LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

UNIVERSIDAD DE GRANADA

Running in the SMEFT

Based on 2012.09017, 2106.05291

M. Chala, G. Guedes, M. Ramos, J. Santiago

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SMEFT approach

Expansion into higher dimensional operators:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

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

Weinberg PRL43(1979)1566
Grzadkowski et al 1008.4884
Alonso, Jenkins, Manohar, Trott 1308.2627,1310.4838,1312.2014
Grojean, Jenkins, Manohar, Trott 1301.2588
Alonso, Chang, Jenkins, Manohar, Shotwell 1405.0486

Remmen and Rodd 1908.09845
Hays, Martin, Sanz, Setford, 1808.00442
Li, Ren, Shu, Xiao, Yu, Zheng 2005.00008
Murphy 2005.00059

This talk

Compute the renormalization group equations (RGEs) of

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM+s}} + \frac{\mathcal{L}_{5+s}}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

$$\mathcal{L}_d = c_i \mathcal{O}_i$$

$$[\mathcal{O}_i] = d$$

SMEFT+ALP up to dimension-5

2012.09017

SMEFT at dimension-8

2106.05291

M.Chala, GG, M.Ramos, J.Santiago

Do we need dim-8?

- May give the **main contribution** to certain observables
  - Vector boson scattering
  - Light by light scattering
- For **small values of Λ** allowed by data, NLO corrections are important
- To keep up with **the precision at the LHC**, higher dimension contributions are needed too

Towards the renormalisation of the Standard Model effective field theory to dimension eight: Bosonic interactions I

M. Chala[1*], G. Guedes[1,2], M. Ramos[1,2], J. Santiago[1],

- **Loop-generated** operators could be **renormalised by tree-level**
  - RGEs would be one of the **main contributions**

- First time we have **co-leading contributions**

$$16\pi^2\mu\frac{dc_i^{(8)}}{d\mu} = \gamma_{ij}c_j^{(8)} + \gamma'_{ijk}c_j^{(6)}c_k^{(6)}$$

- **No non-renormalization** theorems for double dim-6 insertions

Computation

- Off-shell calculations: compute **one-loop divergent amplitudes** generated by 1P1 diagrams up to $1/\Lambda^4$

- *Construct* and **match to the Green/off-shell basis**:

$\phi^4 D^4$	$D_\mu\phi^\dagger D^\mu\phi(\phi^\dagger D^2\phi + \text{h.c.})$	$\mathcal{O}_{\phi^4}^{(4)}$	$D_\mu\phi^\dagger D^\mu\phi(\phi^\dagger \mathrm{i}D^2\phi + \text{h.c.})$	$\mathcal{O}_{\phi^4}^{(5)}$
	$(D_\mu\phi^\dagger\phi)(D^2\phi^\dagger D_\mu\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(6)}$	$(D_\mu\phi^\dagger\phi)(D^2\phi^\dagger \mathrm{i}D_\mu\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(7)}$
	$(D^2\phi^\dagger\phi)(D^2\phi^\dagger\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(8)}$	$(D^2\phi^\dagger\phi)(\mathrm{i}D^2\phi^\dagger\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(9)}$
	$(D^2\phi^\dagger D^2\phi)(\phi^\dagger\phi)$	$\mathcal{O}_{\phi^4}^{(10)}$	$(\phi^\dagger D^2\phi)(D^2\phi^\dagger\phi)$	$\mathcal{O}_{\phi^4}^{(11)}$
	$(D_\mu\phi^\dagger\phi)(D^\mu\phi^\dagger D^2\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(12)}$	$(D_\mu\phi^\dagger\phi)(D^\mu\phi^\dagger \mathrm{i}D^2\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(13)}$

Equations of motion

Equations of motion (EOM) **equivalent** to field redefinitions up to $\mathcal{O}(r^2)$

