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Constraints on anomalous Higgs boson couplings using production and decay information in the four-lepton final state

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A search is performed for anomalous interactions of the recently discovered Higgs boson using matrix element techniques with the information from its decay to four leptons and from associated Higgs boson production with two quark jets in either vector boson fusion or associated production with a vector boson. The data were recorded by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV and correspond to an integrated luminosity of 38.6 fb^{-1}. They are combined with the data collected at center-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 5.1 and 19.7 fb^{-1}, respectively. All observations are consistent with the expectations for the standard model Higgs boson.

1. Introduction

The observation of a boson with a mass of about 125 GeV by the ATLAS and CMS Collaborations [1–3] is consistent with the prediction of the standard model (SM) Higgs (H) boson [4–10]. It has been established that the spin-parity quantum numbers of the H boson are consistent with $J^{PC} = 0^{++}$ [11–18]. However, the data still leave room for anomalous interactions or *CP* violation in the interactions of the H boson. The kinematics of leptons ($\ell = \mu^\pm$ and $e^\pm$) from $H \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4\ell$ decays (through virtual photons or Z bosons), of quark jets produced in association with the H boson in vector boson fusion (VBF), and of the decays of Z or W bosons produced in association with H (VH) allow studies of anomalous interactions of the H boson [19–36].

The CMS Collaboration analyzed the data collected at the CERN LHC at center-of-mass energies of 7 and 8 TeV (Run 1), corresponding to integrated luminosities of 5.1 and 19.7 fb^{-1}, measuring the spin-parity properties of the H boson and searching for anomalous HVV couplings using the H boson's decay modes to two electroweak gauge bosons [13]. That study focused on testing for the presence of anomalous effects in HZZ, HZγ, H$\gamma\gamma$, and HWW interactions under spin-zero, -one, and -two hypotheses. The spin-one hypotheses were excluded at greater than 99.999% confidence level (CL) in the ZZ and WW modes; they were also excluded via the Landau–Yang theorem [37,38] by the observation of the $\gamma\gamma$ decay mode with 5.7σ significance. The spin-two boson hypothesis with gravity-like minimal couplings was excluded at 99.87% CL, and nine other possible hypotheses of spin-two tensor structure of HVV interactions were excluded at 99% CL or higher. Given the exclusion of the spin-one and -two scenarios, constraints were set on the contribution of eleven anomalous couplings to the HZZ, HZγ, H$\gamma\gamma$, and HWW interactions under the hypothesis of a spin-zero state. Among others, these results constrained a *CP*-violation parameter f_{a3}, the fractional pseudoscalar cross section in the $H \to ZZ$ channel, which will be described in more detail in Section 2. The pure pseudoscalar hypothesis was excluded at 99.98% CL, and the limit $f_{a3} < 0.43$ was set at 95% CL. Similar results, for a smaller number of parameters and fewer exotic-spin models, were obtained by ATLAS [17].

All the above studies considered the decay of an on-shell H boson to two vector bosons. The accumulated data in Run 1 were not sufficient for precision tests of anomalous interactions in associated production, in off-shell production, or with fermions. Nonetheless, both CMS [14] and ATLAS [18] performed analyses of anomalous HVV interactions in VH and VBF production, respectively. Finally, the CMS experiment searched for anomalous HVV interactions in off-shell production of the H boson in $pp \to H \to ZZ$ with Run 1 data [15]. Further measurements probing the tensor structure of the HVV and H$f\bar{f}$ interactions can test *CP* invariance and, more generally, any small anomalous contributions [39].

In this Letter, the analysis approach follows our previous Run 1 publication [13], expanded in two important ways. Information from the kinematic correlations of quark jets from VBF and VH

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production is used together with $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 4\ell$ decay information for the first time, applying the relevant techniques discussed in Ref. [33]. Moreover, data sets corresponding to integrated luminosities of 2.7 and $35.9\,\mathrm{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV in Run 2 of the LHC during 2015 and 2016, respectively, are combined with the Run 1 data, increasing the data sample of $\mathrm{H} \to 4\ell$ events by approximately a factor of four.

