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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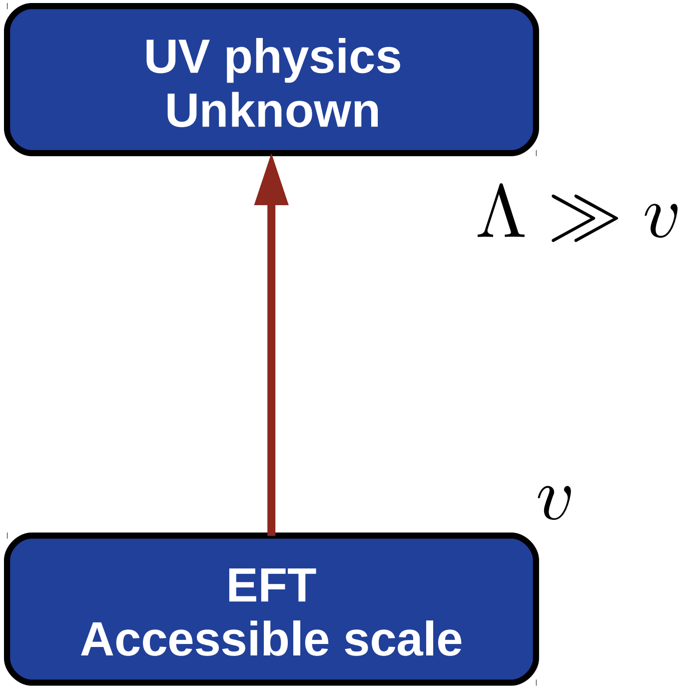
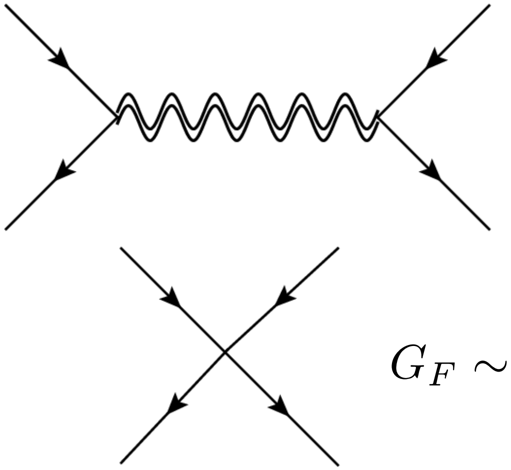
Motivation: EFT approach



e.g. **Fermi theory**



$$G_F \sim \frac{g_\omega^2}{m_W^2}$$

$$\mathcal{L}_{\rm IR} = G_F(\overline{\psi}\gamma_\mu\psi)^2$$

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
- Composite Higgs Models
- Dark Matter
- Anomalies

$$\mathcal{L}_{\rm SM} \supset \theta G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\downarrow$$

$\langle s \rangle$ cancels θ

Peccei, Quinn PRL38 (1977) 1440

Motivation: ALPs

Axion-like particles = CP-odd singlet scalars

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$$SU(3) \times U(1) \to SU(2) \times U(1)$$

$$SO(n)/SO(n-1), \; n > 5$$

$$SU(4) \to S_p(4)$$

$$\cdots$$

Brando Bellazzini, Csaba Csáki and Javi Serra, 1401.2457

Motivation: ALPs

Axion-like particles = CP-odd singlet scalars

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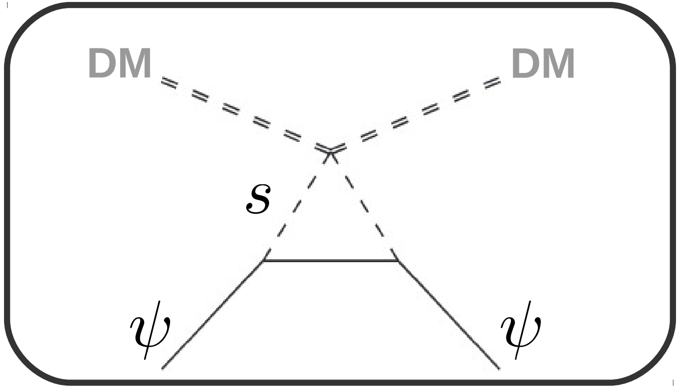

