Going beyond the SM with ALPs and Axions

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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

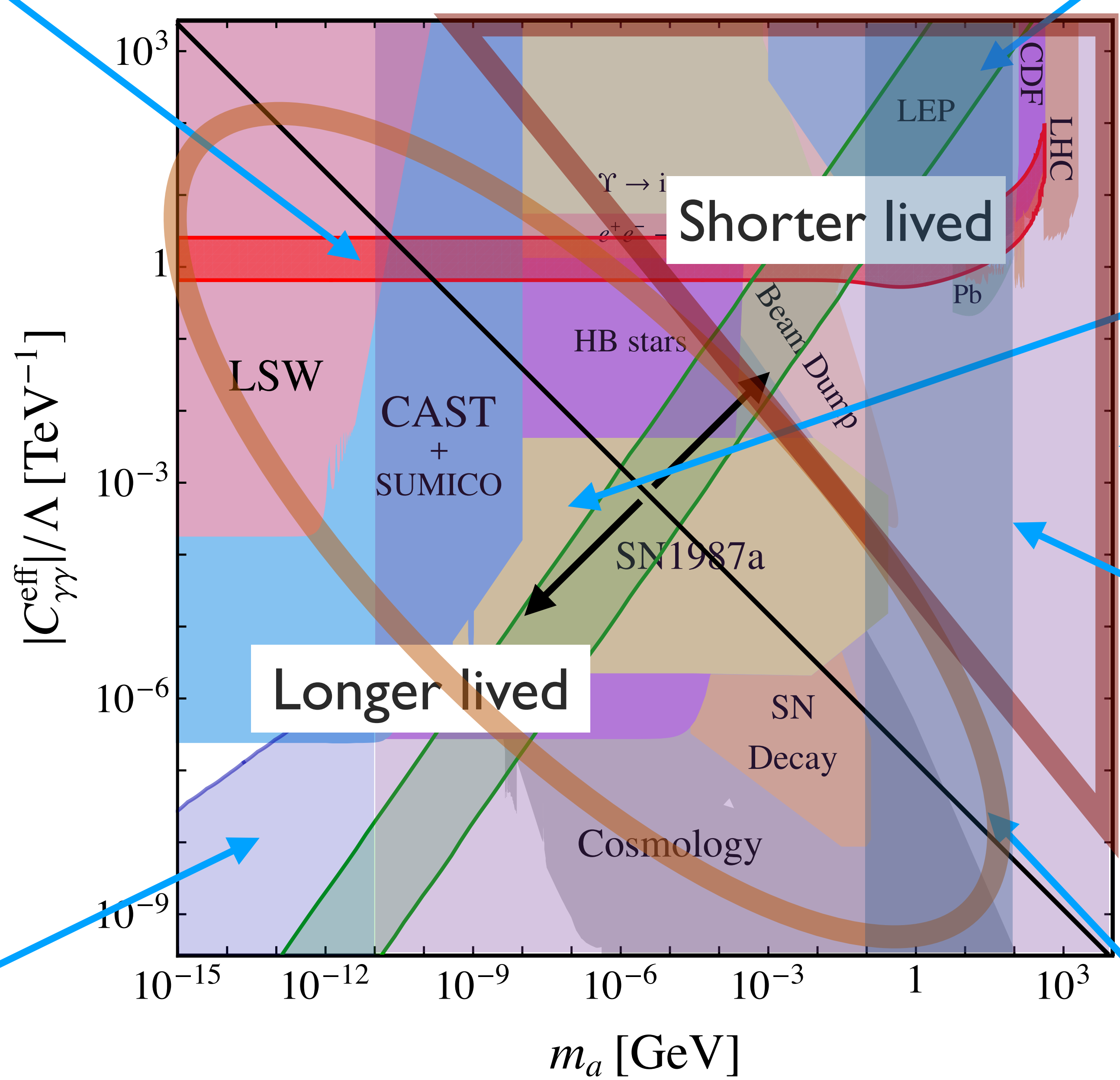
9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

ALPs from sun and stars

ALPs decay within collider

pNGB in supersymmetric or composite models

0902.1483, 1312.5330,1702.02152



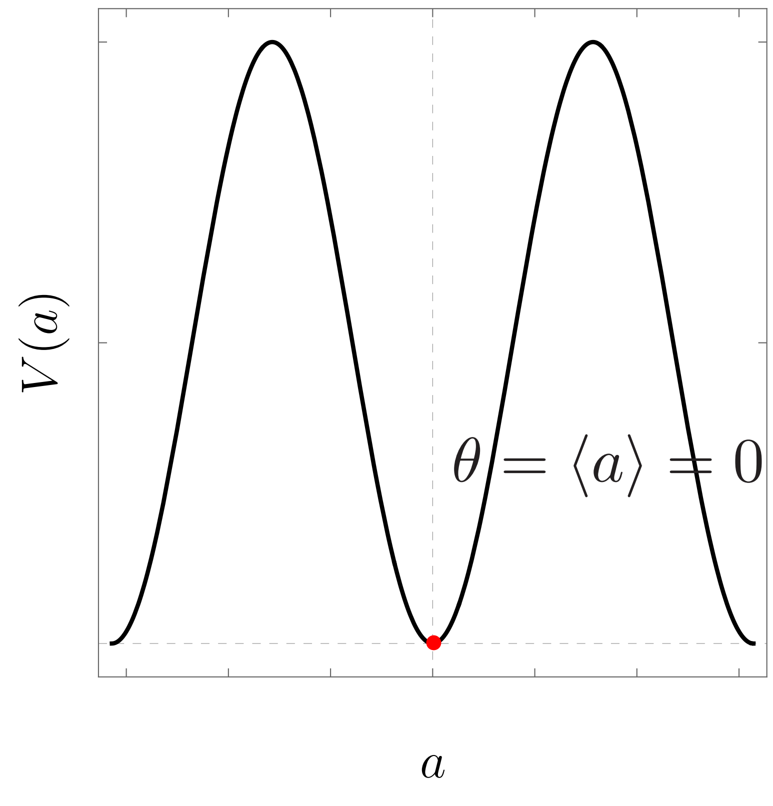
DM candidate

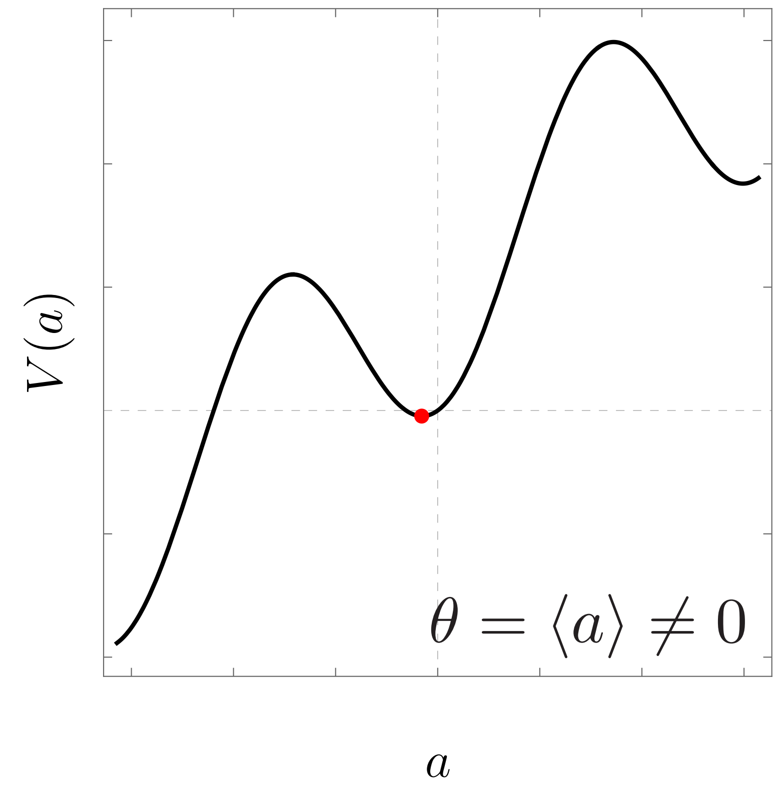
Mediator to the dark sector

Theory Motivation for MeV-GeV ALPs

Axion quality problem

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



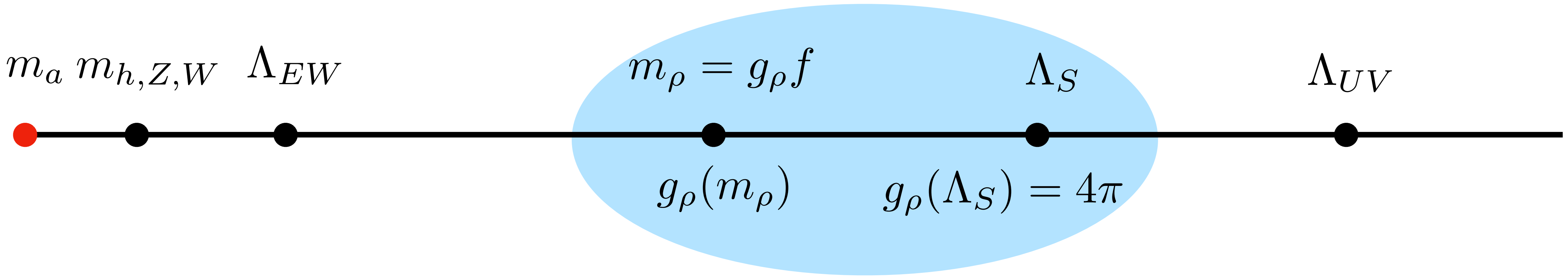


New sector contributes to potential and mass

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Theory Motivation for MeV-GeV ALPs

