Feasibility of Higgs Potential Shape Classification at Future Colliders

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Introduction

SM problems: Baryon asymmetry, Dark Matter, ν-mass, $\cdots$
$\Rightarrow$ Extensions of the Higgs sector
$\Rightarrow$ **How to distinguish extended Higgs sectors experimentally?**

Shape of the Higgs potential

Trilinear Higgs Coupling:

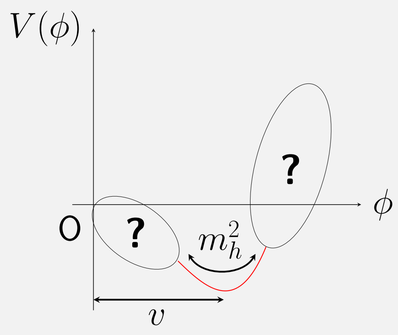
$$\lambda_{hhh} = \left.\frac{\partial^3 V}{\partial \phi^3}\right|_{\phi=v}, \quad \left(\lambda_{hhh}^{\text{tree}} = \frac{3m_h^2}{v}\right)$$

Ratio of the trilinear Higgs coupling:

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{\text{SM}}}$$

$$\frac{\Delta\lambda_{hhh}^{\text{SM, 1-loop}}\big|_{\text{top}}}{\lambda_{hhh}^{\text{tree}}} \sim -\mathcal{O}(10\,\%)$$

$\Rightarrow \lambda_{hhh}^{\text{SM, 1-loop}}\big|_{\text{top}}$ is crucial at future colliders.



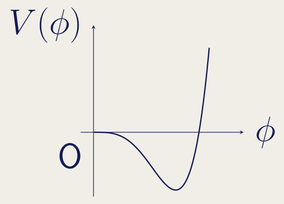
$V(\phi)$: Higgs potential
ϕ : classical field

Type 1: SMEFT

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

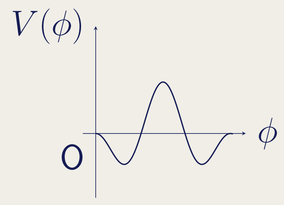
Type 2: Classical Scale Invariance Model

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



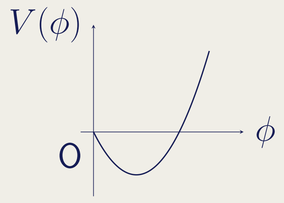
Type 3: Minimal Composite Higgs Model

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



Type 4: Tadpole-induced Model

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



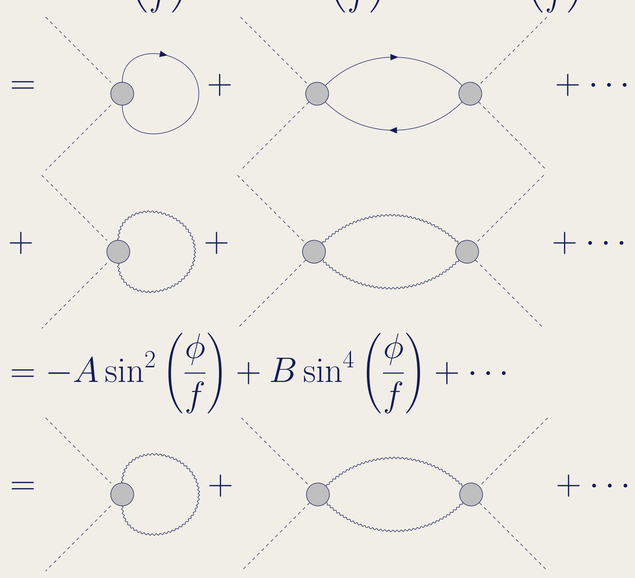
How well can we distinguish the functional form of Higgs potential?

Demonstration: Minimal Composite Higgs Models

The Higgs boson is the pseudo-Nambu-Goldstone boson generated by explicit symmetry breaking $G \to H$ (f: broken scale).

Higgs potential at 1-loop level:

MCHM4: $V = A\cos\left(\frac{\phi}{f}\right) + B\sin^2\left(\frac{\phi}{f}\right) + C\sin^4\left(\frac{\phi}{f}\right) + \cdots$



MCHM5: $V = -A\sin^2\left(\frac{\phi}{f}\right) + B\sin^4\left(\frac{\phi}{f}\right) + \cdots$

Trilinear Higgs Coupling at the 1-loop level ($\xi = v^2/f^2 = \sin^2(v/f)$):

$$\lambda_{hhh}^{\text{MCHM4}} = \lambda_{hhh}^{\text{tree}}\sqrt{1-\xi}\left(1 - 8C\frac{v^2}{m_h^2}\xi\right), \qquad \lambda_{hhh}^{\text{MCHM5}} = \lambda_{hhh}^{\text{tree}}\frac{1-2\xi}{\sqrt{1-\xi}},$$

