→aa

- Higgs portal interaction and loop-mediated processes allow for ALP pair production in Higgs decay:

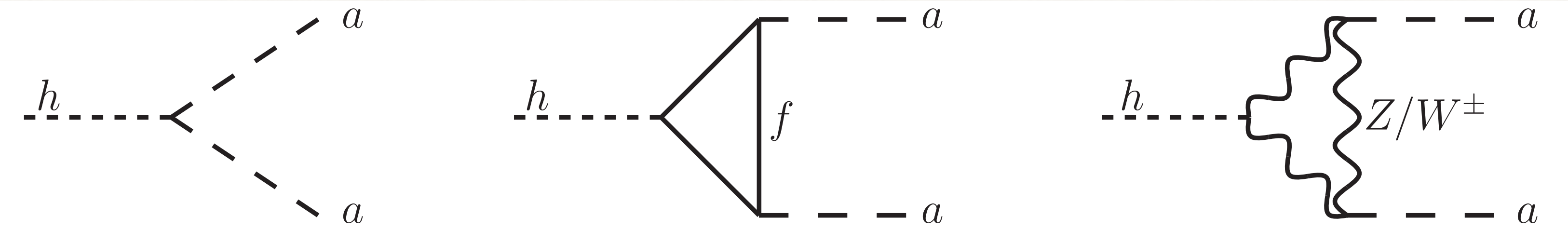
$$\Gamma(h \to aa) = \frac{\left|C_{ah}^{\text{eff}}\right|^2}{32\pi} \frac{v^2 m_h^3}{\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right) \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

with:

$$C_{ah}^{\text{eff}} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln \frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] + \dots$$

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

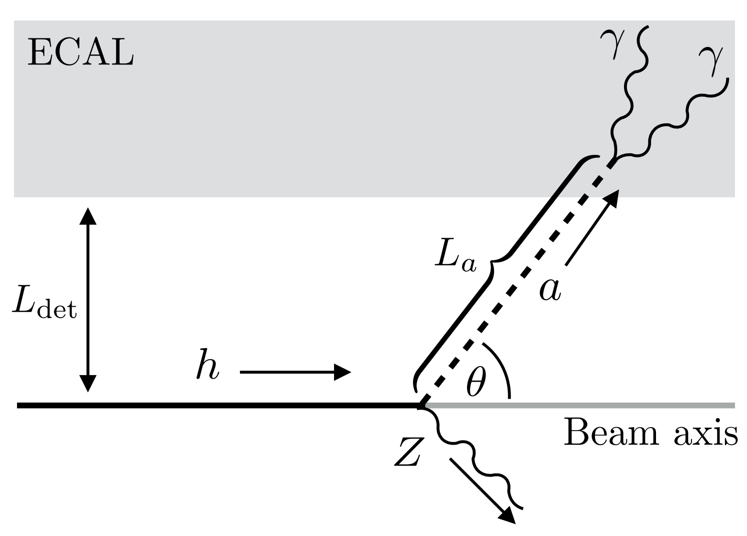
- A 10% branching ratio is obtained for $|C_{ah}^{\text{eff}}| \approx 0.62\,(\Lambda/\text{TeV})^2$



# Example: Exotic decay h→aa

- Depending on ALP decay modes, 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 $m_a >$ ~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 $l=e,\mu,\tau$
  - $h\to aa\to 4j$, including heavy-quark jets, …
- Most of these decays can be reconstructed

# Decay-length effect



- Weakly coupled light ALPs can have a macroscopic decay length, hence only a fraction $f_{\text{dec}}$ decays inside detector
- We define effective branching ratios:

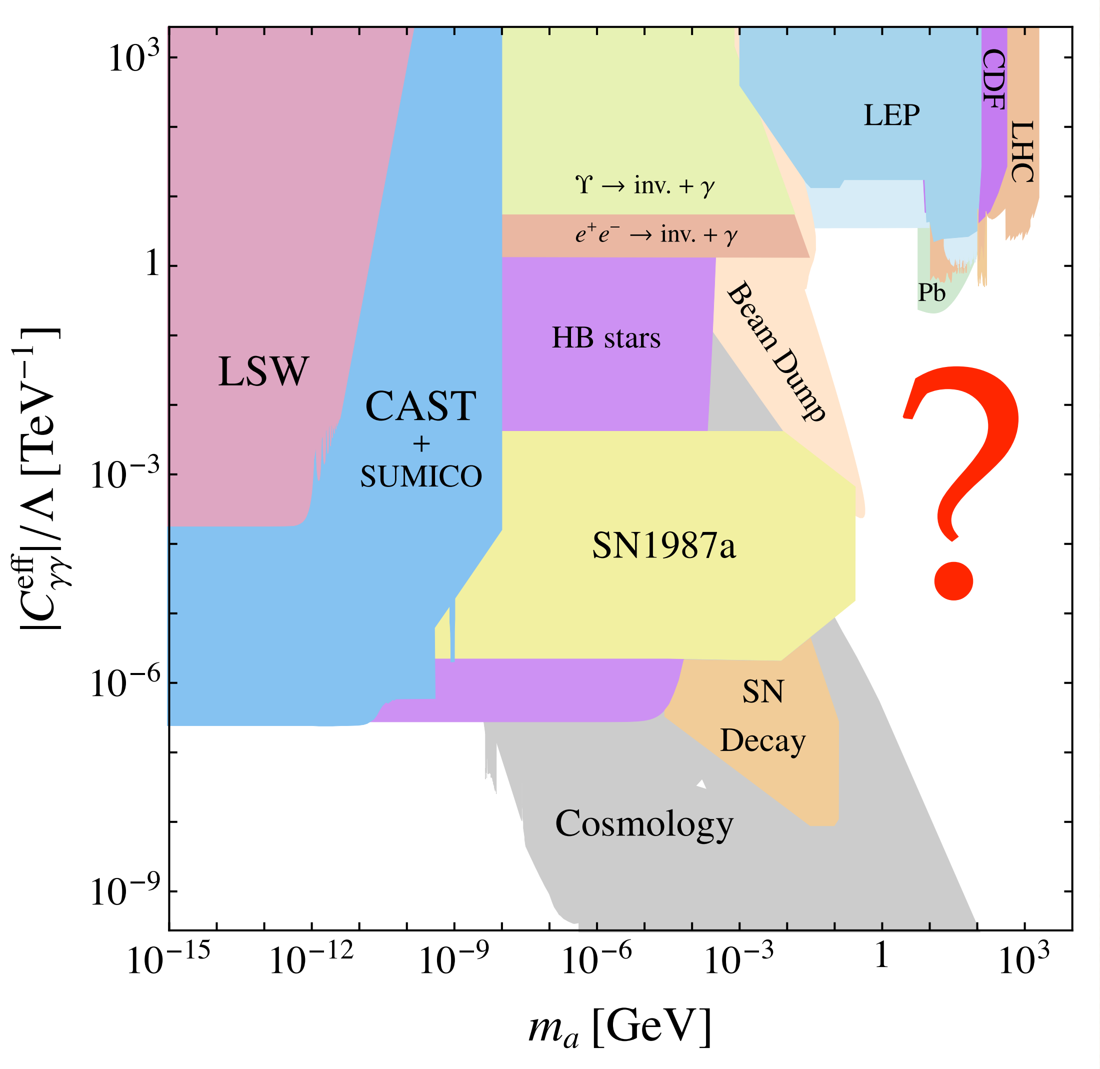
$$\text{Br}(h \to aa \to 4X)\big|_{\text{eff}} = \text{Br}(h \to aa)\,\text{Br}(a \to XX)^2\, f_{\text{dec}}^2$$