Composite Higgs models



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)]

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

[Chala, Guedes, Ramos, Santiago: 2012.09017]

Higgs interactions at dimension-6 and 7

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

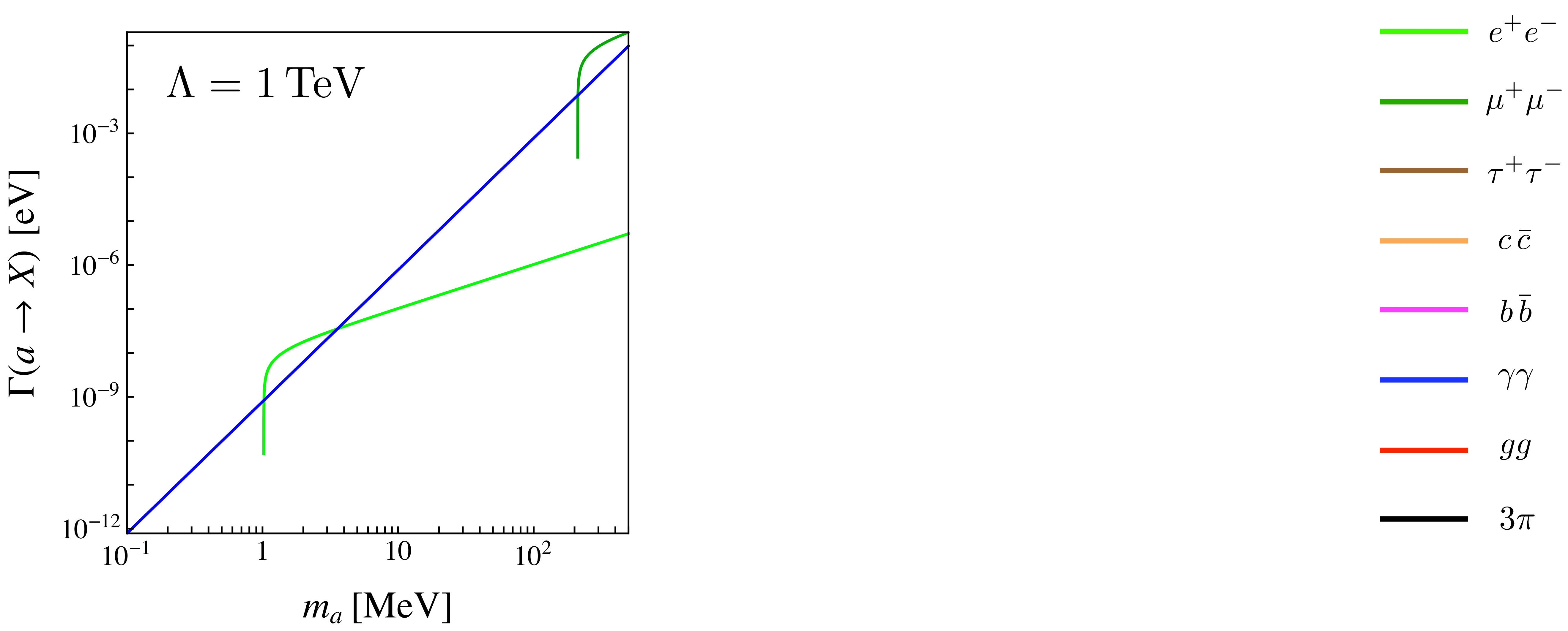
[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

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

Effective Lagrangian and Collider Bounds

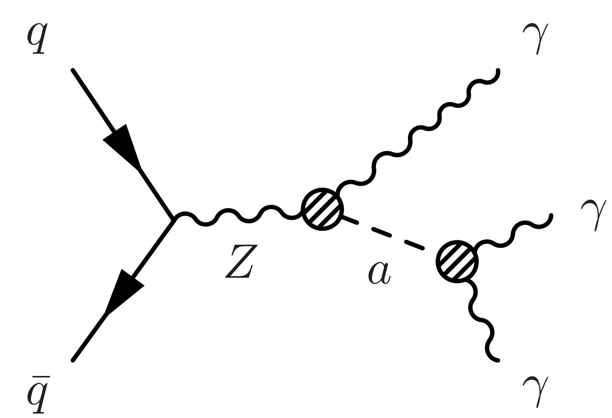
Fermion couplings = 1, Gauge boson couplings = 1 in the plot

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

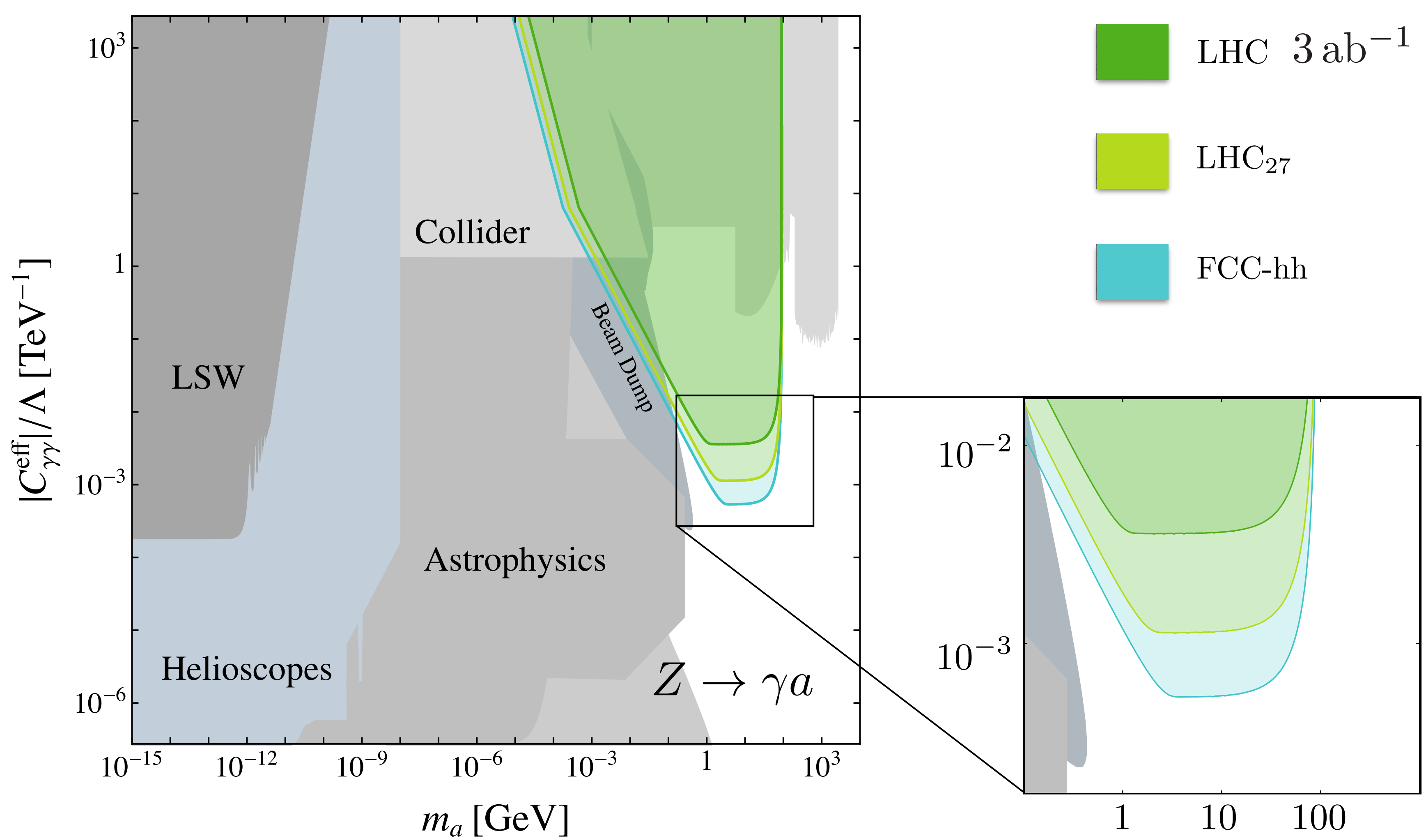


Effective Lagrangian and Collider Bounds

Dominant production mode: exotic Higgs and Z-boson decays



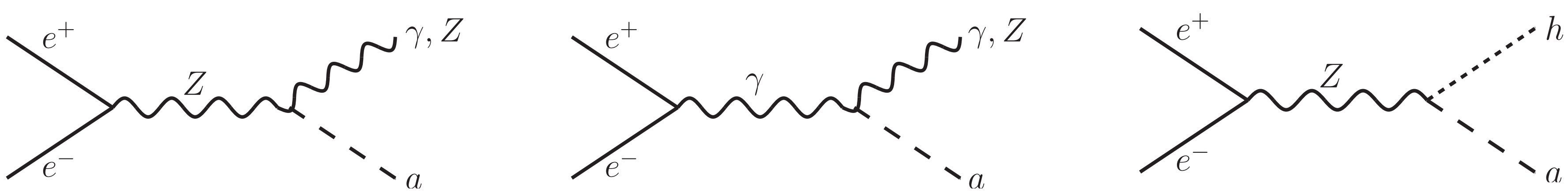
[Bauer, Heiles, Neubert, Thamm: 1808.10323]



