Exotic Higgs Decays and Axion Like Particles

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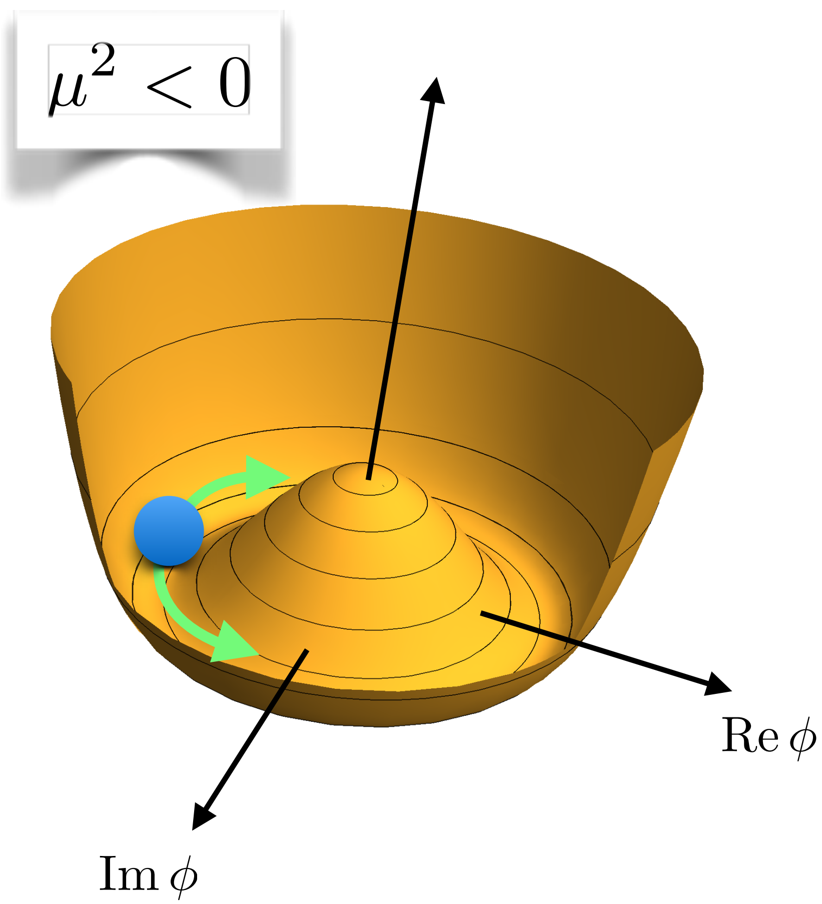
ALPs

Axion-like particles (ALPs) are Goldstone bosons from the breaking of a global symmetry in the UV.

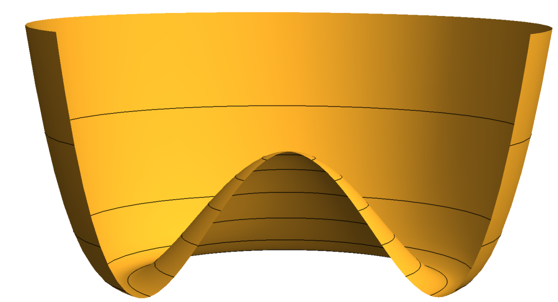
Without explicit symmetry breaking, ALPs are massless and protected by a shift symmetry.



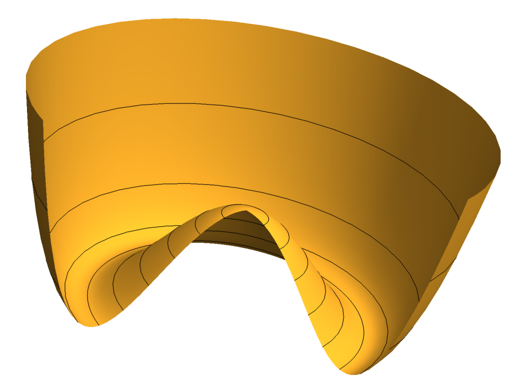
$$\phi = \mathrm{Re}\,\phi + i\,\mathrm{Im}\,\phi \;= h\,e^{i\varphi}$$

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$m_h^2 = |\mu^2| \qquad m_\varphi^2 = 0$$



only spontaneous breaking



spontaneous and explicit breaking

ALP Effective Lagrangian

ALP: A new pseudoscalar particle protected by an approximate shift symmetry

Most general dimension five Lagrangian

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

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

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

ALP Decays into SM particles

Decays into photons

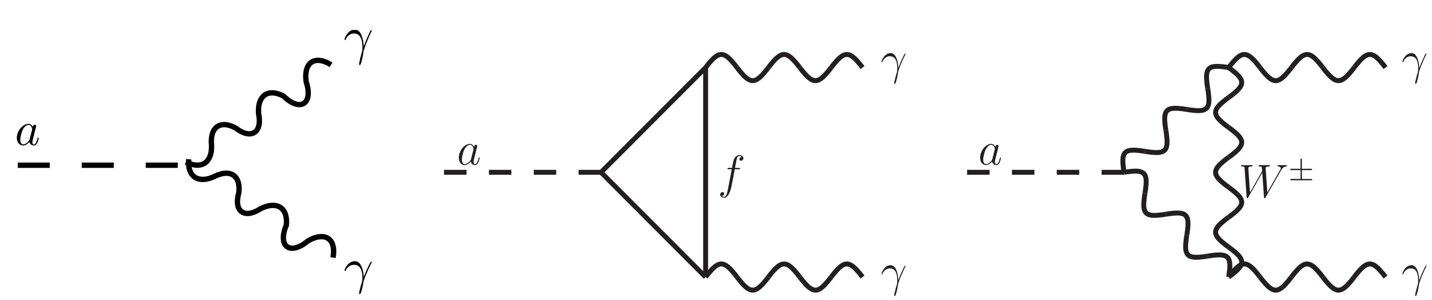
$$\mathcal{L}_{\text{eff}}^{D\le 5} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

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

and loop induced couplings

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

$$B_1(\tau) = 1 - \tau\, f^2(\tau)\,,$$
$$B_2(\tau) = 1 - (\tau - 1)\, f^2(\tau)\,,$$



ALP Decays into SM particles

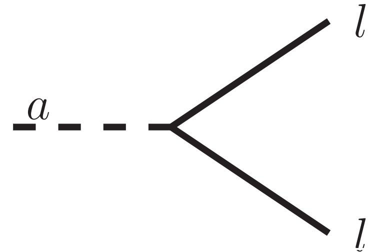
Decays into leptons

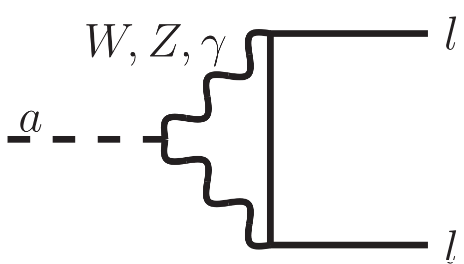
$$\frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar f\,\gamma_\mu\gamma_5\,f = -c_{ff}\,\frac{m_f}{\Lambda}\,a\,\bar f\,i\gamma_5\,f + c_{ff}\,\frac{N_c^f Q_f^2}{16\pi^2}\,\frac{a}{\Lambda}\,e^2 F_{\mu\nu}\,\tilde F^{\mu\nu} + \dots$$

Important loop contributions

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

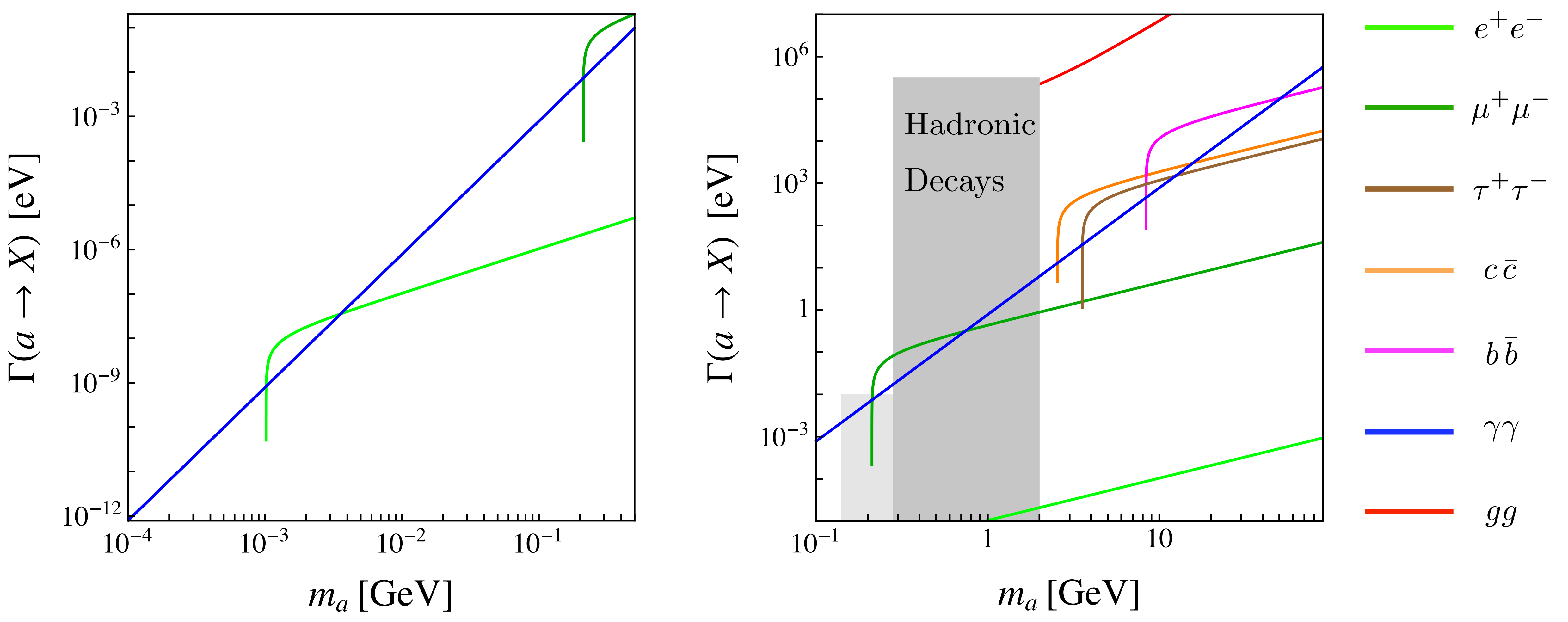
$$\Gamma(a\to\ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2}\left|c_{\ell\ell}^{\rm eff}\right|^2\sqrt{1-\frac{4m_\ell^2}{m_a^2}}$$





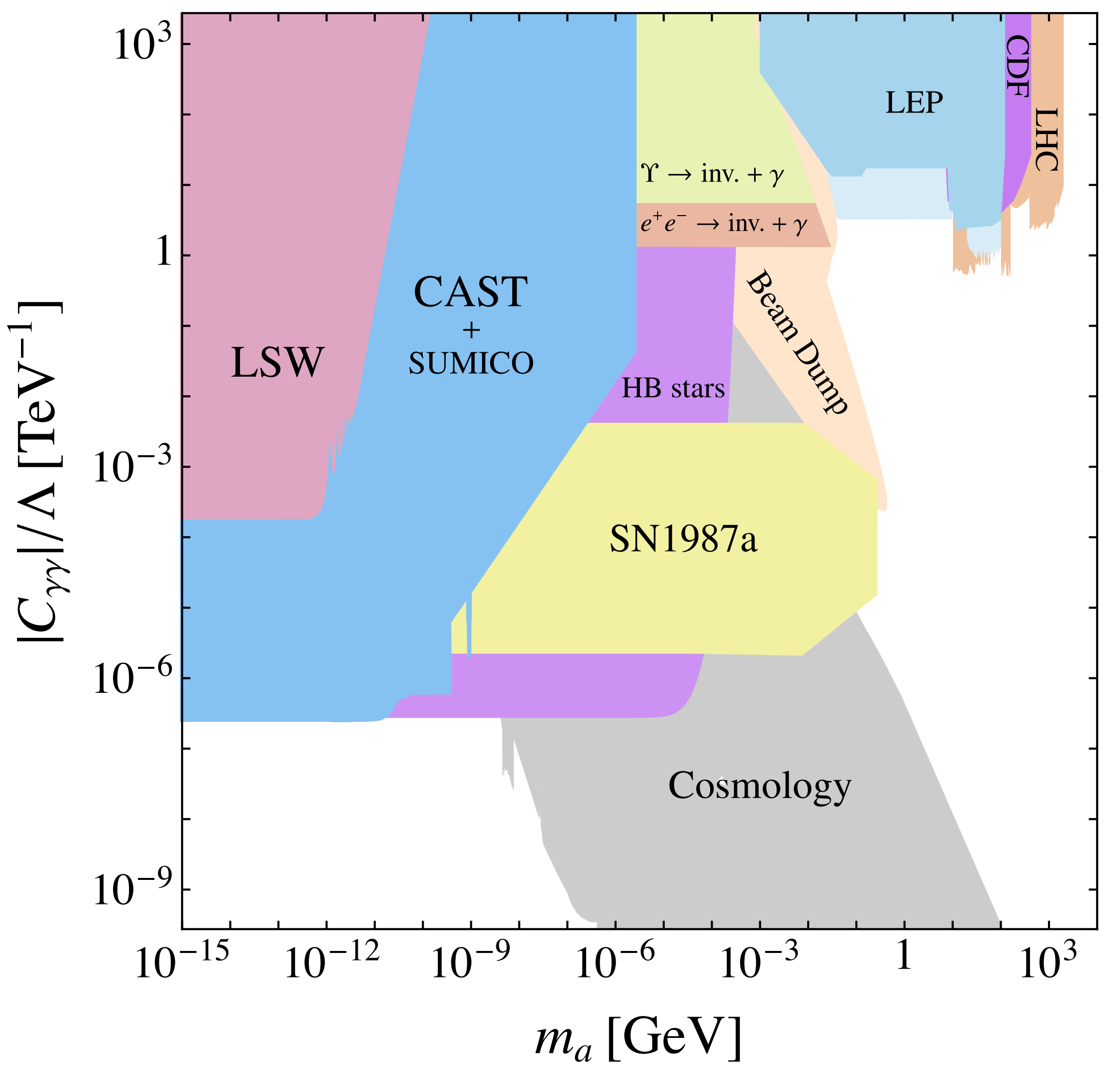
ALP Decays into SM particles

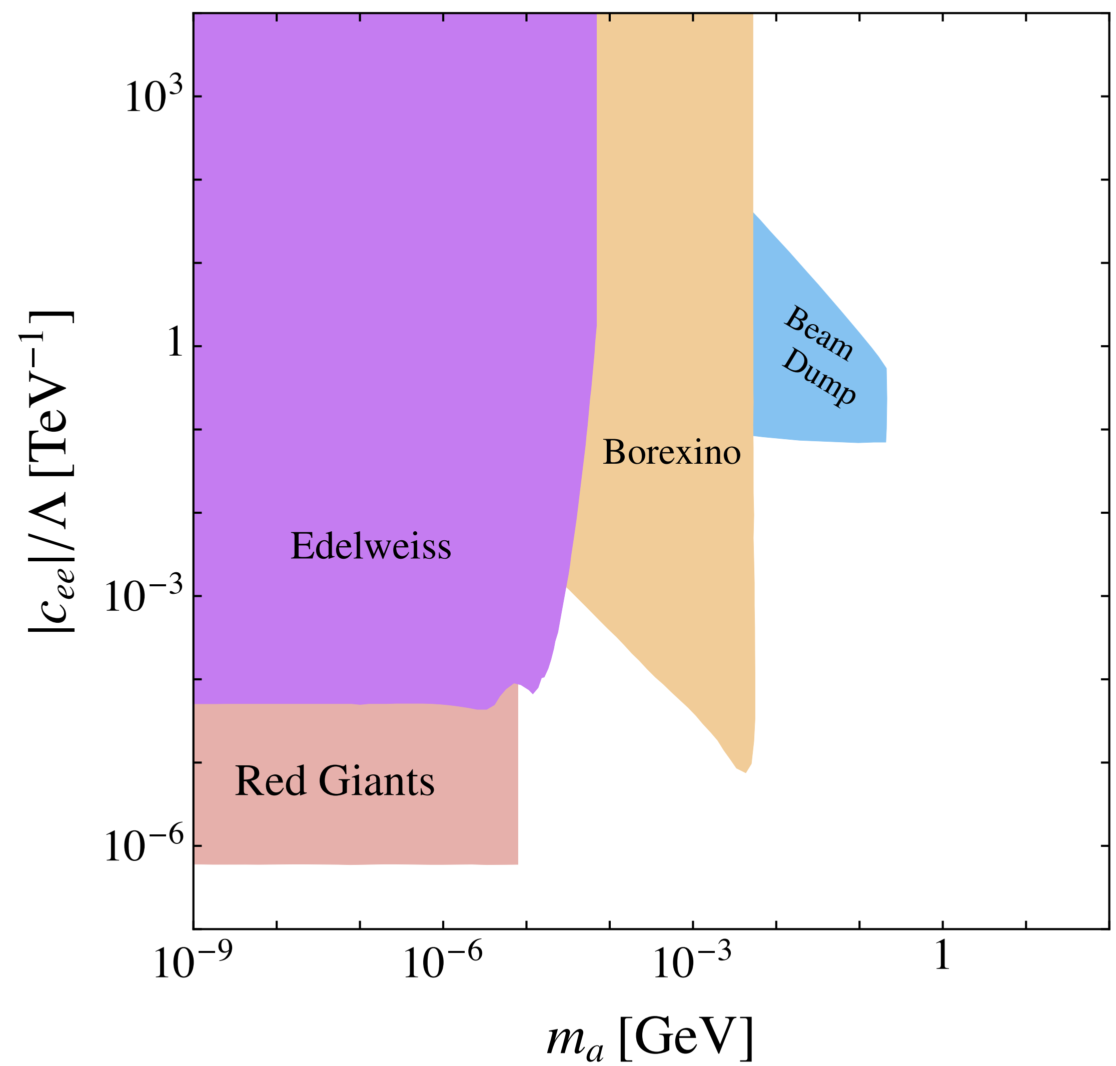
Partial ALP widths for all Wilson coefficients set to 1.



