Accidental Suppression of Wilson Coefficients in Higgs Coupling

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Singlet Extension to SM

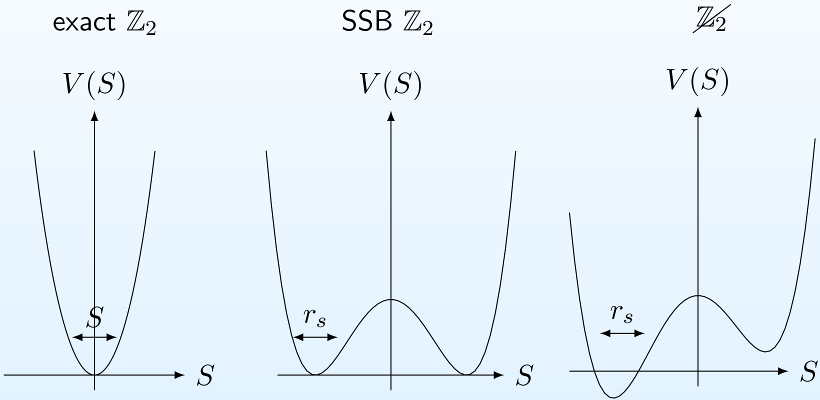
Real scalar $S \sim (\mathbf{1},\mathbf{1},\mathbf{1})_0$ with SM.

$$\mathcal{L} \supset \frac{1}{2}(\partial S)^2 - \frac{1}{2}\mu_S^2 S^2 + \mathcal{L}_{\mathsf{SM}} + \mathcal{L}(H,S). \tag{1}$$

Integrating out S, one finds

$$\mathcal{L}_{H,\mathsf{eff}} \sim |DH|^2 + \mu_h^2|H|^2 - \lambda_h|H|^4 + \frac{c_6}{\Lambda^2}|H|^6 + \frac{c_8}{\Lambda^4}|H|^8 + \dots \tag{2}$$

Three UV Scenarios



Exact $\mathbb{Z}_2$ Model

$$\mathbb{Z}_2 : S \to -S, \quad H \to H.$$

$$\mathcal{L}_{\text{int.}} \supset -\frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4} S^4 + \frac{\lambda_m}{2} |H|^2 S^2 + \mathcal{L}_H, \qquad \mathcal{L}_H = |DH|^2 + \mu_h^2 |H|^2 - \lambda_h |H|^4 \tag{3}$$

Q: What is $\mathcal{L}_{H,\text{eff}}$ at tree level if we integrate out S?

$$\mathcal{L}_{H,\text{eff}} = |DH|^2 + \mu_h^2 |H|^2 - \lambda_h |H|^4 + 0|H|^6 + 0|H|^8 \tag{4}$$

SSB $\mathbb{Z}_2$ Model

$$\mathbb{Z}_2 : S \to -S, \quad H \to H.$$

$$\mathcal{L}_{\text{int.}} \supset +\frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 + \frac{\lambda_m}{2}|H|^2 S^2 + \mathcal{L}_H, \\ \mathcal{L}_H = |DH|^2 + \mu_h^2|H|^2 - \lambda_h|H|^4 \tag{5}$$

Q: What is $\mathcal{L}_{H,\text{eff}}$ at tree level if we integrate out S?

$$\mathcal{L}_{H,\text{eff}} = |DH|^2 + {\mu_h'}^2|H|^2 - \lambda_h'|H|^4 + 0|H|^6 + 0|H|^8 \tag{6}$$

Does Wilson Coefficients "Remember" $\mathbb{Z}_2$ Symmetry?

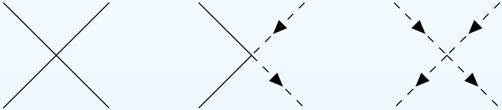
$$\mathcal{L} \supset + \frac{\mu_s^2}{2} S^2 - \frac{\lambda_s}{4} S^4 + \frac{\lambda_m}{2} |H|^2 S^2 + \mathcal{L}_H - \frac{\lambda_{s6}}{6} S^6 \quad (7)$$

Q: What is $\mathcal{L}_{H,\text{eff}}$ at tree level if we integrate out S?

$$\mathcal{L}_{H,\text{eff}} = |DH|^2 + \mu_h^2 |H|^2 - \lambda_h |H|^4 + \frac{c_6}{\Lambda^2} |H|^6 + \frac{c_8}{\Lambda^4} |H|^8 + \dots \quad (8)$$

