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Higgs boson anomalous couplings using the di-photon channel with the CMS experiment

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Summary. — Studies of CP violation and anomalous couplings of the Higgs boson to vector bosons are presented. Data were acquired by the CMS experiment at the LHC and correspond to an integrated luminosity of 138 fb^{-1} at a proton-proton collision energy of 13 TeV. The kinematic effects in the Higgs boson two-photons decay and its production in association with two jets (Vector Boson Fusion) is analyzed. A matrix element technique and multivariate algorithms are employed to identify the production mechanisms and to increase sensitivity to the Higgs boson tensor structure of the interactions, optimized using the full simulation of the detector. The measurement of the strength of the coupling of the Higgs boson to vector boson is performed on data through a fit which considers the simultaneous presence of Standard Model and Beyond Standard Model contributions to the coupling parameters.

1. – Introduction

The Higgs boson (H) discovered in 2012 at the CERN LHC [1,2] has so far been found to have properties consistent with the Standard Model (SM) expectations. Its spin-parity quantum numbers are consistent with $J^{PC} = 0^{++}$ according to measurements performed by the CMS and ATLAS experiments, but leaving room for the possibility of small anomalous HVV couplings, where V stands for vector bosons ($V = W^{\pm}, Z^0$). The Higgs boson couplings, once the Higgs boson mass is defined, are precisely predicted by the Standard Model. Finding a deviation on these values would lead to evidence of the presence of new physics.

The purpose of this analysis is to search for new physics effects Beyond the Standard Model (BSM) through the measurement of the Higgs boson couplings with the vector-bosons $W^{\pm}$ or Z^0. Because non-zero spin assignments of the H boson have been excluded, we focus on the analysis of couplings of a spin-0 Higgs boson.

The analysis is a study of HVV couplings using information from its production in association with two jets (Vector Boson Fusion VBF) decaying into two photons, which has a low branching fraction, but a clean signature in the CMS detector. The data used were recorded by the CMS experiment during LHC Run 2 in 2016, 2017 and 2018 proton-proton collision at a center-of-mass energy of 13 TeV and correspond to an integrated luminosity of $\sim 137\,\mathrm{fb}^{-1}$.

2. – EFT for Higgs boson characterization

Anomalous interactions of a spin-0 H boson with two spin-1 gauge bosons VV are parametrized by a scattering amplitude that includes three tensor structures with expansion of coefficients up to (q^2/Λ^2)

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)^{\mu\nu}} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)^{\mu\nu}}, \tag{1}$$

where q_i, ϵ_{Vi}, and m_{V1} are the 4-momentum, polarization vector, and the mass of the vector boson, indexed by $i = 1, 2$. $f^{(i)\mu\nu} = \epsilon_{Vi}^{\mu} q_i^{\nu} - \epsilon_{Vi}^{\nu} q_i^{\mu}$ is the gauge boson's field strength tensor and $\tilde{f}_{\mu\nu}^{i} = (1/2)\epsilon_{\mu\nu\rho\sigma} f^{(i)\rho\sigma}$ is the dual field strength tensor defined using the Levi-Civita symbol in four dimension ($\epsilon_{\mu\nu\rho\sigma}$). a_i^{VV} are the coupling coefficients. $k_i^{VV}/(\Lambda_1^{VV})^2$ multiply the next term in the q^2 expansion. Λ_1 is the scale of beyond the SM (BSM) physics.

In eq. (1), the only nonzero SM contributions at tree level are a_1^{WW} and a_1^{ZZ}. All other ZZ and WW couplings are considered anomalous contributions, which are either due to BSM physics or small contributions arising in the SM due to loop effects and are not accessible with the current experimental precision. The parity-conserving interaction of a pseudoscalar (CP-odd state) corresponds to the a_3 terms, while the other terms describe the parity-conserving interaction of a scalar (CP-even state). Due to the fact that kinematics of the H boson production in WW fusion and in ZZ fusion are very similar, we will set $a_i^{WW} = a_i^{ZZ} = a_i$ and $k_1^{WW}/(\Lambda_1^{WW})^2 = k_1^{ZZ}/(\Lambda_1^{ZZ})^2 = a_{\Lambda_1}$.

Among the anomalous contributions, considerations of symmetry and gauge invariance require $k_1^{ZZ} = k_2^{ZZ} = -exp(i\phi_{\Lambda_1}^{ZZ})$, $k_1^{\gamma\gamma} = k_2^{\gamma\gamma} = 0$, $k_1^{gg} = k_2^{gg} = 0$, $k_1^{Z\gamma} = 0$ and $k_2^{i\phi_{\Lambda 1}^{Z\gamma}}$, where $\phi_{\Lambda 1}^{Z\gamma}$ is the phase of the corresponding coupling.

The purpose of this analysis is to constrain the three sets of couplings (a_2, a_3 and a_{Λ_1}), under the assumption that the couplings are constant and real ($\phi_{a_i} = 0, \pi$), in the case in which the Higgs boson is produced from VBF production (H_{VBF}) in the channel in which $H \to \gamma\gamma$.

It is convenient to measure the effective cross section ratios f_{ai} rather than the anomalous couplings a_i themselves, as most uncertainties cancel in the ratio. The effective cross section f_{ai} and phase ϕ_{ai} are defined as follows:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3,_1} |a_j|^2 \sigma_j}, \tag{2}$$

where the fraction $f_{a1} = 1 - f_{\Lambda_1} - f_{a2} - f_{a3}$ is the SM tree-level contribution. $f_{ai} = 0$ indicates a pure SM Higgs boson, $f_{ai} = 1$ gives a pure BSM particle and $f_{ai} = 0.5$ means that the two couplings contribute equally to the $H_{VBF} \to \gamma\gamma$ process.

