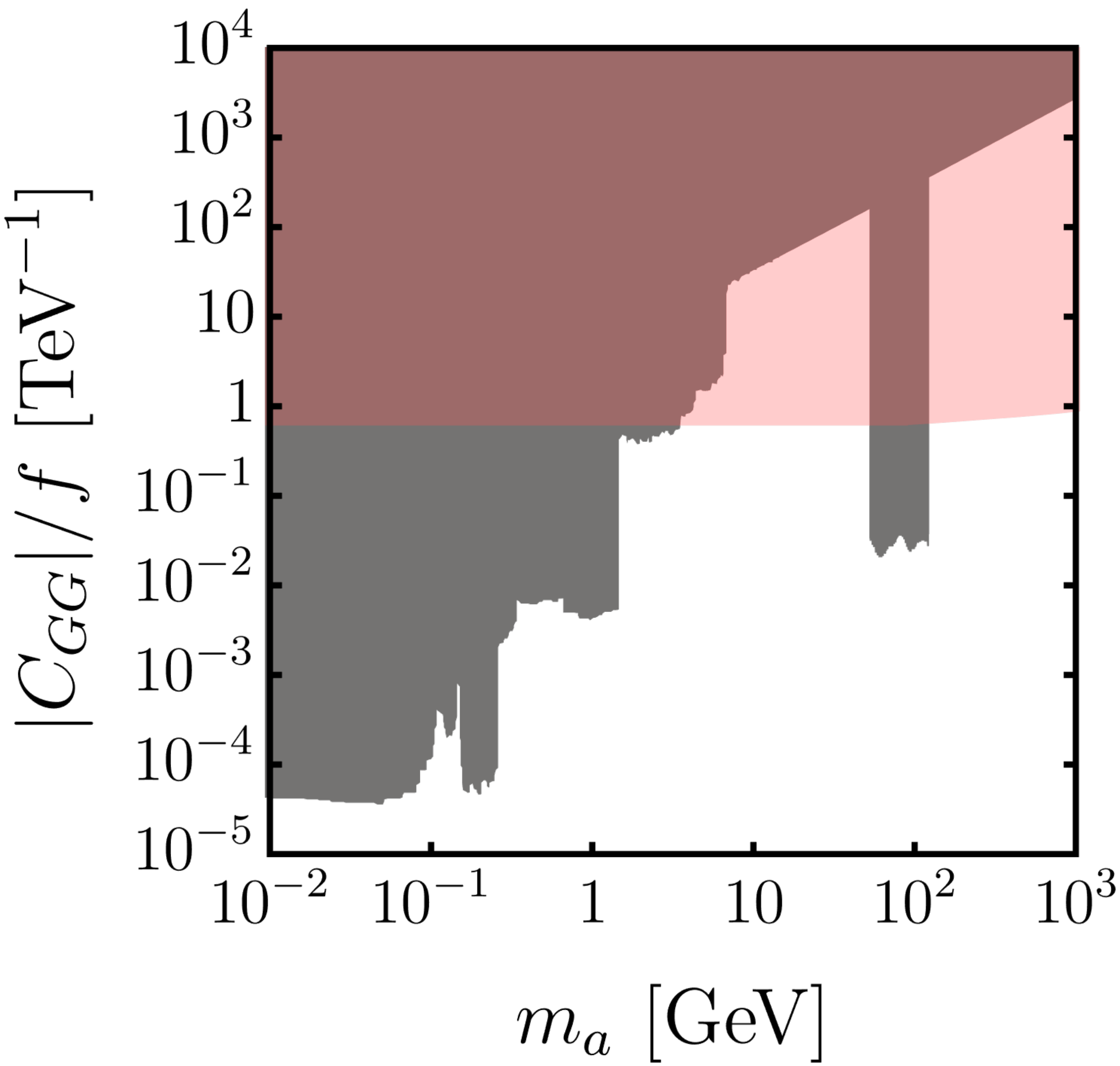
Model-Independent Bounds on Axion-Like Particles from the Standard Model Effective Field Theory



Anne Galda

based on

arXiv: 2105.01078

and

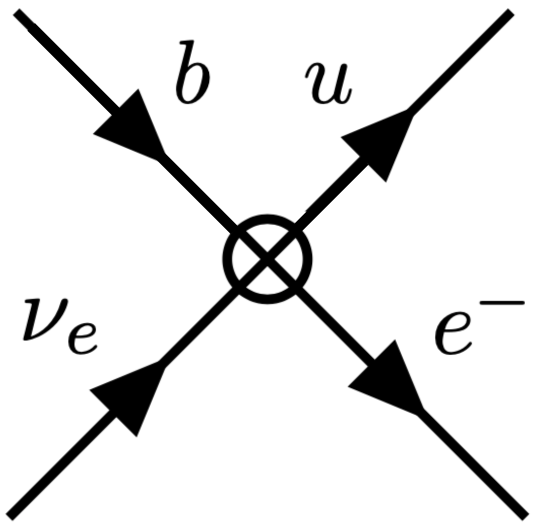
arXiv: 2307.10372

In collaboration with
S. Renner and M. Neubert
and
A. Biekötter, J. Fuentes-Martín
and M. Neubert

Outline

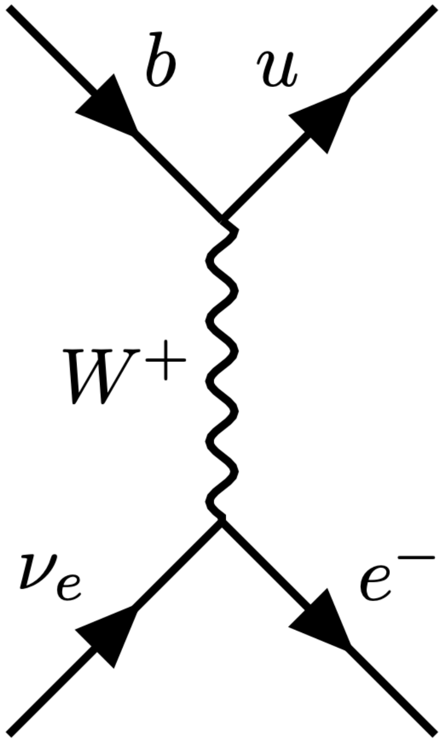
- Introduction to Effective Field Theories
- Renormalization-Group Evolution
- Axion-Like Particles and ALP-SMEFT Interference
- Model-Independent Bounds on ALPs