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

- Even for $L_a >> L_{\text{det}}$ there remains some sensitivity

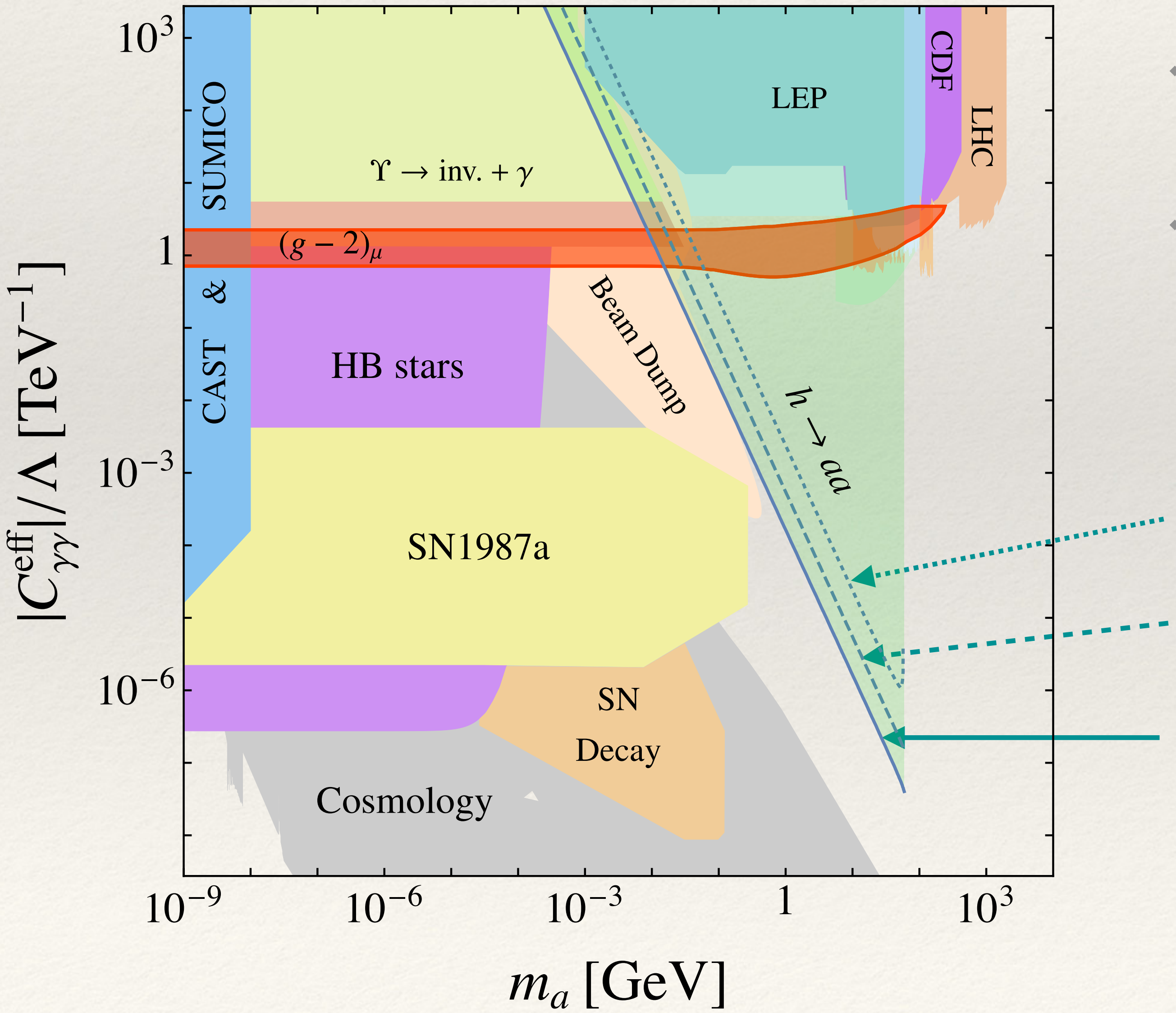
# Probing the ALP-photon coupling

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



