A Green's Basis for the Bosonic SMEFT to Dimension 8

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[2112.12724] Chala, Díaz-Carmona, and Guedes 2022.

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Outline

Introduction

SMEFT Lagrangian

Consider the SMEFT Lagrangian, up to dimension d:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{j=4}^{d} \sum_{i}^{n_{\rm op}} \frac{c_i^{(j)}}{\Lambda^2} \mathcal{O}_i^{(j)}$$

- Field content of the operators defines classes.
- Classes are closed sets for algebraic transformations, IBP and other relations.
- Classes are not closed for the field redefinitions/EoM.
- Redundant operators vanish under EoM. Non-redundant operators are called physical.

Introduction

Physical basis and Green's Basis

Classes of operators have a finite number of independent members which can be known, for example, through `Sym2Int` [1703.05221] Fonseca 2017 and `Basisgen` [1901.03501] Juan Carlos Criado 2019. This means that a **basis** can be created.

- For dimension 6, there are 63 physical and 69 redundant operators.
- For dimension 8 there are 993 physical and 1649 redundant operators.

We call Green's Basis to a set of off-shell independent operators. It can be applied to renormalisation [2003.12525] Gherardi, Marzocca, and Venturini 2020, [2106.05291] Chala, Guedes, et al. 2021, [2205.03301] Das Bakshi et al. 2022. or to matching [2112.10787] Carmona et al. 2021.

Introduction

List of physical and Green's bases available

Dimension	Basis
d_6	[1008.4884] Grzadkowski et al. 2010
d_6	[2003.12525] Gherardi, Marzocca, and Venturini 2020
d_7	[1410.4193] Lehman 2014 + [1607.07309] Liao and Ma 2016
d_7	[2306.03008] Zhang 2023
d_8	[2005.00059] Murphy 2020 & [2005.00008] Li, Ren, Shu, et al. 2021
d_8	This work (bosonic) & [2211.01420] Ren and Yu 2022 (GB only!)
d_9	[2007.08125] Liao and Ma 2020 & [2007.07899] Li, Ren, Xiao, et al. 2021
d_9	...

Building a Green's basis

Working in momentum space

For simplicity, we choose working in momentum space, i.e: setting $\partial_\mu \to -ip_\mu$. We can find a 1 to 1 mapping to all the previous concepts and relations. In particular:

$$\left.\begin{array}{c} D^2\phi^i = \mu^2\phi^i - 2\lambda(\phi^\dagger\phi)\phi^i \\ p_\phi^2 = \mu^2 - 2\lambda(\phi^\dagger\phi) \end{array}\right\} \text{EoM} \Leftrightarrow \text{on-shell field}$$

- A minimal set of physical independent operators is generated by onshell processes.
- A minimal set of redundant independent operators is generated by offshell processes.

- Onshell processes are represented by connected diagrams.
- Offshell processes are represented by 1PI diagrams.

Building a Green's basis

Off-shell method

In the off-shell approach we study the 1PI amplitudes generated by a set of operators $\{\mathcal{O}_i\}_{i=1\ldots N}$ for some processes:

$$\mathcal{A}\,(a \to b) = \sum_{i,\,\alpha} c_i f^i_\alpha\,(\vec{g})\,\kappa_\alpha \quad \vec{g} = (g_1, g_2, g_3, \lambda)$$

κ_α are the kinematic invariants. f^i_α are the amplitude coefficients.

$$\mathcal{O}_1 = \left(\phi^\dagger\phi\right) D_\mu \left(\phi^\dagger\phi\right) D^\mu \left(\phi^\dagger\phi\right)$$
$$\mathcal{O}_2 = \left(\phi^\dagger\phi\right)^2 \left(D^2\phi^\dagger\phi + \phi^\dagger D^2\phi\right)$$
$$\mathcal{O}_3 = \left(\phi^\dagger\phi\right)^2 \left(D_\mu\phi^\dagger D^\mu\phi\right)$$

$$\varphi^0(p_1) \to \varphi^0(p_2)\varphi^+(p_3)\varphi^-(p_4)\varphi^+(p_5)\varphi^-(p_6) \qquad \kappa_{ij} = p_i \cdot p_j$$

