Pair production of Higgs bosons at the LHC in gauged 2HDM

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Pair production of Higgs bosons at the Large Hadron Collider (LHC) is known to be important for the determination of the Higgs boson self-coupling and as a probe of new physics beyond the Standard Model (SM), especially the existence of new fundamental scalar bosons. In this paper we study in detail the pair production of Higgs bosons at the LHC in a well-motivated model—the gauged two-Higgs-doublet model—in which the two Higgs doublets are properly embedded into a gauged $SU(2)_H$ and a dark matter candidate emerges naturally due to the gauge symmetry. Besides the deviations of the Higgs couplings from the SM predictions, the existence of new scalars could significantly enhance the production cross section of Higgs boson pairs at the LHC. However, when we take into account the relic density of dark matter and the null results of direct detection experiments, only a moderate enhancement can be obtained. We also comment on the capability of the LHC to distinguish the Higgs pair signal due to a generic 400 GeV scalar resonance in the $\gamma\gamma b\bar{b}$ final state from the SM prediction, assuming that their Higgs pair production cross sections are the same.

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I. INTRODUCTION

The year 2018 marked the 50th anniversary of the Standard Model (SM) of particle physics since its inception in 1967 [1]. The Higgs boson, the long-sought last particle in the SM, was ultimately discovered in 2012 at the Large Hadron Collider (LHC) with a relatively light mass of 125 GeV. Since then many efforts have been made to determine whether the observed Higgs boson is indeed the one predicted by the SM, in which the simple Higgs mechanism is used for spontaneous symmetry breaking, as opposed to other alternatives involving strongly interacting dynamics like composite-Higgs or technicolor models. In particular, all of the measurements related to the Higgs' couplings with the SM gauge bosons have been analyzed in detail and nothing has been detected outside the norm. Recently, six years after its discovery, the decay of the Higgs boson into its dominant mode—a pair of bottom quarks—was finally observed at a significance above 5 standard deviations and also in line with the SM expectation [2,3].

Despite its many triumphs, the SM leaves us with many questions to be answered, such as the origin of flavor, the hierarchy/fine-tuning problem, and so on. In the Higgs

sector, the self-coupling of the Higgs boson and the related issue of the shape of the Higgs potential need to be determined. Moreover, the observations of neutrino oscillations, the relic density of dark matter (DM), matter-antimatter asymmetry, etc. imply that there must be new physics beyond the SM.

Many new models have been proposed in the literature to address the above issues, and one of the simplest proposals is an extension of the scalar sector of the SM. For example, the general two-Higgs-doublet model (2HDM) is a simple extension [4] that only adds one more Higgs doublet to the SM. One particular type of 2HDM is the inert Higgs-doublet model (IHDM) [5–9] in which the neutral component of the second Higgs doublet is a DM candidate. The stability of this DM candidate is ensured by imposing a discrete Z_2 symmetry on the scalar potential of the model. The presence of the dangerous tree-level flavor-changing neutral current in the 2HDM can also be cured by the Z_2 symmetry [10].

Recently, a gauged two-Higgs-doublet model (G2HDM) [11] was proposed. Like the 2HDM, two Higgs doublets H_1 and H_2 are introduced but they can be rotated into each other by a gauge transformation under a new non-Abelian $SU(2)_H$. Thus, they form a doublet $H = (H_1, H_2)^T$ under $SU(2)_H$. The neutral component of H_2 is stable under the protection of $SU(2)_H$ gauge symmetry and hence can be a DM candidate. The local $SU(2)_H$ gauge symmetry also prevents tree-level flavor-changing neutral currents in the Higgs couplings with the SM fermions. We note that previous studies used an additional Abelian $U(1)$ local

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symmetry in the 2HDM to obtain a dark matter candidate [12] and natural conservation laws for flavor-changing neutral currents [13,14]. To make the G2HDM self-consistent, however, more new particles are introduced, including an additional $SU(2)_H$ doublet, an $SU(2)_H$ triplet, and heavy $SU(2)_L$ singlet Dirac fermions. Some phenomenology of the G2HDM at the LHC was explored previously in Refs. [11,15] for Higgs physics and in Ref. [16] for the new gauge bosons. Recently, a detailed study of the theoretical and Higgs phenomenological constraints in the G2HDM was presented in Ref. [17]. In this paper, we focus on Higgs pair production in the G2HDM at the LHC, a well-known process that can play a crucial role in the determination of the Higgs boson self-coupling. A similar study for the case of the 2HDM can be found in Ref. [18].

After electroweak symmetry breaking, the scalar potential of the SM can be written as

$$V_{\text{SM}} = \frac{m_h^2}{2} h^2 + \lambda_{\text{SM}} v h^3 + \frac{\lambda_{\text{SM}}}{4} h^4, \quad (1)$$

where m_h is the Higgs boson mass ~ 125 GeV and $v = 246$ GeV is the Higgs vacuum expectation value (VEV). In the SM, $\lambda_{\text{SM}} = \frac{m_h^2}{2v^2}$ and has a numerical value of 0.13. While the first term in the above Higgs potential (or Higgs boson mass term) has been measured at the LHC, the second and third terms (Higgs boson self-coupling terms) have not yet been measured. These trilinear and quartic self-couplings of the Higgs are key parameters for the reconstruction of the Higgs potential, which can tell us how electroweak symmetry breaking really happens and whether the Higgs sector agrees with the SM. While more precise measurements of single Higgs production as well as other associated production channels at the LHC are important to pin down the detailed properties of Higgs couplings in the SM,¹ Higgs pair production is quite unique in the sense that it can allow us to directly search for the trilinear Higgs self-coupling in Eq. (1). It has been shown that the Higgs trilinear coupling can be determined with about 50% accuracy at the 14 TeV LHC with 3000 fb⁻¹ of data [21,22]. To probe for the quartic self-coupling term in Eq. (1), one would need to study triple Higgs production which might not be accessible at the LHC due to its minuscule cross section.

