Collider Probes of Axion-like Particles

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with Martin Bauer and Matthias Neubert

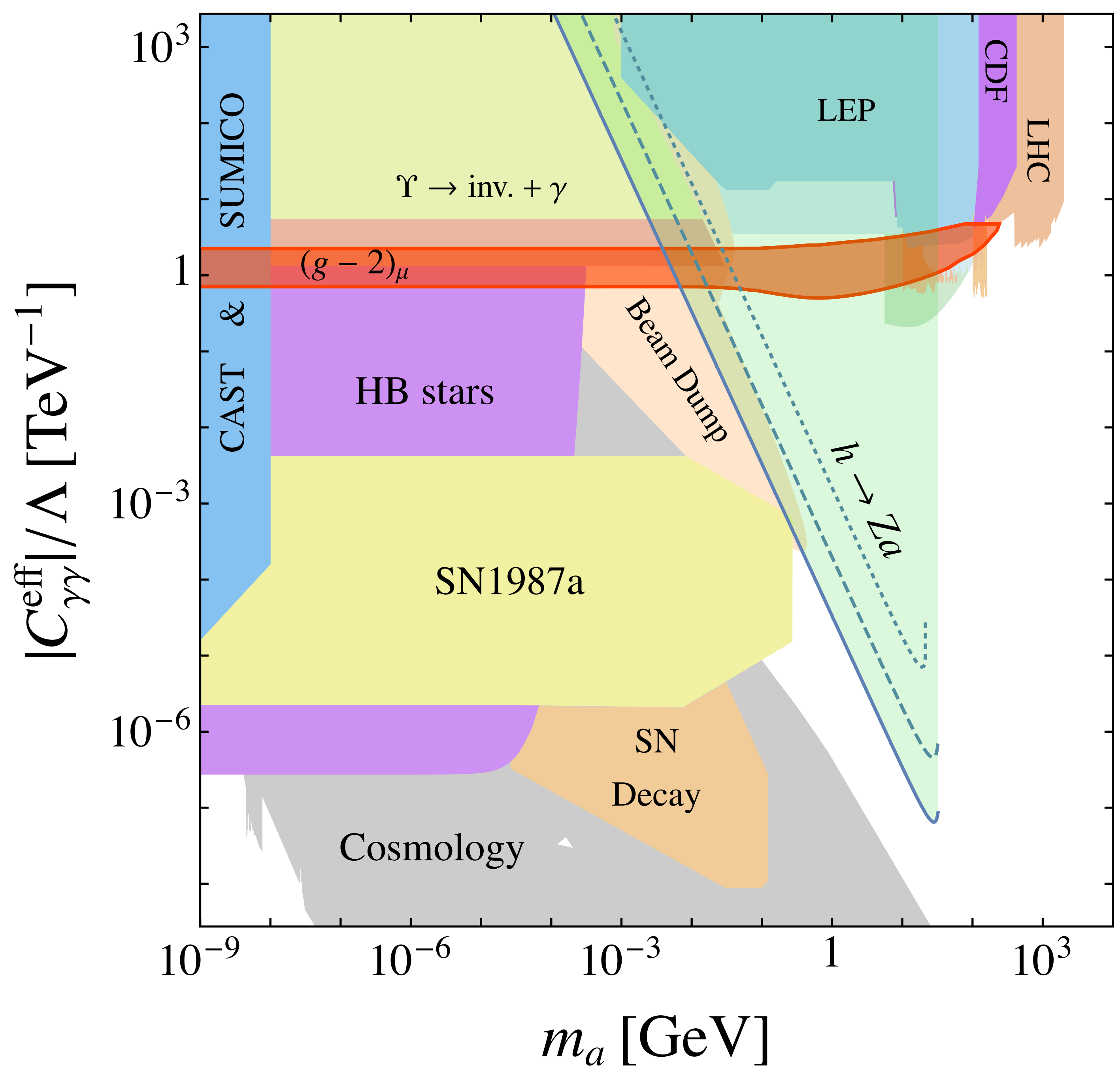
based on arXiv:1610.00009, 1704.08207, 1708.00443
and work in progress

4 April 2018

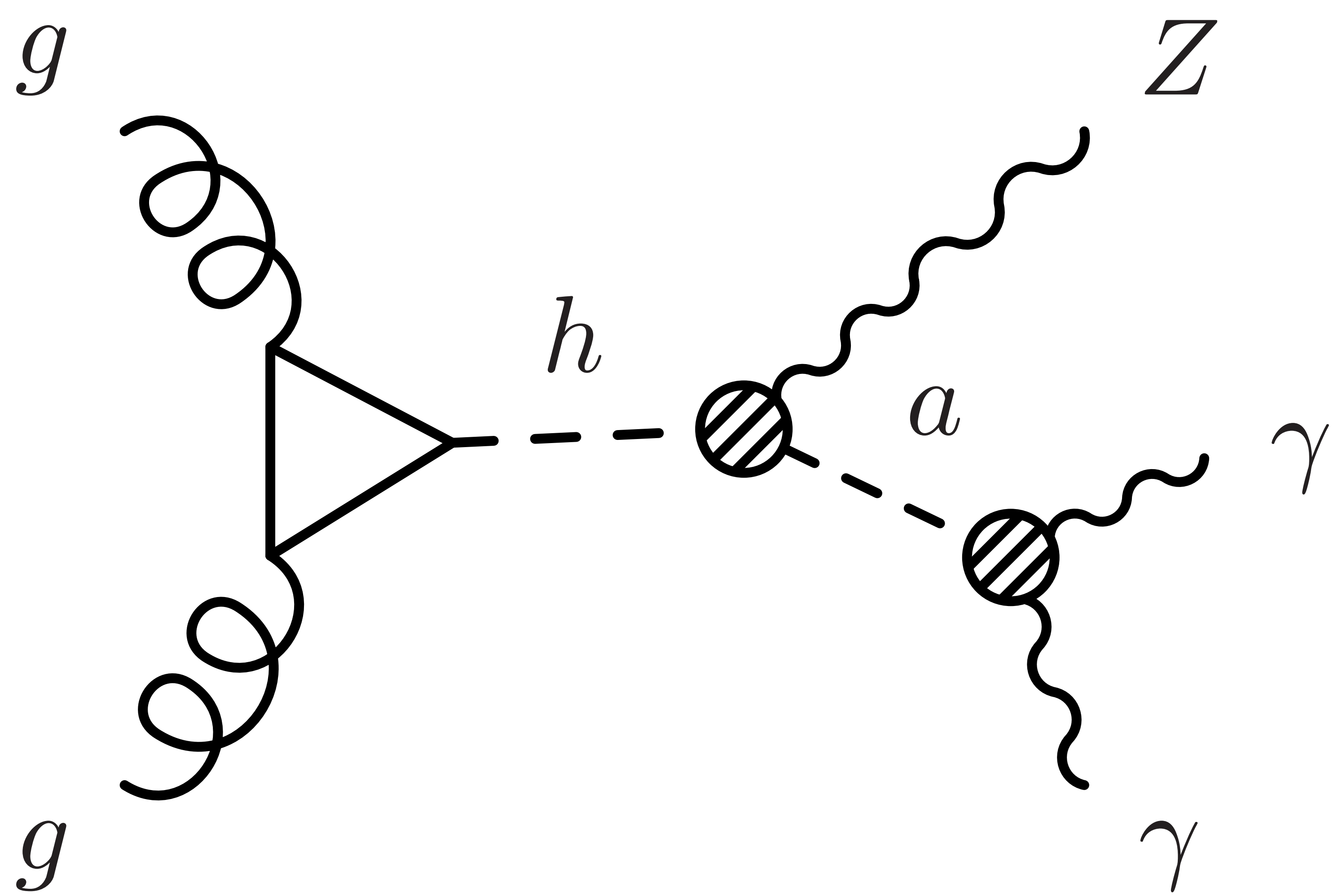
Liverpool

Our main result

[Bauer, Neubert, Thamm: 1704.08207]

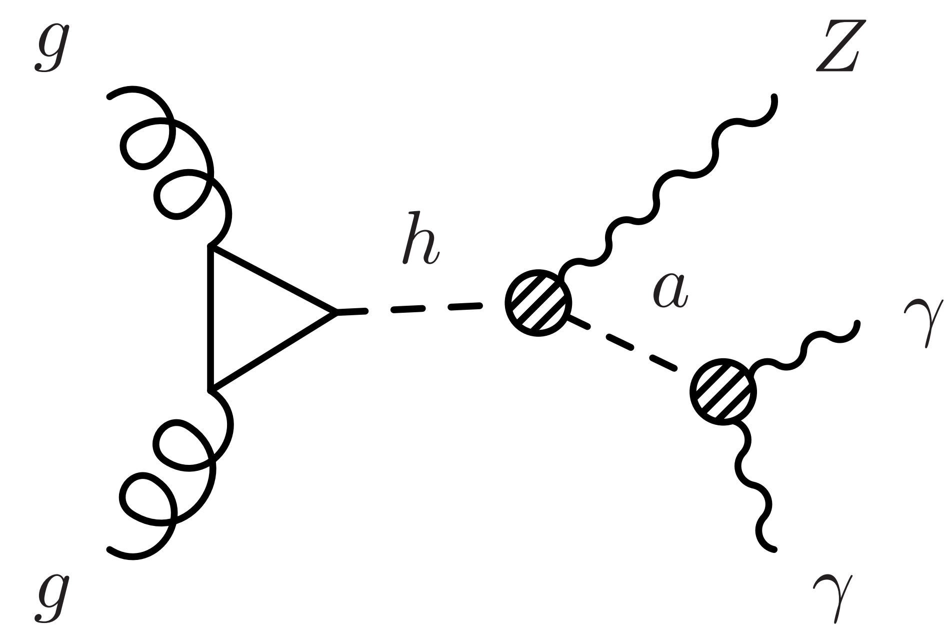


Example process



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



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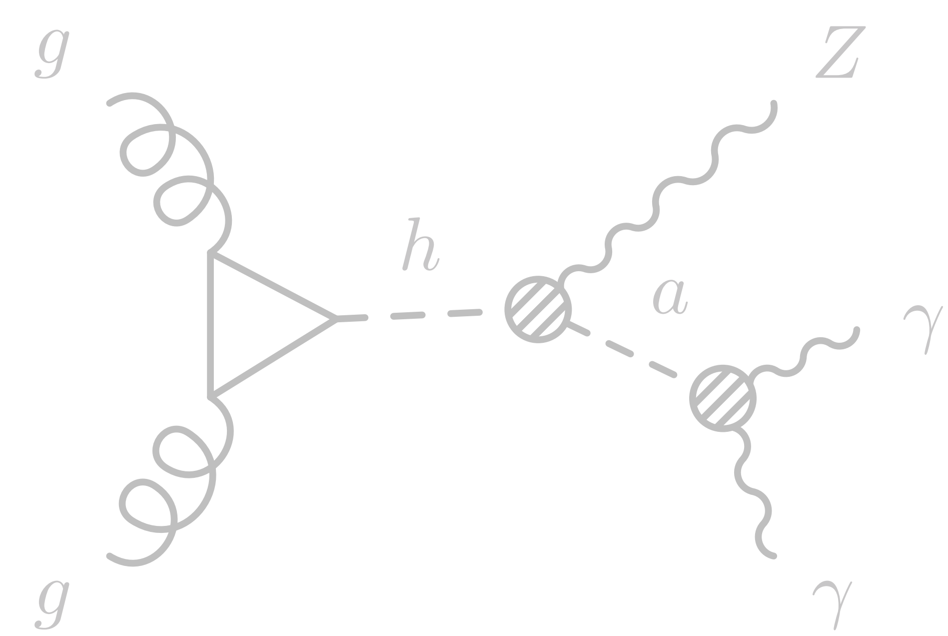

Motivation

- 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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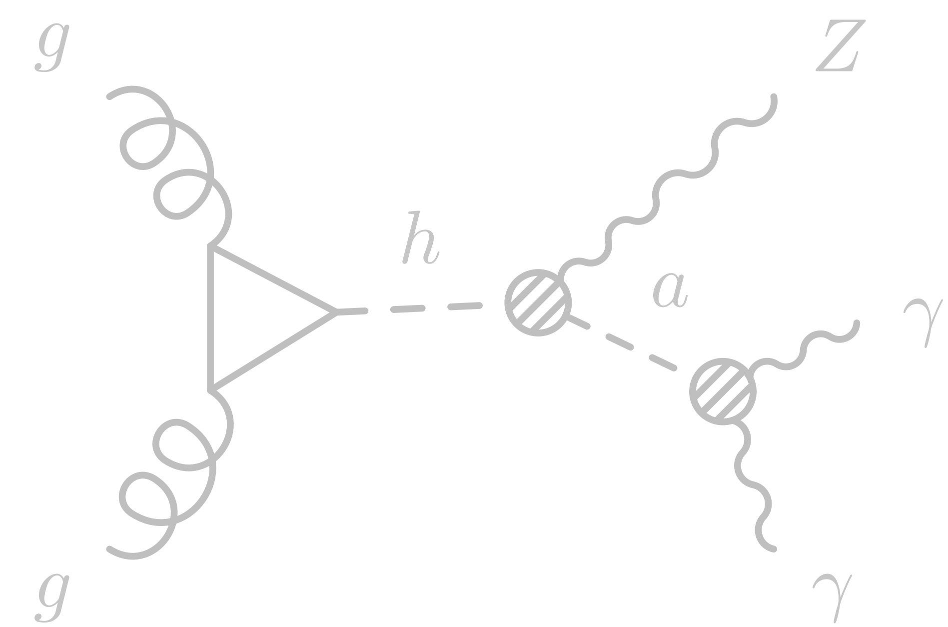

Effective Lagrangian

- Interactions at dimension-5

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

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

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

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- After EWSB

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

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

Effective Lagrangian

- Vanishes through equations of motion

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

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- Higgs interactions at dimension-6 and 7

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

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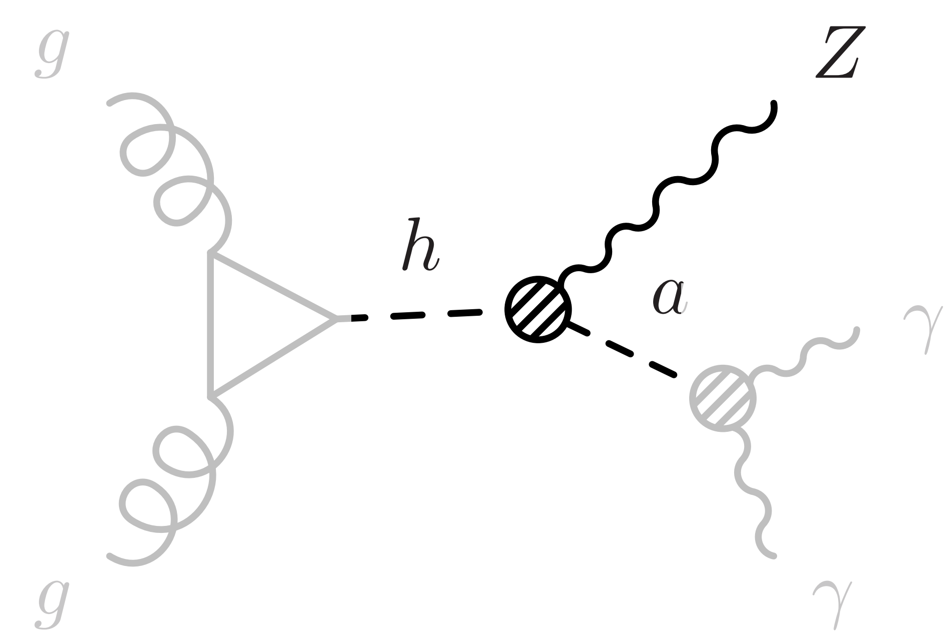
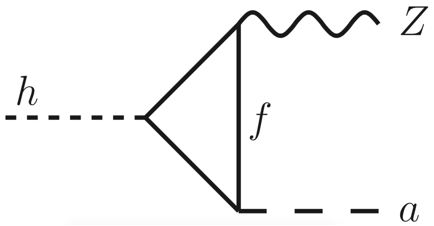
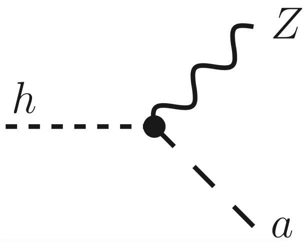


Exotic Higgs Decays $h \to Za$

- Contributions

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





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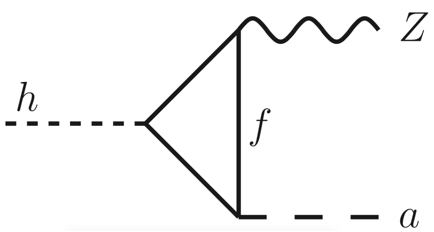
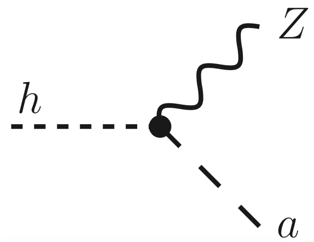
Vanishes through EOM





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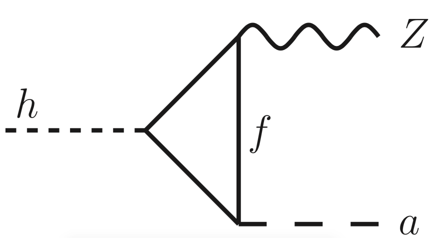
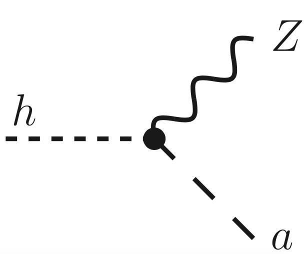




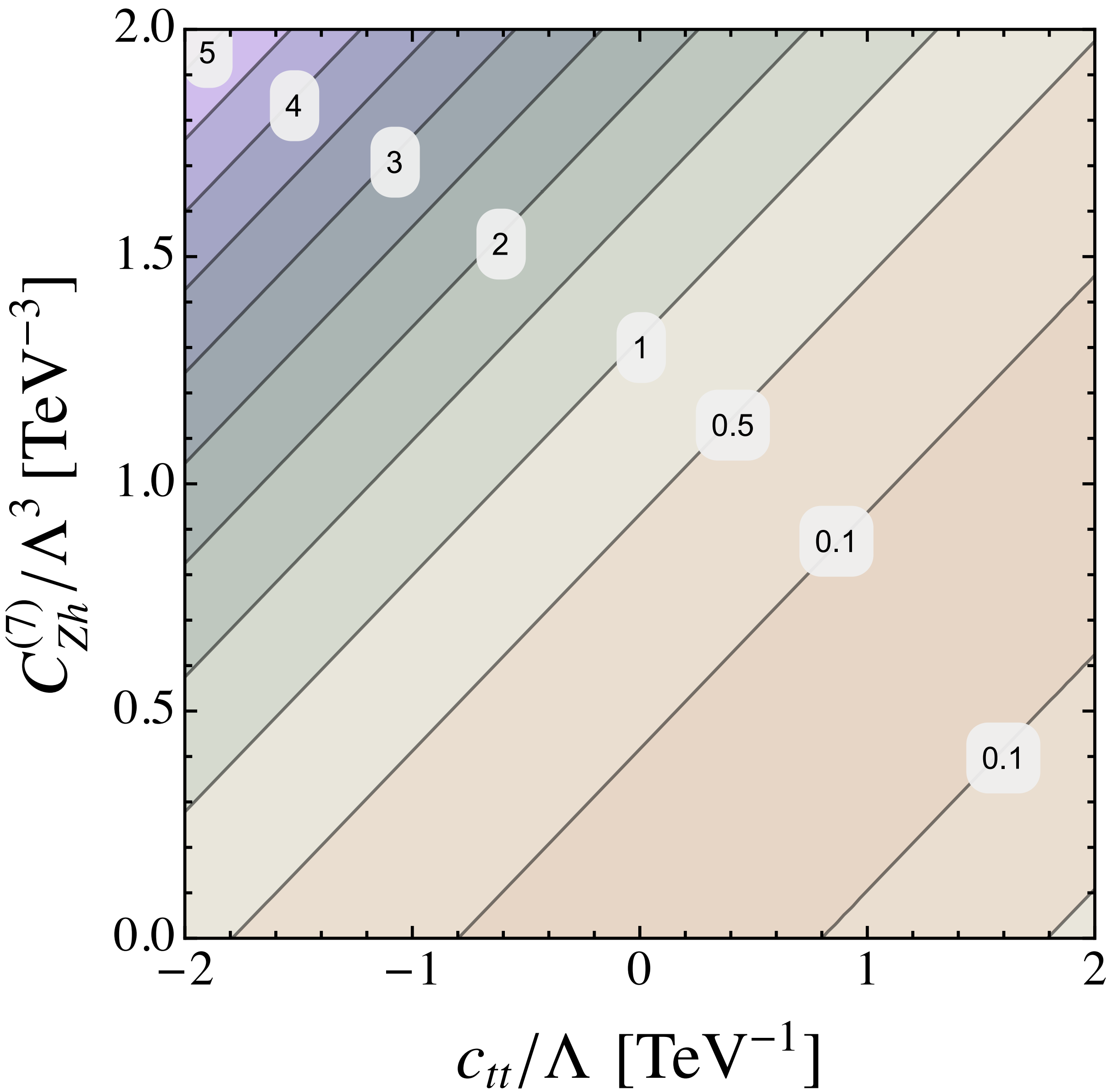
- Numerically

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

[Bauer, Neubert, Thamm:1610.00009]

Exotic Higgs Decays $h \to Za$

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



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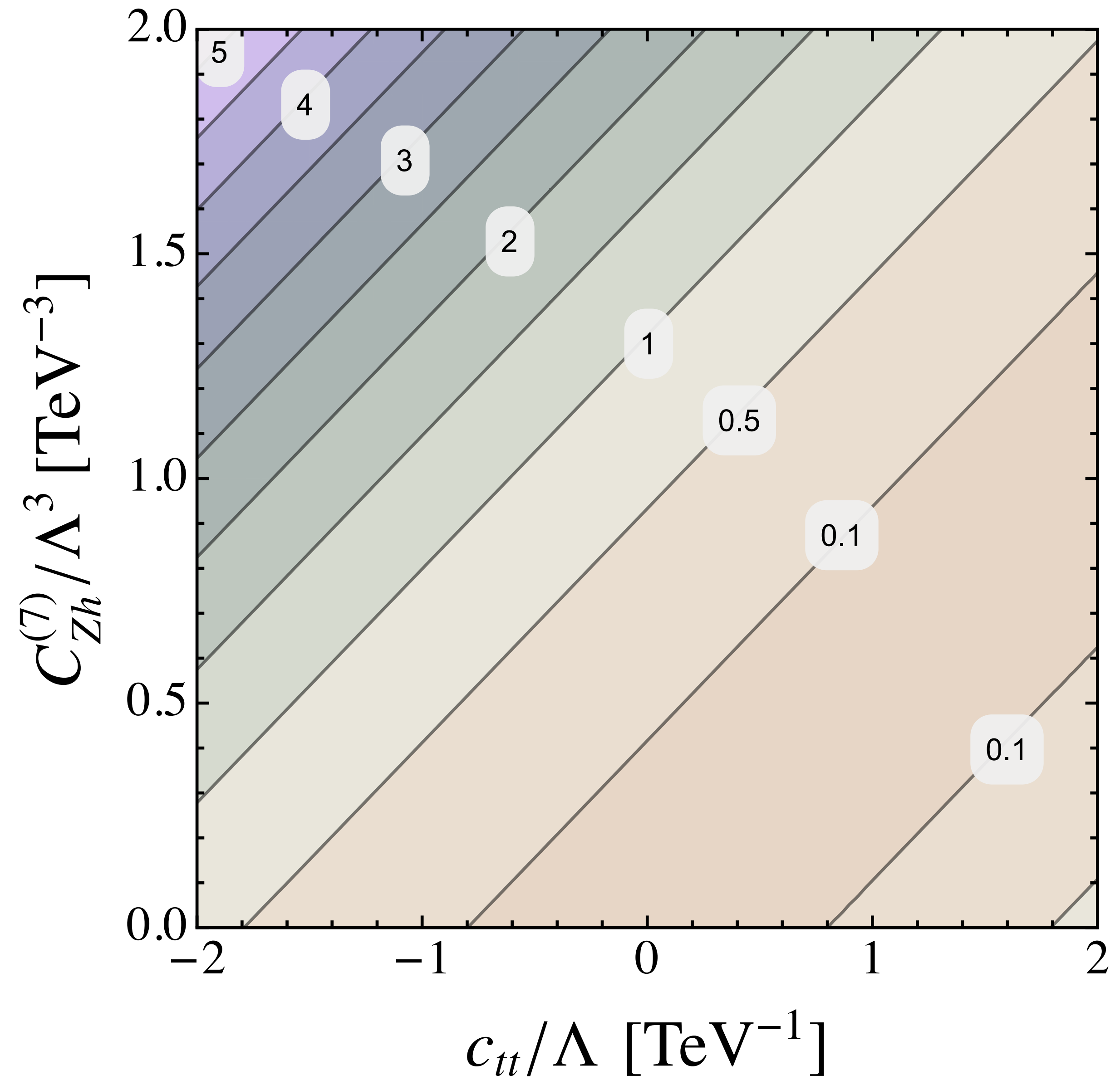

- This channel is a realistic target for discovery at LHC

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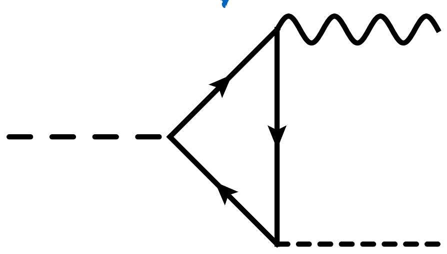

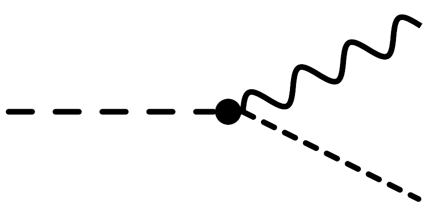

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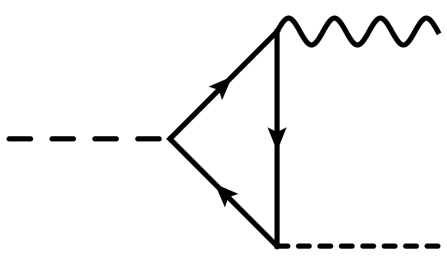

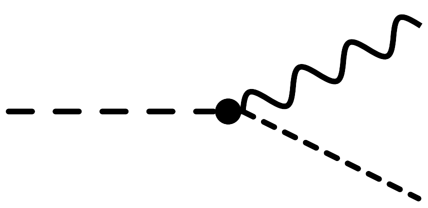

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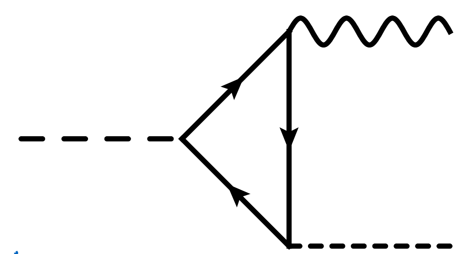

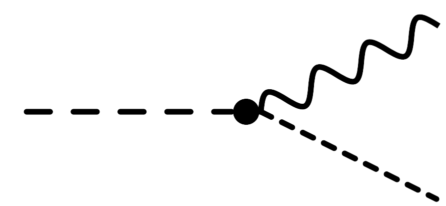

Non-polynomial operator for models with new heavy particles whose mass arises from EWSB

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

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

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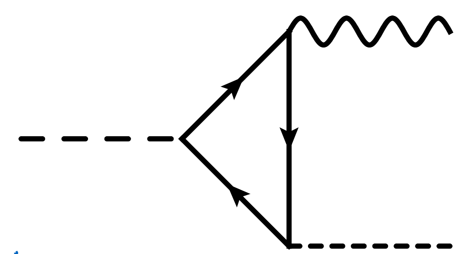

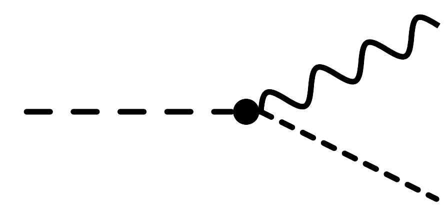

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Exotic Higgs Decays $h \to Za$

- Non-polynomial operator

[Pierce, Thaler, Wang: 0609049]
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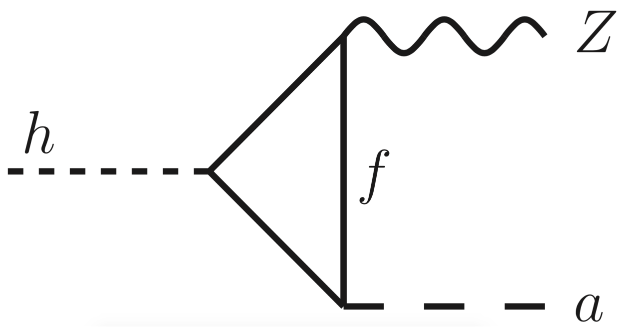
$$\mathcal{L}_{\text{eff}}^{\text{non-pol}} \ni \frac{C_{Zh}^{(5)}}{\Lambda} (\partial^\mu a) \left(\phi^\dagger \, iD_\mu \, \phi + \text{h.c.}\right) \ln \frac{\phi^\dagger \phi}{\mu^2} + \dots \, ,$$

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

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

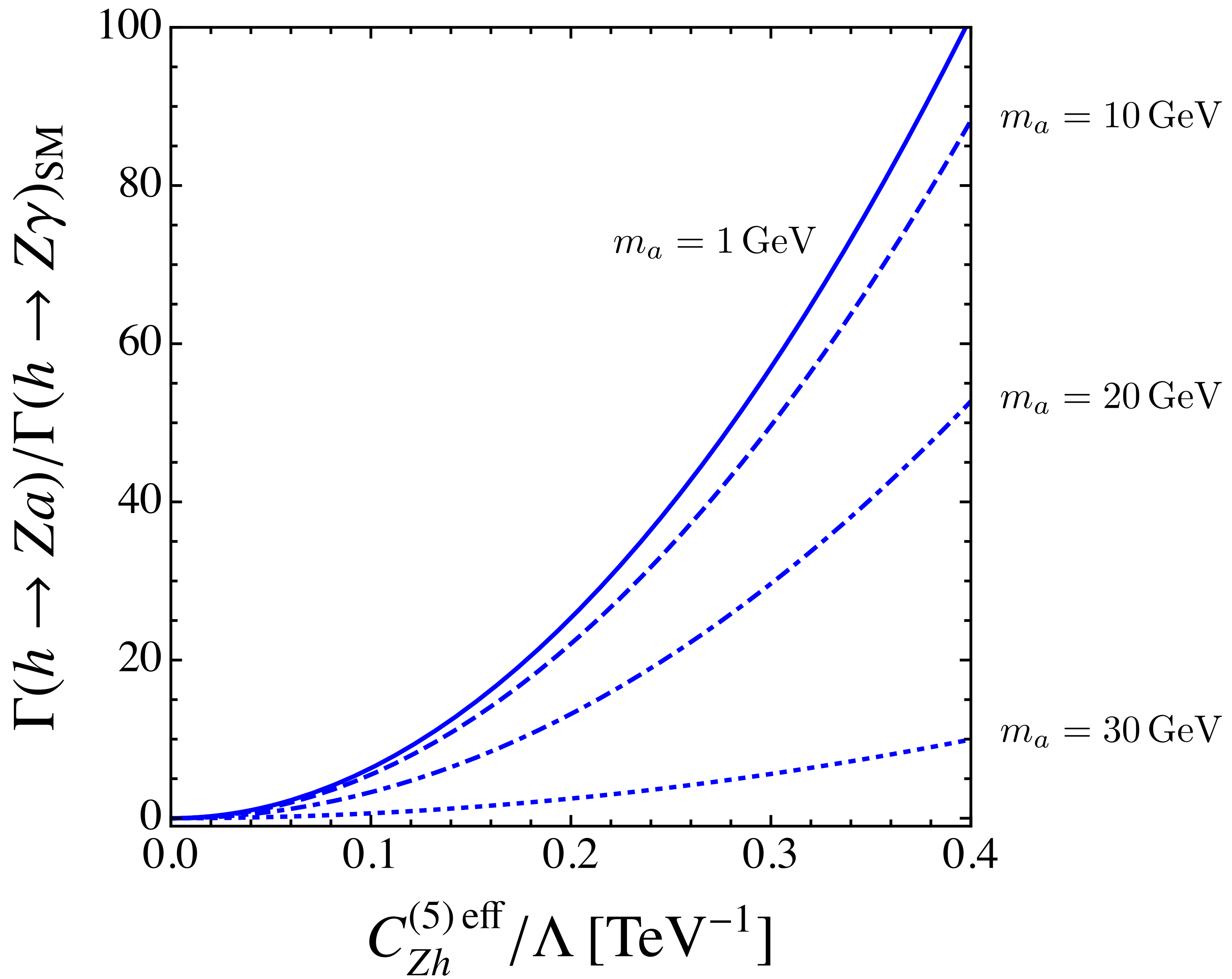


$$F = \int_0^1 d[xyz] \, \frac{2m_t^2 - x m_h^2 - z m_Z^2}{m_t^2 - xy m_h^2 - yz m_Z^2 - xz m_a^2}$$

