LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

UNIVERSIDAD DE GRANADA

Running in the ALPs

Based on 2012.09017

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Motivation: EFT approach

Expansion into higher dimensional operators:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_7}{\Lambda^3} + \frac{\mathcal{L}_8}{\Lambda^4} + \ldots$$

$$\mathcal{L}_d = c_i \mathcal{O}_i \qquad [\mathcal{O}_i] = d$$

If new states exist below electroweak scale, the SMEFT must be extended

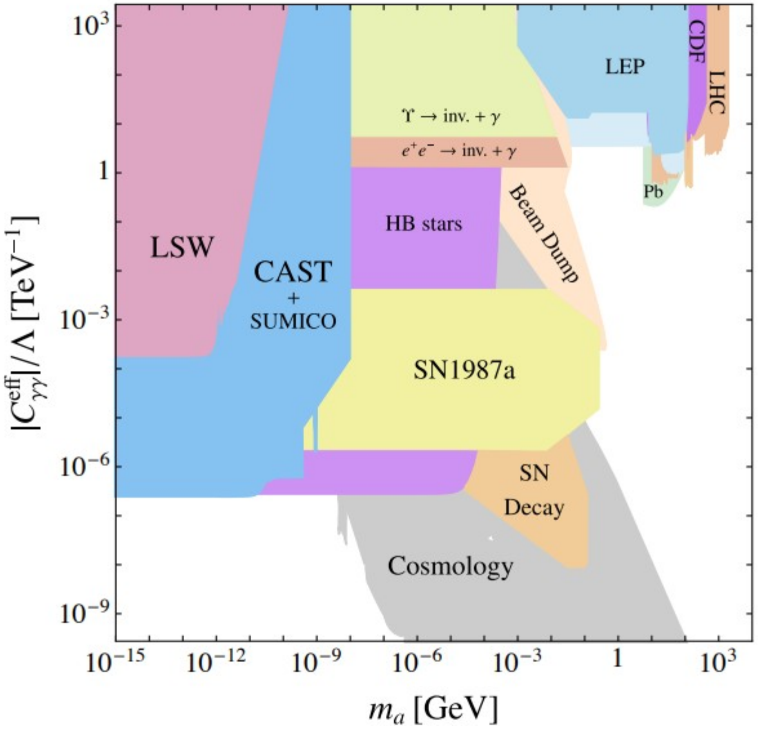
Motivation: ALPs

Axion-like particles = CP-odd singlet scalars

Theoretically well motivated:

- Strong CP-problem — Peccei, Quinn PRL38 (1977) 1440
- Composite Higgs Models — Brando Bellazzini, Csaba Csáki and Javi Serra, 1401.2457
- Dark Matter — M. J. Dolan, F. Kahlhoefer, C. McCabe and K. Schmidt-Hoberg, 1412.5174
- Anomalies — Manuel A. Buen-Abad, Jiji Fan, Matthew Reece and Chen Sun 2104.03267

Motivation: ALPs



- Experiments span a huge range of energies
- Wilson coefficients **run**, and **mix**, following the corresponding RGEs

M. Bauer, M. Neubert, A. Thamm, 1708.00443

SMEFT+ALP

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu s \partial^\mu s - \frac{1}{2}m^2 s^2 - \frac{\lambda_s}{4!}s^4 - \lambda_{s\phi}s^2|\phi|^2 + \sum_i \frac{1}{\Lambda}\alpha_i \mathcal{O}_i^{(5)}$$

$\mathcal{O}_i^{(5)}$ invariant under SM gauge groups

Assume only new physics is CP-even

SMEFT+ALP

Non-redundant basis ⟵ EOM ⟶ **Redundant ops**

$$\mathcal{O}_{su\phi}^{\alpha\beta} = is(\overline{q_L^\alpha}\tilde{\phi}u_R^\beta - \overline{u_R^\beta}\tilde{\phi}^\dagger q_L^\alpha)$$

$$\mathcal{O}_{sd\phi}^{\alpha\beta} = is(\overline{q_L^\alpha}\phi d_R^\beta - \overline{d_R^\beta}\phi^\dagger q_L^\alpha)$$

$$\mathcal{O}_{se\phi}^{\alpha\beta} = is(\overline{l_L^\alpha}\phi e_R^\beta - \overline{e_R^\beta}\phi^\dagger l_L^\alpha)$$

