Constraining the Georgi-Machacek model with a light Higgs boson

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In this work, we investigate the viability of a light Higgs (η) scenario in the Georgi-Machacek (GM) model, where we consider all theoretical and experimental constraints such as the perturbativity, vacuum stability, unitarity, electroweak precision tests, the Higgs diphoton and undetermined decays and the Higgs total decay width. In addition, we consider more recent experimental bounds from the searches for doubly charged Higgs bosons in the vector boson fusion channel $H_5^{++} \to W^+W^+$, Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$, and for the light scalars at LEP $e^-e^+ \to Z\eta$, and at ATLAS and CMS in different final states such as $pp \to \eta \to 2\gamma$ and $pp \to h \to \eta\eta \to 4\gamma, 2\mu 2\tau, 2\mu 2b, 2\tau 2b$. By combining these bounds together, we found a parameter space region that is significant as the case of the SM-like Higgs to be the light CP-even eigenstate, and this part of the parameter space would be tightened by the coming analyses.

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I. INTRODUCTION

Despite the discovery of a Standard Model (SM)-like 125 GeV Higgs boson at the Large Hadron Collider (LHC) [1,2], the SM is not complete since it cannot provide answers to many questions, such as the hierarchy problem, fermions masses, strong CP problem, the dark matter nature, baryon asymmetry at the Universe; and the neutrino oscillation data. The discovered 125 GeV scalar seems to be the SM Higgs, however, it is not clear how the electroweak symmetry breaking (EWSB) occurs: via one single scalar field or more?

In many SM extensions, the EWSB is achieved by more than one scalar, where some of the new scalar fields acquire vacuum expectation values (VEV), and then mix with the SM doublet, which make the 125 GeV Higgs is a composite field. Among the popular models, the so-called Georgi-Machacek (GM) model [3], where the SM is extended by one complex and one real scalar triplets, assigned by a global custodial $SU(2)_V$ symmetry, that is preserved in the scalar potential after the EWSB. The model vacuum is defined in a way that predicts a tree-level custodial symmetry, under which the scalar spectrum manifests in multiplets: a quintet (H_5), a triplet (H_3) and two CP-even singlets (η and h).

The existence of extra scalar degrees of freedom and the non-trivial couplings of the Higgs to the gauge bosons, make GM model phenomenologically very rich [4–24]. In addition, the GM model can address some the SM open questions, such as the neutrino mass [25], dark matter [26], and the electroweak phase transition strength [27]. The GM scalar sector has been confronted with the existing data [28], where direct search constraints for extra Higgs bosons and measurements of the SM-like Higgs properties are considered. In addition, the authors derived bounds from the negative searches of the doubly charged Higgs bosons in the vector boson fusion (VBF) channel $H_5^{++} \to W^+W^+$; and the Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$. In [29], we have investigated the GM parameter space where the SM-like Higgs is considered to be the light CP-even eigenstate $h = h_{125}$; and the eigenstate η is a heavier scalar $m_\eta > m_h$. We have considered all the known theoretical and experimental constraints, including those from the negative searches of the heavy scalar via $pp \to \eta \to hh, \tau\tau, ZZ$; and we have found that a significant part of the parameter space is viable and could be probed soon by future analyses with more data. One has to mention that it turns out that two thirds of the parameter space allowed by the constraints described in the literature, are excluded by some possibly existing scalar potential minima (that either preserve or violate the CP and electric charge symmetries) that are deeper than the electroweak (EW) vacuum [29]. Here, we aim to investigate other part of the parameter space where the SM-like Higgs is the heavy CP-even eigenstate, i.e., $h = h_{125}$ and $m_\eta < m_h$. We will consider all the above-mentioned constraints in addition to constraints from the searches of light CP-even scalar whether are direct at LEP $e^-e^+ \to Z\eta$, and LHC $pp \to \eta \to \gamma\gamma$ [30–32]; or indirect $pp \to h \to \eta\eta \to X\bar{X}Y\bar{Y}$ [33–37].

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In Sec. II, we review the GM model and present the constraints described in the literature. We discuss the physics of a light CP-even scalar at colliders in Sec. III; and discuss our numerical results in Sec. IV. In Sec. V, we give our conclusion.

