Collider Probes of Axion-like Particles

Andrea Thamm
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with Martin Bauer and Matthias Neubert

based on arXiv:1610.00009 and 1704.08207
and work in progress

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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

Effective Lagrangian

- Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f + g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A}$$

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

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- Decay into photons, leptons, hadrons
- Higgs interactions at dimension-6 and 7

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

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$h \to aa$

$h \to Za$

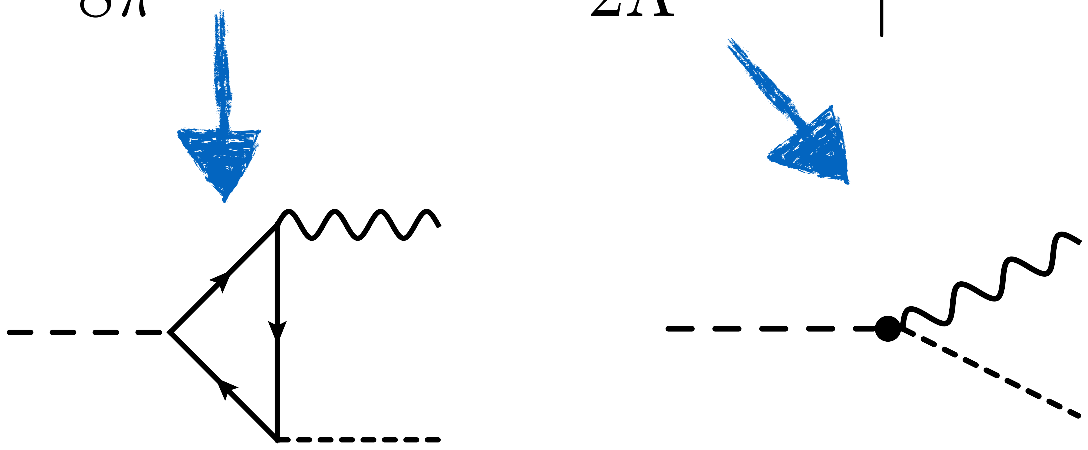
[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

[Bauer, Neubert, Thamm: 1607.01016]

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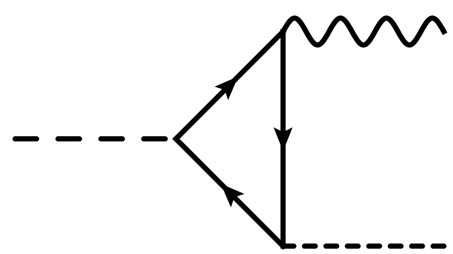
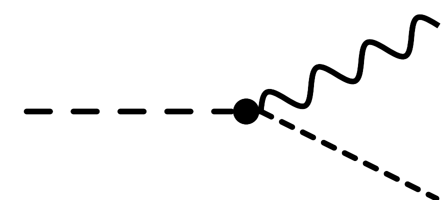
$$\frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right)$$

Vanishes through EOM





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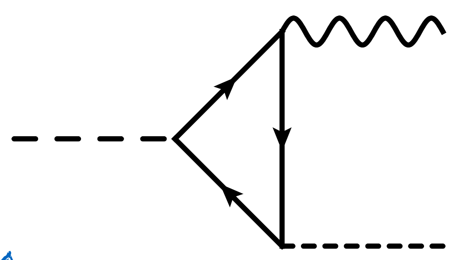

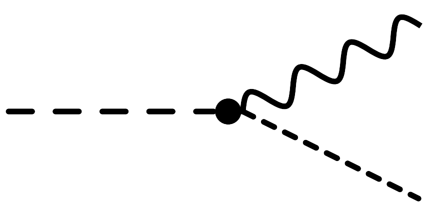

Non-polynomial operator for models with new heavy particles whose mass arises from EWSB

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

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

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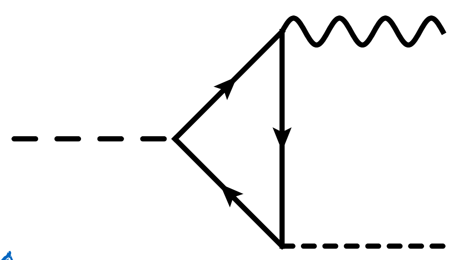

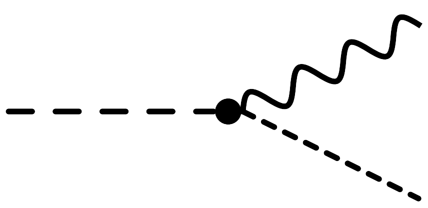

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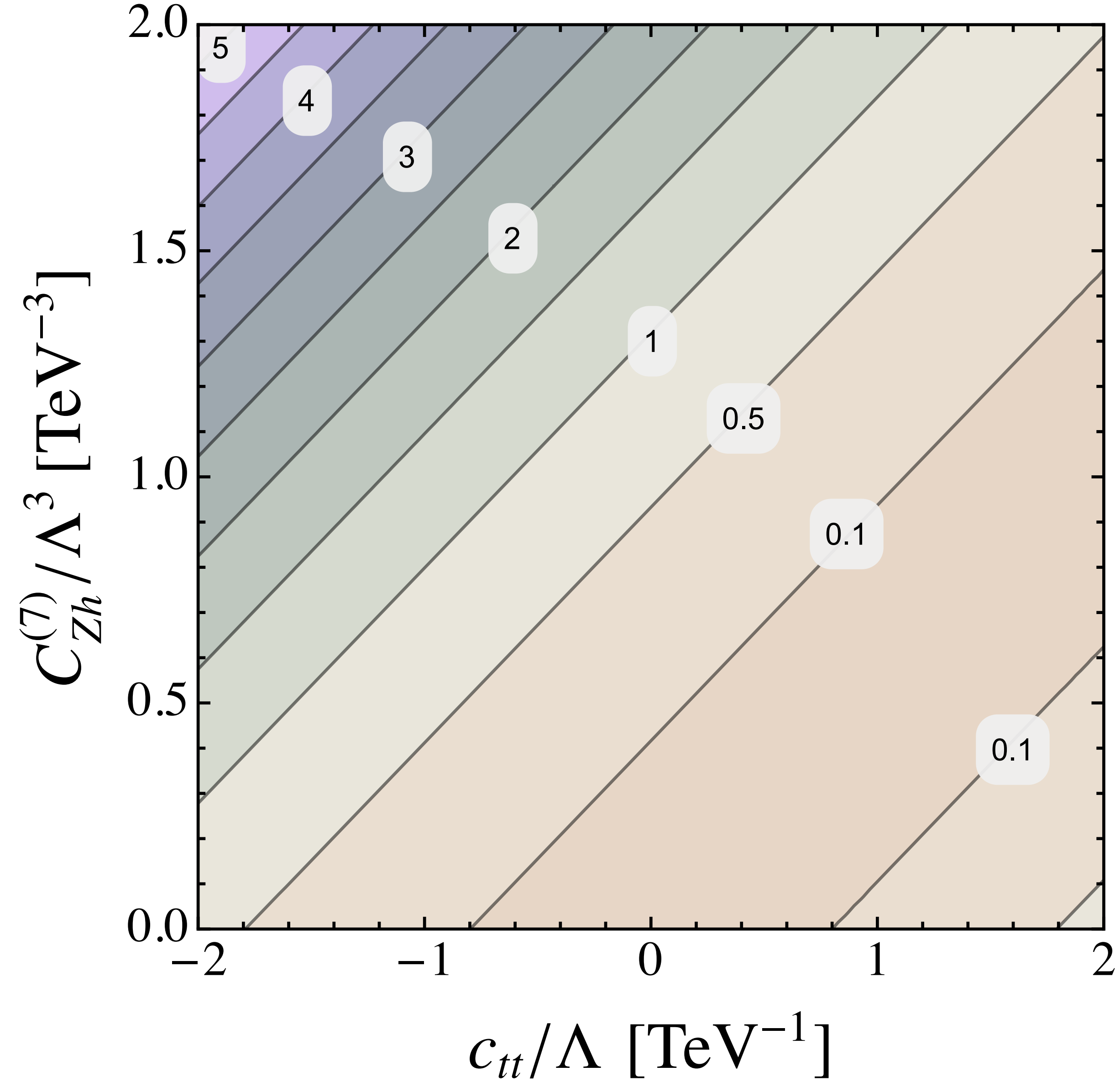
- Numerically

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

Exotic Higgs Decays $h \to Za$

- Decay rate normalised to SM $\Gamma(h \to Z\gamma)_{\rm SM} = 6.32 \cdot 10^{-6}\,\text{GeV}$
- This channel is a realistic target for discovery at LHC



Exotic Higgs Decays $h \to Za$

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

$$h \to Za \to \ell^+\ell^-\gamma\gamma$$

Detecting ALPs in $h \to Za$

- 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

$$f_\text{dec} = 1 - \left\langle e^{-L_\text{det}/L_a^\perp(\theta)} \right\rangle$$

