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EFT interpretations in the Higgs sector at CMS

Irene Dutta for the CMS Collaboration

Abstract

Effective Field Theories provide an interesting way to parameterize indirect BSM physics, when its characteristic scale is larger than the one directly accessible at the LHC, for a large class of models. Even if the Higgs boson is SM-like, BSM effects can manifest itself through higher-dimension effective interactions between SM fields, providing indirect sensitivity through distortions of kinematic distributions. Constraints on such effects derived by measurements of several production and decay modes of the Higgs boson and their combination on the data set collected by the CMS experiment a centre of mass energy of 13 TeV will be presented.

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PROCEEDINGS OF SCIENCE

EFT interpretations in the Higgs sector at CMS

Irene Dutta[a,*] for the CMS collaboration

[a] *Fermi National Accelerator Laboratory, Kirk Rd and Pine St, Batavia, Illinois, USA - 60563*

E-mail: irene.dutta@cern.ch

Effective Field Theories provide an interesting way to parameterize indirect BSM physics, when its characteristic scale is larger than the one directly accessible at the LHC, for a large class of models. Even if the Higgs boson is SM-like, BSM effects can manifest through higher-dimension effective interactions between SM fields, providing indirect sensitivity through distortions in kinematic distributions. Constraints on such effects derived by measurements of several production and decay modes of the Higgs boson and their combination, on the data set collected by the CMS experiment at centre of mass energy of 13 TeV, will be presented here.

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[*] Speaker

1. Introduction

Since the discovery of the Higgs boson, many of its couplings have been accurately measured, though they have not yet reached 1% precision. New particles beyond the Standard Model (BSM) could cause subtle modifications to these couplings through loop corrections, making it crucial to search for signs of new physics in precise single Higgs measurements. Likewise, studying the double Higgs boson production (di-Higgs) process is essential for gaining insight into the Higgs potential structure in nature. Any new physics could alter this potential, so it's equally important to investigate possible BSM hints in di-Higgs measurements.

It is reasonable to assume that the Standard Model (SM) is a low-energy approximation of a more complex theory at higher energy scales. If we consider the scale of new physics to be Λ, its effects would appear as anomalous point-like couplings at the energy scale of the LHC, and these effects would manifest as deviations in the tails of kinematic distributions. Two commonly used effective field theory (EFT) approaches in Higgs physics are Standard Model Effective Field Theory (SMEFT) and Higgs Effective Field Theory (HEFT). These will be explained in greater detail in the following sections, along with certain recent results from CMS discussed within both frameworks.

2. SMEFT results

The SMEFT Lagrangian is an extension of the Standard Model (SM) Lagrangian that incorporates higher-dimensional operators as a series expansion in powers of $\frac{1}{\Lambda}$. It is constructed using the same fields and gauge symmetries (SU(3)xSU(2)xU(1)) as the Standard Model but includes additional terms representing interactions that could arise from the new physics. The SMEFT Lagrangian can be written as,

$$\Delta\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_{5,i} + \sum_i \frac{c_i^{(6)}}{\Lambda} O_{6,i} + \sum_i \frac{c_i^{(7)}}{\Lambda} O_{7,i} + \sum_i \frac{c_i^{(8)}}{\Lambda} O_{8,i} + \ldots, \quad (1)$$

where

- $\mathcal{L}_{SM}$ is the Standard Model Lagrangian, describing known interactions between particles such as gauge interactions, the Higgs mechanism, fermion masses, etc.
- $O_{d,i}$ are higher-dimensional operators of mass dimension d > 4, constructed from the Standard Model fields.
- $c_i^{(d)}$ are dimensionless Wilson coefficients (WCs) that characterize the strength of the new interactions.

We usually ignore lepton and baryon number-violating terms, which are the dimension-5 and dimension-7 operators. Thus we mainly focus our studies on probing the WCs of the dimension-6 operators, which is the leading higher-order correction term. As a single dimension-6 operator can enter into many different processes, and a single process can be affected by many different dimension-6 operators, a global approach to fitting experimental data from electroweak, top quark, and flavor physics, is necessary to constrain the Wilson coefficients. The next few paragraphs summarise three recent results from CMS in this sector.