	κ_{22}	κ_{32}	κ_{33}	κ_{42}	κ_{43}	κ_{44}	κ_{52}	κ_{53}	κ_{54}	κ_{55}	κ_{62}	κ_{63}	κ_{64}	κ_{65}	κ_{66}
c_1	0	0	$4i$	0	$6i$	$4i$	0	$4i$	$6i$	$4i$	0	$6i$	$4i$	$6i$	$4i$
c_2	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$	$-8i$
c_3	$4i$	$4i$	0	$4i$	$-2i$	0	$4i$	0	$-2i$	0	$4i$	$-2i$	0	$-2i$	0

Building a Green's basis

Independence of operators

We can determine the dependancy of a set of operators in momentum space by checking the rank of the matrix $M_{i\alpha} \equiv f^i_\alpha$ for processes involving these operators

$$Rank\,(M) = N \Rightarrow \{\mathcal{O}_i\}_{i=1\ldots N} \text{ indep.}$$

If a process exists such that the amplitude coefficients matrix has maximum rank, then the operators are independent. For example:

$$\text{Class } B^2\phi^2D^2 \rightarrow \{\mathcal{O}_i\}_{i=1\ldots 12} \rightarrow Rank(M_{\phi^0\phi^0\rightarrow BB}) = 12$$

Additional (redundant) operators were generated by applying transformations (except EoM) to other known operators.

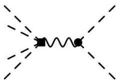
Removing redundancies

Equations of motion

To show the redundancies with respect to the physical basis we can apply the equations of motion (EoM). For example:

$$\mathcal{O}^{(5)}_{W\phi^4D^2} = (\phi^\dagger\phi)\underbrace{D_\nu W^{I\mu\nu}}(D_\mu\phi^\dagger\sigma^I\phi + \text{h.c.})$$

After applying EoM, redundant operators become a linear combination of the physical operators



$$\mathcal{O}^{(5)}_{W\phi^4D^2} = -g_2\mathcal{O}^{(2)}_{\phi^6D^2}$$

which leads to a redefinition of the Wilson Coefficients

$$c^{(2)}_{\phi^6D^2}\mathcal{O}^{(2)}_{\phi^6D^2} + c^{(5)}_{W\phi^4D^2}\mathcal{O}^{(5)}_{W\phi^4D^2} = \left(c^{(2)}_{\phi^6D^2} - 2g_2c^{(5)}_{W\phi^4D^2}\right)\mathcal{O}^{(2)}_{\phi^6D^2}$$

Removing redundancies

Wilson Coefficient shift

The Wilson Coefficient shift absorbs the coefficients of redundant operators contributing to a certain physical operator.

Wilson Coefficient shift for $\mathcal{O}^{(2)}_{\phi^6}$:

$$
\begin{aligned}
c^{(2)}_{\phi^6} \to\ & c^{(2)}_{\phi^6} + \frac{1}{4}g_1^2 g_2^2 c_{B^2D^4} - \frac{g_1^2}{2}c^{(8)}_{B^2\phi^2D^2} - 2g_1\lambda c^{(1)}_{B\phi^2D^4} - g_1 c^{(3)}_{B\phi^4D^2} \\
& + \left(-\frac{1}{8}g_1 g_2^2 + 2g_1\lambda\right) c^{(3)}_{B\phi^2D^4} + g_1^2\lambda c_{\phi^2} - 2\lambda c^{(6)}_{\phi^4} + 2\lambda c^{(12)}_{\phi^4} + g_1^2 g_2^2 c_{W^2D^4} \\
& - \frac{g_1 g_2}{4}c^{(8)}_{WB\phi^2D^2} + \frac{g_1 g_2}{2}c^{(10)}_{WB\phi^2D^2} - \frac{3g_1 g_2}{8}c^{(11)}_{WB\phi^2D^2} - g_1 g_2 c^{(13)}_{WB\phi^2D^2} \\
& - \frac{1}{2}g_1^2 g_2 c^{(3)}_{W\phi^2D^4} - \frac{g_2}{4}c^{(7)}_{W\phi^4D^2}\,,
\end{aligned}
$$

The list of all shifts is the last requirement for the Green's Basis to be well-defined.

