

ALPs and Axions: A Theoretical Perspective

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Outline

1. Theory Motivations for MeV-GeV ALPs
2. Effective Lagrangian and Collider Bounds
3. Operator Evolution and Collider/Flavour Bounds
4. Conclusions

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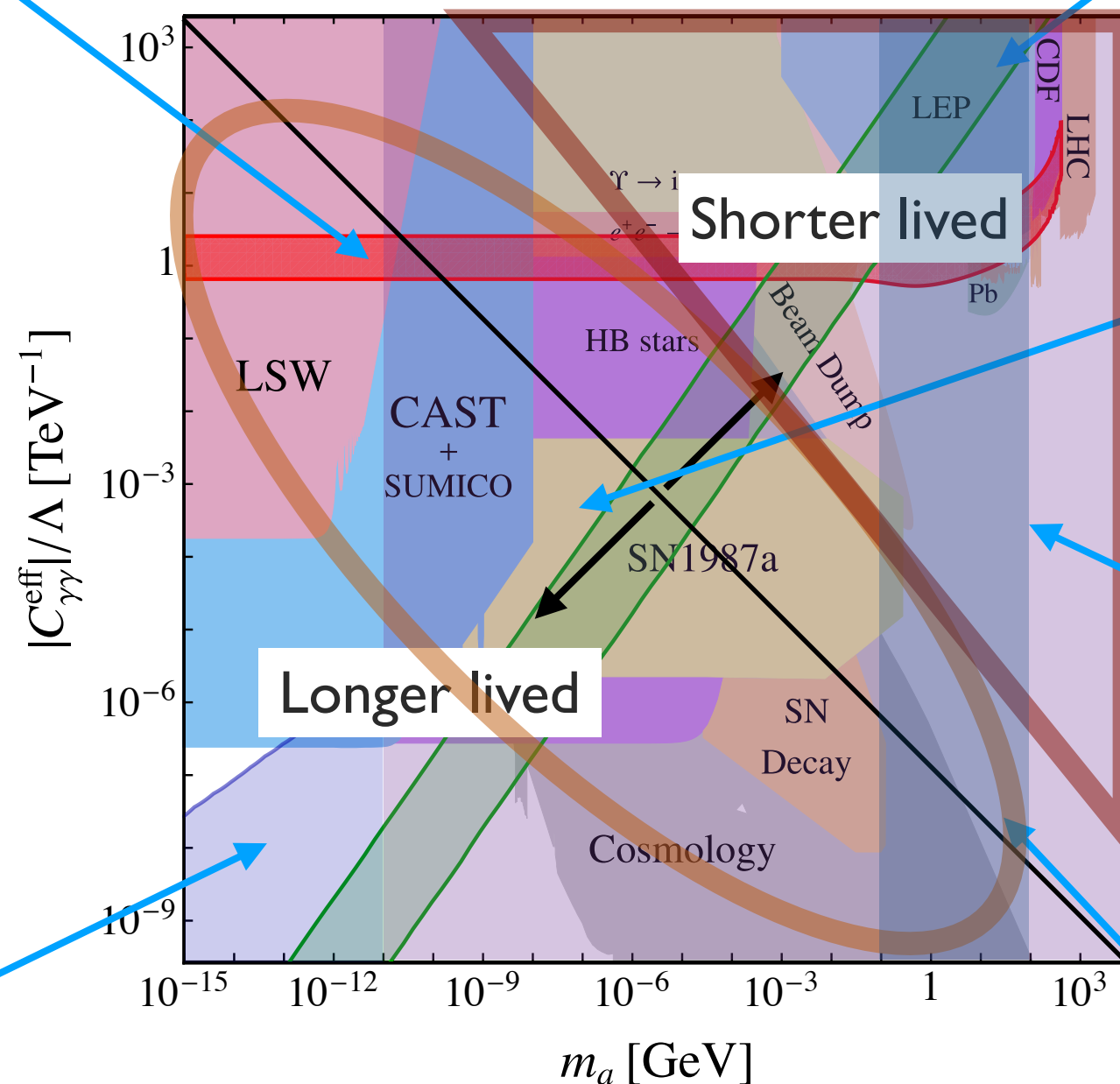
Theory Motivation for ALPs

Axion-like particles are pseudo-Nambu Goldstone bosons

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

QCD axion

9703409, 0009290, 1711.3325, 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

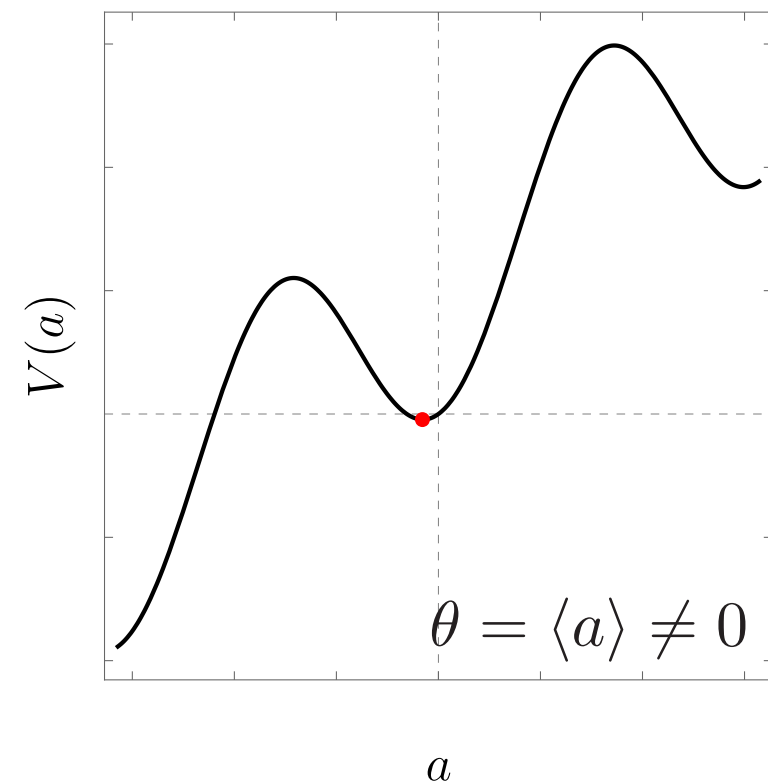
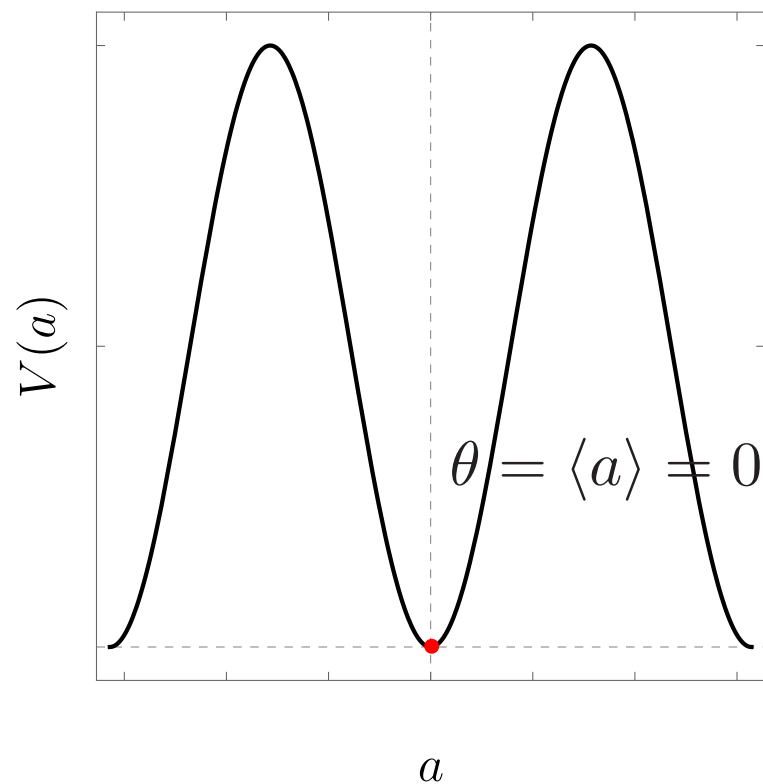
Mediator to the dark sector

Theory Motivation for MeV-GeV ALPs

Axion quality problem

$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos \left(\frac{a}{f_a} \right) \right]$$

$$+ a \frac{f_a^{\Delta-1}}{M_{pl}^{\Delta-4}}$$

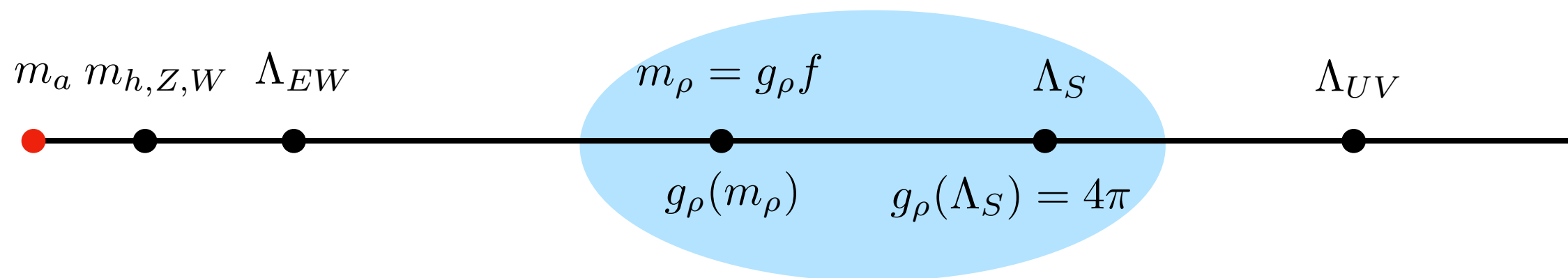


New sector contributes to potential and mass

9703409, 0009290, 1711.3325, 1504.06084,
1604.01127, 1606.03097

Theory Motivation for MeV-GeV ALPs

Composite Higgs models



Specify details about heavy sector

G	H	N_G	NGBs rep. $[H] = \text{rep.}[\text{SU}(2) \times \text{SU}(2)]$
SO(5)	SO(4)	4	$4 = (\mathbf{2}, \mathbf{2})$

[Agashe, Contino, Pomarol,...]

