Collider Probes of Axion-like Particles

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with Martin Bauer and Matthias Neubert

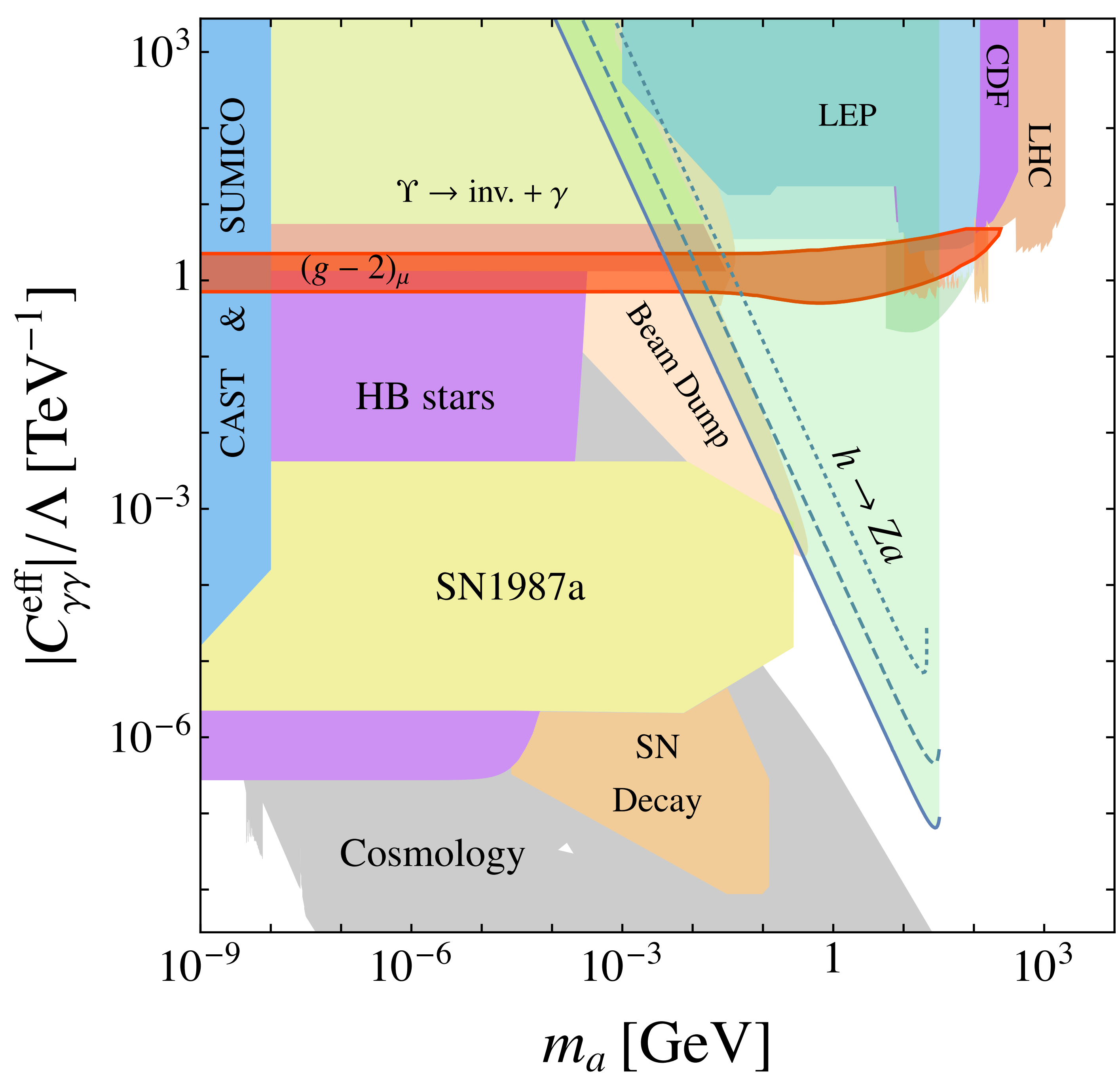
based on arXiv:1610.00009, 1704.08207, 1708.00443
and work in progress

12 December 2017

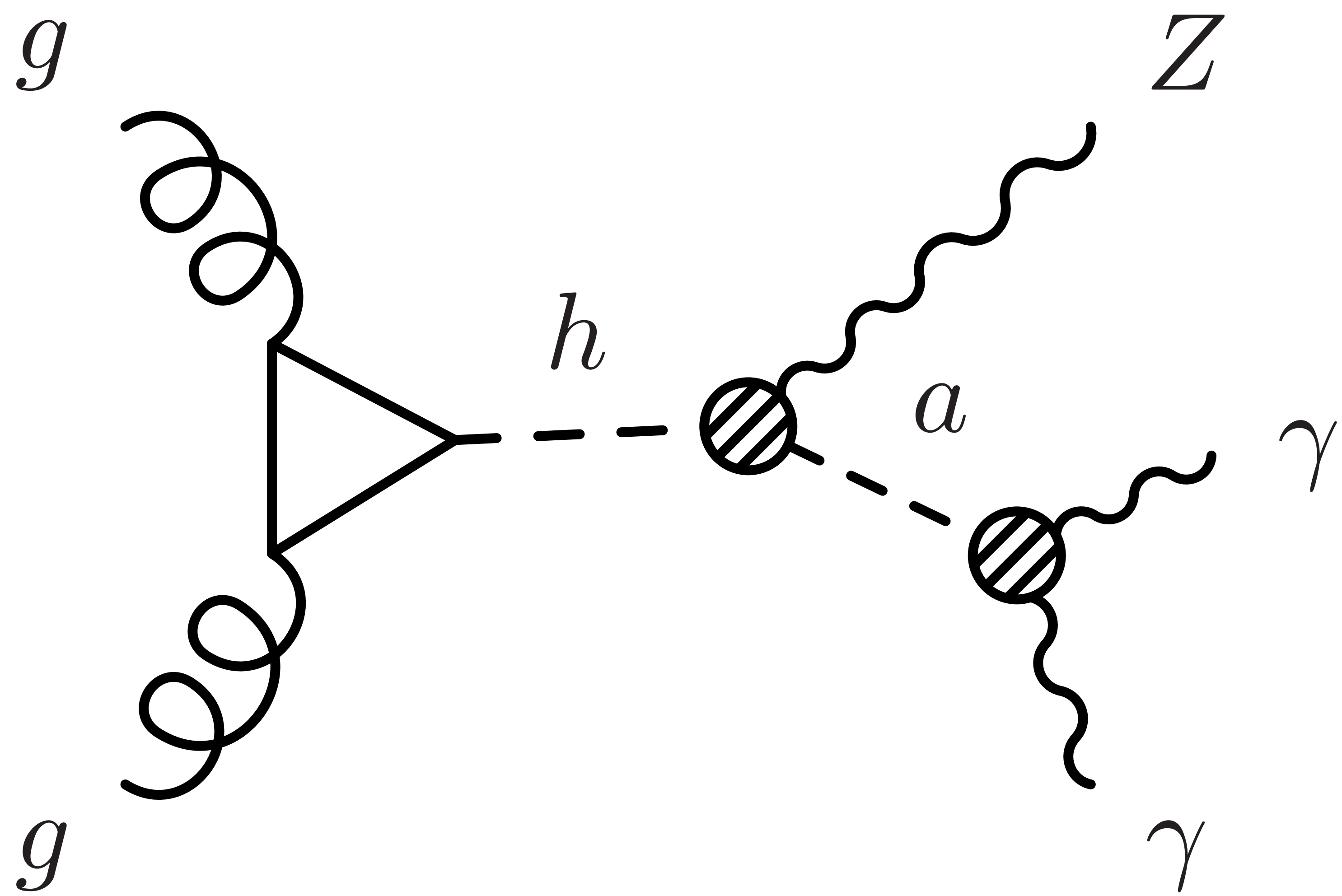
Zurich

Our main result

[Bauer, Neubert, Thamm: 1704.08207]

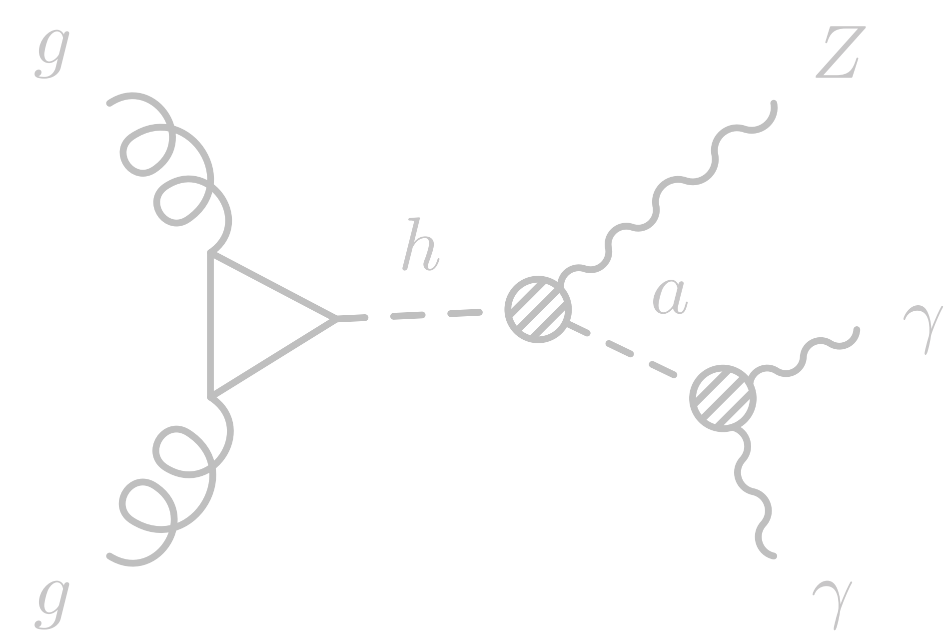


Example process



Outline

- Motivation
- ALPs and collider probes
  - Effective Lagrangian
  - Exotic Higgs decays
  - ALP Decays
  - Probing the ALP parameter space
  - Muon $(g-2)_\mu$
  - Future Colliders
- Conclusions and Outlook



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

Motivation

- Consider a singlet: (1,1,0) under $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Pseudoscalar and light
- Shift symmetry protects mass $a \to a + c$
- Mass obtained through explicit soft breaking or non-perturbative dynamics

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]

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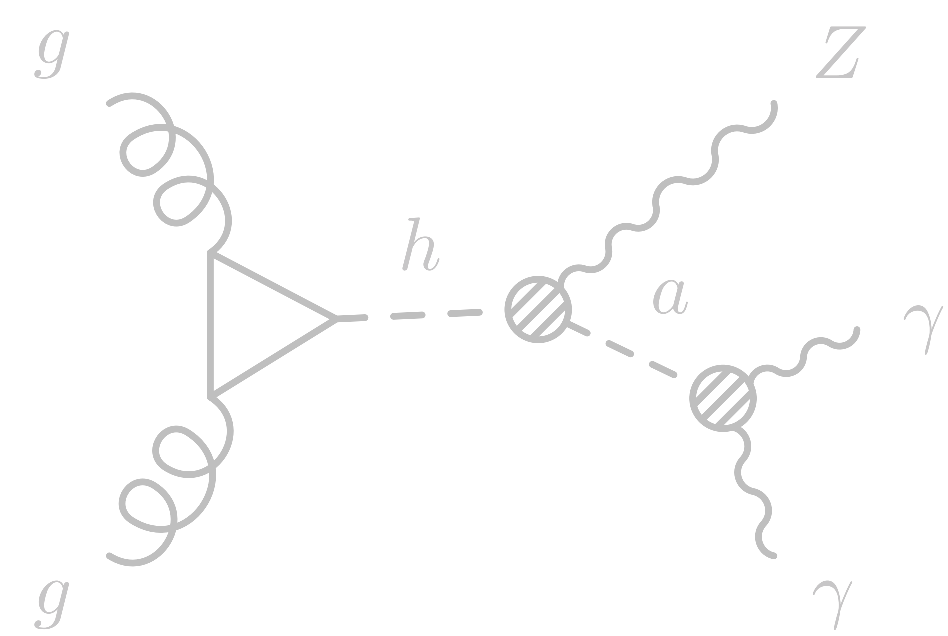

Effective Lagrangian

- Interactions at dimension-5

[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \frac{1}{2} m_a^2 a^2 + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f$$

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

- After EWSB

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

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

Effective Lagrangian

- Vanishes through equations of motion

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

- Higgs interactions at dimension-6 and 7

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

$h \to aa$

$h \to Za$

[Bauer, Neubert, Thamm: 1607.01016]

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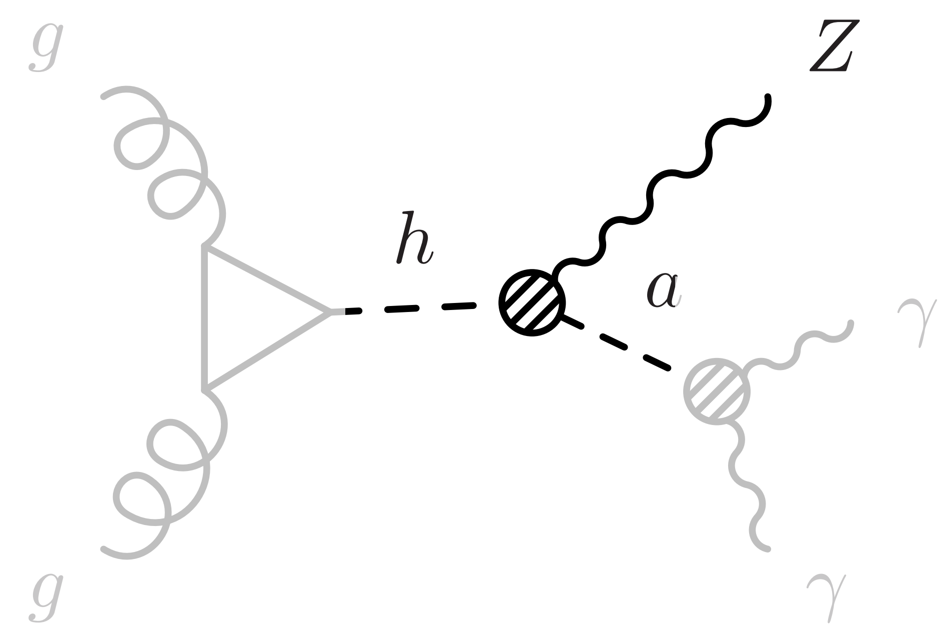


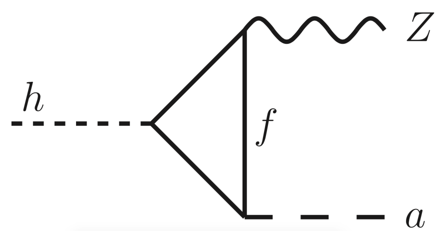
Exotic Higgs Decays $h \to Za$

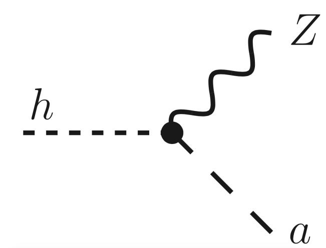
- Contributions

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

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

Vanishes through EOM





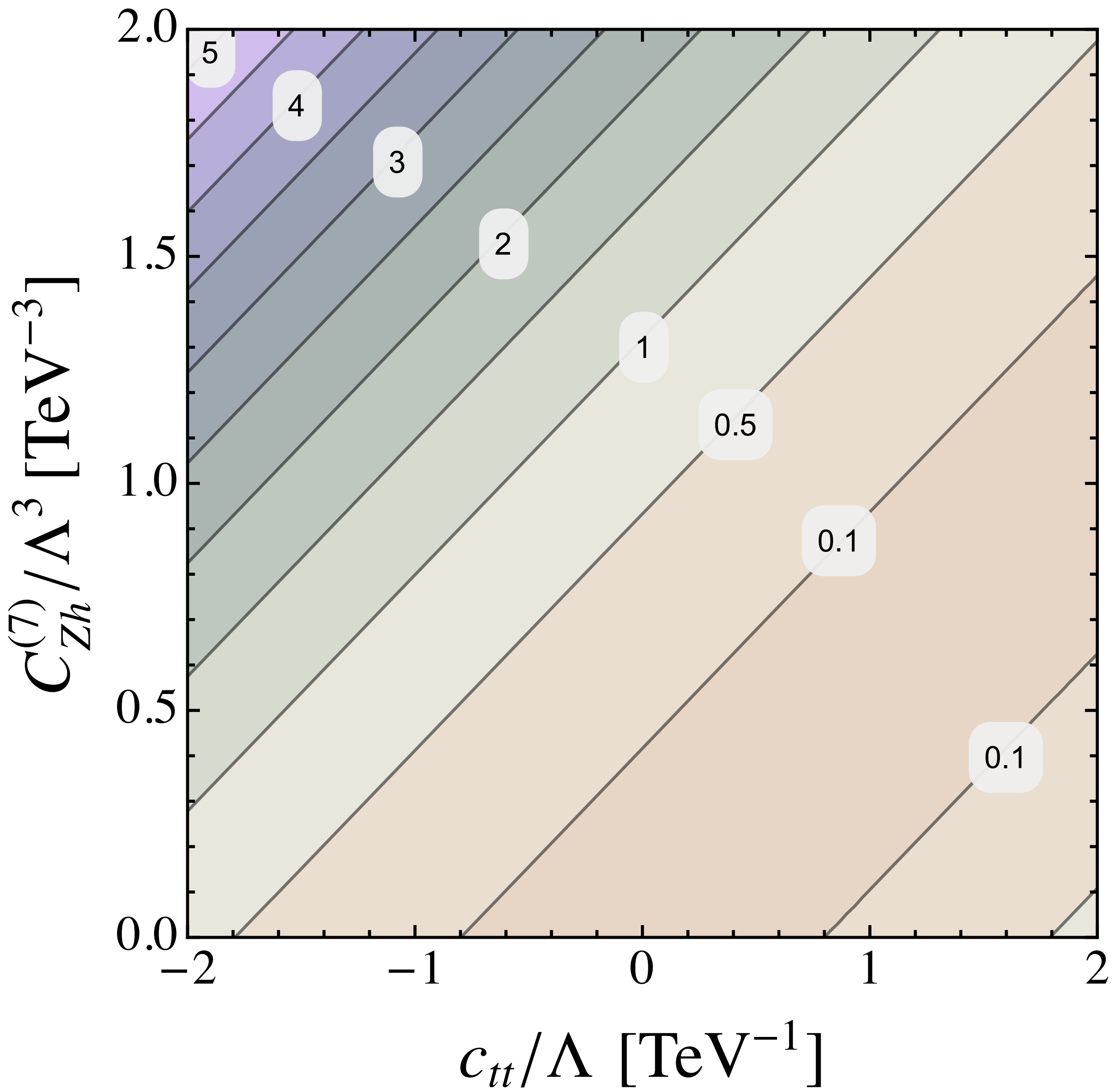
- Numerically

$$C_{Zh}^{\text{eff}} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

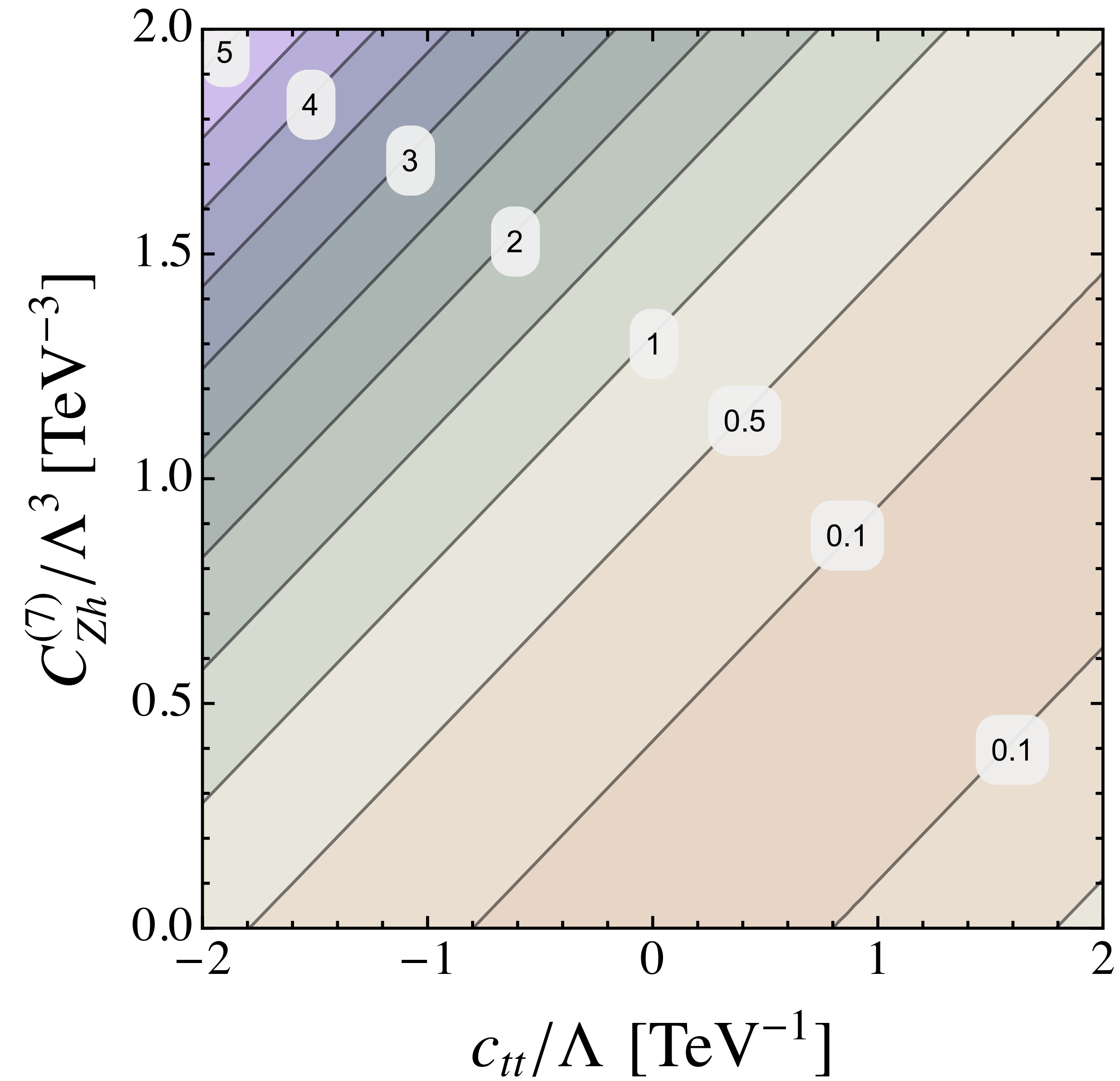
[Bauer, Neubert, Thamm:1610.00009]