3. – Analysis

The final state of the channel of interest will be characterized by two isolated photons and two jets. These jets are energetic, with high di-jets invariant mass distribution (M_{jj}) and with a large rapidity gap between the two. To study possible BSM contributions we use MC samples generated using an extension of the JHUGen generator [3]. The MC samples used for SM couplings are generated using aMC@NLO and PYTHIA. The two photons and two jets are reconstructed and identified with standard loose selection used in previous VBF analysis [4]. In our analysis, signal events are the ones in which the Higgs boson is produced in VBF with a coupling not foreseen by the Standard Model. Due to the excellent diphoton mass resolution in CMS, the Higgs boson signal appears as a narrow peak in this distribution. The parameter of interest (f_{ai}) is estimated by using a fit function composed of a smoothly falling background distribution plus a signal peak of the diphoton invariant mass spectrum in data. Notice that Higgs production different than the VBF (as the gluon-gluon fusion) is considered resonant background in the analysis. To increase sensitivity, the events are categorized in order to increase the signal to background ratio. Two of the three dimensions used to categorize data are the output of a DNN trained to discriminate between 3 classes (VBF production with SM coupling, VBF production with BSM coupling and not VBF production). The third dimension is built by exploiting the Matrix Element Likelihood Approach (MELA) [5]. To categorize data, the binning $2 \times 2 \times 2$ which maximizes the significance in the 3D space is chosen.

4. – Signal and background model

Interpreting the data recorded by CMS requires a description of the expected signal for a Standard Model Higgs boson which includes the overall number of events as a function of the Higgs boson mass and the shape of the distribution of the invariant photon mass distribution in each category. Then the categories will be statistically recombined to perform a global fit as shown in fig. 1. The resolution on the photon opening angle has a negligible contribution to the mass resolution, compared to the ECAL energy resolution, when the interaction point is known to be within about 1 cm. For this reason, the two scenarios are considered separately for each Higgs-production process when constructing the signal model. To keep track of the year-dependent resolution effects and the year-dependent systematic uncertainties, the signal model will also be constructed separately for each year.

To model the falling background distribution deriving from $pp \to \gamma\gamma$ events, the data in side-bands around the expected signal peak is used, and a set of candidate function families is considered, including exponential functions, Bernstein polynomials, Laurent series and power law functions.

5. – Results of the fit for anomalous couplings contributions

Let $S_{ALT_{ai}}$ be the signal model in the invariant mass deriving from a VBF alternative complings' hypothesis, and S_{SM} the ones deriving from a VBF SM hypothesis. The VBF signal model will be defined as $S_{VBF}(f_{ai}) = \mu \times [f_{ai} \times S_{ALT_{ai}} + (1 - f_{ai}) \times S_{SM}]$ in which μ is the overall signal strength (*i.e.*, the ratio of the measured cross section for a given category and the one predicted by the Standard Model) and will be a floating parameter in the model. The simple case is studied, in which only one of the BSM amplitudes contributes

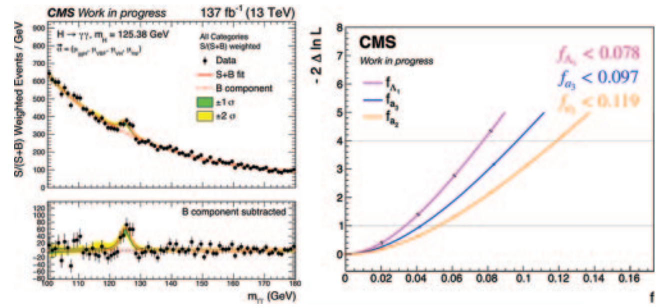

Fig. 1. – On the left: the diphoton invariant mass distribution with each event weighted by the S/(S+B) value of its category. By S we mean the events participating to the invariant mass peak. The lines represent the fitted background and signal, and the coloured bands represent the ±1 and ±2 standard deviation uncertainties. On the right: the profile Likelihood ratio expected and observed as a function of f_{ai}.

to the production cross-section, simultaneously to the SM, *i.e.*, only one f_{ai} at a time is different from 0. The signal and background process model are used to perform a global fit and estimate the parameters of interest using the likelihood method. The expected constraints at 95% C.L. observed on the CP-violating parameter, f_{a3}, and on the CP-conserving parameters are found: $f_{a3} < 0.099$, $f_{a2} < 0.119$ and $f_{\Lambda_1} < 0.078$ (1). The f_{ai} and the signal strength measured ($\mu = 1.00^{+0.18}_{-0.17}$) are consistent with the expectations for the Standard Model Higgs boson and the previous analysis. The obtained limits on the three f_{ai} effective fraction of anomalous cross section are competitive with the best ones from the combination of $H \to ZZ \to 4l$ [6] and $H \to \tau^-\tau^+$ [7] analyses. A futher extension of the analysis would be to consider simultaneous BSM amplitudes and their interference effects to probe the complete BSM Lagrangian of the HVV interaction.

REFERENCES

[1] The CMS Collaboration, *Phys. Lett. B*, **716** (2012) 30.
[2] The ATLAS Collaboration, *Phys. Lett. B*, **716** (2012) 1.
[3] Gritsan A. V., Roskes J., Sarica U., Schulze M., Xiao M. and Zhou Y., *Phys. Rev. D*, **102** (2020) 056022.
[4] The CMS Collaboration, *Phys. Rev. D*, **98** (2018) 052005.
[5] Sumowidagdo S., *J. Phys.: Conf. Ser.*, **988** (2018) 012003.
[6] The CMS Collaboration, *Phys. Rev. D*, **104** (2021) 052004.
[7] The CMS Collaboration, *Phys. Rev. D*, **100** (2019) 112002.