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

Exotic Higgs Decays $h \to Za$

- Enhanced rates for this process



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

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- 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

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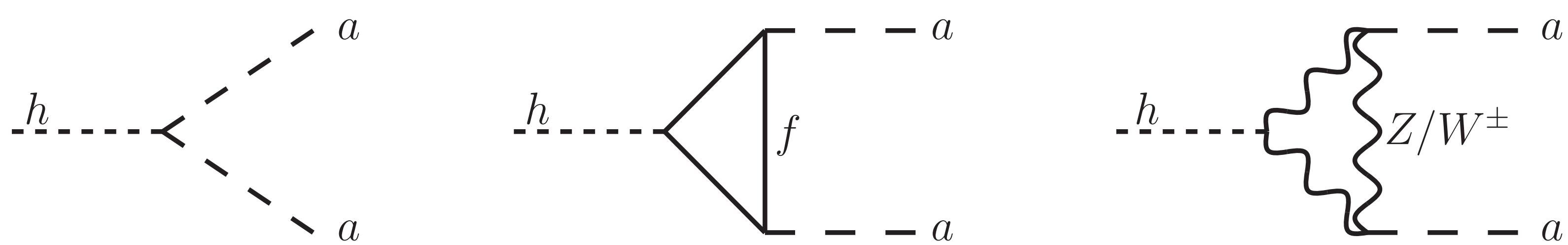
- All these modes can be reconstructed at run II

Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

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



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

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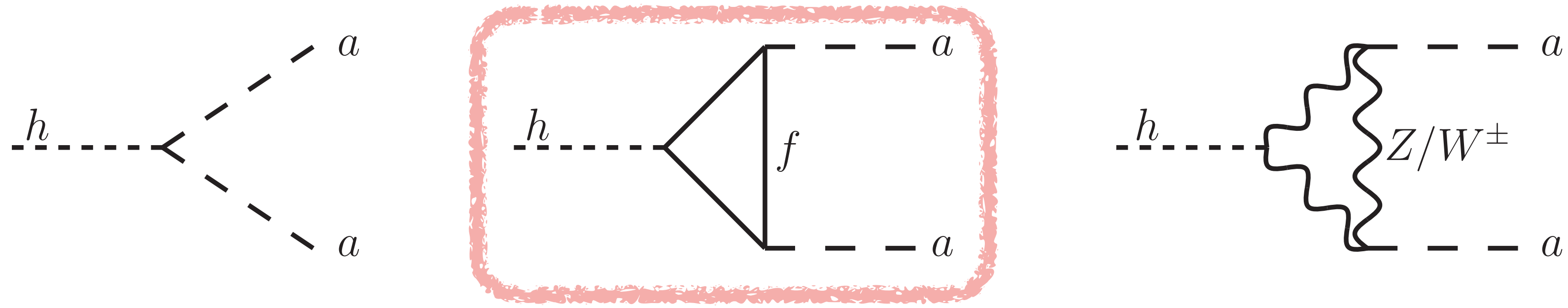

$$C^{\text{eff}}_{ah} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln\frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] - \frac{3\alpha}{2\pi s_w^2}\left(g^2 C_{WW}\right)^2 \left[\ln\frac{\mu^2}{m_W^2} + \delta_1 - g_2(\tau_{W/h})\right]$$
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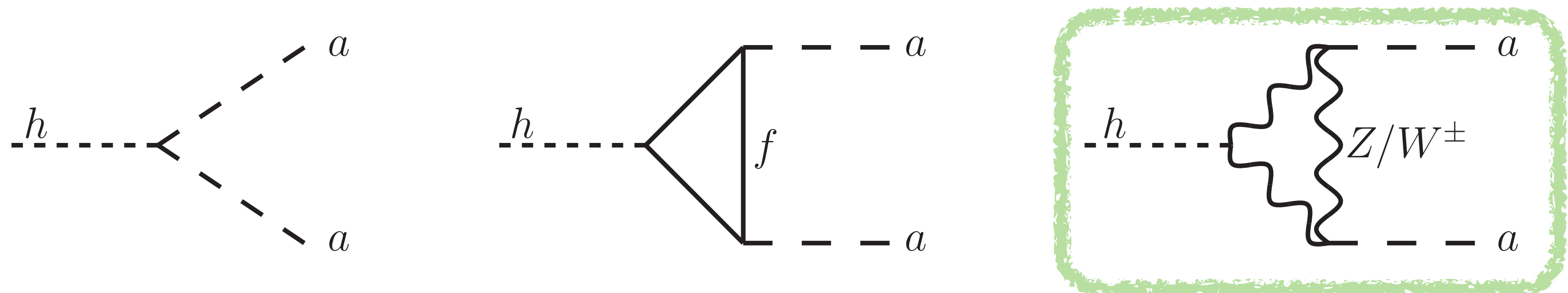
Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

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



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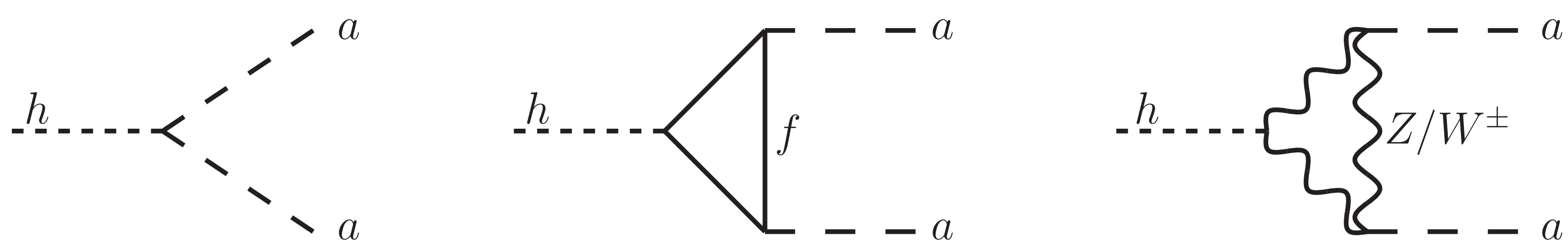

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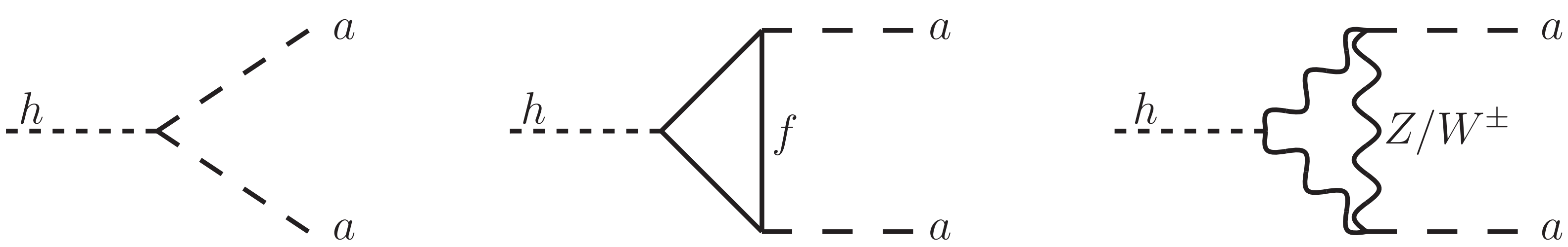

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Exotic Higgs Decays $h \to aa$

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

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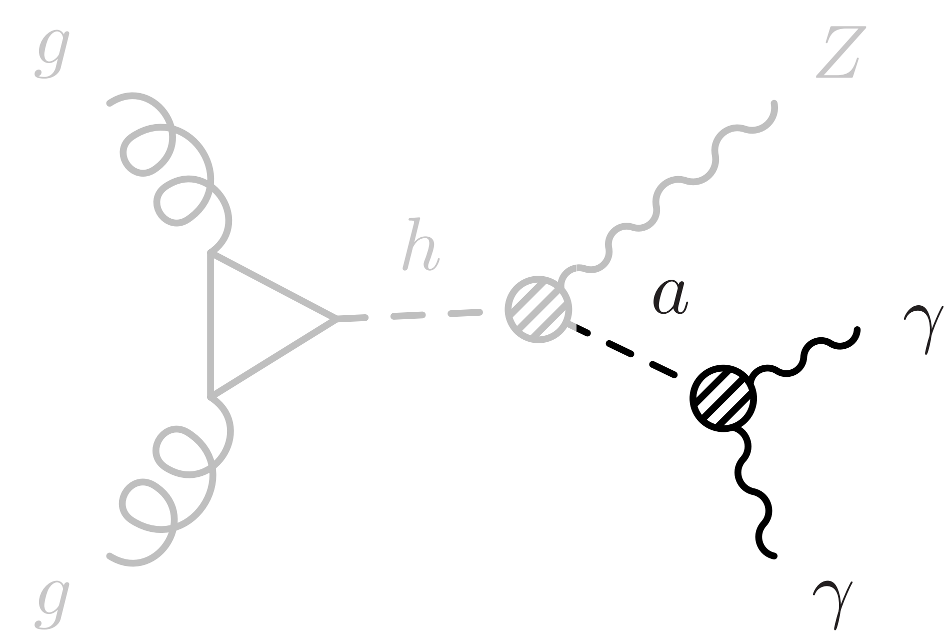
- Interesting final states
  - $h \to aa \to \gamma\gamma\gamma\gamma$
  - $h \to aa \to l^+l^-l^+l^-$
  - $h \to aa \to 4\mathrm{jets}$
  - $h \to aa \to \mathrm{invisible}$

- All these modes can be reconstructed at run II

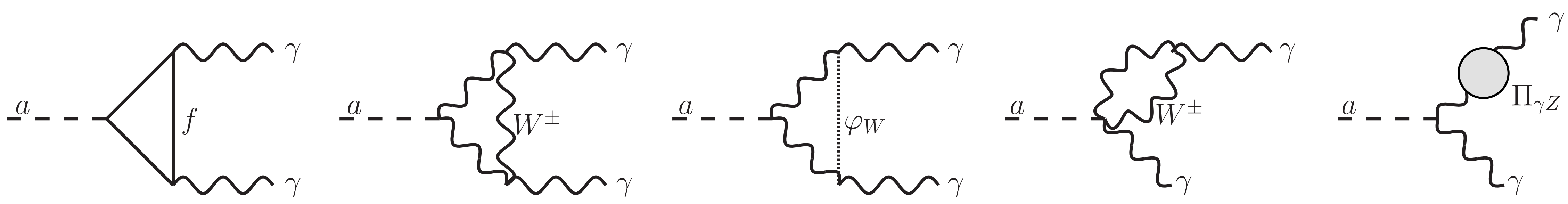
Outline

- 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



ALP decays into photons

- Often considered as the dominant decay mode



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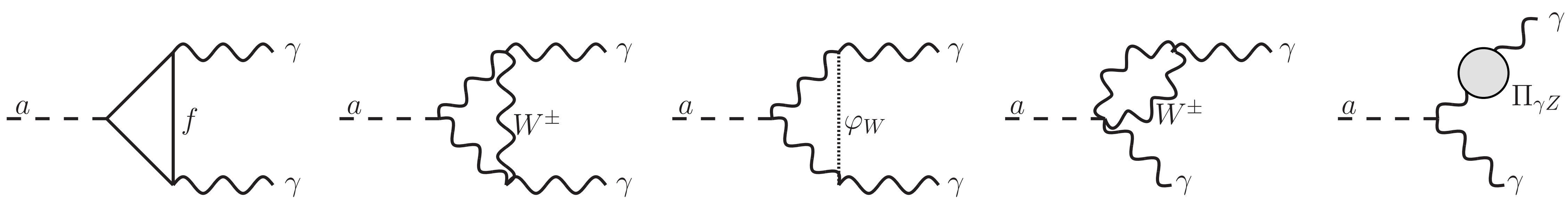


$$\Gamma(a \to \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma} + \sum_f \frac{N_c^f Q_f^2}{16\pi^2}\, c_{ff}\, B_1(\tau_f) + \frac{2\alpha}{\pi}\, \frac{C_{WW}}{s_w^2}\, B_2(\tau_W) \right|^2$$

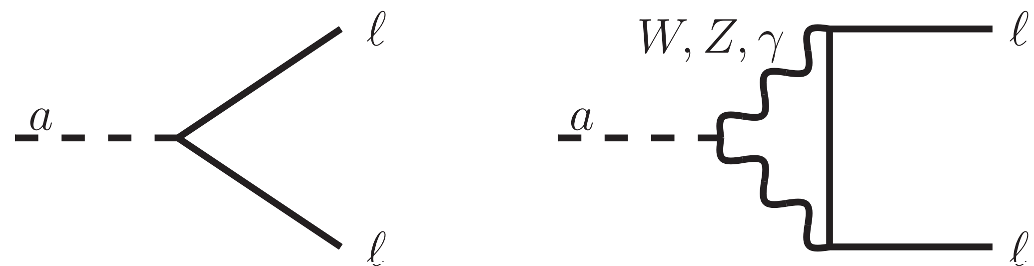
$$\equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma}^{\text{eff}} \right|^2$$

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

- Only mode for $m_a < 2m_e$

ALP decays into leptons

- For $m_a > 2m_e$



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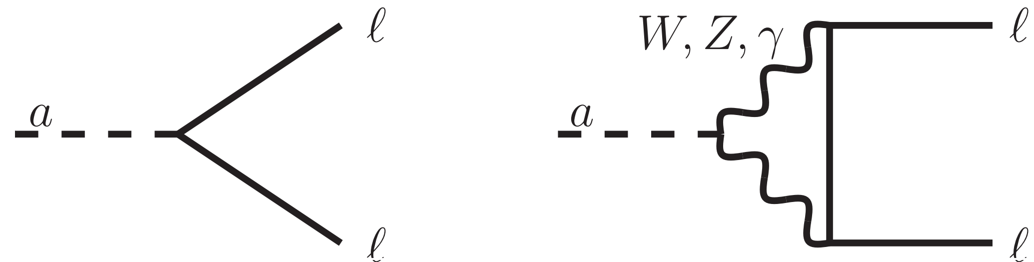

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$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2}\left|c_{\ell\ell}^{\text{eff}}\right|^2\sqrt{1-\frac{4m_\ell^2}{m_a^2}}$$

ALP decays into hadrons

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

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

[Spira, Djouadi, Graudenz, Zerwas: 9504378]

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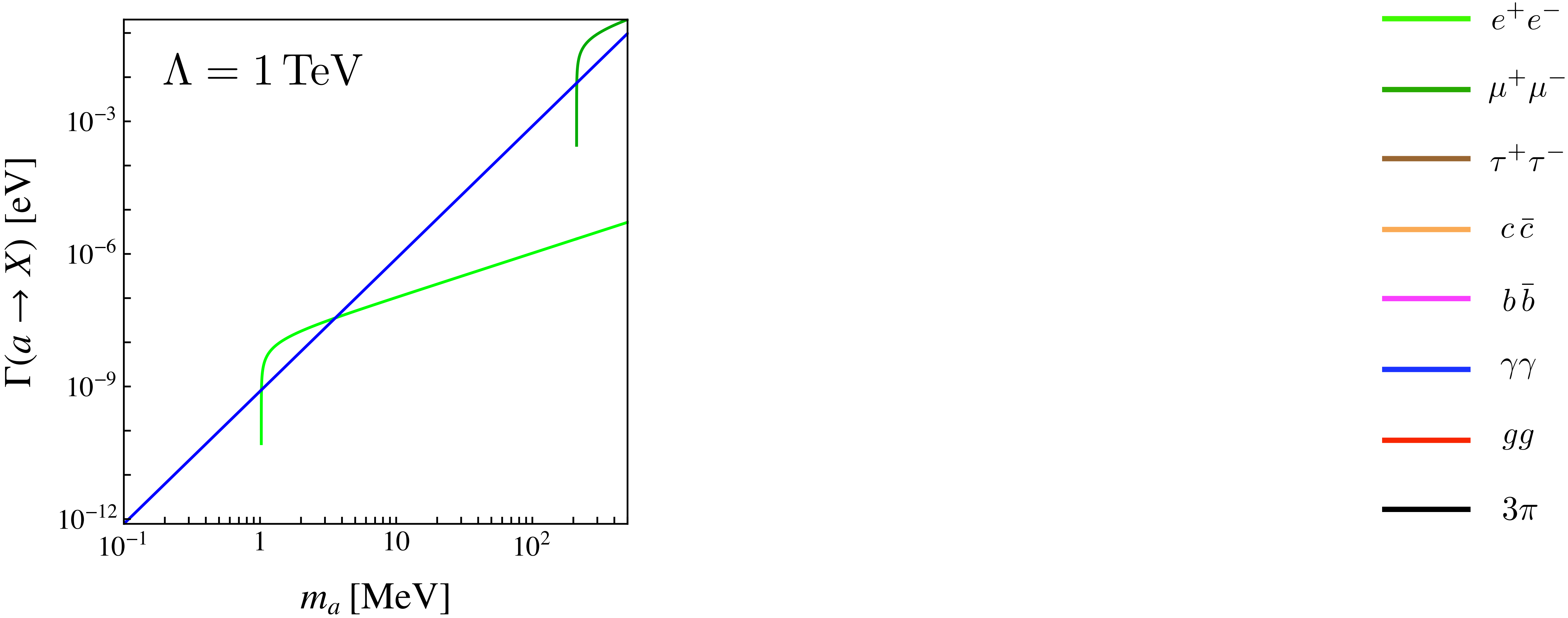
[Spira, Djouadi, Graudenz, Zerwas: 9504378]

- 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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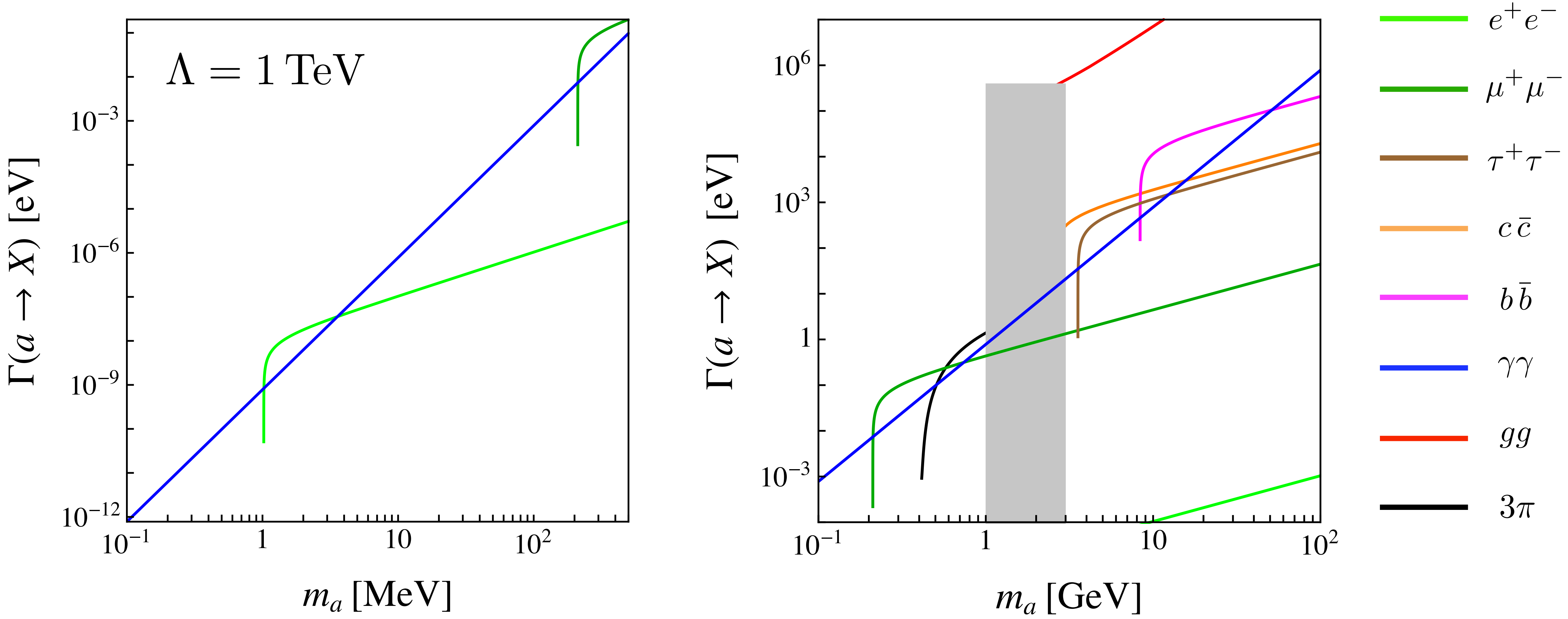

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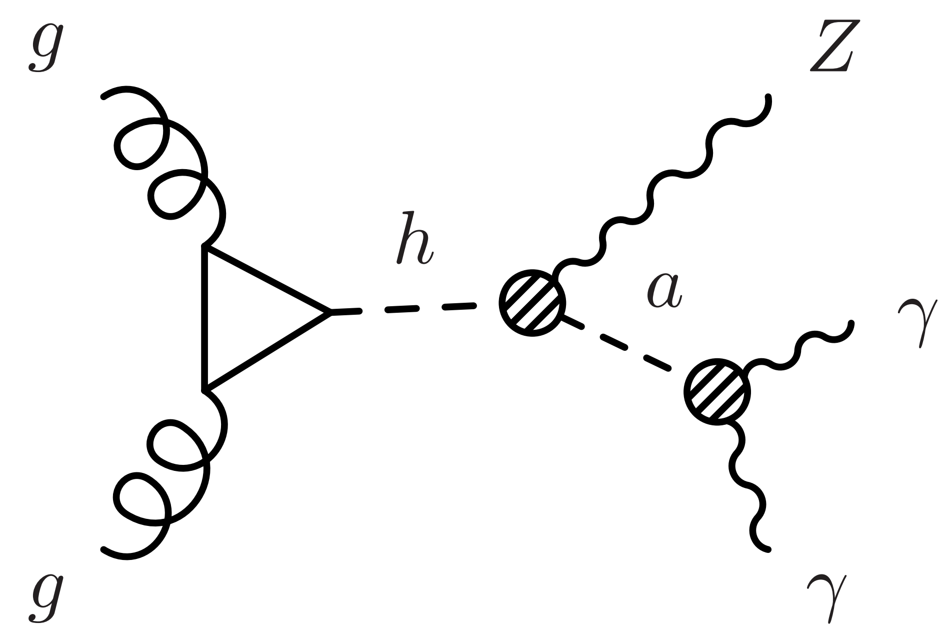
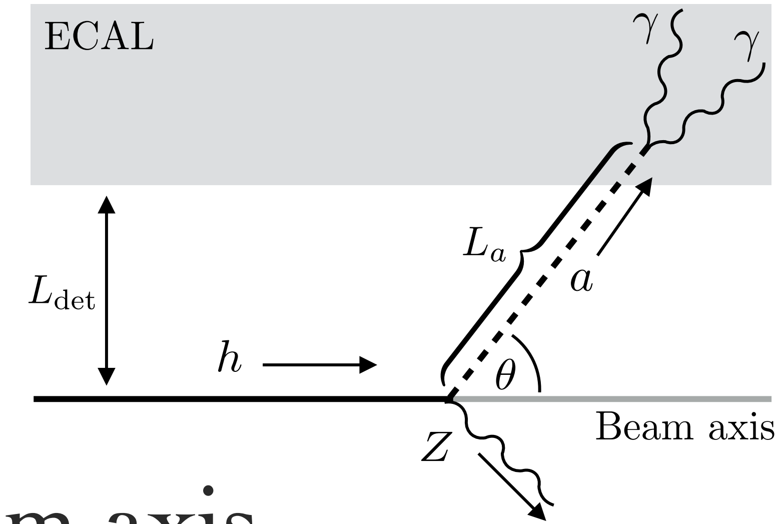


Detecting ALPs



- Average decay length perpendicular to beam axis

$$L_a^{\perp}(\theta) = \sin\theta \, \frac{\beta_a \gamma_a}{\Gamma_a}$$

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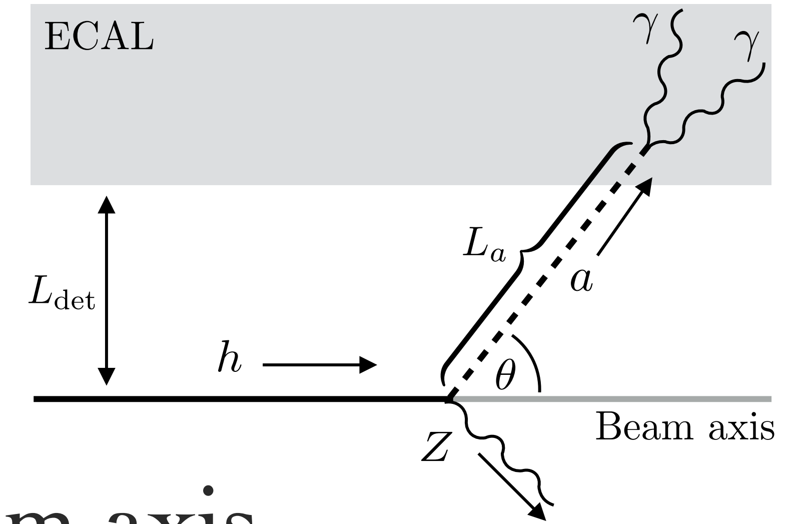

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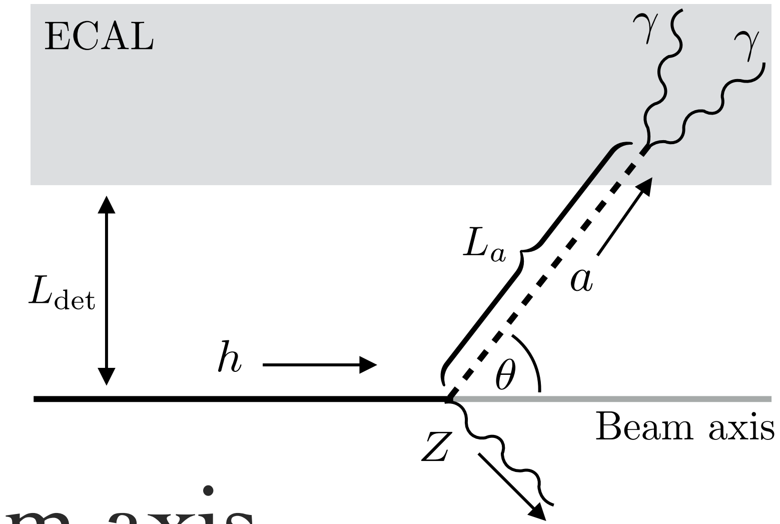

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$$f_{\rm det} = \int_0^{\pi/2} d\theta\,\sin\theta \left(1 - e^{-L_{\rm det}/L_a^{\perp}(\theta)}\right)$$

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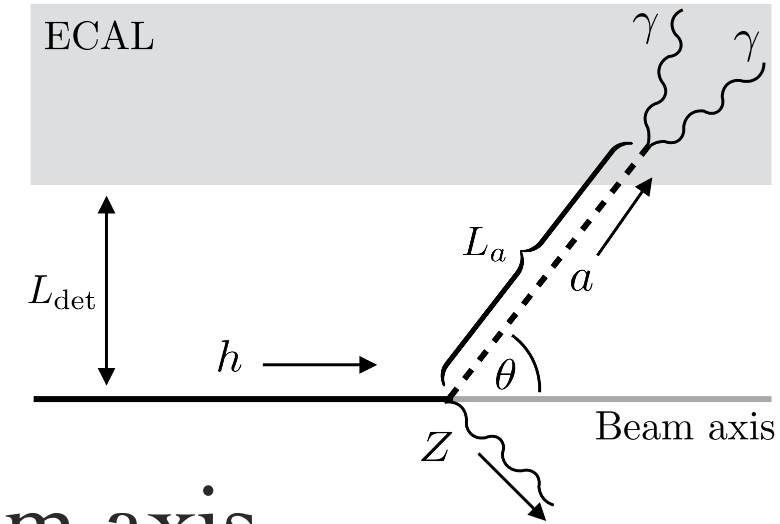

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Decay into photons before EM calorimeter

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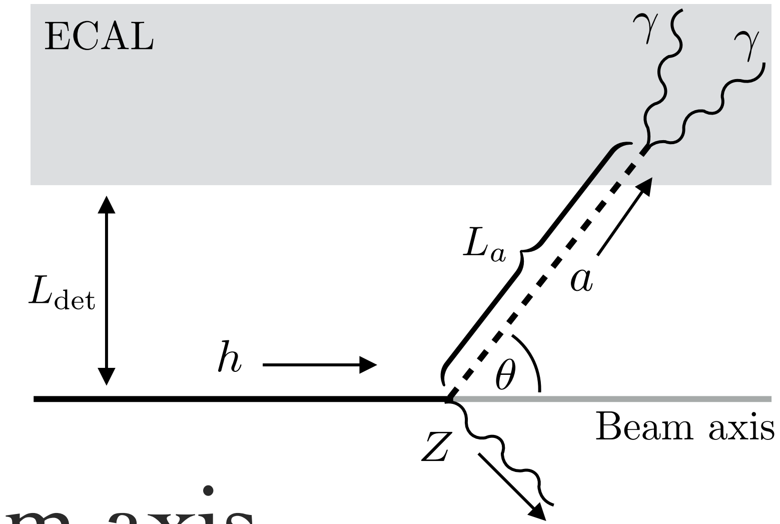

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Decay into photons before EM calorimeter

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

Decay into electrons before inner tracker

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

Detecting ALPs

- Effective branching ratios

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

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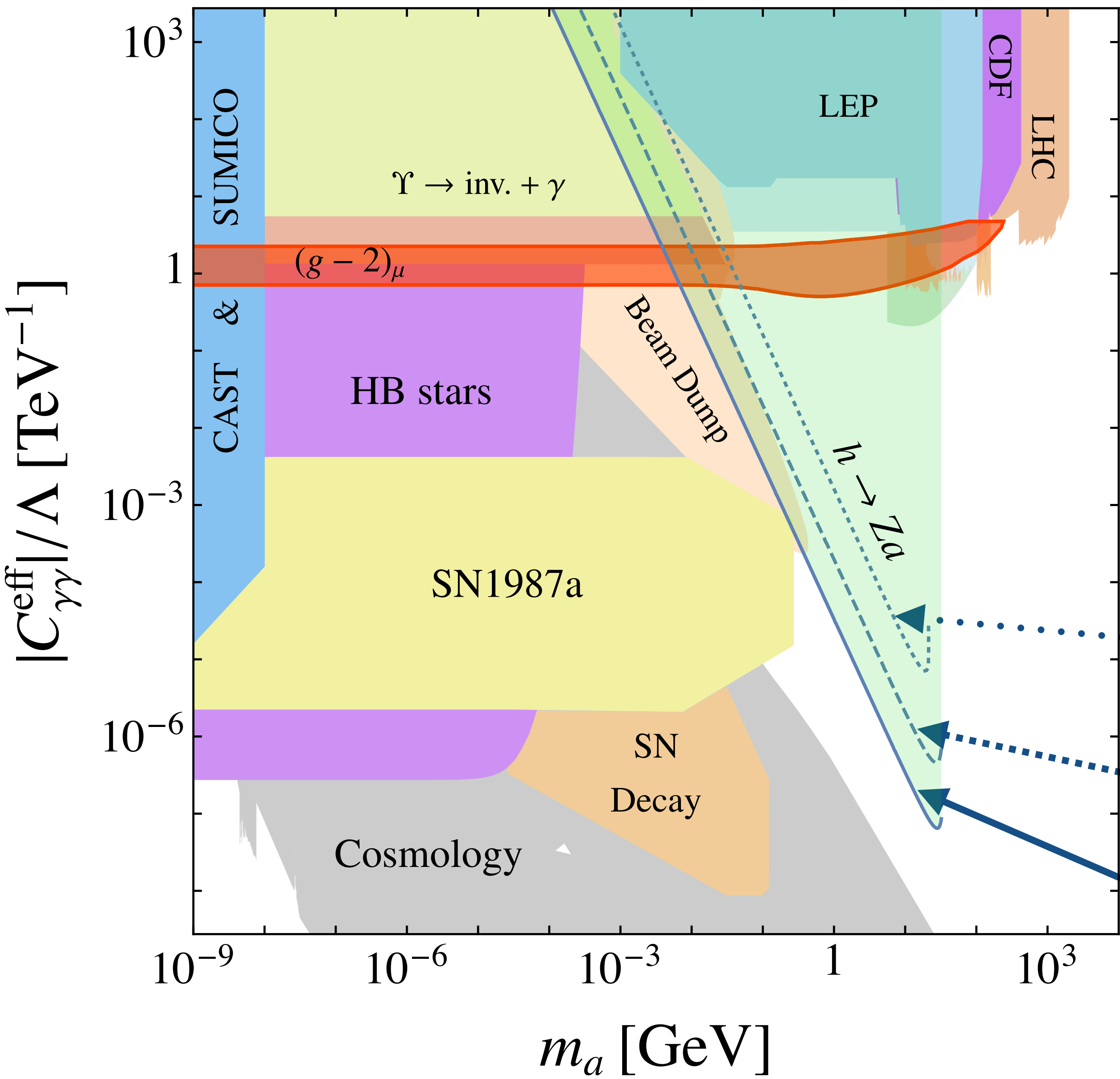
- Requiring 100 events at $\sqrt{s} = 13\,\mathrm{TeV}$ with $300\,\mathrm{fb}^{-1}$ in

