Discovering Axion-like Particles in Exotic Higgs Decays

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Martin Bauer

$$\mathrm{Br}(H \to \ ?\ ) \lesssim 34\%$$

ATLAS & CMS 1606.02266

What can light New Physics tell us about the UV?

What can light New Physics tell us about the UV?

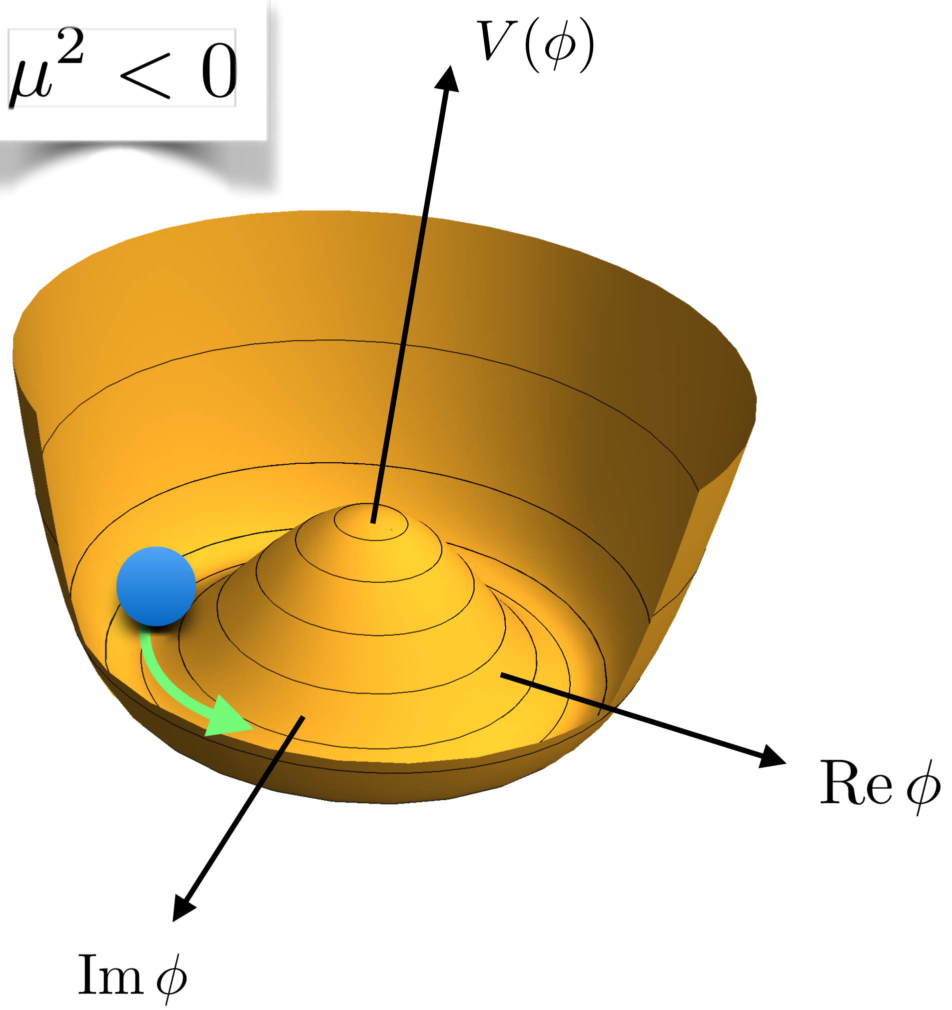
$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f} \quad \text{with} \quad \langle s \rangle = f = \sqrt{-\frac{\mu^2}{2\lambda}}$$

$$m_s^2 = 4\lambda f^2$$

$$m_a^2 = 0$$

$\mu^2 < 0$



results in a massless Goldstone Boson.

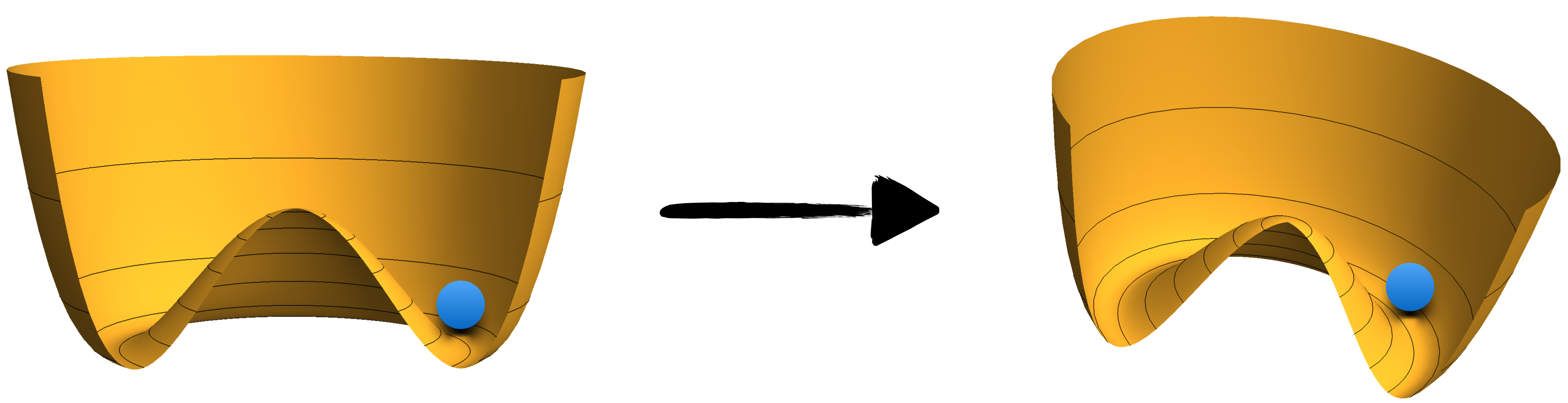
Two ways for Goldstone bosons to become massive (Pseudo-Nambu-Goldstone bosons)

- Explicit (external) symmetry breaking

$$\mathcal{L} \ni m^2(\phi\phi + \phi^\dagger\phi^\dagger) \qquad m_a^2 = m^2$$

- Anomalous symmetry breaking

$$\mathcal{L} \ni \Lambda_{\rm QCD}^4 \cos\frac{\varphi}{f} \qquad m_a^2 = \frac{\Lambda_{\rm QCD}^4}{f^2}$$



What can light New Physics tell us about the UV?

ψ, s, A_μ

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\, (\phi\phi^\dagger)^2 + y_\psi \bar{\psi}\phi\psi$$

any other particle would be massive

$$m_s^2 = 4\lambda f^2 \qquad m_\psi = y_\psi f$$

$$m_a^2 = 0$$

A pseudo-Nambu-Goldstone boson can therefore be the harbinger of an otherwise (currently) inaccessible UV theory.

a

The most famous example is the pion

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}_L i \not{D}\, q_L + \bar{q}_R i \not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\mathrm{QCD}} \approx \mathrm{GeV}^3$$

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\mathrm{QCD}} \quad \approx (140\,\mathrm{MeV})^2$$

ALP Effective Lagrangian

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

Most general dimension five Lagrangian

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

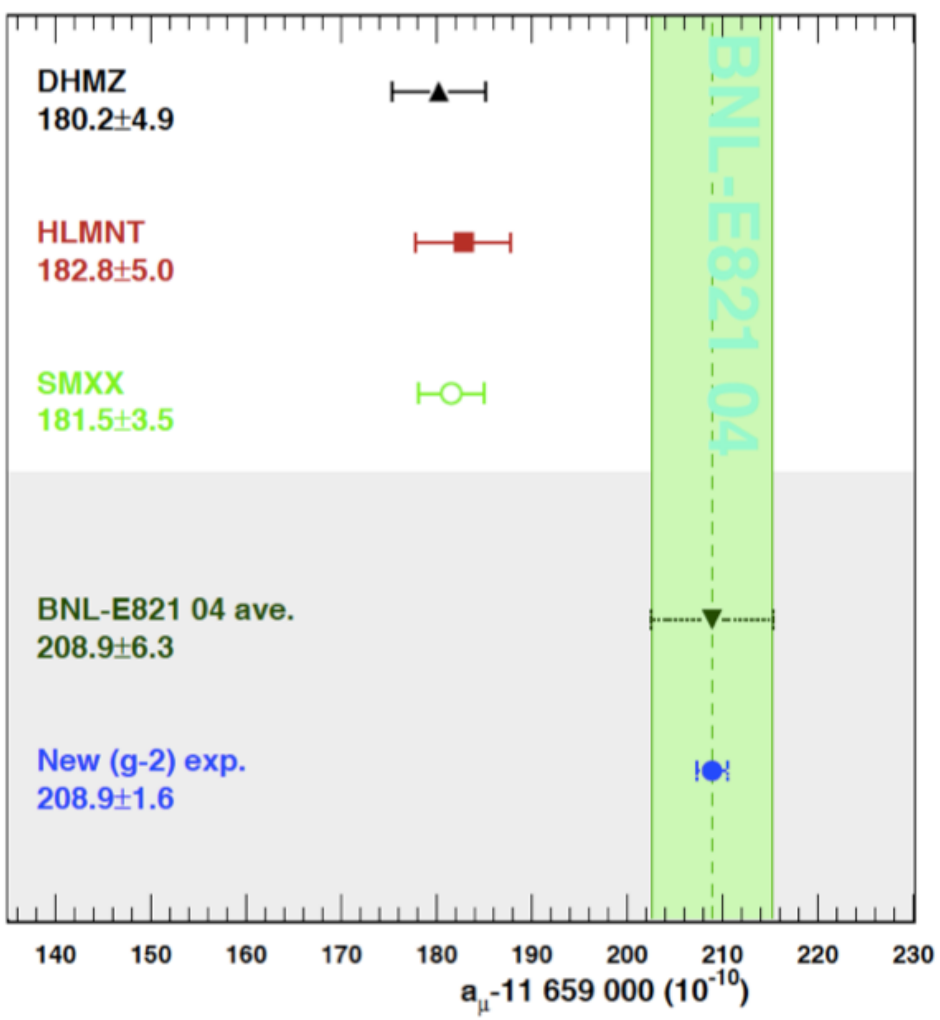
change of notation: $\Lambda = 4\pi f$

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

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

The anomalous magnetic moment of the muon

$$a_\mu = (g-2)_\mu/2 \qquad a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$



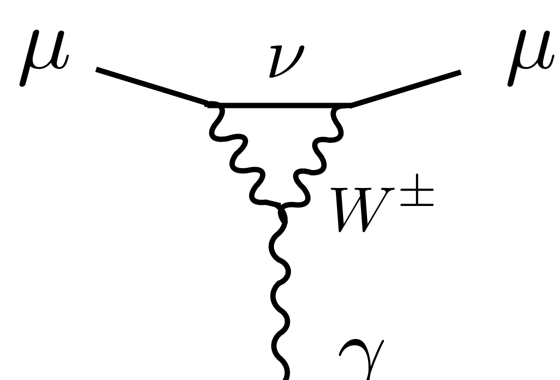
[Gohn 1506.00608]

Currently: $3.6\,\sigma$ discrepancy

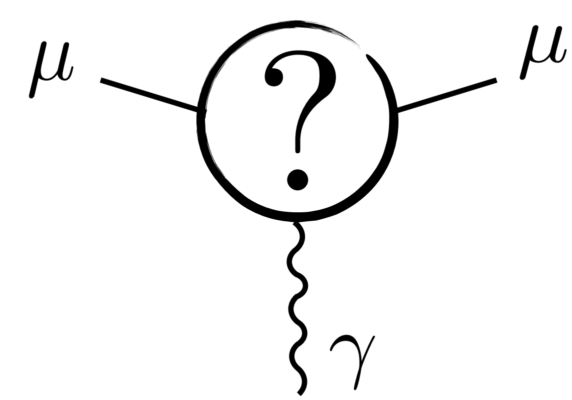
Future: $\gtrsim 5\,\sigma$?

SM

$$\delta a_\mu^W \approx \frac{g^2}{20\pi^2}\frac{m_\mu^2}{M_W^2} \approx 400 \times 10^{-11}$$