The production of Higgs pairs in the G2HDM will differ from the SM prediction in a number of ways:

- (1) Modified Yukawa couplings.
- (2) Modified trilinear Higgs self-coupling.

- (3) Presence of new colored particles which can flow inside the triangle and box loops.
- (4) Presence of new heavy scalars which can decay into a pair of 125 GeV Higgs bosons via new trilinear scalar couplings. This has important implications for the resonant Higgs boson pair production cross section.

We will include all of these new features in our analysis of Higgs pair production in the G2HDM at the LHC.

This paper is organized as follows. In Sec. II we first review the setup of the G2HDM with a special focus on the scalar sector, i.e., the symmetry breaking of the scalar potential and the resulting scalar spectra. In Sec. III we review the theoretical and phenomenological constraints imposed on this model that have been studied recently in Ref. [17]. In Sec. IV we discuss the Higgs pair production cross section in the G2HDM and present the numerical results. In Sec. V, we present a detailed Monte Carlo simulation study for the two final states of $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ from double Higgs production. Finally, we conclude our study in Sec. VI.

II. THE MODEL

To make this paper somewhat self-contained, we will briefly review the G2HDM in this section and refer our readers to Refs. [11,17] for more details. The gauge group of the G2HDM is $\mathcal{G}_{\text{G2HDM}} = \mathcal{G}_{\text{SM}} \times SU(2)_H \times U(1)_X$, where $\mathcal{G}_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$ is the SM gauge group. The scalar sector includes not only the two $SU(2)_L$ Higgs doublets H_1, H_2 which form a doublet $H = (H_1, H_2)^T$ under the $SU(2)_H$ gauge group, but also a triplet Δ_H and a doublet Φ_H of this new gauge group. Note that both Δ_H and Φ_H are singlets under $\mathcal{G}_{\text{SM}}$. Furthermore, H and Φ_H are assigned to carry an additional $U(1)_X$ charge.² For the fermion sector, the SM left-handed $SU(2)_L$ doublets Q_L, L_L are singlets under $SU(2)_H$, while the SM right-handed $SU(2)_L$ singlets u_R, d_R, ν_R, e_R ³ are now paired up with new right-handed singlets $u_R^H, d_R^H, \nu_R^H, e_R^H$ to form doublets U_R, D_R, N_R, E_R under $SU(2)_H$. Furthermore, for anomaly cancellations, new heavy left-handed fermions $u_L^H, d_L^H, \nu_L^H, e_L^H$ are needed, which are singlets under both $SU(2)_L$ and $SU(2)_H$ gauge groups. In Table I, we summarize the matter content and their quantum number assignments in the G2HDM.

A. Higgs potential

The most general renormalizable Higgs potential invariant under both $SU(2)_L \times U(1)_Y$ and $SU(2)_H \times U(1)_X$ is given by [17]

¹Actually, single Higgs boson production at the LHC can probe the trilinear Higgs self-coupling indirectly via the electroweak one-loop correction [19,20]. With 3000 fb⁻¹ luminosity, it was shown that the deviation of single Higgs boson production data could reach the 2σ level if the Higgs trilinear coupling is about 9 times larger or about -4 times smaller than its SM value.

²This additional $U(1)_X$ was introduced to simplify the scalar potential and to avoid possible mixings between the SM fermions and new heavy fermions in the G2HDM.

³We also add right-handed neutrinos ν_R s to the SM.

TABLE I. Matter content and their quantum number assignments in the G2HDM.

Matter Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(2)_H$	$U(1)_X$
$H = (H_1 H_2)^T$	1	2	1/2	2	1
Δ_H	1	1	0	3	0
Φ_H	1	1	0	2	1
$Q_L = (u_L d_L)^T$	3	2	1/6	1	0
$U_R = (u_R u_R^H)^T$	3	1	2/3	2	1
$D_R = (d_R^H d_R)^T$	3	1	-1/3	2	-1
u_L^H	3	1	2/3	1	0
d_L^H	3	1	-1/3	1	0
$L_L = (\nu_L e_L)^T$	1	2	-1/2	1	0
$N_R = (\nu_R \nu_R^H)^T$	1	1	0	2	1
$E_R = (e_R^H e_R)^T$	1	1	-1	2	-1
ν_L^H	1	1	0	1	0
e_L^H	1	1	-1	1	0

$$V_T = V(H) + V(\Phi_H) + V(\Delta_H) + V_{\text{mix}}(H, \Delta_H, \Phi_H), \quad (2)$$

where

$$V(H) = \mu_H^2 (H_1^\dagger H_1 + H_2^\dagger H_2) + \lambda_H (H_1^\dagger H_1 + H_2^\dagger H_2)^2 + \lambda'_H (-H_1^\dagger H_1 H_2^\dagger H_2 + H_1^\dagger H_2 H_2^\dagger H_1), \quad (3)$$

$$V(\Phi_H) = \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi (\Phi_H^\dagger \Phi_H)^2, \quad (4)$$