Effective Field Theories



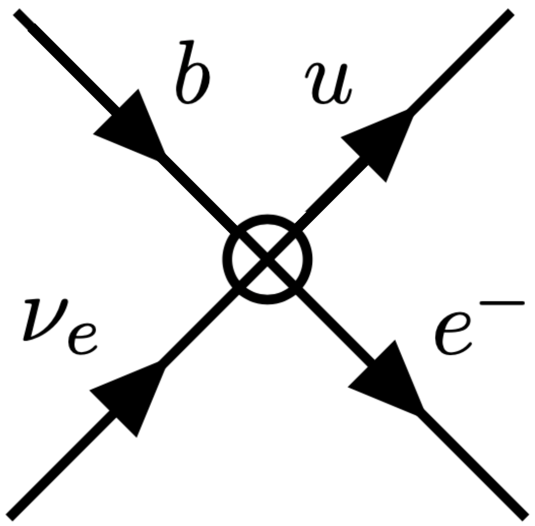
<u>local</u>
4-fermi interaction

<u>What connects these interactions?</u>



<u>full</u>
Standard-Model interaction

Effective Field Theories



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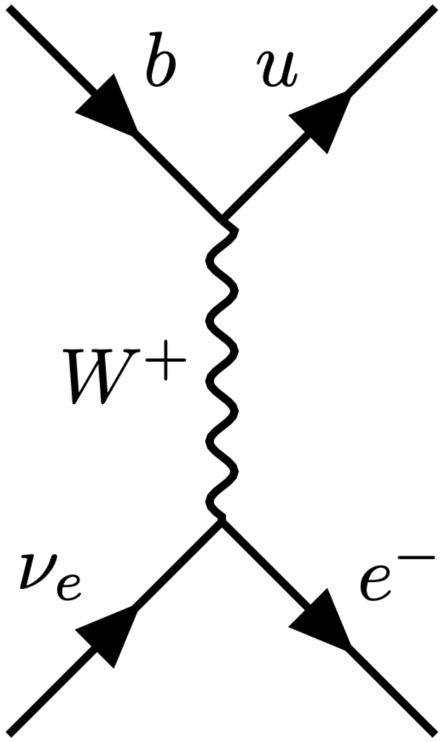
<u>**What connects these interactions?**</u>



<u>**full**</u>
Standard-Model interaction

Effective Field Theories!

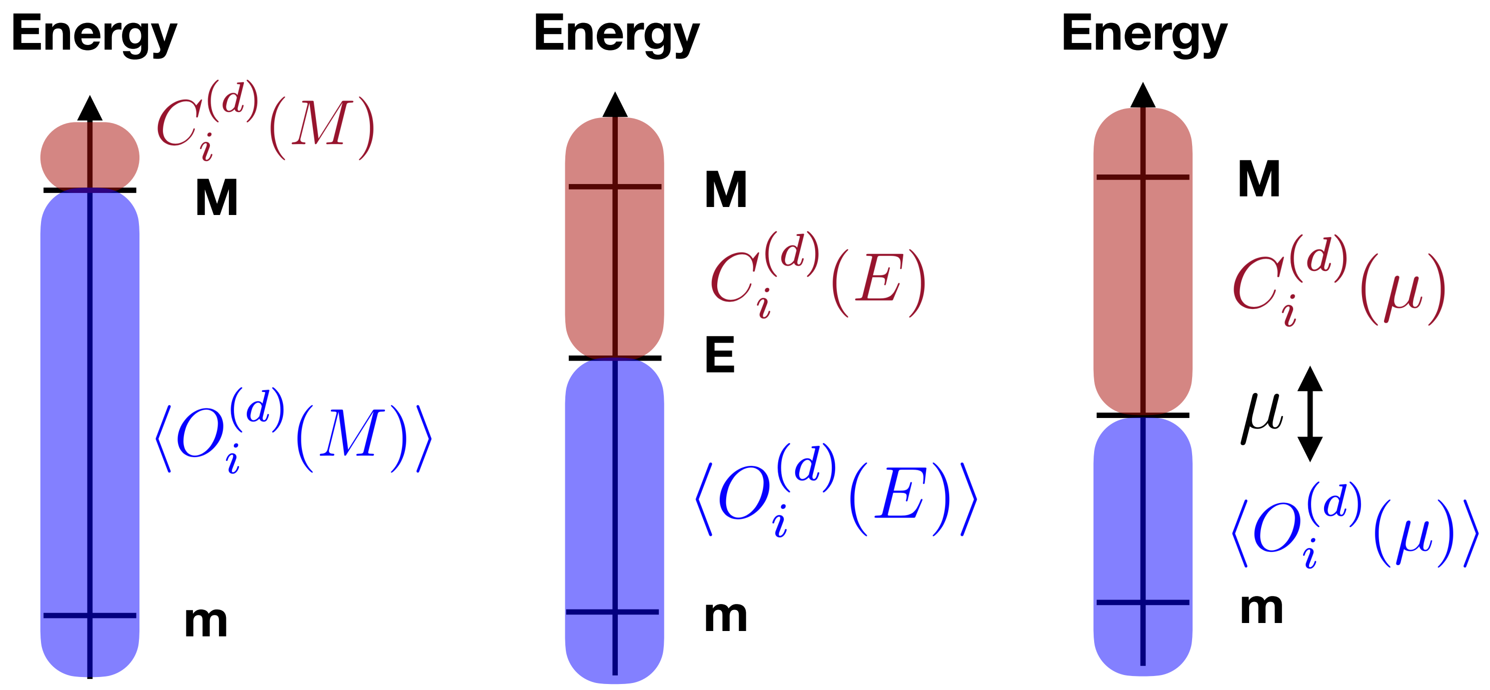
Effective Field Theories

Basic idea: At a given scale, determine the relevant degrees of freedom!

