ALP—SMEFT Interference

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based on work with Anne Galda & Sophie Renner
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Workshop on the Standard Model and Beyond
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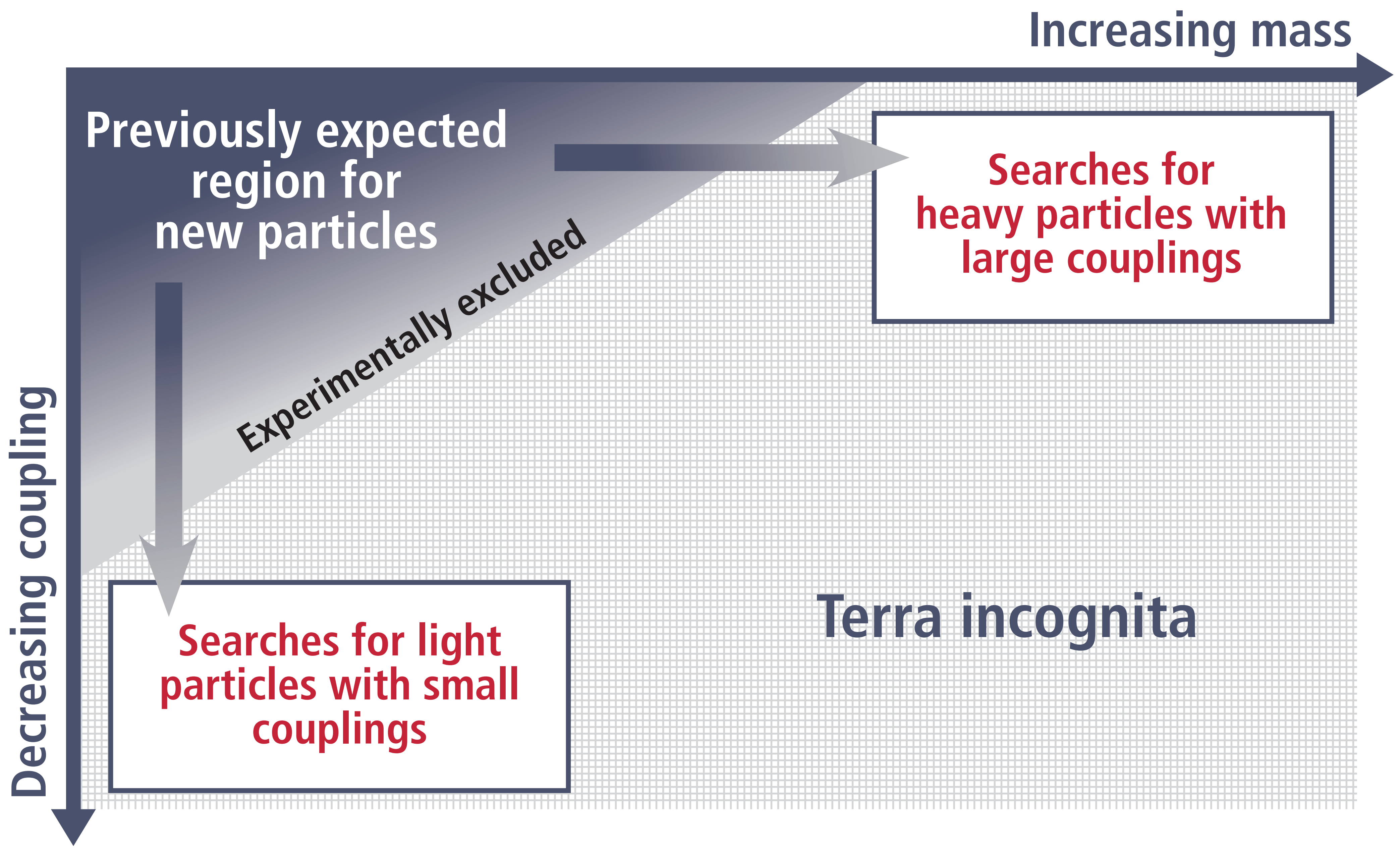
Mainz Institute for Theoretical Physics

remembering Graham Ross

Introduction

- SMEFT offers a systematic framework for describing the effects of **heavy new physics** on “low-energy” observables involving SM particles only
- Assumes the SM gauge group and electroweak symmetry breaking hold up to some high scale $\Lambda_{\rm UV} \gg v_{\rm EWSB}$
- But what if the SM is extended by a light new particle with feeble interactions with SM fields?



Introduction

- Are there any implications for SMEFT if the SM is extended by a weakly coupled light new particle and nothing else?
- If the new particle is described by a renormalizable Lagrangian ($D \le 4$ operators), the answer is NO:
  - for observables involving SM fields only, the effects of the new particle can be absorbed into the renormalized parameters of the SM Lagrangian
  - 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

Introduction

- The situation described above 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!
- Most important example:

Axions and axion-like particles

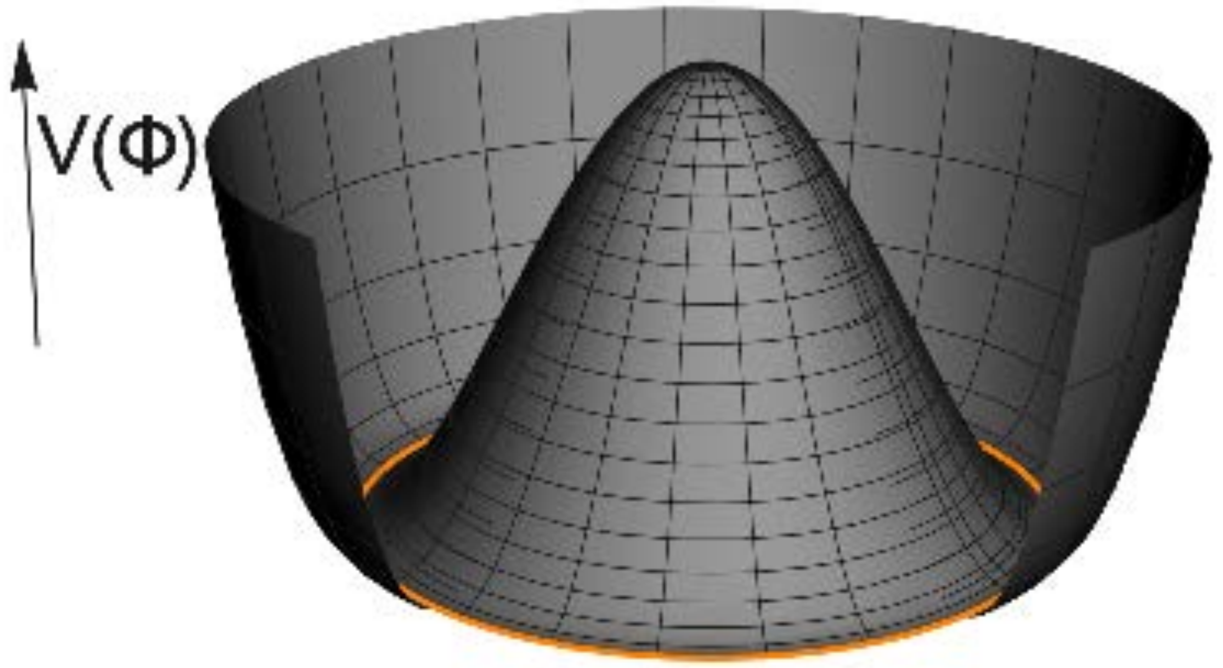
Motivation for ALPs

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

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

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

- introduce scalar field $\Phi = \left|\Phi\right| e^{ia/f_a}$ charged under a new U(1)$_{\text{PQ}}$
- field gets a VEV from spontaneous symmetry breaking:



shift symmetry: $a \to a + \text{const.}$

Motivation for ALPs

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

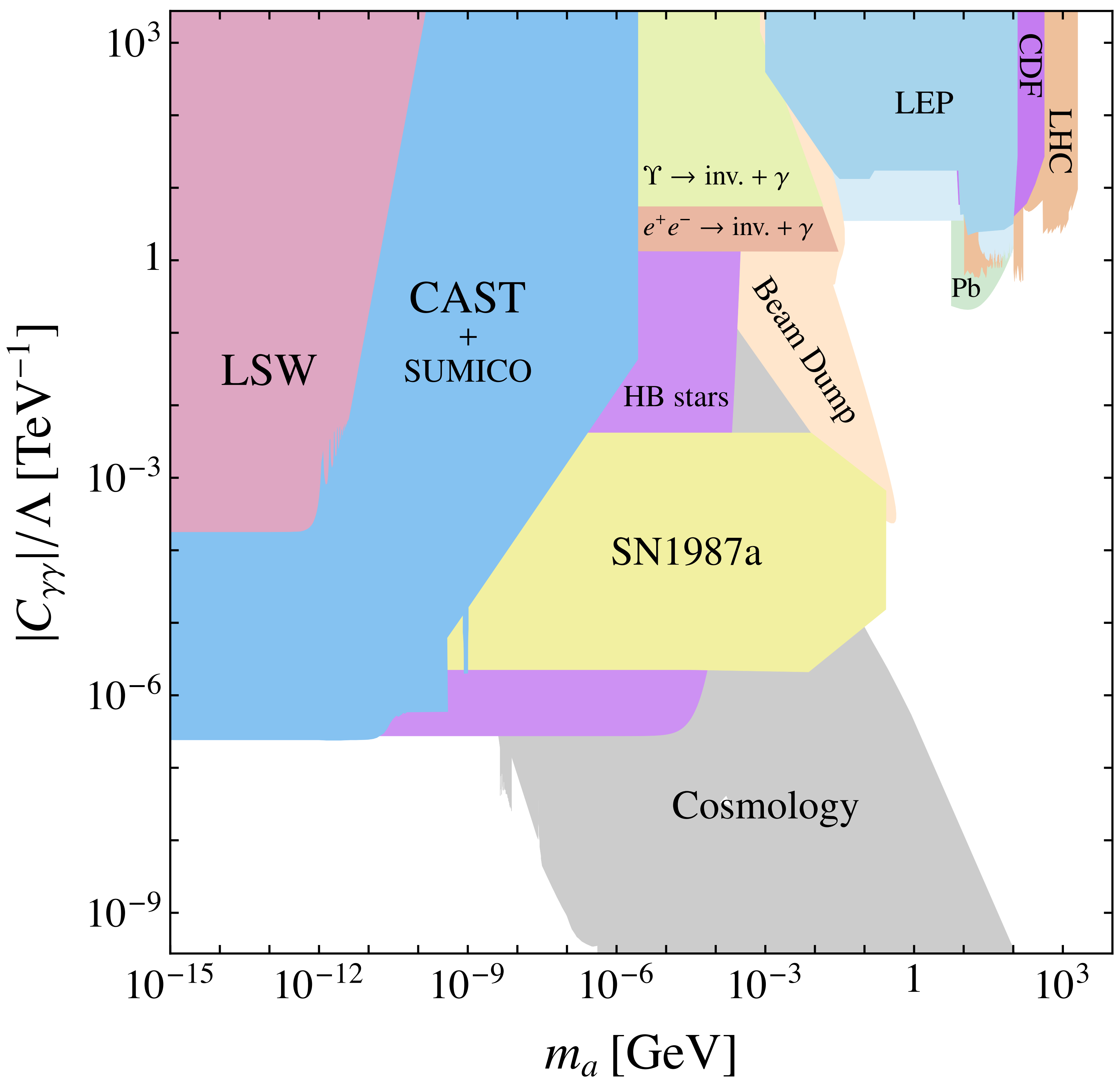
minimum has $\theta + \langle a\rangle/f_a = 0$ modulo 2π

⇒ 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

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F$$

$$+\,c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}$$

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

$$\mathcal{L}_{\rm eff}^{D\ge 6} = \frac{C_{ah}}{f^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{ah}'}{f^2}\,m_{a,0}^2\,a^2\phi^\dagger\phi + \frac{C_{Zh}}{f^3}\,(\partial^\mu a)\left(\phi^\dagger\,iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

Effective ALP Lagrangian

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

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

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

[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:

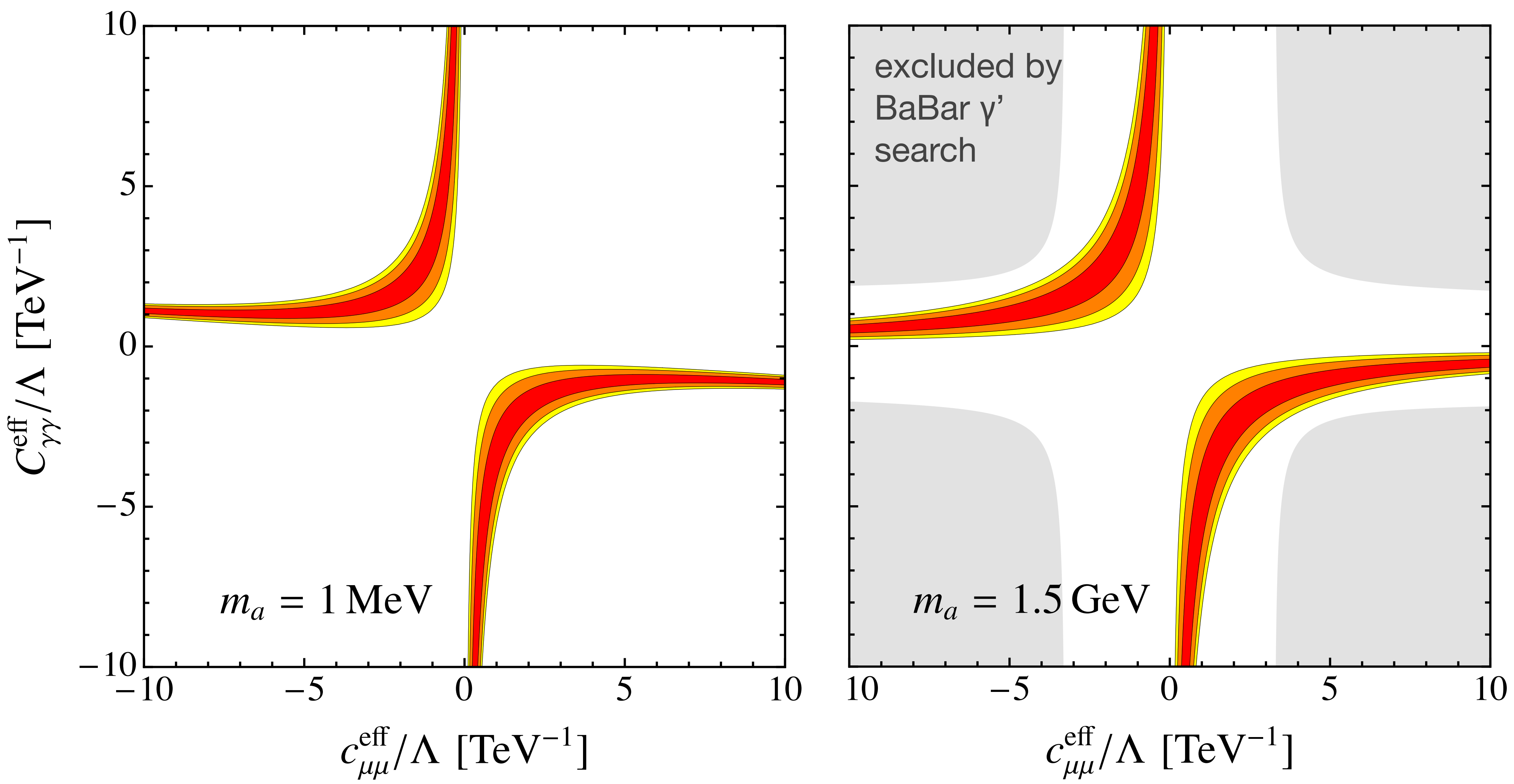
- sensitivity to many different ALP couplings entering the production, decay and lifetime of the ALP
- searches probe high-dimensional parameter spaces ⇒ need for strong model assumptions, e.g. existence of a single non-zero ALP coupling (strong biases)
- long-lived ALPs and ALPs decaying into hadrons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

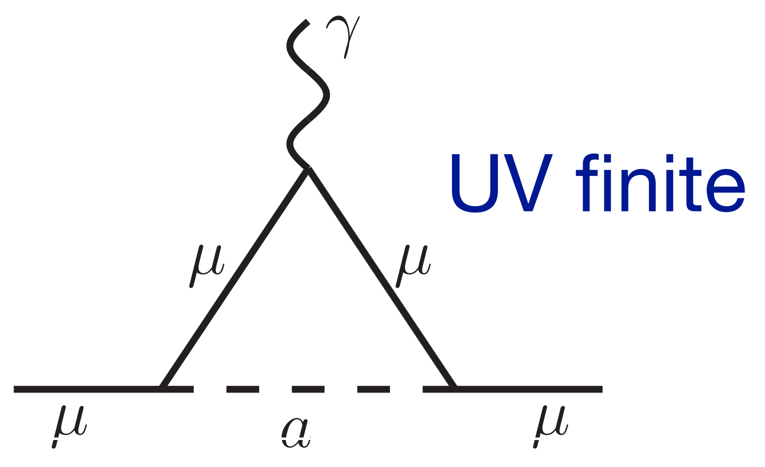
Indirect searches (effects of virtual ALPs) offer a promising alternative!

ALP—SMEFT interference

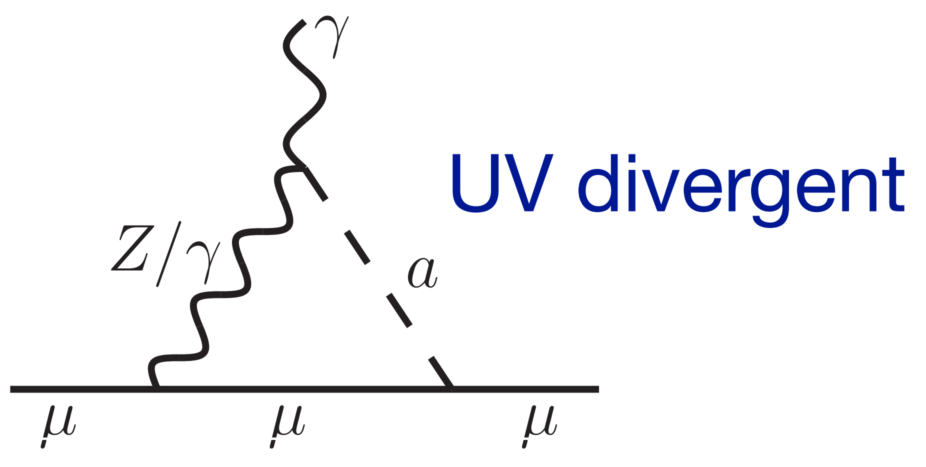
It is well-known that one-loop diagrams with virtual ALP exchange can be UV divergent. This was first studied in the context of $(g\text{-}2)_\mu$:

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





UV finite



UV divergent

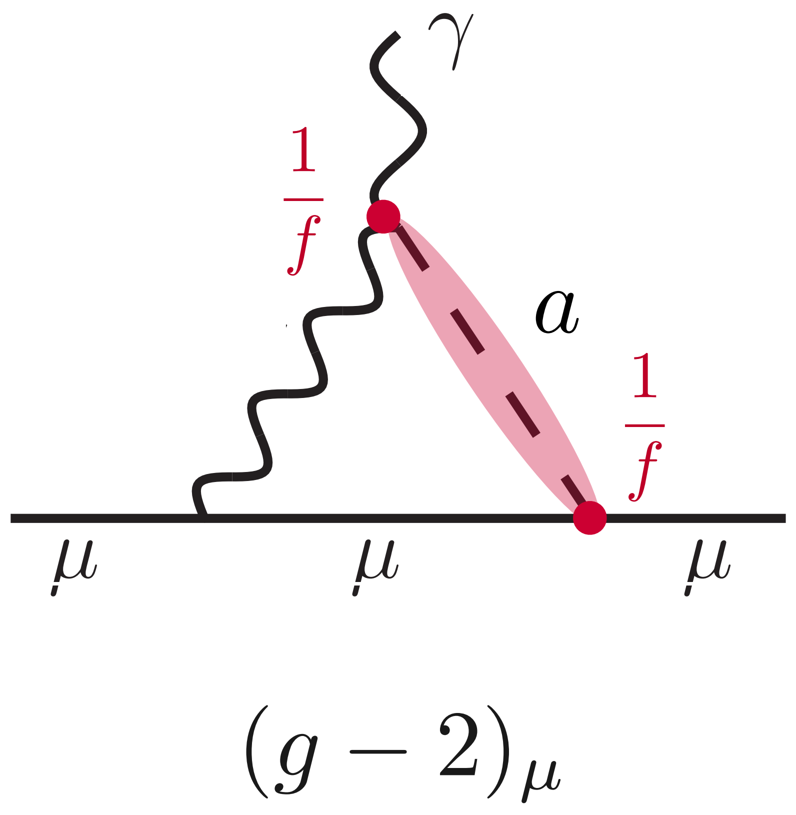
$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} + \delta_2 + 3 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right]\right.$$
$$\left.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

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

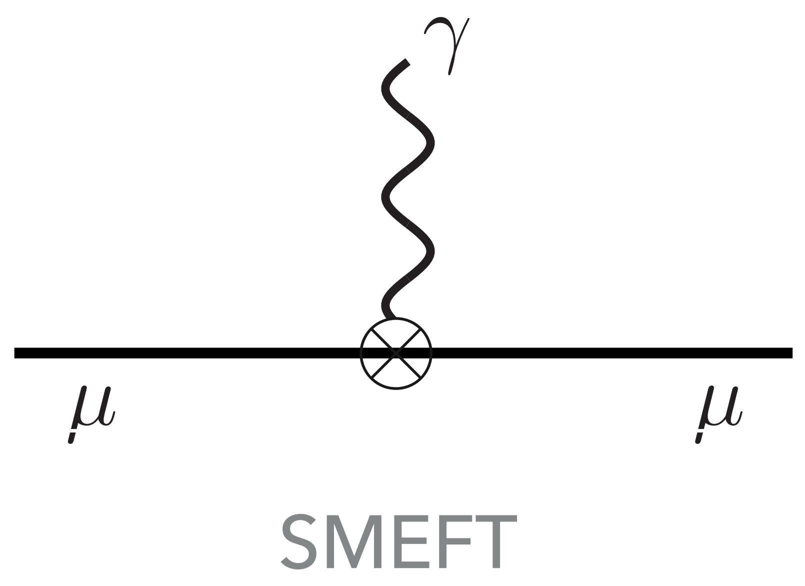
$$(\Lambda = 4\pi f)$$

ALP—SMEFT interference

Schematically:



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



Consistent effective field theory:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{f} \underset{\substack{\uparrow \\ \text{direct searches}}}{\mathcal{L}_{\text{ALP}}^{(D \geq 5)}} + \frac{1}{f^2} \underset{\substack{\uparrow \\ \text{indirect searches}}}{\mathcal{L}_{\text{SMEFT}}^{(D \geq 6)}}$$

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:

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

[Galda, MN, Renner: 2105.01078]