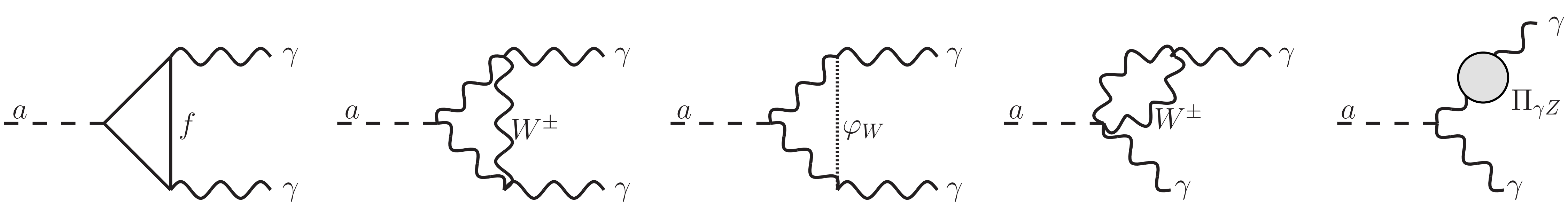
Effective Lagrangian and Collider Bounds

[Bauer, Heiles, Neubert, Thamm: 1808.10323]
[Knapen, Thamm: 2108.08949]

Dominant production mode: ALP associated production



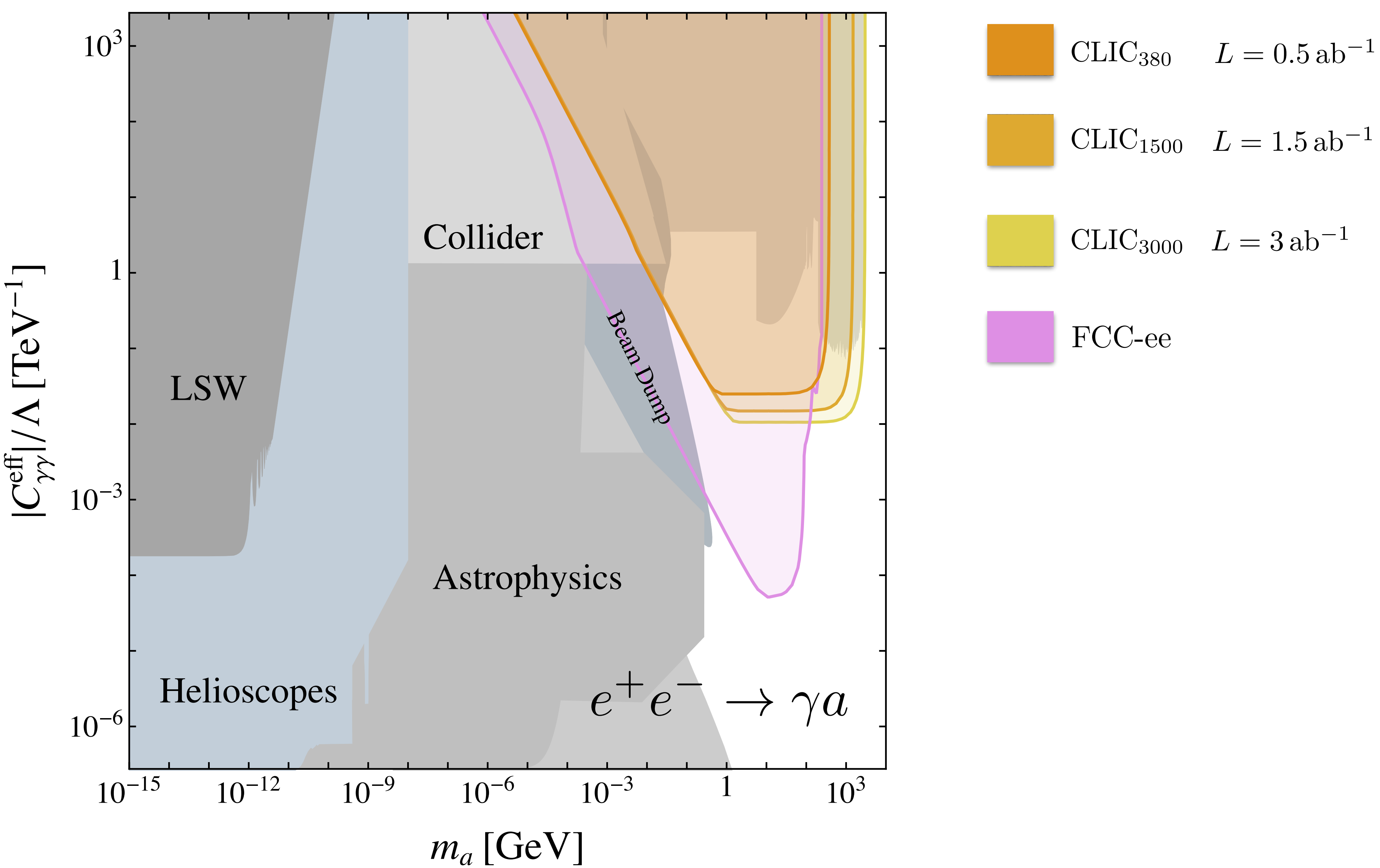
Decay mode into photons



Effective Lagrangian and Collider Bounds

Discovery potential

[Bauer, Heiles, Neubert, Thamm: 1808.10323]



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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]

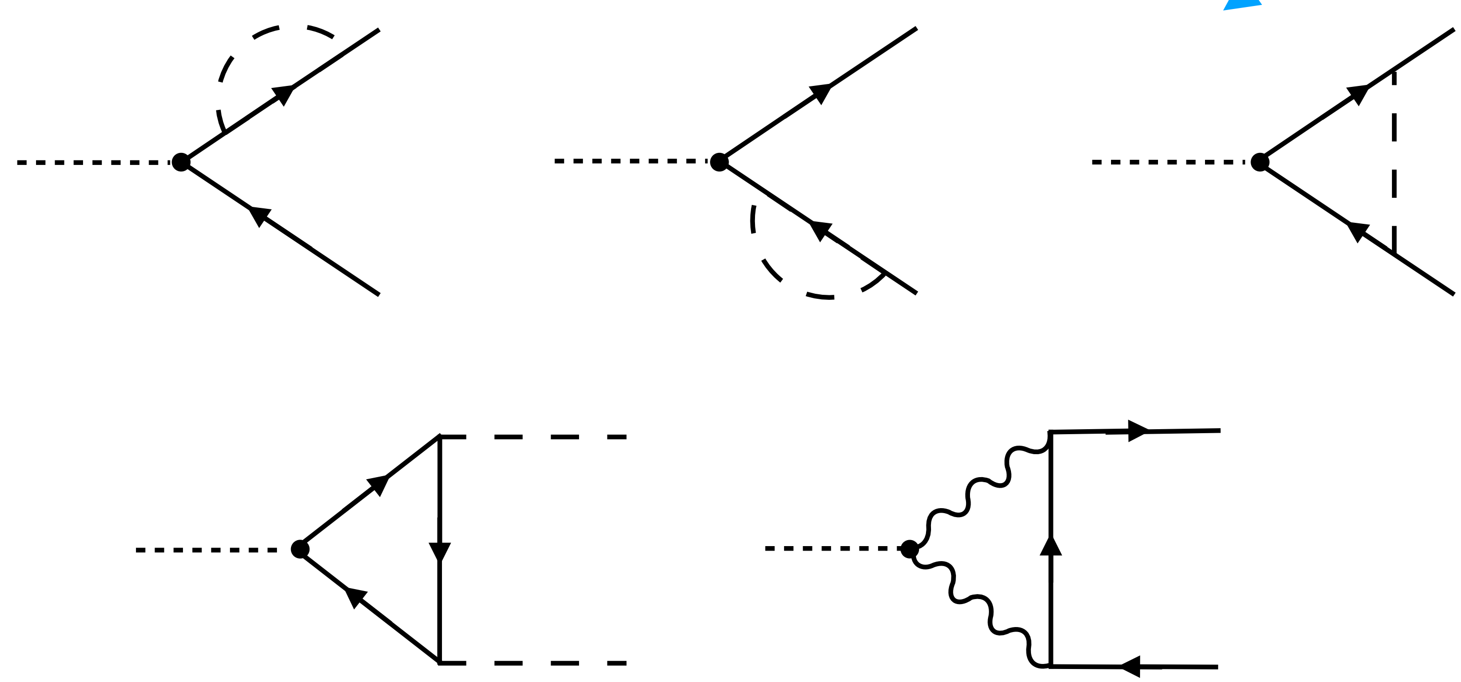
Operator Evolution to the Weak Scale

[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

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

1308.2627

2012.09017, 2021.12272

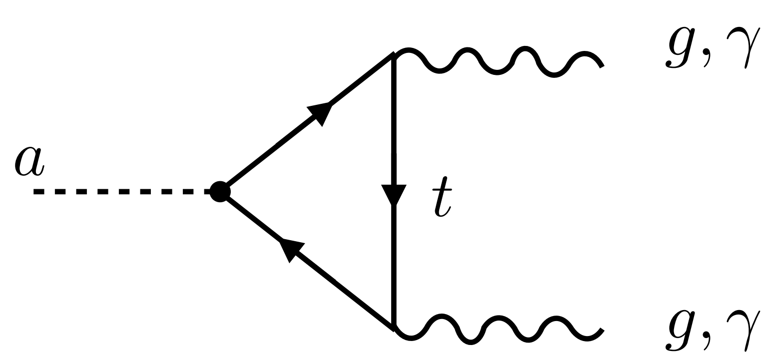
Mixing of ALP-boson operators into ALP-fermions