$$\mathcal{O}_{s\tilde{G}} = sG_{\mu\nu}^A\tilde{G}_A^{\mu\nu}$$

$$\mathcal{O}_{s\tilde{W}} = sW_{\mu\nu}^A\tilde{W}_A^{\mu\nu}$$

$$\mathcal{O}_{s\tilde{B}} = sB_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\mathcal{R}_{s\phi\Box} = \mathrm{i}s(\phi^\dagger D^2\phi - (D^2\phi)^\dagger\phi)$$

$$\mathcal{R}_{sq}^{\alpha\beta} = s(\overline{q_L^\alpha}\not{D}q_L^\beta + \overline{q_L^\beta}\overleftarrow{\not{D}}q_L^\alpha)$$

$$\mathcal{R}_{sl}^{\alpha\beta} = s(\overline{l_L^\alpha}\not{D}l_L^\beta + \overline{l_L^\beta}\overleftarrow{\not{D}}l_L^\alpha)$$

$$\mathcal{R}_{su}^{\alpha\beta} = s(\overline{u_R^\alpha}\not{D}u_R^\beta + \overline{u_R^\beta}\overleftarrow{\not{D}}u_R^\alpha)$$

$$\mathcal{R}_{sd}^{\alpha\beta} = s(\overline{d_R^\alpha}\not{D}d_R^\beta + \overline{d_R^\beta}\overleftarrow{\not{D}}d_R^\alpha)$$

$$\mathcal{R}_{se}^{\alpha\beta} = s(\overline{e_R^\alpha}\not{D}e_R^\beta + \overline{e_R^\beta}\overleftarrow{\not{D}}e_R^\alpha)$$

Complete Green basis of operators

SMEFT+ALP

Approximate shift symmetry: $s \to s + \sigma$

$$\mathcal{L}^{(5)} = \sum_{\Psi} (\partial_\mu s) \bar{\Psi} C_\Psi \gamma^\mu \Psi + C_X s X_{\mu\nu} \tilde{X}^{\mu\nu}$$

SMEFT+ALP

Approximate shift symmetry: $s \to s + \sigma$

$$\mathcal{L}^{(5)} = \sum_{\Psi} (\partial_\mu s) \bar{\Psi} C_\Psi \gamma^\mu \Psi + C_X s X_{\mu\nu} \tilde{X}^{\mu\nu}$$

Lepton sector:

9 + 9 independent parameters: $C_\ell + C_e$

9 + 9 independent parameters: $a_{se\phi} + a_{\widetilde{se\phi}}$

$\mathcal{O}_{se\phi}$ CP-even

$\mathcal{O}_{\widetilde{se\phi}}$ CP-odd

SMEFT+ALP

Approximate shift symmetry: $s \to s + \sigma$

$$\mathcal{L}^{(5)} = \sum_{\Psi} (\partial_\mu s) \bar{\Psi} C_\Psi \gamma^\mu \Psi + C_X s X_{\mu\nu} \tilde{X}^{\mu\nu}$$

Lepton sector:

9 + 9 independent parameters: $C_\ell + C_e$ (only shift symmetric)

9 + 9 independent parameters: $a_{se\phi} + a_{\widetilde{se\phi}}$

$\mathcal{O}_{se\phi}$ CP-even

$\mathcal{O}_{\widetilde{se\phi}}$ CP-odd

SMEFT+ALP

Performing the appropriate chiral rotations, the necessary conditions to ensure shift-symmetry are:

$$a_{se\phi} = \mathrm{Re}(H_\ell y^e + y^e H_e)$$

$$a_{\widetilde{se\phi}} = -\mathrm{Im}(H_\ell y^e + y^e H_e)$$

Limit of 1 lepton family: $a_{se\phi}$ **VS** $C_e + C_\ell$ **parameters**

SMEFT+ALP

- Computation of divergences generated by 1PI diagrams at one-loop
- Up to $\mathcal{O}(1/\Lambda)$ divergences are absorbed by operators of off-shell basis