Combination of single Higgs cross section measurements [1]: This new result is a combination of several single Higgs measurements from H→ $\gamma\gamma$, H → ZZ, H → WW, H → $\tau\tau$ and H → $\tau\tau$ (boosted). This analysis measures combined differential cross-sections in many kinematic variables, such as p_T^H (See Fig. 1 left). In the context of SMEFT, it performs fits on pairs of CP-even and CP-odd pairs of Wilson coefficients using for example, the p_T^H and $\Delta\phi_{jj}$ spectra in events with two reconstructed jets, where the latter is defined as the azimuthal angle difference between leading and subleading jet. Two-dimensional likelihood scans for the Wilson coefficients c_{HG} and $\bar{c}_{HG}$, which affect the two gluons to a single Higgs interaction, are shown in Fig 1 (right). A principal component analysis is also performed to construct linear combinations of Wilson coefficients (called eigenvectors), which can then be fitted to constrain a multidimensional parameter space.

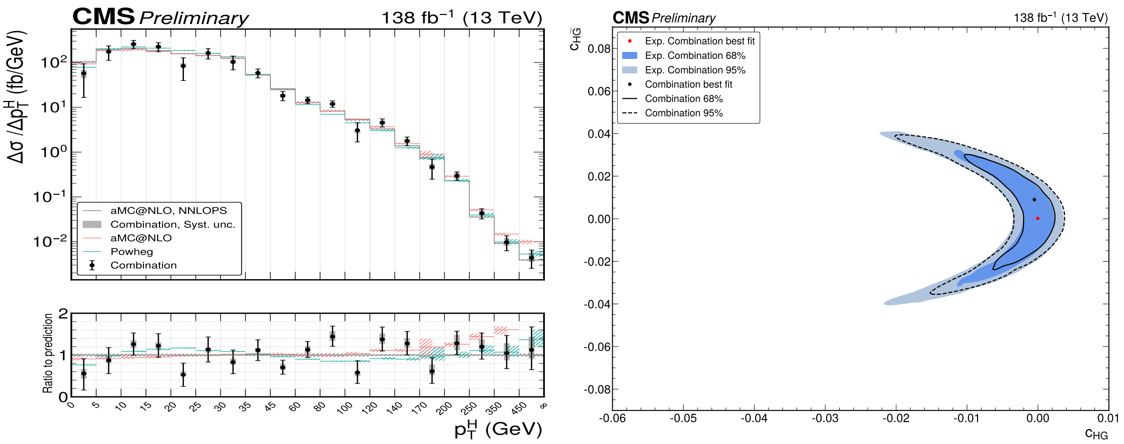

Figure 1: Results from [1]: (Left) Measurement of the total differential cross section as a function of p_T^H. (Right) Observed and expected two-dimensional scans for the c_{HG} and $\bar{c}_{HG}$ obtained from the p_T^H spectra.

ttX decays [2]: This measurement searches for signs of new physics using EFT techniques in top quark pair production with additional final state leptons. The signal processes considered include tt$l\nu$, ttll, ttH, tZq, tHq and tttt. The analysis has 43 different categories based on lepton and jet multiplicity, and each category is further subdivided based on the p_T of the most energetic pair of leptons or jets, or the p_T of the Z boson candidate. A simultaneous fit of 26 different WCs is performed. An example two-dimensional likelihood scan of $c_{\varphi t}/\Lambda^2$ (top Yukawa) and $\bar{c}_{\varphi Q}/\Lambda^2$ (quark interactions with Higgs boson) is shown in Fig 2 (left).

Semi-leptonic ttX (X = H, Z) decays with boosted $X \to b\bar{b}$ **[3]**: This measurement searches for signs of new physics using EFT techniques in decays of top quark pairs produced in association with a Lorentz-boosted Z or Higgs boson. Selected events contain a single lepton and hadronic jets, including two identified with the decay of bottom quarks, plus an additional large-radius jet with high transverse momentum identified as a $Z \to b\bar{b}$ or $H \to b\bar{b}$ candidate. Eight simultaneous WCs are fitted that most affect the ttH and ttZ processes. An example two-dimensional likelihood scan of $c_{\varphi t}/\Lambda^2$ (top Yukawa) and $\bar{c}_{\varphi Q}/\Lambda^2$ (quark interactions with Higgs boson) is shown in Fig. 2 (right).