Operator Evolution at the Weak Scale

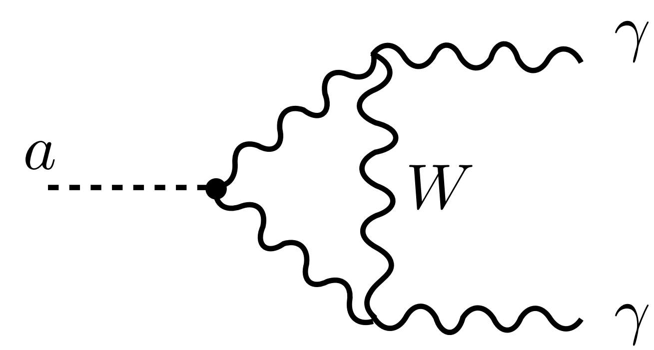
[Chala, Guedes, Ramos, Santiago: 2012.09017]
[Bauer, Neubert, Renner, Schnubel, Thamm: 2012.12272]

ALP couplings to gauge bosons

[Bauer, Neubert, Thamm: 1708.00443]



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



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

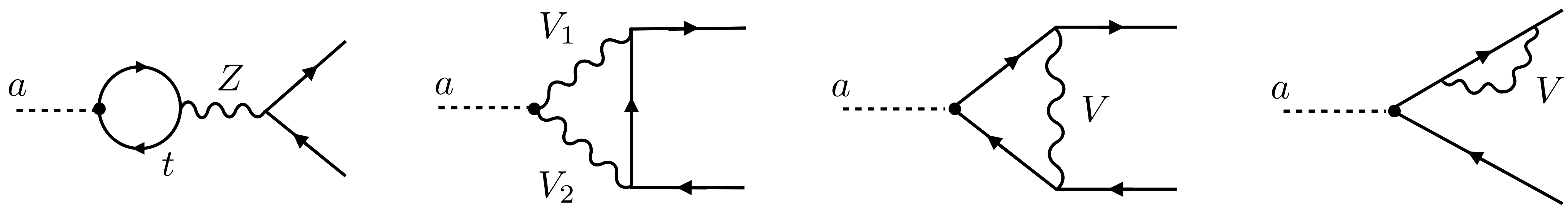
$$\Delta c_{GG}(\mu_w) = 0\,, \qquad \Delta c_{\gamma\gamma}(\mu_w) = 0$$

Operator Evolution at the Weak Scale

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

ALP couplings to fermions

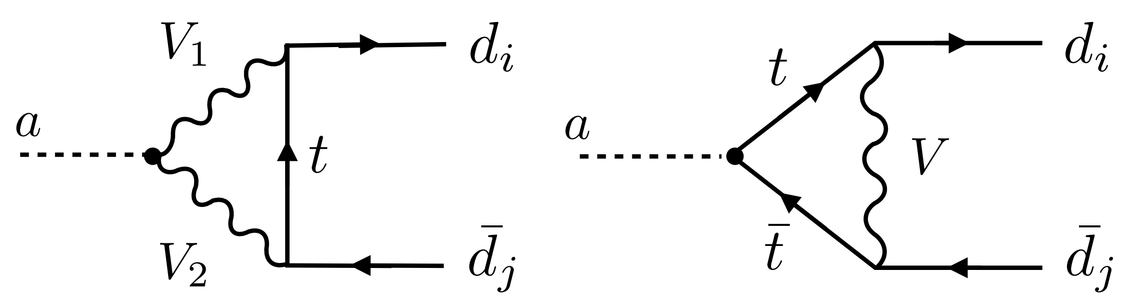
1708.00443



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 $f = 1\,\mathrm{TeV}$

- Flavor diagonal couplings

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

$$c_{uu,cc}(m_t) \simeq c_{uu,cc}(\Lambda) - 0.116\,c_{tt}(\Lambda) - \Big[6.35\,\tilde{c}_{GG}(\Lambda) + 0.19\,\tilde{c}_{WW}(\Lambda) + 0.02\,\tilde{c}_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{dd,ss}(m_t) \simeq c_{dd,ss}(\Lambda) + 0.116\,c_{tt}(\Lambda) - \Big[7.08\,\tilde{c}_{GG}(\Lambda) + 0.22\,\tilde{c}_{WW}(\Lambda) + 0.005\,\tilde{c}_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{bb}(m_t) \simeq c_{bb}(\Lambda) + 0.097\,c_{tt}(\Lambda) - \Big[7.02\,\tilde{c}_{GG}(\Lambda) + 0.19\,\tilde{c}_{WW}(\Lambda) + 0.005\,\tilde{c}_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

$$c_{e_ie_i}(m_t) \simeq c_{e_ie_i}(\Lambda) + 0.116\,c_{tt}(\Lambda) - \Big[0.37\,\tilde{c}_{GG}(\Lambda) + 0.22\,\tilde{c}_{WW}(\Lambda) + 0.05\,\tilde{c}_{BB}(\Lambda)\Big]\cdot 10^{-3}$$

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 changing couplings

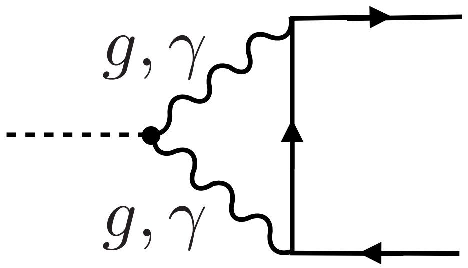
$$\mathcal{L}_{\rm ferm}^{\rm FCNC}(\mu) = -\frac{ia}{2f}\sum_f \Big[(m_{f_i} - m_{f_j})\,(k_f + k_F)_{ij}\,\bar f_i f_j + (m_{f_i} + m_{f_j})\,(k_f - k_F)_{ij}\,\bar f_i \gamma_5 f_j\Big]$$

$$\begin{aligned}
[k_u(\mu_w)]_{ij} &= [k_u(\Lambda)]_{ij}\,; \quad i,j \neq 3 \\
[k_U(\mu_w)]_{ij} &= [k_U(\Lambda)]_{ij}\,; \quad i,j \neq 3 \\
[k_d(\mu_w)]_{ij} &= [k_d(\Lambda)]_{ij} \\
[k_e(\mu_w)]_{ij} &= [k_e(\Lambda)]_{ij} \\
[k_L(\mu_w)]_{ij} &= [k_L(\Lambda)]_{ij} \\
[k_D(m_t)]_{ij} &\simeq [k_D(\Lambda)]_{ij} + 0.019\,V_{ti}^* V_{tj}\Big[c_{tt}(\Lambda) - 0.0032\,\tilde c_{GG}(\Lambda) - 0.0057\,\tilde c_{WW}(\Lambda)\Big]
\end{aligned}$$