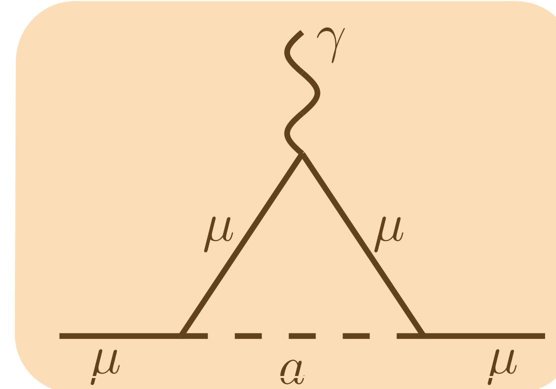


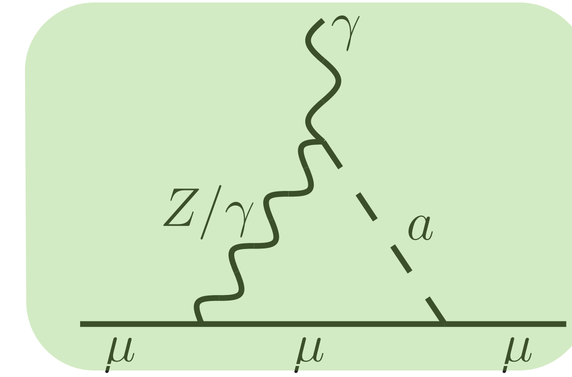
NP



$$M = \mathcal{O}(\text{TeV})$$

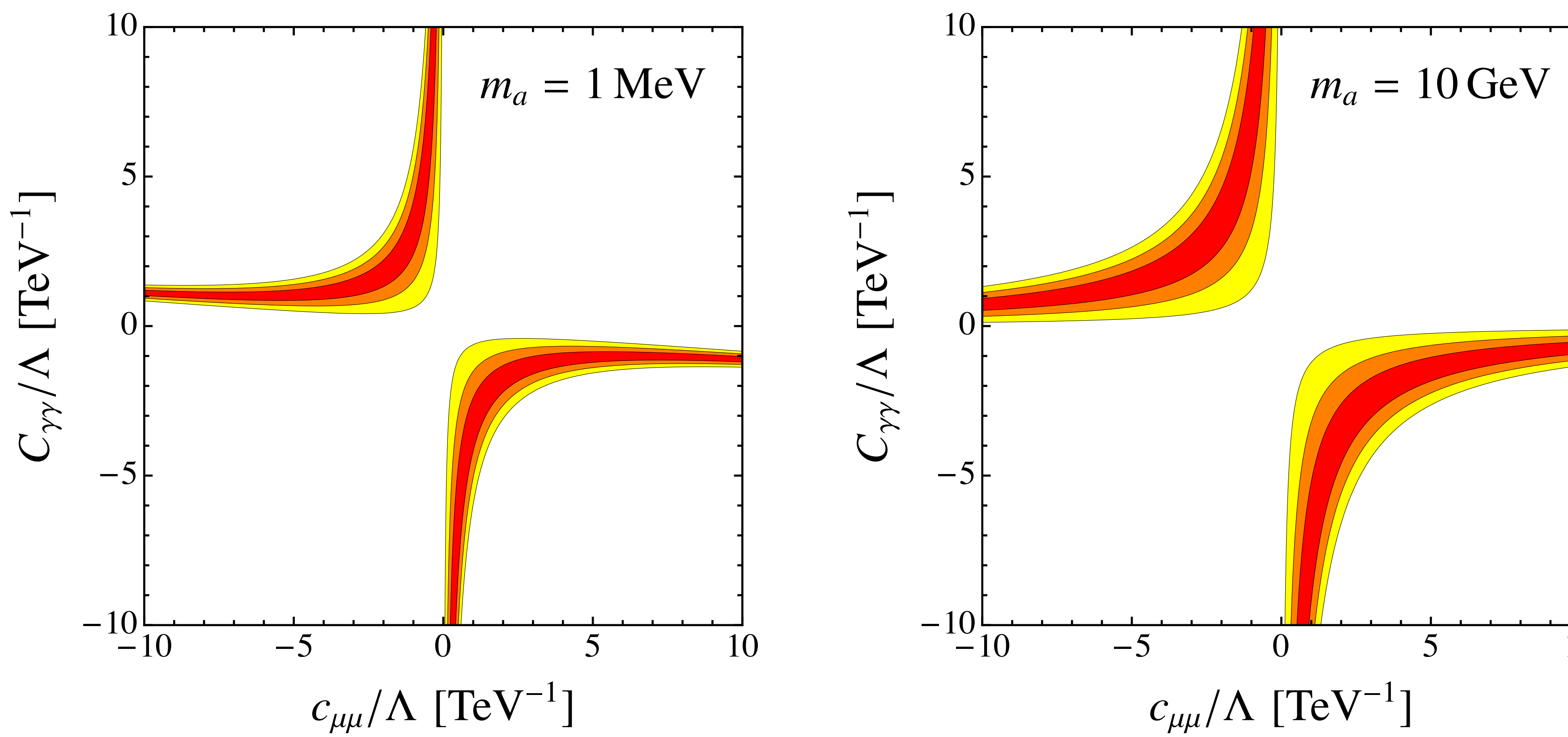
ALPs and (g-2)μ





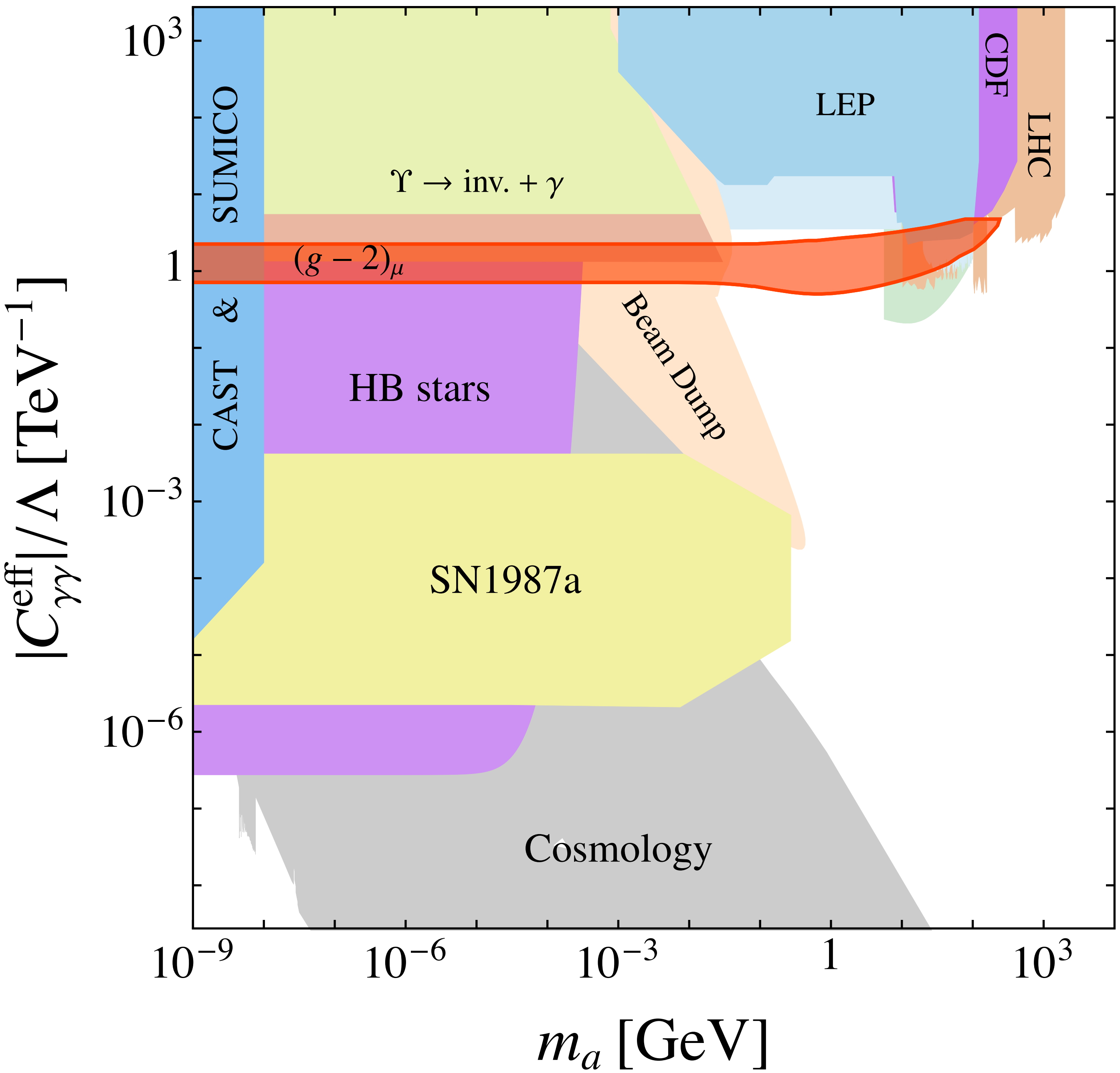
$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\, h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\, c_{\mu\mu}\, C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right] - \frac{\alpha}{2\pi}\,\frac{1-4s_w^2}{s_w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

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



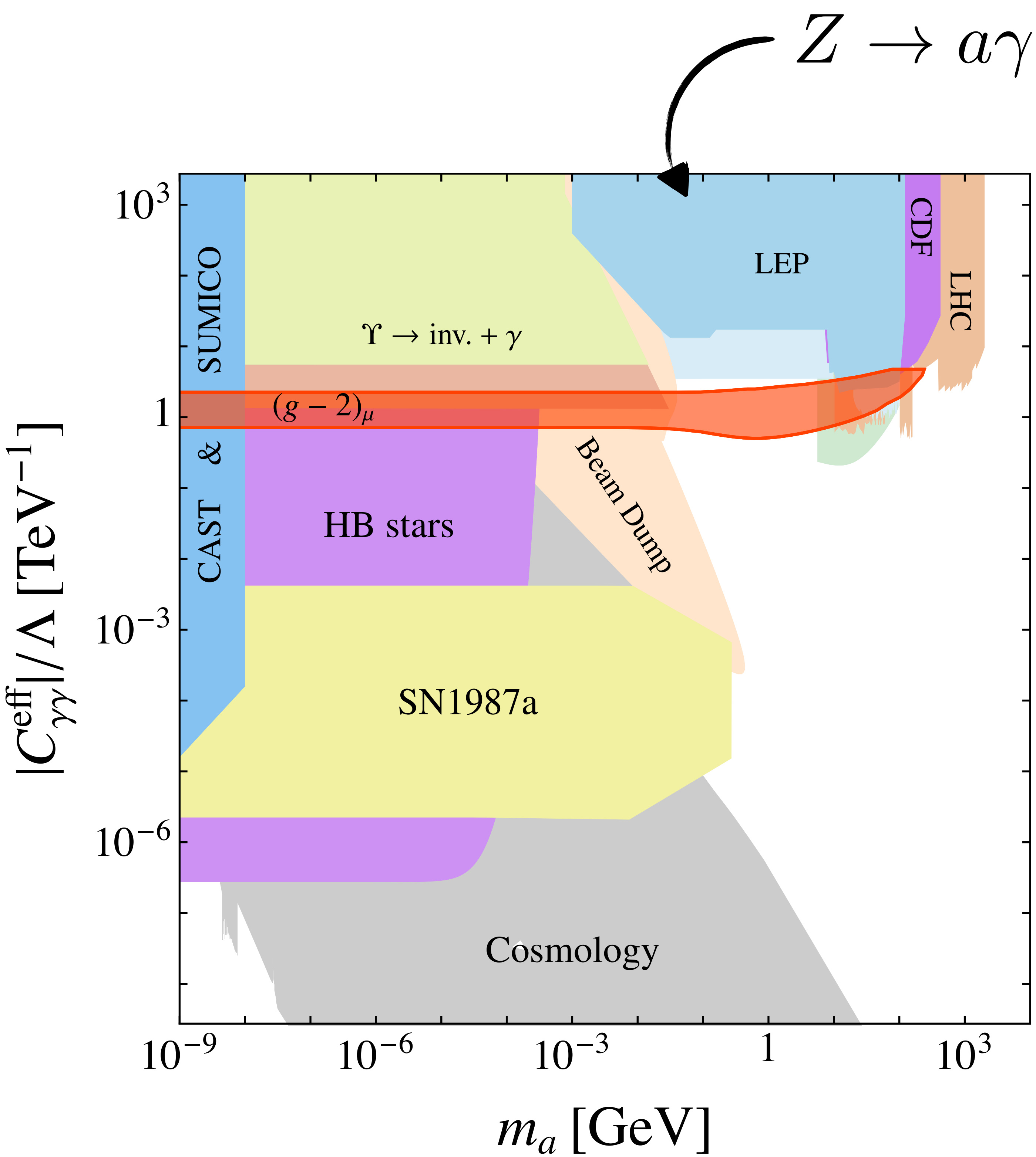
Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94, 115033 (2016)

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

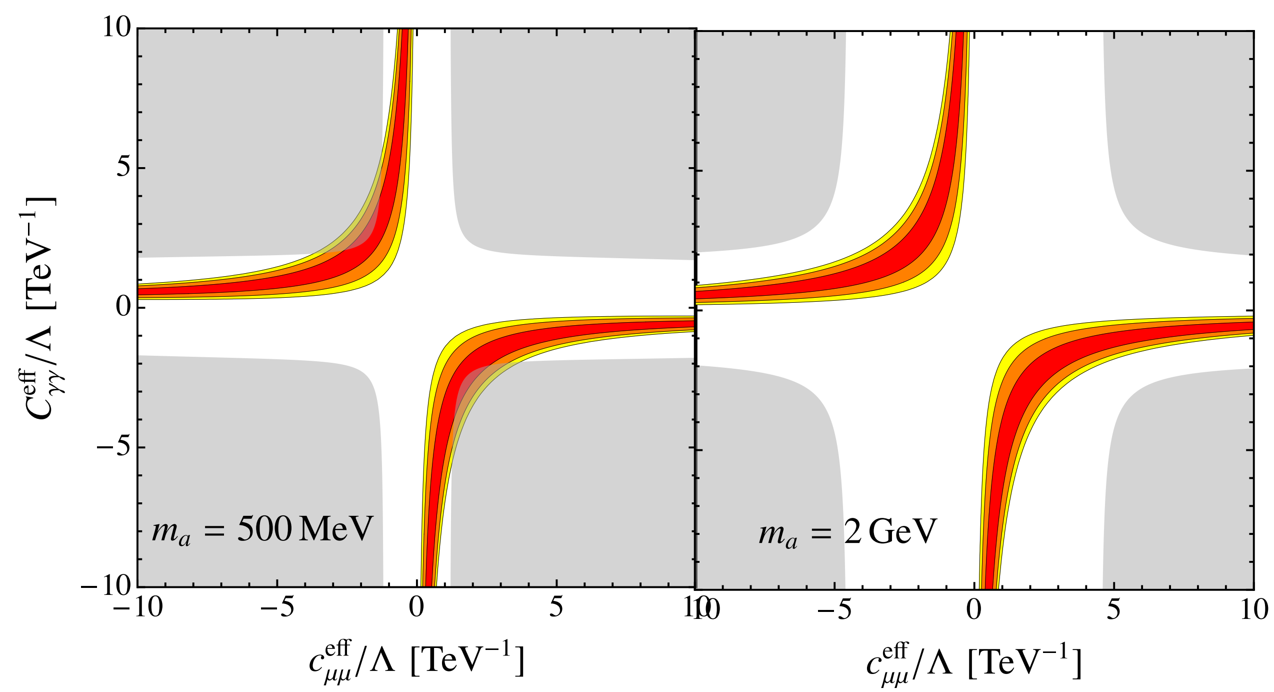


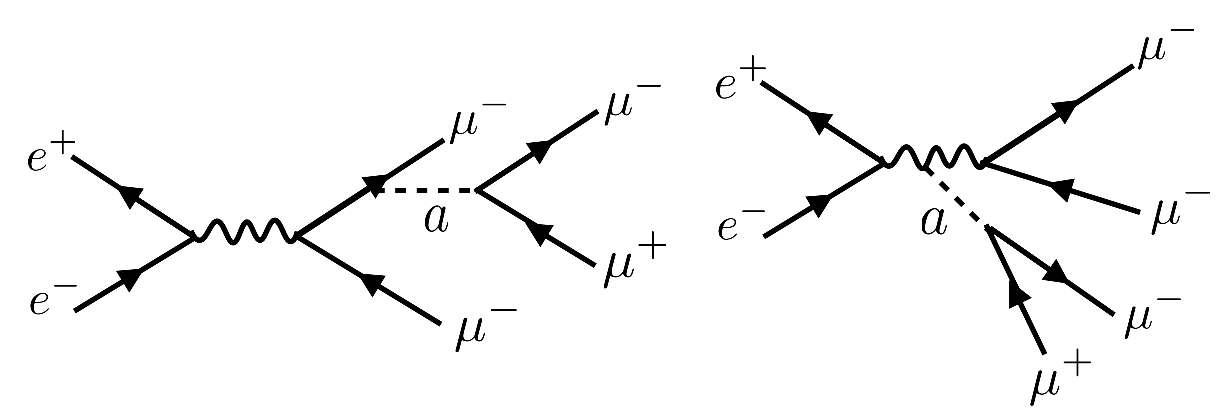
This explanation is strongly constrained.