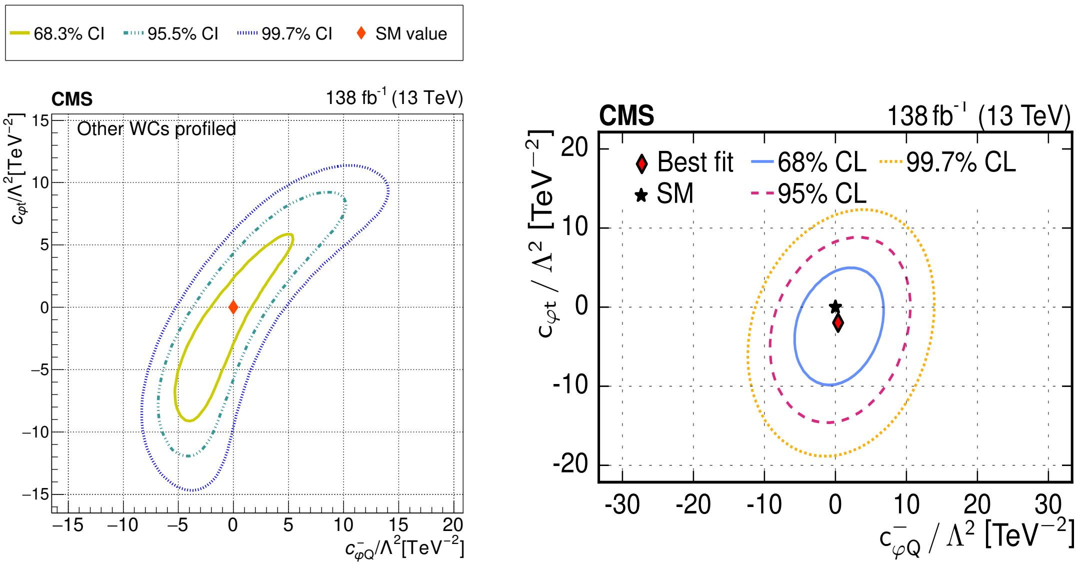

Figure 2: (Left) Results from [2]: Observed two-dimensional scans of the negative log-likelihood as a function of $c_{\varphi t}/\Lambda^2$ - $\bar{c}_{\varphi Q}/\Lambda^2$ where other WCs are also profiled. (Right) Results from [3]: Observed two-dimensional scans of the negative log-likelihood as a function of $c_{\varphi t}/\Lambda^2$ - $\bar{c}_{\varphi Q}/\Lambda^2$ when all other WCs are fixed to their SM values.

3. HEFT results

The HEFT framework describes physics beyond the Standard Model by extending the interactions of the Higgs boson by considering possible deviations in its properties (like coupling strengths) while keeping the electroweak symmetry-breaking mechanism intact. This approach is relevant in models where new physics modifies the structure of the Higgs sector or where composite Higgs models are considered. Unlike the SMEFT, the Higgs field is treated as an electroweak singlet in HEFT, and there are no expansion terms in powers of the energy scale of new physics. The HEFT framework is widely studied in di-Higgs searches to understand the deviations in the Higgs potential from SM prediction. The HEFT Lagrangian can be written as :

$$\Delta\mathcal{L}_{HEFT} = -m_t(\kappa_t\frac{h}{v} + c_2\frac{h^2}{v^2})\bar{t}t - \kappa_\lambda\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}(c_g\frac{h}{v} + c_{2g}\frac{h^2}{v^2})G^a_{\mu\nu}G^{\mu\nu,a} \qquad (2)$$

where h is the Higgs EW singlet field, m_t is mass of the top quark, m_h is the mass of the Higgs boson, κ_t and κ_λ are the top Yukawa coupling and the tri-linear Higgs self-coupling in the κ-framework, $G^a_{\mu\nu}$ is the gluon field strength tensor and α_s is the strong-coupling constant. The coefficients c_2, c_g and c_{2g} are all zero in the SM, and describe the $tt - HH$ (two tops and two Higgses), $gg - H$ (two gluons and one Higgs) and $gg - HH$ (two gluons and two Higgses) interactions, respectively. Feynman diagrams of the terms considered in Eqn. 2 is shown in Fig. 3.