Operator Evolution below the Weak Scale

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

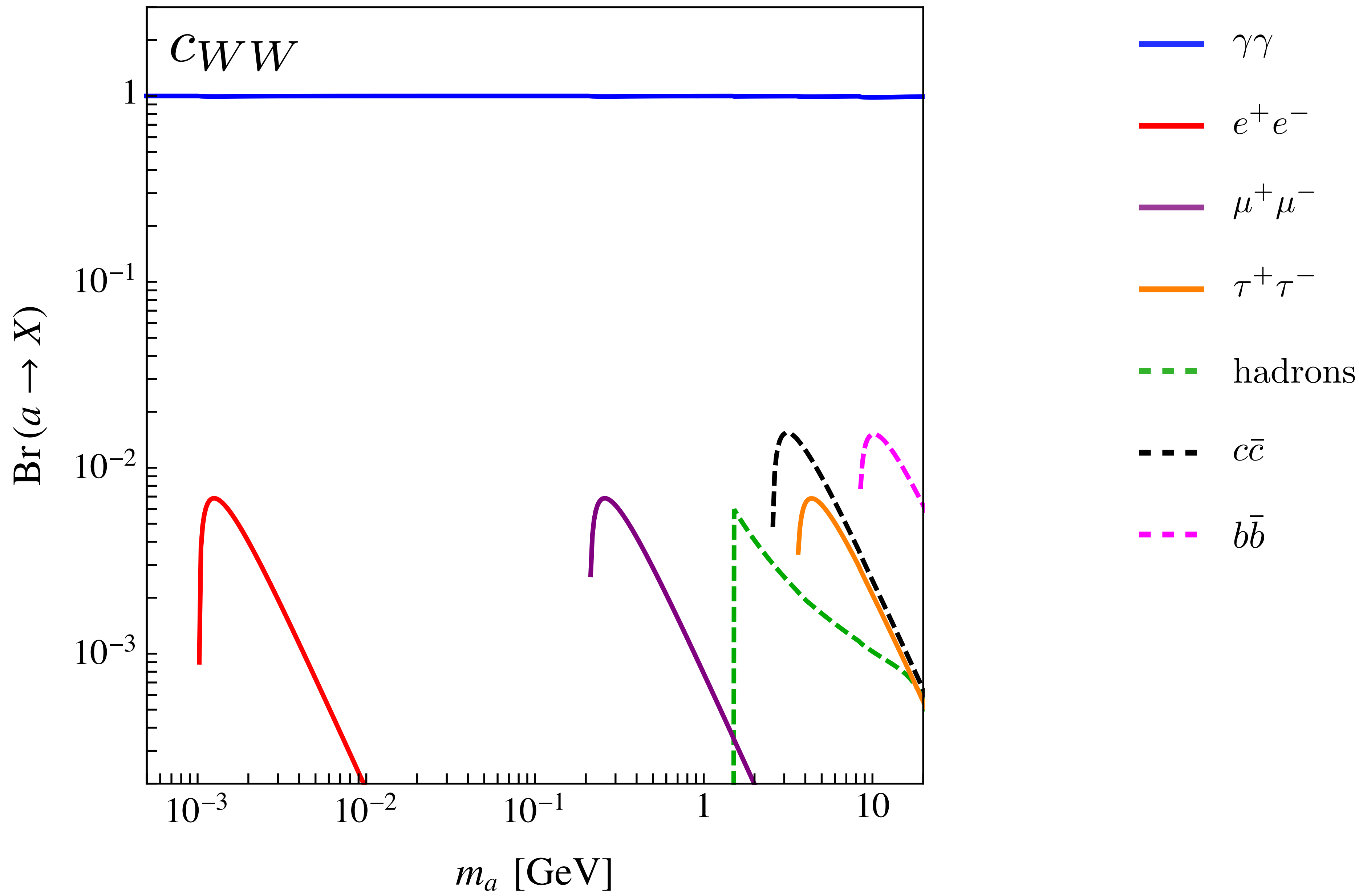
Only relevant diagram



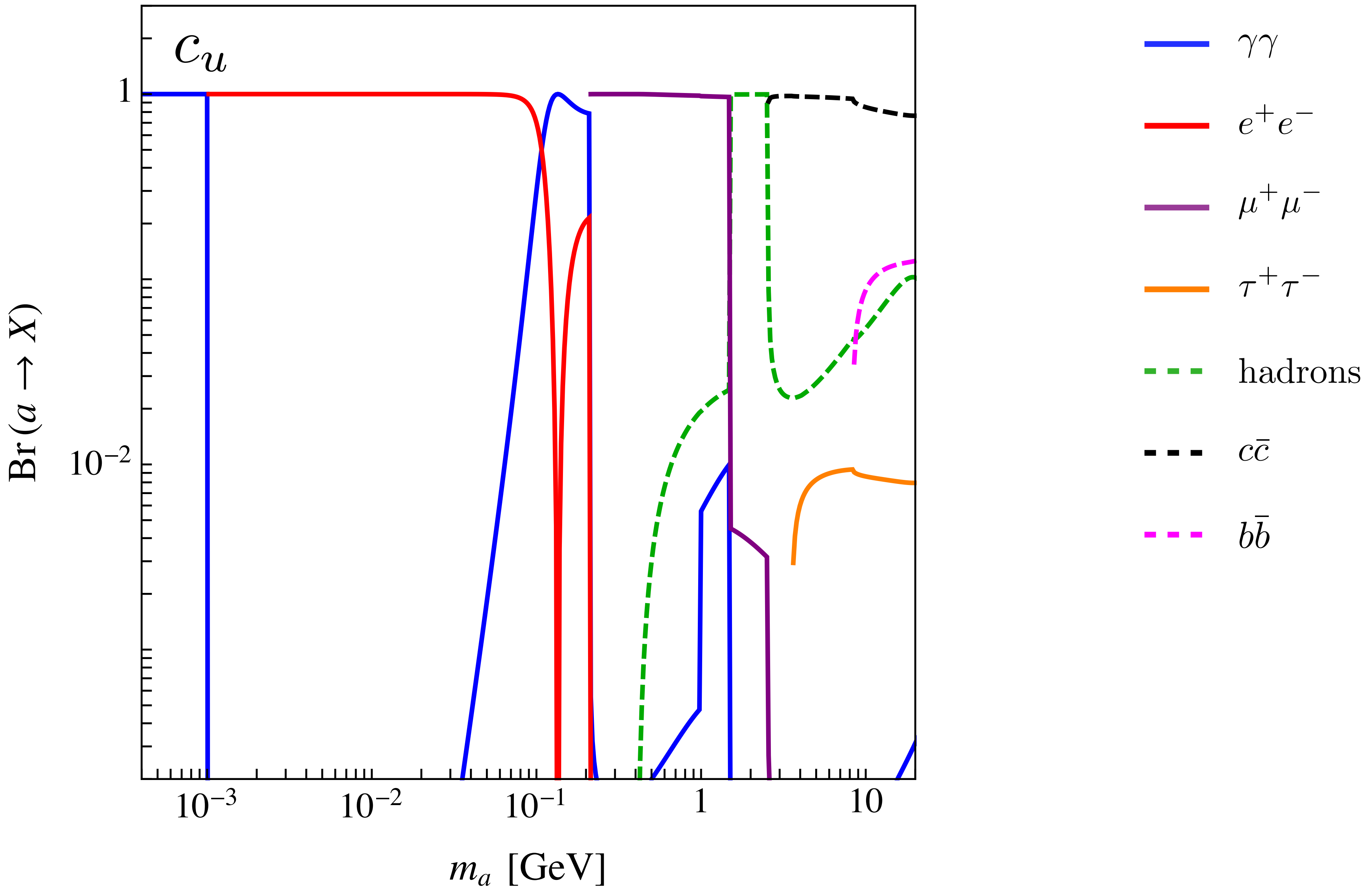
Small effect at $\mu_0 = 2\,\mathrm{GeV}$

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

Operator Evolution and Collider Bounds



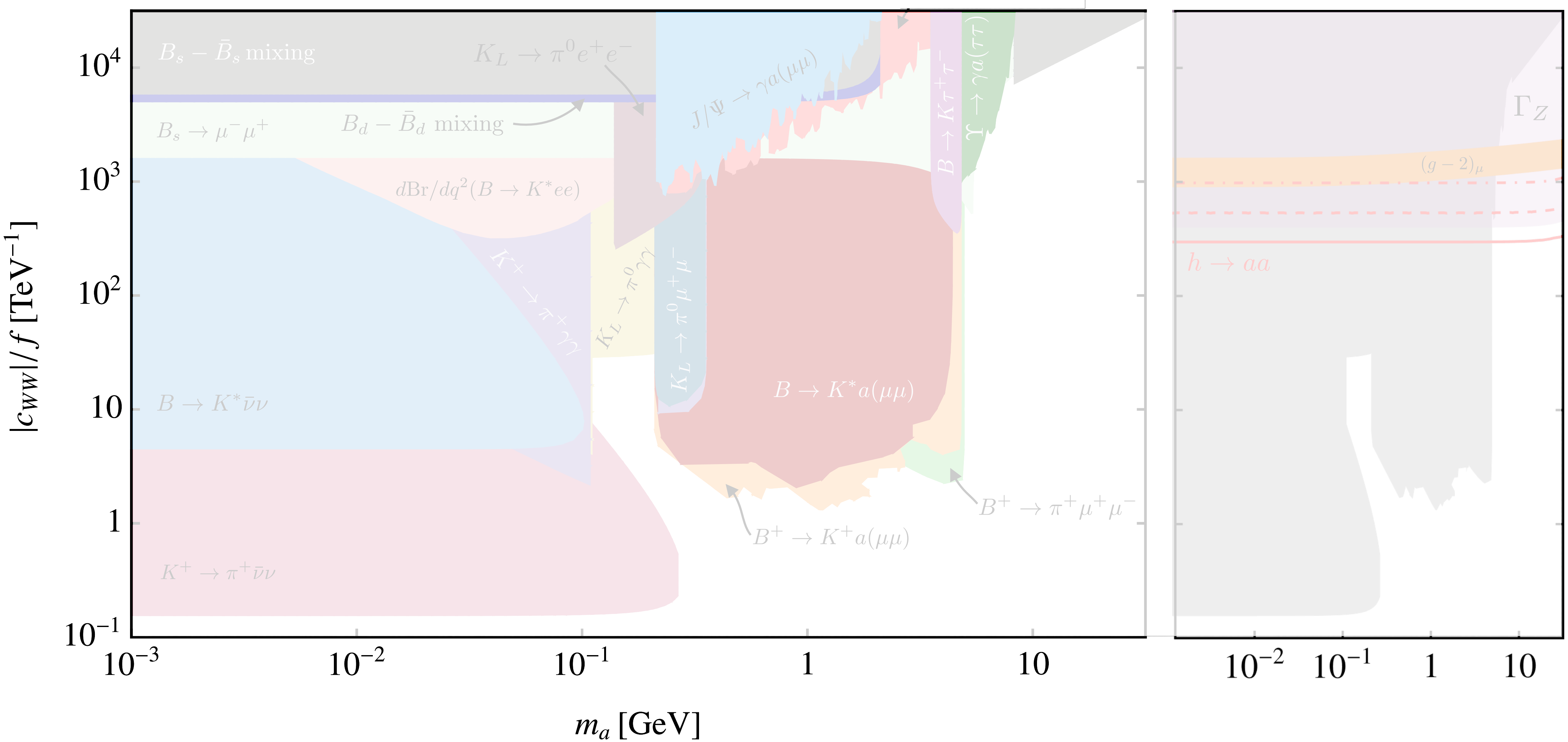
Operator Evolution and Collider Bounds



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

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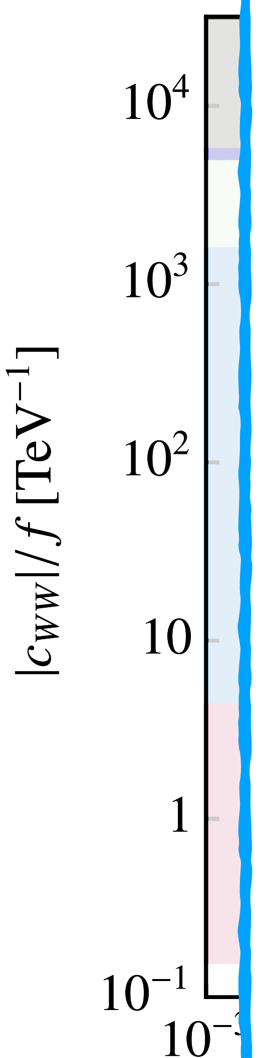
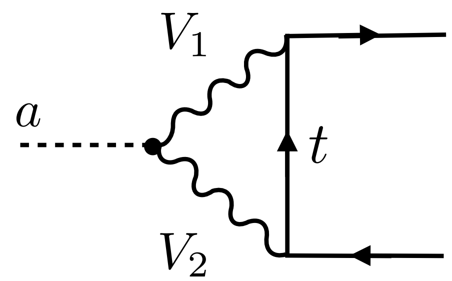
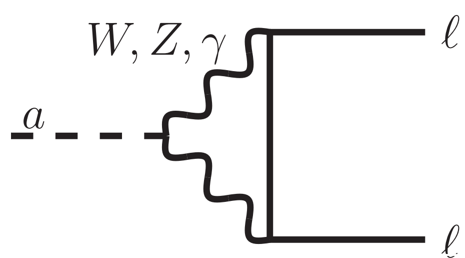