Light pseudo-scalar particles = axion-like particles

[Ferretti 1604.06467]

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Effective Lagrangian

Interactions at dimension-5

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

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

[Chala, Guedes, Ramos, Santiago: 2012.09017]

Higgs interactions at dimension-6 and 7

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

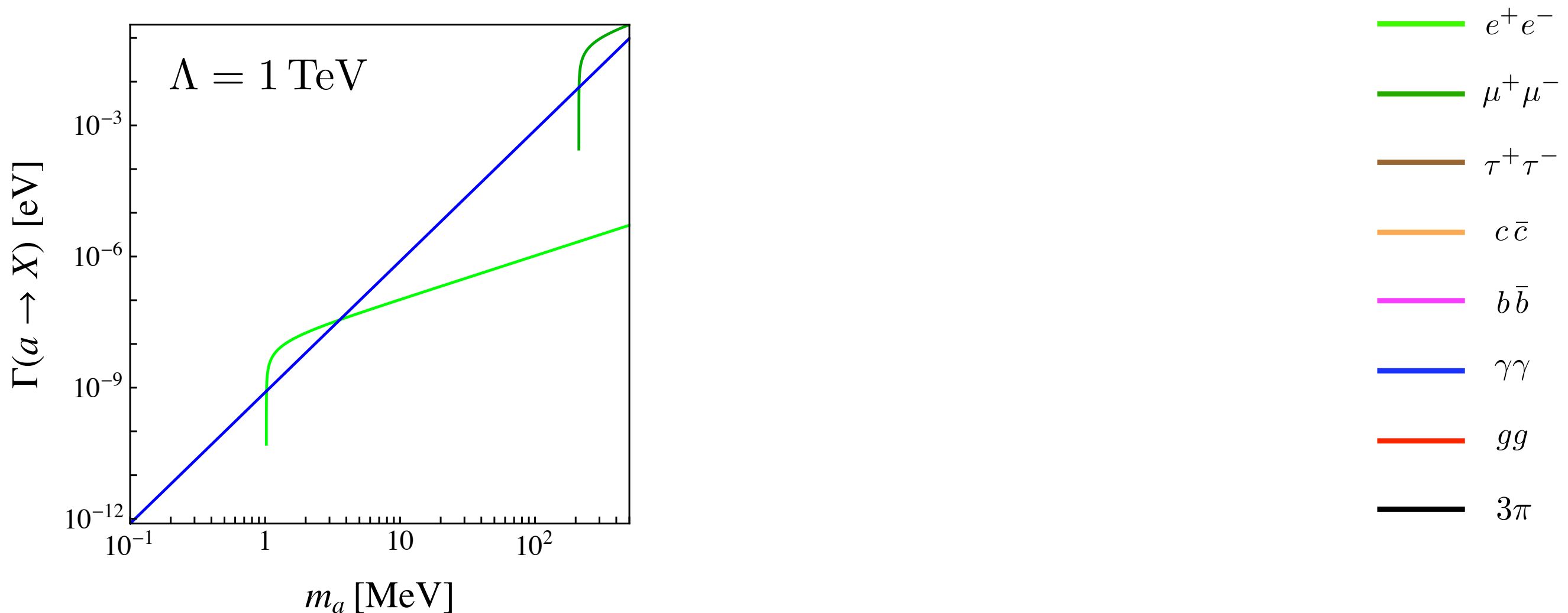
[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

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

Effective Lagrangian and Collider Bounds

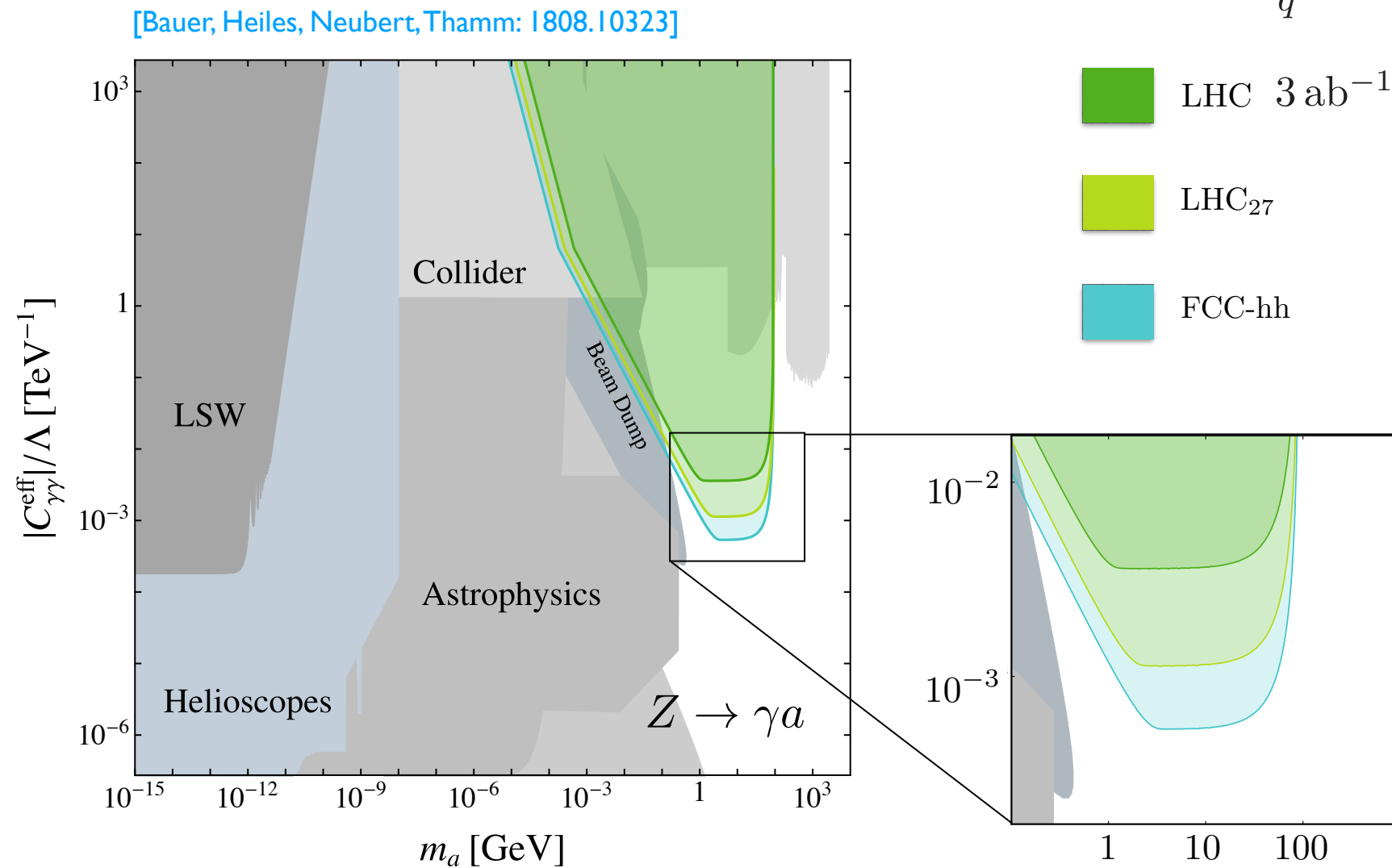
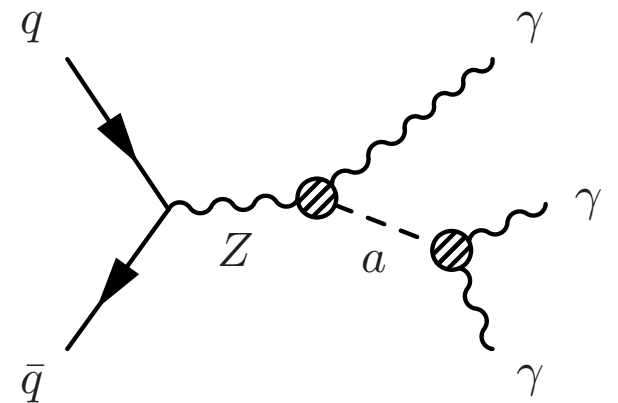
Fermion couplings = 1, Gauge boson couplings = 1 in the plot

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



Effective Lagrangian and Collider Bounds

Dominant production mode: exotic Higgs and Z-boson decays



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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

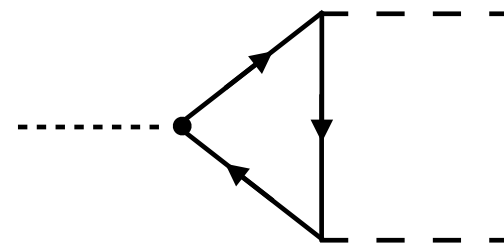
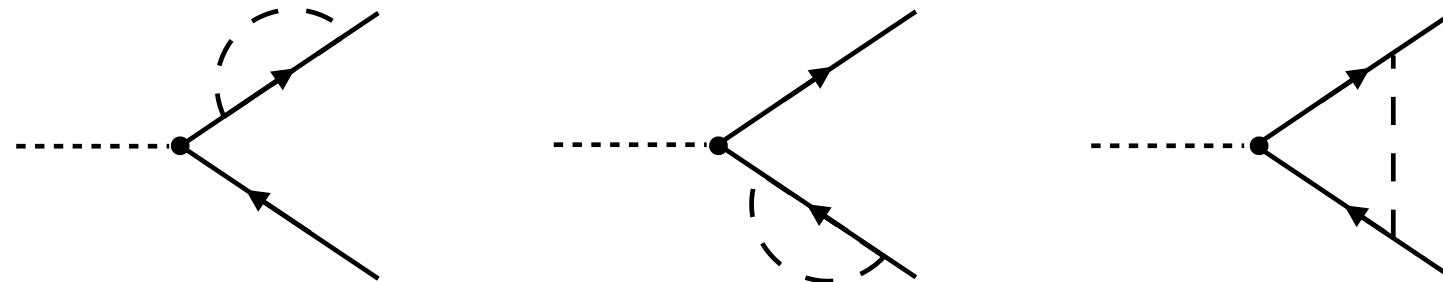
[Chala, Guedes, Ramos, Santiago: 2012.09017]

