ALPs
SMEFT extensions at future colliders

Andrea Thamm

The University of Melbourne

with Martin Bauer, Mathias Heiles, Matthias Neubert, Sophie Renner, Marvin Schnubel

based on arXiv: 1808.10323, 2108.08949, 2110.10698

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WG1-GLOB Meeting

Outline

1. ALPs - UV Models
2. ALPs - EFT
3. ALPs at Future Colliders
4. ALP Operator Evolution
5. Conclusions

ALP - UV Models

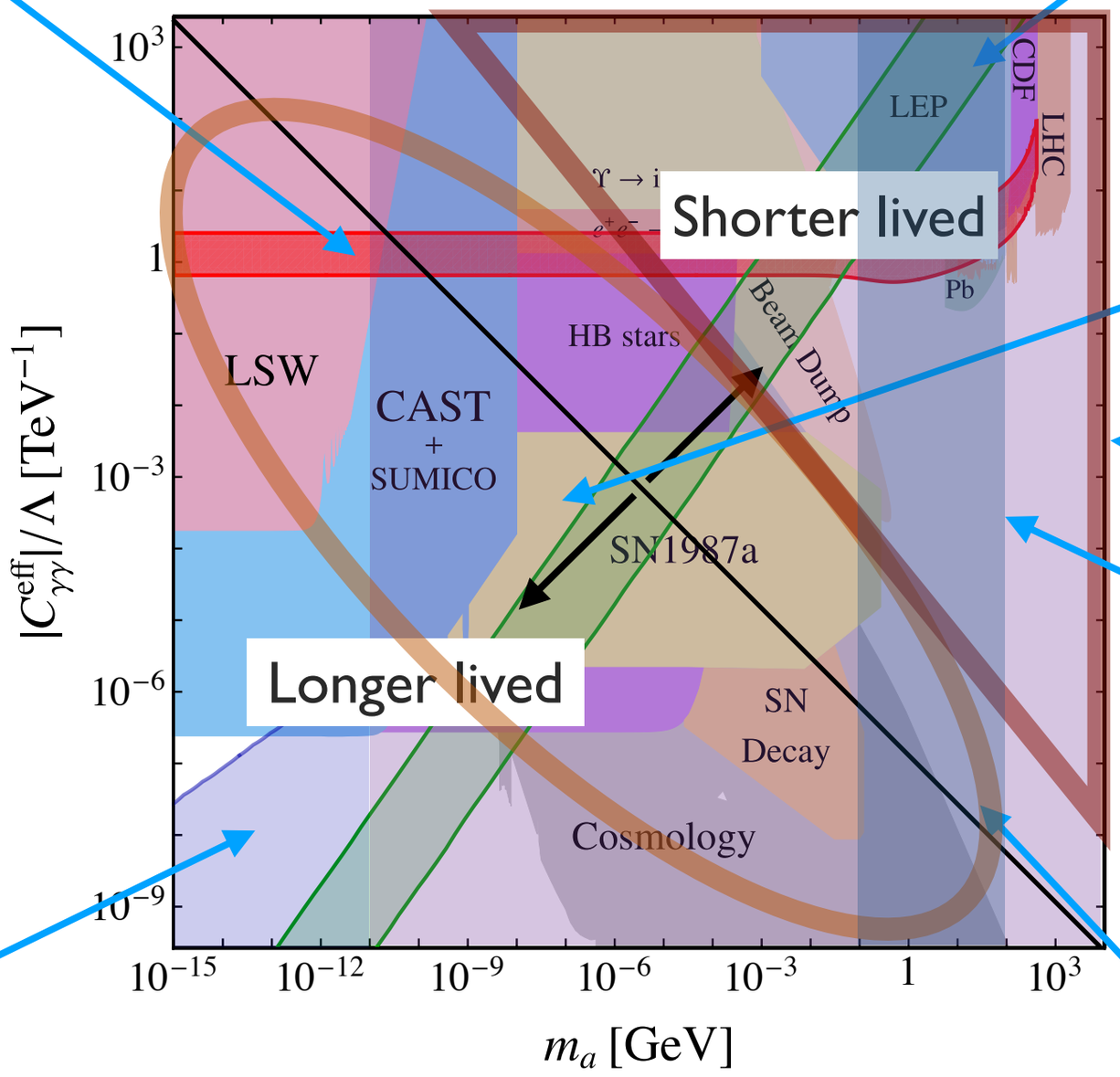
Axion-like particles are pseudo-Nambu Goldstone bosons

Solves $(g-2)_\mu$ anomaly

QCD axion

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

ALPs from sun and stars



ALPs decay within collider

pNGB in supersymmetric or composite models

0902.1483, 1312.5330,1702.02152

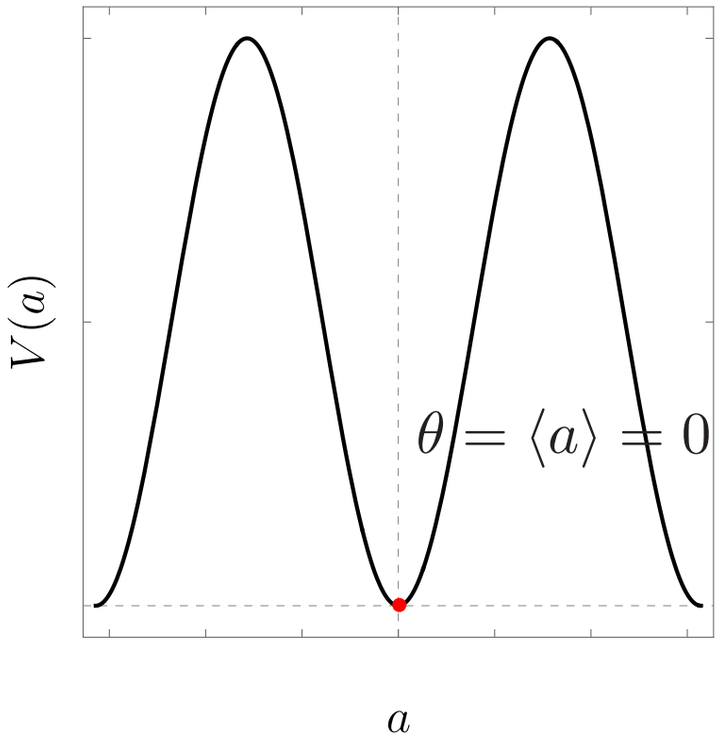
DM candidate

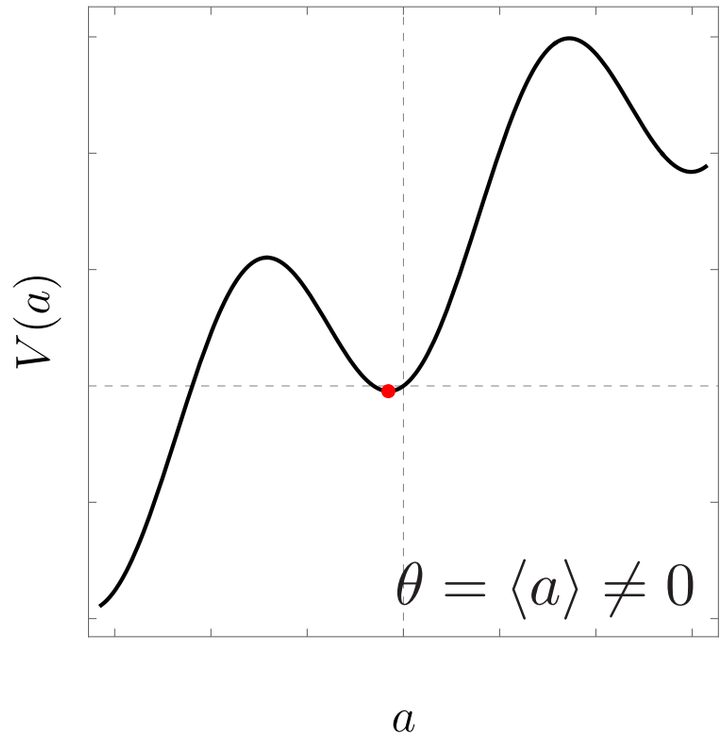
Mediator to the dark sector

ALP - UV Models

Axion quality problem

$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right] + a\,\frac{f_a^{\Delta-1}}{M_{pl}^{\Delta-4}}$$





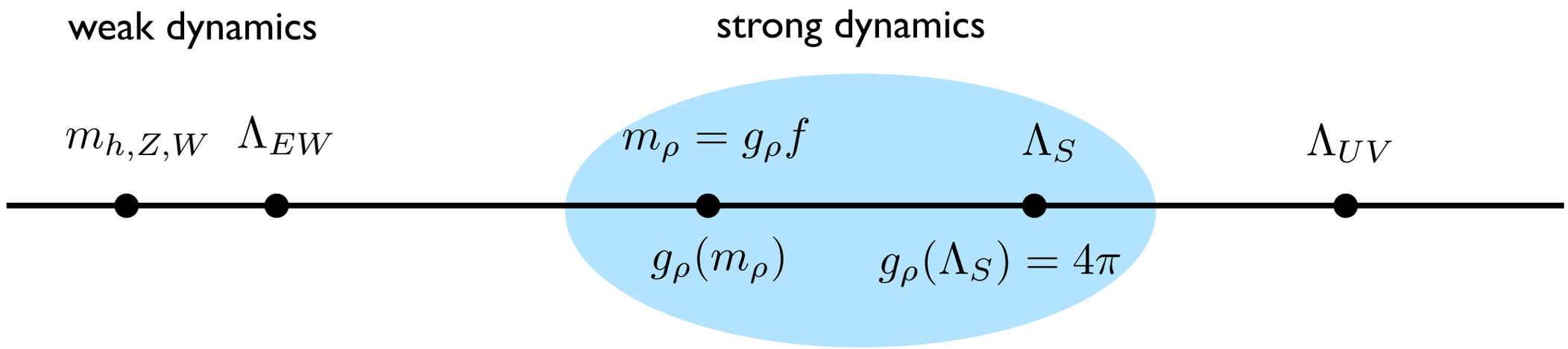
New sector contributes to potential and mass