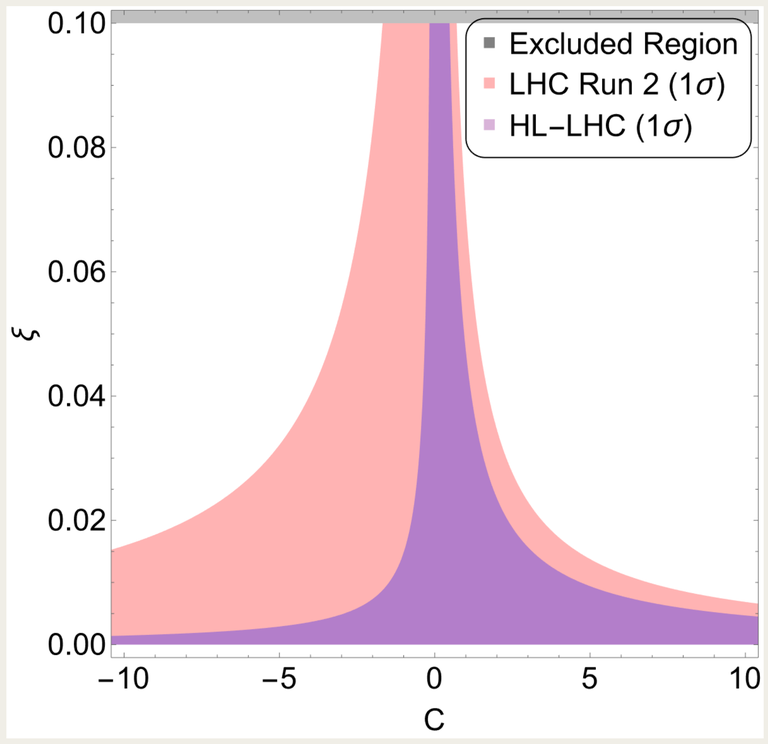


Figure 1. Constraint based on κ_λ-measurement at LHC and HL-LHC.

- Expected constraint on C at LHC for $\xi = 0.1$: $\underline{-1.6 < C < 0.7}$
- Expected constraint on C at HL-LHC for $\xi = 0.1$: $\underline{-0.17 < C < 0.48}$

$\Rightarrow$ 10 times stronger than current LHC limits.

Results & Summary

- Tadpole-induced model $\to$ verifiable at the HL-LHC.
- CSI model $\to$ verifiable at the ILC $1\,\text{TeV}$ with $\kappa_\lambda = 1$
- SMEFT ($D = 0.1$, $\Lambda = 1\,\text{TeV}$) $\to$ verifiable at the ILC $1\,\text{TeV}$ with $\kappa_\lambda = 1$
- MCHM4 ($\xi = 0.1$, $C = 0.1$) $\to$ verifiable at the ILC $1\,\text{TeV}$ with $\kappa_\lambda = 1$
- MCHM5 ($\xi = 0.1$) $\to$ non-verifiable

Model	**HL-LHC**	**ILC($1\,\text{TeV}$)**	**Muon Col.**	**pp Col.($100\,\text{TeV}$)**
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	$\circ$	$\circledcirc$	$\circledcirc$	$\circledcirc$

$\begin{cases} \circledcirc : \text{detectable at } 2\sigma \text{ or higher} \\ \circ : \text{detectable at } 1\sigma \\ \times : \text{non-detectable} \end{cases}$

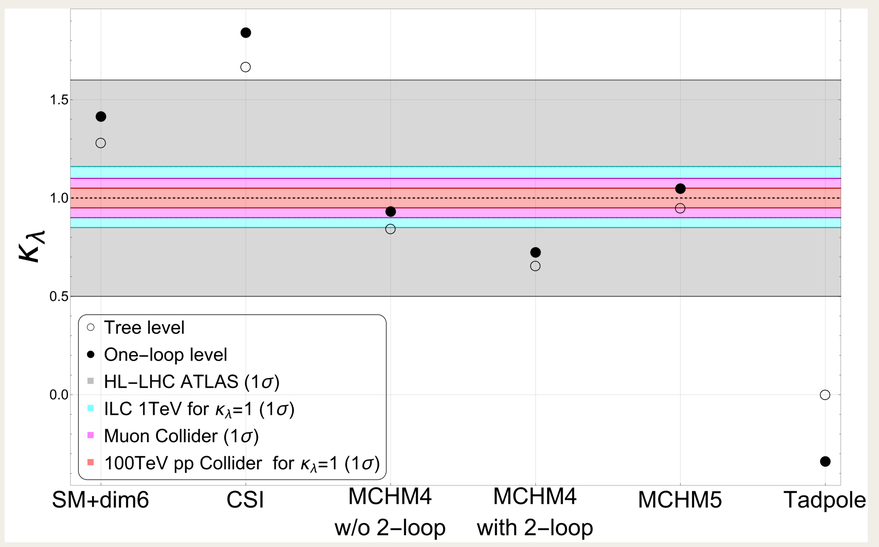


Figure 2. Predictions on κ_λ for each model at 1-loop level.

Summary

- We discussed how we distinguish the functional forms of the Higgs potential at future collider experiments.
- We have computed trilinear couplings, including the 1-loop contribution, in representative nearly aligned Higgs models.
- We have identified the constraints of the MCHM4(2) parameters at HL-LHC.