Computation: Feynrules + FeynArts + FormCalc

T. Hahn, hep-ph/0012260

T. Hahn and M. Perez-Victoria hep-ph/9807565

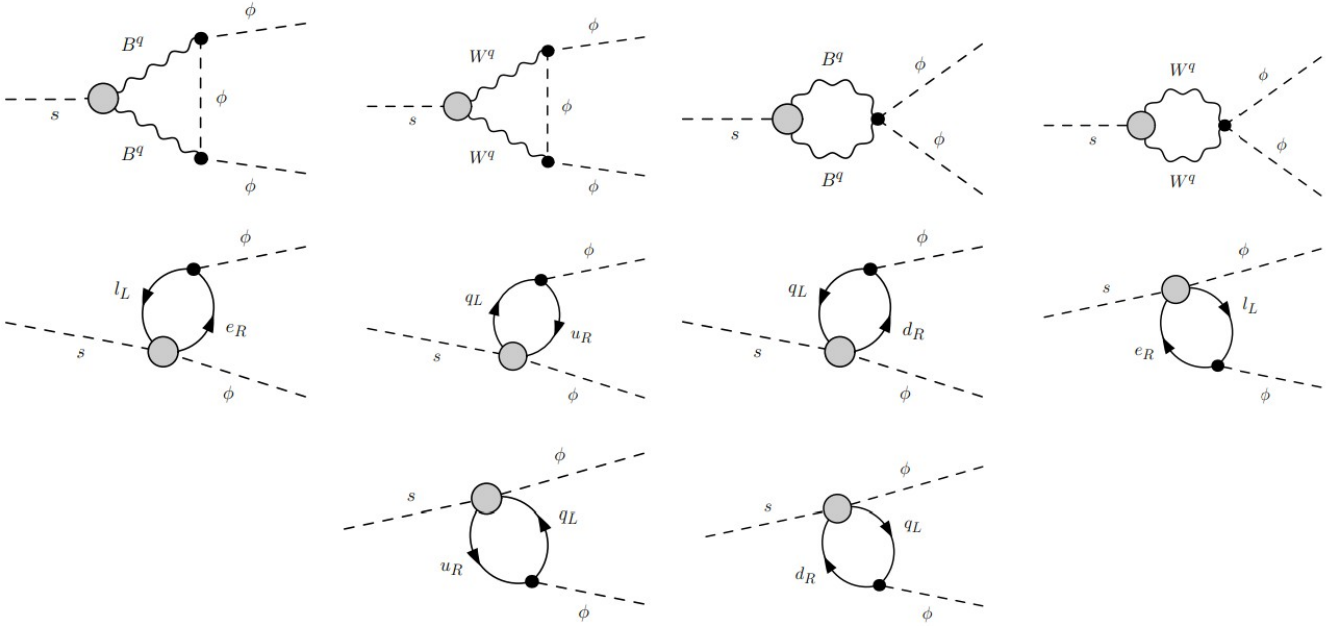
Manual check: Feynrules + QGRAF

A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, B. Fuks, 1310.1921

P. Nogueira, JCP 105 (1993) 279

SMEFT+ALP: removing redundancies

$$s \to \phi \, \phi^\dagger$$



SMEFT+ALP: removing redundancies

$$i\mathcal{M}_{\text{loop}} = \left\{ \frac{1}{16\pi^2\epsilon} \text{Tr}[y^e a^T_{se\phi}] + 3\text{Tr}[y^d a^T_{sd\phi} - a_{su\phi} y^{u\dagger}] \right\} (p_2^2 - p_3^2)$$

$$i\mathcal{M}_{EFT} = r_{s\phi\Box}(p_2^2 - p_3^2)$$

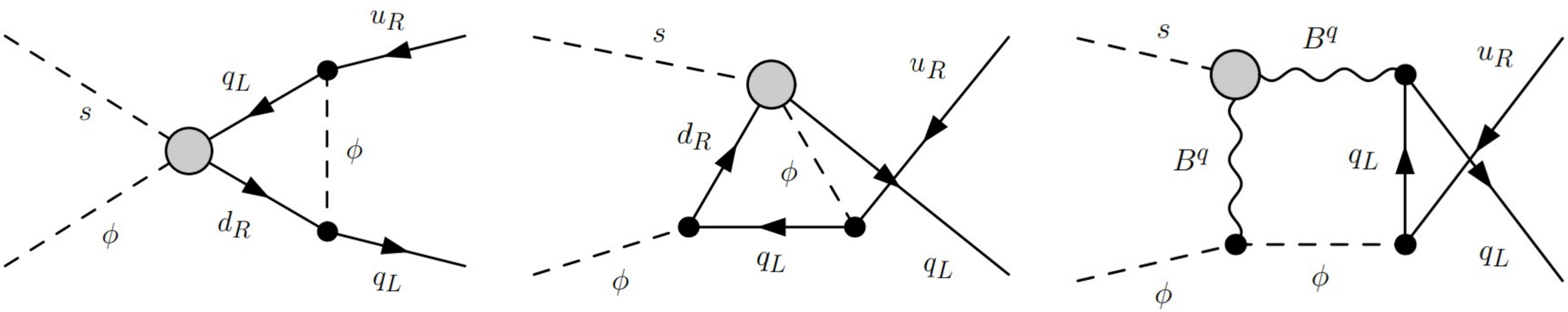
$$\mathcal{R}_{s\phi\Box} = is\phi^\dagger \overleftrightarrow{D}^2 \phi$$

$$r_{s\phi\Box}\mathcal{R}_{s\phi\Box} = r_{s\phi\Box}\left(\text{Re}(y^u)\mathcal{O}_{su\phi} + \text{Re}(y^d)\mathcal{O}_{sd\phi} + \text{Re}(y^e)\mathcal{O}_{se\phi}\right)$$