# 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:



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

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

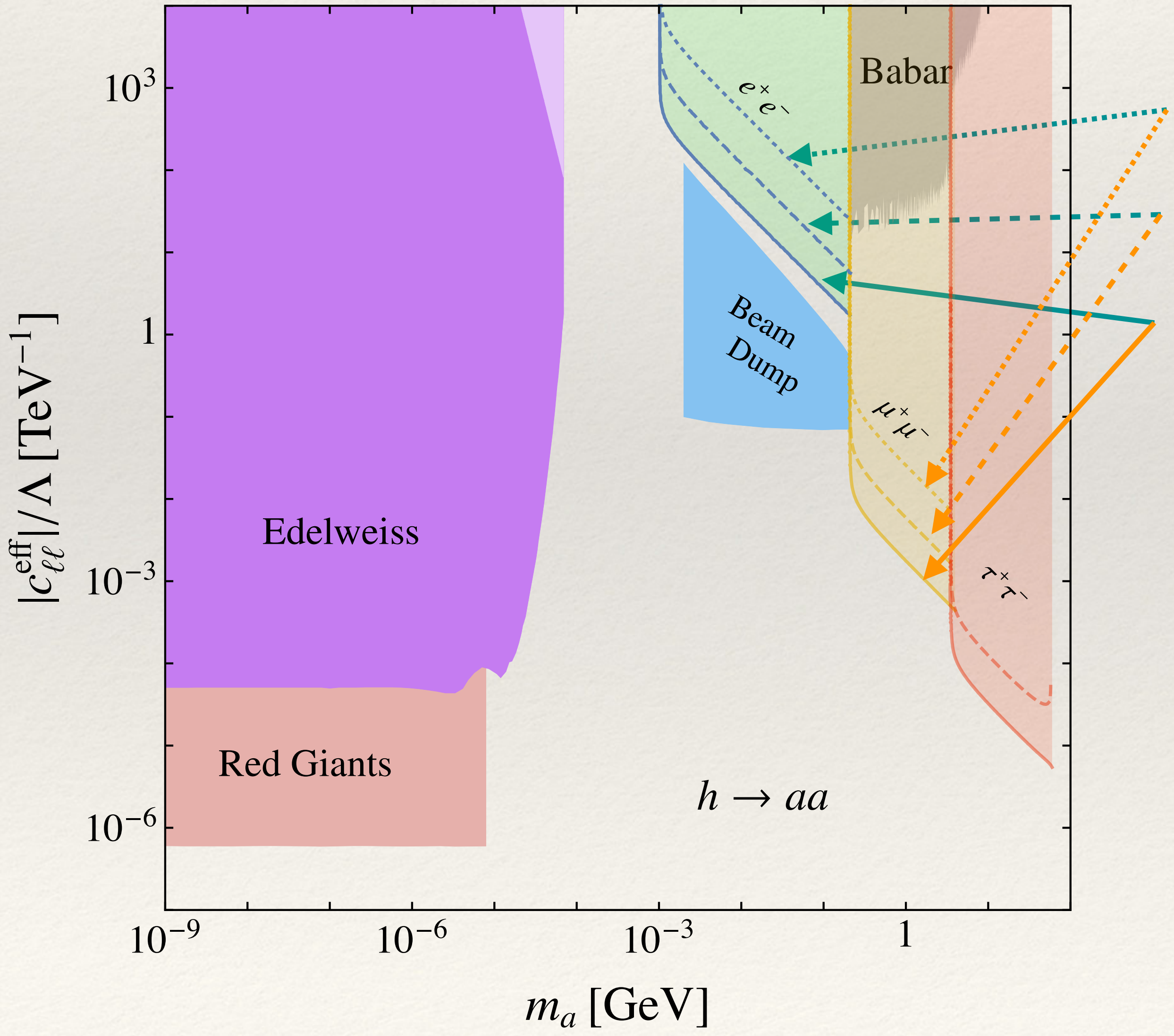
$$|C_{ah}^{\text{eff}}| = 0.1,\ \text{Br}(a \to \gamma\gamma) > 0.049$$

