Model-Independent Constraints on ALP Couplings from ALP—SMEFT Interference

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based on work with Anne Galda & Sophie Renner JHEP 06 (2021) 135 [arXiv:2105.01078]
and work in progress with Anke Biekötter, Javier Fuentes-Martín & Anne Galda

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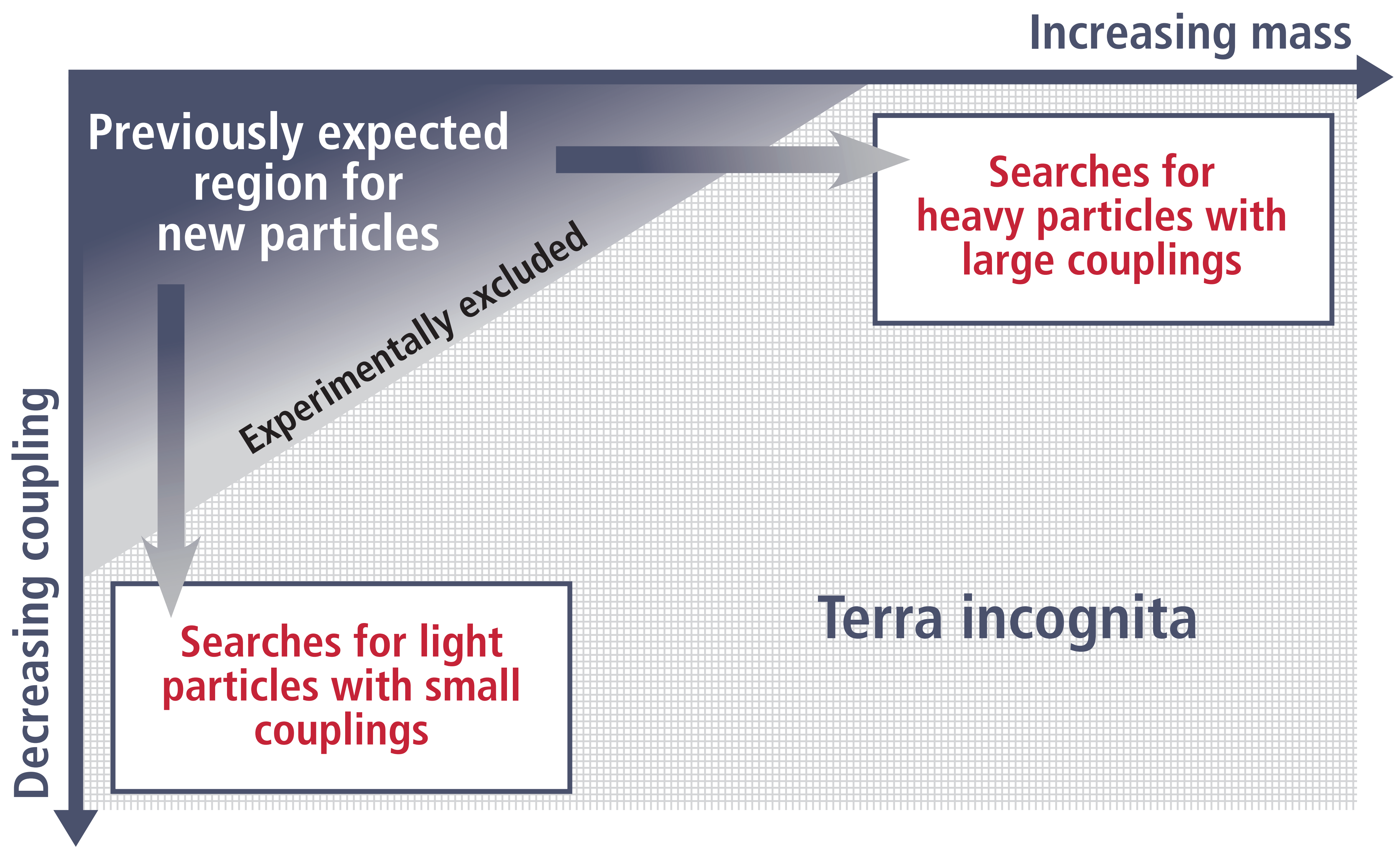
Introduction

- SMEFT: systematic framework for describing effects of **heavy new physics** on “low-energy” observables involving SM particles only

- Assumes SM gauge group and EWSB hold up to some high scale $\Lambda_{\mathrm{UV}} \gg v_{\mathrm{EWSB}}$

- But what if the SM is extended by a light new particle with feeble inter- with SM fields? Are there any implications for SMEFT?



Introduction

- If the new particle is described by a renormalizable Lagrangian ($D \leq 4$ operators), the answer is NO:
  - for observables involving SM fields only, the effects of the new particle can be absorbed into the renormalized SM parameters
  - only trace of its existence lies in its contributions to the β-functions of the SM parameters, which are small in the case of weak coupling
- Statement is rather generic, but an important exception exists
- BSM theories featuring **light new particles with only higher-dimensional interactions with the SM** give rise to different, more interesting effects!

Axions and axion-like particles

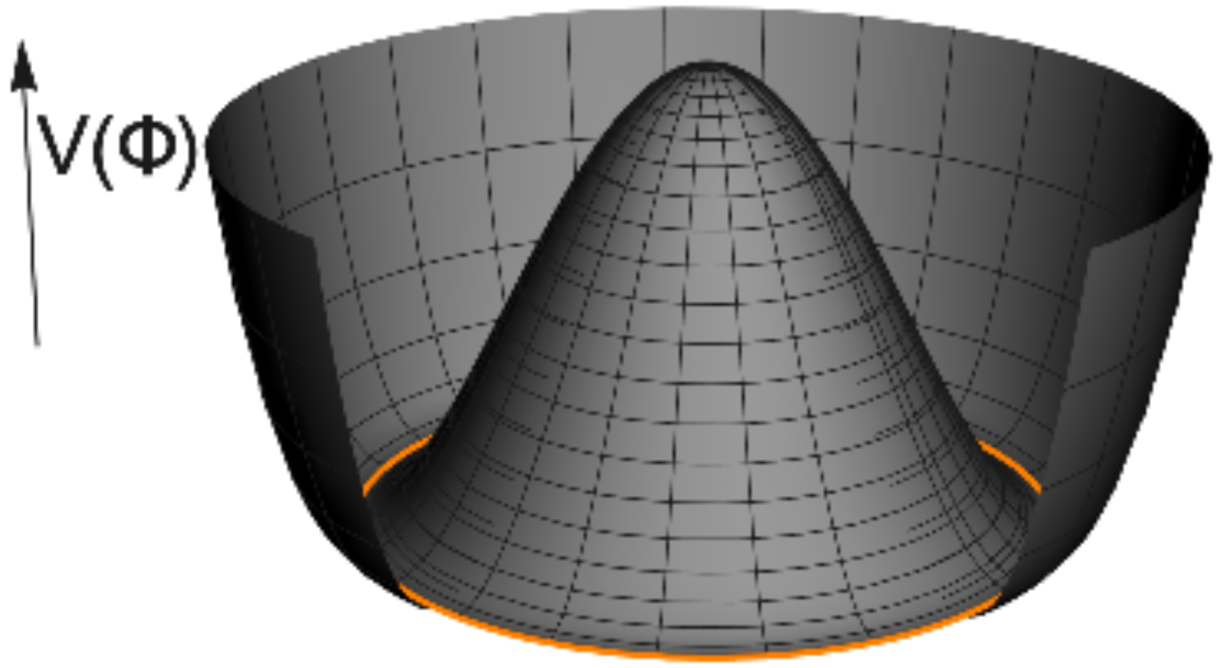
Motivation for ALPs

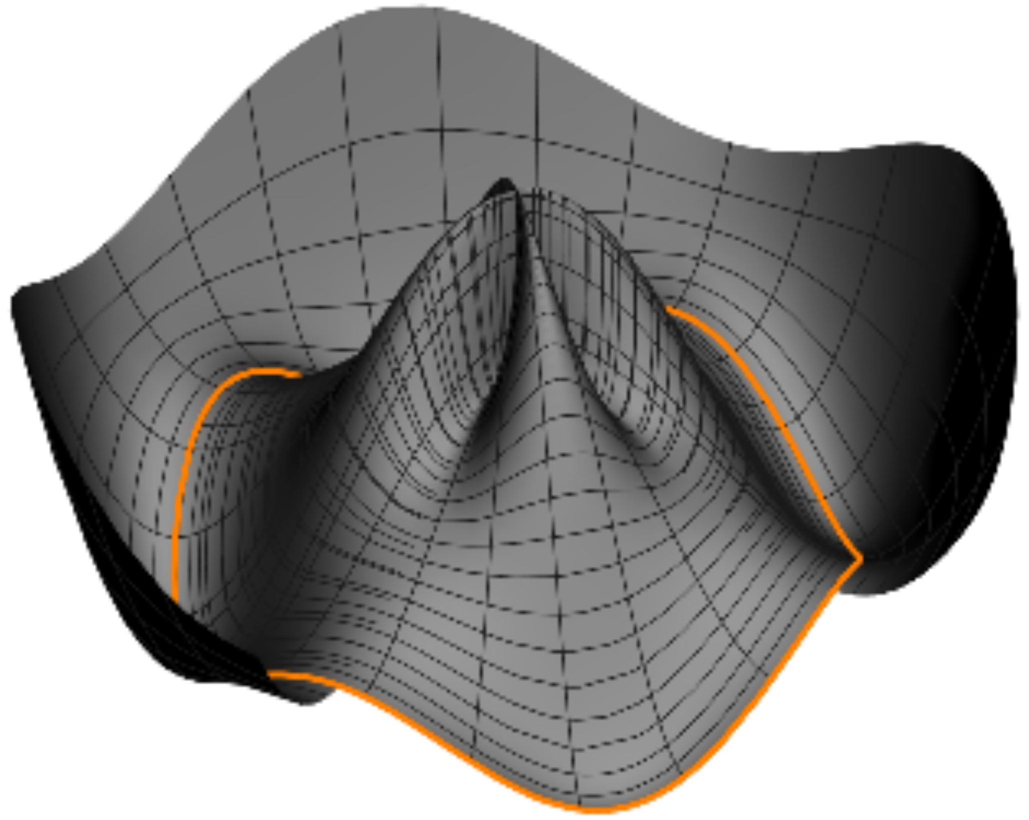
Axions and axion-like particles (ALPs) are well motivated theoretically:

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

$$\mathcal{L} = \frac{\theta \alpha_s}{8\pi}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} + \frac{a}{f_a}\,\frac{\alpha_s}{8\pi}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} + \dots$$

- introduce scalar field $\Phi = |\Phi|\, e^{ia/f_a}$ charged under a new $U(1)_{PQ}$
- QCD instantons break the continuous shift symmetry to a discrete subgroup:





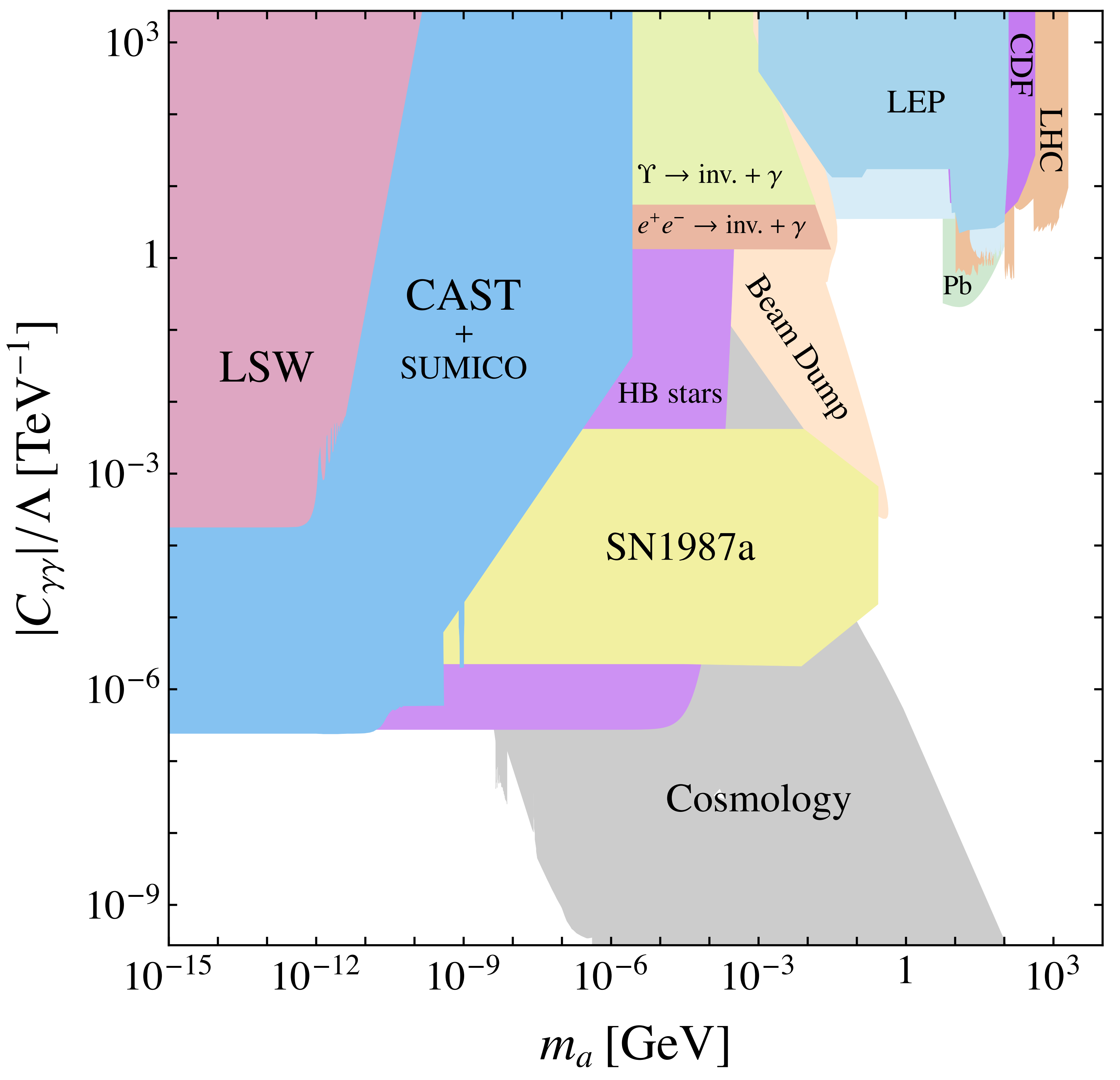
minimum has $\theta + \langle a \rangle / f_a = 0$ modulo 2π

⇒ generates an ALP mass!

Motivation for ALPs

Axions and axion-like particles (ALPs) are well motivated theoretically:

- Peccei-Quinn solution to strong CP problem
- more generally: ALPs as pseudo Nambu-Goldstone bosons of a spontaneously broken global symmetry
- light ALPs can be promising Dark Matter candidates or mediators to the dark sector
- low-energy processes are important in constraining the ALP couplings to the SM fields



[Bauer, MN, Thamm (2017)]

Effective ALP Lagrangian

- Assume the scale of global symmetry breaking $\Lambda = 4\pi f$ is above the weak scale, and consider the most general effective Lagrangian for a pseudoscalar boson a coupled to the SM via classically shift-invariant interactions, broken only by a soft mass term: [Georgi, Kaplan, Randall (1986)]

hermitian matrices

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

- Couplings to Higgs bosons arise in higher orders only: [Dobrescu, Landsberg, Matchev (2000); Bauer, MN, Thamm (2017)]

$$\mathcal{L}_{\text{eff}}^{D\ge 6} = \frac{C_{ah}}{f^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C'_{ah}}{f^2}\,m_{a,0}^2\,a^2\phi^\dagger\phi + \ \dots$$

Effective ALP Lagrangian

A useful alternative form of the Lagrangian involves non-derivative couplings:

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 - \frac{a}{f}\left(\bar{Q}\,\phi\,\tilde{\boldsymbol{Y}}_d\,d_R + \bar{Q}\,\tilde{\phi}\,\tilde{\boldsymbol{Y}}_u\,u_R + \bar{L}\,\phi\,\tilde{\boldsymbol{Y}}_e\,e_R + \text{h.c.}\right)$$

$$+\; C_{GG}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W_{\mu\nu}^I\,\tilde{W}^{\mu\nu,I} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

[Bauer, MN, Renner, Schnubel, Thamm (2020)]

where:

$$\tilde{\boldsymbol{Y}}_d = i\left(\boldsymbol{Y}_d\,\boldsymbol{c}_d - \boldsymbol{c}_Q\,\boldsymbol{Y}_d\right), \qquad \tilde{\boldsymbol{Y}}_u = i\left(\boldsymbol{Y}_u\,\boldsymbol{c}_u - \boldsymbol{c}_Q\,\boldsymbol{Y}_u\right), \qquad \tilde{\boldsymbol{Y}}_e = i\left(\boldsymbol{Y}_e\,\boldsymbol{c}_e - \boldsymbol{c}_L\,\boldsymbol{Y}_e\right)$$

$$C_{GG} = \frac{\alpha_s}{4\pi}\left[c_{GG} + \frac{1}{2}\,\text{Tr}\left(\boldsymbol{c}_d + \boldsymbol{c}_u - 2\,\boldsymbol{c}_Q\right)\right]$$

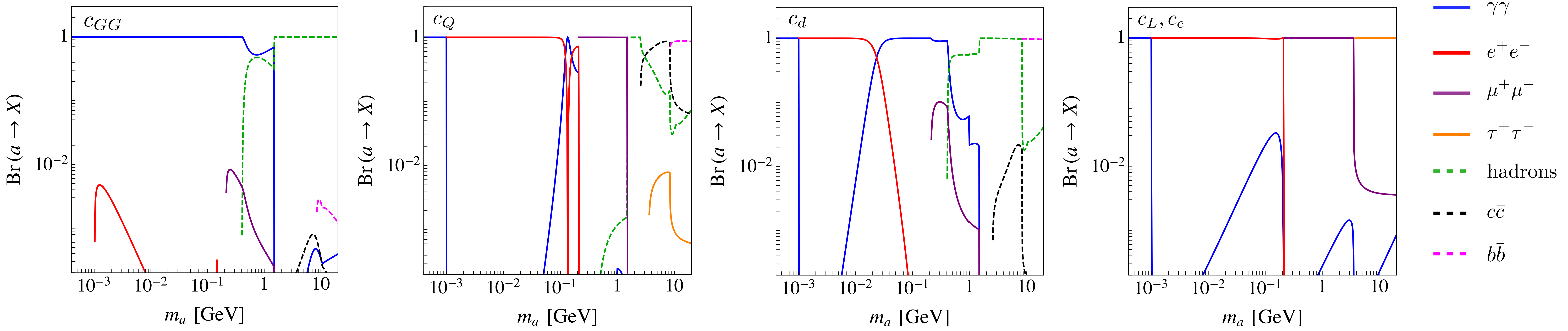
$$C_{WW} = \frac{\alpha_2}{4\pi}\left[c_{WW} - \frac{1}{2}\,\text{Tr}\left(N_c\,\boldsymbol{c}_Q + \boldsymbol{c}_L\right)\right]$$

$$C_{BB} = \frac{\alpha_1}{4\pi}\left[c_{BB} + \text{Tr}\left[N_c\left(\mathcal{Y}_d^2\,\boldsymbol{c}_d + \mathcal{Y}_u^2\,\boldsymbol{c}_u - 2\,\mathcal{Y}_Q^2\,\boldsymbol{c}_Q\right) + \mathcal{Y}_e^2\,\boldsymbol{c}_e - 2\,\mathcal{Y}_L^2\,\boldsymbol{c}_L\right]\right]$$

