Comparing BSM Scenarios using EFT

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Abstract

Augmenting the SM renormalizable Lagrangian with effective operators to enhance the prediction has been a common practice. This is popularly known as the bottom-up approach. Connecting the SMEFT operators to a UV model is complicated and arduous. In this article, we propose a diagrammatic approach to establish selection criteria for the allowed heavy field representations corresponding to each SMEFT operator. This, in turn, paves the way to construct observable-driven new physics models.

Introduction

The shortcoming of the Standard Model (SM) Conducting a comparative analysis of every single BSM scenario becomes tedious and impractical, and a systematic procedure must be developed to address this. It is desirable to have a more structured method of cataloguing the UV models that lead to specific SMEFT operators, which in turn can be correlated with observables. Clearly, instead of starting with a different BSM Lagrangian each time and comparing the various subsets of SMEFT each of them leads to, it is more economical if we approach this issue in a retrograde manner, where based on the observables under study we first identify the necessary operators and then attempt to enumerate the specific list of heavy fields that can generate the particular operator(s). This allows us to conduct our analysis in a minimal sense and also highlights which combinations of heavy fields may lead to redundant contributions.

This operator-driven BSM model building is what we have addressed in this work, i.e., our primary aim has been to identify the possible UV roots of each SMEFT operator when considering 1-particle-irreducible (1PI) diagrams up to one-loop-level built of interactions involving the SM as well as heavy fields.

Procedure

- The building blocks of our analysis are Feynman diagrams.
- The next step is the "unfolding" of the effective operators, using the renormalizable vertices through tree- and one-loop-level diagrams.
- Fixing the external legs of the diagrams with light particles in our case SM particles.
- Calculate the quantum numbers of the heavy particles as an internal line.

Example: Unfolding $(H^\dagger H)^3$ operator

Here we consider the SMEFT operator $(H^\dagger H)^3$ to illustrate our procedure. This operator contributes to the precision observables such as Higgs decays. If any deviation from the prediction of the SM is recorded that could be explained by this effective operator, we could follow this procedure to pin down the UV complete scenario.

Firstly, we enlist a subset of allowed vertices. We fix some legs and use particles from low-energy theory. In our case that would be the SM Higgs (H) and calculate the quantum numbers of the other remaining leg which will appear as an internal line in a Feynman diagram.

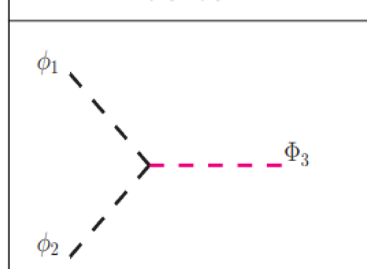
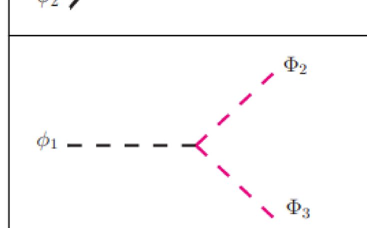
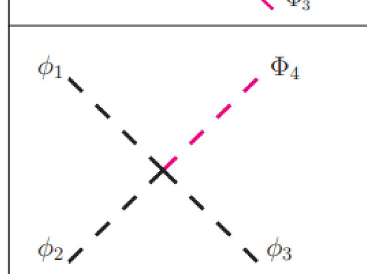
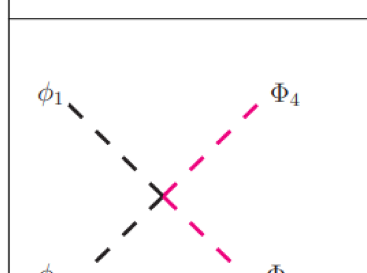
Vertex	S. No.	Light fields	Heavy field(s)
	V1-(i)	$\phi_1 = \phi_2 = H_{(1,2,\frac{1}{2})}$ or $H^\dagger_{(1,2,-\frac{1}{2})}$	$\Phi_3 \in \{(1,3,\pm1),\ (1,1,\pm1)\}$
	V1-(ii)	$\phi_1 = H,\quad \phi_2 = H^\dagger$	$\Phi_3 \in \{(1,3,0),\ (1,1,0)\}$
	V2	$\phi_1 = H$ or $H^\dagger$	$\Phi_2 \in (R_{C_2}, R_{L_2}, Y_2)$, $\Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$ with $R_{C_2} \otimes R_{C_3} \equiv 1$, $R_{L_2} \otimes R_{L_3} \equiv 2$ and $Y_2 + Y_3 = \pm\frac{1}{2}$.
	V3-(i)	$\phi_1 = \phi_2 = \phi_3 = H$ or $H^\dagger$	$\Phi_4 \in \{(1,4,\pm\frac{3}{2}),\ (1,2,\pm\frac{3}{2})\}$
	V3-(ii)	$\phi_1 = \phi_2 = H,\quad \phi_3 = H^\dagger$	$\Phi_4 \in \{(1,4,\pm\frac{1}{2}),\ (1,2,\pm\frac{1}{2})\}$
	V4-(i)	$\phi_1 = H,\quad \phi_2 = H^\dagger$	$\Phi_3 \in (\{1,R_C\},\{1,R_L\},\{0,Y\}),\quad \Phi_4 = \Phi_3^{\dagger}$
	V4-(ii)	$\phi_1 = \phi_2 = H$ or $H^\dagger$	$\Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$, $\Phi_4 \in (R_{C_4}, R_{L_4}, Y_4)$ with $R_{C_3} \otimes R_{C_4} \equiv 1$, $R_{L_3} \otimes R_{L_4} \equiv 1$ or 3 and $Y_3 + Y_4 = \pm 1$.