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

ALP couplings to fermions

1708.00021, 2002.04623

Contribution from Yukawas

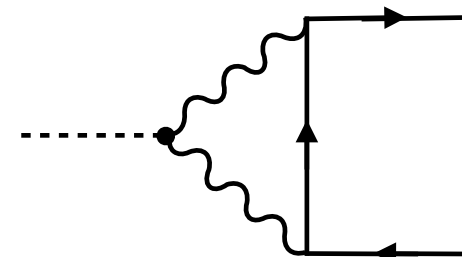


Require redundant operator
as counterterm

$$O_\phi \rightarrow \sum_F \beta_F O_F$$

1308.2627

2012.09017, 2021.12272



Mixing of ALP-boson
operators into ALP-fermions

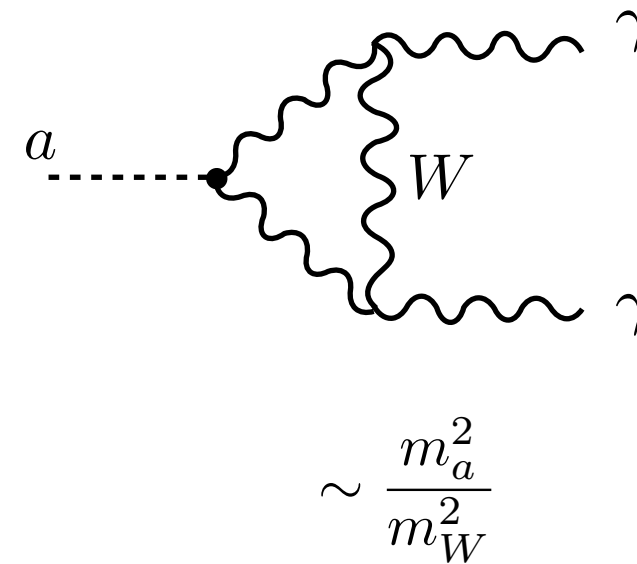
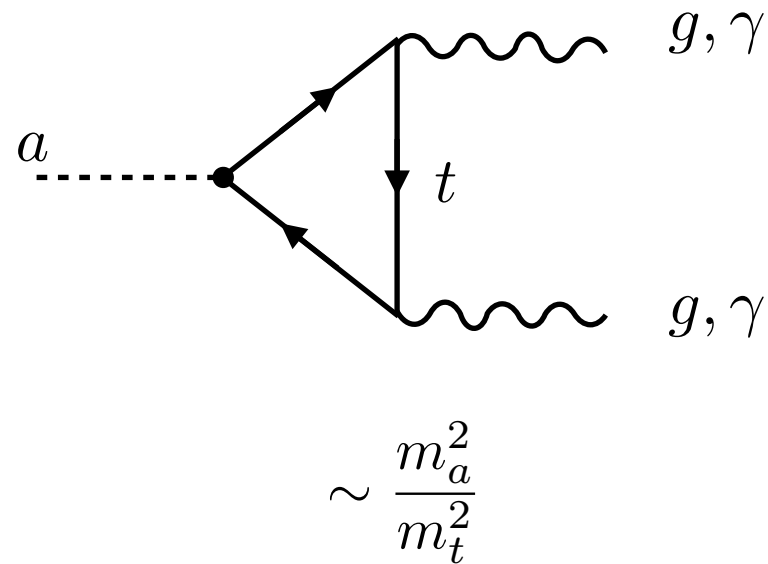
Operator Evolution at the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]

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

ALP couplings to gauge bosons

[Bauer, Neubert, Thamm: 1708.00443]



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

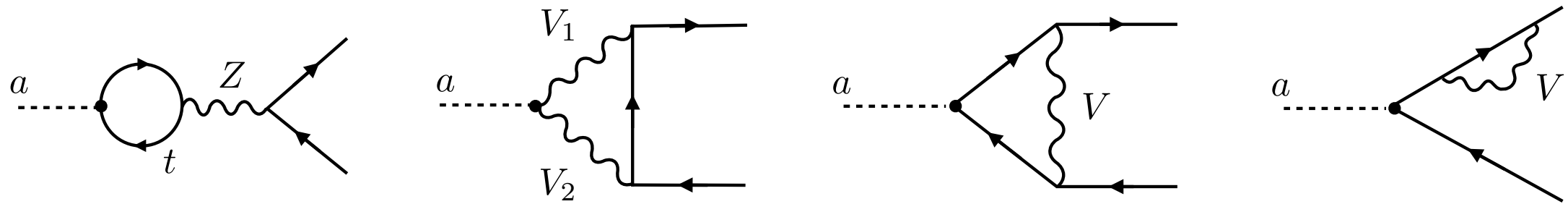
Operator Evolution at the Weak Scale

[Chala, Guedes, Ramos, Santiago: 2012.09017]

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

ALP couplings to fermions

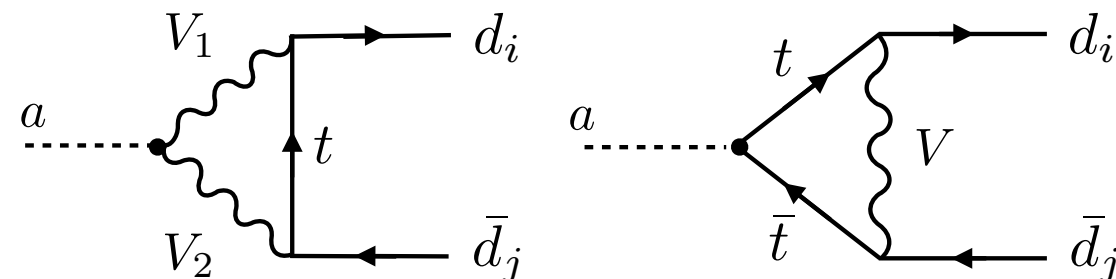
1708.00443



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 $f = 1 \text{ TeV}$

- Flavor diagonal couplings

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

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

Operator Evolution at the Weak Scale

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

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

- Flavor changing couplings

$$\mathcal{L}_{\text{ferm}}^{\text{FCNC}}(\mu) = -\frac{ia}{2f} \sum_f \left[(m_{f_i} - m_{f_j}) (k_f + k_F)_{ij} \bar{f}_i f_j + (m_{f_i} + m_{f_j}) (k_f - k_F)_{ij} \bar{f}_i \gamma_5 f_j \right]$$

$$[k_u(\mu_w)]_{ij} = [k_u(\Lambda)]_{ij}; \quad i, j \neq 3$$

$$[k_U(\mu_w)]_{ij} = [k_U(\Lambda)]_{ij}; \quad i, j \neq 3$$

$$[k_d(\mu_w)]_{ij} = [k_d(\Lambda)]_{ij}$$

$$[k_e(\mu_w)]_{ij} = [k_e(\Lambda)]_{ij}$$

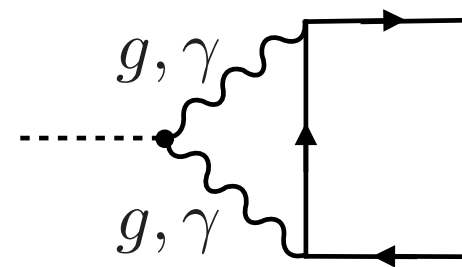
$$[k_L(\mu_w)]_{ij} = [k_L(\Lambda)]_{ij}$$

$$[k_D(m_t)]_{ij} \simeq [k_D(\Lambda)]_{ij} + 0.019 V_{ti}^* V_{tj} \left[c_{tt}(\Lambda) - 0.0032 \tilde{c}_{GG}(\Lambda) - 0.0057 \tilde{c}_{WW}(\Lambda) \right]$$