Exotic Higgs Decays $h \to Za$

- Decay rate normalised to SM $\Gamma(h \to Z\gamma)_{\rm SM} = 6.32 \cdot 10^{-6}\,\text{GeV}$



Exotic Higgs Decays $h \to Za$



- This channel is a realistic target for discovery at LHC

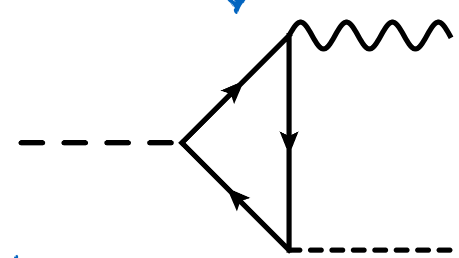
Exotic Higgs Decays $h \to Za$

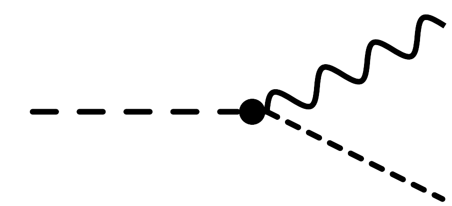
- Contributions

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

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

Vanishes through EOM





Non-polynomial operator for models with new heavy particles whose mass arises from EWSB

$$\frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right) \ln\frac{\phi^\dagger\phi}{\mu^2}$$

[Pierce, Thaler, Wang: 0609049]
[Bauer, Neubert, Thamm: 1607.01016]
[Bauer, Neubert, Thamm: 1610.00009]

- Numerically

$$C_{Zh}^{\text{eff}} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

Exotic Higgs Decays $h \to Za$

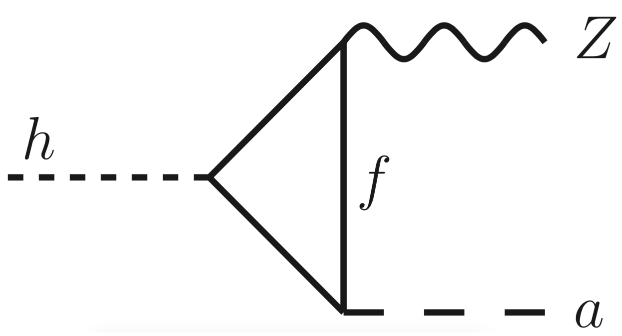
- Non-polynomial operator

[Pierce, Thaler, Wang: 0609049]
[Bauer, Neubert, Thamm: 1607.01016]
[Bauer, Neubert, Thamm: 1610.00009]

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

$$= -\frac{C_{Zh}^{(5)}}{\Lambda}a\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\frac{\partial^\mu(\phi^\dagger\phi)}{\phi^\dagger\phi} + \dots$$

$$\to -\frac{C_{Zh}^{(5)}}{\Lambda}\,\frac{g}{c_w}aZ_\mu(v+h)\partial^\mu h$$

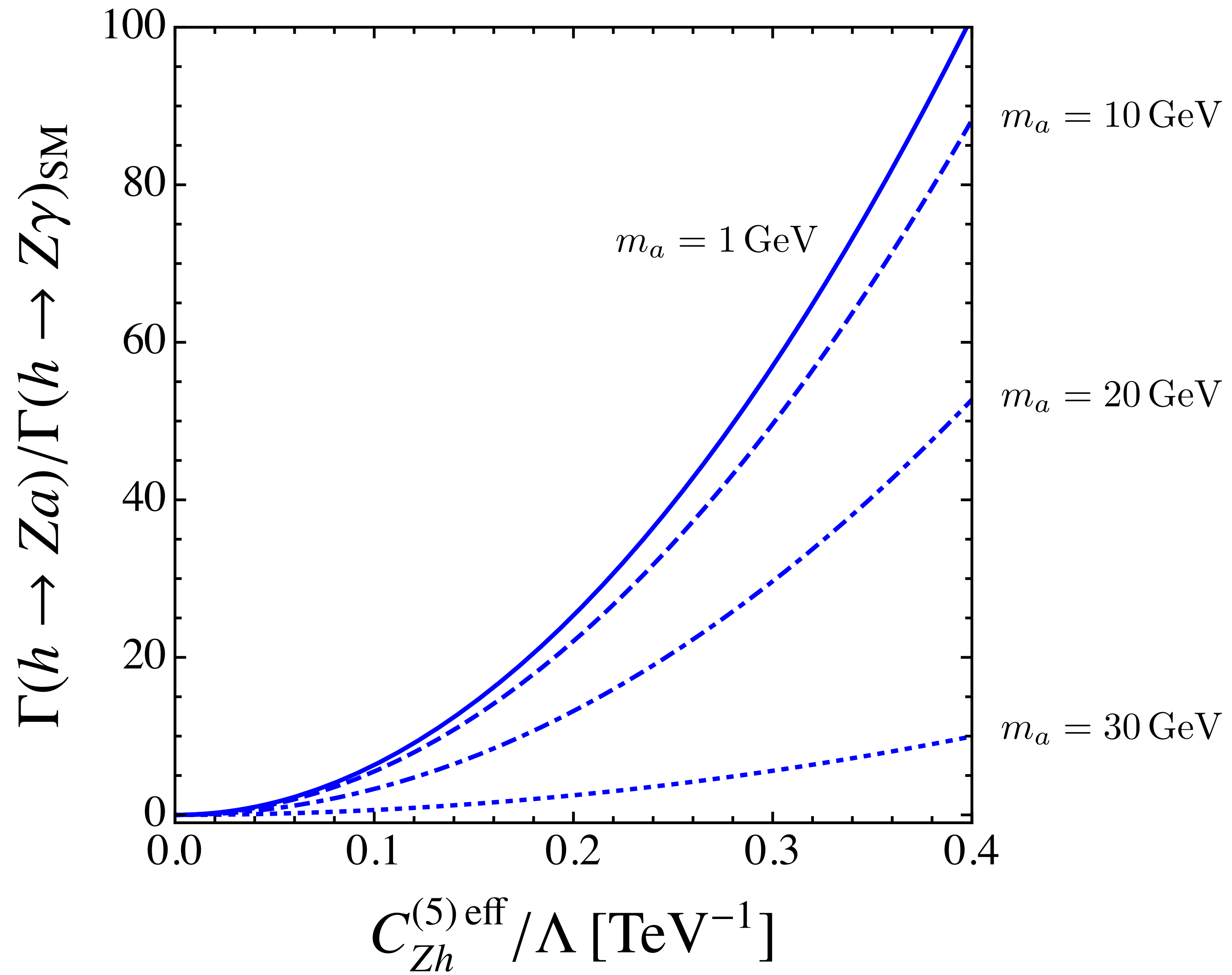


$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xym_h^2 - yzm_Z^2 - xzm_a^2}$$

$$C_{Zh}^{(5)} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

Exotic Higgs Decays $h \to Za$

- Enhanced rates for this process



Exotic Higgs Decays $h \to Za$

- Current upper limit $\mathrm{Br}(h \to \mathrm{BSM}) < 0.34$ [ATLAS and CMS:1606.02266]

$$\Longrightarrow \quad \Gamma(h \to \mathrm{BSM}) < 2.1\,\mathrm{MeV}$$

$$\Longrightarrow \quad \frac{|C_{Zh}^{\mathrm{eff}}|}{\Lambda} < 0.72\,\mathrm{TeV}^{-1}$$

- For $\mathrm{Br}(h \to Za) = 0.1$ need $|C_{Zh}|/\Lambda \approx 0.34\,\mathrm{TeV}^{-1}$
- From top loop and dim-7: $\mathrm{Br}(h \to Za) = \mathcal{O}(10^{-3})$

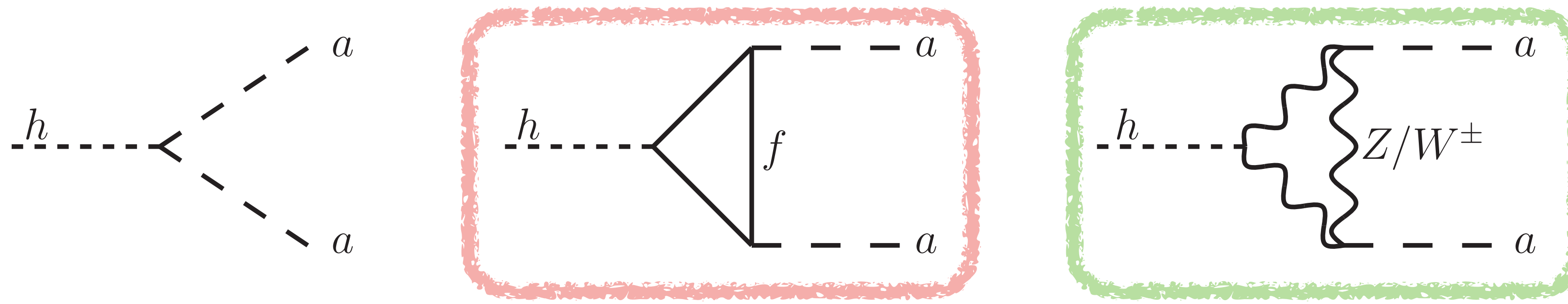
- Interesting final states
  - $h \to Za \to Z\gamma\gamma$
  - $h \to Za \to Zll$
  - $h \to Za \to Z\,2jets$
  - $h \to Za \to Z$+invisible

- All these modes can be reconstructed at run II

Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]
[Chang, Fox, Weiner: 0608310]



$$C_{ah}^{\text{eff}} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln\frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] - \frac{3\alpha}{2\pi s_w^2}\left(g^2 C_{WW}\right)^2 \left[\ln\frac{\mu^2}{m_W^2} + \delta_1 - g_2(\tau_{W/h})\right]$$
$$- \frac{3\alpha}{4\pi s_w^2 c_w^2}\left(\frac{g^2}{c_w^2}\, C_{ZZ}\right)^2 \left[\ln\frac{\mu^2}{m_Z^2} + \delta_1 - g_2(\tau_{Z/h})\right]$$

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

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

Exotic Higgs Decays $h \to aa$

- Current upper limit $\text{Br}(h \to \text{BSM}) < 0.34$ [ATLAS and CMS:1606.02266]

$$\implies \Gamma(h \to \text{BSM}) < 2.1\,\text{MeV}$$
$$\implies |C_{ah}^{\text{eff}}| < 1.34 \left[\frac{\Lambda}{1\,\text{TeV}}\right]^2$$

- For $\text{Br}(h \to aa) = 0.1$ need $|C_{ah}|/\Lambda^2 \approx 0.62\,\text{TeV}^{-2}$
- From top-loop only: $\text{Br}(h \to aa) = 0.01$ for $|c_{tt}|/\Lambda \approx 1.04\,\text{TeV}^{-1}$

- Interesting final states
  - $h \to aa \to \gamma\gamma\gamma\gamma$
  - $h \to aa \to l^+l^-l^+l^-$
  - $h \to aa \to 4\text{jets}$
  - $h \to aa \to \text{invisible}$

- All these modes can be reconstructed at run II

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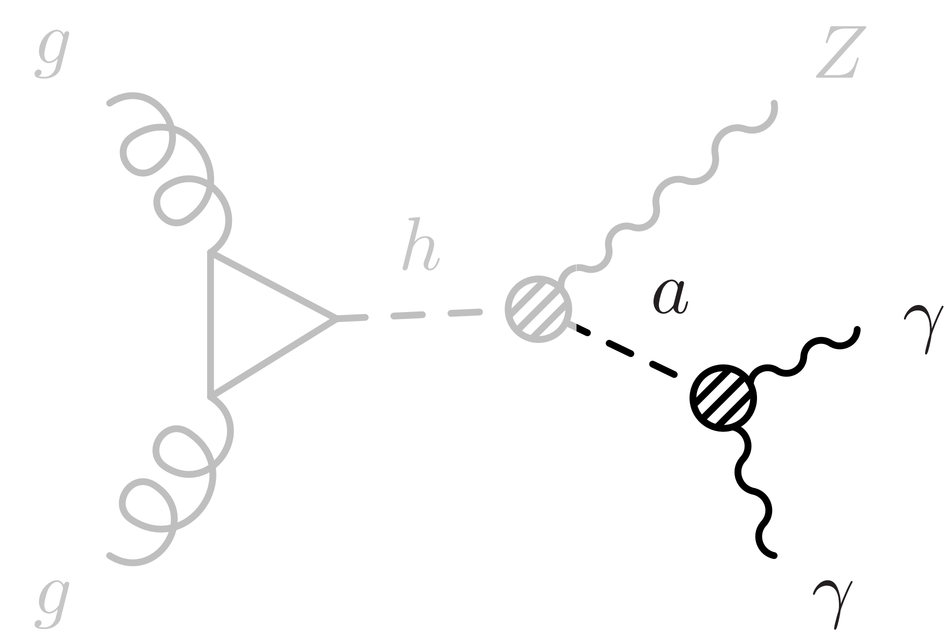
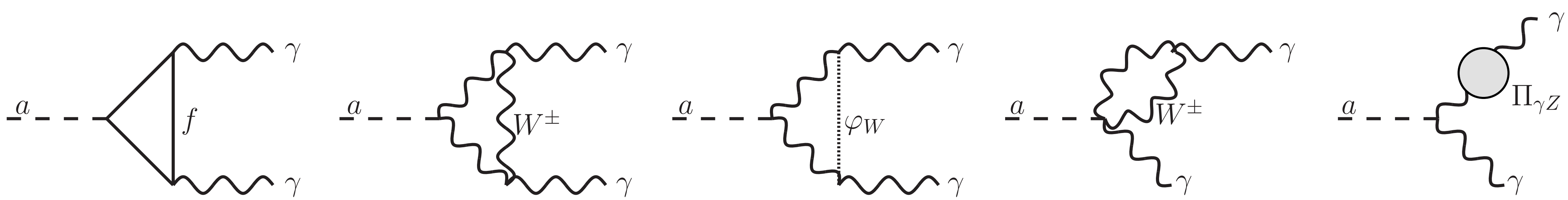


ALP decays into photons

- Often considered as the dominant decay mode



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

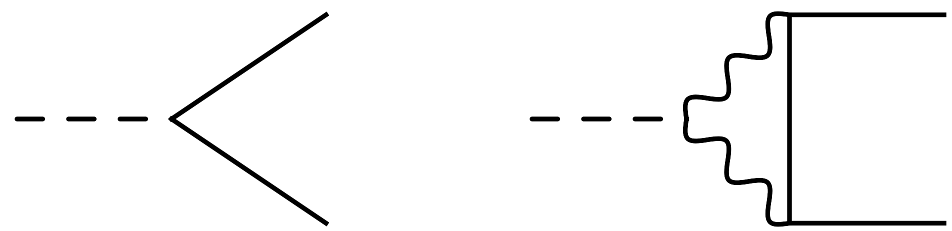
$$\equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma}^{\text{eff}} \right|^2$$

$$\tau_i \equiv 4m_i^2/m_a^2$$

- Only mode for $m_a < 2m_e$

ALP decays into leptons

- For $m_a > 2m_e$



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

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

ALP decays into hadrons

- Decays into gluons and quarks
- For $m_a > 2m_\pi$
- Can be computed only in perturbative regime for $m_a \gg \Lambda_{\rm QCD}$

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

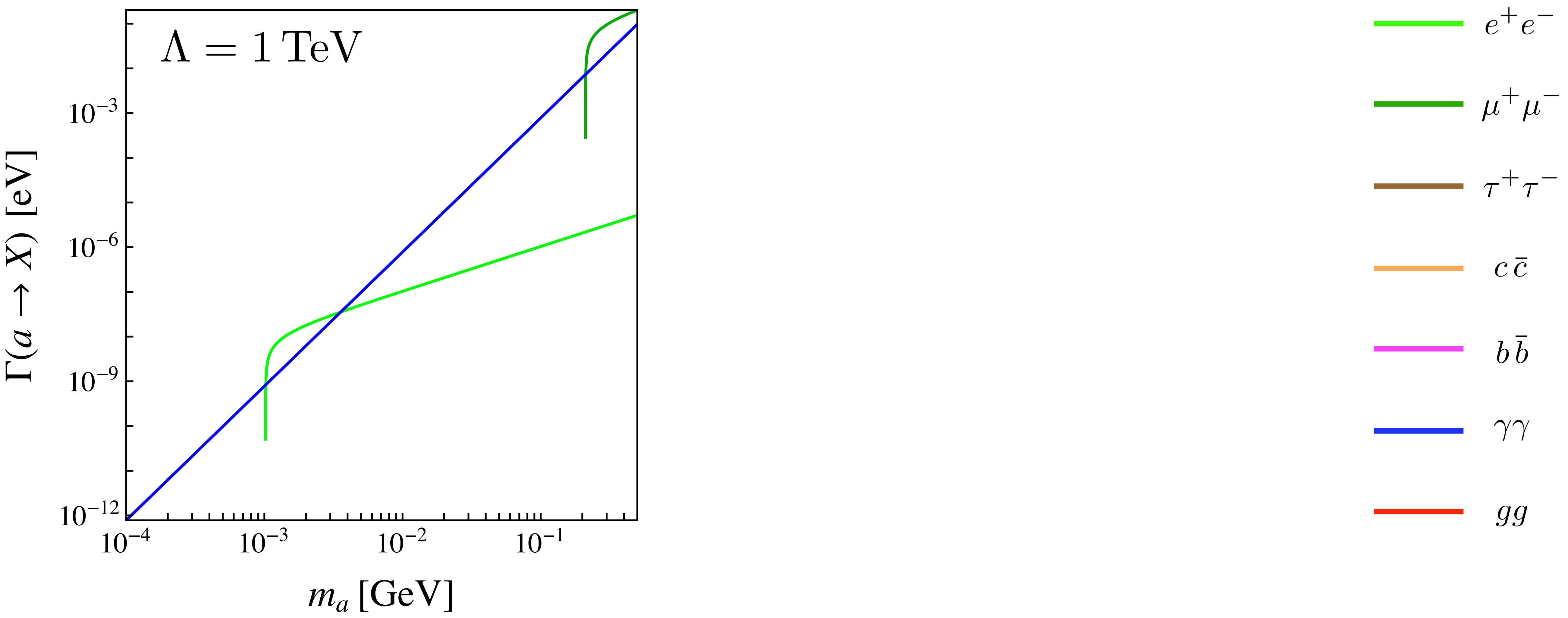
[Spira, Djouadi, Graudenz, Zerwas: 9504378]