In what follows, the phenomenology of anomalous HVV interactions is discussed in Section 2. The CMS detector, reconstruction techniques, and Monte Carlo (MC) simulation are introduced in Section 3. Details of the analysis are discussed in Section 4, and results are presented in Section 5. We summarize in Section 6.

2. Phenomenology of anomalous H boson interactions

We assume that the H boson couples to two gauge bosons VV, such as ZZ, $\mathrm{Z}\gamma$, $\gamma\gamma$, WW, or gg, which in turn couple to quarks or leptons [19–34]. Three general tensor structures that are allowed by Lorentz symmetry are tested. Each term includes a form factor $F_i(q_1^2, q_2^2)$, where q_1 and q_2 are the four-momenta of the two difermion states, such as $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ in the $\mathrm{H} \to \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$ decay. The H boson coupling to fermions is assumed not to be mediated by a new heavy state V′, generating the so-called contact terms [35,36]. We therefore study the process $\mathrm{H} \to \mathrm{VV} \to 4\mathrm{f}$ and the equivalent processes in production, rather than $\mathrm{H} \to \mathrm{VV}' \to 4\mathrm{f}$ or equivalent processes. Nonetheless, those contact terms are equivalent to the anomalous HVV couplings already tested using the $f_{\Lambda 1}$ and $f_{\Lambda 1}^{\mathrm{Z}\gamma}$ parameters, defined below. It is assumed that all lepton and quark couplings to vector bosons follow the SM predictions. Relaxing this requirement would be equivalent to allowing the contact terms to vary with flavor, which would result in too many unconstrained parameters to be tested with the present amount of data. Only the lowest order operators, or lowest order terms in the (q_j^2/Λ^2) form-factor expansion, are tested, where Λ is an energy scale of new physics.

Anomalous interactions of a spin-zero H boson with two spin-one gauge bosons VV, such as ZZ, $\mathrm{Z}\gamma$, $\gamma\gamma$, WW, and gg, are parameterized with a scattering amplitude that includes three tensor structures with expansion of coefficients up to (q^2/Λ^2):

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}, \tag{1}$$

where q_i, $\epsilon_{\mathrm{V}i}$, and $m_{\mathrm{V}1}$ are the four-momentum, polarization vector, and pole mass of a gauge boson, $f^{(i)\mu\nu} = \epsilon_{\mathrm{V}i}^{\mu} q_i^{\nu} - \epsilon_{\mathrm{V}i}^{\nu} q_i^{\mu}$, $\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$ [13,33], and a_i^{VV} and $\kappa_i^{\mathrm{VV}}/\left(\Lambda_1^{\mathrm{VV}}\right)^2$ are parameters to be determined from data.

In Eq. (1), the only leading tree-level contributions are $a_1^{\mathrm{ZZ}} \neq 0$ and $a_1^{\mathrm{WW}} \neq 0$, and we assume custodial symmetry, so that $a_1^{\mathrm{ZZ}} = a_1^{\mathrm{WW}}$. The rest of the couplings are considered anomalous contributions. Tiny anomalous terms arise in the SM due to loop effects, and new, beyond standard model (BSM) contributions could make them larger. The SM values of those couplings are not yet accessible experimentally. Considerations of gauge invariance and symmetry between two identical bosons require $\kappa_1^{\mathrm{ZZ}} = \kappa_2^{\mathrm{ZZ}} = -\exp(i\phi_{\Lambda 1}^{\mathrm{ZZ}})$, $\kappa_{1,2}^{\gamma\gamma} = \kappa_{1,2}^{\mathrm{gg}} = \kappa_1^{\mathrm{Z}\gamma} = 0$, and $\kappa_2^{\mathrm{Z}\gamma} = -\exp(i\phi_{\Lambda 1}^{\mathrm{Z}\gamma})$, where $\phi_{\Lambda 1}^{\mathrm{VV}}$ is the phase of the corresponding coupling. The $a_{2,3}^{\mathrm{Z}\gamma}$ and $a_{2,3}^{\gamma\gamma}$ terms were tested in the Run 1 analysis [13], but have tighter constraints from on-shell photon measurements in $\mathrm{H} \to \mathrm{Z}\gamma$ and $\gamma\gamma$. We therefore do not repeat those measurements. The HWW couplings appear in VBF and WH production. We relate those couplings to the HZZ measurements assuming $a_i^{\mathrm{WW}} = a_i^{\mathrm{ZZ}}$ and drop the ZZ labels in what follows. Four anomalous couplings are left to be tested: a_2, a_3, κ_2/Λ_1^2, and $\kappa_2^{\mathrm{Z}\gamma}/\left(\Lambda_1^{\mathrm{Z}\gamma}\right)^2$. The generic notation a_i refers to all four of these couplings, as well as the SM coupling a_1.