Decay into photons before EM calorimeter

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

Decay into electrons before inner tracker

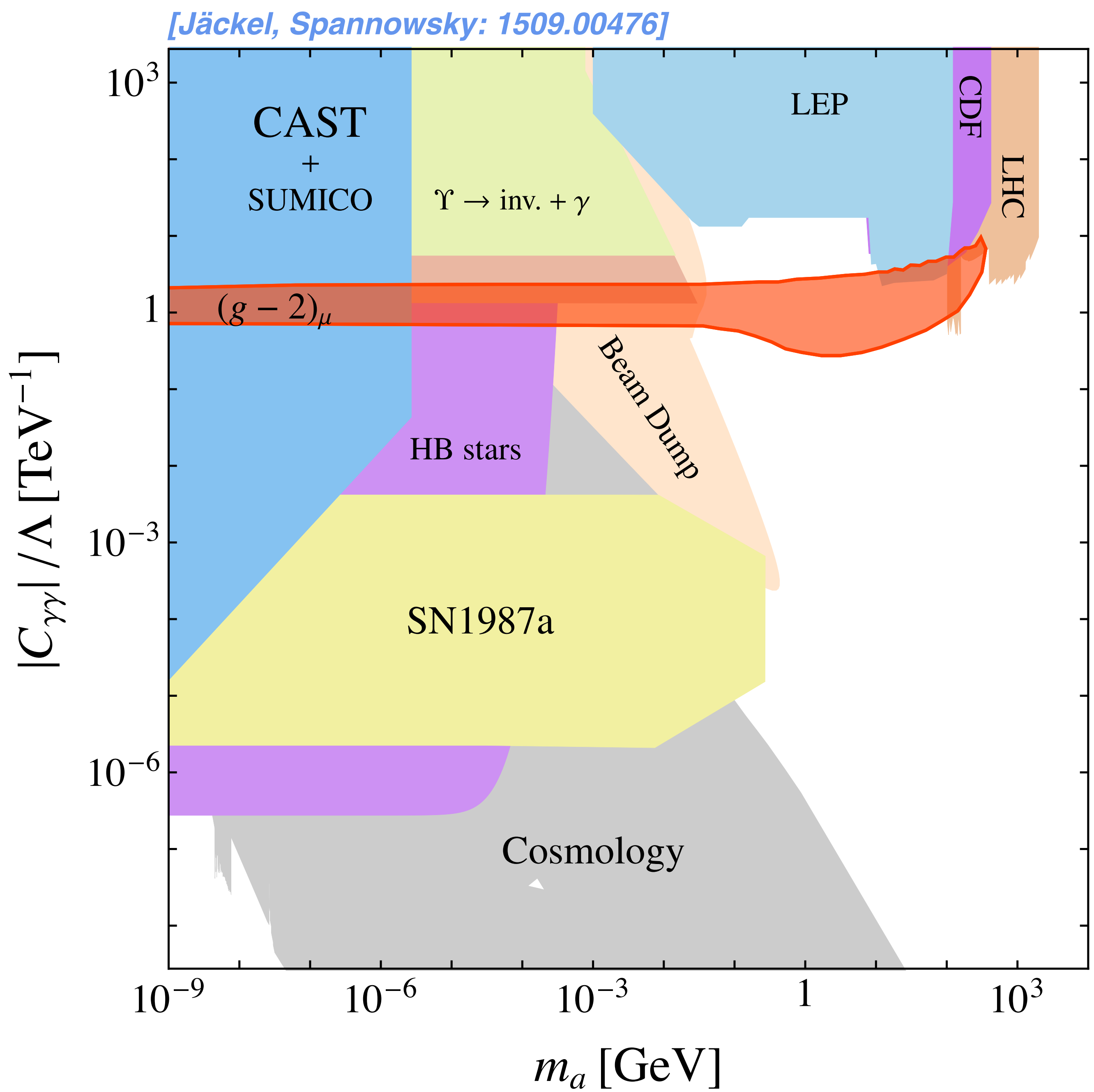
$L_\text{det} = 2\,\text{cm}$

- Effective branching ratios

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

Probing the parameter space

- Constraints on ALP mass and coupling to photons



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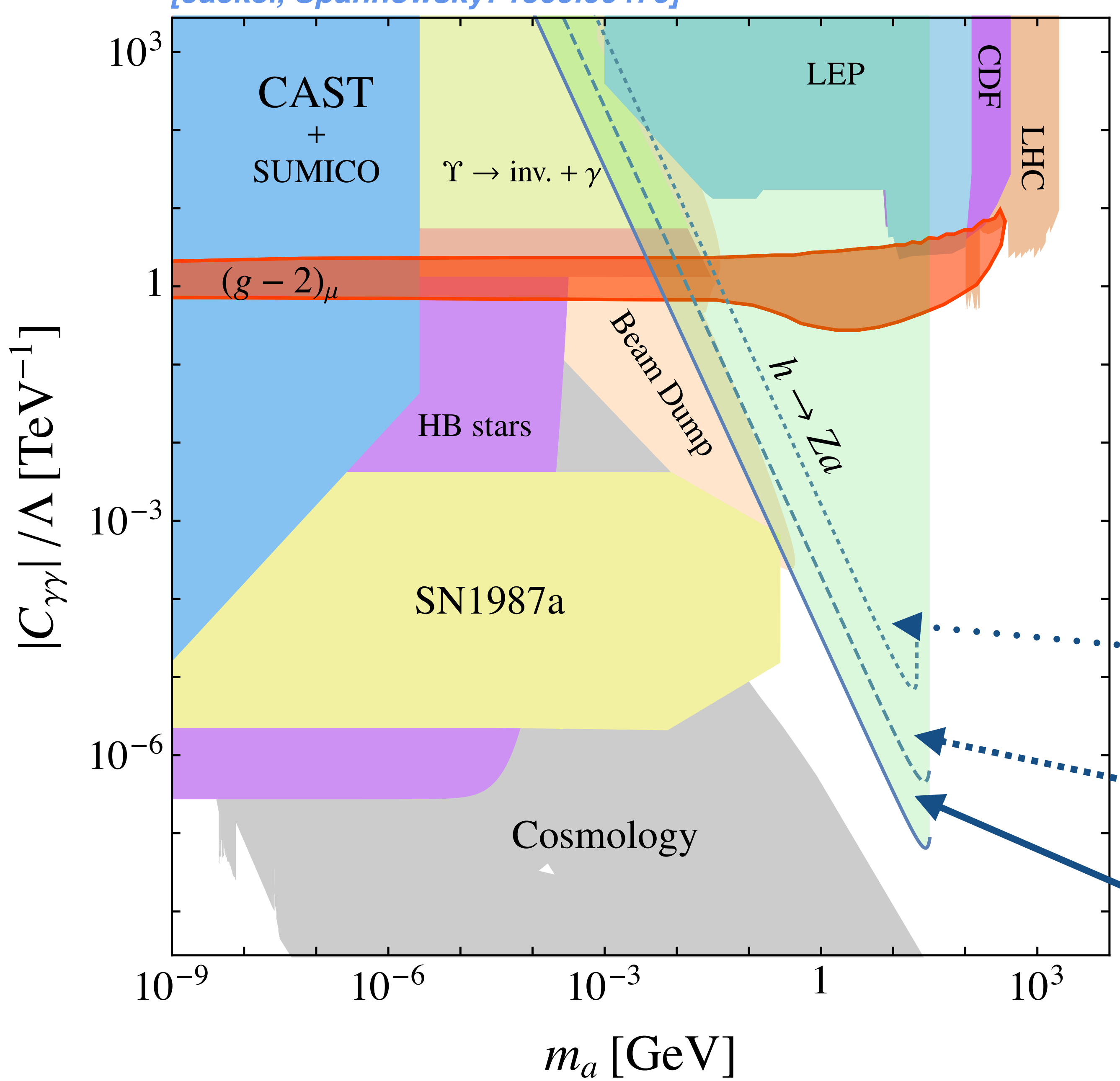
[Jäckel, Spannowsky: 1509.00476]



$|C_{Zh}| = 0.0015,\ \mathrm{Br}(a \to \gamma\gamma) > 0.46$

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

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

(for $\Lambda = 1$ TeV)

[Bauer, Neubert, Thamm: 1704.08207]

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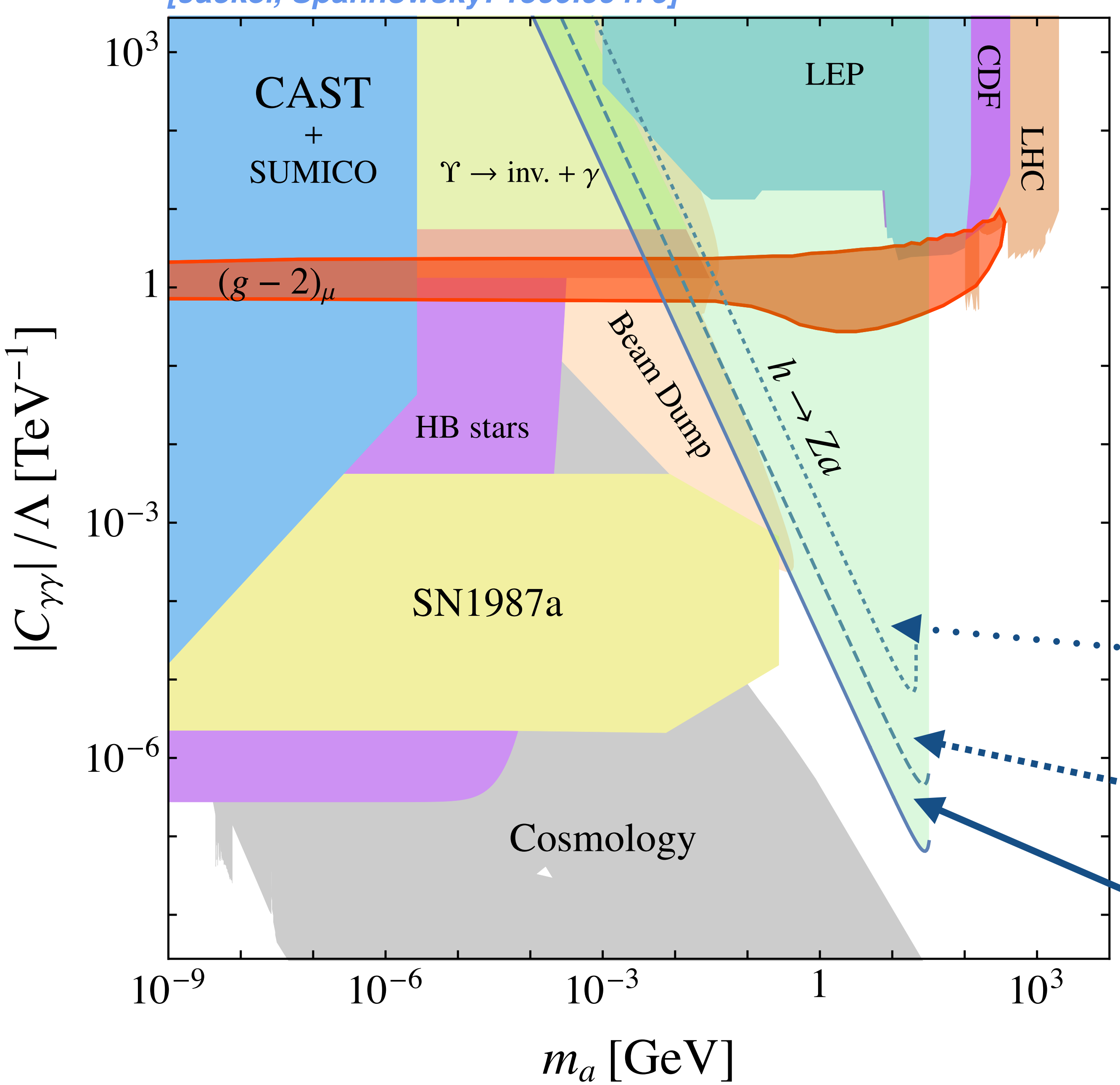

- ALP-photon coupling can be probed even if ALP decays predominantly into other particles
- Region preferred by $(g-2)_\mu$ almost completely covered

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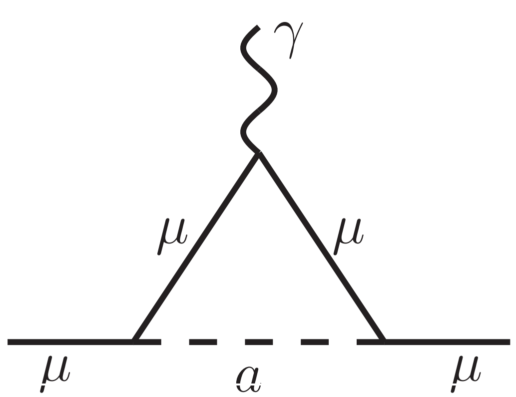
Muon $(g-2)_\mu$