CMS analyses use 20 HEFT benchmark scenarios covering different kinematics phase space from [5, 6] to set cross-section upper limits on the HH production in a 5-dimensional coupling space of (κ_t, κ_λ, c_2, c_g, c_{2g}). The next few paragraphs briefly discuss three recent analyses from the CMS Experiment with HEFT results.

HH $\rightarrow \gamma\gamma\tau\tau$ [4]: This is the first search in this final state, covering both the tau lepton's hadronic

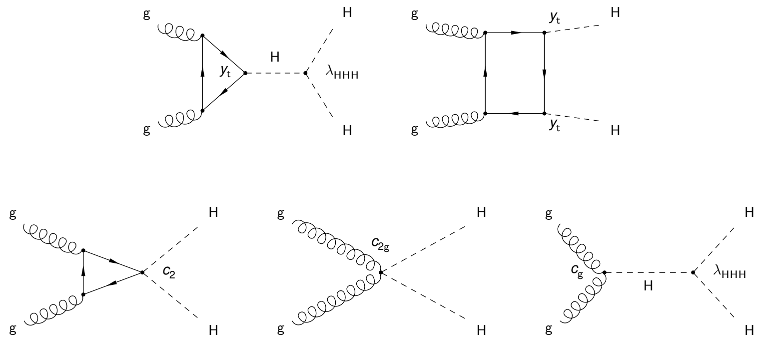

Figure 3: Feynman diagrams describing the HEFT Lagrangian [4].

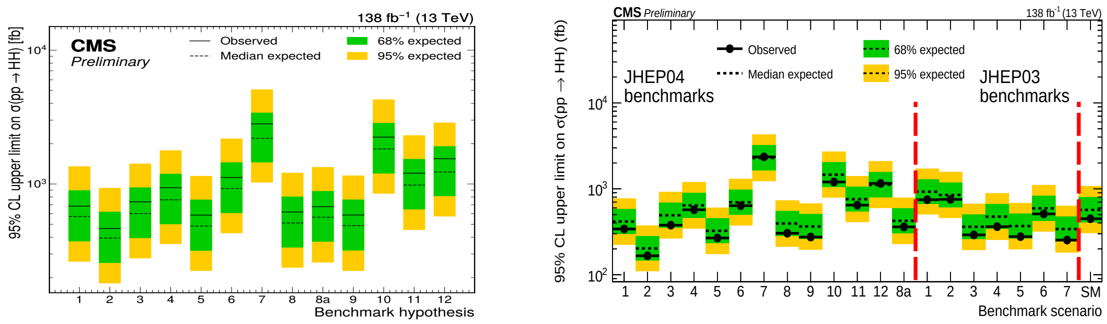

Figure 4: (Left) HEFT results from [4]: 95% CL upper limits on HH production cross-section for thirteen different HEFT benchmark scenarios of [5]. (Right) HEFT results from [7]: 95% CL upper limits on HH production cross-section for twenty different HEFT benchmark scenarios of [5, 6].

and leptonic decay modes. Despite the small SM $HH \rightarrow \gamma\gamma\tau\tau$ branching fraction, the diphoton pair offers a clean experimental signature to trigger on with a good mass resolution, whilst the additional tau leptons in the event help further isolate signal from backgrounds. This analysis sets upper limits at the 95% CL for the thirteen HEFT benchmark scenarios from [5], and the results are shown in Fig. 4 (left).

