Available on CMS information server **CMS CR -2024/144**

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

18 July 2024 (v4, 26 August 2024)

Higgs self-coupling measurements with the CMS Experiment

Oguz Guzel on behalf of the CMS Collaboration

Abstract

Since the discovery of the Higgs boson in 2012, the CMS Experiment at the Large Hadron Collider has conducted numerous precision measurements that affirm the predictions of the Standard Model. However, one of the remaining fundamental aspects yet to be directly measured is the self-coupling of the Higgs boson, which is pivotal for understanding the shape of the Higgs potential and the mechanism of electroweak symmetry breaking. This paper presents the current results by the CMS Collaboration reporting on the Higgs self-coupling.

Presented at *PASCOS2024 29th International Symposium on Particles, Strings and Cosmology*

Higgs self-coupling measurements with the CMS Experiment

Oguz Guzel on behalf of the CMS Collaboration
Research Institute in Mathematics and Physics, Université catholique de Louvain
2 Chemin du Cyclotron,
Louvain-la-Neuve 1348, Belgium

Since the discovery of the Higgs boson in 2012, the CMS Experiment at the Large Hadron Collider has conducted numerous precision measurements that affirm the predictions of the Standard Model. However, one of the remaining fundamental aspects yet to be directly measured is the self-coupling of the Higgs boson, which is pivotal for understanding the shape of the Higgs potential and the mechanism of electroweak symmetry breaking. This paper presents the current results by the CMS Collaboration reporting on the Higgs self-coupling.

1 Introduction to the Higgs boson self-coupling

The discovery of the Higgs boson [1,2,3] at the Large Hadron Collider (LHC) marked a significant milestone in particle physics. Another important discovery would be the role of the Higgs potential in the mechanism of electroweak symmetry breaking, which gives mass to the W and Z bosons as well as to fermions in the Standard Model (SM). This potential is generally expressed as [4]:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 \tag{1}$$

where H represents the Higgs field, m_H is the mass of the Higgs boson, $\lambda_{3,4}$ are the Higgs boson self-coupling parameters, and v is the vacuum expectation value (VEV) of the Higgs field, approximately 246 GeV. This potential leads to spontaneous symmetry breaking when the Higgs field acquires a non-zero VEV. The terms in the equation are described as in the followings.

1. Quadratic Term ($\frac{1}{2}m_H^2 H^2$): This term is responsible for the mass of the Higgs boson.

2. Cubic Term ($\lambda_3 v H^3$): The cubic term in the Higgs potential arises after electroweak symmetry breaking and is directly linked to the self-interaction of the Higgs boson. The coefficient λ_3 is the trilinear self-coupling parameter and measuring this term would provide crucial insights into the shape of the Higgs potential and the nature of electroweak symmetry breaking.

3. Quartic Term ($\frac{1}{4}\lambda_4 H^4$): This term governs the stability of the potential and ensures that the potential is bounded from below, leading to a stable vacuum. The quartic coupling λ_4 also contributes to the Higgs boson self-interaction.

The Higgs boson self-coupling can be probed through processes involving multiple Higgs bosons, such as double Higgs production (HH).

1.1 Effective Field Theory Approach

In the context of effective field theory (EFT), the Higgs potential can be extended to include higher-dimensional operators that parameterise new physics effects:

$$V_{\mathrm{EFT}}(H) = V(H) + \frac{c_6}{\Lambda^2}H^6 + \frac{c_8}{\Lambda^4}H^8 + \cdots \tag{2}$$

where c_6, c_8, etc., are the Wilson coefficients of the higher-dimensional operators, and Λ is the scale of new physics. These operators can lead to modifications in the Higgs self-coupling, making precise measurements of Higgs boson pair production processes crucial for probing the EFT contributions. In BSM scenarios, the Higgs potential can include higher-dimensional operators, such as the dimension-6 term $\frac{c_6}{\Lambda^2}H^6$. This term introduces additional couplings that modify the interactions involving Higgs boson, leading to potential changes in the trilinear and quartic Higgs couplings along with others beyond the Standard Model (BSM) predictions. These modifications can be probed through precision measurements of HH production. Two separate conventions, JHEP03 [5] and JHEP04 [6], are the main frameworks where the measurements on the EFT parameters have been performed. Both of the conventions provide several benchmarks that are sensitive to the shape differences in di-Higgs mass, m_{HH}.

1.2 Production Modes to Access λ_3

The direct measurement of the Higgs self-coupling can be achieved through double Higgs (HH) production via various production modes, that are:

- **Gluon-Gluon Fusion (GGF)**: The dominant production mode, though it involves destructive interference in the Feynman diagrams. Its cross section at 13 TeV center-of-mass energy at the proton-proton colliders is 31.05 fb.
- **Vector Boson Fusion (VBF)**: The second most dominant mode, providing a cleaner signal compared to GGF. Its cross section at 13 TeV center-of-mass energy at the proton-proton colliders is 1.71 fb.
- **Rare Processes**: Including vector boson pair production in association with a Higgs boson (VHH), ttHH, and single Higgs productions which also contribute to the measurement.