M. J. Dolan, F. Kahlhoefer, C. McCabe and K. Schmidt-Hoberg, 1412.5174
M. Ramos, 1912.11061

Motivation: ALPs

Axion-like particles = CP-odd singlet scalars

Theoretically well motivated:

- Strong CP-problem
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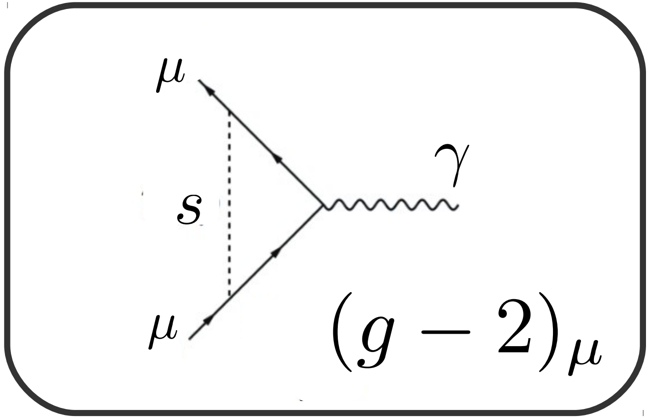
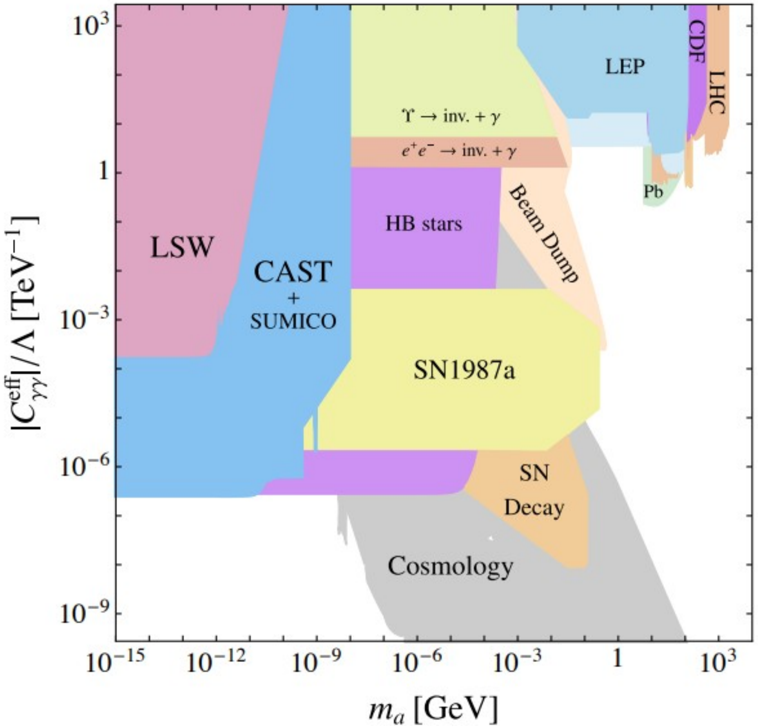
- Dark Matter
- <u>Anomalies</u>



J. Liu, C. Wagner and X. Wang, 1810.11028

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

Running in the ALPs

Some partial results in the literature:

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

M. Bauer, C. Horner and M. Neubert, 1603.05978

K. Choi, et. al, 1708.00021

What's new:

- Full anomalous dimension matrix calculation
- Comparison between shift-invariant/breaking basis
- Matching and running below the electroweak scale

SMEFT+ALP

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

$\mathcal{O}_i^{(5)}$ 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: $a_{se\phi} + a_{\widetilde{se\phi}}$