II. THE MODEL: PARAMETERS AND CONSTRAINTS

The GM model scalar sector includes a doublet $(\phi^+, \phi^0)^T$; and two triplets $(\chi^{++}, \chi^+, \chi^0)^T$ and $(\xi^+, \xi^0, -\xi^-)^T$ with the hypercharge $Y = 1, 2, 0$, respectively;

$$\Phi = \begin{pmatrix} \frac{v_\phi + h_\phi - i a_\phi}{\sqrt{2}} & \phi^+ \\ -\phi^- & \frac{v_\phi + h_\phi + i a_\phi}{\sqrt{2}} \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \frac{v_\chi + h_\chi - i a_\chi}{\sqrt{2}} & \xi^+ & \chi^{++} \\ -\chi^- & v_\xi + h_\xi & \chi^+ \\ \chi^{--} & -\xi^- & \frac{v_\chi + h_\chi + i a_\chi}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

where the vacuum expectation values (VEV's) satisfy the relations $v_\chi = \sqrt{2} v_\xi$ and $v_\phi^2 + 8 v_\xi^2 \equiv v^2 = (246.22\ \mathrm{GeV})^2$; to ensure the tree-level custodial symmetry. The scalar potential that is invariant under the global symmetry $SU(2)_L \times SU(2)_R \times U(1)_Y$ in the GM model is

$$\begin{aligned} V(\Phi, \Delta) = {} & \frac{m_1^2}{2} \mathrm{Tr}[\Phi^\dagger \Phi] + \frac{m_2^2}{2} \mathrm{Tr}[\Delta^\dagger \Delta] + \lambda_1 (\mathrm{Tr}[\Phi^\dagger \Phi])^2 + \lambda_2 \mathrm{Tr}[\Phi^\dagger \Phi] \mathrm{Tr}[\Delta^\dagger \Delta] + \lambda_3 \mathrm{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 (\mathrm{Tr}[\Delta^\dagger \Delta])^2 \\ & - \lambda_5 \mathrm{Tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] \mathrm{Tr}[\Delta^\dagger T^a \Delta T^b] - \mu_1 \mathrm{Tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] (U \Delta U^\dagger)_{ab} - \mu_2 \mathrm{Tr}[\Delta^\dagger T^a \Delta T^b] (U \Delta U^\dagger)_{ab}, \end{aligned} \tag{2}$$

with $\sigma^{1,2,3}$ are the Pauli matrices and $T^{1,2,3}$ correspond to the generators of the $SU(2)$ triplet representation and the matrix U is given in [3]. After the EWSB, we are left with: three CP-even eiegenstaes $\{h, \eta, H_5^0\}$, one CP-odd eigenstate H_3^0, two singly charged scalars $\{H_3^\pm, H_5^\pm\}$, and one doubly charged scalar $H_5^{\pm\pm}$, that are defined as

$$\begin{aligned} & h = c_\alpha h_\phi - \frac{s_\alpha}{\sqrt{3}} (\sqrt{2} h_\chi + h_\xi), \qquad \eta = s_\alpha h_\phi + \frac{c_\alpha}{\sqrt{3}} (\sqrt{2} h_\chi + h_\xi), \qquad H_5^0 = \sqrt{\frac{2}{3}} h_\xi - \sqrt{\frac{1}{3}} h_\chi, \\ & H_3^0 = -s_\beta a_\phi + c_\beta a_\chi, \qquad H_3^\pm = -s_\beta \phi^\pm + c_\beta \frac{1}{\sqrt{2}} (\chi^\pm + \xi^\pm), \qquad H_5^\pm = \frac{1}{\sqrt{2}} (\chi^\pm - \xi^\pm), \qquad H_5^{\pm\pm} = \chi^{\pm\pm}, \end{aligned} \tag{3}$$

with $\tan\beta = 2\sqrt{2} v_\xi / v_\phi$ and $\tan 2\alpha = 2 M_{12}^2 / (M_{22}^2 - M_{11}^2)$, where M^2 is the mass squared matrix in the basis $\{h_\phi, \sqrt{\frac{2}{3}} h_\chi + \frac{1}{\sqrt{3}} h_\xi\}$. In this setup where η is the light CP-even eigenstate, the quartic couplings λ's can be expressed as

$$\begin{aligned} & \lambda_1 = \frac{1}{8 v^2 c_\beta^2} (m_h^2 c_\alpha^2 + m_\eta^2 s_\alpha^2), \qquad \lambda_2 = \frac{1}{12 v^2 s_\beta c_\beta} (2\sqrt{6} (m_h^2 - m_\eta^2) s_\alpha c_\alpha + 12 m_3^2 c_\beta c_\beta - 3\sqrt{2} v c_\beta \mu_1), \\ & \lambda_3 = \frac{1}{v^2 s_\beta^2} (m_5^2 - 3 m_3^2 c_\beta^2 + \sqrt{2} v \mu_1 c_\beta^2 / s_\beta - 3\sqrt{2} v s_\beta \mu_2), \qquad \lambda_5 = \frac{2 m_3^2}{v^2} - \frac{\sqrt{2} \mu_1}{v s_\beta}, \\ & \lambda_4 = \frac{1}{6 v^2 s_\beta^2} (2 m_\eta^2 c_\alpha^2 + 2 m_h^2 s_\alpha^2 - 2 m_5^2 + 6 c_\beta^2 m_3^2 - 3\sqrt{2} v \mu_1 c_\beta^3 / s_\beta^2 + 9\sqrt{2} v \mu_2 s_\beta). \end{aligned} \tag{4}$$