2 Results from Different Channels

The Higgs self-coupling measurements from the CMS Experiment [7] rely on several decay channels, each providing unique constraints and sensitivities.

2.1 $HH \to 4b$ (boosted)

This analysis [8] makes use of the GGF and VBF production modes, and uses advanced algorithms such as ParticleNet (a graph neural network) for particle reconstruction, and boosted decision trees (BDT) for background and signal discrimination. This channel provides strong constraints due to the high branching ratio and clean signal from the boosted topology. The m_{HH} distribution is fitted to extract signal in this analysis. The observed constraint on κ_λ at 95% confidence level (CL) is: $-9.9(-5.1) < \kappa_\lambda < 16.9(12.2)$ (expected), where κ_λ represents the ratio of λ_3 to its SM value. The scan of κ_λ vs κ_{2V} is shown in the left plot of figure 1, where $\kappa_{2V} = 0$ hypothesis is also excluded with a 6.3σ statistical significance.

2.2 $HH \to WW\gamma\gamma$

Targeting the GGF production mode only, the $HH \to WW\gamma\gamma$ analysis [4] benefits from the good mass resolution provided by the $\gamma\gamma$ leg of the decay. Since the single Higgs boson production is considered as a background process in this analysis, it is modeled by Monte Carlo (MC) simulations whereas the continuum background is modeled from data. Neural networks and cut-based approaches are used to help to extract the signal, which is done by fitting the $m_{\gamma\gamma}$ distribution. The observed (expected) constraint on κ_λ at 95% CL is reported as $-25.8(14.4) < \kappa_\lambda < 24.1(18.3)$. This analysis provides also the upper limits on the EFT benchmarks. The observed (expected) values are ranging from $1.7(1.0)pb$ to $6.2(3.9)pb$ at 95% CL.

2.3 $HH \to$ *multilepton*

This analysis [9] includes several final states such as $HH \to WWWW$, $HH \to WW\tau\tau$, and $HH \to \tau\tau\tau\tau$, and makes use of only the GGF production mode. The presence of multiple leptons helps to significantly reduce background contributions from non-Higgs processes, and provides a clean and powerful probe for the Higgs self-coupling despite having a lower branching ratio compared to other channels. BDTs are employed to separate signal and background processes. The observed and expected constraints at 95% CL on the Higgs self-coupling parameter κ_λ for the multilepton channel are given by $-6.9(-6.9) < \kappa_\lambda < 11.1(11.7)$ (expected). Upper limits on the EFT benchmarks are also set. The observed (expected) values are ranging from $0.21(0.16)pb$ to $1.09(1.16)pb$ at 95% CL.

2.4 $HH \to bb\tau\tau$

The di-Higgs decaying to a b quark and a tau lepton pair channel is a promising decay mode due to its high branching ratio and the distinct τ signatures in the final state. The analysis [10] in this channel utilises both GGF and VBF production modes to maximise sensitivity. DNNs help distinguish signal from significant backgrounds like $t\bar{t}$ production, and their score distributions are used to extract signal. Optimizing event selection criteria, the observed constraint at 95% CL on the Higgs self-coupling parameter κ_λ is $-1.7(-2.9) < \kappa_\lambda < 8.7(9.8)$ (expected), contributing significantly to combined measurements, helping to constrain deviations from the Standard Model.

2.5 $HH \to bbWW$

This is a crucial channel due to its high branching ratio. It involves one Higgs boson decaying into bottom quarks ($b\bar{b}$) and the other into W bosons (WW), which further decay into leptons or one leptonically and the other hadronically. Both GGF and VBF production modes are utilised to maximise sensitivity in this analysis [11]. Deep neural networks (DNNs) are employed to distinguish the signal from backgrounds, using various kinematic variables and event topologies. The observed constraint at 95% CL on the Higgs self-coupling parameter κ_λ is $-7.2(-8.7) < \kappa_\lambda < 13.8(15.2)$ (expected), and the observed (expected) EFT benchmark upper limits are from 0.16(0.2)pb to 2.3(2.2)pb at 95% CL.

2.6 $VHH \to 4b$

A search [12] for the rare VHH production mode (0.85 fb cross section), focuses on a channel that has the highest branching ratio among the HH decays, namely the final state with 4b quarks. It also benefits from reduced background by using the associated vector boson (V) in the event selection. BDTs are employed to distinguish the signal from backgrounds, and the regions dominated by the κ_λ and κ_{VV} (Higgs boson coupling to vector bosons). Accurate b-jet identification is achieved with the ParticleNet algorithm. The observed constraint at 95% CL the Higgs self-coupling parameter κ_λ is $-37.7(-30.1) < \kappa_\lambda < 37.2(28.9)$ (expected).