$$\phi \to \phi + \frac{r}{\Lambda^2}\mathcal{O}$$

J. Criado, M. Pérez-Victoria
1811.09413

These $\mathcal{O}(r^2)$ terms correspond to a **2-loop effect.**

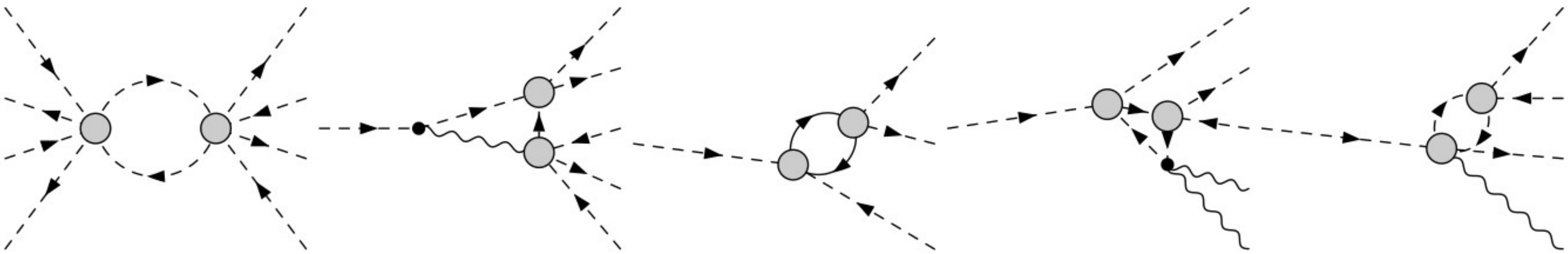
Use SMEFT EOMs up to ***O*(1/Λ²):**

$$\mathcal{O}_{BD\phi} = \frac{g_1}{2}\left[\mathcal{O}_{\phi\Box} + 4\mathcal{O}_{\phi D} - \frac{\mu^2}{\Lambda^2}c_{\phi D}\mathcal{O}_{\phi}\right] + \frac{g_1}{2}\frac{c_{\phi D}}{\Lambda^2}\left[-2\lambda\mathcal{O}_{\phi^8} + 3\mathcal{O}^{(1)}_{\phi^6} + 2\mathcal{O}^{(2)}_{\phi^6}\right] + \cdots$$

Setup to renormalize bosonic dim-8

$$\mathcal{L}_{UV} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}(H6 + H4D2 + \psi DH2 + \psi H3)$$

All tree-level generated



$$\mathcal{O} \sim \{\phi^8,\, \phi^6 D^2,\, \phi^4 D^4,\, X^2\phi^4,\, X\phi^4 D^2\}$$

Results

where $\emptyset$ is a zero only in the physical basis

$\gamma'_{c^{(1)}_{\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\times$	$\times$	0	0	0	0	0
$c_{\phi\Box}$			$\times$	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\times$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					$\times$	0	0	0
$c_{\phi\psi_R}$						$\times$	0	0
$c_{\phi ud}$							$\times$	0
$c_{\psi_R\phi}$								0

$\gamma'_{c^{(1)}_{W^2\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\times$	$\emptyset$	0	0	0	0	0
$c_{\phi\Box}$			0	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\times$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					$\times$	0	0	0
$c_{\phi\psi_R}$						$\times$	0	0
$c_{\phi ud}$							$\times$	0
$c_{\psi_R\phi}$								0

$$\mathcal{O}^{(1)}_{\phi^4} = (D_\mu\phi^\dagger D_\nu\phi)(D^\nu\phi^\dagger D^\mu\phi) \qquad \mathcal{O}^{(1)}_{W^2\phi^4} = (\phi^\dagger\phi)^2 W^I_{\mu\nu}W^{I\mu\nu}$$

Results

where $\emptyset$ is a zero only in the physical basis.

$\gamma'_{c^{(1)}_{WB\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\emptyset$	$\emptyset$	0	0	0	0	0
$c_{\phi\Box}$			0	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\emptyset$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					0	0	0	0
$c_{\phi\psi_R}$						$\emptyset$	0	0
$c_{\phi ud}$							$\emptyset$	0
$c_{\psi_R\phi}$								0

$\gamma'_{c^{(3)}_{W^2\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\emptyset$	$\emptyset$	0	0	0	0	0
$c_{\phi\Box}$			0	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\emptyset$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					0	0	0	0
$c_{\phi\psi_R}$						$\emptyset$	0	0
$c_{\phi ud}$							$\emptyset$	0
$c_{\psi_R\phi}$								0

$$\mathcal{O}^{(1)}_{WB\phi^4} = (\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)W^I_{\mu\nu}B^{\mu\nu} \qquad \mathcal{O}^{(3)}_{W^2\phi^4} = (\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J\phi)W^I_{\mu\nu}W^{J\mu\nu}$$

Results

- ***S*** and ***U*** parameters are not renormalized, at one-loop, by tree-level dimension six interactions

$$\frac{1}{16\pi}S = \frac{v^2}{\Lambda^2}\left[c_{\phi WB} + c^{(1)}_{WB\phi^4}\frac{v^2}{\Lambda^2}\right], \qquad \frac{1}{16\pi}U = \frac{v^4}{\Lambda^4}c^{(3)}_{W^2\phi^4}$$

R.Alonso, E.Jenkins,A.Manohar, M.Trott 1312.2014

$$\mathcal{O}^{(1)}_{WB\phi^4} = (\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)W^I_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}^{(3)}_{W^2\phi^4} = (\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J\phi)W^I_{\mu\nu}W^{J\mu\nu}$$

$$\mathcal{O}_{\phi WB} = (\phi^\dagger\sigma^I\phi)W^I_{\mu\nu}B^{\mu\nu}$$

Results

- Renormalized operators arise at **tree-level** in UV completions, in contrast with what is expected from the running **triggered by dimension-eight interactions**