Bounds on ALPs

Even very small couplings are constrained.

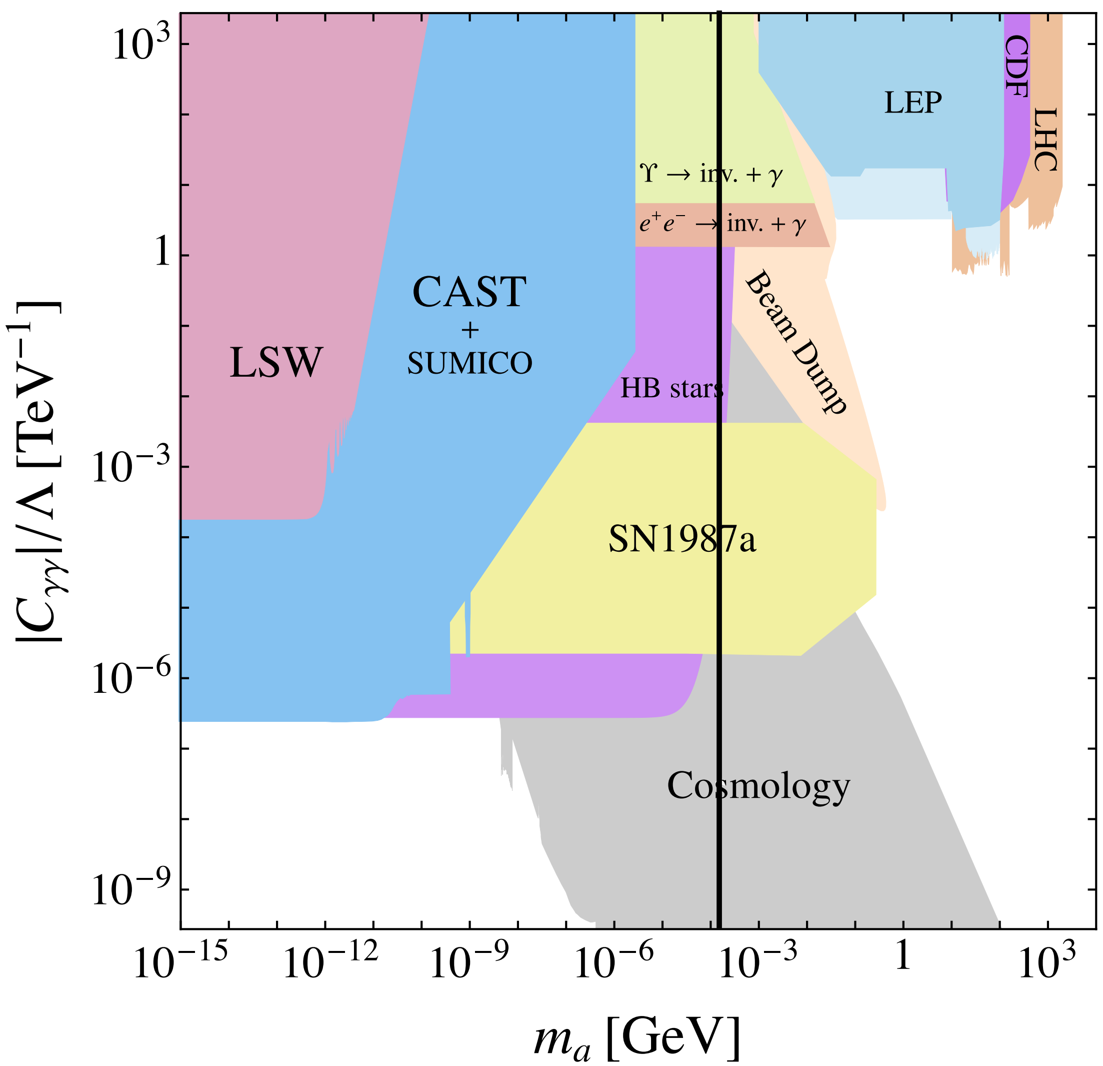




Jaeckel, Spannowsky, Phys. Lett. B 753, 482 (2016)

Armengaud et al., JCAP 1311, 067 (2013) …and others

Bounds on ALPs



Example:

$$C_{\gamma\gamma}^{\text{eff}}(m_a = 100\,\text{keV}) \approx$$

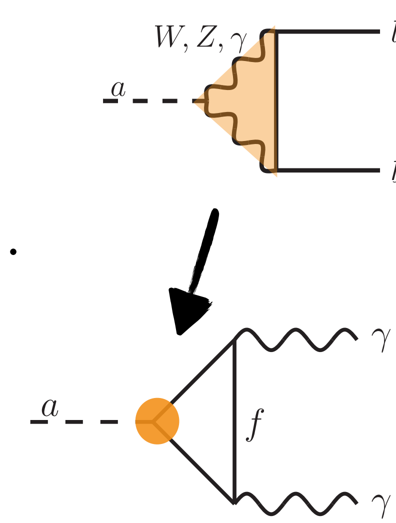
$$C_{\gamma\gamma} - 2\cdot 10^{-5}\, c_{ee} - 5\cdot 10^{-10}\, c_{\mu\mu} - 2\cdot 10^{-12}\, c_{\tau\tau} - \ldots$$

$$- 4\cdot 10^{-12}\, c_{cc} - 1\cdot 10^{-13}\, c_{bb} - 3\cdot 10^{-16}\, c_{tt} + 5\cdot 10^{-15}\, C_{WW}$$

In some cases even 2-loop contributions are relevant

$$\delta c_{ee} \approx -0.8\cdot 10^{-2}\, C_{WW}$$

$$\delta C_{\gamma\gamma}^{\text{eff}}\Big|_{2\text{ Loop}} = 5\cdot 10^{-5}\, C_{WW} + \ldots$$



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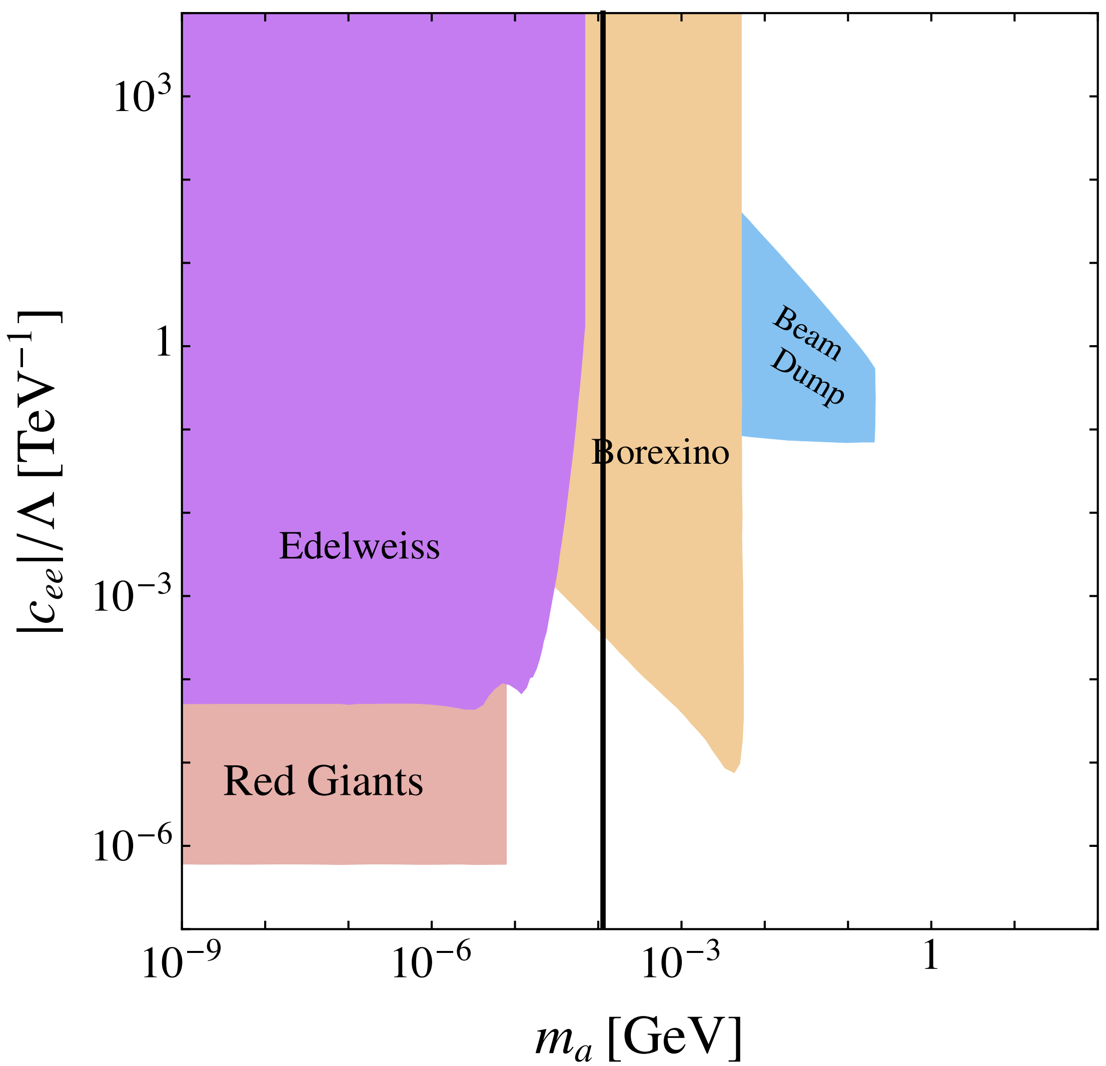
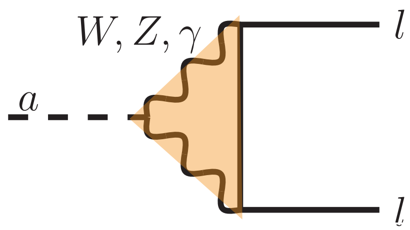


Example:



$$\delta c_{ee} \approx -0.8 \cdot 10^{-2}\, C_{WW}$$

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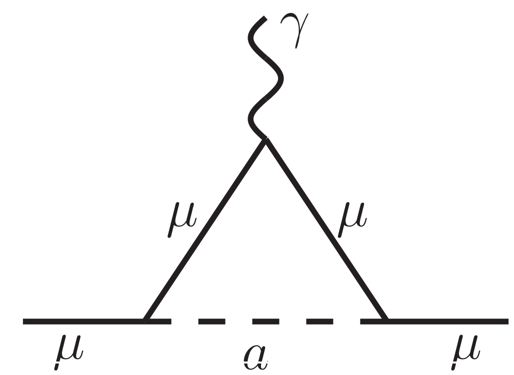
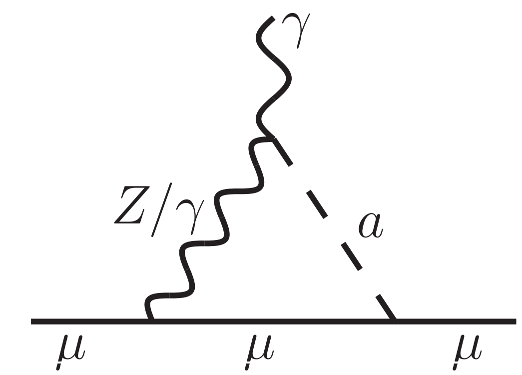
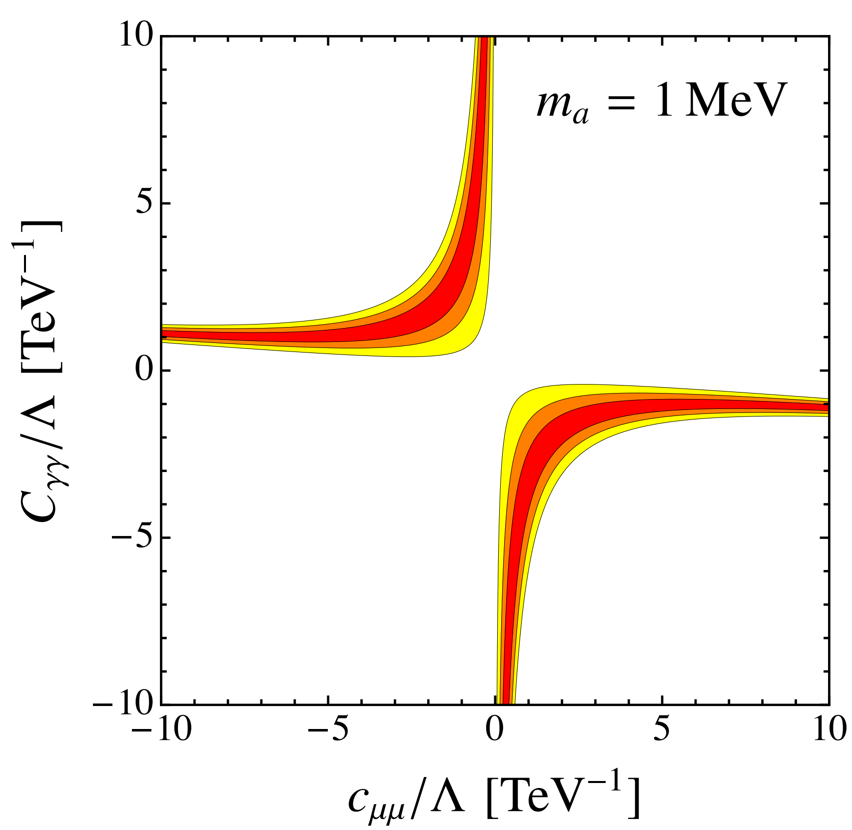
ALPs and (g-2)μ

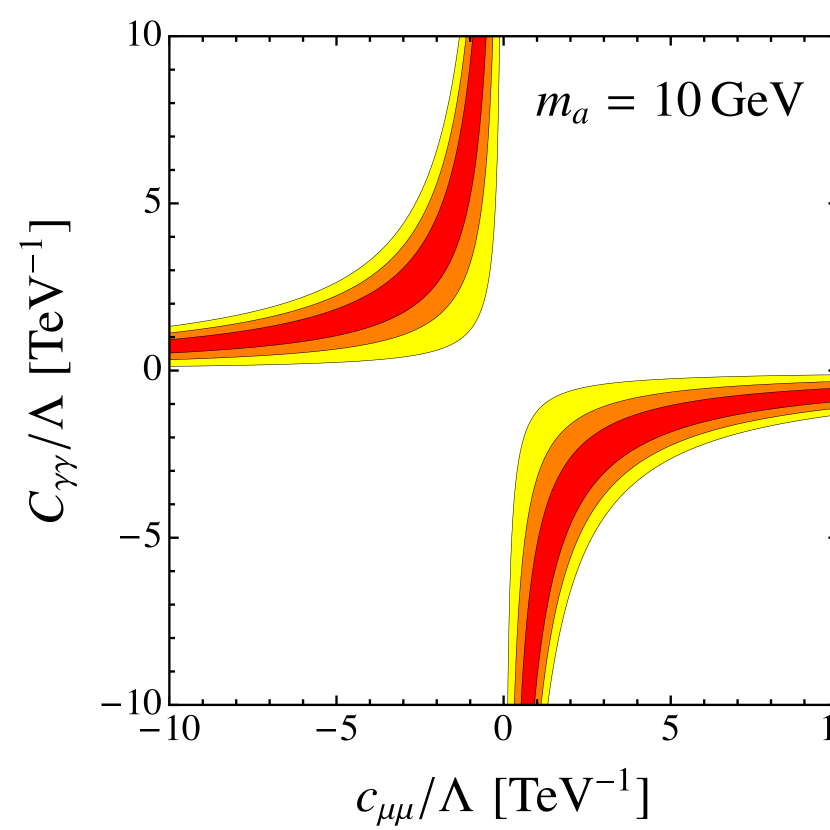




$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\, h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\, c_{\mu\mu}\, C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right] - \frac{\alpha}{2\pi}\,\frac{1-4s_w^2}{s_w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

