Constraints on Trilinear Higgs Couplings Including One-loop Correction in Nearly Aligned Higgs Models

Work in progress

Shuhei Ohzawa (U. of Toyama)

Collaborators: Mitsuru Kakizaki[A], Nagisa Hiroshima[B, C]

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[A]U. of Toyama

[B]Yokohama National U.

[C]RIKEN iTHEMS

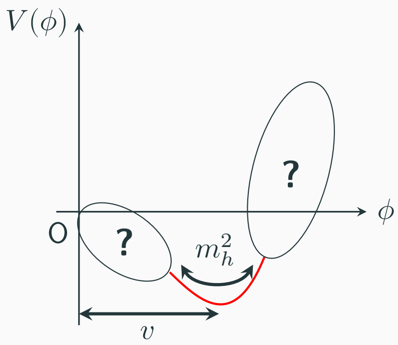
Introduction

- The Standard Model (SM): Well-established at the scale $\Lambda < \mathcal{O}(1)$ TeV
- **Phenomenological Problems**:
  Phenomena beyond the SM.
  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 spices?

The extended Higgs sector can explain phenomena beyond the SM.

How precise can we distinguish the extended Higgs model through the trilinear Higgs coupling?

Higgs Potential



$V(\phi)$: Higgs potential

ϕ: classical field

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

Observation: $v = 246\,\text{GeV}$

[S. Navas et al. (Particle Data Group), 2024]

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

Observation: $m_h = 125.11 \pm 0.11\,\text{GeV}$

[ATLAS Collaboration, 2023]

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

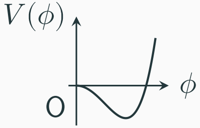
Ratio of the trilinear Higgs coupling: $\kappa_\lambda := \frac{\lambda_{hhh}}{\lambda_{hhh}^{\text{SM}}}$

λ_{hhh} is important for determining the global shape of the Higgs potential.

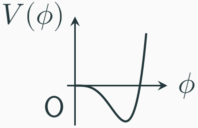
Shapes of the Higgs Potential

Samples in this talk: 4 types of Higgs potentials in nearly aligned Higgs models [P. Agrawal *et al.*, 2020]

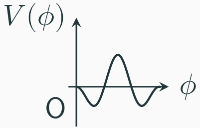
Nearly aligned Higgs model: A good approximation with one classical field ϕ



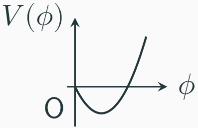
Type 1: Standard Model



Type 2: Classical Scale Invariance



Type 3: pseudo-Nambu-Goldstone



Type 4: Tadpole-induced

Trilinear Higgs Coupling at Colliders (1)

Current observation: [ATLAS Collaboration, 2024; CMS Collaboration, 2024]

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

Future upgrade:

- High Luminosity LHC (HL-LHC) [ATLAS Collaboration, 2022; CMS Collaboration, 2021]
  - ATLAS ($\sqrt{s} = 14\,\text{TeV}$, $\mathcal{L} = 3000$ fb^{-1}): $0.5 < \kappa_\lambda < 1.6$ at 68% C.L.
  - CMS ($\sqrt{s} = 14\,\text{TeV}$, $\mathcal{L} = 3000$ fb^{-1}): $0.35 < \kappa_\lambda < 1.9$ at 68% C.L.

Trilinear Higgs Coupling at Colliders (2)

Future experiments:

- International Linear Collider (ILC) [ILC International Development Team, 2022]
  - $\sqrt{s} = 1\,\mathrm{TeV},\ \mathcal{L} = 5\,\mathrm{ab}^{-1}$:
    The measurement accuracy is about $10\,\%$ for $\kappa_\lambda = 1$ at 68% C.L.
- $100\,$TeV pp Collider (FCC-hh and SppC) [B. Di Micco, M. Gouzevitch, J. Mazzitelli, C. Vernieri, J. Alison, K. Androsov, J. Baglio, E. Bagnaschi, S. Banerjee and P. Basler, *et al.*, 2020]
  - $\mathcal{L} = 30\,\mathrm{ab}^{-1}$:
    The measurement accuracy is about $5\,\%$ for $\kappa_\lambda = 1$ at 68% C.L.
- Muon Collider [C. Accettura, D. Adams, R. Agarwal, C. Ahdida, C. Aimè, N. Amapane, D. Amorim, P. Andreetto, F. Anulli and R. Appleby, *et al.*, 2023]
  - $\sqrt{s} = 3\,\mathrm{TeV},\ \mathcal{L} = 2\,\mathrm{ab}^{-1}$: $0.85 < \kappa_\lambda < 1.16$ at 68% C.L.

The loop contribution to λ_{hhh}

In the SM,

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

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

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

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

Standard Model Effective Field Theory (SMEFT)

Features [B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, 2010]

- New Physics effects can be treated in the framework of the SM gauge group.