2499 x 2499 entries

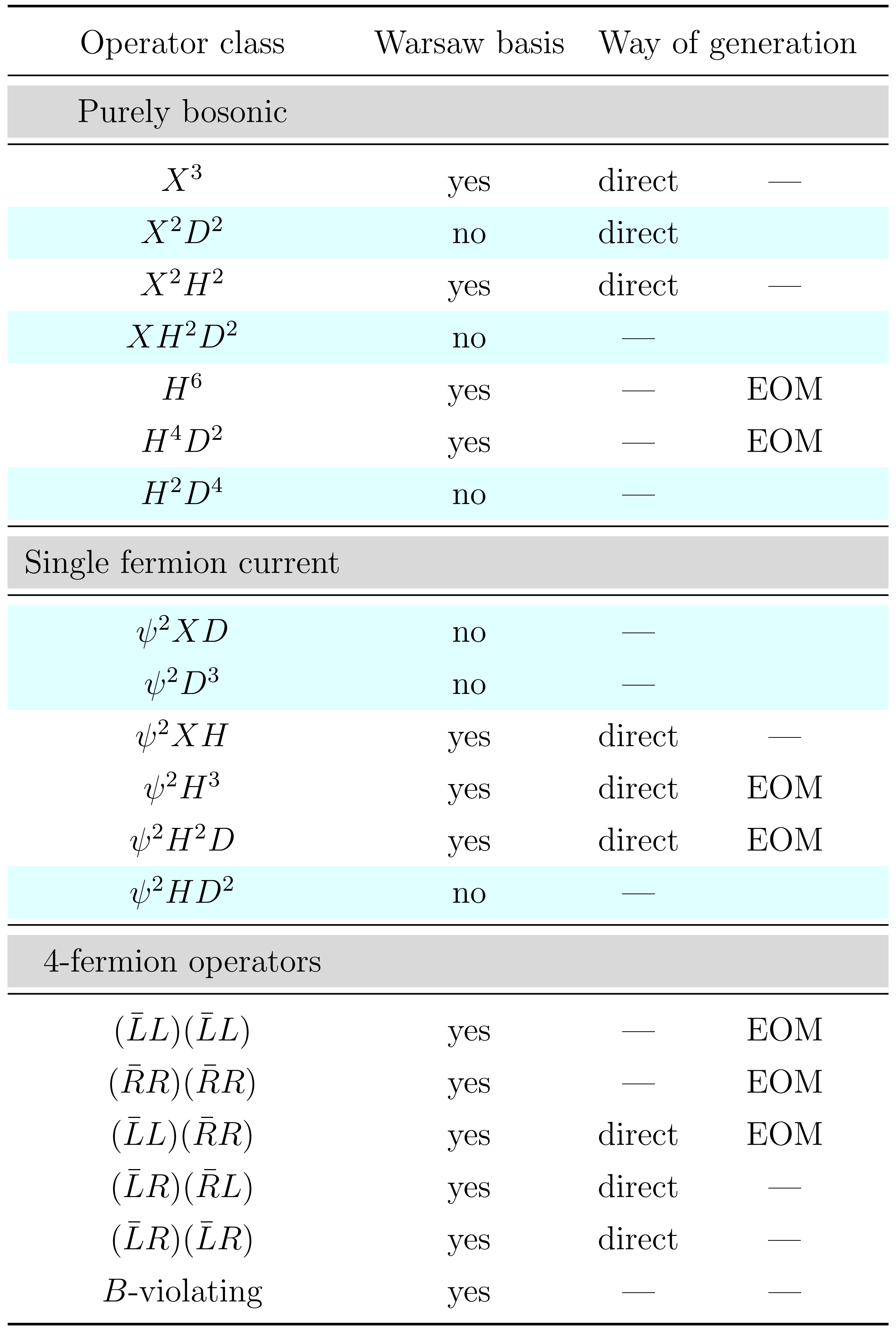
ALP source terms

- 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

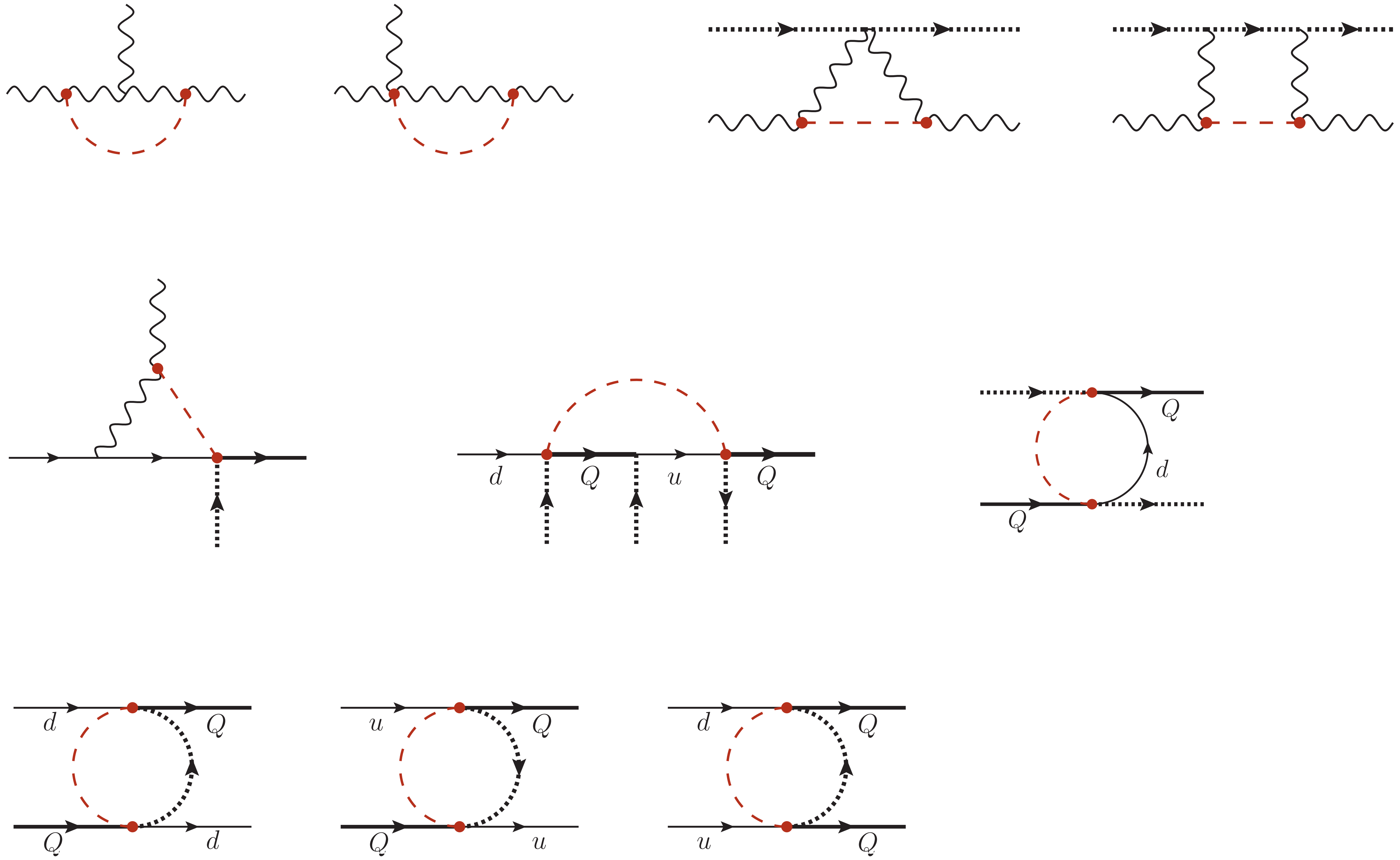
Systematic study of divergent Green's functions with ALP exchange