Results and applications

Results

- In [2112.12724] Chala, Díaz-Carmona, and Guedes 2022, we feature the explicit form of 89 physical and 86 redundant independent operators, classified by their field content.
- The relation of the redundant operators to the physical ones is explicitly shown.

$\phi^4 D^4$	$(D_\mu\phi^\dagger D_\nu\phi)(D^\nu\phi^\dagger D^\mu\phi)$	$\mathcal{O}_{\phi^4}^{(1)}$	$(D_\mu\phi^\dagger D_\nu\phi)(D^\mu\phi^\dagger D^\nu\phi)$	$\mathcal{O}_{\phi^4}^{(2)}$
	$(D^\mu\phi^\dagger D_\mu\phi)(D^\nu\phi^\dagger D_\nu\phi)$	$\mathcal{O}_{\phi^4}^{(3)}$	$D_\mu\phi^\dagger D^\mu\phi(\phi^\dagger D^2\phi + \text{h.c.})$	$\mathcal{O}_{\phi^4}^{(4)}$
	$D_\mu\phi^\dagger D^\mu\phi(\phi^\dagger \mathrm{i}D^2\phi + \text{h.c.})$	$\mathcal{O}_{\phi^4}^{(5)}$	$(D_\mu\phi^\dagger\phi)(D^2\phi^\dagger D_\mu\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(6)}$
	$(D_\mu\phi^\dagger\phi)(D^2\phi^\dagger \mathrm{i}D_\mu\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(7)}$	$(D^2\phi^\dagger\phi)(D^2\phi^\dagger\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(8)}$
	$(D^2\phi^\dagger\phi)(\mathrm{i}D^2\phi^\dagger\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(9)}$	$(D^2\phi^\dagger D^2\phi)(\phi^\dagger\phi)$	$\mathcal{O}_{\phi^4}^{(10)}$
	$(\phi^\dagger D^2\phi)(D^2\phi^\dagger\phi)$	$\mathcal{O}_{\phi^4}^{(11)}$	$(D_\mu\phi^\dagger\phi)(D^\mu\phi^\dagger D^2\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(12)}$
	$(D_\mu\phi^\dagger\phi)(D^\mu\phi^\dagger \mathrm{i}D^2\phi) + \text{h.c.}$	$\mathcal{O}_{\phi^4}^{(13)}$		
$X^3\phi^2$	$f^{ABC}(\phi^\dagger\phi)G_\mu^{A,\nu}G_\nu^{B,\rho}G_\rho^{C,\mu}$	$\mathcal{O}_{G^3\phi^2}^{(1)}$	$f^{ABC}(\phi^\dagger\phi)G_\mu^{A,\nu}G_\nu^{B,\rho}\tilde{G}_\rho^{C,\mu}$	$\mathcal{O}_{G^3\phi^2}^{(1)}$
	$\epsilon^{IJK}(\phi^\dagger\phi)W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{W^3\phi^2}^{(1)}$	$\epsilon^{IJK}(\phi^\dagger\phi)W_\mu^{I\nu}W_\nu^{J\rho}\widetilde{W}_\rho^{K\mu}$	$\mathcal{O}_{W^3\phi^2}^{(2)}$
	$\epsilon^{IJK}(\phi^\dagger\sigma^I\phi)B_\mu^{\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{W^2B\phi^2}^{(1)}$	$\epsilon^{IJK}(\phi^\dagger\sigma^I\phi)(\widetilde{B}^{\mu\nu}W_{\nu\rho}^J W_\mu^{K\rho} + B^{\mu\nu}W_{\nu\rho}^J\widetilde{W}_\mu^{K\rho})$	$\mathcal{O}_{W^2B\phi^2}^{(2)}$
$X^2\phi^4$	$(\phi^\dagger\phi)^2 G_{\mu\nu}^A G^{A\mu\nu}$	$O_{G^2\phi^4}^{(1)}$	$(\phi^\dagger\phi)^2 \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$O_{G^2\phi^4}^{(2)}$
	$(\phi^\dagger\phi)^2 W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{W^2\phi^4}^{(1)}$	$(\phi^\dagger\phi)^2 \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{W^2\phi^4}^{(2)}$