SMEFT+ALP: mixing

$$s\phi^\dagger \to q_L \overline{u}_R$$

$$\mathcal{O}_{su\phi} = is\bar{q}_L\tilde{\phi}u_R + h.c.$$



SMEFT+ALP: RGEs

$$\mathcal{L}_{div} = \mathcal{O}_n a'_n \equiv \mathcal{O}_n \frac{C_{nm}}{32\pi^2\epsilon} a_m$$

dim-4 couplings

$$\beta_{a_n} = 16\pi^2 \mu \frac{da_n}{d\mu} = \gamma_{nm} a_m$$

anomalous dimension matrix (AD matrix)

$$\gamma_{nm} = -(\mathcal{C}_{nm} + K_n^F \delta_{nm})$$

$$Z_n^F = 1 + \frac{K_n^F}{32\pi^2\epsilon}$$

Wave function renormalization

SMEFT+ALP: AD matrix

$$\begin{pmatrix} \beta_{a^{\alpha}_{su\phi}} \\ \beta_{a^{\alpha}_{sd\phi}} \\ \beta_{a^{\alpha}_{se\phi}} \\ \beta_{a_{s\tilde{G}}} \\ \beta_{a_{s\tilde{W}}} \\ \beta_{a_{s\tilde{B}}} \end{pmatrix} = \begin{pmatrix} \gamma_{11} + 6y_u^{\alpha}y_u^{\rho} & y_d^{\alpha}y_u^{\alpha} - 6y_u^{\alpha}y_d^{\rho} & -2y_u^{\alpha}y_e^{\rho} & -32g_3^2y_u^{\alpha} & -9g_2^2y_u^{\alpha} & -\frac{17}{3}g_1^2y_u^{\alpha} \\ y_u^{\alpha}y_d^{\alpha} - 6y_d^{\alpha}y_u^{\rho} & \gamma_{22} + 6y_d^{\alpha}y_d^{\rho} & 2y_d^{\alpha}y_e^{\rho} & -32g_3^2y_d^{\alpha} & -9g_2^2y_d^{\alpha} & -\frac{5}{3}g_1^2y_d^{\alpha} \\ -6y_e^{\alpha}y_u^{\rho} & 6y_e^{\alpha}y_d^{\rho} & \gamma_{33} + 2y_e^{\alpha}y_e^{\rho} & 0 & -9g_2^2y_e^{\alpha} & -15g_1^2y_e^{\alpha} \\ \hline 0 & 0 & 0 & -14g_3^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{19}{3}g_2^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{41}{3}g_1^2 \end{pmatrix} \begin{pmatrix} a^{\rho}_{su\phi} \\ a^{\rho}_{sd\phi} \\ a^{\rho}_{se\phi} \\ a_{s\tilde{G}} \\ a_{s\tilde{W}} \\ a_{s\tilde{B}} \end{pmatrix}$$

SMEFT+ALP: AD matrix

$$\begin{pmatrix} \beta_{a^\alpha_{su\phi}} \\ \beta_{a^\alpha_{sd\phi}} \\ \beta_{a^\alpha_{se\phi}} \\ \beta_{a_{s\tilde{G}}} \\ \beta_{a_{s\tilde{W}}} \\ \beta_{a_{s\tilde{B}}} \end{pmatrix} = \begin{pmatrix} \gamma_{11} + 6y_u^\alpha y_u^\rho & y_d^\alpha y_u^\alpha - 6y_u^\alpha y_d^\rho & -2y_u^\alpha y_e^\rho & -32g_3^2 y_u^\alpha & -9g_2^2 y_u^\alpha & -\frac{17}{3}g_1^2 y_u^\alpha \\ y_u^\alpha y_d^\alpha - 6y_d^\alpha y_u^\rho & \gamma_{22} + 6y_d^\alpha y_d^\rho & 2y_d^\alpha y_e^\rho & -32g_3^2 y_d^\alpha & -9g_2^2 y_d^\alpha & -\frac{5}{3}g_1^2 y_d^\alpha \\ -6y_e^\alpha y_u^\rho & 6y_e^\alpha y_d^\rho & \gamma_{33} + 2y_e^\alpha y_e^\rho & 0 & -9g_2^2 y_e^\alpha & -15g_1^2 y_e^\alpha \\ \hline 0 & 0 & 0 & -14g_3^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{19}{3}g_2^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{41}{3}g_1^2 \end{pmatrix} \begin{pmatrix} a^\rho_{su\phi} \\ a^\rho_{sd\phi} \\ a^\rho_{se\phi} \\ a_{s\tilde{G}} \\ a_{s\tilde{W}} \\ a_{s\tilde{B}} \end{pmatrix}$$