Operator Evolution below the Weak Scale

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

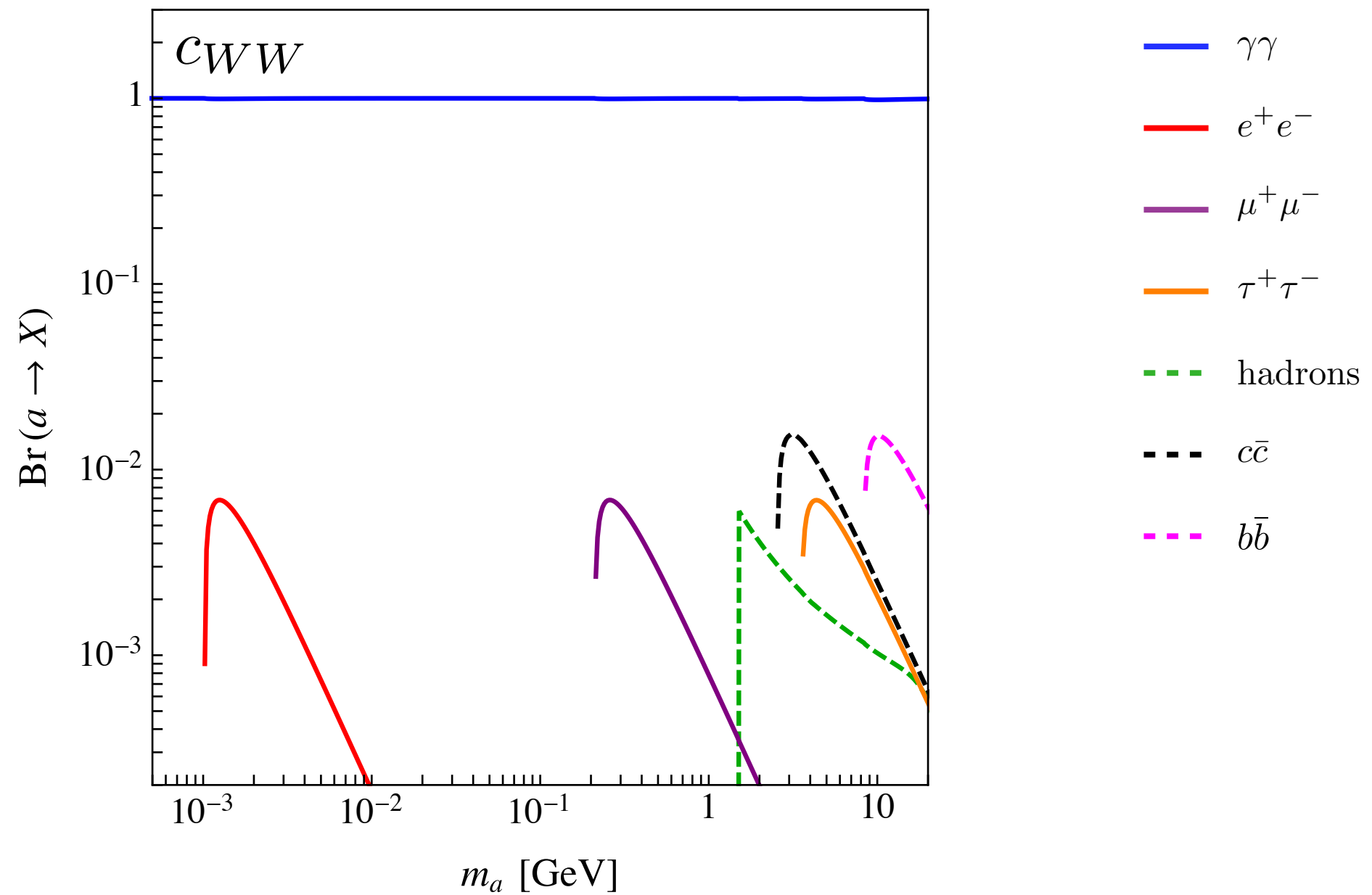
Only relevant diagram



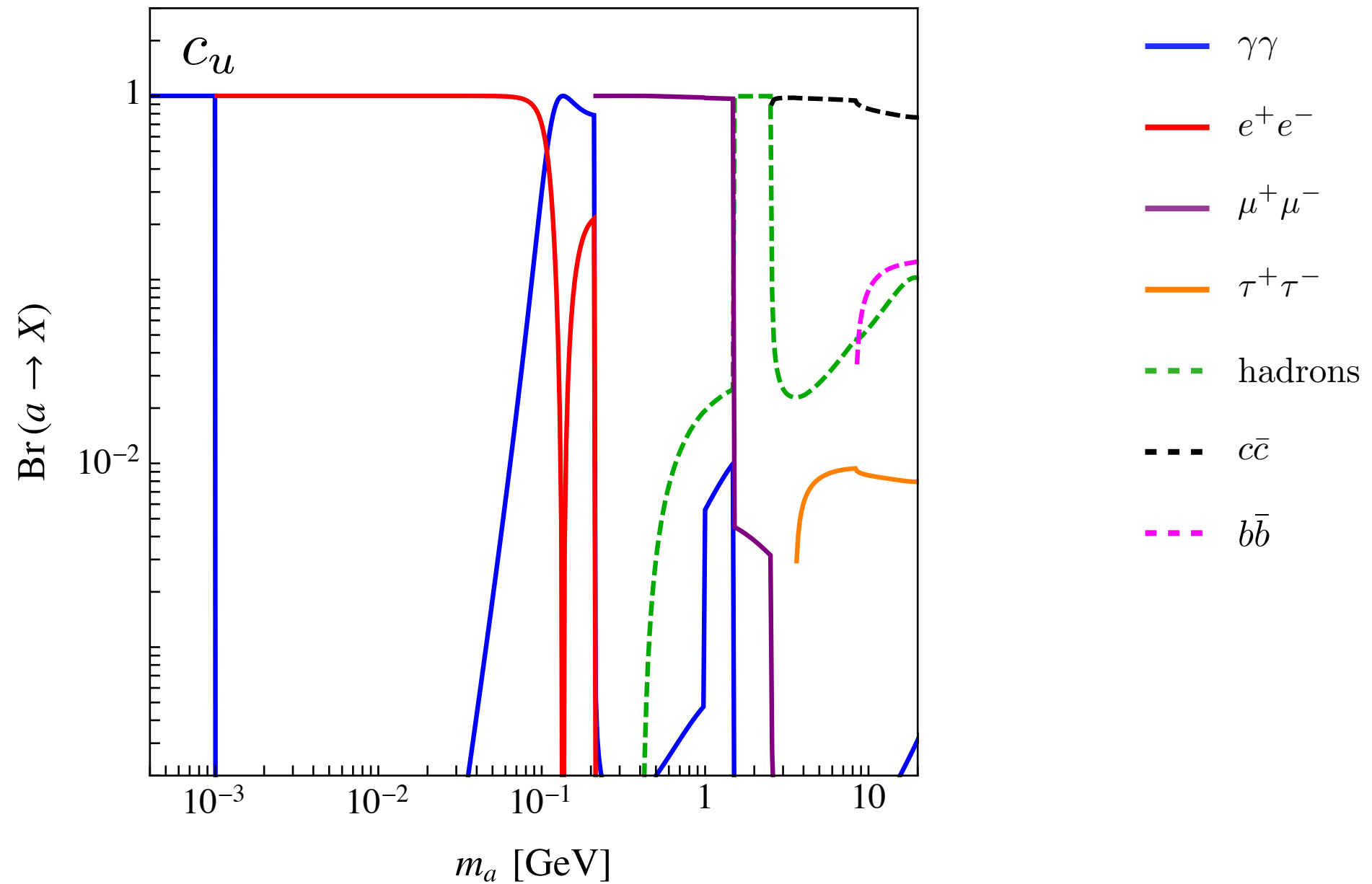
Small effect at $\mu_0 = 2 \text{ GeV}$

$$\begin{aligned} c_{qq}(\mu_0) &= c_{qq}(m_t) + \left[3.0 \tilde{c}_{GG}(\Lambda) - 1.4 c_{tt}(\Lambda) - 0.6 c_{bb}(\Lambda) \right] \cdot 10^{-2} \\ &\quad + Q_q^2 \left[3.9 \tilde{c}_{\gamma\gamma}(\Lambda) - 4.7 c_{tt}(\Lambda) - 0.2 c_{bb}(\Lambda) \right] \cdot 10^{-5} \\ c_{\ell\ell}(\mu_0) &= c_{\ell\ell}(m_t) + \left[3.9 \tilde{c}_{\gamma\gamma}(\Lambda) - 4.7 c_{tt}(\Lambda) - 0.2 c_{bb}(\Lambda) \right] \cdot 10^{-5} \end{aligned}$$