C. Murphy
2005.00059

$\bar{w}$ \ w	0	2	4	6	8
8	X_L^4	$X_L^3H^2$, $X_L^2\psi^2H$, $X_L\psi^4$	$X_L^2H^4$, $X_L\psi^2H^3$, ψ^4H^2	ψ^2H^5	H^8
6		$X_L^2H^2D^2$, $X_L^2\psi\bar{\psi}D$, $X_L\psi^2HD^2$, ψ^4D^2	$X_LH^4D^2$, $X_L^2\bar{\psi}^2H$, $X_L\psi\bar{\psi}H^2D$, $\psi^2H^3D^2$, $X_L\psi^2\bar{\psi}^2$, $\psi^3\bar{\psi}HD$	H^6D^2, $\psi\bar{\psi}H^4D$, $\psi^2\bar{\psi}^2H^2$	$\bar{\psi}^2H^5$
4			$X_L^2X_R^2$, $X_LX_RH^2D^2$, H^4D^4, $X_LX_R\psi\bar{\psi}D$, $X_R\psi^2HD^2$, $X_L\bar{\psi}^2HD^2$, $\psi\bar{\psi}H^2D^3$, $\psi^2\bar{\psi}^2D^2$	$X_RH^4D^2$, $X_R^2\psi^2H$, $X_R\psi\bar{\psi}H^2D$, $\bar{\psi}^2H^3D^2$, $X_R\psi^2\bar{\psi}^2$, $\psi\bar{\psi}^3HD$	$X_R^2H^4$, $X_R\bar{\psi}^2H^3$, $\bar{\psi}^4H^2$
2				$X_R^2H^2D^2$, $X_R^2\psi\bar{\psi}D$, $X_R\bar{\psi}^2HD^2$, $\bar{\psi}^4D^2$	$X_R^3H^2$, $X_R^2\bar{\psi}^2H$, $X_R\bar{\psi}^4$
0					X_R^4

Results

- Important corrections to the EW phase transition

$$V \sim -\mu^2|\phi|^2 + \lambda|\phi|^4 + \frac{c_\phi}{\Lambda^2}\left(1 - \frac{108}{16\pi^2}\lambda \log\frac{\Lambda}{v}\right)|\phi|^6 + \frac{126}{16\pi^2\Lambda^4}\log\frac{\Lambda}{v}c_\phi^2\,|\phi|^8$$

This work

EWPT is strong and first order for:

C.Caprini *et al* 1910.13125 (2020)

$$1.7\,\mathrm{TeV}^{-2} \lesssim c_\phi \lesssim 3.7\,\mathrm{TeV}^{-2}$$

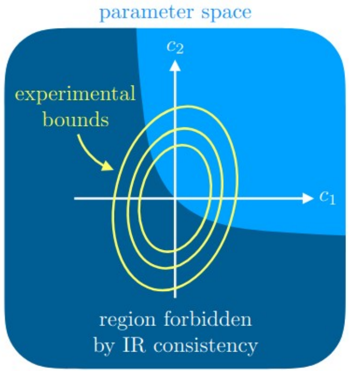
$$1.5\,\mathrm{TeV}^{-2} \lesssim c_\phi \lesssim 2.6\,\mathrm{TeV}^{-2}$$

30% correction

Results – positivity bounds

From fundamental principles such as unitarity and analiticity we can **constrain the parameter space of Wilson coefficients**

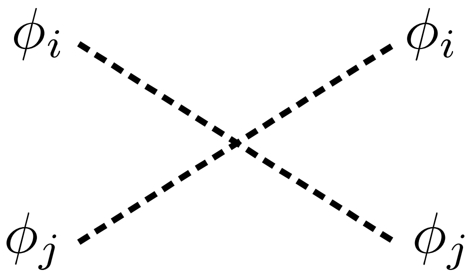
$$\frac{d^2\mathcal{M}(s,t=0)}{ds^2} > 0 \quad \Longrightarrow$$



Remmen and Rodd 1908.09845

Dimension 6 operators can impact **positivity bounds through RGEs**

Positivity



$\mathcal{O}^{(1)}_{H^4D^2}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}^{(2)}_{H^4D^2}$	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
$\mathcal{O}^{(1)}_{H^4D^4}$	$(D_\mu H^\dagger D_\nu H)(D^\nu H^\dagger D^\mu H)$
$\mathcal{O}^{(2)}_{H^4D^4}$	$(D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$
$\mathcal{O}^{(3)}_{H^4D^4}$	$(D_\mu H^\dagger D^\mu H)(D^\nu H^\dagger D_\nu H)$

12→12
$$c^{(2)}_{H^4D^4} > 0$$

13→13
$$c^{(1)}_{H^4D^4} + c^{(2)}_{H^4D^4} > 0$$

11→11
$$c^{(1)}_{H^4D^4} + c^{(2)}_{H^4D^4} + c^{(3)}_{H^4D^4} > 0$$

Positivity

Positivity bounds respected by RGEs

$$16\pi^2 \beta^{(1)}_{H^4D^4} = \frac{8}{3}\Big[-2(c^{(1)}_{H^4D^2})^2 - \frac{11}{8}(c^{(2)}_{H^4D^2})^2 + 4c^{(1)}_{H^4D^2}c^{(2)}_{H^4D^2} + 3c^2_{Hd} + c^2_{He} + 2(c^{(1)}_{Hl})^2 - 2(c^{(3)}_{Hl})^2 + 6(c^{(1)}_{Hq})^2 - 6(c^{(3)}_{Hq})^2 + 3c^2_{Hu} - 3c^2_{Hud}\Big],$$