$\hookrightarrow$ ***Operator-Product Expansion***

$$\mathcal{L}_{\text{eff}} = \sum_d \frac{1}{\Lambda^{d-4}} \sum_{i=1}^{n_d} C_i^{(d)}(\mu)\, O_i^{(d)}(\mu)$$

Wilson coefficients: Parametrize the (heavy) UV-physics
Operators: Built out of the relevant degrees of freedom



Effective Field Theories

Factorisation scale μ is arbitrary

↪ ***Unobservable quantity***

$$\frac{d}{d\ln\mu}\mathcal{L}_{\text{eff}} = \sum_d \frac{1}{\Lambda^{d-4}}\sum_{i=1}^{n_d} C_i^{(d)}(\mu)\, O_i^{(d)}(\mu) = 0$$

$$\left(\frac{d\, C_i^{(d)}(\mu)}{d\ln\mu}\right) O_i^{(d)}(\mu) + C_i^{(d)}(\mu)\left(\frac{d\, O_i^{(d)}(\mu)}{d\ln\mu}\right) = 0$$

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$\hookrightarrow$ **define:**

$$\frac{dO_i^{(d)}(\mu)}{d\ln\mu} \equiv -\gamma_{ij}(\mu) O_j^{(d)}(\mu)$$

“anomalous dimension matrix”

Effective Field Theories

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$\hookrightarrow$ **define:**

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"anomalous dimension matrix"

Renormalization-Group Evolution Equation

$$\frac{d\, C_i^{(d)}(\mu)}{d\ln\mu} = \gamma_{ji}(\mu)\, C_j^{(d)}(\mu)$$

RG Evolution Equation

$$\frac{d\,C_i^{(d)}(\mu)}{d\ln\mu} = \gamma_{ji}(\mu)\,C_j^{(d)}(\mu)$$

$\hookrightarrow$ **Central equation of this talk!**

- Describes the scale μ dependence of the Wilson coefficients (couplings).

- Anomalous dimension matrix $\gamma_{ji}(\mu)$ couples the equations of different Wilson coefficients.

  $\hookrightarrow$ (Very) large set of coupled differential equations!

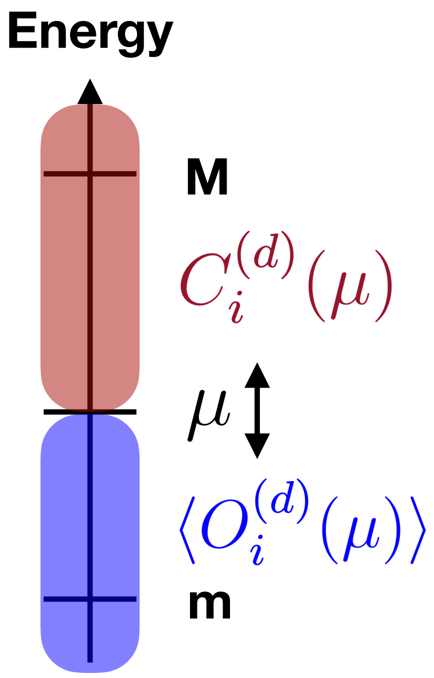
- Even if a Wilson coefficient is zero at a high scale, it can still be generated via a “running effect”!

The Standard Model Effective Field Theory (SMEFT)

Assume there are **new, unknown particles coupling to** the known **Standard Model particles**.

$\hookrightarrow$ What would be the consequences?

- If the new particle is heavy, it is not a valid degree of freedom at “low” energies!
- This means it will not appear as an external state in scattering amplitudes.
- **But**: it can still modify physical processes by modifying Wilson coefficients (“couplings”)



New, unknown particles can generate operators made purely out of SM particles that are zero in the SM!

$\hookrightarrow$ **Generation of higher dimensional operators!**

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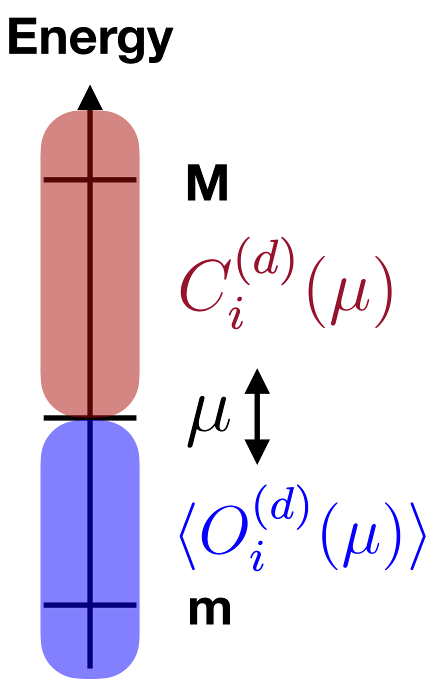
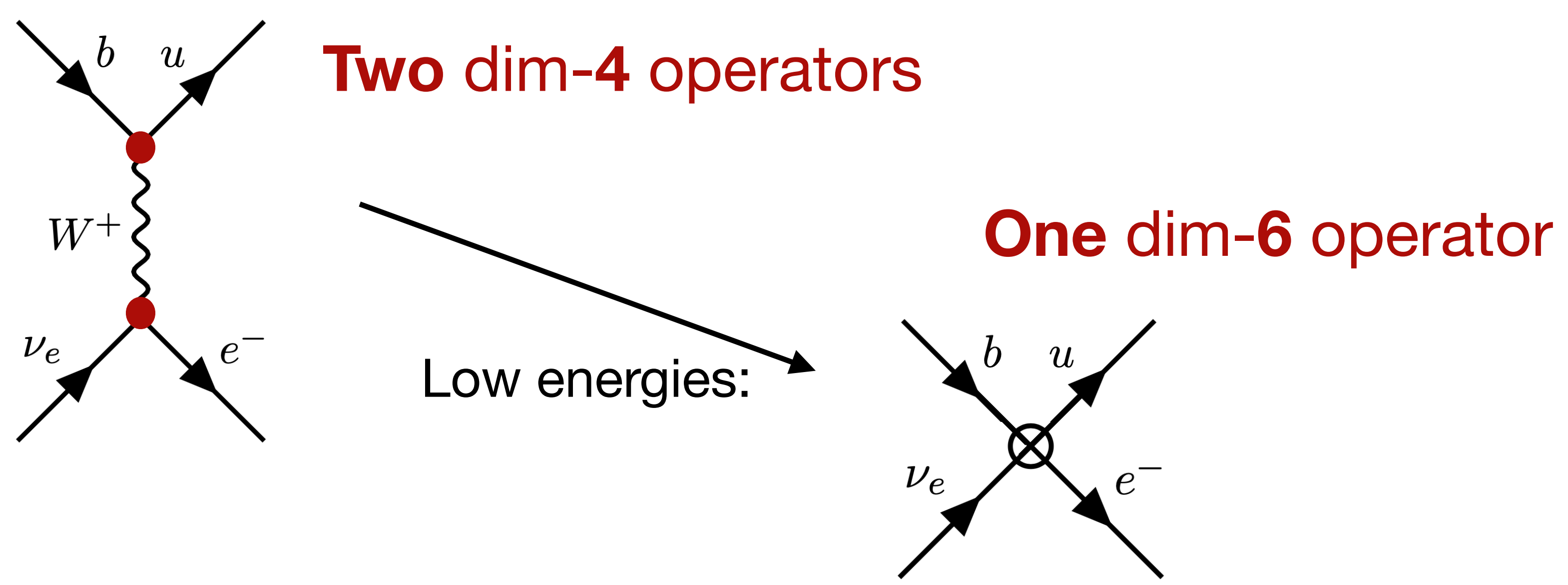