Operator Evolution and Collider Bounds



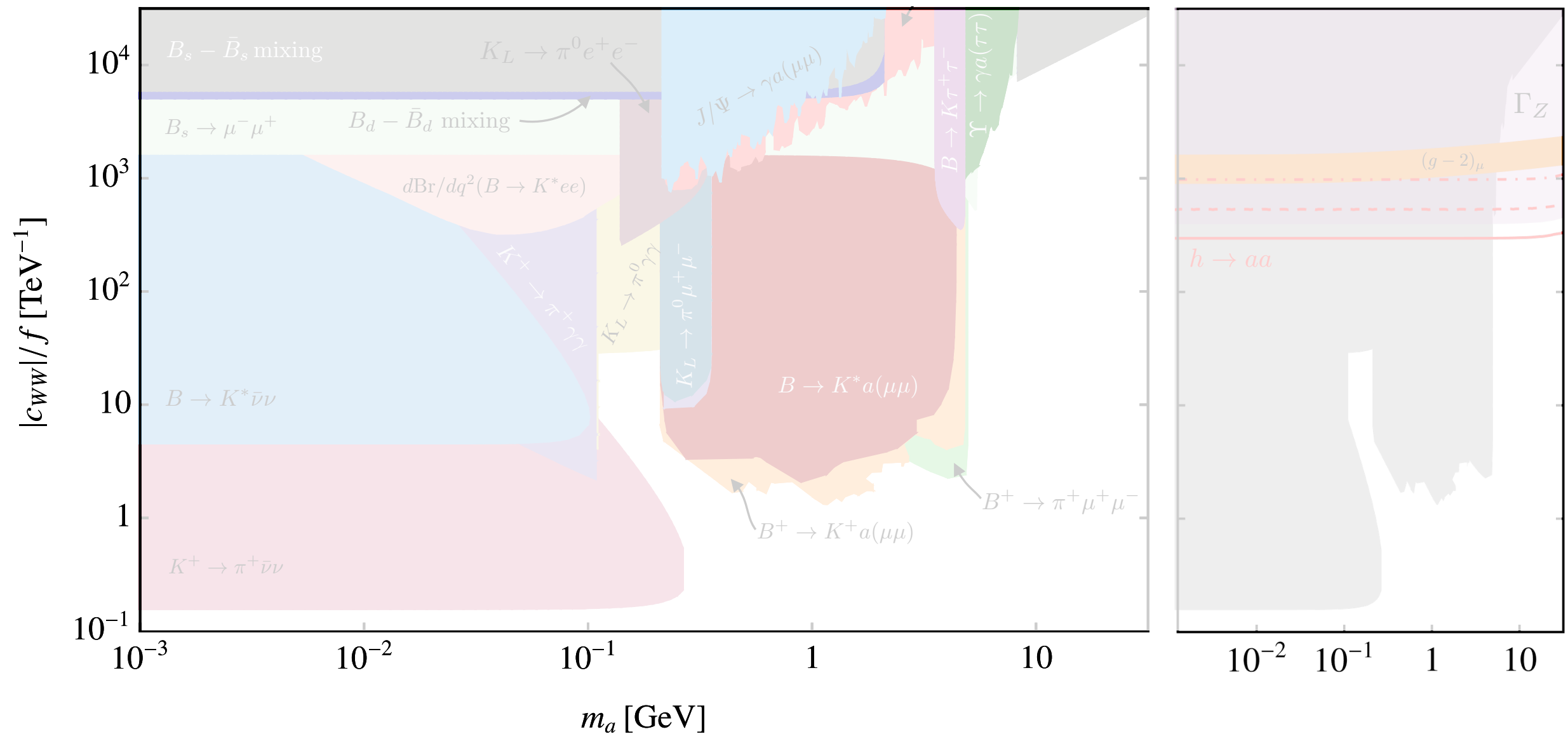
Operator Evolution and Collider Bounds



Operator Evolution and Collider Bounds

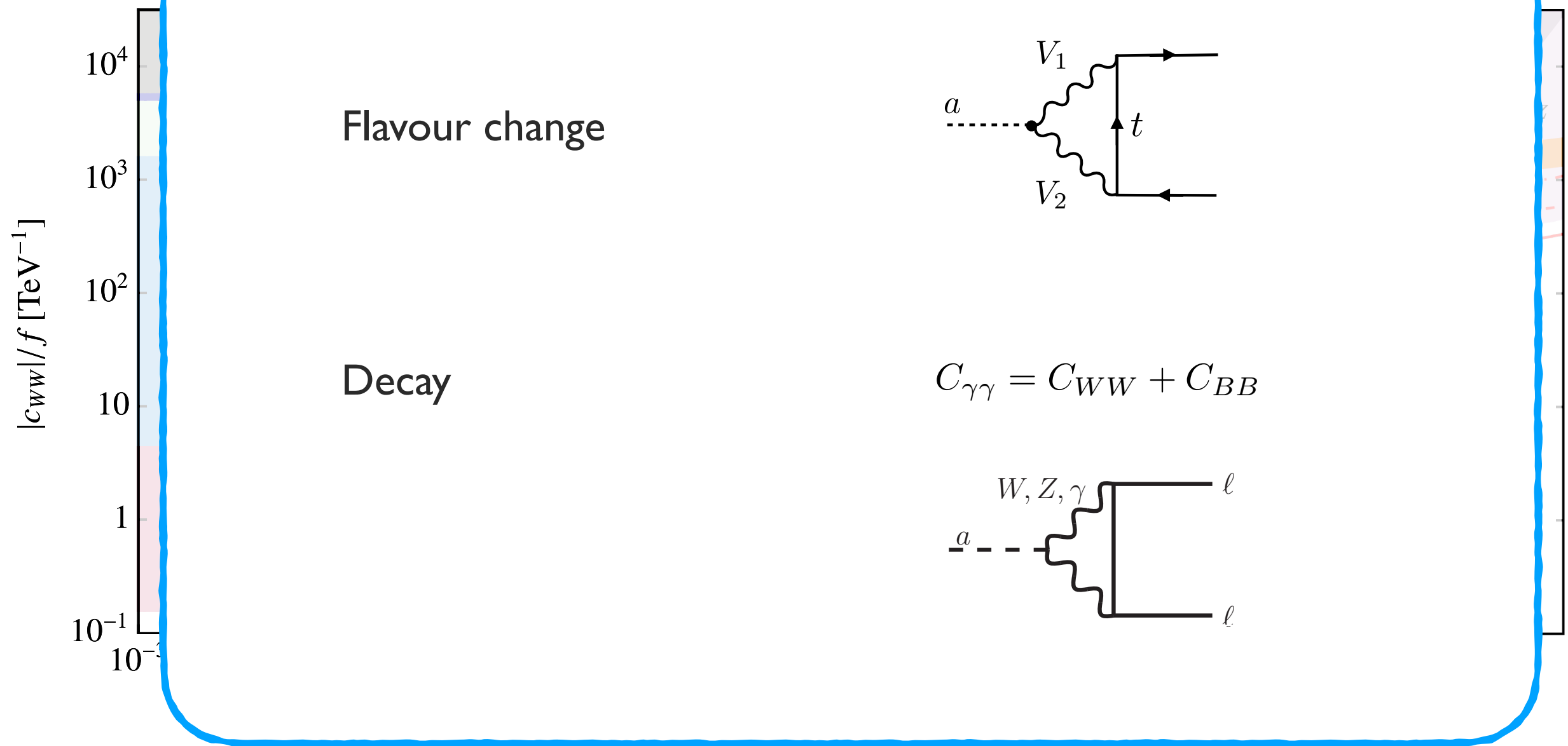
$$c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A}$$