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

ALP - UV Models

Strongly coupled heavy sector at scale m_ρ

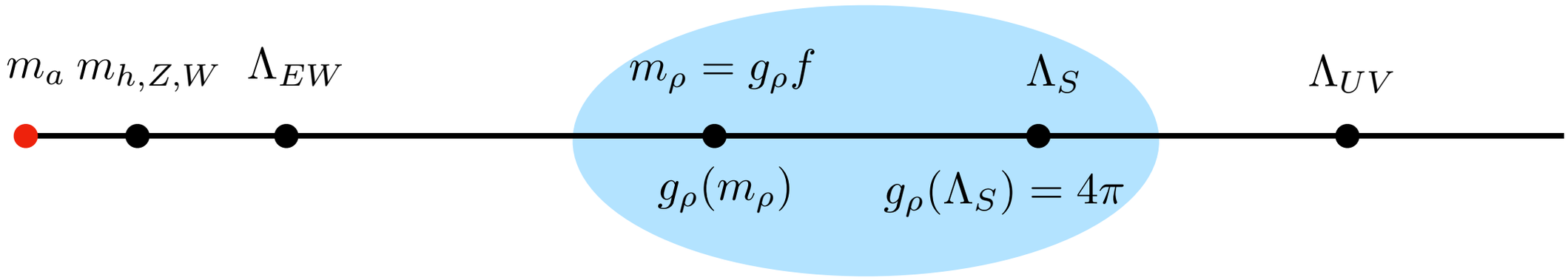
[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]



- Spontaneous breaking of global symmetry
- Higgs arises as a pseudo-Nambu-Goldstone boson
- Above Λ_S H no longer elementary d.o.f. ⟶ solves hierarchy problem

ALP - UV Models

Composite Higgs models



Light pseudo-scalar particles = axion-like particles

[Ferretti 1604.06467]

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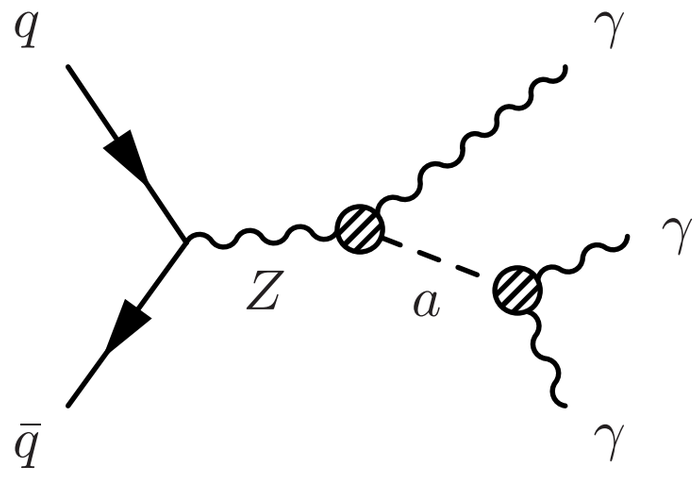
ALPs - EFT

Interactions at dimension-5

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

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F$$
$$+ c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

Exotic Z-decays



ALPs - EFT

Higgs interactions at dimension-6 and 7

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

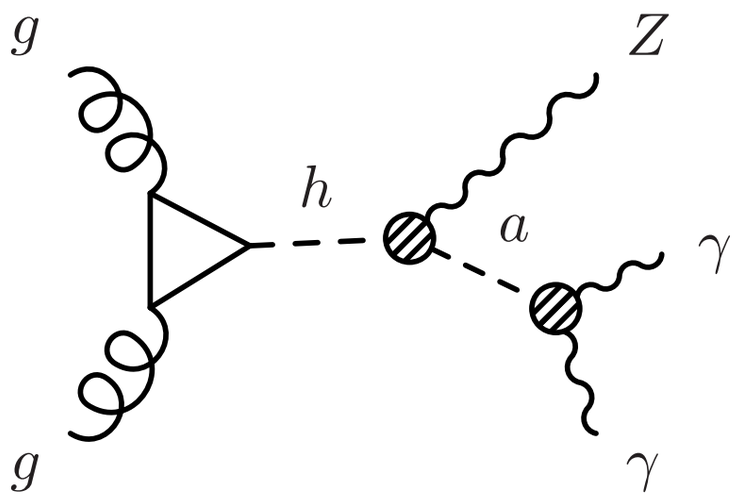
$h \to aa$

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

$h \to Za$

[Bauer, Neubert, Thamm: 1610.00009]
[Bauer, Neubert, Thamm: 1704.08207]
[Bauer, Neubert, Thamm: 1708.004433]

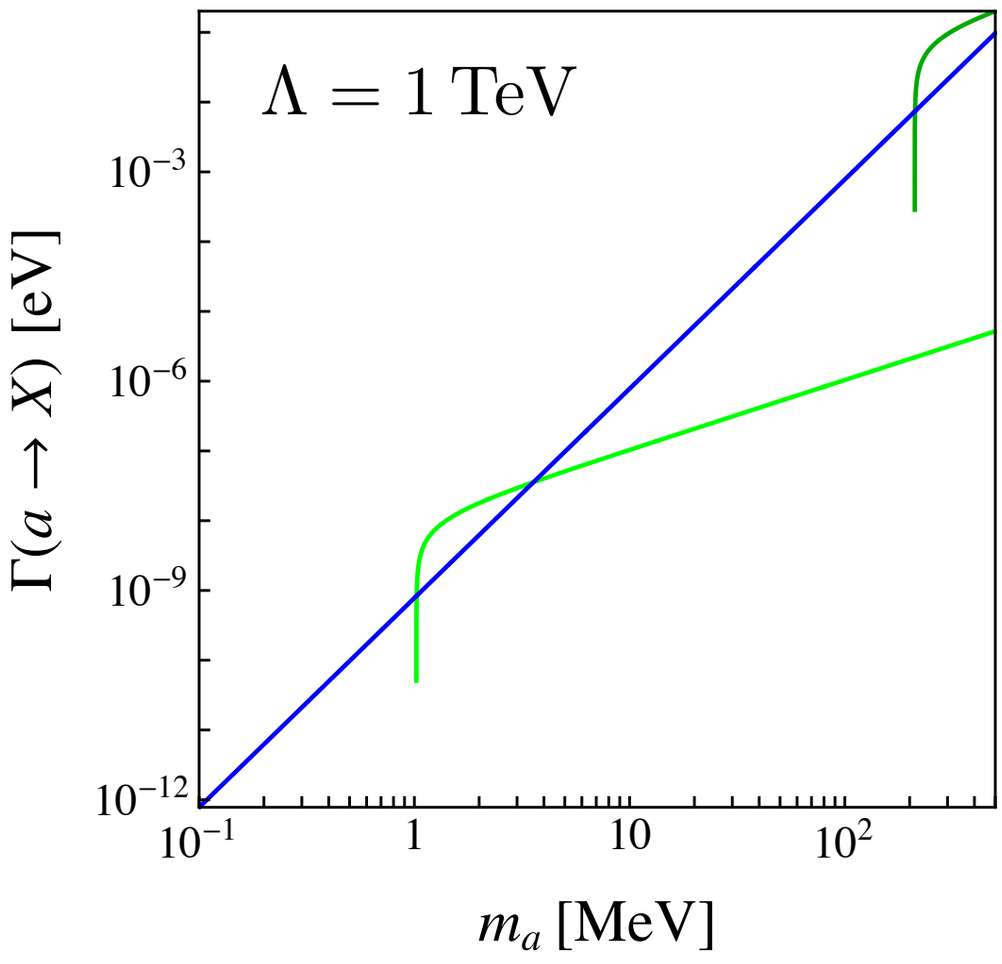
Exotic Higgs decays

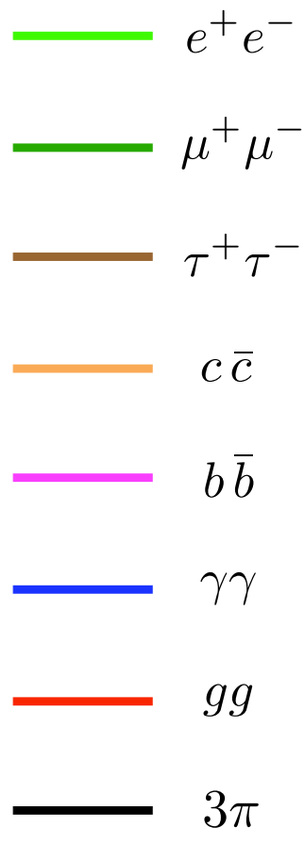


ALPs at Colliders

Fermion couplings = 1, Gauge boson couplings = 1 in the plot

More motivated: gauge couplings = $1/(4\pi)^2$





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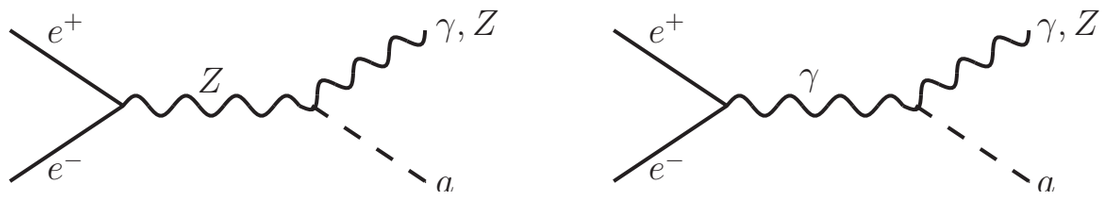
ALPs at Future Colliders

- Resonant production
- Vector boson fusion [Buttazzo, Redigolo, Sala, Tesi: 1807.04743]
- ALP associated production [Bauer, Heiles, Neubert, Thamm: 1808.10323]
- ALP production through exotic decay of H or Z [Bauer, Heiles, Neubert, Thamm: 1808.10323]