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

$a_{\widetilde{se\phi}} \to \mathcal{O}_{\widetilde{se\phi}}$ 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: RGEs

bare coupling

$$\mathcal{L} = \partial_\mu s_0 \partial^\mu s_0 + \lambda_s^0 s_0^4$$

In DR, [L] = 4−2e

$$s_0 \to \sqrt{Z_s} s \qquad \lambda_s^0 \to \mu^{2\epsilon} Z_{\lambda_s} \lambda_s$$

$$\mathcal{L} = \partial_\mu s \partial^\mu s + \mu^{2\epsilon}\lambda_s s^4 + (Z_s - 1)\partial_\mu s \partial^\mu s + (Z_s^2 Z_{\lambda_s} - 1)\mu^{2\epsilon}\lambda_s s^4$$

Calculate Z-factors in order to cancel generated divergences

SMEFT+ALP: RGEs

bare coupling

$$\mathcal{L} = \partial_\mu s_0 \partial^\mu s_0 + \lambda_s^0 s_0^4$$

In DR, [L] = 4−2e

$$s_0 \to \sqrt{Z_s} s \qquad \lambda_s^0 \to \mu^{2\epsilon} Z_{\lambda_s} \lambda_s$$

$$\mathcal{L} = \partial_\mu s \partial^\mu s + \mu^{2\epsilon}\lambda_s s^4 + (Z_s - 1)\partial_\mu s \partial^\mu s + (Z_s^2 Z_{\lambda_s} - 1)\mu^{2\epsilon}\lambda_s s^4$$

RGE: $$0 = \mu \frac{d}{d\mu}\lambda_s^0 = \mu \frac{d}{d\mu}(\lambda_s \mu^{2\epsilon} Z_{\lambda_s})$$