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

Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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

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

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

(for $\Lambda = 1$ TeV)

[Bauer, Neubert, Thamm: 1704.08207]

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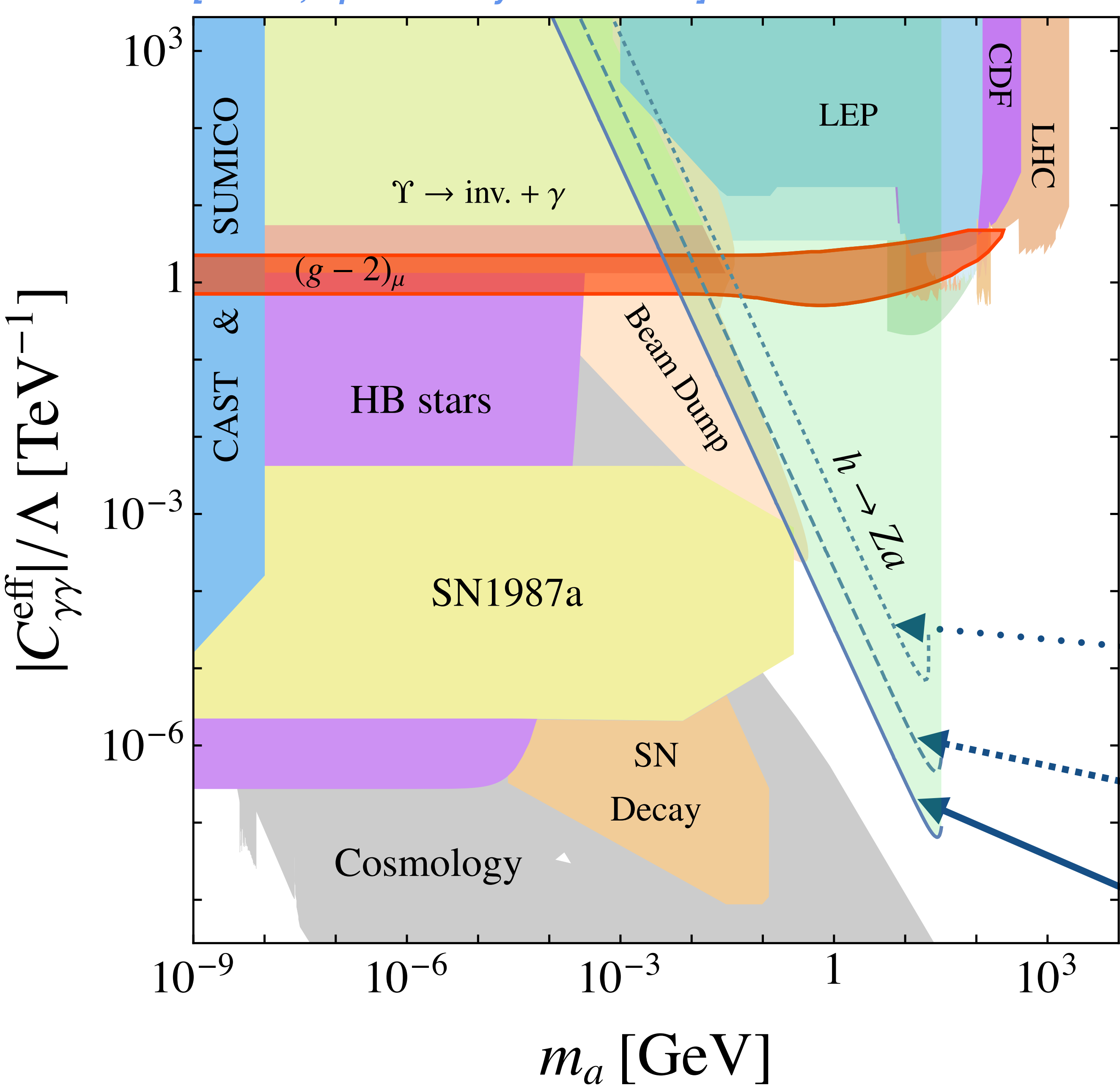

- ALP-photon coupling can be probed if ALP decays predominantly into other particles
- Region preferred by $(g-2)_\mu$ almost completely covered

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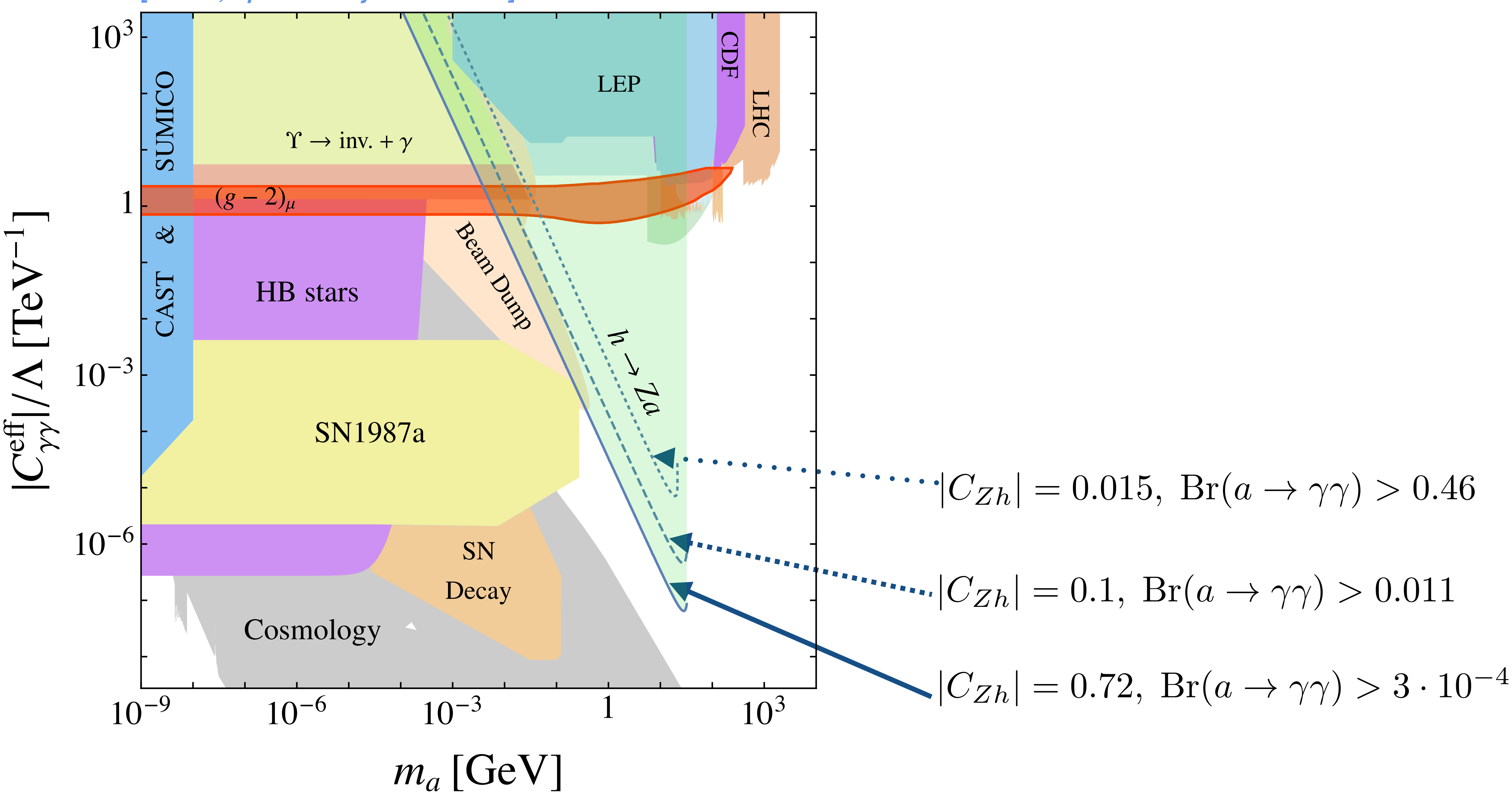
- For $L_a \gg L_{\mathrm{det}}$, effective BR independent of $\mathrm{Br}(a \to X\bar{X})$

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

Probing the parameter space

- Large hierarchy in couplings can be plausible

[Jäckel, Spannowsky: 1509.00476]



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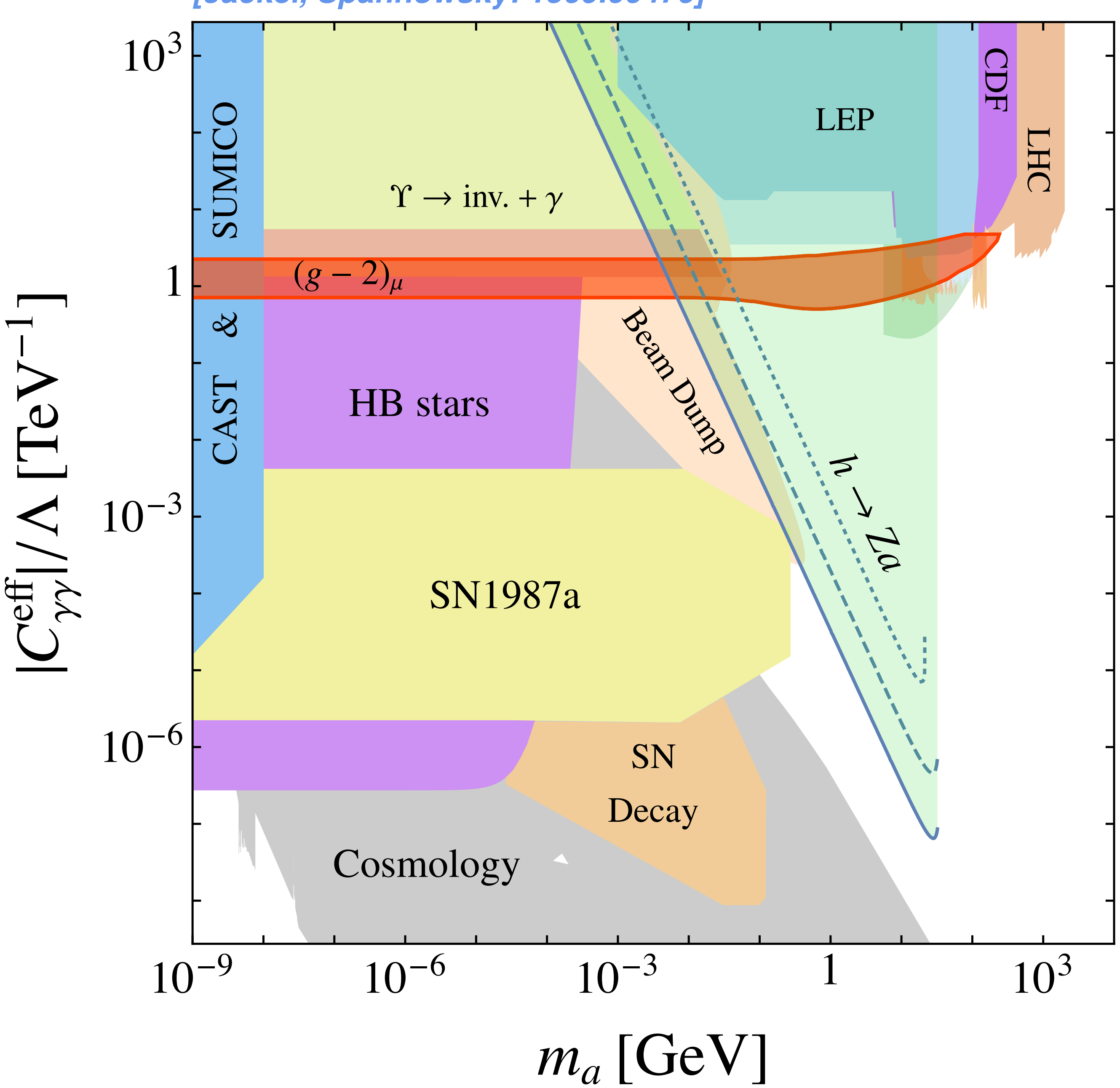
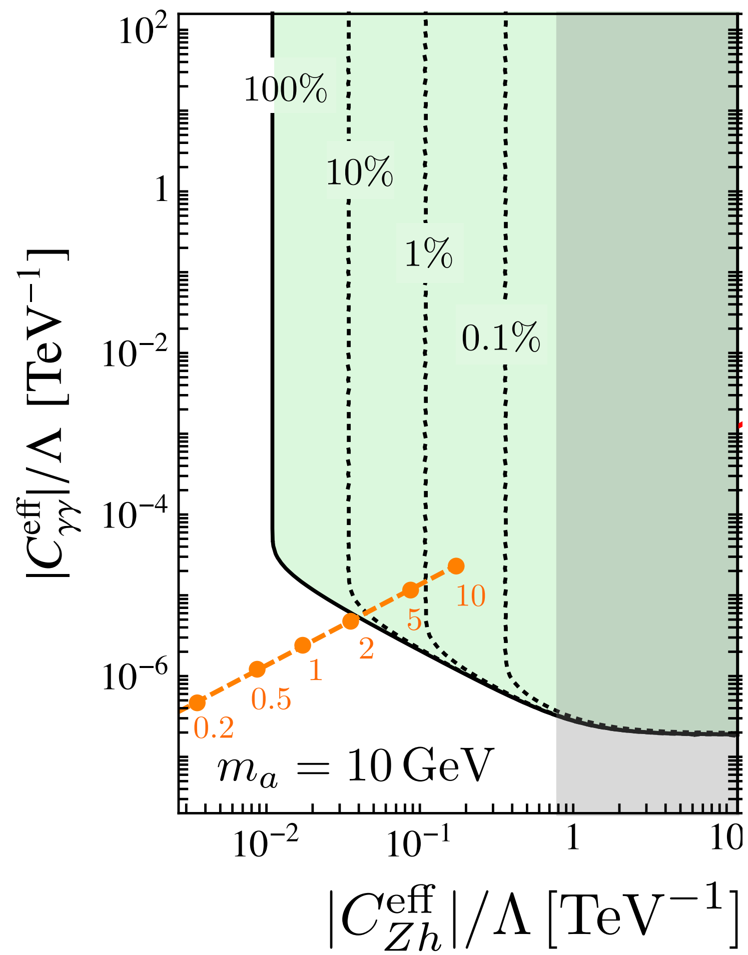
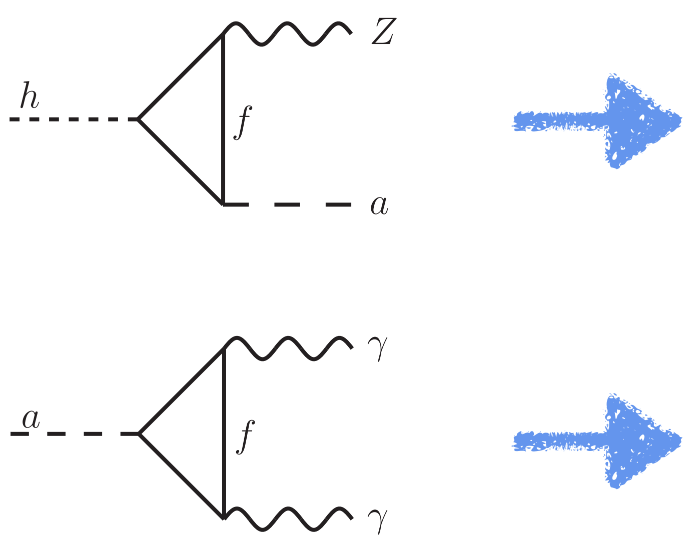




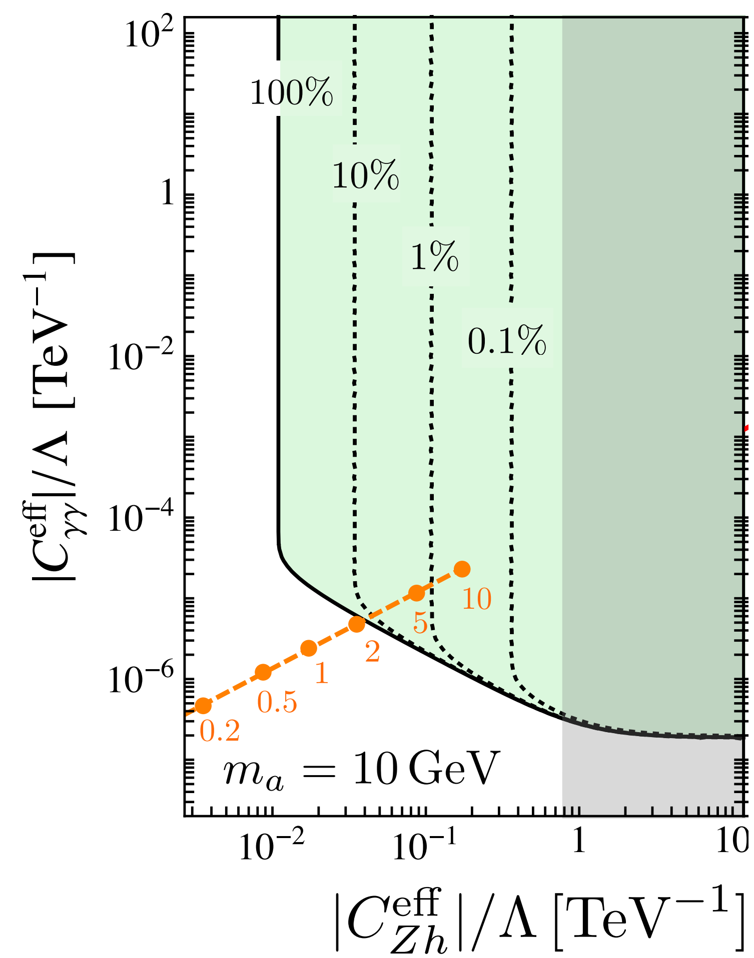
Probing the parameter space

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



$C_{\gamma\gamma}$

C_{Zh}



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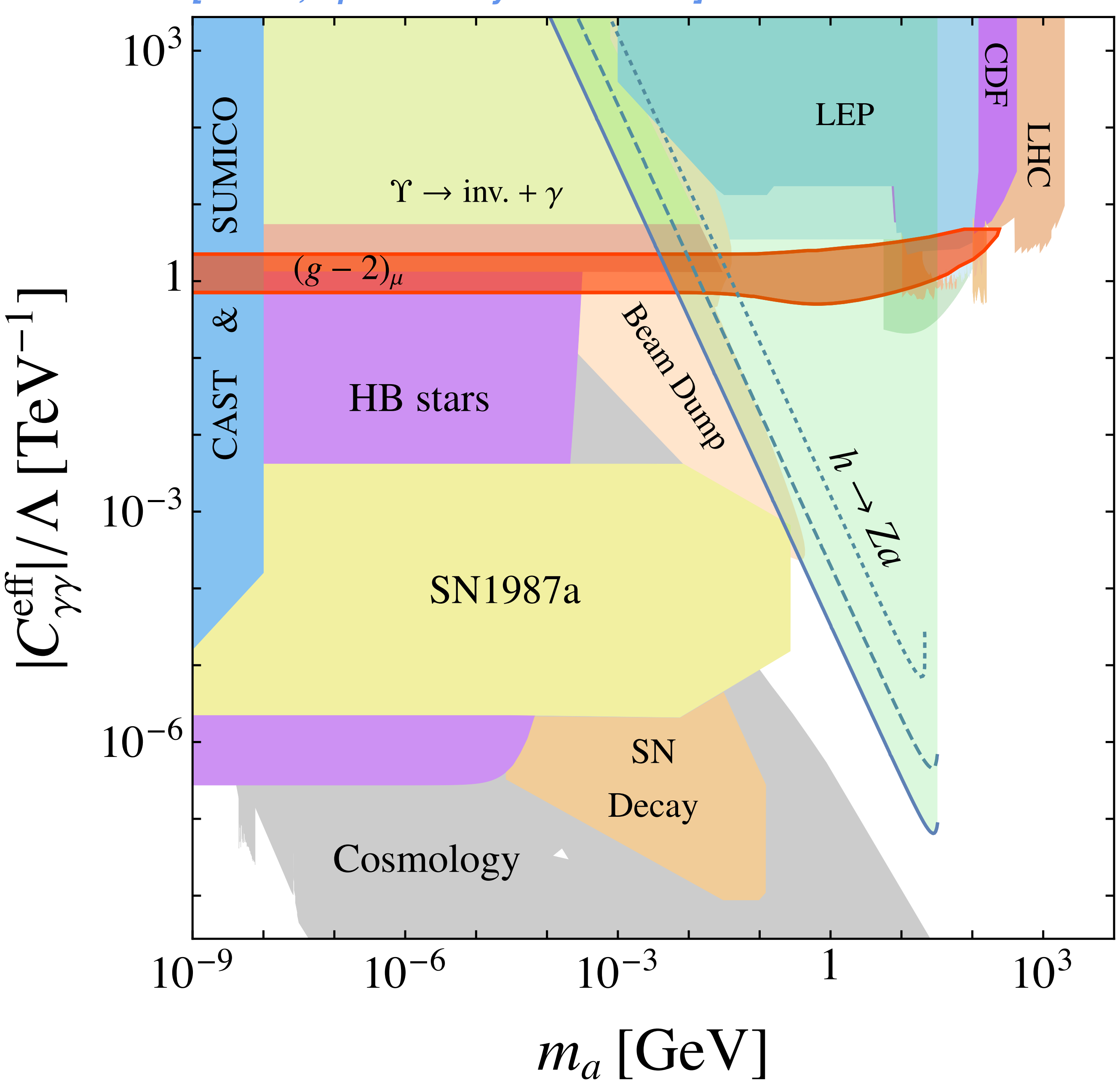
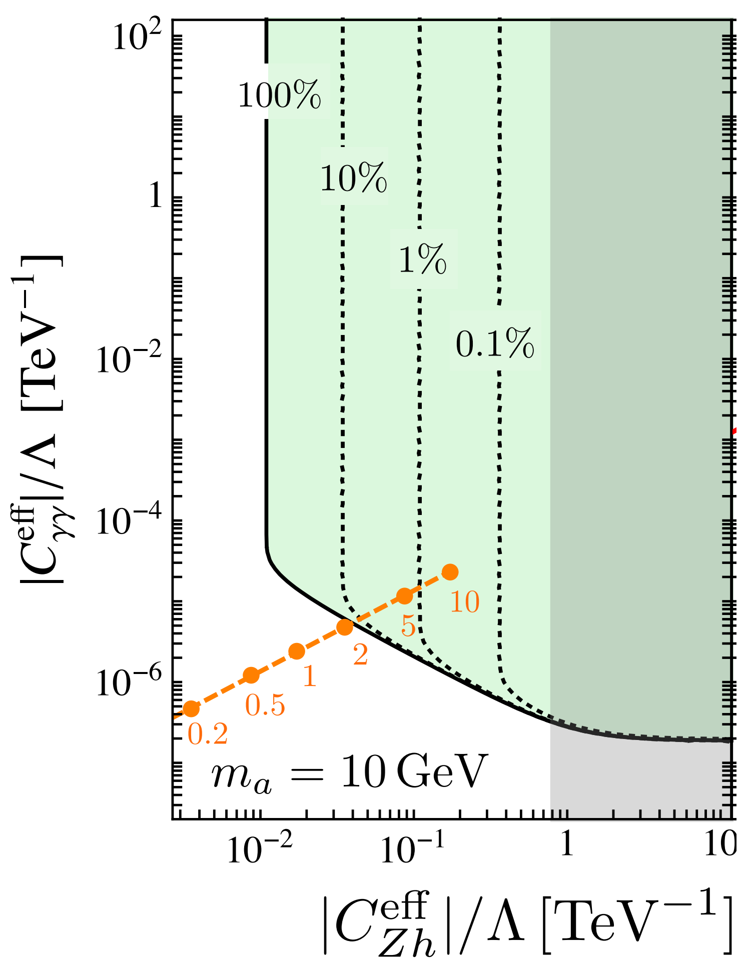
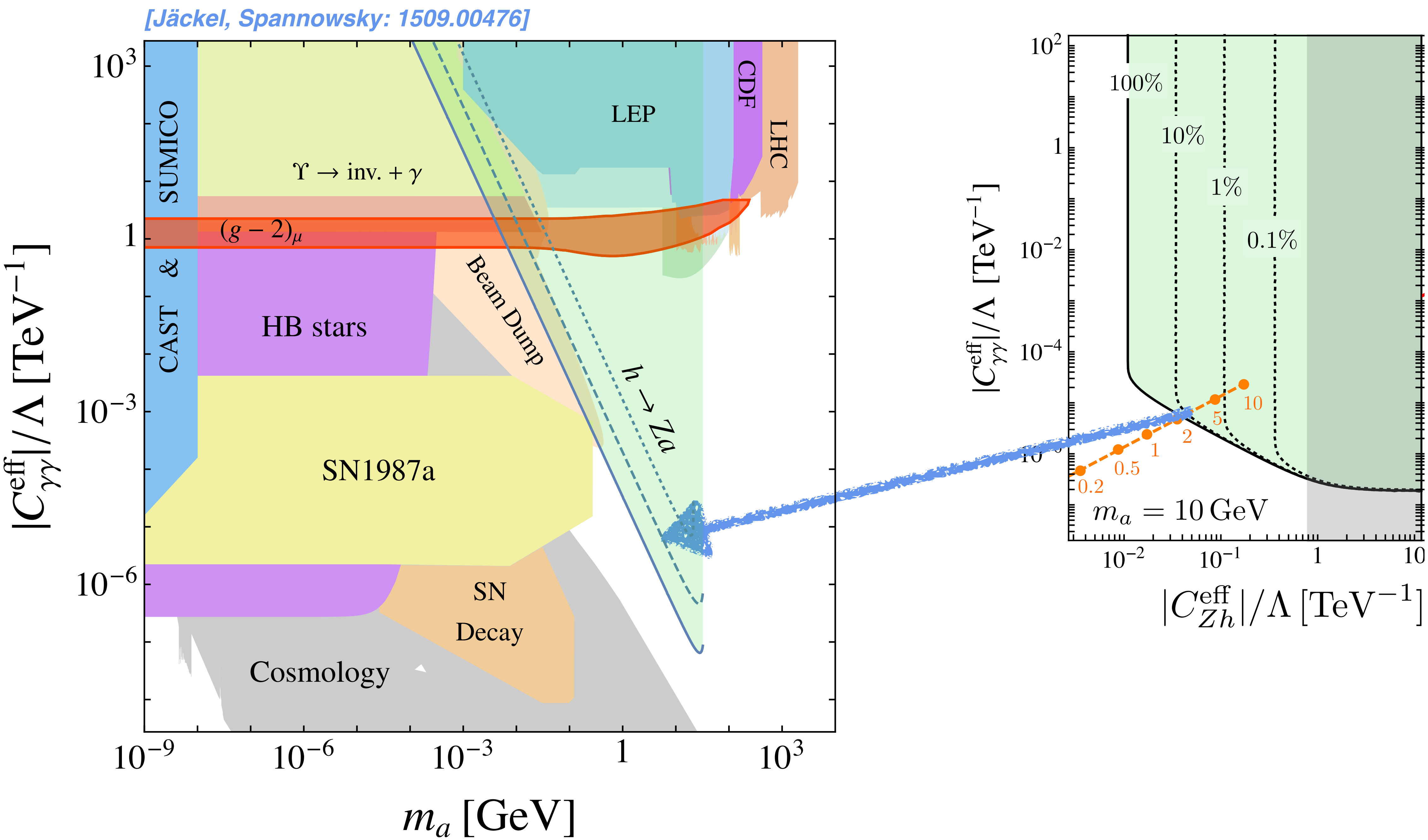
[Jäckel, Spannowsky: 1509.00476]





Probing the parameter space

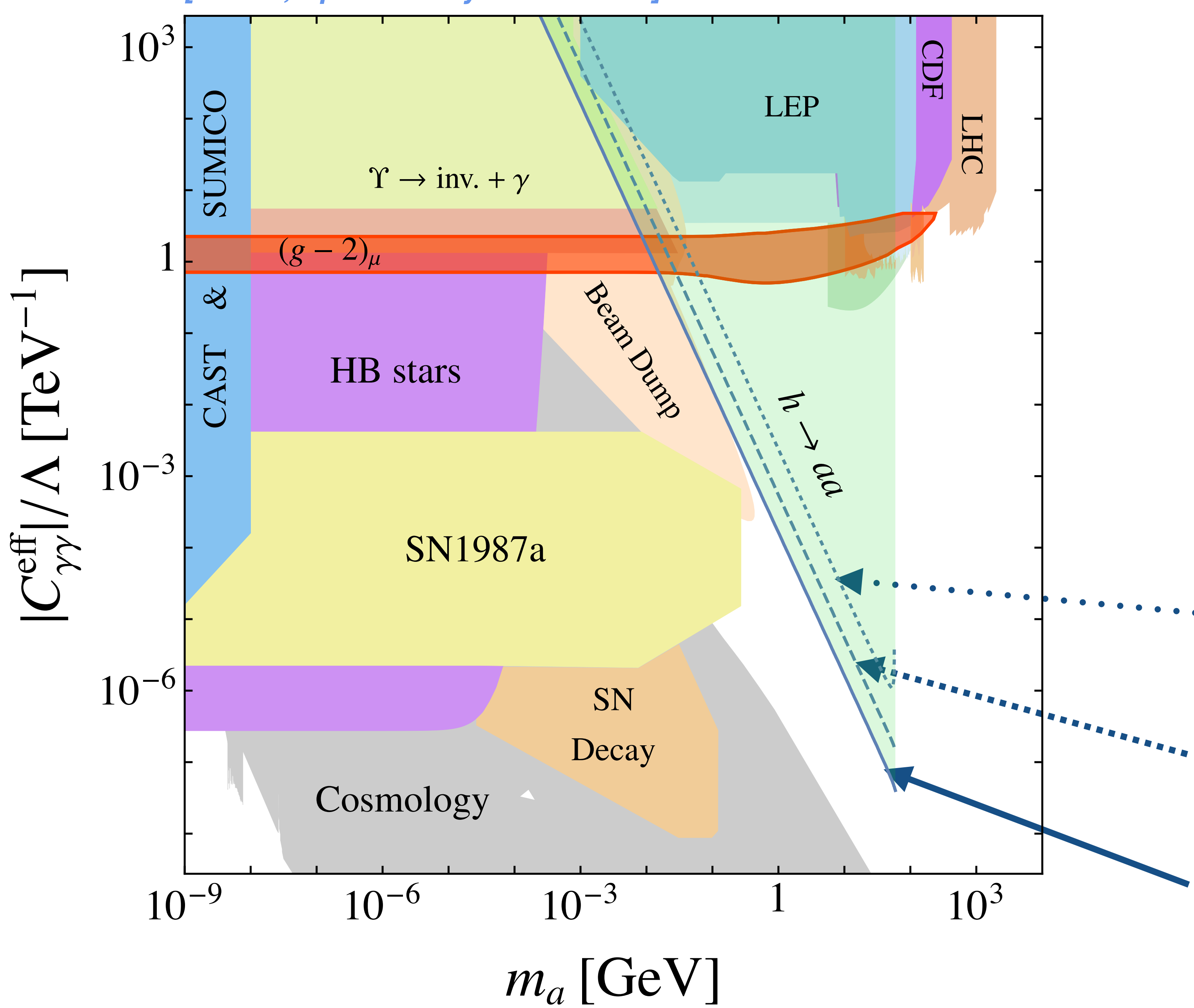
- Large hierarchy in couplings can be plausible



Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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

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

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

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

[Bauer, Neubert, Thamm: 1704.08207]