ALPs at Future Colliders

- ALP associated production with a photon or Z



- Includes exotic Z decays at the Z pole

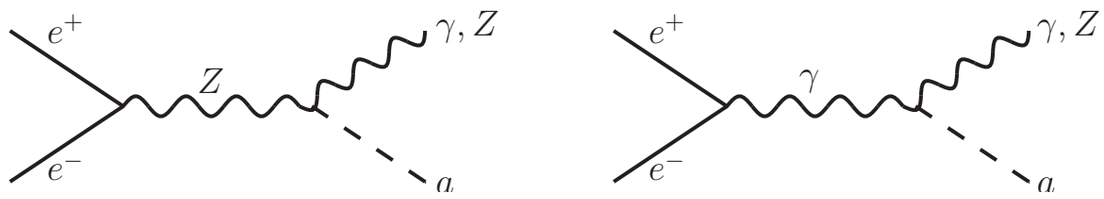
- ALP decay into photons

→ Process depends on only one coupling

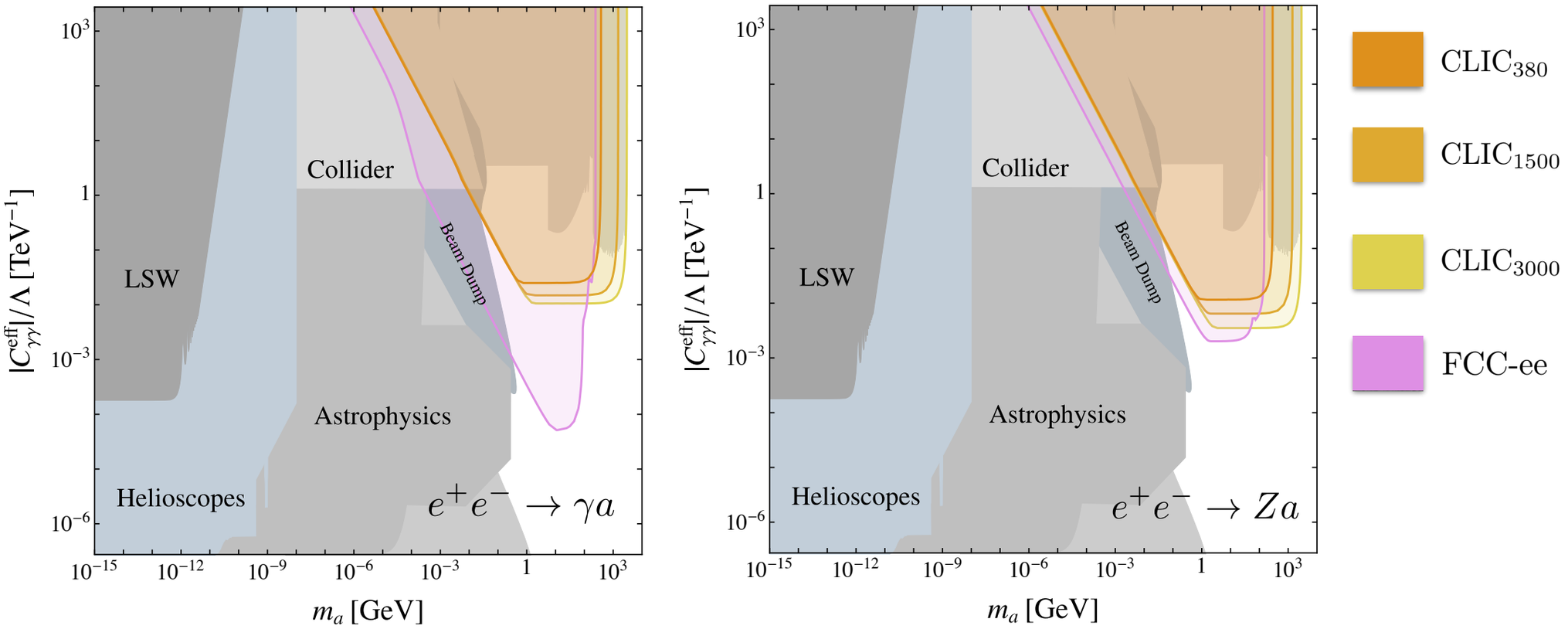
$$C_{\gamma\gamma} = C_{WW} + C_{BB}\,, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB} \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

ALPs at Future Colliders

- ALP associated production with a photon or Z

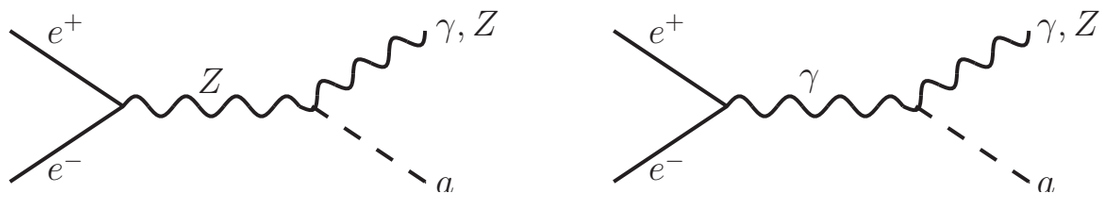


- ALP decay into photons



ALPs at Future Colliders

- ALP associated production with a photon or Z

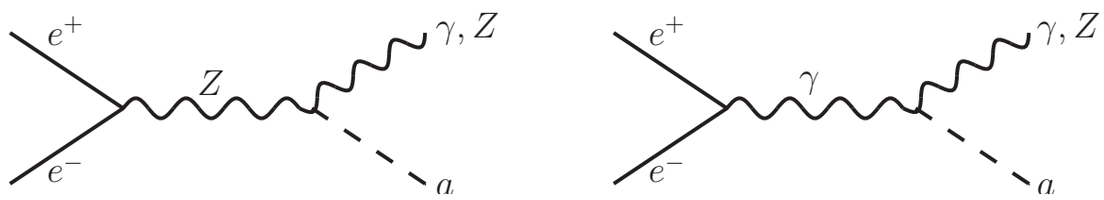


- Includes exotic Z decays at the Z pole
- ALP coupling via lepton loop
- ALP decay into leptons

