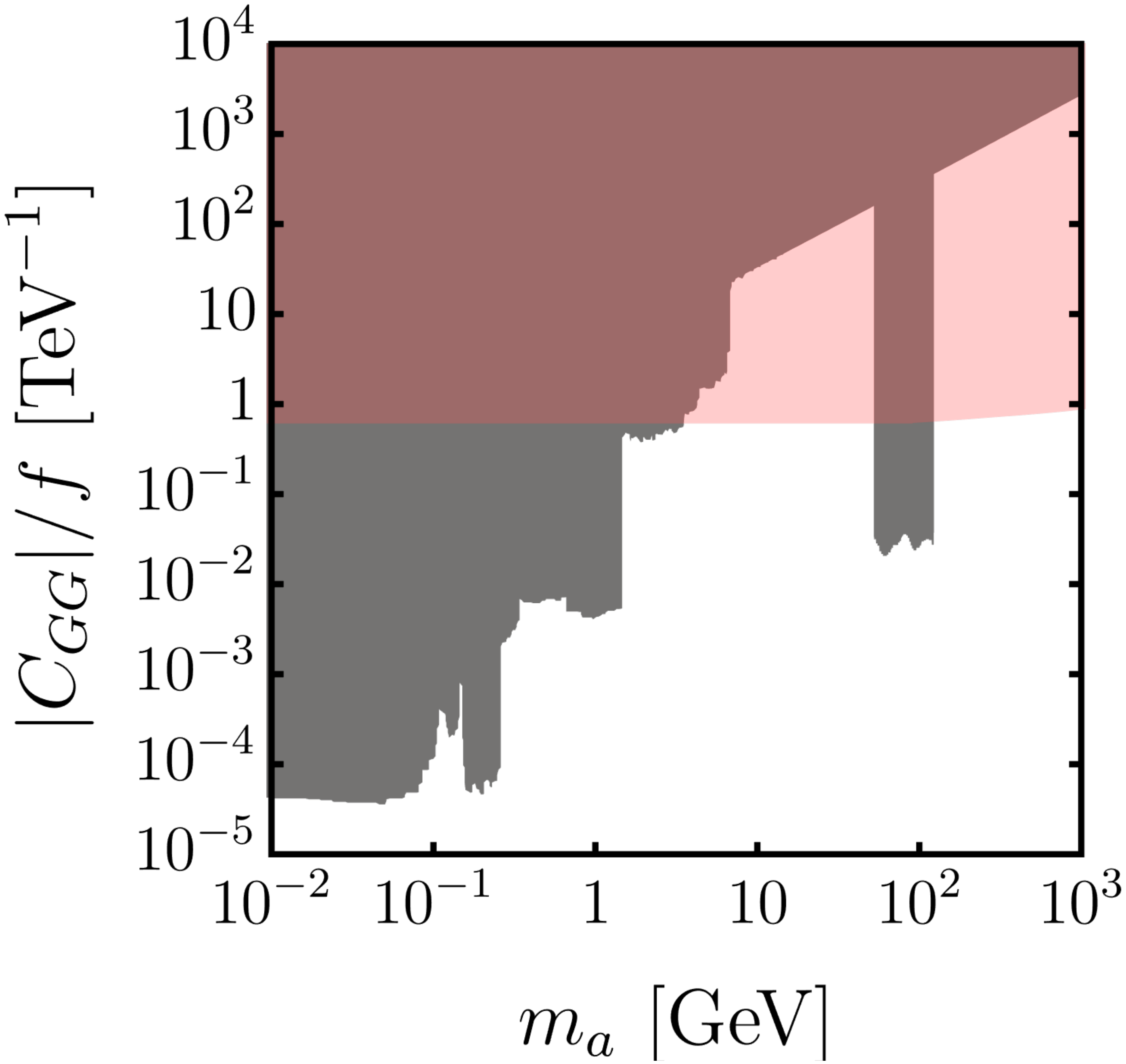
Constraining ALP Couplings with SMEFT Interference



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based on arXiv: 2307.10372 [hep-ph]

