PROCEEDINGS OF SCIENCE

EFT interpretations in the Higgs sector at the CMS experiment

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The search for new physics beyond the Standard Model continues to be a focal point in contemporary particle physics research. Despite exhaustive direct searches at the Large Hadron Collider yielding no definitive evidence of new particles, the scientific community is propelled towards indirect search methodologies. Effective Field Theories offer an intriguing approach to parameterize indirect beyond the Standard Model physics, particularly when its characteristic scale exceeds the direct accessibility at the Large Hadron Collider, across a broad spectrum of models. Even if the Higgs boson retains its Standard Model-like properties, beyond the Standard Model effects may reveal themselves through higher-dimensional effective interactions among Standard Model fields, thereby providing indirect sensitivity via distortions in kinematic distributions. The Standard Model Effective Field Theory serves to extend the Standard Model Lagrangian by integrating higher-dimensional operators, thus furnishing a framework to parameterize potential new physics effects. Constraints on such effects, derived from measurements spanning various production and decay modes of the Higgs boson, alongside their combination using the data collected by the CMS experiment at a center-of-mass energy of 13 TeV, will be presented.

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1. Introduction

The Standard Model (SM) has been extraordinarily successful in describing a plethora of phenomena within particle physics; however, it is widely accepted to be an incomplete theory. The discovery of the Higgs boson at the Large Hadron Collider (LHC) has unveiled new avenues for probing physics beyond the SM [1–3]. One particularly potent approach for these investigations is the utilization of Effective Field Theory (EFT), which is capable of capturing the effects of new physics occurring at scales beyond the direct reach of the LHC. Standard Model Effective Field Theory (SMEFT) provides a systematic approach to achieve this by expanding the SM Lagrangian with additional terms. These terms are expressed as

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i,$$

where O_i represent additional higher-order terms, typically of dimension-6, which is the lowest order beyond the SM at which new physics effects can arise. The coefficients c_i are the corresponding Wilson coefficients, and Λ denotes the scale of new physics which is conventionally set to 1 TeV. This approach preserves the SM field content, ensuring a coherent extension of the theory.

The Higgs sector in SMEFT is particularly sensitive to various higher-dimensional operators that can alter Higgs boson production and decay rates. At the CMS (Compact Muon Solenoid) experiment [4], different Higgs boson production mechanisms such as gluon-gluon fusion (ggF), vector boson fusion (VBF), and vector boson associated production (VH) are meticulously analyzed to constrain anomalous couplings (ACs). These couplings can be parameterized in the Warsaw basis [5], which is advantageous for minimizing the number of independent operators.

2. Recent CMS Analyses and Results

The CMS experiment at the LHC is a general-purpose detector, designed to measure the momentum and energy of particles produced in high-energy proton-proton collisions, enabling precise studies of the Higgs boson, dark matter candidates, and other phenomena beyond the Standard Model (BSM). The analyses performed with this apparatus is explained in the following sections.

2.1 HVV Constraints in $H \to WW$

A comprehensive study was performed to analyze anomalous couplings in the $H \to WW$ decay channel [6]. This analysis employed the Matrix Element Likelihood Approach (MELA) discriminant to distinguish between the SM and possible BSM scenarios by scrutinizing kinematic differences. The enhanced sensitivity of this methodology facilitated more precise constraints on the anomalous couplings at the HVV vertex.

This analysis measures the constraints on the anomalous couplings at the HVV vertex derived from the $H \to WW$ decay channel. It examines contributions from anomalous couplings, both with other couplings varying and with them fixed to the SM expectation. The results significantly improved sensitivity to potential deviations from the SM predictions, compared to the full Run 1 analysis in the same channel, thereby allowing stringent constraints on the anomalous HVV couplings.

PoS(DIS2024)156

2.2 $H \to \tau\tau$ Analysis

The $H \to \tau\tau$ decay channel is analyzed [7] across different production modes to probe EFT vertices. In vector boson fusion (VBF) production mode, the emphasis is placed on constraining the HVV vertex, while in gluon-gluon fusion (ggH) production, the Hgg vertex is the primary focus. Neural networks are deployed to enhance signal-to-background separation, and MELA discriminants assist in differentiating between various signal hypotheses. This analysis yields effective cross-section measurements and constraints on CP-odd operators, contributing to a more nuanced understanding of Higgs interactions.

The presence of CP-violating effects in Higgs couplings to fermions (Hff) was also investigated in the ggH production mode, combining several decay channels such as $H \to ZZ$, $t\bar{t}H \to \gamma\gamma$, and $H \to \tau\tau$. This study enhanced the sensitivity, leading to an approximate 25% improvement in limits on anomalous couplings, and excluded the pure CP-odd hypothesis for the Higgs-gluon coupling with a significance of 2.4σ. This comprehensive approach ensures robust constraints on potential CP-violating effects in the Higgs sector.