Nonrenormalization theorems

C. Cheung and C.-H. Shen, 1505.01844

SMEFT+ALP: AD matrix

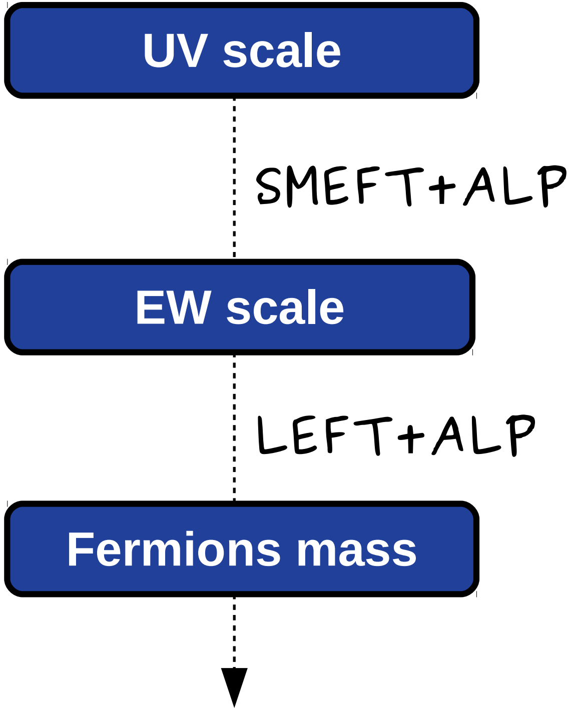
$$
\begin{pmatrix} \beta_{a^\alpha_{su\phi}} \\ \beta_{a^\alpha_{sd\phi}} \\ \beta_{a^\alpha_{se\phi}} \\ \beta_{a_{s\tilde{G}}} \\ \beta_{a_{s\tilde{W}}} \\ \beta_{a_{s\tilde{B}}} \end{pmatrix} = \begin{pmatrix} \gamma_{11} + 6y_u^\alpha y_u^\rho & y_d^\alpha y_u^\alpha - 6y_u^\alpha y_d^\rho & -2y_u^\alpha y_e^\rho & -32g_3^2 y_u^\alpha & -9g_2^2 y_u^\alpha & -\frac{17}{3} g_1^2 y_u^\alpha \\ y_u^\alpha y_d^\alpha - 6y_d^\alpha y_u^\rho & \gamma_{22} + 6y_d^\alpha y_d^\rho & 2y_d^\alpha y_e^\rho & -32g_3^2 y_d^\alpha & -9g_2^2 y_d^\alpha & -\frac{5}{3} g_1^2 y_d^\alpha \\ -6y_e^\alpha y_u^\rho & 6y_e^\alpha y_d^\rho & \gamma_{33} + 2y_e^\alpha y_e^\rho & 0 & -9g_2^2 y_e^\alpha & -15g_1^2 y_e^\alpha \\ \hline 0 & 0 & 0 & -14g_3^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{19}{3} g_2^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{41}{3} g_1^2 \end{pmatrix} \begin{pmatrix} a^\rho_{su\phi} \\ a^\rho_{sd\phi} \\ a^\rho_{se\phi} \\ a_{s\tilde{G}} \\ a_{s\tilde{W}} \\ a_{s\tilde{B}} \end{pmatrix}
$$

Nonrenormalization theorems

C. Cheung and C.-H. Shen, 1505.01844

$g_3^2 C_{G\tilde{G}} \mathcal{O}_{sG\tilde{G}}$

LEFT – below EW scale



Below the electroweak scale:

- Write most general LEFT+ALP (without W, Z, H and top quark)
- Match to SMEFT+ALP