Flavour change



Decay

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



Operator Evolution and Collider Bounds

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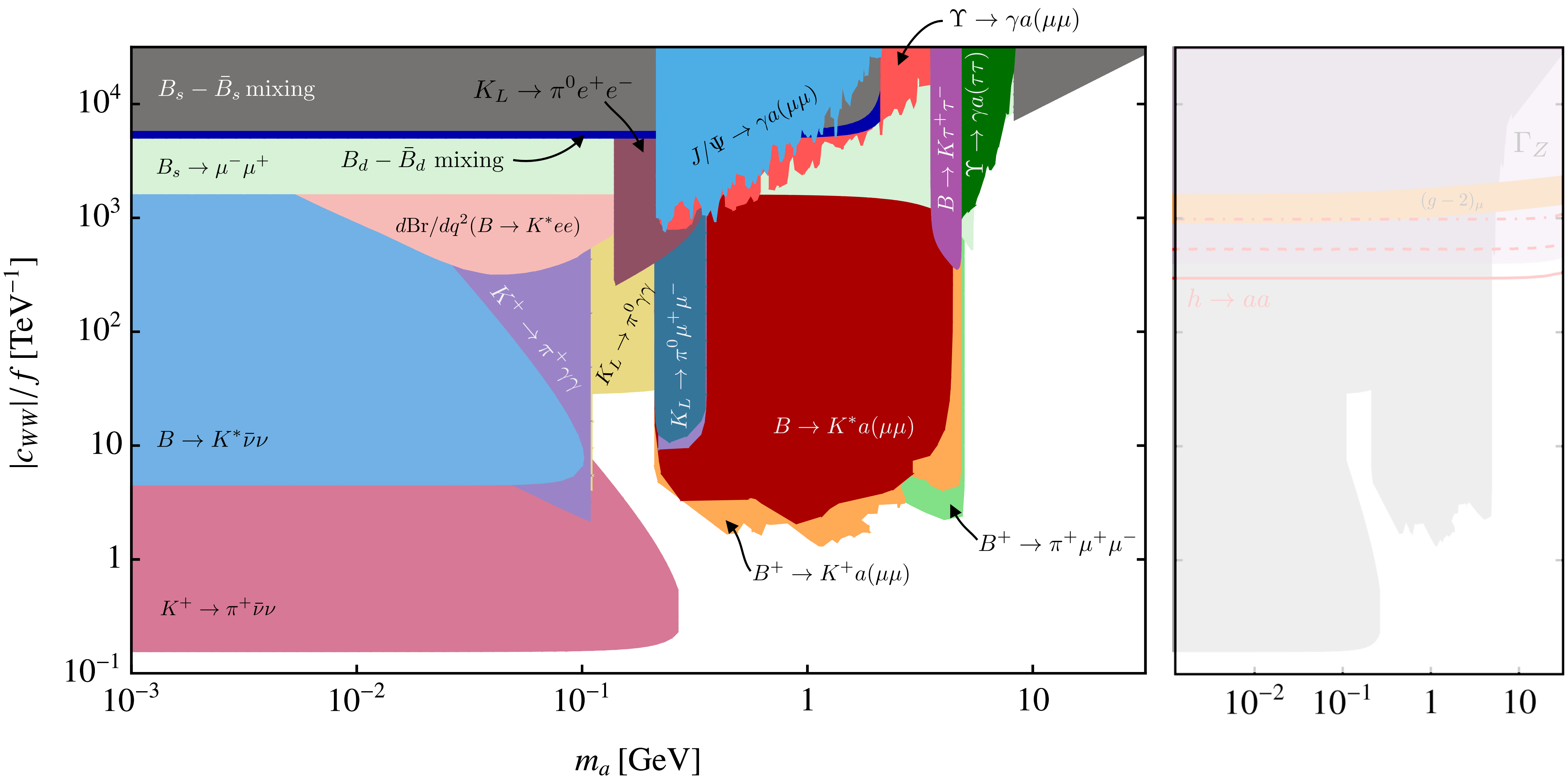

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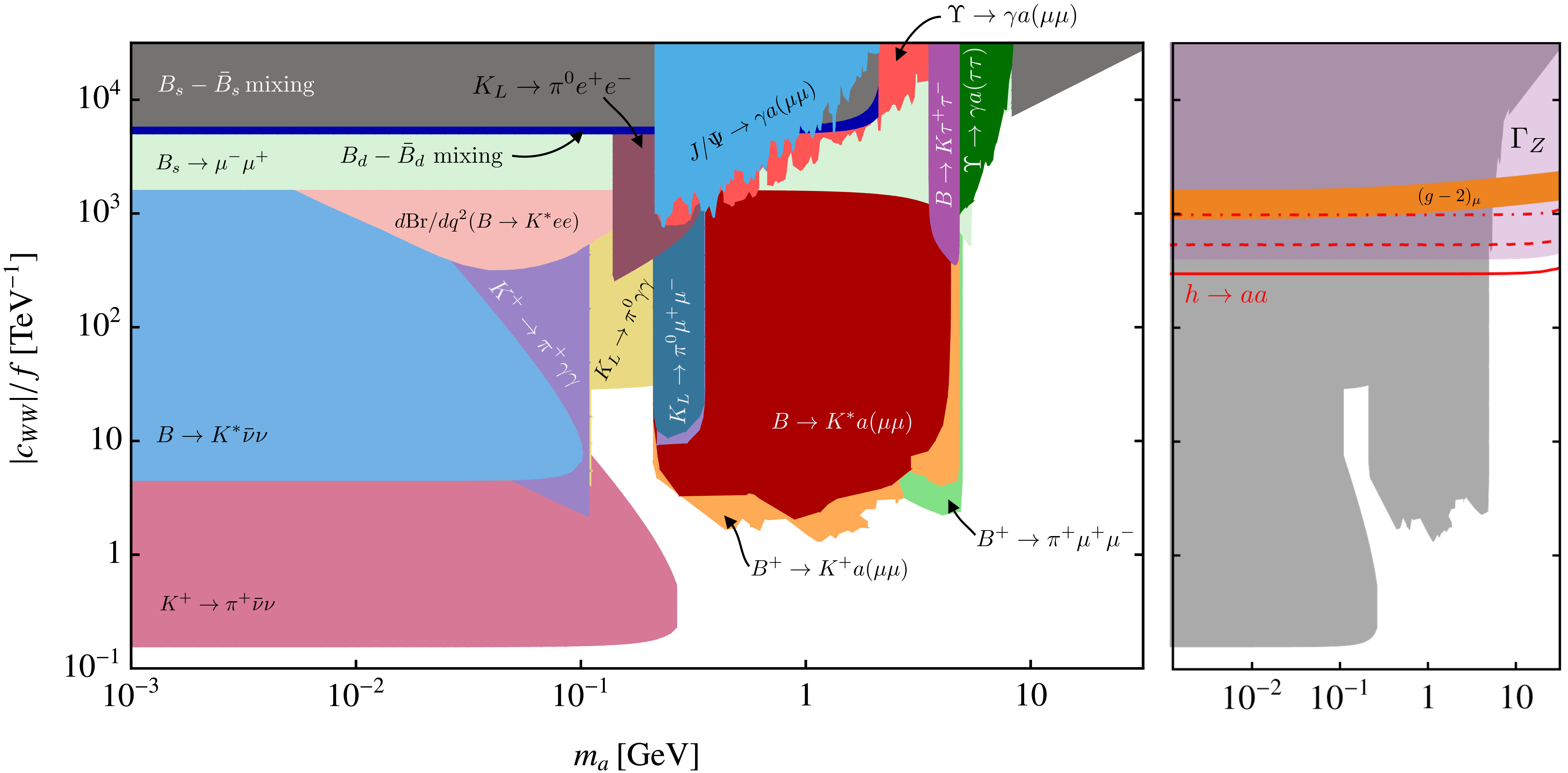
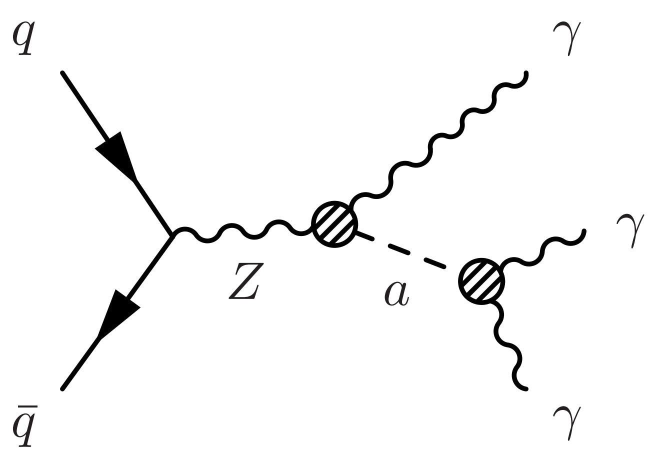