$$V(\Delta_H) = -\mu_\Delta^2 \text{Tr}(\Delta_H^2) + \lambda_\Delta (\text{Tr}(\Delta_H^2))^2, \quad (5)$$

with

$$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix} = \Delta_H^\dagger \quad \text{with} \\ \Delta_m = (\Delta_p)^* \quad \text{and} \quad (\Delta_3)^* = \Delta_3, \quad (6)$$

and the last term

$$V_{\text{mix}}(H, \Delta_H, \Phi_H) \\ = +M_{H\Delta} (H^\dagger \Delta_H H) - M_{\Phi\Delta} (\Phi_H^\dagger \Delta_H \Phi_H) \\ + \lambda_{H\Phi} (H^\dagger H) (\Phi_H^\dagger \Phi_H) + \lambda'_{H\Phi} (H^\dagger \Phi_H) (\Phi_H^\dagger H) \\ + \lambda_{H\Delta} (H^\dagger H) \text{Tr}(\Delta_H^2) + \lambda_{\Phi\Delta} (\Phi_H^\dagger \Phi_H) \text{Tr}(\Delta_H^2). \quad (7)$$

We note that the scalar potential in the G2HDM is CP conserving due to the fact that all terms in $V(H)$, $V(\Phi_H)$, $V(\Delta_H)$, and $V_{\text{mix}}(H, \Delta_H, \Phi_H)$ are Hermitian, implying that all of the coefficients are necessarily real.

B. Spontaneous symmetry breaking and scalar mass spectrum

1. Spontaneous symmetry breaking

To facilitate spontaneous electroweak symmetry breaking, we shift the scalar fields as follows:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i \frac{G^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}, \\ \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi + \phi_2}{\sqrt{2}} + i \frac{G_H^0}{\sqrt{2}} \end{pmatrix}, \quad \Delta_H = \begin{pmatrix} \frac{-v_\Delta + \delta_3}{2} & \frac{1}{\sqrt{2}} \Delta_p \\ \frac{1}{\sqrt{2}} \Delta_m & \frac{v_\Delta - \delta_3}{2} \end{pmatrix}, \quad (8)$$

where v , v_Φ , and v_Δ are the VEVs to be determined by minimization of the potential. The set $\Psi_G \equiv \{G^0, G^+, G_H^0, G_H^p\}$ are Goldstone bosons, while the rest are physical fields. Inserting Eq. (8) into the potential V_T given by Eq. (2) and keeping only those terms involving the VEVs leads us to

$$V_T(v, v_\Delta, v_\Phi) = \frac{1}{4} [\lambda_H v^4 + \lambda_\Phi v_\Phi^4 + \lambda_\Delta v_\Delta^4 \\ + 2(\mu_H^2 v^2 + \mu_\Phi^2 v_\Phi^2 - \mu_\Delta^2 v_\Delta^2) \\ - (M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2) v_\Delta + \lambda_{H\Phi} v^2 v_\Phi^2 \\ + \lambda_{H\Delta} v^2 v_\Delta^2 + \lambda_{\Phi\Delta} v_\Phi^2 v_\Delta^2]. \quad (9)$$

To determine the ground state of the model, we take the derivatives of Eq. (9) with respect to v , v_Φ , and v_Δ and set them to zero. We can then obtain the following equations satisfied by the VEVs for the minimum energy configuration:

$$v \cdot (2\lambda_H v^2 + 2\mu_H^2 - M_{H\Delta} v_\Delta + \lambda_{H\Phi} v_\Phi^2 + \lambda_{H\Delta} v_\Delta^2) = 0, \quad (10)$$

$$v_\Phi \cdot (2\lambda_\Phi v_\Phi^2 + 2\mu_\Phi^2 - M_{\Phi\Delta} v_\Delta + \lambda_{H\Phi} v^2 + \lambda_{\Phi\Delta} v_\Delta^2) = 0, \quad (11)$$

$$4\lambda_\Delta v_\Delta^3 - 4\mu_\Delta^2 v_\Delta - M_{H\Delta} v^2 - M_{\Phi\Delta} v_\Phi^2 \\ + 2v_\Delta (\lambda_{H\Delta} v^2 + \lambda_{\Phi\Delta} v_\Phi^2) = 0. \quad (12)$$

By solving this set of coupled algebraic equations, one can get nontrivial solutions for all of the VEVs (v , v_Φ , and v_Δ) in terms of the fundamental parameters in the potential [17].

2. Scalar mass spectrum

After the electroweak symmetry is broken, we obtain three diagonal blocks in the scalar mass matrix. The first 3×3 block in the basis of $S = \{h, \phi_2, \delta_3\}$ is given by

$$\mathcal{M}_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\Phi} v v_\Phi & \frac{v}{2}(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta) \\ \lambda_{H\Phi} v v_\Phi & 2\lambda_\Phi v_\Phi^2 & \frac{v_\Phi}{2}(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta) \\ \frac{v}{2}(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta) & \frac{v_\Phi}{2}(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta) & \frac{1}{4v_\Delta}(8\lambda_\Delta v_\Delta^3 + M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2) \end{pmatrix}. \quad (13)$$

This matrix can be diagonalized by an orthogonal matrix O^H ,

$$(O^H)^T \cdot \mathcal{M}_H^2 \cdot O^H = \text{Diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2). \quad (14)$$

The lightest eigenvalue m_{h_1} is the mass of h_1 , which is identified as the 125 GeV Higgs boson observed at the LHC, while m_{h_2} and m_{h_3} are the masses of the heavier

Higgses h_2 and h_3 , respectively. These physical Higgs bosons h_i ($i = 1, 2, 3$) are a mixture of the three components of S : $h_i = O_{ji}^H S_j$. Thus, the SM-like Higgs boson in this model is a linear combination of the neutral components of the two $SU(2)$ doublets H_1 and Φ_H and the real component of the $SU(2)_H$ triplet Δ_H .