  See also M. Bauer, M. Neubert, S. Renner, M. Schnubel, A. Thamm, 2012.12272

- Integrate out fermions as mass thresholds are passed

LEFT: independent basis

$$\mathcal{L}_{\rm LEFT} = \frac{1}{2}(\partial_\mu s)(\partial^\mu s) - \frac{1}{2}\tilde{m}^2 s^2 - \frac{\tilde{\lambda}_s}{4!}s^4 - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$+ \sum_{\psi=u,d,e}\left\{\overline{\psi^\alpha}\mathrm{i}\not{D}\psi^\alpha - \left[(\tilde{m}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R - s\,\mathrm{i}(\tilde{c}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R + \mathrm{h.c.}\right]\right\}$$
$$+ \tilde{a}_{s\tilde{G}}s\,G^A_{\mu\nu}\widetilde{G}^{A\,\mu\nu} + \tilde{a}_{s\tilde{A}}sA_{\mu\nu}\widetilde{A}^{\mu\nu}$$
$$+ \sum_{\psi=u,d,e}\left\{(\tilde{a}_{\psi A})_{\alpha\beta}\overline{\psi^\alpha_L}\sigma^{\mu\nu}\psi^\beta_R A_{\mu\nu} + (\tilde{a}_{\psi G})_{\alpha\beta}\overline{\psi^\alpha_L}\sigma^{\mu\nu}T_A\psi^\beta_R G^A_{\mu\nu} + s^2(\tilde{a}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R + \mathrm{h.c.}\right\}$$

c: dim-4

a: dim-5

dim-5 purely SMEFT

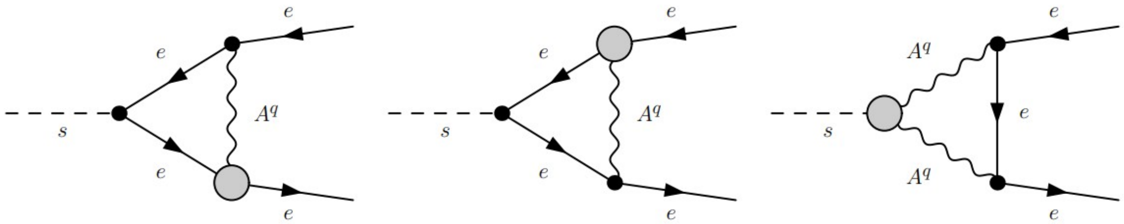
LEFT: masses

Effective operators can renormalize **lower** dimension operators:

$$
\begin{aligned}
\beta_{\tilde{c}_e} = & -6\tilde{e}^2\tilde{c}_e + 3\tilde{c}_e\tilde{c}_e^\dagger\tilde{c}_e + 2\left[\mathrm{Tr}(\tilde{c}_e\tilde{c}_e^\dagger) + 6\mathrm{Tr}(\tilde{c}_d\tilde{c}_d^\dagger) + 6\mathrm{Tr}(\tilde{c}_u\tilde{c}_u^\dagger)\right]\tilde{c}_e \\
& -8\left[3\tilde{e}^2\tilde{a}_{s\tilde{A}}\right]\tilde{m}_e + 2\left[\tilde{a}_e\left(\tilde{c}_e^\dagger\tilde{m}_e - 2\tilde{m}_e^\dagger\tilde{c}_e\right) + \left(\tilde{m}_e\tilde{c}_e^\dagger - 2\tilde{c}_e\tilde{m}_e^\dagger\right)\tilde{a}_e\right] \\
& -12\tilde{e}\left[\tilde{m}_e\tilde{c}_e^\dagger\tilde{a}_{eA} + \tilde{a}_{eA}\tilde{c}_e^\dagger\tilde{m}_e - \tilde{c}_e\tilde{m}_e^\dagger\tilde{a}_{eA} - \tilde{a}_{eA}\tilde{m}_e^\dagger\tilde{c}_e\right];
\end{aligned}
$$