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

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

# Probing the ALP-lepton couplings

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



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

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

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

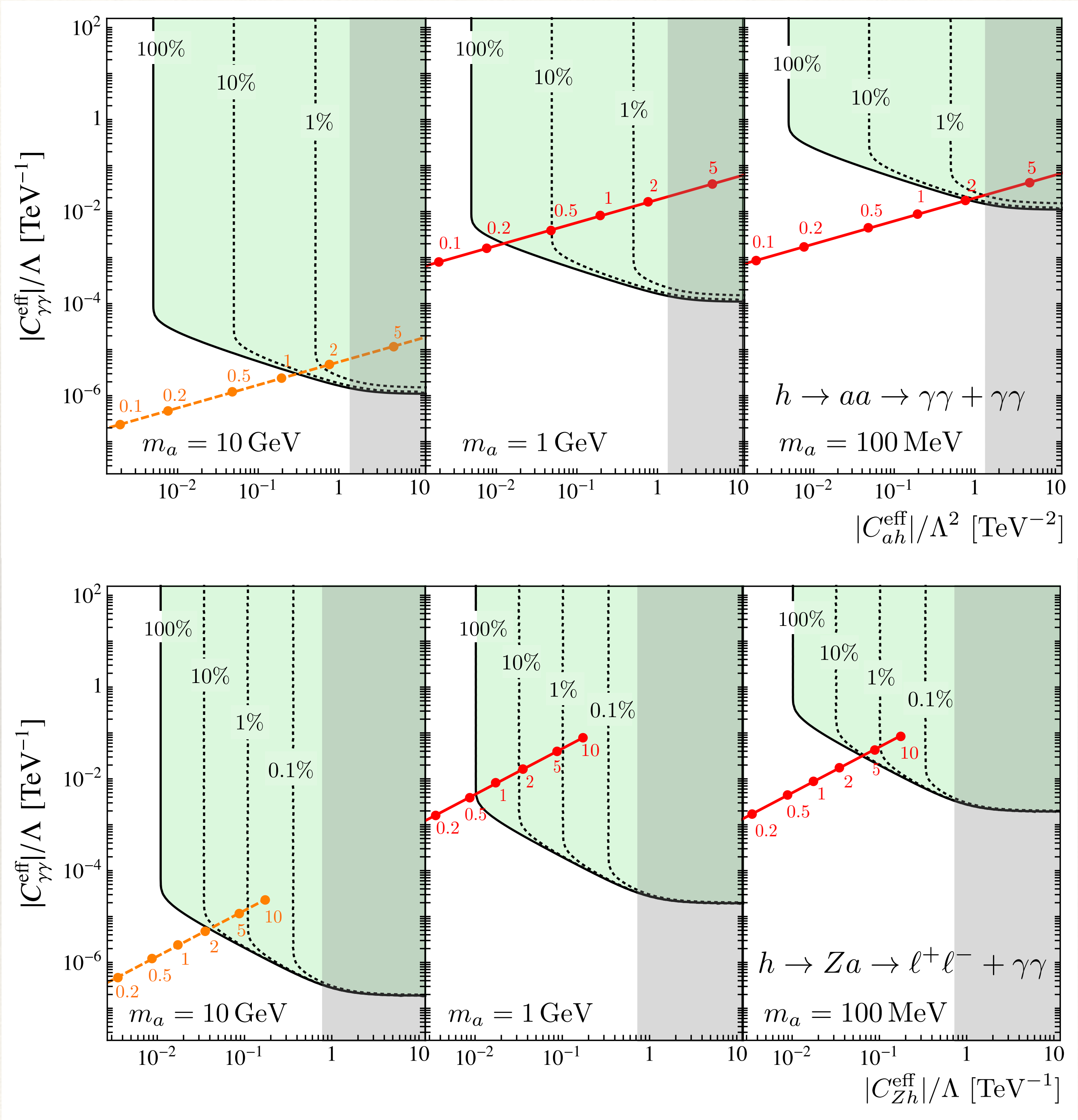
(for $\Lambda = 1\,\text{TeV}$)