SM analogy:



The Standard Model Effective Field Theory (SMEFT)

Minimal basis: "Warsaw" basis

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

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$			
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$			
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	

Parametrization of new heavy physics in terms of SM fields

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q^{(1)}_{quqd}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q^{(1)}_{lequ}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q^{(3)}_{lequ}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

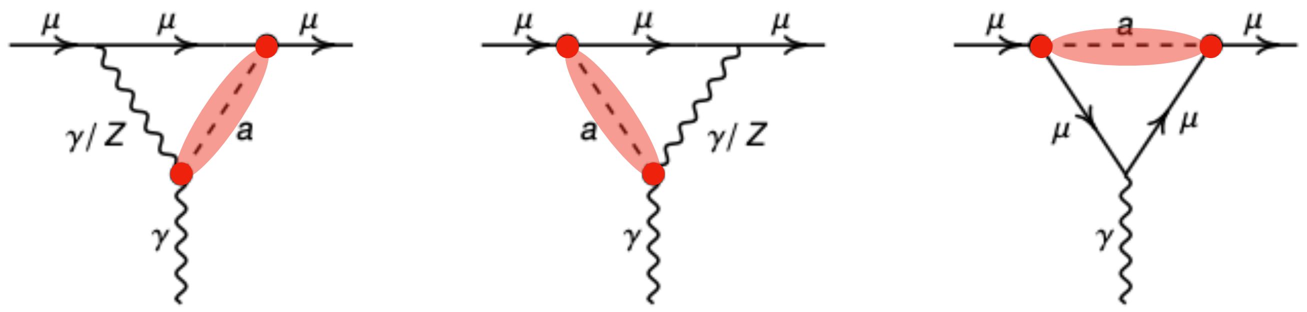
at dimension-6: 59 operators
[omitting flavor indices]

Axions and Axion-Like Particles (ALPs)

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

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

- **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:

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

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

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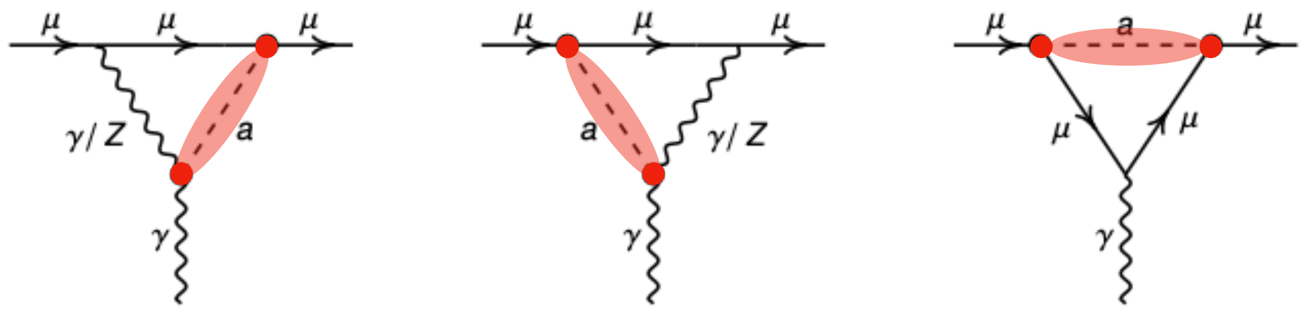


Most general Lagrangian for a classically shift symmetric, gauge singlet, pseudoscalar ALP:

field redefinition

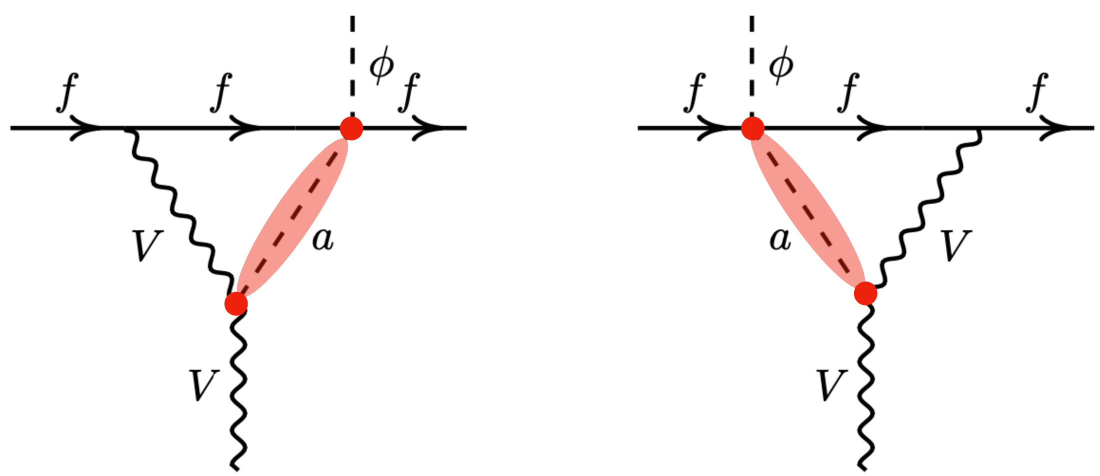
$$\mathcal{L}^{D=5\,\prime}_{\rm SM+ALP} = C_{GG}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W^I_{\mu\nu}\,\tilde{W}^{\mu\nu,I} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\widetilde{\boldsymbol{Y}}_u\,u_R + \bar{Q}\,H\,\widetilde{\boldsymbol{Y}}_d\,d_R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

$$\psi_F \to \psi_F + i\,\frac{a}{f}\,\boldsymbol{c}_F\,\psi_F$$

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

ALP-SMEFT Interference

Virtual ALP-exchange **with only SM external states in one-loop diagrams, i.e.:**