1611.09355, 1901.02031



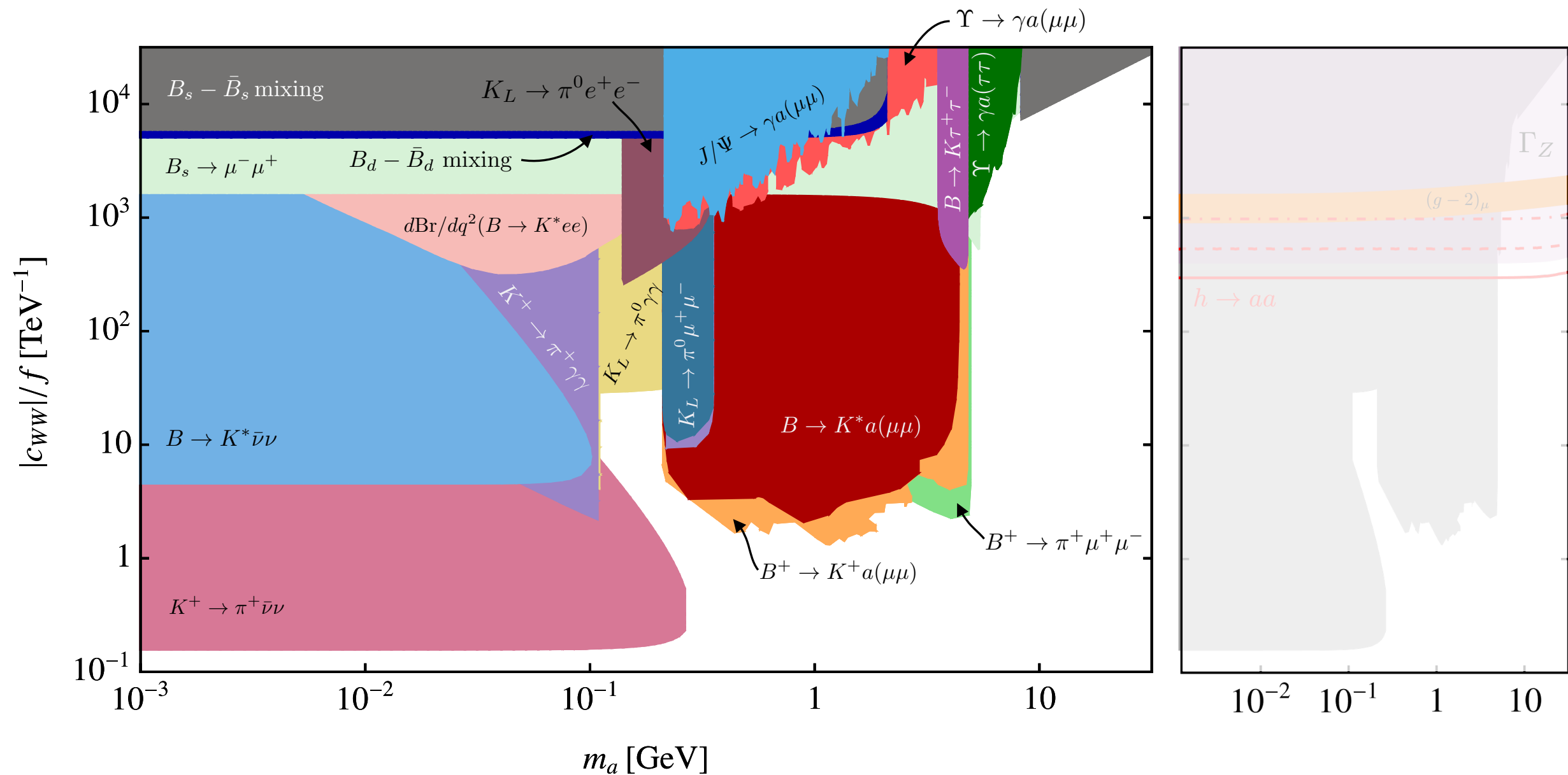
Operator Evolution and Collider Bounds

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



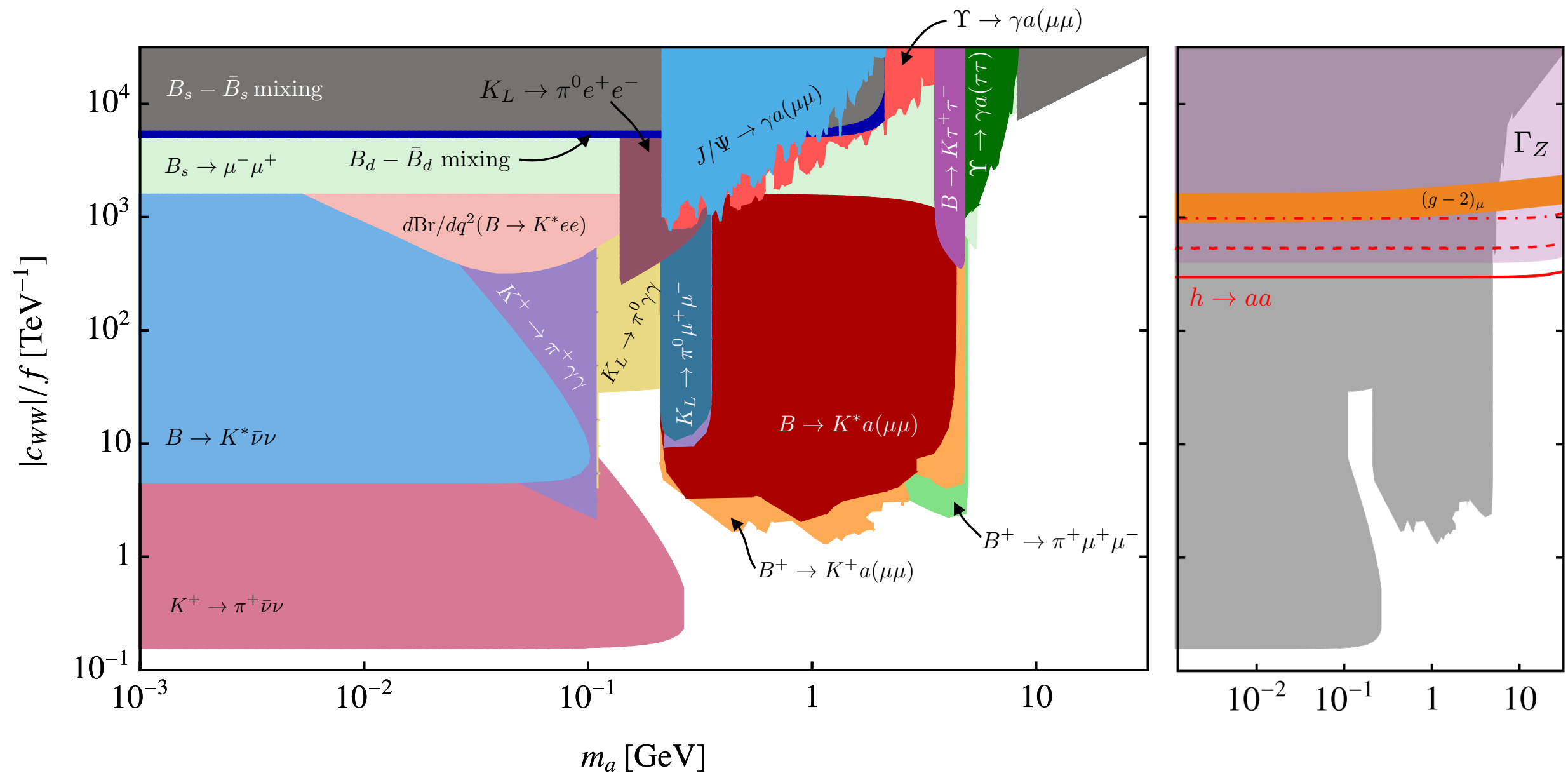
Operator Evolution and Collider Bounds

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



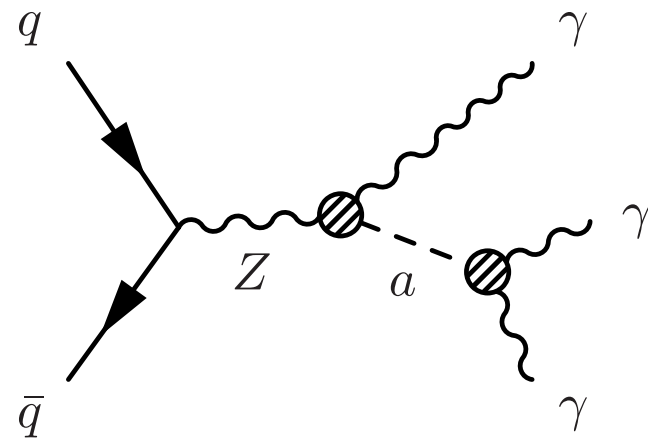
Operator Evolution and Collider Bounds

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



Operator Evolution and Collider Bounds

Z widths

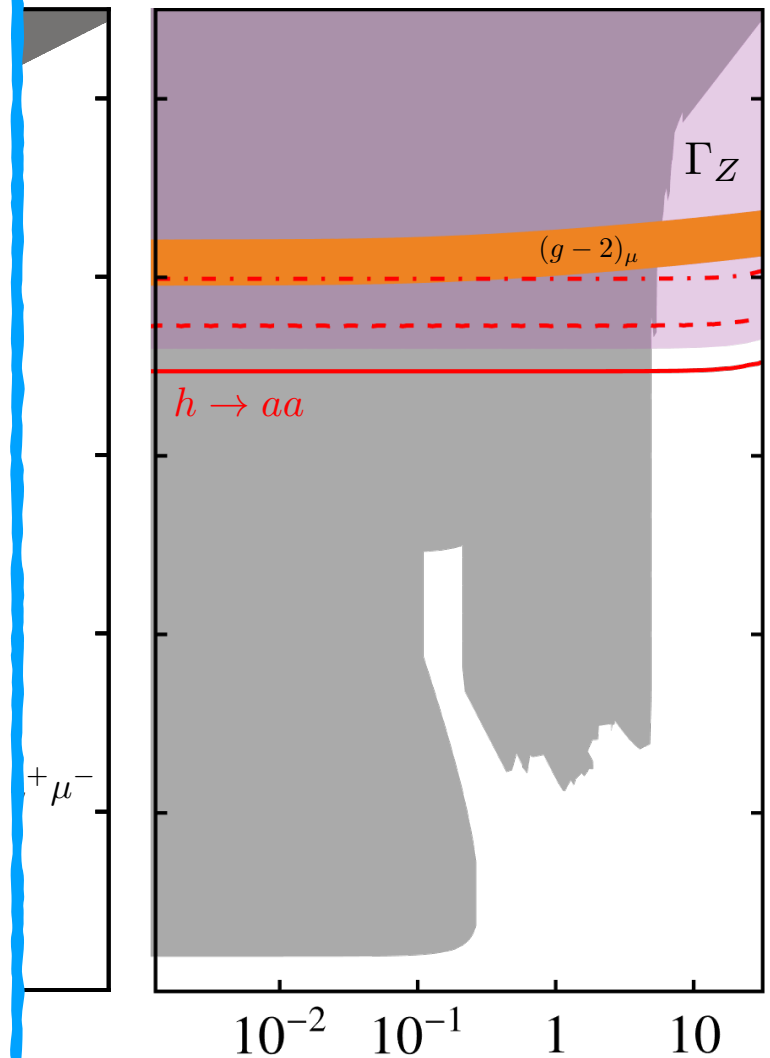


$$\Gamma_Z = (2.495 \pm 0.0023) \text{ GeV}$$

$$|C_{\gamma Z}^{\text{eff}}| < 1.48 \left[\frac{\Lambda}{1 \text{ TeV}} \right]$$