	$(\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J\phi)W_{\mu\nu}^I W^{J\mu\nu}$	$\mathcal{O}_{W^2\phi^4}^{(3)}$	$(\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J\phi)\widetilde{W}_{\mu\nu}^I W^{J\mu\nu}$	$\mathcal{O}_{W^2\phi^4}^{(4)}$
	$(\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{WB\phi^4}^{(1)}$	$(\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{WB\phi^4}^{(2)}$
	$(\phi^\dagger\phi)^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{B^2\phi^4}^{(1)}$	$(\phi^\dagger\phi)^2 \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{B^2\phi^4}^{(2)}$
$X\phi^2D^4$	$i(D_\nu\phi^\dagger\sigma^I D^2\phi - D^2\phi^\dagger\sigma^I D_\nu\phi)D_\mu W^{I\mu\nu}$	$\mathcal{O}_{W\phi^2D^4}^{(1)}$	$(D_\nu\phi^\dagger\sigma^I D^2\phi + D^2\phi^\dagger\sigma^I D_\nu\phi)D_\mu W^{I\mu\nu}$	$\mathcal{O}_{W\phi^2D^4}^{(2)}$
	$i(D_\rho D_\nu\phi^\dagger\sigma^I D^\rho\phi - D^\rho\phi^\dagger\sigma^I D_\rho D_\nu\phi)D_\mu W^{I\mu\nu}$	$\mathcal{O}_{W\phi^2D^4}^{(3)}$		
	$i(D_\nu\phi^\dagger D^2\phi - D^2\phi^\dagger D_\nu\phi)D_\mu B^{\mu\nu}$	$\mathcal{O}_{B\phi^2D^4}^{(1)}$	$(D_\nu\phi^\dagger D^2\phi + D^2\phi^\dagger D_\nu\phi)D_\mu B^{\mu\nu}$	$\mathcal{O}_{B\phi^2D^4}^{(2)}$
	$i(D_\rho D_\nu\phi^\dagger D^\rho\phi - D^\rho\phi^\dagger D_\rho D_\nu\phi)D_\mu B^{\mu\nu}$	$\mathcal{O}_{B\phi^2D^4}^{(3)}$		
$X\phi^4D^2$	$\mathrm{i}(\phi^\dagger\phi)(D^\mu\phi^\dagger\sigma^I D^\nu\phi)W_{\mu\nu}^I$	$\mathcal{O}_{W\phi^4D^2}^{(1)}$	$\mathrm{i}(\phi^\dagger\phi)(D^\mu\phi^\dagger\sigma^I D^\nu\phi)\widetilde{W}_{\mu\nu}^I$	$\mathcal{O}_{W\phi^4D^2}^{(2)}$
	$\mathrm{i}\epsilon^{IJK}(\phi^\dagger\sigma^I\phi)(D^\mu\phi^\dagger\sigma^J D^\nu\phi)W_{\mu\nu}^K$	$\mathcal{O}_{W\phi^4D^2}^{(3)}$	$\mathrm{i}\epsilon^{IJK}(\phi^\dagger\sigma^I\phi)(D^\mu\phi^\dagger\sigma^J D^\nu\phi)\widetilde{W}_{\mu\nu}^K$	$\mathcal{O}_{W\phi^4D^2}^{(4)}$
	$(\phi^\dagger\phi)D_\nu W^{I\mu\nu}(D_\mu\phi^\dagger\sigma^I\phi + \text{h.c.})$	$\mathcal{O}_{W\phi^4D^2}^{(5)}$	$(\phi^\dagger\phi)D_\nu W^{I\mu\nu}(D_\mu\phi^\dagger \mathrm{i}\sigma^I\phi + \text{h.c.})$	$\mathcal{O}_{W\phi^4D^2}^{(6)}$
	$\epsilon^{IJK}(D_\mu\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J D_\nu\phi)W^{K\mu\nu}$	$\mathcal{O}_{W\phi^4D^2}^{(7)}$	$\mathrm{i}(\phi^\dagger\phi)(D^\mu\phi^\dagger D^\nu\phi)B_{\mu\nu}$	$\mathcal{O}_{B\phi^4D^2}^{(1)}$
	$\mathrm{i}(\phi^\dagger\phi)(D^\mu\phi^\dagger D^\nu\phi)\widetilde{B}_{\mu\nu}$	$\mathcal{O}_{B\phi^4D^2}^{(2)}$	$(\phi^\dagger\phi)D_\nu B^{\mu\nu}(D_\mu\phi^\dagger \mathrm{i}\phi + \text{h.c.})$	$\mathcal{O}_{B\phi^4D^2}^{(3)}$