- Decays into heavy quarks

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

ALP decays

- Assuming effective Wilson coefficients to be 1



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  - Electroweak precision test
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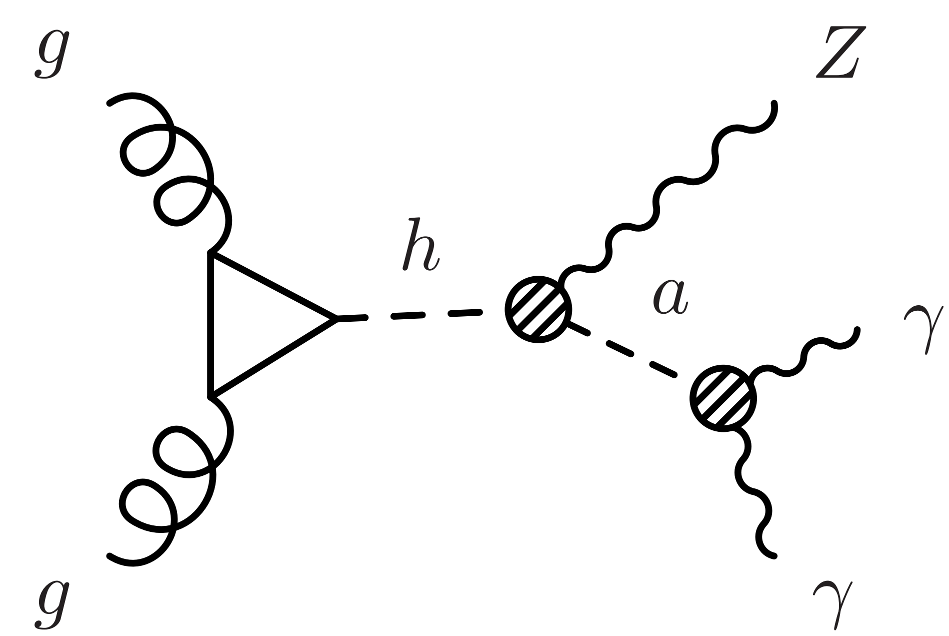
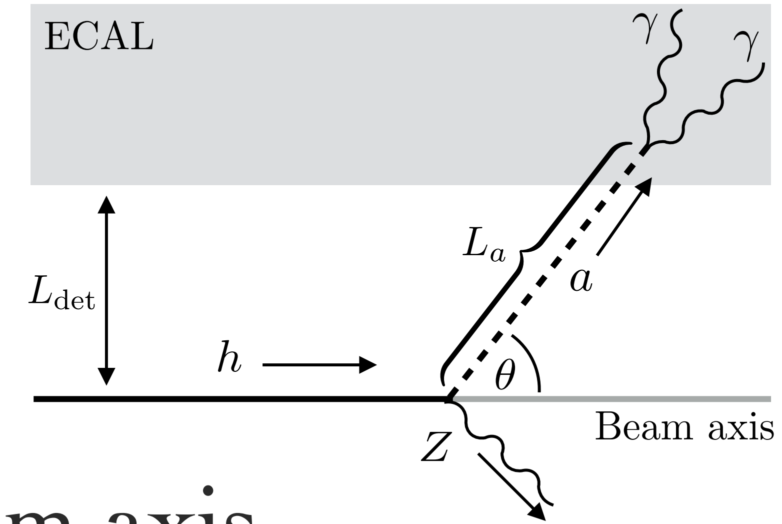


Detecting ALPs



- Average decay length perpendicular to beam axis

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

- Fraction of ALPs decaying before travelling a certain distance

$$f_{\text{det}} = \int_0^{\pi/2} d\theta \, \sin\theta \left(1 - e^{-L_{\text{det}}/L_a^\perp(\theta)}\right)$$

Decay into photons before EM calorimeter

$L_{\text{det}} = 1.5\,\text{m}$

Decay into electrons before inner tracker

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

Detecting ALPs

- Effective branching ratios

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

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

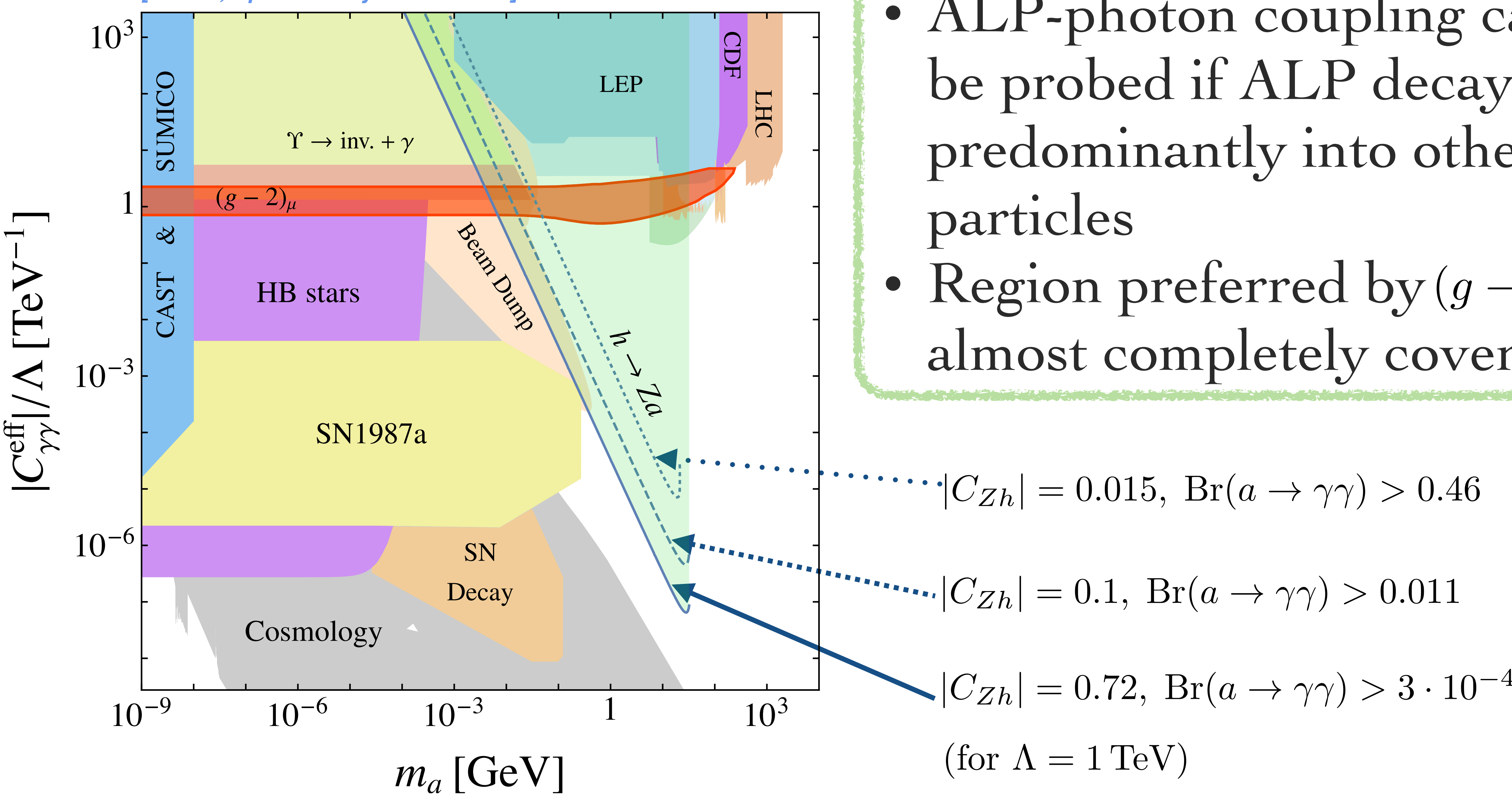
- Requiring 100 events at $\sqrt{s} = 13\,\mathrm{TeV}$ with $300\,\mathrm{fb}^{-1}$ in

$h \to Za \to \ell^+\ell^-\gamma\gamma$ $\qquad$ $h \to aa \to 4\gamma$

Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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

[Bauer, Neubert, Thamm: 1704.08207]

Detecting ALPs

- Effective branching ratios

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

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

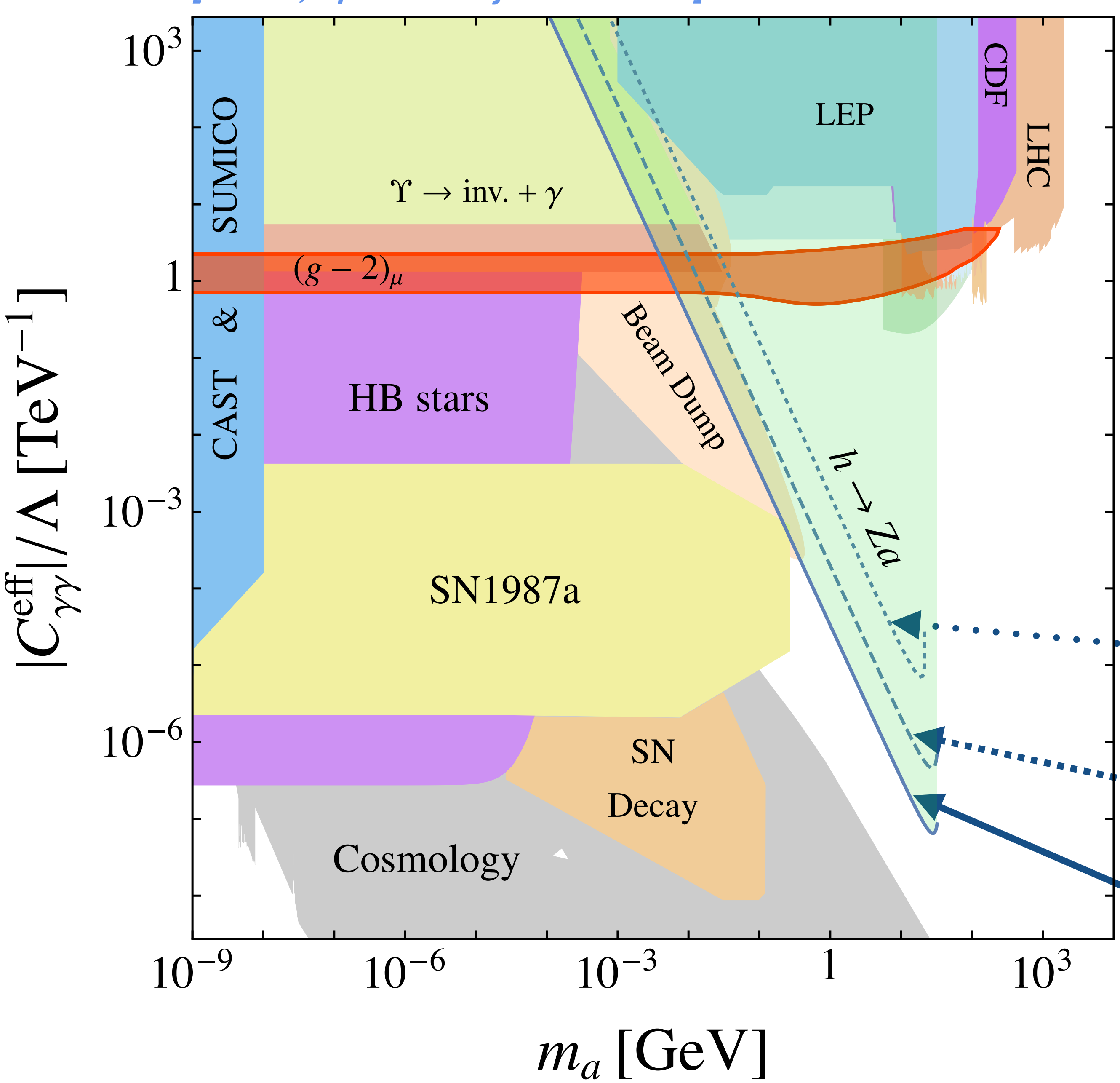
- For $L_a \gg L_{\mathrm{det}}$, effective BR independent of $\mathrm{Br}(a \to X\bar{X})$

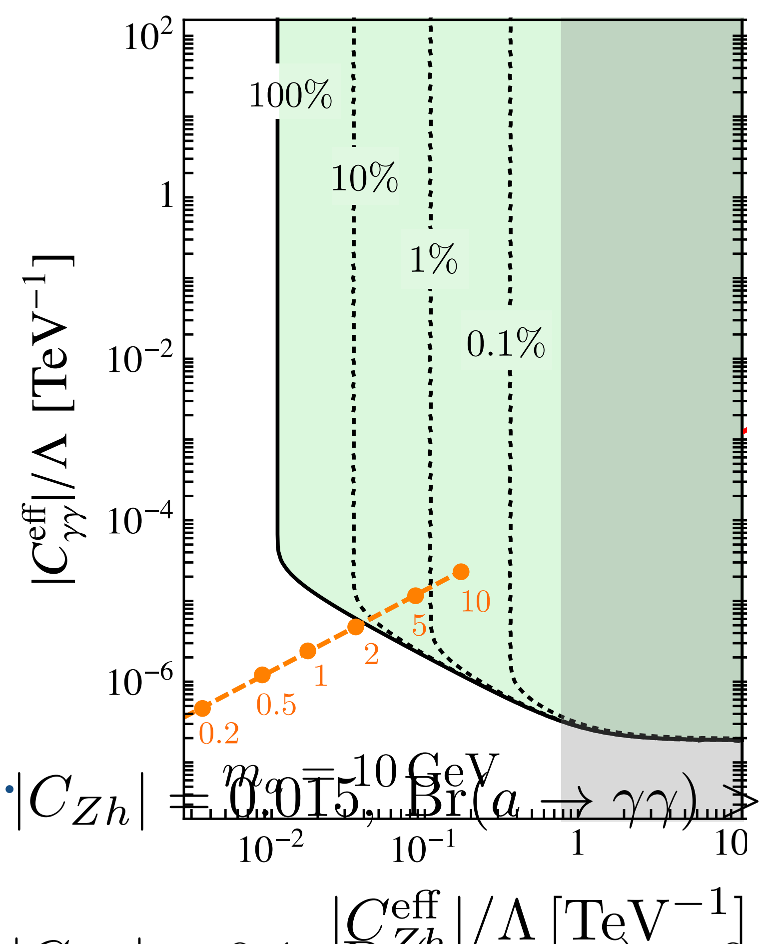
$$f_{\mathrm{dec}} \approx (\pi/2)\, \frac{L_{\mathrm{det}}}{L_a} \propto \frac{\Gamma(a \to X\bar{X})}{\mathrm{Br}(a \to X\bar{X})}$$

Probing the parameter space

- Large hierarchy in couplings can be plausible

[Jäckel, Spannowsky: 1509.00476]





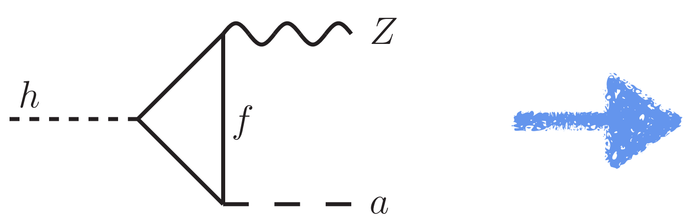
$|C_{Zh}| = 0.015, \;\mathrm{Br}(a \to \gamma\gamma) > 0.46$

$|C_{Zh}| = 0.1, \;\mathrm{Br}(a \to \gamma\gamma) > 0.011$

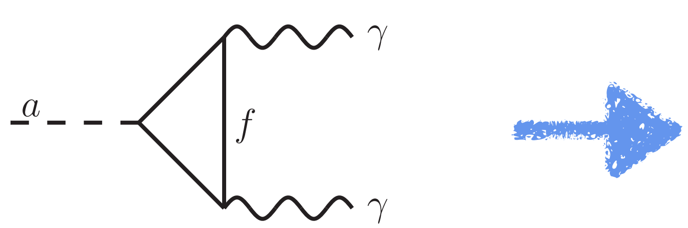
$|C_{Zh}| = 0.72, \;\mathrm{Br}(a \to \gamma\gamma) > 3 \cdot 10^{-4}$

Probing the parameter space

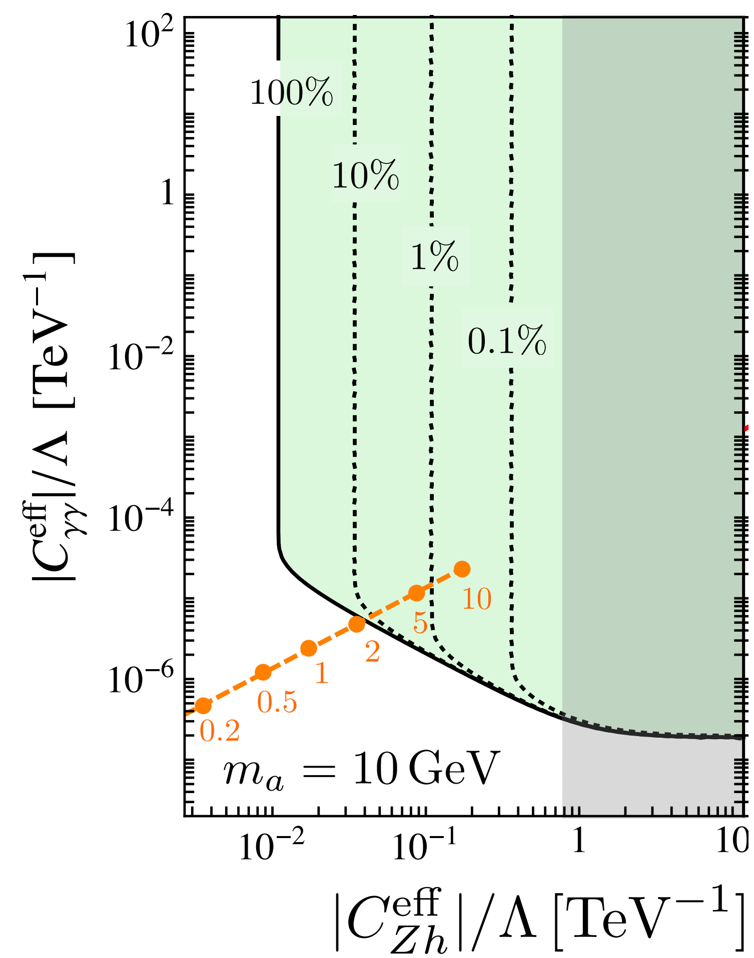
- Large hierarchy in couplings can be plausible
- Integrating out the top