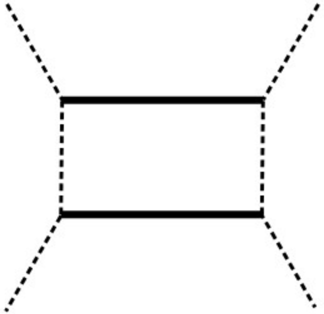
$$16\pi^2 \beta^{(2)}_{H^4D^4} = \frac{8}{3}\Big[-2(c^{(1)}_{H^4D^2})^2 - \frac{5}{8}(c^{(2)}_{H^4D^2})^2 - 2c^{(1)}_{H^4D^2}c^{(2)}_{H^4D^2} - 3c^2_{Hd} - c^2_{He} - 2(c^{(1)}_{Hl})^2 - 2(c^{(3)}_{Hl})^2 - 6(c^{(1)}_{Hq})^2 - 6(c^{(3)}_{Hq})^2 - 3c^2_{Hu}\Big],$$

$$16\pi^2 \beta^{(3)}_{H^4D^4} = \frac{8}{3}\Big[-5(c^{(1)}_{H^4D^2})^2 + \frac{7}{8}(c^{(2)}_{H^4D^2})^2 - 2c^{(1)}_{H^4D^2}c^{(2)}_{H^4D^2} + 4(c^{(3)}_{Hl})^2 + 12(c^{(3)}_{Hq})^2 + 3c^2_{Hud}\Big]$$

Positivity

Singlet neutral scalar: $\mathcal{L}_{\text{UV}} = \kappa_{\mathcal{S}} \mathcal{S} \phi^\dagger \phi$

$$\left(c^{(1)}_{H^4D^4},\, c^{(2)}_{H^4D^4},\, c^{(3)}_{H^4D^4}\right)^{\text{tree}} = \left(0,\, 0,\, 2\frac{\kappa_{\mathcal{S}}^2}{M^2}\right)$$



$$c^{(1)\,\text{loop}}_{H^4D^4} = -\frac{39}{144\pi^2}\frac{\kappa_{\mathcal{S}}^4}{M^4}$$

$$c^{(2)\,\text{loop}}_{H^4D^4} = -\frac{39}{144\pi^2}\frac{\kappa_{\mathcal{S}}^4}{M^4}$$

$$c^{(3)\,\text{loop}}_{H^4D^4} = -\frac{187}{720\pi^2}\frac{\kappa_{\mathcal{S}}^4}{M^4}$$

M.Chala,J.Santiago 2110.01624

Positivity

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Considering a perturbative expansion for the couplings,

$$c^{(j)}_{H^4D^4} = g\, c^{(j)\,\text{tree}}_{H^4D^4} + g^2\, c^{(j)\,\text{loop}}_{H^4D^4} + \cdots ,$$

$$\mathcal{A}(s) \sim -2g\lambda^{\text{tree}} + g^2[-2\lambda^{\text{loop}} + \frac{3}{2\pi^2}(\lambda^{\text{tree}})^2 \log\frac{\Lambda^2}{s}] + (g\, c^{(2)\,\text{tree}}_{H^4D^4} + g^2 c^{(2)\,\text{loop}}_{H^4D^4} - \frac{\beta^{(2)}_{H^4D^4}}{2}\log\frac{\Lambda^2}{s})\frac{s^2}{\Lambda^4} ,$$

If nothing is generated at tree-level

$$\mathcal{A}(s) \sim c^{(2)\,\text{loop}}_{H^4D^4}\frac{s^2}{\Lambda^4} \longrightarrow c^{(2),\,\text{loop}}_{H^4D^4} > 0$$

Positivity

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Considering a perturbative expansion for the couplings,

$$c^{(j)}_{H^4D^4} = g\, c^{(j)\,\text{tree}}_{H^4D^4} + g^2\, c^{(j)\,\text{loop}}_{H^4D^4} + \cdots\,,$$

$$\mathcal{A}(s) \sim -2g\lambda^{\text{tree}} + g^2[-2\lambda^{\text{loop}} + \frac{3}{2\pi^2}(\lambda^{\text{tree}})^2 \log\frac{\Lambda^2}{s}]$$
$$+ (g\, c^{(2)\,\text{tree}}_{H^4D^4} + g^2 c^{(2)\,\text{loop}}_{H^4D^4} - \frac{\beta^{(2)}_{H^4D^4}}{2}\log\frac{\Lambda^2}{s})\frac{s^2}{\Lambda^4}\,,$$

If dim6 @ tree-level, but no dim8

$$\mathcal{A}(s) \sim \underbrace{-g^2\frac{\gamma'_{ij}}{2}\log\frac{\Lambda^2}{m^2}c^{(i)\,\text{tree}}_{H^4D^2}c^{(j)\,\text{tree}}_{H^4D^2}}_{<0}\frac{s^2}{\Lambda^4} + \mathcal{O}(s^3)$$

Non-renormalization directions?