It has been shown in [29] that the scalar potential (2) could acquire some minima that could violate the CP-symmetry and/or electric charge, where they could be deeper than the electroweak vacuum $\{v_\phi, \sqrt{2} v_\xi, v_\xi\}$. Then, this part of the parameter space would be ignored. Here, we impose the constraints from (1) vacuum stability, (2) unitarity, (3) the electroweak precision tests, (4) the diphoton and undetermined Higgs branching ratios and total decay width; in addition to (5) the constraints from negative searches for light scalar resonances at LEP [38]. For the constraints (1-3), we used the results described in [29].

In this setup, the SM-like Higgs h (the CP-even scalar $m_h = 125.18$ GeV) decays mainly into pairs of fermions $(cc, \mu\mu, \tau\tau, b\bar{b})$ and gauge bosons WW^* and ZZ^*, in addition to a pair of light scalars $\eta\eta$ when kinematically allowed. Since the Higgs couplings to SM fields are scaled by the coefficients

$$\kappa_F = \frac{g_{hff}^{\rm GM}}{g_{hff}^{\rm SM}} = \frac{c_\alpha}{c_\beta}, \qquad \kappa_V = \frac{g_{hVV}^{\rm GM}}{g_{hVV}^{\rm SM}} = c_\alpha c_\beta - \sqrt{\frac{8}{3}} s_\alpha s_\beta, \qquad (5)$$

then, its total decay width can be written as

$$\Gamma_h^{\rm tot} = \Gamma_h^{\rm SM} \sum_{X={\rm SM}} \kappa_X^2 \mathcal{B}^{\rm SM}(h \to XX) + \Theta(m_h - 2m_\eta) \times \frac{g_{h\eta\eta}^{\rm GM}}{32\pi m_h}(1 - 4m_\eta^2/m_h^2)^{1/2}, \qquad (6)$$

where the last term represents the partial decay width $\Gamma(h \to \eta\eta)$, $\Gamma_h^{\rm SM} = 4.08$ MeV [39] and $\mathcal{B}^{\rm SM}(h \to XX)$ are the SM values for total decay width and the branching ratios for the Higgs, respectively. Here, $g_{h\eta\eta}^{\rm GM}$ is the scalar triple coupling $h\eta\eta$. Since the light scalar η can be seen at detectors via its decay to light fermions $\eta \to f\bar{f}$, then, the Higgs decay $h \to \eta\eta$ does not match any of the known SM final states, and hence called undetermined channel, which is constrained by ATLAS as $\mathcal{B}_{und} < 0.22$ [40,41]. The total Higgs decay width recent measurements give the upper bound $\Gamma_h < 14.4$ MeV at 68% CL [42], however, a more conservative value coming looking at the off-shell Higgs production in the final state $h \to ZZ^* \to \ell\ell\nu\nu$ will be considered here: $\Gamma_h = 3.2_{-1.7}^{+2.4}$ MeV [43].

In the case of heavy scalar η [29], it has been shown that the measurements of the Higgs signal strength modifiers imply constraints on the coefficients $\kappa_{F,V}$. Here, another factor is constrained in addition, which is the undetermined Higgs decay; or the scalar η mass and the triple coupling $g_{h\eta\eta}^{\rm GM}$. The Higgs decays $h \to \gamma\gamma, \gamma Z$ are modified with respect to the SM, however, the ratios $R_{\gamma\gamma,\gamma Z} = \mathcal{B}(h \to \gamma\gamma, \gamma Z)/\mathcal{B}^{\rm SM}(h \to \gamma\gamma, \gamma Z)$ in this setup (light η) are modified by the factor $(1 - \mathcal{B}_{und})$ with respect to the case of heavy η [29]. According to the recent data, we consider the very recent range $R_{\gamma\gamma} = 1.04_{-0.90}^{+0.10}$ that is obtained by ATLAS at $\sqrt{s} = 13$ TeV using 139 fb^{-1} integrated luminosity [44].