ALPs and (g-2)$_\mu$



LHC competes with e+ e- colliders





BABAR, Phys. Rev. D 94, 011102

Higgs Couplings to ALPs

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

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

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

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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 ALPs

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

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

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

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

…unless New Physics get a sizable part of their masses from the electroweak scale

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

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

The Puzzle of the top contribution

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

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

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

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

The Puzzle of the top contribution

Vectorlike Quarks

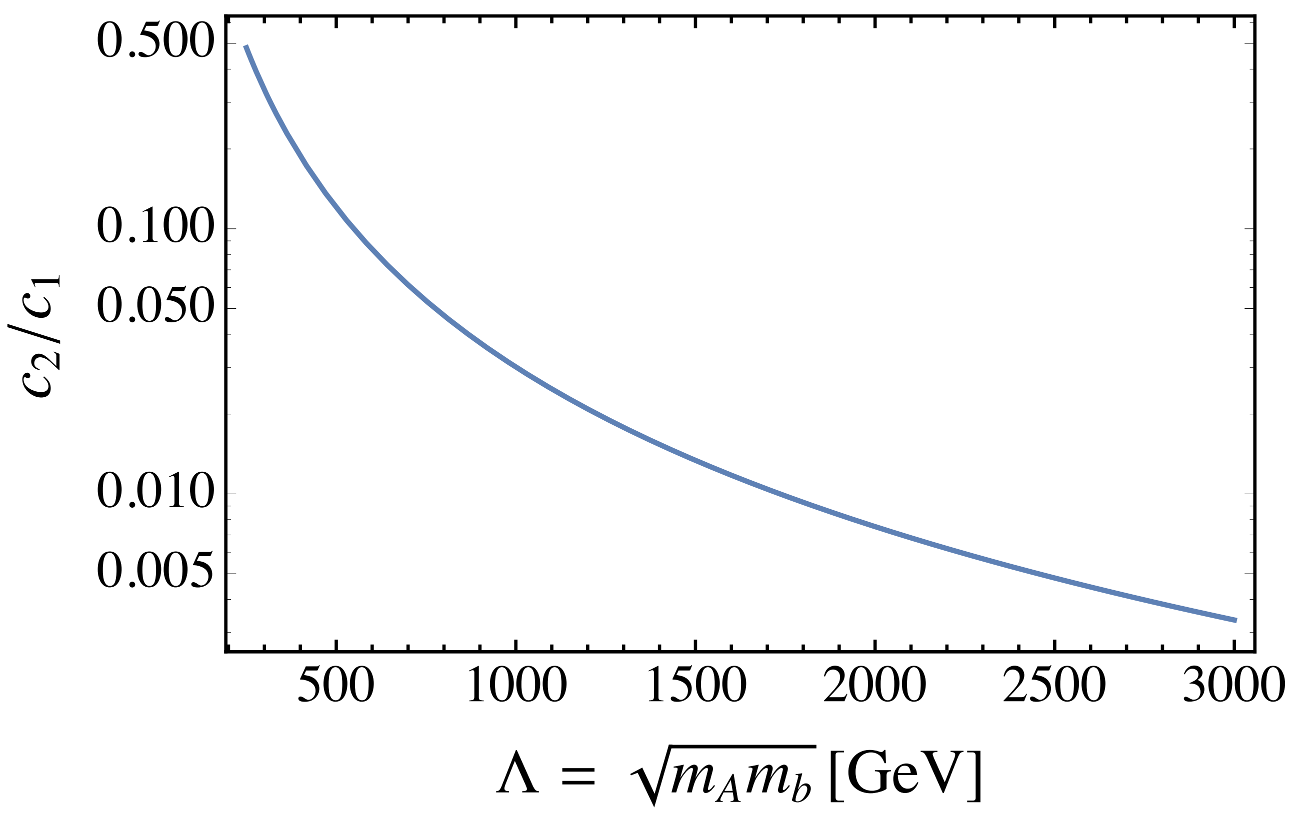
$$-\mathcal{L}_{\text{mass}} = \lambda_1 \left(QHT^c + Q\tilde{H}B^c\right) + \lambda_2 \left(Q^c\tilde{H}T + Q^cHB\right) + m_A QQ^c + m_B(TT^c + BB^c) + \text{h.c.},$$

generate

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

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

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



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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.

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

Particles which do not get their masses dominantly from the electroweak scale only contribute at dimension 7.

This can be confirmed in the non-linear language

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

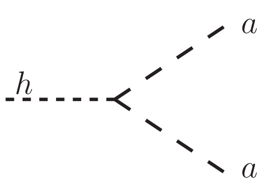
Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, 1701.05379

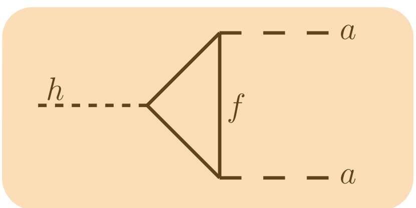
This gives a non-trivial handle on the UV completion.

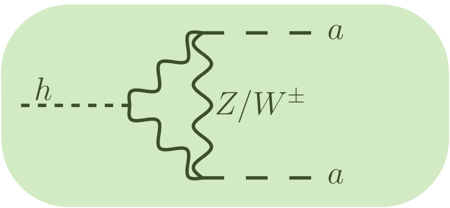
Exotic Higgs Decays

$h \to aa$

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



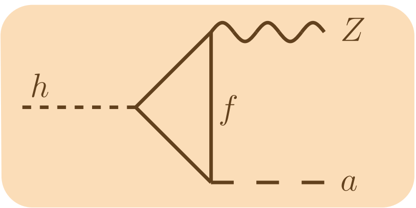


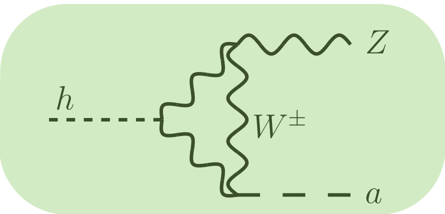


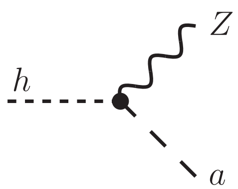
$$C_{ah}^{\text{eff}} \approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\,(C_{WW}^2 + C_{ZZ}^2)$$

$h \to Za$

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







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

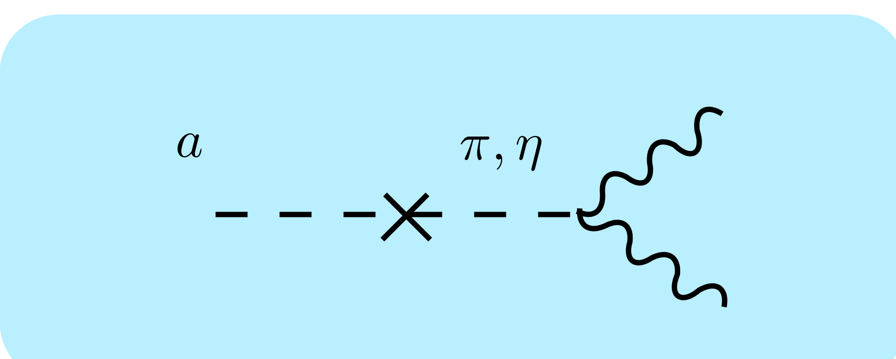
ALP Decays into SM particles

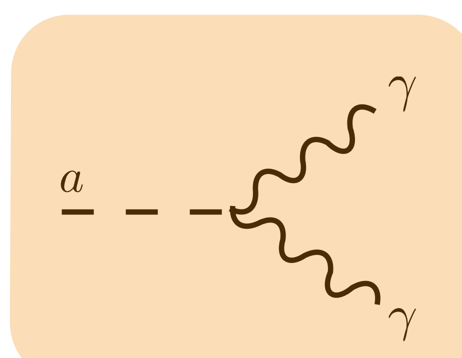
Decays into photons

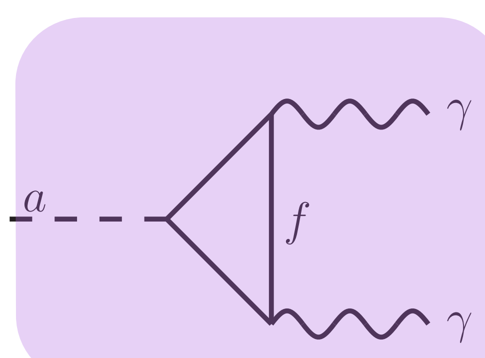
$$\mathcal{L}_{\rm eff}^{D\le 5} \ni e^2\, C_{\gamma\gamma}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\,C_{\gamma Z}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\,C_{ZZ}\,\frac{a}{\Lambda}\,Z_{\mu\nu}\,\tilde{Z}^{\mu\nu}$$

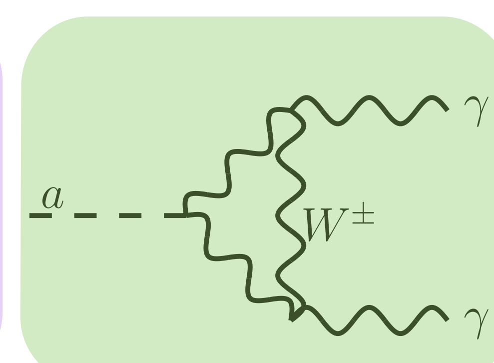
and loop induced couplings

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









ALP Decays into SM particles

fermions: $B_1(\tau) = 1 - \tau\, f^2(\tau)\,, \longrightarrow \begin{cases} 1\,, & \text{for} \quad m_a \ll m_f \\ -\dfrac{m_a^2}{12 m_f^2}\,, & \text{for} \quad m_f \gg m_a \end{cases}$

as a consequence of the anomaly equation:

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

$$C_{\gamma\gamma}^{\text{eff}}(m_a \lesssim 1\,\text{GeV}) \approx C_{\gamma\gamma} - (1.92 \pm 0.04)\,C_{GG} - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[C_{GG}\,\frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32\pi^2}\right]$$
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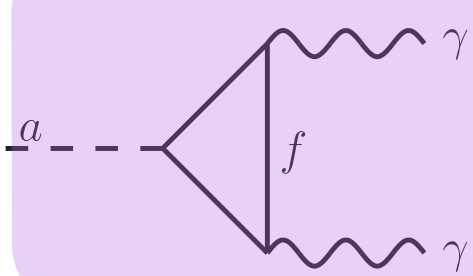
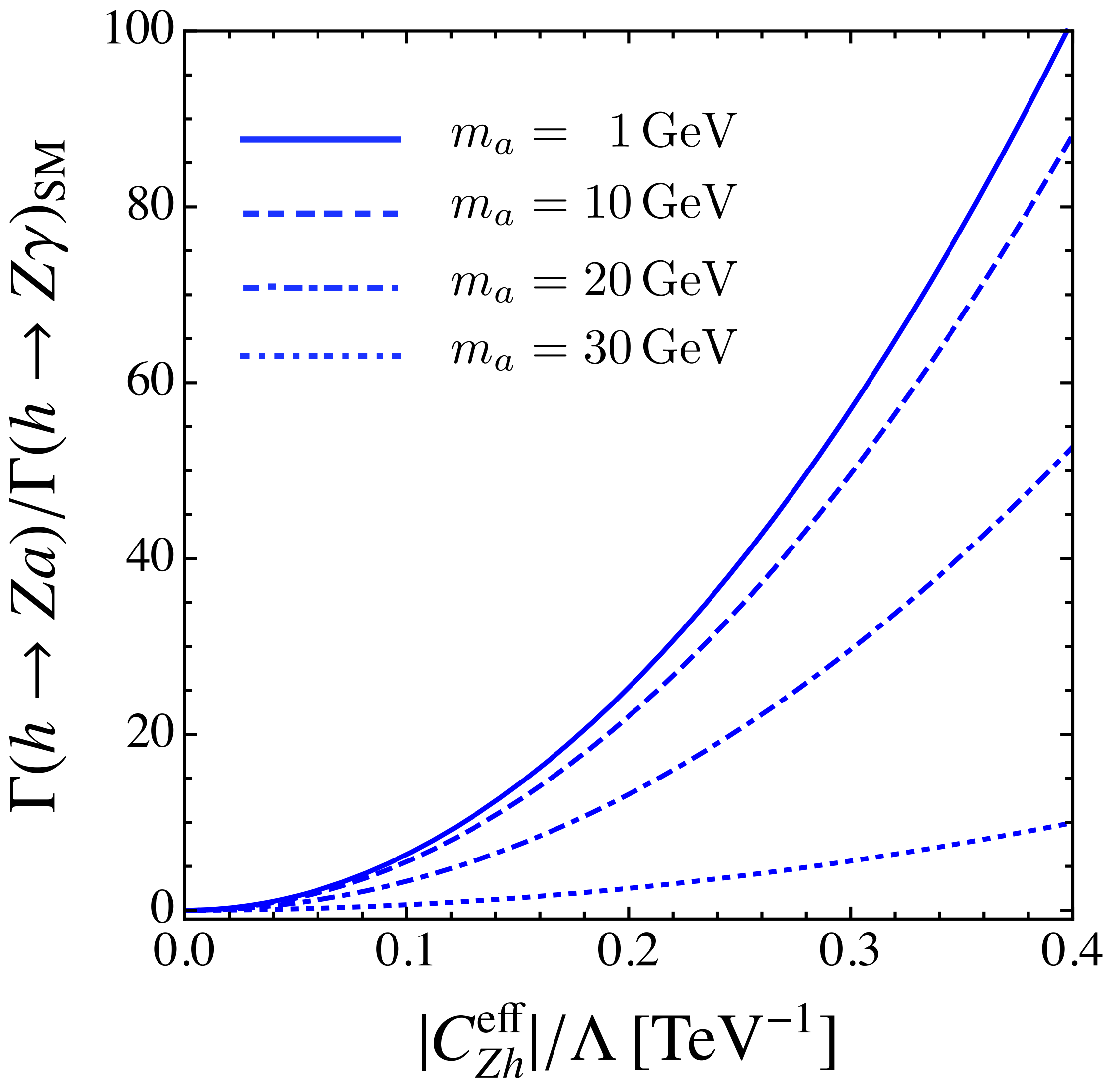
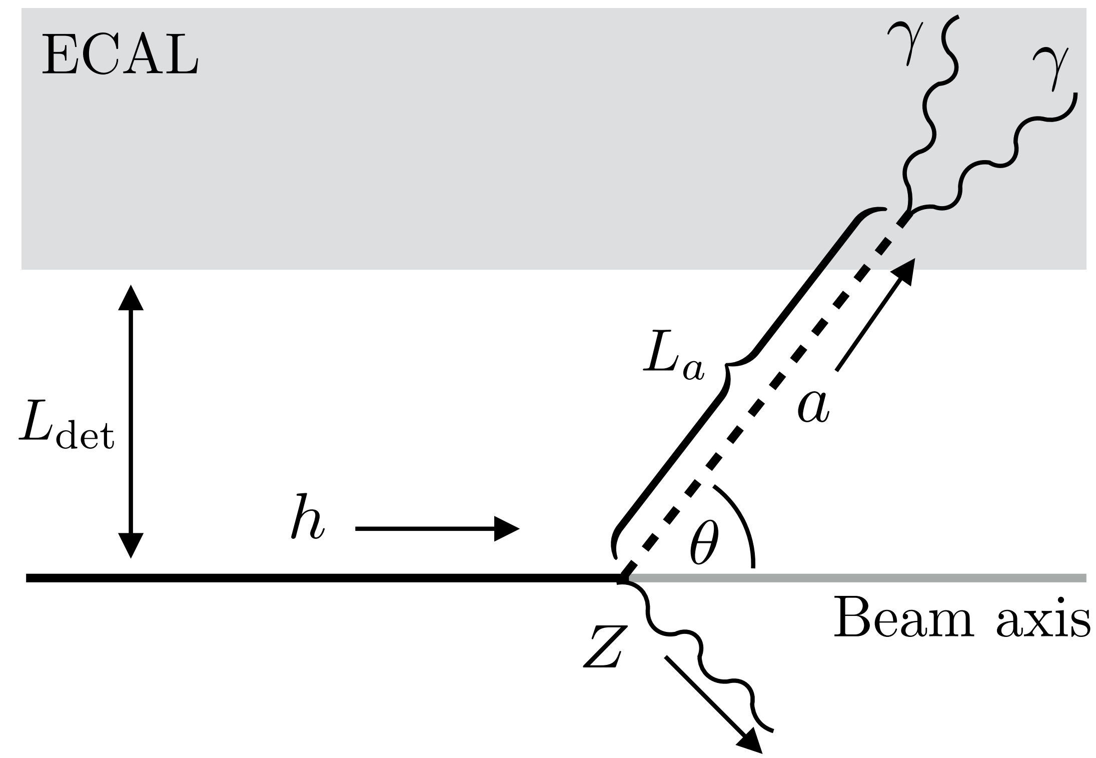


Exotic Higgs Decays: $h \to Za$



This decay can have sizable branching ratios, exceeding h -> Z gamma.

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

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

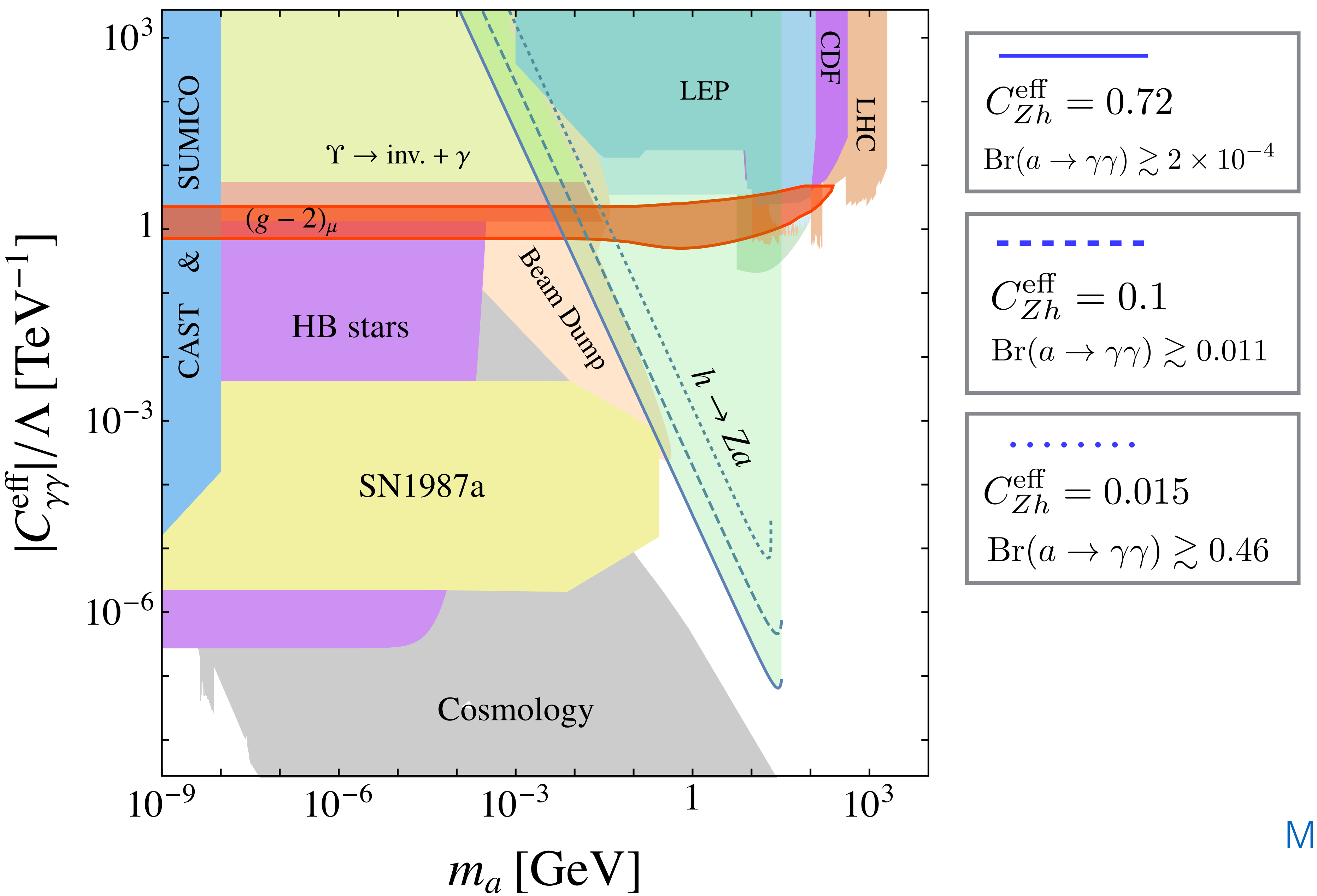
Define effective BRs

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

MB, Neubert, Thamm, 1708.00443

Future Searches $h \to Za$

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

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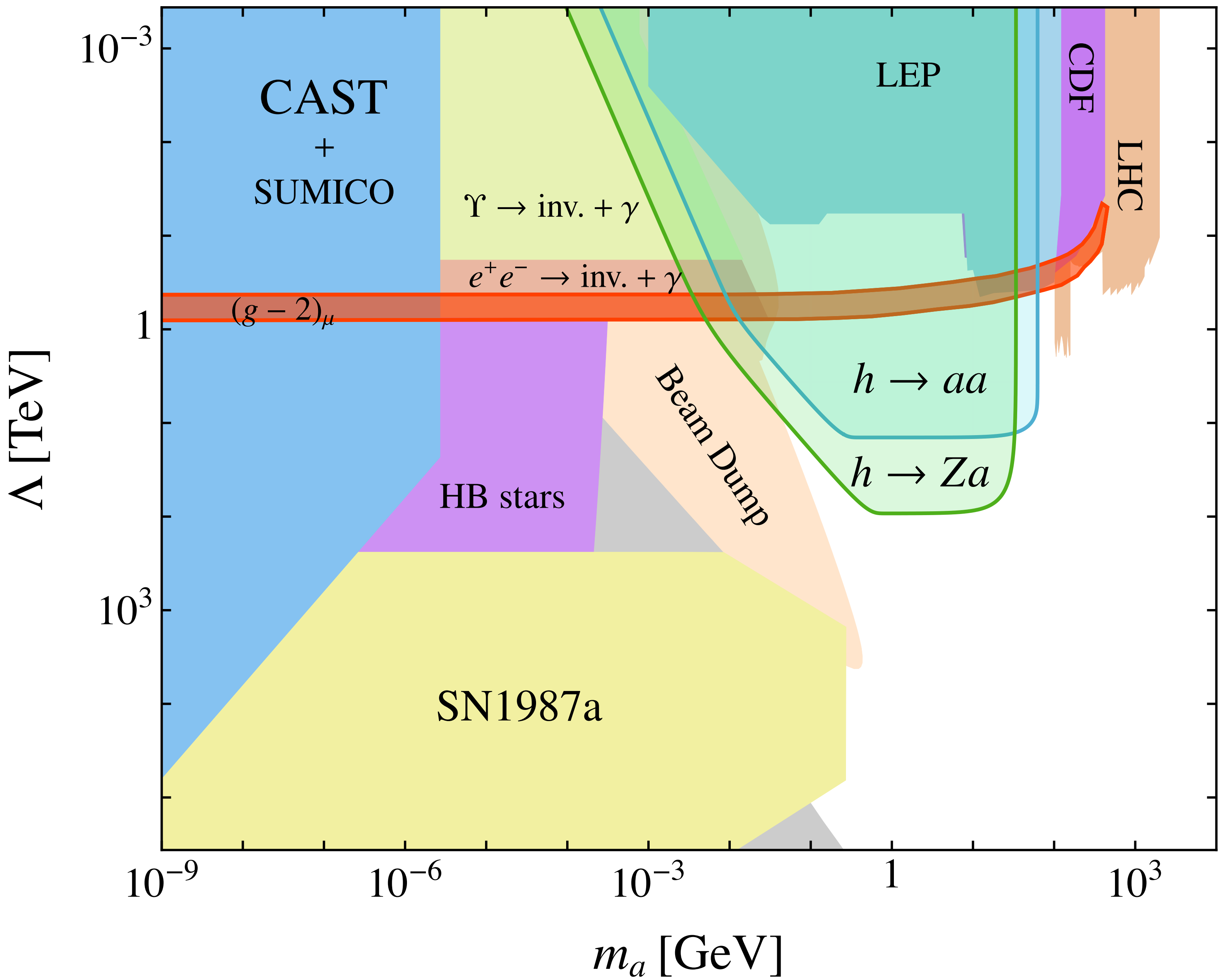
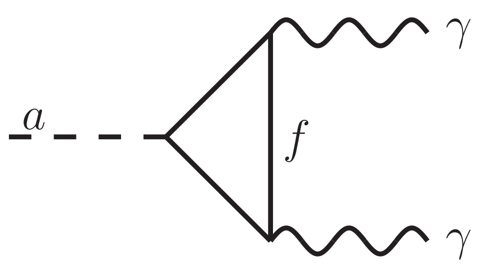


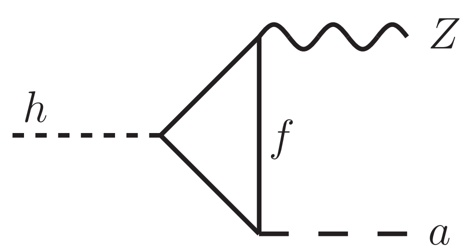
As a bound on the New Physics scale.

