Trilinear Higgs Coupling as a Probe for Extended Higgs Sectors

Work in preparation

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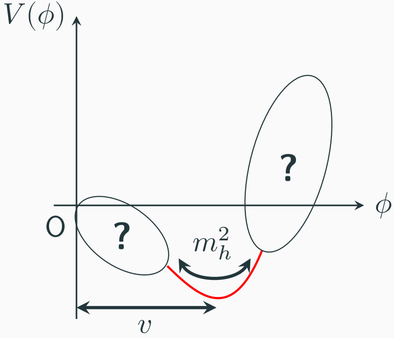
Introduction

- The Standard Model (SM) | Well-established at the scale $\Lambda < \mathcal{O}(1)$ TeV
- **Phenomenological Problems** |
  Phenomena beyond the SM exist.
  E.g., Baryon Asymmetry of the Universe, Existence of Dark Matter, etc.
- **Theoretical Problems** |
  The structure of the Higgs sector is still unknown.
  E.g., No guiding principle $\cdots$ elementary or composite? multiple species?

The extended Higgs sector can explain phenomena beyond the SM.

How precisely can we distinguish the extended Higgs model through the shape of the Higgs potential?

Higgs Potential



$V(\phi)$: Higgs potential

ϕ: classical field

Vacuum Expectation Value (VEV) | $0 = \left.\frac{\partial V}{\partial \phi}\right|_{\phi=v}$

Observation | $v = 246\,\mathrm{GeV}$

Square of the mass of the Higgs boson | $m_h^2 = \left.\frac{\partial^2 V}{\partial \phi^2}\right|_{\phi=v}$

Observation | $m_h = 125.11 \pm 0.11\,\mathrm{GeV}$

Trilinear Higgs Coupling | $\lambda_{hhh} = \left.\frac{\partial^3 V}{\partial \phi^3}\right|_{\phi=v}$

Deviation from the SM prediction | $\kappa_\lambda := \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}}$

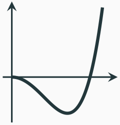
λ_{hhh} is important to determine the global shape of the Higgs potential.

Shapes of the Higgs Potential

[P. Agrawal *et al.*, 2020]

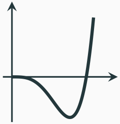
Type 1 | SMEFT

$V = -\#\phi^2 + \#\phi^4 + \#\phi^6$



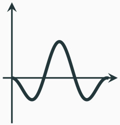
Type 2 | Classical Scale Invariance Model

$V = \#\phi^4 + \#\phi^4 \ln\left(\frac{\phi^2}{Q^2}\right)$



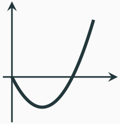
Type 3 | Minimal Composite Higgs Model 5

$V = -\#\sin^2\left(\phi^2/f^2\right) + \#\sin^4\left(\phi^2/f^2\right)$



Type 4 | Tadpole-induced Model

$V = \#\phi - \#\phi^2$



Trilinear Higgs Coupling at Colliders

Current limit [ATLAS Collaboration, 2024; CMS Collaboration, 2024]

- ATLAS ($\sqrt{s} = 13$ TeV, $L = 126 - 139$ fb^{-1}) | $-0.4 < \kappa_\lambda < 6.3$ at 95% C.L.
- CMS ($\sqrt{s} = 13$ TeV, $L = 138$ fb^{-1}) | $-1.2 < \kappa_\lambda < 7.5$ at 95% C.L.

Example of Future experiments

- High Luminosity LHC (HL-LHC) [ATLAS Collaboration, 2022; CMS Collaboration, 2021]
  - ATLAS ($\sqrt{s} = 14\,\mathrm{TeV}$, $L = 3000$ fb^{-1}) | $0.5 < \kappa_\lambda < 1.6$ at $68\,\%$ C.L.
  - CMS ($\sqrt{s} = 14\,\mathrm{TeV}$, $L = 3000$ fb^{-1}) | $0.35 < \kappa_\lambda < 1.9$ at $68\,\%$ C.L.
- International Linear Collider (ILC) [ILC International Development Team, 2022]
  - $\sqrt{s} = 1\,\mathrm{TeV}$, $L = 5\,\mathrm{ab}^{-1}$ | $0.9 < \kappa_\lambda < 1.1$ for $\kappa_\lambda = 1$ at $68\,\%$ C.L.

