Erratum: Constraining the Georgi-Machacek model with a light Higgs boson [Phys. Rev. D 107, 015006 (2023)]

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We have addressed this erratum for two reasons: (1) we have detected an error in the code where the $b \to s$ bounds were not properly included; and (2) we realized that the possible parameter space was not fully considered, since we ignored the negative values of the mixing $\tan\beta$ according to the referee's suggestion.

Here, we take advantage of this erratum to correct a typo in (4) where it becomes

$$\lambda_1 = \frac{\varrho_1 c_\alpha^2 + \varrho_2 s_\alpha^2}{8\upsilon^2 c_\beta^2}, \qquad \lambda_2 = \frac{m_3^2}{\upsilon^2} - \frac{c_\alpha s_\alpha}{\sqrt{6}\upsilon^2 c_\beta s_\beta}(\varrho_1 - \varrho_2) - \frac{\mu_1}{2\sqrt{2}\upsilon s_\beta},$$
$$\lambda_3 = \frac{\sqrt{2}(\mu_1 c_\beta^2 - 3\mu_2 s_\beta^2)}{s_\beta^3 \upsilon} - \frac{3c_\beta^2 m_3^2}{s_\beta^2 \upsilon^2} + \frac{m_5^2}{s_\beta^2 \upsilon^2}, \qquad \lambda_5 = -\frac{\sqrt{2}\mu_1}{\upsilon s_\beta} + \frac{2m_3^2}{\upsilon^2},$$
$$\lambda_4 = -\frac{\mu_1 c_\beta^2 - 3\mu_2 s_\beta^2}{\sqrt{2}s_\beta^3 \upsilon} + \frac{c_\beta^2 m_3^2}{s_\beta^2 \upsilon^2} - \frac{m_5^2}{3s_\beta^2 \upsilon^2} + \frac{\varrho_1 s_\alpha^2 + \varrho_2 c_\alpha^2}{3s_\beta^2 \upsilon^2}, \tag{1}$$

with $\varrho_1 = \min(m_h^2, m_\eta^2)$ and $\varrho_2 = \max(m_h^2, m_\eta^2)$. The formulas of $\lambda_{1,2,4}$ here are valid for both cases of $m_h < m_\eta$ and $m_h > m_\eta$.

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

$$78\ \text{GeV} < m_{3,5} < 3\ \text{TeV}, \qquad 10\ \text{GeV} < m_\eta < m_h, \qquad |\lambda_{2,4}| \le 20, \qquad |t_\beta| \le 3, \tag{2}$$

where for the lower bound on $m_{3,5}$, we considered lower mass bound on this singly charged scalar obtained from the direct search at the LEP II [1].

Here, the negative values of t_β are considered for the following reason. In the GM model, there exists an invariance under the transformation $(\upsilon_\xi, \mu_{1,2}) \to (-\upsilon_\xi, -\mu_{1,2})$, which means $V(\Phi, \Delta, \mu_{1,2}) = V(\Phi, -\Delta, -\mu_{1,2})$. Consequently, the scalar mass matrix elements also remain invariant under this transformation. However, because the physical scalar eigenstates are mixtures of the components of Φ and Δ, most of the physical vertices that involve scalars are not invariant under $(\upsilon_\xi, \mu_{1,2}) \to (-\upsilon_\xi, -\mu_{1,2})$. This means that these vertices change; and therefore any two benchmark points (BPs) with the same input parameters but with different signs of $(\pm t_\beta, \pm\mu_{1,2})$ are physically different. This can be seen in the formulas of the scaling factors $\kappa_{F,V}$ and $\zeta_{F,V}$. This makes the BPs with negative t_β values in (2) an independent part of the parameter space that should not be ignored.

After combining all the first step constraints, we show in Fig. 1 the viable parameters' space and the different physical observables using 34.7k BPs.