3. EFT Interpretation with Simplified Template Cross Sections (STXS)

The STXS framework was designed to maximize the sensitivity of Higgs boson measurements to potential BSM effects by partitioning the phase space into regions that are differentially sensitive to new physics [8]. This method mitigates theoretical uncertainties and provides a structured approach for EFT interpretations, allowing for the measured cross sections to be interpreted as constraints on the EFT Wilson coefficients. The CMS Experiment applied this framework in a partial Run 2 combination, with analyses from $H \to \gamma\gamma$, $H \to 4l$, $H \to l\nu l\nu$, $H \to \tau\tau$, and $ttH \to$ multi-lepton channels. In this analysis [9], EFT couplings were extracted utilizing the Higgs effective Lagrangian (HEL) parameters. Multiple Wilson coefficients such as c_G, c_A, c_u, c_d, c_l, c_{HW}, c_{WW}, and c_B were fitted simultaneously. This approach facilitated the observation of correlations between different coefficients and provided constraints that were consistent with the SM. Figure 1 depicts the results from the partial Run 2 combination in the STXS framework.

4. EFT interpretations in the Double Higgs Production

Double Higgs (HH) production is a rare process within the SM, providing a sensitive probe for new physics effects. EFT interpretations in this sector involve analyzing various decay channels such as $HH \to bb\gamma\gamma$ [10], $HH \to WWbb$ [11], $HH \to WW\gamma\gamma$ [12], and multi-lepton [13] final states. These analyses re-weight signal samples to match EFT benchmark points, allowing for the extraction of limits on EFT parameters, utilizing the gluon-gluon fusion and vector boson fusion production modes. The plots in fig. 2 present some of the EFT interpretations in the analyses targeting double Higgs production. The plot on the left shows the upper limits using two different benchmark scenerios, known as JHEP04[14] and JHEP03[15]. The plot on the right shows a 2-dimensional scan of the c_2 versus κ_λ parameters. The parameter c_2 represents the coupling strength of interactions involving two Higgs bosons and two top quarks, while κ_λ is a scaling factor for the Higgs boson self-coupling relative to its SM value. These analyses report that the results are consistent with the SM expectation.

PoS(DIS2024)156

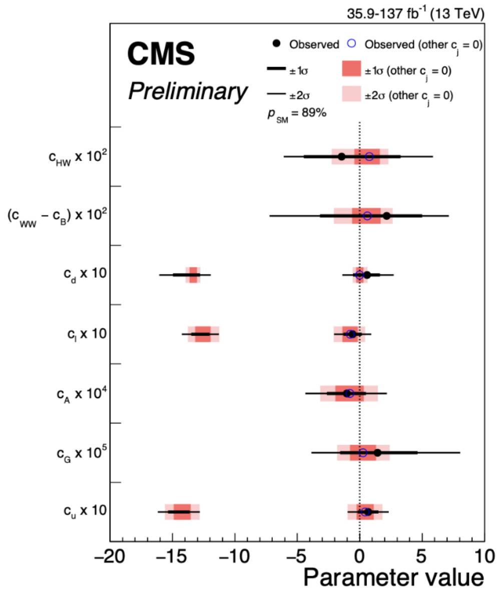

Figure 1: Partial Run 2 combination results in the STXS framework, showing the fit of multiple Wilson coefficients with results consistent with the SM [9].

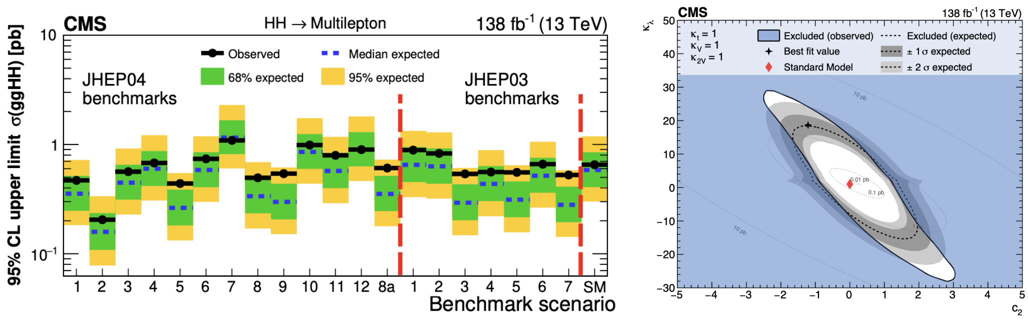

Figure 2: EFT interpretations in $HH \to$ Multilepton [13], (left) and $HH \to WWbb$ [16] (right) channels.

5. Conclusions

Precision measurements of Higgs processes are crucial for uncovering deviations from the SM. The CMS experiment continues to make significant strides in probing the Higgs sector through the lens of EFT, offering profound insights into potential new physics. The analyses targeting to measure HVV constraints, CP-violating effects, HEL parameters, and double Higgs production highlight the experiment's capability to impose stringent constraints on BSM theories. Future efforts will further enhance our understanding of the Higgs boson's properties and its interactions, driving the pursuit of new physics.

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