Probing the parameter space

- Constraints on ALP mass and coupling to photons

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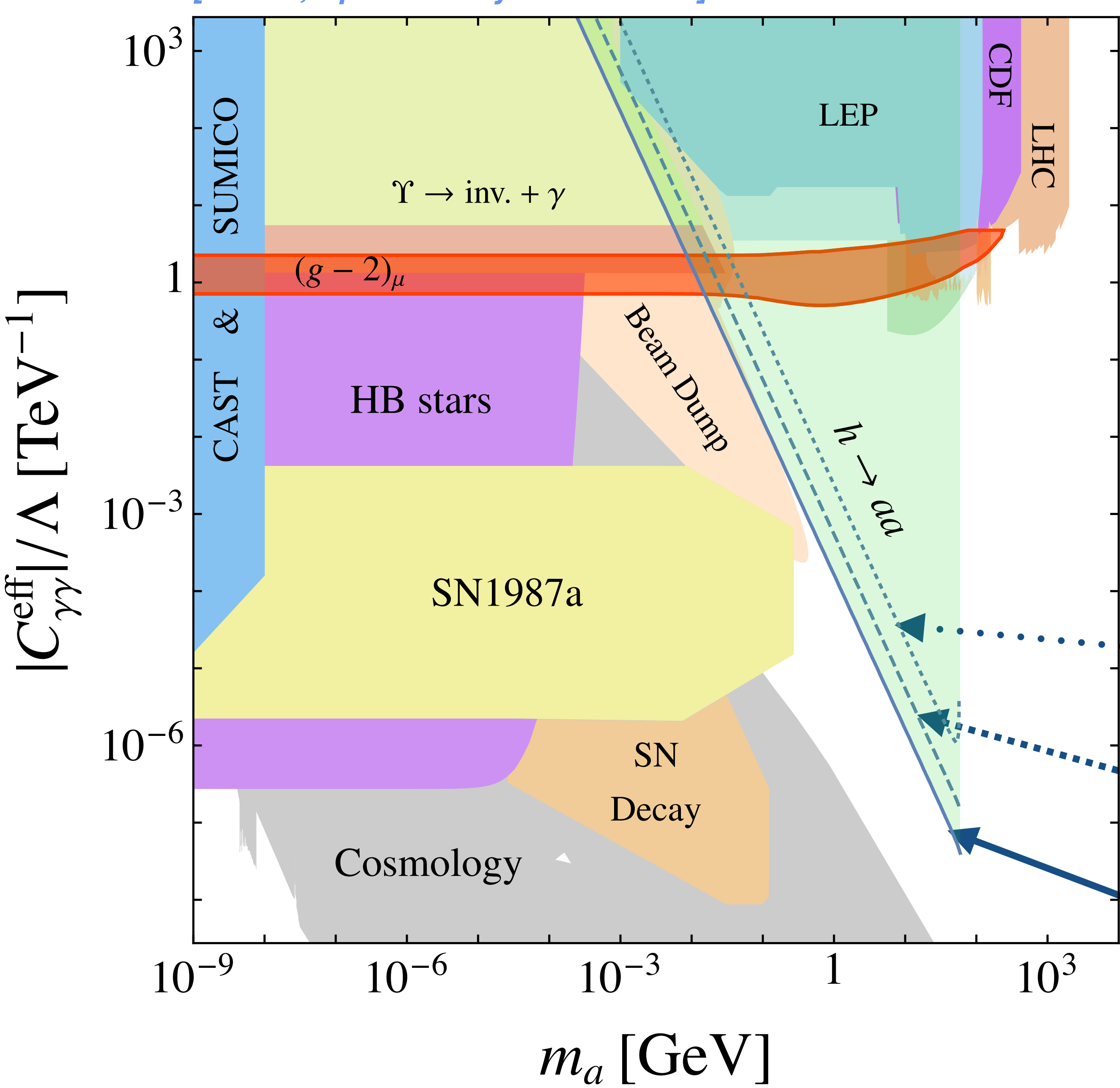

- ALP-photon coupling can be probed if ALP decays predominantly into other particles
- Region preferred by $(g-2)_\mu$ almost completely covered

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

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

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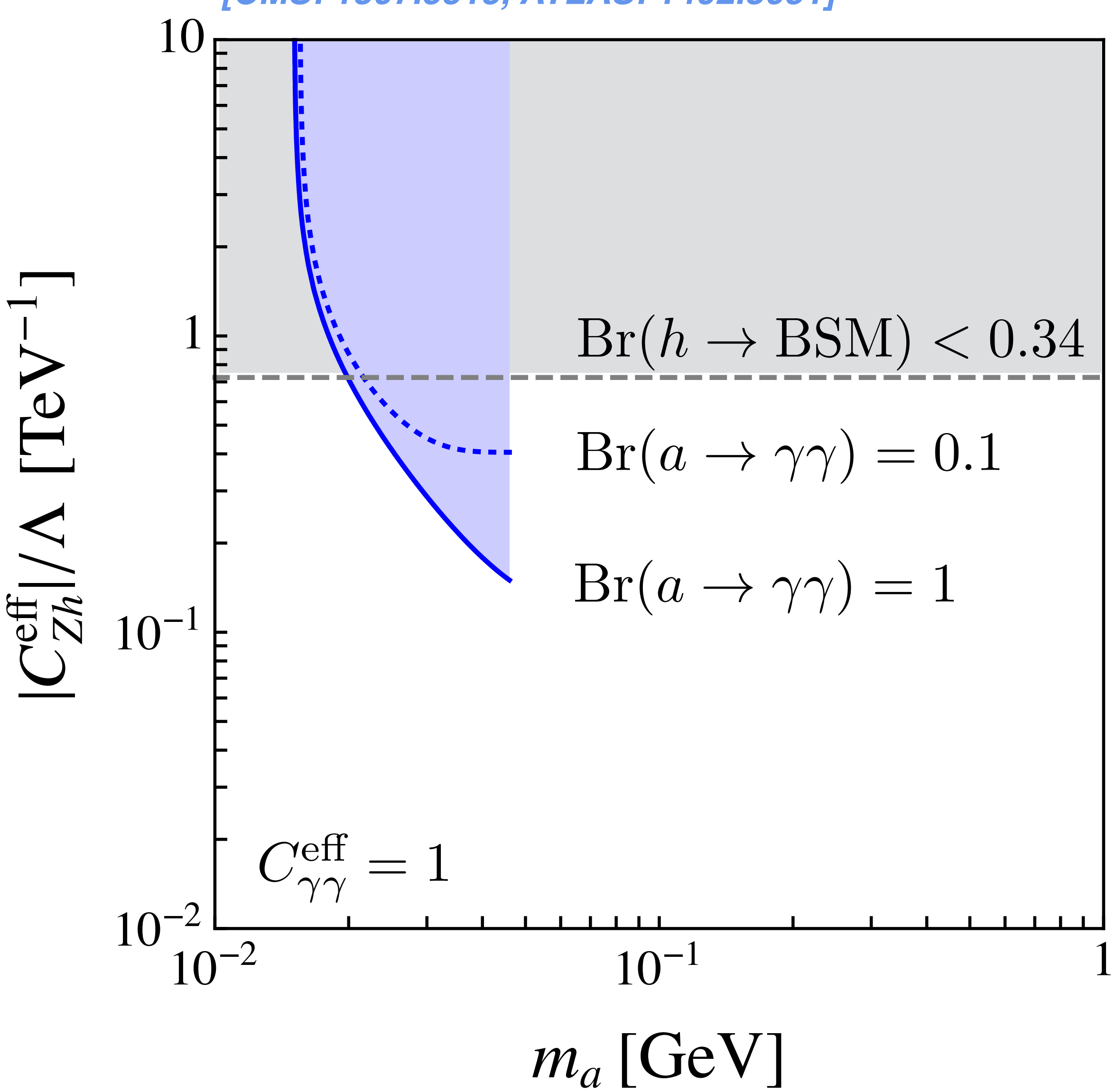
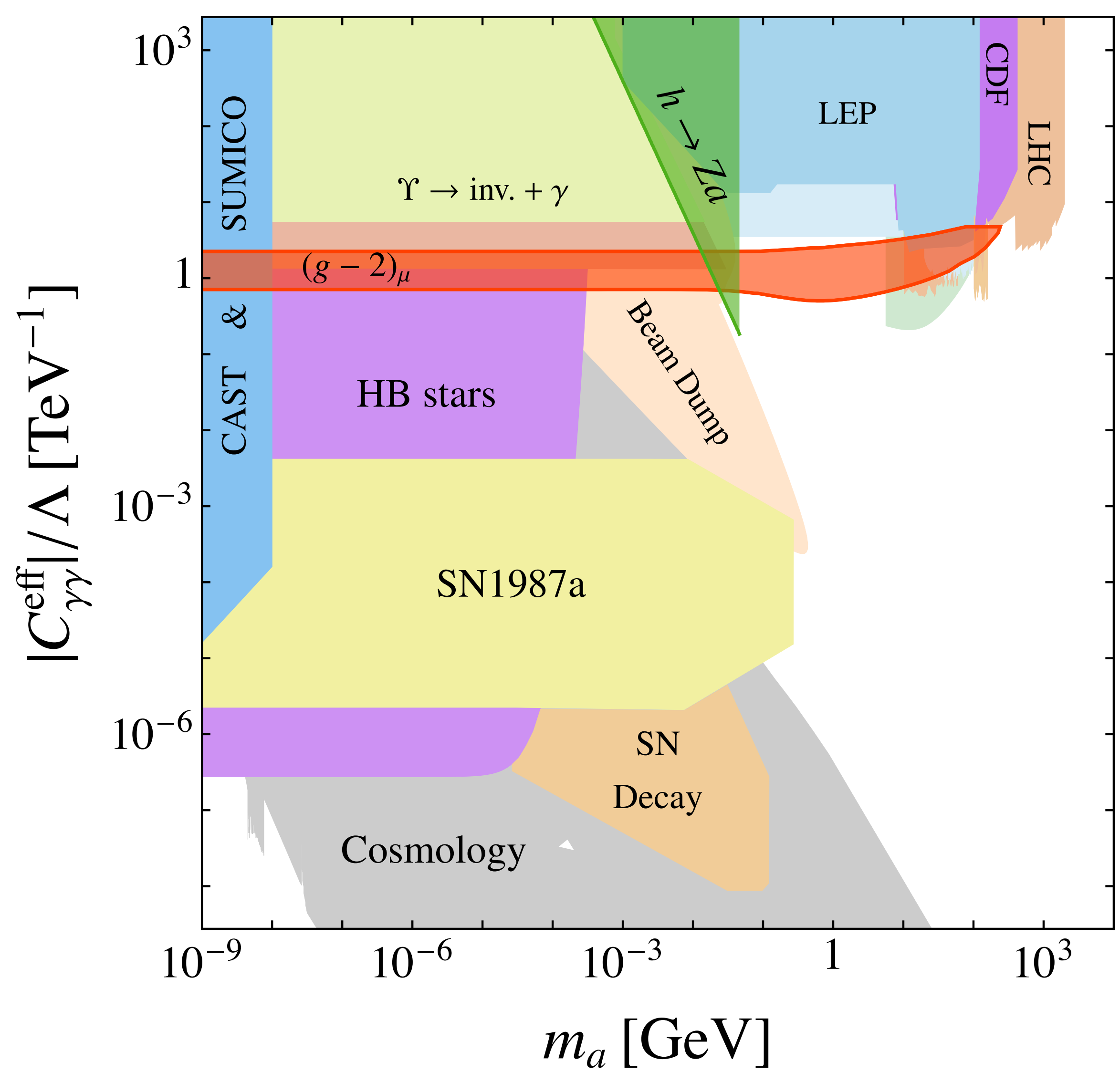
[Bauer, Neubert, Thamm: 1704.08207]

Current exclusion bounds

- Current bounds on $h \to Za$

[CMS: 1307.5515, ATLAS: 1402.3051]





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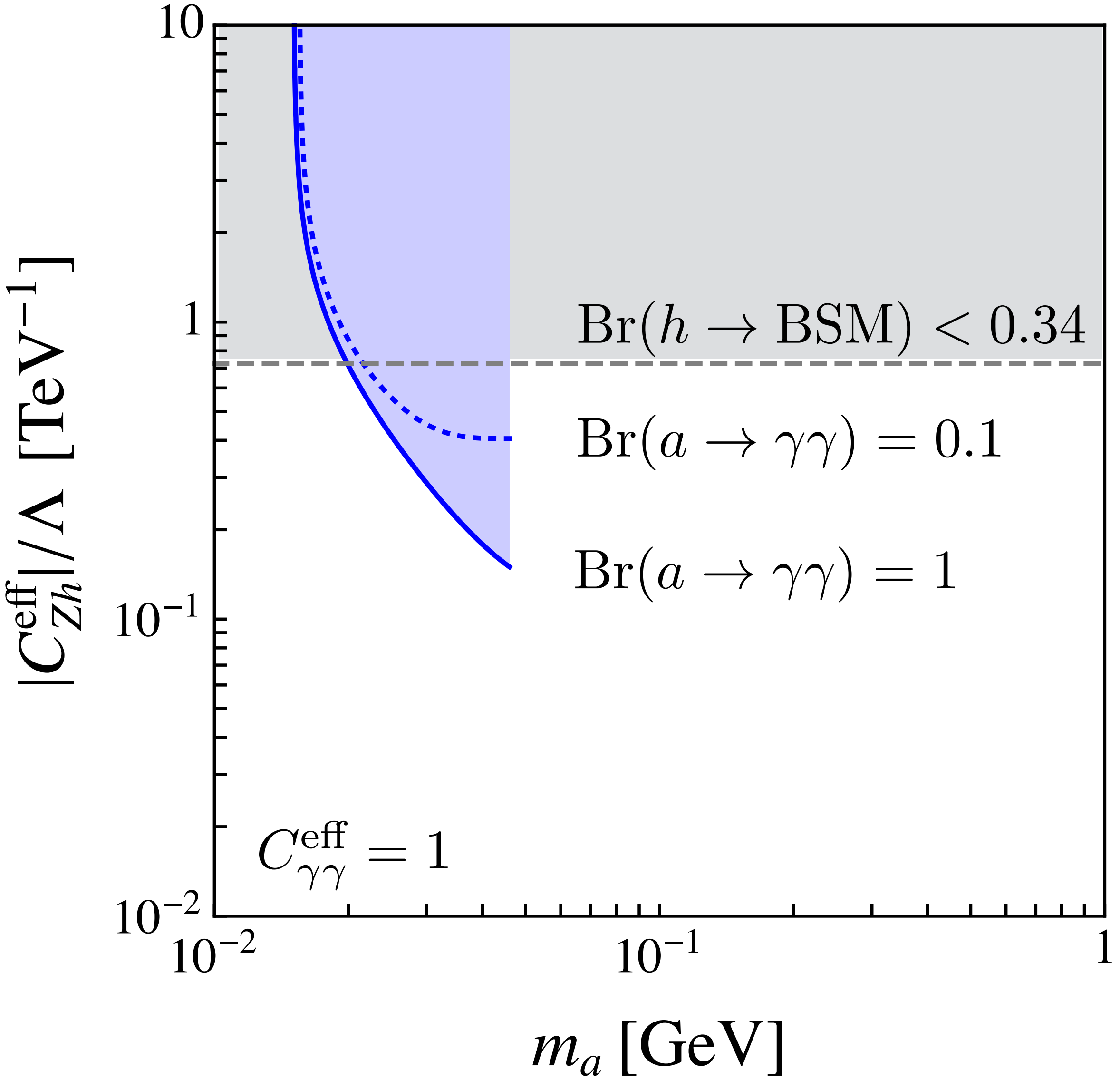

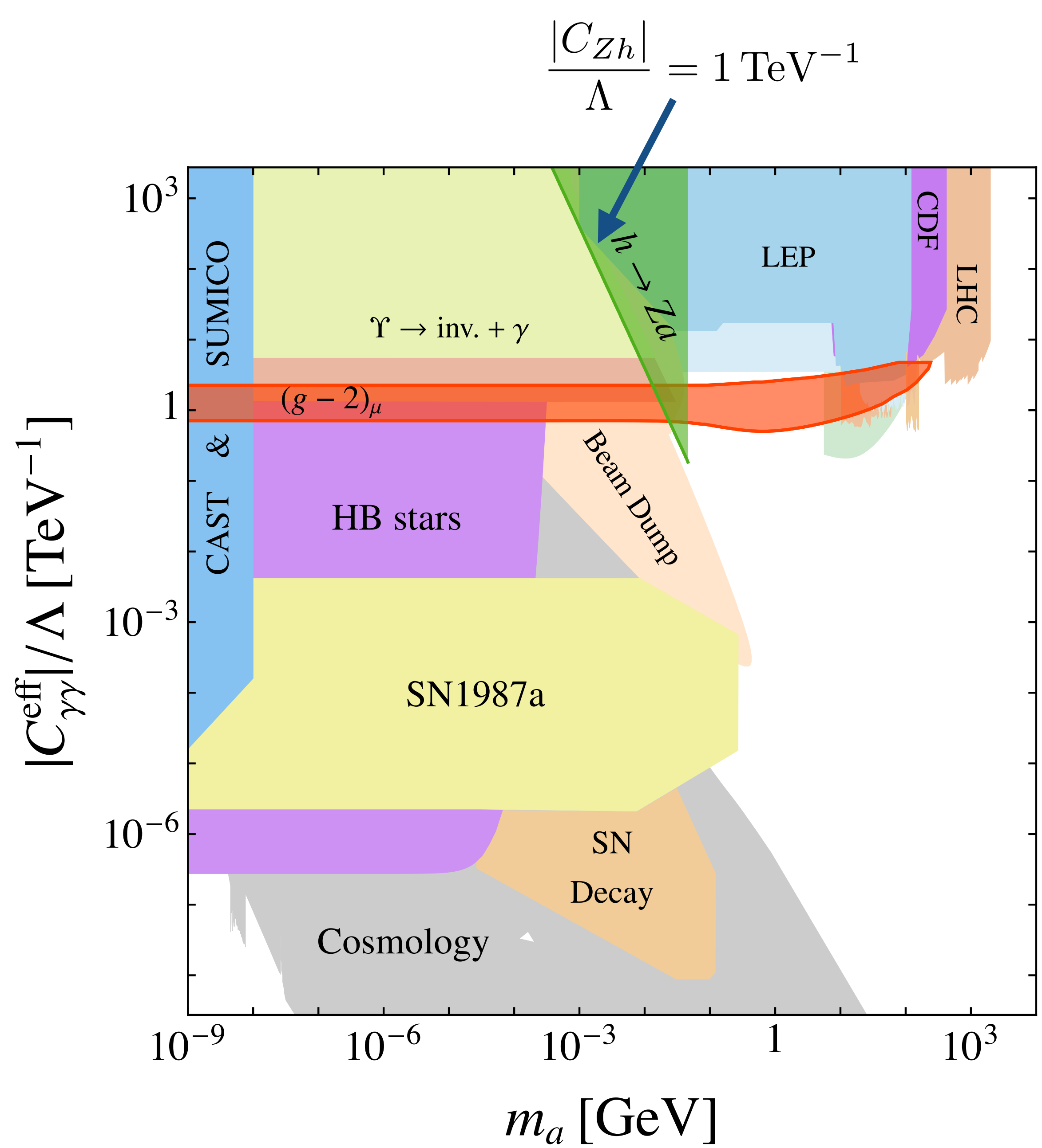

[Bauer, Neubert, Thamm: 1708.00443]

Current exclusion bounds

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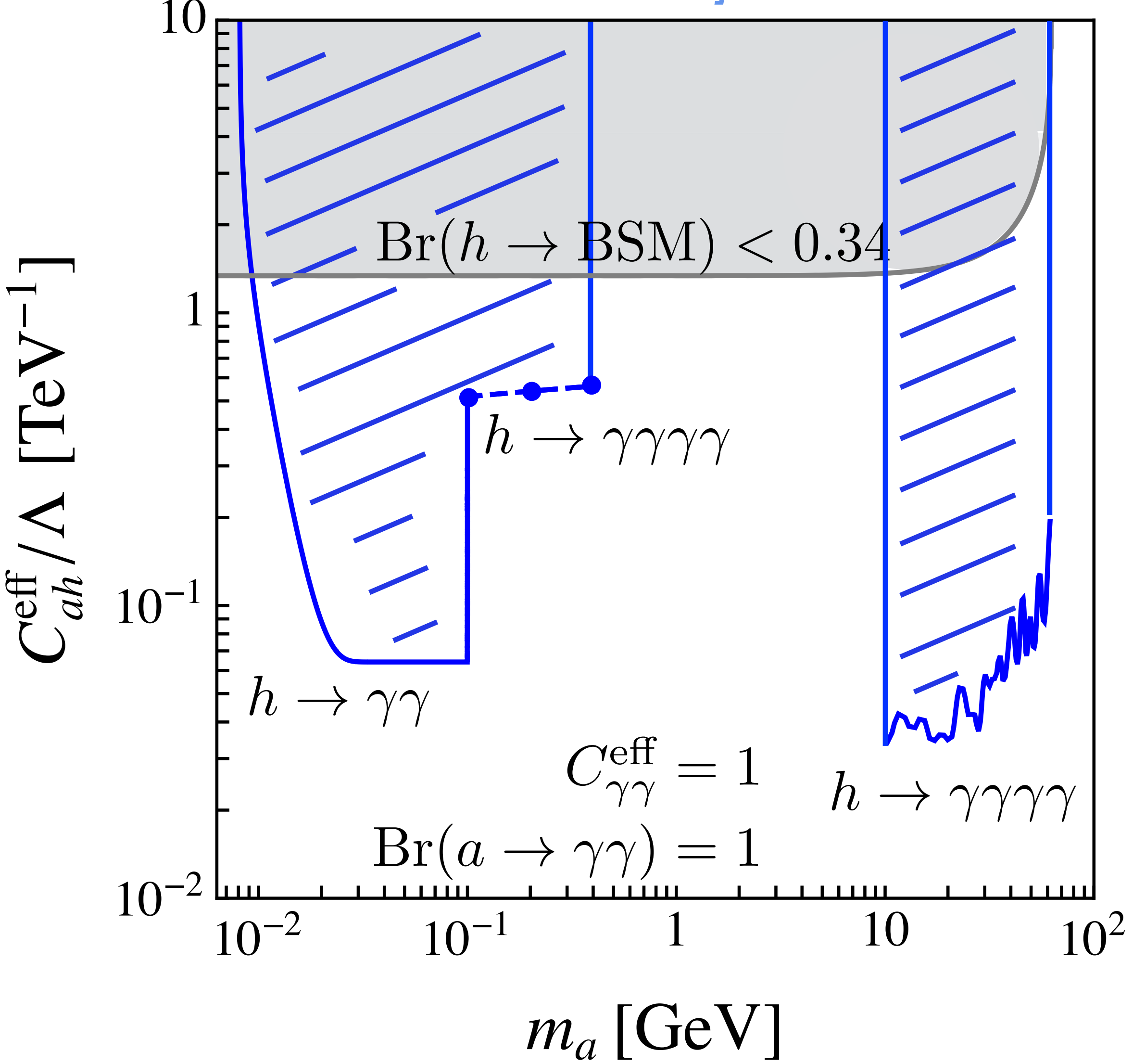
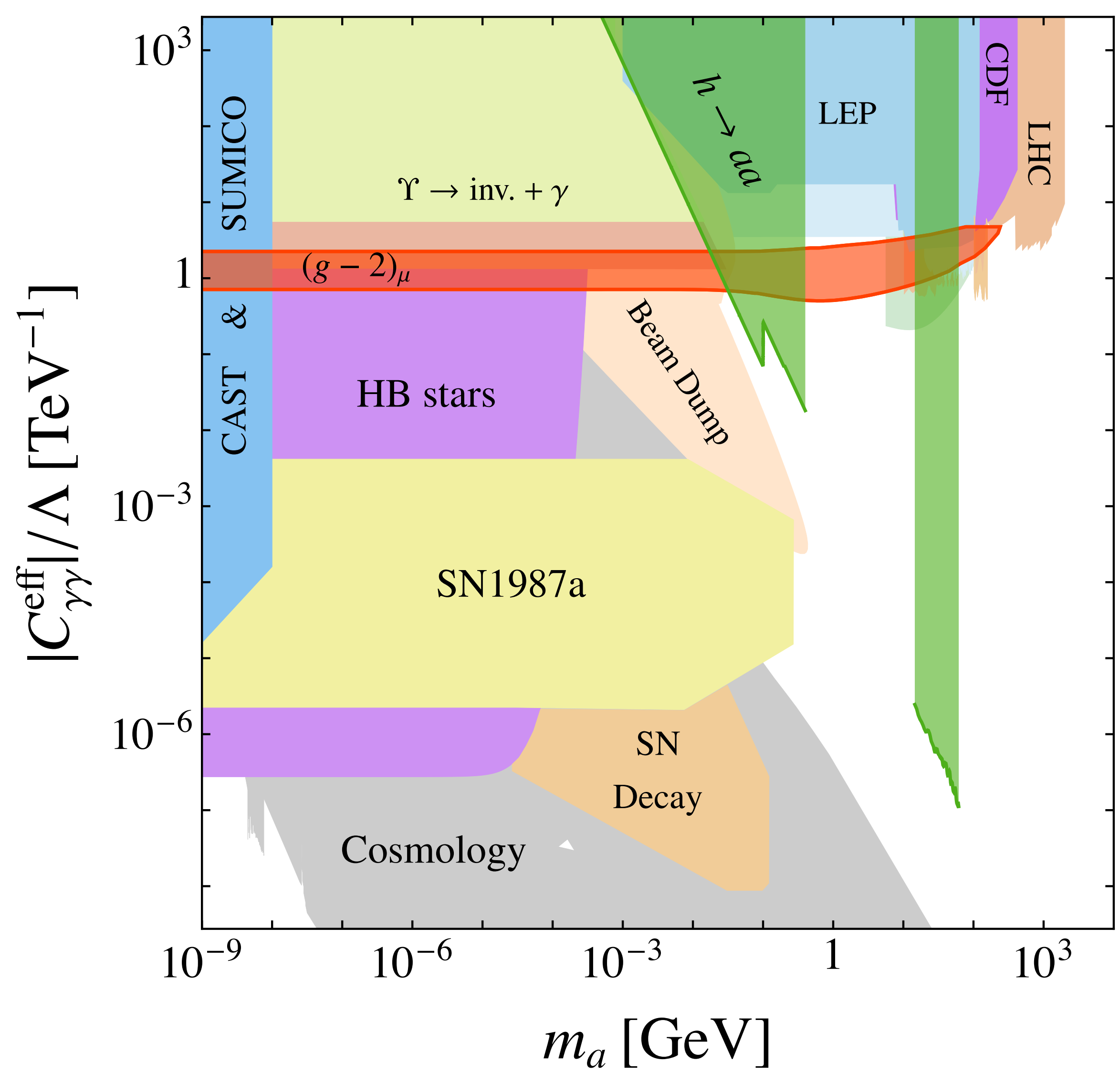
[ATLAS-CONF-2012-079, ATLAS: 1509.05051, ATLAS and CMS: 1606.02266]





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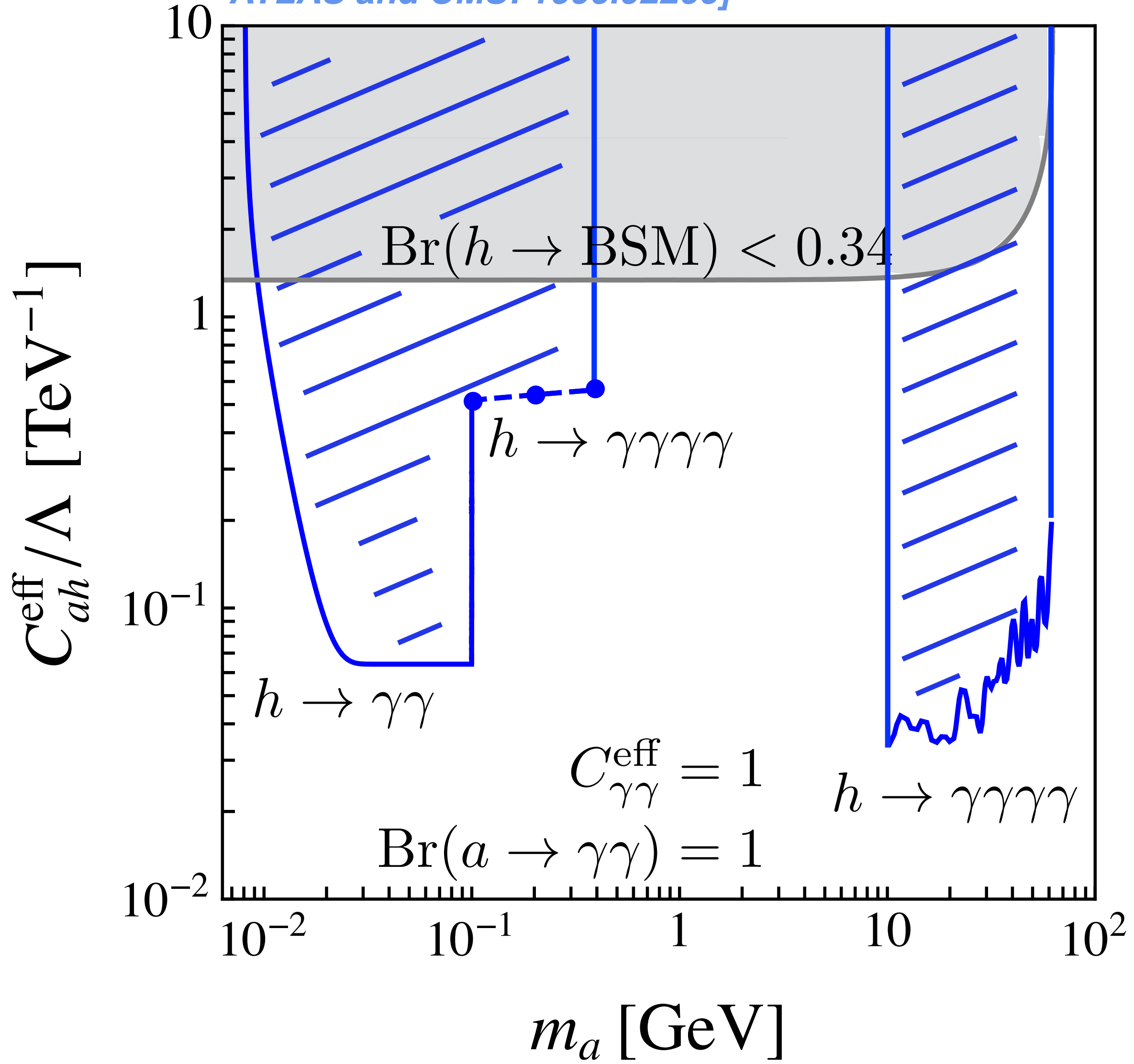
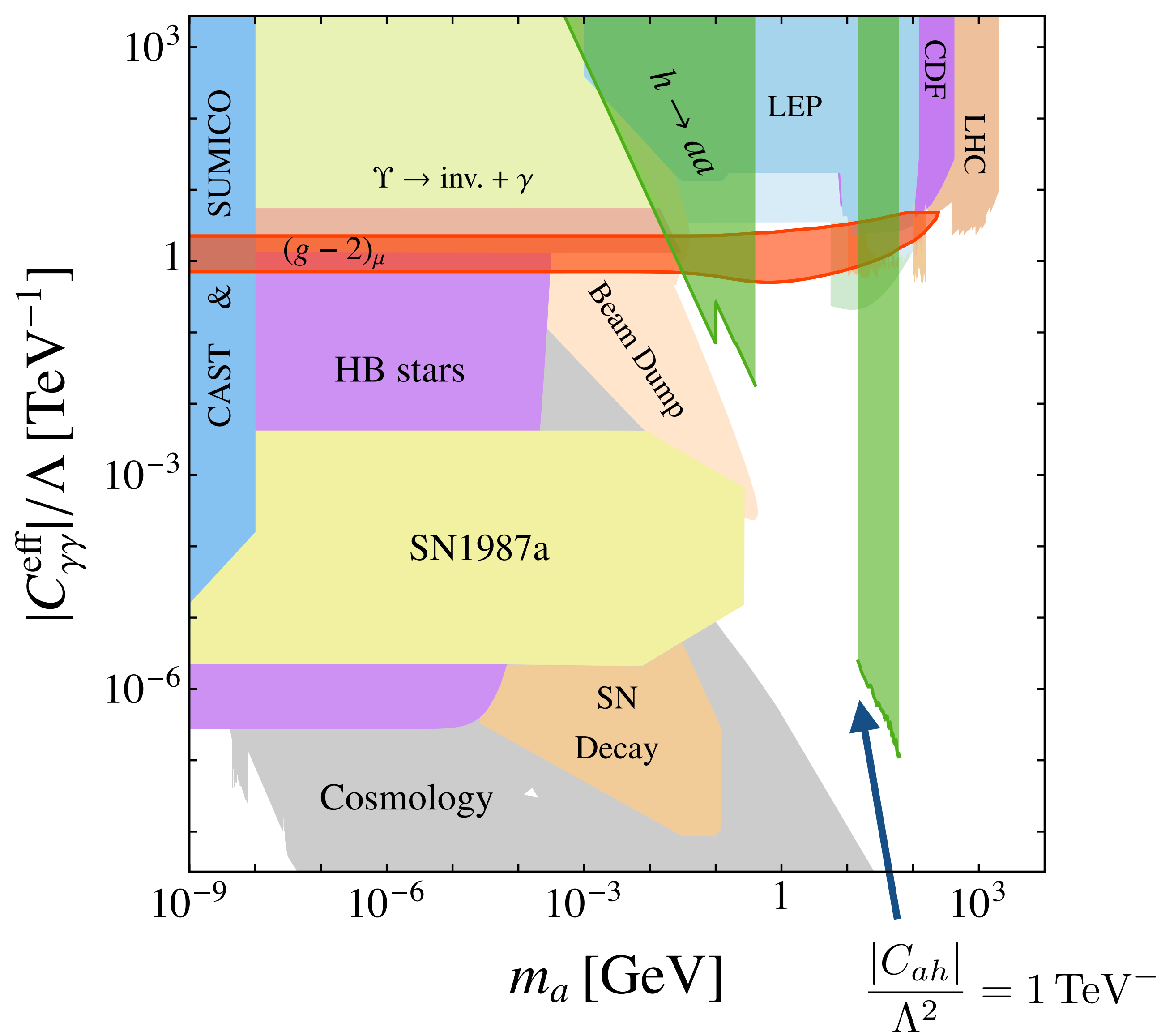