[Galda, MN, Renner: 2105.01078]



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

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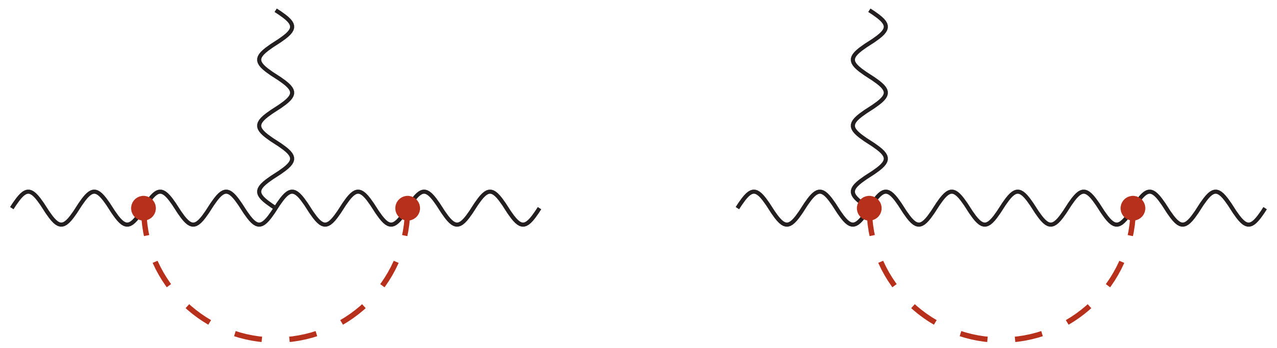
Sample calculation: UV divergences of the three-gluon amplitude



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

Source term for Weinberg operator:

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

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

$$\begin{aligned}\widehat{Q}_{G,2} &\cong g_s^2\left(\bar{Q}\gamma_\mu T^a Q + \bar{u}\gamma_\mu T^a u + \bar{d}\gamma_\mu T^a d\right)^2\\ &= g_s^2\Big[\frac{1}{4}\Big([Q_{qq}^{(1)}]_{prrp} + [Q_{qq}^{(3)}]_{prrp}\Big) - \frac{1}{2N_c}[Q_{qq}^{(1)}]_{pprr} + \frac{1}{2}[Q_{uu}]_{prrp} - \frac{1}{2N_c}[Q_{uu}]_{pprr}\\ &\qquad + \frac{1}{2}[Q_{dd}]_{prrp} - \frac{1}{2N_c}[Q_{dd}]_{pprr} + 2\,[Q_{qu}^{(8)}]_{pprr} + 2\,[Q_{qd}^{(8)}]_{pprr} + 2\,[Q_{ud}^{(8)}]_{pprr}\Big]\end{aligned}$$

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

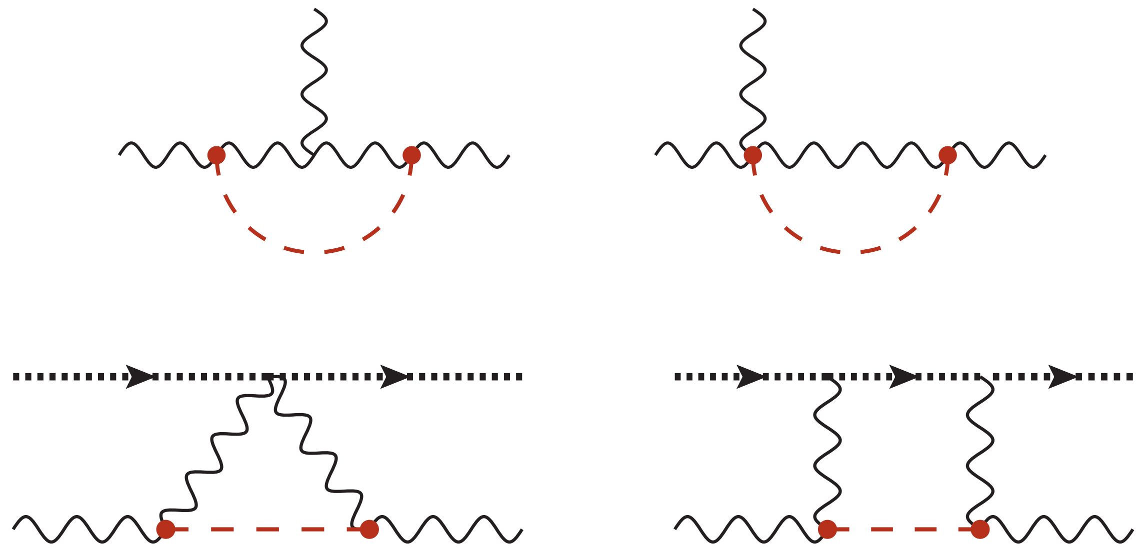
→ generates further source terms

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)]