Equation (1) parameterizes both the $\mathrm{H} \to \mathrm{VV}$ decay and the production of the H boson via either VBF or VH. All three of these processes, which are illustrated in Fig. 1, are considered. While q_i^2 in the $\mathrm{H} \to \mathrm{VV}$ process does not exceed $(100\,\mathrm{GeV})^2$ due to the kinematic bound, in associated production no such bound exists. In the present analysis it is assumed that the q_i^2 range is not restricted within the allowed phase space.

The effective fractional cross sections f_{ai} and phases ϕ_{ai} are defined as follows:

$$f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j, \text{ and } \phi_{ai} = \arg\left(a_i/a_1\right). \tag{2}$$

This definition of f_{ai} is valid for both the SM coupling a_1 and the anomalous couplings, but there is no need for a separate measurement of f_{a1} because $\sum f_{ai} = 1$. The cross sections σ_i in Eq. (2) are calculated for each corresponding coupling a_i. They are evaluated for the $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ process, where $a_i = 1$ and all other $a_j = 0$ in Eq. (1). The resulting ratios are $\sigma_1/\sigma_3 = 6.53$, $\sigma_1/\sigma_2 = 2.77$, $\sigma_1/\sigma_{\Lambda 1} = 1.47 \times 10^4\,\mathrm{TeV}^{-4}$, and $\sigma_1/\sigma_{\Lambda 1}^{\mathrm{Z}\gamma} = 5.80 \times 10^3\,\mathrm{TeV}^{-4}$. In the case of the $\mathrm{HZ}\gamma$ coupling the requirement $\sqrt{|q_i^2|} \geq 4\,\mathrm{GeV}$ is introduced in the cross section calculations to avoid infrared divergence. Equation (2) can be inverted to recover the coupling ratio,

$$\left|\frac{a_i}{a_1}\right| = \sqrt{\frac{f_{ai}}{f_{a1}}}\sqrt{\frac{\sigma_1}{\sigma_i}}. \tag{3}$$

It is convenient to measure the effective cross-section ratios (f_{ai}) rather than the anomalous couplings themselves (a_i). First of all, most systematic uncertainties cancel in the ratio. Moreover, the effective fractions are conveniently bounded by 0 and 1 and do not depend on the normalization convention in the definition of the couplings. Until the effects of interference become important, the statistical uncertainties in these measurements scale with the integrated luminosity as $1/\sqrt{\mathcal{L}}$, in the same way as cross section measurements. The f_{ai} values have a simple interpretation as the fractional size of the BSM contribution for the $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ decay. For example, $f_{ai} = 0$ 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 $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ process. In particular, f_{a3} is the fractional pseudoscalar cross section in the $\mathrm{H} \to \mathrm{ZZ} \to 2\mathrm{e}2\mu$ channel. A value $0 < f_{a3} < 1$ would indicate *CP* violation, with a possible mixture of scalar and pseudoscalar states, while $f_{a3} = 1$ would indicate that the H boson is a pure pseudoscalar resonance, which has been excluded at 99.98% CL [13].

The above approach allows a general test of the kinematic distributions associated with the couplings of H to 4 fermions, whether in the decay or in the associated production channels, as shown in Fig. 1. If deviations from the SM are detected, a more detailed study of the (q_j^2/Λ^2) form-factor expansion can be performed, eventually providing a measurement of the double-differential cross section for each tested tensor structure. Under the assumption that the couplings are constant and real (i.e., $\phi_{ai} = 0$ or π), the above formulation is equivalent to an effective Lagrangian [13]. It is also equivalent to the formulation involving contact terms [35,36] if the contact terms are assumed to satisfy lepton universality.