Discrimination of Extended Higgs Sectors through Higher-Order Contributions to the Higgs Trilinear Coupling

Work in progress

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Introduction

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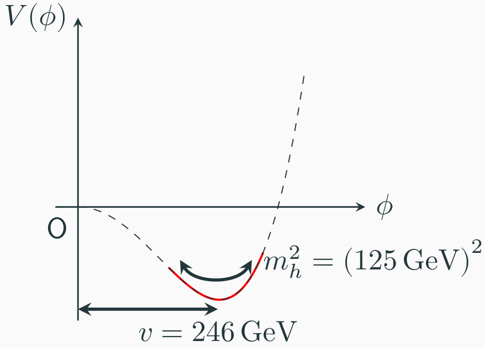
- The Standard Model (SM) is consistent with the results of collider experiments.
- **Phenomenological Problems**:
  Phenomena beyond the SM are reported.
  Ex. Baryon asymmetry of the Universe, Existence of Dark Matter, etc.
- **Theoretical Problems**:
  The structure of the Higgs sector is still unknown.
  Ex. Guiding principle $\cdots$ elementary or composite? multiple spices?
  The extended Higgs sector can explain phenomena beyond the SM.

How can we select models with extended Higgs sectors?

Higgs Potential



$V(\phi)$: Higgs potential

ϕ: classical field

Vacuum Expectation Value (VEV):

$$0 = \left.\frac{\partial V}{\partial \phi}\right|_{\phi=v}$$

Observation: $v = 246\,\mathrm{GeV}$ [PDG, 2022]

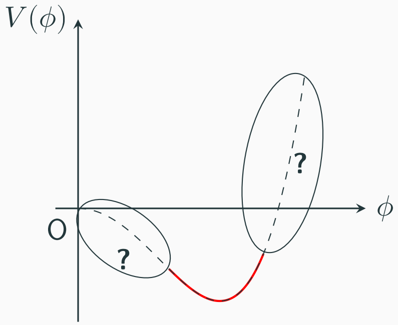
Square of the mass of the Higgs boson:

$$m_h^2 = \left.\frac{\partial^2 V}{\partial \phi^2}\right|_{\phi=v}$$

Observation: $m_h = 125.22 \pm 0.14\,\mathrm{GeV}$

[ATLAS Collaboration, arXiv:2308.07216]

Higgs Trilinear Coupling



$V(\phi)$: Higgs potential
ϕ: classical field

Higgs trilinear coupling:

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

Self-coupling modifier:

$$\kappa_\lambda := \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}}$$

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

Higgs Trilinear Coupling at Colliders

Current observation: [ATLAS Collaboration, Phys.Lett.B 843 (2023); CMS Collaboration, Nature 607 (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.

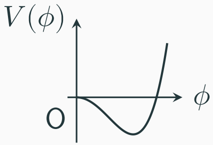
Future experiments:

- High Luminosity LHC (HL-LHC) [ATLAS Collaboration, ATL-PHYS-PUB-2022-053; CMS Collaboration, CMS PAS FTR-21-004]
  - ATLAS ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3000$ fb^{-1}): $0.5 < \kappa_\lambda < 1.6$ at 68% C.L.
  - CMS ($\sqrt{s} = 14$ TeV, $\mathcal{L} = 3000$ fb^{-1}): $0.35 < \kappa_\lambda < 1.9$ at 68% C.L.
- International Linear Collider (ILC) [ILC International Development Team, DESY-22-045]
  - $\sqrt{s} = 1$ TeV, $\mathcal{L} = 5$ ab^{-1}:
    The measurement accuracy is about 10 % for $\kappa_\lambda = 1$ at 68% C.L.

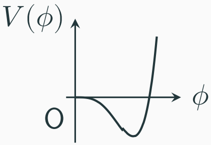
Models

Shapes of the Higgs Potential

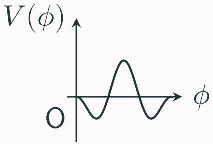
Representative samples of the Higgs potential of extended models
(See P. Agrawal, et. al., Phys.Rev.D 101 (2020).)



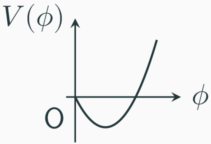
Type 1: Standard Model



Type 2: Classical Scale Invariance



Type 3: pseudo-Nambu-Goldstone



Type 4: Tadpole-induced

Importance of the loop contribution

In the SM,

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

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

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

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

Classical Scale Invariance (CSI) Type

Features [E. Gildener, S. Weinberg, Phys.Rev.D 13 (1976) 3333; K. Hashino, et. al., Phys.Lett.B 752 (2016) 217-220]

- 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.

Higgs trilinear coupling at the 1-loop level:

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

pseudo-Nambu-Goldstone Boson (pNGB) Type

Features [D. B. Kaplan, H. Georgi, Phys.Lett.B 136 (1984); D. Marzocca, et. al., JHEP 08 (2012) 013]

- 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 $G \to H$.

Higgs trilinear coupling at the 1-loop level:

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

Tadpole-induced (Tadpole) Type

Features [J. Galloway, et. al., Phys.Rev.D 89 (2014) 7, 075003]

- Introduces an additional scalar particle in the SM.
- Linear terms for the Higgs boson and additional scalar particle cause symmetry breaking.

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.

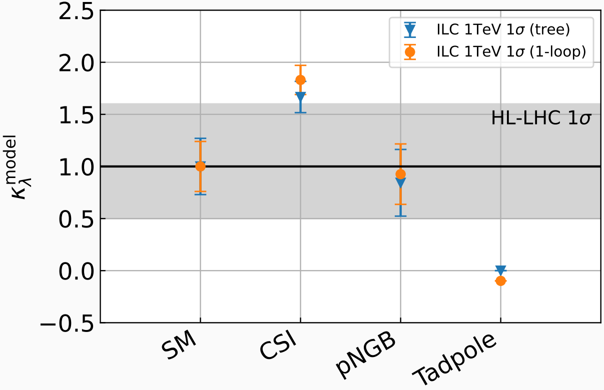
Higgs trilinear coupling at the 1-loop level:

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

Results

Results

Higgs trilinear couplings at the 1-loop level for each model expected at future colliders



- The tadpole-induced model becomes verifiable at the HL-LHC.
- At the ILC1TeV, the CSI model becomes verifiable when $\kappa_\lambda = 1$.

for pNGB $\xi = \sin^2(v/f) = 0.1$

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.