$$S_G = 8g_s C_{GG}^2\,, \qquad S_{\tilde{G}} = 0$$

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

$$S_{HG} = 0\,, \qquad S_{H\tilde{G}} = 0$$

$$S_{HW} = -2g_2^2\, C_{WW}^2\,, \qquad S_{H\widetilde{W}} = 0$$

$$S_{HB} = -2g_1^2\, C_{BB}^2\,, \qquad S_{H\tilde{B}} = 0$$

$$S_{HWB} = -4g_1 g_2\, C_{WW}\, C_{BB}\,, \qquad S_{H\widetilde{W}B} = 0$$

$$S_H = \frac{8}{3}\,\lambda g_2^2\, C_{WW}^2\,,$$

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

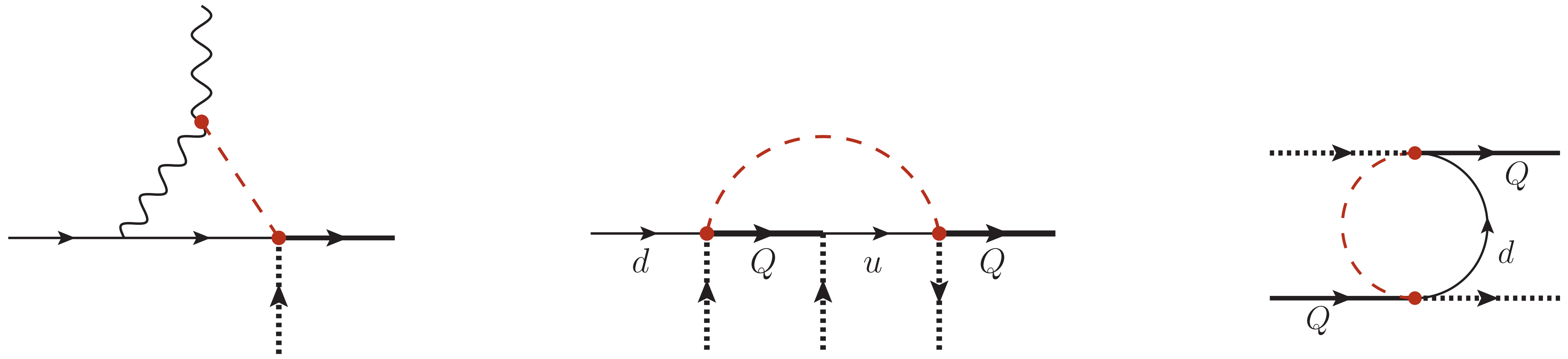
$$S_{HD} = \frac{32}{3}\, g_1^2\, \mathcal{Y}_H^2\, C_{BB}^2\,.$$

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			
$\psi^2 XD$	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	—	

$$
\begin{aligned}
\boldsymbol{S}_{eW} &= -ig_2\, \widetilde{\boldsymbol{Y}}_e\, C_{WW} \\
\boldsymbol{S}_{eB} &= -2ig_1\, (\mathcal{Y}_L + \mathcal{Y}_e)\, \widetilde{\boldsymbol{Y}}_e\, C_{BB} \\
\boldsymbol{S}_{uG} &= -4ig_s\, \widetilde{\boldsymbol{Y}}_u\, C_{GG} \\
\boldsymbol{S}_{uW} &= -ig_2\, \widetilde{\boldsymbol{Y}}_u\, C_{WW} \\
\boldsymbol{S}_{uB} &= -2ig_1\, (\mathcal{Y}_Q + \mathcal{Y}_u)\, \widetilde{\boldsymbol{Y}}_u\, C_{BB} \\
\boldsymbol{S}_{dG} &= -4ig_s\, \widetilde{\boldsymbol{Y}}_d\, C_{GG} \\
\boldsymbol{S}_{dW} &= -ig_2\, \widetilde{\boldsymbol{Y}}_d\, C_{WW} \\
\boldsymbol{S}_{dB} &= -2ig_1\, (\mathcal{Y}_Q + \mathcal{Y}_d)\, \widetilde{\boldsymbol{Y}}_d\, C_{BB}
\end{aligned}
$$



ALP—SMEFT interference

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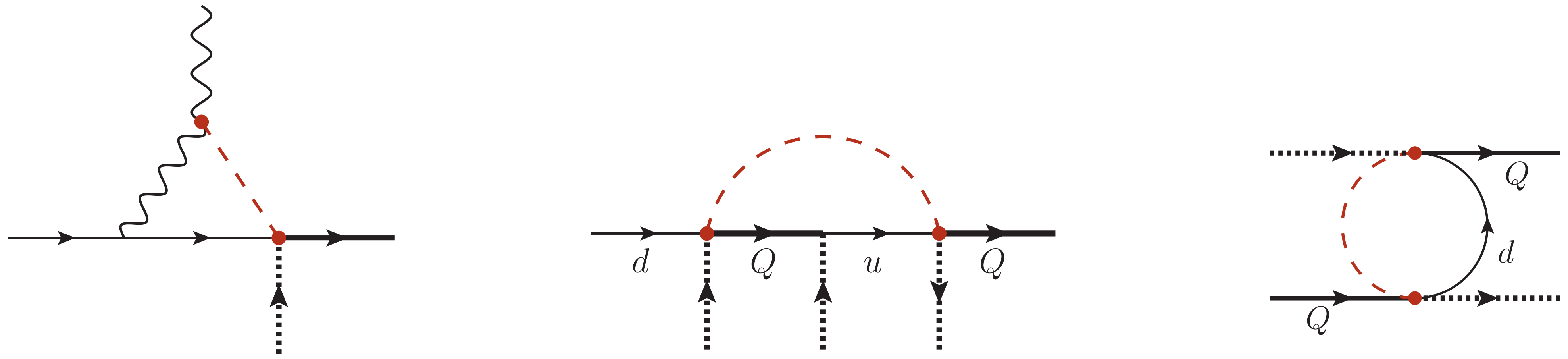

$$\boldsymbol{S}_{Hl}^{(1)} = \frac{1}{4}\,\widetilde{\boldsymbol{Y}}_e \widetilde{\boldsymbol{Y}}_e^\dagger + \frac{16}{3}\,g_1^2\,\mathcal{Y}_H \mathcal{Y}_L\,C_{BB}^2\,\mathbf{1}$$