Operator Evolution and Collider Bounds

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

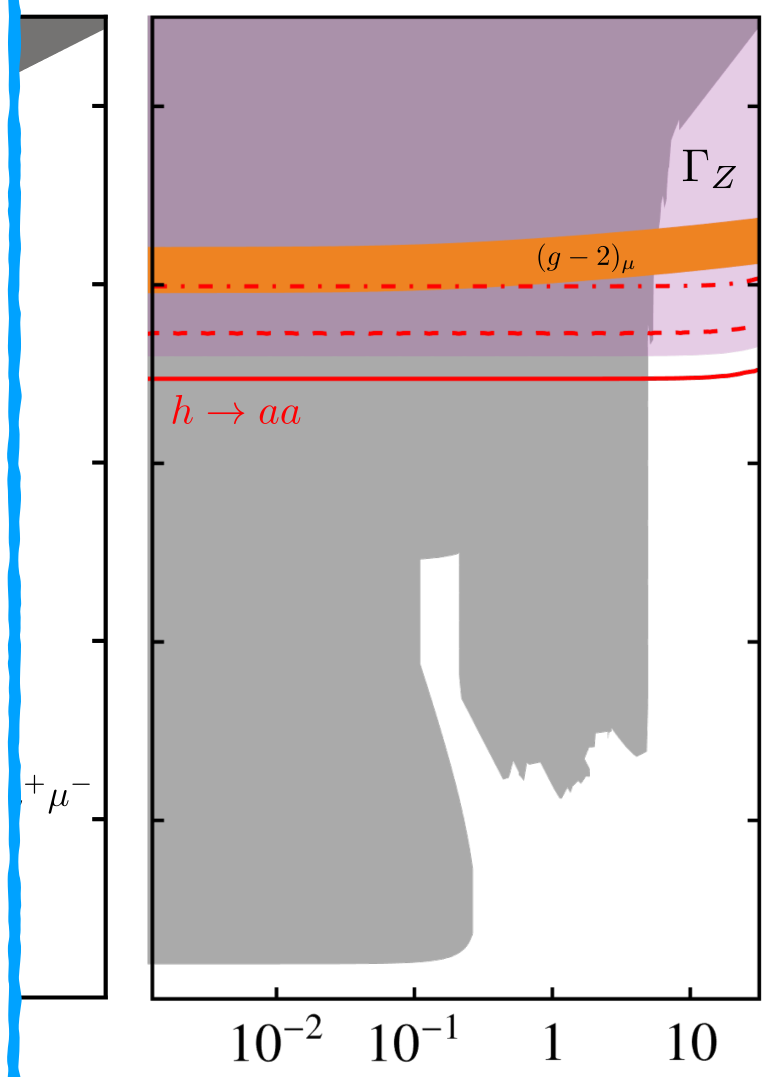
Z widths



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

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

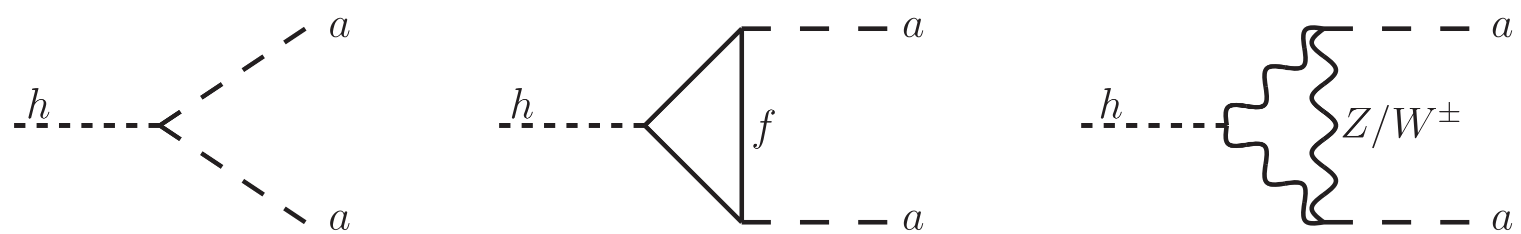
LEP: 0509008



Operator Evolution and Collider Bounds

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

Higgs Branching Ratio

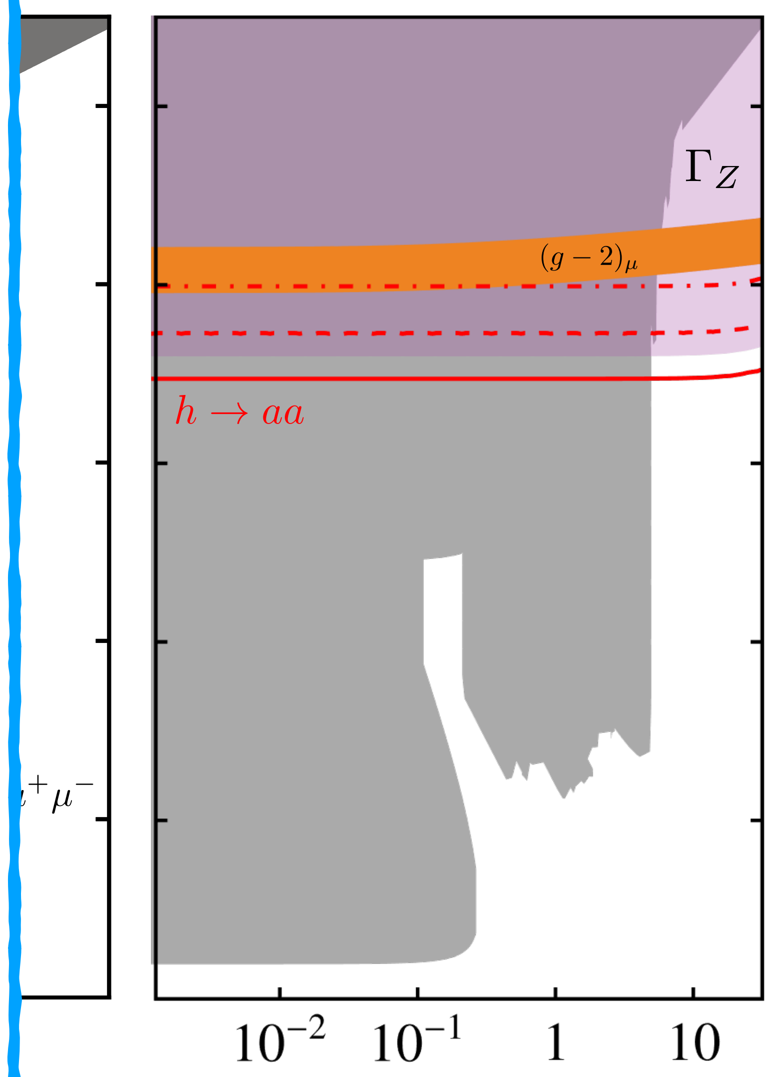


$$\mathrm{Br}(h \to \mathrm{BSM}) < 0.34$$