The second block is also 3×3 . In the basis of $G = \{G_H^p, H_2^{0*}, \Delta_p\}$, it is given by

$$\mathcal{M}_D^2 = \begin{pmatrix} M_{\Phi\Delta} v_\Delta + \frac{1}{2}\lambda'_{H\Phi} v^2 & \frac{1}{2}\lambda'_{H\Phi} v v_\Phi & -\frac{1}{2}M_{\Phi\Delta} v_\Phi \\ \frac{1}{2}\lambda'_{H\Phi} v v_\Phi & M_{H\Delta} v_\Delta + \frac{1}{2}\lambda'_{H\Phi} v_\Phi^2 & \frac{1}{2}M_{H\Delta} v \\ -\frac{1}{2}M_{\Phi\Delta} v_\Phi & \frac{1}{2}M_{H\Delta} v & \frac{1}{4v_\Delta}(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2) \end{pmatrix}. \quad (15)$$

This matrix can also be diagonalized by an orthogonal matrix O^D ,

$$(O^D)^T \cdot \mathcal{M}_D^2 \cdot O^D = \text{Diag}(m_{\tilde{G}^p}^2, m_D^2, m_{\tilde{\Delta}}^2). \quad (16)$$

One eigenvalue of Eq. (15) is zero (i.e., $m_{\tilde{G}^p} = 0$) and identified as the unphysical Goldstone boson $\tilde{G}^p$. m_D and $m_{\tilde{\Delta}}$ ($m_D < m_{\tilde{\Delta}}$) are the masses of the two physical fields D and $\tilde{\Delta}$, respectively. D could be a DM candidate in the G2HDM.

The final block is a 4×4 diagonal matrix with the following entries:

$$m_{H^\pm}^2 = -\frac{1}{2}\lambda'_H v^2 + \frac{1}{2}\lambda'_{H\Phi} v_\Phi^2 + M_{H\Delta} v_\Delta, \quad (17)$$

$$m_{G^\pm}^2 = m_{G^0}^2 = m_{G_H^0}^2 = 0, \quad (18)$$

where $m_{H^\pm}$ is the mass of the physical charged Higgs $H^\pm$, and $m_{G^\pm}$, m_{G^0} , and $m_{G_H^0}$ are the masses of the four Goldstone boson fields $G^\pm$, G^0 , and G_H^0 , respectively. Note that we have used the minimization conditions (10), (11), and (12) to simplify various matrix elements of the above mass matrices. The six Goldstone particles $G^\pm$, G^0 , G_H^0 , and $\tilde{G}^{p,m}$ will be absorbed by the longitudinal components of the massive gauge bosons $W^\pm$, Z , Z' , and $W'^{(p,m)}$ after electroweak symmetry breaking. For details about the gauge boson masses, we refer our readers to Refs. [11,17].

III. CONSTRAINTS

Before embarking on our numerical study, we summarize in this section the allowed parameter space of the scalar sector of the model.

The constraints were obtained in Ref. [17], through the requirements of vacuum stability (VS), perturbative unitarity (PU), and Higgs physics (HP), the latter of which includes the Higgs boson mass of 125 GeV and signal strengths of Higgs boson decays into a diphoton and $\tau^+\tau^-$ measured at the LHC. It should be noted that, in the numerical study of Ref. [17], the two parameters $M_{H\Delta}$ and $M_{\Phi\Delta}$ in V_{mix} were set to vary in the range $[-1, 1]$ TeV and $v_\Delta \in [0.5, 20]$ TeV, while v and v_Φ were fixed to be 246 GeV and 10 TeV, respectively.

We show a summary of the allowed regions of parameter space in Fig. 1 obtained in Ref. [17]. The upper red triangular block corresponds to (VS + PU) constraints, while the lower magenta triangular block corresponds to the (VS + PU + HP) constraints. The diagonal panels indicate the allowed ranges of the eight couplings $\lambda_{H,\Phi,\Delta}$, λ'_H , and $\lambda_{H\Phi,H\Delta,\Phi\Delta}$, $\lambda'_{H\Phi}$ under the combined constraints of (VS + PU + HP). It turns out that among the eight λ parameters, only two of them (λ_H and $\lambda_{H\Phi}$) are significantly constrained by (VS + PU + HP). In particular, λ_H (the Higgs self-coupling in the G2HDM) no longer has the fixed SM value of 0.13 but rather is allowed to vary in the range (0.13, 4.00). We note that some of the parameters such as $M_{H\Delta}$, $M_{\Phi\Delta}$, and the VEVs are only constrained by HP, and not by (VS + PU).

We should also emphasize that the VS and PU constraints that we consider in this work are tree-level results. Higher-order corrections like renormalization group

FIG. 1. Summary of the parameter space allowed by the theoretical and phenomenological constraints. The red regions show the results from the theoretical constraints (VS + PU). The magenta regions are constrained by Higgs physics as well as the theoretical constraints (VS + PU + HP). Diagonal blocks indicate the allowed ranges for the scalar couplings from (VS+PU+HP) constraints. This figure is taken from Ref. [17].

evolution effects in the quartic scalar couplings are important. However, they are beyond the scope of this work and we leave them to future studies.