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

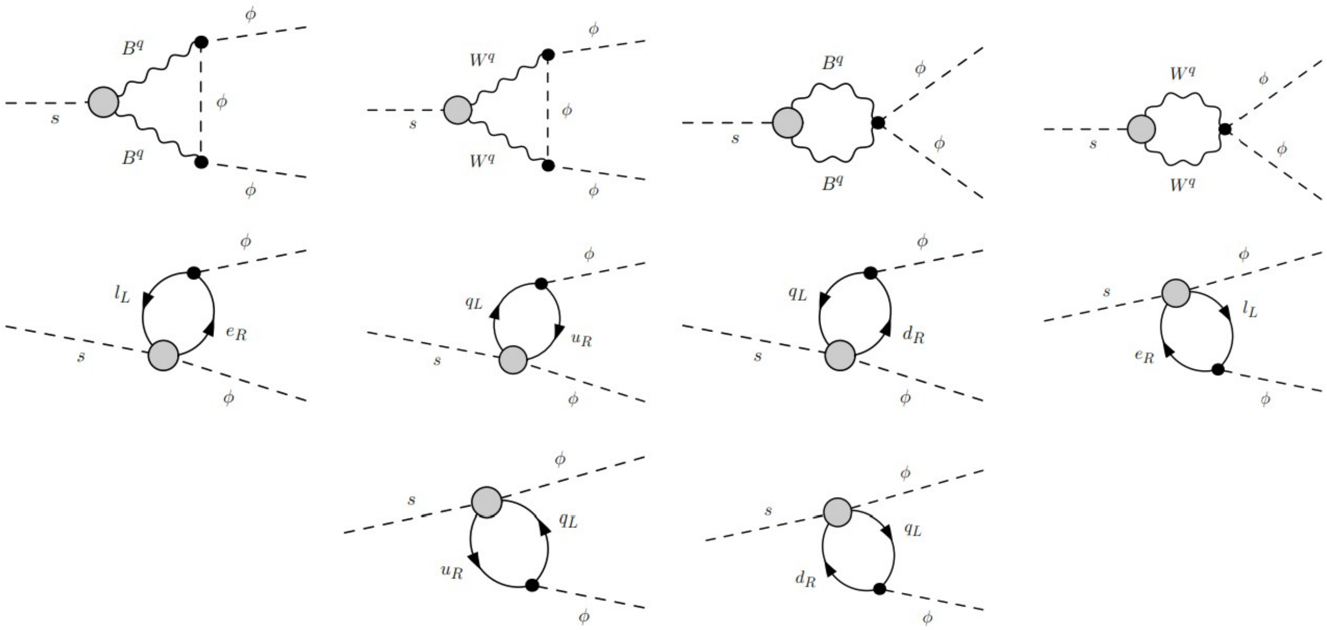
Manual check: `Feynrules` + `QGRAF`

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

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

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

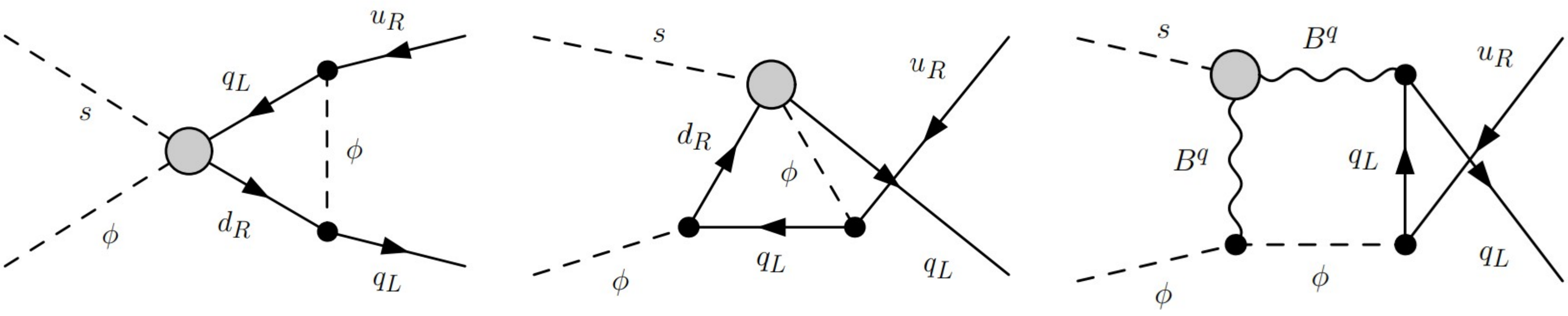
$$\mathcal{R}_{s\phi\Box} = is\phi^\dagger \overleftrightarrow{D}^2 \phi$$

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

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: RGEs

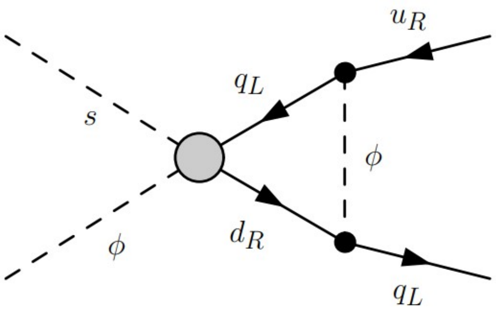
e.g: $$Z^F_{\mathcal{O}_{su\phi}} = \sqrt{Z_{q_L} Z_\phi Z_{u_R}}$$

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

$$Z_\phi = 1 + \frac{1}{32\pi^2\epsilon}\left[g_1^2 + 3g_2^2 - 2\gamma_\phi^{(Y)}\right]$$

$$Z_{u_R} = 1 - \frac{1}{48\pi^2\epsilon}\left[\frac{4}{3}g_1^2 + 4g_3^2 + 3y^{u\dagger}y^u\right]$$

$$Z_{q_L} = 1 - \frac{1}{96\pi^2\epsilon}\left[\frac{1}{6}g_1^2 + \frac{9}{2}g_2^2 + 8g_3^2 + 3y^u y^{u\dagger} + 3y^d y^{d\dagger}\right]$$