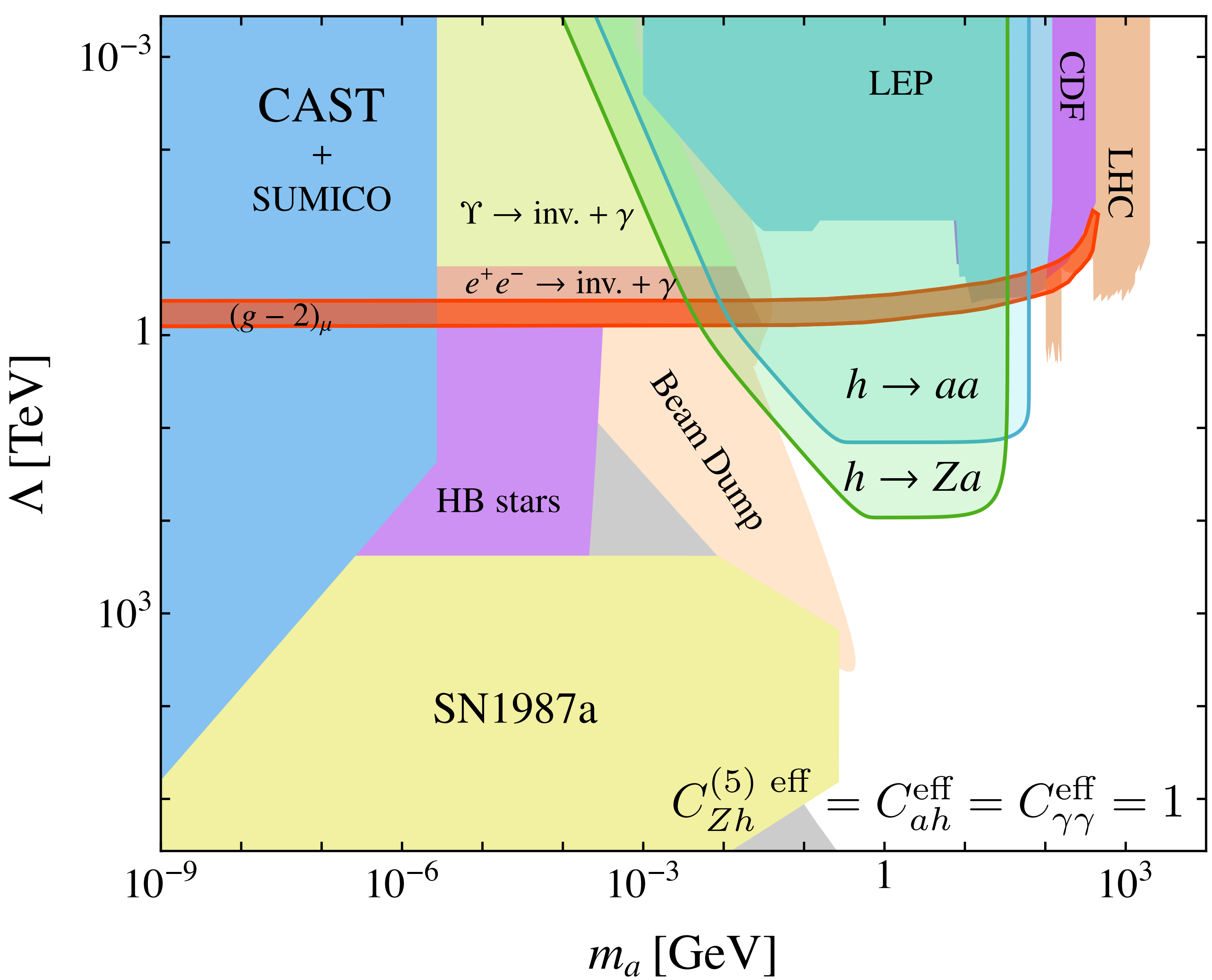


Andrea Thamm

[Bauer, Neubert, Thamm: 1708.00443]

Probing the parameter space

- Constraints on ALP mass and coupling to photons



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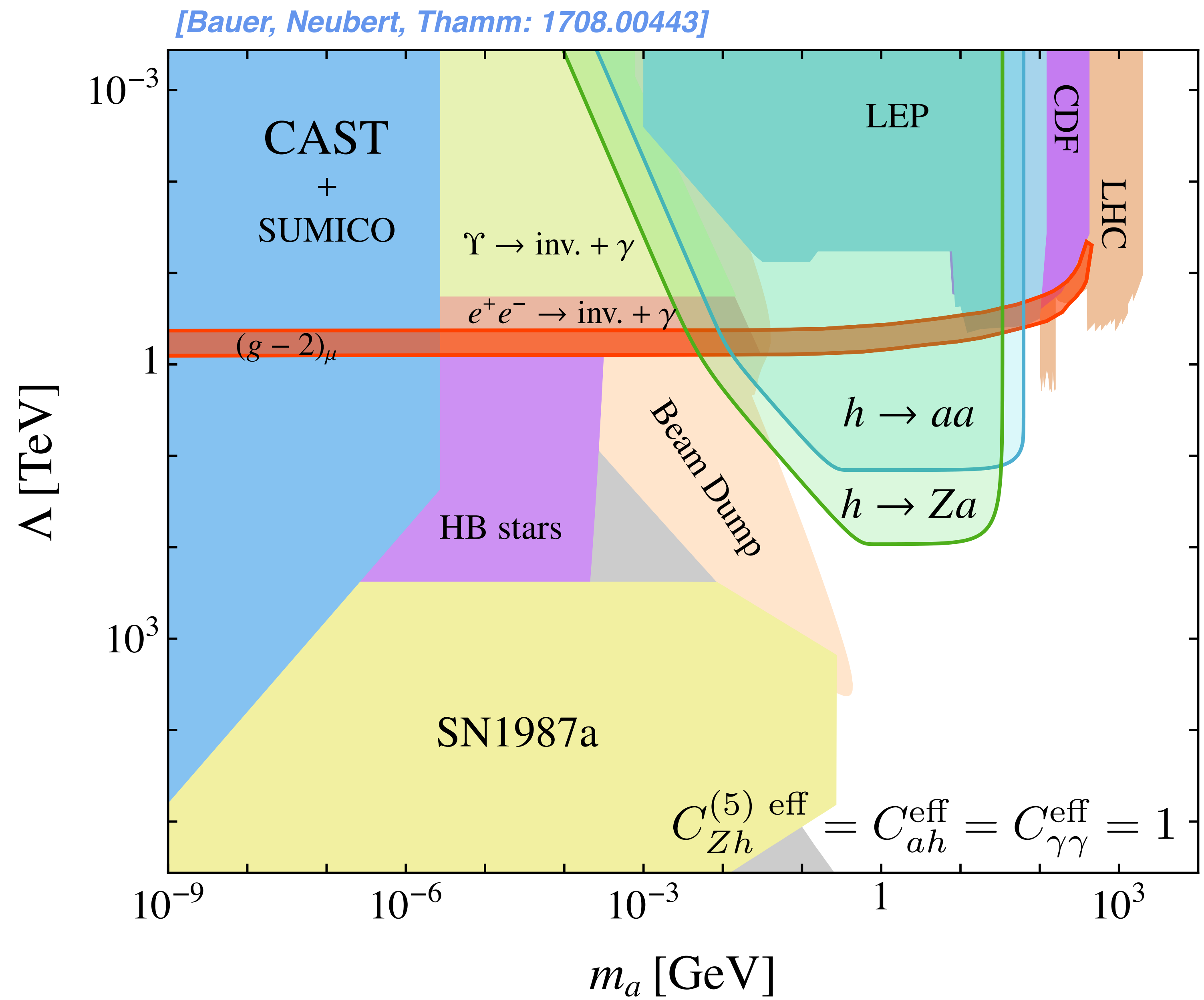
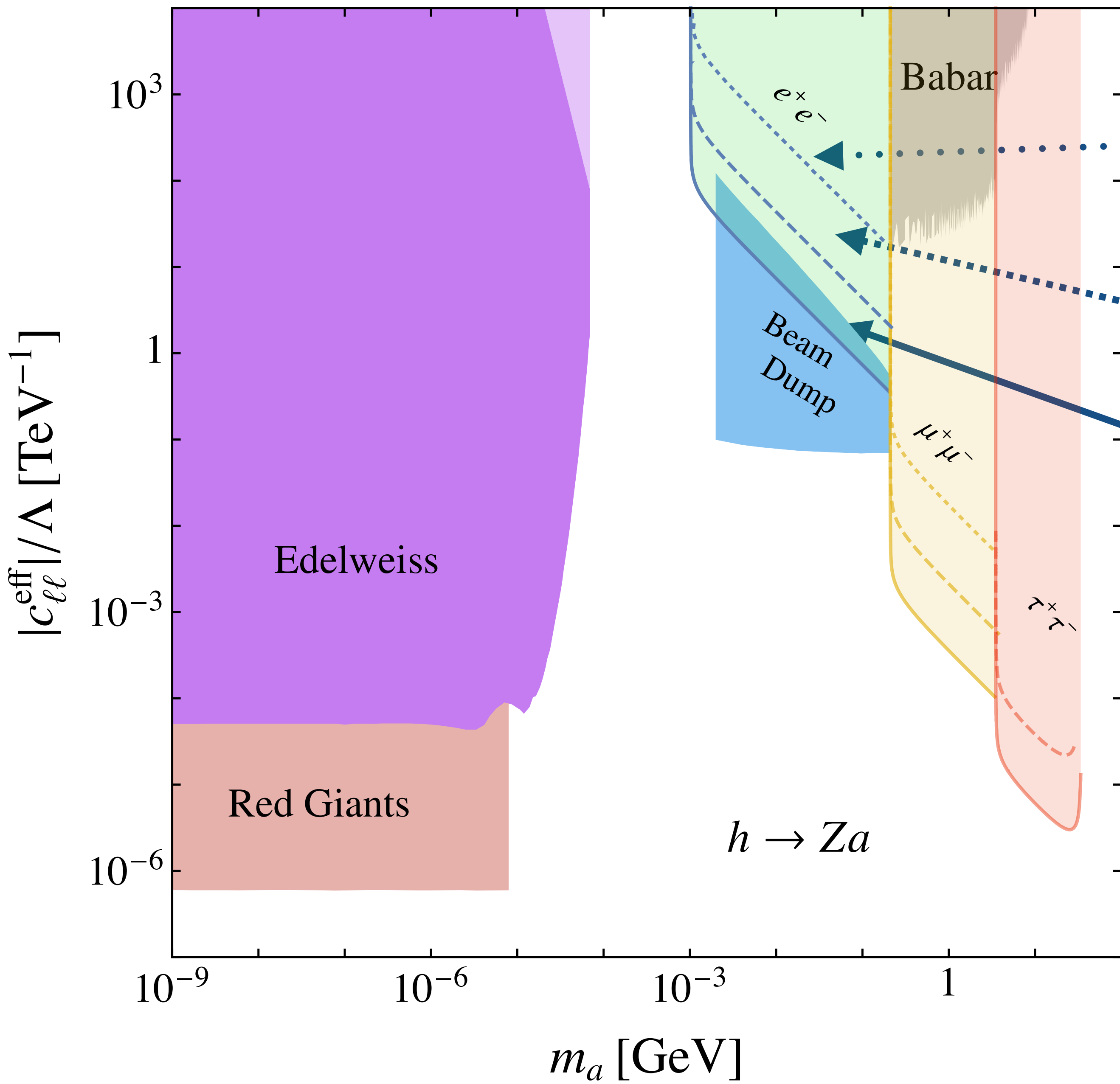


Probing the parameter space

- 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

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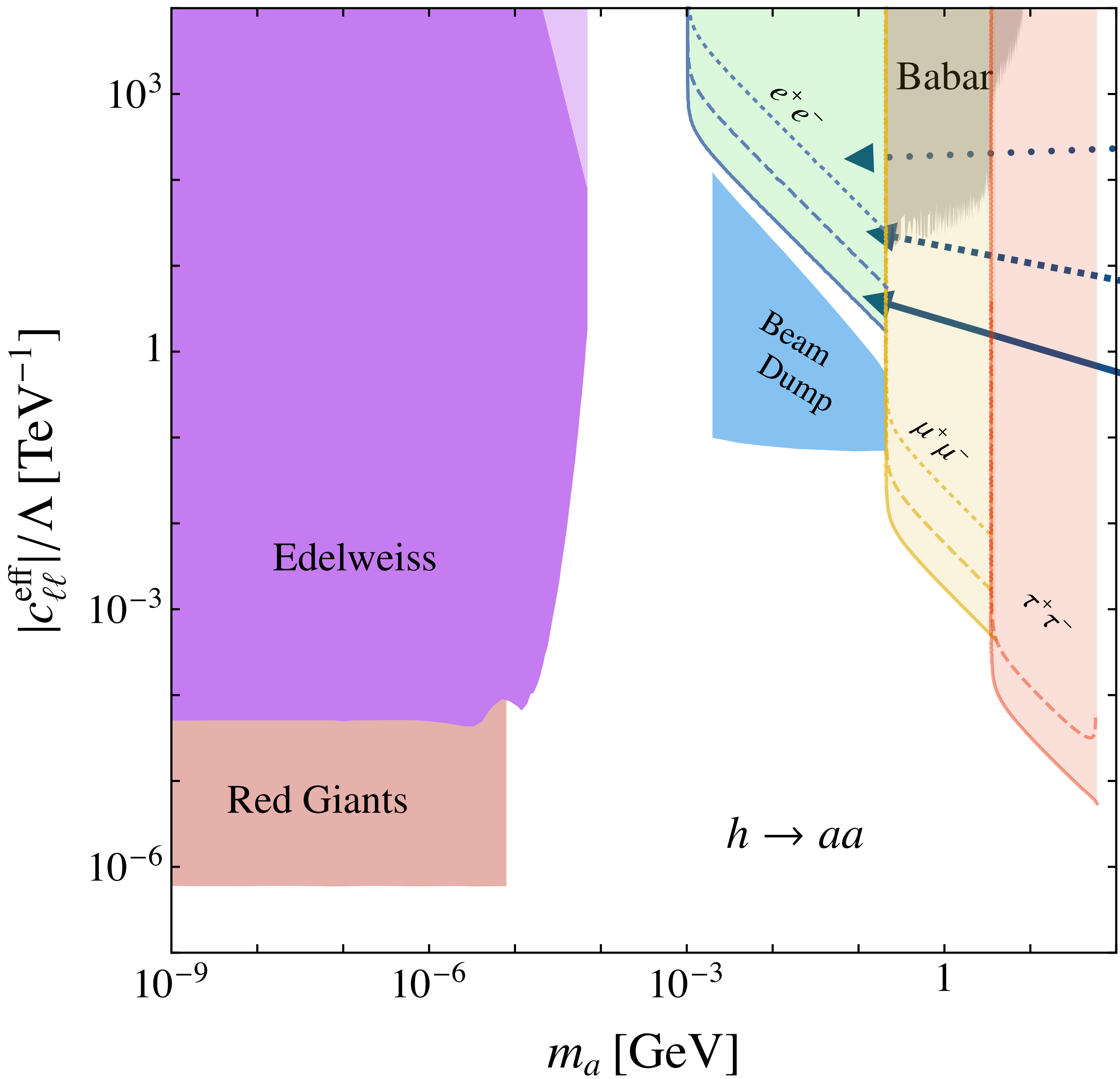

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(for $\Lambda = 1$ TeV)

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

Outline

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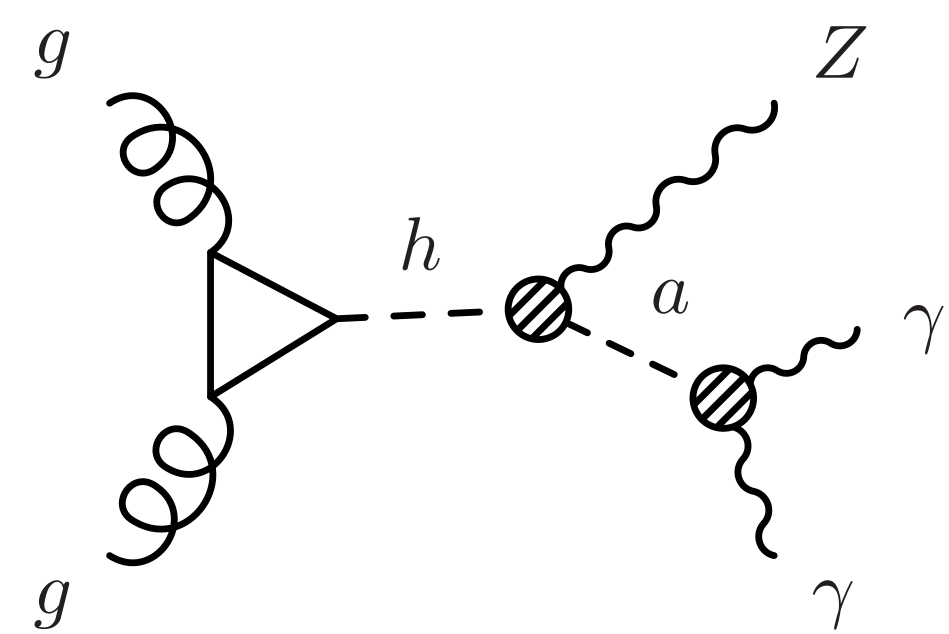
  - Muon $(g-2)_\mu$
  - Future Colliders
- Conclusions and Outlook



Muon $(g-2)_\mu$

- Persistent deviation

[Particle Data Group 2016]

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

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3σ

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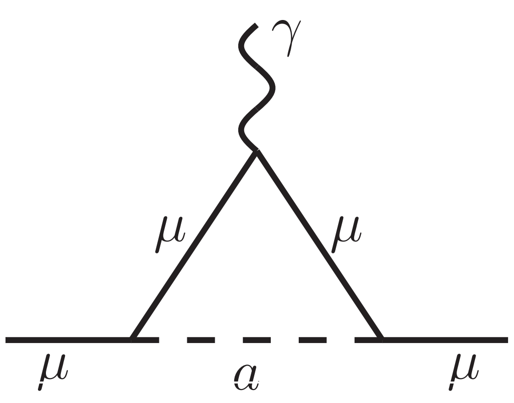

[Haber, Kane, Sterling: Nucl. Phys. B 161 (1979)]

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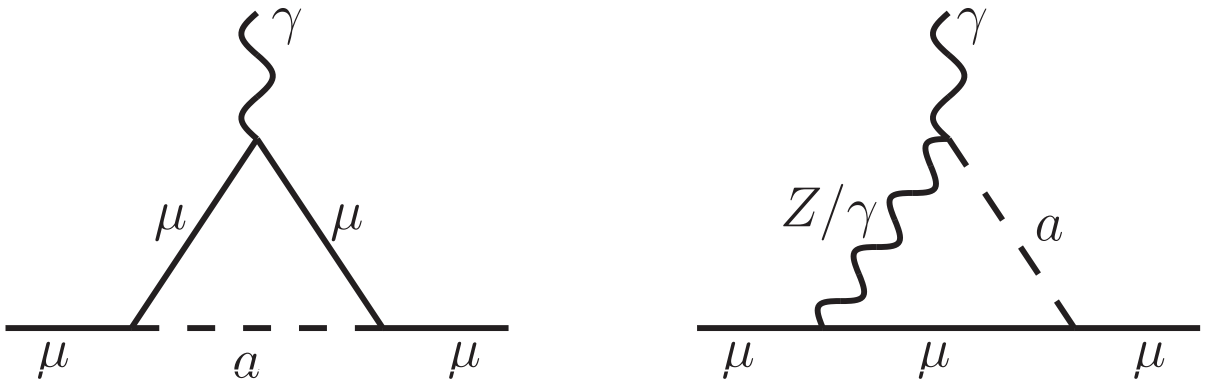

[Haber, Kane, Sterling: Nucl. Phys. B 161 (1979)]

[Chang, Chang, Chou, Keung: 0009292]
[Marciano, Masiero, Paradisi, Passera: 1607.010122]

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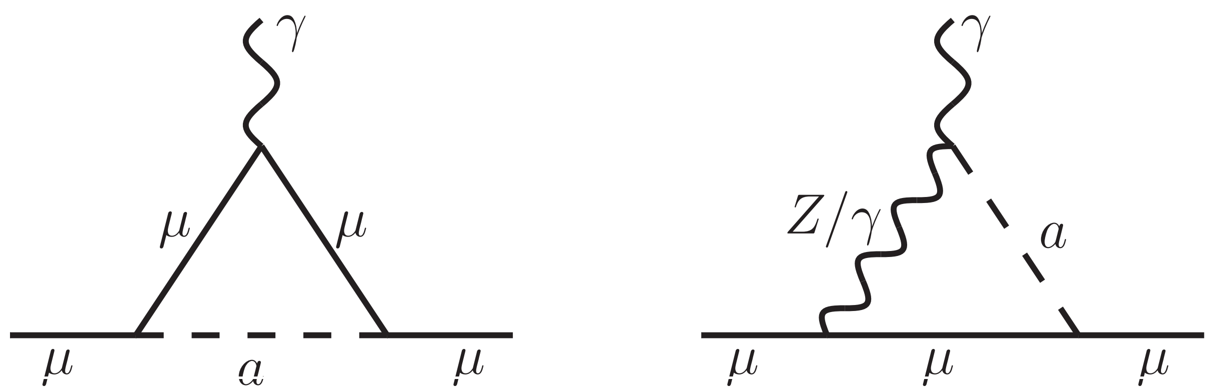

$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} + \delta_2 + 2 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right]\right.$$
$$\left.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

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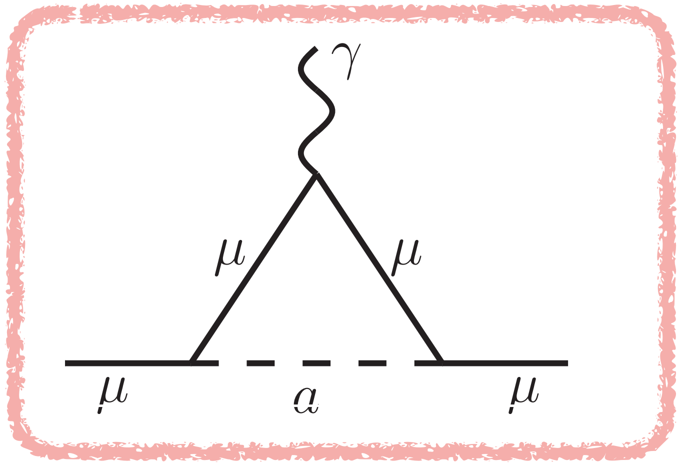

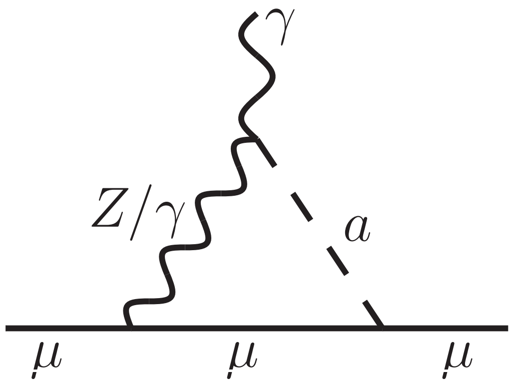

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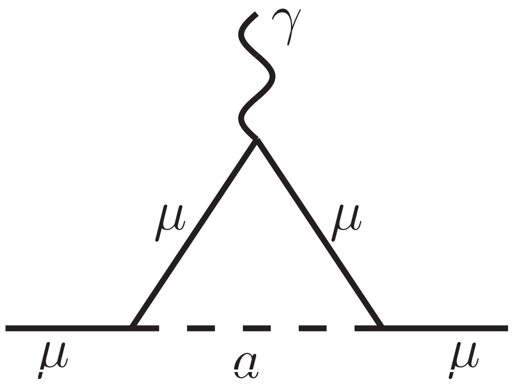

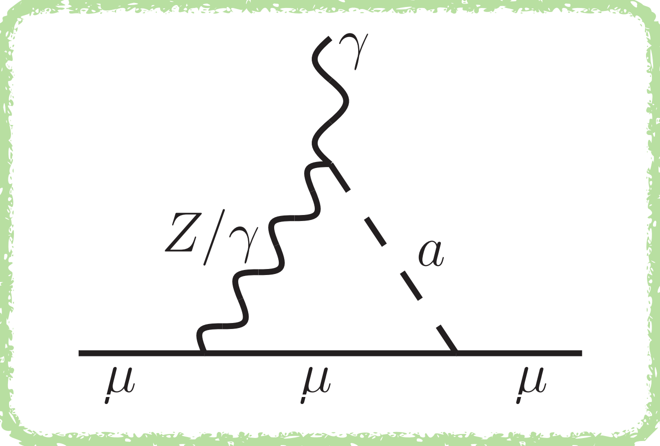

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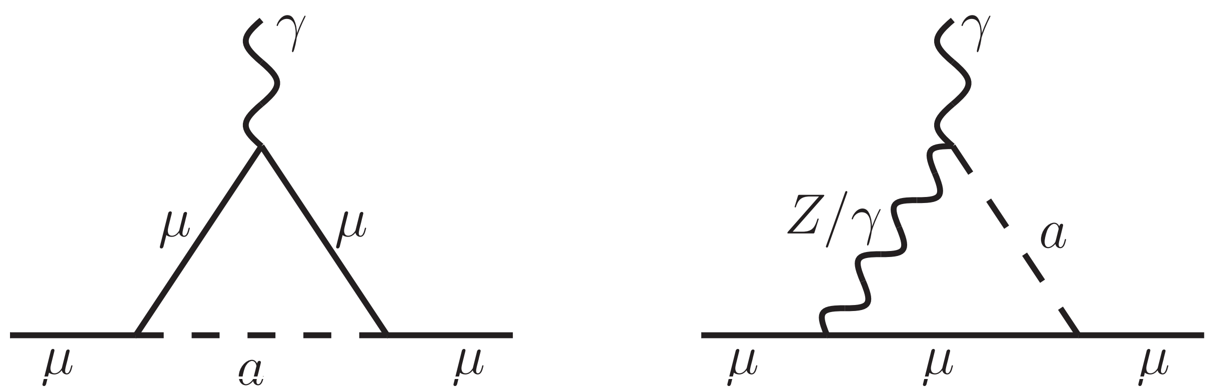

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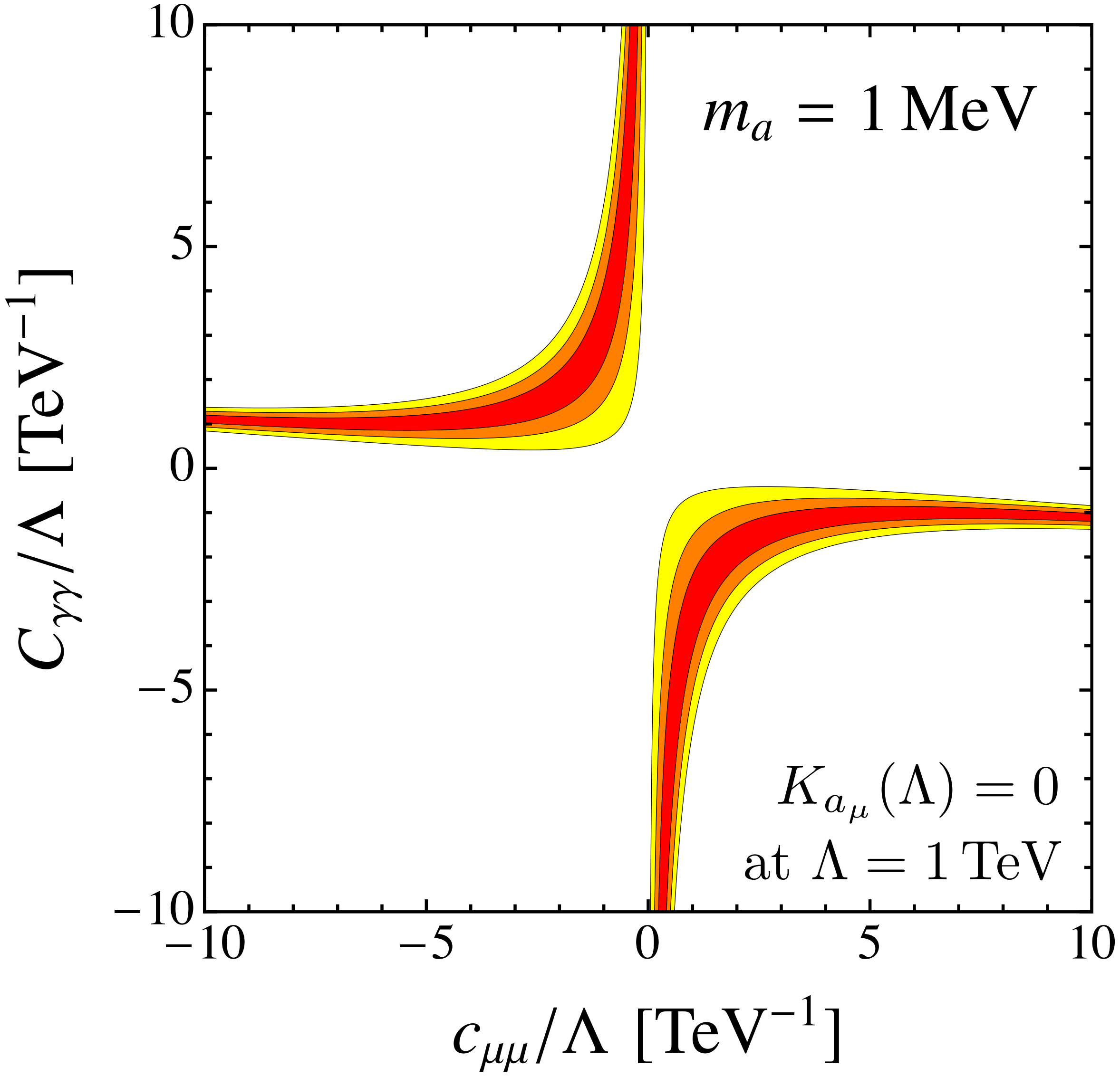
$$\mathcal{L}_{\text{eff}}^{D=6} \ni -K_{a_\mu}\,\frac{e m_\mu}{4\Lambda^2}\,\bar\mu\,\sigma_{\mu\nu}F^{\mu\nu}\mu$$