IV. HIGGS BOSON PAIR PRODUCTION IN THE G2HDM AT THE LHC

In the SM, a pair of Higgs bosons can be produced via two channels at the LHC: a triangle loop diagram with a Higgs boson as the mediator, and a box loop diagram.

However, the small Higgs boson pair production rate, which is roughly a thousand times smaller than single Higgs boson production at the 14 TeV LHC [23–33], makes the measurement very challenging. We quote here a recent combined observed (expected) limit by ATLAS [34] on the nonresonant Higgs boson pair cross section of 0.22 pb (0.35 pb) at the 95% confidence level, which corresponds to 6.7 (10.4) times the predicted SM cross section. Clearly, these limits are rather loose and not very useful for deducing meaningful constraints in any model.

FIG. 2. Box (a) and triangle (b) Feynman diagrams for the production of a pair of 125 GeV Higgs bosons in the G2HDM. Note that $q_i^H = u^H, d^H, c^H, s^H, t^H, b^H$ and $h_i = h_1, h_2, h_3$.

Nevertheless, in the G2HDM the Higgs boson pair production rate can be significantly enhanced since more diagrams contribute, including the new heavy quarks q^H in the loop and heavy scalars h_2, h_3 as mediators. In addition, the 125 GeV SM-like Higgs boson h_1 is a mixture of h, ϕ_2 , and δ_3 , and this mixing effect will modify both the quark Yukawa couplings and the trilinear Higgs self-coupling. The Feynman diagrams for the production of a pair of h_1 's in the G2HDM are shown in Fig. 2. In the SM the top-quark loop contribution is dominant, while the bottom-quark

contribution is negative and negligible. The contributions between the box and triangle diagrams also interfere destructively in the SM. The relevant couplings for the production of a pair of h_1 's in the G2HDM are as follows:

$$g_{qqh_i} = O_{1i}^H \frac{m_q}{v}, \quad (19)$$

$$g_{q^H q^H h_i} = O_{2i}^H \frac{m_{q^H}}{v_\Phi}, \quad (20)$$

$$g_{h_1 h_1 h_1} = 6(\lambda_H v (O_{11}^H)^3 + \lambda_\Phi v_\Phi (O_{21}^H)^3 - \lambda_\Delta v_\Delta (O_{31}^H)^3) + \frac{3}{2}((M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta)(O_{11}^H)^2 O_{31}^H + (M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta)(O_{21}^H)^2 O_{31}^H) + 3(\lambda_{H\Phi})(v O_{11}^H (O_{21}^H)^2 + v_\Phi (O_{11}^H)^2 O_{21}^H) + 3(\lambda_{H\Delta} v O_{11}^H (O_{31}^H)^2 + \lambda_{\Phi\Delta} v_\Phi O_{21}^H (O_{31}^H)^2), \quad (21)$$

$$g_{h_2 h_1 h_1} = 6(\lambda_H v (O_{11}^H)^2 O_{12}^H + \lambda_\Phi v_\Phi (O_{21}^H)^2 O_{22}^H - \lambda_\Delta v_\Delta (O_{31}^H)^2 O_{32}^H) + \frac{1}{2} M_{H\Delta} O_{11}^H (O_{11}^H O_{32}^H + 2 O_{12}^H O_{31}^H) + \frac{1}{2} M_{\Phi\Delta} O_{21}^H (O_{21}^H O_{32}^H + 2 O_{22}^H O_{31}^H) + \lambda_{H\Delta} [v((O_{31}^H)^2 O_{12}^H + 2 O_{11}^H O_{31}^H O_{32}^H) - v_\Delta((O_{11}^H)^2 O_{32}^H + 2 O_{11}^H O_{12}^H O_{31}^H)] + \lambda_{\Phi\Delta} [v_\Phi((O_{31}^H)^2 O_{22}^H + 2 O_{21}^H O_{31}^H O_{32}^H) - v_\Delta((O_{21}^H)^2 O_{32}^H + 2 O_{21}^H O_{22}^H O_{31}^H)] + \lambda_{H\Phi} [v((O_{21}^H)^2 O_{12}^H + 2 O_{11}^H O_{21}^H O_{22}^H) + v_\Phi(O_{11}^H (O_{11}^H O_{22}^H + 2 O_{12}^H O_{21}^H))], \quad (22)$$

where g_{qqh_i} , $g_{q^H q^H h_i}$, $g_{h_1 h_1 h_1}$, and $g_{h_2 h_1 h_1}$ are the SM quark Yukawa couplings, new heavy quark Yukawa couplings, trilinear h_1 self-coupling, and coupling between the heavier scalar h_2 and two h_1 's, respectively. One can see that the SM quark Yukawa couplings g_{qqh_1} are now smaller by a factor of the mixing element O_{11}^H as compared to the SM values. Since the modifications of the SM Yukawa couplings are always suppressed by the same factor of O_{11}^H for the top and bottom quarks, the role of the bottom quark is never significant for double h_1 production in the G2HDM. Furthermore, the scalar self-couplings $g_{h_1 h_1 h_1}$ and $g_{h_2 h_1 h_1}$ in the G2HDM are comprised of many new parameters which can affect the double h_1 production. In what follows, we will ignore the heaviest scalar mediator h_3 in our analysis due to its negligible contribution to the double h_1 production cross section from Fig. 2(b).