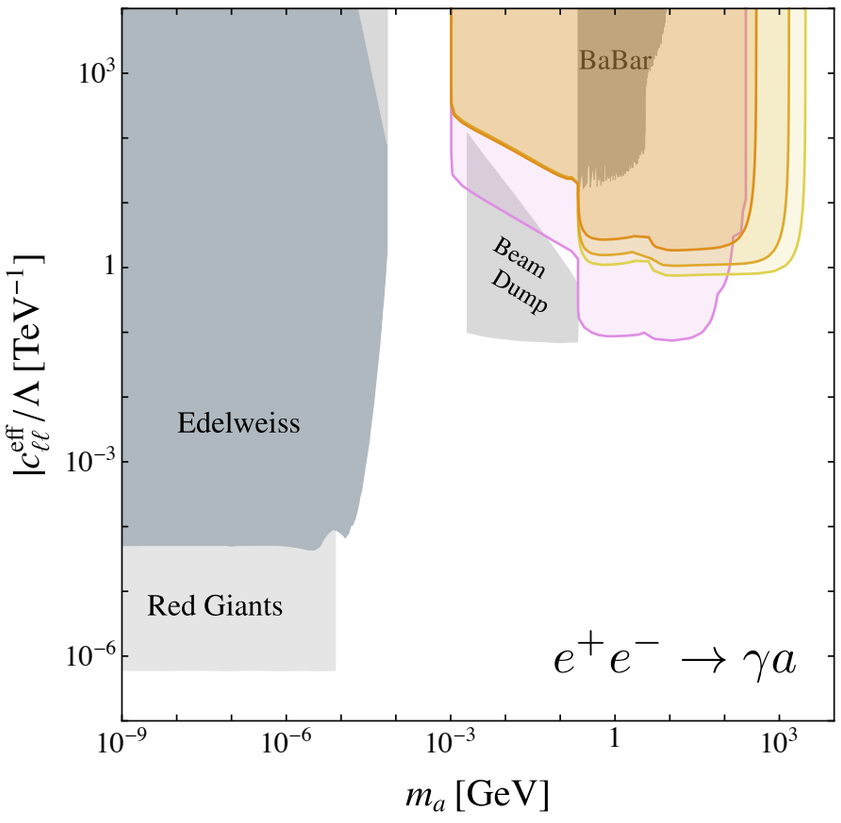
→ Process depends on only one coupling

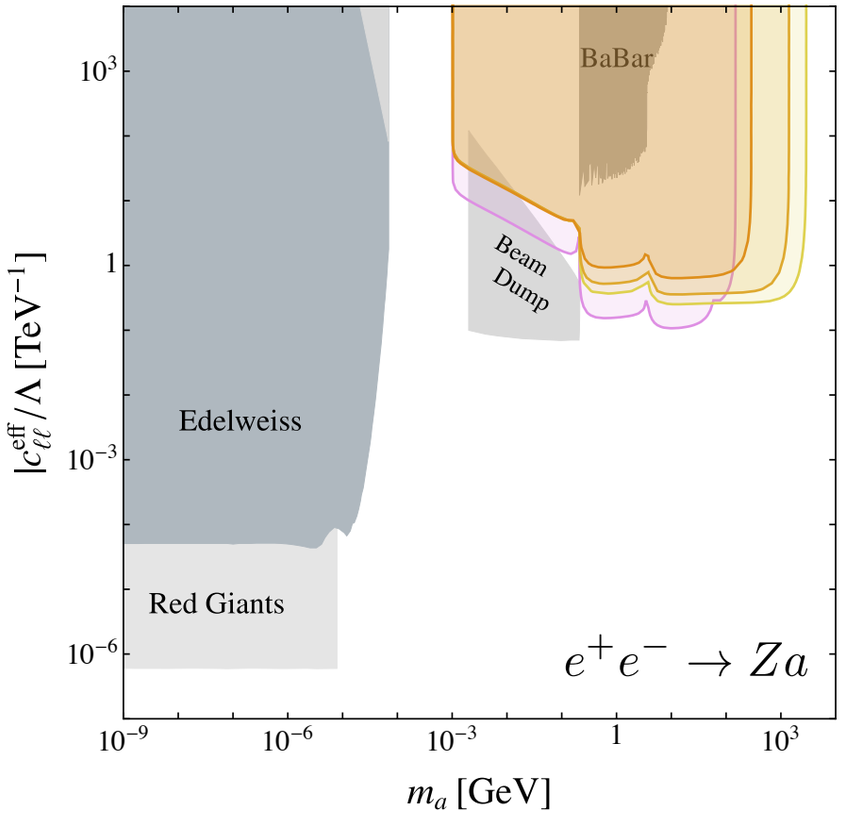
ALPs at Future Colliders

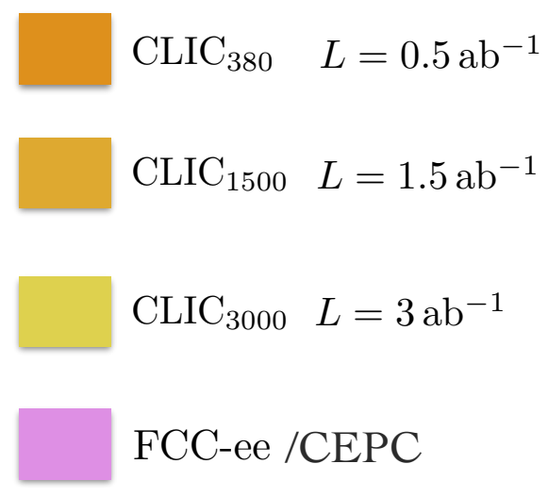
- ALP associated production with a photon or Z



- ALP decay into leptons

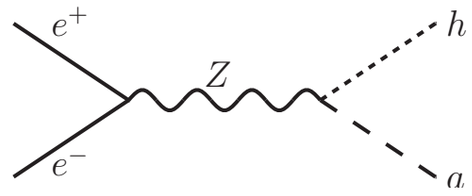




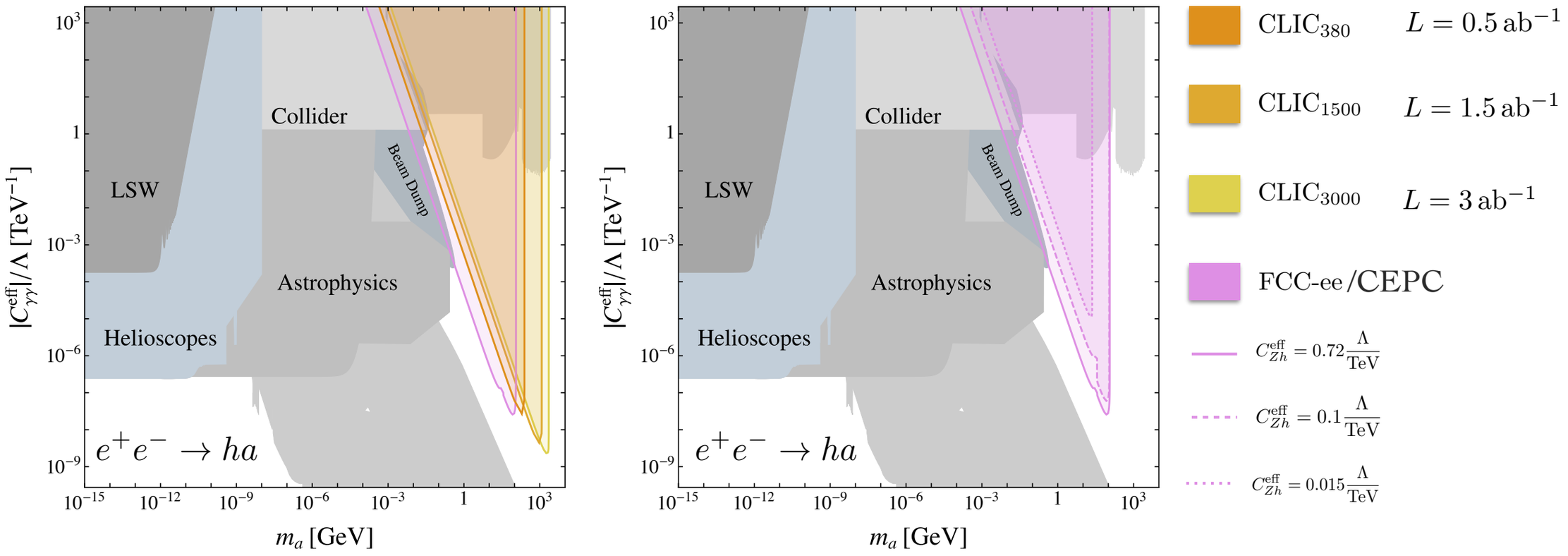


ALPs at Future Colliders

- ALP associated production with a H



- ALP decay into photons



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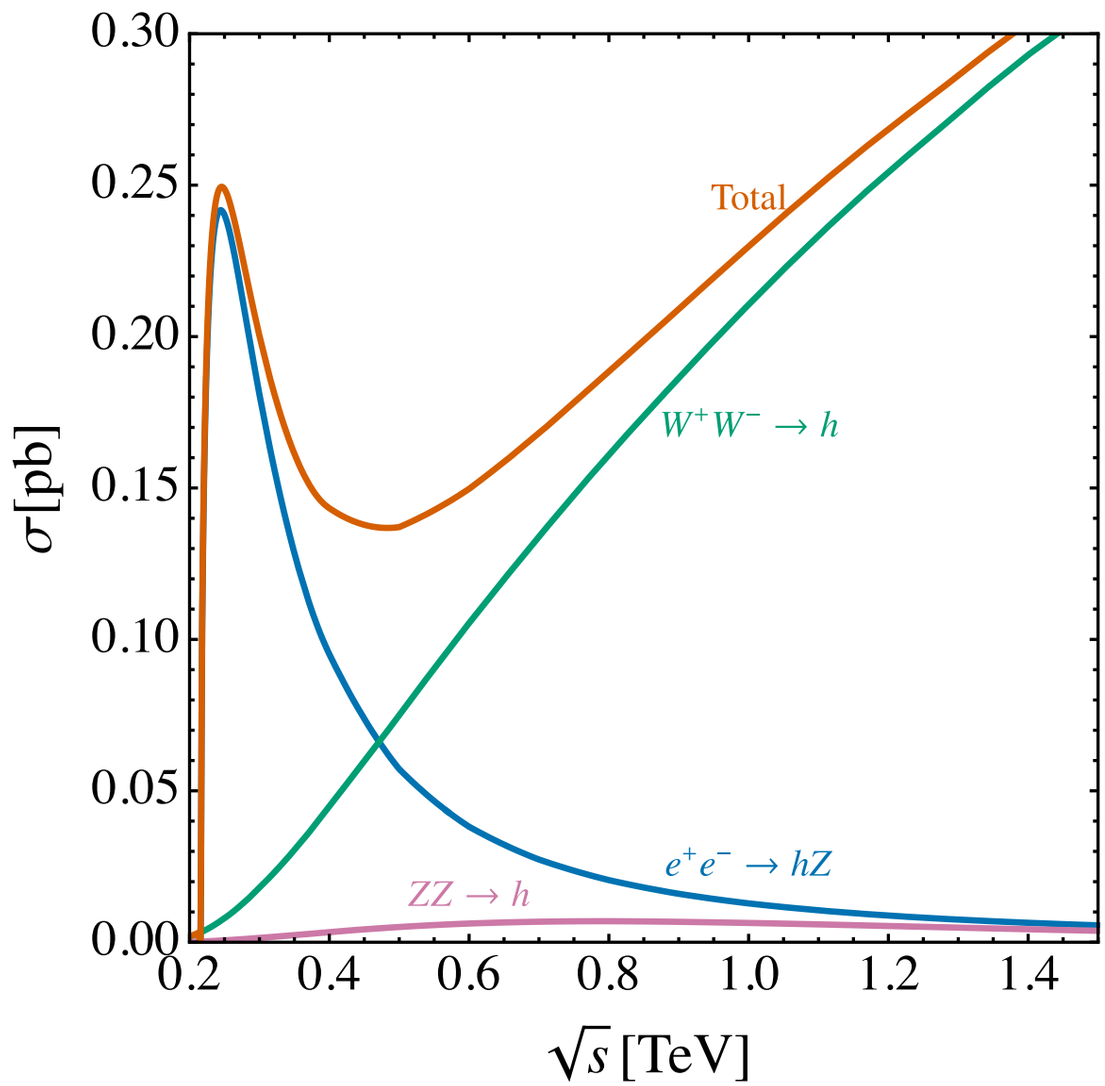
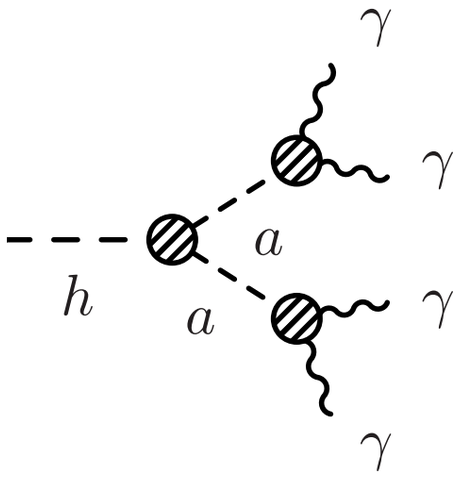
ALPs at Future Colliders