Besides the above mentioned constraints, the negative searches for doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$; and from Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$; give strong bounds on the parameter space [28]. It has been shown in [28], that the doubly charged Higgs bosons in the VBF channel leads to a constraint from CMS on $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ [45]. While the relevant quantity for the constraints on $H_5^0 \to \gamma\gamma$ is the fiducial cross section times branching ratio $\sigma_{\rm fid} = (\sigma_{H_5^0 H_5^+} \times \epsilon_+ + \sigma_{H_5^0 H_5^-} \times \epsilon_-)\mathcal{B}(H_5^0 \to \gamma\gamma)$, that is constrained by ATLAS at 8 TeV [46] and at 13 TeV [47]. Here, we used the decay rate formulas, the cross section and efficiency values used in [28] to include these constraints in our numerical analysis.

III. THE LIGHT SCALAR η IN THE COLLIDER

After the discovery of the Higgs boson with $m_h = 125.18$ GeV, efforts have been devoted to search for light neutral scalar boson through different channels over a wide range of mass. Such results can also be used to impose constraints on models with many neutral scalars such as the GM model.

The two CP-even eigenstates h and η are defined through a mixing angle α and $(m_\eta < m_h)$, where the heavy eigenstate h is identified to be the SM-like Higgs with the measured mass $m_h = 125.18$ GeV. Here, the light scalar η has similar couplings as the SM Higgs, but modified with the factors

$$\zeta_V = \frac{g_{\eta VV}^{\rm GM}}{g_{hVV}^{\rm SM}} = s_\alpha c_\beta + \sqrt{\frac{8}{3}} c_\alpha s_\beta, \qquad \zeta_F = \frac{g_{\eta FF}^{\rm GM}}{g_{hFF}^{\rm SM}} = \frac{s_\alpha}{c_\beta}, \qquad (7)$$

then, the partial decay width of the light scalar η into SM final states can be written as $\Gamma(\eta \to X\bar{X}) = \zeta_X^2 \Gamma^{\rm SM}(\eta \to X\bar{X})$, where $\Gamma^{\rm SM}(\eta \to X\bar{X})$ is the Higgs partial decay width estimated at $m_h \to m_\eta$ [48]. Thus, its total decay width can be written as

$$\Gamma_\eta^{\rm tot} = \Gamma_\eta^{\rm SM} \sum_{X={\rm SM}} \zeta_X^2 \mathcal{B}^{\rm SM}(\eta \to X\bar{X}), \qquad (8)$$

where $\Gamma_\eta^{\rm SM}$ and $\mathcal{B}^{\rm SM}(\eta \to X\bar{X})$ are the Higgs total decay width and the branching ratios estimated at $m_h \to m_\eta$ [48]. At colliders, there have been many searches for light scalars which are translated into constraints on the light scalar mass and its couplings to SM particles. In what follows, we will focus on two types of searches of the light scalar η: (1) direct production like $e^-e^+, pp \to \eta + X$, where the scalar could be identified via one of its SM-like decays $\eta \to \gamma\gamma, \mu\mu, \tau\tau, cc, bb$, and (2) indirect production via the Higgs decay $pp \to h \to \eta\eta \to X\bar{X}Y\bar{Y}$, where the light scalar is identified via its SM decays $X, Y = \gamma$, μ, τ, c, b. Here, we will consider the constraints from the negative searches for $pp \to \eta \to \gamma\gamma$ at CMS at $8 + 13$ TeV [30], and at ALTAS at 13 TeV with integrated luminosity 80 fb^{-1} [31]; and at 138 fb^{-1} [32].

At LEP, many searches for Higgs at low mass range $m_h < 100$ GeV have been performed, and bounds on the form factor [38]; that can be simplified in our setup as

$$\kappa_{Z\eta} = \frac{\sigma(e^-e^+ \to \eta Z)}{\sigma^{\rm SM}(e^-e^+ \to \eta Z)} = \zeta_V^2. \qquad (9)$$