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

$h_2(0) = 0$ $\quad$ $h_2(x) \approx (\ln x + \frac{1}{2})$

Muon $(g-2)_\mu$

- Allowed parameter space



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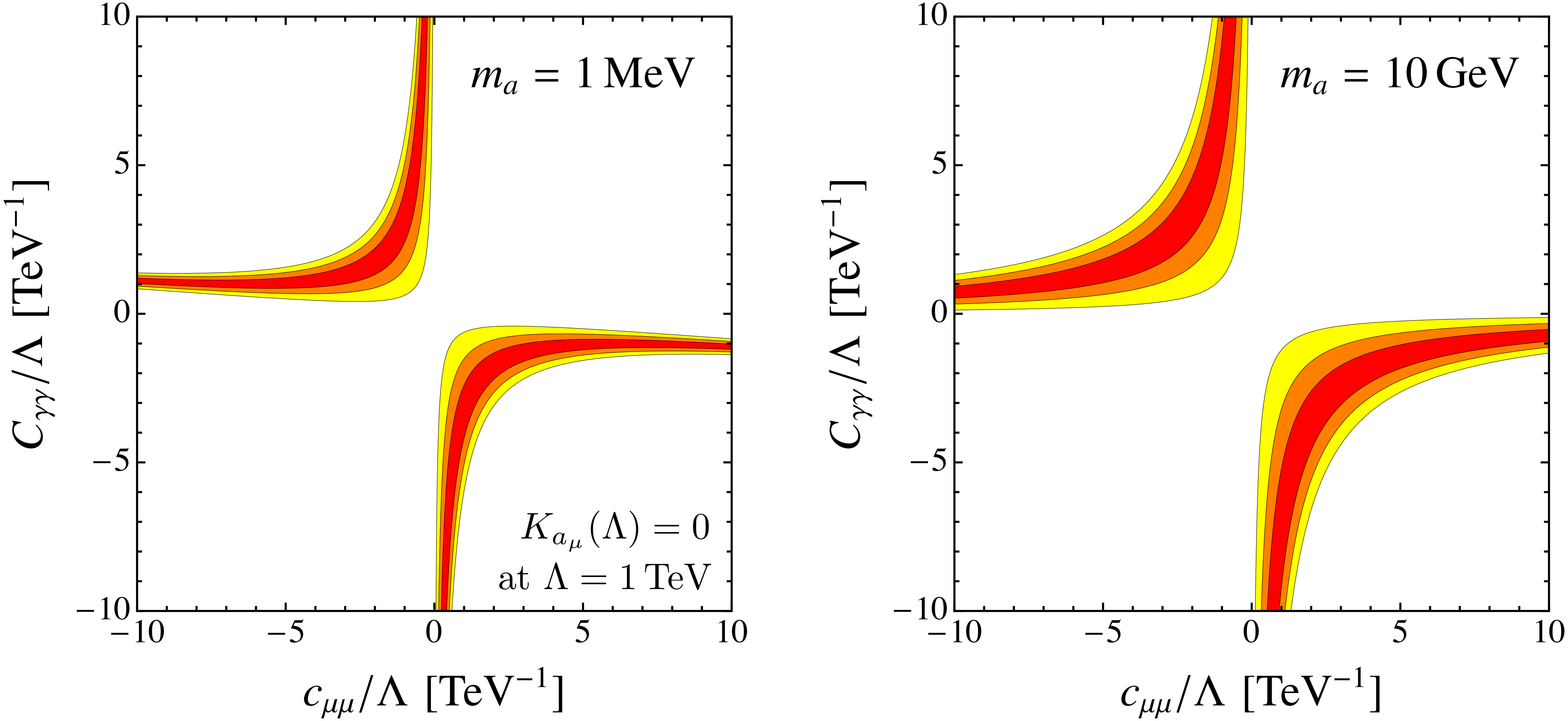

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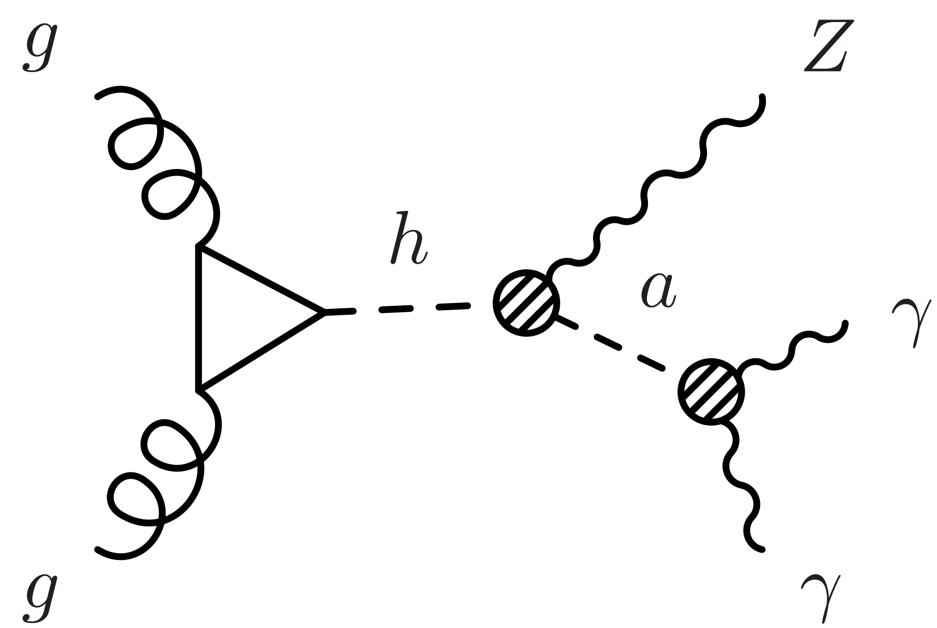


Conclusions

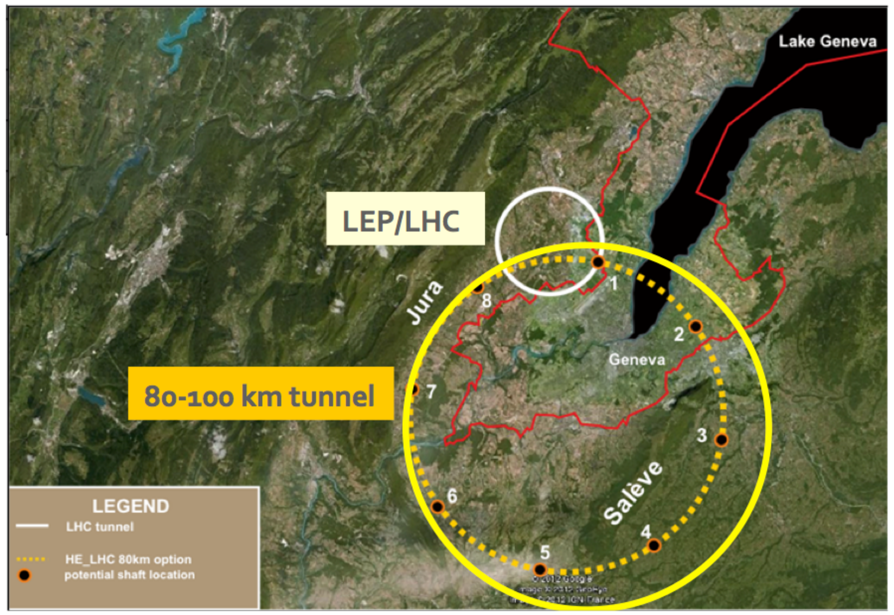
- Rare Higgs decays provide a powerful way to probe the existence of ALPs with masses between 30 MeV and 60 GeV and couplings suppressed by the 1 - 100 TeV scale
- Connection to low-energy physics probes such as $(g-2)_\mu$

Outlook

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

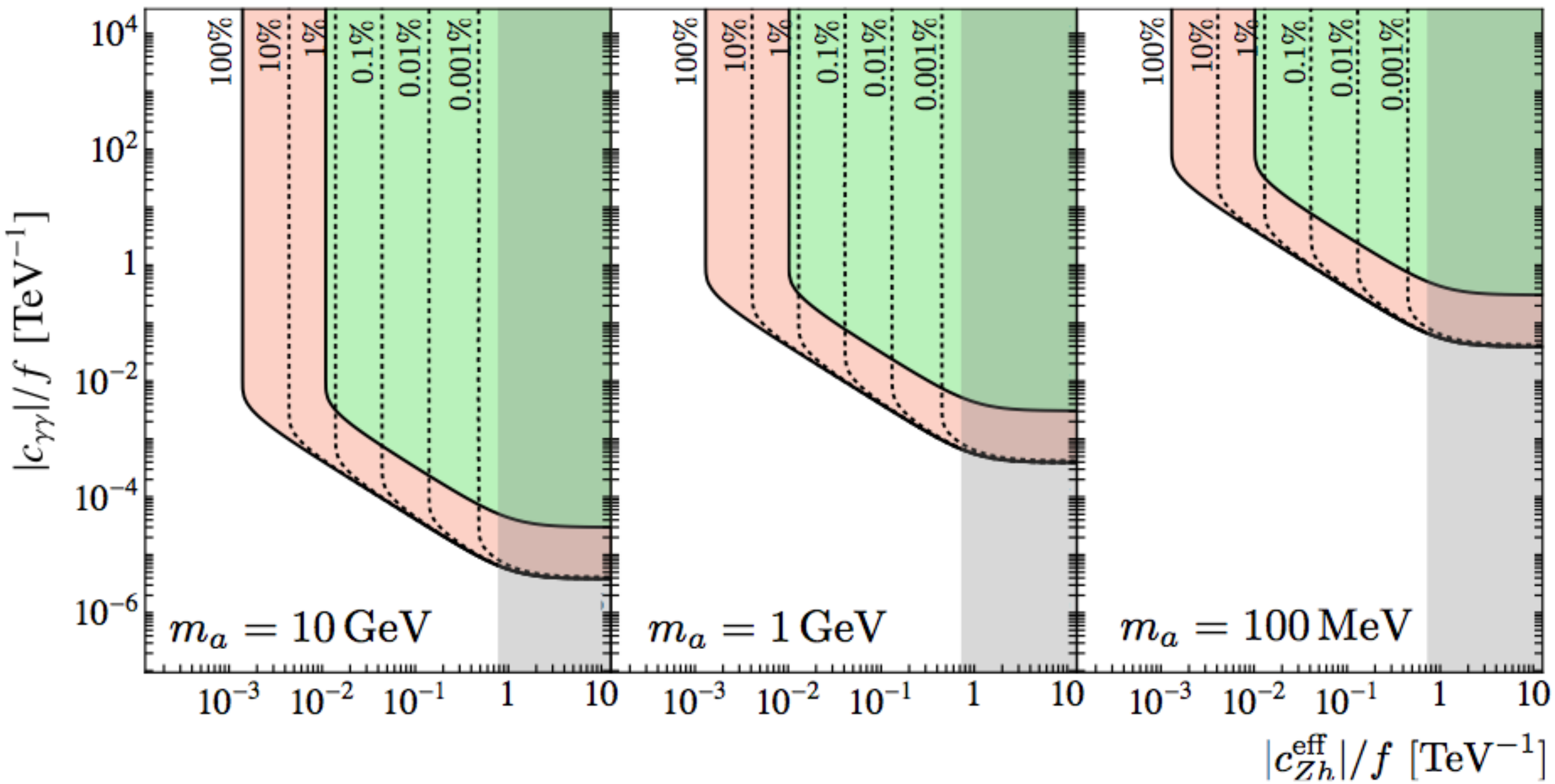
Backup

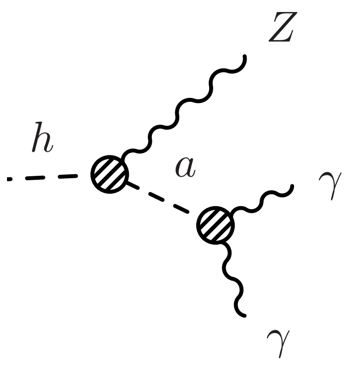
Parameter space at the FCC-ee



[arXiv:1308.6176]

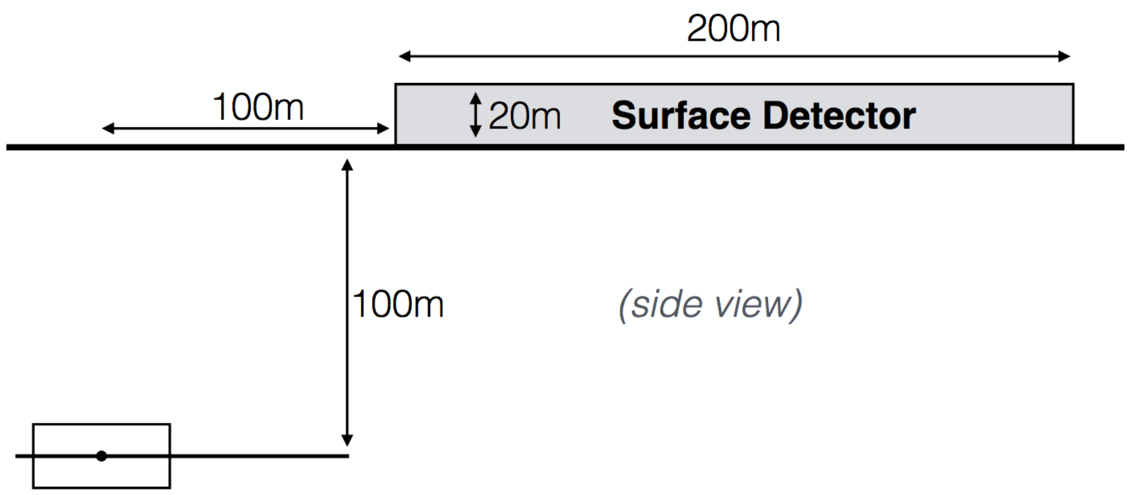
- e^+e^- collider
- 240 and 350 GeV
- 3 million Higgses



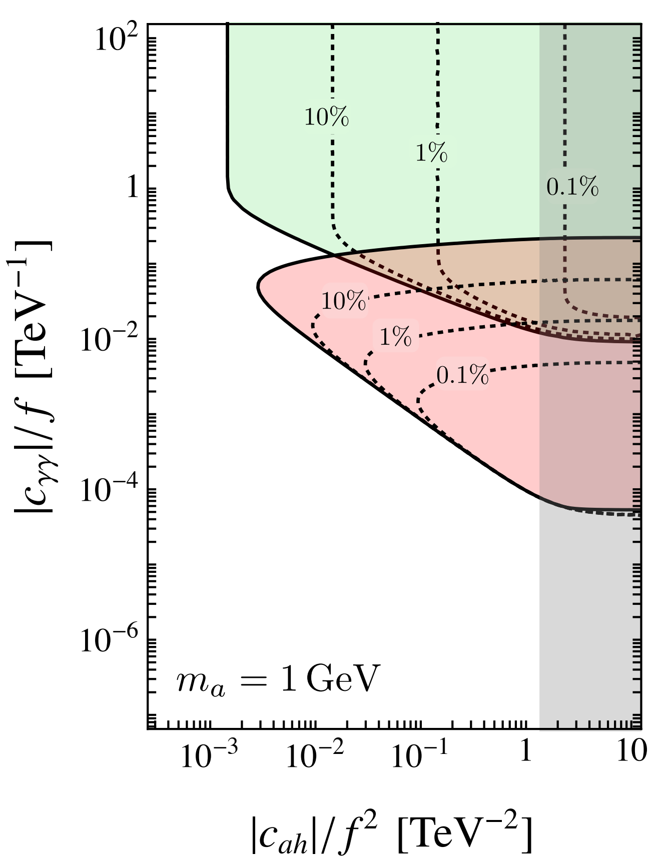


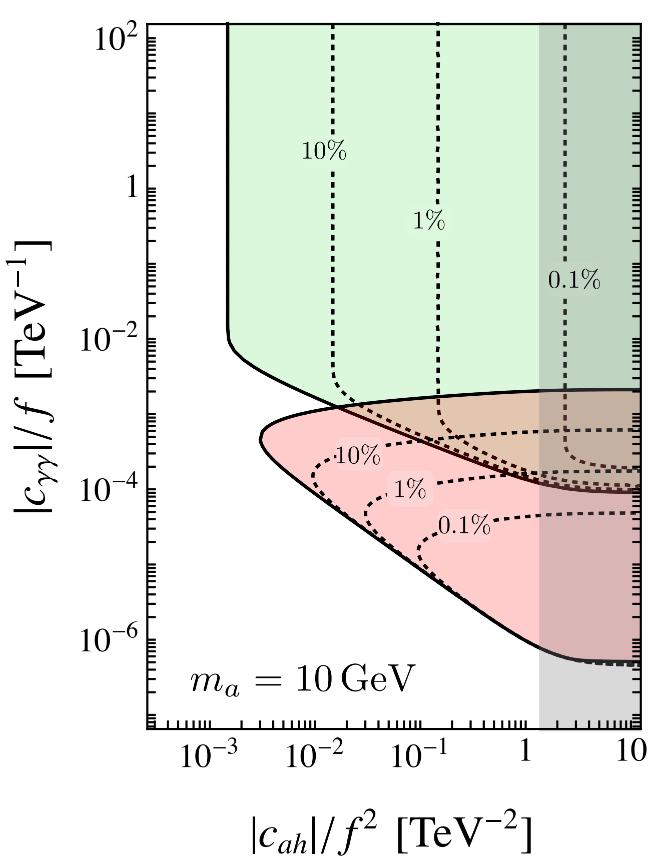
Parameter space at MATHUSLA

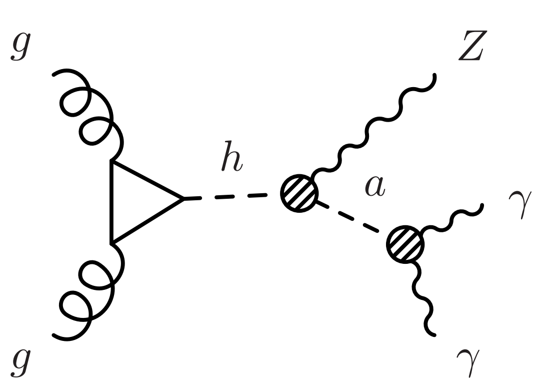
[Chou, Curtin, Lubatti: 1606.06298]



- Long-lived particles at LHC







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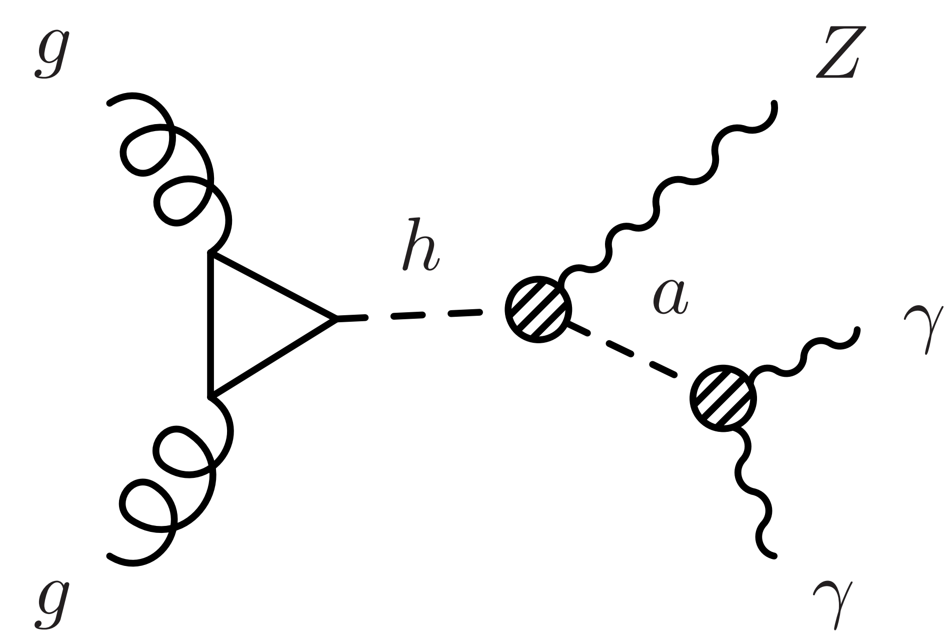
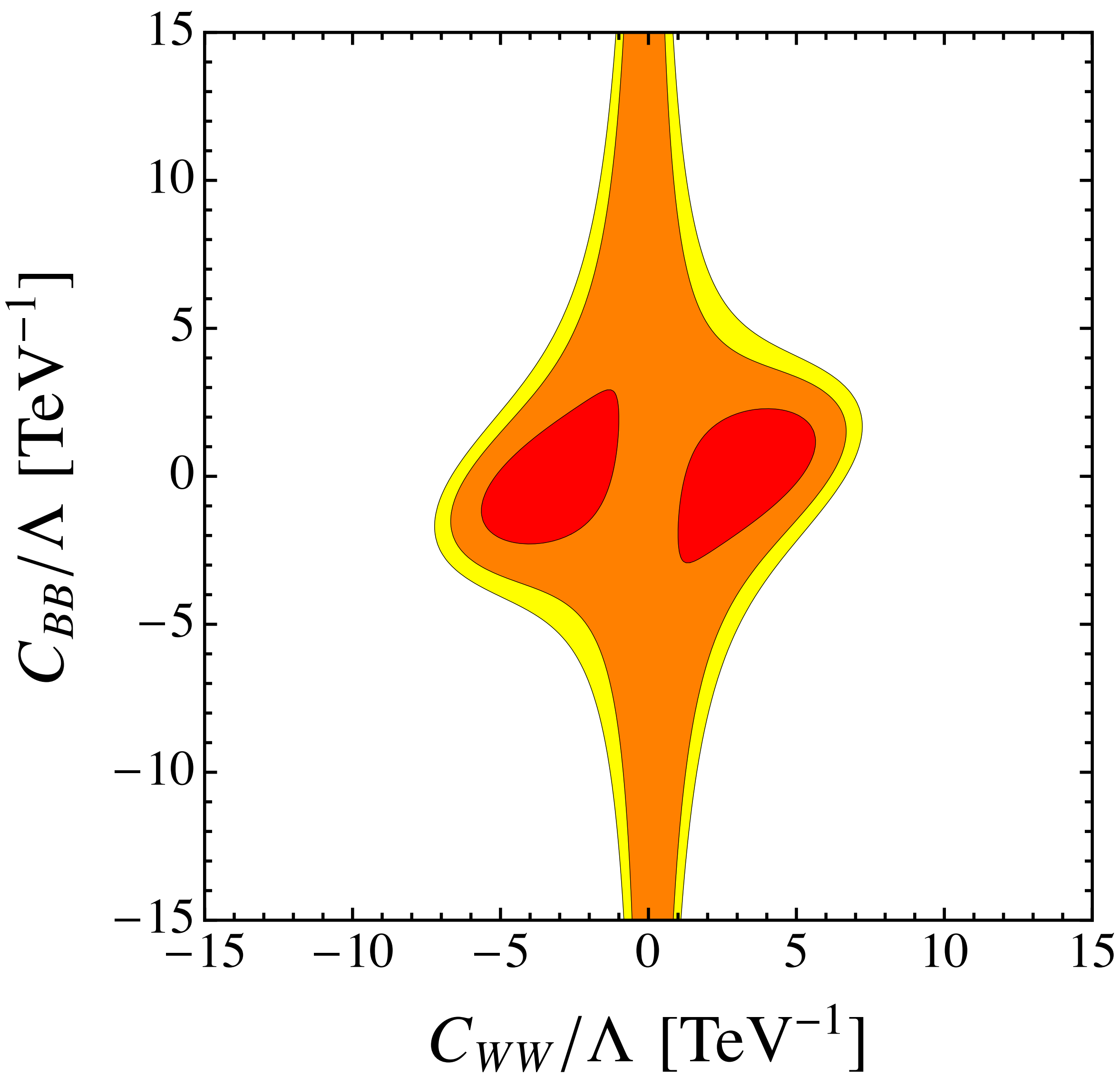


Electroweak precision tests

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

[Baak et al.: 1407.3792]



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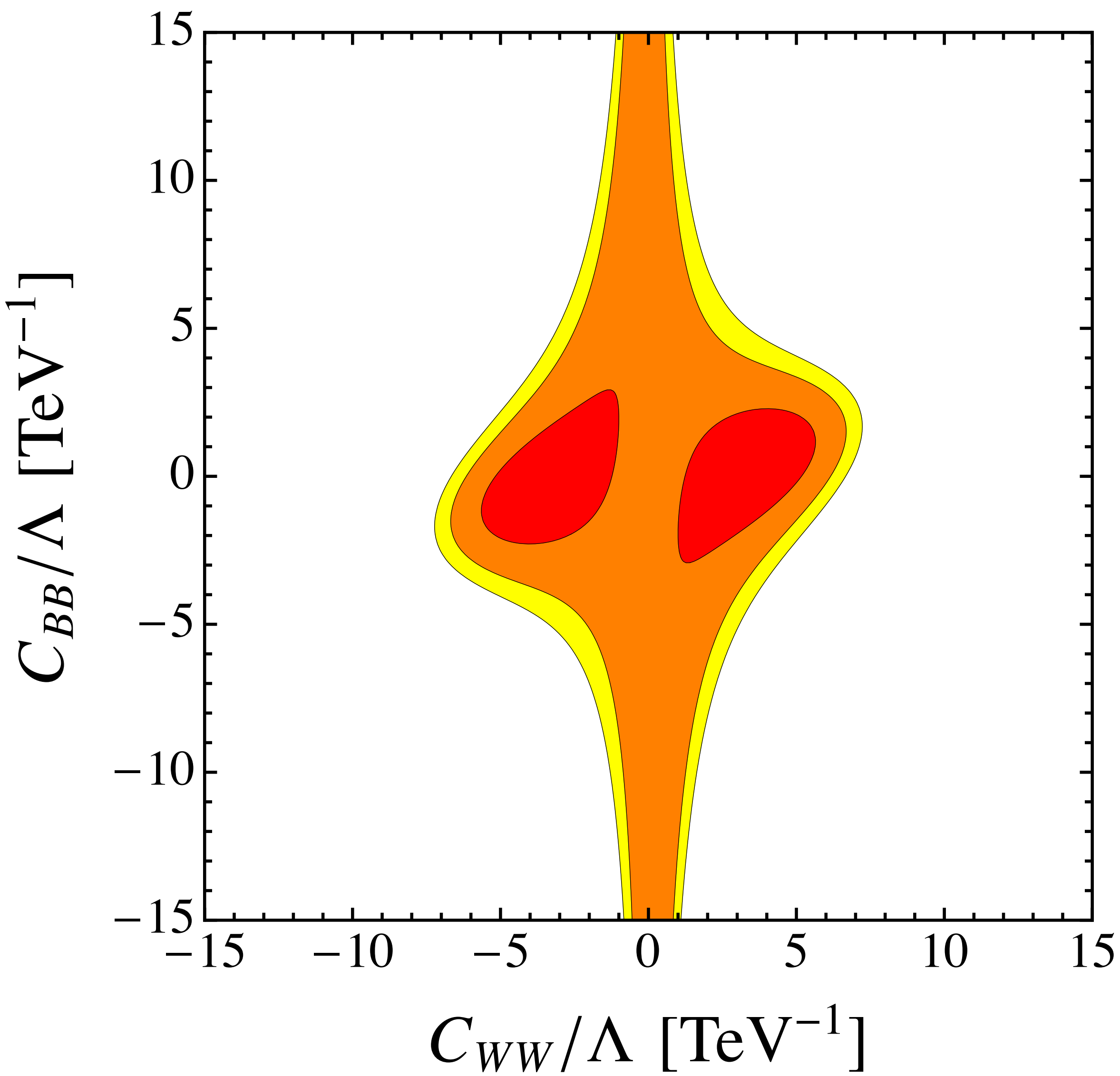
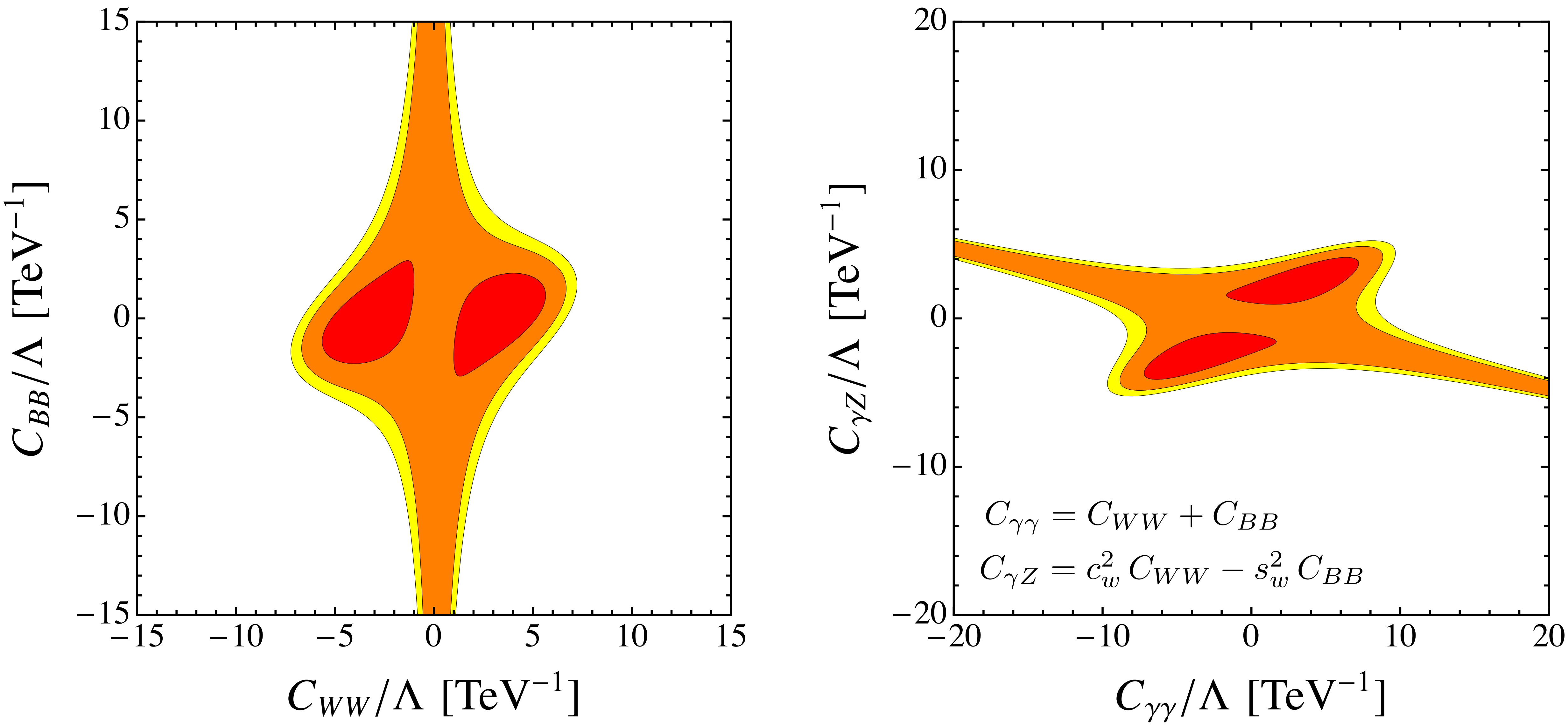


$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$
$$C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB}$$

Electroweak precision tests

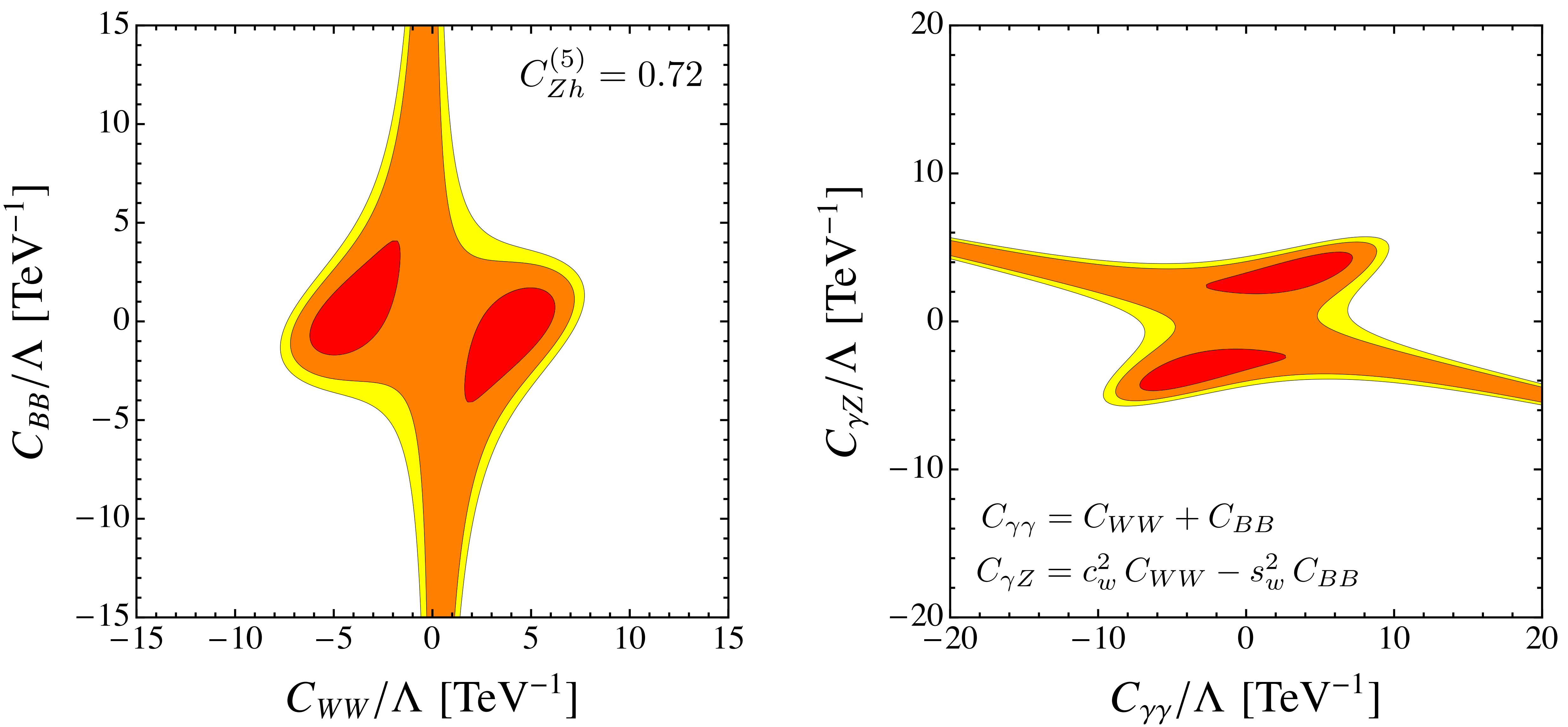
- Allowed parameter space for $C_{Zh}^{(5)} = 0$ [Baak et al.: 1407.3792]