Effective ALP Lagrangian

Direct searches for ALPs are strongly model dependent:

- sensitivity to many different ALP couplings entering the production, decay and lifetime of the ALP
- branching fractions assuming a single non-zero coupling at $\Lambda = 4\pi f$, with $f = 1$ TeV:



[Bauer, MN, Renner, Schnubel, Thamm (2021)]

Effective ALP Lagrangian

Direct searches for ALPs are strongly model dependent:

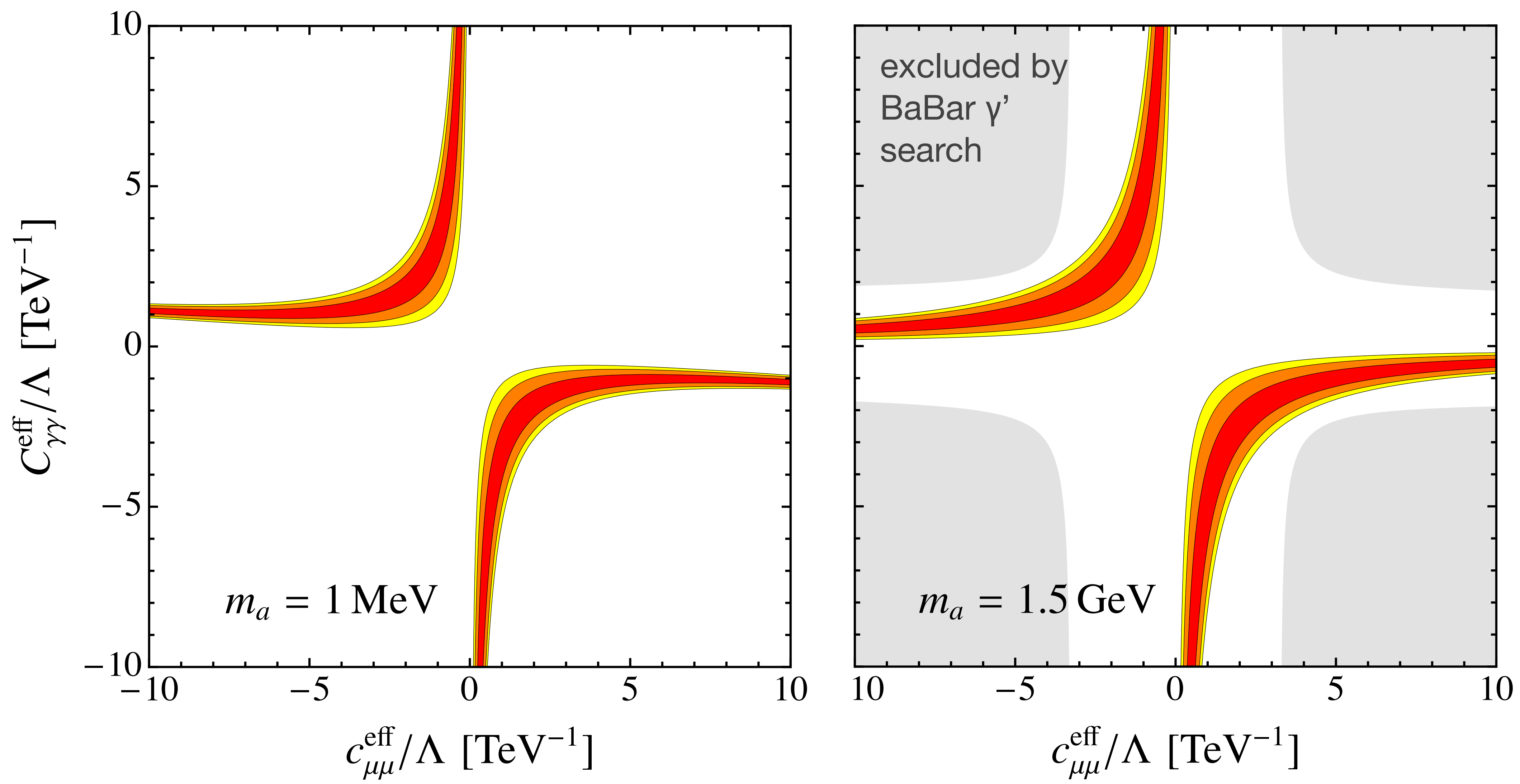
- sensitivity to many different ALP couplings entering the production, decay and lifetime of the ALP
- searches probe high-dimensional parameter spaces ⇒ need for strong model assumptions, e.g. existence of a single non-zero ALP coupling (strong biases)
- long-lived ALPs and ALPs decaying into hadrons or heavy fermions can escape detection

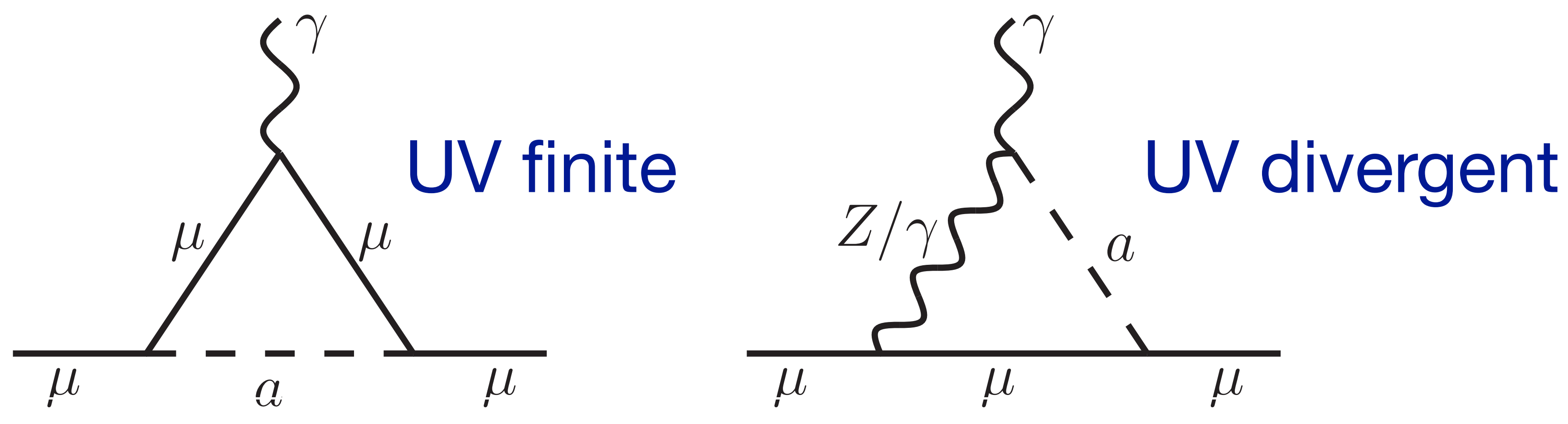
Indirect searches (effects of virtual ALPs) offer a promising alternative!

ALP—SMEFT interference

It is well-known that one-loop diagrams with virtual ALP exchange can be UV divergent. This was first studied in the context of $(g-2)_\mu$:

[Marciano, Masiero, Paradisi, Passera (2016); Bauer, MN, Thamm (2017)]





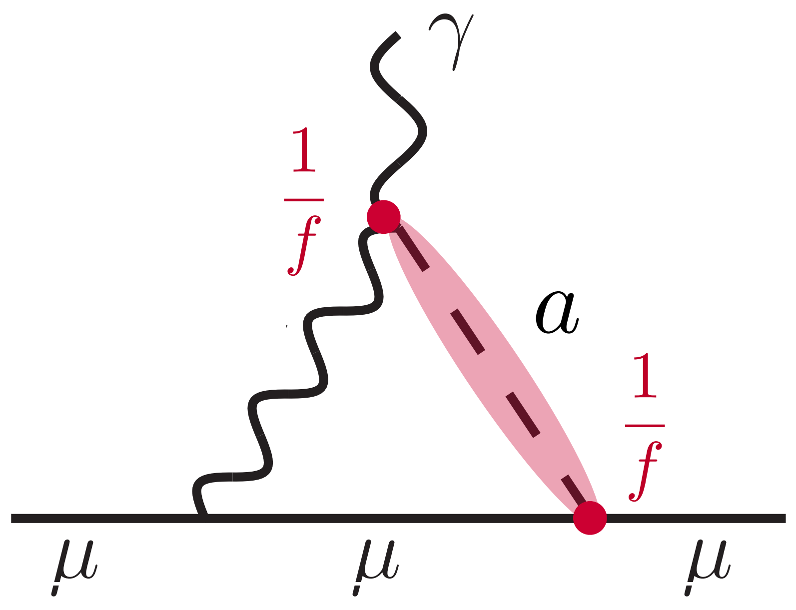
$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} + \delta_2 + 3 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right]\right.$$
$$\left. - \frac{\alpha}{2\pi}\,\frac{1-4s_w^2}{s_w c_w}\,c_{\mu\mu}\,C_{\gamma Z}\left(\ln\frac{\mu^2}{m_Z^2} + \delta_2 + \frac{3}{2}\right)\right\}$$

needs a D=6 counterterm not contained in the ALP effective Lagrangian

$(\Lambda = 4\pi f)$

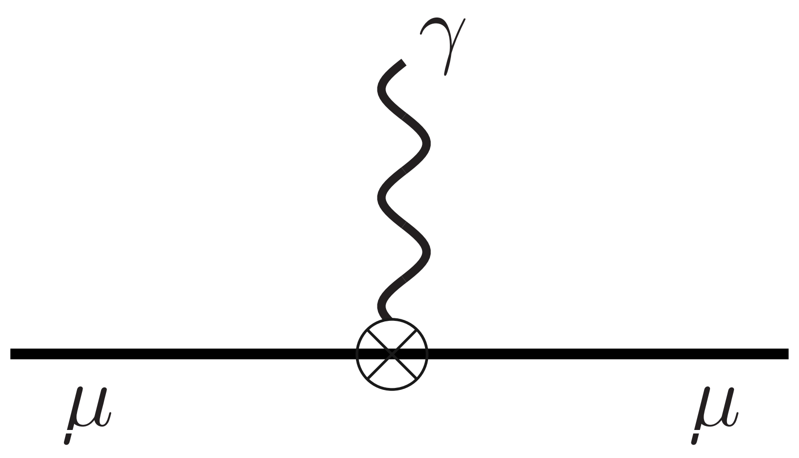
ALP—SMEFT interference

Schematically:



$(g-2)_\mu$

$$\longrightarrow \frac{1}{f^2}\ln\frac{(4\pi f)^2}{m_a^2}\times$$



SMEFT

Consistent effective field theory:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{f}\,\mathcal{L}_{\text{ALP}}^{(D\geq 5)} + \frac{1}{f^2}\,\mathcal{L}_{\text{SMEFT}}^{(D\geq 6)}$$

direct searches (↑ $\mathcal{L}_{\text{ALP}}^{(D\geq 5)}$) — indirect searches (↑ $\mathcal{L}_{\text{SMEFT}}^{(D\geq 6)}$)

ALP—SMEFT interference

Irrespective of the existence of other new physics, the presence of a light ALP provides source terms S_i for the D=6 SMEFT Wilson coefficients:

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

[Galda, MN, Renner (2021)]

2499 x 2499 entries

ALP source terms

- Global new-physics searches using SMEFT can serve as indirect probes of the ALP couplings
- **Exciting prospect: constrain all ALP couplings in a model-independent way, insensitive to the ALP lifetime and branching fractions!**

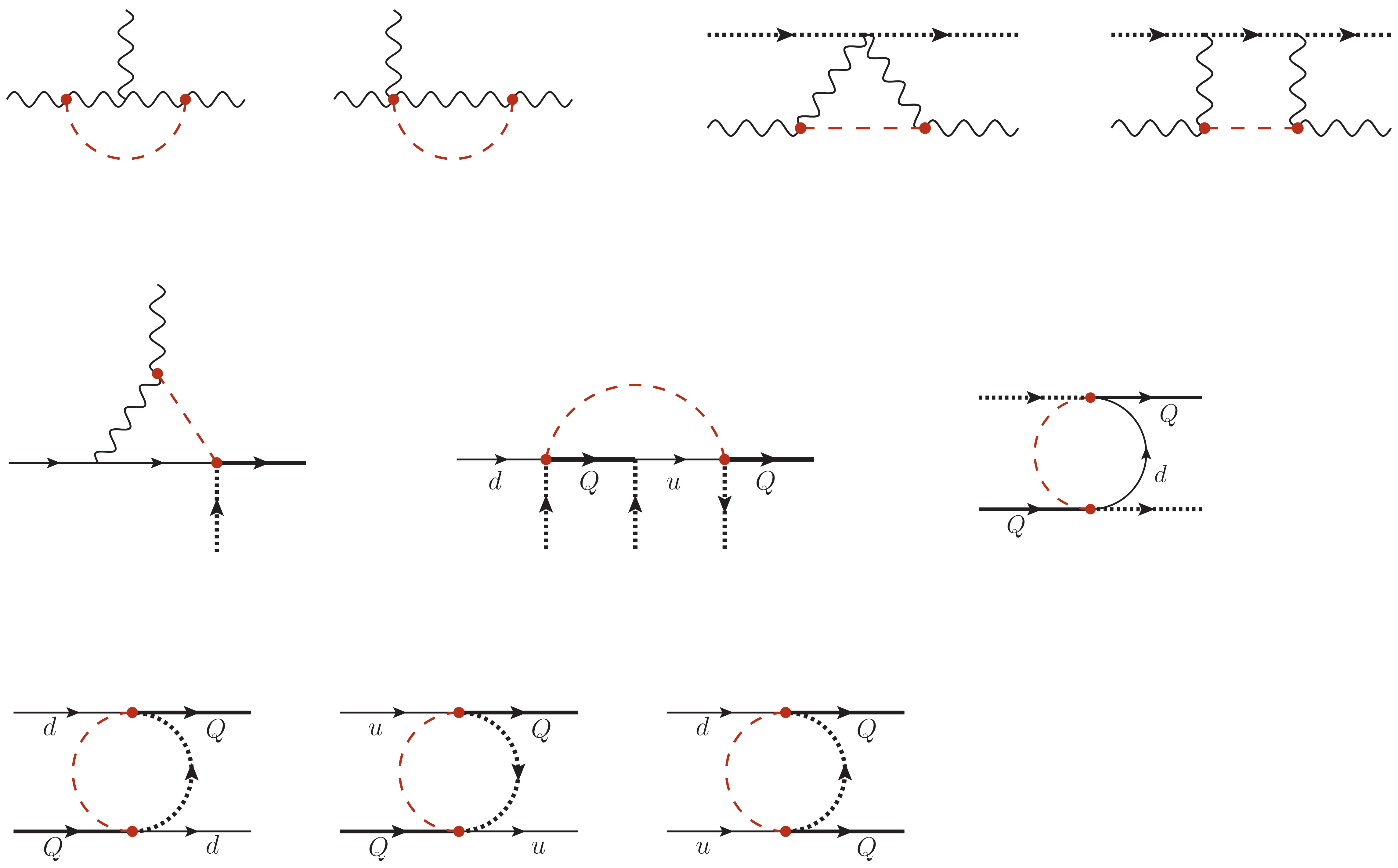
ALP—SMEFT interference

Systematic study of divergent Green's functions with ALP exchange

[Galda, MN, Renner (2021)]

Operator class	Warsaw basis	Way of generation	
Purely bosonic			
X^3	yes	direct	—
X^2D^2	no	direct	
X^2H^2	yes	direct	—
XH^2D^2	no	—	
H^6	yes	—	EOM
H^4D^2	yes	—	EOM
H^2D^4	no	—	
Single fermion current			
ψ^2XD	no	—	
ψ^2D^3	no	—	
ψ^2XH	yes	direct	—
ψ^2H^3	yes	direct	EOM
ψ^2H^2D	yes	direct	EOM
ψ^2HD^2	no	—	
4-fermion operators			
$(\bar{L}L)(\bar{L}L)$	yes	—	EOM
$(\bar{R}R)(\bar{R}R)$	yes	—	EOM
$(\bar{L}L)(\bar{R}R)$	yes	direct	EOM
$(\bar{L}R)(\bar{R}L)$	yes	direct	—
$(\bar{L}R)(\bar{L}R)$	yes	direct	—
B-violating	yes	—	—

[Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]

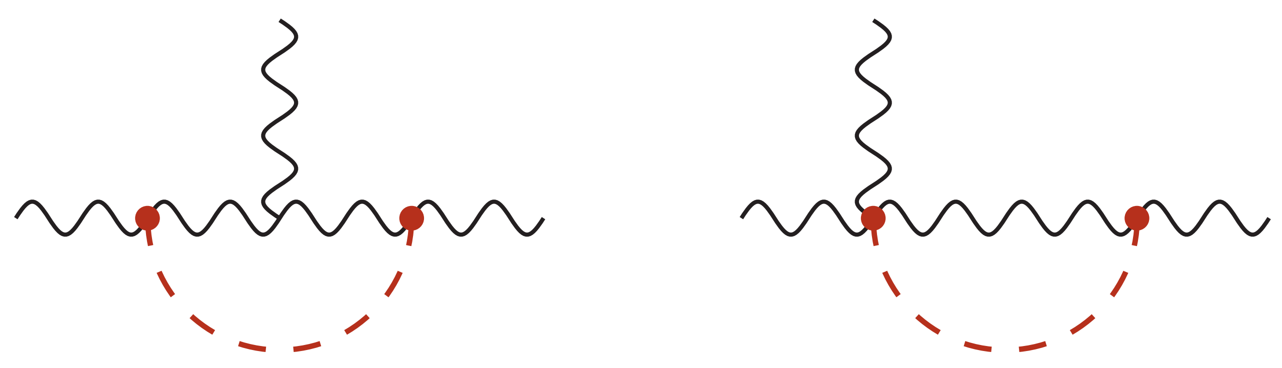


ALP—SMEFT interference

Systematic study of divergent Green's functions with ALP exchange

[Galda, MN, Renner (2021)]

Sample calculation: UV divergences of the three-gluon amplitude



$$\mathcal{A}(gg(g)) = -\frac{C_{GG}^2}{\epsilon}\left[4g_s\langle Q_G\rangle + \frac{4}{3}\langle\widehat{Q}_{G,2}\rangle - 2m_a^2\langle G_{\mu\nu}^a G^{\mu\nu,a}\rangle\right] + \text{finite}$$