dim-4 contributions

dim-5 contributions



$$\tilde{a}_{s\tilde{A}}\, s A_{\mu\nu}\tilde{A}^{\mu\nu}$$

$$\tilde{a}_{\psi A}\overline{\psi}\sigma^{\mu\nu}\psi A_{\mu\nu}$$

LEFT: ALP-gauge couplings

$$\tilde{a}_{s\tilde{A}} s A_{\mu\nu} \tilde{A}^{\mu\nu}$$

$$\tilde{a}_{\psi A} \overline{\psi} \sigma^{\mu\nu} \psi A_{\mu\nu}$$

$$\beta_{\tilde{a}_{s\tilde{A}}} = 4\tilde{e}\mathrm{Tr}\Big[\left(\tilde{c}_e \underline{\tilde{a}^\dagger_{eA}} + \tilde{c}^\dagger_e \underline{\tilde{a}_{eA}}\right) + \left(\tilde{c}_d \underline{\tilde{a}^\dagger_{dA}} + \tilde{c}^\dagger_d \underline{\tilde{a}_{dA}}\right) - 2\left(\tilde{c}_u \underline{\tilde{a}^\dagger_{uA}} + \tilde{c}^\dagger_u \underline{\tilde{a}_{uA}}\right)\Big]$$
$$+ 2\mathrm{Tr}\left[\tilde{c}_e \tilde{c}^\dagger_e + 3\left(\tilde{c}_d \tilde{c}^\dagger_d + \tilde{c}_u \tilde{c}^\dagger_u\right)\right] \tilde{a}_{s\tilde{A}} + \frac{8}{3}\tilde{e}^2 \left[n_\ell + \frac{1}{3} n_d + \frac{4}{3} n_u\right] \tilde{a}_{s\tilde{A}} \,,$$

NEW pheno: ALP-gauge boson couplings no longer run only proportional to itself. They can be generated by dipole operator

LEFT: ALP-gauge couplings

$$\tilde{a}_{s\tilde{A}} s A_{\mu\nu} \tilde{A}^{\mu\nu}$$

$$\tilde{a}_{\psi A} \overline{\psi} \sigma^{\mu\nu} \psi A_{\mu\nu}$$

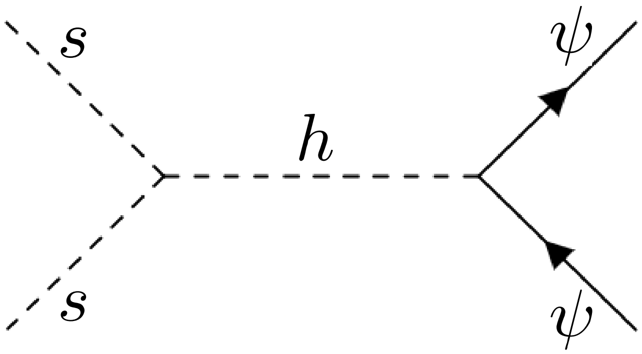
$$\beta_{\tilde{a}_{s\tilde{A}}} = 4\tilde{e}\,\mathrm{Tr}\left[\left(\tilde{c}_e \tilde{a}^\dagger_{eA} + \tilde{c}^\dagger_e \tilde{a}_{eA}\right) + \left(\tilde{c}_d \tilde{a}^\dagger_{dA} + \tilde{c}^\dagger_d \tilde{a}_{dA}\right) - 2\left(\tilde{c}_u \tilde{a}^\dagger_{uA} + \tilde{c}^\dagger_u \tilde{a}_{uA}\right)\right] + 2\mathrm{Tr}\left[\tilde{c}_e \tilde{c}^\dagger_e + 3\left(\tilde{c}_d \tilde{c}^\dagger_d + \tilde{c}_u \tilde{c}^\dagger_u\right)\right] \tilde{a}_{s\tilde{A}} + \frac{8}{3}\tilde{e}^2 \left[n_\ell + \frac{1}{3} n_d + \frac{4}{3} n_u\right] \tilde{a}_{s\tilde{A}}\,,$$

Result of integrating out fermions

NEW pheno: ALP-gauge boson couplings no longer run only proportional to itself. They can be generated by dipole operator

LEFT: matching to SMEFT+ALP

The SMEFT+ALP alone does not generate all couplings, for example:



$$\sim \lambda_{s\phi} \frac{y^{\psi}}{v} \sim \lambda_{s\phi} \frac{m_{\psi}}{v^2}$$

higher order in the low energy power counting

Different completions above EW could generate them

Phenomenological applications

Photophobic ALP:

N. Craig, A. Hook and S. Kasko, 1805.06538

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu s \partial^\mu s + \frac{1}{2}\tilde{m}^2 s^2 + \frac{a_{s\tilde{Z}}}{c_\omega^2 - s_\omega^2} s \left(c_\omega^2 W_{\mu\nu}\widetilde{W}^{\mu\nu} - s_\omega^2 B_{\mu\nu}\widetilde{B}^{\mu\nu} \right)$$

Direct constraints from mono-Z:

$a_{s\tilde{Z}} < 0.2\ \text{TeV}^{-1}$ @LHC Run II

$a_{s\tilde{Z}} < 0.04\ \text{TeV}^{-1}$ @LHC-HL

I. Brivio, M. Gavela, L. Merlo, K. Mimasu, J. No, R. del Rey and V. Sanz, 1701.05379

Phenomenological applications

The ALP-Z coupling generates the electron coupling through running:

$$\beta_{a_{se\phi}} = 2\Big[a_{se\phi}\Big(\lambda_{s\phi} - \frac{15g_1^2}{8} - \frac{9g_2^2}{8} + \frac{1}{2}\gamma_\phi^{(Y)}\Big) + \frac{5}{4}y^e y^{e\dagger} a_{se\phi} + a_{se\phi} y^{e\dagger} y^e$$
$$- \Big(\frac{15g_1^2}{2} a_{s\tilde{B}} + \frac{9g_2^2}{2} a_{s\widetilde{W}} - \mathrm{Tr}\left[y^e a_{se\phi}^\intercal + 3y^d a_{sd\phi}^\intercal - 3a_{su\phi} y^{u\dagger})\right]\Big) y^e\Big]$$

Strong constraints on the ALP-electron coupling through Red Giant cooling @KeV

Phenomenological applications

Translate the **ALP-ee** bound into an **ALP-ZZ** bound**:**

- Run LEFT coupling to electron up to EW scale
  (plus, match at fermion masses)
- Match at eletroweak scale to get bound on $a_{se\phi}$
- Compute ALP-Z coupling at high energy whose running generates the bound on $a_{se\phi}$

$$a_{s\tilde{Z}} < 4.8 \times 10^{-6}\ \mathrm{TeV}^{-1} \quad \text{vs} \quad a_{s\tilde{Z}} < 0.04\ \mathrm{TeV}^{-1}$$

Phenomenological applications

Top-philic ALP:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu s \partial^\mu s + \frac{1}{2}\tilde{m}^2 s^2 + a_t s[i\bar{q}_L\tilde{\phi}t_R + \text{h.c.}]$$

J. Ebadi, S. Khatibi and M. M. Najafabadi, 1901.03061

$$a_t \lesssim \text{TeV}^{-1}$$

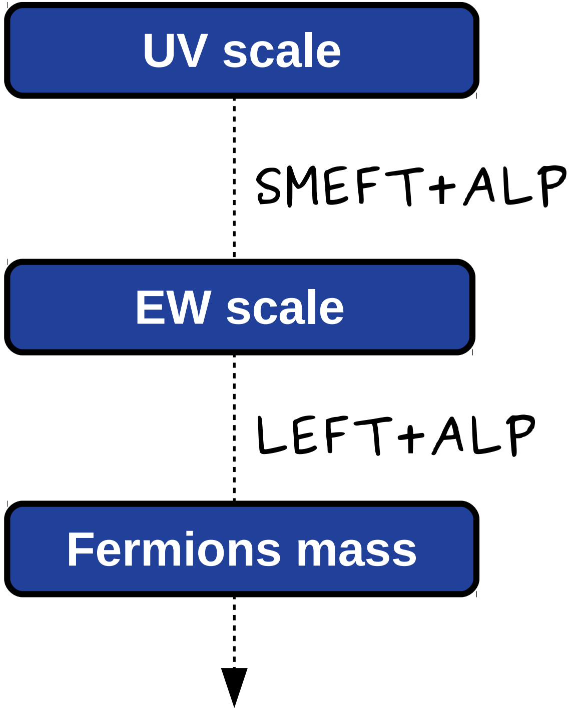
$$a_t < 4.3 \times 10^{-6}\ \text{TeV}^{-1}$$

indirect bound

vs

RGE constraint

Conclusions



- Important to use RGEs to correctly interpret experimental bounds
- Mixing effects can have significant contributions
- LEFT running can lead to interesting new pheno results

Thanks

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Back-up slides

Periodic Axion

Starting from a periodic axion:

$$\mathcal{L} \supset \partial_\mu(s)\left(\bar{\ell}_L k_L \gamma^\mu \ell_L + \bar{\ell}_R k_R \gamma^\mu \ell_R\right) + \sum_{n\in Z} (M_n \bar{\ell}_R e^{(ina/f_a)} \ell_L + \text{h.c.})$$

$$+c_{gg}\frac{\alpha_s}{8\pi} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + c_{\gamma\gamma}\frac{\alpha}{4\pi} a A_{\mu\nu}\tilde{A}^{\mu\nu}$$

Manuel A. Buen-Abad, Jiji Fan, Matthew Reece and Chen Sun 2104.03267