Future Searches

It is not as implausible as it may seem to have a large hierarchy of Wilson coefficients

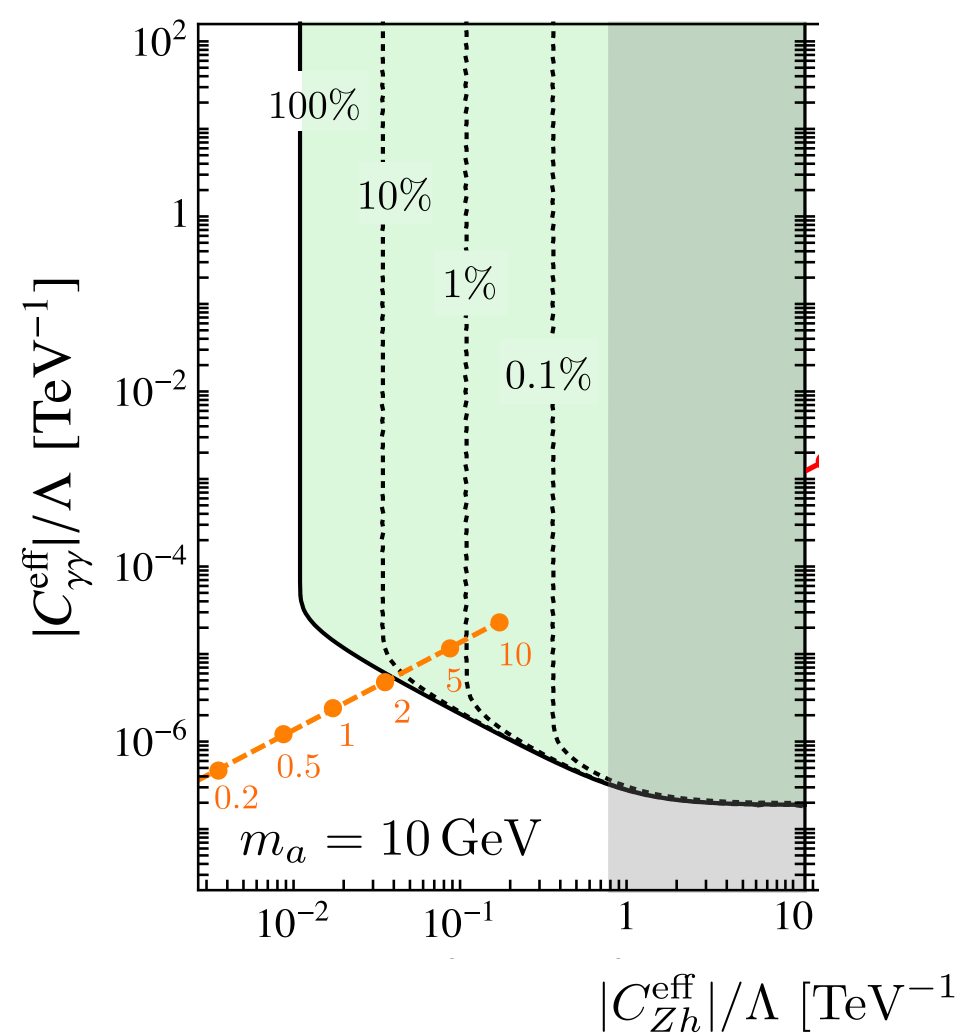


$$\longrightarrow \quad C^{\text{eff}}_{\gamma\gamma}$$



$$\longrightarrow \quad C_{Zh}$$

Integrating out the top quark gives



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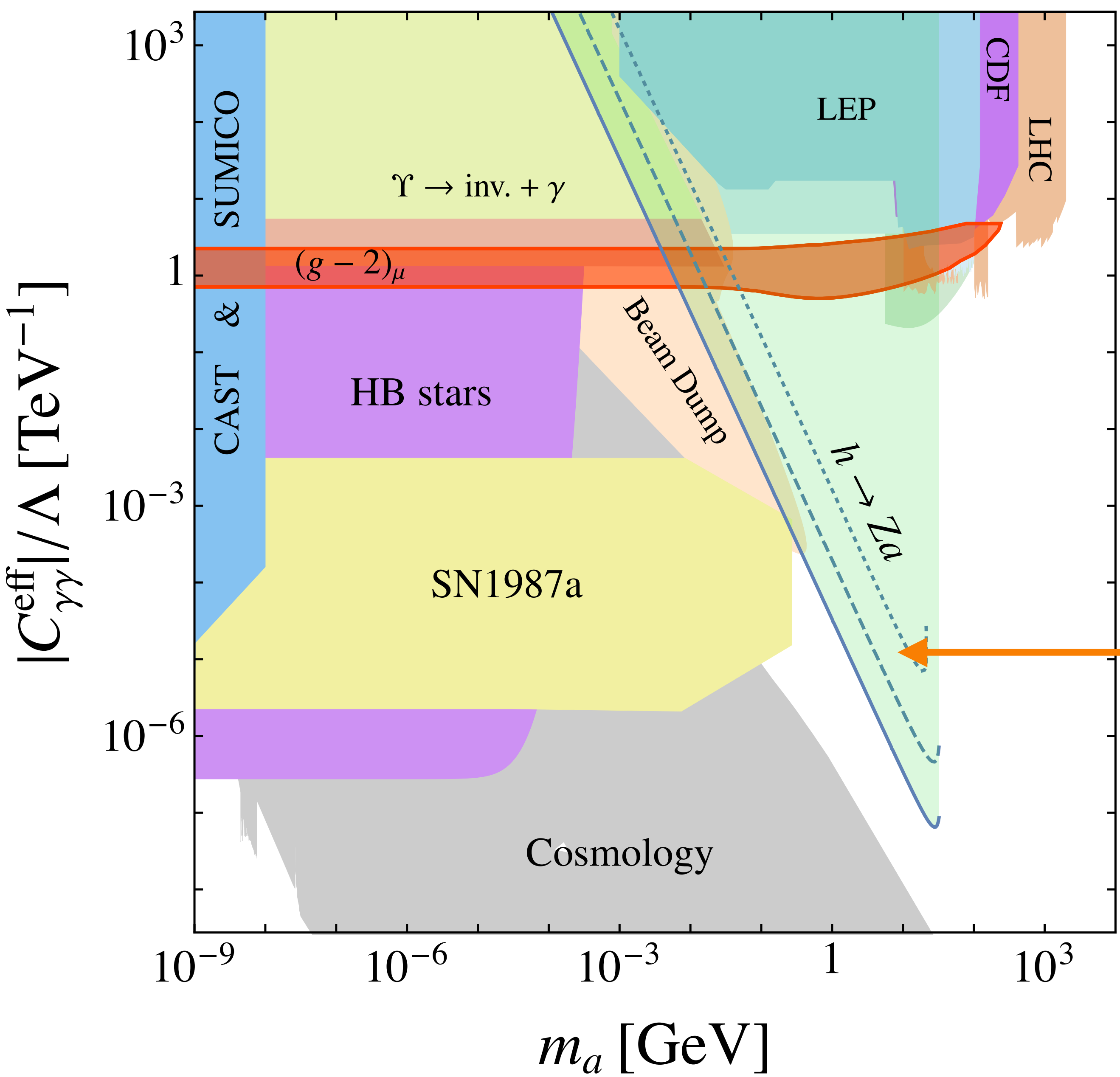
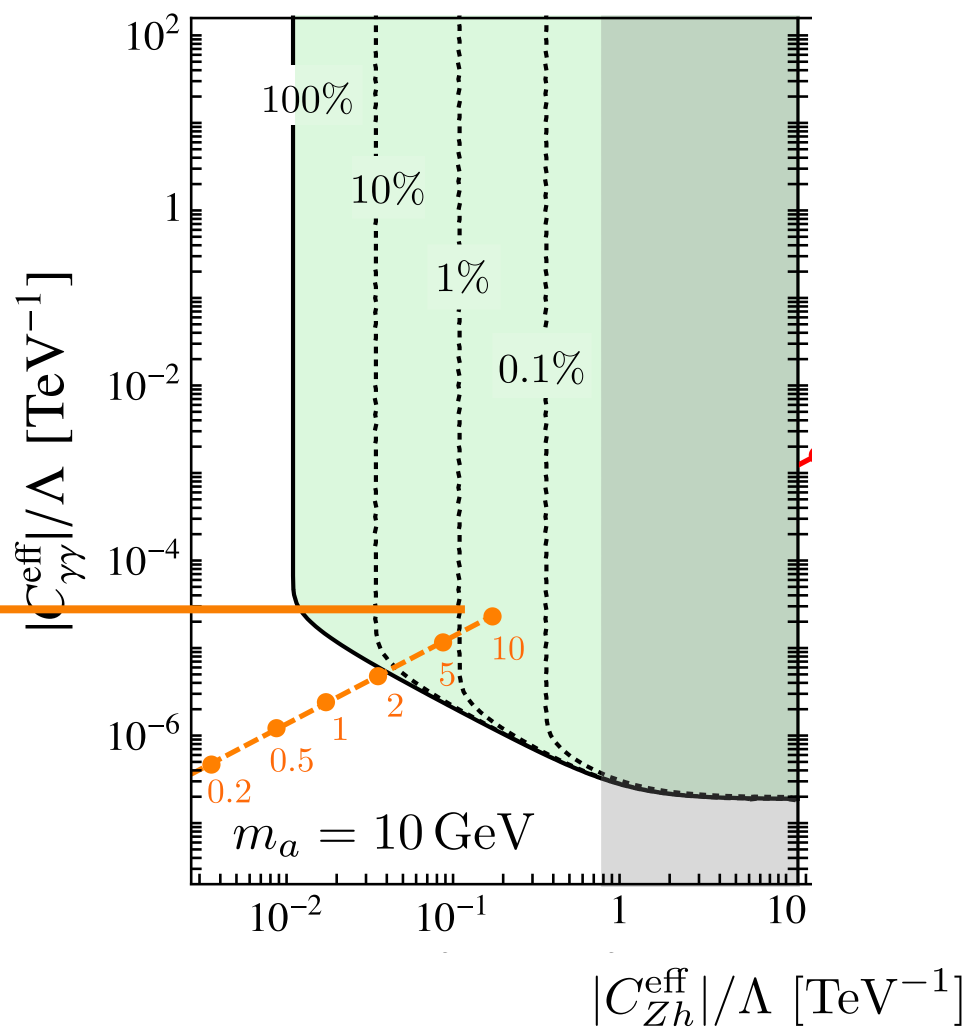




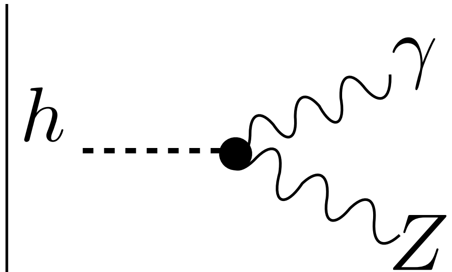
Macroscopic Lifetime

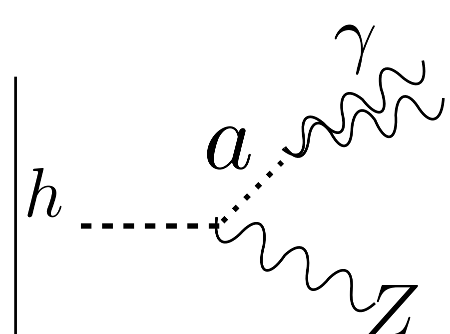
If the alps are light, they are strongly boosted! The LHC only has a finite angular resolution putting a limit on the angle for which single photons can be separated from pairs,

$$\gamma_a < 625 \qquad\qquad \gamma_a = \begin{cases} \dfrac{m_h^2 - m_Z^2 + m_a^2}{2m_a m_h}\,, & \text{for } h \to Za\,, \\[2ex] \dfrac{m_h}{2m_a}\,, & \text{for } h \to aa\,. \end{cases}$$

Exciting possibility:

$\sigma_{\text{eff}}(h \to Z\gamma) = \left| \quad \right|^2 + \left| \quad \right|^2$





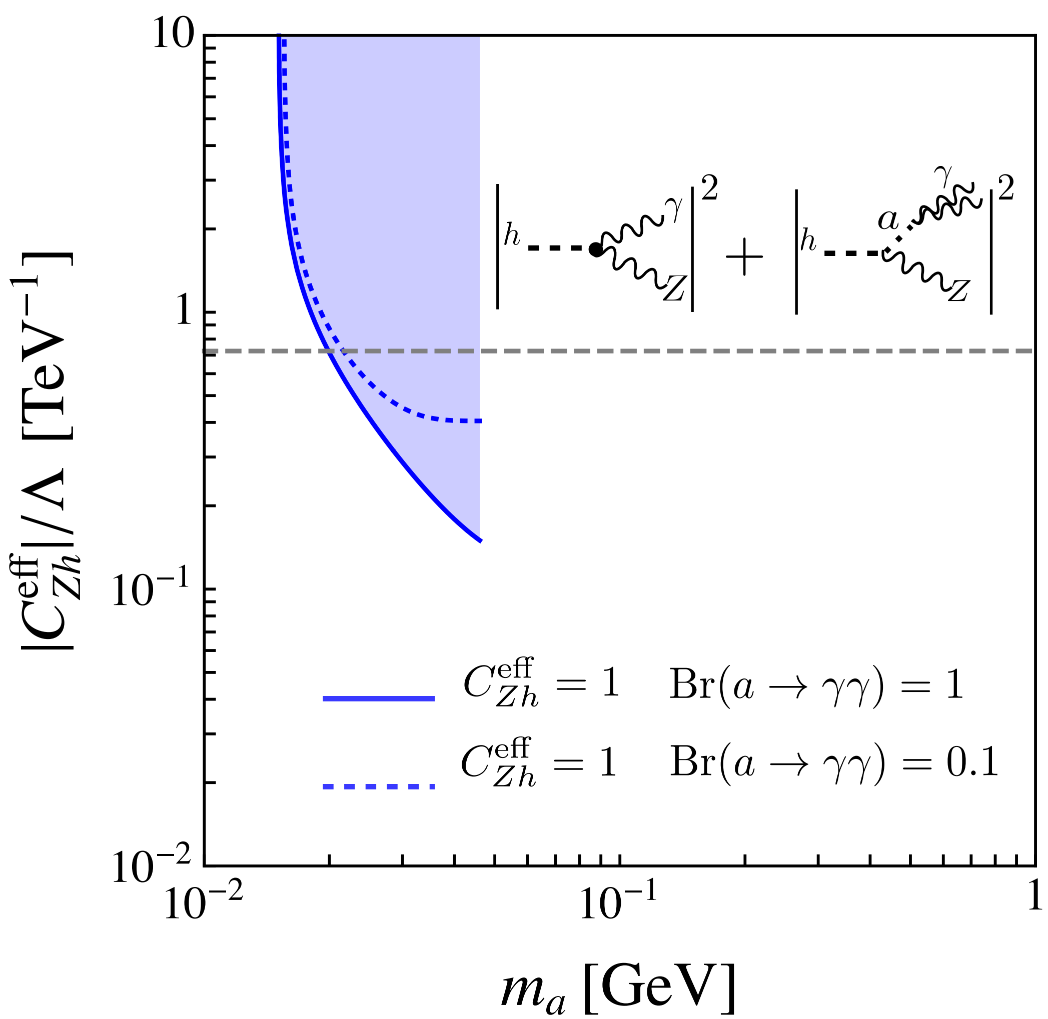
ATLAS Collaboration, ATLAS-CONF-2012-079.