Source term for Weinberg operator:

$$S_G = 8g_s C_{GG}^2$$

Eliminate redundant operator $\widehat{Q}_{G,2} = (D^\rho G_{\rho\mu})^a\,(D_\omega G^{\omega\mu})^a$ using the EOMs:

$$\widehat{Q}_{G,2} \cong g_s^2\left(\bar{Q}\gamma_\mu T^a Q + \bar{u}\gamma_\mu T^a u + \bar{d}\gamma_\mu T^a d\right)^2$$

$$= g_s^2\left[\frac{1}{4}\left([Q_{qq}^{(1)}]_{prrp} + [Q_{qq}^{(3)}]_{prrp}\right) - \frac{1}{2N_c}[Q_{qq}^{(1)}]_{pprr} + \frac{1}{2}[Q_{uu}]_{prrp} - \frac{1}{2N_c}[Q_{uu}]_{pprr} + \frac{1}{2}[Q_{dd}]_{prrp} - \frac{1}{2N_c}[Q_{dd}]_{pprr} + 2\,[Q_{qu}^{(8)}]_{pprr} + 2\,[Q_{qd}^{(8)}]_{pprr} + 2\,[Q_{ud}^{(8)}]_{pprr}\right]$$

[Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]

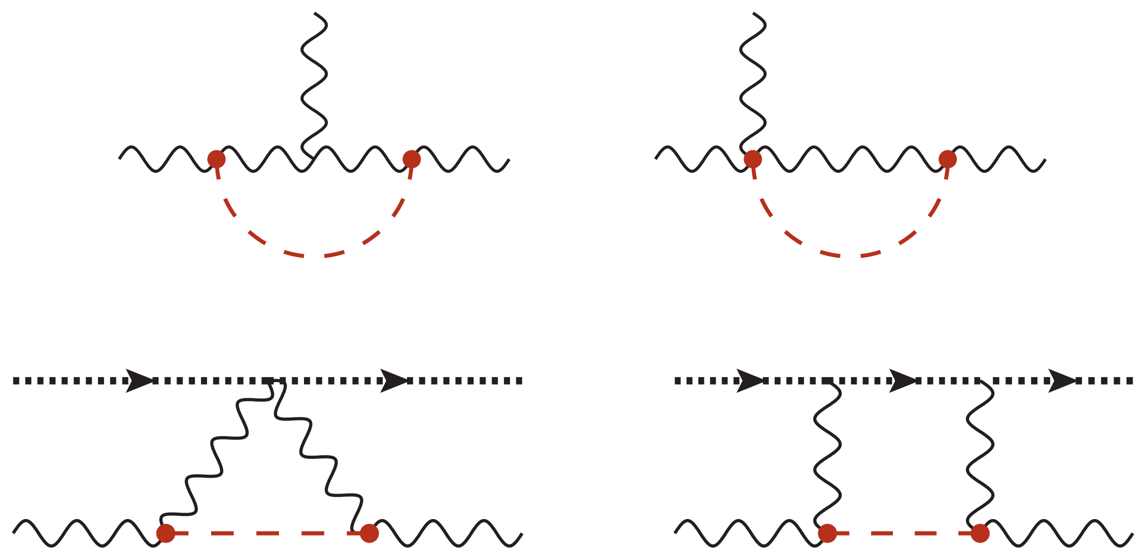
→ generates further source terms

ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
Purely bosonic			
X^3	yes	direct	—
X^2D^2	no	direct	
X^2H^2	yes	direct	—
XH^2D^2	no	—	
H^6	yes	—	EOM
H^4D^2	yes	—	EOM
H^2D^4	no	—	

[Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]



$$S_G = 8 g_s C_{GG}^2\,, \qquad S_{\widetilde{G}} = 0$$
$$S_W = 8 g_2 C_{WW}^2\,, \qquad S_{\widetilde{W}} = 0$$

$$S_{HG} = 0\,, \qquad S_{H\widetilde{G}} = 0$$
$$S_{HW} = -2 g_2^2\, C_{WW}^2\,, \qquad S_{H\widetilde{W}} = 0$$
$$S_{HB} = -2 g_1^2\, C_{BB}^2\,, \qquad S_{H\widetilde{B}} = 0$$
$$S_{HWB} = -4 g_1 g_2\, C_{WW}\, C_{BB}\,, \qquad S_{H\widetilde{W}B} = 0$$

$$S_H = \frac{8}{3}\,\lambda g_2^2\, C_{WW}^2\,,$$
$$S_{H\Box} = 2 g_2^2\, C_{WW}^2 + \frac{8}{3}\, g_1^2\, \mathcal{Y}_H^2\, C_{BB}^2$$
$$S_{HD} = \frac{32}{3}\, g_1^2\, \mathcal{Y}_H^2\, C_{BB}^2\,.$$

ALP — SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
Single fermion current			
$\psi^2 X D$	no	—	
$\psi^2 D^3$	no	—	
$\psi^2 X H$	yes	direct	—
$\psi^2 H^3$	yes	direct	EOM
$\psi^2 H^2 D$	yes	direct	EOM
$\psi^2 H D^2$	no	—	

$$\boldsymbol{S}_{eW} = -ig_2\, \widetilde{\boldsymbol{Y}}_e\, C_{WW}$$

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

$$\boldsymbol{S}_{uG} = -4ig_s\, \widetilde{\boldsymbol{Y}}_u\, C_{GG}$$

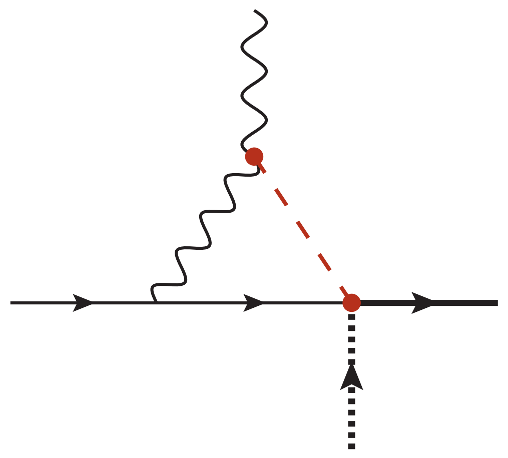
$$\boldsymbol{S}_{uW} = -ig_2\, \widetilde{\boldsymbol{Y}}_u\, C_{WW}$$

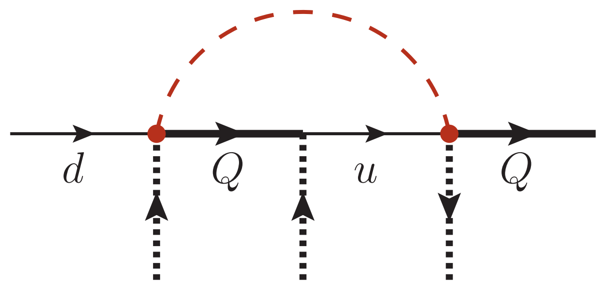
$$\boldsymbol{S}_{uB} = -2ig_1\, (\mathcal{Y}_Q + \mathcal{Y}_u)\, \widetilde{\boldsymbol{Y}}_u\, C_{BB}$$

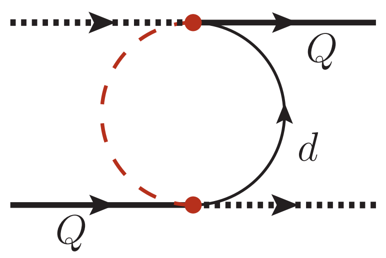
$$\boldsymbol{S}_{dG} = -4ig_s\, \widetilde{\boldsymbol{Y}}_d\, C_{GG}$$

$$\boldsymbol{S}_{dW} = -ig_2\, \widetilde{\boldsymbol{Y}}_d\, C_{WW}$$

$$\boldsymbol{S}_{dB} = -2ig_1\, (\mathcal{Y}_Q + \mathcal{Y}_d)\, \widetilde{\boldsymbol{Y}}_d\, C_{BB}$$



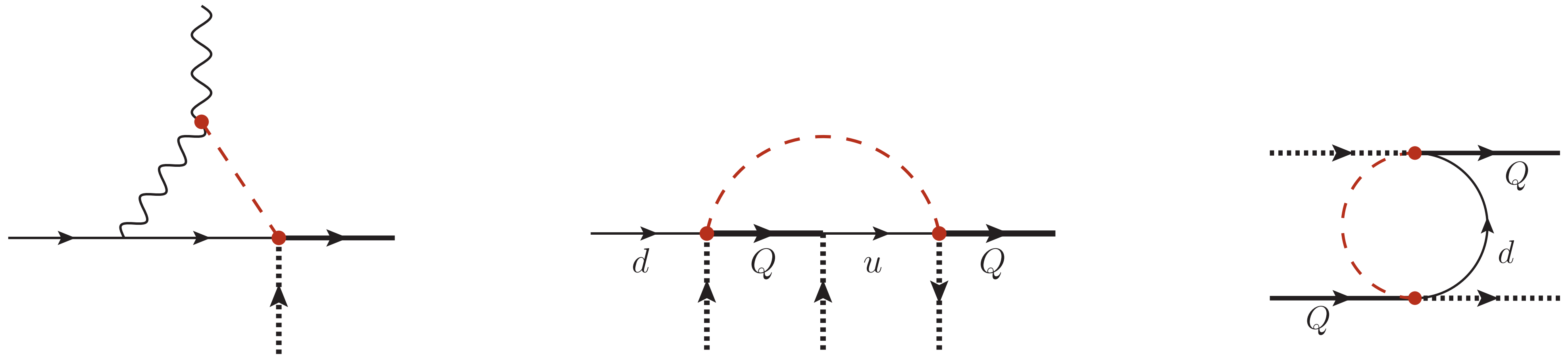




ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
Single fermion current			
$\psi^2 XD$	no	—	
$\psi^2 D^3$	no	—	
$\psi^2 XH$	yes	direct	—
$\psi^2 H^3$	yes	direct	EOM
$\psi^2 H^2 D$	yes	direct	EOM
$\psi^2 HD^2$	no	—	