SMEFT+ALP: AD matrix

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

SMEFT+ALP: AD matrix

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

Nonrenormalization theorems

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

SMEFT+ALP: AD matrix

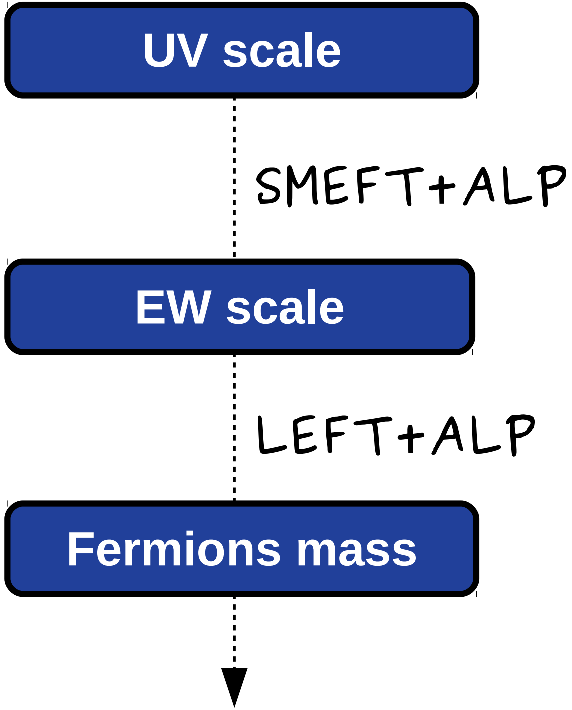
$$
\begin{pmatrix} \beta_{a^\alpha_{su\phi}} \\ \beta_{a^\alpha_{sd\phi}} \\ \beta_{a^\alpha_{se\phi}} \\ \beta_{a_{s\tilde{G}}} \\ \beta_{a_{s\tilde{W}}} \\ \beta_{a_{s\tilde{B}}} \end{pmatrix}
=
\begin{pmatrix}
\gamma_{11} + 6y_u^\alpha y_u^\rho & y_d^\alpha y_u^\alpha - 6y_u^\alpha y_d^\rho & -2y_u^\alpha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

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
- Integrate out fermions as mass thresholds are passed

LEFT: independent basis

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

c: dim-4
a: dim-5

dim-5 purely SMEFT

LEFT: chiral rotation ambiguity

Removing redundant operators:

Terms with ALP

$$\mathcal{L}_R = \sum_\psi \left[\tilde{r}_{\psi\Box}\overline{\psi_L^\alpha} D^2 \psi_R^\beta + \text{h.c.}\right] + \ldots$$

$$D^2 = \not{D}^2 + \frac{\sigma_{\mu\nu}}{2}\left(\tilde{e}QA^{\mu\nu} + \tilde{g}_3 G_A^{\mu\nu} T_A\right)$$

EOM:

$$\mathrm{i}\not{D}\psi_\alpha = m_{\alpha\beta}\psi_R^\beta + m^\dagger_{\alpha\beta}\psi_L^\beta - \mathrm{i}\left(\tilde{c}_\psi\right)_{\alpha\beta} s\psi_R^\beta + \mathrm{i}(\tilde{c}_\psi^\dagger)_{\alpha\beta} s\psi_L^\beta$$

LEFT: chiral rotation ambiguity

We conveniently **choose** to split the covariant derivative as:

$$\frac{\tilde{r}_{\psi\Box}}{2}\overline{\psi_L^\alpha}\left(\not{D}^2+\overleftarrow{\not{D}}^2\right)\psi_R^\beta+\frac{\tilde{r}^\dagger_{\psi\Box}}{2}\overline{\psi_R^\alpha}\left(\not{D}^2+\overleftarrow{\not{D}}^2\right)\psi_L^\beta$$

EOM

$$\rightarrow -\overline{\psi_L}\frac{\tilde{r}_{\psi\Box}\tilde{m}^\dagger_\psi+\tilde{m}_\psi\tilde{r}^\dagger_{\psi\Box}}{2}\mathrm{i}\not{D}\psi_L+\ldots$$

Apparent ambiguity if we had not **IBP**: disappears after chiral rotation

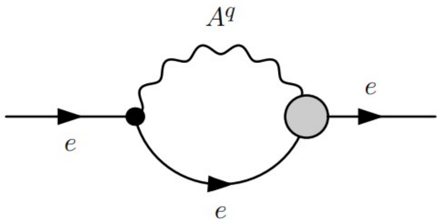
See Also E. E. Jenkins, A. V. Manohar and P. Stoffer , 1709.04486