The loop contribution to λ_{hhh}

$$\lambda_{hhh}^{\text{tree}} = 3m_h^2/v$$

$$\lambda_{hhh}^{\text{1-loop}} = \frac{3m_h^2}{v}\left(1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2}\right) = \lambda_{hhh}^{\text{tree}} - \frac{3}{\pi^2}\frac{m_t^4}{v^3}$$

The top quark contribution gives about a $10\,\%$ correction to λ_{hhh} in the SM.
$\rightarrow$This contribution cannot be neglected at future collider experiments.

To scrutinize the shape of the Higgs potential in the extended model, we need to consider 1-loop corrections.

Standard Model Effective Field Theory (SMEFT)

Features [B. Grzadkowski, *et al.*, 2010]

A, B, C, D : model-dependent parameters
Q : renormalization scale

- The Higgs potential is introduced as the Landau-Ginzburg potential.
- New Physics effects are treated in the framework of the SM gauge group.
- The 5-dimensional operator is excluded because it assumes Z_2 symmetry of the Higgs potential.

Higgs potential at the 1-loop level |

$$V(\phi) = A\phi^2 + B\phi^4 + C\phi^4 \ln\frac{\phi^2}{Q^2} + \frac{D}{\Lambda^2}\phi^6 = V_{\rm SM}(\phi) + \frac{D}{\Lambda^2}\phi^6$$

Trilinear Higgs Coupling at the 1-loop level |

$$\lambda_{hhh}^{\rm SMEFT} = \frac{3}{v}\left\{m_h^2 + \frac{16}{3}\left(C + \frac{3Dv^2}{\Lambda^2}\right)v^2\right\} = \lambda_{hhh}^{\text{1-loop}} + \frac{48Dv^3}{\Lambda^2}$$

Classical Scale Invariance (CSI) Type

Features [E. Gildener, *et al.*, 1976]

- Scale invariance is assumed at the classical level.
- Radiative corrections cause spontaneous symmetry breaking via such a log term.
- New scalar particles are introduced.

Higgs potential at the 1-loop level |

$$V(\phi) = A\phi^4 + B\phi^4 \ln \frac{\phi^2}{Q^2}$$

Trilinear Higgs Coupling at the 1-loop level |

$$\lambda_{hhh}^{\mathrm{CSI}} = \frac{5}{3} \cdot \frac{3m_h^2}{v} = \frac{5}{3}\lambda_{hhh}^{\mathrm{tree}}$$

Minimal Composite Higgs Model (MCHM5) Type

Features [R. Contino, *et al.*, 2006]

f : broken scale $G \to H$

$\xi = v^2/f^2 = \sin^2 \frac{v}{f}$

- Global symmetry $G = \mathrm{SO}(5)$ is explicitly broken to the partial symmetry $H = \mathrm{SO}(4)$.
- The pNGB boson is identified as the Higgs boson.
- Fermion representations belong to $\mathbf{5}$-rep. in $\mathrm{SO}(5)$.