$$\boldsymbol{S}_{Hl}^{(1)} = \frac{1}{4}\,\tilde{\boldsymbol{Y}}_e\tilde{\boldsymbol{Y}}_e^\dagger + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H\mathcal{Y}_L\,C_{BB}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hl}^{(3)} = \frac{1}{4}\,\tilde{\boldsymbol{Y}}_e\tilde{\boldsymbol{Y}}_e^\dagger + \frac{4}{3}\,g_2^2\,C_{WW}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{He} = -\frac{1}{2}\,\tilde{\boldsymbol{Y}}_e^\dagger\tilde{\boldsymbol{Y}}_e + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H\mathcal{Y}_e\,C_{BB}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hq}^{(1)} = \frac{1}{4}\left(\tilde{\boldsymbol{Y}}_d\tilde{\boldsymbol{Y}}_d^\dagger - \tilde{\boldsymbol{Y}}_u\tilde{\boldsymbol{Y}}_u^\dagger\right) + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H\mathcal{Y}_Q\,C_{BB}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hq}^{(3)} = \frac{1}{4}\left(\tilde{\boldsymbol{Y}}_d\tilde{\boldsymbol{Y}}_d^\dagger + \tilde{\boldsymbol{Y}}_u\tilde{\boldsymbol{Y}}_u^\dagger\right) + \frac{4}{3}\,g_2^2\,C_{WW}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hu} = \frac{1}{2}\,\tilde{\boldsymbol{Y}}_u^\dagger\tilde{\boldsymbol{Y}}_u + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H\mathcal{Y}_u\,C_{BB}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hd} = -\frac{1}{2}\,\tilde{\boldsymbol{Y}}_d^\dagger\tilde{\boldsymbol{Y}}_d + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H\mathcal{Y}_d\,C_{BB}^2\,\mathbf{1}$$

$$\boldsymbol{S}_{Hud} = -\tilde{\boldsymbol{Y}}_u^\dagger\tilde{\boldsymbol{Y}}_d$$

ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

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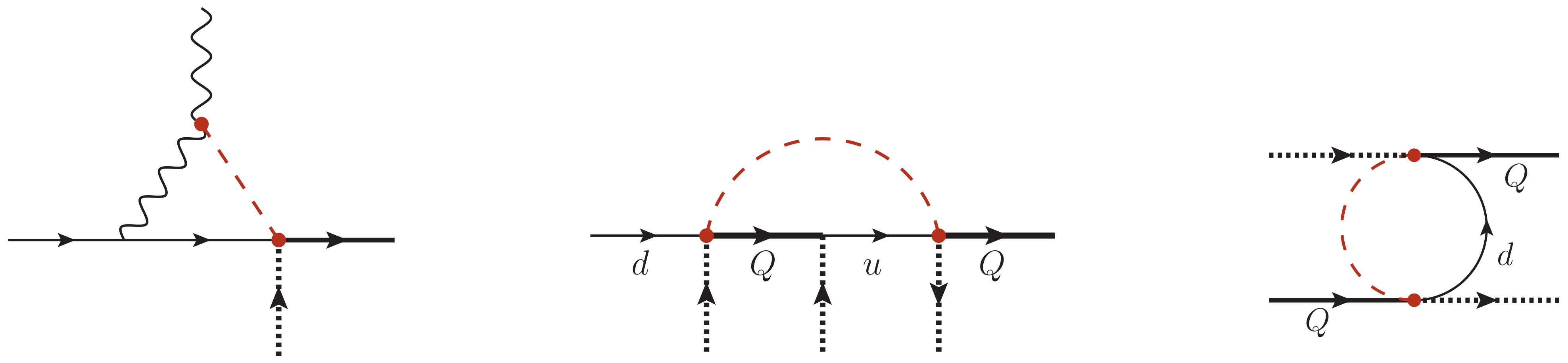
Single fermion current			
$\psi^2 XD$	no	—	
$\psi^2 D^3$	no	—	
$\psi^2 XH$	yes	direct	—
$\psi^2 H^3$	yes	direct	EOM
$\psi^2 H^2 D$	yes	direct	EOM
$\psi^2 HD^2$	no	—	

$$\boldsymbol{S}_{eH} = -2\widetilde{\boldsymbol{Y}}_e \boldsymbol{Y}_e^\dagger \widetilde{\boldsymbol{Y}}_e - \frac{1}{2}\widetilde{\boldsymbol{Y}}_e \widetilde{\boldsymbol{Y}}_e^\dagger \boldsymbol{Y}_e - \frac{1}{2}\boldsymbol{Y}_e \widetilde{\boldsymbol{Y}}_e^\dagger \widetilde{\boldsymbol{Y}}_e + \frac{4}{3} g_2^2\, C_{WW}^2\, \boldsymbol{Y}_e$$

$$\boldsymbol{S}_{uH} = -2\widetilde{\boldsymbol{Y}}_u \boldsymbol{Y}_u^\dagger \widetilde{\boldsymbol{Y}}_u - \frac{1}{2}\widetilde{\boldsymbol{Y}}_u \widetilde{\boldsymbol{Y}}_u^\dagger \boldsymbol{Y}_u - \frac{1}{2}\boldsymbol{Y}_u \widetilde{\boldsymbol{Y}}_u^\dagger \widetilde{\boldsymbol{Y}}_u + \frac{4}{3} g_2^2\, C_{WW}^2\, \boldsymbol{Y}_u$$

$$\boldsymbol{S}_{dH} = -2\widetilde{\boldsymbol{Y}}_d \boldsymbol{Y}_d^\dagger \widetilde{\boldsymbol{Y}}_d - \frac{1}{2}\widetilde{\boldsymbol{Y}}_d \widetilde{\boldsymbol{Y}}_d^\dagger \boldsymbol{Y}_d - \frac{1}{2}\boldsymbol{Y}_d \widetilde{\boldsymbol{Y}}_d^\dagger \widetilde{\boldsymbol{Y}}_d + \frac{4}{3} g_2^2\, C_{WW}^2\, \boldsymbol{Y}_d$$



ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
4-fermion operators			
$(\bar{L}L)(\bar{L}L)$	yes	—	EOM
$(\bar{R}R)(\bar{R}R)$	yes	—	EOM
$(\bar{L}L)(\bar{R}R)$	yes	direct	EOM
$(\bar{L}R)(\bar{R}L)$	yes	direct	—
$(\bar{L}R)(\bar{L}R)$	yes	direct	—
B-violating	yes	—	—

$$\big[S_{ll}\big]_{prst} = \frac{2}{3}\, g_2^2\, C_{WW}^2\, (2\delta_{pt}\,\delta_{sr} - \delta_{pr}\,\delta_{st}) + \frac{8}{3}\, g_1^2\, \mathcal{Y}_L^2\, C_{BB}^2\, \delta_{pr}\,\delta_{st}$$

$$\big[S_{qq}^{(1)}\big]_{prst} = \frac{2}{3}\, g_s^2\, C_{GG}^2 \left(\delta_{pt}\,\delta_{sr} - \frac{2}{N_c}\,\delta_{pr}\,\delta_{st}\right) + \frac{8}{3}\, g_1^2\, \mathcal{Y}_Q^2\, C_{BB}^2\, \delta_{pr}\,\delta_{st}$$

$$\big[S_{qq}^{(3)}\big]_{prst} = \frac{2}{3}\, g_s^2\, C_{GG}^2\, \delta_{pt}\,\delta_{sr} + \frac{2}{3}\, g_2^2\, C_{WW}^2\, \delta_{pr}\,\delta_{st}$$

$$\big[S_{lq}^{(1)}\big]_{prst} = \frac{16}{3}\, g_1^2\, \mathcal{Y}_L\, \mathcal{Y}_Q\, C_{BB}^2\, \delta_{pr}\,\delta_{st}$$

$$\big[S_{lq}^{(3)}\big]_{prst} = \frac{4}{3}\, g_2^2\, C_{WW}^2\, \delta_{pr}\,\delta_{st}$$

ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

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4-fermion operators			
$(\bar{L}L)(\bar{L}L)$	yes	—	EOM
$(\bar{R}R)(\bar{R}R)$	yes	—	EOM
$(\bar{L}L)(\bar{R}R)$	yes	direct	EOM
$(\bar{L}R)(\bar{R}L)$	yes	direct	—
$(\bar{L}R)(\bar{L}R)$	yes	direct	—
B-violating	yes	—	—

$$[S_{ee}]_{prst} = \frac{8}{3}\, g_1^2\, \mathcal{Y}_e^2\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

$$[S_{uu}]_{prst} = \frac{4}{3}\, g_s^2\, C_{GG}^2 \left(\delta_{pt}\, \delta_{sr} - \frac{1}{N_c}\, \delta_{pr}\, \delta_{st} \right) + \frac{8}{3}\, g_1^2\, \mathcal{Y}_u^2\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

$$[S_{dd}]_{prst} = \frac{4}{3}\, g_s^2\, C_{GG}^2 \left(\delta_{pt}\, \delta_{sr} - \frac{1}{N_c}\, \delta_{pr}\, \delta_{st} \right) + \frac{8}{3}\, g_1^2\, \mathcal{Y}_d^2\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

$$[S_{eu}]_{prst} = \frac{16}{3}\, g_1^2\, \mathcal{Y}_e \mathcal{Y}_u\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

$$[S_{ed}]_{prst} = \frac{16}{3}\, g_1^2\, \mathcal{Y}_e \mathcal{Y}_d\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