Electroweak precision tests

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

[Baak et al.: 1407.3792]



Electroweak precision tests

- Measurement of OPAL at per-cent level
- Compatible with c_{WW} and c_{BB} of order ~30

[Abbiendi et al.: 0309052]

Electroweak precision tests

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[Blas, Cuichini, Franco, Mishima, Pierini, Reina, Silvestrini: 1608.01509]

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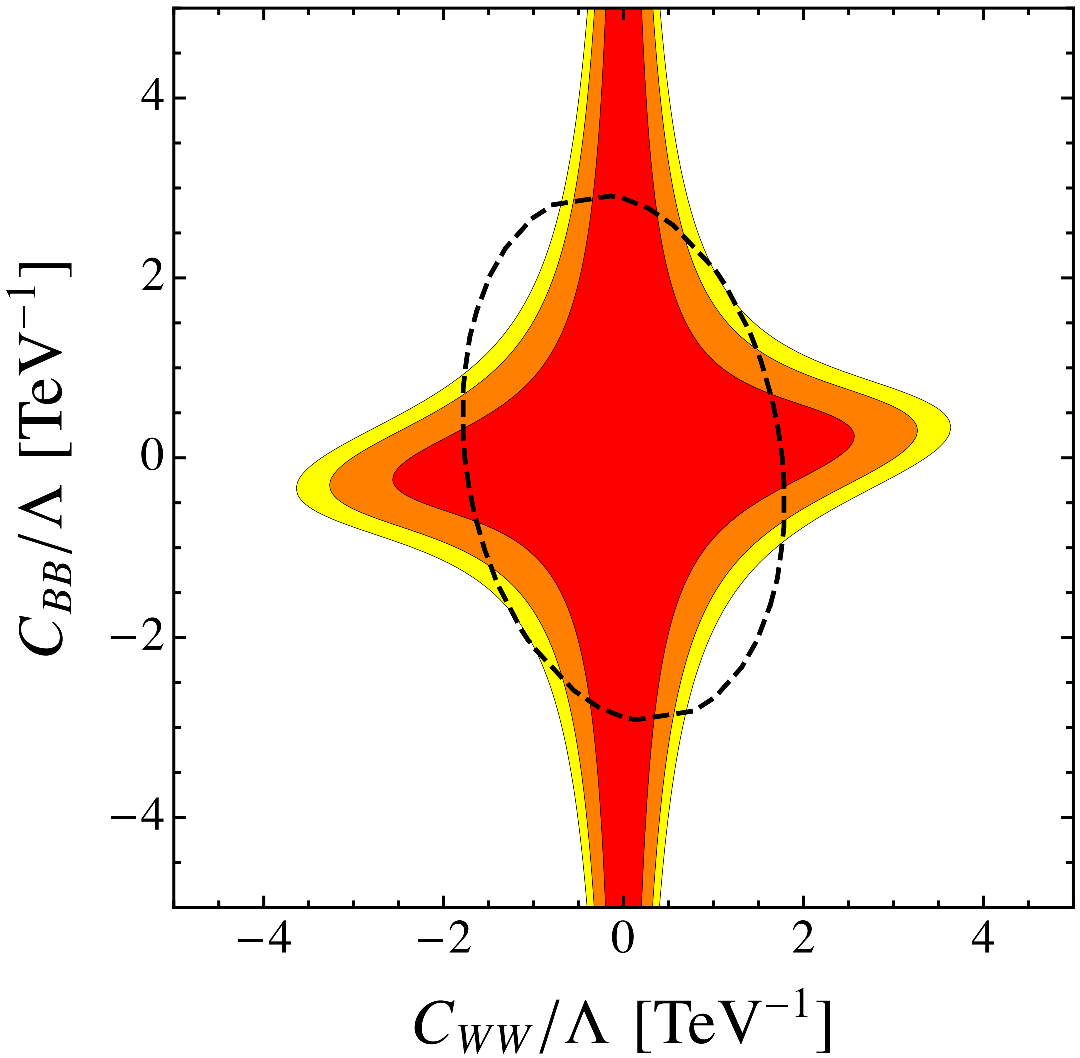

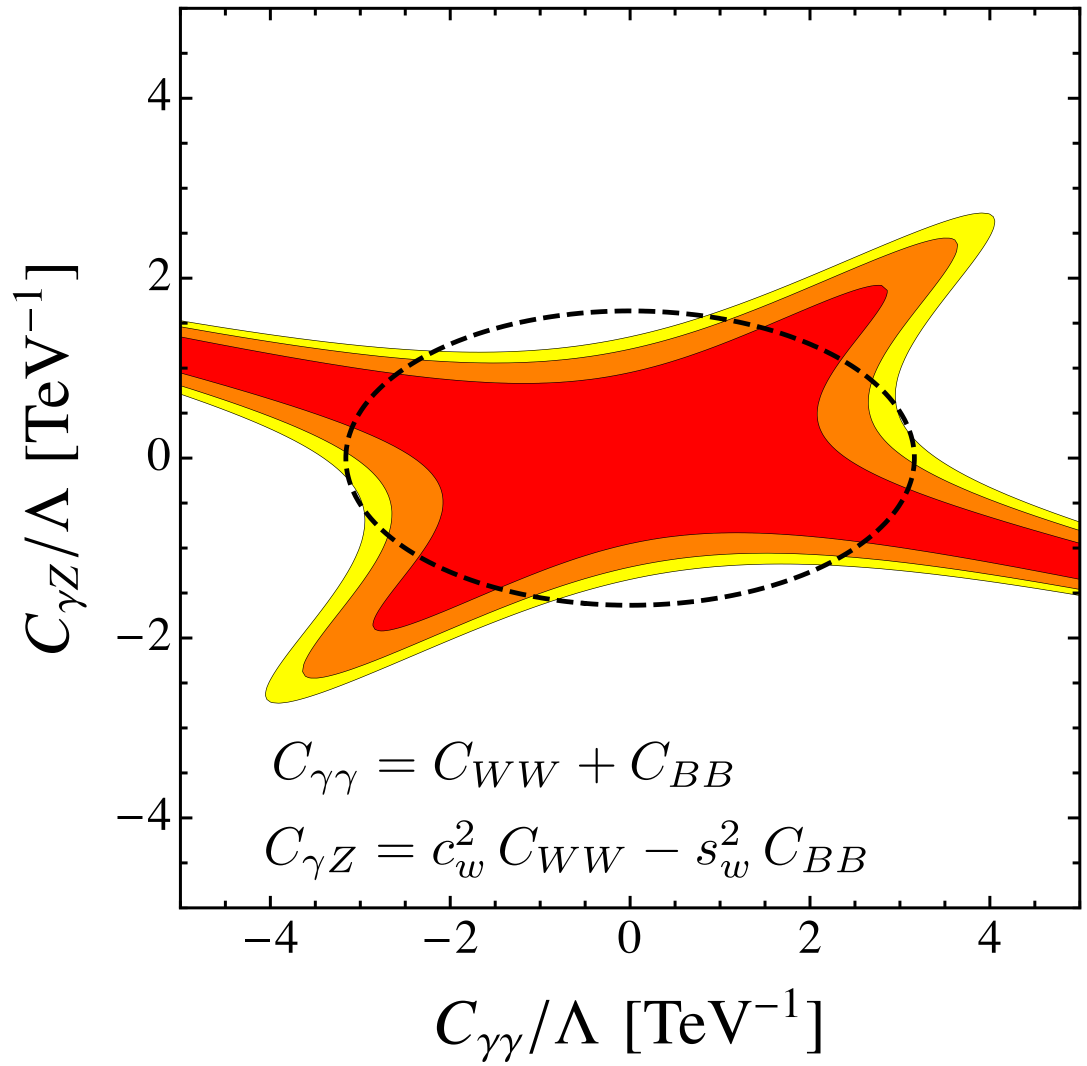

Probing the parameter space

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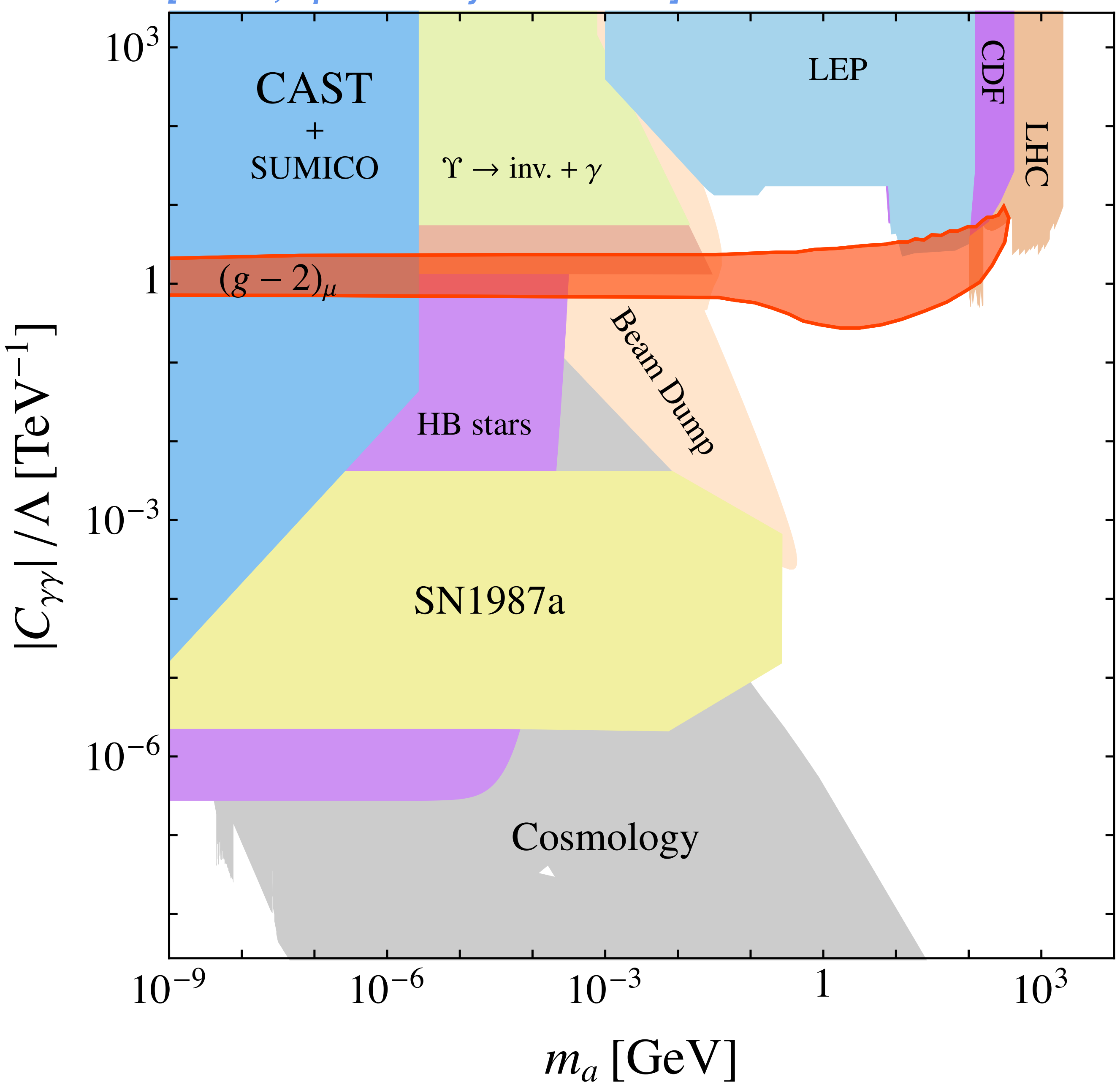
[Jäckel, Spannowsky: 1509.00476]



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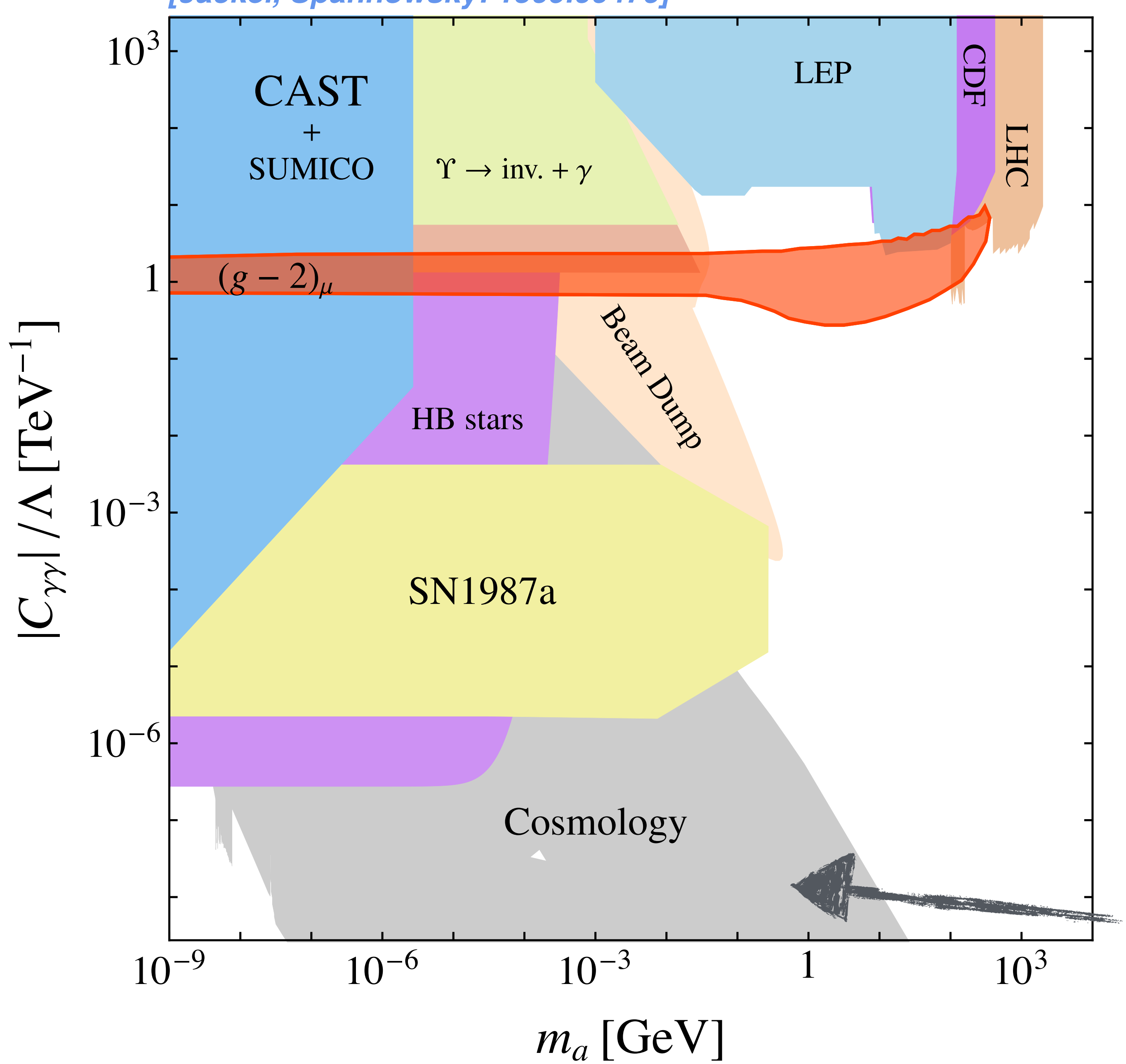
- Constraints on ALP mass and coupling to photons

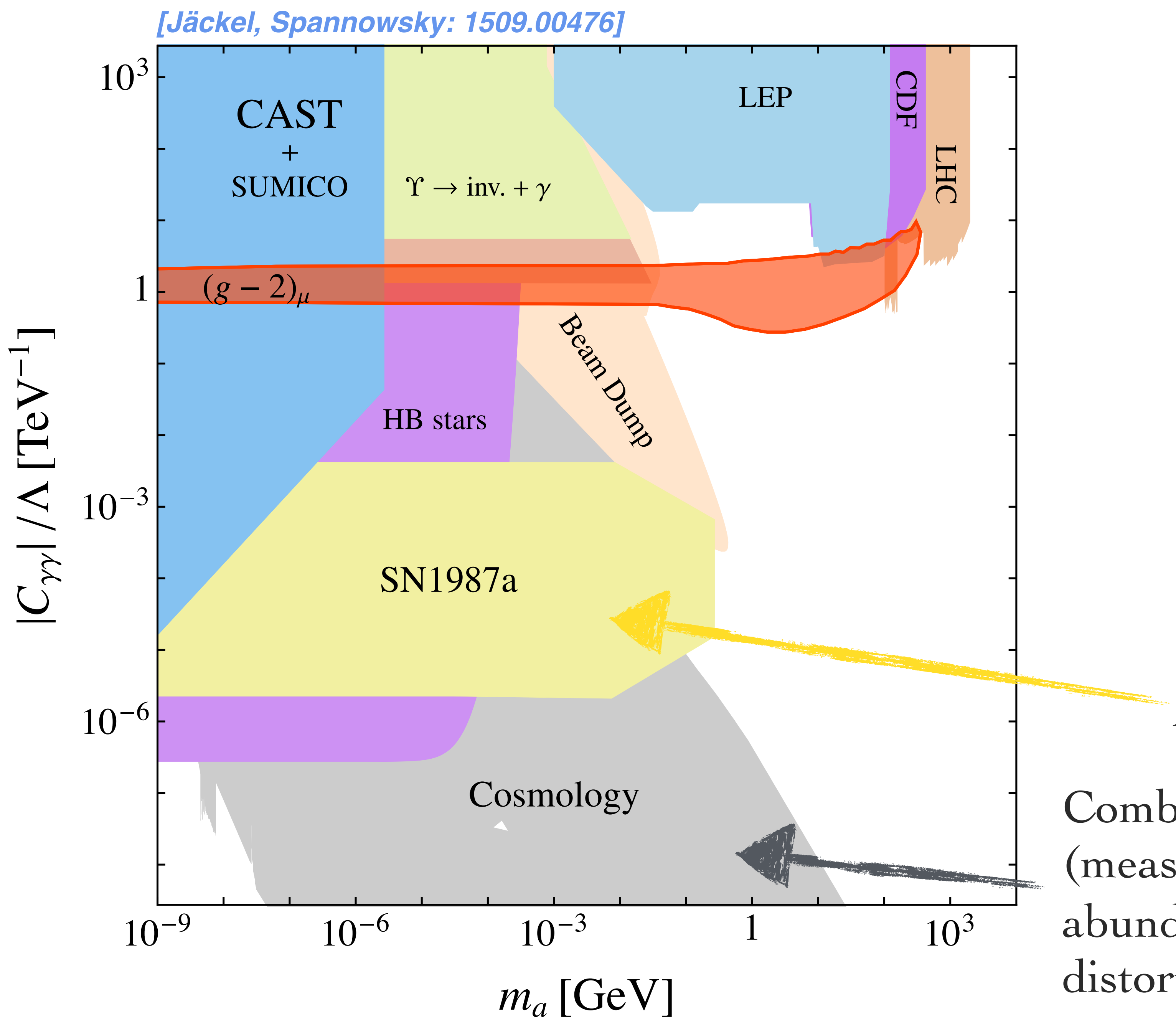
[Jäckel, Spannowsky: 1509.00476]



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

Probing the parameter space

- Constraints on ALP mass and coupling to photons



Absence of photon burst after supernova

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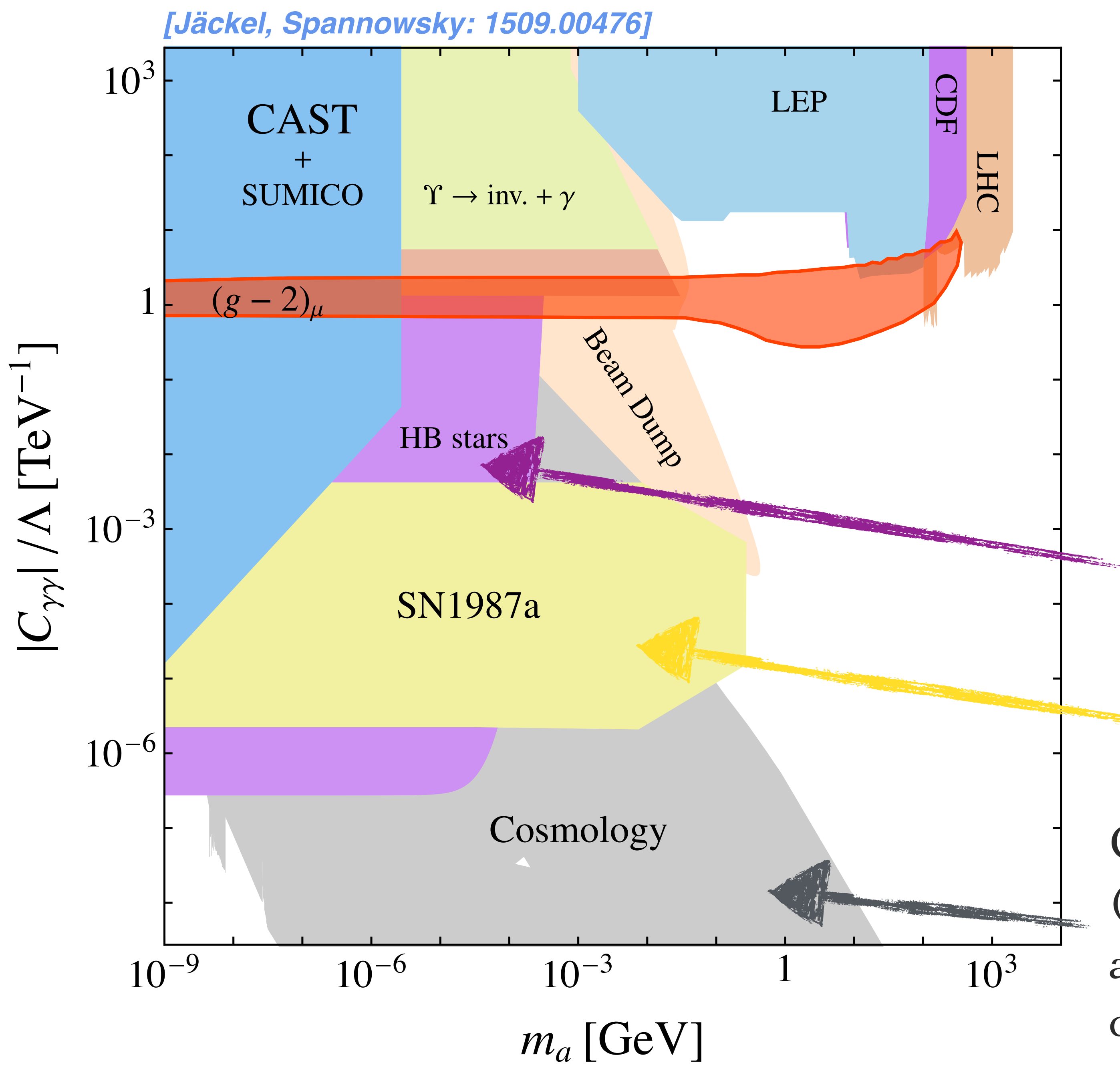

Energy loss of stars constrained by ratio of red giant to younger stars of horizontal branch

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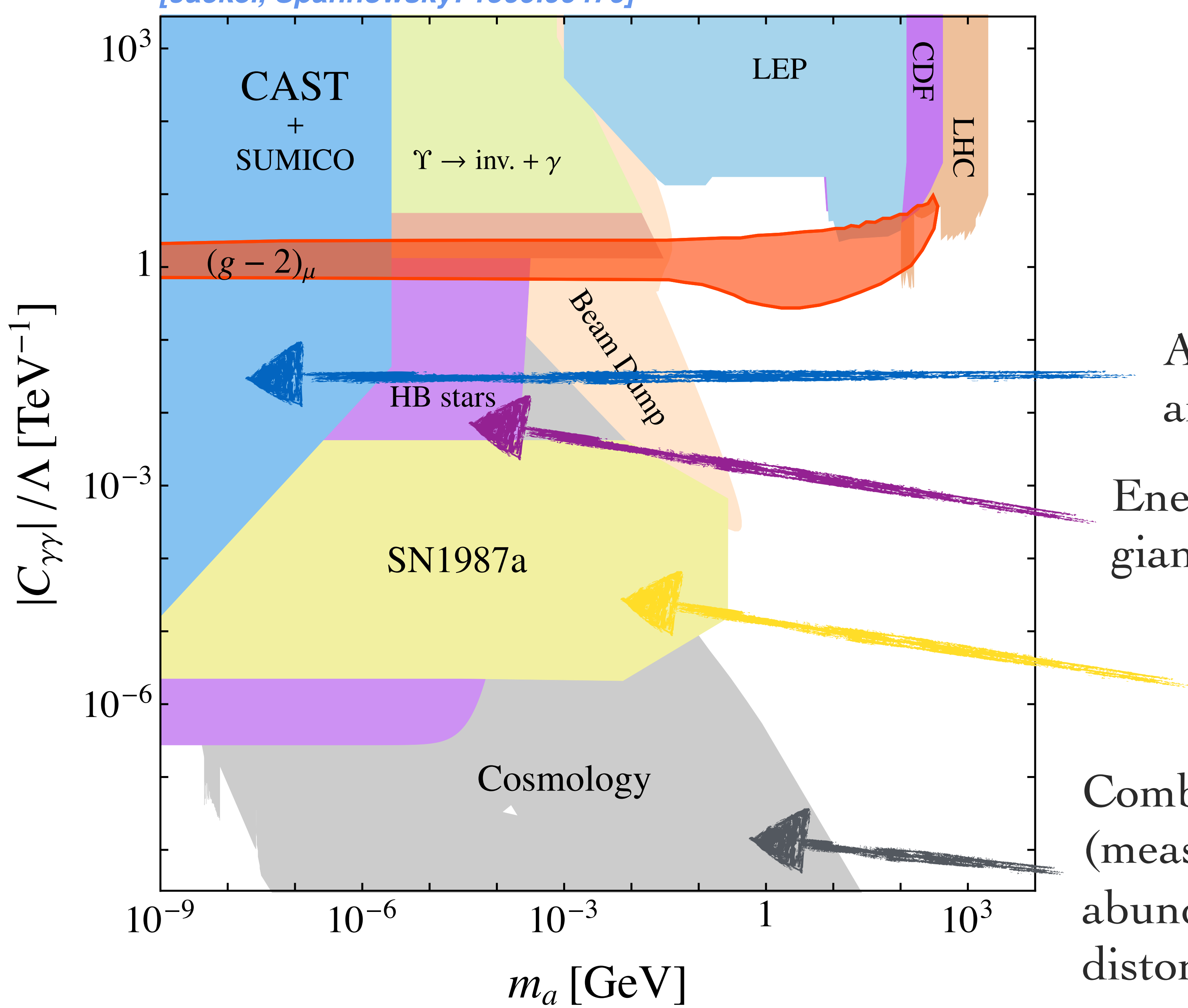

Axion helioscopes: Tokyo Axion Helioscope and CERN axion solar telescope

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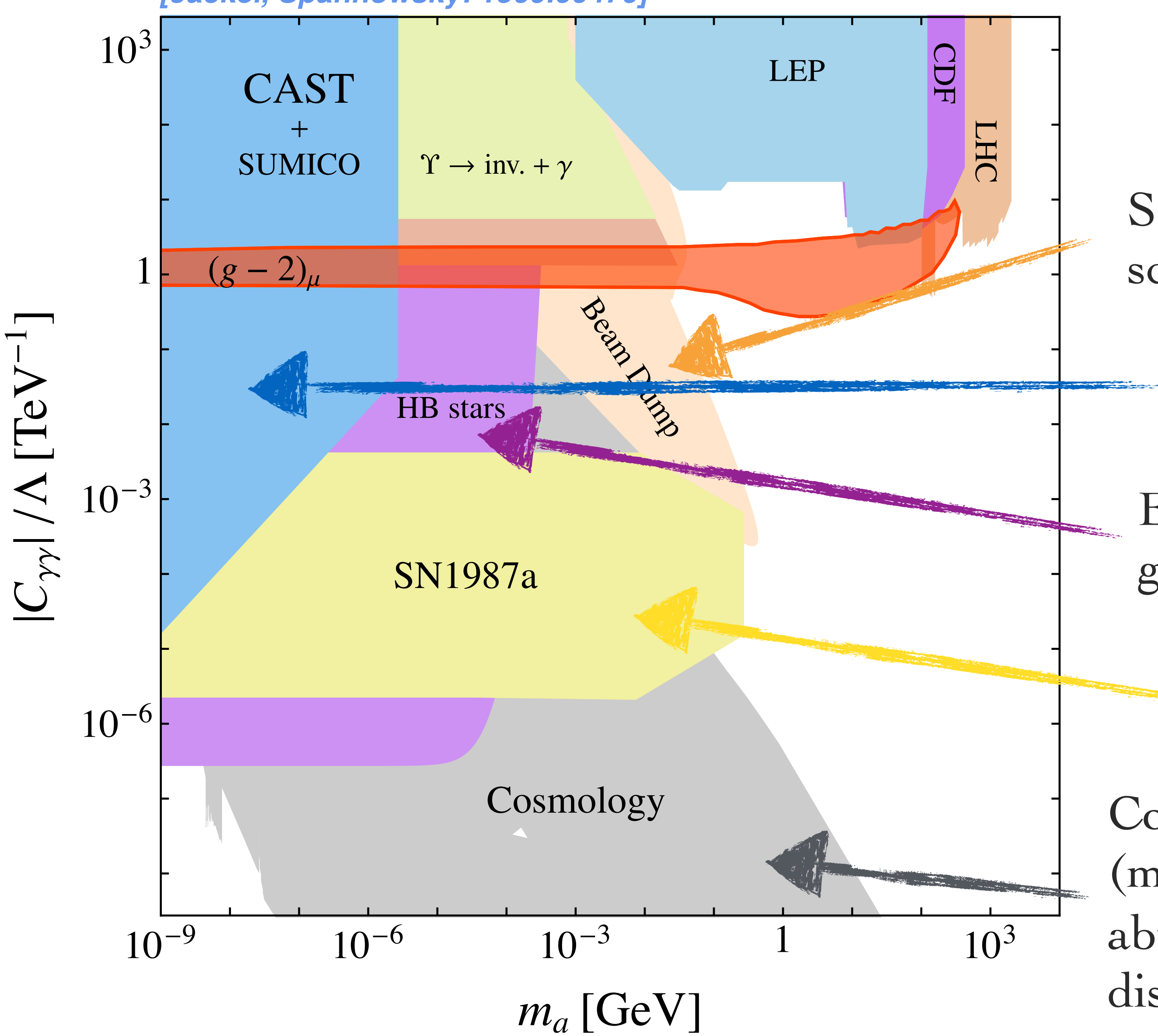

SLAC: measurement of photon - nuclei scattering (Primakoff effect)