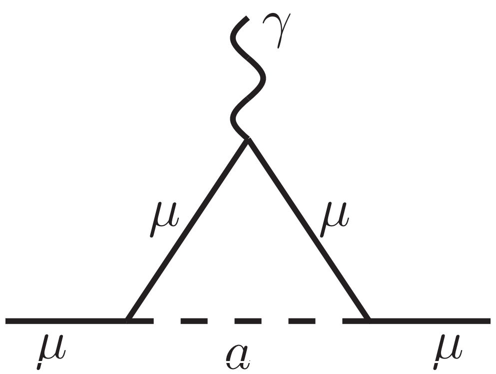
ALPs can explain (g-2)μ for rather sizable photon couplings

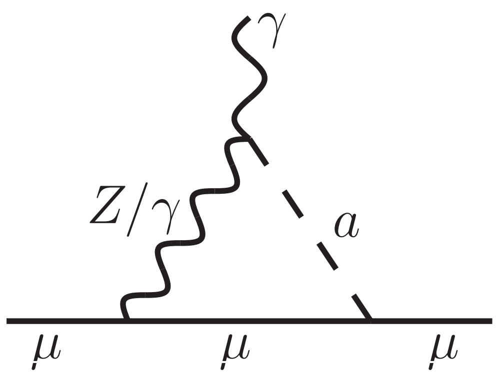


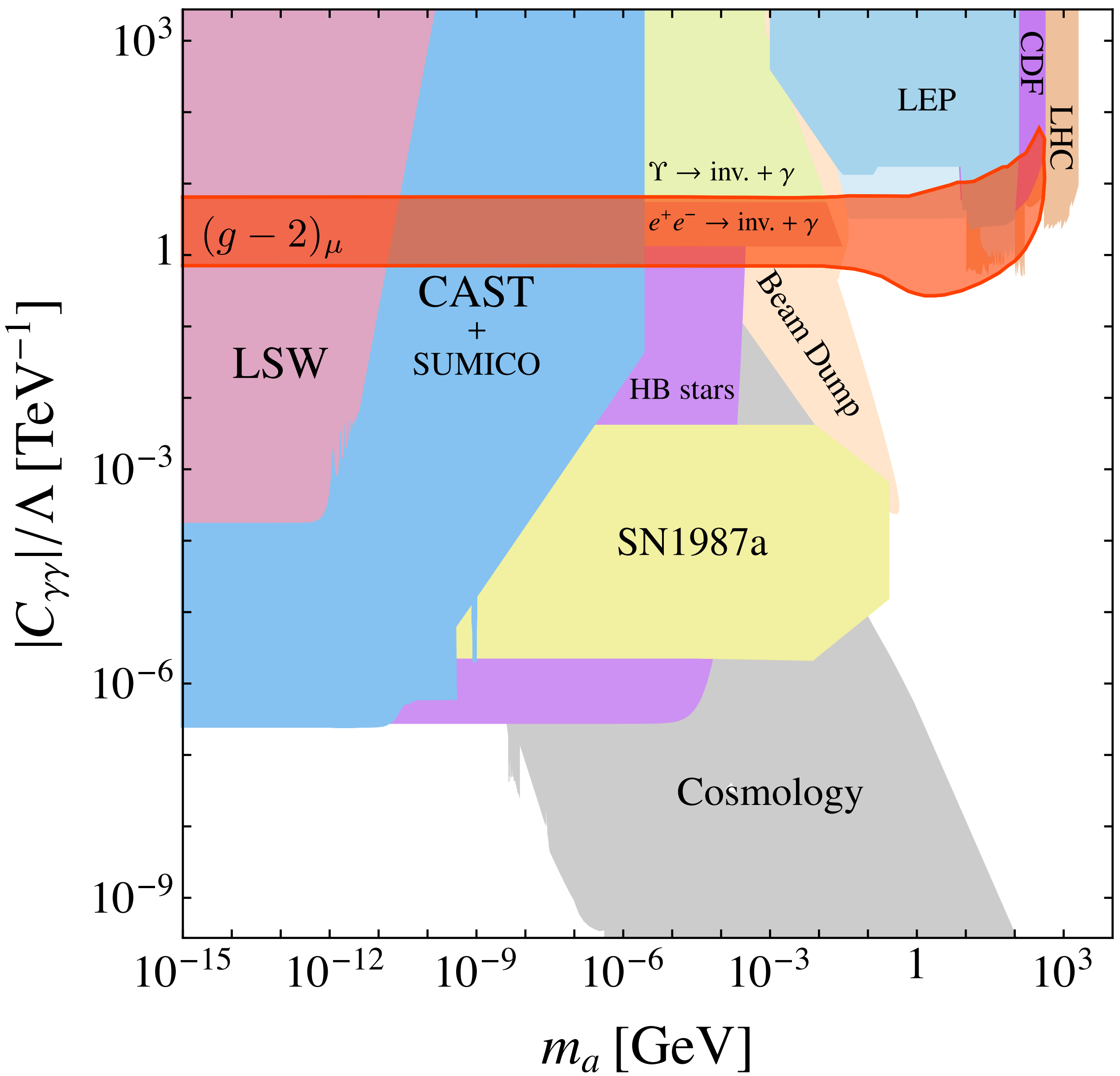


Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94, 115033 (2016)

ALPs and $(g\text{-}2)_\mu$







This explanation is strongly constrained, unless the ALP mass is above ~ 100 MeV.

MB, Neubert, Thamm, 1704.08207

Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94, 115033 (2016)

Higgs Couplings to ALP

At dimension six and seven, derivative couplings to the Higgs appear

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

Dobrescu, Matchev, JHEP 0009, 031 (2000)
Chang, Fox, Weiner, Phys. Rev. Lett 98, 111802 (2007)
Draper, McKeen, Phys. Rev. D 85, 115023 (2012)

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$$h \to aa \qquad\qquad h \to Za$$

Dobrescu, Matchev, JHEP 0009, 031 (2000)
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$$h \to aa \qquad\qquad h \to Za$$

What about the Dimension 5 operator?

$$O_{Zh} = \frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right) \to -\frac{g}{2c_w}\,\frac{(\partial^\mu a)}{\Lambda}\,Z_\mu\,(v+h)^2$$

Higgs Couplings to ALP

At first sight, the h-> aZ decay can be mediated at dimension 5

$$O_{Zh} = \frac{(\partial^\mu a)}{\Lambda} \left(\phi^\dagger \, iD_\mu \, \phi + \mathrm{h.c.}\right) \to -\frac{g}{2c_w} \frac{(\partial^\mu a)}{\Lambda} Z_\mu \, (v+h)^2$$

But this operator can be eliminated using the EoMs for the Higgs current

$$\partial^\mu \left(\phi^\dagger iD_\mu \, \phi + \mathrm{h.c.}\right) \to -\left(1+\frac{h}{v}\right) \sum_f 2T_3^f \, m_f \, \bar{f} \, i\gamma_5 f$$

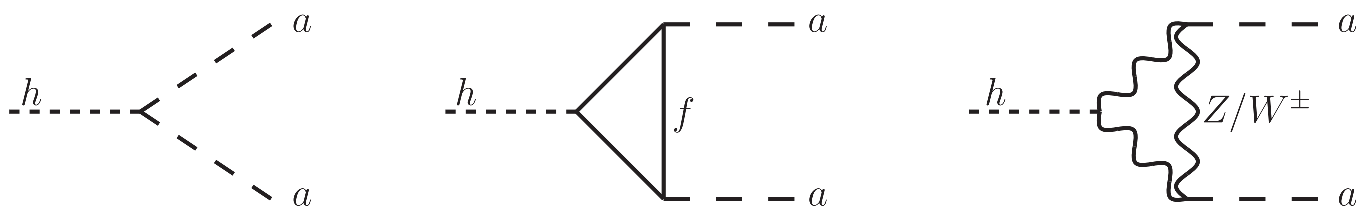
Exotic Higgs decays cannot be mediated by this operator.

Exotic Higgs Decays: $h \to aa$

Due to the shift symmetry, h -> aa is mediated at dimension 6

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

Contributions at tree- and loop level



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

$$- \frac{3\alpha}{4\pi s_w^2 c_w^2}\left(\frac{g^2}{c_w^2}\, C_{ZZ}\right)^2 \left[\ln\frac{\mu^2}{m_Z^2} + \delta_1 - g_2(\tau_{Z/h})\right]$$

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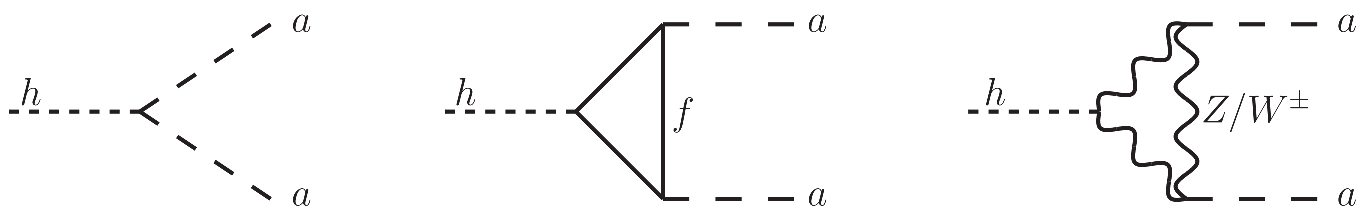


Can give sizable contributions

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

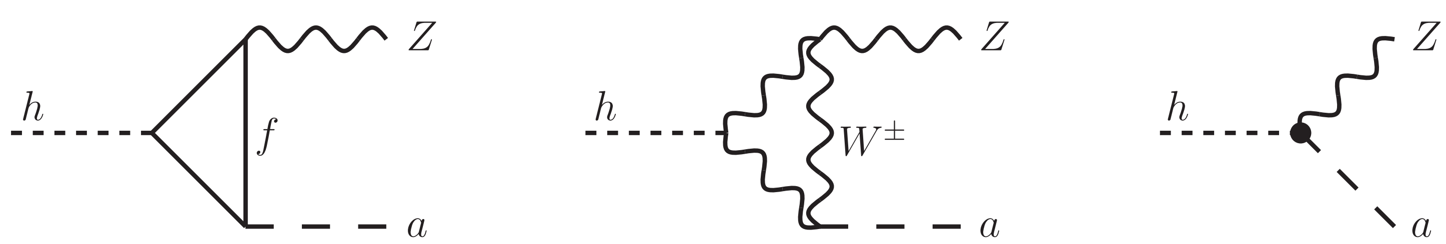
Exotic Higgs Decays: $h \to Za$

Turning to h -> Za

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left|C_{Zh}^{\text{eff}}\right|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right) \qquad \lambda(x,y) = (1-x-y)^2 - 4xy$$

Contributions at tree- and loop level

$$C_{Zh}^{\text{eff}} = C_{Zh}^{(5)} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \qquad \lim_{m_t \to \infty} F \to 1$$



MB, Neubert, Thamm, PRL 117, 181801 (2016)

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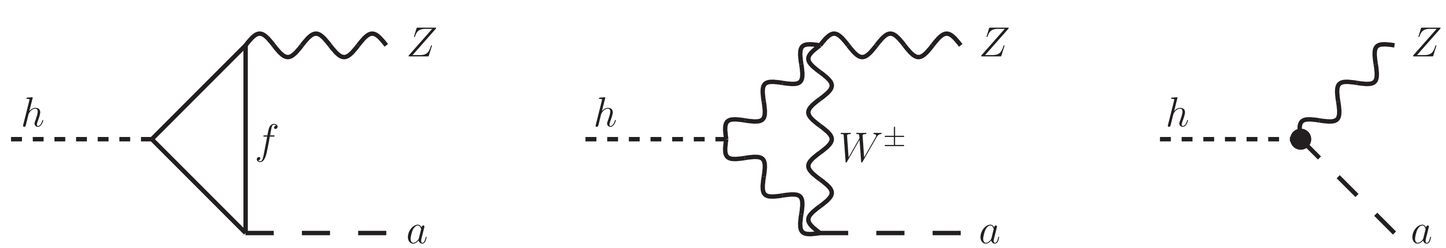
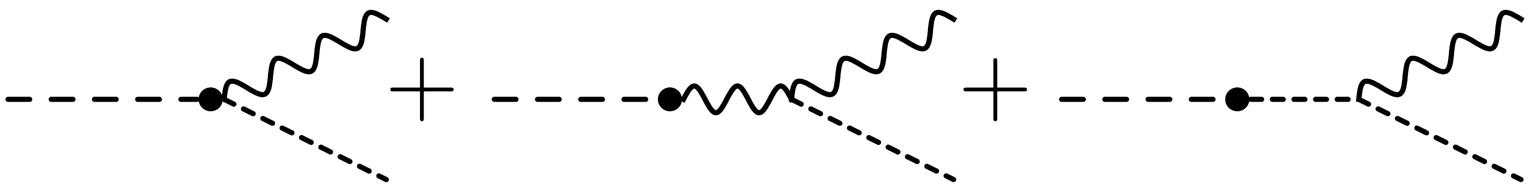


this seems to be a contradiction…

The Puzzle of the top contribution

The dimension five contribution does, in fact, vanish

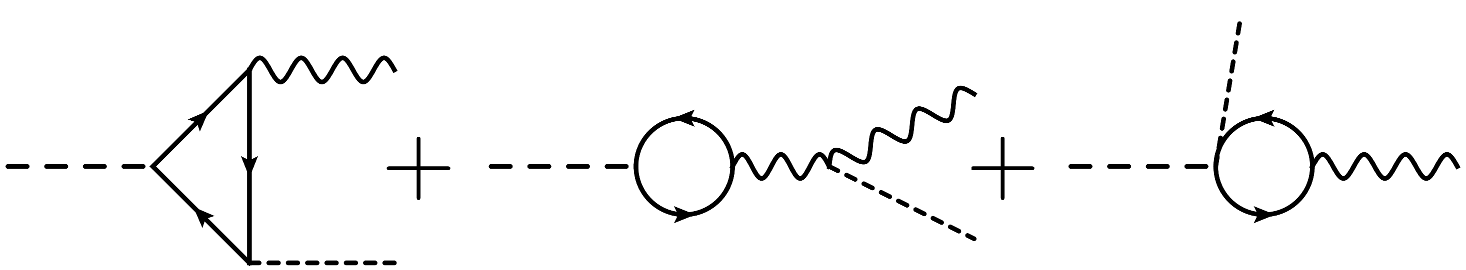


$$= 0$$

in accordance with the EoMs

$$O_{Zh} = \frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\,\phi + \mathrm{h.c.}\right) \;\to\; -\frac{a}{\Lambda}\Big(1+\frac{h}{v}\Big)\sum_f 2T_3^f\, m_f\, \bar{f}\, i\gamma_5 f$$

but the top contribution does not



$$= \; -\frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F$$

…what t.. h.. is going on?

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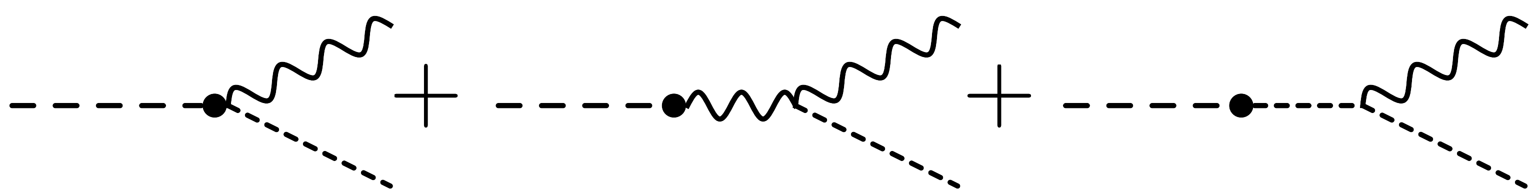

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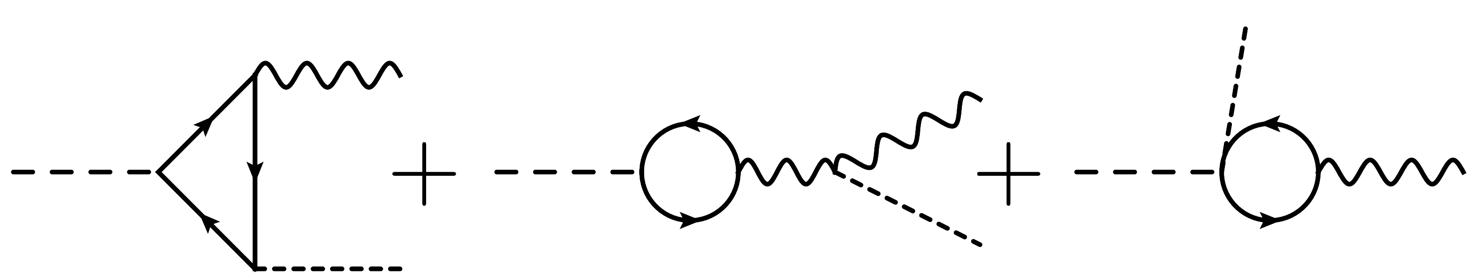


$$= \; - \frac{N_c \, y_t^2}{8\pi^2} \, T_3^t \, c_{tt} \, F$$

...what t.. h.. is going on?