$C_{\gamma\gamma}$



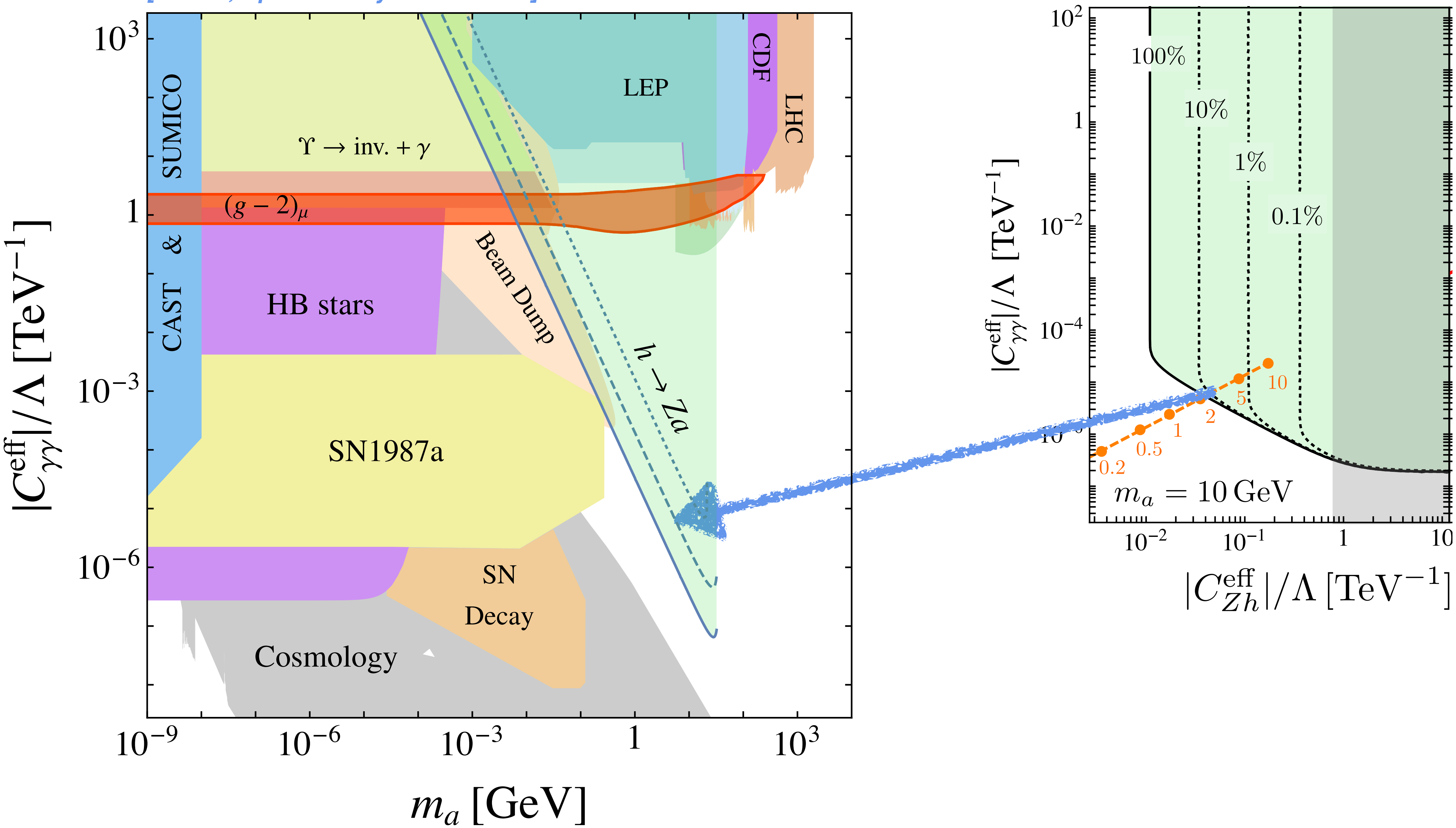
C_{Zh}



Probing the parameter space

- Large hierarchy in couplings can be plausible

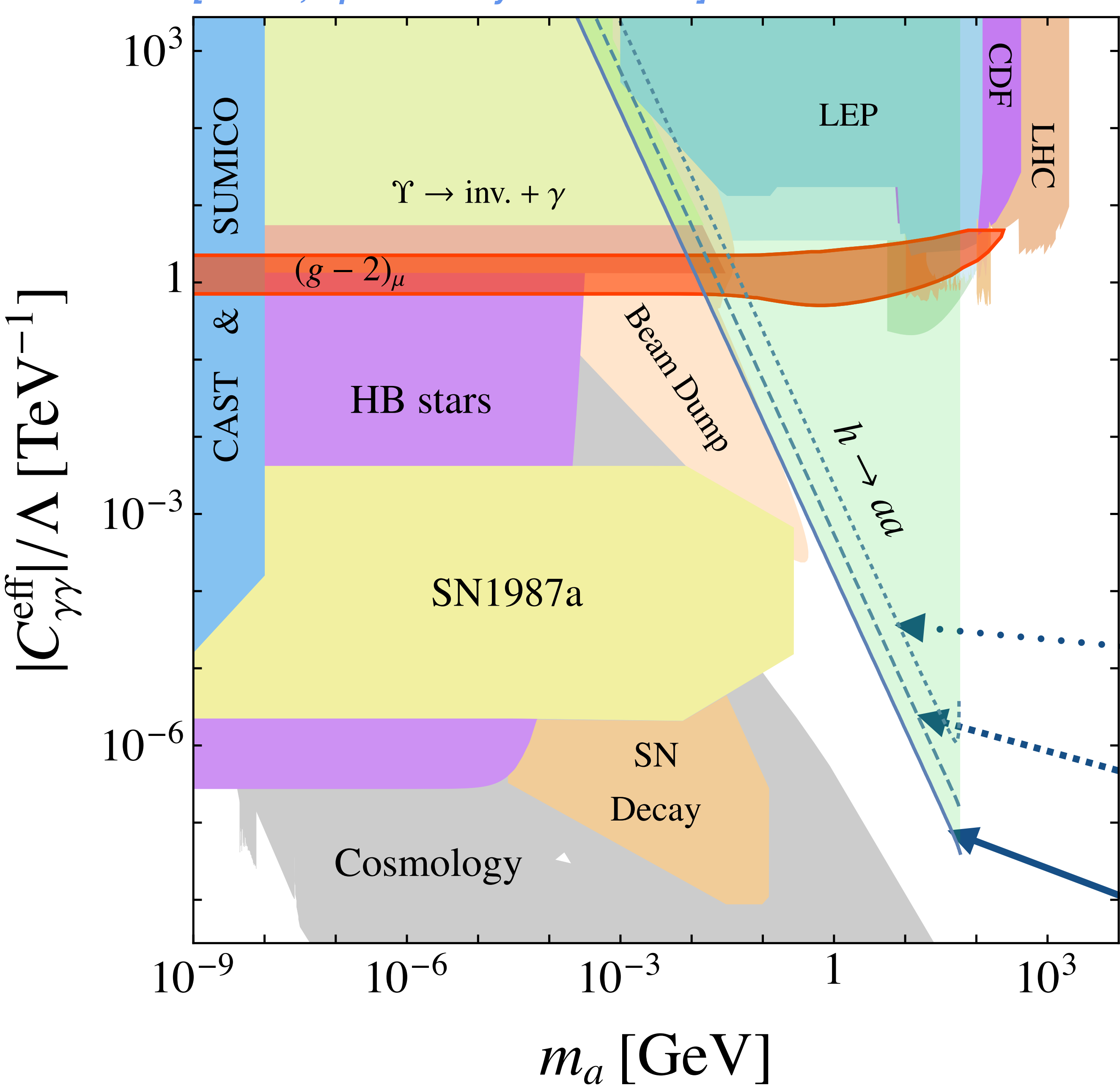
[Jäckel, Spannowsky: 1509.00476]



Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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

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

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

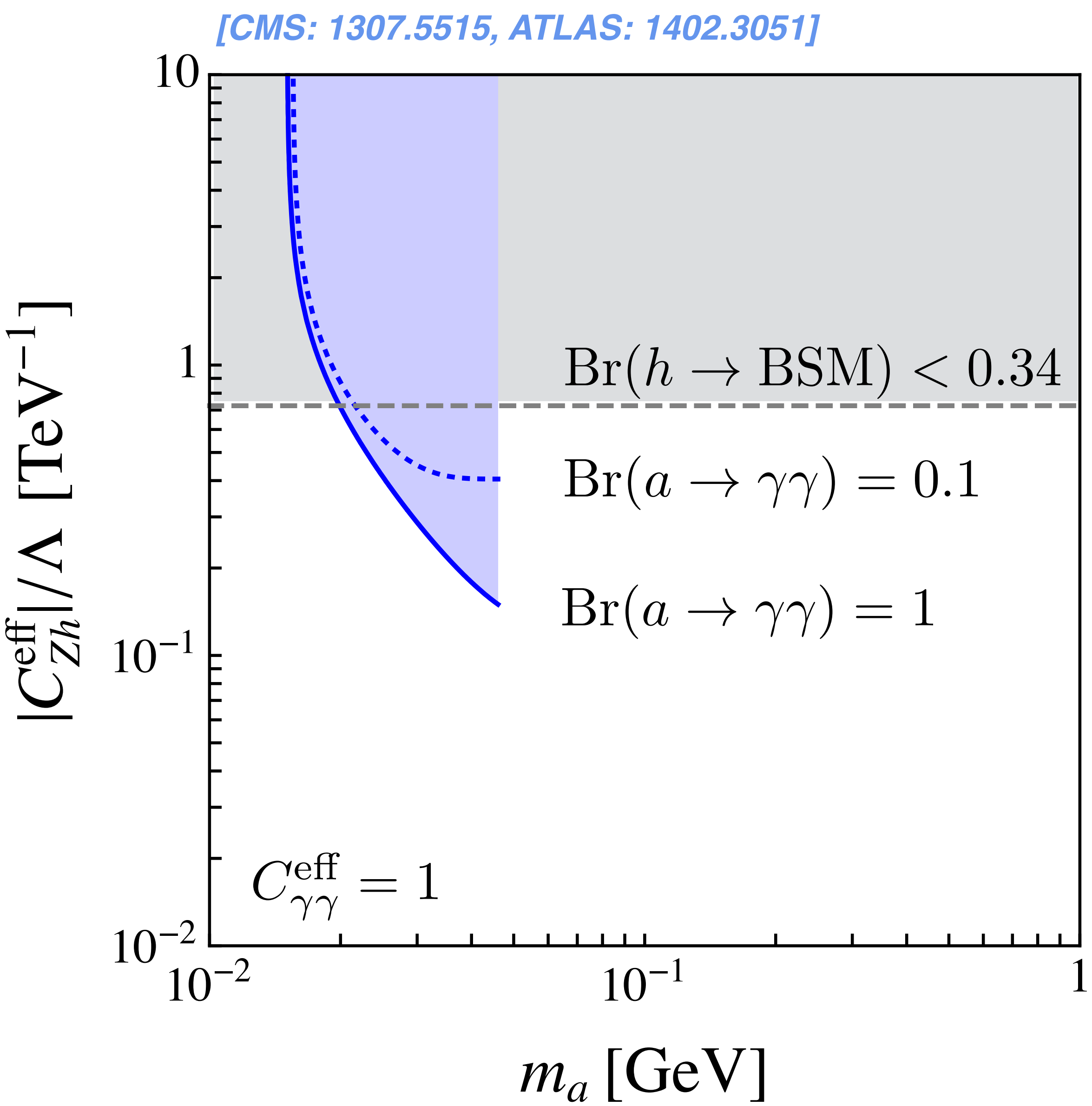
$|C_{ah}| = 1,\ \text{Br}(a \to \gamma\gamma) > 0.006$

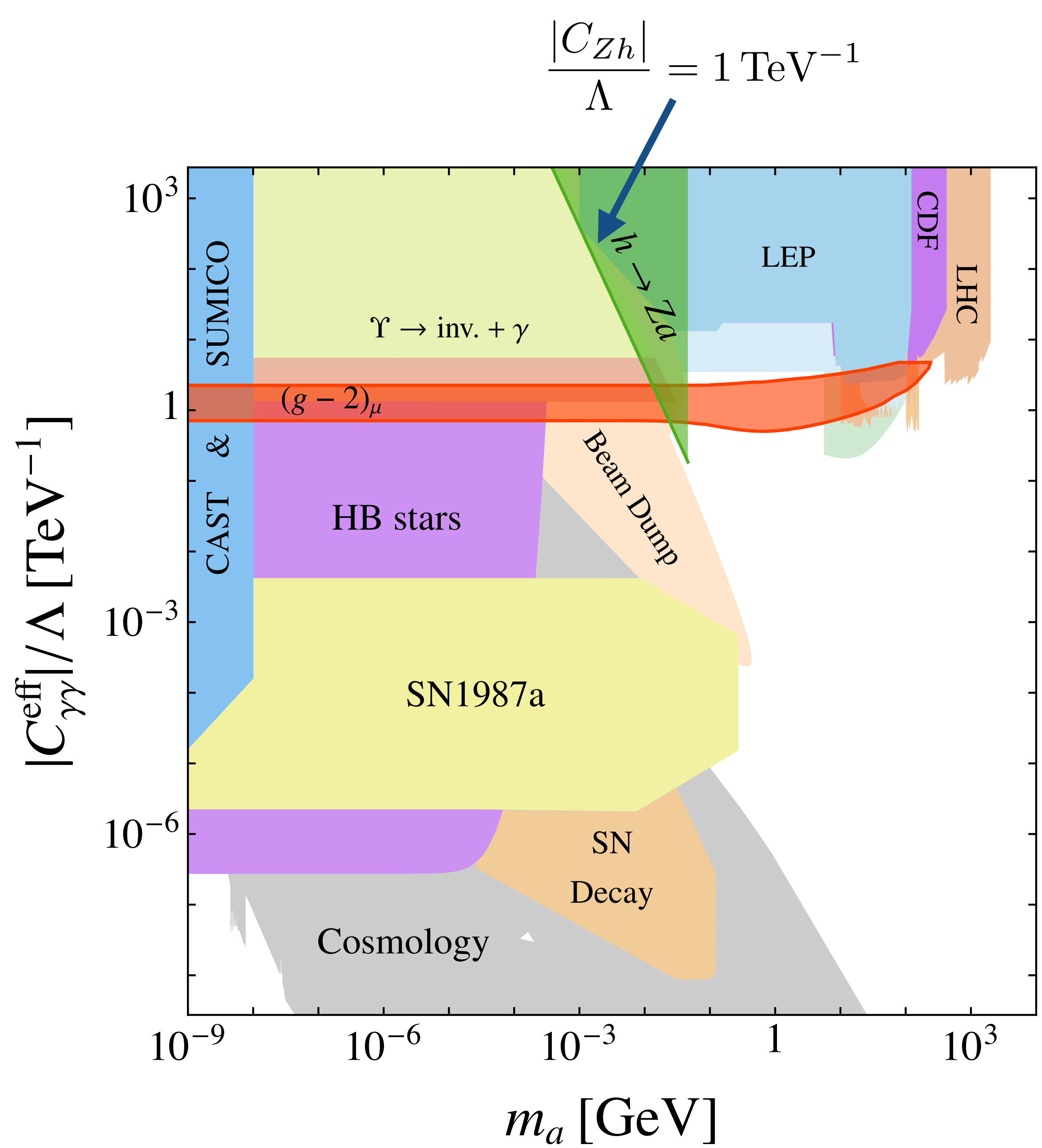
(for $\Lambda = 1\,\text{TeV}$)

[Bauer, Neubert, Thamm: 1704.08207]

Current exclusion bounds

- Current bounds on $h \to Za$

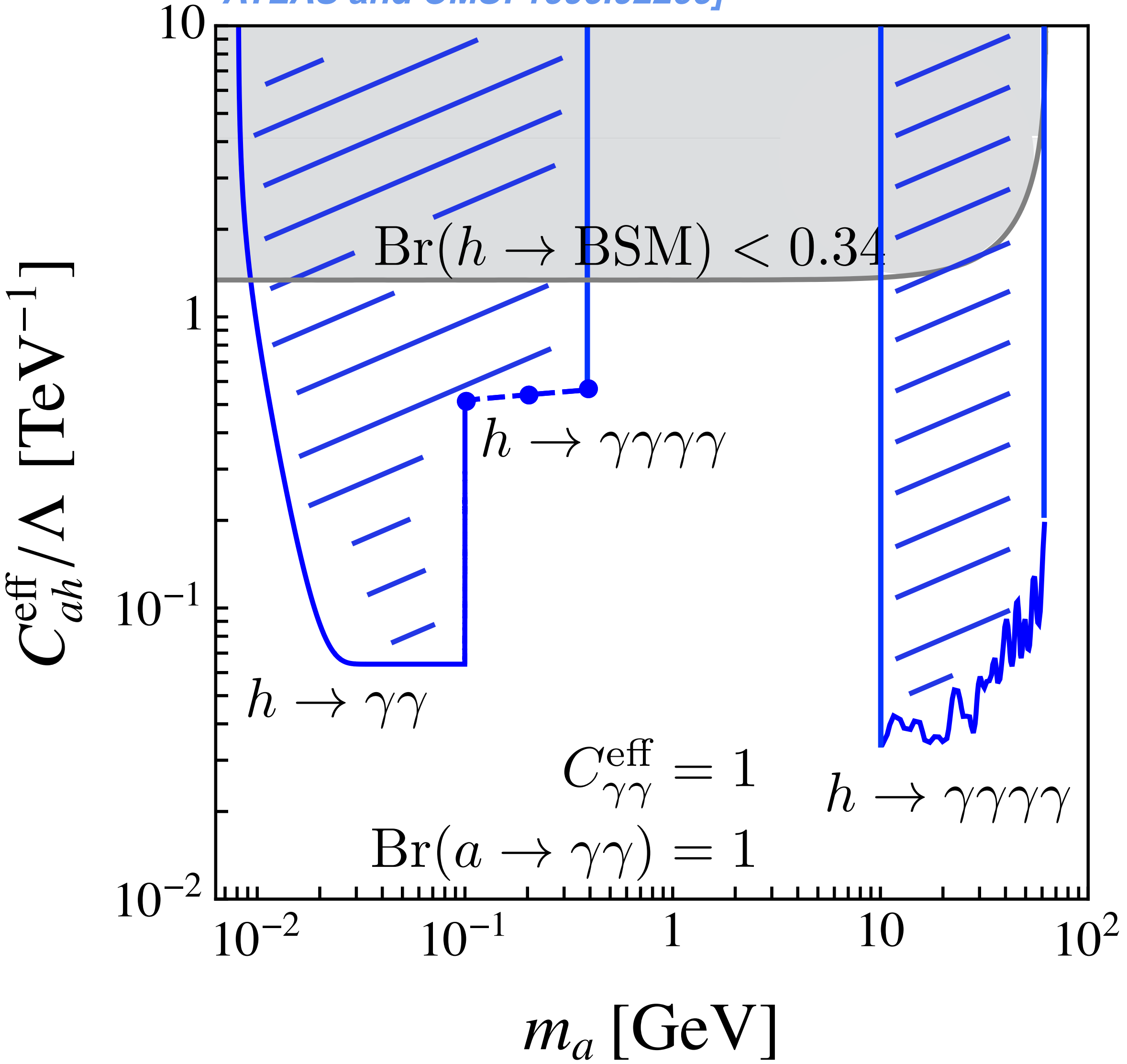


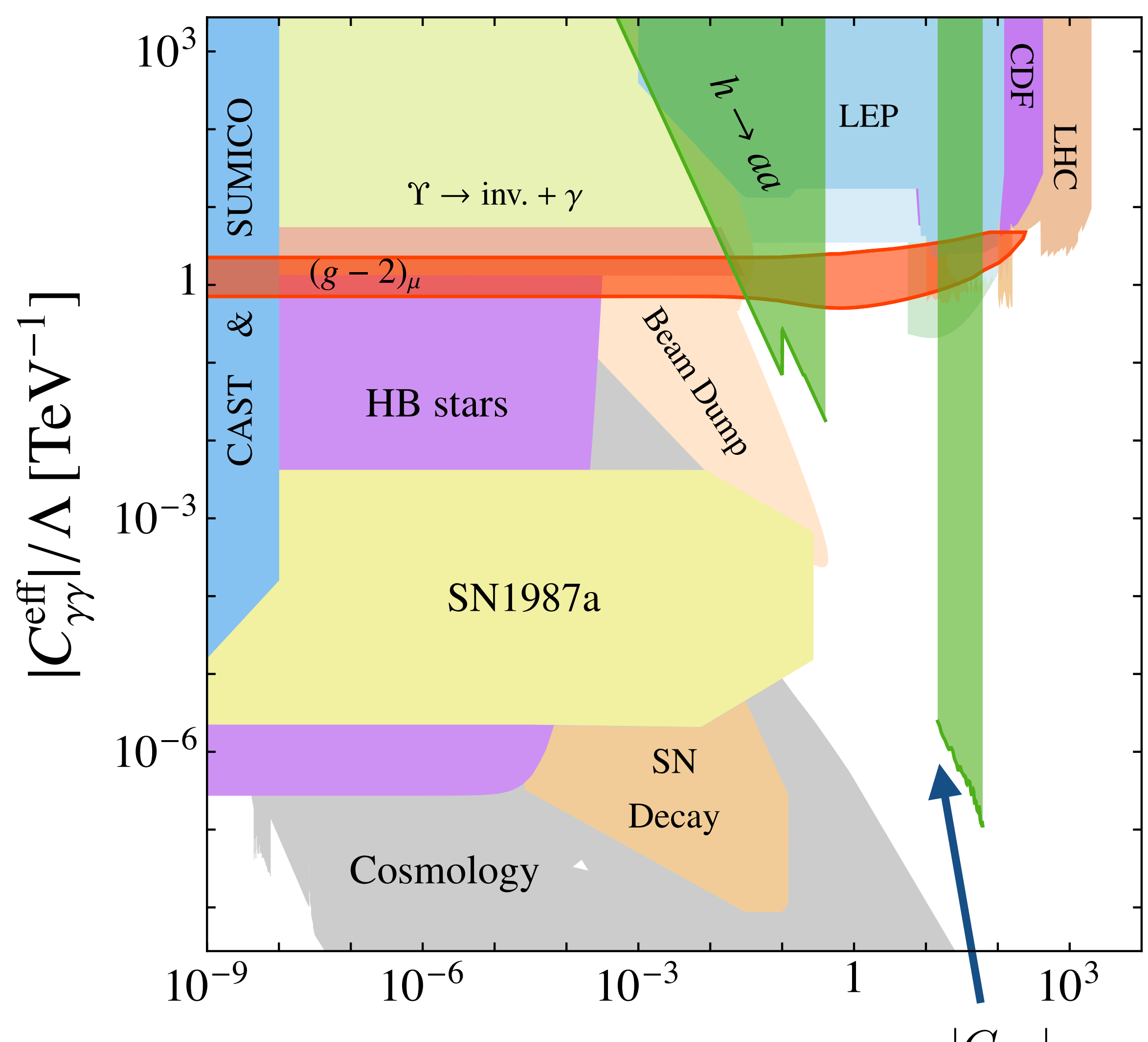


Current exclusion bounds

- Current bounds on $h \to aa$

[ATLAS-CONF-2012-079, ATLAS: 1509.05051, ATLAS and CMS: 1606.02266]