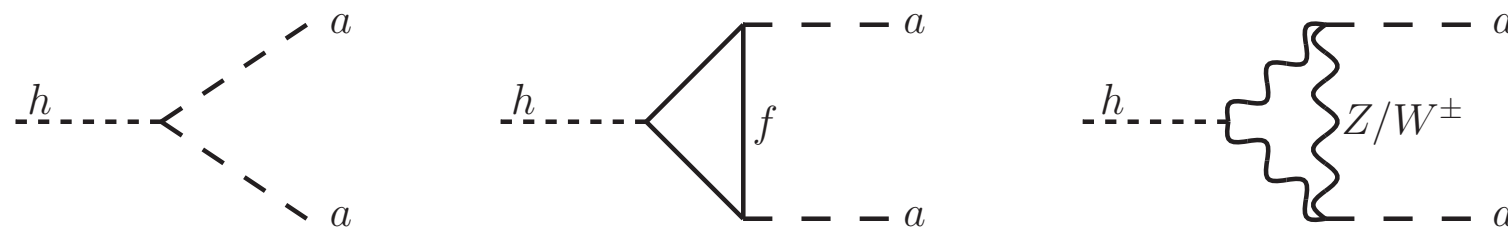
LEP: 0509008

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



Operator Evolution and Collider Bounds

Higgs Branching Ratio

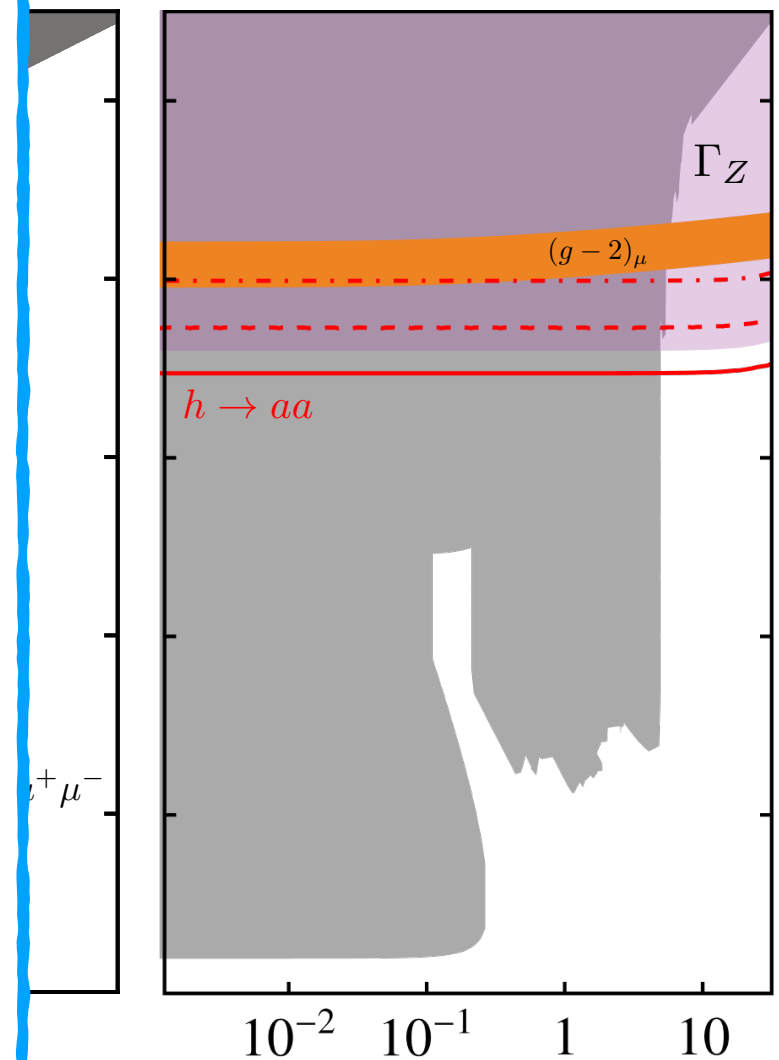


$$\text{Br}(h \rightarrow \text{BSM}) < 0.34$$

$$\Rightarrow \Gamma(h \rightarrow \text{BSM}) < 2.1 \text{ MeV}$$

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

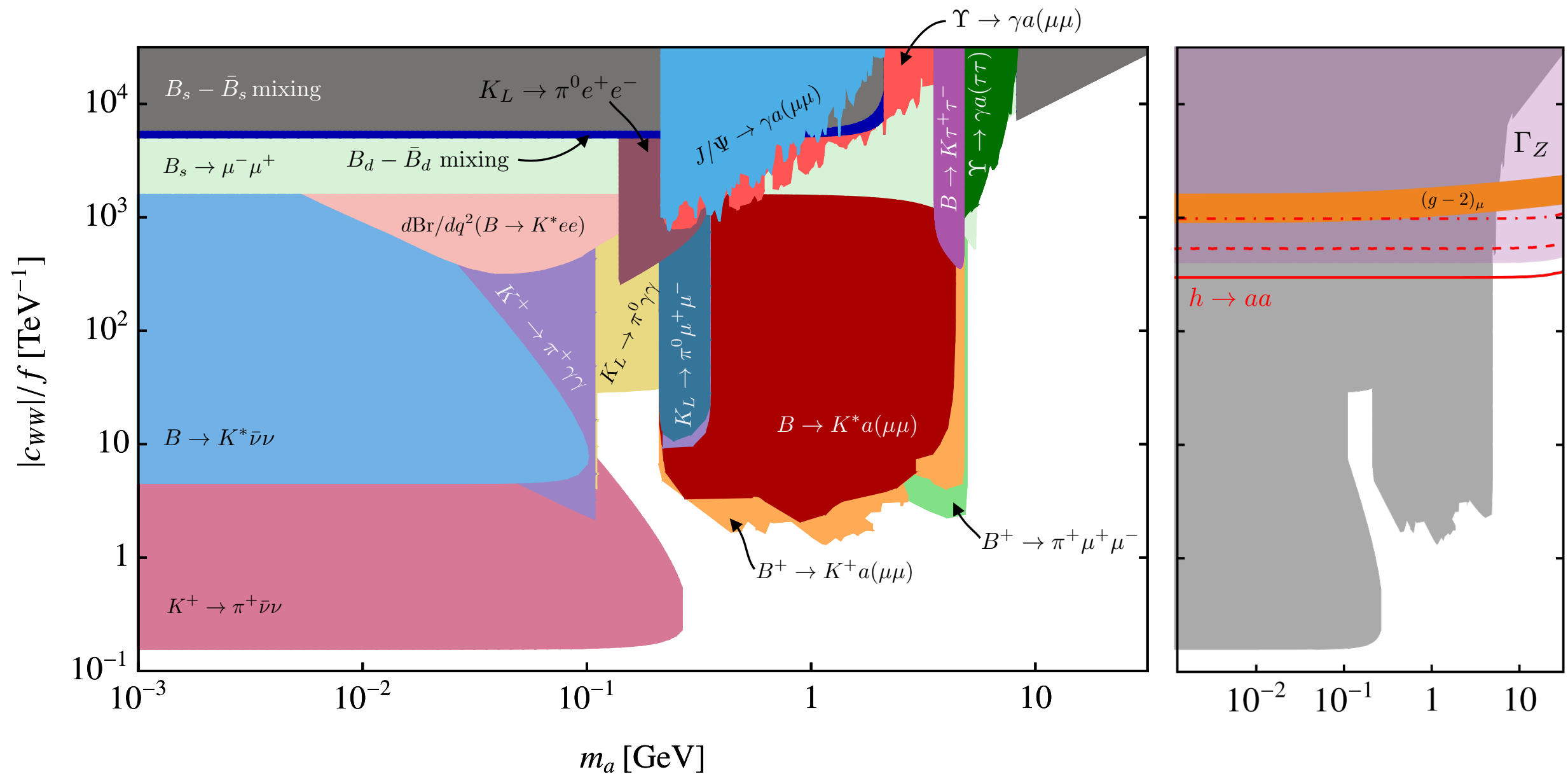
$$c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A}$$



ATLAS and CMS: I606.02266

Operator Evolution and Collider Bounds

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



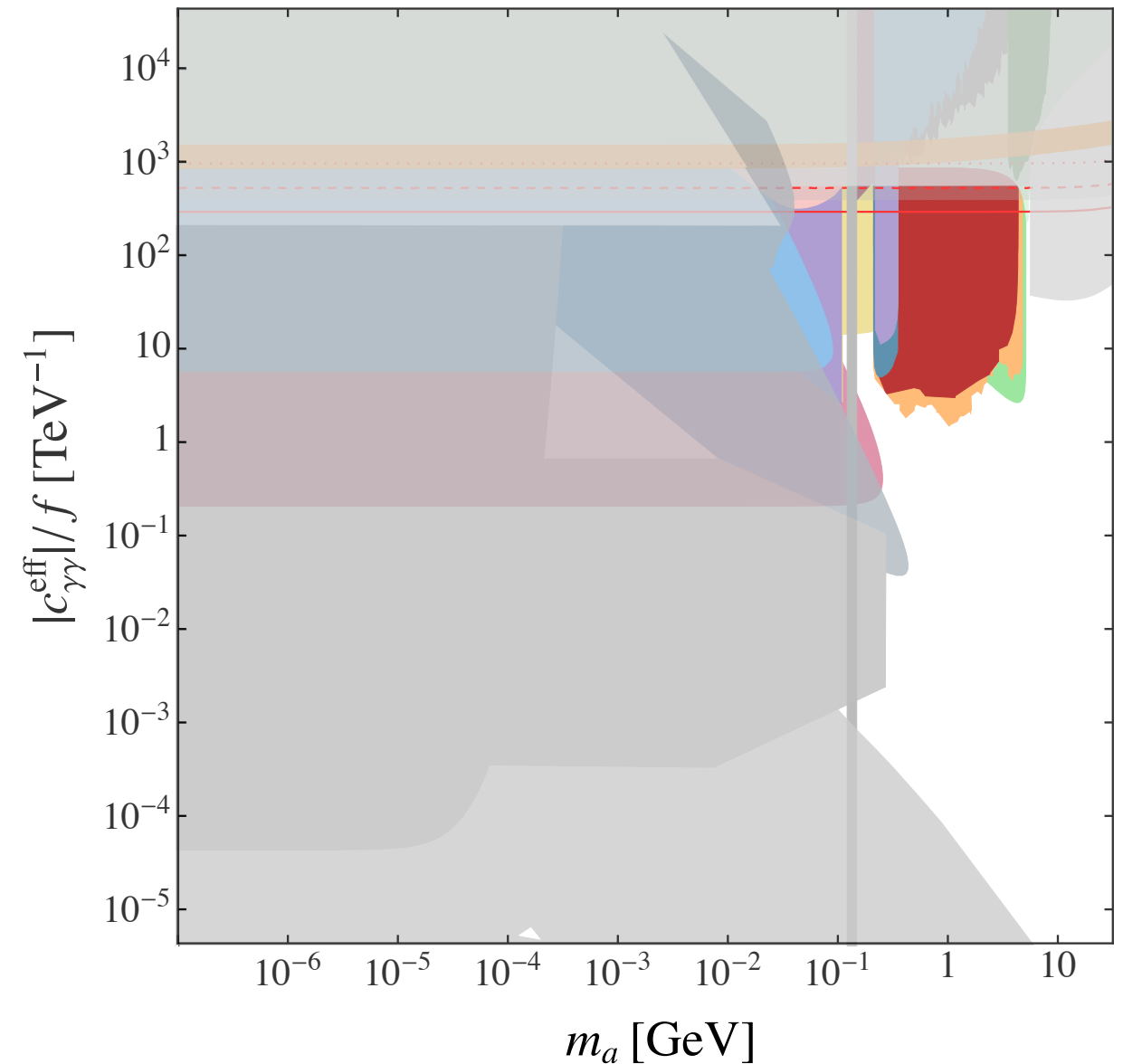
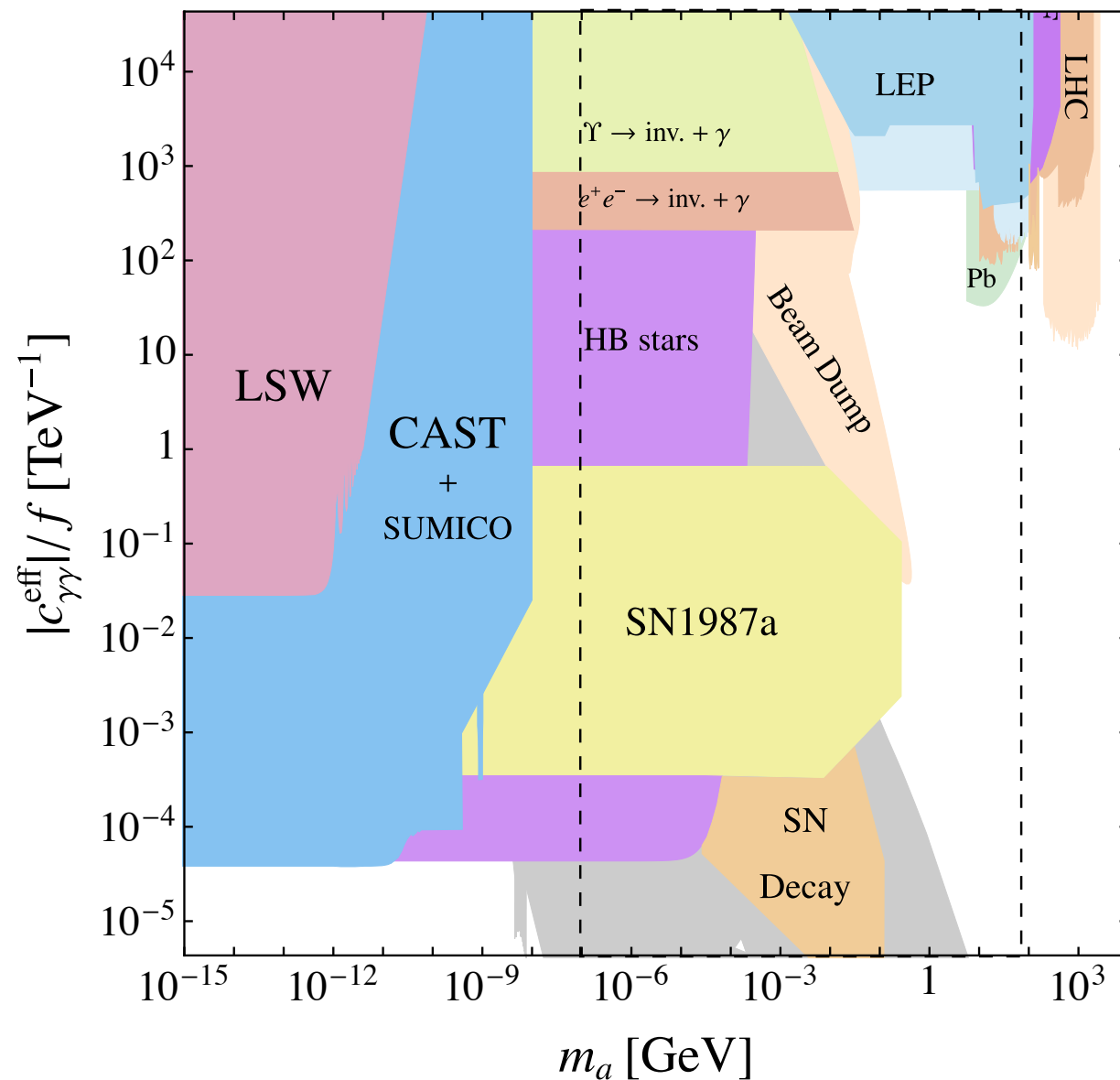
Flavour bounds are complementary to other collider bounds