From Fig. 1, one notices a significant parameter space comparable to the case where the SM-like Higgs is the light CP-even eigenstate. The parameter space in the plan $\{m_3, m_5\}$ is different than the case of the GM model with heavy scalar η, while in the plans $\{t_\beta, s_\alpha\}$, $\{\kappa_F, \kappa_V\}$, and $\{\zeta_F, \zeta_V\}$ they are similar [2]. One has to notice that imposing different theoretical and experimental constraints, especially the Higgs total width, the Higgs signal strength modifiers and the B physics flavor constraints, makes the parameter space well constrained. It is separated into three distinct islands in the plan $\{t_\beta, s_\alpha\}$, where the first one corresponds to positive t_β values, the second corresponds to negative t_β and positive s_α values,

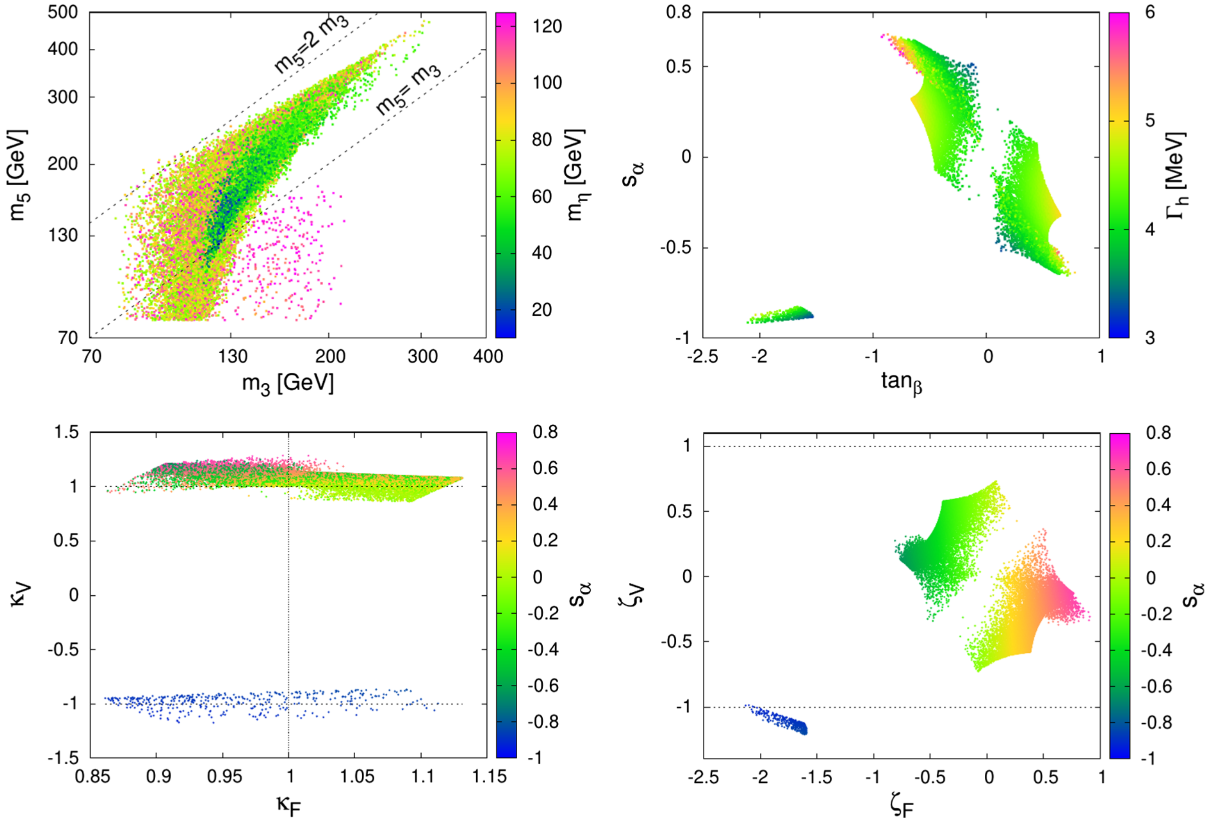

FIG. 1. Different physical observables estimated in the GM model by taking into account the constraints from perturbativity, vacuum stability, electroweak precision tests, the diphoton and undetermined Higgs decays, and the total Higgs decay width.

while the region of negative t_β and negative s_α values represents the third island. The Higgs fermion couplings ($hf\bar{f}$) are always positive and can be modified by a ratio up to 15%, while the Higgs gauge couplings (hVV) can be modified by a few percent and could be negative for negative s_α. The second and third islands that were not considered previously in the literature (negative t_β) correspond to negative ($hf\bar{f}$) couplings. The magnitude of these couplings can be enhanced up to 120%, which makes the searches for SM-like light scalars in the light fermion channels efficient to probe this part of the viable parameter space.