Higgs potential at the 1-loop level via top quark and weak bosons loops |

$$V(\phi) = -A\, f^4 \sin^2\left(\frac{\phi}{f}\right) + B\, f^4 \sin^4\left(\frac{\phi}{f}\right)$$

Trilinear Higgs Coupling at the 1-loop level |

$$\lambda_{hhh}^{\mathrm{MCHM5}} = \frac{3m_h^2}{v}\frac{1-2\xi}{\sqrt{1-\xi}} = \lambda_{hhh}^{\mathrm{tree}}\frac{1-2\xi}{\sqrt{1-\xi}}$$

Minimal Composite Higgs Model (MCHM4) Type

Features [K. Agashe, *et al.*, 2004]

- Global symmetry $G = \mathrm{SO}(5)$ is explicitly broken to the partial symmetry $H = \mathrm{SO}(4)$.
- The pNGB boson is identified as the Higgs boson.
- Fermion representations belong to $\mathbf{4}$-rep. in $\mathrm{SO}(5)$.

Higgs potential at the 1-loop level via top quark and weak bosons loops |

$$V(\phi) = A\, f^4 \cos\left(\frac{\phi}{f}\right) - B \sin^2\left(\frac{\phi}{f}\right) + C\, f^4 \sin^4\left(\frac{\phi}{f}\right)$$

Trilinear Higgs Coupling at the 1-loop level |

$$\lambda_{hhh}^{\mathrm{MCHM4}} = \frac{3m_h^2}{v}\sqrt{1-\xi}\left(1 - \frac{8v^2}{m_h^2}C\xi\right) = \lambda_{hhh}^{\mathrm{tree}}\sqrt{1-\xi}\left(1 - \frac{8v^2}{m_h^2}C\xi\right)$$

Tadpole-induced (Tadpole) Type

Features [J. Galloway, *et al.*, 2014]

A and B : positive model-dependent parameters.

- An additional heavy scalar particle is introduced | $V = m_H^2|H|^2 + m_\Sigma^2|\Sigma|^2 - \kappa^2(\Sigma^\dagger H + \mathrm{h.c.}) + \lambda_\Sigma|\Sigma|^4$
- Linear terms for the Higgs boson and additional scalar particle cause symmetry breaking.
- The quartic coupling λ of the Higgs doublet is negligible.

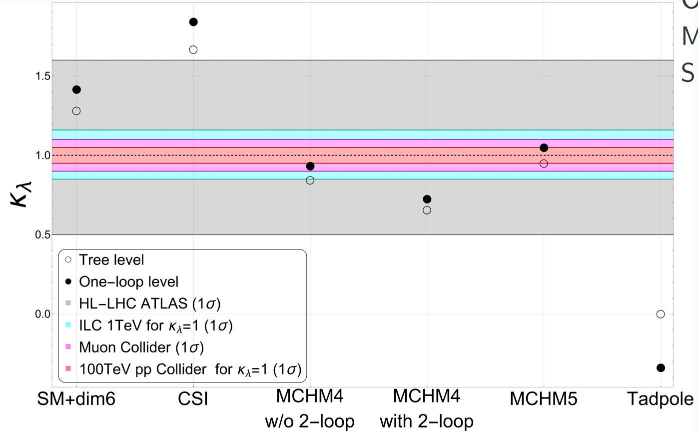
Higgs potential at the 1-loop level |

$$V(\phi) \simeq A\phi^2 - B\phi + C\phi^4 \ln\frac{\phi^2}{v^2}$$

Trilinear Higgs Coupling at the 1-loop level |

$$\lambda_{hhh}^{\mathrm{tadpole}} = -\frac{3}{\pi^2}\frac{m_t^4}{v^3}$$

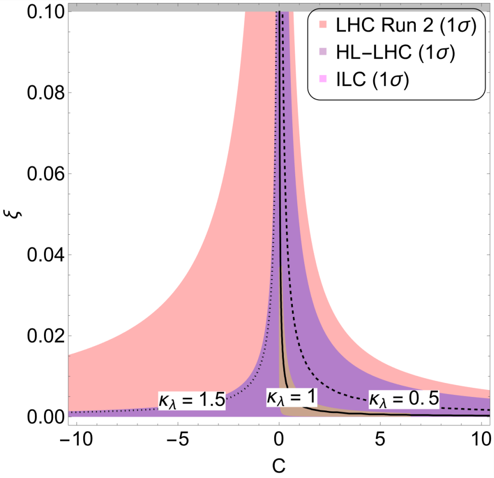
Results | Ratios of Trilinear Higgs Couplings