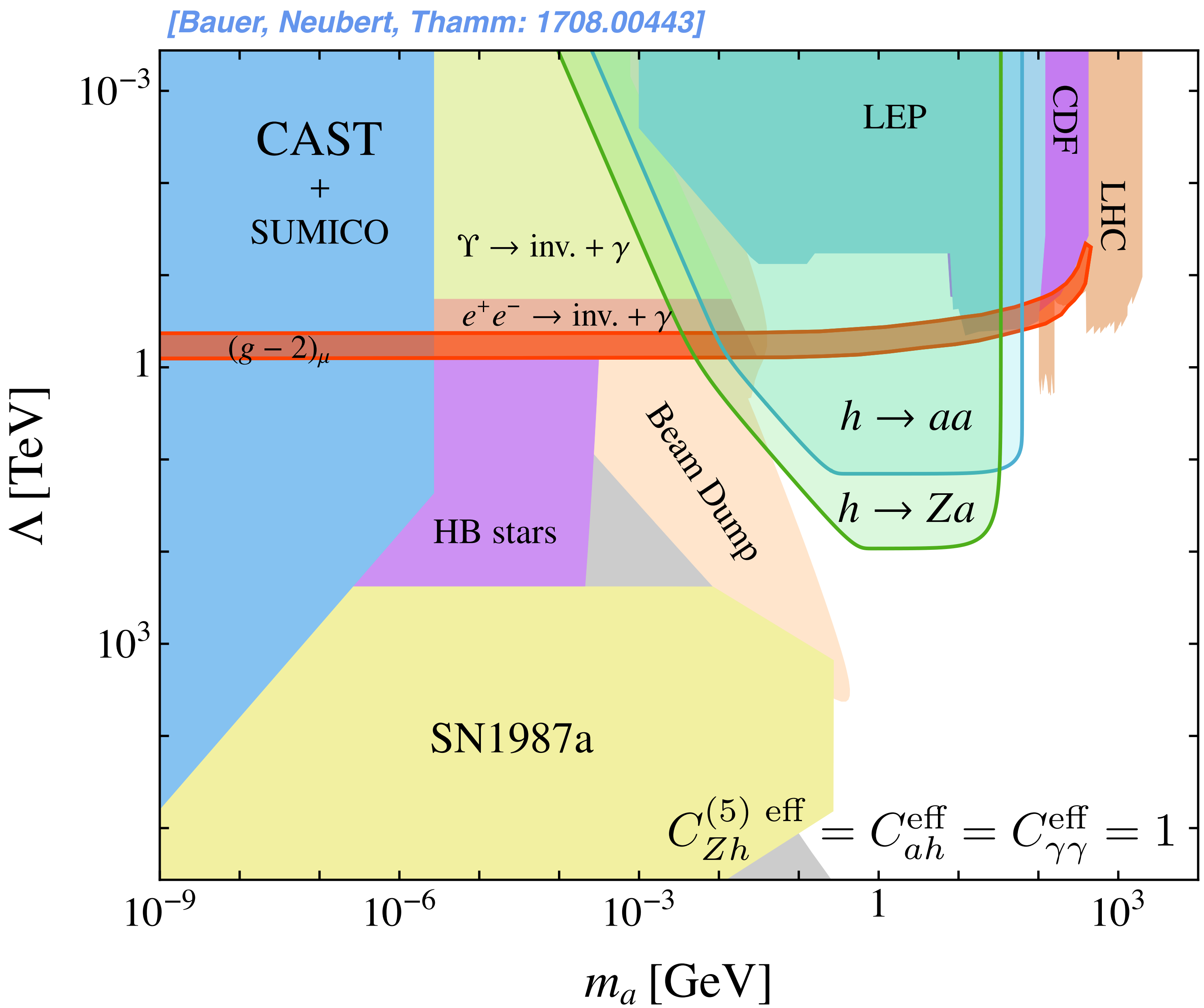




[Bauer, Neubert, Thamm: 1708.00443]

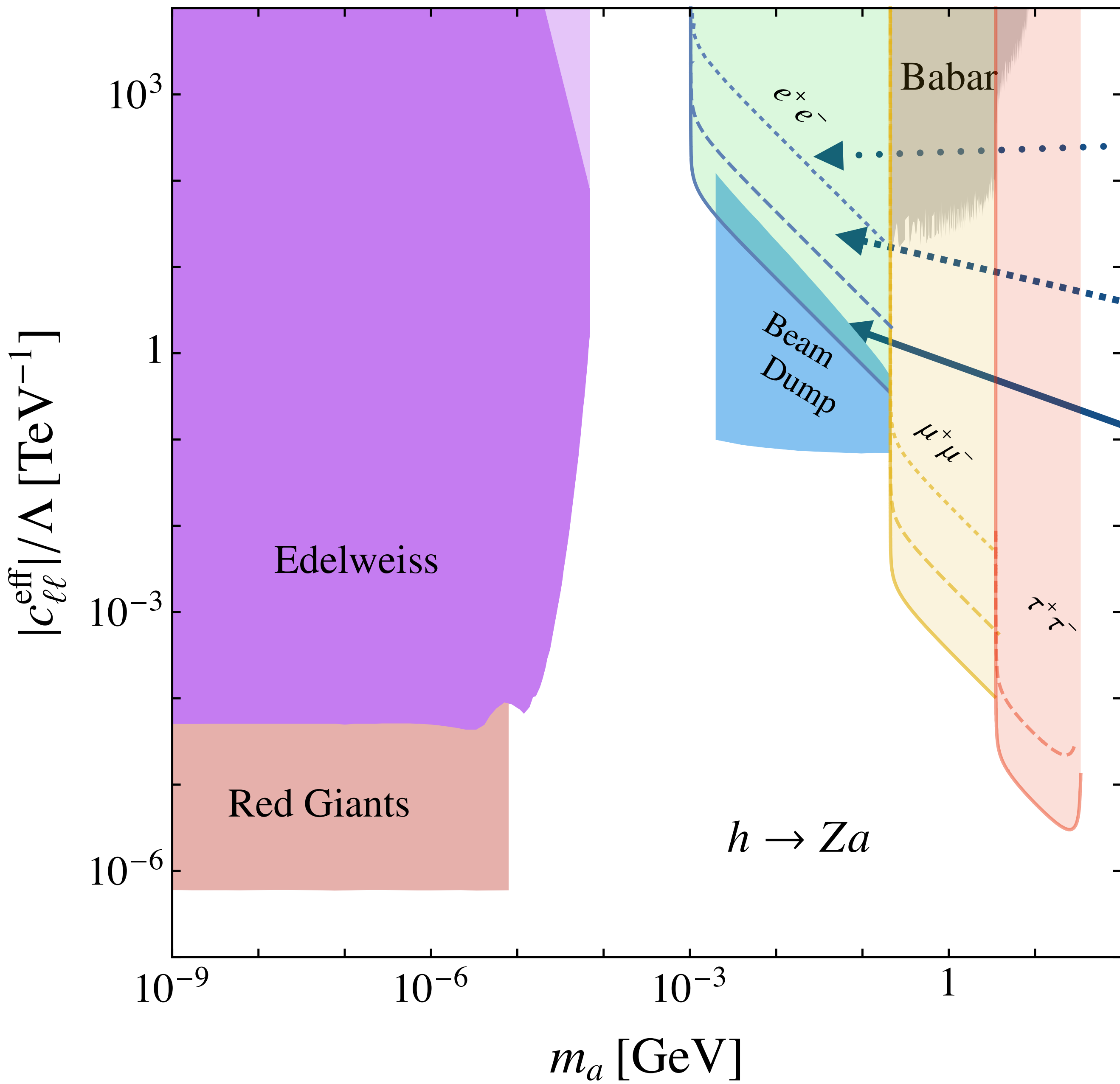
Probing the parameter space

- Constraints on ALP mass and coupling to photons



Probing the parameter space

- Constraints on ALP mass and coupling to leptons



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

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

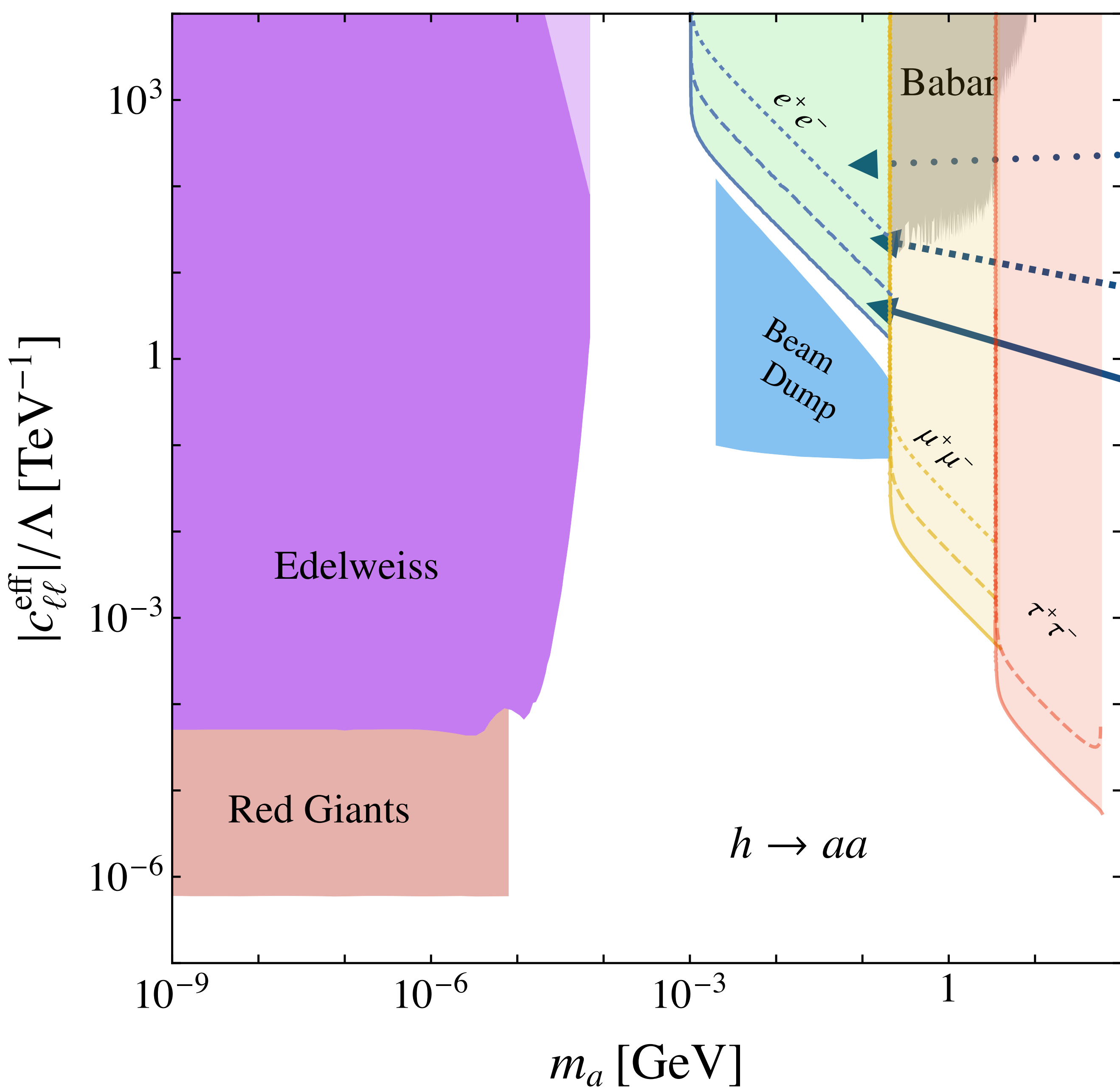
$|C_{Zh}| = 0.72,\ \mathrm{Br}(a \to e^+e^-) > 2 \cdot 10^{-4}$

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

[Armengaud: 1307.1488]
[Essig, Harnik, Kaplan, Toro: 1008.0636]
[Bauer, Neubert, Thamm: 1704.08207]

Probing the parameter space

- Constraints on ALP mass and coupling to leptons



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[Armengaud: 1307.1488]
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Outline

- Motivation
- ALPs and collider probes
  - Effective Lagrangian
  - Exotic Higgs decays
  - ALP Decays
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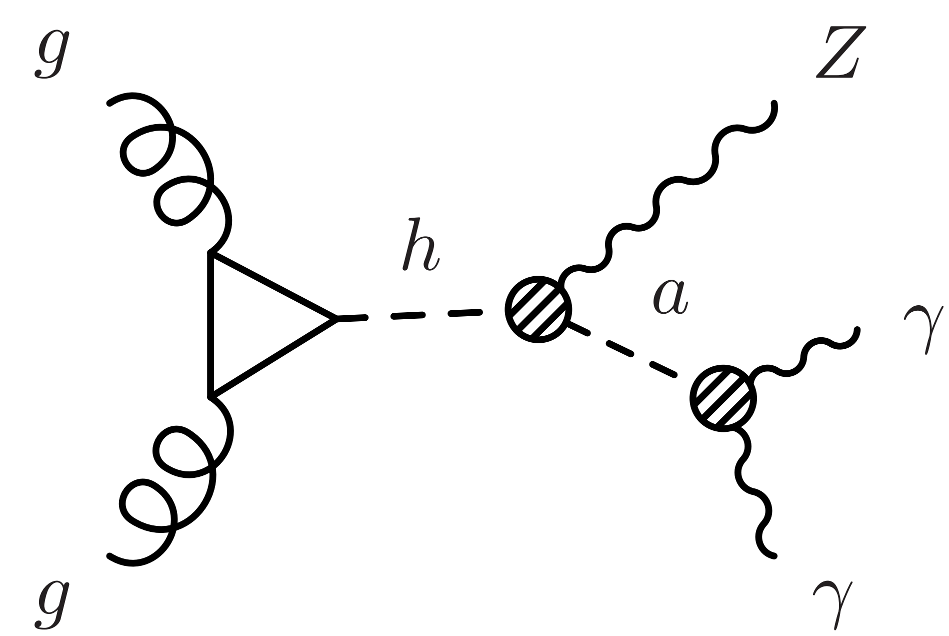
  - Muon $(g-2)_\mu$
  - Future Colliders
- Conclusions and Outlook



Muon $(g-2)_\mu$

rsistent dev

[Particle Data Group 2016]

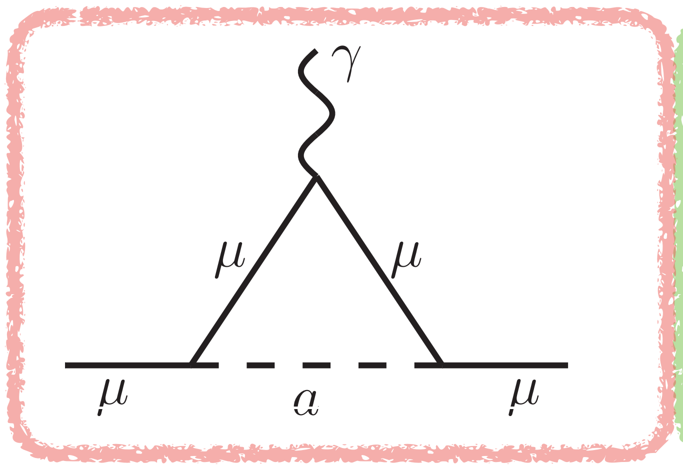
$$a_\mu^{\mathrm{exp}} \;\; a_\mu^{\mathrm{SM}} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$

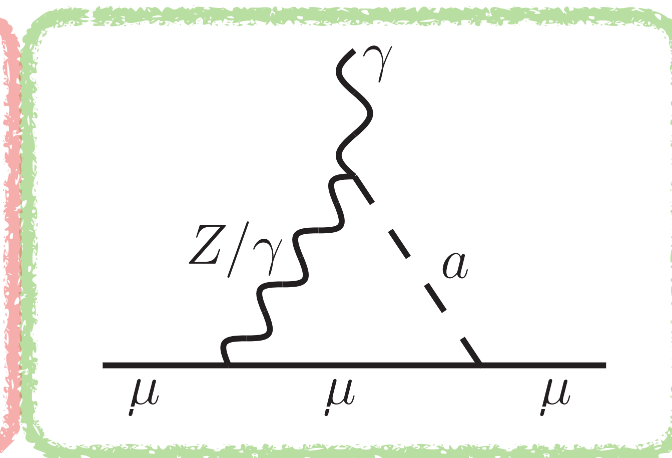
- Differs fro ro by more than
- ALP can acco r discrepa

Phys. B 161 (1979)]

3σ

Muon $(g-2)_\mu$





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

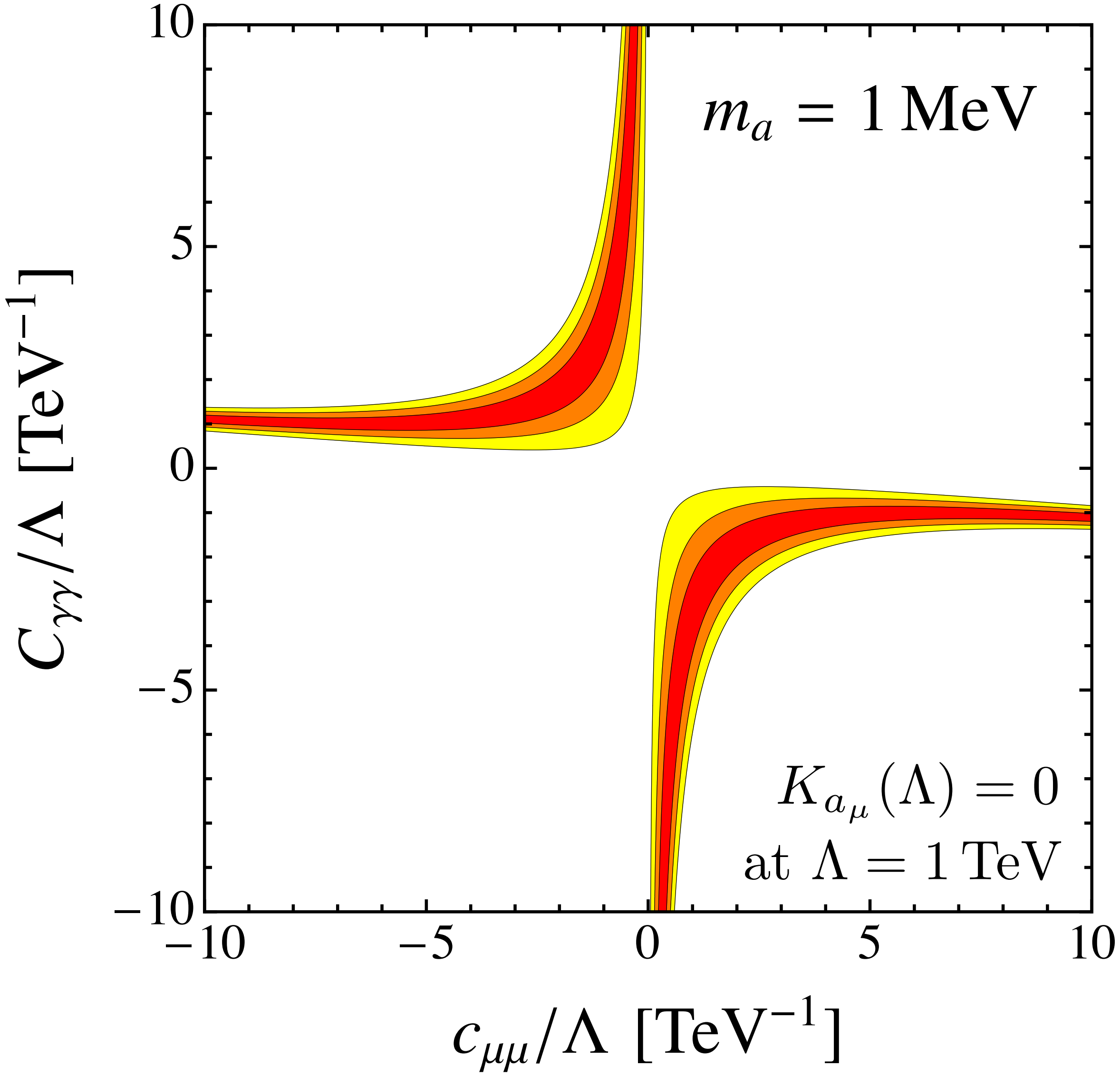
$$\mathcal{L}_{\rm eff}^{D=6} \ni -K_{a_\mu}\,\frac{e m_\mu}{4\Lambda^2}\,\bar\mu\,\sigma_{\mu\nu}F^{\mu\nu}\mu$$