$\gamma'_{c^{(3)}_{W^2\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\emptyset$	$\emptyset$	0	0	0	0	0
$c_{\phi\Box}$			0	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\emptyset$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					0	0	0	0
$c_{\phi\psi_R}$						$\emptyset$	0	0
$c_{\phi ud}$							$\emptyset$	0
$c_{\psi_R\phi}$								0

$\gamma'_{c^{(1)}_{WB\phi^4}}$	c_ϕ	$c_{\phi D}$	$c_{\phi\Box}$	$c^{(1)}_{\phi\psi_L}$	$c^{(3)}_{\phi\psi_L}$	$c_{\phi\psi_R}$	$c_{\phi ud}$	$c_{\psi_R\phi}$
c_ϕ	0	0	0	0	0	0	0	0
$c_{\phi D}$		$\emptyset$	$\emptyset$	0	0	0	0	0
$c_{\phi\Box}$			0	0	0	0	0	0
$c^{(1)}_{\phi\psi_L}$				$\emptyset$	0	0	0	0
$c^{(3)}_{\phi\psi_L}$					0	0	0	0
$c_{\phi\psi_R}$						$\emptyset$	0	0
$c_{\phi ud}$							$\emptyset$	0
$c_{\psi_R\phi}$								0

$$\mu\frac{dc_8}{d\mu} = \gamma_{11}\left(c_6^{(1)}\right)^2 + \gamma_{12}c_6^{(1)}c_6^{(2)} + \gamma_{22}\left(c_6^{(2)}\right)^2$$

necessarily if $c_8>0$

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Constructing the off-shell basis

M. Chala, A. Díaz-Carmona, G.G.
2111.XXXX

Contribution of operator $\mathcal{O}_i$

SM gauge couplings

$$\mathcal{A}(a \to b) = \sum_{\alpha \in I} c_i {f^i}_\alpha(\vec{g})\kappa_\alpha$$

Kinematic structures

If operator i and j are independent, there must be an amplitude such that

$$f^i_\alpha = (f^i_{\alpha_1}, f^i_{\alpha_2}, \ldots) \text{ and } f^j_\alpha = (f^j_{\alpha_1}, f^j_{\alpha_2}, \ldots)$$

are non-collinear vectors

Constructing the off-shell basis example:

$$\varphi^0(p_1) \to \varphi^0(p_2)\varphi^+(p_3)\varphi^-(p_4)\varphi^+(p_5)\varphi^-(p_6)$$

$$\begin{aligned}\mathcal{O}_1 &= (\phi^\dagger\phi)D_\mu(\phi^\dagger\phi)D^\mu(\phi^\dagger\phi)\,,\\ \mathcal{O}_2 &= (\phi^\dagger\phi)^2(D^2\phi^\dagger\phi+\phi^\dagger D^2\phi)\,,\\ \mathcal{O}_3 &= (\phi^\dagger\phi)^2 D_\mu\phi^\dagger D^\mu\phi\,.\end{aligned}
\quad\to\quad
\begin{bmatrix} 0 & 0 & 4i \\ -4i & 0 & 0 \\ 0 & 4i & 0 \end{bmatrix}
\quad\to\quad
\sum p_i = 0$$

Rank 3 → **Rank 2**

→ $$\mathcal{O}_2 = -2\,(\mathcal{O}_1 + \mathcal{O}_3)$$

Related by IBP

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Constructing the off-shell basis

4d relations

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$$T_{[\mu\nu]} X^{\mu}{}_{\rho} \widetilde{F}^{\nu\rho} = T_{[\mu\nu]} \widetilde{X}^{\mu}{}_{\rho} F^{\nu\rho} \,,$$

$$T_{\{\mu\nu\}} X^{\mu}{}_{\rho} \widetilde{F}^{\nu\rho} = -\frac{1}{2} \left(T_{\{\mu\nu\}} \widetilde{X}^{\mu}{}_{\rho} F^{\nu\rho} + T^{\mu}_{\mu} X^{\nu\rho} F_{\nu\rho} \right)$$

$$T_{\mu\nu} X^{\mu\rho} \widetilde{X}^{\nu}{}_{\rho} = \frac{1}{4} T^{\mu}_{\mu} X^{\nu\rho} \widetilde{X}_{\nu\rho} \,,$$

→ **Imply the existence of evanescent bosonic operators**

Only at 4d they vanish or become dependent of others in the basis

Enforce them at the amplitude level by considering that no more than 4 vectors can be linearly independent

This talk

Compute the renormalization group equations (RGEs) of

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}+\text{s}} + \frac{\mathcal{L}_{5+s}}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

$$\mathcal{L}_d = c_i \mathcal{O}_i$$

$$[\mathcal{O}_i] = d$$

SMEFT+ALP up to dimension-5

2012.09017

SMEFT at dimension-8

2106.05291

M.Chala, GG, M.Ramos, J.Santiago

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

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

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

$$\ldots$$

Brando Bellazzini, Csaba Csáki and Javi Serra, 1401.2457

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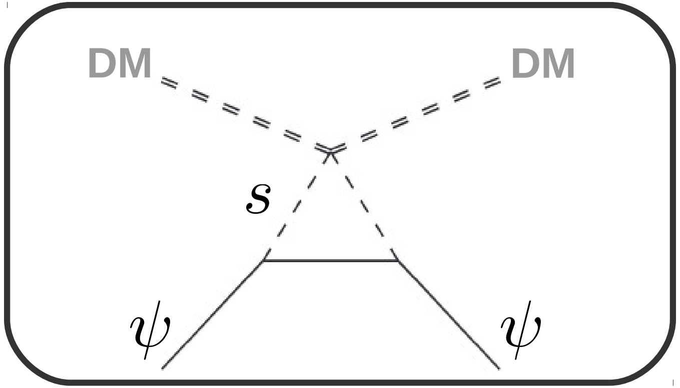
- Anomalies