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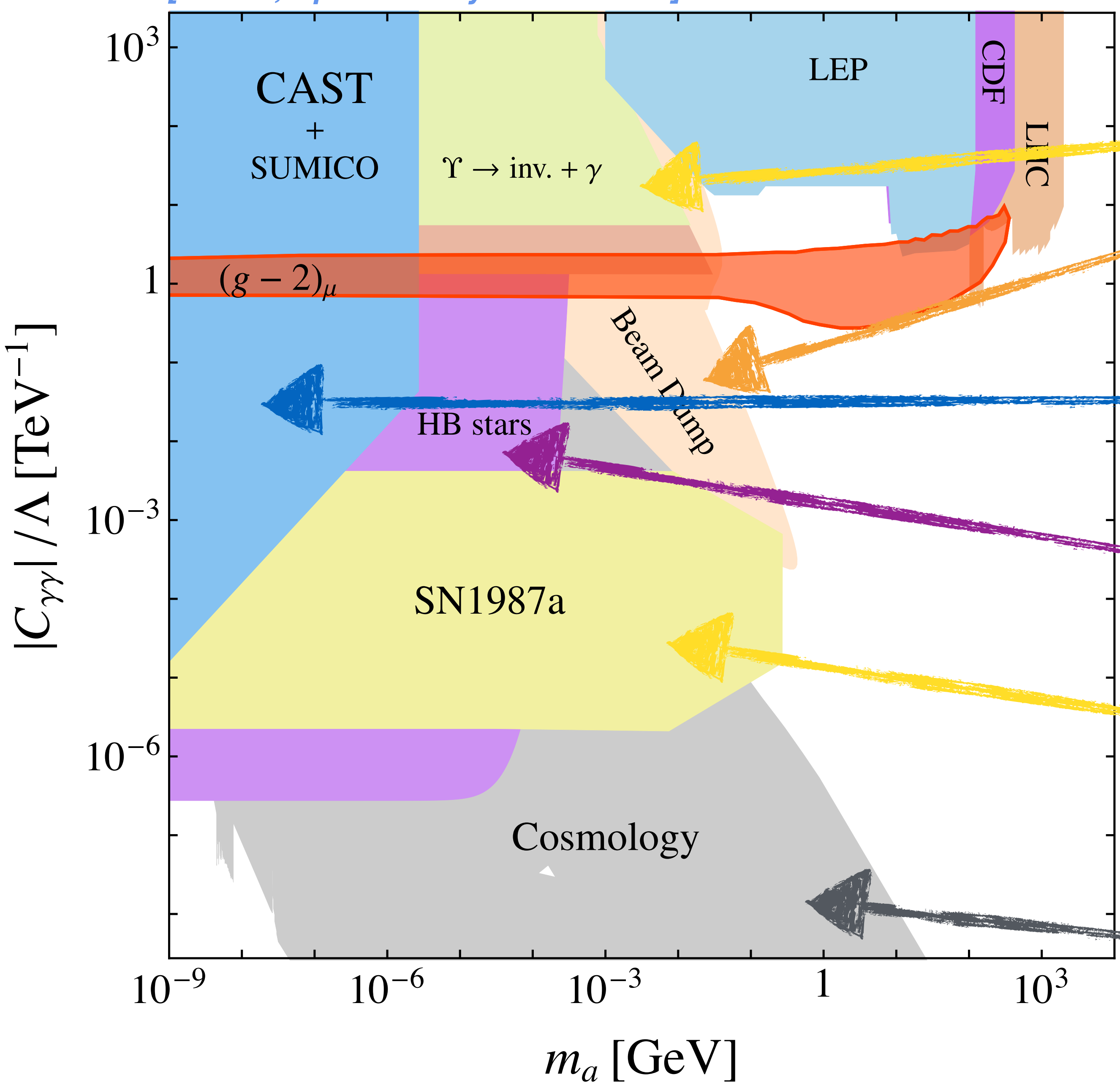

CLOE and BaBar: $\Upsilon \to a + \gamma$

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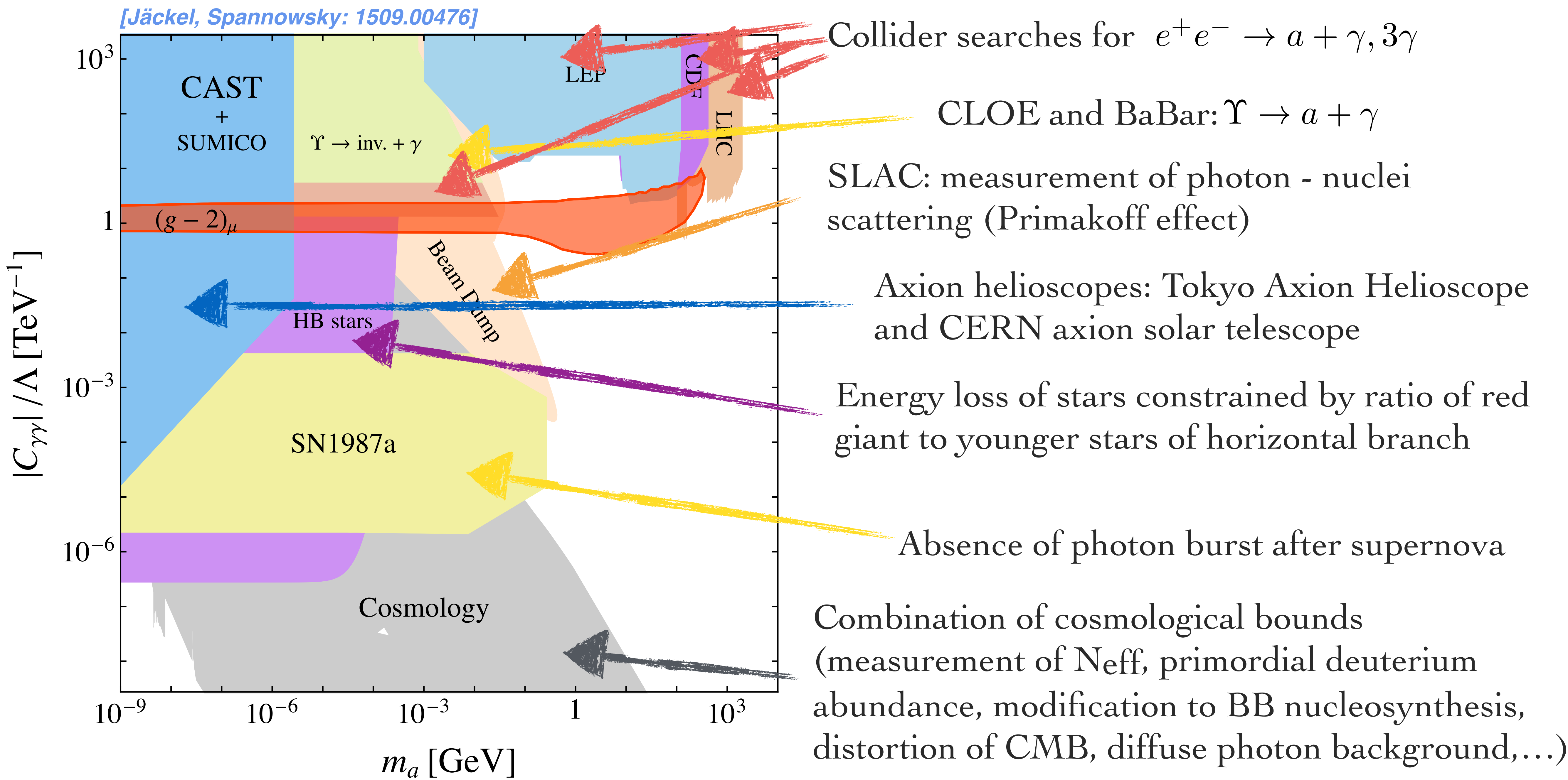
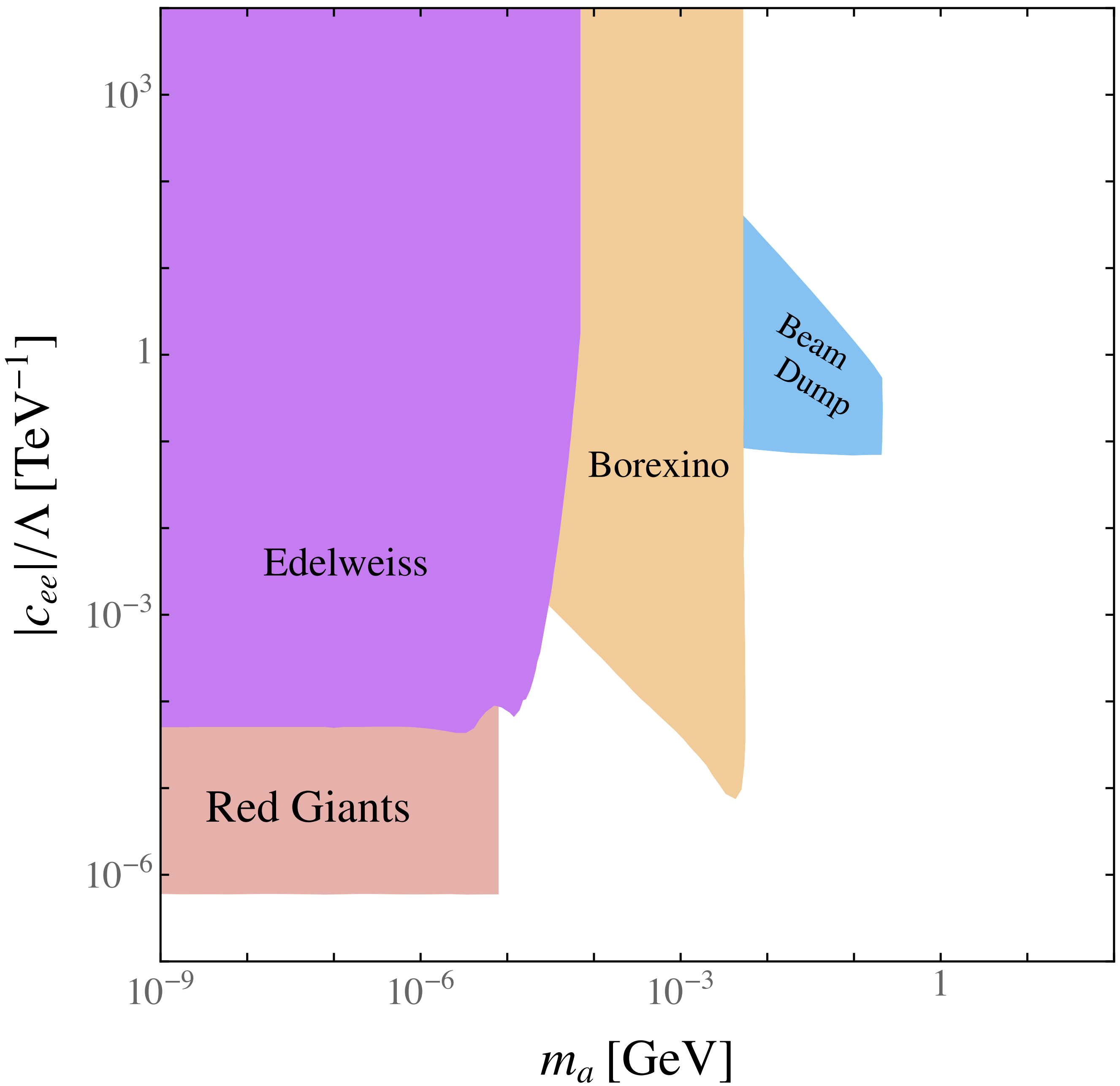


Probing the parameter space

- Constraints on ALP mass and coupling to electrons



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

Probing the parameter space

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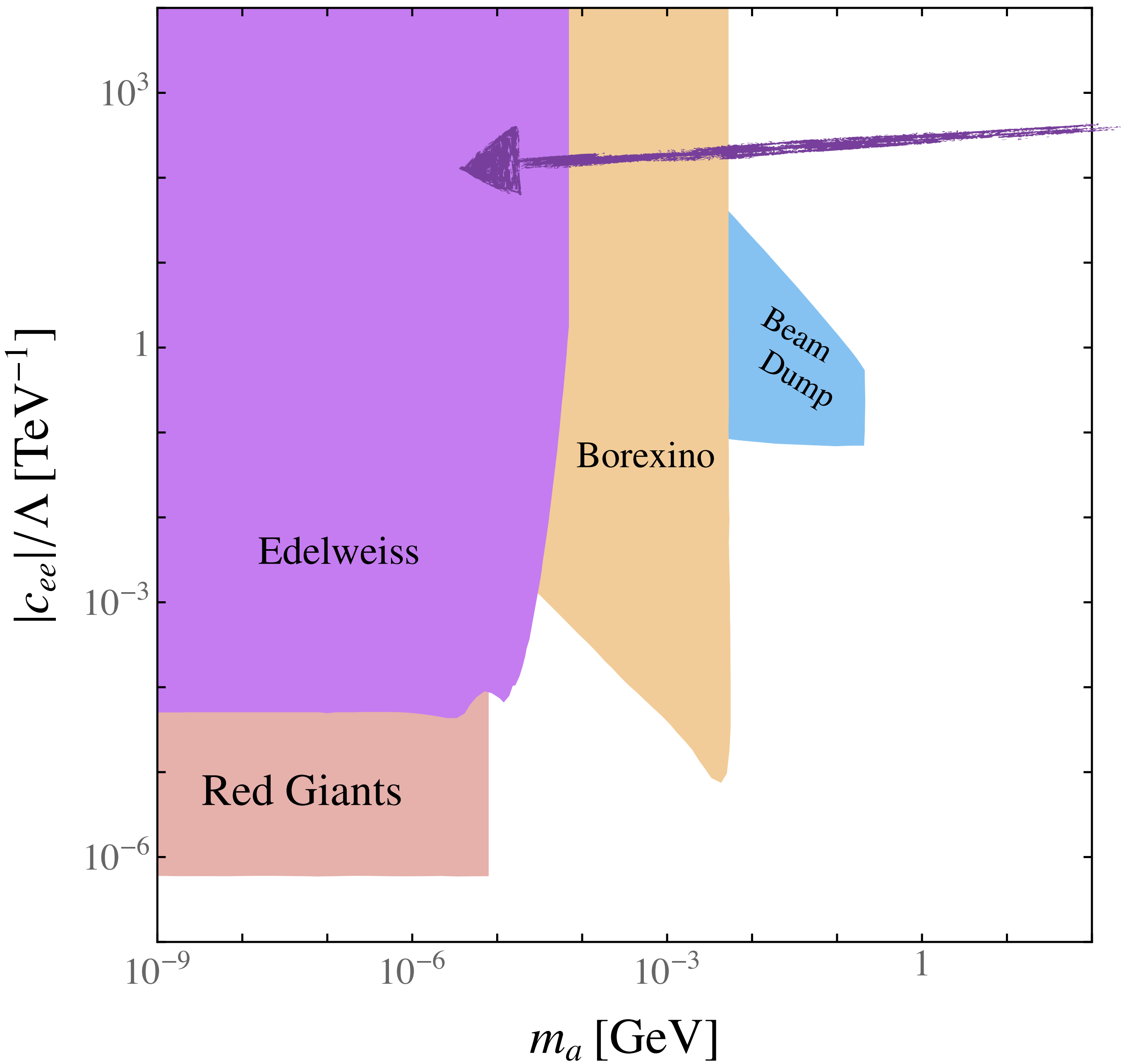

Low energy electron recoils of solar axions

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[Essig, Harnik, Kaplan, Toro: 1008.0636]

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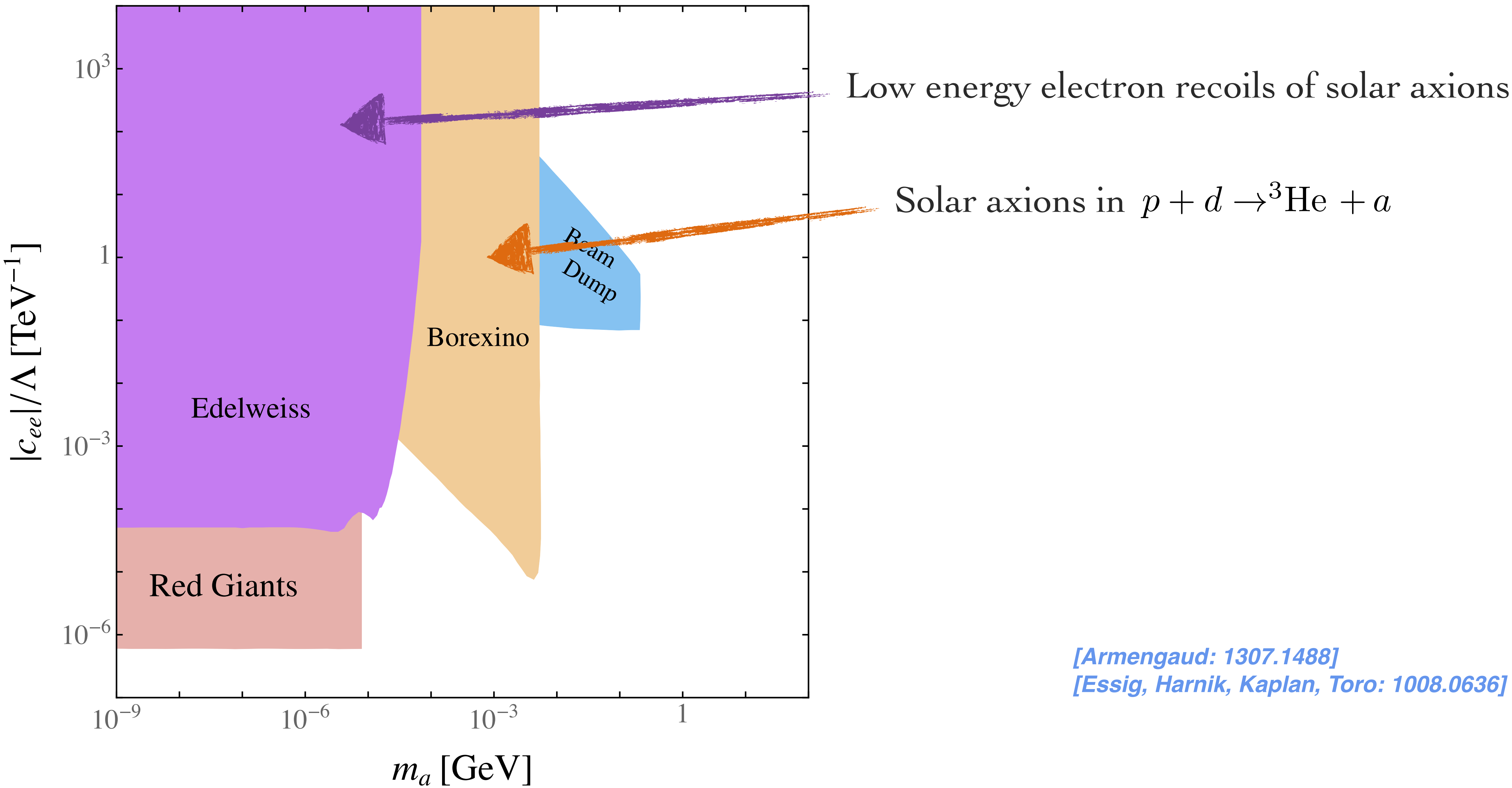

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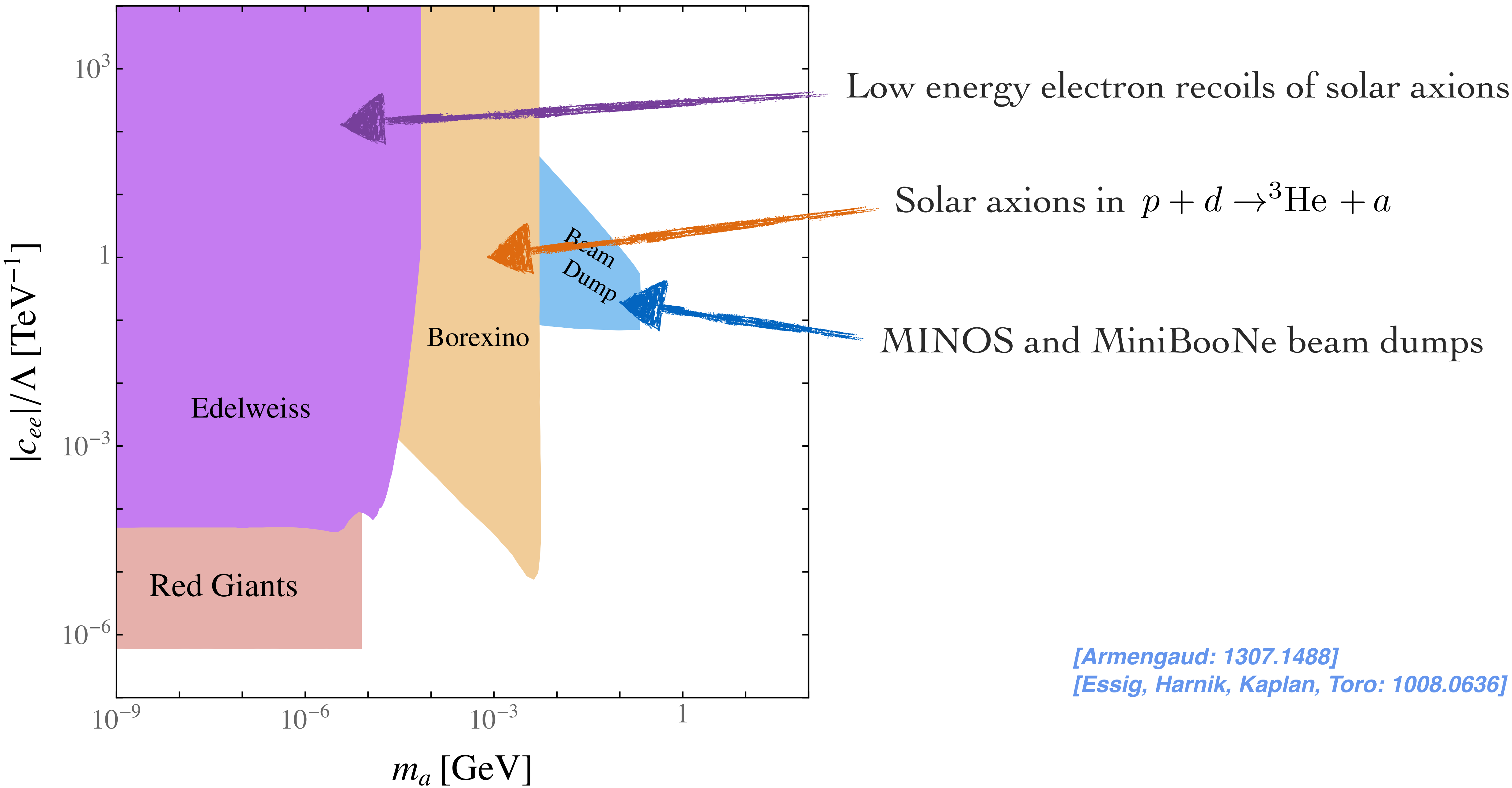

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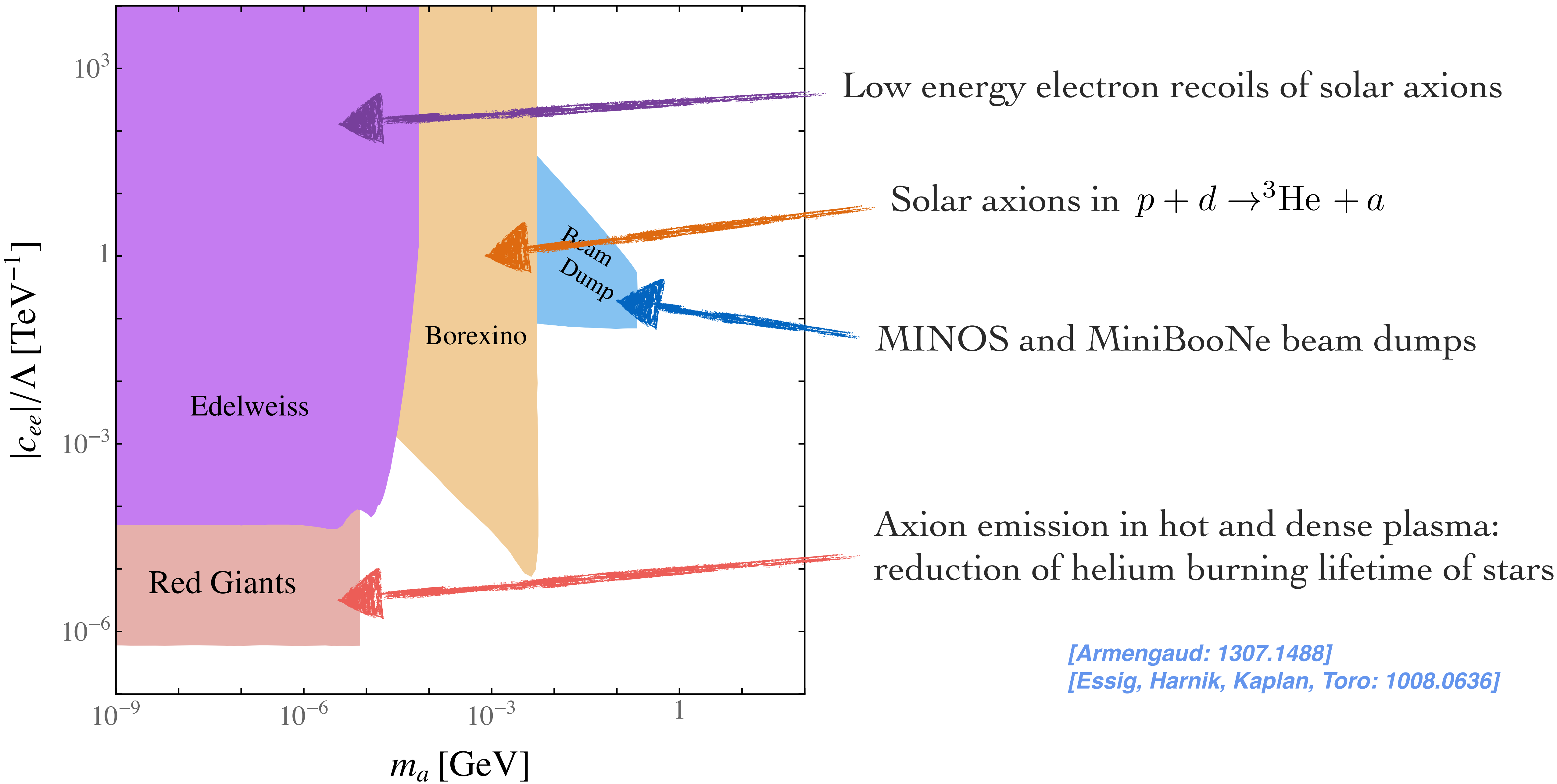

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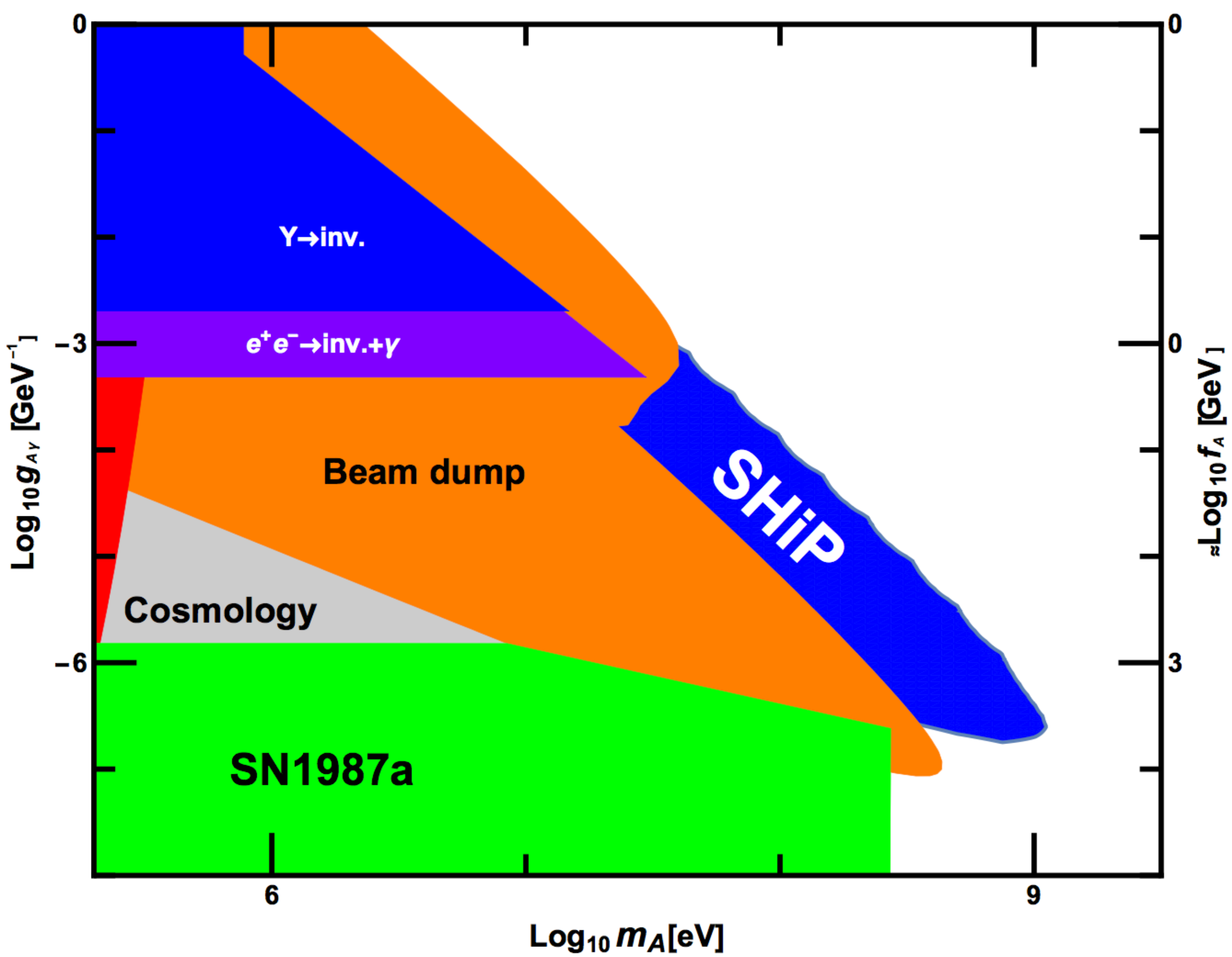
SHiP expected reach

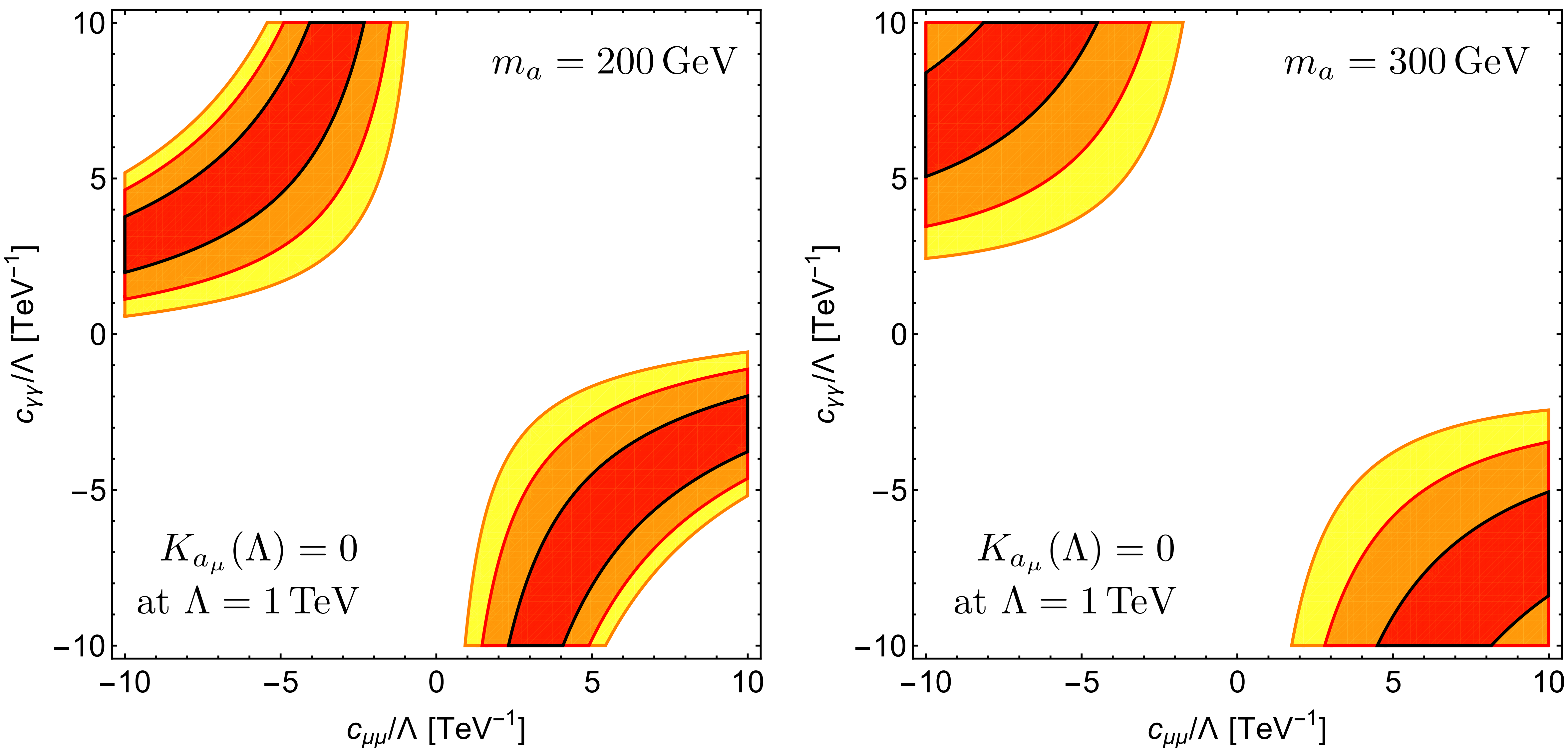
- Fixed target facility at CERN SPS (Search for Hidden Particles)



[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 $Z \to \gamma a$