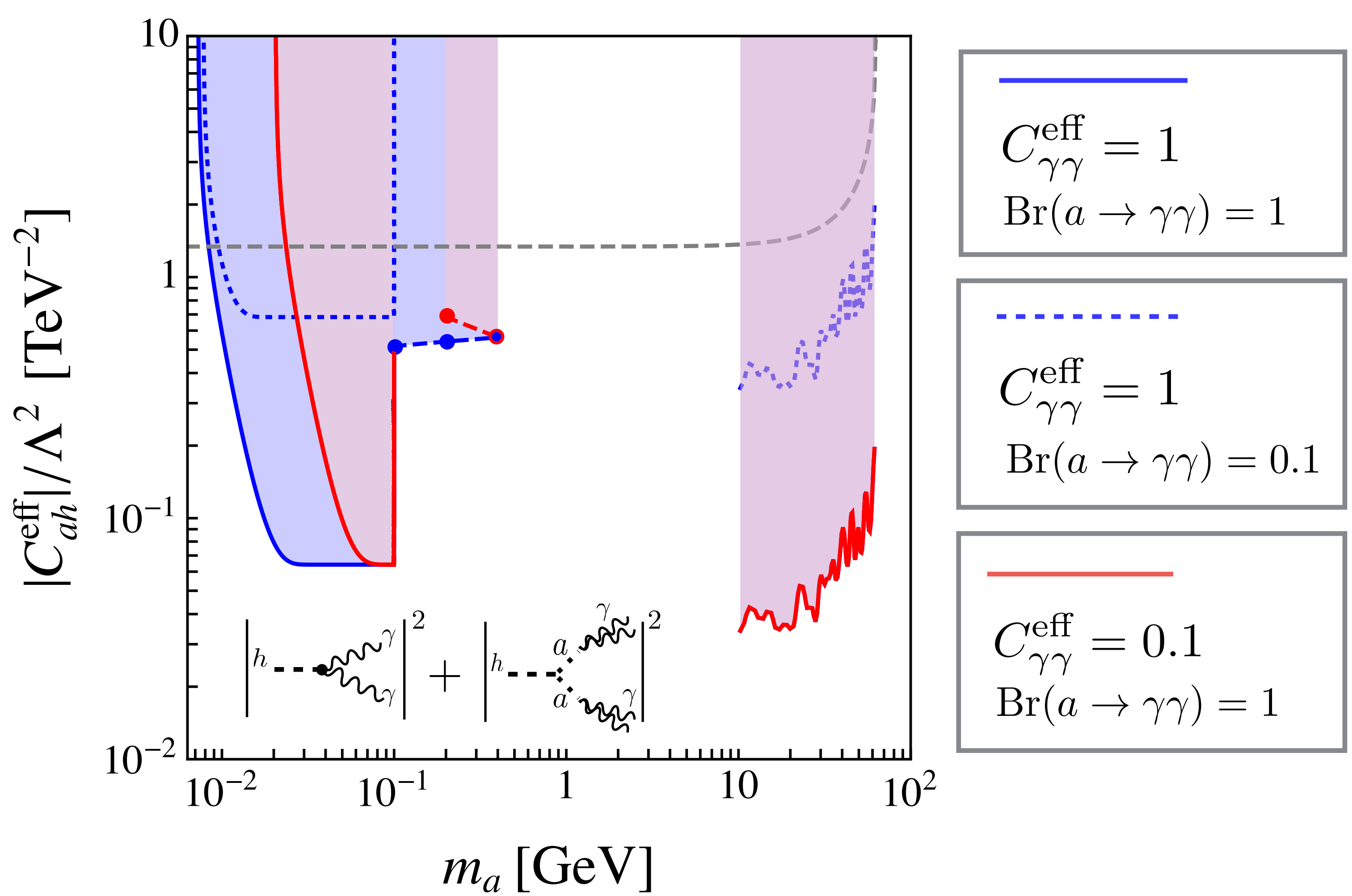
MB, Neubert, Thamm, 1708.00443

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



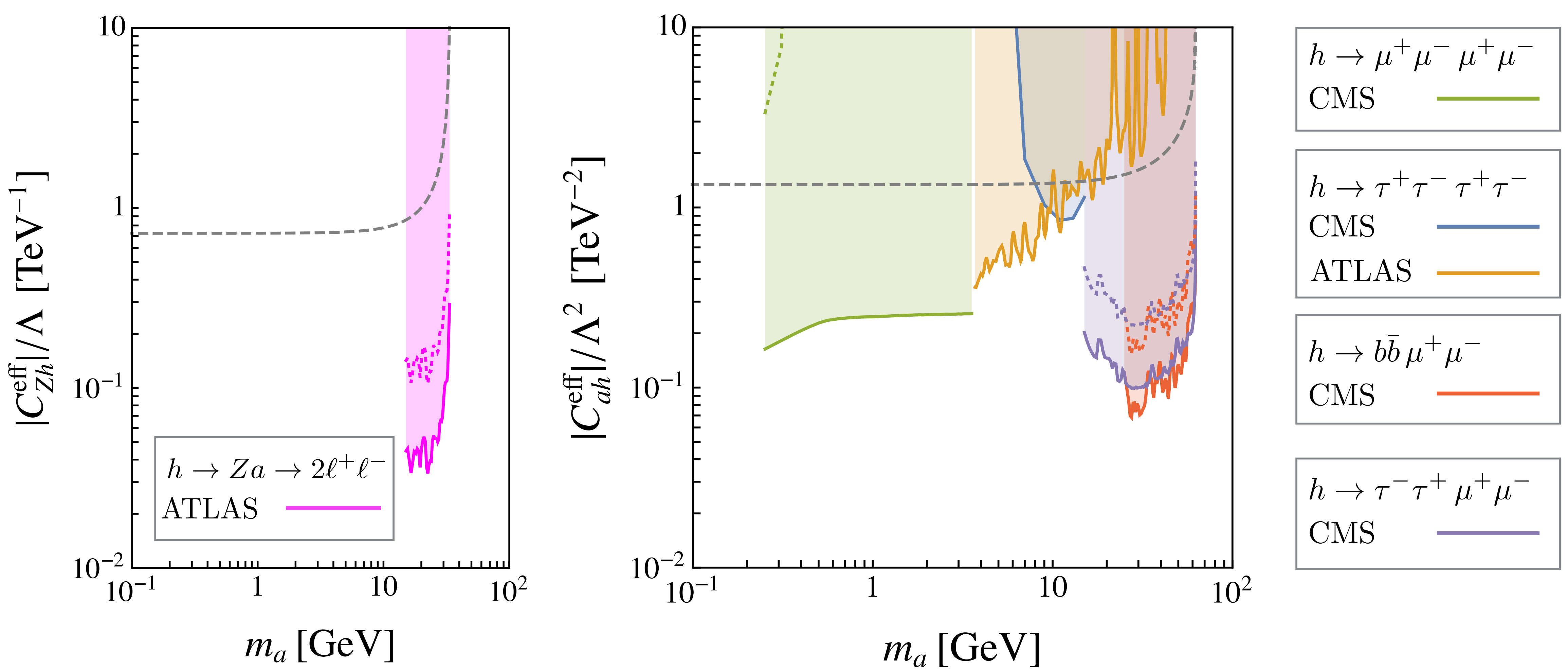


MB, Neubert, Thamm, 1704.08207

Exotic Higgs Decays

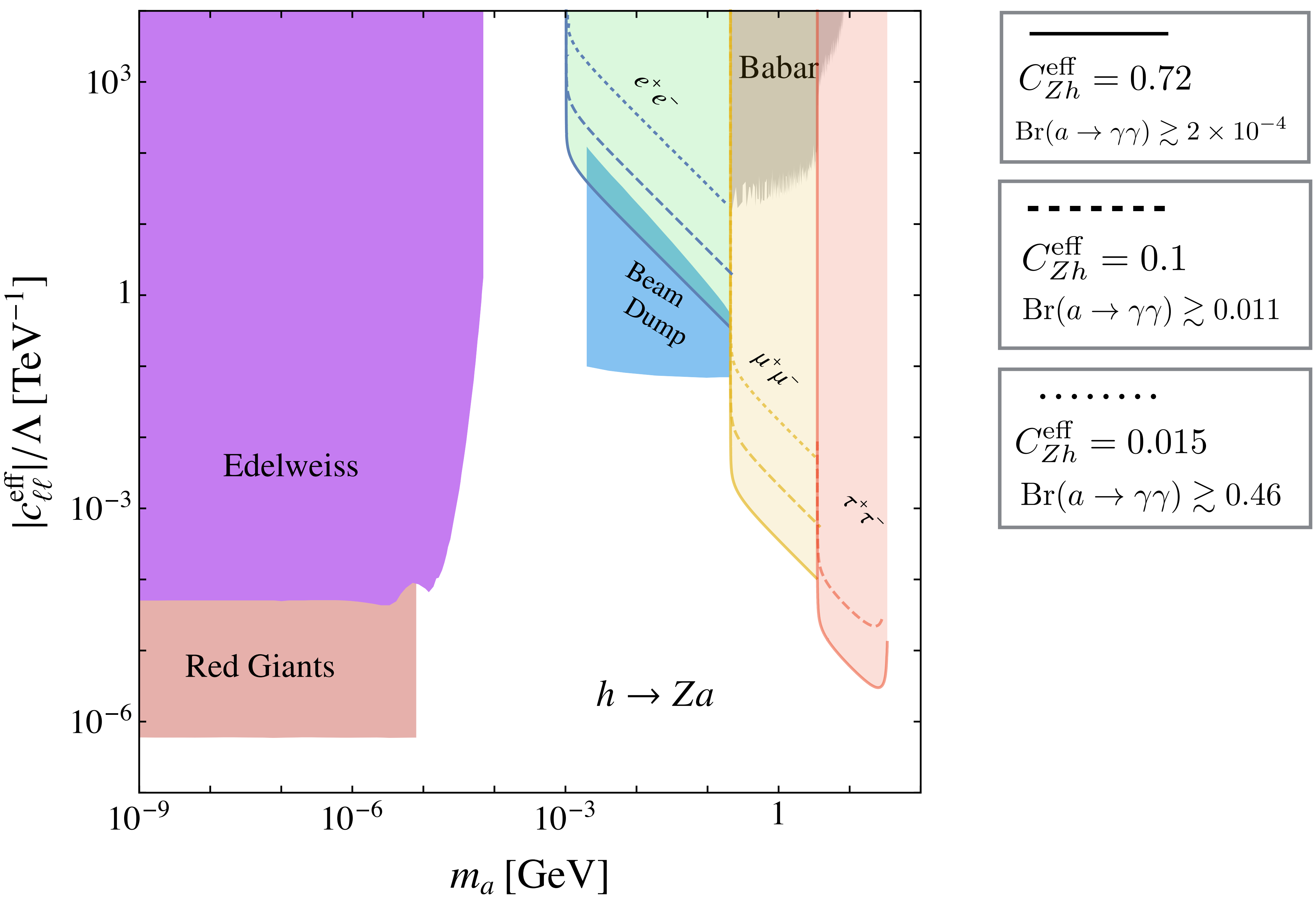
Searches for h -> aa and h -> Za are strongly motivated in various final states. Current constraints:

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



MB, Neubert, Thamm, 1708.00443

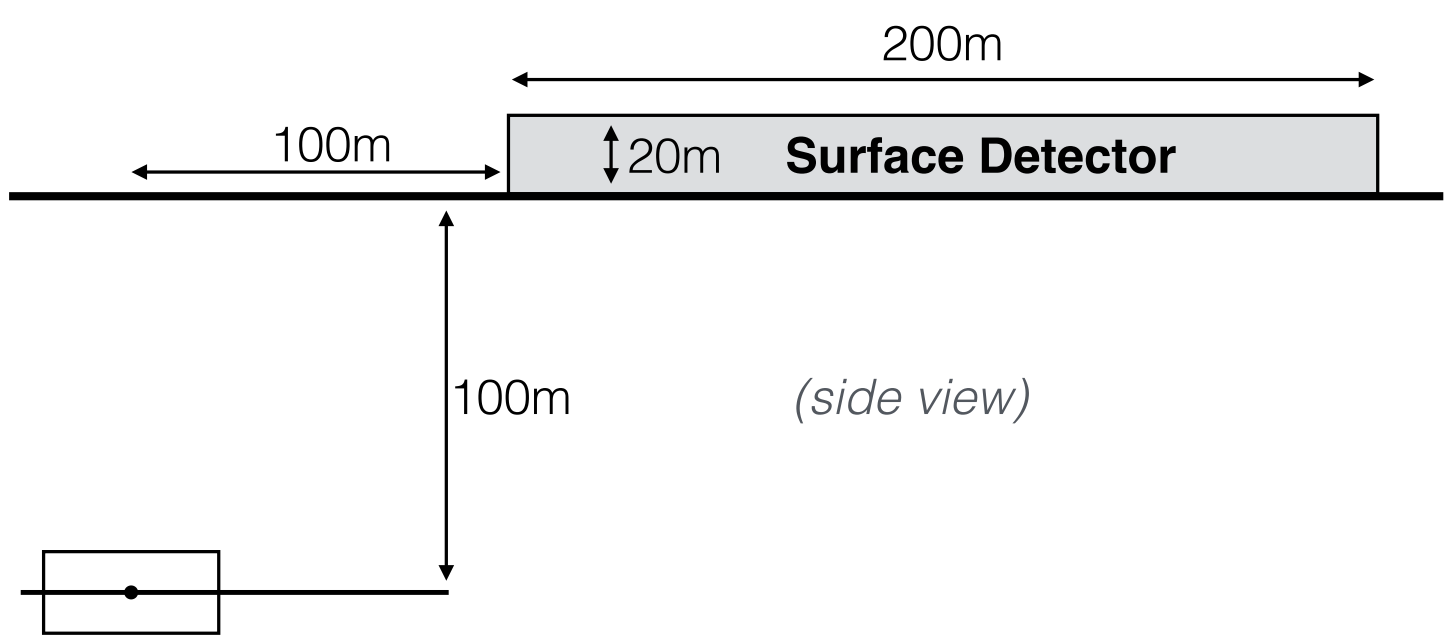
Exotic Higgs Decays



MB, Neubert, Thamm, 1708.00443

Very displaced Vertices

Currently we have constraints on long-lived particles with a lifetime of cosmological scales and ~10 m. What about the length scales in-between?