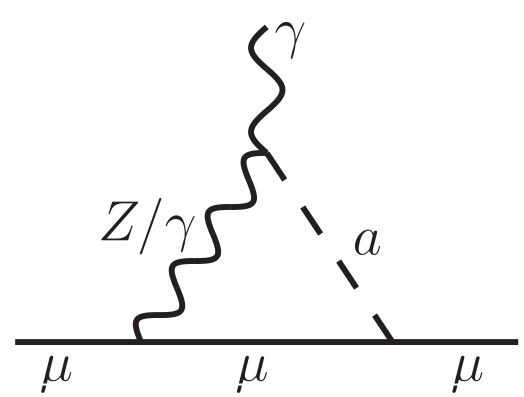
- Persistent 3σ deviation

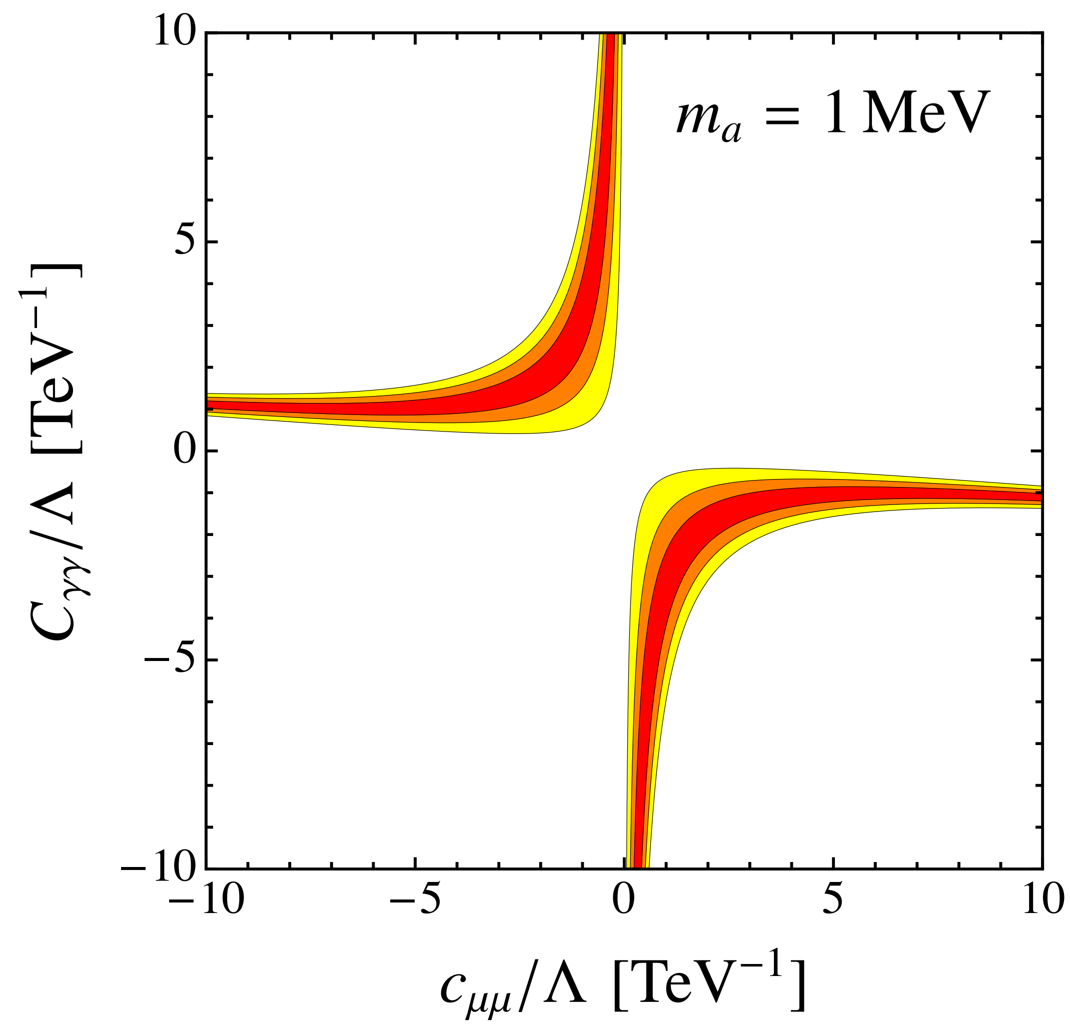
[Particle Data Group 2016]

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

- ALP can account for discrepancy







[Haber, Kane, Sterling: Nucl. Phys. B 161 (1979)]
[Chang, Chang, Chou, Keung: 0009292]
[Marciano, Masiero, Paradisi, Passera: 1607.010122]

Conclusions

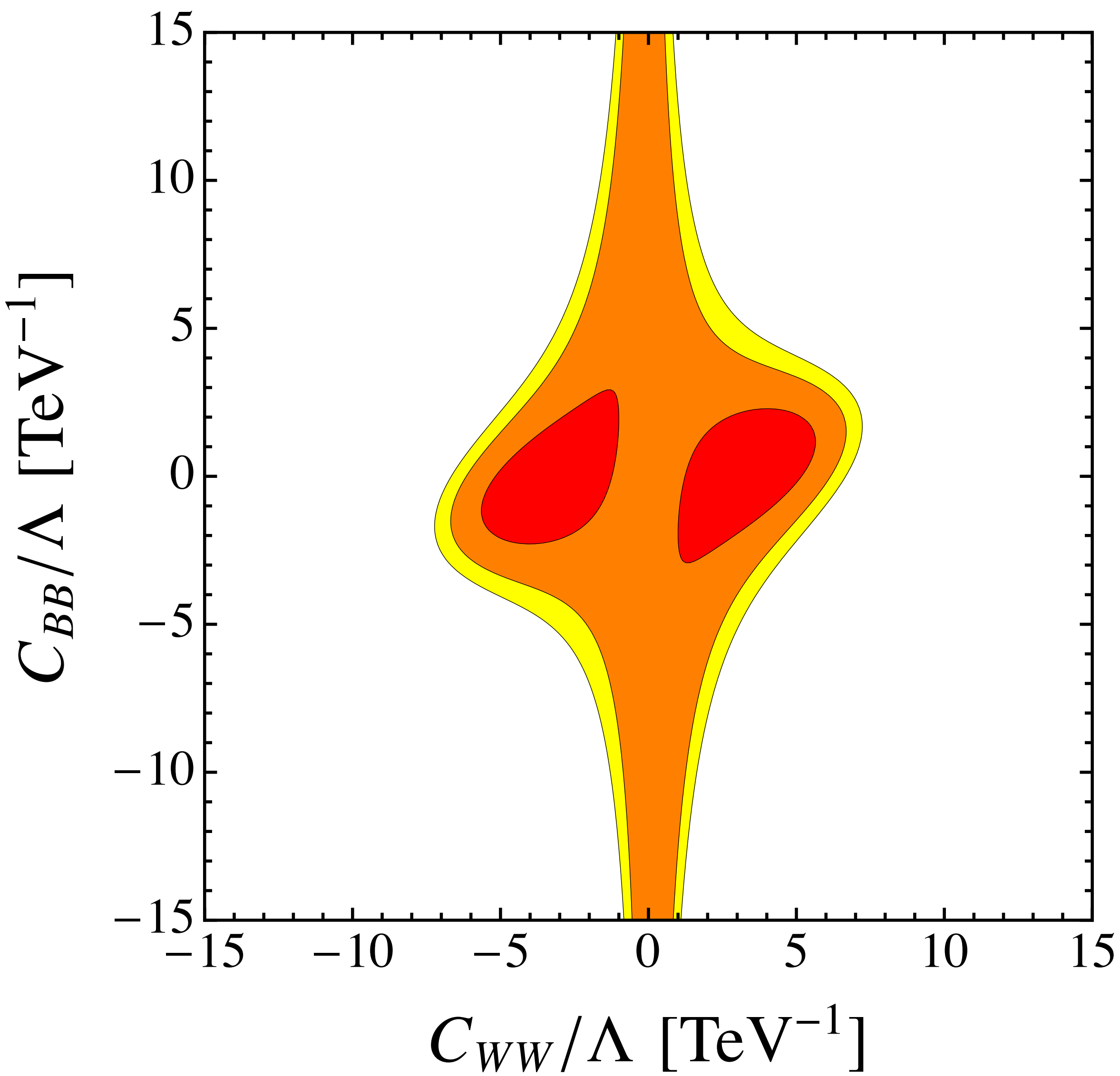
- Rare Higgs decays at the LHC provide a powerful way to probe the existence of ALPs with masses between 30 MeV and 60 GeV and couplings suppressed by the 1 - 100 TeV scale
- Connection to low-energy physics probes such as $(g-2)_\mu$

Backup

Electroweak precision tests

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

[Baak et al.: 1407.3792]



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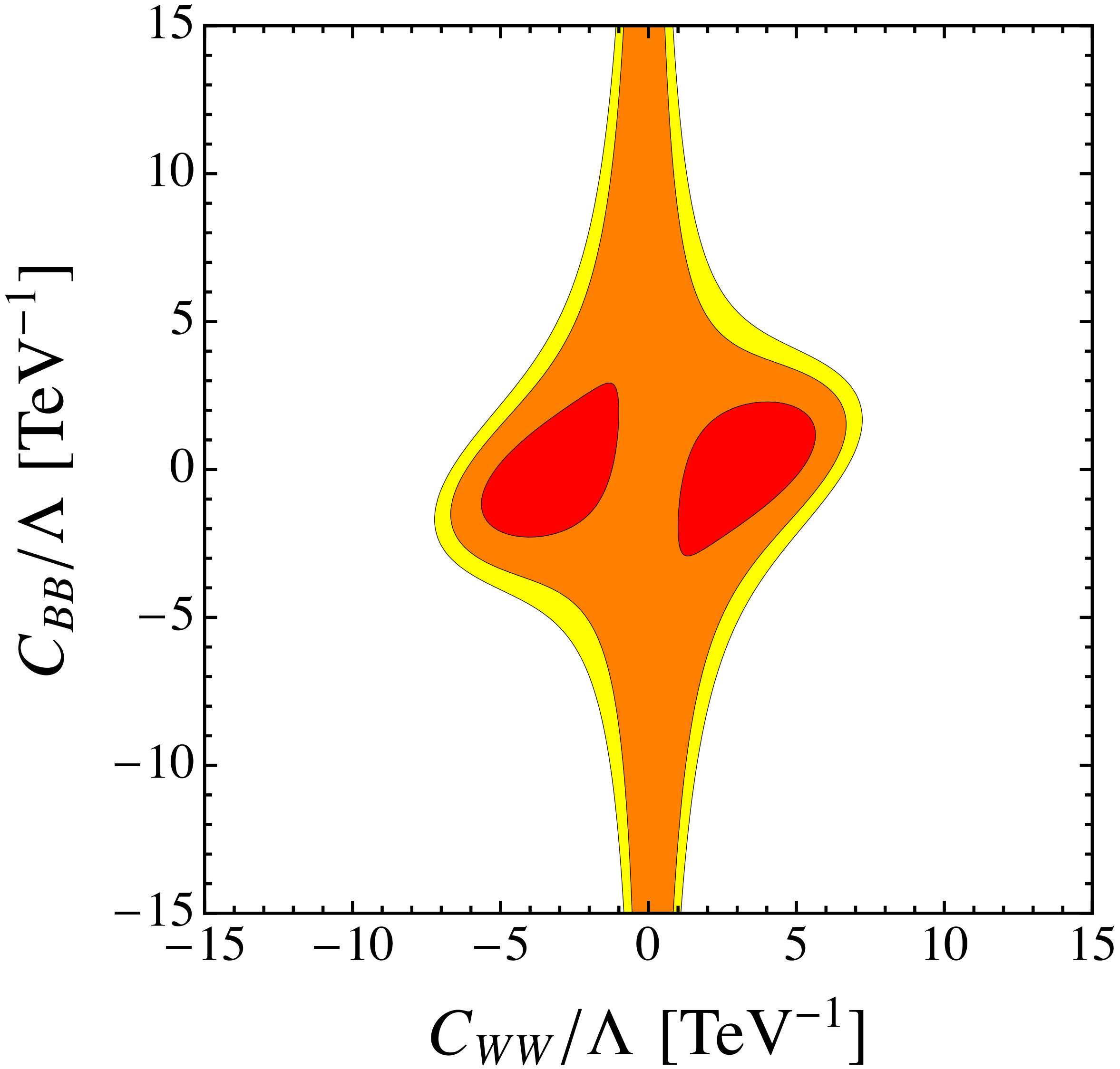

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$
$$C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB}$$