Applications

Integrating out a scalar singlet to one loop

SM extended with a heavy singlet scalar $\mathcal{S}$ with a $\mathbb{Z}_2$ symmetry such that $\mathcal{S} \to -\mathcal{S}$. The New Physics Lagrangian is:

$$\mathcal{L}_{NP} = \frac{1}{2}(D_\mu \mathcal{S})(D^\mu \mathcal{S}) - \frac{1}{2} m_{\mathcal{S}}^2 \mathcal{S}^2 - \lambda_{\mathcal{S}\phi} \mathcal{S}^2 \phi^\dagger \phi - \lambda_{\mathcal{S}} \mathcal{S}^4$$

and can be matched at 1L with our Green's basis just presented using `MatchMakerEFT` [2112.10787] Carmona et al. 2021

$$\frac{c_{\phi^6}^{(1)}}{\Lambda^4} = \frac{1}{1920\, m_{\mathcal{S}}^4 \pi^2} \lambda_{\mathcal{S}\phi}^2 \left(5\lambda_{\mathcal{S}\phi} - 8\lambda\right), \qquad \frac{c_{\phi^4}^{(3)}}{\Lambda^4} = \frac{1}{960\, m_{\mathcal{S}}^4 \pi^2} \lambda_{\mathcal{S}\phi}^2$$

Results and applications

Reduction of Lagrangian to a physical basis (I)

Functional methods perform matching by integrating out the heavy fields. A basis is not needed in this case but can be very useful.

For example, if we extend the SM with a real vector triplet $\mathcal{W} \sim (1,3)_0$, where

$$\mathcal{L}_{NP} = \frac{1}{2}\Big[D_\mu \mathcal{W}_\nu^\dagger D^\nu \mathcal{W}^\mu - D_\mu \mathcal{W}_\nu^\dagger D^\mu \mathcal{W}^\nu + m_{\mathcal{W}}^2 \mathcal{W}_\mu^\dagger \mathcal{W}^\mu + (g_{\mathcal{W}}^\phi \mathcal{W}^\mu \phi^{I\dagger} \sigma^I i D_\mu \phi + \text{h.c.})\Big]$$

and we want to integrate it out at Tree-Level.

Applications

Reduction of Lagrangian to a physical basis (II)

Matching with `MatchingTools` [1710.06445] Juan C. Criado 2018 yields the following output:

$$
\begin{aligned}
\mathcal{L}_{\mathsf{EFT}}^{(8)} = \frac{(g_{\mathcal{W}}^{\phi})^2}{m_{\mathcal{W}}^4} \Big[& 2(D_\mu\phi^\dagger D_\nu\phi)(D^\mu\phi^\dagger D^\nu\phi) + 4(D_\nu\phi^\dagger D^\nu D^\mu\phi)(D_\mu\phi^\dagger\phi) \\
& - 2(D_\mu\phi^\dagger D_\nu\phi)(\phi^\dagger D^\mu D^\nu\phi) \underline{-4(D_\mu\phi^\dagger\phi)(D^\mu D_\nu\phi^\dagger D^\nu\phi)} \\
& + 2(D_\mu\phi^\dagger D_\nu\phi)(D^\mu D^\nu\phi^\dagger\phi) - 4(D_\mu\phi^\dagger D^\mu\phi)(D_\nu\phi^\dagger D^\nu\phi) \\
& + 2(D_\mu\phi^\dagger D_\nu\phi)(D^\nu\phi^\dagger D^\mu\phi) + \frac{1}{2}(\phi^\dagger D_\mu D_\nu\phi)(\phi^\dagger D^\mu D^\nu\phi) \\
& - 2(D_\nu D_\rho\phi^\dagger D^\nu D^\rho\phi)(\phi^\dagger\phi) + (D_\mu D_\nu\phi^\dagger\phi)(\phi^\dagger D^\mu D^\nu\phi) \\
& - 4(\phi^\dagger D_\rho\phi)(D_\nu\phi^\dagger D^\rho D^\nu\phi) + 2(\phi^\dagger D_\nu D_\mu\phi)(D^\mu\phi^\dagger D^\nu\phi) \\
& + \frac{1}{2}(D_\mu D_\nu\phi^\dagger\phi)(D^\mu D^\nu\phi^\dagger\phi) \underline{+4(D_\rho D_\nu\phi^\dagger D^\rho\phi)(D^\nu\phi^\dagger\phi)} \\
& - 2(D_\nu D_\mu\phi^\dagger\phi)(D^\mu\phi^\dagger D^\nu\phi) - \frac{1}{2}(\phi^\dagger D_\nu D_\mu\phi)(\phi^\dagger D^\mu D^\nu\phi) \\
& + 2(D_\rho D_\nu\phi^\dagger D^\nu D^\rho\phi)(\phi^\dagger\phi) - (D^\nu D^\mu\phi^\dagger\phi)(\phi^\dagger D_\mu D_\nu\phi) - \frac{1}{2}(D_\nu D_\mu\phi^\dagger\phi)(D^\mu D^\nu\phi^\dagger\phi) \Big].
\end{aligned}
$$