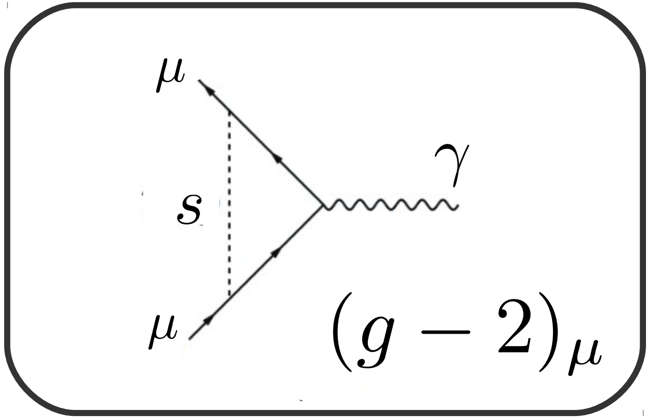
M. J. Dolan, F. Kahlhoefer, C. McCabe and K. Schmidt-Hoberg, 1412.5174
M. Ramos, 1912.11061

Motivation: ALPs

Axion-like particles = CP-odd singlet scalars

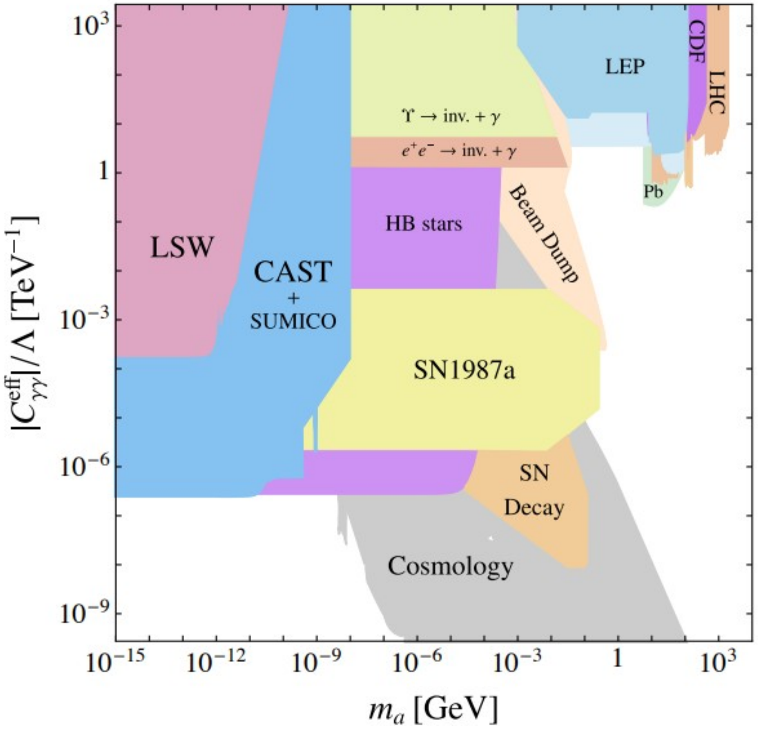
Theoretically well motivated:

- Strong CP-problem
- Composite Higgs Models
- 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

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**

$$\mathcal{O}^{\alpha\beta}_{su\phi} = is(\overline{q^\alpha_L}\tilde{\phi}u^\beta_R - \overline{u^\beta_R}\tilde{\phi}^\dagger q^\alpha_L)$$

$$\mathcal{O}^{\alpha\beta}_{sd\phi} = is(\overline{q^\alpha_L}\phi d^\beta_R - \overline{d^\beta_R}\phi^\dagger q^\alpha_L)$$

$$\mathcal{O}^{\alpha\beta}_{se\phi} = is(\overline{l^\alpha_L}\phi e^\beta_R - \overline{e^\beta_R}\phi^\dagger l^\alpha_L)$$

$$\mathcal{O}_{s\tilde{G}} = sG^A_{\mu\nu}\tilde{G}^{\mu\nu}_A$$

$$\mathcal{O}_{s\tilde{W}} = sW^A_{\mu\nu}\tilde{W}^{\mu\nu}_A$$

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

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

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

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

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

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

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

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 ← $a_{se\phi}$; $a_{\widetilde{se\phi}}$ → $\mathcal{O}_{\widetilde{se\phi}}$ 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