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

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

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

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

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

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

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

ALP—SMEFT interference

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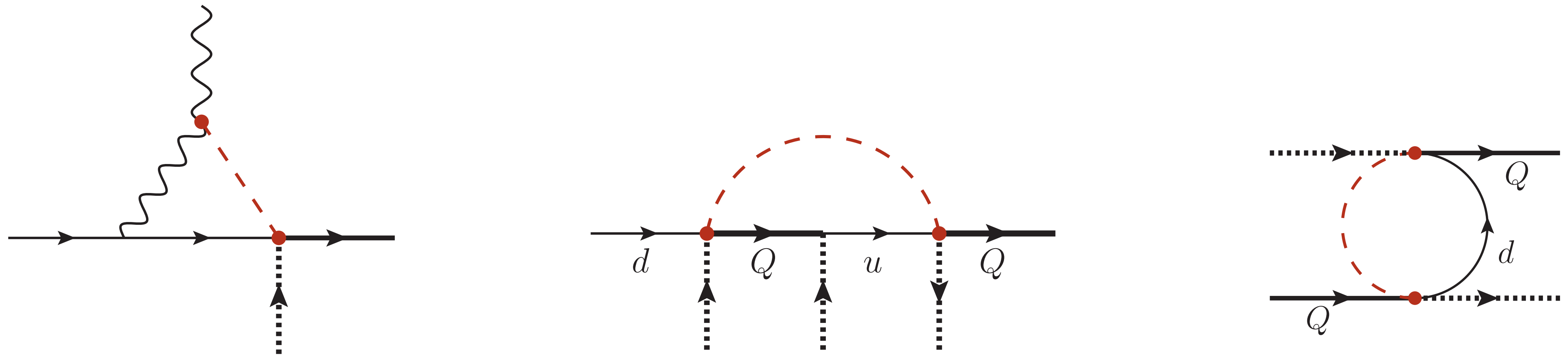
$\psi^2 D^3$	no	—	
$\psi^2 XH$	yes	direct	—
$\psi^2 H^3$	yes	direct	EOM
$\psi^2 H^2 D$	yes	direct	EOM
$\psi^2 HD^2$	no	—	

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

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

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



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	—	—

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

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

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

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

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

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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	—	—

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

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

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

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

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

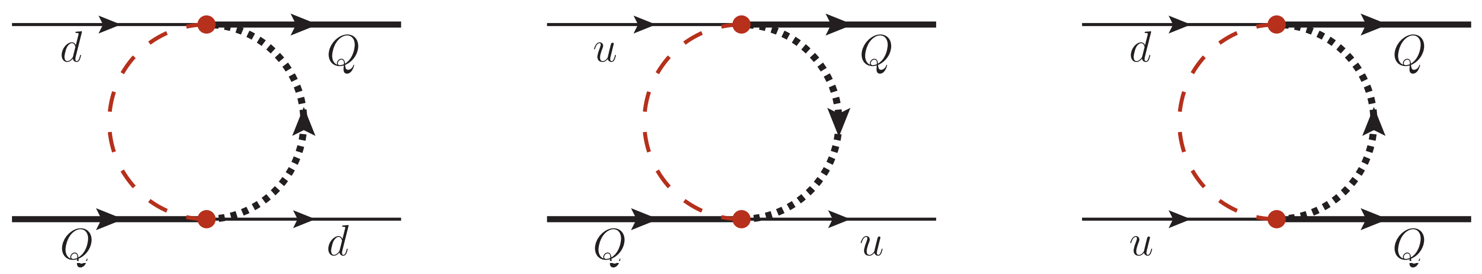
$$\big[S_{ud}^{(1)}\big]_{prst} = \frac{16}{3}\,g_1^2\,\mathcal{Y}_u\,\mathcal{Y}_d\,C_{BB}^2\,\delta_{pr}\,\delta_{st}$$

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

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	—	—



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

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

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

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

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

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

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

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

ALP—SMEFT interference

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

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

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

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

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

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

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

Top chromo-magnetic moment

Sample application: chromo-magnetic dipole moment of the top quark

$$\mathcal{L}_{t\bar{t}g} = g_s \left(\bar{t}\gamma^\mu T^a t\, G_\mu^a + \frac{\hat{\mu}_t}{2m_t}\, \bar{t}\,\sigma^{\mu\nu} T^a t\, G_{\mu\nu}^a + \frac{i\,\hat{d}_t}{2m_t}\, \bar{t}\,\sigma^{\mu\nu}\gamma_5\, T^a t\, G_{\mu\nu}^a \right)$$

with:

$$\hat{\mu}_t = \frac{y_t v^2}{g_s}\, \Re e\, C_{uG}^{33} \,, \qquad \hat{d}_t = \frac{y_t v^2}{g_s}\, \Im m\, C_{uG}^{33}$$

ALP-induced contribution follows from the solution of:

$$\begin{aligned} \frac{d}{d\ln\mu}\, \Re e\, C_{uG}^{33} &= \frac{S_{uG}^{33}}{(4\pi f)^2} + \left(\frac{15\alpha_t}{8\pi} - \frac{17\alpha_s}{12\pi} \right) \Re e\, C_{uG}^{33} + \frac{9\alpha_s}{4\pi}\, y_t\, C_G + \frac{g_s y_t}{4\pi^2}\, C_{HG} \\ \frac{d}{d\ln\mu}\, C_G &= \frac{S_G}{(4\pi f)^2} + \frac{15\alpha_s}{4\pi}\, C_G \\ \frac{d}{d\ln\mu}\, C_{HG} &= \left(\frac{3\alpha_t}{2\pi} - \frac{7\alpha_s}{2\pi} \right) C_{HG} + \frac{g_s y_t}{4\pi^2}\, \Re e\, C_{uG}^{33} \end{aligned}$$

Top chromo-magnetic moment

At leading logarithmic order, one finds: [Galda, MN, Renner: 2105.01078]

$$\hat{\mu}_t \approx -\frac{8m_t^2}{(4\pi f)^2}\left[c_{tt}\,C_{GG}\,\ln\frac{4\pi f}{m_t} - \frac{9\alpha_s}{4\pi}\,C_{GG}^2\,\ln^2\frac{4\pi f}{m_t}\right]$$

$$\approx -\left(5.87\,c_{tt}\,C_{GG} - 1.98\,C_{GG}^2\right)\cdot 10^{-3} \times \left[\frac{1\,\text{TeV}}{f}\right]^2$$

Combined with experimental bounds from CMS (2019), we obtain:

$$-0.68 < \Big(\underset{\substack{\uparrow \\ \text{color dipole} \\ \text{operator}}}{c_{tt}\,C_{GG}} - 0.34\,\underset{\substack{\uparrow \\ \text{Weinberg 3-gluon} \\ \text{operator}}}{C_{GG}^2}\Big) \times \left[\frac{1\,\text{TeV}}{f}\right]^2 < 2.38 \qquad (95\%\ \text{CL})$$

Comparable to strongest bounds following from collider and flavor physics!

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 a global fit to precision data: electroweak precision test, top and Higgs physics, flavor physics, $(g-2)_\mu$, …