The Puzzle of the top contribution

The top quark gets its mass from the electroweak scale. Integrating it out therefore induces a non-polynomial operator

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

MB, Neubert, Thamm, PRL 117, 181801 (2016)

This is not new. Integrating out New Physics leads to the operators

$$\mathcal{O}_1 = c_1 \frac{\alpha_s}{4\pi v^2} G_{\mu\nu}^a G_a^{\mu\nu} H^\dagger H \qquad \mathcal{O}_2 = c_2 \frac{\alpha_s}{8\pi} G_{\mu\nu}^a G_a^{\mu\nu} \log\left(\frac{H^\dagger H}{\mu^2}\right)$$

with consequences for Higgs pair production. The top only generates c_2 and $C_{Zh}^{(5)}$.

Pierce, Thaler, Wang, JHEP 0705, 070 (2007)

The Puzzle of the top contribution

Vectorlike Quarks

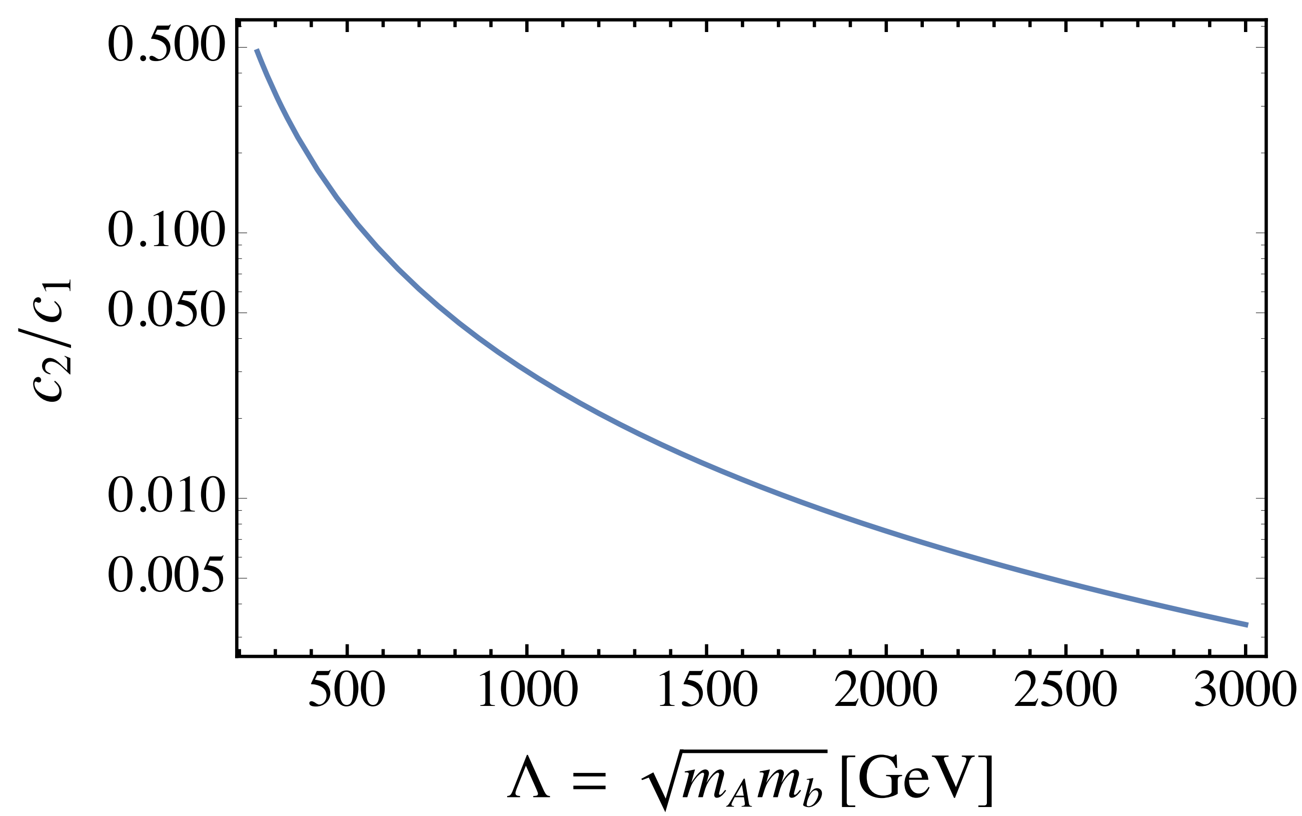
$$-\mathcal{L}_{\text{mass}} = \lambda_1 \left(QHT^c + Q\tilde{H}B^c \right) + \lambda_2 \left(Q^c\tilde{H}T + Q^cHB \right) + m_A QQ^c + m_B(TT^c + BB^c) + \text{h.c.},$$

generate

$$c_1 = \frac{4}{3}\frac{-\beta}{(1-\beta)^2}$$

$$c_2 = \frac{4}{3}\frac{1}{(1-\beta)^2}$$

$$\beta \equiv \frac{2m_A m_B}{\lambda_1\lambda_2 v^2}.$$



Pierce, Thaler, Wang, JHEP 0705, 070 (2007)

Exotic Higgs Decays: $h \to Za$

What makes h -> Za special, is that the non-polynomial operator is the only dimension 5 operator that mediates that process.

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

Non-electroweak scale contributions only contribute at dimension 7.

This can be confirmed in the non-linear language

$$\mathcal{A}_{2D}(h) = iv^2 {\rm Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a} \mathcal{F}_{2D}(h)$$

Ilarias Talk

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, 1701.05379

This gives a non-trivial handle on the UV completion.

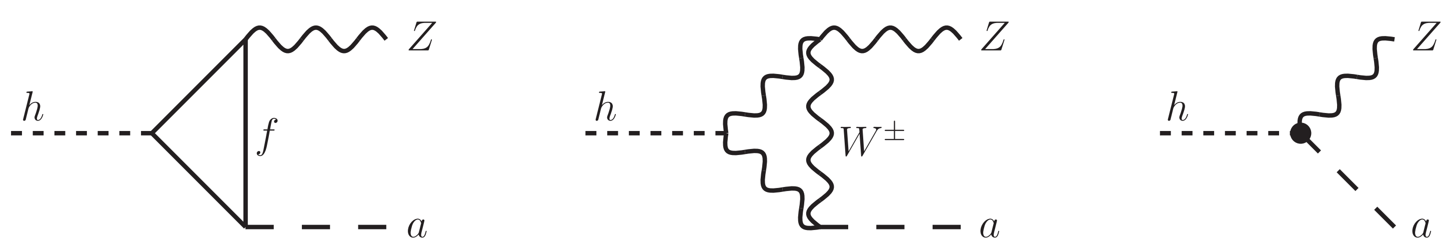
Exotic Higgs Decays: $h \to Za$

Turning to h -> Za

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left|C_{Zh}^{\rm eff}\right|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right) \qquad \lambda(x,y) = (1-x-y)^2 - 4xy$$

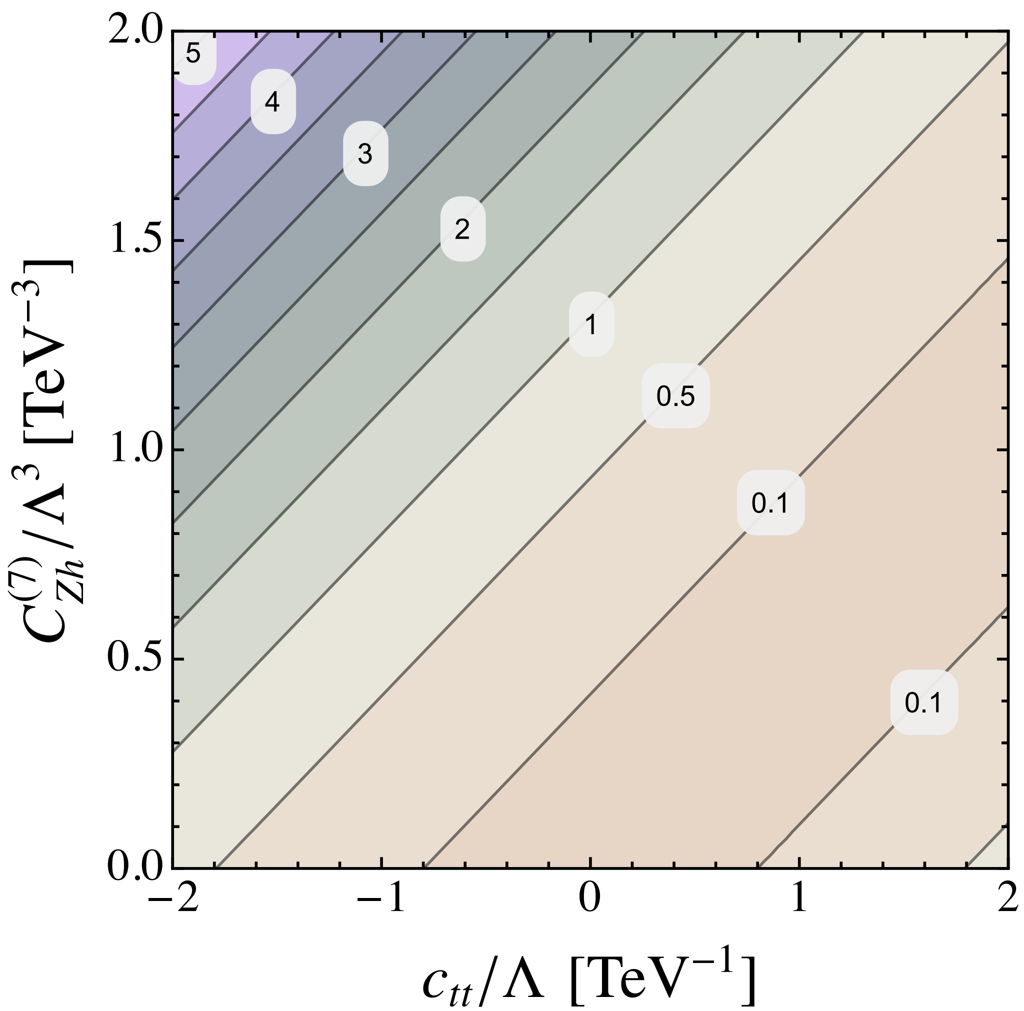
Contributions at tree- and loop level

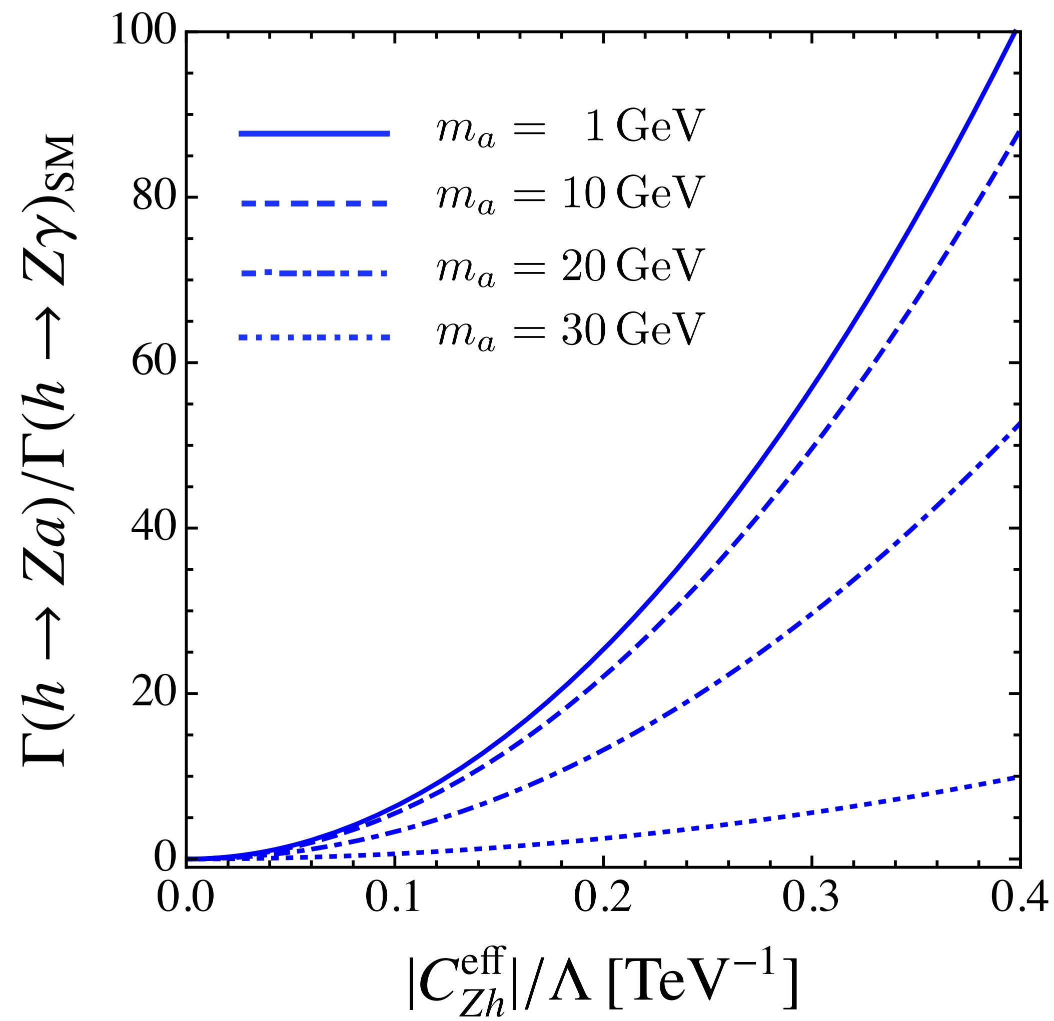
$$C_{Zh}^{\rm eff} = C_{Zh}^{(5)} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \qquad \lim_{m_t \to \infty} F \to 1$$



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

Exotic Higgs Decays: $h \to Za$





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

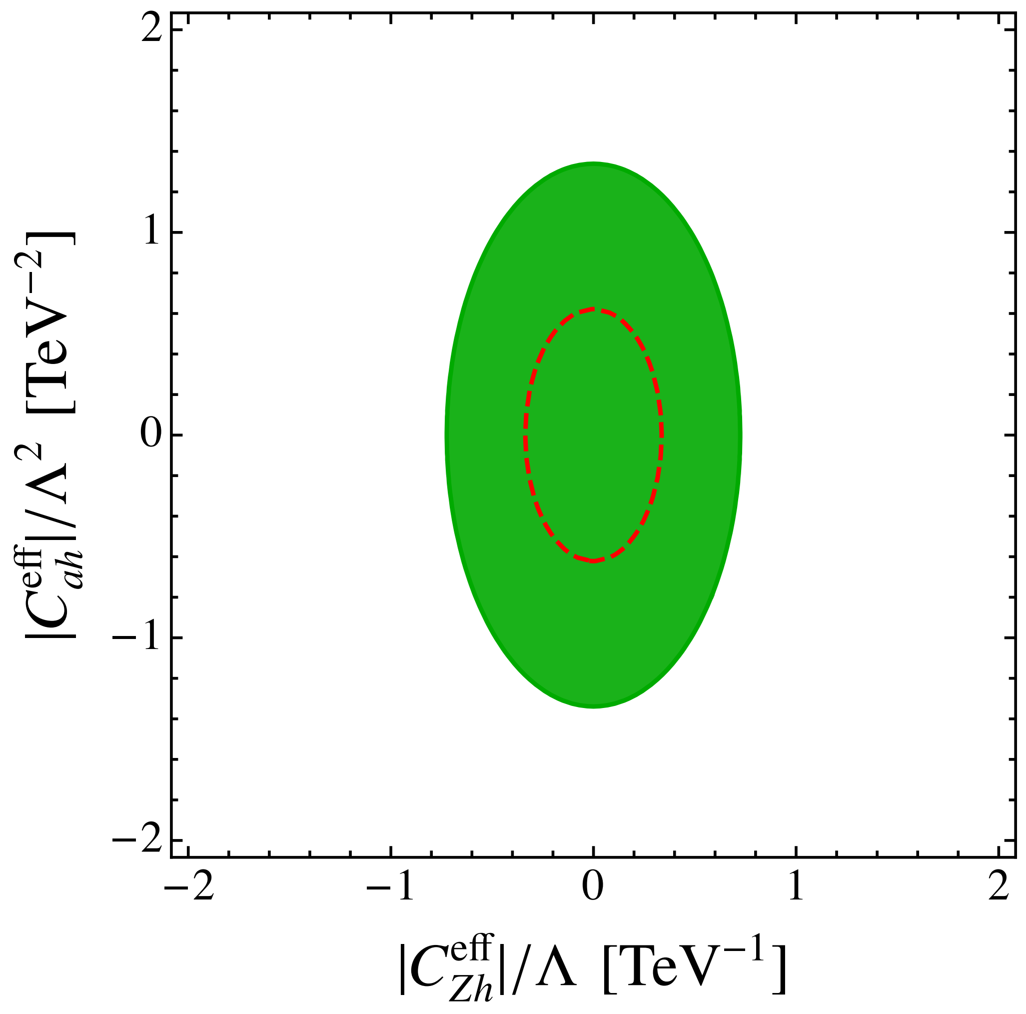
Exotic Higgs Decays

Searches for h -> aa and h -> Za are strongly motivated in various final states. Current constraints:

From h -> BSM decays

$$\left|C_{Zh}^{\text{eff}}\right| < 0.72\left[\frac{\Lambda}{1\,\text{TeV}}\right]^2$$

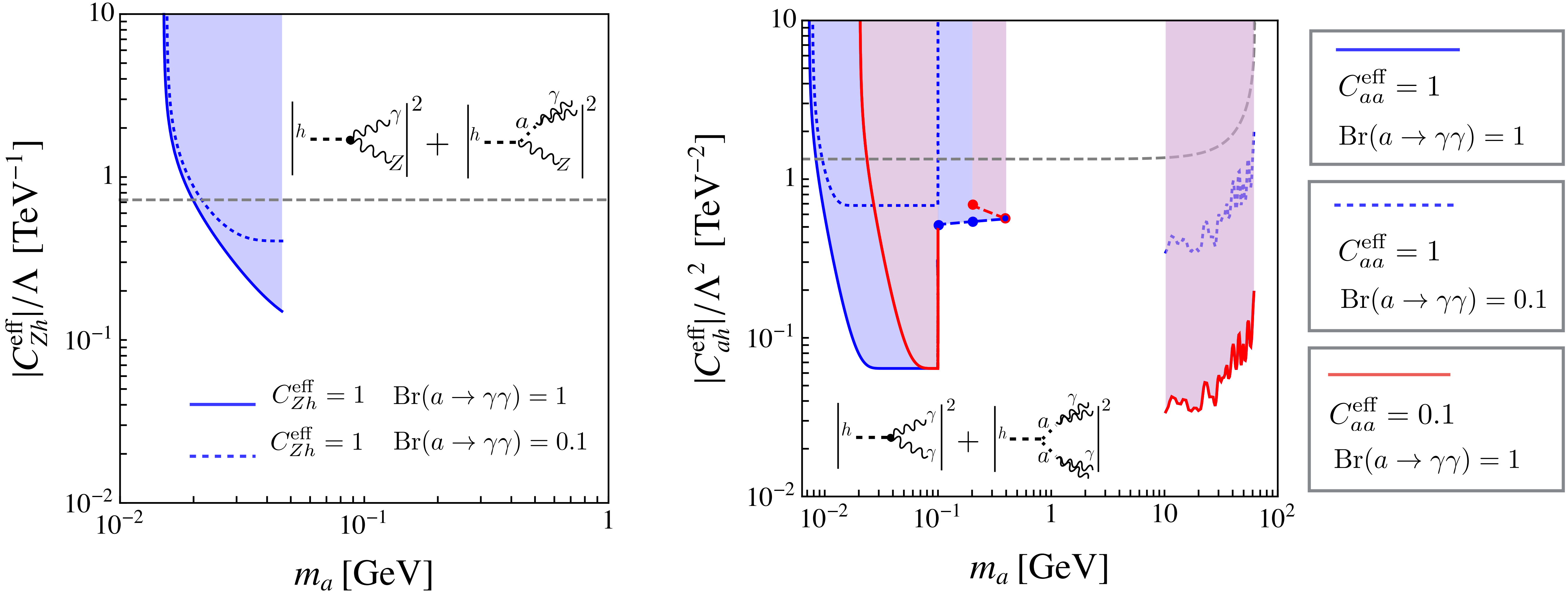
$$\left|C_{ah}^{\text{eff}}\right| < 1.34\left[\frac{\Lambda}{1\,\text{TeV}}\right]^2$$



Exotic Higgs Decays

Searches for h -> aa and h -> Za are strongly motivated in various final states. Current constraints:

From a $a \to \gamma\gamma$ decays

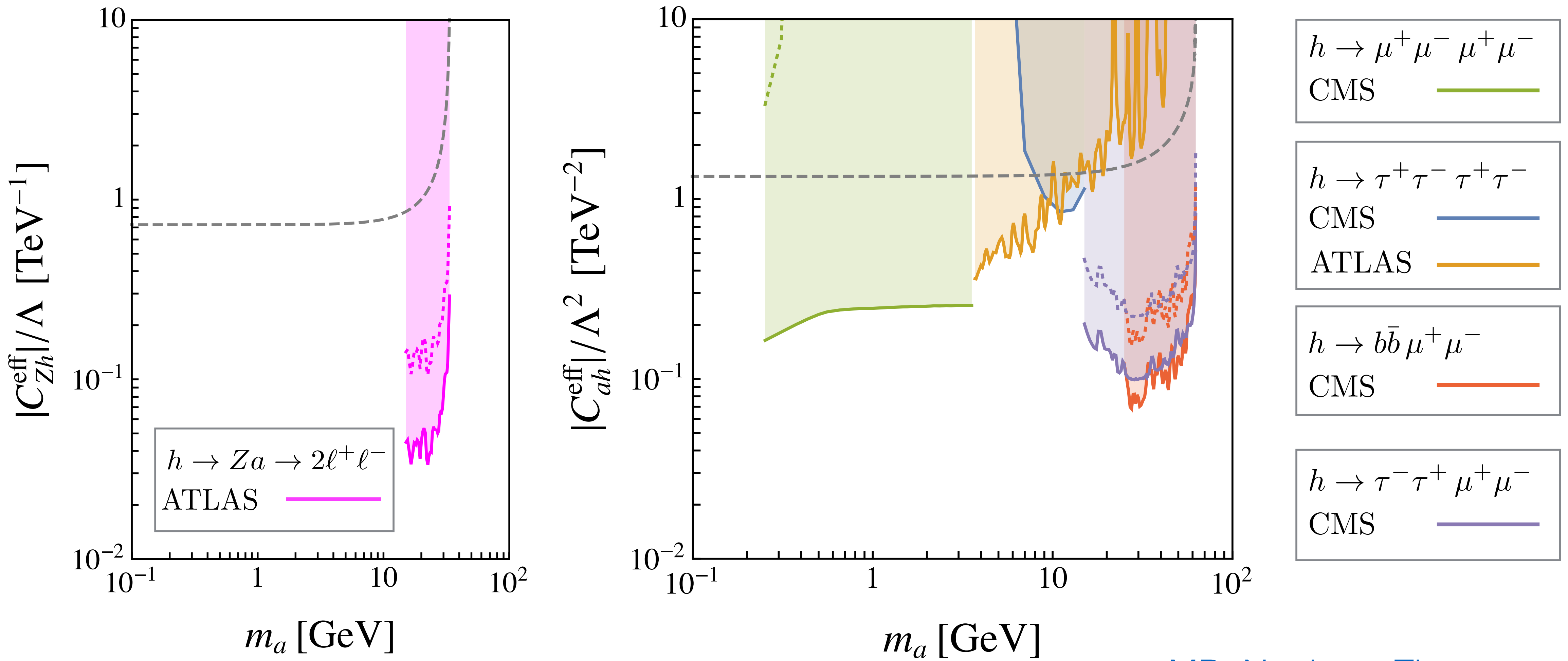


MB, Neubert, Thamm, 1704.08207

Exotic Higgs Decays

Searches for h -> aa and h -> Za are strongly motivated in various final states. Current constraints:

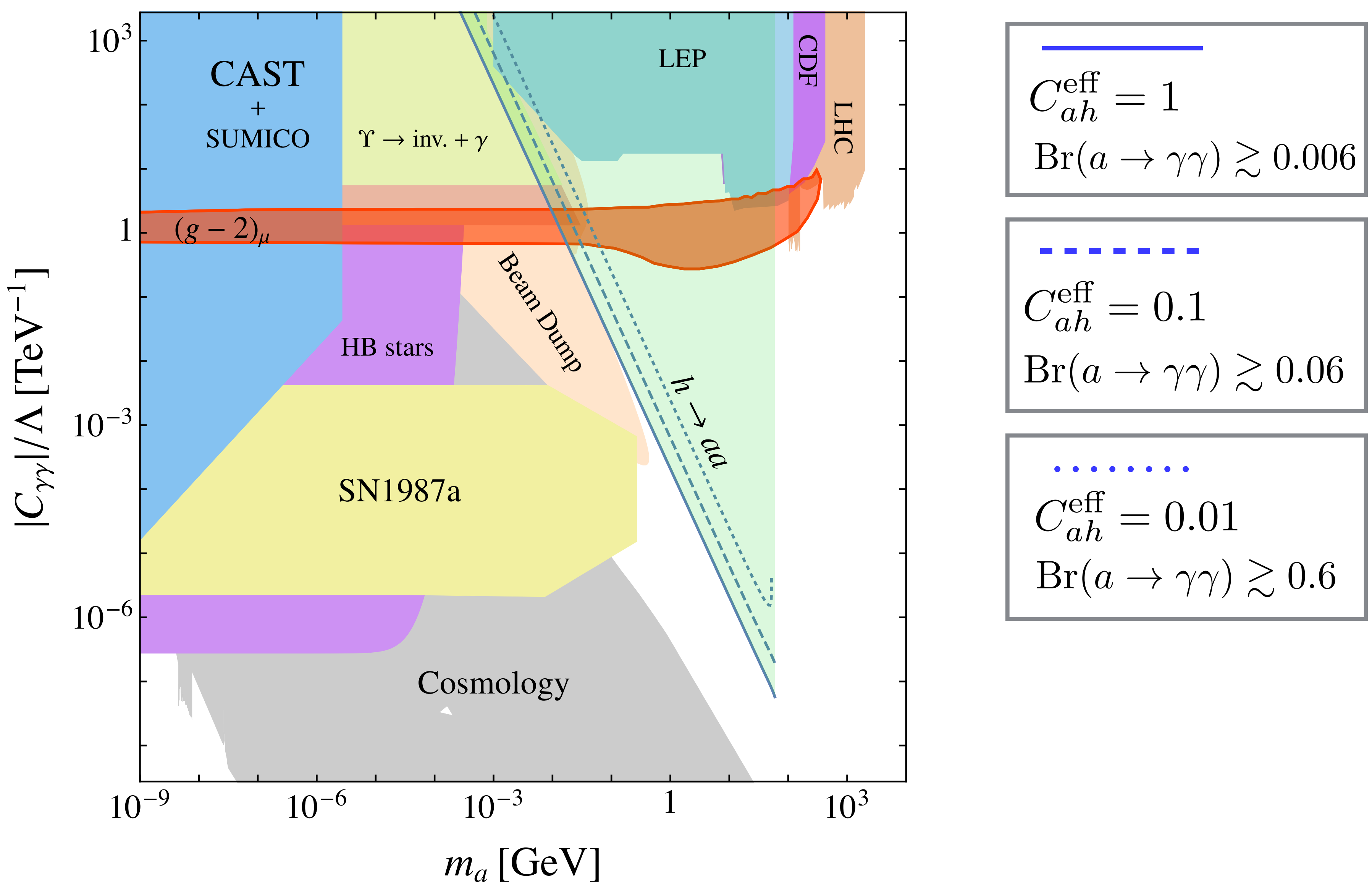
From a $a \to f\bar{f}$ decays



MB, Neubert, Thamm, to appear

Future Searches $h \to aa$

The reach for future searches for h -> Za and h -> aa decays is immense



Ask for 100 events within the full 300 /fb dataset

MB, Neubert, Thamm, 1704.08207

Future Searches $h \to aa$

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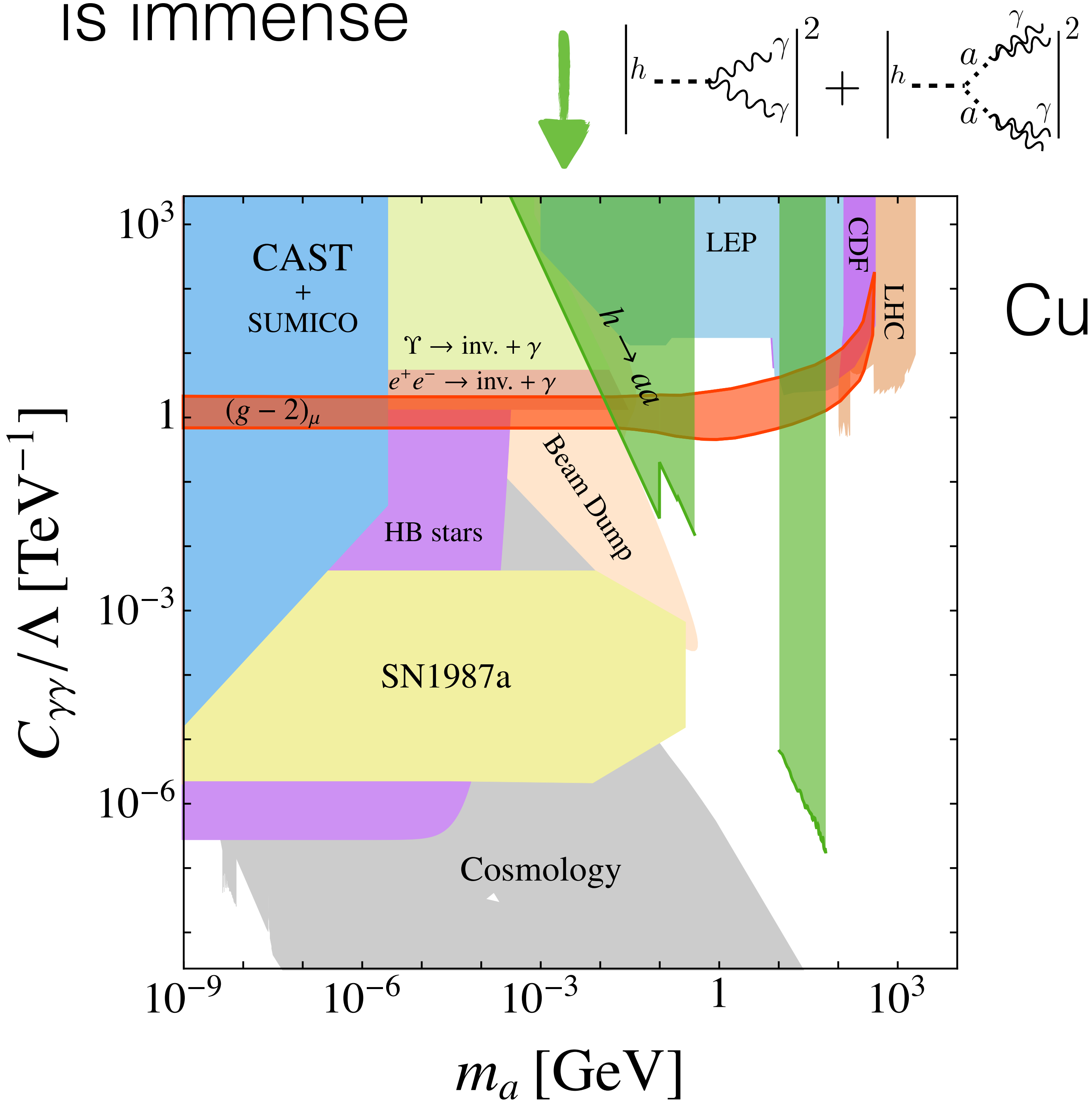