Higgs potential at the 1-loop level:

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

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

Trilinear Higgs Coupling at the 1-loop level:

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

Classical Scale Invariance (CSI) Type

Features [E. Gildener and S. Weinberg, 1976; K. Hashino, S. Kanemura and Y. Orikasa, 2016]

- Scale invariance is assumed.
- Spontaneous symmetry breaking is caused by radiative corrections.
- New scalar particles are introduced.

Higgs potential at the 1-loop level:

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

where Q is a renormalization scale.

Trilinear Higgs Coupling at the 1-loop level:

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

pseudo-Nambu-Goldstone Boson (pNGB) Type 1

Features [D. B. Kaplan and H. Georgi, 1984; R. Contino, 2010]

- Global symmetry G is explicitly broken to the partial symmetry H.
- Identification of the pseudo-Nambu-Goldstone boson appearing in symmetry breaking $G \to H$ as the Higgs boson.

Higgs potential at the 1-loop level when weak bosons contribution dominant:

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

where f is the broken scale at $G \to H$.

Trilinear Higgs Coupling at the 1-loop level:

$$\lambda_{hhh}^{\mathrm{pNGB}} = \frac{3m_h^2}{v}\frac{1-2\xi}{\sqrt{1-\xi}} = \lambda_{hhh}^{\mathrm{tree}}\frac{1-2\xi}{\sqrt{1-\xi}} \qquad \left(\xi := \frac{v^2}{f^2} = \sin^2\frac{v}{f}\right)$$

pseudo-Nambu-Goldstone Boson (pNGB) Type 2

Features [D. B. Kaplan and H. Georgi, 1984; R. Contino, 2010]

- Global symmetry G is explicitly broken to the partial symmetry H.
- The pNG boson is identified as the Higgs boson.

Higgs potential at the 1-loop level when weak bosons and top quark contribution dominant:

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

where f is the broken scale at $G \to H$.

Trilinear Higgs Coupling at the 1-loop level:

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

Tadpole-induced (Tadpole) Type

Features [J. Galloway, M. A. Luty, Y. Tsai and Y. Zhao, 2014; S. Chang, J. Galloway, M. Luty, E. Salvioni and Y. Tsai, 2015]

- An additional heavy scalar particle is introduced.
- 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:

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

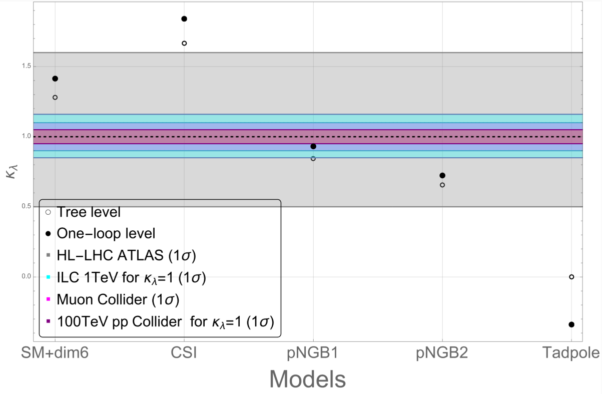
where A and B are positive model-dependent parameters.

Trilinear Higgs Coupling at the 1-loop level:

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

Results: Ratios of Trilinear Higgs Couplings

Trilinear Higgs Couplings at the 1-loop level for each model expected at future colliders

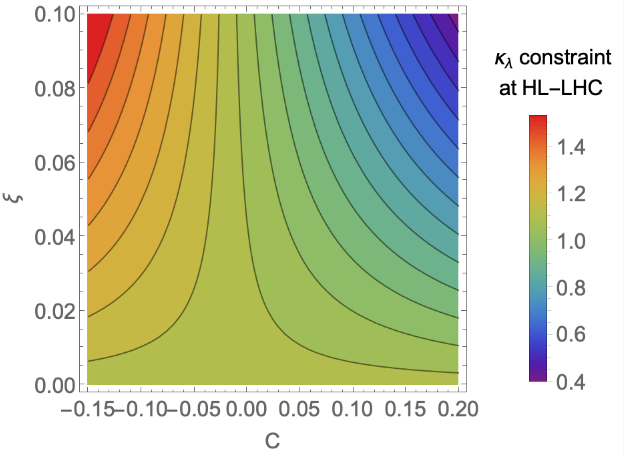


for pNGB type 1 and type 2 $\xi = \sin^2(v/f) = 0.1$,
SMEFT $D/\Lambda^2 = 10^{-6}$

Tree level: $\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM,\,tree}}$
One-loop level: $\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM,\,one-loop}}$

- The region of the ILC at $1\,$TeV (Cyan) is the accuracy at 1σ level for the SM value.
- The tadpole-induced model can be verifiable at the HL-LHC.
- At the ILC $1\,$TeV, the CSI model can be verifiable when $\kappa_\lambda = 1$.

