Higher-order effects in the trilinear Higgs coupling for future collider experiments

Work in progress

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Introduction

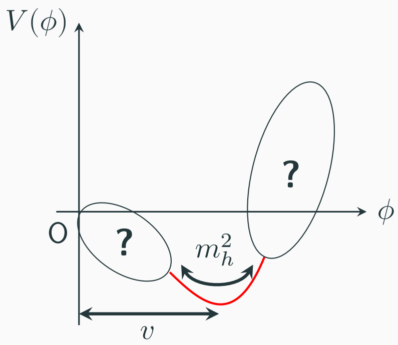
Introduction

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

The extended Higgs sector can explain phenomena beyond the SM.

Focus:
The characterization of extended models with the detailed 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: $v = 246\,\text{GeV}$

[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.

Trilinear Higgs Coupling at Colliders (1)

Current observation: [ATLAS Collaboration, 2023; CMS Collaboration, 2022]

- 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}): $-1.24 < \kappa_\lambda < 6.49$ 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.

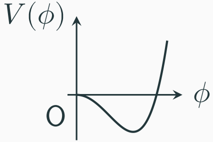
Trilinear Higgs Coupling at Colliders (2)

Future experiments:

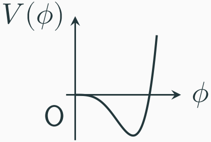
- International Linear Collider (ILC) [ILC International Development Team, 2022]
  - $\sqrt{s} = 1\,\mathrm{TeV},\ \mathcal{L} = 5\,\mathrm{ab}^{-1}$:
    The measurement accuracy is about $10\,\%$ for $\kappa_\lambda = 1$ at 68% C.L.
- 100 TeV pp Collider (FCC-hh and SppC) [B. Di Micco, M. Gouzevitch, J. Mazzitelli, C. Vernieri, J. Alison, K. Androsov, J. Baglio, E. Bagnaschi, S. Banerjee and P. Basler, *et al.*, 2020]
  - $\mathcal{L} = 30\,\mathrm{ab}^{-1}$: $\kappa_\lambda = 1 \pm 5\%$ 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.

Shapes of the Higgs Potential

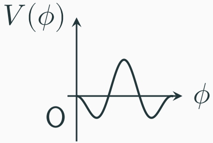
Samples in this talk: 4 types of Higgs potentials
(See P. Agrawal, D. Saha, L. X. Xu, J. H. Yu and C. P. Yuan, 2020.)



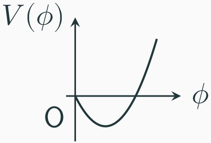
Type 1: Standard Model



Type 2: Classical Scale Invariance



Type 3: pseudo-Nambu-Goldstone



Type 4: Tadpole-induced

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

Models

Standard Model Effective Field Theory (SMEFT)

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

- New Physics effects can be treated within the framework of the SM.

Higgs potential at the 1-loop level:

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

where A, B, C, D are arbitrary 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]

- Assuming scale invariance at the classical level.
- Spontaneous symmetry breaking is caused by radiative corrections.
- Introduces new scalar particles.

Higgs potential at the 1-loop level:

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

where A and B are model dependent parameters, and 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

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:

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

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

Trilinear Higgs Coupling at the 1-loop level:

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

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]

- Introduces an additional scalar particle in the SM.
- Linear terms for the Higgs boson and additional scalar particle cause symmetry breaking.
- The quartic coupling λ with the SM is negligible.

Higgs potential at the 1-loop level:

$$V(\phi) = A\phi^2 - B\phi - \frac{3}{16\pi^2}\frac{m_t^4}{v^4}\phi^4 \ln\frac{\phi^2}{v^2}$$

where A and B are positive model-dependent parameters.

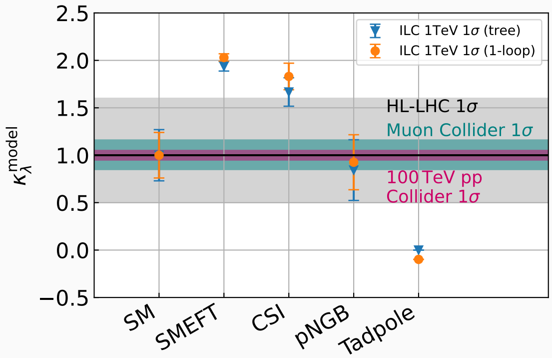
Trilinear Higgs Coupling at the 1-loop level:

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

Results

Results

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



- The tadpole-induced model can be verifiable at the HL-LHC.
- At the ILC $1\,\text{TeV}$, the CSI model can be verifiable when $\kappa_\lambda = 1$.

for pNGB $\xi = \sin^2(v/f) = 0.1$, SMEFT $D = 2$, $\Lambda = 1\,\text{TeV}$

Summary

- Extensions of the Higgs sector are proposed as a way to explain phenomena beyond the Standard Model
- It is necessary to constrain the extendability of Higgs models
- We have computed trilinear couplings including the 1-loop contribution in representative models
- Trilinear Higgs Couplings at 1-loop level can be shifted to about $10\,\%$ compared to tree-level values.
- For example, the tadpole-induced model can be identified at the HL-LHC at the $68\,\%$ C.L.