Assume (absence of LFV transitions):

$$c_{ee} \approx c_{\mu\mu} \approx c_{\tau\tau}$$

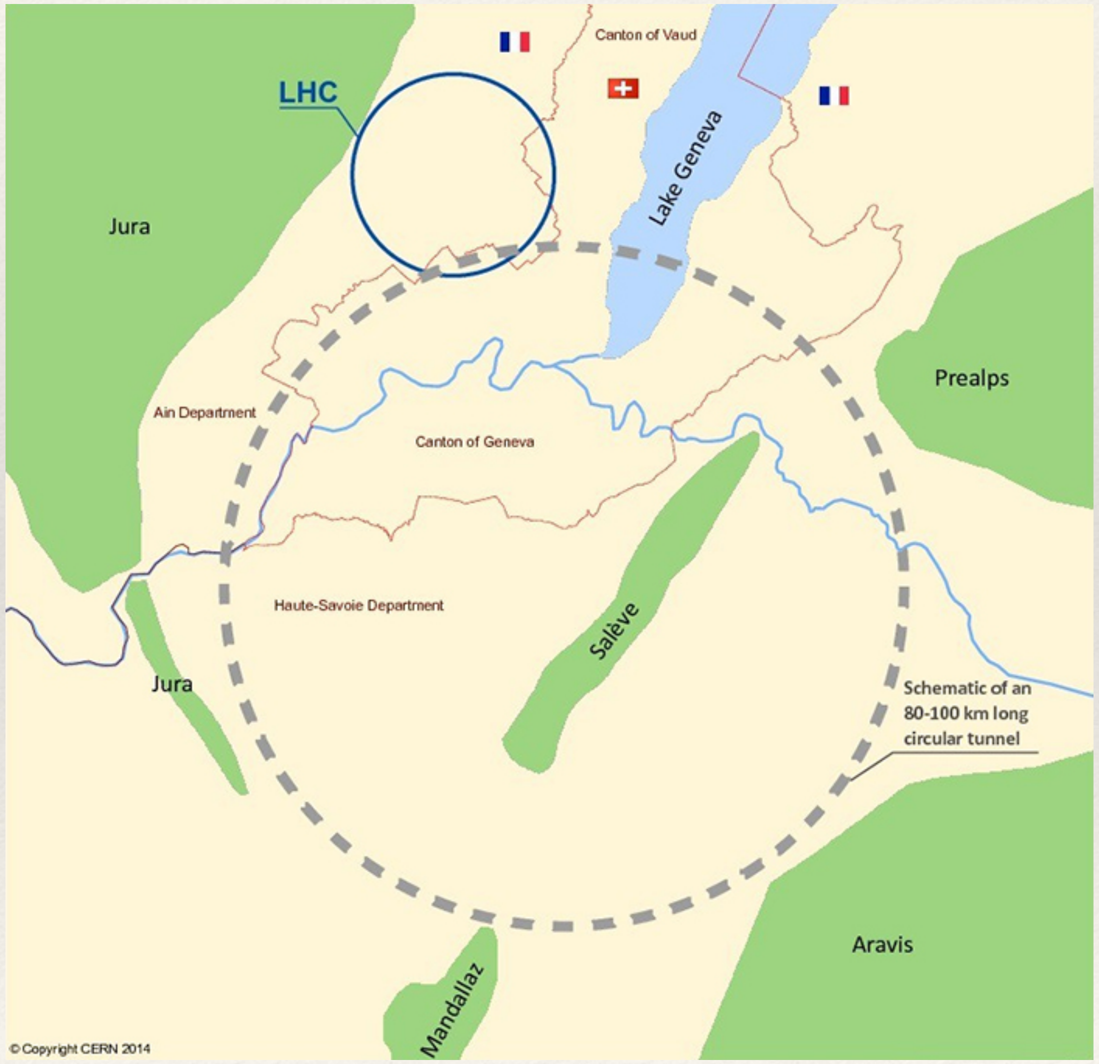
# Probing the ALP-photon coupling

- 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