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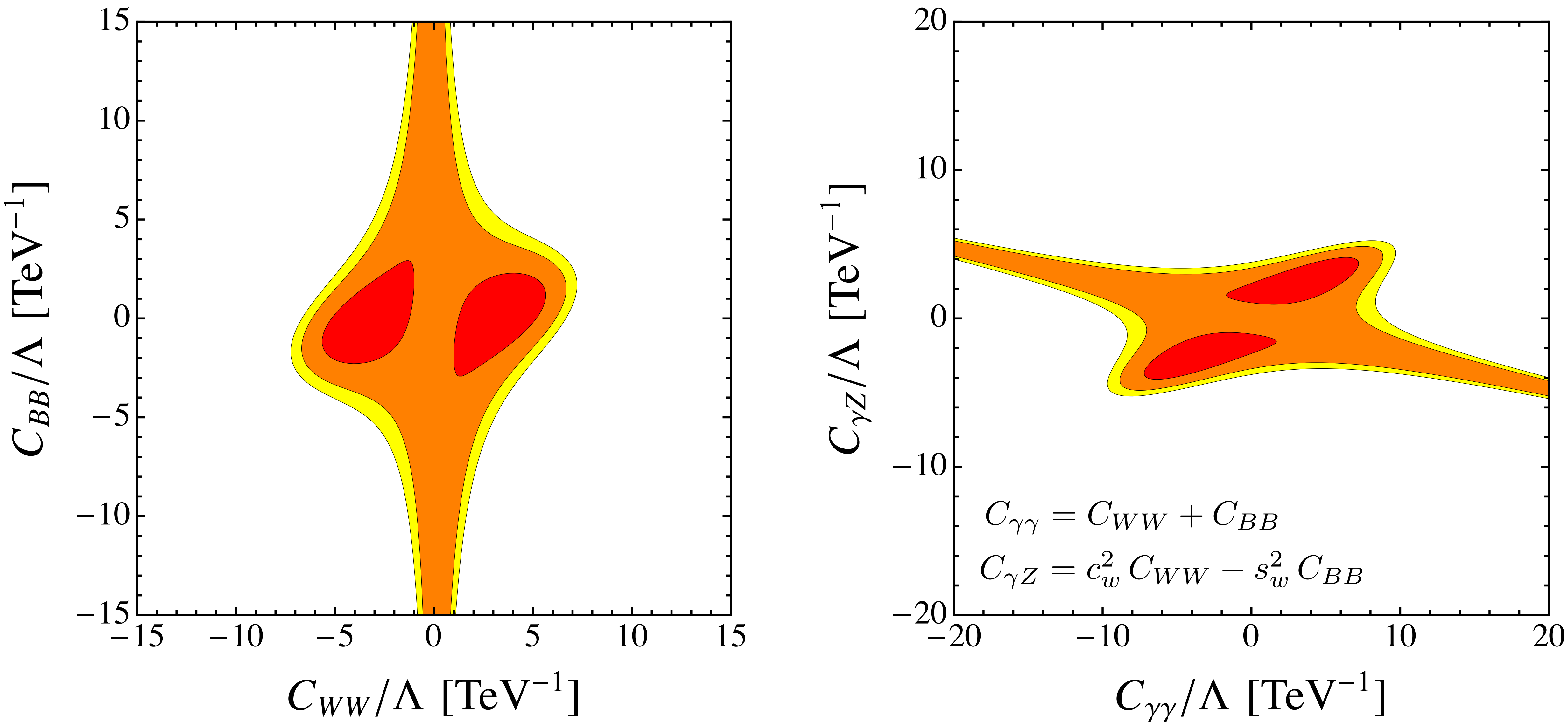

Electroweak precision tests

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

[Abbiendi et al.: 0309052]

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

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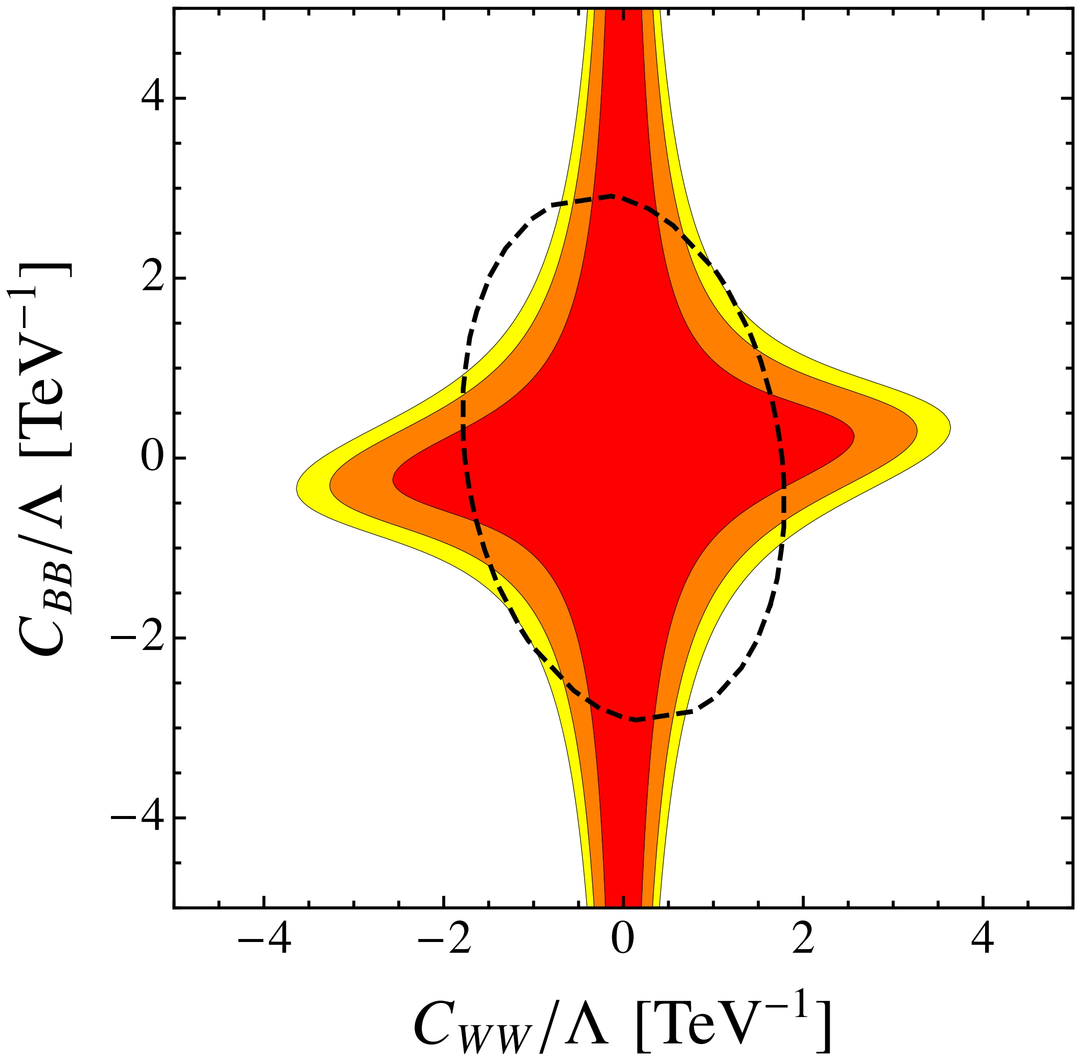
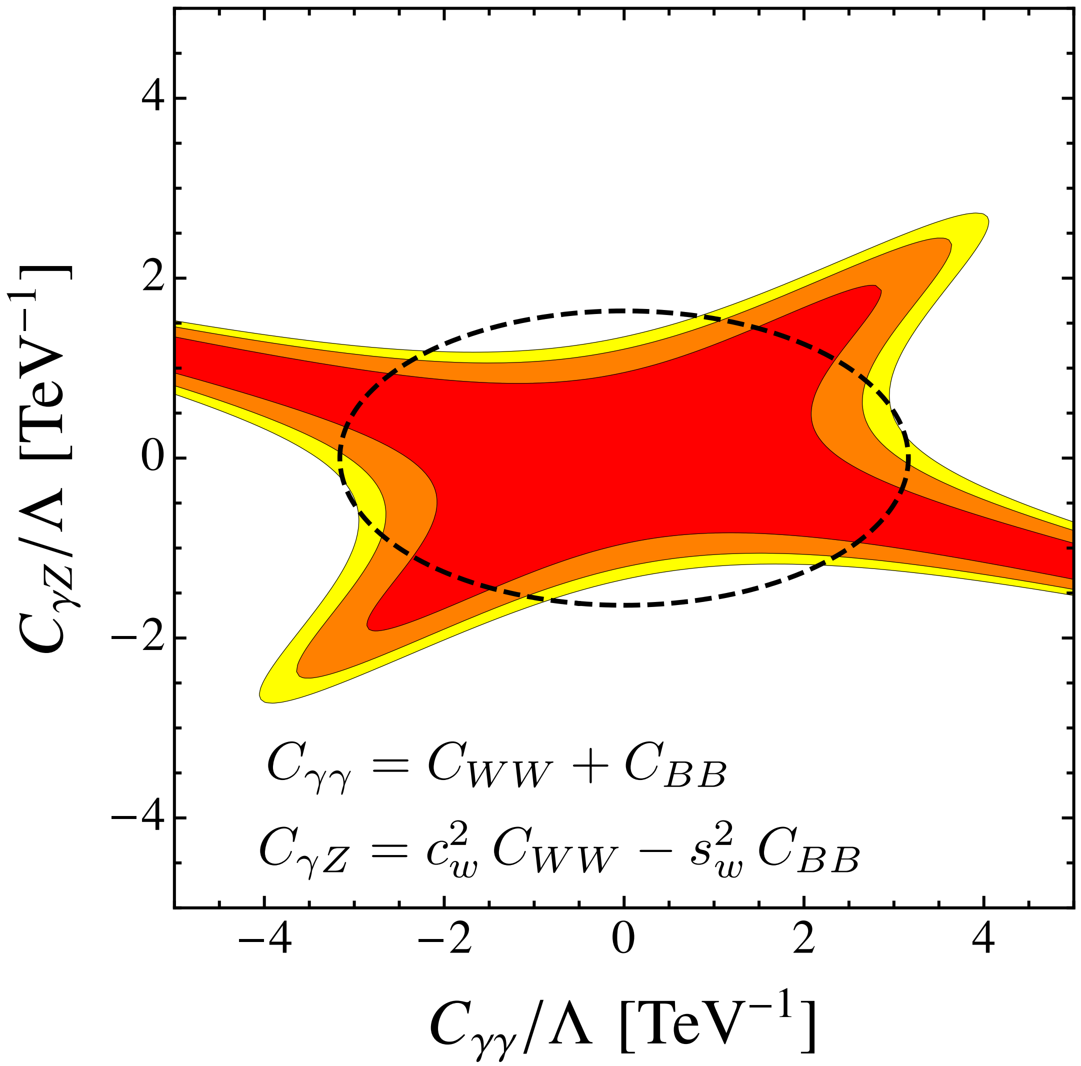
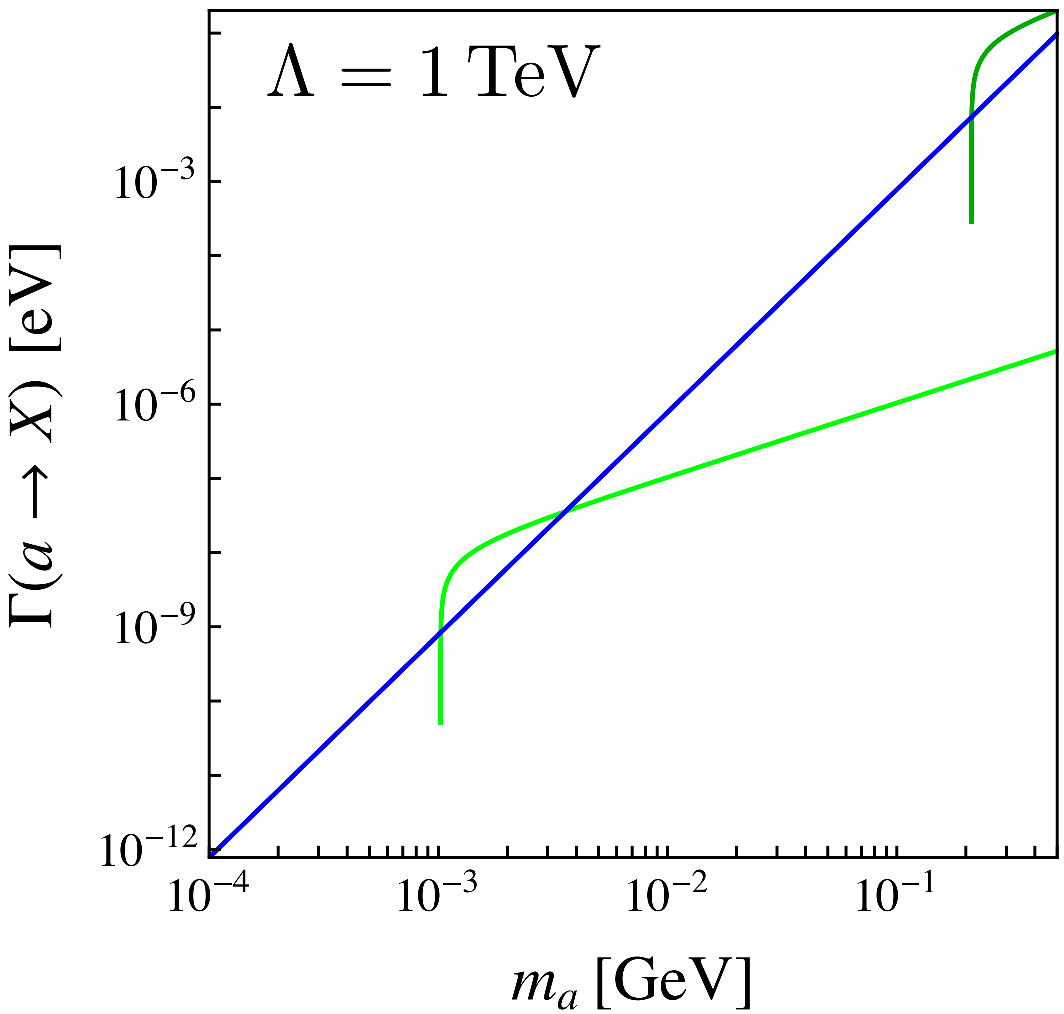
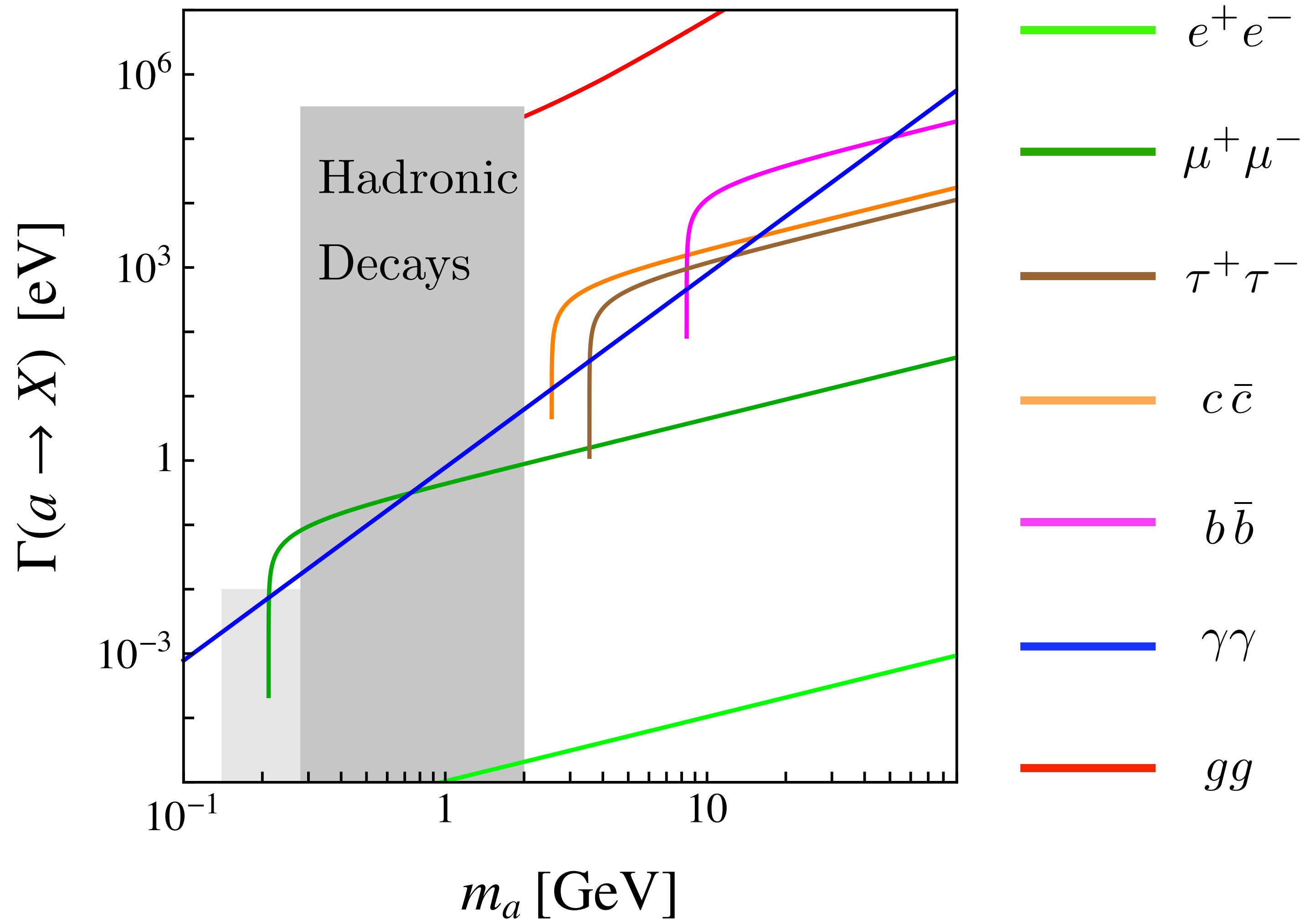