Figure 1: Allowed heavy field representations when the light degrees of freedom are the Standard Model ones. Here, ϕ_i denote the SM Higgs and Φ_i the various heavy scalars. R_C and R_L denote representations under $SU(3)_C$ and $SU(2)_L$ gauge groups and Y refers to the $U(1)_Y$ hypercharge of the field. Their appearance describes the cases where the vertex is not constituted by a unique heavy field representation but can involve a plethora of them.

Then we "unfold" the effective operator using the vertices mentioned above. Since the heavy field are to be integrated out we only consider the diagrams where these heavy fields only appear as internal lines.

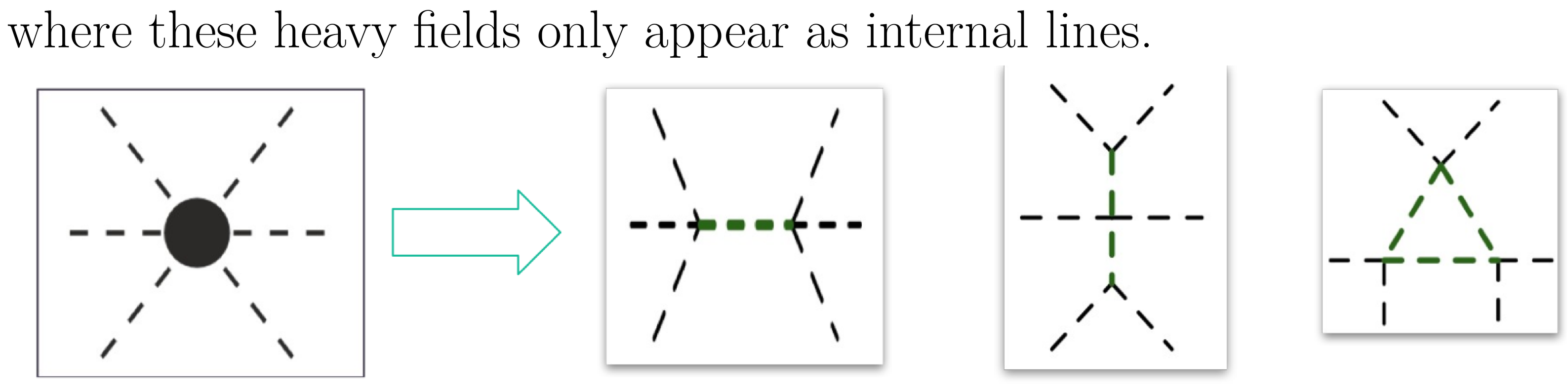


Figure 2: On the left hand side of the arrow, we have the $(H^\dagger H)^3$ effective vertex, then we "unfold" it using the renormailizable vertices shown in Fig. .

Now we fix the quantum numbers of the external leg, keeping in mind the operators structure. So the fields that constitute the operator will appear as the external particle.