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

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

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

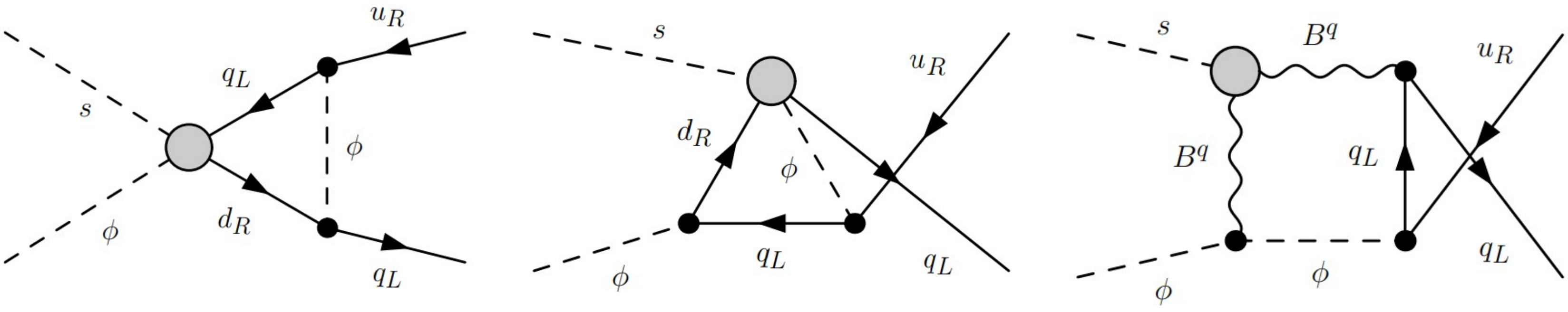
$$a_{\widetilde{se\phi}} = -\mathrm{Im}(H_\ell y^e + y^e H_e)$$

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

SMEFT+ALP: 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: AD matrix

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

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

SMEFT+ALP: AD matrix

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

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

Nonrenormalization theorems

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

SMEFT+ALP: AD matrix

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

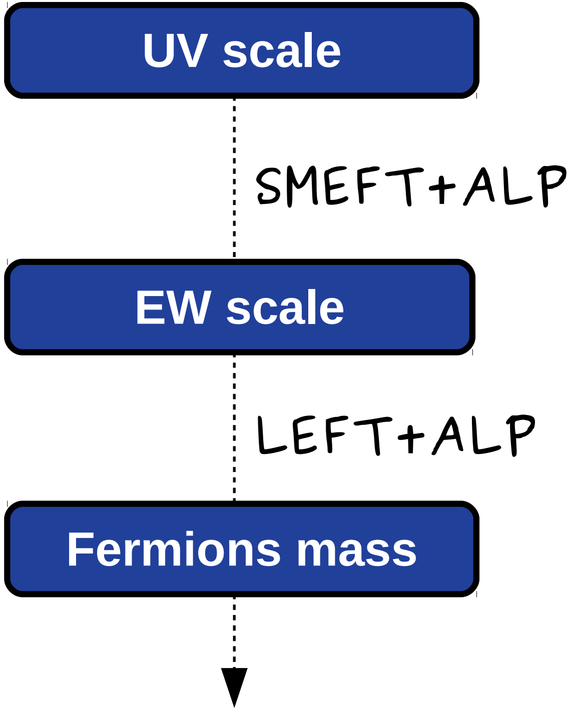
$$\begin{pmatrix} \beta_{a^\alpha_{su\phi}} \\ \beta_{a^\alpha_{sd\phi}} \\ \beta_{a^\alpha_{se\phi}} \\ \beta_{a_{s\tilde{G}}} \\ \beta_{a_{s\tilde{W}}} \\ \beta_{a_{s\tilde{B}}} \end{pmatrix} = \begin{pmatrix} \gamma_{11} + 6y_u^\alpha y_u^\rho & y_d^\alpha y_u^\alpha - 6y_u^\alpha y_d^\rho & -2y_u^\alpha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

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

$$\mathcal{L}_{\rm LEFT} = \frac{1}{2}(\partial_\mu s)(\partial^\mu s) - \frac{1}{2}\tilde{m}^2 s^2 - \frac{\tilde{\lambda}_s}{4!}s^4 - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\,\mu\nu}$$

$$+ \sum_{\psi=u,d,e}\left\{\overline{\psi^\alpha}\mathrm{i}\not{D}\psi^\alpha - \left[(\tilde{m}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R - s\,\mathrm{i}(\tilde{c}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R + \mathrm{h.c.}\right]\right\}$$

$$+ \tilde{a}_{s\widetilde{G}}s\,G^A_{\mu\nu}\widetilde{G}^{A\,\mu\nu} + \tilde{a}_{s\widetilde{A}}sA_{\mu\nu}\widetilde{A}^{\mu\nu}$$

$$+ \sum_{\psi=u,d,e}\left\{(\tilde{a}_{\psi A})_{\alpha\beta}\overline{\psi^\alpha_L}\sigma^{\mu\nu}\psi^\beta_R A_{\mu\nu} + (\tilde{a}_{\psi G})_{\alpha\beta}\overline{\psi^\alpha_L}\sigma^{\mu\nu}T_A\psi^\beta_R G^A_{\mu\nu} + s^2(\tilde{a}_\psi)_{\alpha\beta}\overline{\psi^\alpha_L}\psi^\beta_R + \mathrm{h.c.}\right\}$$