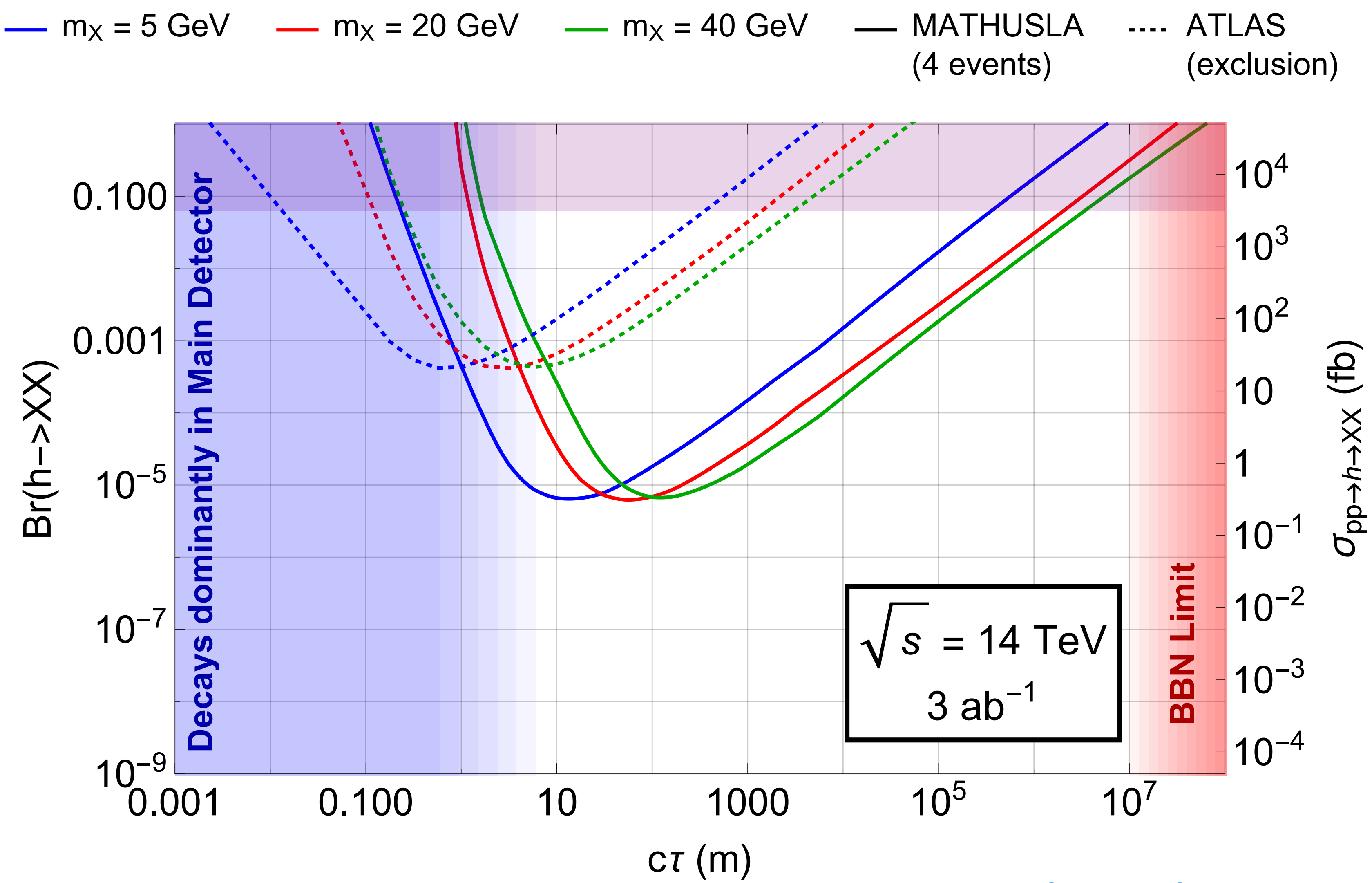


The idea is to probe these length scales with a dedicated detector during the high luminosity run of the LHC.

Chou, Curtin, Loubatti, 1606.06298

Very displaced Vertices

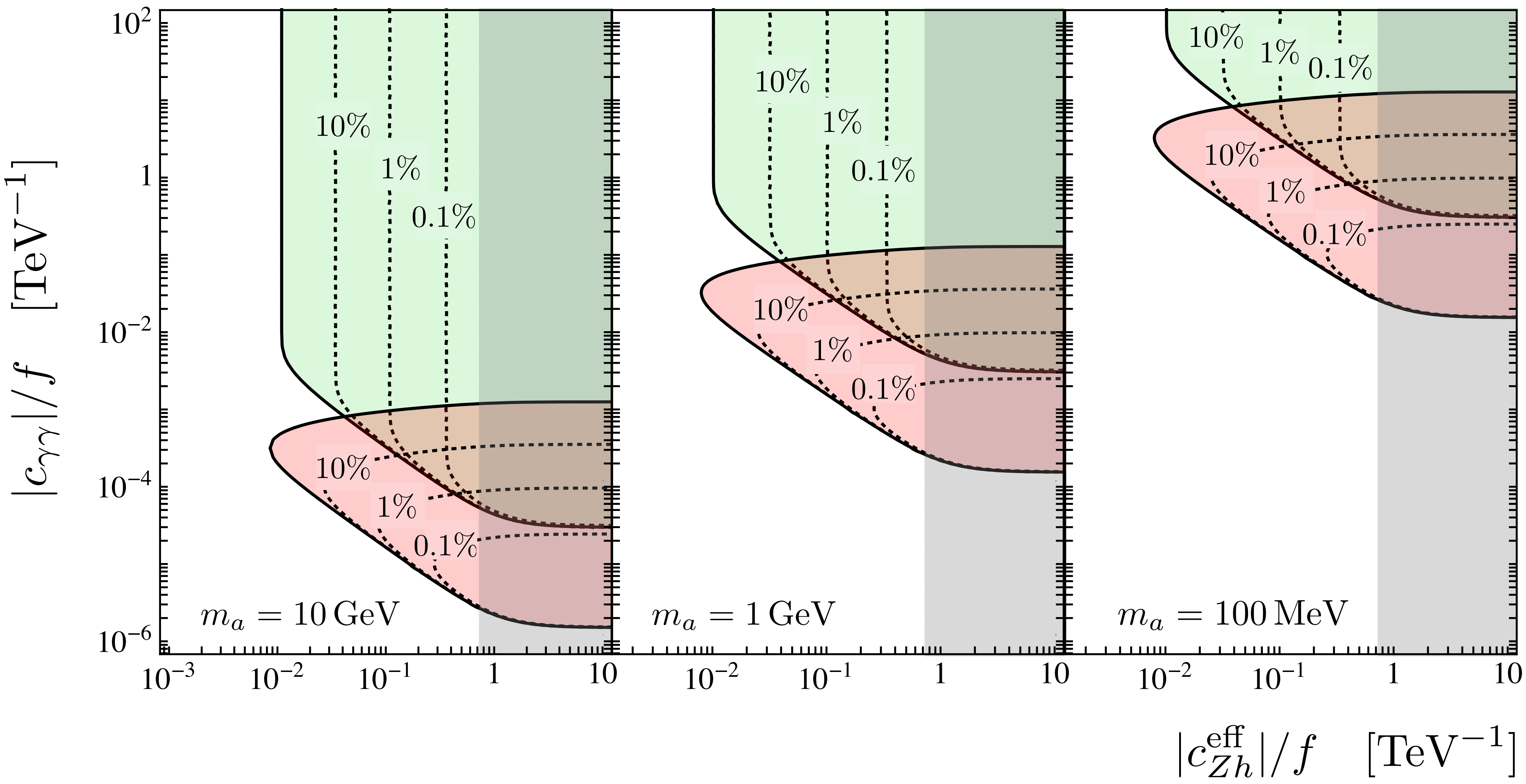
Currently we have constraints on long-lived particles with a lifetime of cosmological scales and ~10 m. What about the length scales in-between?



Chou, Curtin, Loubatti, 1606.06298

Very displaced Vertices

The reach for future searches for h -> Za decays



MATHUSLA physics case, to appear…1713….

What can light New Physics tell us about the UV?

A lot!

ALPs can be discovered in Higgs decays.

Different processes (h -> aa, h-> a Z, Z -> a gamma) would provide information on the scale and structure of the UV sector.

A UFO file is available. An ATLAS group works on the analysis.

Thank you!

Backup

ALP Effective Lagrangian

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

Most general dimension five Lagrangian

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

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

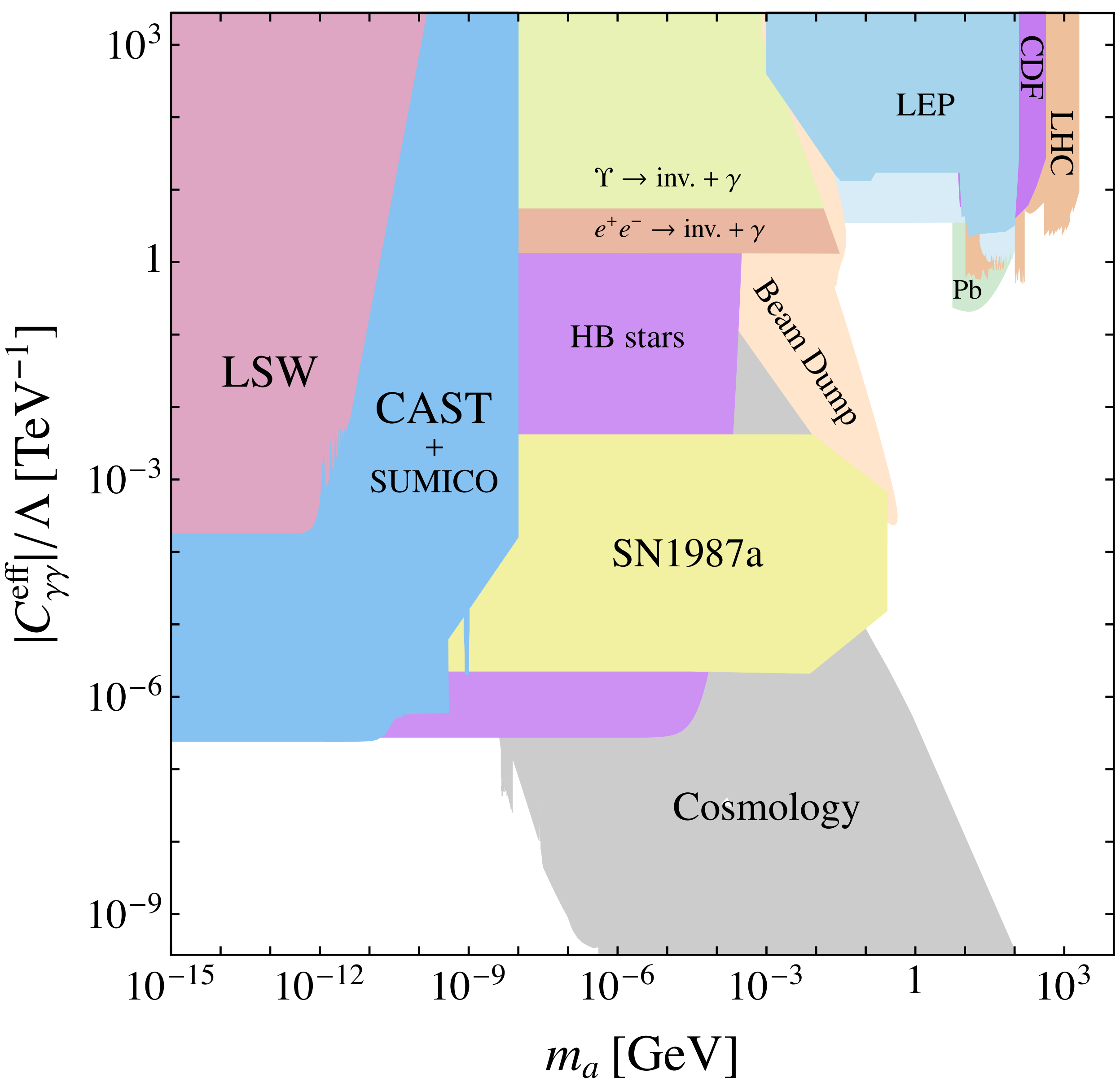
below the QCD scale

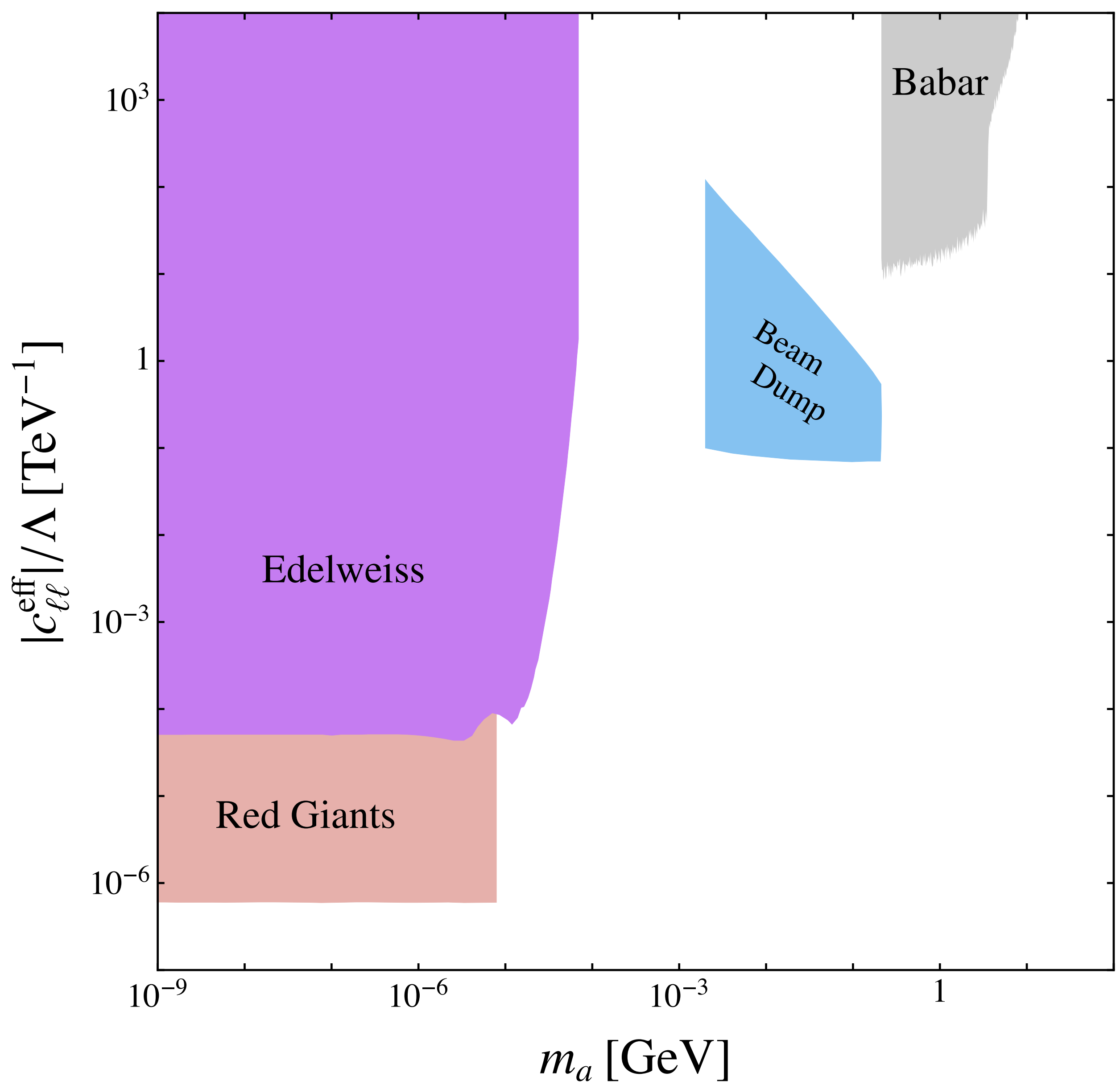
$$\mathcal{L}_{\chi PT} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{m_a^2}{2}\, a^2 + e^2 \left[C_{\gamma\gamma} - \frac{2}{3}\,(4\kappa_u + \kappa_d)\, C_{GG} \right] \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