Applications

Reduction of Lagrangian to a physical basis (III)

By using a simple script we can match $\mathcal{L}_{\text{EFT}}^{(8)}$ at tree-level to the SMEFT where we embedded our Green's basis.

$$\mathcal{L}_{\text{EFT}}^{(8)} = \frac{(g_{\mathcal{W}}^{\phi})^2}{m_{\mathcal{W}}^4}\Big[2\mathcal{O}_{\phi^4}^{(1)} + 2\mathcal{O}_{\phi^4}^{(2)} - 4\mathcal{O}_{\phi^4}^{(3)} - \frac{1}{4}g_2^2\mathcal{O}_{W^2\phi^4}^{(1)} + \frac{1}{2}g_1 g_2\mathcal{O}_{WB\phi^4}^{(1)} + \frac{3}{4}g_1^2\mathcal{O}_{B^2\phi^4}^{(1)} - 2g_2\mathcal{O}_{W\phi^4D^2}^{(1)} + 6g_1\mathcal{O}_{B\phi^4D^2}^{(1)} + 2g_1\mathcal{O}_{B\phi^4D^2}^{(3)}\Big].$$

We get an equivalent Lagrangian with simpler and fewer operators.

Conclusions

A Green's Basis for the Bosonic SMEFT to Dimension 8

- The SMEFT extends the SM with **all possible operators**, but they are related through algebraic relations, IBP or Equations of Motion.
- We have presented a Green's basis for bosonic interactions up to dimension 8. Computation and algebraic manipulation was simplified by **working in momentum space**.
- The Green's basis operators are explicitly translated to a physical basis via the Equations of Motion. **Renormalization** can also be achieved.
- This basis is essential for **off-shell matching methods**, and can be extended for fermionic operators.

Conclusions

A Green's Basis for the Bosonic SMEFT to Dimension 8

Thanks for your attention!

This work was based on our paper 10.1007/JHEP05(2022)138

[2112.12724] Chala, Díaz-Carmona, and Guedes 2022.

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APPENDIX

Removing redundancies

Other transformations and identities

By using algebraic transformations and other relations, the redundant operators are expressed in terms of physical operators:

$$[D_\mu, D_\nu]\,\phi = -i\frac{g_1}{2}B_{\mu\nu}\phi - i\frac{g_2}{2}\sigma^I W^I_{\mu\nu}\phi$$
$$[D_\mu, D_\nu]\,W^{I\rho\lambda} = g_2\epsilon^{IJK}W^J_{\mu\nu}W^{K\rho\lambda}$$
$$[D_\mu, D_\nu]\,G^{A\rho\lambda} = g_3 f^{ABC}G^B_{\mu\nu}G^{C\rho\lambda}$$

$$0 = \partial_\mu F_{\nu\rho} + \partial_\rho F_{\mu\nu} + \partial_\nu F_{\rho\mu} \qquad \text{Bianchi}$$
$$0 = D_\mu(\mathcal{O}_1\mathcal{O}_2) = D_\mu\mathcal{O}_1\mathcal{O}_2 + \mathcal{O}_1 D_\mu\mathcal{O}_2 \qquad \text{IBP}$$