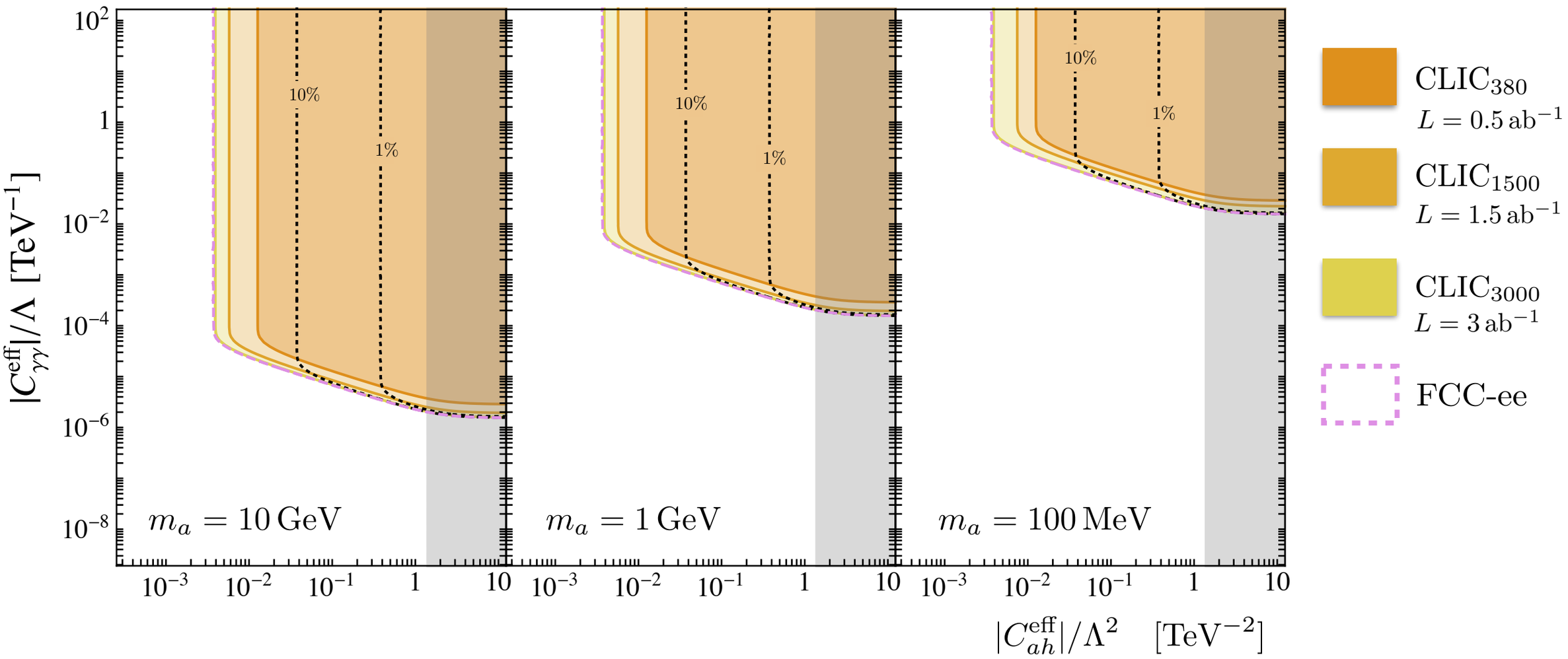
- Exotic Higgs decay: number of Higgses



ALPs at Future Colliders

- Exotic Higgs decay: $h \to aa$





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For more on ALP-SMEFT interference see 2105.01078

Operator Evolution to the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to gauge fields

$$\frac{d}{d\ln\mu}\, c_{VV}(\mu) = 0\,; \quad V = G, W, B$$

[Chetyrkin, Kniehl, Steinhauser, Bardeen: 9807241]

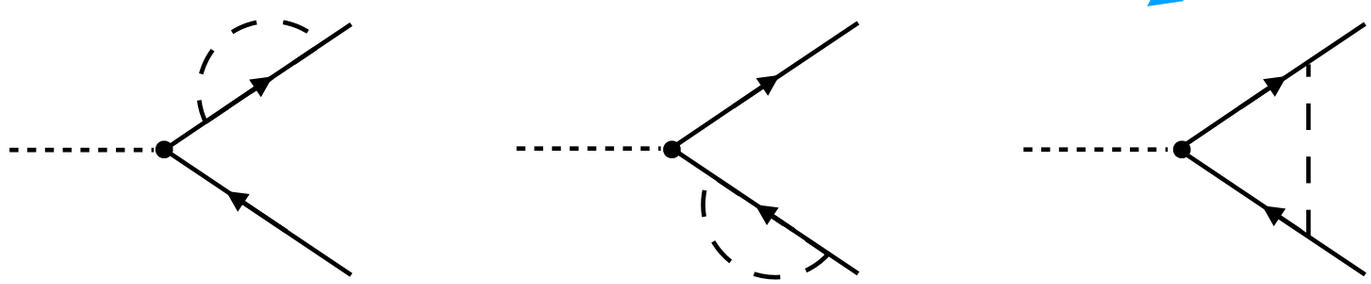
Operator Evolution to the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to fermions

1708.00021, 2002.04623

Contribution from Yukawas



Require redundant operator as counterterm

$$O_\phi \to \sum_F \beta_F \, O_F$$

1308.2627
2012.09017, 2021.12272

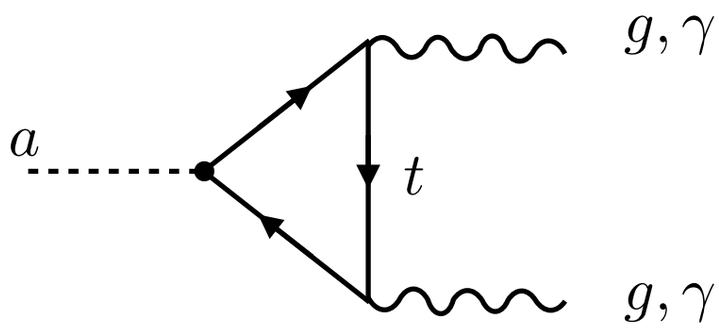
Mixing of ALP-boson operators into ALP-fermions

Operator Evolution at the Weak Scale

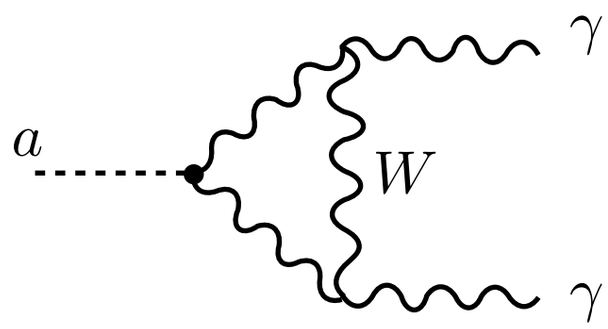
[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to gauge bosons

[Bauer, Neubert, Thamm: 1708.00443]



$$\sim \frac{m_a^2}{m_t^2}$$



$$\sim \frac{m_a^2}{m_W^2}$$

$$\Delta c_{GG}(\mu_w) = 0\,, \qquad \Delta c_{\gamma\gamma}(\mu_w) = 0$$

Operator Evolution at the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]
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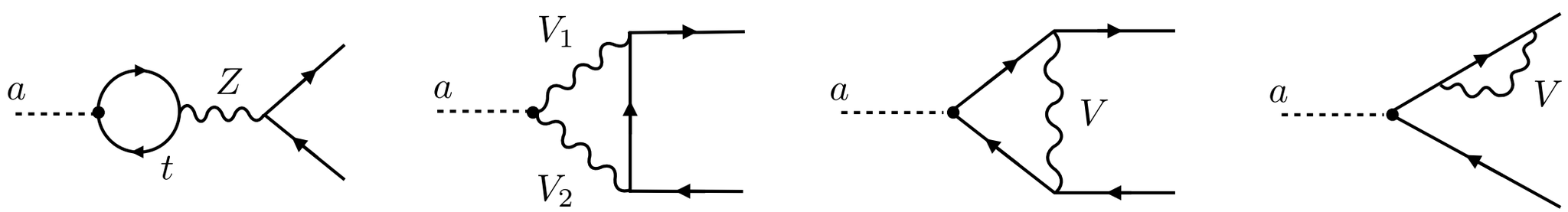
ALP couplings to fermions