Result: pNGB Type 2

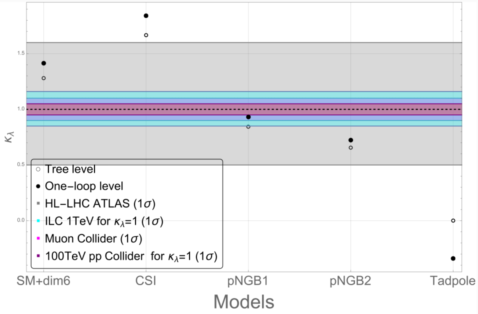


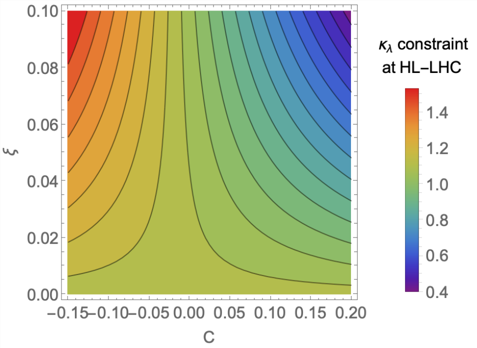
Contour plot of $\kappa_\lambda^{\text{pNGB}}$ in ξ and C

- The coefficient C of $\sin^4(\phi/f)$ can be limited by the constraint of κ_λ and ξ.
- We assume that C is the $\mathcal{O}(1)$ parameter since the calculation of the effective potential can be perturbative.
- The expected constraint of C at HL-LHC: $-0.15 < C < 0.2$.

Summary

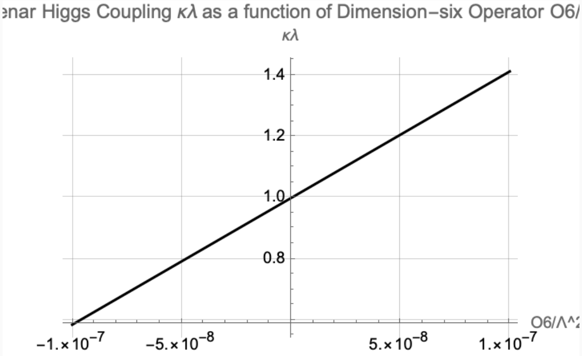
- We have computed trilinear couplings including the 1-loop contribution in representative nearly aligned Higgs models.
- We classified nearly aligned Higgs models by trilinear Higgs coupling and explored the feasibility of this classification at future collider experiments.





Backup

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

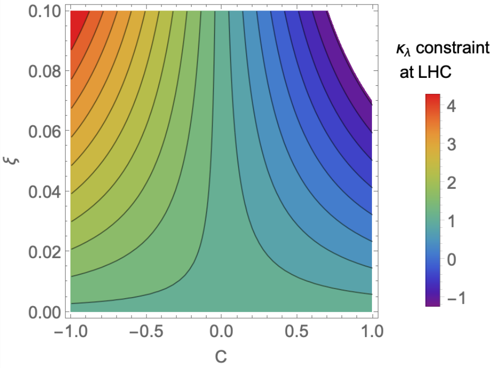


Figure 1: Contour plot of the ratio of trilinear Higgs coupling $\kappa_\lambda^{\rm pNGB}$ allowed from LHC observations

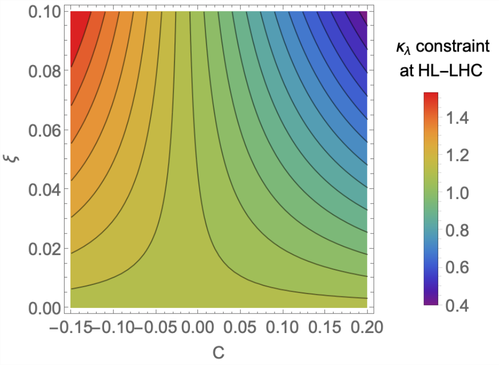
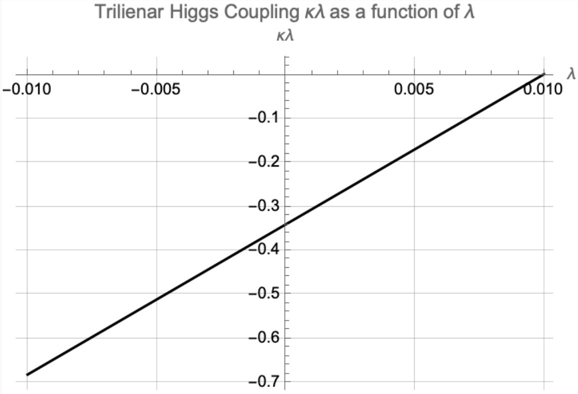


Figure 2: Contour plot of the ratio of trilinear Higgs coupling $\kappa_\lambda^{\rm pNGB}$ allowed from HL-LHC observations

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.