A similar search for light SM-like Higgs in the diphoton channel with masses in the range 70–110 GeV has been done by CMS at 8 TeV and 13 TeV [30], where some upper bounds are established on the production cross section scaled by its SM value $\kappa_F^2.\kappa_{\gamma\gamma}^\eta = \kappa_F^2.\frac{\sigma(pp\to\eta)\times\mathcal{B}(\eta\to\gamma\gamma)}{\sigma^{\rm SM}(pp\to\eta)\times\mathcal{B}^{\rm SM}(\eta\to\gamma\gamma)}$. In our setup, this ratio can be simplified as

$$\kappa^{\eta}_{\gamma\gamma} = \zeta_F^2 \frac{\Gamma^{\rm tot}_{\rm SM}(\eta)}{\Gamma^{\rm tot}(\eta)} \left| \frac{\frac{\upsilon}{2}\sum_X \frac{g_{\eta XX}}{m_X^2} Q_X^2 A_0^{\gamma\gamma}(4m_X^2/m_\eta^2) + \zeta_V A_1^{\gamma\gamma}(4m_W^2/m_\eta^2) + \zeta_F \frac{4}{3} A_{1/2}^{\gamma\gamma}(4m_t^2/m_\eta^2)}{A_1^{\gamma\gamma}(4m_W^2/m_\eta^2) + \frac{4}{3} A_{1/2}^{\gamma\gamma}(4m_t^2/m_\eta^2)} \right|^2, \qquad (10)$$

with $X = H_3^\pm, H_5^\pm, H_5^{\pm\pm}$; and the functions $A^{\gamma\gamma}_{0,1,1/2}$ are given in the literature [49].

Concerning the indirect searches via the Higgs decay into a pairs of light scalars in the channels $h \to HH \to X\bar{X}Y\bar{Y}$ (H could be a CP-odd scalar a or a CP-even one like η in our setup), many searches by ATLAS and CMS at 8 TeV and/or 13 TeV and at different values for the integrated luminosity values; have been performed in many final states, among them that decay into photons or light fermions. For instance, negative searches for $pp \to h \to \eta\eta \to X\bar{X}Y\bar{Y}$ established bounds either on the branching ratio $\mathcal{B}(h \to \eta\eta \to X\bar{X}Y\bar{Y})$, the ratio $\frac{\sigma(pp\to h)}{\sigma^{\rm SM}(pp\to h)}\mathcal{B}(h \to \eta\eta \to X\bar{X}Y\bar{Y})$ and/or the cross section $\sigma(pp \to h) \times \mathcal{B}(h \to \eta\eta \to X\bar{X}Y\bar{Y})$. In our work, we will consider the constraints coming from the CMS and ATLAS searches for the Higgs decay into a pair of light pseudoscalars in the final state $h \to 2a \to 2b2\tau$ [33], $h \to 2a \to 2\tau 2\mu$ at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 35.9\ \mathrm{fb}^{-1}$ [34], $h \to 2a \to 4\gamma$ at CMS $\sqrt{s} = 13$ TeV and $\mathcal{L} = 132\ \mathrm{fb}^{-1}$ [35], $h \to 2a \to 2b2\mu$ at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 36.1\ \mathrm{fb}^{-1}$ [36], $h \to 2a \to 2b2\mu$ at ATLAS $\sqrt{s} = 13$ TeV and $\mathcal{L} = 139\ \mathrm{fb}^{-1}$ [37]. All these analyses were performed using the ggF Higgs production mode at the LHC.

IV. NUMERICAL ANALYSIS AND DISCUSSION

Here, we have considered the heavy CP-even scalar to be the 125 GeV SM-like Higgs; and have taken into account the different theoretical and experimental constraints described in Secs. II and III, such as the constraints from perturbativity, vacuum stability, electroweak precision tests, the diphoton and undetermined Higgs decays; and the total Higgs decay width. In addition, we have considered also the constraints from the fact that the EW vacuum $(\upsilon_\phi, \sqrt{2}\upsilon_\xi, \upsilon_\xi)$ must be the deepest among possible minima that may preserve or violate the CP and electric charge symmetries as described in [29]. As a first step of this numerical study, we perform a full numerical scan over the GM model parameter space, then, in a second step we have imposes the constraints from the negative searches for