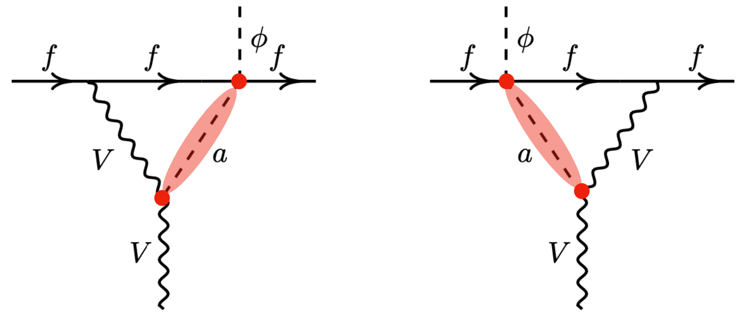


$\sim\ 1/\epsilon$ where $\epsilon \to 0$

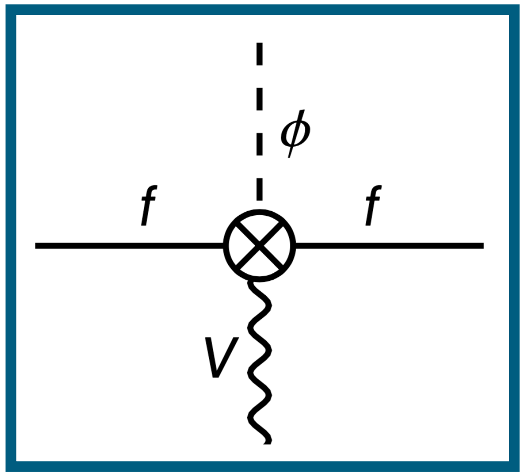
UV-divergent amplitudes!

Physics needs to be finite! → **Divergence needs to be absorbed!**

Shrink loop to a point:



→ C_0^{dipole} x



"bare" UV-divergent quantity

"dipole operator"

ALP-SMEFT Interference

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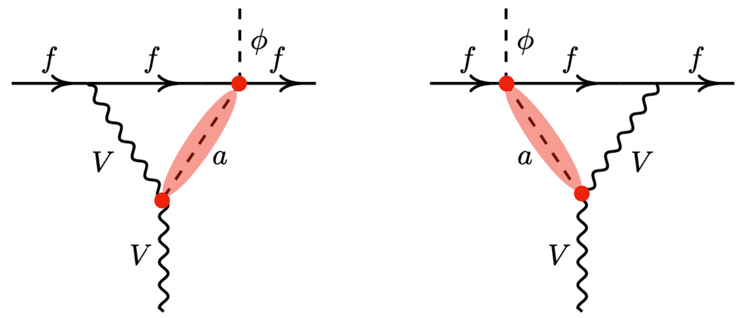
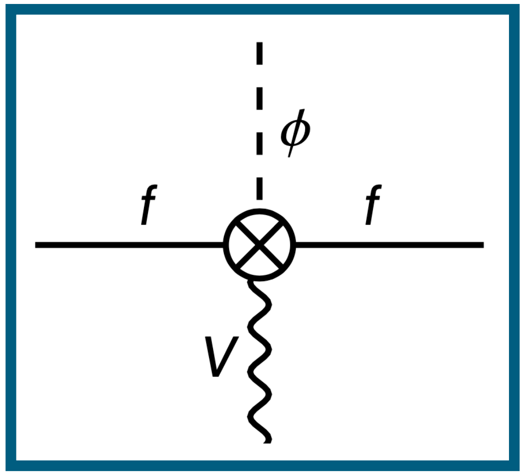


$$C_0^{\text{dipole}} \quad \text{x}$$



“bare” UV-divergent quantity

“dipole operator”

In detail: (still schematically)

$$\mathcal{A}^{\text{dipole}} = \frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{M^2}\right) + \dots \right) \langle \mathcal{O}^{\text{dipole}} \rangle$$

ALP-SMEFT Interference

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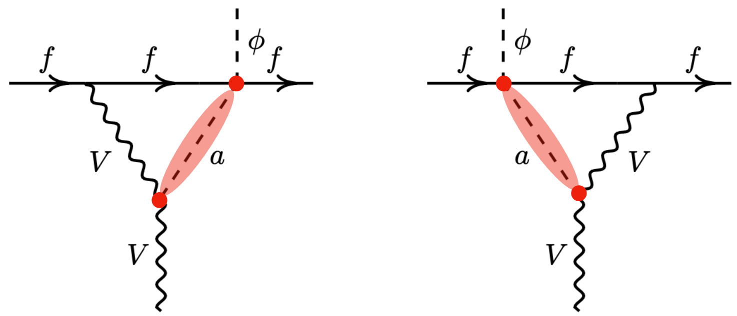
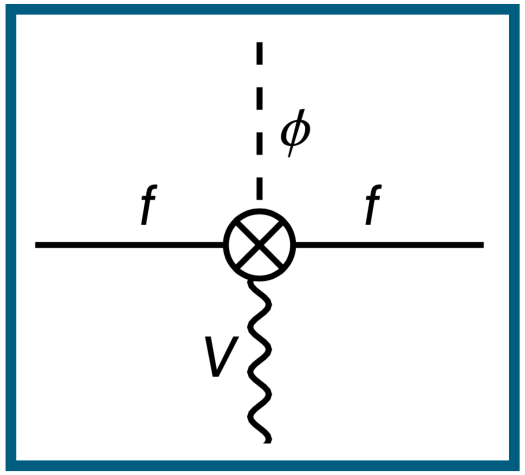


$$C_0^{\text{dipole}}$$ x



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Absorption of the pole in the bare dipole operator Wilson coefficient:

$$C_0^{\text{dipole}} = -\frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{M^2}\right) + \dots \right)$$