LEFT: chiral rotation ambiguity

We conveniently **choose** to split the covariant derivative as:

$$Z_{e_L} = (\text{dim-4}) - \frac{3\tilde{e}}{16\pi^2\epsilon}\left(\tilde{m}_e \tilde{a}^\dagger_{eA} + \tilde{a}_{eA}\tilde{m}^\dagger_e\right) + \frac{1}{2}\left(\tilde{r}_{e\Box}\tilde{m}^\dagger_e + \tilde{m}_e\tilde{r}^\dagger_{e\Box}\right)$$

where $$\tilde{r}_{e\Box} = \frac{3}{8\pi^2\epsilon} e\tilde{a}_{eA}$$

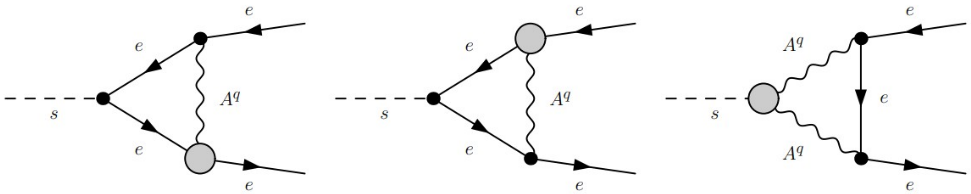


$$Z_{e_L} = (\text{dim-4})$$ up to 1/M at 1-loop

LEFT: masses

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

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



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

$$\beta_{\tilde{c}_e} = -6\tilde{e}^2\tilde{c}_e + 3\tilde{c}_e\tilde{c}_e^\dagger\tilde{c}_e + 2\left[\mathrm{Tr}(\tilde{c}_e\tilde{c}_e^\dagger) + 6\mathrm{Tr}(\tilde{c}_d\tilde{c}_d^\dagger) + 6\mathrm{Tr}(\tilde{c}_u\tilde{c}_u^\dagger)\right]\tilde{c}_e$$

dim−4 contributions

$$-8\left[3\tilde{e}^2\tilde{a}_{s\tilde{A}}\right]\tilde{m}_e + 2\left[\tilde{a}_e\left(\tilde{c}_e^\dagger\tilde{m}_e - 2\tilde{m}_e^\dagger\tilde{c}_e\right) + \left(\tilde{m}_e\tilde{c}_e^\dagger - 2\tilde{c}_e\tilde{m}_e^\dagger\right)\tilde{a}_e\right]$$
$$-12\tilde{e}\left[\tilde{m}_e\tilde{c}_e^\dagger\tilde{a}_{eA} + \tilde{a}_{eA}\tilde{c}_e^\dagger\tilde{m}_e - \tilde{c}_e\tilde{m}_e^\dagger\tilde{a}_{eA} - \tilde{a}_{eA}\tilde{m}_e^\dagger\tilde{c}_e\right];$$