Current bounds hold for $C_{ah}^{\text{eff}} = 1$

MB, Neubert, Thamm, to appear

Future Searches $h \to aa$

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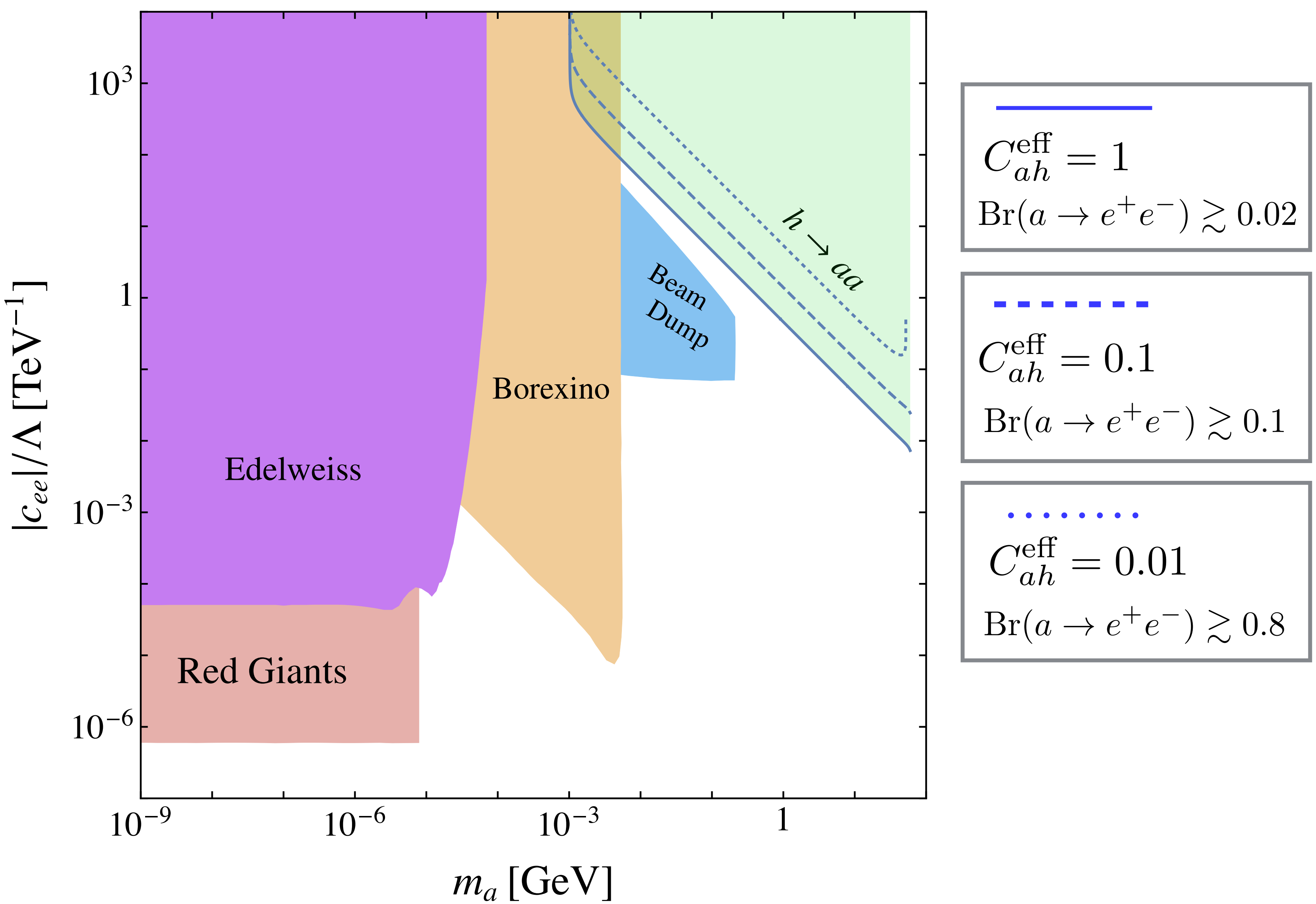


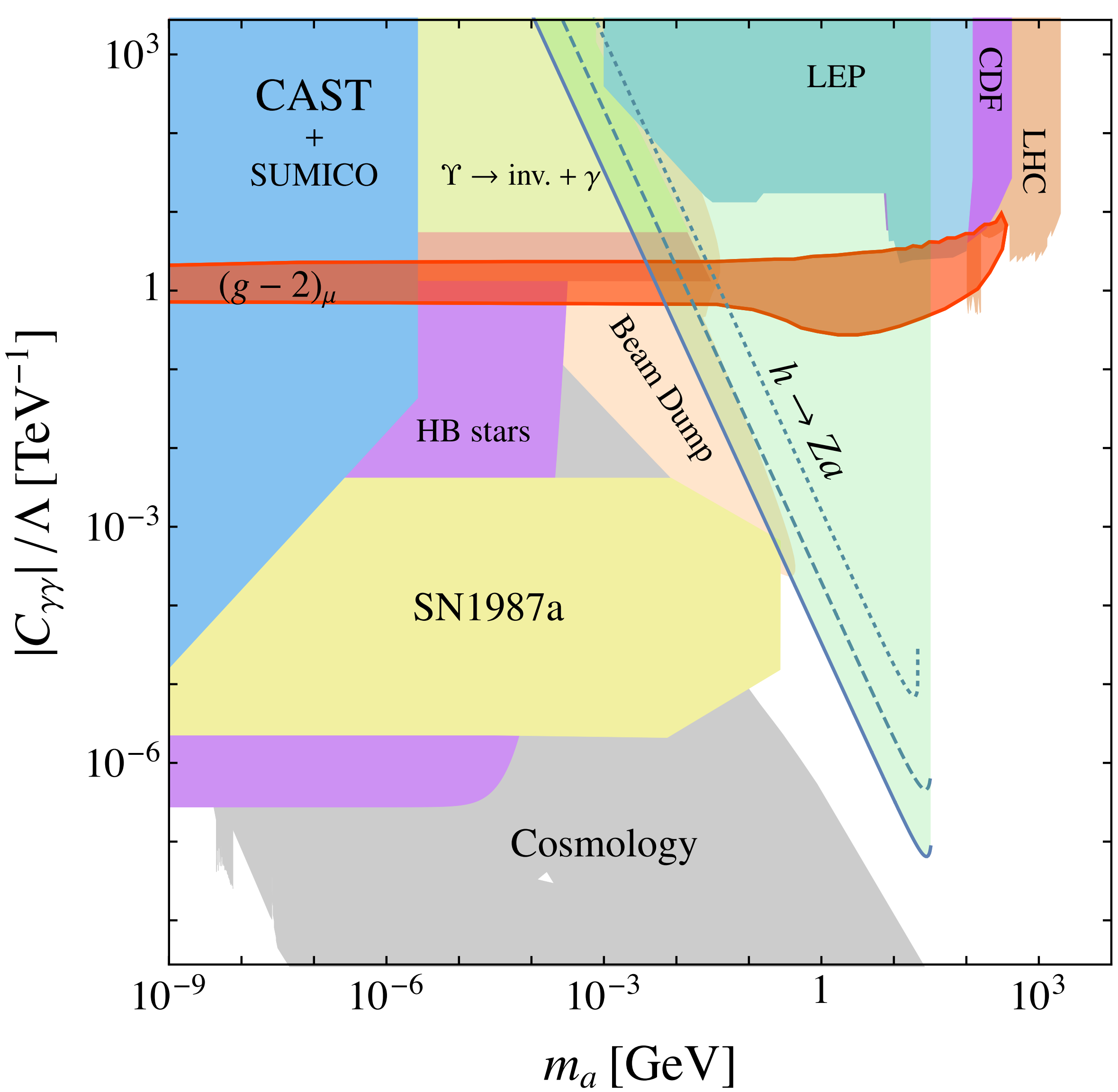
Decays into electrons

Ask for 100 events within the full 300 /fb dataset.

MB, Neubert, Thamm, 1704.08207

Future Searches $h \to Za$

The reach for future searches for h -> Za and h -> aa decays is immense



$C_{Zh}^{\rm eff} = 0.72$
$\mathrm{Br}(a \to \gamma\gamma) \gtrsim 2 \times 10^{-4}$

$C_{Zh}^{\rm eff} = 0.1$
$\mathrm{Br}(a \to \gamma\gamma) \gtrsim 0.011$

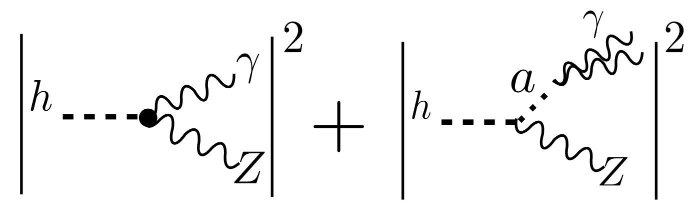
$C_{Zh}^{\rm eff} = 0.015$
$\mathrm{Br}(a \to \gamma\gamma) \gtrsim 0.46$

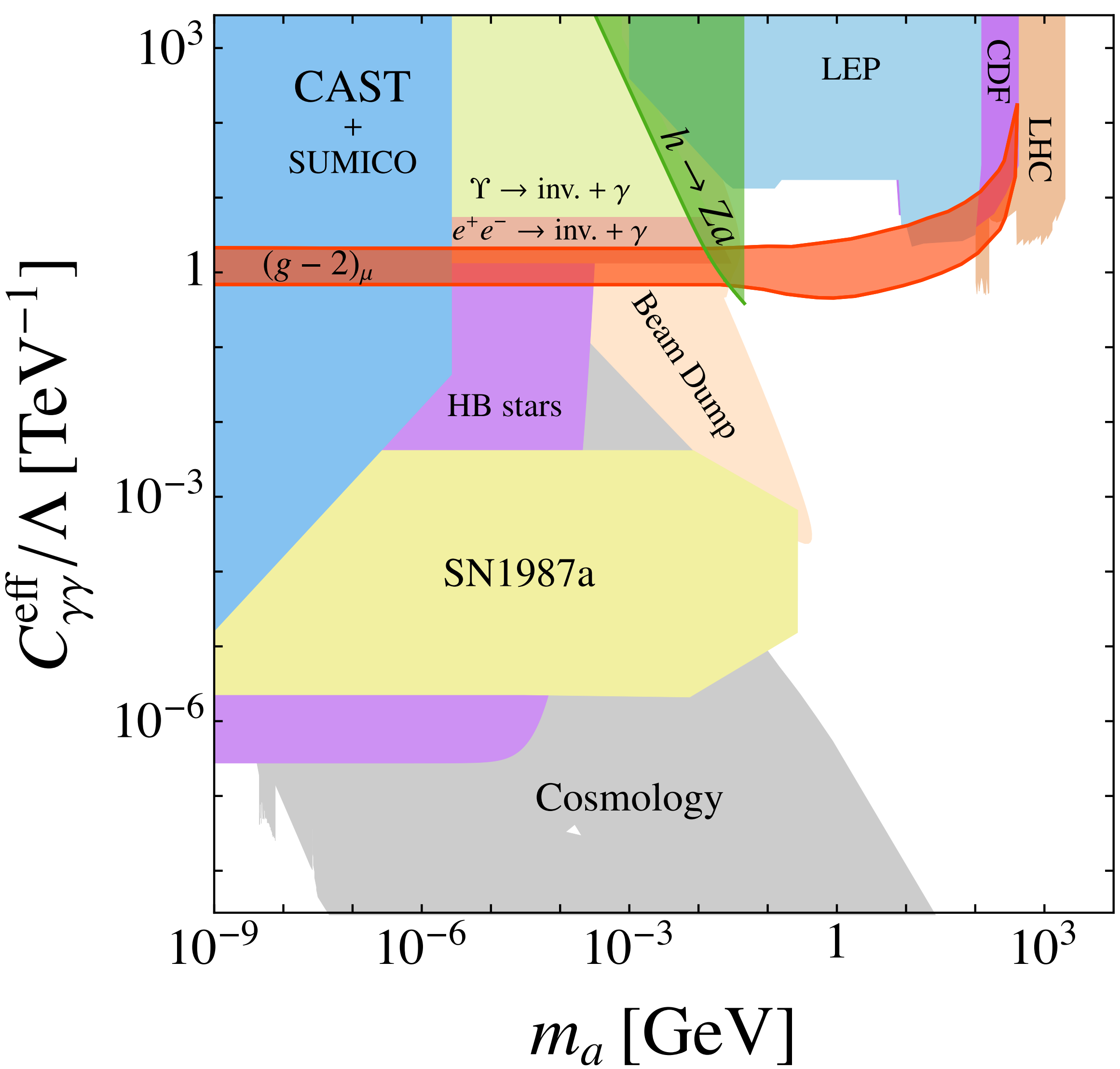
Ask for 100 events within the full 300 /fb dataset.

MB, Neubert, Thamm, 1704.08207

Future Searches $\quad h \to Za$

The reach for future searches for h -> Za and h -> aa decays is immense





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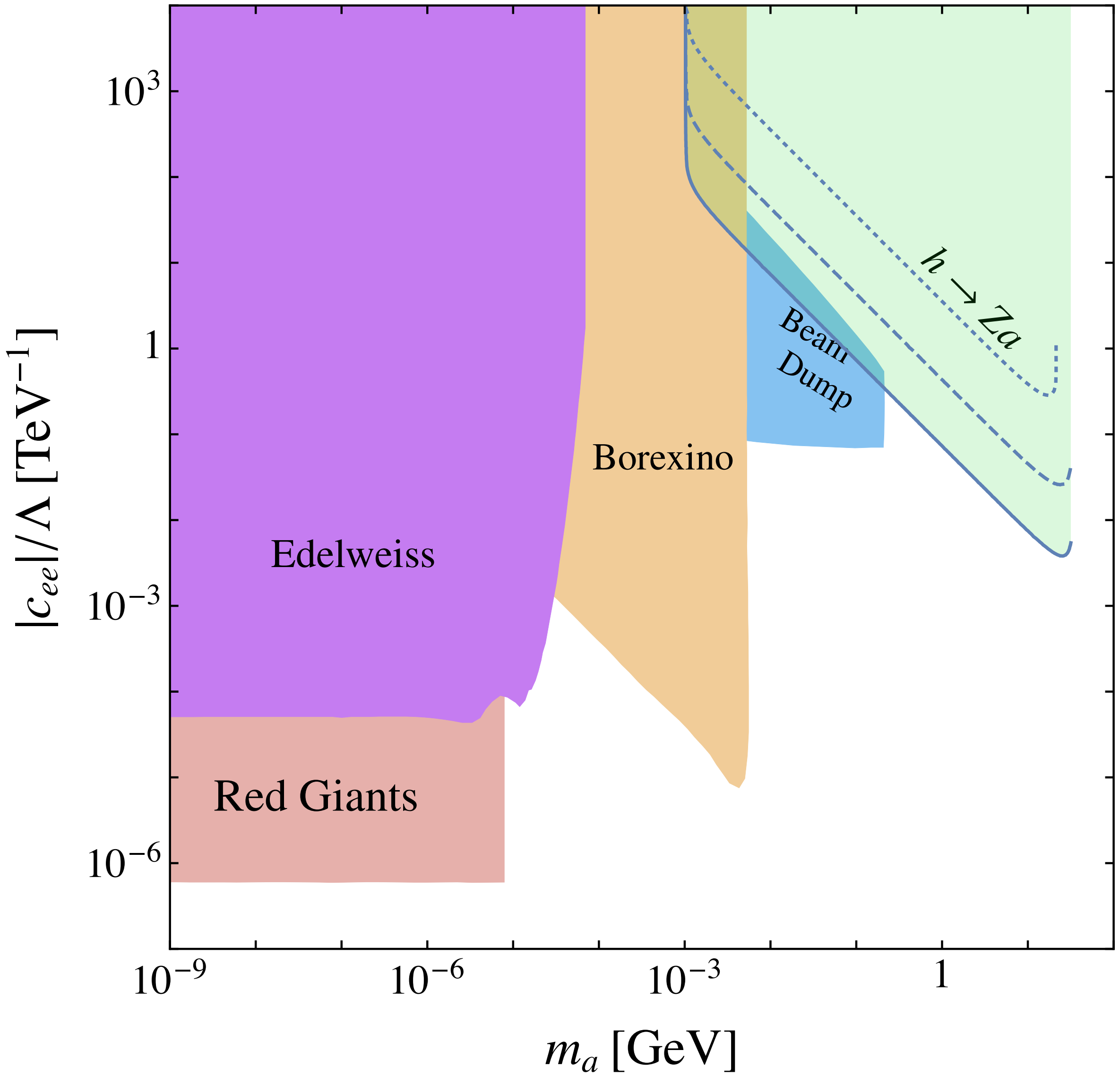
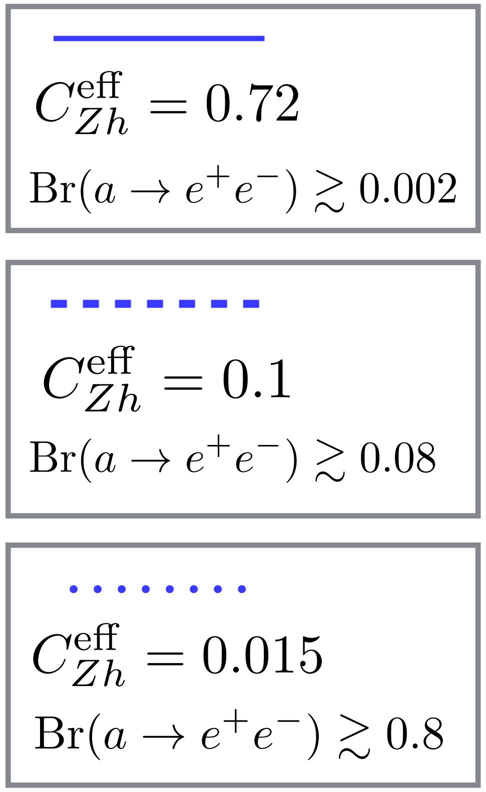
Future Searches $h \to Za$