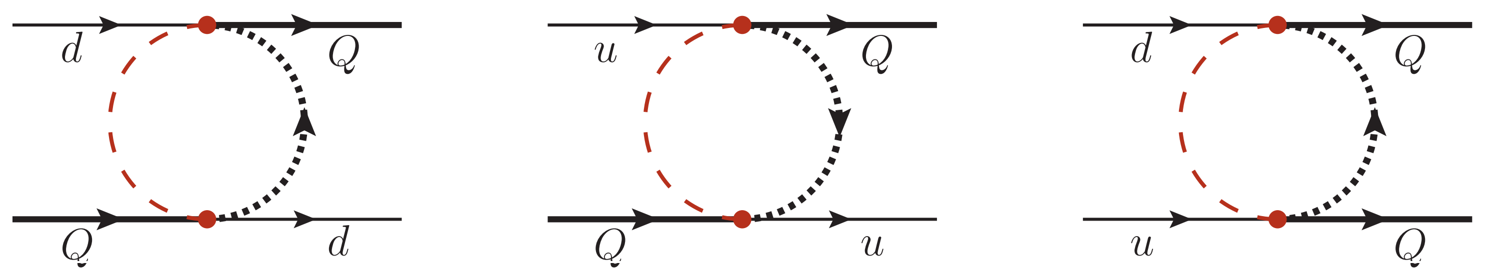
$$[S_{ud}^{(1)}]_{prst} = \frac{16}{3}\, g_1^2\, \mathcal{Y}_u \mathcal{Y}_d\, C_{BB}^2\, \delta_{pr}\, \delta_{st}$$

$$[S_{ud}^{(8)}]_{prst} = \frac{16}{3}\, g_s^2\, C_{GG}^2\, \delta_{pr}\, \delta_{st}$$

ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
4-fermion operators			
$(\bar{L}L)(\bar{L}L)$	yes	—	EOM
$(\bar{R}R)(\bar{R}R)$	yes	—	EOM
$(\bar{L}L)(\bar{R}R)$	yes	direct	EOM
$(\bar{L}R)(\bar{R}L)$	yes	direct	—
$(\bar{L}R)(\bar{L}R)$	yes	direct	—
B-violating	yes	—	—



$$[S_{le}]_{prst} = \big(\tilde{\boldsymbol{Y}}_e\big)_{pt}\big(\tilde{\boldsymbol{Y}}_e^\dagger\big)_{sr} + \frac{16}{3}\,g_1^2\,\mathcal{Y}_L\mathcal{Y}_e\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$[S_{lu}]_{prst} = \frac{16}{3}\,g_1^2\,\mathcal{Y}_L\mathcal{Y}_u\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$[S_{ld}]_{prst} = \frac{16}{3}\,g_1^2\,\mathcal{Y}_L\mathcal{Y}_d\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$[S_{qe}]_{prst} = \frac{16}{3}\,g_1^2\,\mathcal{Y}_Q\mathcal{Y}_e\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$\big[S_{qu}^{(1)}\big]_{prst} = \frac{1}{N_c}\big(\tilde{\boldsymbol{Y}}_u\big)_{pt}\big(\tilde{\boldsymbol{Y}}_u^\dagger\big)_{sr} + \frac{16}{3}\,g_1^2\,\mathcal{Y}_Q\mathcal{Y}_u\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$\big[S_{qu}^{(8)}\big]_{prst} = 2\big(\tilde{\boldsymbol{Y}}_u\big)_{pt}\big(\tilde{\boldsymbol{Y}}_u^\dagger\big)_{sr} + \frac{16}{3}\,g_s^2\,C_{GG}^2\,\delta_{pr}\,\delta_{st}$$

$$\big[S_{qd}^{(1)}\big]_{prst} = \frac{1}{N_c}\big(\tilde{\boldsymbol{Y}}_d\big)_{pt}\big(\tilde{\boldsymbol{Y}}_d^\dagger\big)_{sr} + \frac{16}{3}\,g_1^2\,\mathcal{Y}_Q\mathcal{Y}_d\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

$$\big[S_{qd}^{(8)}\big]_{prst} = 2\big(\tilde{\boldsymbol{Y}}_d\big)_{pt}\big(\tilde{\boldsymbol{Y}}_d^\dagger\big)_{sr} + \frac{16}{3}\,g_s^2\,C_{GG}^2\,\delta_{pr}\,\delta_{st}$$

ALP—SMEFT interference

One-loop results for the ALP source terms in the Warsaw basis:

Operator class	Warsaw basis	Way of generation	
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$(\bar{R}R)(\bar{R}R)$	yes	—	EOM
$(\bar{L}L)(\bar{R}R)$	yes	direct	EOM
$(\bar{L}R)(\bar{R}L)$	yes	direct	—
$(\bar{L}R)(\bar{L}R)$	yes	direct	—
B-violating	yes	—	—

$$\big[S_{ledq}\big]_{prst} = -2\big(\tilde{\boldsymbol{Y}}_e\big)_{pr}\big(\tilde{\boldsymbol{Y}}_d^\dagger\big)_{st}$$

$$\big[S_{quqd}^{(1)}\big]_{prst} = -2\big(\tilde{\boldsymbol{Y}}_u\big)_{pr}\big(\tilde{\boldsymbol{Y}}_d\big)_{st}$$

$$\big[S_{quqd}^{(8)}\big]_{prst} = 0 \quad \text{(starts at 2 loops)}$$

$$\big[S_{lequ}^{(1)}\big]_{prst} = 2\big(\tilde{\boldsymbol{Y}}_e\big)_{pr}\big(\tilde{\boldsymbol{Y}}_u\big)_{st}$$

$$\big[S_{lequ}^{(3)}\big]_{prst} = 0 \quad \text{(starts at 2 loops)}$$

With very few exceptions, all operators in the Warsaw basis are generated at one-loop order in the ALP model!

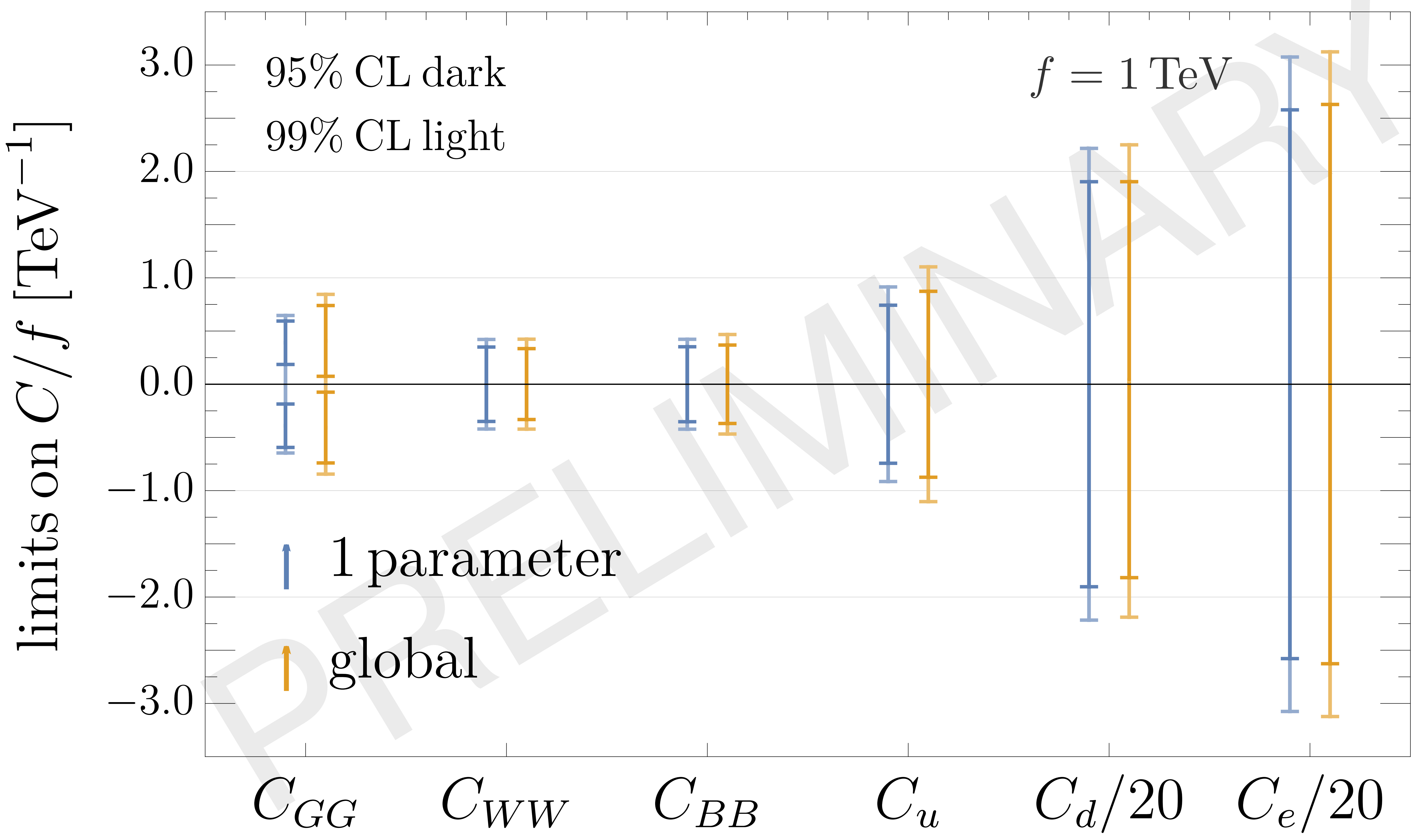
ALP constraints from SMEFT fits

Assuming the SM plus a light ALP (and nothing else), **model-independent** constraints on ALP couplings can be derived from global SMEFT fits using data on electroweak precision observables, top physics, Higgs physics, and low-energy precision measurements