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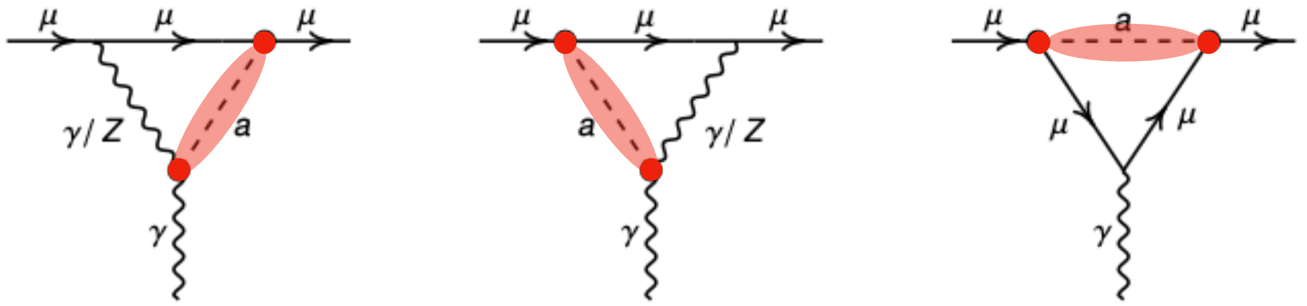
Peccei-Quinn solution to the strong CP-problem [Peccei, Quinn (1977); Weinberg (1978); Wilczek (1978)]

Potential Dark Matter candidates [Preskill, Wise, Wilczek (1983)]

Give a contribution to $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 4.2\sigma$ [B. Abi et al. (2021)]



Most general Lagrangian for a classically shift symmetric, gauge singlet, pseudoscalar ALP:

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

[H. Georgi, D. B. Kaplan, L. Randall (1986)]

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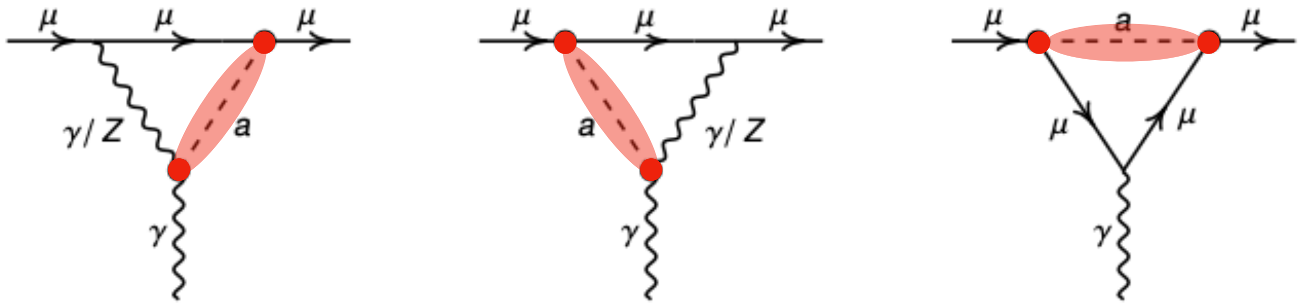
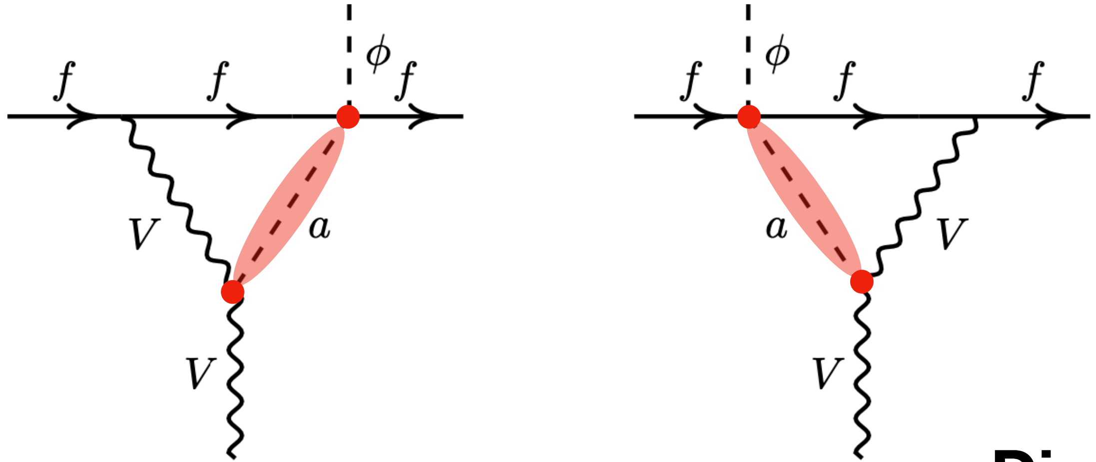