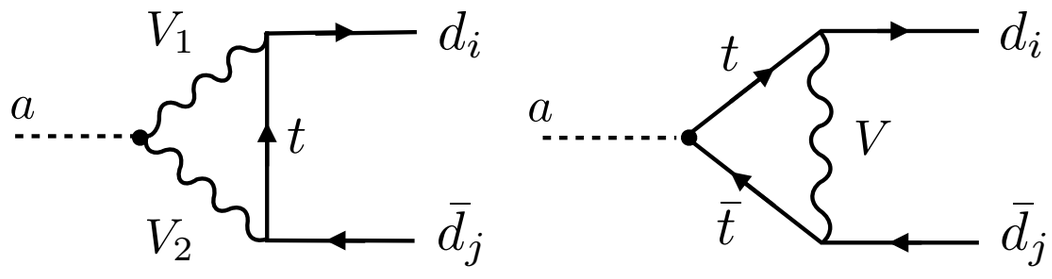
1708.00443



only non-zero for internal t quarks

Non-trivial flavor structure

1412.5174



Operator Evolution at the Weak Scale

[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

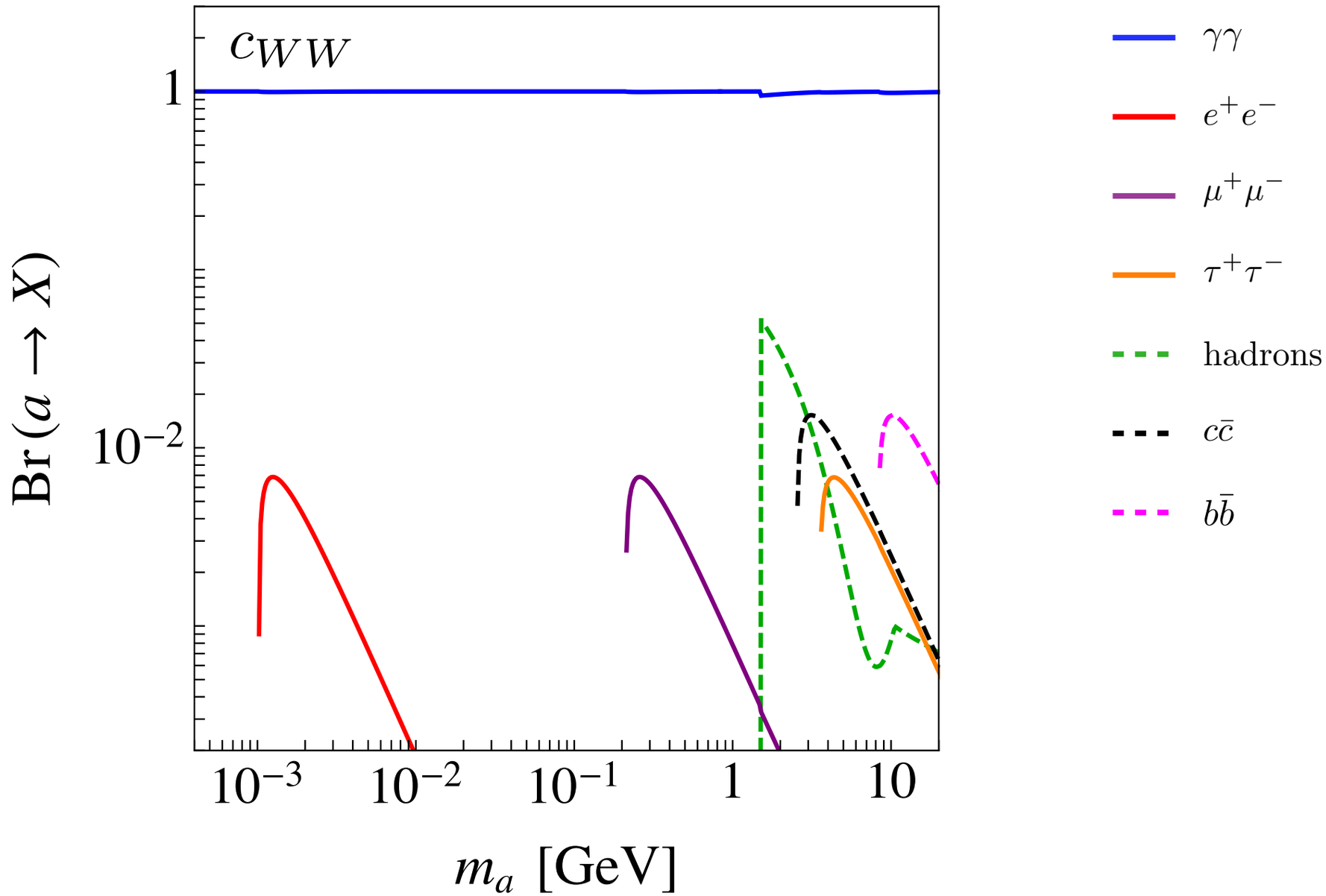
Numerical solution for $\Lambda = 4\pi f$ with $f = 1\,\mathrm{TeV}$

- Flavor diagonal couplings

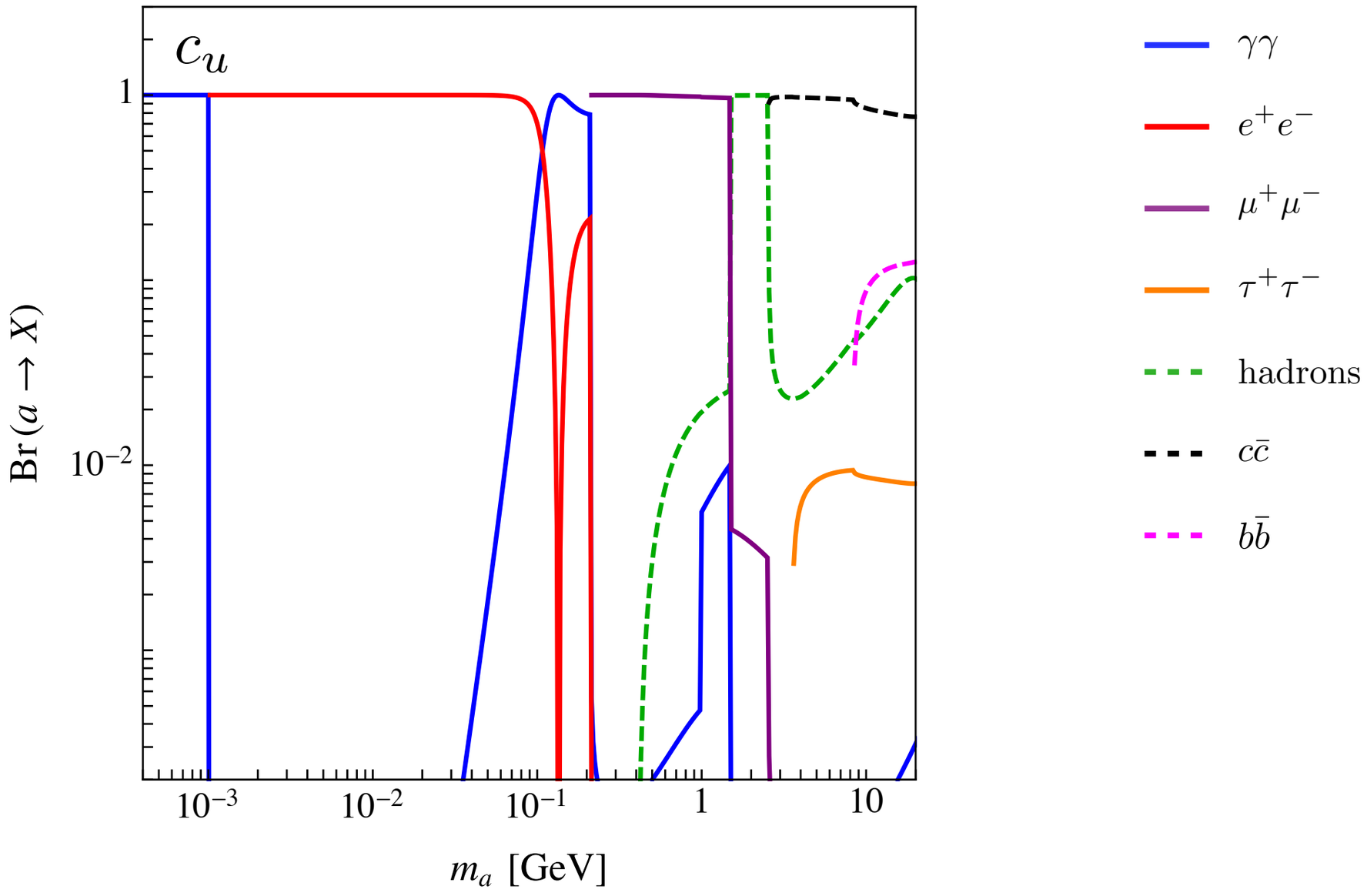
$$\mathcal{L}^{\mathrm{diag}}_{\mathrm{ferm}}(\mu) = \sum_{f \neq t} \frac{c_{ff}(\mu)}{2} \frac{\partial^\mu a}{f} \bar{f} \gamma_\mu \gamma_5 f$$

$$\begin{aligned}
c_{uu,cc}(m_t) &\simeq c_{uu,cc}(\Lambda) - 0.116\, c_{tt}(\Lambda) - \Big[6.35\, \tilde{c}_{GG}(\Lambda) + 0.19\, \tilde{c}_{WW}(\Lambda) + 0.02\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3} \\
c_{dd,ss}(m_t) &\simeq c_{dd,ss}(\Lambda) + 0.116\, c_{tt}(\Lambda) - \Big[7.08\, \tilde{c}_{GG}(\Lambda) + 0.22\, \tilde{c}_{WW}(\Lambda) + 0.005\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3} \\
c_{bb}(m_t) &\simeq c_{bb}(\Lambda) + 0.097\, c_{tt}(\Lambda) - \Big[7.02\, \tilde{c}_{GG}(\Lambda) + 0.19\, \tilde{c}_{WW}(\Lambda) + 0.005\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3} \\
c_{e_i e_i}(m_t) &\simeq c_{e_i e_i}(\Lambda) + 0.116\, c_{tt}(\Lambda) - \Big[0.37\, \tilde{c}_{GG}(\Lambda) + 0.22\, \tilde{c}_{WW}(\Lambda) + 0.05\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}
\end{aligned}$$