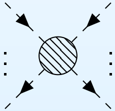
Wilson Coefficients in Exact $\mathbb{Z}_2$ Model

$$\mathcal{L} \supset -\frac{\lambda_s}{4} S^4 + \frac{\lambda_m}{2} S^2 |H|^2 - \lambda_h |H|^4 \tag{9}$$



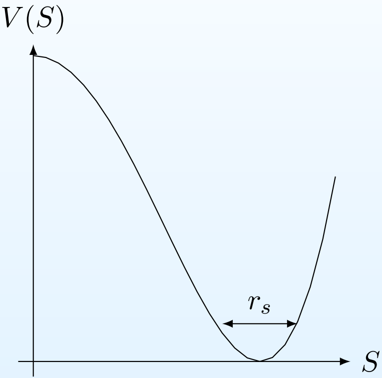
with $\langle S \rangle = 0$

Q: What is the tree-level Wilson coefficients for $|H|^{2n}$?

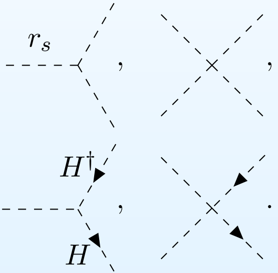


A: No tree-level $|H|^{2n}$ diagrams with internal S. They appears at one-loop level.

Wilson Coefficients in SSB $\mathbb{Z}_2$ Model

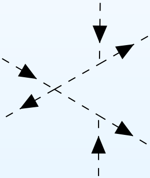
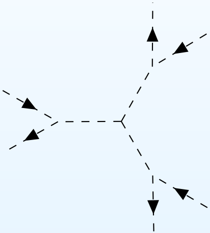


$$\mathcal{L} \supset -\frac{\lambda_m}{2}|H|^2(v_s + r_s)^2 \qquad (10)$$



(11)

Extract $|H|^6$ Wilson Coefficient

$\mathcal{A} = \#_1$  $+ \#_2$  (12)

$i^3 \cdot i^2 \cdot \#$ $\qquad$ $i^4 \cdot i^3 \cdot 3\#$

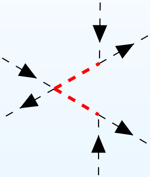
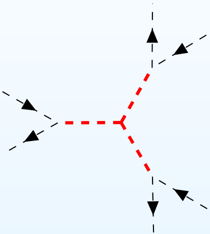
Two types of diagrams cancel!

Extract $|H|^{2n}$ Wilson Coefficients

$\mathcal{O}$	# of diagram types	# of diagrams	$c_{\mathcal{O}}$
$|H|^6$	2	24	0
$|H|^8$	4	28	0
$|H|^{10}$	7	180	0
$\vdots$	$\vdots$	$\vdots$	0?

Q: Is $c_{\mathcal{O}}$ always zero? How can we check this?

Extract $\sim \partial^2 |H|^6$ Wilson Coefficient

$\mathcal{A} = \#_1$  $+ \#_2$  (13)

$$\sim \frac{1}{p^2 - m^2} \sim -\frac{1}{m^2} - \frac{p^2}{m^4} + \dots \qquad (14)$$

Q: $\mathcal{L}_{H,\text{eff}} \supset 0 \cdot \partial^2 |H|^6$? A: No. $\mathcal{L}_{H,\text{eff}} \supset \frac{\lambda_m^2}{8\lambda_s} \frac{|H|^2 \left(\partial |H|^2\right)^2}{\mu_s^4}$.

Tree-level Effective Potential

STEP 1 Find $S_c(H)$ such that

$$\left.\frac{\partial \mathcal{L}_{\text{int.}}}{\partial S}\right|_{S_c(H)} = 0$$

STEP 2 Evaluate $\mathcal{L}_{\text{int.}}(S = S_c(H))$.