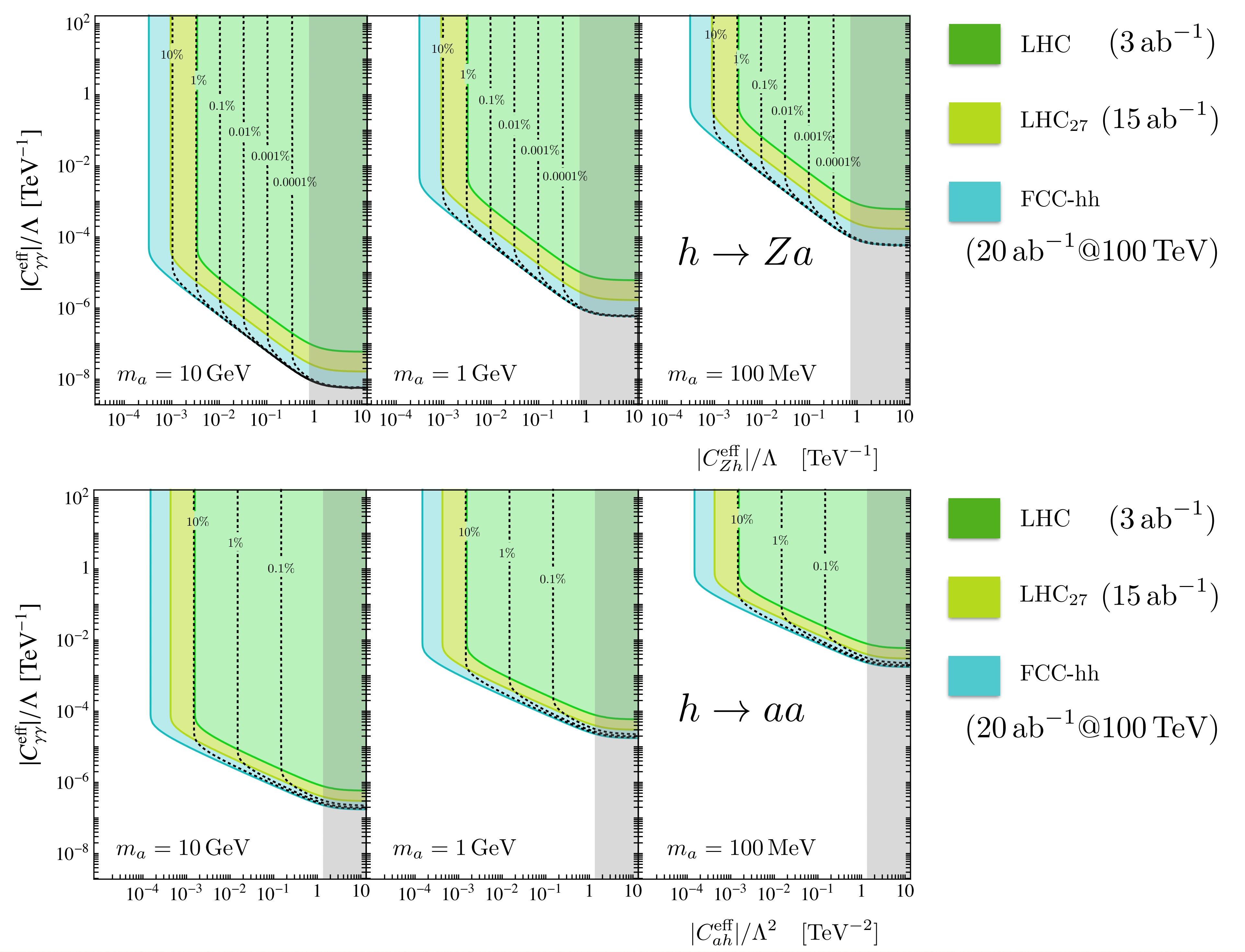


# Probing ALPs at Future Colliders

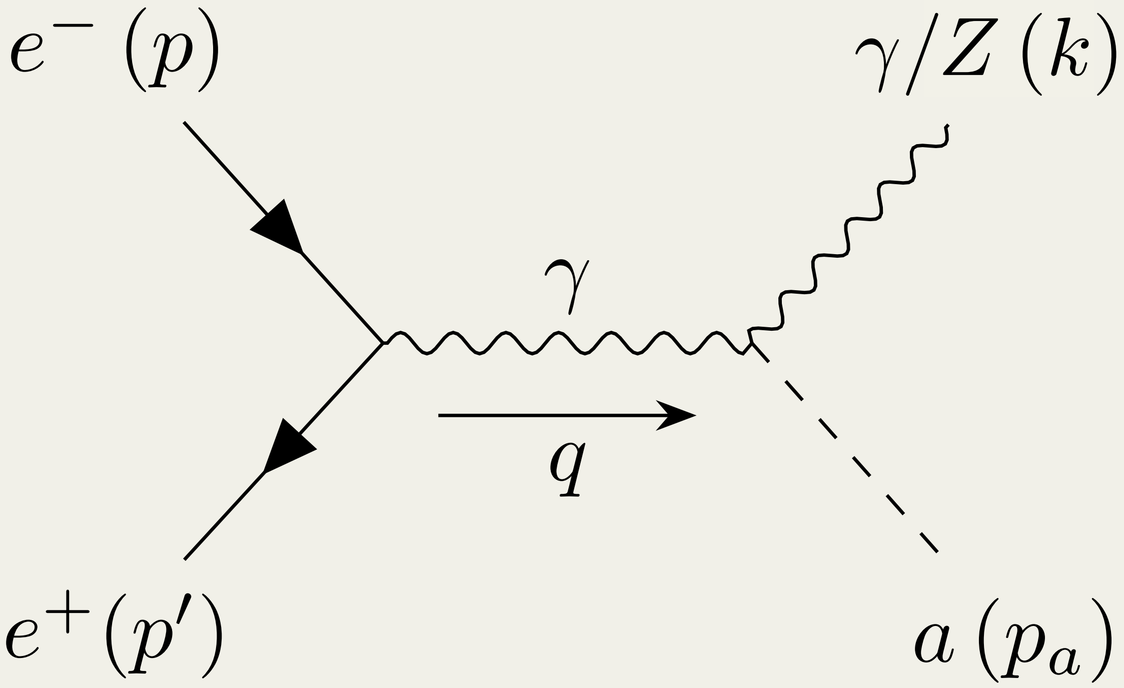
- We focus on ALP decay $a \to \gamma\gamma$ but similar results hold for ALP decays into leptons, jets or heavy quarks