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 34.7 k BPs are in agreement all the above mentioned constraints, including those that are considered in the second step of our analysis. For instance, we show in Fig. 2 some of the observables like the form factor ($\kappa_{Z\eta} = \zeta_V^2$) that is constrained by OPAL [3], the ratio $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ constrained by CMS [4], and the cross section at $8 + 13$ TeV $\sigma(pp \to \eta \to \gamma\gamma)$ constrained by CMS [5].

From Fig. 2-left and -right, one learns that the first and second islands in Fig. 1-top-right is in agreement with the OPAL bounds (i.e., the lower green island in Fig. 2-left that corresponds to $|\zeta_V| \lesssim 0.7$). The third island is also in agreement with OPAL since it corresponds to 80 GeV $\le m_\eta \le$ 120 GeV, i.e., the pink island in Fig. 2-left.

From Fig. 2-right, one notices that the BPs with the η mass in the range 80–110 GeV that are in agreement with the bound form $pp \to \eta \to \gamma\gamma$ are those that belong to the first and second islands. From Fig. 2-middle, one remarks that the majority of the BPs with open decay channels $H_5^{++} \to W^+H_3^+, H_3^+H_3^+$, which makes the branching ratio $\mathcal{B}(H_5^{++} \to W^+W^+)$ significantly smaller than unity. Indeed, some of the BPs with $\mathcal{B}(H_5^{++} \to W^+W^+) = 1$ are also in agreement with the bounds on $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ [4].

Clearly, the constraints we have considered in our second step analysis seem to be interesting and efficient. For instance, the constraints from the doubly charged Higgs bosons in the VBF channel $H_5^{++} \to W^+W^+$ excludes 41.75% 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 only 1.7%. The negative direct searches of the scalar η exclude 0.9% of the BPs. By combining all these constraints, we got 44.1% of the BPs excluded. In Fig. 3, we reproduce Fig. 1 by considering only the viable 19.4k BPs.

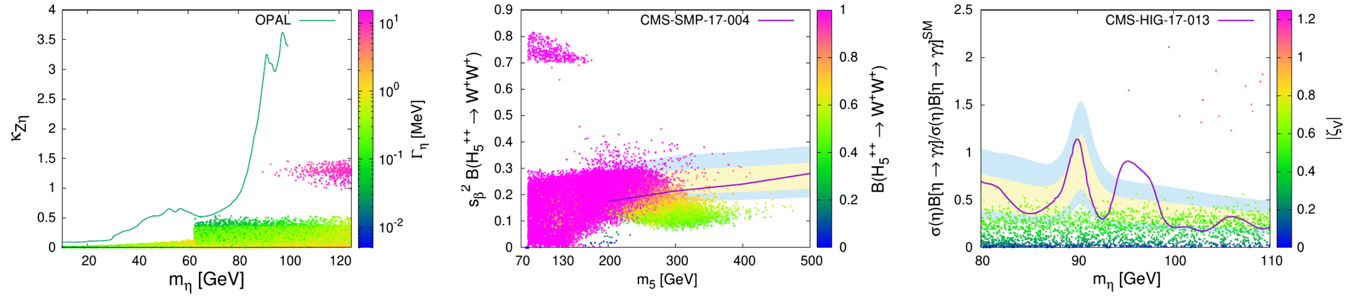

FIG. 2. Left: the form factor $\kappa_{Z\eta}$ versus the light scalar mass m_η, where the palette shows the light scalar total decay width. The green curve represents the OPAL bounds [3]. Middle: the ratio $s_\beta^2 \times \mathcal{B}(H_5^{++} \to W^+W^+)$ compared with the CMS bounds [4], where the yellow (blue) region corresponds to 68% (95%) C.L., 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 with the CMS bounds for the mass range 80 GeV $< m_\eta <$ 110 GeV [5], where the palette shows the factor ζ_V 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%) C.L.