ALP decays

- Assuming effective Wilson coefficients to be 1





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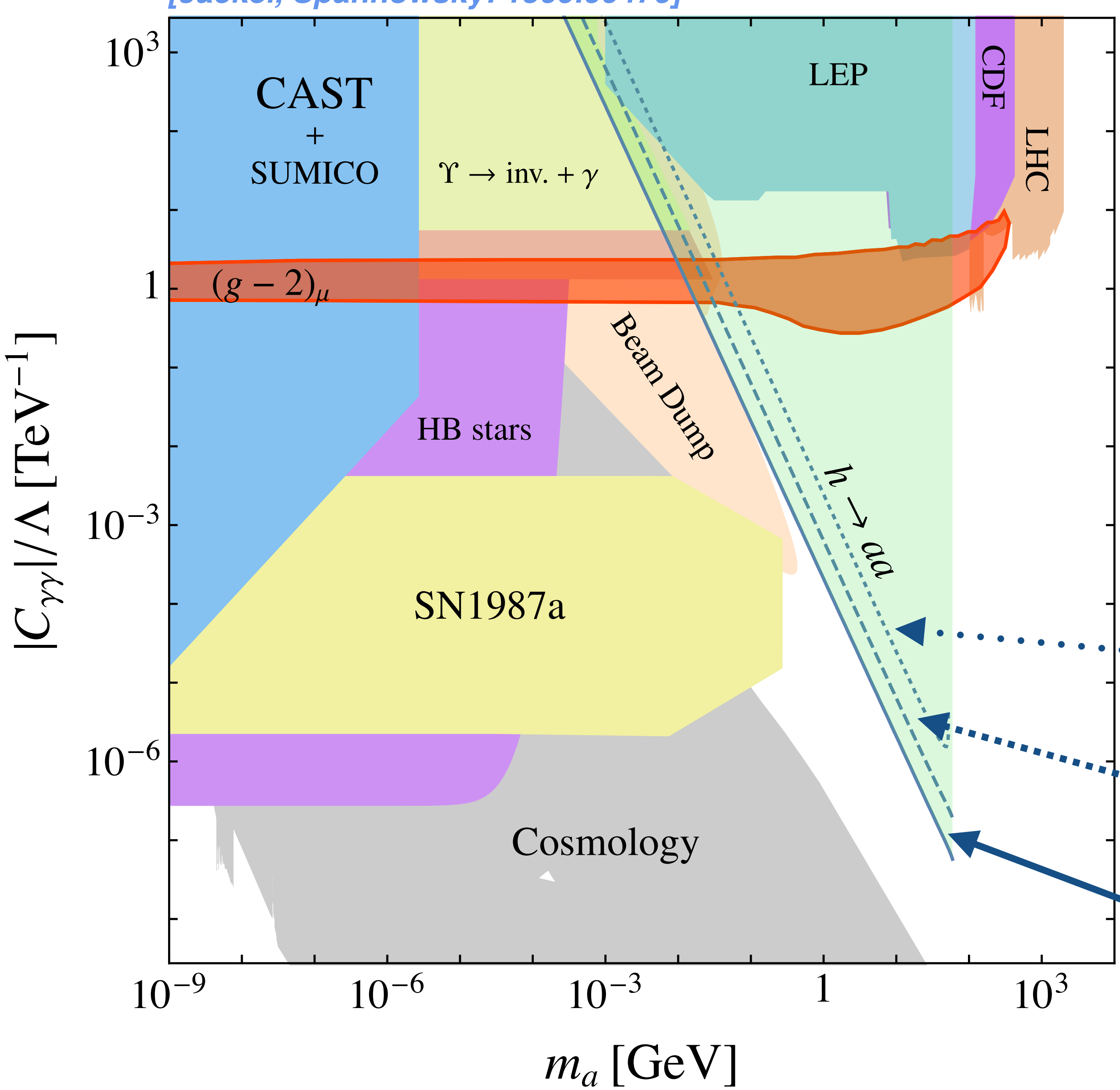

$|C_{ah}| = 0.01,\ \mathrm{Br}(a \to \gamma\gamma) > 0.49$

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

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

(for $\Lambda = 1$ TeV)

[Bauer, Neubert, Thamm: 1704.08207]

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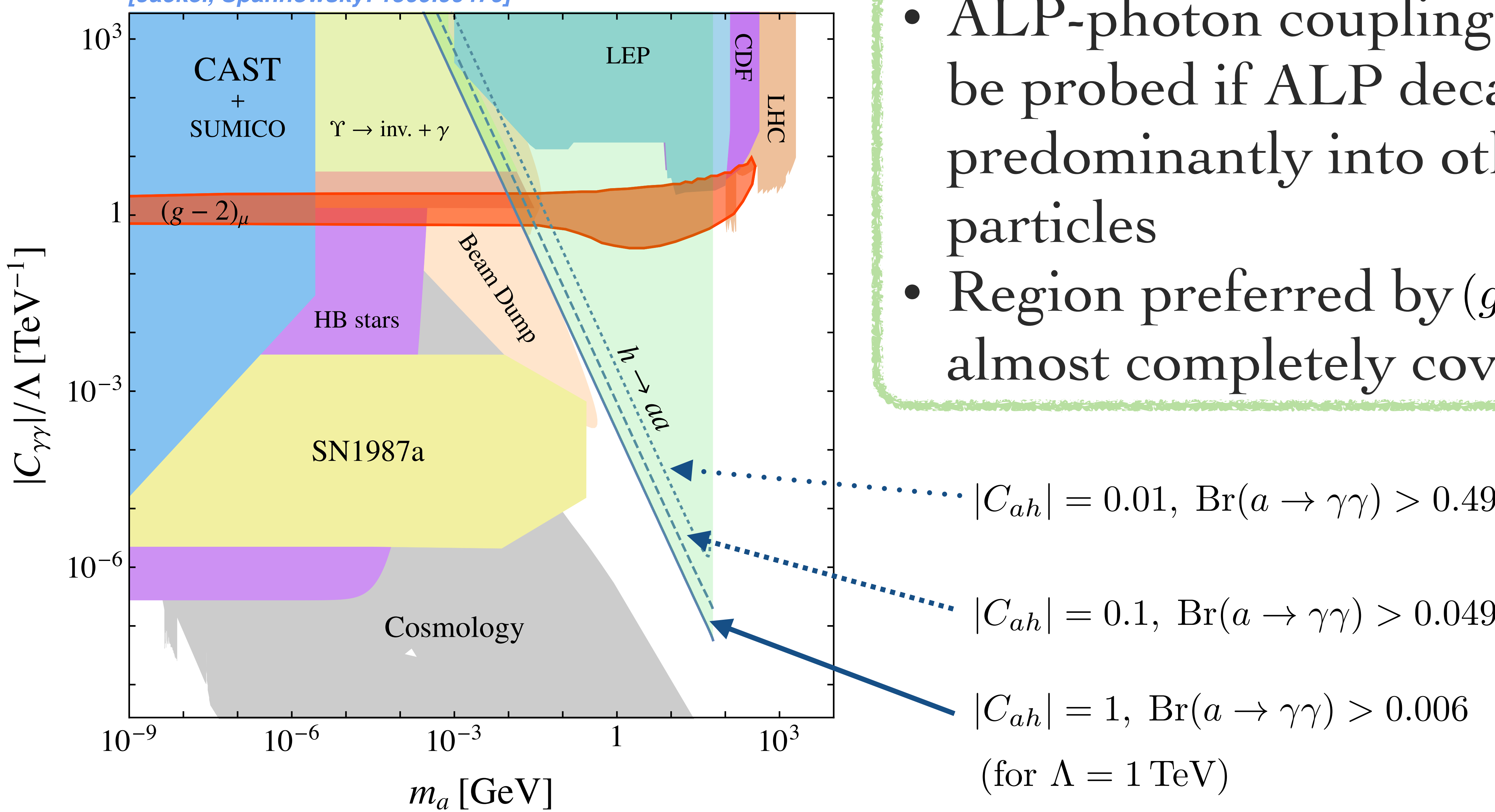