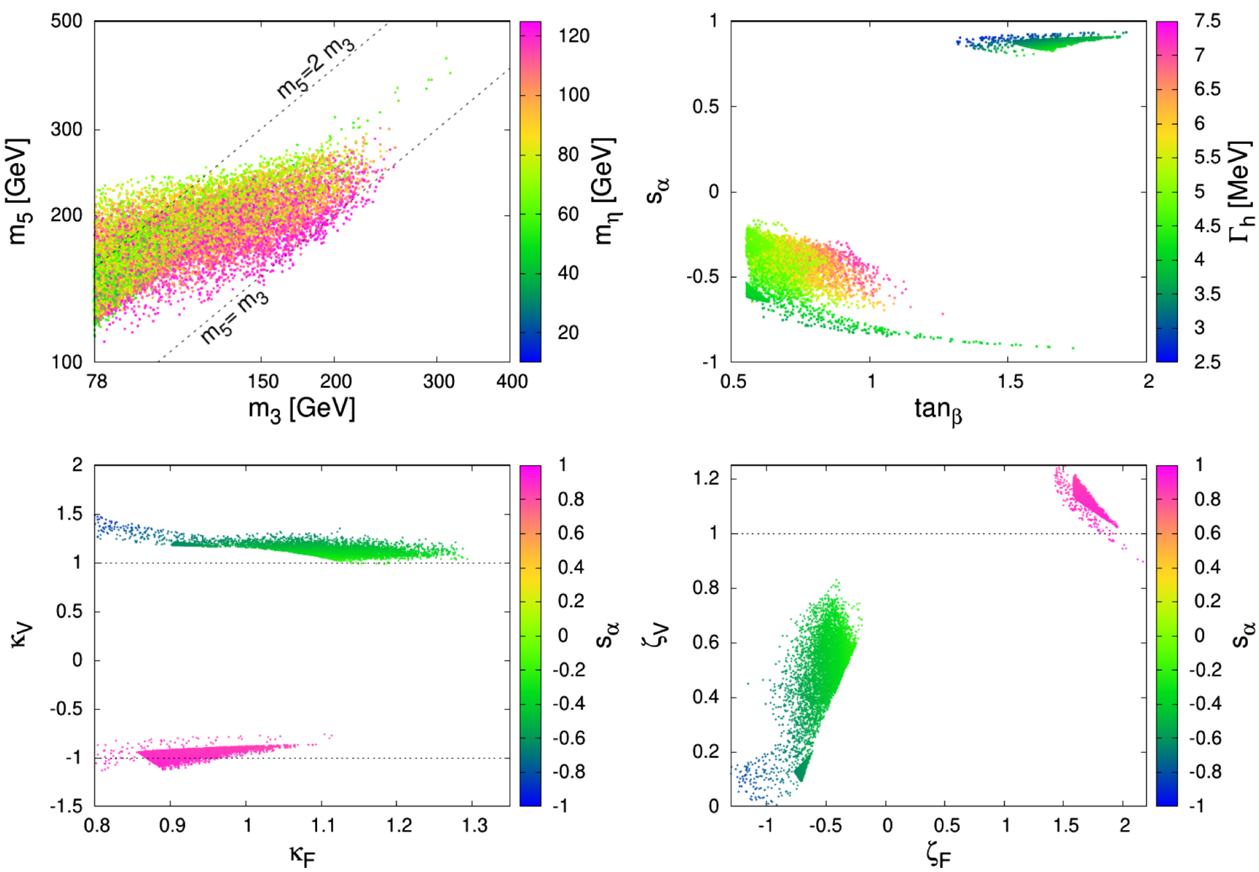

FIG. 1. Different physical observables estimated in the GM model by taking into account the constraints from perturbativity, vacuum stability, electroweak precision tests, the diphoton and undetermined Higgs decays; and the total Higgs decay width.

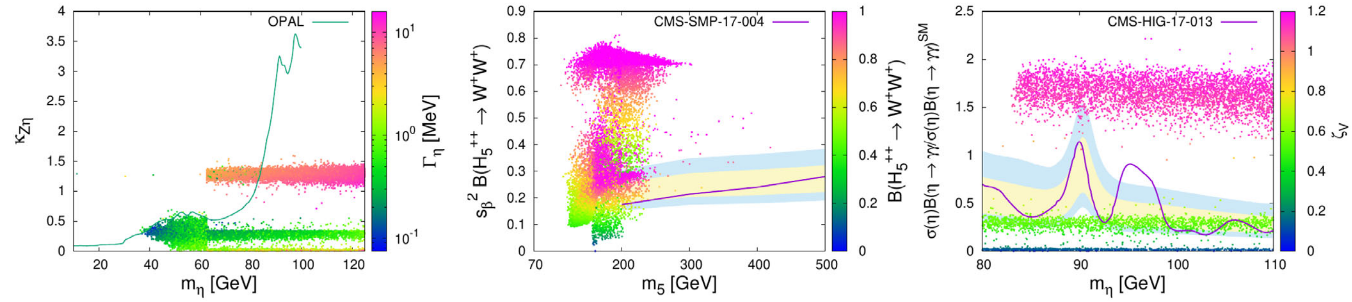

FIG. 2. Left: the form factor (9) versus the light scalar mass m_η,where the palette shows the light scalar total decay width. The green curve represents the OPAL bounds [38]. Middle: the ratio $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ compared to the CMS bounds [45], where the yellow (blue) region corresponds to 68% (95%) CL, and the palette shows the branching ratio $\mathcal{B}(H_5^{++} \to W^+W^+)$. Right: the combined cross section at 8+13 TeV $\sigma(pp \to \eta \to \gamma\gamma)$ scaled by the SM values compared to the CMS bounds for the mass range 80 GeV $< m_\eta <$ 110 GeV [30], where the palette shows the factor (10) that represents the enhancement effect on the decay $\eta \to \gamma\gamma$ due to the coupling with charged scalars. The yellow (blue) region corresponds to 68% (95%) CL.

doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$; and from Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$; negative searches for a light Higgs at LEP $e^-e^+ \to \eta Z$ [38], the direct search for a light resonance at the LHC [30] and the indirect searches for light resonance via the final states $h \to \eta\eta \to X\bar{X}Y\bar{Y}$ [33–37]. The GM parameter space is described by the free parameters $\lambda_2, \lambda_4, m_\eta, m_3, m_5, s_\alpha$ and $t_\beta = \tan\beta \equiv 2\sqrt{2}\upsilon_\xi/\upsilon_\phi$, within the ranges

$$70\ \text{GeV} < m_{3,5} < 3\ \text{TeV},\ 10\ \text{GeV} < m_\eta < m_h,$$
$$|\lambda_{2,4}| \leq 20,\ |t_\beta| \leq 3. \tag{11}$$

As considered in [29], we consider here also the case of negative υ_ξ ($t_\beta < 0$) since there is no reason to consider only positive values. After combining all the first step constraints, we show in Fig. 1 the viable parameters space and the different physical observables using 25k benchmark points (BPs).

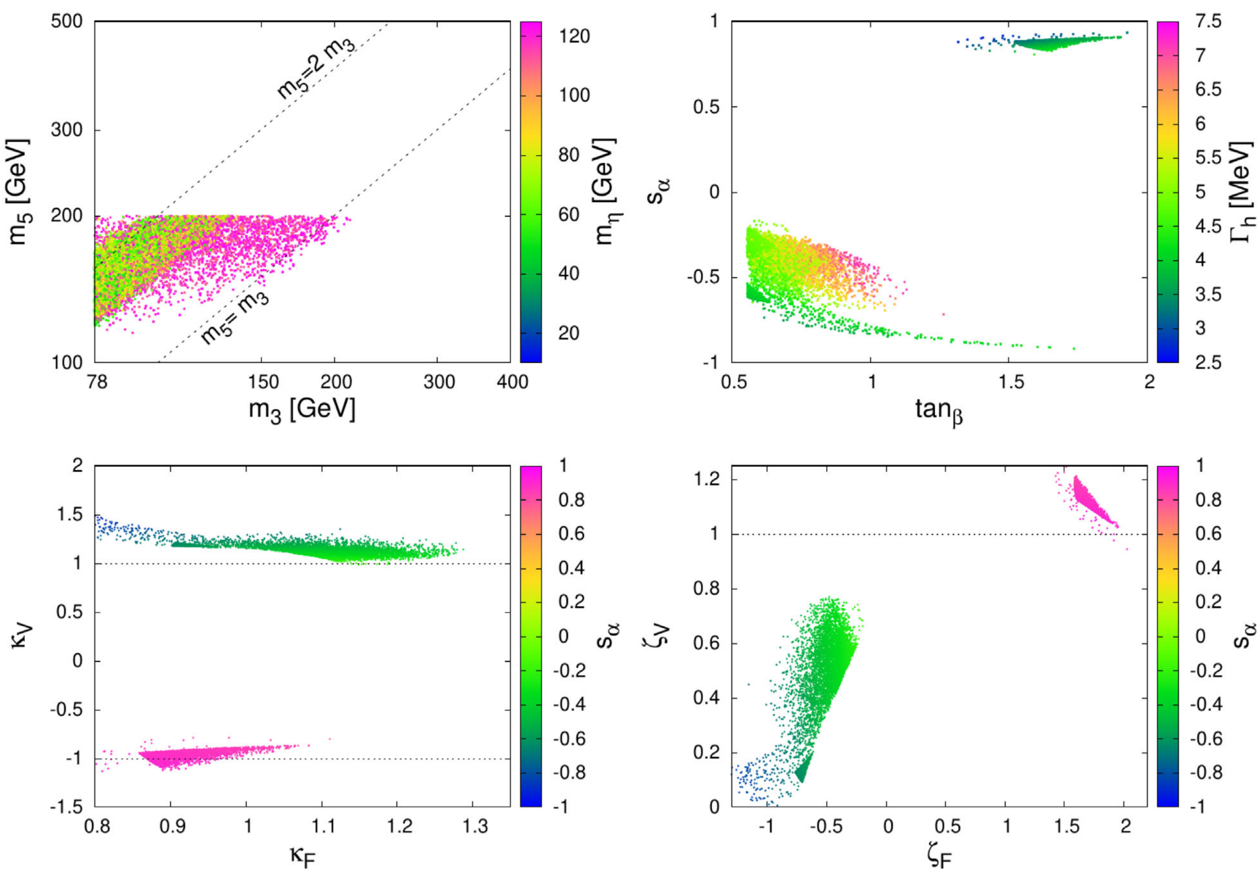

FIG. 3. Different physical observables estimated in the GM model by taking into account all the constraints.

From Fig. 1, one notices a significant parameter space comparable to the case where the SM-like Higgs is the light CP-even eigenstate. Here, one has to mention that most of the allowed light scalar mass values are for $m_\eta > m_h/2$ due to the conflict between the constraints from the undetermined ($h \to \eta\eta$) and diphoton ($h \to \gamma\gamma$) Higgs decays.

Some of these 25k BPs are in agreement all the above-mentioned constraints, including those are considered in the second step of our analysis. For instance, we show in Fig. 2 some of the observables like the form factor (9) that is constrained by OPAL [38], the ratio $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ constrained by CMS [45]; and cross section at $8+13$ TeV $\sigma(pp \to \eta \to \gamma\gamma)$ constrained by CMS [30].

Clearly, the constraints we have considered in our second step analysis seems to interesting and efficient. For instance, the constraints from the doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$ excludes 41% of the BPs; and those from the Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$ excludes 9.2%. The negative direct searches of the scalar η exclude 10.4% of the BPs, while the constraints from the indirect searches exclude only 0.01% of the BPs. When combining all the constraints together, we have around 44.9% of the BPs allowed. In Fig. 3, we reproduce Fig. 1 by considering only the viable 11.3k BPs.