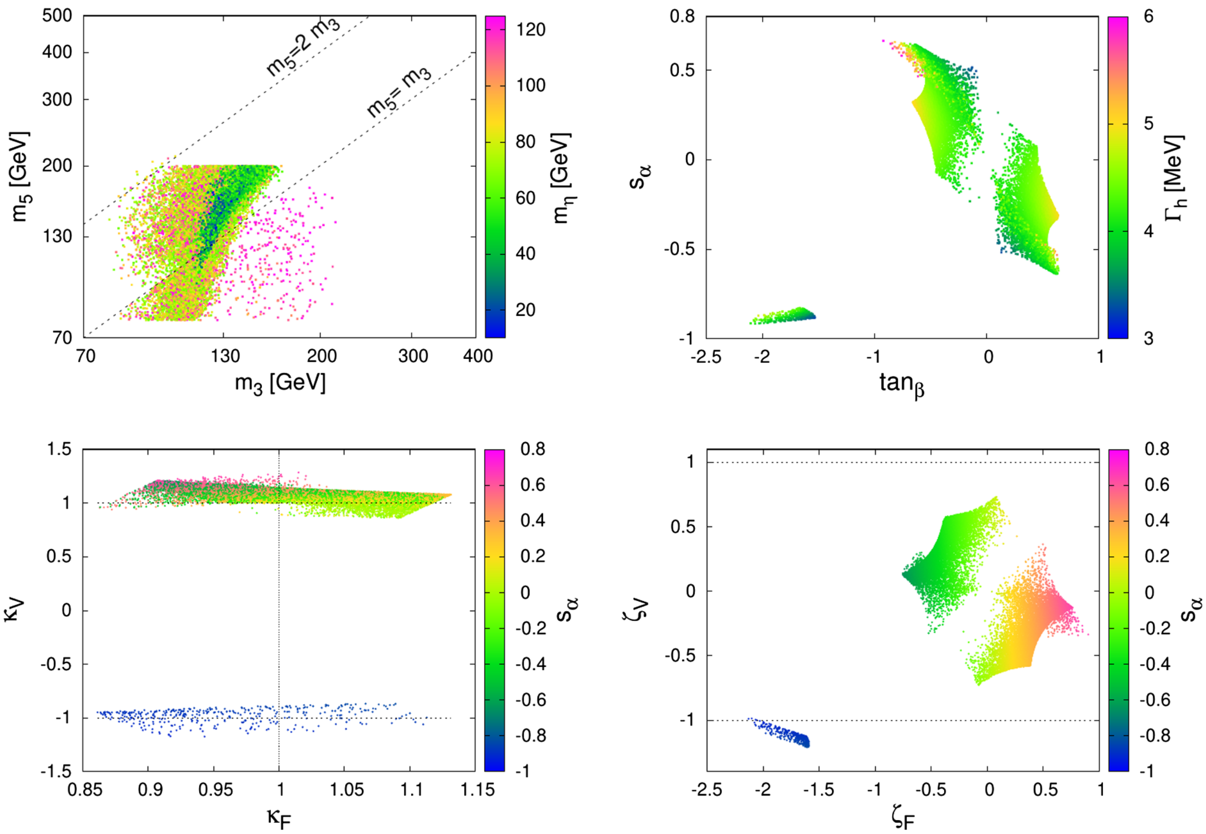

FIG. 3. Different physical observables estimated in the GM model by taking into account all the constraints.

The previous discussion remains correct, and only one statement in the conclusion needs to be corrected:

For this we generated around 34.7k 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) $pp \to h \to \eta\eta \to 4\gamma, 2\mu 2\tau, 2\mu 2b, 2\tau 2b$. We found that only 55.9% of the BPs survives against these three constraints, where they exclude 41.75, 1.7, and 0.9% of the BPs, respectively.

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