ALP-SMEFT Interference

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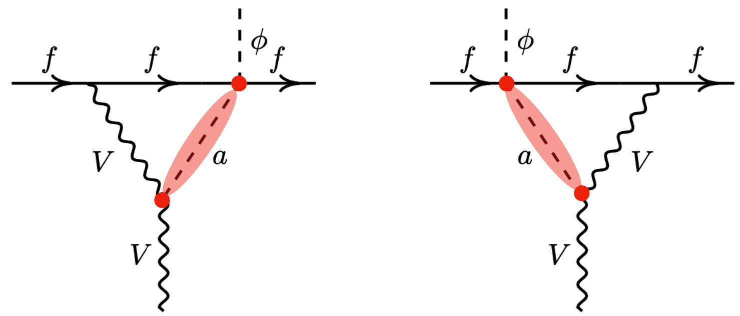
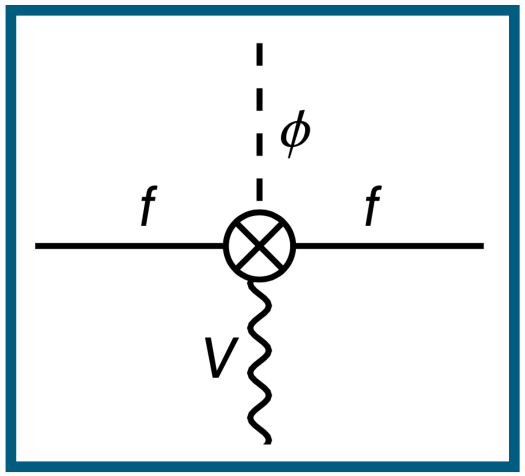


$$C_0^{\text{dipole}} \quad \text{x}$$



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$$C_{\text{ren}}^{\text{dipole}} = -\frac{1}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \left(\cancel{\frac{1}{\epsilon}} + \ln\left(\frac{\mu^2}{M^2}\right) + \dots \right)$$

ALP-SMEFT Interference

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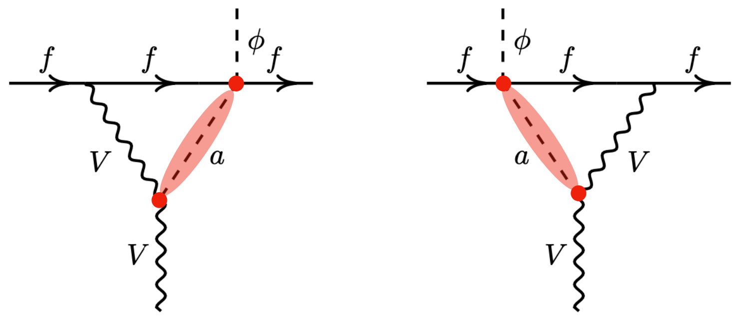
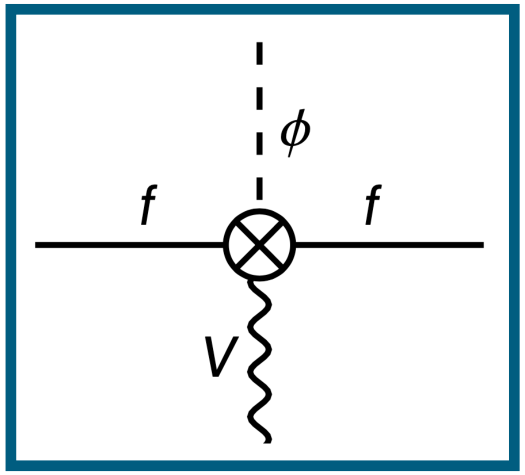


C_0^{dipole} x



"bare" UV-divergent quantity

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In detail: (still schematically)

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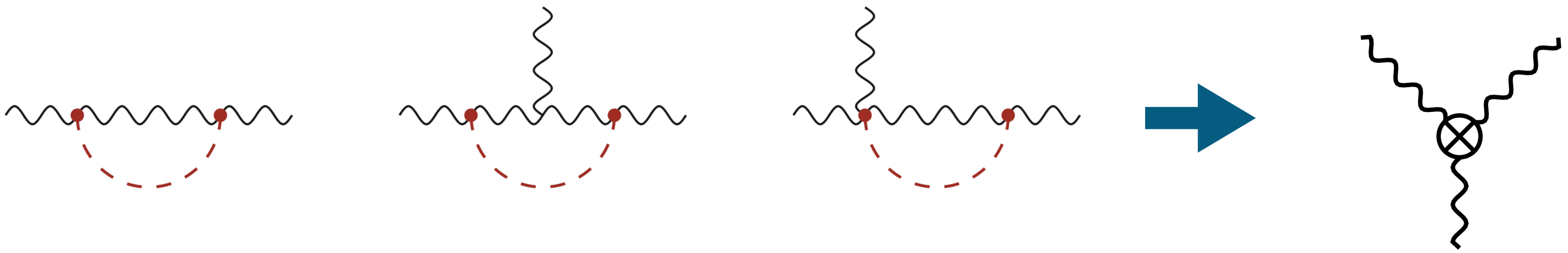
Derivative wrt. scale

$$\frac{d}{d\ln\mu} C_{\text{ren}}^{\text{dipole}} = -\frac{2}{(4\pi f)^2} f(C_\alpha^{\text{ALP}}, C_\beta^{\text{ALP}}) \equiv \frac{S^{\text{dipole}}}{(4\pi f)^2}$$