$$\Longrightarrow \quad \Gamma(h \to \mathrm{BSM}) < 2.1\,\mathrm{MeV}$$

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

ATLAS and CMS:1606.02266



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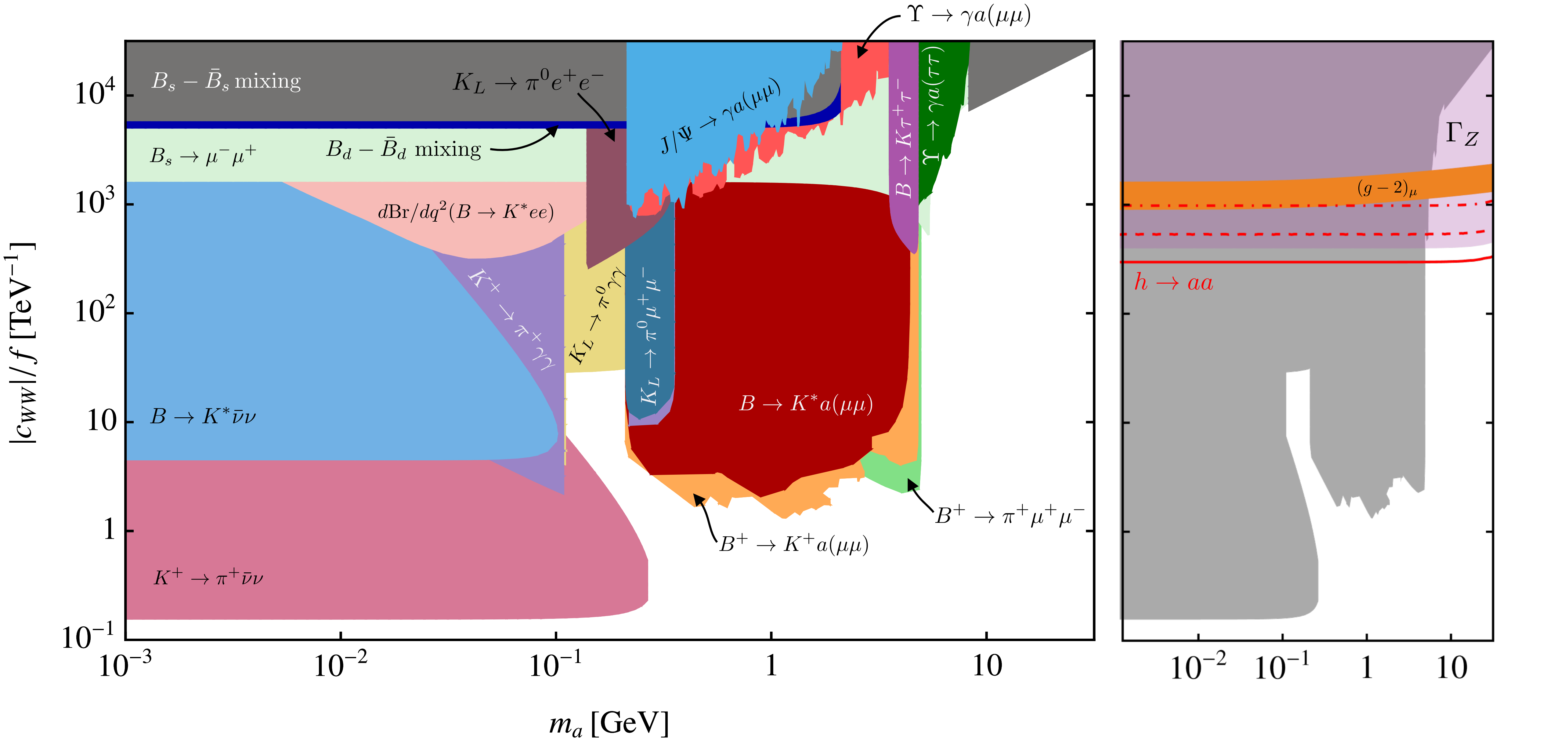
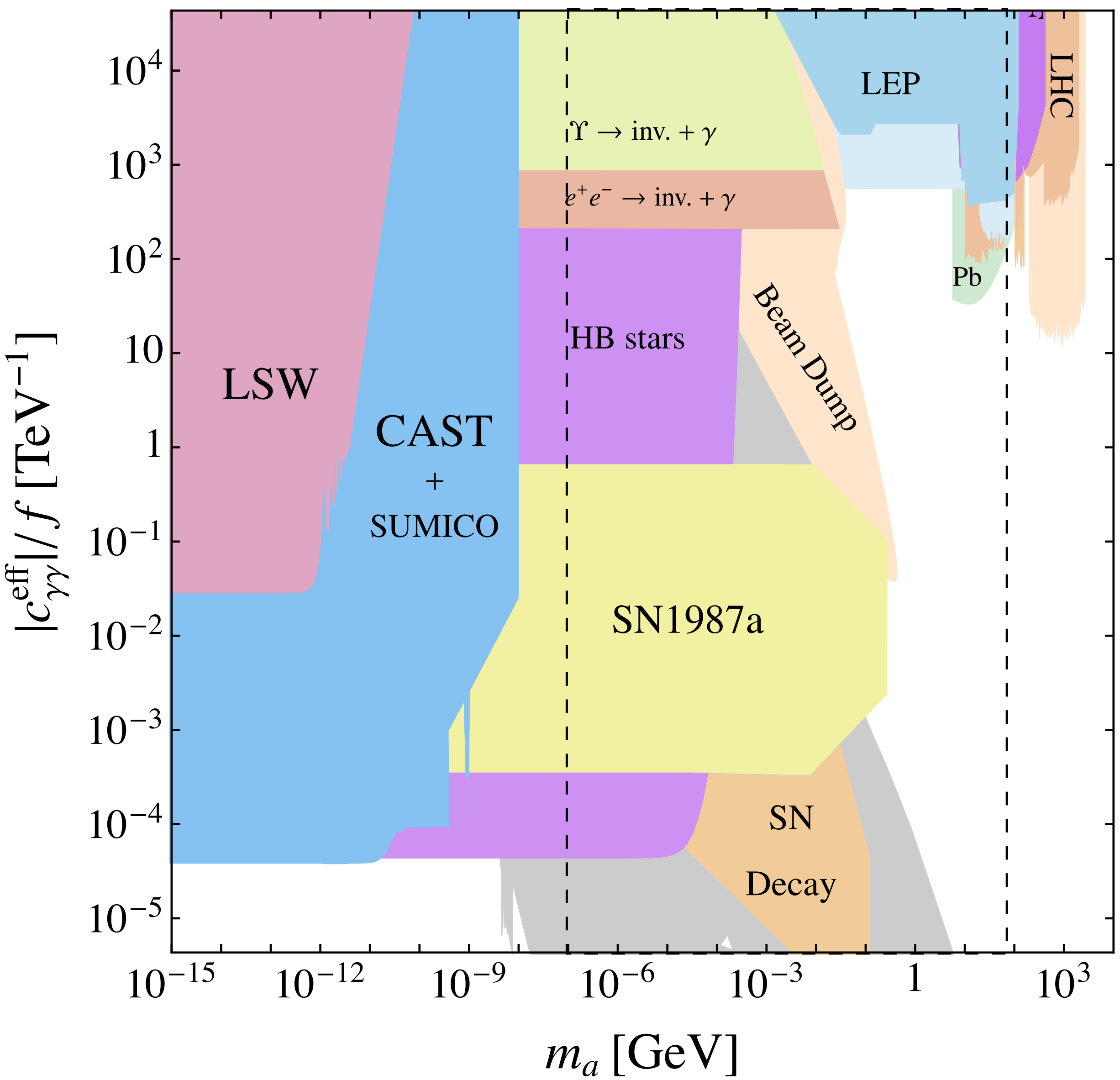


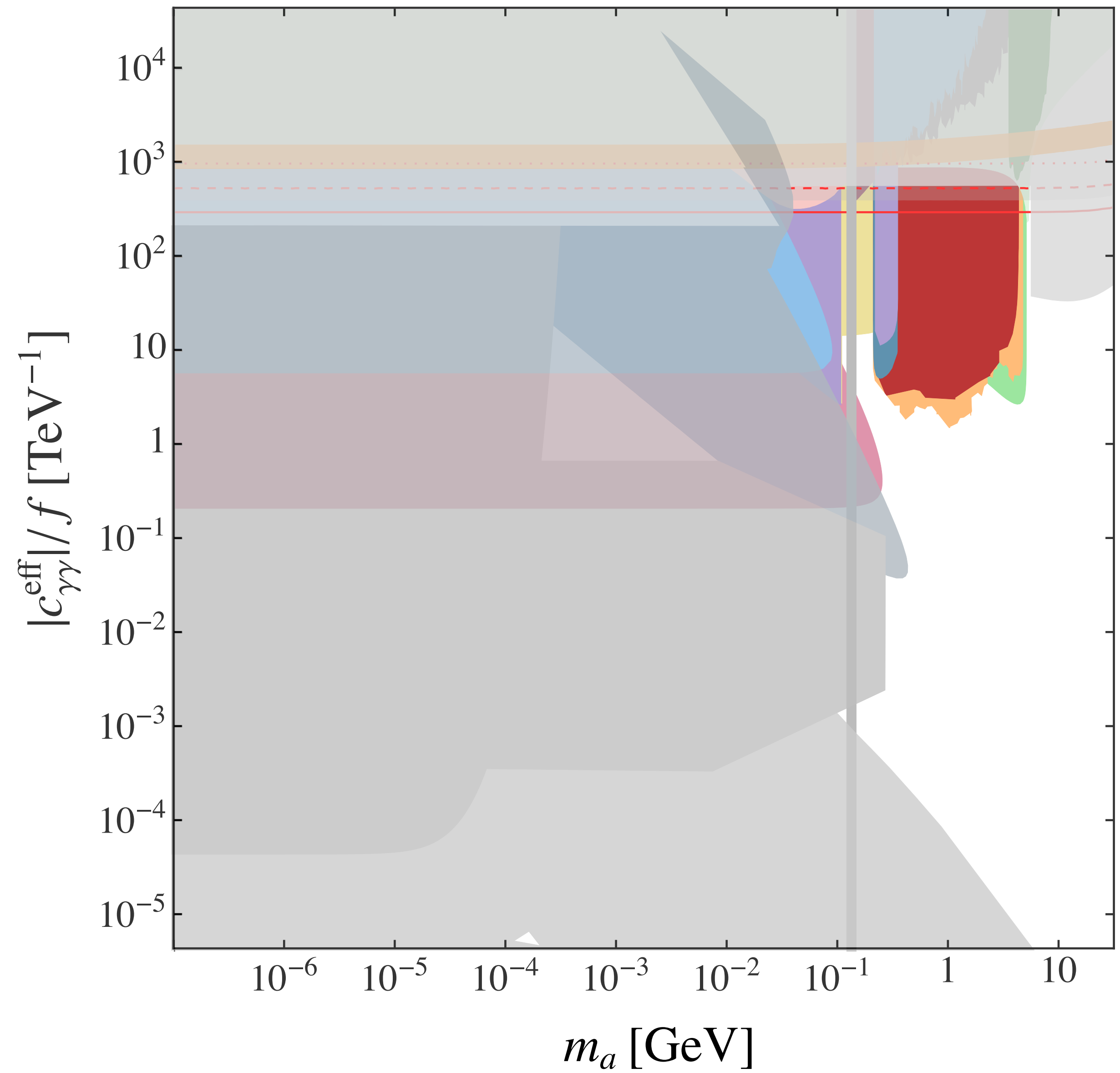
Flavour bounds are complementary to other collider bounds

Operator Evolution and Collider Bounds

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

[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