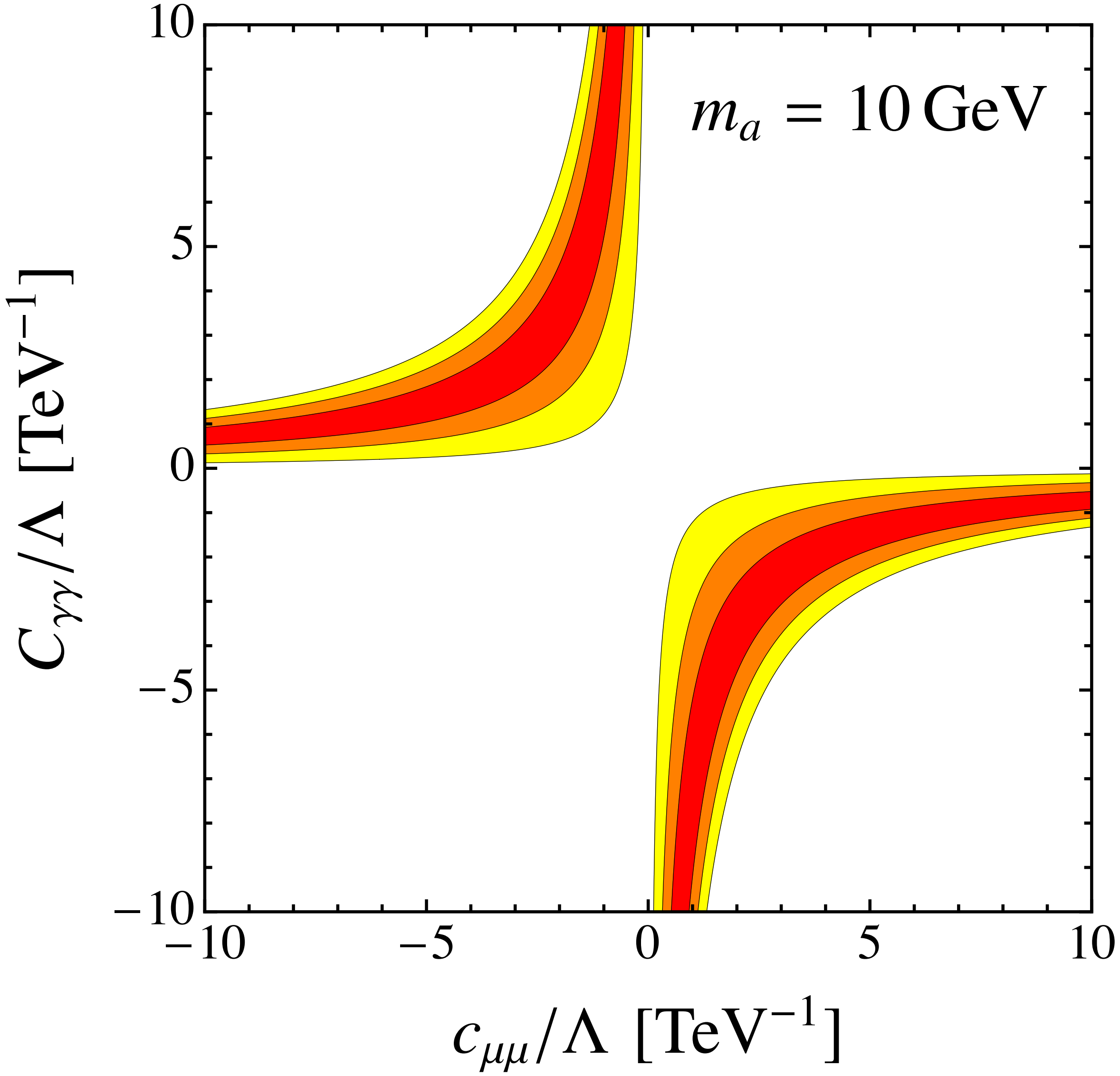
$$h_1(0) = 1 \qquad h_1(x) \approx (2/x)(\ln x - \tfrac{11}{6}) \text{ for } x \gg 1$$

$$h_2(0) = 0 \qquad h_2(x) \approx (\ln x + \tfrac{1}{2})$$

Muon $(g-2)_\mu$

- Allowed parameter space





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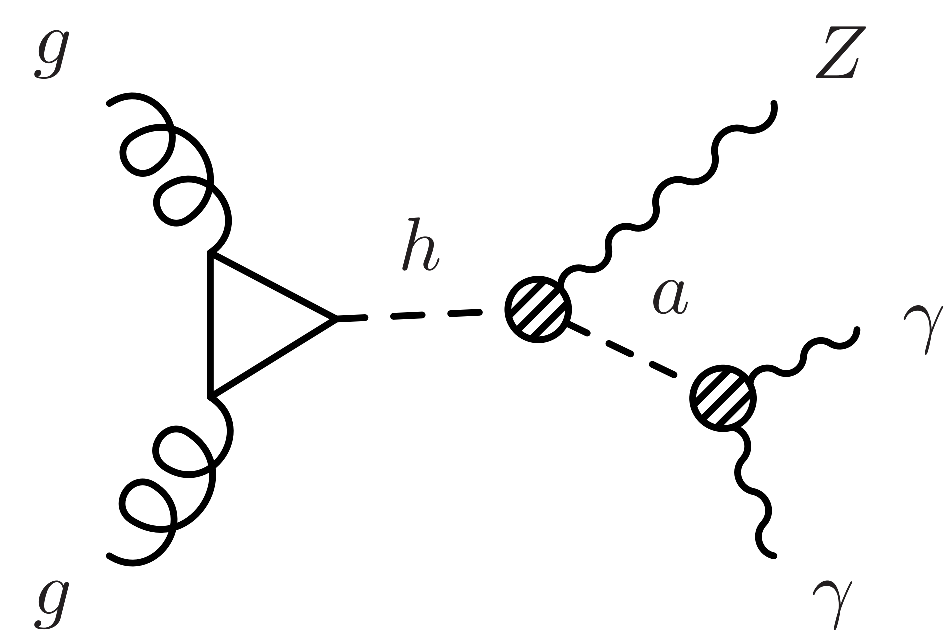


Conclusions

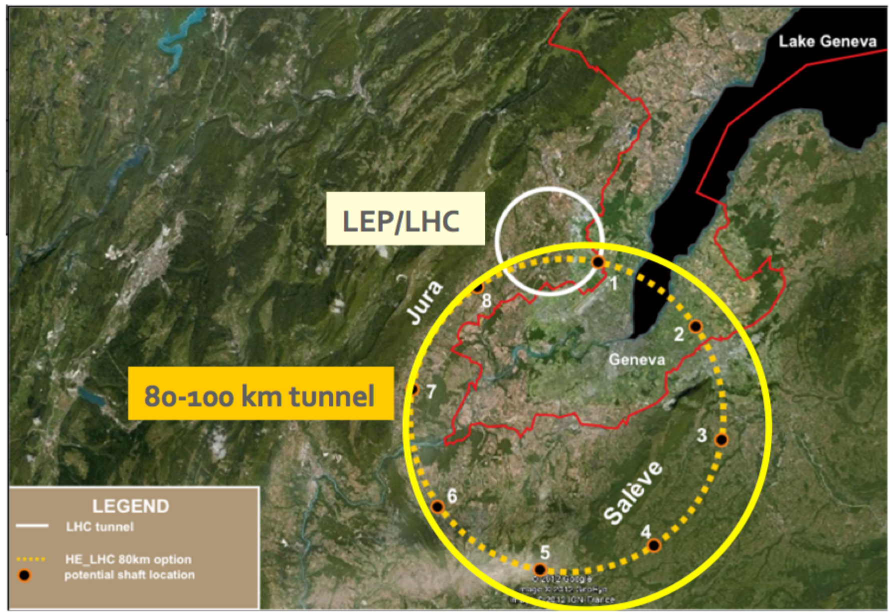
- Rare Higgs decays provide a powerful way to probe the existence of ALPs with masses between 30 MeV and 60 GeV and couplings suppressed by the 1 - 100 TeV scale
- Connection to low-energy physics probes such as $(g-2)_\mu$

Outlook

- Dedicated analyses with reconstruction efficiencies and exploiting displaced-vertex signatures
- Investigating the flavour sector *[Bauer, Neubert, Thamm: to appear]*
- Looking at various anomalies

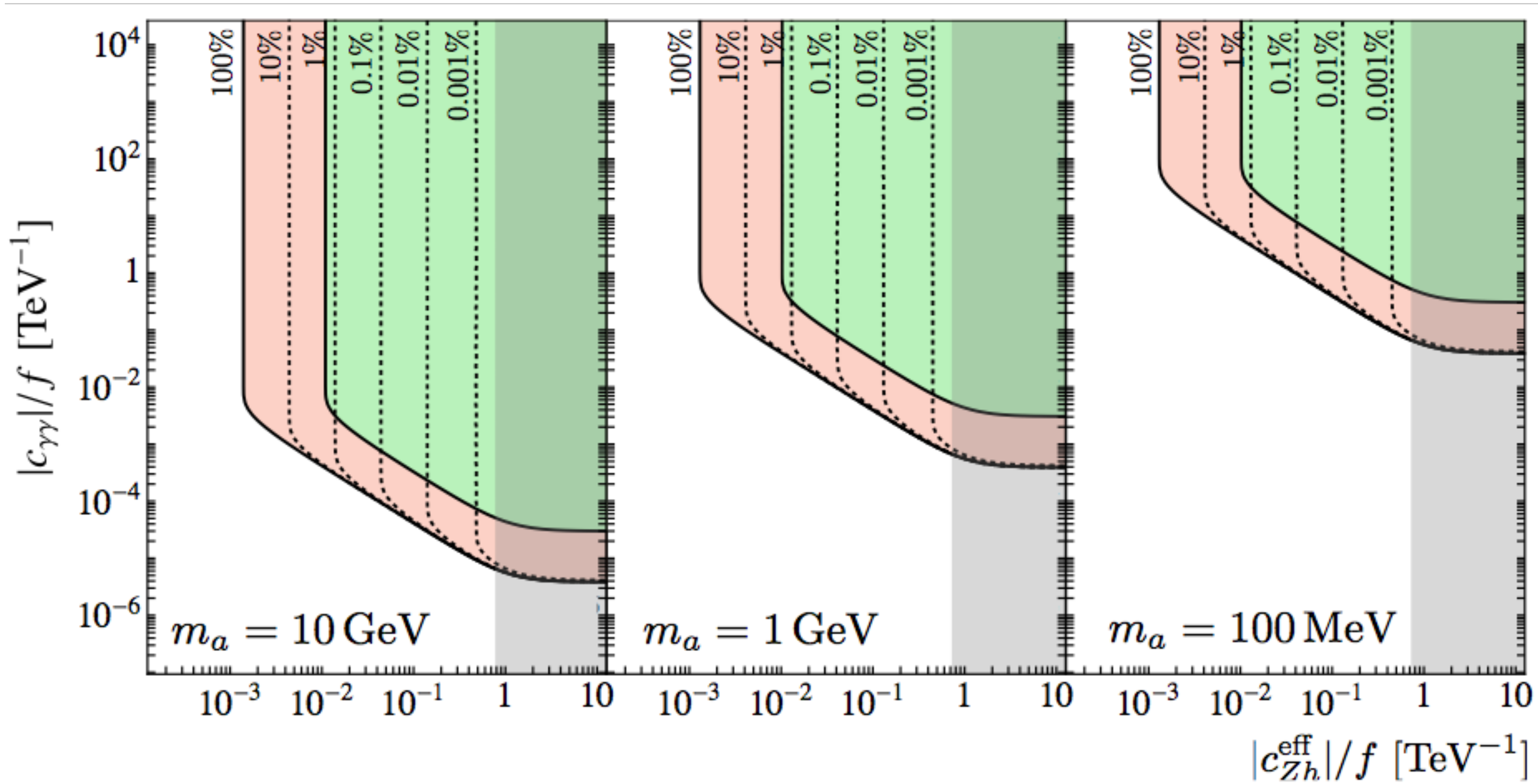
Backup

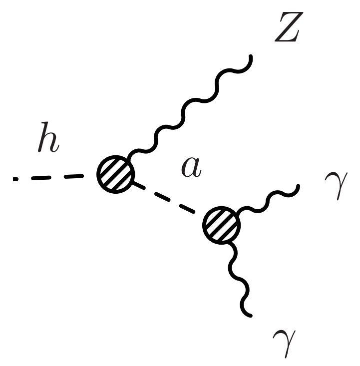
Parameter space at the FCC-ee



[arXiv:1308.6176]

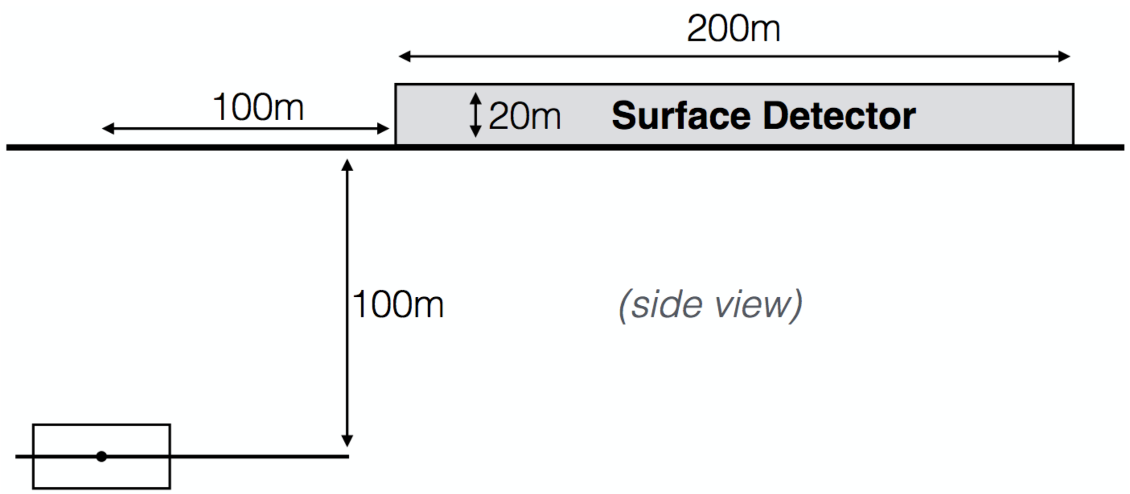
- e^+e^- collider
- 240 and 350 GeV
- 3 million Higgses



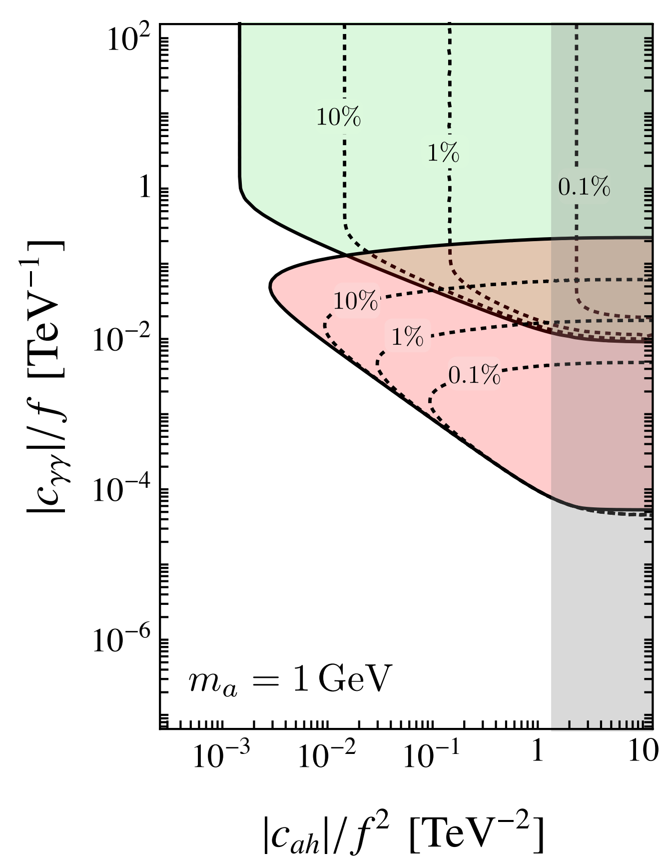


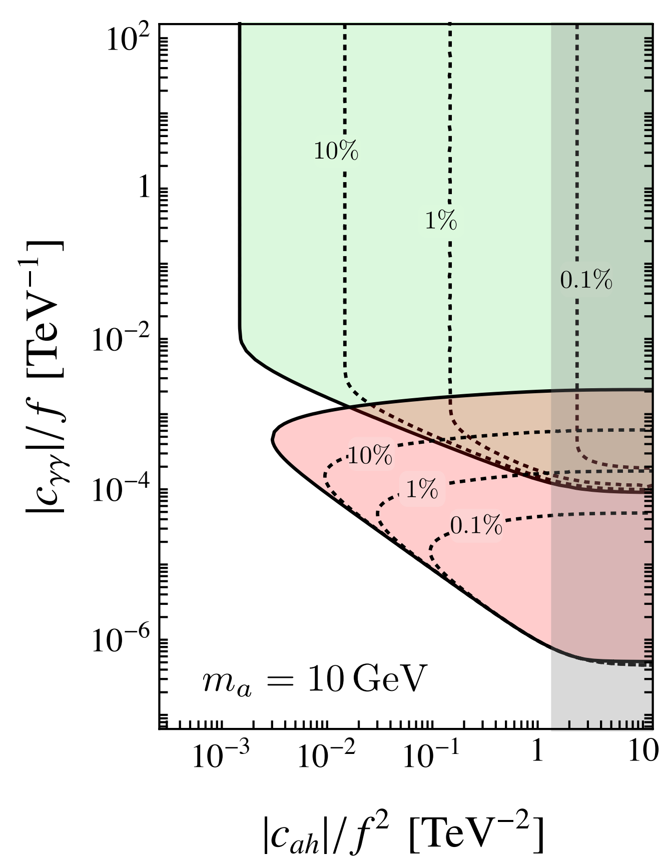
Parameter space at MATHUSLA

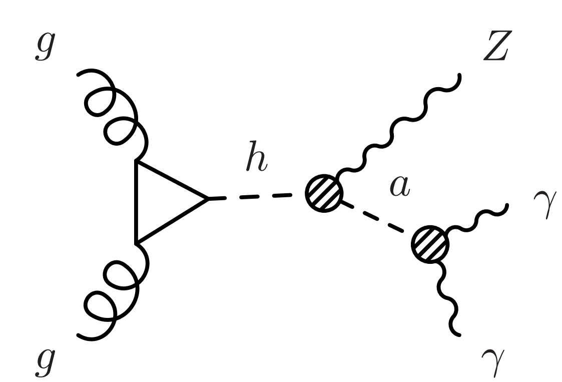
[Chou, Curtin, Lubatti: 1606.06298]



- Long-lived particles at LHC







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  - Electroweak precision test
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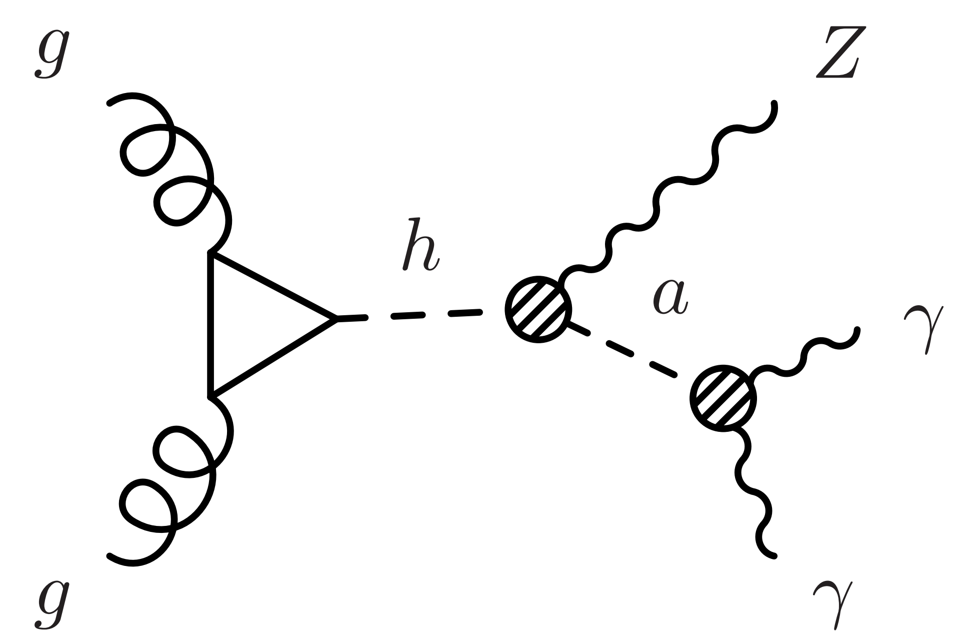


Electroweak precision tests

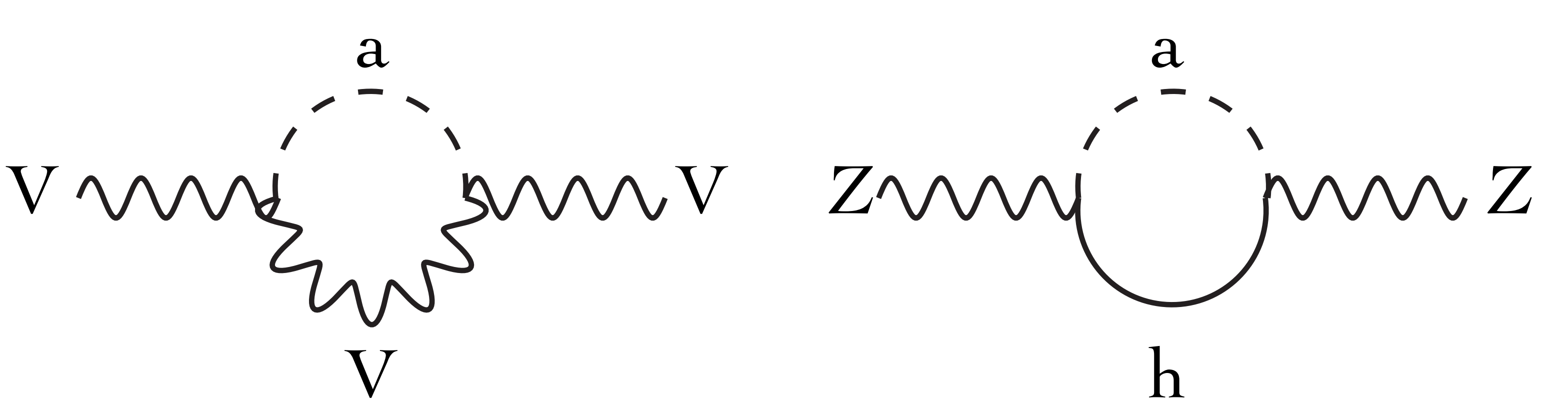
- Consider ALP induced 1-loop correction to three definitions of sine squared of weak mixing angle [Peskin, Takeuich: Phys. Rev. D 46 (1992) 381]

$$s_*^2 = \frac{g'^2}{g^2+g'^2} - s_w c_w \frac{\Pi_{\gamma Z}(m_Z^2)}{m_Z^2}$$

$$s_W^2 = \frac{g'^2}{g^2+g'^2} - c_w^2 \left[\frac{\Pi_{WW}(m_W^2)}{m_W^2} - \frac{\Pi_{ZZ}(m_Z^2)}{m_Z^2}\right]$$

$$s_0^2 = \frac{g'^2}{g^2+g'^2} + \frac{s_w^2 c_w^2}{c_w^2 - s_w^2}\left[\frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2} + \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(m_Z^2)}{m_Z^2}\right]$$

$$\rho_* = 1 + \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{2s_w}{c_w}\frac{\Pi_{\gamma Z}(0)}{m_Z^2}$$