The reach for future searches for h -> Za and h -> aa decays is immense





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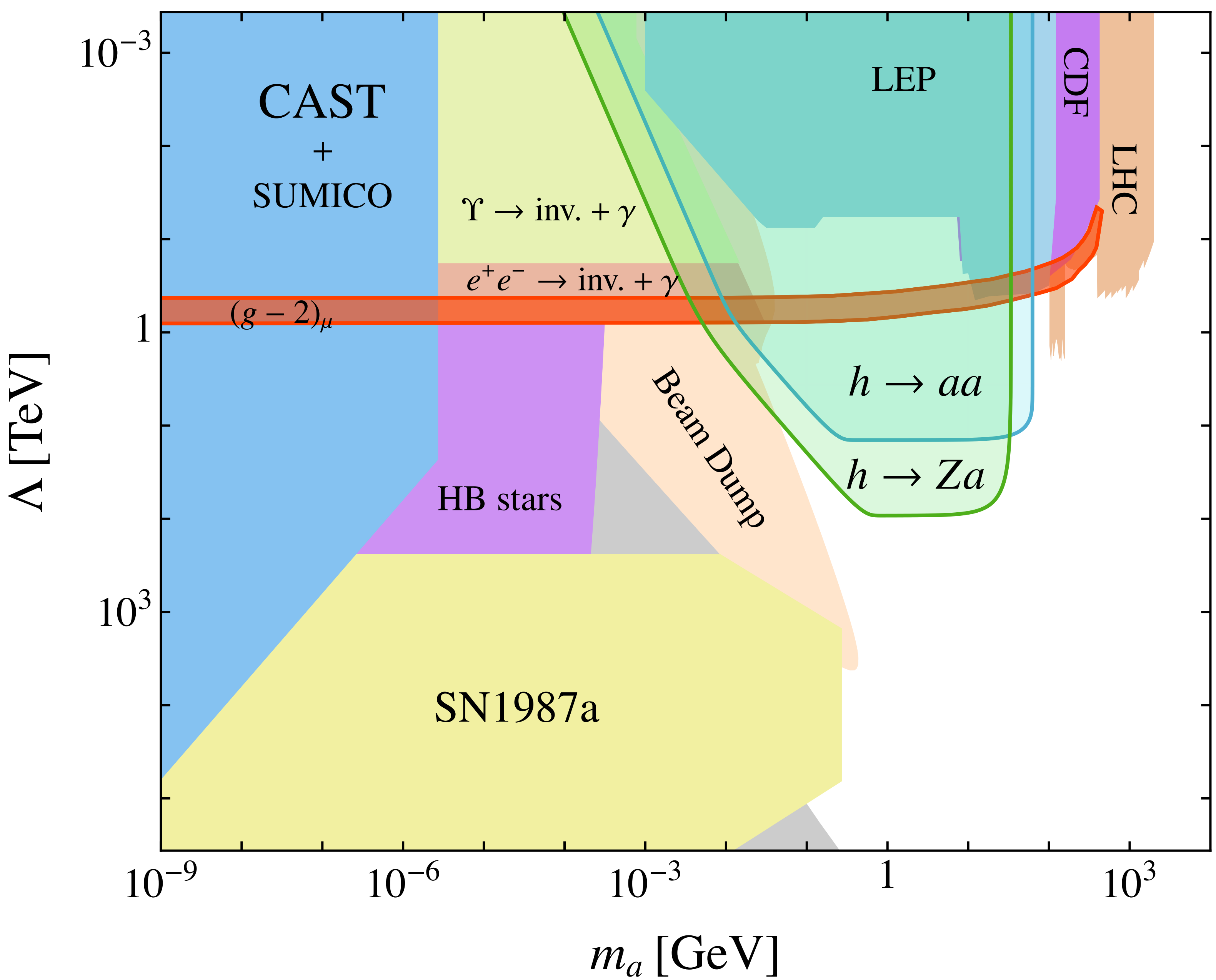
Future Searches

The reach for future searches for h -> Za and h -> aa decays is immense

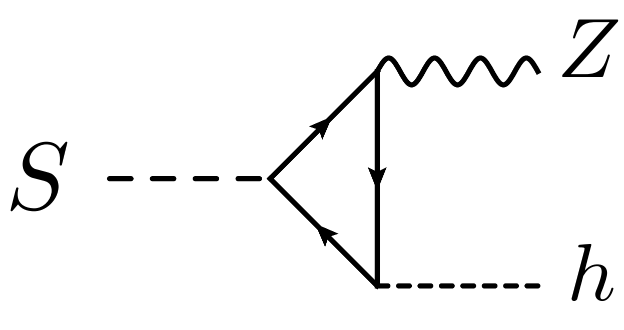


As a bound on the New Physics scale.

MB, Neubert, Thamm, to appear

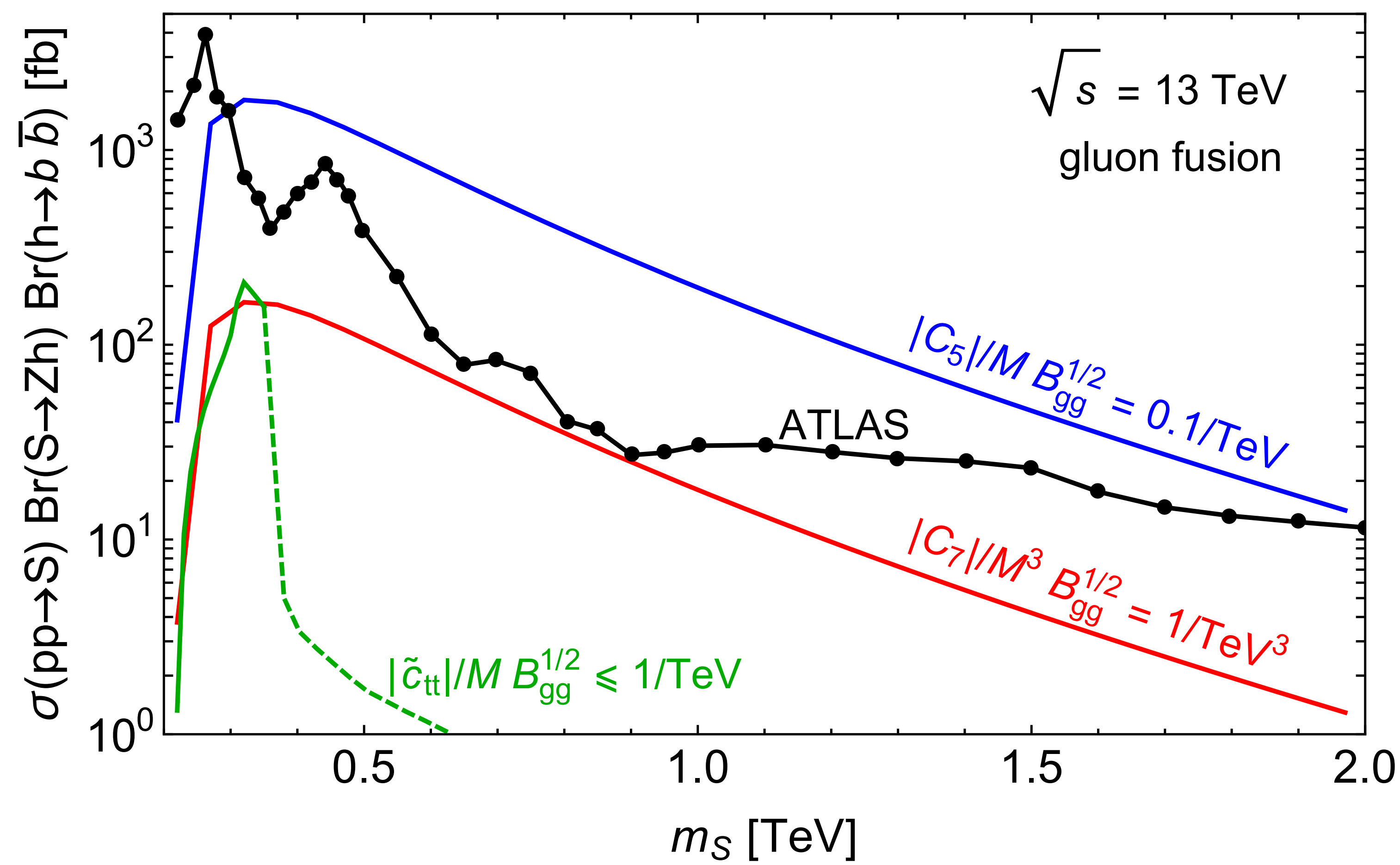
Sidenote: What about S -> Z h ?

If there is a new heavy singlet pseudoscalar S, the process S -> Z h is a cut-and-count CP analyzer.



$$i\mathcal{A}(S \to Zh) = -\frac{2m_Z\,\epsilon_Z^* \cdot p_h}{M}\,C_5^{\rm top}$$

$$\text{with} \quad C_5^{\rm top} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F\,,$$



MB, Neubert, Thamm, PRL 117, 181801 (2016)

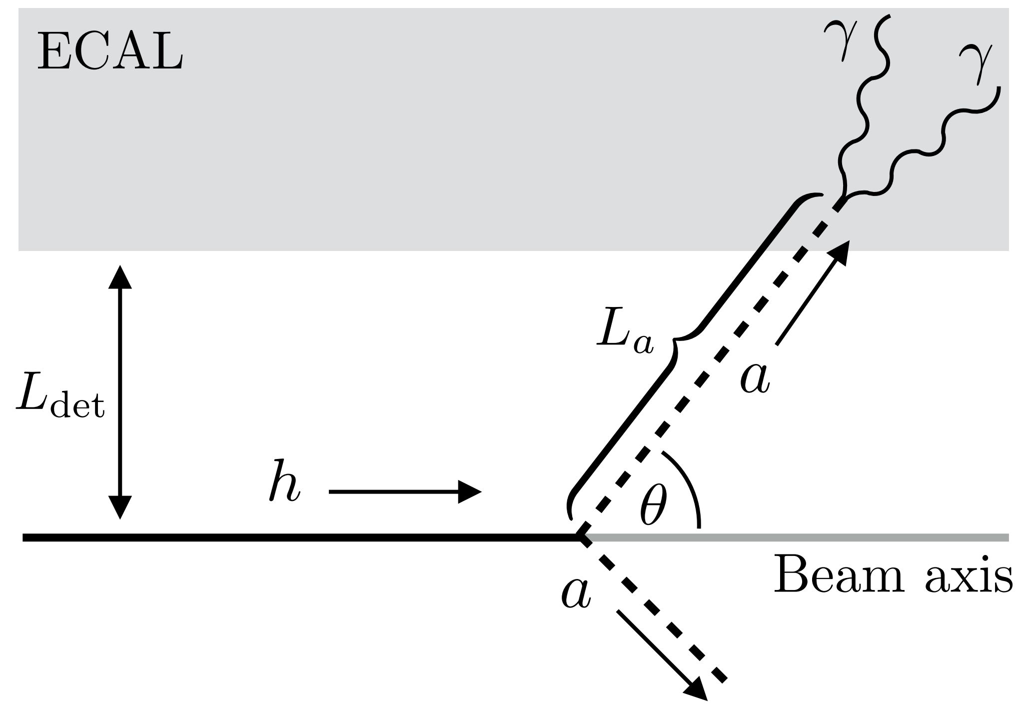
Conclusions

The reach for future searches for h -> Za and h -> aa decays is immense.

They should be done!*

*We have a group in ATLAS actively pursuing this analysis.

Macroscopic Lifetime



Perpendicular decay length

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

Take into account isotropic Higgs decays

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

$$f_{\rm dec}^{aa} = \int_0^{\pi/2} d\theta\,\sin\theta\left(1 - e^{-L_{\rm det}/L_a^\perp(\theta)}\right)^2 \xrightarrow{L_a \gg L_{\rm det}} \left(\frac{L_{\rm det}}{L_a}\right)^2 \ln\frac{1.258 L_a}{L_{\rm det}}$$

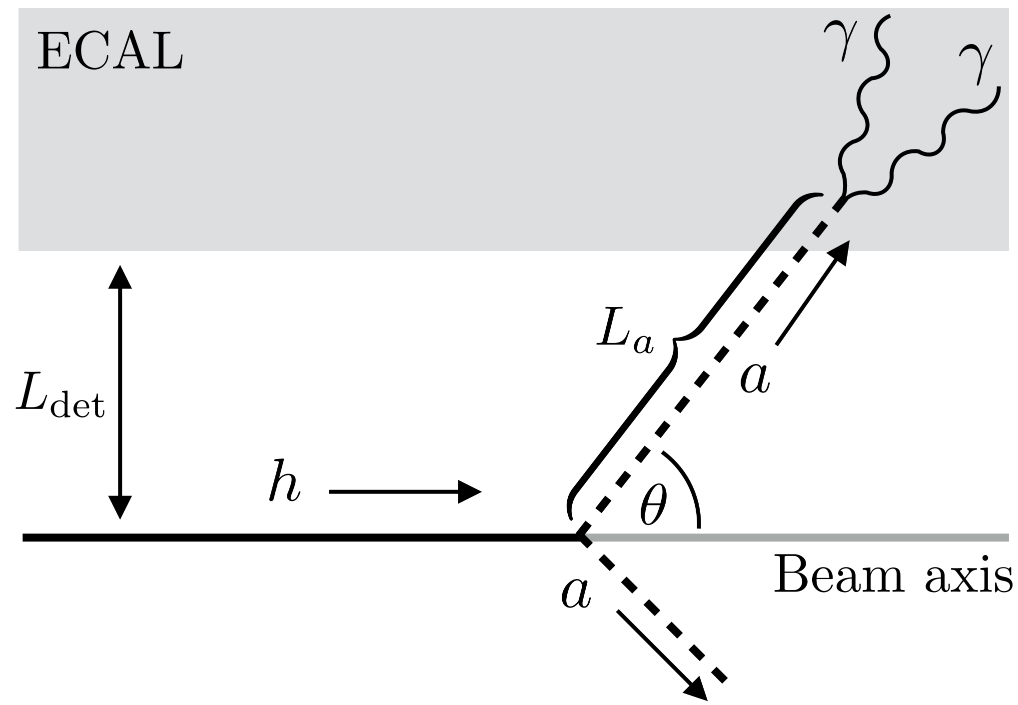
Define effective BRs

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

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

MB, Neubert, Thamm, to appear

Macroscopic Lifetime



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BR drops out for large lifetime

Define effective BRs

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

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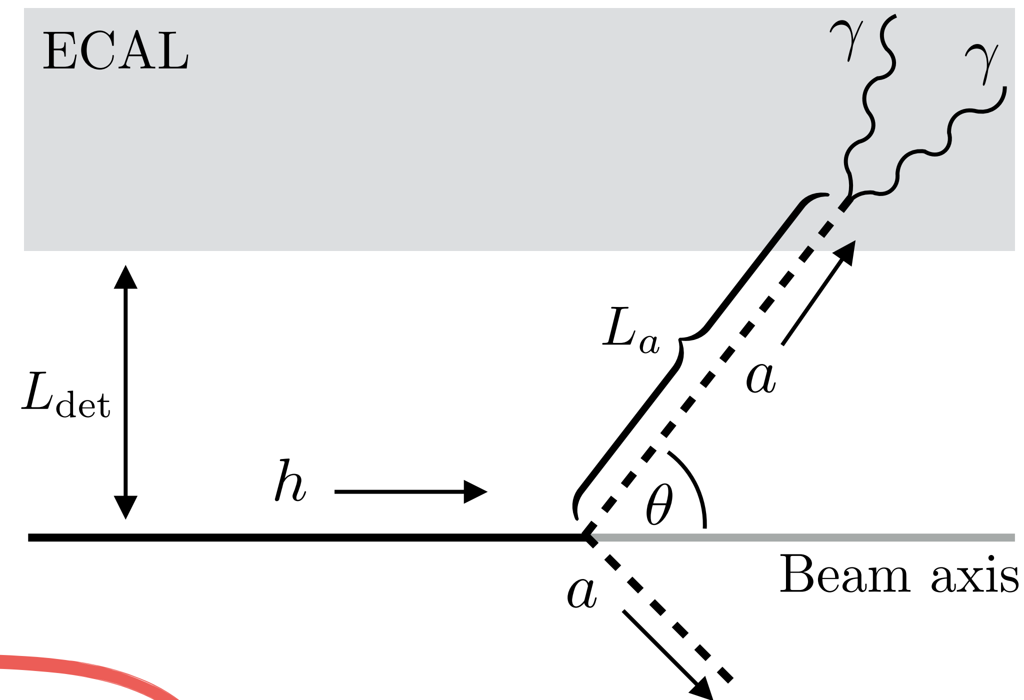
MB, Neubert, Thamm, to appear

Macroscopic Lifetime



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WC dependence drops out for short lifetime