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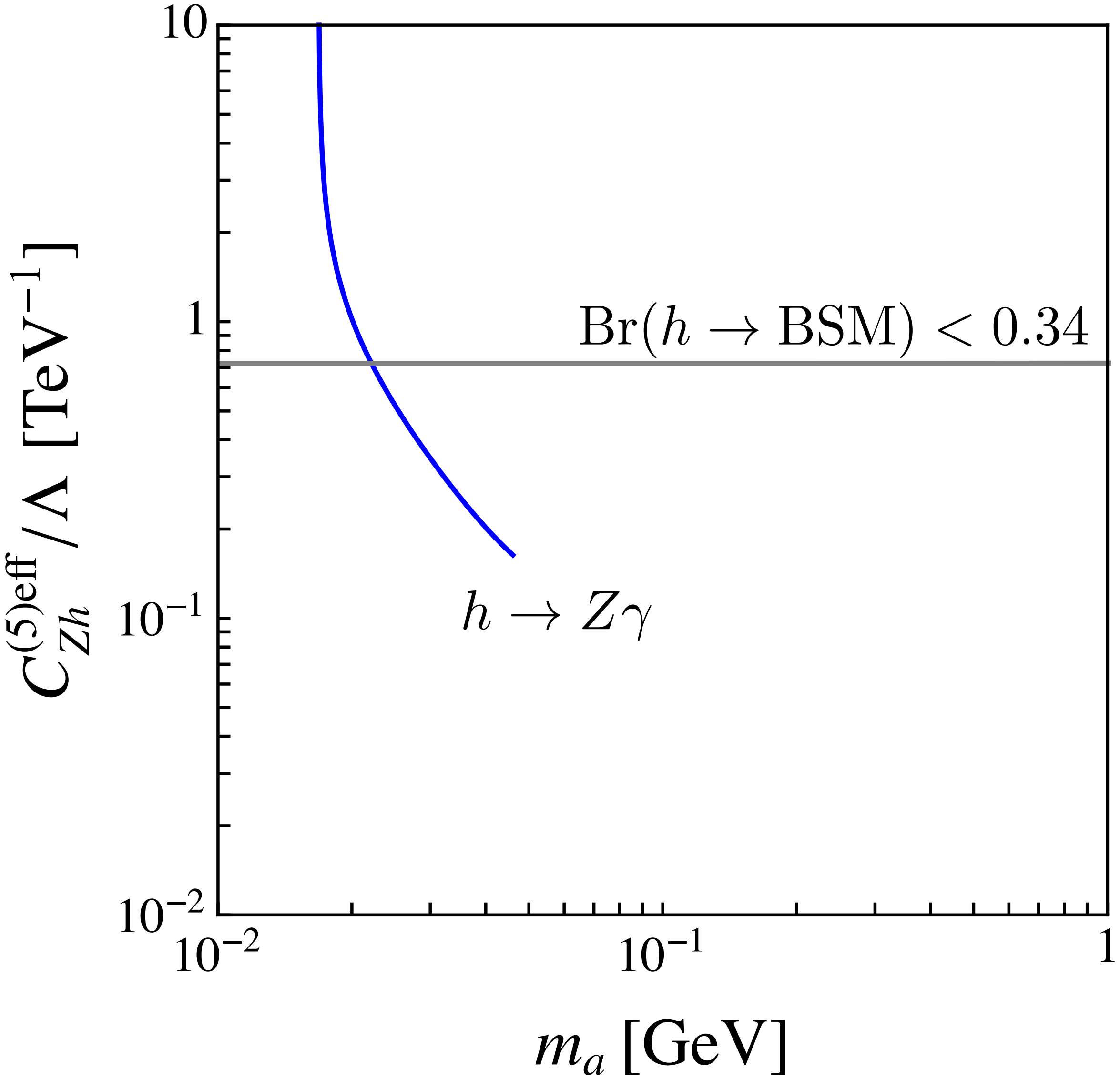
Current exclusion bounds

- Current bounds on $h \to Za$

[CMS: 1307.5515, ATLAS: 1402.3051]



[Bauer, Neubert, Thamm: to appear]

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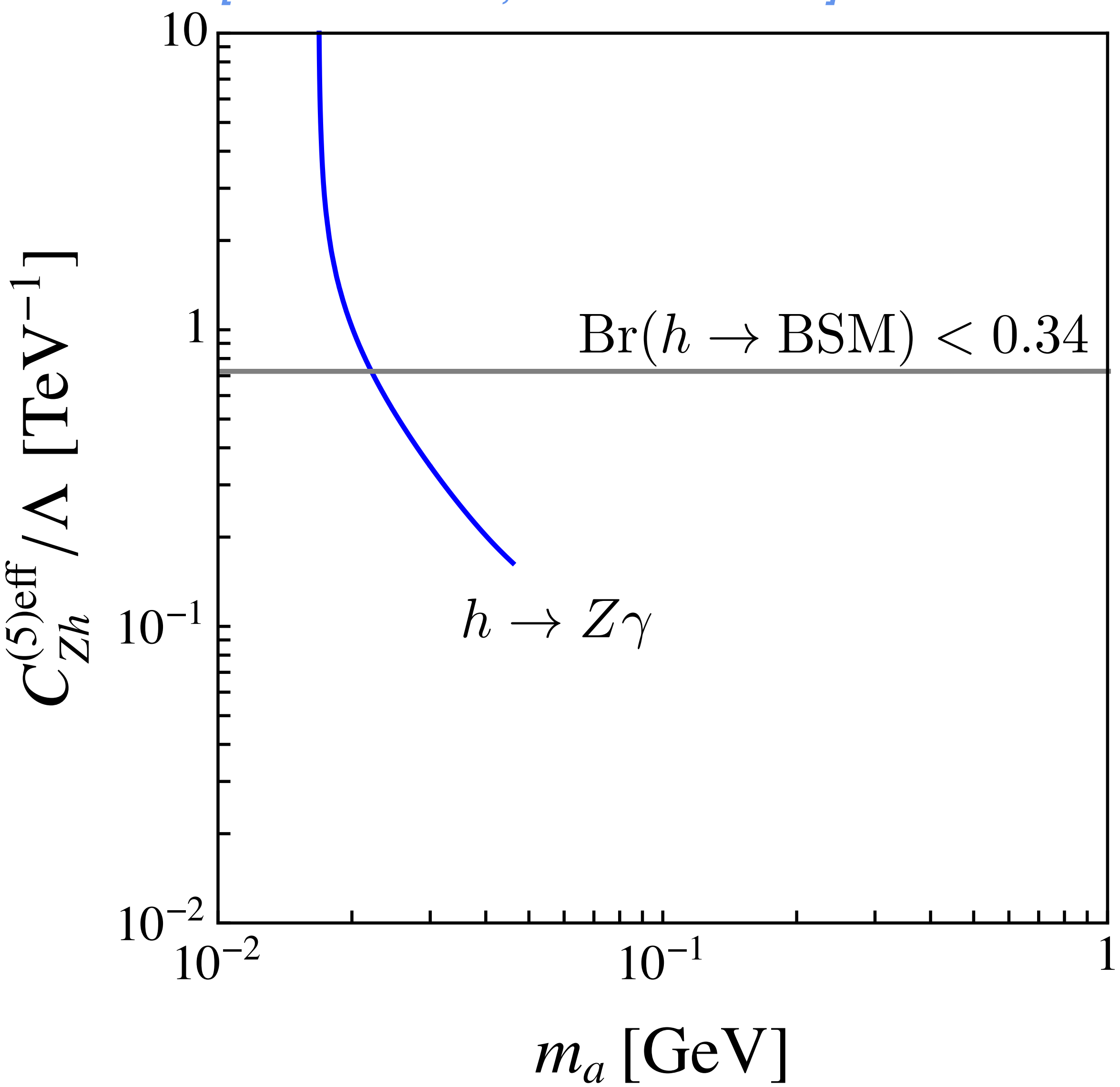