Most general Lagrangian for a classically shift symmetric, gauge singlet, pseudoscalar ALP:

field redefinition

$$\mathcal{L}_{\text{SM+ALP}}^{D=5\,\prime} = C_{GG}\,\frac{a}{f}\,G_{\mu\nu}^{a}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W_{\mu\nu}^{I}\,\tilde{W}^{\mu\nu,I} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\widetilde{\boldsymbol{Y}}_u\,u_R + \bar{Q}\,H\,\widetilde{\boldsymbol{Y}}_d\,d_R + \bar{L}\,H\,\widetilde{\boldsymbol{Y}}_e\,e_R + \text{h.c.}\right)$$

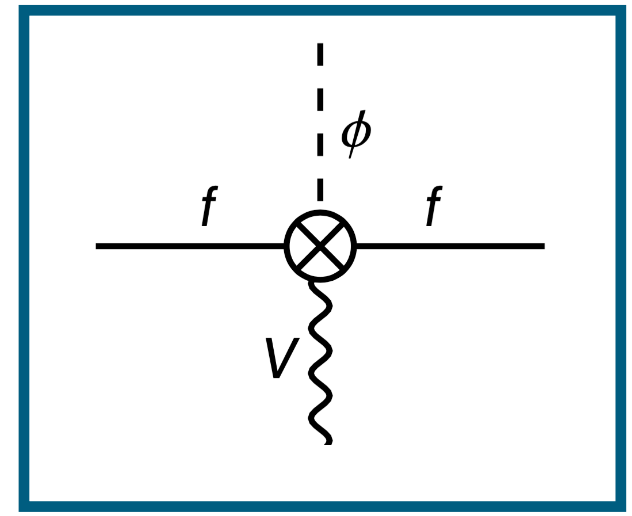
$$\widetilde{\boldsymbol{Y}}_u \equiv i\,\boldsymbol{Y}_u\,C_u\,, \quad \widetilde{\boldsymbol{Y}}_d \equiv i\,\boldsymbol{Y}_d\,C_d\,, \quad \widetilde{\boldsymbol{Y}}_e \equiv i\,\boldsymbol{Y}_e\,C_e$$



UV-divergent amplitudes

$\sim 1/\epsilon$

Divergence absorbed in bare dimension-6 SMEFT Wilson-coefficients together with the μ-dependence.