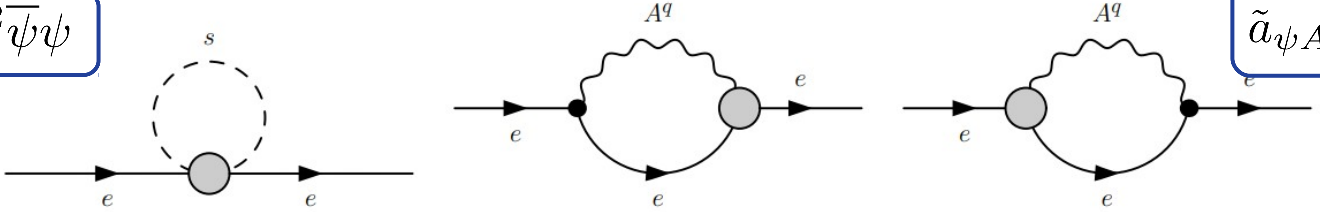
dim−5 contributions

LEFT: masses

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

$\tilde{a}_\psi s^2 \overline{\psi}\psi$

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



$$
\begin{aligned}
\beta_{\tilde{m}_e} = &-6\tilde{e}^2\tilde{m}_e + \frac{1}{2}(\tilde{m}_e\tilde{c}_e^\dagger\tilde{c}_e + \tilde{c}_e\tilde{c}_e^\dagger\tilde{m}_e + 4\tilde{c}_e\tilde{m}_e^\dagger\tilde{c}_e) \\
&+ \mathrm{Tr}(\tilde{c}_e\tilde{m}_e^\dagger + \tilde{c}_e^\dagger\tilde{m}_e + 3\tilde{c}_u\tilde{m}_u^\dagger + 3\tilde{c}_u^\dagger\tilde{m}_u + 3\tilde{m}_d\tilde{c}_d^\dagger + 3\tilde{m}_d^\dagger\tilde{c}_d)\tilde{c}_e \\
&+12\tilde{e}\left(\tilde{m}_e\tilde{m}_e^\dagger\tilde{a}_{eA} + \tilde{a}_{eA}\tilde{m}_e^\dagger\tilde{m}_e\right) - \underline{2\tilde{m}^2\tilde{a}_e}
\end{aligned}
$$

dim−4 contributions

dim−5 contributions

LEFT: ALP-gauge couplings

$$a_{s\tilde{A}} s A_{\mu\nu} \tilde{A}^{\mu\nu}$$

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

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

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

LEFT: ALP-gauge couplings

$a_{s\tilde{A}} s A_{\mu\nu} \tilde{A}^{\mu\nu}$

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

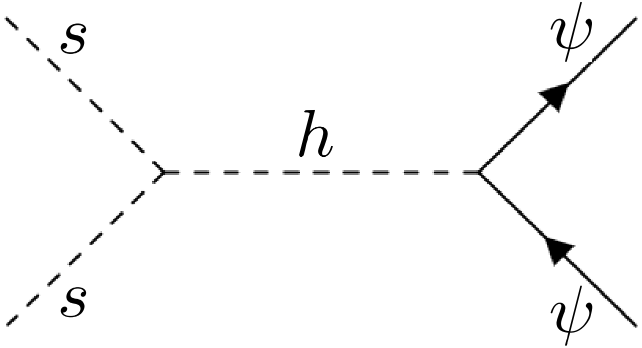
$$\beta_{\tilde{a}_{s\tilde{A}}} = 4\tilde{e}\,\mathrm{Tr}\Big[\left(\tilde{c}_e \tilde{a}^\dagger_{eA} + \tilde{c}^\dagger_e \tilde{a}_{eA}\right) + \left(\tilde{c}_d \tilde{a}^\dagger_{dA} + \tilde{c}^\dagger_d \tilde{a}_{dA}\right) - 2\left(\tilde{c}_u \tilde{a}^\dagger_{uA} + \tilde{c}^\dagger_u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