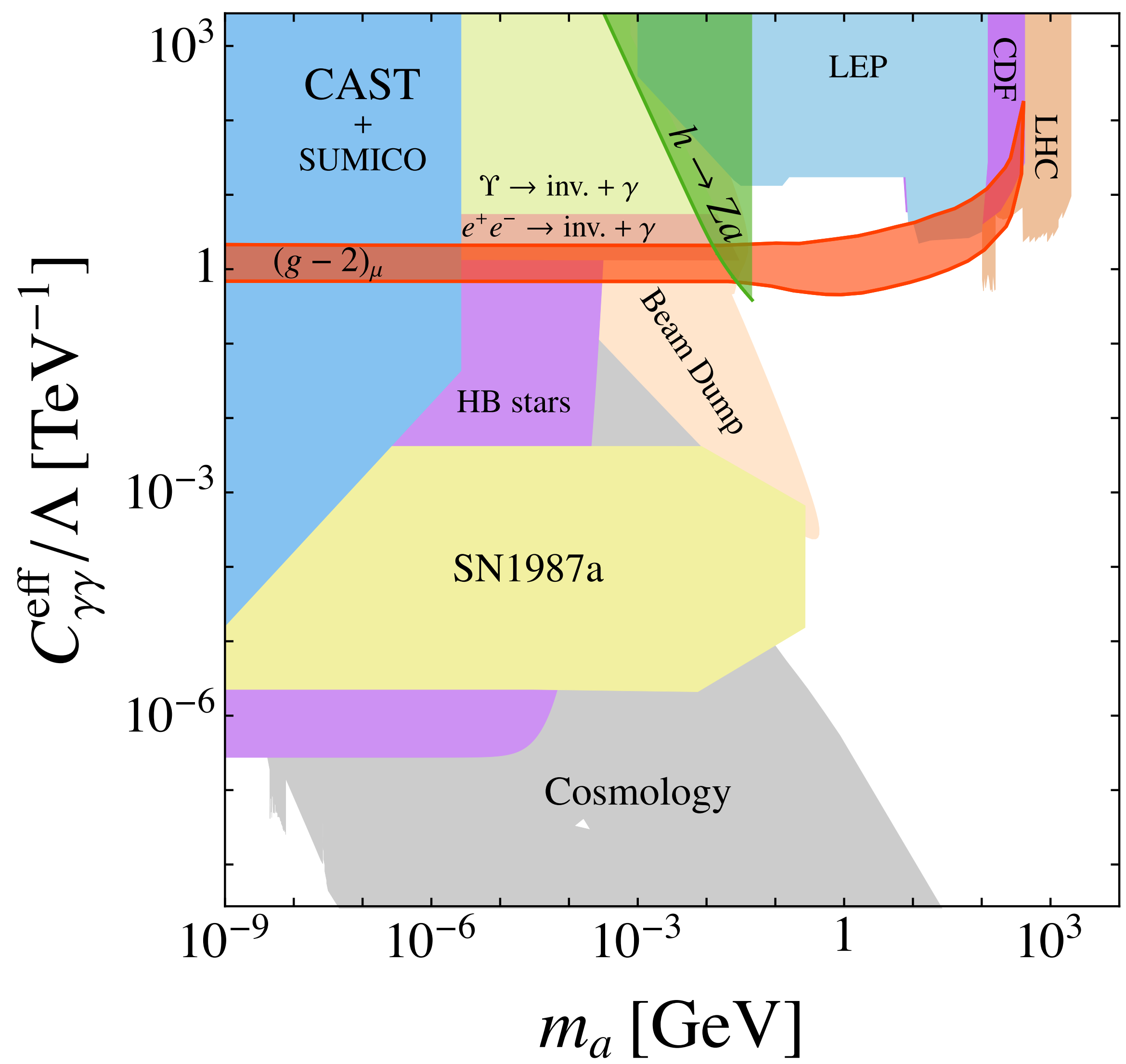

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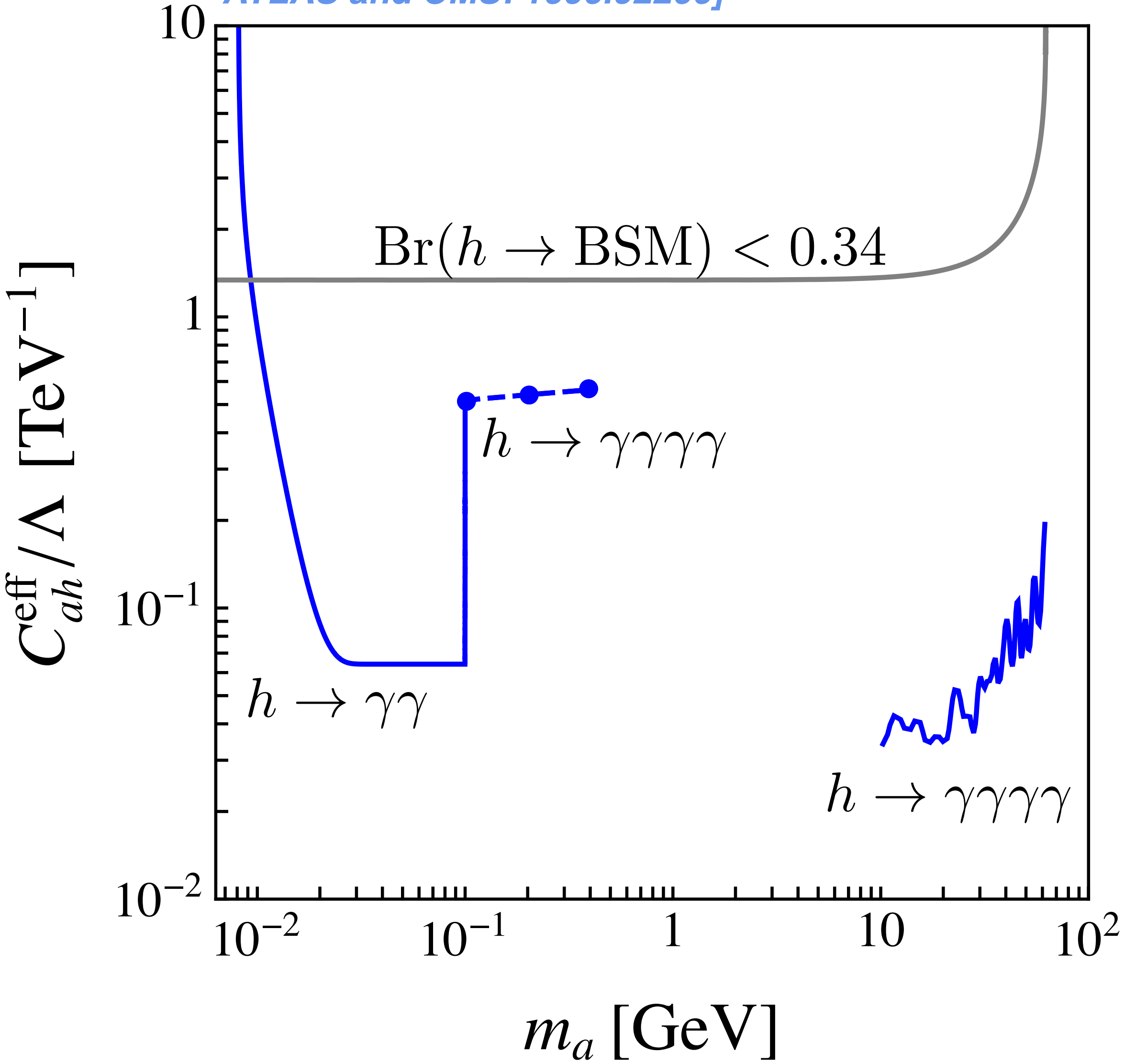
[ATLAS-CONF-2012-079, ATLAS: 1509.05051, ATLAS and CMS: 1606.02266]



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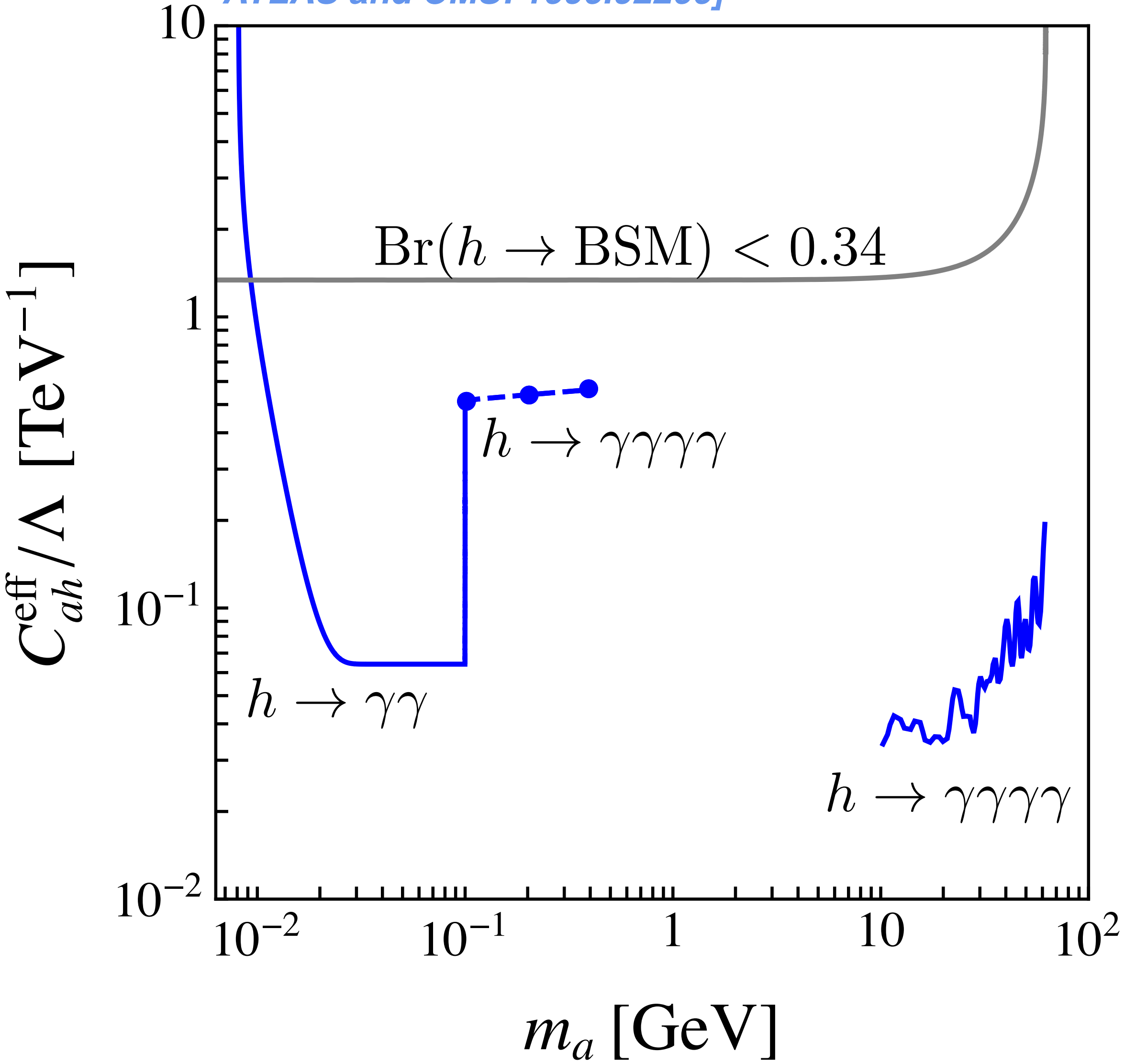