Tree level : $\lambda_{hhh}/\lambda_{hhh}^{\rm SM,\,tree}$
One-loop level : $\lambda_{hhh}/\lambda_{hhh}^{\rm SM,\,one-loop}$
MCHM : $\xi = \sin^2(v/f) = 0.1,$
SMEFT : $D/\Lambda^2 = 10^{-6}$

- The tadpole-induced model can be verifiable at the HL-LHC.
- At the ILC $1\,$TeV, the CSI model can be verifiable when $\kappa_\lambda = 1$.
- The potential shape is a good proxy to classify models.

Results | MCHM4 with the 2-loop correction



Contour plot of $\kappa_\lambda^{\rm MCHM4}$ in ξ and C

- The coefficient C of $\sin^4(\phi/f)$ can be constrainted from κ_λ and ξ.
- We assume that C is the $\mathcal{O}(1)$ parameter.
- The expected constraint of C at HL-LHC for $\xi = 0.1$ | $-0.15 < C < 0.2$
- Large values of C cannot be taken in ILC for the SM prediction. $\rightarrow$ C is an order-one parameter is reasonable.

Summary

$\circledcirc$: detectable at 2σ or higher, $\circ$: detectable at 1σ, $\times$: non-detectable

- We have computed trilinear couplings, including the 1-loop contribution, in representative extended Higgs models.
- We classified extended Higgs models by trilinear Higgs coupling and explored the feasibility of this classification at future collider experiments.

Model	**HL-LHC**	**ILC**	**Muon Col.**	**pp Col.**
SMEFT ($D = 0.1$, $\Lambda = 1$ TeV)	$\times$	$\circ$	$\circ$	$\circledcirc$
CSI model	$\circ$	$\circ$	$\circledcirc$	$\circledcirc$
MCHM4 ($\xi = 0.1$, $C = 0.1$)	$\times$	$\circ$	$\circ$	$\circ$
MCHM5 ($\xi = 0.1$)	$\times$	$\times$	$\times$	$\times$
Tadpole-induced model	$\circ$	$\circledcirc$	$\circledcirc$	$\circledcirc$

Backup

Other Trilinear Higgs Coupling at Colliders

Other future experiments:

- Muon Collider [C. Accettura, *et al.*, 2023]
  - $\sqrt{s} = 3\,\mathrm{TeV},\ L = 2\,\mathrm{ab}^{-1}$ | $0.85 < \kappa_\lambda < 1.16$ at 68% C.L.
- 100 TeV pp Collider (FCC-hh and SppC) [B. Di Micco, *et al.*, 2020]
  - $L = 30\,\mathrm{ab}^{-1}$ | $0.95 < \kappa_\lambda < 1.05$ for $\kappa_\lambda = 1$ at 68% C.L.

SM + $O(N)$ Singlet Scalar model

Features [S. Kanemura, et. al., 2021]

- Add N real gauge singlet scalar bosons $\vec{S} = (S_1, \dots, S_N)$ to SM

Higgs potential at the 1-loop level:

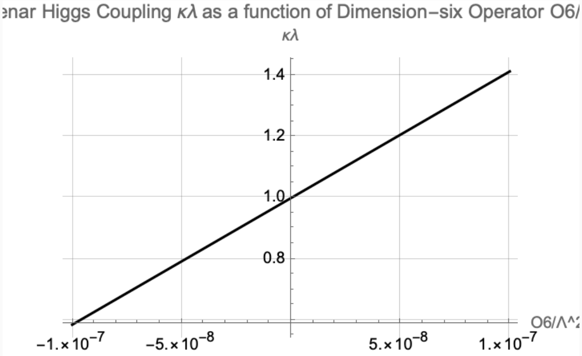
$$V(\phi) = A\phi^2 + B\phi^4 + C\phi^4 \ln \frac{\phi^2}{Q^2} + \frac{D}{\Lambda^2}\phi^6 = V_{\rm SM}(\phi) + \frac{D}{\Lambda^2}\phi^6$$

where A, B, C, D are model-dependent parameters.