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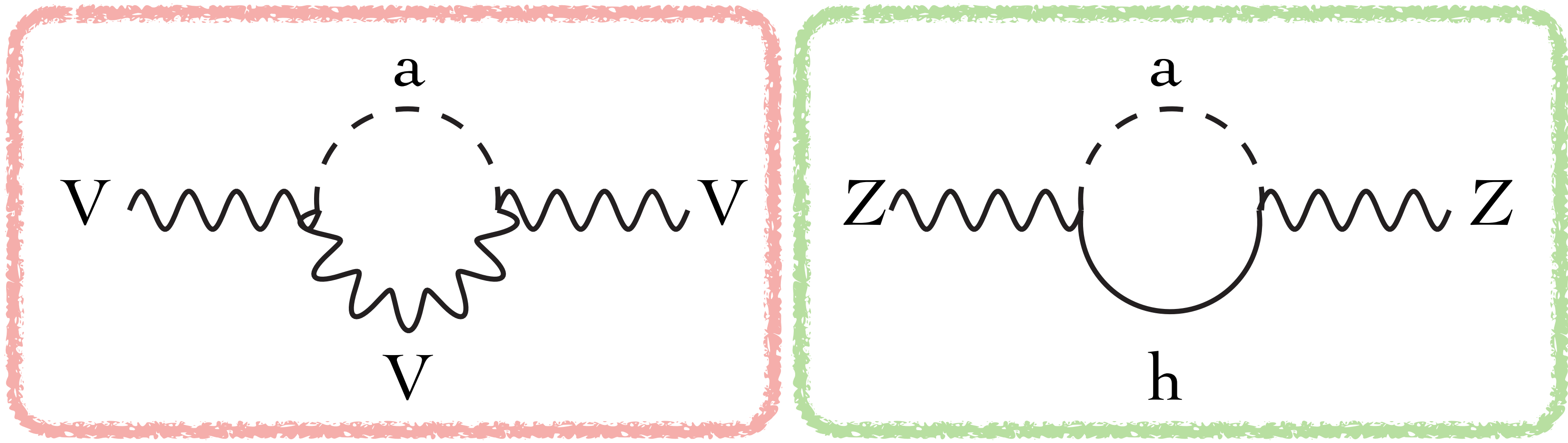


$$S = 32\alpha \frac{m_Z^2}{\Lambda^2} C_{WW} C_{BB} \left(\ln \frac{\Lambda^2}{m_Z^2} - 1 \right) - \frac{\left(C_{Zh}^{(5)}\right)^2}{12\pi} \frac{v^2}{\Lambda^2} \left[\ln \frac{\Lambda^2}{m_h^2} + \frac{3}{2} + p\left(\frac{m_Z^2}{m_h^2}\right) \right]$$

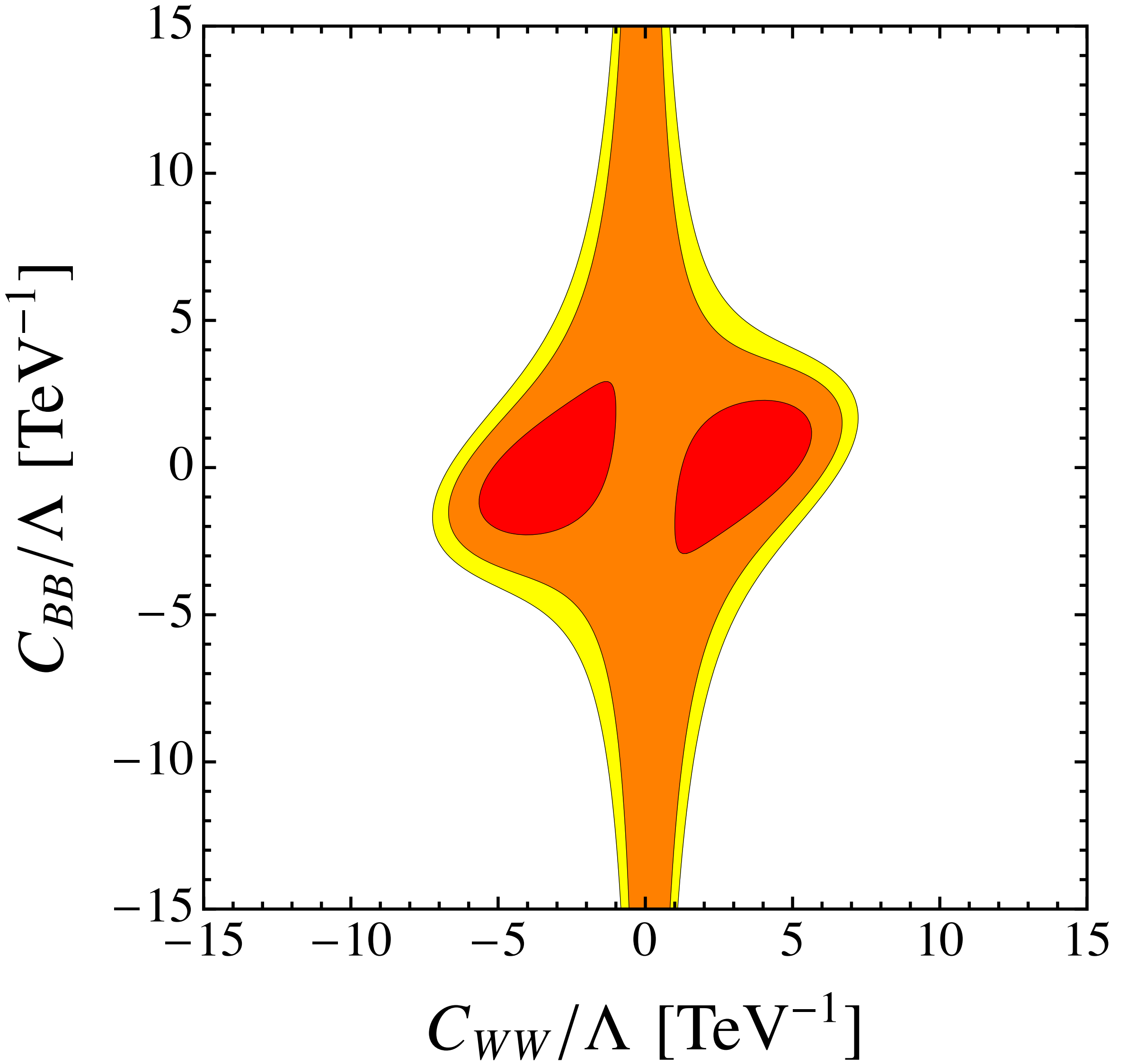
$$T = -\frac{\left(C_{Zh}^{(5)}\right)^2}{4\pi e^2} \frac{m_h^2}{\Lambda^2} \left(\ln \frac{\Lambda^2}{m_h^2} + \frac{3}{2} \right)$$

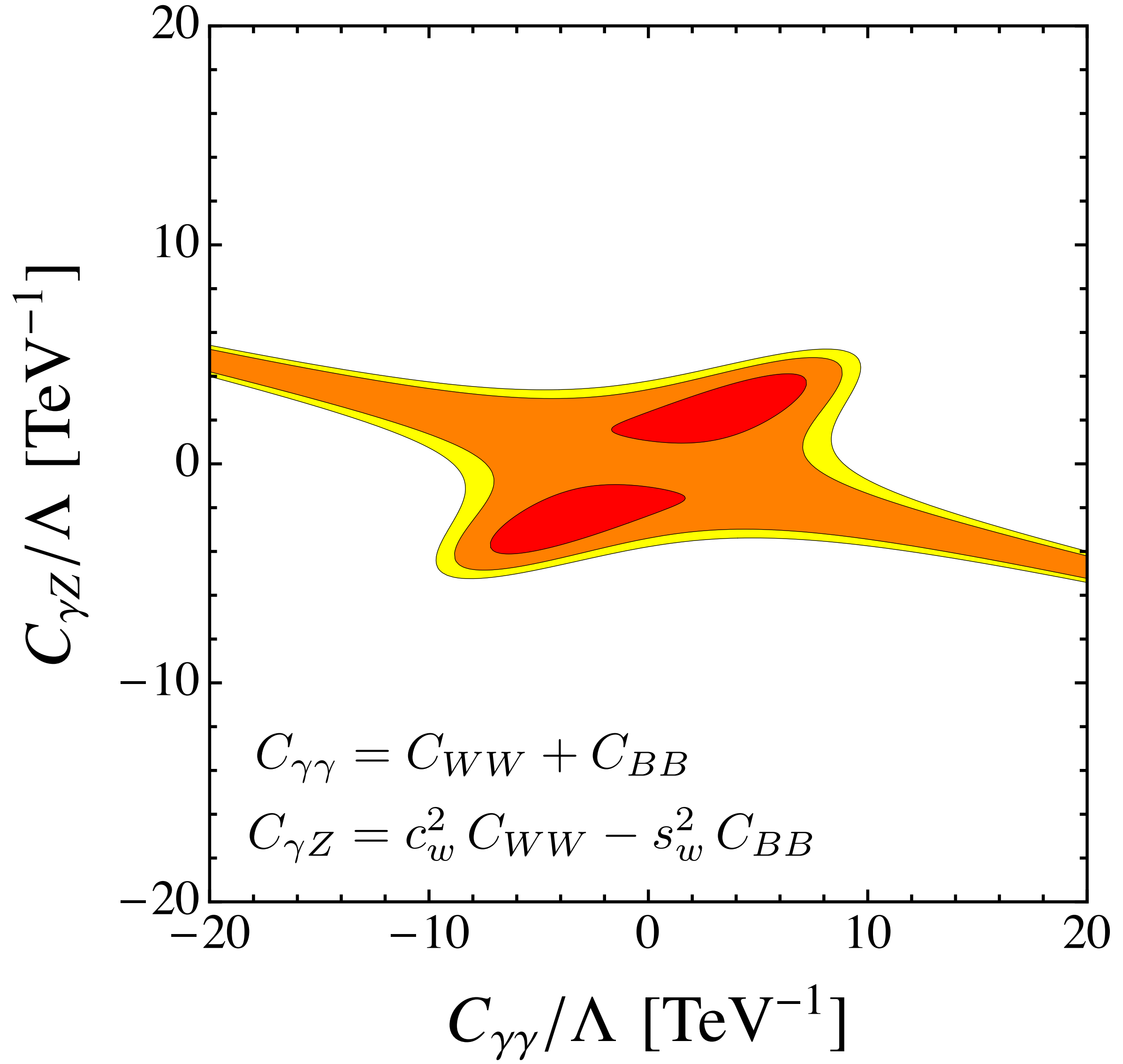
$$U = \frac{32\alpha}{3} \frac{m_Z^2}{\Lambda^2} C_{WW}^2 \left(\ln \frac{\Lambda^2}{m_Z^2} - \frac{1}{3} - \frac{2c_w^2}{s_w^2} \ln c_w^2 \right) + \frac{\left(C_{Zh}^{(5)}\right)^2}{12\pi} \frac{v^2}{\Lambda^2} \left[\ln \frac{\Lambda^2}{m_h^2} + \frac{3}{2} + p\left(\frac{m_Z^2}{m_h^2}\right) \right]$$

Electroweak precision tests

- Allowed parameter space for $C_{Zh}^{(5)} = 0$

[Baak et al.: 1407.3792]

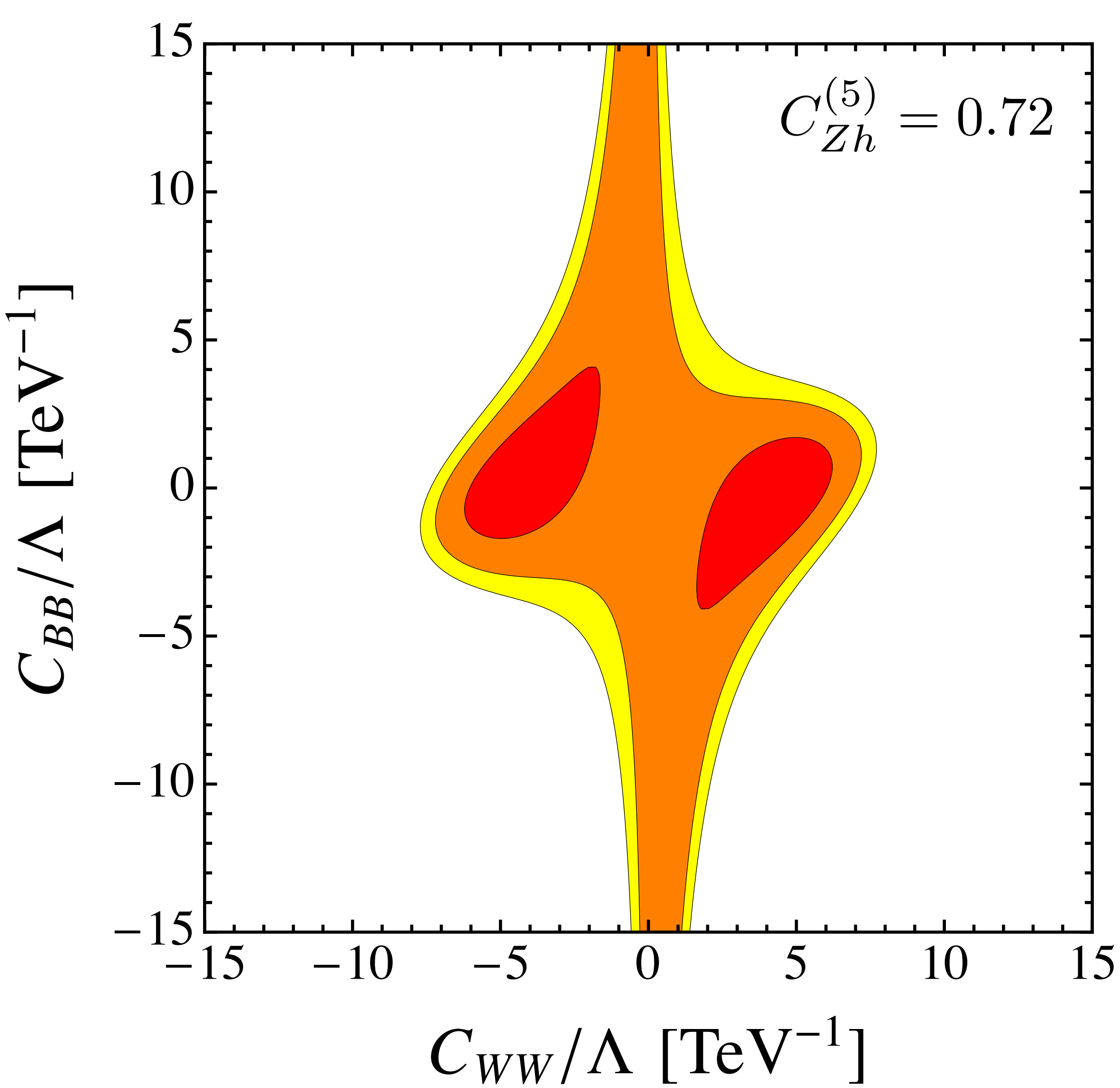


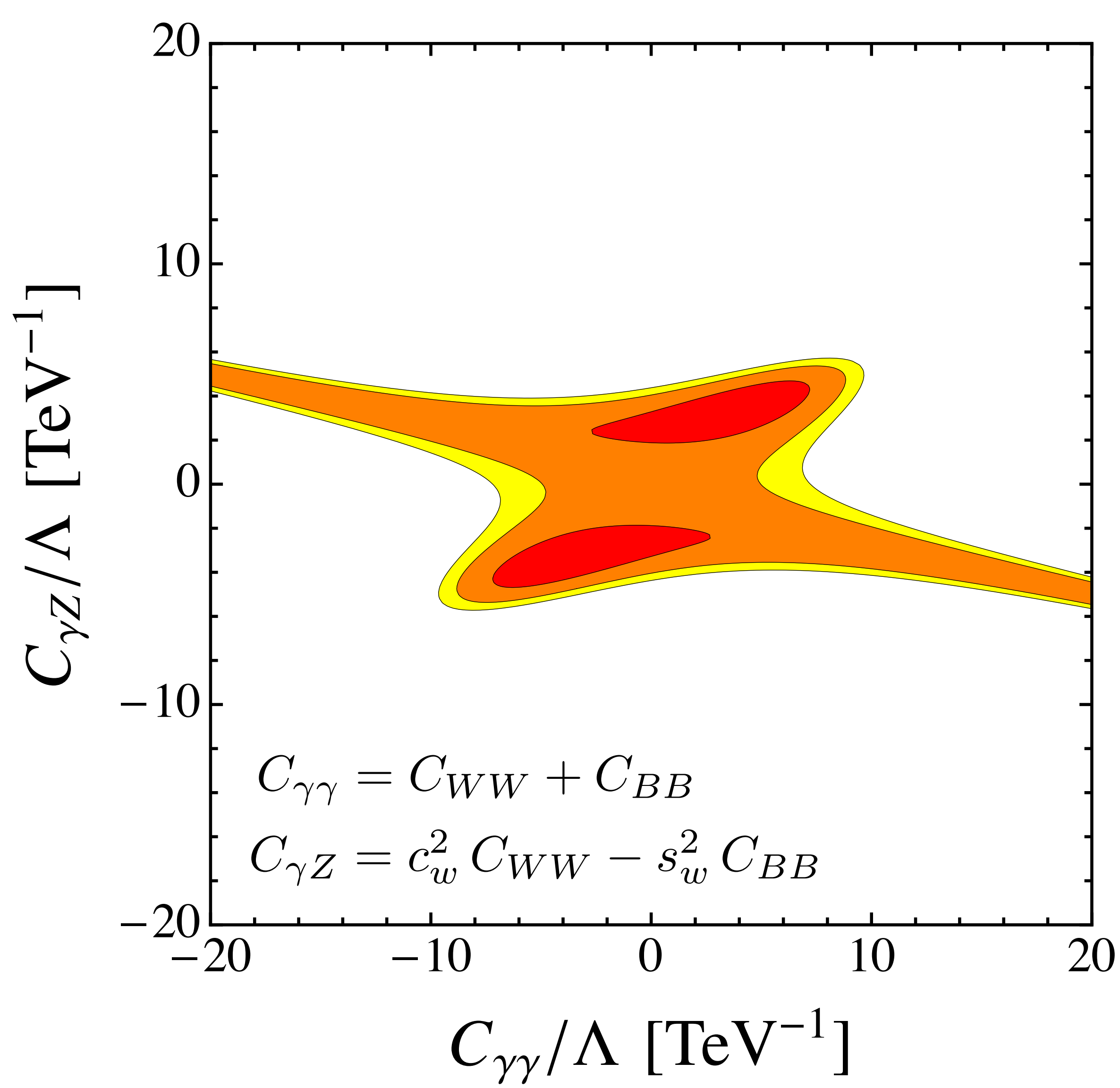


Electroweak precision tests

- Allowed parameter space for $C_{Zh}^{(5)} \neq 0$

[Baak et al.: 1407.3792]

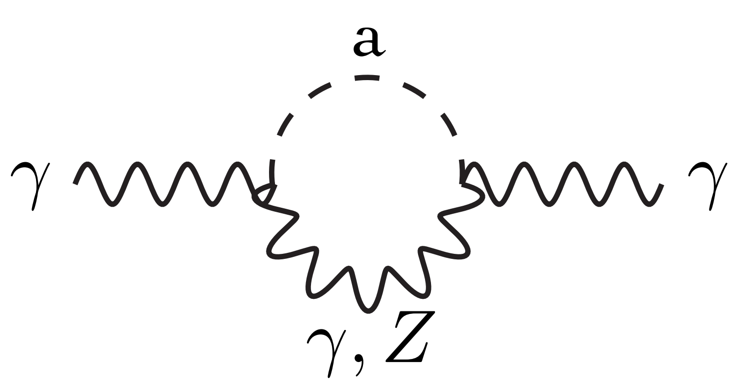




Electroweak precision tests

- Running of electromagnetic coupling constant from $q^2 = 0$ to $q^2 = m_Z^2$

$$\frac{\alpha(0)}{\alpha(m_Z)} = \frac{\alpha(0)}{\alpha(m_Z)}\bigg|_{\text{SM}} - \left[\frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2} - \Pi'_{\gamma\gamma}(0)\right]_{\text{ALP}}$$