Applications

Integrating out a scalar quadruplet to one loop

SM extended with a $SU(2)_L$ quadruplet scalar Θ with $Y = 1/2$:

$$\mathcal{L}_{NP} = D_\mu\Theta^\dagger D^\mu\Theta - m_\Theta^2\Theta^\dagger\Theta - \lambda_\Theta(\phi^\dagger\sigma^I\phi)C^\alpha_{I\beta}\tilde{\phi}^\beta\epsilon_{\alpha\gamma}\Theta^\gamma + h.c.$$

and can be matched at 1L as well.

$$\frac{c^{(1)}_{B^4}}{\Lambda^4} = \frac{7g_1^4}{92160\, m_\Theta^4\, \pi^2}\,, \qquad \frac{c^{(1)}_{\phi^6}}{\Lambda^4} = \frac{|\lambda_\Theta|^2}{3\, m_\Theta^2} + \frac{-6440\, g_1^2\, |\lambda_\Theta|^2 + 103040\, |\lambda_\Theta|^2\lambda}{80640\, m_\Theta^4\, \pi^2}\,,$$

$$\frac{c^{(2)}_{B^4}}{\Lambda^4} = \frac{g_1^4}{92160\, m_\Theta^4\, \pi^2}\,, \qquad \frac{c^{(2)}_{\phi^6}}{\Lambda^4} = -\frac{|\lambda_\Theta|^2}{2\, m_\Theta^2} + \frac{+3640\, g_1^2|\lambda_\Theta|^2 - 655200\, |\lambda_\Theta|^2\, \lambda}{483840\, m_\Theta^4\, \pi^2}\,,$$

$$\frac{c^{(1)}_{\phi^4}}{\Lambda^4} = \frac{4480\, |\lambda_\Theta|^2 - 3g_1^4}{40320\, m_\Theta^4\, \pi^2}\,, \qquad \frac{c^{(2)}_{\phi^4}}{\Lambda^4} = \frac{3g_1^4 + 1120\, |\lambda_\Theta|^2}{40320\, m_\Theta^4\, \pi^2}\,, \qquad \frac{c^{(3)}_{\phi^4}}{\Lambda^4} = -\frac{|\lambda_\Theta|^2}{18\, m_\Theta^4\, \pi^2}\,,$$

$$\frac{c^{(1)}_{B^2\phi^4}}{\Lambda^4} = \frac{1960\, g_1^2|\lambda_\Theta|^2 - 3g_1^6}{322560\, m_\Theta^4\, \pi^2}\,, \qquad \frac{c^{(1)}_{B\phi^4D^2}}{\Lambda^4} = -\frac{g_1^5}{13440\, m_\Theta^4\, \pi^2}\,.$$

Appendix

Subsequent lines of work

- Computing the anomalous dimension matrix. Bosonic sector has been computed in [2205.03301] Das Bakshi et al. 2022:

$$
\begin{array}{c} \\ \dot{c}^{(1)}_{W^2H^4} \\ \dot{c}^{(2)}_{W^2H^4} \\ \dot{c}^{(3)}_{W^2H^4} \\ \dot{c}^{(4)}_{W^2H^4} \end{array}
\begin{array}{c}
\begin{matrix} c^{(1)}_{BH^4D^2} & c^{(2)}_{BH^4D^2} & c^{(1)}_{WH^4D^2} & c^{(2)}_{WH^4D^2} \end{matrix} \\
\begin{pmatrix}
-\frac{g_1 g_2^2}{8} & 0 & \frac{g_1^2 g_2}{3} + \frac{41 g_2^3}{24} - 5 g_2 \lambda & 0 \\
0 & -\frac{g_1 g_2^2}{8} & 0 & \frac{g_1^2 g_2}{3} + \frac{15 g_2^3}{8} - 5 g_2 \lambda \\
-\frac{g_1 g_2^2}{8} & 0 & -\frac{5 g_1^2 g_2}{24} & 0 \\
0 & -\frac{g_1 g_2^2}{8} & 0 & -\frac{5 g_1^2 g_2}{24}
\end{pmatrix}
\end{array}
$$

- Including fermionic operators to make a complete dimension 8 Green's basis with onshell relations.