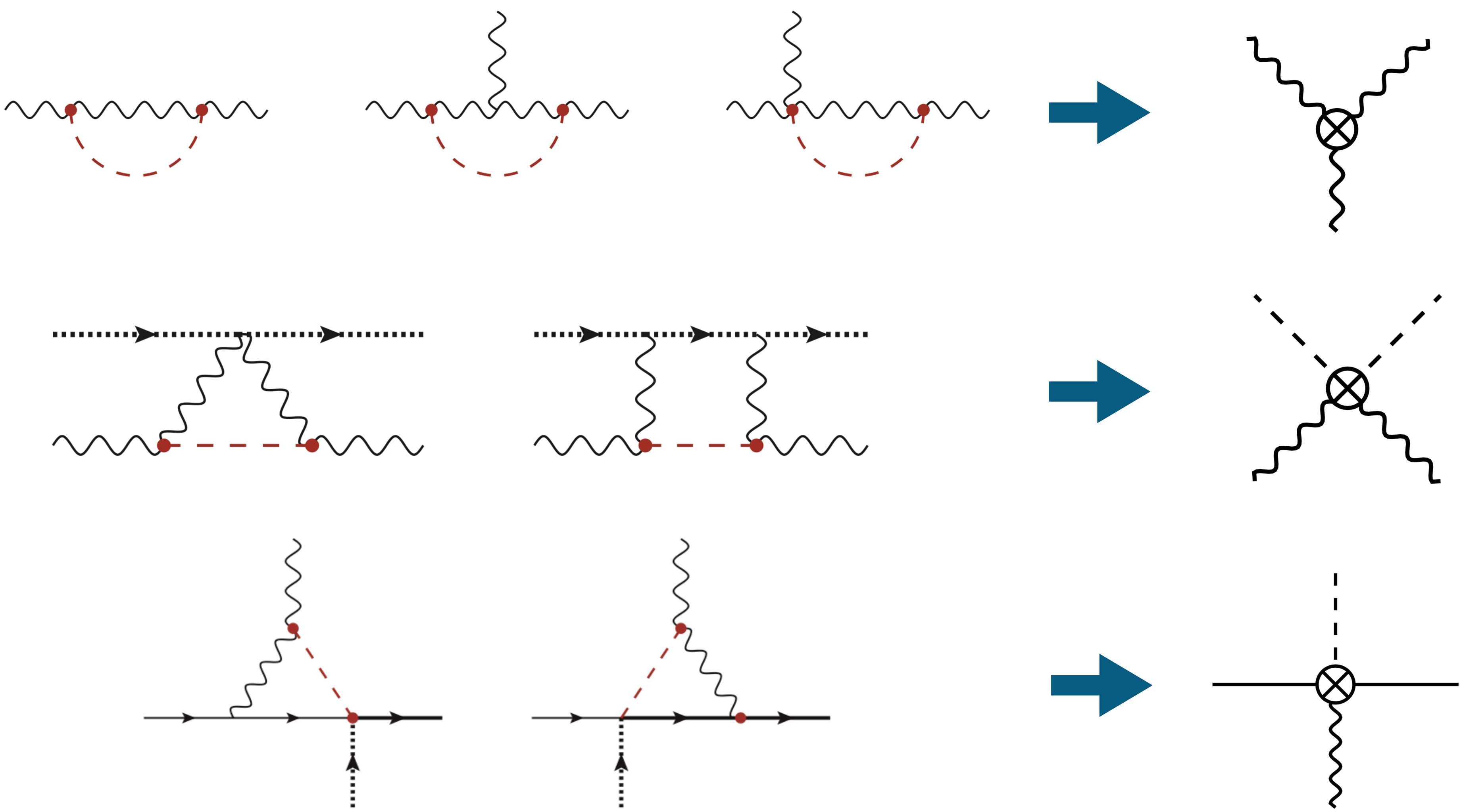
Dimension-6 SMEFT Wilson coefficients are generated via modification of the RG evolution even if the ALP is very light!

$$\frac{d}{d\ln\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \frac{S_i}{(4\pi f)^2} \qquad (\text{for } \mu < 4\pi f)$$

[AG, Neubert, Renner (2021)]

A consistent effective theory **necessarily** includes the **dimension-6 SMEFT Lagrangian**!

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SM+ALP}} + \mathcal{L}_{\text{SMEFT}}$$



$$S_G = 8\, g_s\, C_{GG}^2$$
$$S_W = 8\, g_2\, C_{WW}^2$$

$$S_{HW} = -2\, g_2^2\, C_{WW}^2$$
$$S_{HB} = -2\, g_1^2\, C_{BB}^2$$
$$S_{HWB} = -4\, g_1\, g_2\, C_{BB}\, C_{WW}$$

e.g. leptonic:

$$\boldsymbol{S}_{eB} = -2ig_1\, (\mathcal{Y}_L + \mathcal{Y}_e)\, \widetilde{\boldsymbol{Y}}_e\, C_{BB}$$
$$\boldsymbol{S}_{eW} = -2ig_2\, \widetilde{\boldsymbol{Y}}_e\, C_{WW}$$

[AG, Neubert, Renner (2021)]

...etc!

$$\frac{d}{d\ln\mu} C_i^{\rm SMEFT} - \gamma_{ji}^{\rm SMEFT} C_j^{\rm SMEFT} = \frac{S_i}{(4\pi f)^2} \qquad (\text{for } \mu < 4\pi f)$$