- have implemented the ALP source terms in the RGEs for the D=6 SMEFT operators in DsixTools, running from $\Lambda = 4\pi f$ down to the scale of the measurements
- perform leading-log resummation in all couplings, combined with tree-level matrix elements
- Caveat: neglect matching corrections at the scale Λ, which would require a concrete UV completion of the ALP model

ALP constraints from SMEFT fits

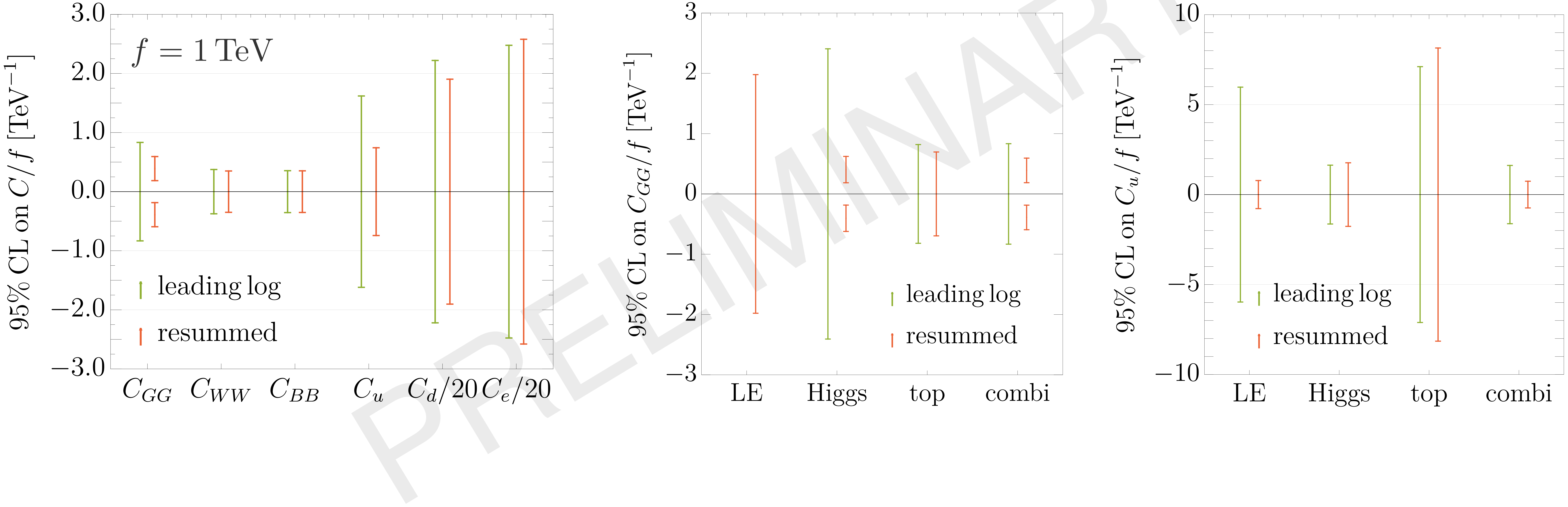
95% CL (dark) and 99% CL (light) limits on ALP couplings from an individual fit (blue) and a global analysis marginalizing over the remaining parameters (orange): [Biekötter, Fuentes-Martín, Galda, MN: to appear]



ALP constraints from SMEFT fits

Limits on ALP couplings obtained using the leading-log approximation (green) vs. the full one-loop RG evolution (red):

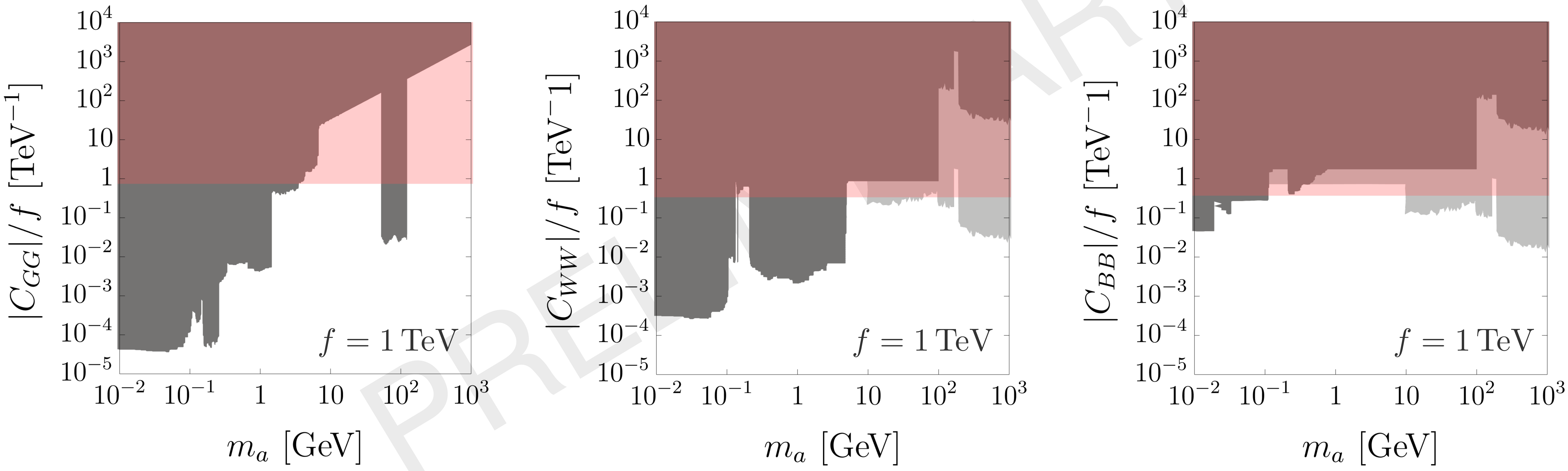
[Biekötter, Fuentes-Martín, Galda, MN: to appear]



ALP constraints from SMEFT fits

Indirect 95% CLM limits on ALP—boson couplings from ALP-SMEFT interference (red) compared to **highly model-dependent** direct bounds from flavor, beam-dump and collider experiments as well as supernova data. **Direct bounds assume all other couplings to be zero.** The light grey region is obtained from bounds on the ALP-photon coupling and assumes a 100% $a \to \gamma\gamma$ branching ratio:

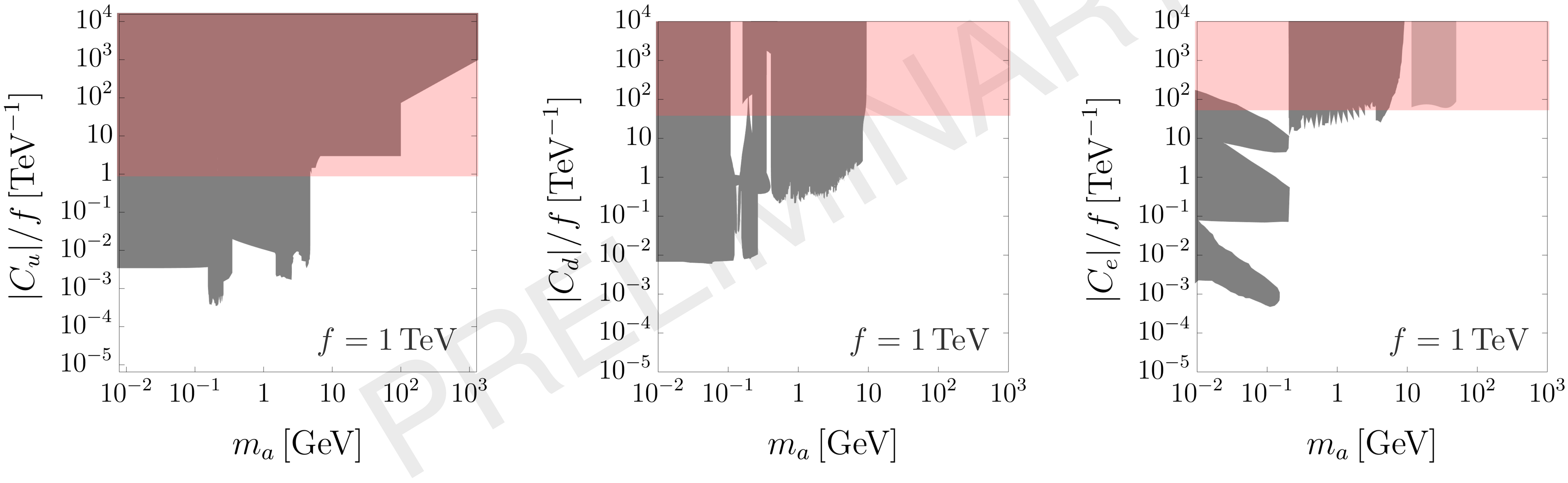
[Biekötter, Fuentes-Martín, Galda, MN: to appear]



ALP constraints from SMEFT fits

Indirect 95% CLM limits on ALP—fermion couplings from ALP-SMEFT interference (red) compared to **highly model-dependent** direct bounds from flavor, beam-dump and collider experiments as well as supernova data. **Direct bounds assume all other couplings to be zero.** The light grey region is obtained from bounds on the ALP-photon coupling and assumes a 100% $a \to \gamma\gamma$ branching ratio:

[Biekötter, Fuentes-Martín, Galda, MN: to appear]



Summary

- Axions and axion-like particles belong to a class of BSM particles which interact via higher-dimensional operators with the SM
- They are an interesting target for searches in high-energy physics, using flavor, collider and precision probes; however direct searches are strongly model dependent
- Even a light ALP provides source terms for (almost) all D=6 SMEFT operators: **ALP-SMEFT interference**
- Indirect searches thus provide a complementary way to constrain ALP couplings using global fits to precision data