$$+\, \frac{f_\pi^2}{8}\,\mathrm{tr}\big[D^\mu\Sigma\, D_\mu\Sigma^\dagger\big] + \frac{f_\pi^2}{4}\, B_0\, \mathrm{tr}\big[m_q(\Sigma + \Sigma^\dagger)\big] + \frac{i f_\pi^2}{4}\, \frac{\partial^\mu a}{2\Lambda}\, \mathrm{tr}\big[\hat{c}_{qq}(\Sigma^\dagger D_\mu \Sigma - \Sigma\, D_\mu \Sigma^\dagger)\big]$$

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

Bounds on ALPs





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

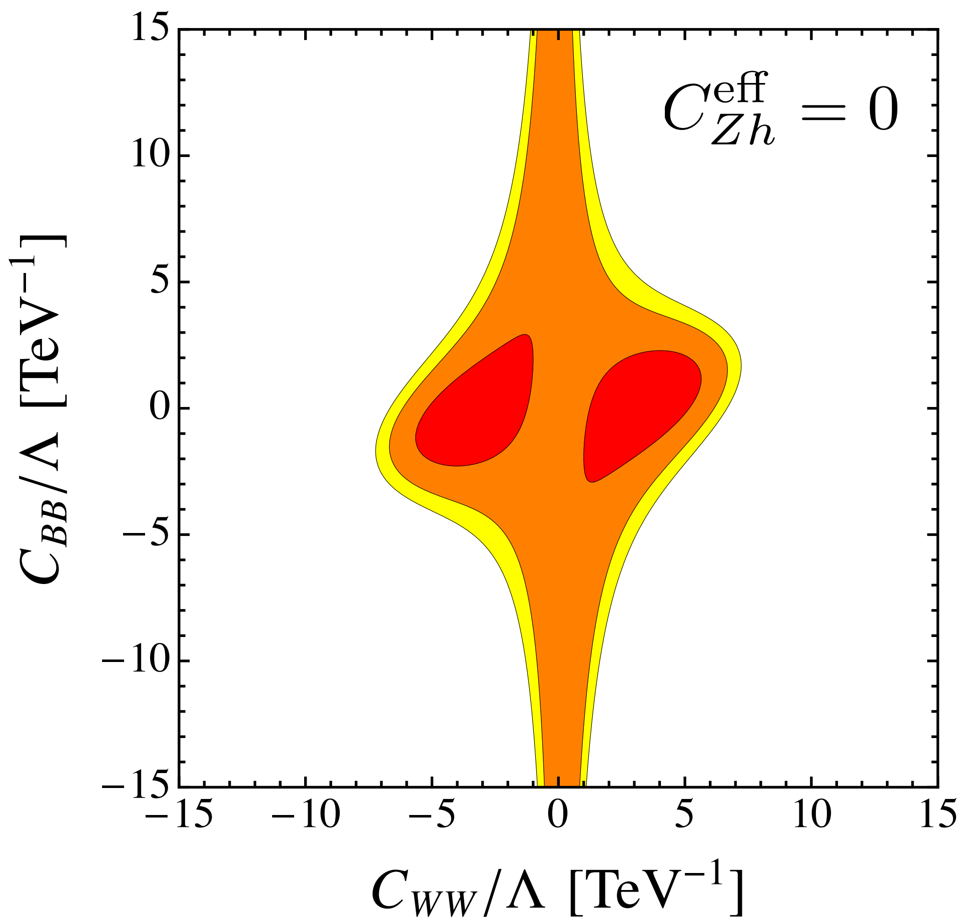
Armengaud et al., JCAP 1311, 067 (2013) …and others

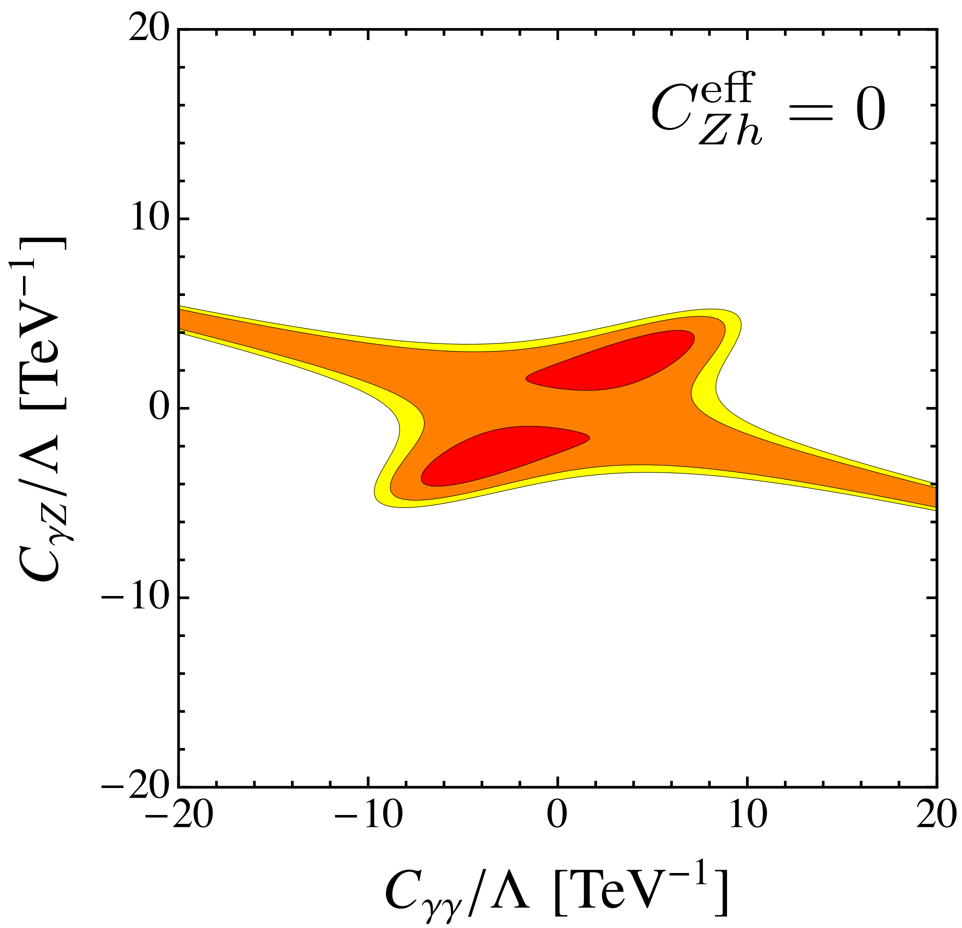
Bounds from Precision Observables

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

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

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



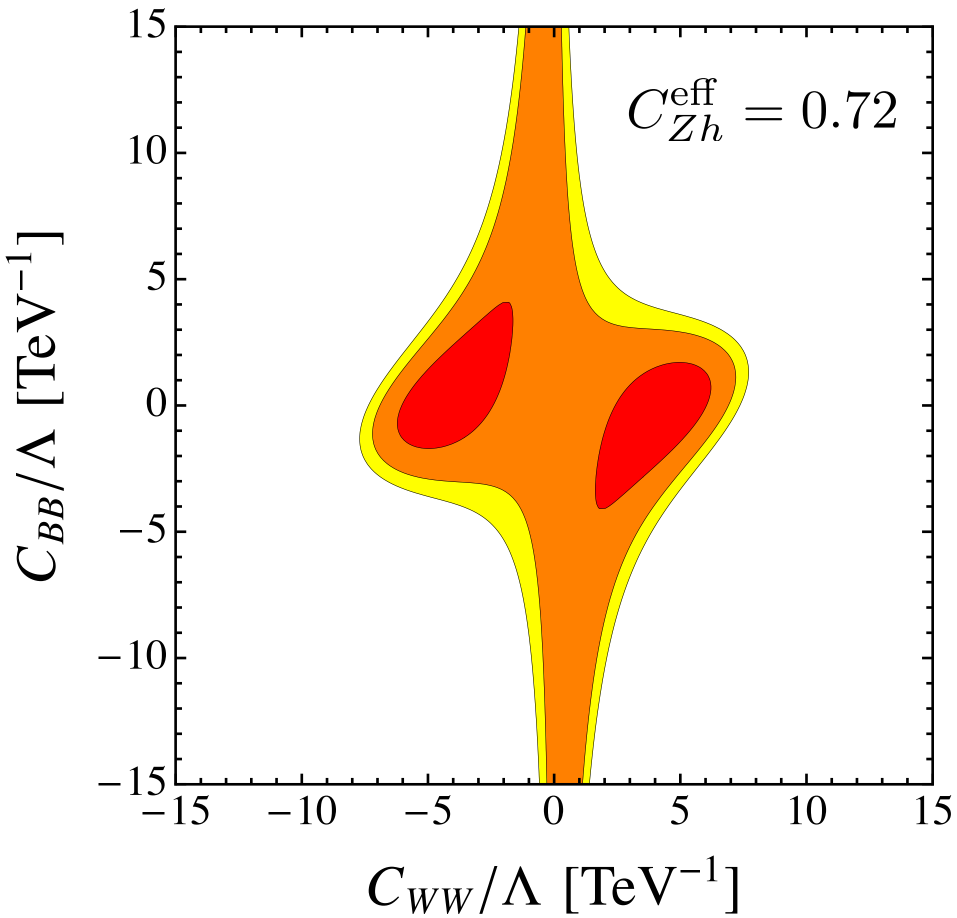


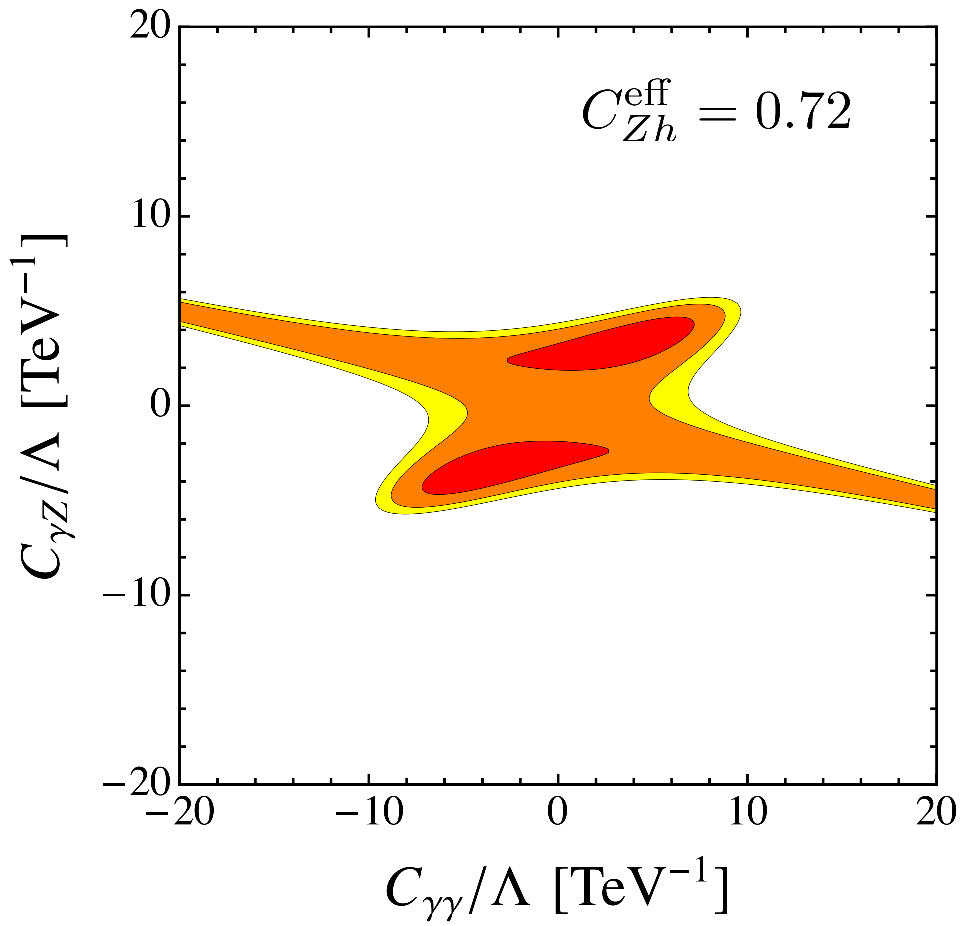
Bounds from Precision Observables

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

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

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





ALP Decays into SM particles

Partial ALP widths for all Wilson coefficients set to 1.