Operator Evolution and Collider Bounds



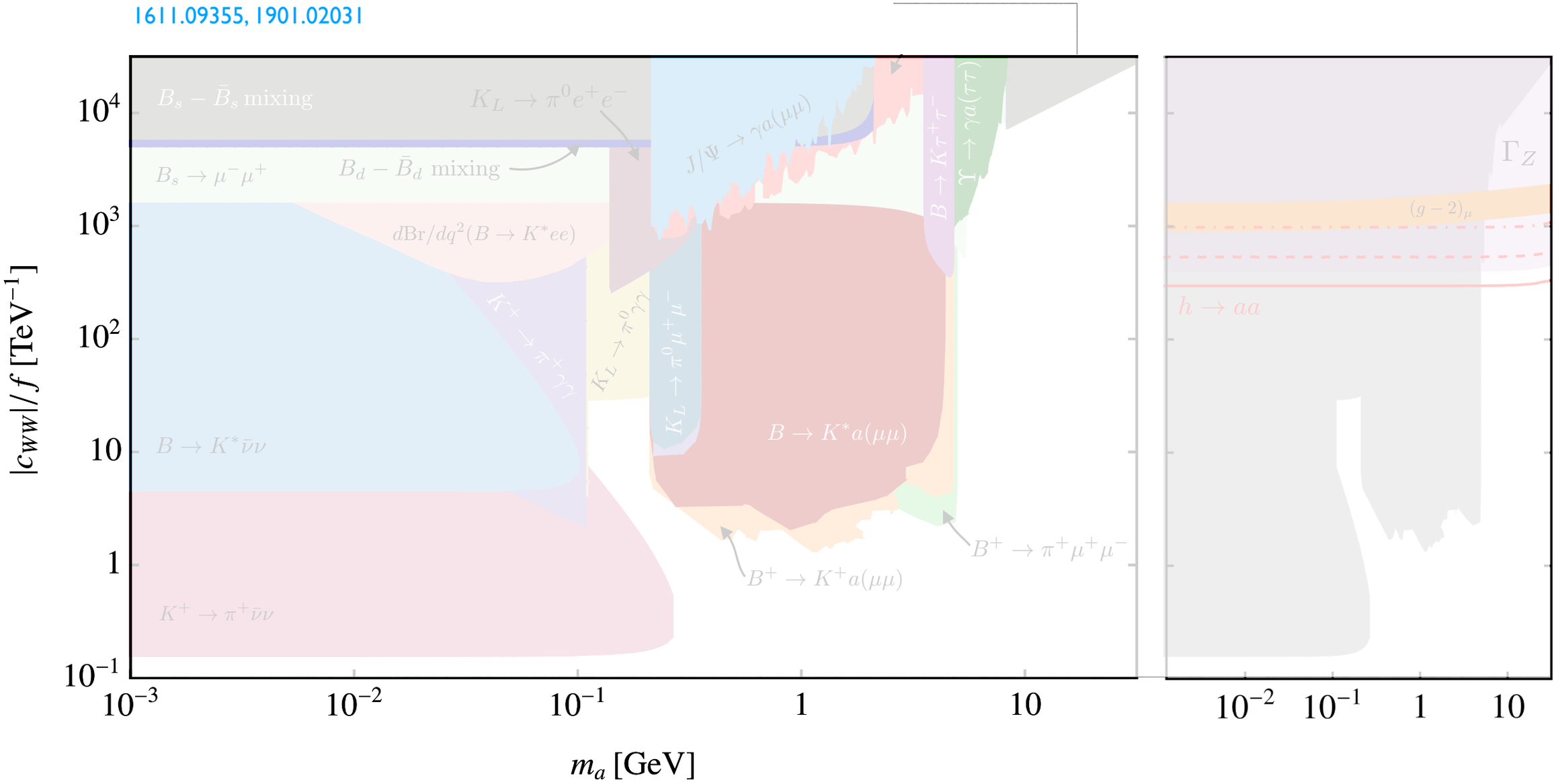
Operator Evolution and Collider Bounds



Operator Evolution and Collider Bounds

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

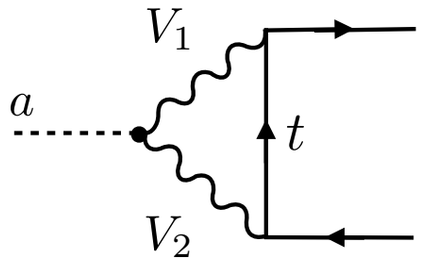
1611.09355, 1901.02031



Operator Evolution and Collider Bounds

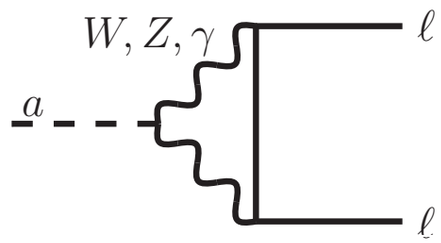
$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