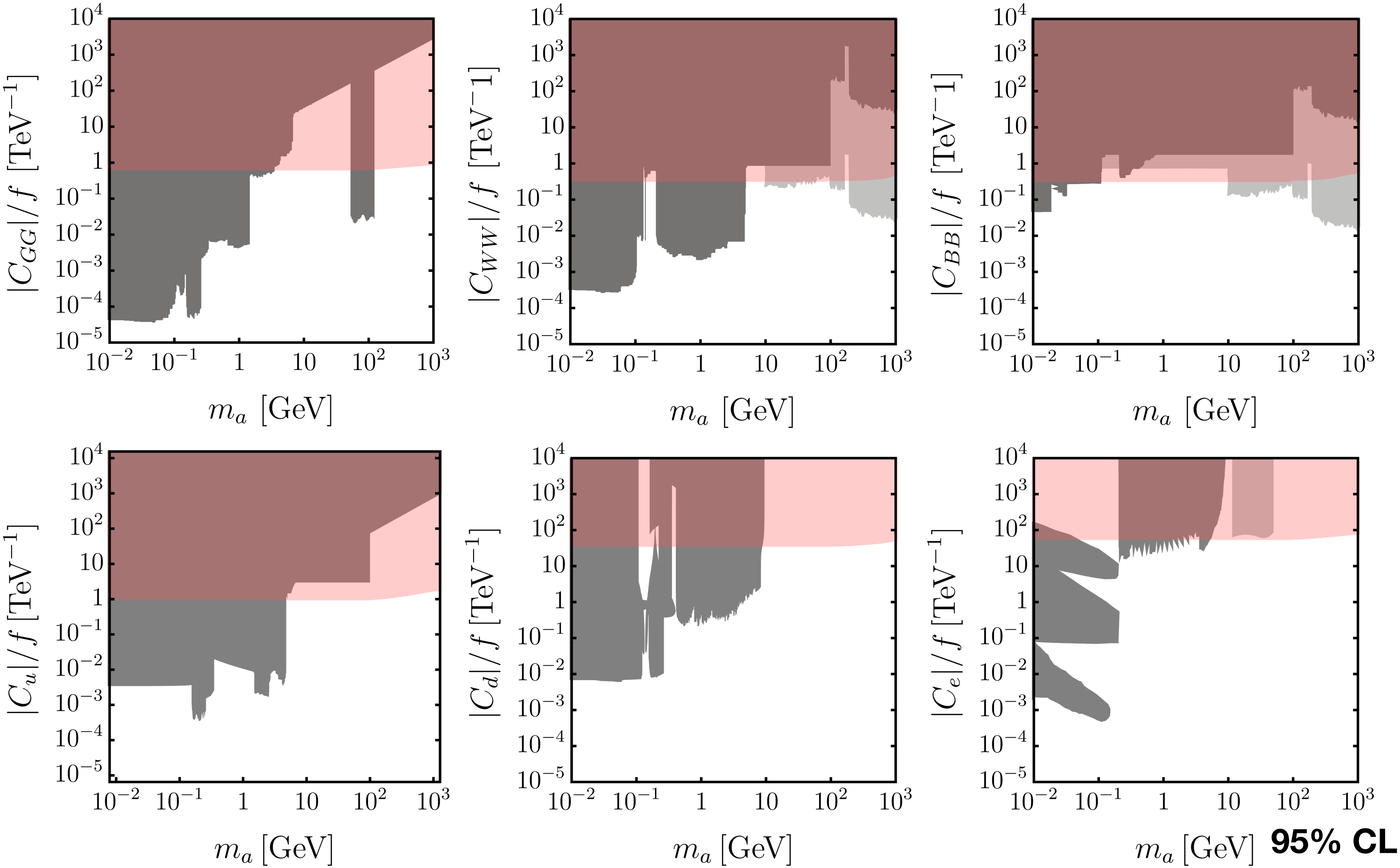
- **Large set of coupled differential equations!**
- **Solved numerically using a modified version of** `DsixTools` [Celis, Fuentes-Martín, Vicente, Virto (2017), Fuentes-Martín, Ruiz-Femenia, Vicente, Virto (2020)]

Result: **SMEFT Wilson coefficients at a low scale μ in terms of ALP-couplings at the scale Λ.**

We use SMEFT constraints from low-energy, Higgs and top data in a χ^2 fit to constrain the ALP-coefficients.

$$\chi^2(C_i) = \left[\vec{d} - \vec{p}(C_i)\right]^T \boldsymbol{V}^{-1} \left[\vec{d} - \vec{p}(C_i)\right]$$

from e.g. [Ellis, Madigan, Mimasu, Sanz, You (2021)]



Our bounds on the ALP-couplings are model-independent and are competitive or stronger for $m_a \sim \mathcal{O}(\mathrm{TeV{-}GeV})$ than existing direct bounds that often depend on a variety of assumption on branching ratios, lifetime etc.