Trilinear Higgs Coupling at the 1-loop level:

$$\lambda_{hhh}^{\rm SMEFT} = \frac{3}{v}\left\{m_h^2 + \frac{16}{3}\left(C + \frac{3Dv^2}{\Lambda^2}\right)v^2\right\} = \lambda_{hhh}^{\rm 1\text{-}loop} + \frac{48Dv^3}{\Lambda^2}$$

Result: SMEFT Type



Preliminary Plot of κ_λ dependence on the coefficient D/Λ^2 of the dimension-six operator

- The coefficient D/Λ^2 of dimension-six operator can be limited by the constraint of κ_λ.
- The constraint at the HI-LHC: $-1 \times 10^{-7} < D^2/\Lambda^2 < 1 \times 10^{-7}$

Result: pNGB Type 2 at LHC and Hl-LHC

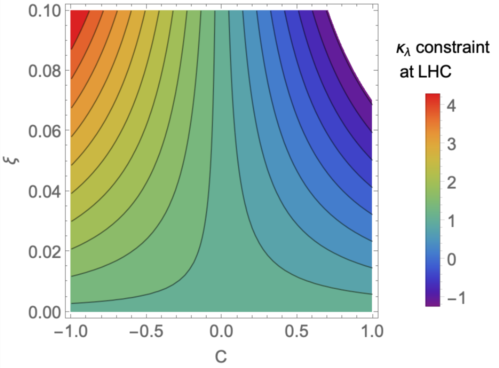


Figure 1: Contour plot of the ratio of trilinear Higgs coupling $\kappa_\lambda^{\rm pNGB}$ allowed from LHC observations

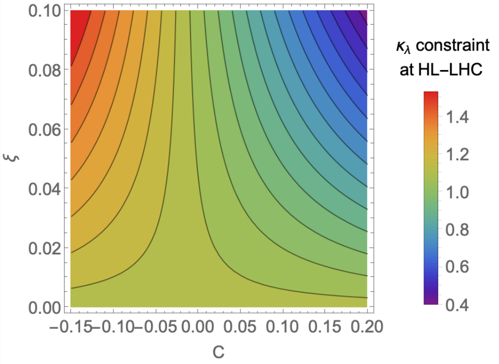
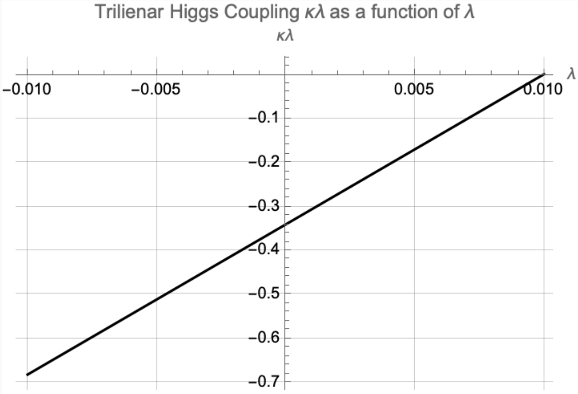


Figure 2: Contour plot of the ratio of trilinear Higgs coupling $\kappa_\lambda^{\rm pNGB}$ allowed from HL-LHC observations

Result: Tadpole Type



Preliminary Plot of κ_λ dependence on the coefficient $\lambda\,(\ll 1)$ of ϕ^4

- The coefficient λ of ϕ^4 can be limited by the constraint of κ_λ.
- $\kappa_\lambda^{\mathrm{Tadpole}}$ is only negative in the region of λ, which is sufficiently small compared to the tadpole coupling B.