Flavour change



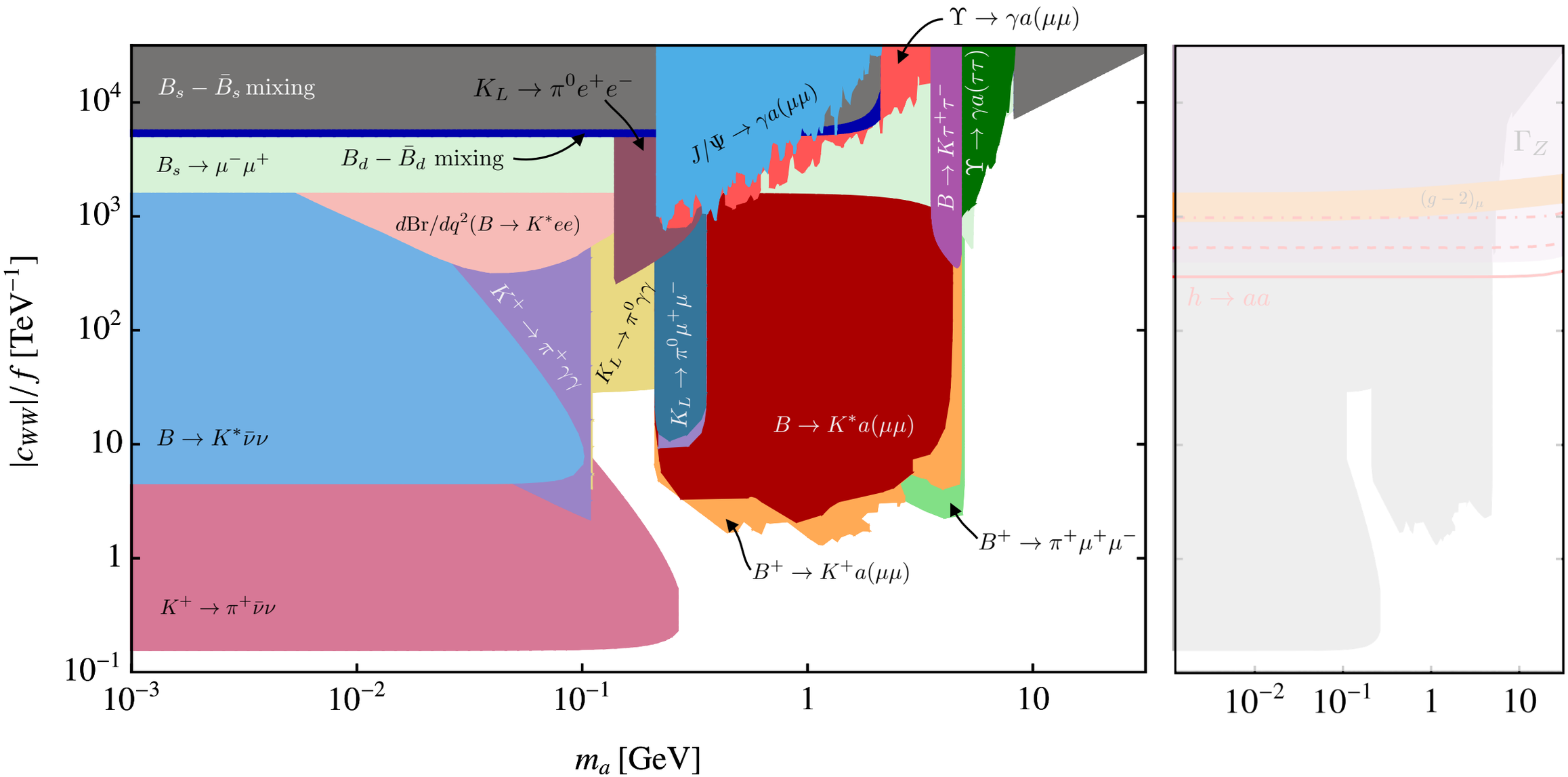
Decay

$$C_{\gamma\gamma} = C_{WW} + C_{BB}$$



Operator Evolution and Collider Bounds

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$



Operator Evolution and Collider Bounds

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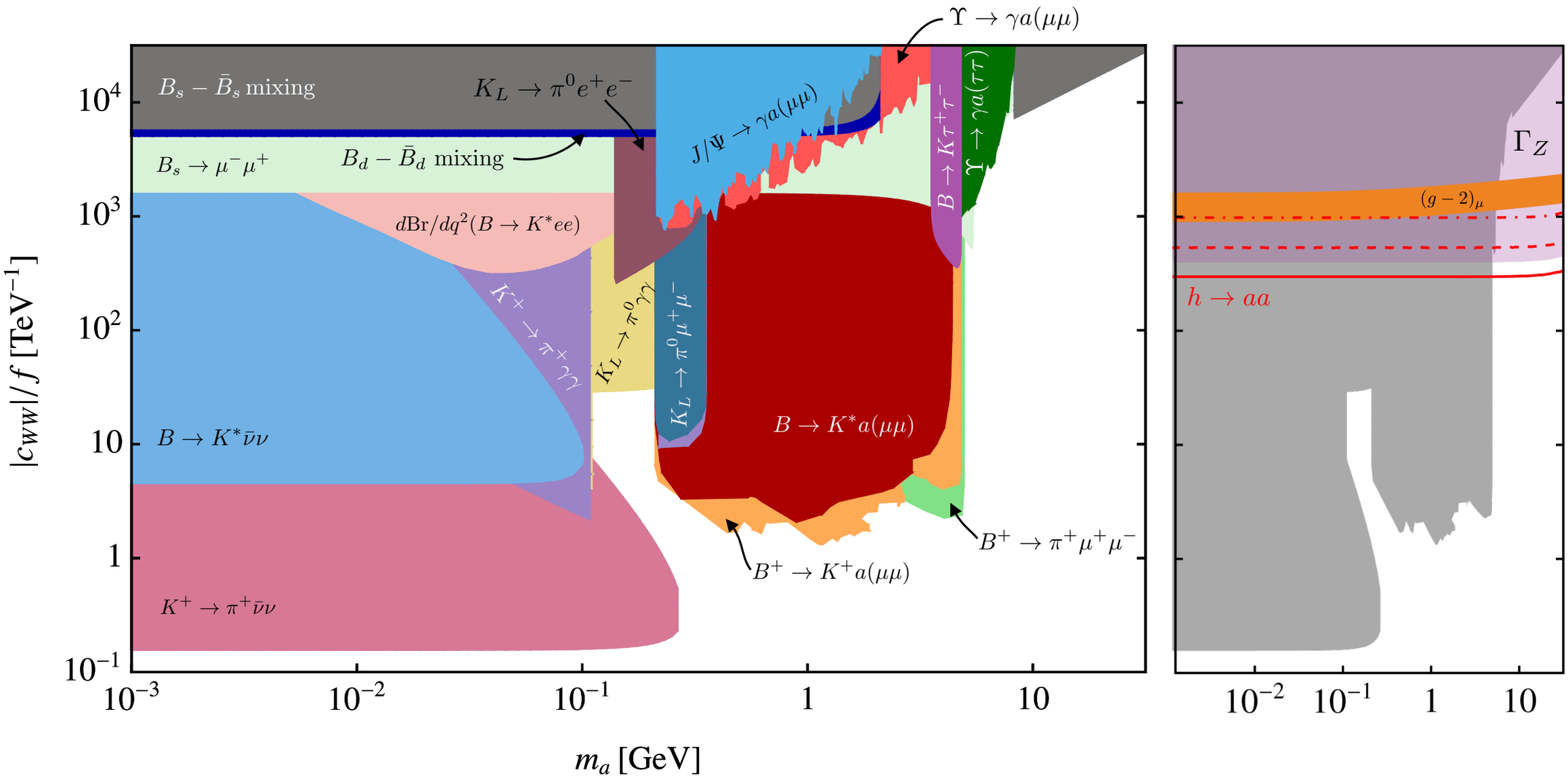
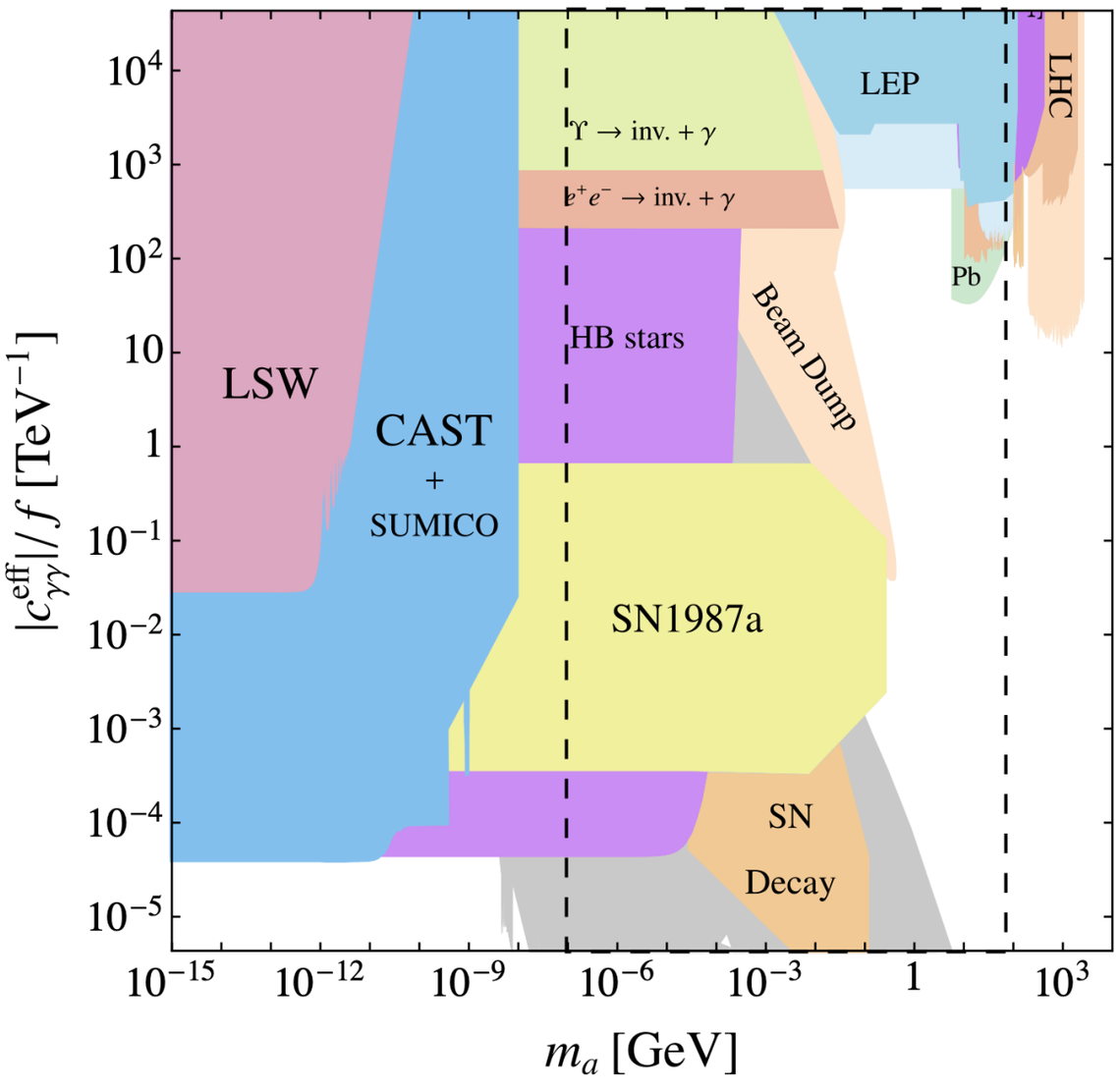
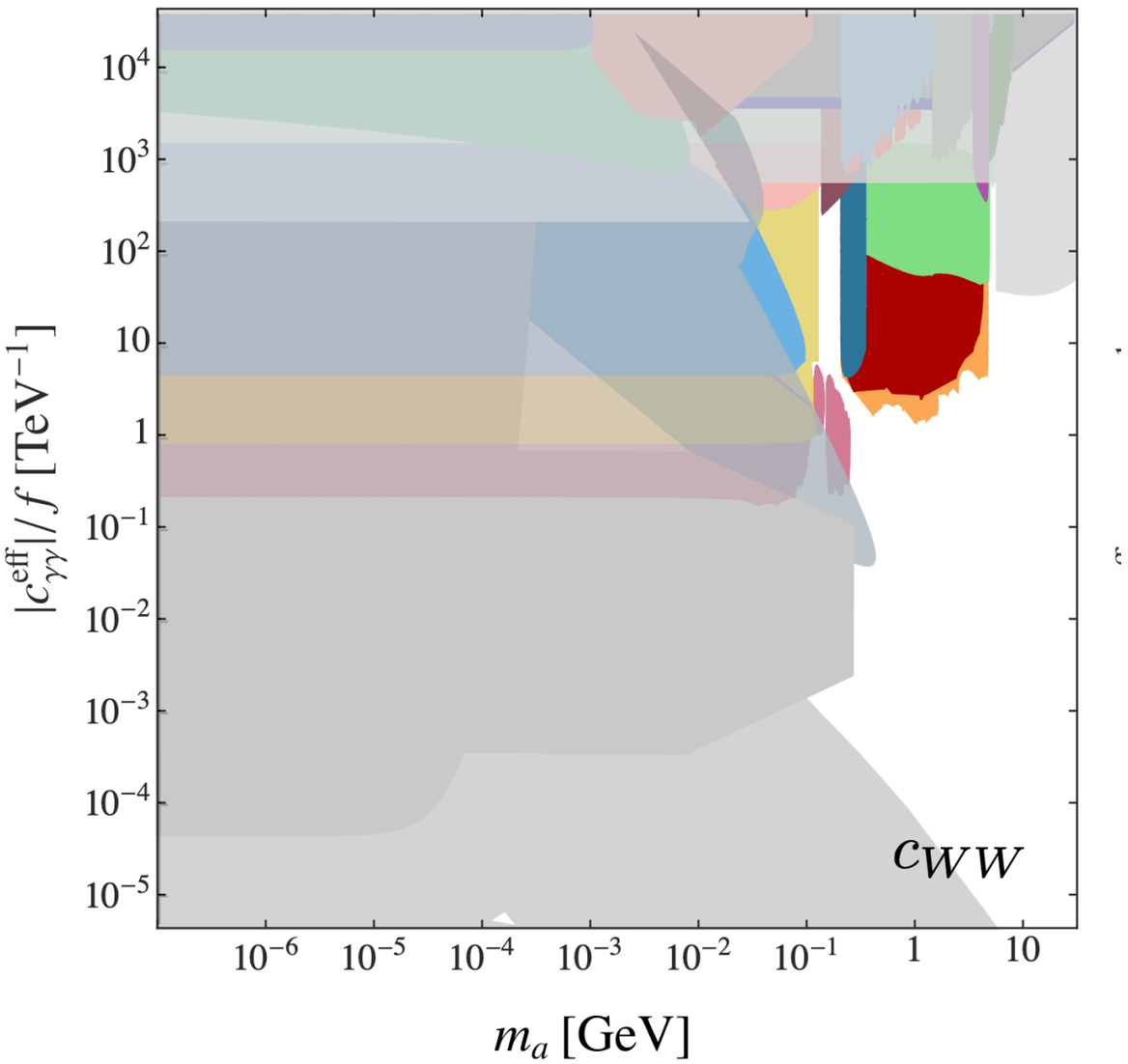


Operator Evolution and Collider Bounds

$$c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A}$$

[Jaeckel, Jankowiak, Spannowsky: 1212.3620]
[ATLAS High mass di-photon final states: 1707.04147]





Flavour bounds are complementary to other collider bounds

Conclusions

- MeV-GeV ALPs and Axions well motivated
- Lepton colliders can probe well motivated parameter space
- Significant impact of RG evolution on phenomenology
- Collider probes complementary to flavor probes