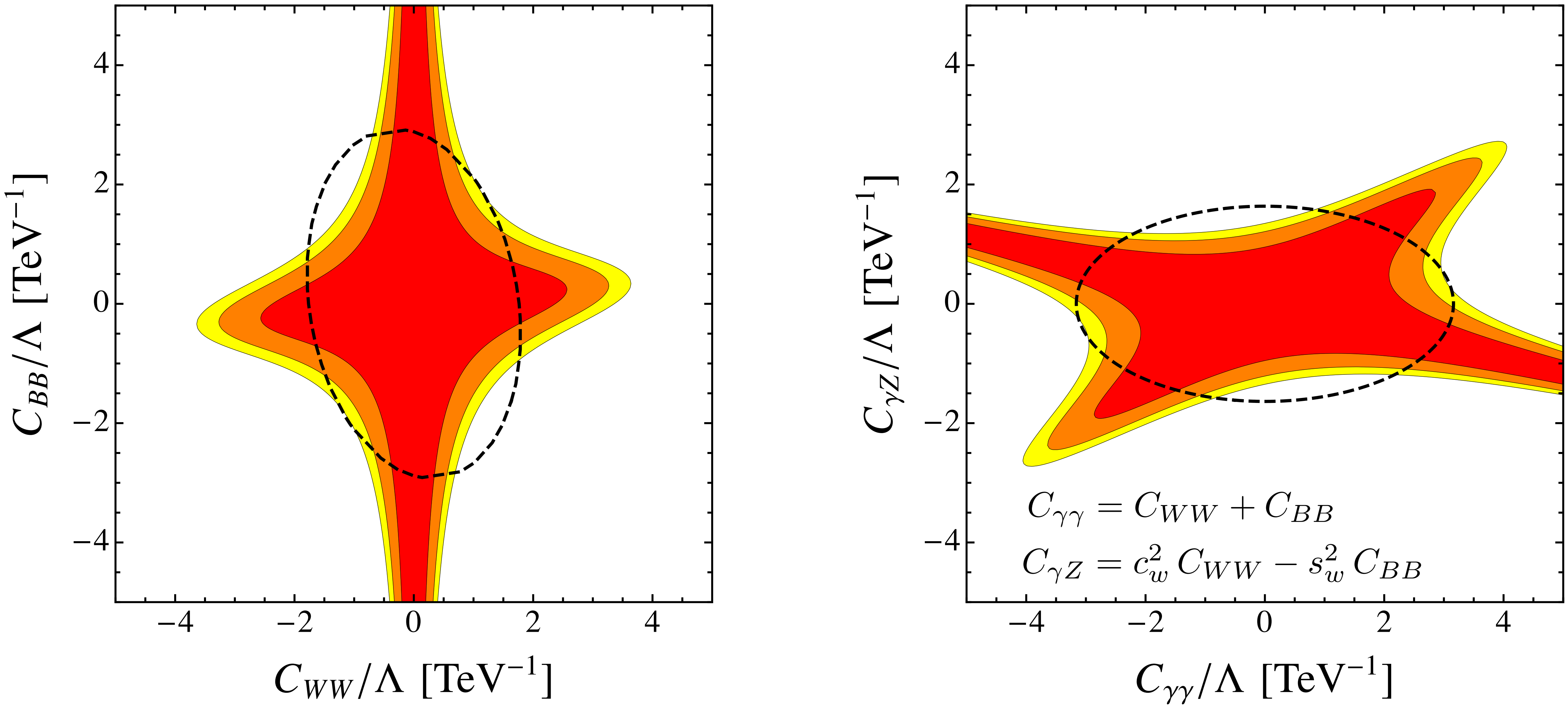


$$\frac{\alpha(0)}{\alpha(m_Z)} = \frac{\alpha(0)}{\alpha(m_Z)}\bigg|_{\text{SM}} + \frac{8\alpha^2}{3}\frac{m_Z^2}{\Lambda^2}\left[C_{\gamma\gamma}^2\left(\ln\frac{\Lambda^2}{m_Z^2} - \frac{1}{3}\right) + \frac{C_{\gamma Z}^2}{s_w^2 c_w^2}\left(\ln\frac{\Lambda^2}{m_Z^2} - \frac{11}{6}\right)\right]$$

Electroweak precision tests

- Measurement of OPAL at per-cent level
- Compatible with C_{WW} and C_{BB} of order ~30
- FCC-ee expectation of 10^{-5} uncertainty

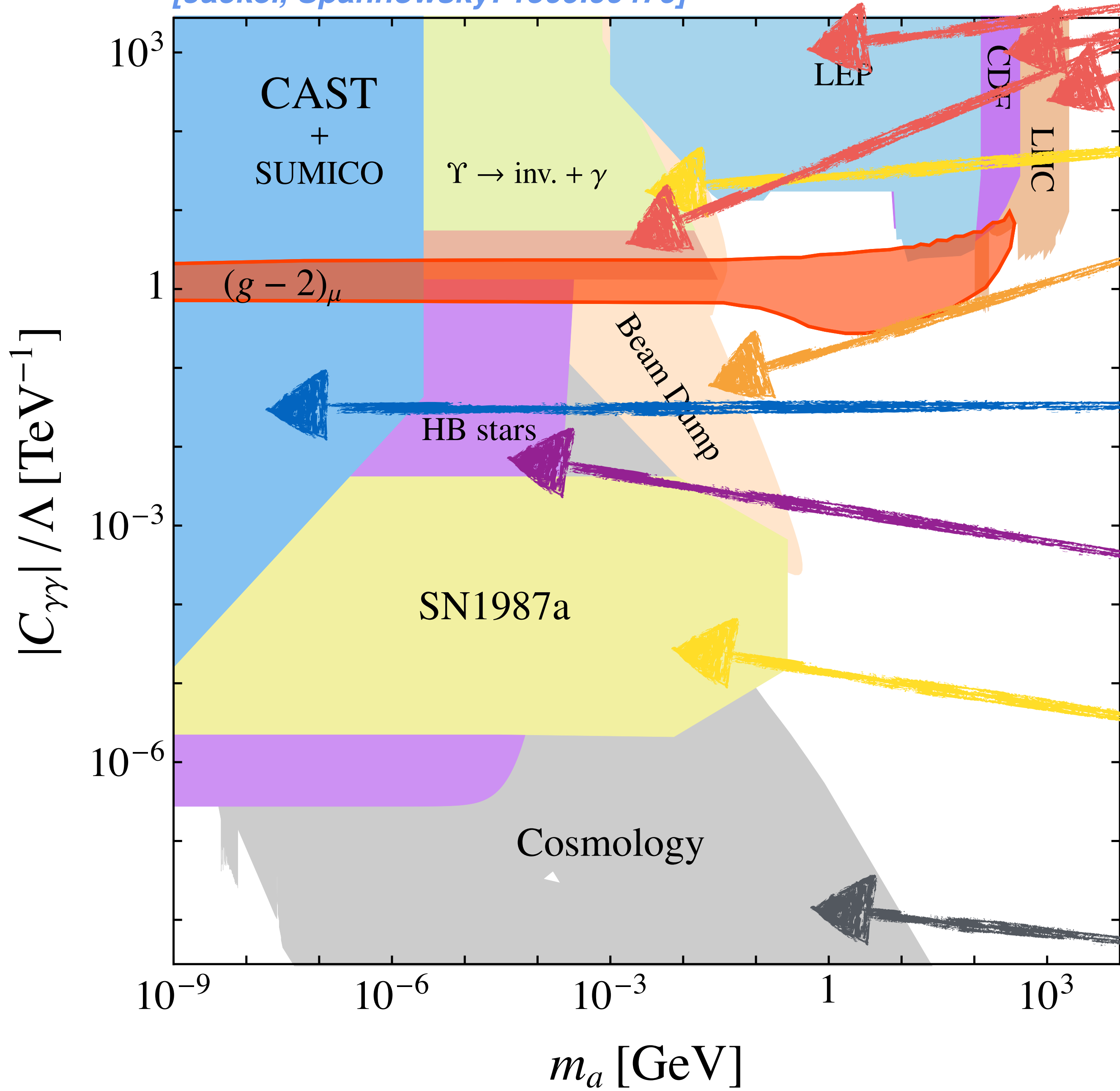
[Abbiendi et al.: 0309052]
[Janot: 1512.05544]
[Blas, Cuichini, Franco, Mishima, Pierini, Reina, Silvestrini: 1608.01509]



Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



Collider searches for $e^+e^- \to a + \gamma, 3\gamma$

CLOE and BaBar: $\Upsilon \to a + \gamma$

SLAC: measurement of photon - nuclei scattering (Primakoff effect)

Axion helioscopes: Tokyo Axion Helioscope and CERN axion solar telescope

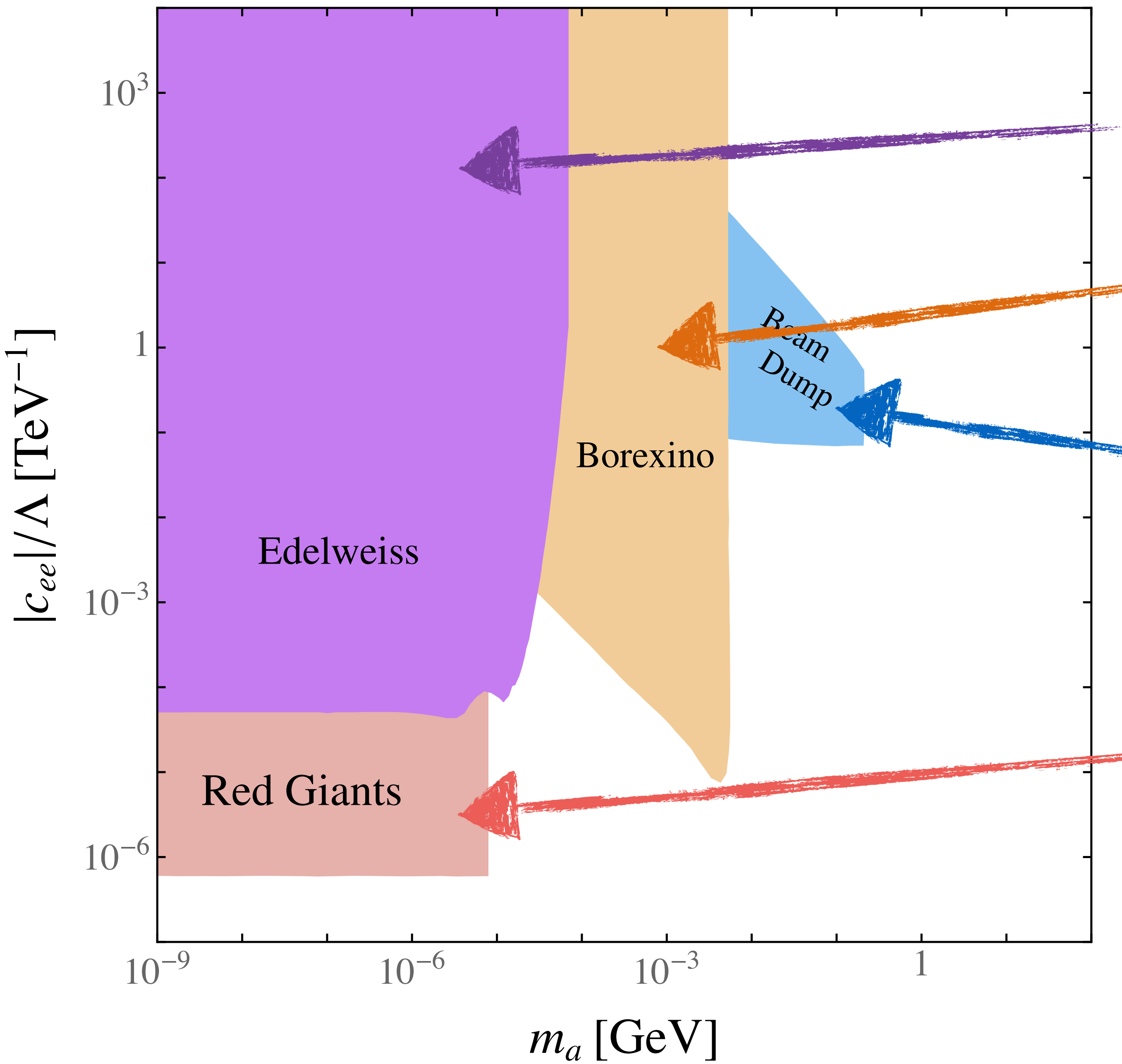
Energy loss of stars constrained by ratio of red giant to younger stars of horizontal branch

Absence of photon burst after supernova

Combination of cosmological bounds (measurement of Neff, primordial deuterium abundance, modification to BB nucleosynthesis, distortion of CMB, diffuse photon background,…)

Probing the parameter space

- Constraints on ALP mass and coupling to electrons



Low energy electron recoils of solar axions

Solar axions in $p + d \to {}^3\mathrm{He} + a$

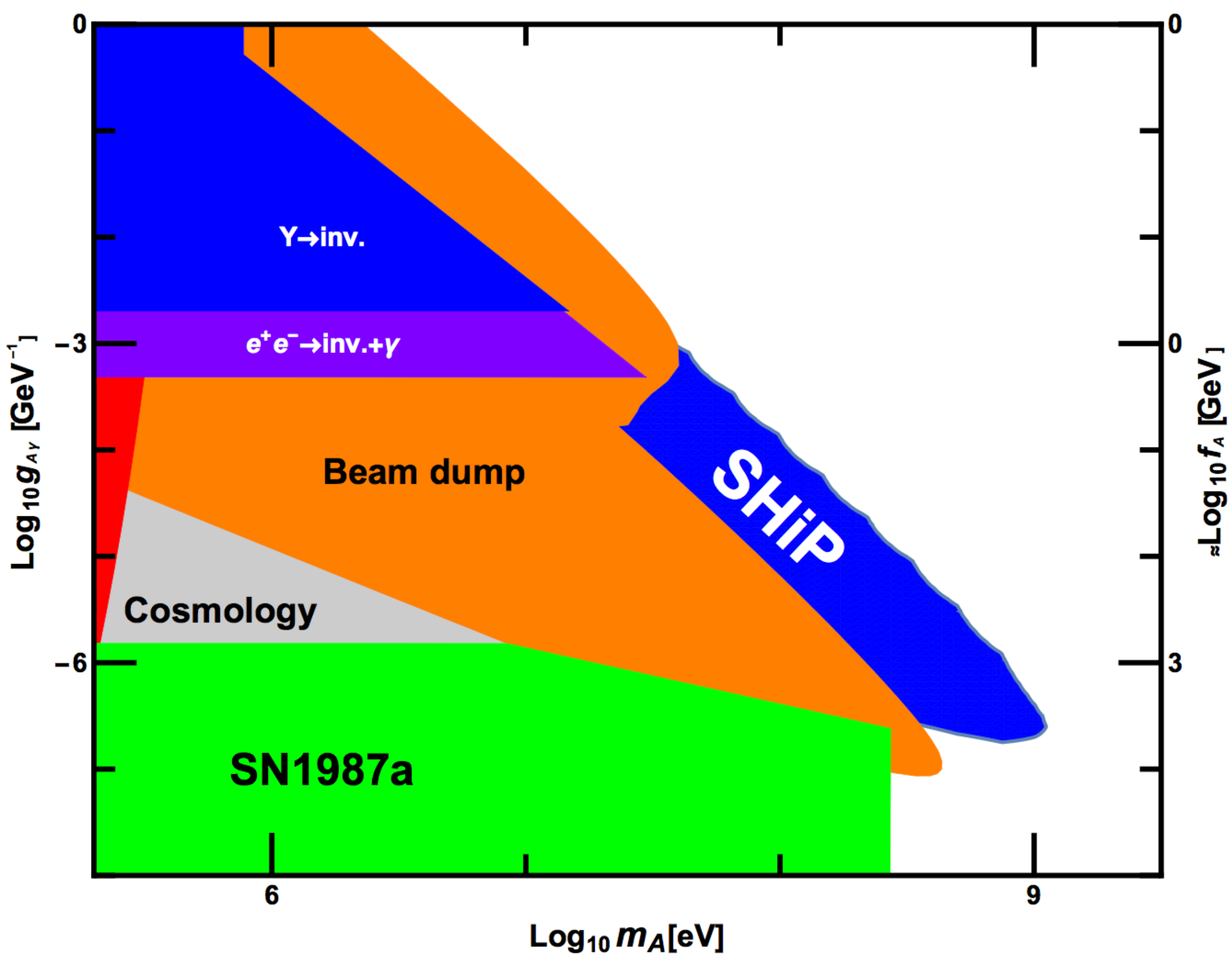
MINOS and MiniBooNe beam dumps

Axion emission in hot and dense plasma: reduction of helium burning lifetime of stars

[Armengaud: 1307.1488]
[Essig, Harnik, Kaplan, Toro: 1008.0636]

SHiP expected reach

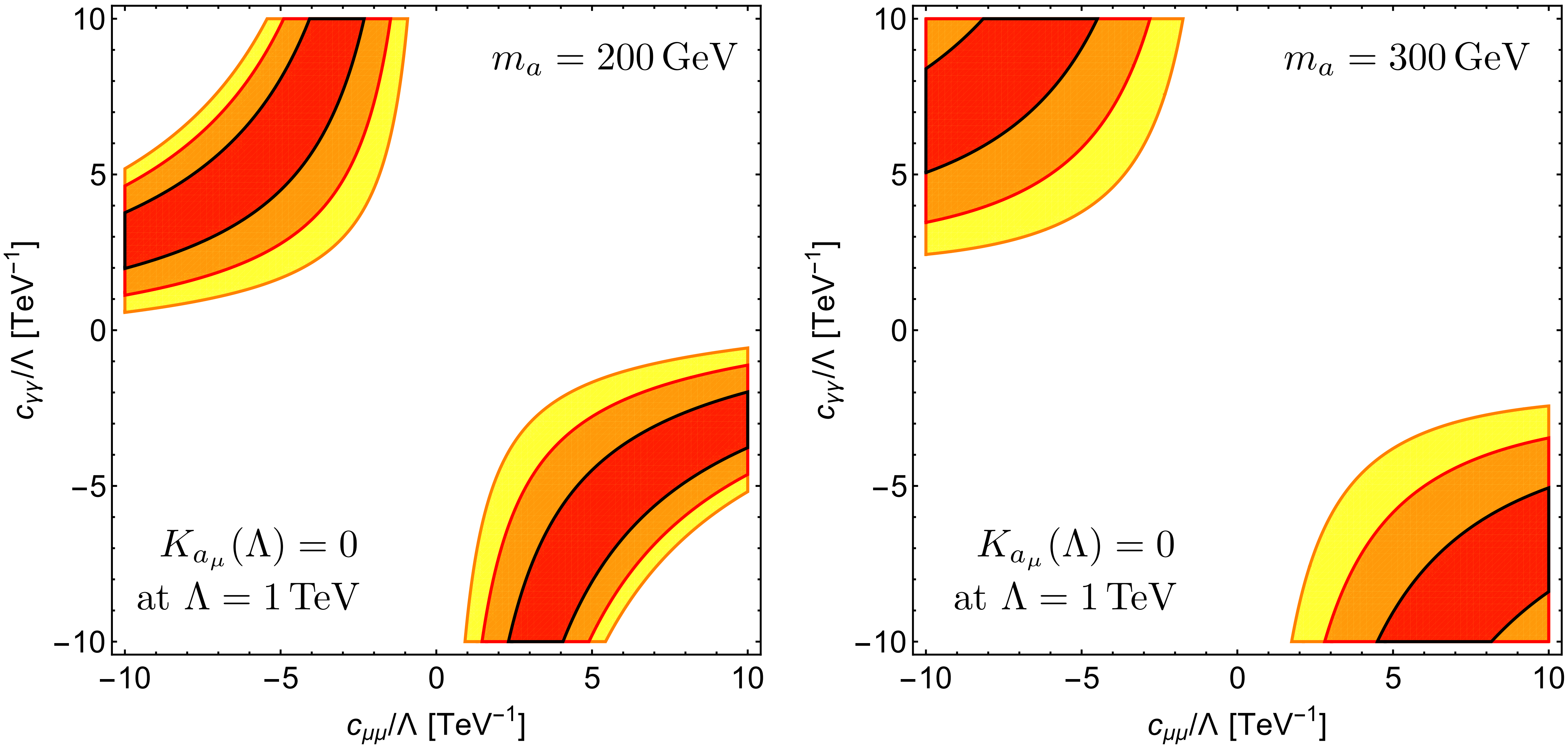
- Fixed target facility at CERN SPS
  (Search for Hidden Particles)



[Alekhin et al.: 1504.04855]

Muon $(g-2)_\mu$

- Allowed parameter space moves into corners
- Coupling-mass plots require: $|C_{\gamma\gamma}|/\Lambda \lesssim 2\,\mathrm{TeV}^{-1}$ and $|c_{\mu\mu}| \geq |C_{\gamma\gamma}|$



Probing the parameter space

- Reach in $Z \to \gamma a$