The differential cross section for double h_1 production from gluon fusion in the G2HDM can be straightforwardly translated from the SM formulas [33],

$$\frac{d\hat{\sigma}(gg \rightarrow h_1 h_1)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \times \left\{ \left| \sum_{f=q, q^H} \sum_{i=1}^2 \kappa_{ffh_i} g_{h_i h_1 h_1} v D_{h_i}(\hat{s}) F_\Delta(\hat{s}, \tau_{fi}) + \sum_{f=q, q^H} \kappa_{ffh_1}^2 F_\square(\hat{s}, \tau_{fi}) \right|^2 + \left| \sum_{f=q, q^H} \kappa_{ffh_1}^2 G_\square(\hat{s}, \tau_{fi}) \right|^2 \right\}, \quad (23)$$

where G_F and α_s are the Fermi constant and strong coupling constant, respectively,

$$\kappa_{qqh_i} = O_{1i}^H, \quad (24)$$

$$\kappa_{q^H q^H h_i} = O_{2i}^H \frac{v}{v_\Phi}, \quad (25)$$

$$D_{h_i}(\hat{s}) = \frac{1}{(\hat{s} - m_{h_i}^2 + im_{h_i}\Gamma_{h_i})}, \quad (26)$$

and $F_\Delta(\hat{s}, \tau_{fi})$, $F_\square(\hat{s}, \tau_{fi})$, $G_\square(\hat{s}, \tau_{fi})$ with $\tau_{fi} = 4m_f^2/m_{h_i}^2$ are form factors that can be found in Appendix A.1 of Ref. [33]. For later purposes, we also define $\lambda_{h_1 h_1 h_1} = g_{h_1 h_1 h_1}/g_{hhh}^{\text{SM}}$ where $g_{hhh}^{\text{SM}} = 6\lambda_{\text{SM}}v = 192 \text{ GeV}$.

In this section we present the numerical analysis for the double h_1 production cross section in the G2HDM at the LHC and compare the results with SM predictions. Monte Carlo studies of the two final states $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ from the h_1 pair decay will be presented in the next section.

Before we proceed, let us present the setup of the model parameter space used in our analysis. We adopt similar procedures as in the previous work [17]. For the eight λ parameters $\lambda_{H,\Phi,\Delta}$, λ'_H , $\lambda_{H\Phi,H\Delta,\Phi\Delta}$, $\lambda'_{H\Phi}$, we impose their allowed ranges from the theoretical constraints of (VS + PU) as obtained in Ref. [17]. Recall that only these quartic couplings in the scalar potential are relevant for the theoretical constraints of (VS + PU). For the HP constraints, the other four parameters v_Δ , v_Φ , $M_{H\Delta}$, and $M_{\Phi\Delta}$ in the scalar potential are also involved, and they vary in the following ranges:

$$0.1 \text{ GeV} < v_\Delta < 4 \text{ TeV}, \quad (27)$$

$$30 \text{ TeV} < v_\Phi < 100 \text{ TeV}, \quad (28)$$

$$-3 \text{ TeV} < M_{H\Delta} < 3 \text{ TeV}, \quad (29)$$

$$0 < M_{\Phi\Delta} < 15 \text{ GeV}. \quad (30)$$

The SM VEV v is fixed at 246 GeV. First, we scan all of the parameters in the ranges defined above and require them to pass all of the (VS + PU + HP) constraints presented in Ref. [17]. The constraints from direct Z' resonance searches using the latest ATLAS and CMS 13 TeV results [35–38] have been taken into account in our scan. Furthermore, the dark matter candidate D is set to be heavier than half of the Higgs boson mass so that the invisible mode of $h_1 \rightarrow DD^*$ is not kinematically allowed. For simplicity, the masses of the new heavy fermions f_i^H are assumed to be degenerate and set to 3 TeV. Finally, we focus on the situation in which $m_{h_2} > 2m_{h_1}$ to allow h_2 decays on shell into $h_1 h_1$.

In Fig. 3, we show the scatter plots of the ratio of the production cross sections for a pair of 125 GeV Higgs bosons between the G2HDM and SM in the planes $(\lambda_{h_1 h_1 h_1}, \text{BR}(h_2 \rightarrow h_1 h_1))$ [Fig. 3(a)], $(\lambda_{h_1 h_1 h_1}, m_{h_2})$ [Fig. 3(b)],

$(\lambda_{h_1 h_1 h_1}, \kappa_{qqh_1})$ [Fig. 3(c)], and $(\lambda_{h_1 h_1 h_1}, \kappa_{qqh_2})$ [Fig. 3(d)]. The color palette on the right of each of the plots in Fig. 3 indicates the signal strength of the double h_1 Higgs boson production. From these four plots in Fig. 3, one can see that the trilinear self-coupling of the 125 GeV Higgs boson $\lambda_{h_1 h_1 h_1}$ in the G2HDM can significantly deviate from its SM value. Even its sign can become negative. From Fig. 3(a), one observes that the branching ratio of the heavier scalar h_2 decaying into a pair of h_1 's can vary from 0 up to 100%. As expected, as $|\lambda_{h_1 h_1 h_1}|$ and $\text{BR}(h_2 \rightarrow h_1 h_1)$ increase, the triangle diagram becomes the dominant channel and enhances the production cross section. Note that when $\lambda_{h_1 h_1 h_1}$ becomes negative, there is constructive interference between the box and triangle Feynman diagrams in Fig. 2, whereas in the SM these two diagrams interfere destructively. However, when one of the channels (either the box or triangle Feynman diagram) becomes the dominant contribution to the total production cross section, the interference effect is no longer significant. It is also shown in Fig. 3(b) that for a heavier h_2 mass the cross section of double h_1 production will be much smaller. This is also the reason why one can neglect the contribution from the mediator h_3 since it is much heavier than h_2 . Furthermore, due to the constraints from Higgs physics, the absolute values of the Yukawa couplings of SM quarks with h_1 cannot deviate too much from their SM values, which is demonstrated in Fig. 3(c), while Fig. 3(d) shows that the Yukawa couplings between the SM quark and h_2 could be small due to the smallness of the mixing between the $SU(2)_L$ doublet scalar H and $SU(2)_H$ doublet scalar Φ_H , encapsulated by the matrix element O_{12}^H . The contributions from the new heavy quarks q^H in the G2HDM are found to be small because the Yukawa couplings $\kappa_{q^H q^H h_i}$ in Eq. (25) are scaled by the small VEV ratio v/v_Φ .