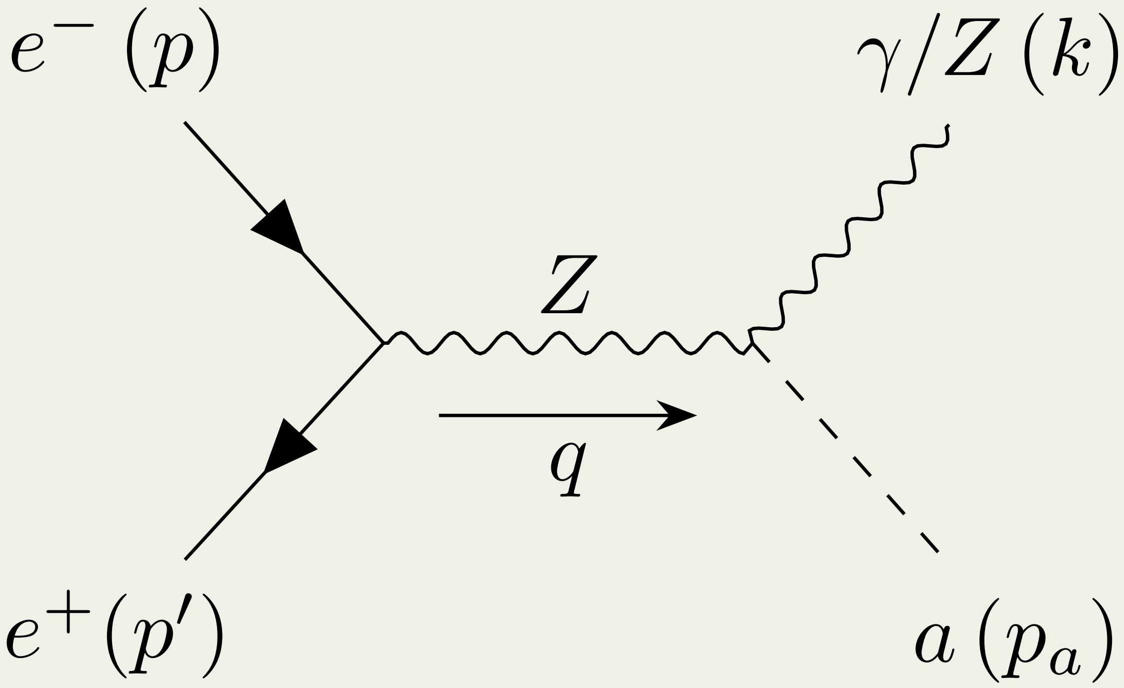


# ALP searches at future hadron colliders



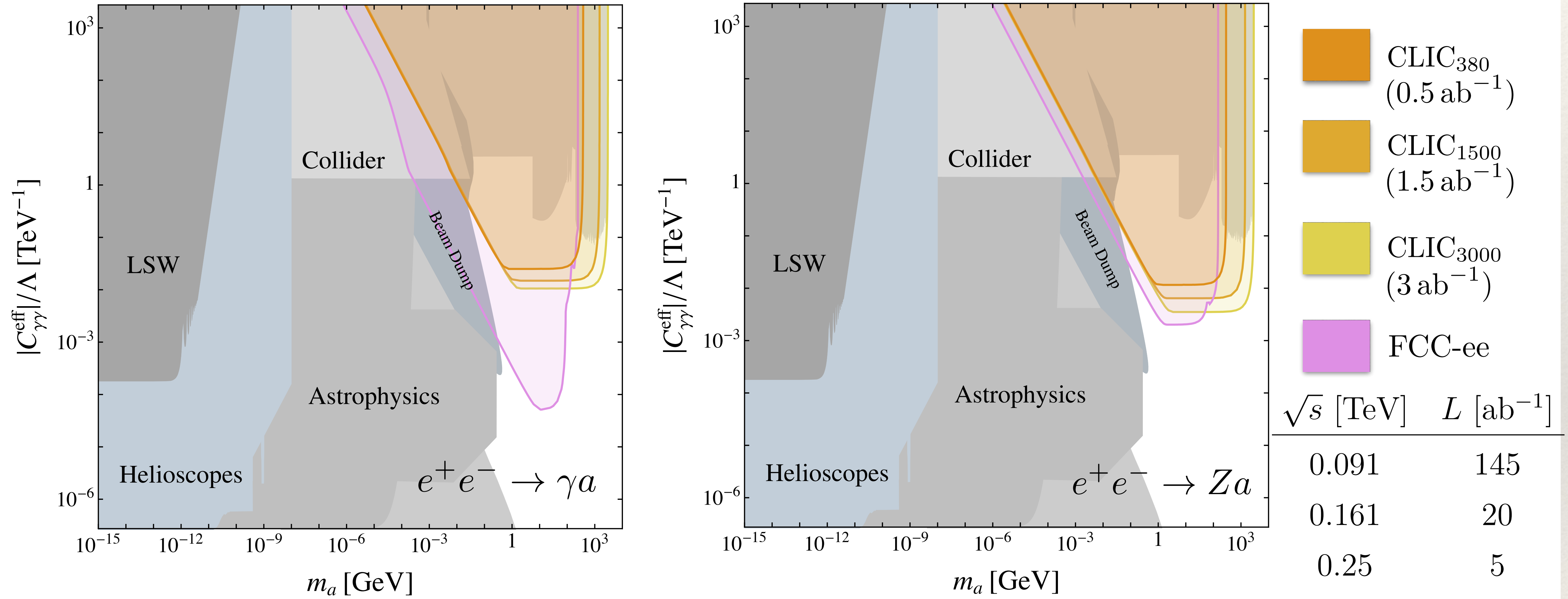
# ALP searches at future $e^+e^-$ colliders





(assuming $C_{WW}$=0, so that $C_{\gamma\gamma}$ and $C_{\gamma Z}$ are correlated)

# ALP searches at future $e^+e^-$ colliders



| $\sqrt{s}$ [TeV] | $L$ [ab$^{-1}$] |
|---|---|
| 0.091 | 145 |
| 0.161 | 20 |
| 0.25 | 5 |

based on work with Mathias Heiles

assumes $\mathrm{Br}(a \to \gamma\gamma) = 1$

# Conclusions

- Exotic Higgs and Z decays provide new probes for ALPs with masses between 1 MeV and 90 GeV, and couplings suppressed by Λ~1-100 TeV and beyond

- Searches for final states such as $h \to 4\gamma$, $h \to \ell^+\ell^-\gamma\gamma$, $h \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ and final states with jets need to be devised

- Accessible parameter space could be significantly enlarged at future hadron and lepton colliders

Thank you!