Take into account isotropic Higgs decays

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

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

Define effective BRs

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

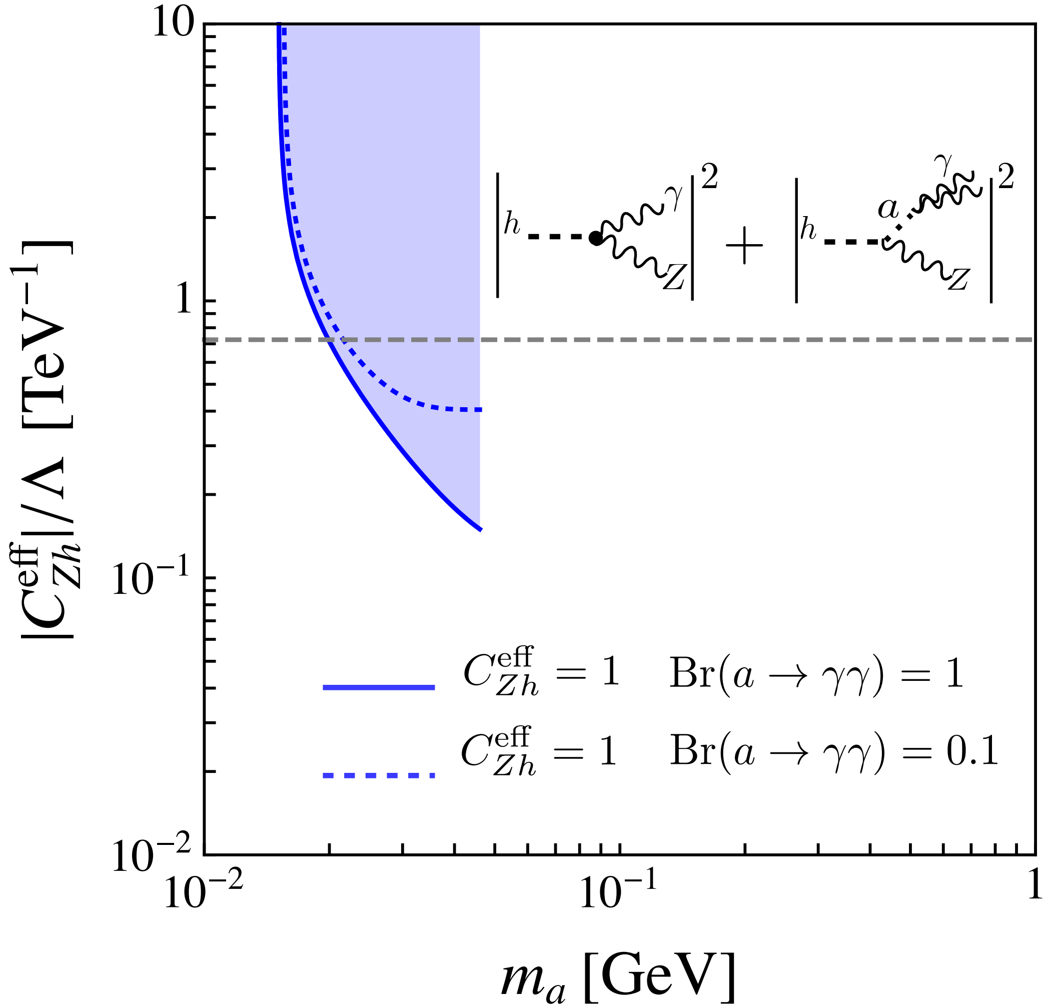
$$\mathrm{Br}(h\to aa\to 4X)\big|_{\rm eff} = \mathrm{Br}(h\to aa)\,\mathrm{Br}(a\to X\bar{X})^2\,f_{\rm dec}^{aa}$$

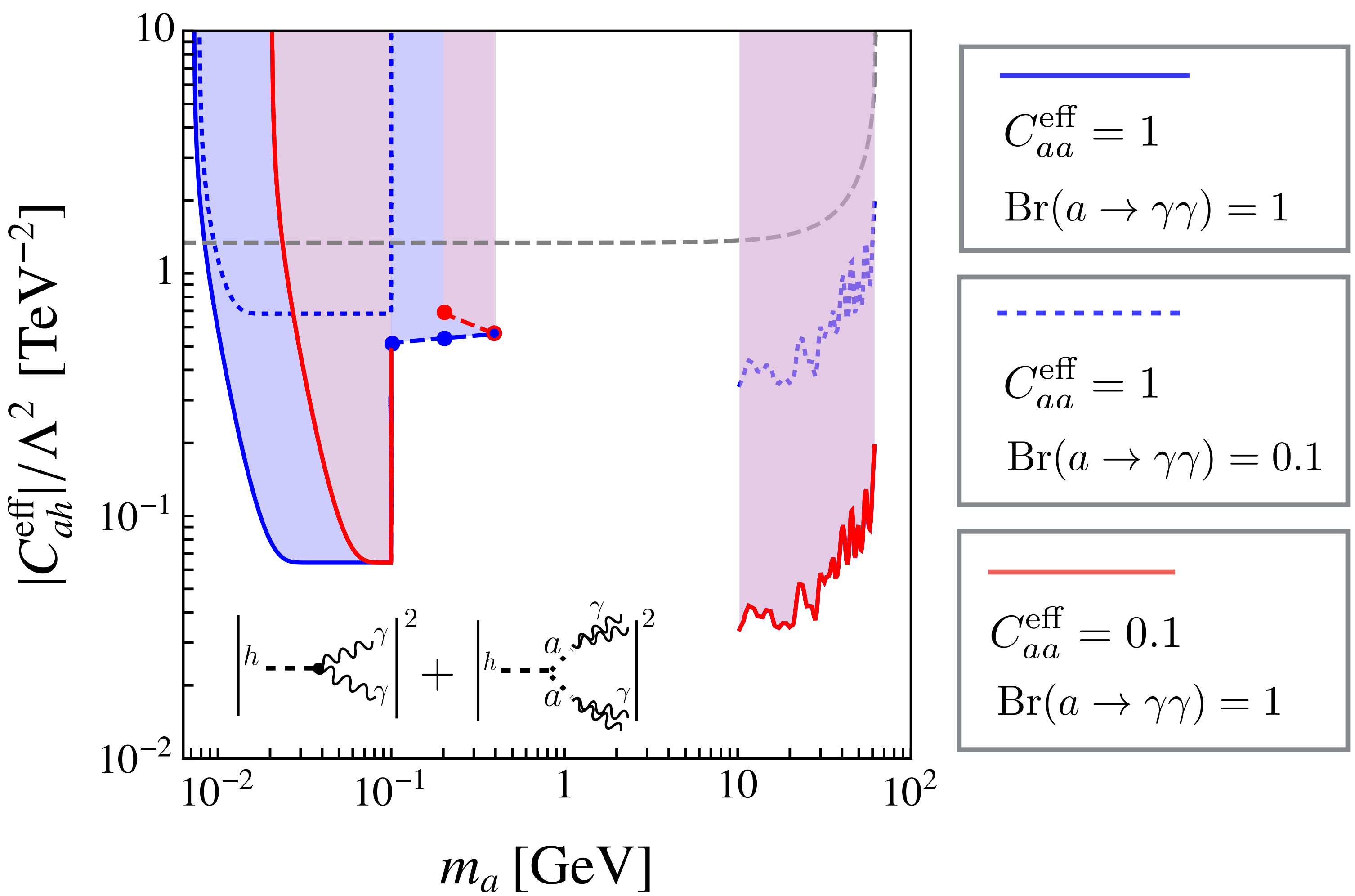
MB, Neubert, Thamm, to appear

Exotic Higgs Decays

Searches for h -> aa and h -> Za are strongly motivated in various final states. Current constraints:

From a $a \to \gamma\gamma$ decays





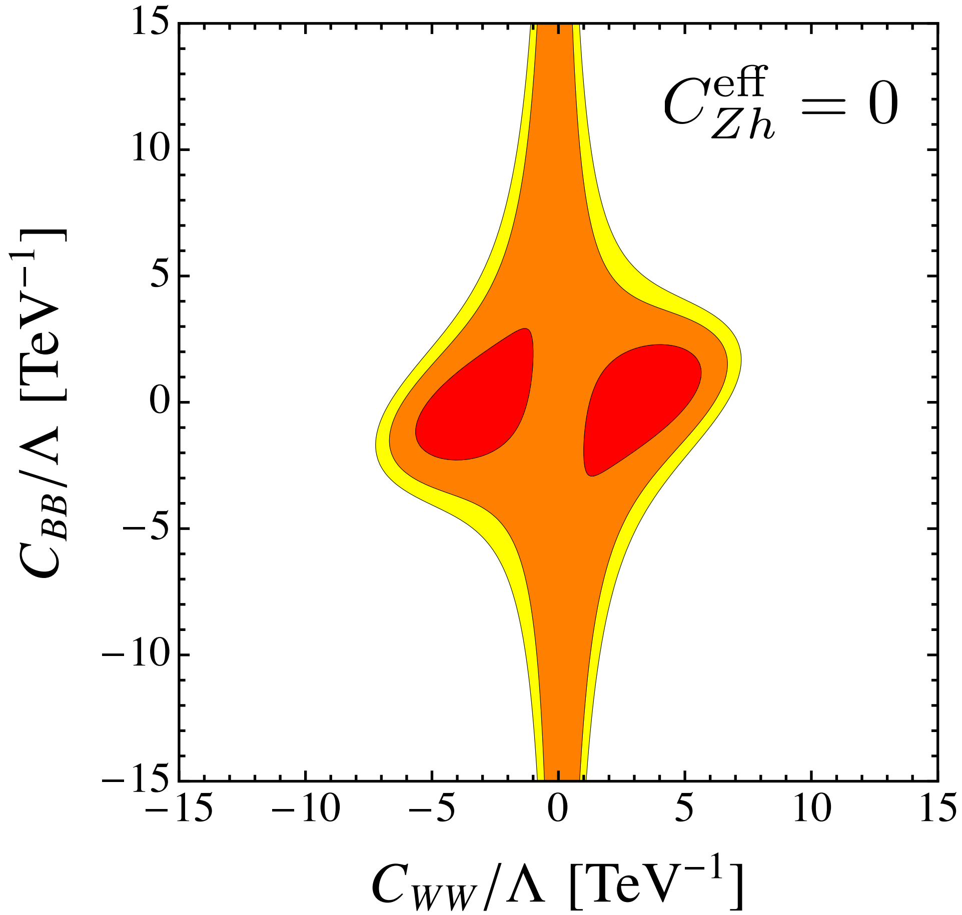
MB, Neubert, Thamm, 1704.08207

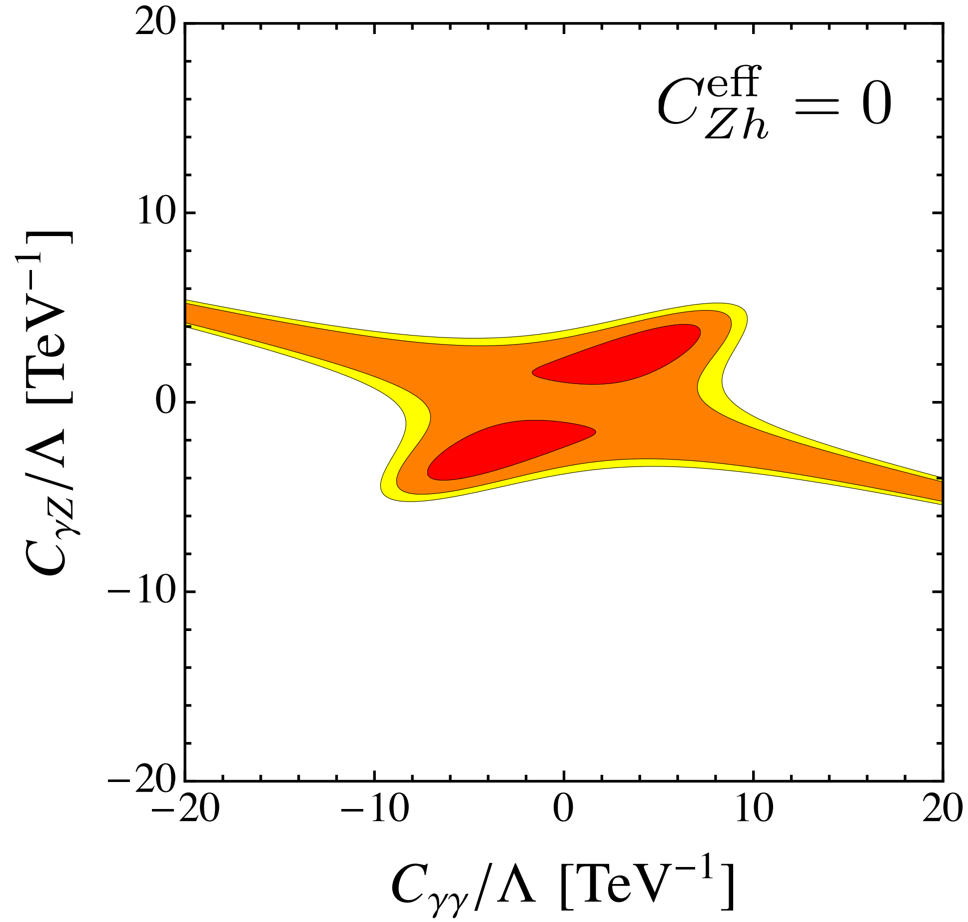
Bounds from Precision Observables

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

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

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





MB, Neubert, Thamm, to appear

Bounds from Precision Observables

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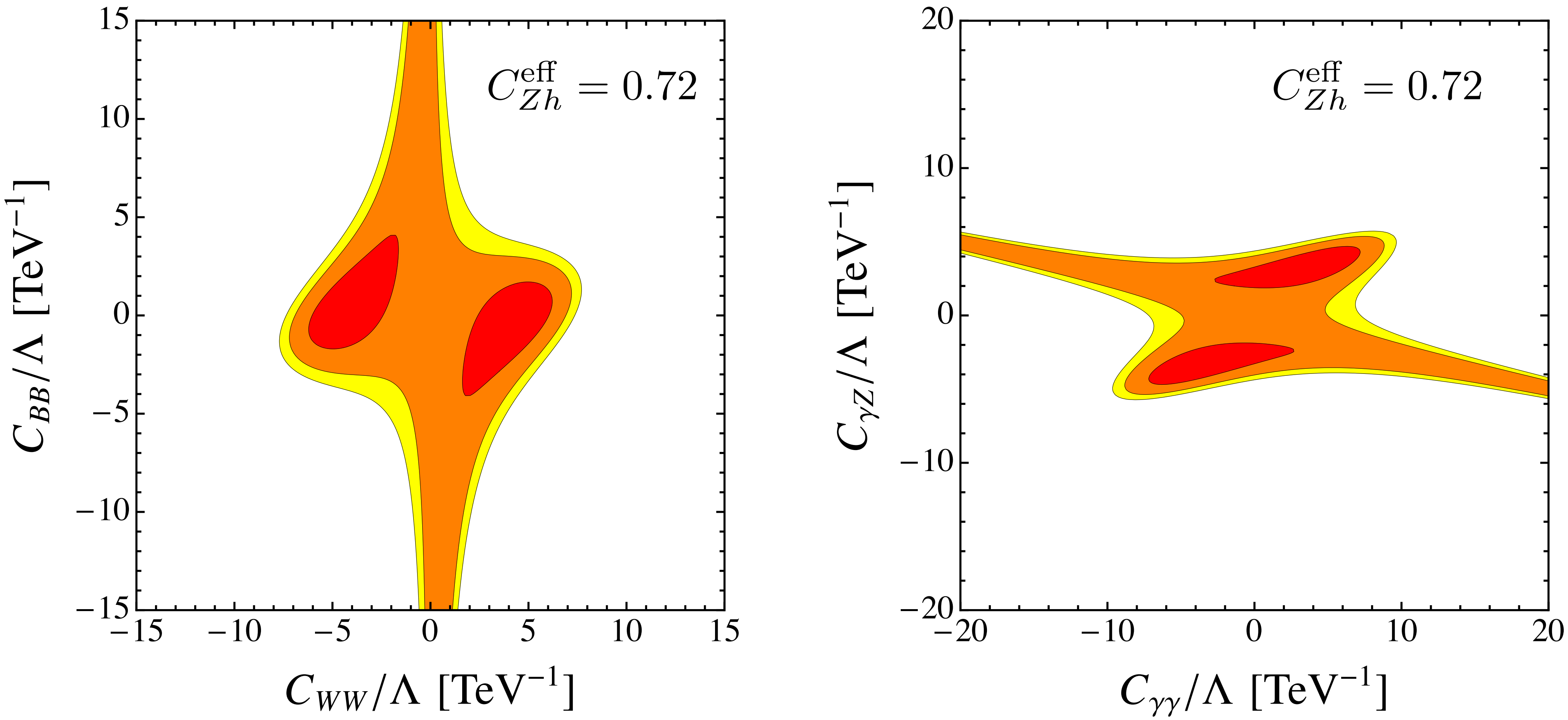

MB, Neubert, Thamm, to appear