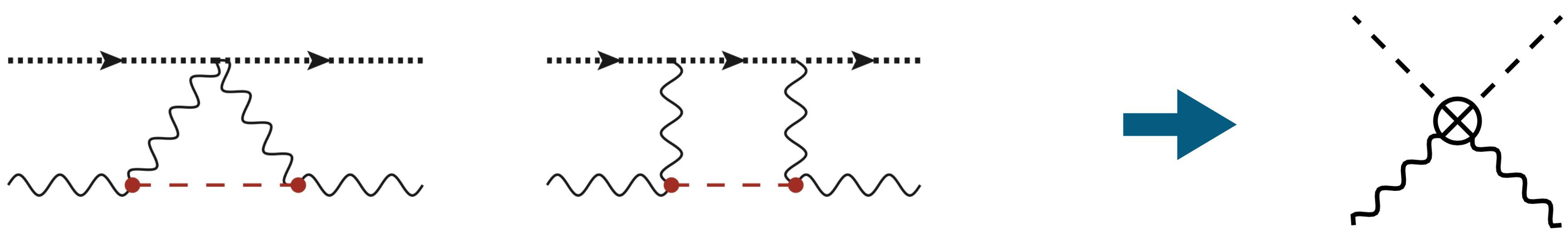
ALP-SMEFT Interference

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

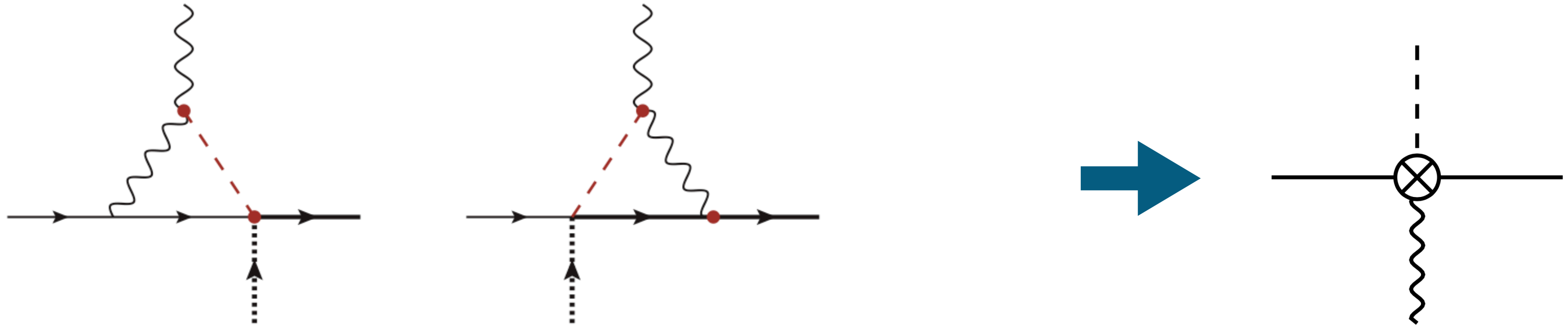
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SM+ALP}} + \mathcal{L}_{\text{SMEFT}}$$



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



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



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!

ALP-SMEFT Interference

Main message of this talk:

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

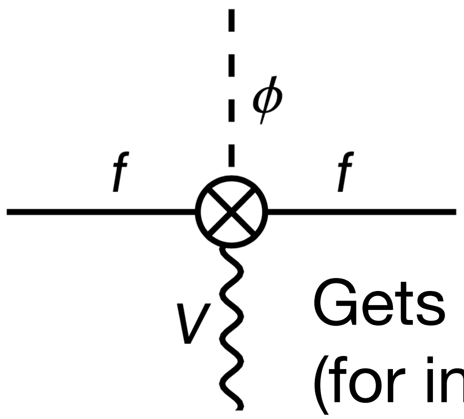
$$\frac{d}{d\ln\mu} C_i^{\rm SMEFT} - \gamma_{ji}^{\rm SMEFT}\, C_j^{\rm SMEFT} = \frac{S_i}{(4\pi f)^2} \quad (\text{for } \mu < 4\pi f)$$

[AG, Neubert, Renner (2021)]

ALP constraints from SMEFT fits

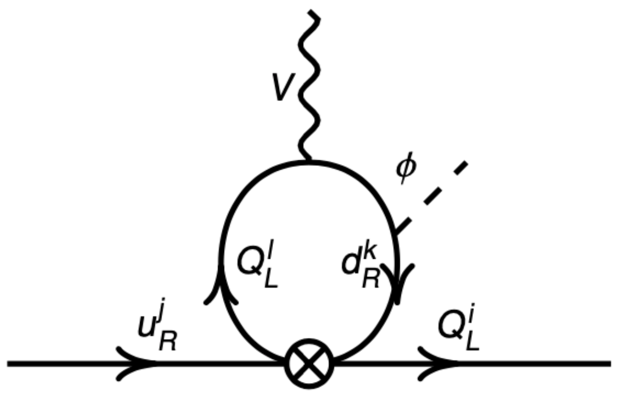
$$\frac{d}{d\ln\mu} C_i^{\text{SMEFT}} - \gamma_{ji}^{\text{SMEFT}} C_j^{\text{SMEFT}} = \frac{S_i}{(4\pi f)^2} \qquad (\text{for } \mu < 4\pi f)$$

- **Large set of coupled differential equations!**

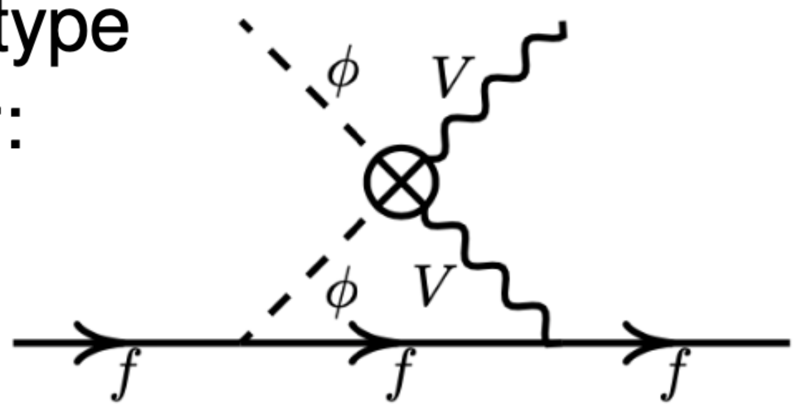


Gets contributions from (for instance)

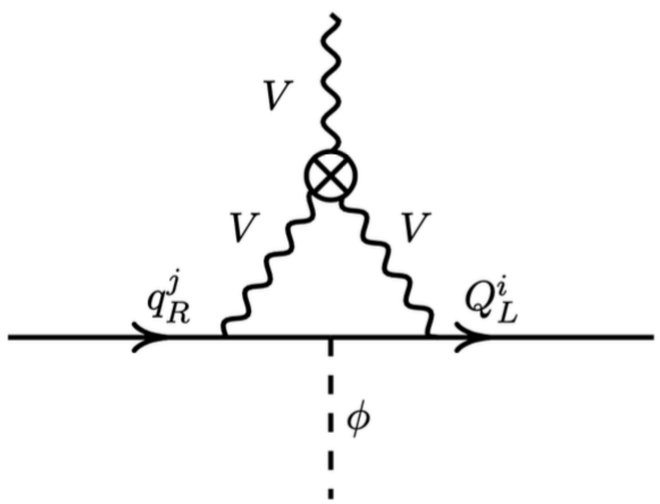
four-fermion operator:



$Q_{HV(V')}$-type operator:



Weinberg operator:



ALP constraints from SMEFT fits

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

- **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)]

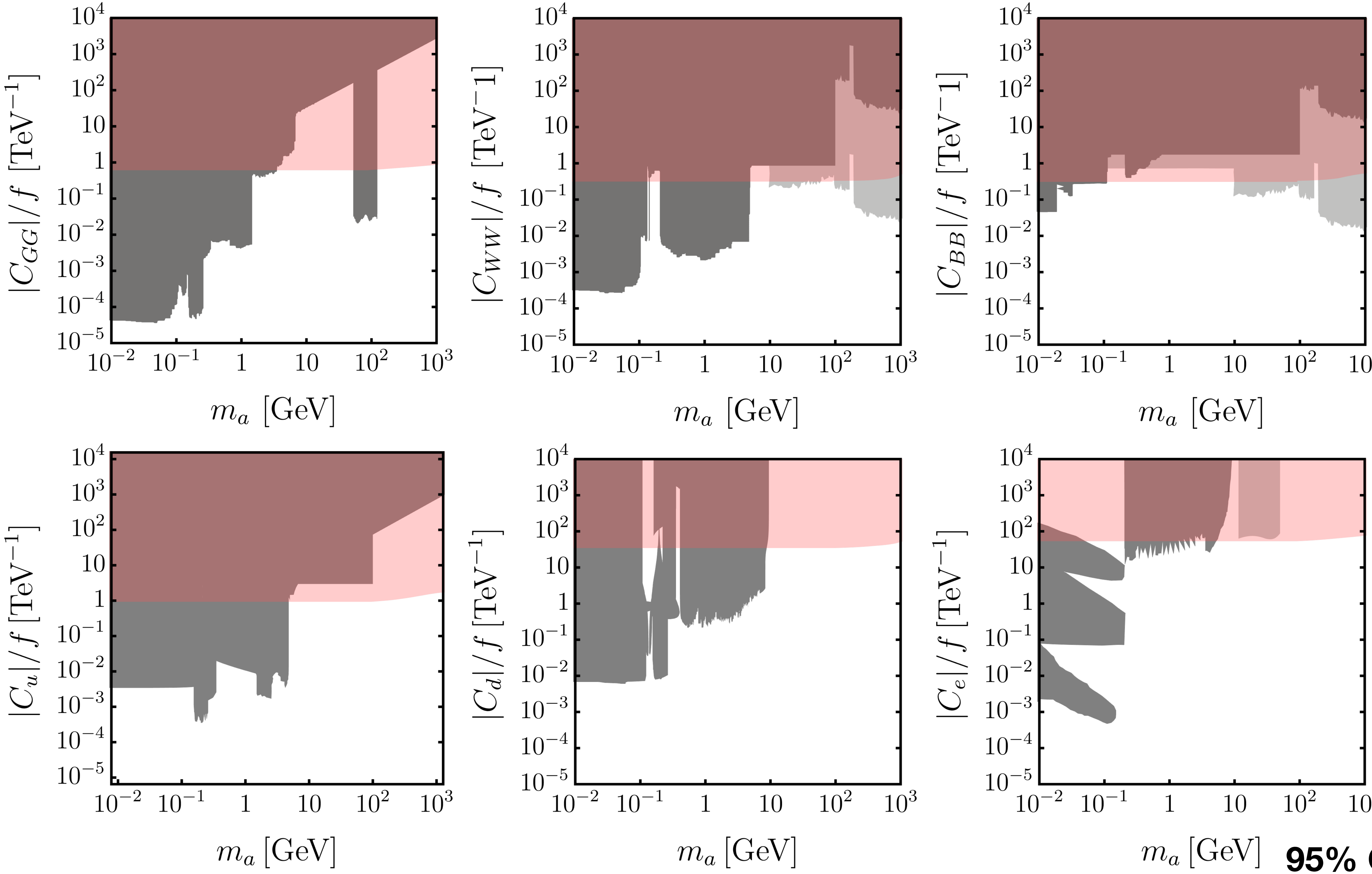
Result: **SMEFT Wilson coefficients at a low scale μ in terms of ALP-couplings at the scale Λ.**

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)]

Model-Independent Bounds on Axion-Like Particles



95% CL

red: our new model-independent bounds gray: direct, model-dependent bounds

Model-Independent Bounds on the Axion-Like Particles

- SMEFT searches are independent of axion-like particles!
- Direct searches often need to make assumptions on the decay of the ALP, on its mass, lifetime etc!

  $\hookrightarrow$ Often very model-dependent statements

- Only caveat:

  Discussion valid if the ALP is the only source of new physics between and the electroweak scale.

  Matching of concrete ALP models could generate non-zero SMEFT coefficients on top of the inhomogeneous source terms.

  $\hookrightarrow$ Discussed for two models in our paper: arXiv: 2307.10372

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red: our new model-independent bounds gray: direct, model-dependent bounds

Summary

In this talk we have seen..

- ✓ **how to derive the RG evolution equations for Wilson coefficients.**
- ✓ **that ALPs couple to the SM via dimension-5 interactions (or higher).**
- ✓ **that divergences from one-loop virtual ALP exchange with external SM particles are absorbed in SMEFT Wilson coefficients and the ALP thus generates nearly the whole dim-6 SMEFT basis at one-loop order .**
- ✓ **how RG running and ALP-independent SMEFT bounds can be used to obtain model-independent bounds on ALP coefficients.**

→ **Indirect bounds from global fits are a model-independent way to constrain ALPs and the results are competitive to or even exceed current constraints!**

Take Home Message

ALPs generate nearly all dimension-6 SMEFT operators at one-loop order allowing for a derivation of model-independent bounds!


$|C_{GG}|/f$ [TeV^{-1}]
$|C_{WW}|/f$ [TeV^{-1}]
$|C_{BB}|/f$ [TeV^{-1}]
$|C_u|/f$ [TeV^{-1}]
$|C_d|/f$ [TeV^{-1}]
$|C_e|/f$ [TeV^{-1}]
m_a [GeV]

Thank you!