From Fig. 3-left, one remarks that all the viable BPs with $m_5 > 200$ GeV, have the decay channels $H_5^{++} \to H_3^+H_3^+, H_3^+W^+$ open, and therefore branching ratio for $\mathcal{B}(H_5^{++} \to W^+W^+)$ significantly smaller than unity, as shown in Fig. 2-middle. Most of the BPs with $m_5 <$ 200 GeV are not constrained, and therefore future analysis should consider the range 70 GeV $< m_5 <$ 200 GeV. It is clear that this viable parameter space would tightened by taking into account future analyses with more data.

V. CONCLUSION

In this work, we studied the GM scalar sector in the case where the SM-like Higgs corresponds to the heavy CP-even eigenstate. We have shown the viability of an important region of the parameter space, that is significant as the case of the light CP-even scalar to be the SM-like Higgs. In our analysis, we considered the constraints from perturbativity, unitarity, boundness from below, the electroweak precision tests, the di-photon and undetermined Higgs decays; and the total Higgs decay width. For this we generated around 25k BPs that fulfill all the previously mentioned constraints. In addition, we have imposed more bounds from the searches for (1) doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$, (2) Drell-Yan production of a neutral Higgs boson $pp \to H_5^0(\gamma\gamma)H_5^+$, and for the light scalars by ATLAS and CMS in different final states such as (3) $e^-e^+ \to Z\eta$ and $pp \to \eta \to 2\gamma$ and (4) $pp \to h \to \eta\eta \to 4\gamma, 2\mu 2\tau, 2\mu 2b, 2\tau 2b$. We found that only 44.9% of the BPs survives against these four constraints, where they exclude 41%, 9.2%, 10.4% and 0.01% of the BPs, respectively.

We have noticed that most of the allowed BPs corresponds to the scalar mass values $m_\eta > m_h/2$ due to the conflict between the constraints from the undetermined ($h \to \eta\eta$) and diphoton ($h \to \gamma\gamma$) Higgs decays. After imposing all constraints, we found that the negative searches of the doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$ exclude all BPs with $\mathcal{B}(H_5^{++} \to W^+W^+) = 1$ and $m_5 > 200$ GeV, while all surviving BPs have the decay channels $H_5^{++} \to H_3^+H_3^+, H_3^+W^+$ open, $m_5 > 2m_3$. It is important if the future searches for doubly charged scalars would consider masses below 200 GeV to probe this scenario. In the near future, the coming analyses with more data will make the parameter space more constrained.

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