Since a dark matter candidate exists in the G2HDM, we consider further the dark matter constraints from cosmological observations and direct search experiments. We use MICROMEAS 5.0 [39] to calculate the relic density of the DM candidate and its elastic scattering cross sections with the nucleon. In Fig. 4, we present the scatter plots for the ratio of the production cross sections $\sigma_{gg \rightarrow h_1 h_1}/\sigma_{\text{SM}}$ for a pair of 125 GeV Higgs bosons between the G2HDM and SM in the planes of DM mass m_D versus its relic density Ωh^2 [Fig. 4(a)] and versus the spin-independent cross section of DM and the nucleon σ_{SI}^n [Fig. 4(b)]. The lime (yellow) band corresponds to the 1σ (3σ) range of Planck's DM relic density measurement [40]. The orange and black lines represent the upper limits on the spin-independent cross section of DM and the nucleon from the PandaX-II experiment [41] and XENON1T [42], respectively. Imposing the mass of the dark matter candidate D to be the lightest among $\tilde{\Delta}$, $W^{(p,m)}$, $H^\pm$, and the new heavy fermions f_i^H means that m_D must be less than $\sim 2.7 \text{ TeV}$. In the region $m_D > 500 \text{ GeV}$, there are correlations between

FIG. 3. Scatter plots of relevant parameters for Higgs boson pair production without the experimental constraints from DM relic density and direct searches. The color palette indicates the ratio of double Higgs boson production cross sections between the G2HDM and SM. Note that $\lambda_{h_1 h_1 h_1} = g_{h_1 h_1 h_1} / g_{hhh}^{SM}$ with $g_{hhh}^{SM} = 6\lambda_{SM}v$, $\kappa_{qqh_1} = q_{qqh_1} / q_{qqh}^{SM}$, and $\kappa_{qqh_2} = q_{qqh_2} / q_{qqh}^{SM}$ with $q_{qqh}^{SM} = m_q / v$.

the Higgs boson pair production cross section and DM relic density as well as the eDM-nucleon cross section. In particular, the cross section of gluon-gluon fusion to double h_1 tends to be larger when the DM relic density becomes smaller or the DM-nucleon cross section becomes larger. The first correlation, shown in Fig. 4(a), is due to the fact that $|\lambda_{h_1 h_1 h_1}|$ and $BR(h_2 \rightarrow h_1 h_1)$ can control not only Higgs boson pair production at the LHC but also the annihilation cross section of DM into Higgs boson pairs for the relic density calculation. Indeed, when they both become bigger, the DM annihilation process will be dominated by the $DD^* \rightarrow h_i \rightarrow h_1 h_1$ channel, implying that the DM annihilation cross section becomes larger or the DM relic density becomes smaller. The second correlation, shown in Fig. 4(b), is due to the fact that the DM-nucleon cross section receives about half of its

contributions from the one-loop heavy quarks (mainly the top quark) in the triangle diagram which also appear in the double Higgs boson production process.

The DM relic density and direct searches put stringent constraints on the parameter space of the G2HDM. As shown in Fig. 4(a), Planck's relic density measurements constrain the parameter space in a small 3σ band, while from Fig. 4(b) one can also see that the DM direct search constraints cut off almost all of the parameter space which significantly enhances the cross section of double Higgs boson production. To be more specific, when both the relic density and direct search constraints are imposed, only about 2% of the data points survive.

As in Fig. 3, we show in Fig. 5 the scatter plots of the relevant parameters for Higgs boson pair production after taking into account the constraints from DM relic density

FIG. 4. Scatter plots for the ratio of the production cross sections for a pair of 125 GeV Higgs bosons between the G2HDM and SM in the planes of DM mass versus its relic density (a) and versus the spin-independent cross section of DM and the nucleon (b). The lime (yellow) band corresponds to the 1σ (3σ) range of Planck's DM relic density measurement [40]. The orange and black lines represent the upper limits on the spin-independent cross section of DM and the nucleon from the PandaX-II experiment [41] and XENON1T [42], respectively.

and direct searches. The allowed points in the parameter space are selected within 3σ of Planck's DM relic density measurement [40] and below the upper limits of the DM direct detection searches from PandaX-II [41] and XENON1T [42]. Under these combined constraints of (VS + PU + HP + DM), the parameter space of the model is further reduced. For example, we now have that $-1 \leq \lambda_{h_1 h_1 h_1} \leq 1.3$ and $\text{BR}(h_2 \rightarrow h_1 h_1)$ is less than about 80%. The negative value of $\lambda_{h_1 h_1 h_1}$ provides an enhancement of the production cross section because constructive interference occurs between the box and triangle diagrams. Overall, the production cross section of h_1 pairs is about 1 order of magnitude lower compared to the result before imposing the DM constraints.