$\mathcal{L}_{H,\text{eff}}$ in SSB $\mathbb{Z}_2$

$$\mathcal{L}_{\text{int.}} = \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 + \frac{\lambda_m}{2}|H|^2 S^2. \tag{15}$$

$$\implies S_c^2 = \# + \#|H|^2.$$

$$\mathcal{L}_{H,\text{eff}} = \# + \#|H|^2 + \#|H|^4. \tag{16}$$

$\mathcal{L}_{H,\text{eff}}$ in SSB $\mathbb{Z}_2 + S^6$

$$\mathcal{L}_{\text{int.}} = \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 + \frac{\lambda_m}{2}|H|^2 S^2 - \frac{\lambda_{s6}}{6}S^6. \tag{17}$$

$$0 \stackrel{!}{=} \frac{\partial \mathcal{L}_{\text{int.}}}{\partial S} = S\left[\mu_s^2 - \lambda_m |H|^2 - \lambda_s S^2 - \lambda_{s6} S^4\right] \implies S_c^2 = \#-$$

$$\mathcal{L}_{H,\text{eff}} = \#``\sqrt{\# + \#|H|^2}" + \dots. \tag{18}$$

Tree-level $\sim \partial^2 |H|^{2n}$ Terms

STEP 1 Find $S_c(H)$ such that

$$\left.\frac{\partial \mathcal{L}_{\text{int.}}}{\partial S}\right|_{S_c(H)} = 0$$

STEP 2 Evaluate $\left.\frac{1}{2}(\partial_\mu S)^2\right|_{S=S_c}$.

[Cohen, Craig, Lu, Sutherland: 2008.08597]

$\partial^2|H|^{2n}$ Terms in SSB $\mathbb{Z}_2$

$$\mathcal{L}_{\text{int.}} = \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 + \frac{\lambda_m}{2}|H|^2 S^2. \tag{15}$$

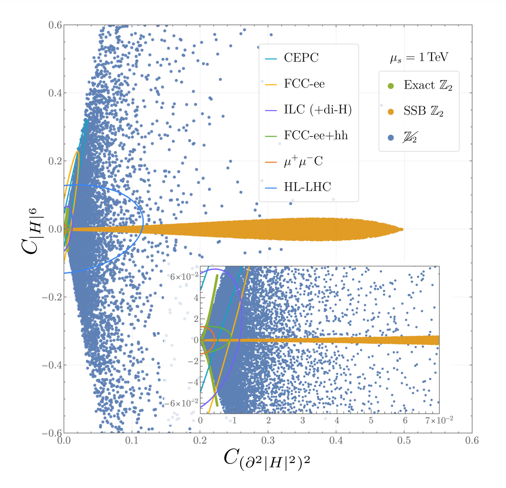
$$S_c^2 = \# + \#|H|^2$$

$$\mathcal{L}_{\text{kin.}} = \frac{1}{2}\left(\partial_\mu\sqrt{\# + \#|H|^2}\right)\left(\partial^\mu\sqrt{\# + \#|H|^2}\right) \tag{19}$$

Different Patterns in Wilson Coefficients

	$C_{\lvert H\rvert^6}$	$C_{\left(\partial\lvert H\rvert^2\right)^2}$
Exact $\mathbb{Z}_2$	1-loop	1-loop
SSB $\mathbb{Z}_2$	1-loop	tree
$\not{\mathbb{Z}_2}$	tree	tree

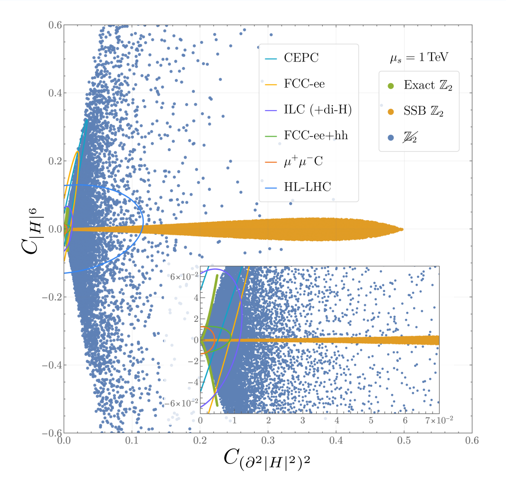
Wilson Coefficients of Different Models



Uniform sampling over UV parameters $\{\lambda_s, \lambda_m, \ldots\}$ with the restriction:

1) reproduce v_{EW} & m_h
2) perturbative unitarity

Concluding Remarks



- $\mathbb{Z}_2$ does not suppress high-dim operators in $\mathcal{L}_{H,\text{eff}}$
- Demanding $\mathcal{L}(S_c)$ is a finite polynomial in IR fields truncates the EFT
- EFT measurements complement resonant searches