3 Combination, Projections and Outlook

A combination of results from various channels using full Run2 data shows [13] that the Higgs boson self-coupling cross-section is confined with an upper limit at 3.4 times the SM value. The combined constraint at 95% CL is $-1.24 < \kappa_\lambda < 6.49$, shown in the right plot of figure 1. Another combination in the single Higgs analyses has been performed by the CMS Experiment in the same publication [13] with $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW$, $H \to bb$, $H \to \tau\tau$, $ttH \to multiplepton$, $H \to \mu\mu$ and $H \to invisible$ channels. This measurement yielded the following constraints at 95% CL on κ_λ: $-3.54 < \kappa_\lambda < 12.62$.

A projection study is also performed aiming the High-Luminosity LHC. The analysis [14] with $3000\,\mathrm{fb}^{-1}$ integrated luminosity at 14 TeV suggest $-0.8 < \kappa_\lambda < 3.6$ at 95% CL.

The CMS Collaboration has made significant progress in measuring the Higgs self-coupling, though direct measurements remain challenging. Current results indicate that the Higgs potential is consistent with the SM within the measured constraints. Ongoing efforts aim to include more channels and improve the precision of these measurements.

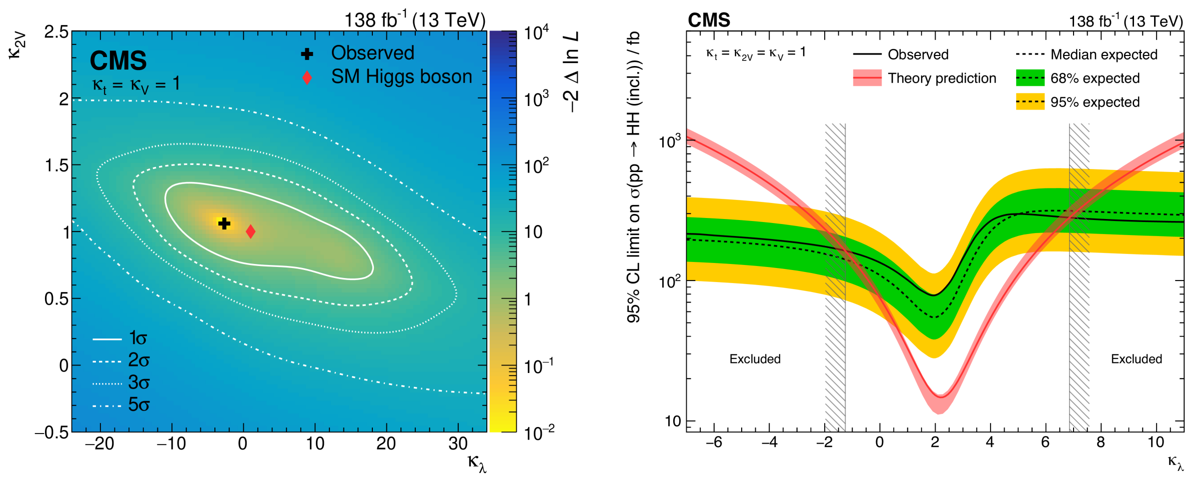

Figure 1 – Left plot shows the κ_λ vs κ_{2V} scan from the $HH \to 4b(boosted)$ analysis (from Ref.[8]), and right plot shows the κ_λ scan from the partial Run 2 combination (from Ref.[13])

References

1. ATLAS Collaboration. *PLB*, 716(1):1–29, 2012.
2. CMS Collaboration. *PLB*, 716(1):30–61, 2012.
3. CMS Collaboration. *JHEP*, 2013(6):81, 2013.
4. CMS Collaboration report no. CMS-PAS-HIG-21-014, 2021. cds.cern.ch/record/2840773.
5. M. Capozi and G. Heinrich. *JHEP*, 2020(3), 2020.
6. Alexandra Carvalho, Martino Dall'Osso, Tommaso Dorigo, Florian Goertz, Carlo A. Gottardo, and Mia Tosi. *JHEP*, 2016(4):1–28, 2016.
7. CMS Collaboration. *JINST*, 3(08):S08004, 2008.
8. CMS Collaboration. *PRL*, 131:041803, 2023.
9. CMS Collaboration. *JHEP*, 2023(7), 2023.
10. CMS Collaboration. *PLB*, 842:137531, 2023.
11. CMS Collaboration, report no. CMS-PAS-HIG-21-005, 2024. arxiv.org/abs/2403.09430.
12. CMS Collaboration report no. CMS-PAS-HIG-22-006, 2023. arxiv.org/abs/2404.08462.
13. CMS Collaboration. *Nature*, 607(7917):60–68, 2022.
14. Editors: M. Cepeda, S. Gori, P Ilten, M. Kado, and F. Riva. *CERN Yellow Reports: Monographs*, Vol. 7, 2019.