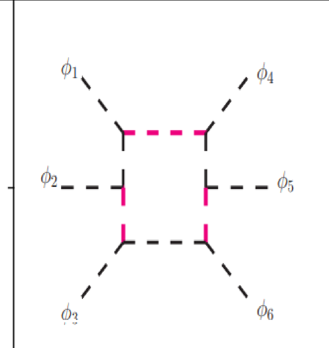
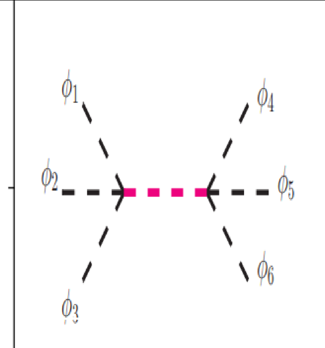
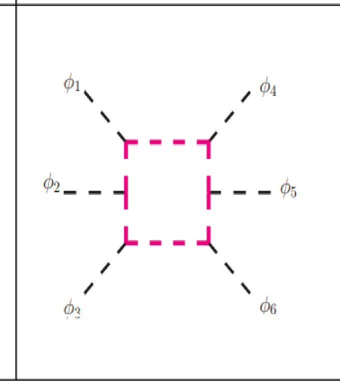
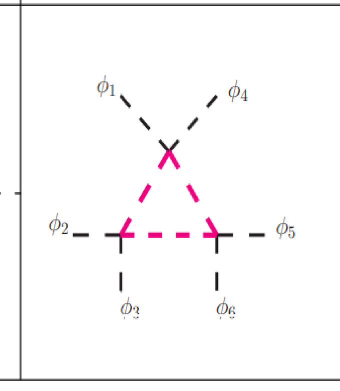
$\mathcal{Q}_H : (H^\dagger H)^3$					
Heavy fields	**Diagram**	**Vertices**	**Heavy fields**	**Diagram**	**Vertices**
$(1,3,1),\ (1,1,1)$		V1-(i)	$(1,4,\frac{3}{2}),\ (1,2,\frac{3}{2})$		V3-(i)
$(1,3,0),\ (1,1,0)$		V1-(ii)	$(1,4,\frac{1}{2}),\ (1,2,\frac{1}{2})$		V3-(ii)
$(R_{C_2}, R_{L_2}, Y_2) \oplus (R_{C_3}, R_{L_3}, Y_3)$		V2	$(\{1,R_C\},\{1,R_L\},\{0,Y\})$		V4-(i)
			$(R_{C_3}, R_{L_3}, Y_3) \oplus (R_{C_4}, R_{L_4}, Y_4)$		V4-(ii)

Figure 3: Heavy field representations that are obtained by unfolding the ϕ^6 operator into non-trivial tree- and(or) one-loop-level diagrams and the corresponding vertices.

It must be noted that in each diagram the black and colored lines represent light and heavy fields respectively.

Discussion

- In ref. [1] we unfold all the CP-conserving operators at dimension-six.
- We notice that by involving more and more operators or observables we can pin down UV scenarios or a set of UV scenarios more precisely.
- In ref. [2] we extend our approach to the CP-violating operators and also to the bosonic operators of dimension-eight.
- One interesting finding is some of the operators share a common origin, like the CP-violating operators in $\Phi^2 X^2$ class. Now the CP-conserving operators contribute to the electroweak precision observables.

Conclusion

In this work, we have highlighted the principles and salient features of an operator driven prescription for UV model building. Starting from the bottom-up extension of a low energy theory, we have described how to catalogue heavy field representations that provide non-zero contributions to specific processes and observables of the low-energy theory.

Acknowledgement

The author would like to acknowledge Supratim Das Bakshi, Joydeep Chakrabortty, Wrishik Naskar, and Suraj Prakash for their contribution to the aforementioned paper. The author is supported by the research grant by MHRD, Government of India.

References

[1] Supratim Das Bakshi, Joydeep Chakrabortty, Suraj Prakash, Shakeel Ur Rahaman, and Michael Spannowsky. EFT diagrammatica: UV roots of the CP-conserving SMEFT. *JHEP*, 06:033, 2021.

[2] Wrishik Naskar, Suraj Prakash, and Shakeel Ur Rahaman. EFT Diagrammatica. Part II. Tracing the UV origin of bosonic D6 CPV and D8 SMEFT operators. *JHEP*, 08:190, 2022.