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

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

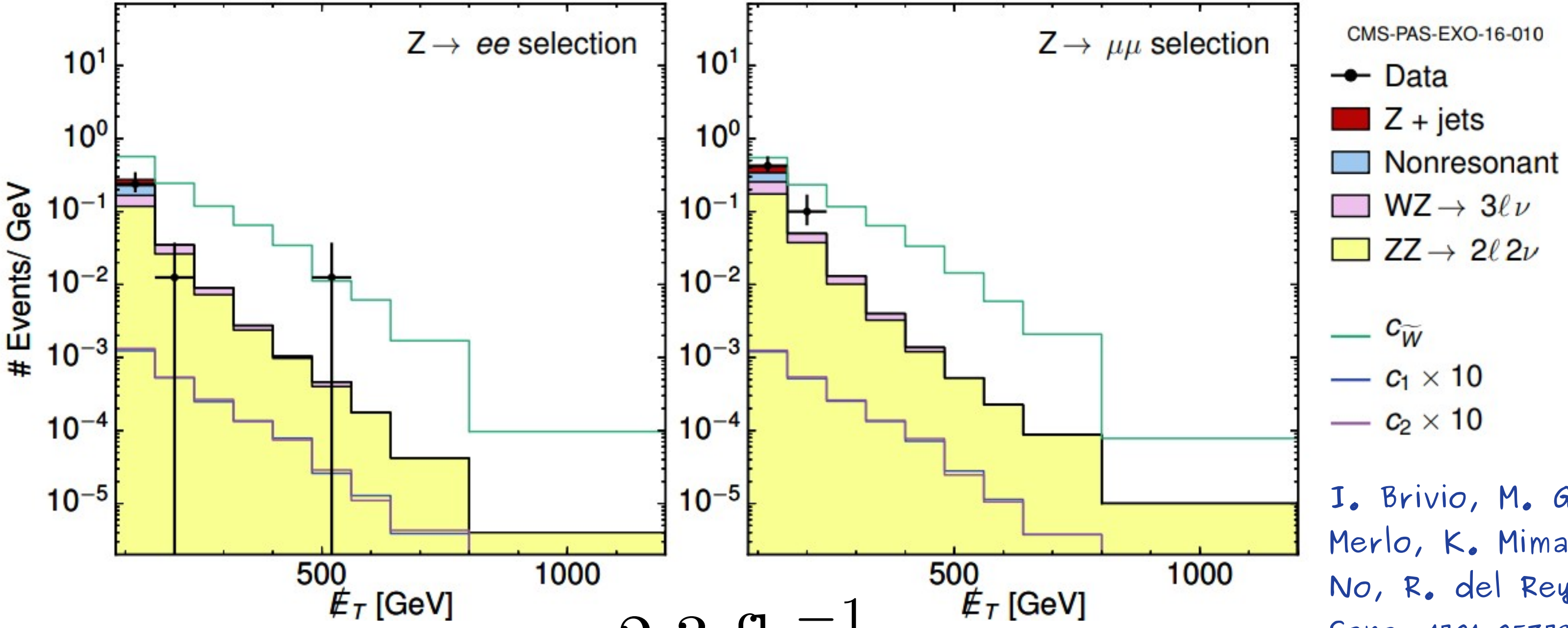
Direct constraints from mono-Z:

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



$2.3\ \mathrm{fb}^{-1}$

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:

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

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 $a_{se\phi}$

Phenomenological applications

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

>4 orders of magnitude better than direct bounds

- **Effect of LEFT running is ~6%**
- Could just be taken as a **systematic error** when only using **SMEFT + ALP**

Phenomenological applications

Top-philic ALP:

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

The ALP-top coupling generates the electron coupling:

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

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

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

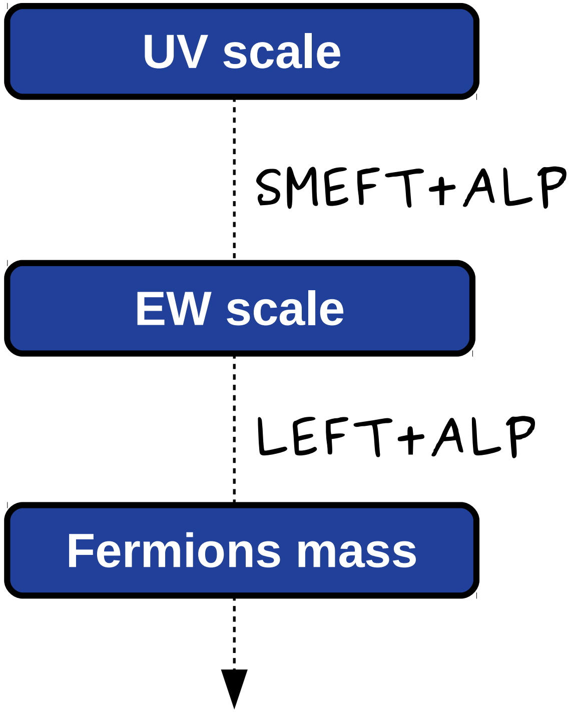
indirect bound

vs

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

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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