Operator Evolution and Collider Bounds

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

[Jaeckel, Jankowiak, Spannowsky: 1212.3620]

[ATLAS High mass di-photon final states: 1707.04147]



Flavour bounds are complementary to other collider bounds

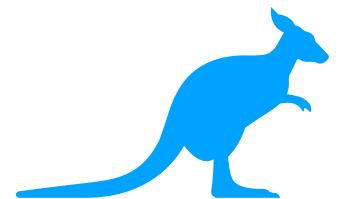
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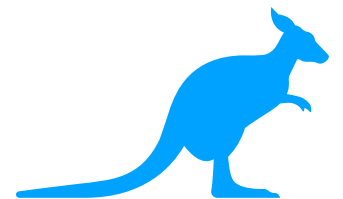
Conclusions

- MeV-GeV ALPs and Axions well motivated
- Significant impact of RG evolution on phenomenology
- Collider probes complementary to flavor probes

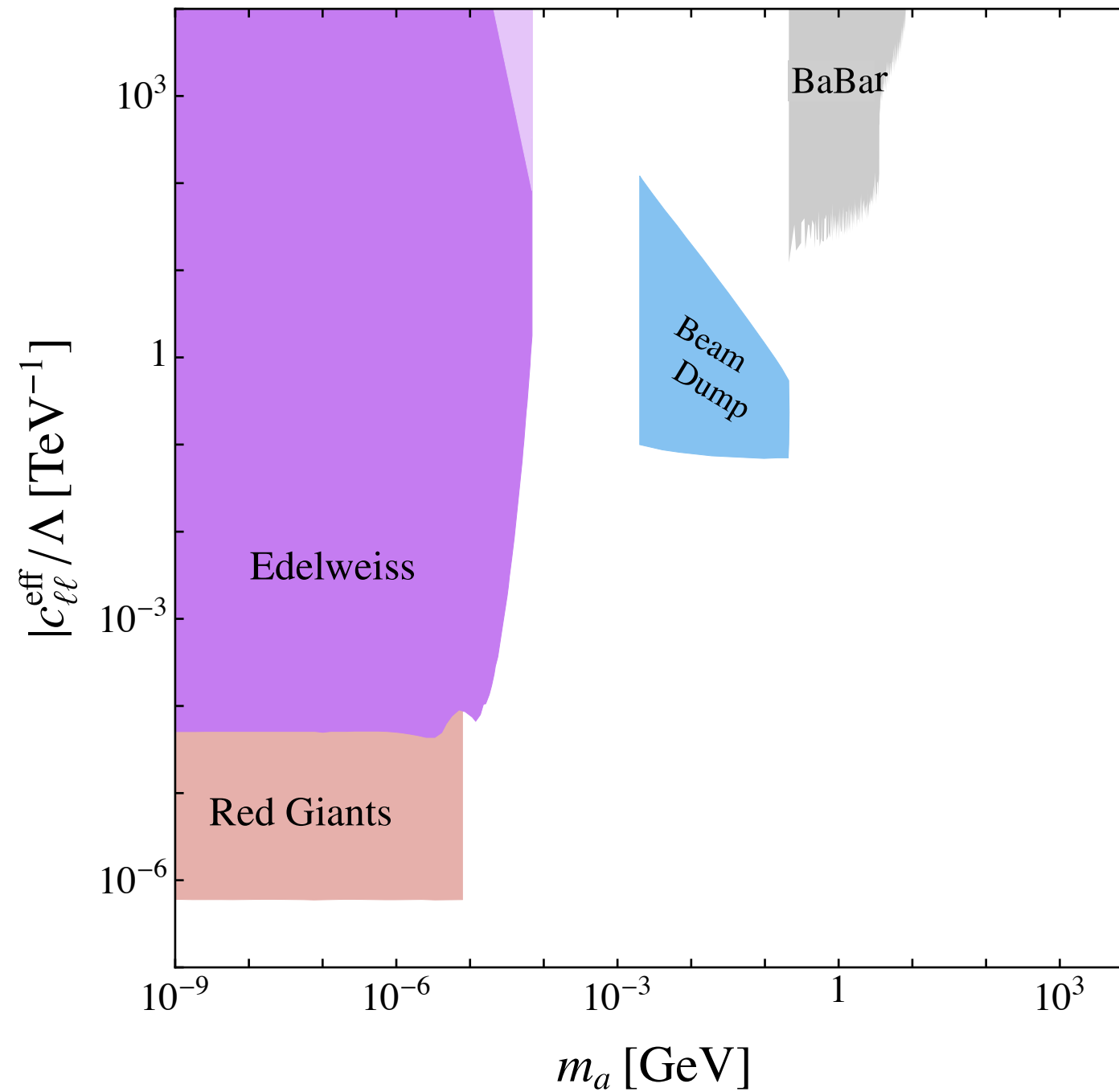
Thank you!



Backup



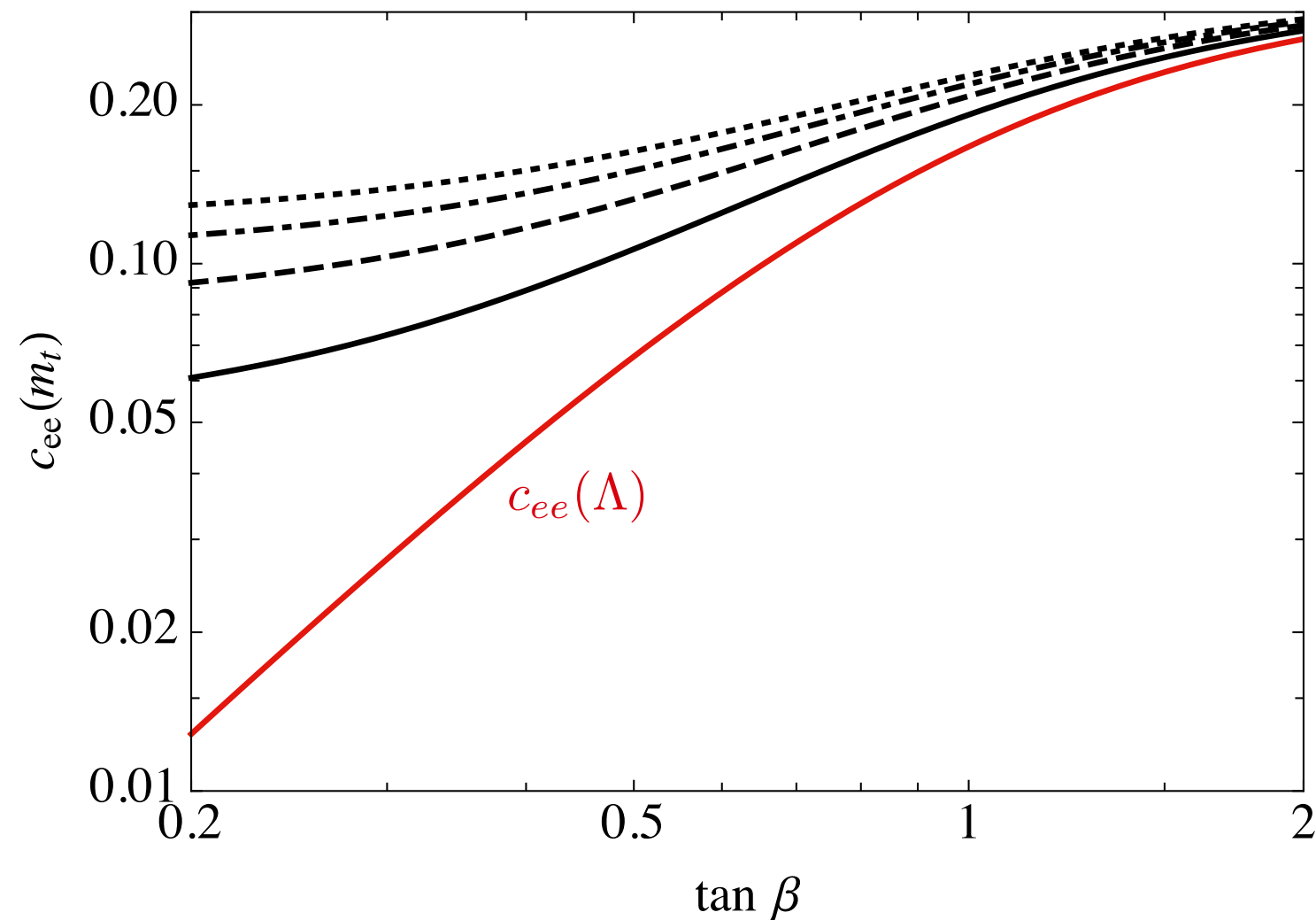
Lepton coupling only



Operator Evolution at the Weak Scale

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

Example: DFSZ QCD axions



$$c_{u_i u_i}(\Lambda) = \frac{1}{3} \cos^2 \beta, \quad c_{d_i d_i}(\Lambda) = c_{e_i e_i}(\Lambda) = \frac{1}{3} \sin^2 \beta, \quad c_{GG} = -\frac{1}{2}$$