HH → bbWW [7]: The bbWW final state has the second largest branching fraction among all HH decays (~24%). This analysis considers two final states: single-lepton (SL) i.e. bblνqq and di-lepton (DL) i.e. bblνlν. This analysis sets upper limits at the 95% CL for the twenty HEFT benchmark scenarios from [5, 6] as shown in Fig. 4 (right). Cross-section limits as a function of c_2 are also derived, as depicted in Fig. 5 (left). The c_2 coupling is constrained between [-0.8,1.3] (expected [-1.0,1.4]).

HH → Multileptons [8]: This analysis searches for HH production in the WW^*WW^*, WW$\tau\tau$, and $\tau\tau\tau\tau$ decay modes. Analyzed events contain two, three, or four reconstructed leptons, including electrons, muons, and hadronically decaying tau leptons. The analysis sets cross-section upper limits on the twenty HEFT benchmarks from [5, 6], provides cross-section upper limits as a function of the c_2 coupling, and performs a two-dimensional scan in the $c_2 - \kappa_t$ plane, constraining c_2 to an interval of [-1.06, 1.49] (expected: [-0.97, 1.37]). The 2D $c_2 - \kappa_t$ scan is shown in Fig. 5 (right).

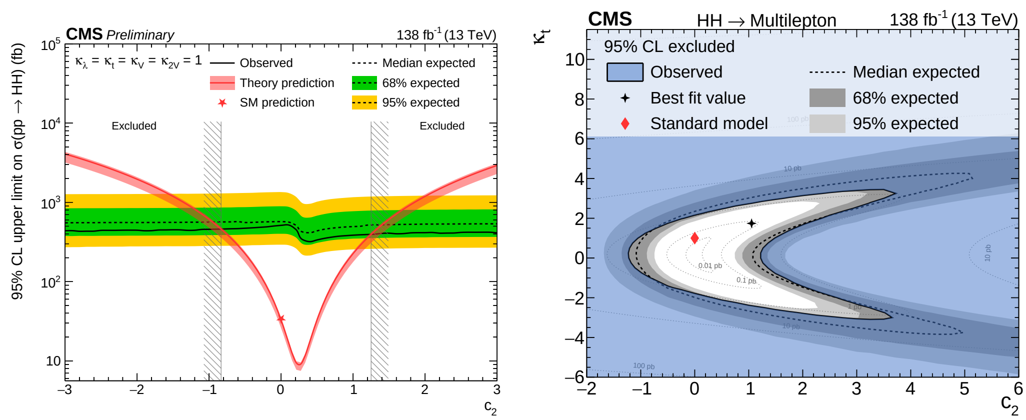

Figure 5: (Left) HEFT results from [7]: 95% CL upper limits on inclusive HH production cross-section as a function of the c_2 parameter. (Right) HEFT results from [8]: Observed and expected excluded regions at 95% CL in the $c_2 - \kappa_t$ plane.

4. Summary

EFT is a valuable tool for testing the precision of the Standard Model and exploring potential new physics in a more model-independent way. CMS collaboration is applying a global data analysis approach from various physics processes to constrain various EFT parameters in the SMEFT and HEFT context for analyses based on the Run 2 data-set. With the addition of the Run 3 data, CMS will continue to look for signs of new physics using the EFT approach.

References

[1] The CMS Collaboration, CMS-PAS-HIG-23-013, https://cds.cern.ch/record/2905139

[2] The CMS Collaboration, JHEP 12 (2023) 68, https://doi.org/10.1007/JHEP12(2023)068

[3] The CMS Collaboration, Phys.Rev.D 108 (2023) 032008, https://doi.org/10.1103/PhysRevD.108.032008

[4] The CMS Collaboration, CMS-PAS-HIG-22-012, https://cds.cern.ch/record/2893031

[5] A. Carvalho et. al., JHEP 04 (2016) 126, https://doi.org/10.1007/JHEP04(2016)126

[6] M. Capozi and G. Heinrich, JHEP 03 (2020) 91, https://doi.org/10.1007/JHEP03(2020)091

[7] The CMS Collaboration, JHEP 07 (2024) 293, https://doi.org/10.1007/JHEP07(2024)293

[8] The CMS Collaboration, JHEP 07 (2023) 095, https://doi.org/10.1007/JHEP07(2023)095