c: dim-4

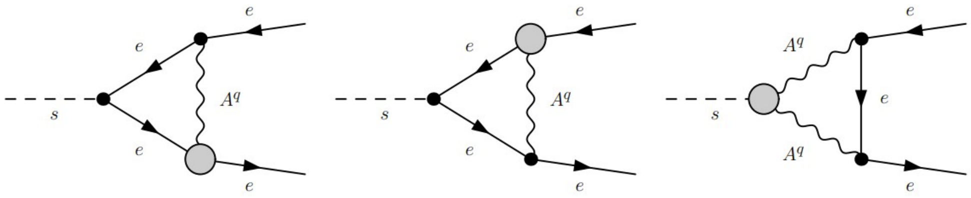
a: dim-5

dim-5 purely SMEFT

LEFT: masses

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

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



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

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

dim−4 contributions

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

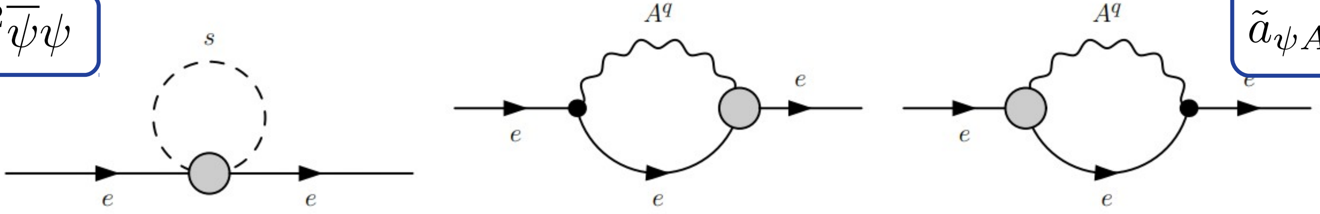
dim−5 contributions

LEFT: masses

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

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

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



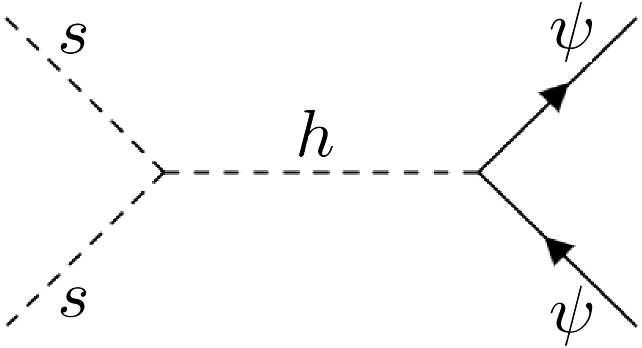
$$\beta_{\tilde{m}_e} = -6\tilde{e}^2 \tilde{m}_e + \frac{1}{2}\left(\tilde{m}_e \tilde{c}_e^\dagger \tilde{c}_e + \tilde{c}_e \tilde{c}_e^\dagger \tilde{m}_e + 4\tilde{c}_e \tilde{m}_e^\dagger \tilde{c}_e\right)$$
$$+ \mathrm{Tr}(\tilde{c}_e \tilde{m}_e^\dagger + \tilde{c}_e^\dagger \tilde{m}_e + 3\tilde{c}_u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

dim-4 contributions

dim-5 contributions

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:

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

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 $a_{se\phi}$

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:

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

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

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

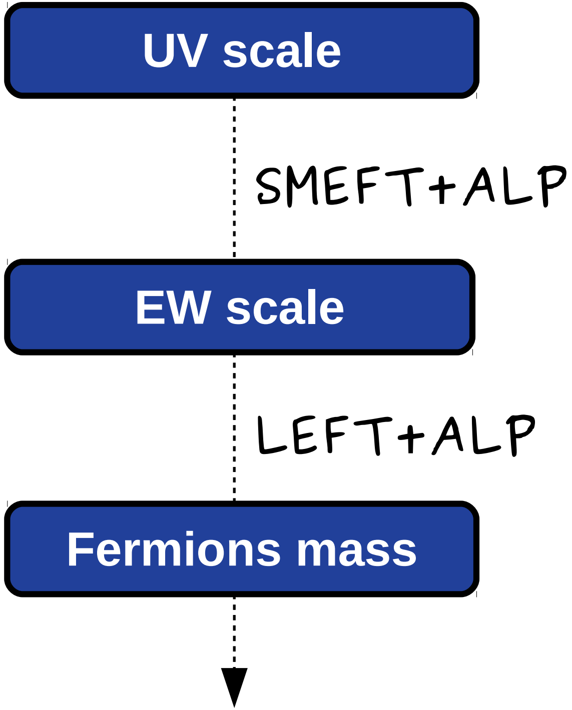
indirect bound

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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FCT, COMPETE2020-Portugal2020, FEDER, POCI-01-0145-FEDER-007334

Positivity

$$\mathcal{S} \sim (1,1)_0$$
$$\Xi \sim (1,3)_0$$
$$\mathcal{B} \sim (1,1)_0$$
$$\mathcal{B}_1 \sim (1,1)_1$$
$$\mathcal{W} \sim (1,3)_0$$

If no dim-6 @ tree-level,

$$\mathcal{A}(s) \sim \frac{g^2}{2}\left[\frac{3}{2\pi^2}(\lambda^{\text{tree}})^2\frac{\Lambda^4}{m^4} - \gamma_i \lambda^{\text{tree}} c^{(i)\,\text{tree}}_{H^4D^4} \log\frac{\Lambda^2}{m^2}\right]\frac{s^2}{\Lambda^4}$$

dominates when *m*$^2 \to 0$

So RGE of dim-8 doesn't need to be negative

M.Chala,J.Santiago 2110.01624