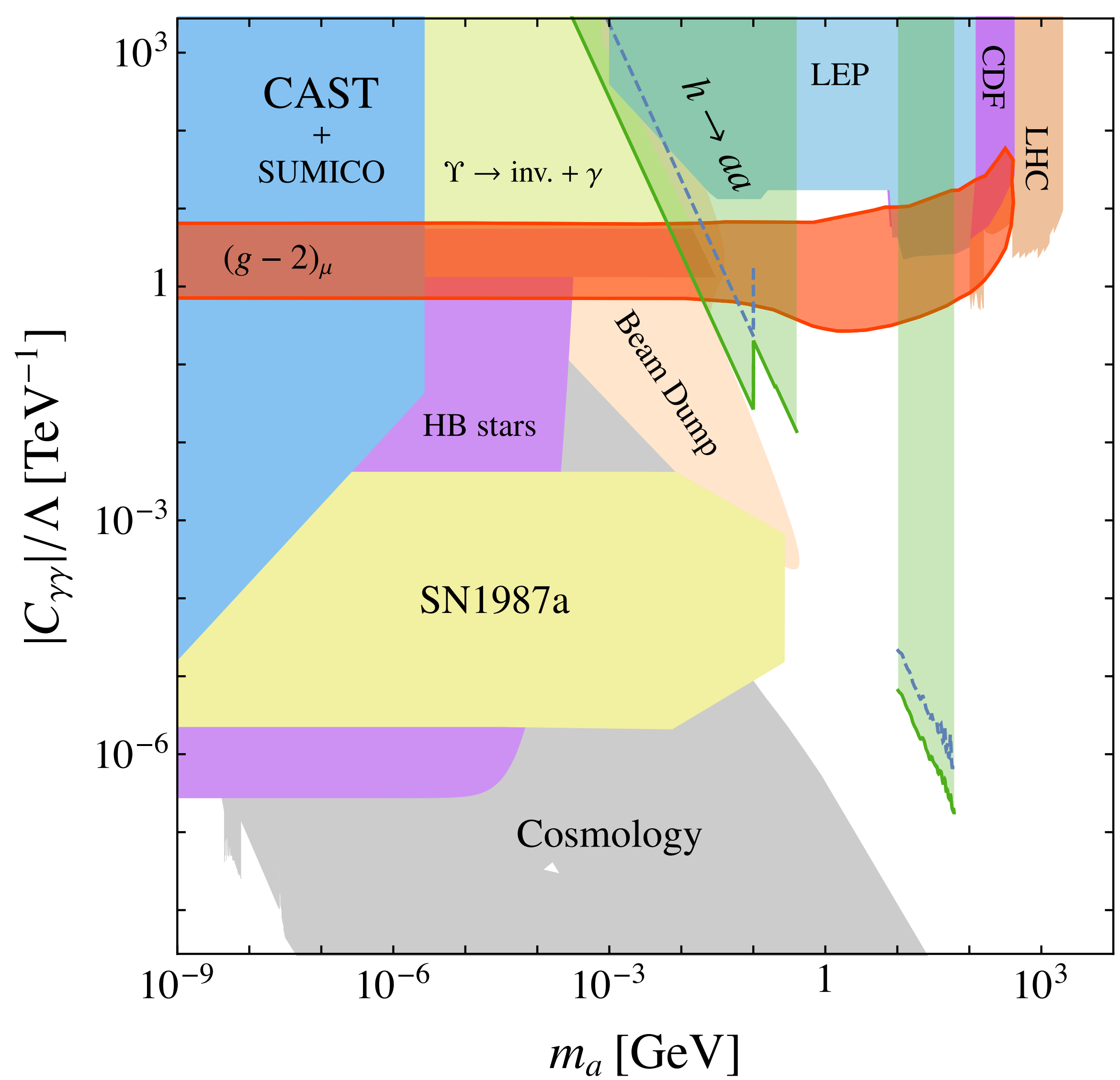

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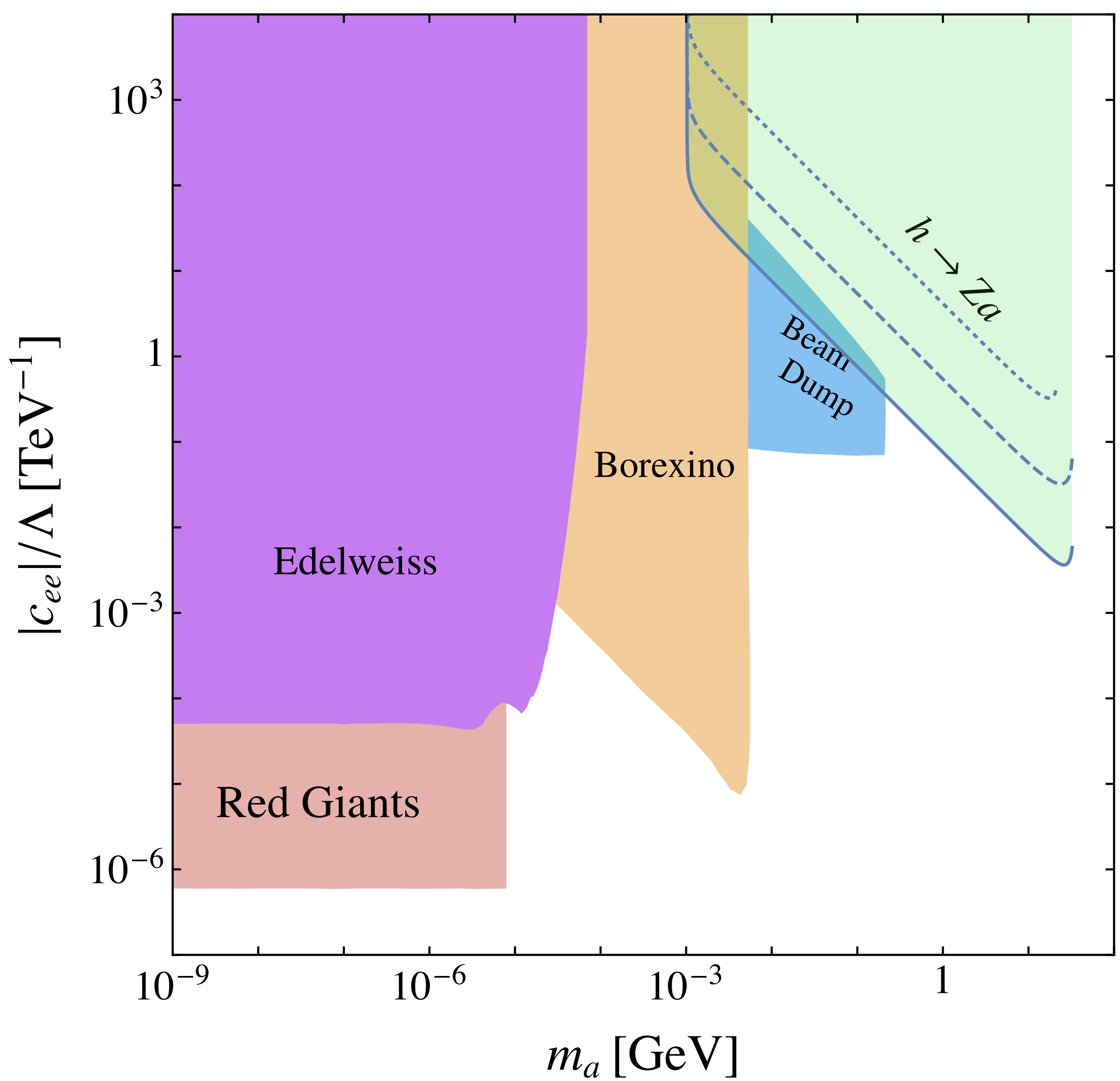

[Armengaud: 1307.1488]
[Essig, Harnik, Kaplan, Toro: 1008.0636]
[Bauer, Neubert, Thamm: 1704.08207]

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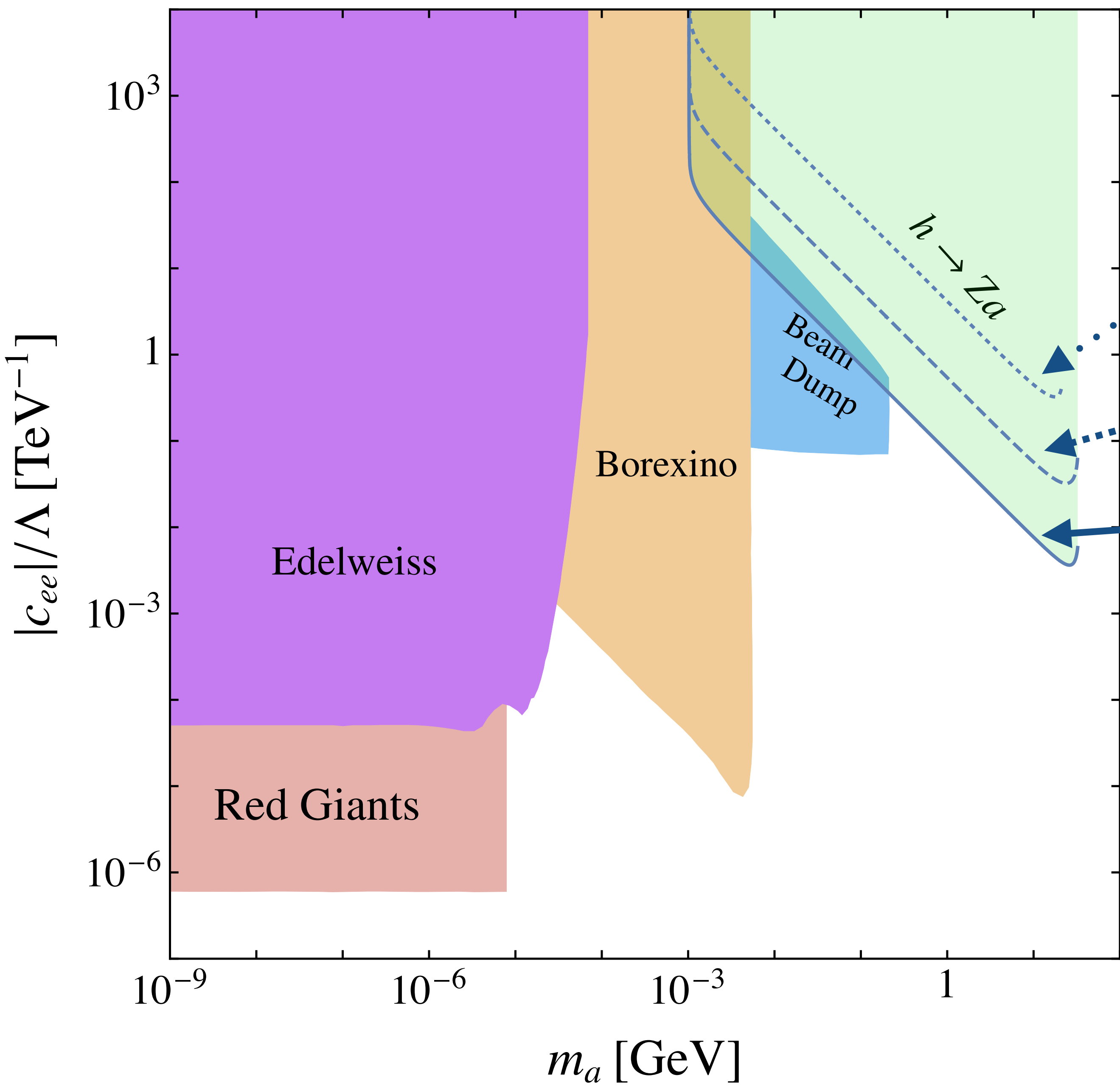

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$|C_{Zh}| = 0.1,\ \mathrm{Br}(a \to e^+e^-) > 0.011$

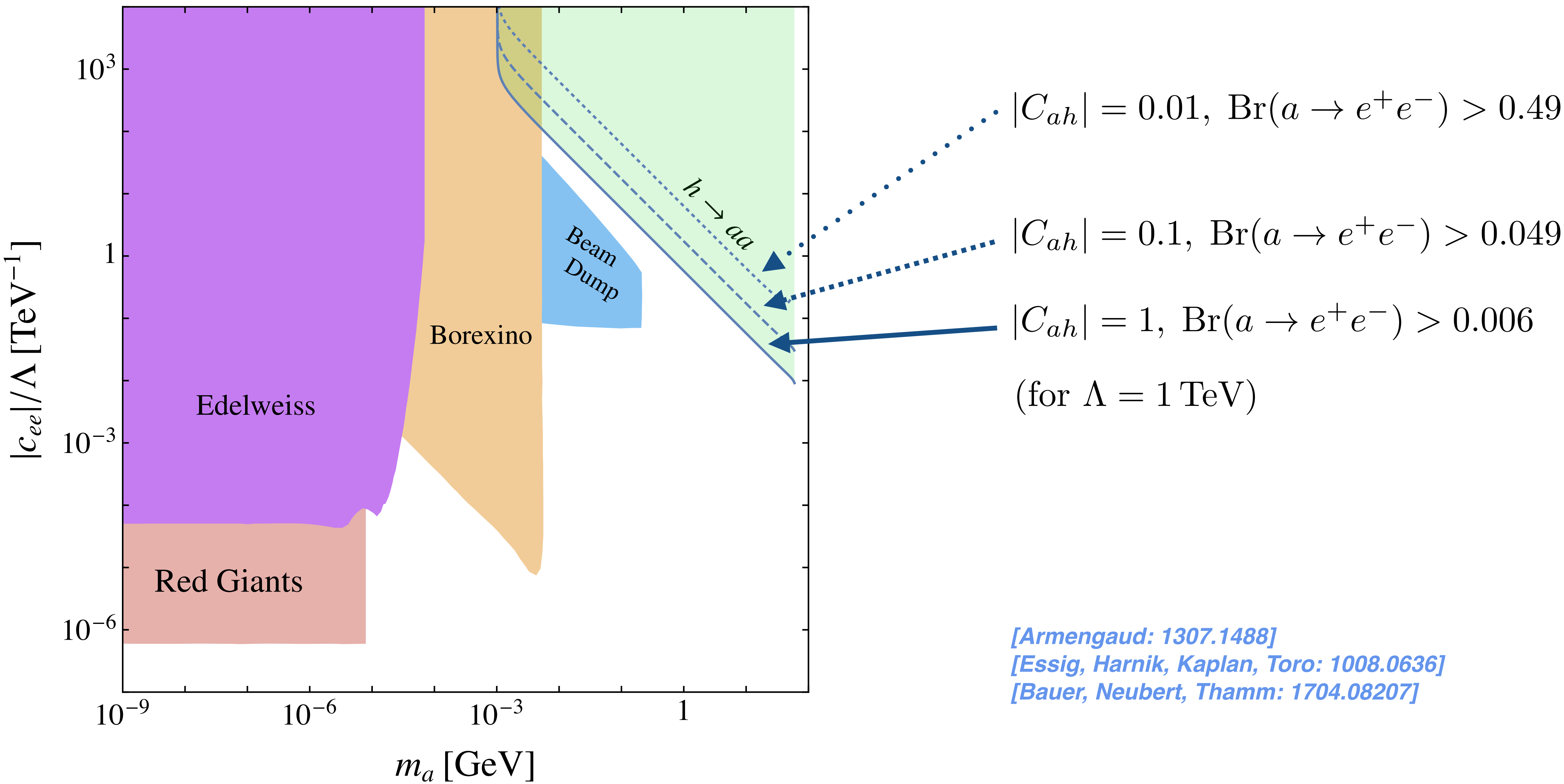
$|C_{Zh}| = 0.72,\ \mathrm{Br}(a \to e^+e^-) > 2 \cdot 10^{-4}$

(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 electrons



[Armengaud: 1307.1488]
[Essig, Harnik, Kaplan, Toro: 1008.0636]
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Probing the parameter space

- Constraints on ALP mass and coupling to muons