V. MONTE CARLO SIMULATIONS

To proceed with our analysis, we pick seven benchmark points from the final allowed parameter space satisfying the (VS + PU + HP + DM) constraints, in which the mass of the heavier scalar h_2 varies from 300 to 900 GeV in increments of 100 GeV, and label these benchmark points as A, B, C, D, E, F, and G respectively. In Table II, we show the fundamental parameters of the scalar potential, derived couplings, mass spectra of the scalars, and the signal strength for Higgs boson pair production at each benchmark point. Benchmark point A allows for a large branching ratio of $h_2 \rightarrow h_1 h_1$, which will allow us to study the enhancement effects of a heavy scalar resonance on the production cross section (see Table III), while for benchmark point D we have negative values for $\lambda_{h_1 h_1 h_1}$ which can lead to constructive interference between the box and

triangle diagrams. For benchmark points E, F, and G, the production cross sections are about twice the SM value. One can see that both the magnitudes and signs of the Yukawa couplings between SM quarks and the h_1 Higgs boson are close to the SM values for all benchmark points except benchmark point D, which has the opposite sign. In Table III, we show the branching ratios of h_2 decays into all two-body final states for our benchmark points. We observe that the heavy scalar h_2 mainly decays into the SM-like Higgs boson h_1 pair, W/Z boson pairs, and to a lesser extent a top-quark pair. The branching ratio for h_2 decaying into a bottom quark pair is vanishingly small.

In order to perform detailed simulations at the LHC, we first implement the G2HDM model using FEYNRULES [43] and pass the Universal Feynrules Output model files to MADGRAPH5 AMC@NLO [44] to generate the h_1 pair production events to next-to-leading order in QCD in the heavy top-quark mass limit. The Higgs boson decay is done with MADSPIN [45], and we focus on two decay modes: $h_1 \rightarrow b\bar{b}$ and $h_1 \rightarrow \gamma\gamma$. Finally, PYTHIA8 [46] is used for parton showering and hadronization, while DELPHES3 [47] (with the ATLAS setting) is used as the fast detector simulation.

In the next two subsections, we concentrate on the $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ final states. According to the current Higgs boson pair production searches at the LHC, the $\gamma\gamma b\bar{b}$ final-state channel is a good search channel for the lower-mass regime of the heavy scalar mediator [48,49], while the $b\bar{b}b\bar{b}$ search channel has better sensitivity for the heavier-mass regime of the heavy scalar mediator [50,51]. Thus, we use our benchmark points A, B, C, and D to study the $\gamma\gamma b\bar{b}$ final-state channel, while the benchmark points E, F, and G are used for the $b\bar{b}b\bar{b}$ final-state channel.

FIG. 5. Same as Fig. 3 but after taking into account the experimental constraints from Planck’s DM relic density measurements [40] and direct searches from the ePandaX-II experiment [41] and XENON1T [42].

A. The $\gamma\gamma b\bar{b}$ final-state channel

In this section, we investigate various kinematic distributions of the $\gamma\gamma b\bar{b}$ final state. We select the four benchmark points A, B, C, and D at which the mass of the heavy scalar h_2 is 300, 400, 500, and 600 GeV respectively, to study this channel. Here, we follow the cuts used in the ATLAS experiment for the $\gamma\gamma b\bar{b}$ channel analysis [48], which we summarize as follows:

- (1) First, we isolate the two photons with opening angle $\Delta R = 0.2$.
- (2) Next, using the anti- k_T algorithm jets are reconstructed with cone radius $R = 0.4$ and required to have a pseudorapidity $|\eta| < 2.5$ and transverse momentum $p_T > 25$ GeV.

- (3) We require at least two photons and exactly two jets with b -tagging efficiency set at the default value of MADGRAPH5.
- (4) The leading b jet must have $p_T > 55$ GeV, while the subleading b jet is required to have $p_T > 35$ GeV.
- (5) Furthermore, the diphoton invariant mass $m_{\gamma\gamma}$ is required to lie between 105 and 160 GeV and the b -jet pair invariant mass $m_{b\bar{b}}$ is required to lie between 95 and 135 GeV.

In Fig. 6, we present various normalized kinematic distributions of the $\gamma\gamma b\bar{b}$ channel for (a) the invariant mass of $\gamma\gamma b\bar{b}$, (b) the opening angle $\Delta R_{\gamma\gamma}$ of the two photons, and (c) the opening angle ΔR_{bb} of the two b jets, in both the SM and G2HDM with $m_{h_2} = 300, 400, 500$, and 600 GeV at

TABLE II. Seven benchmark points allowed by the combined (VS + PU + HP + DM) constraints.

Benchmark point	A	B	C	D	E	F	G
m_{h_2} (GeV)	300	400	500	600	700	800	900
m_{h_3} (TeV)	141.35	68.23	93.59	87.86	88.35	69.67	92.71
m_D (GeV)	1051.7	814.6	905.4	487.2	883.3	880.4	767.1
$m_{\tilde{\Delta}}$ (TeV)	71.20	84.42	48.26	109.34	44.38	65.18	72.86
$m_{H^\pm}$ (TeV)	71.21	84.41	48.26	109.34	44.39	65.18	72.86
λ_H	0.36	1.24	0.53	1.15	0.66	0.99	1.72
λ_Φ	3.67	1.45	2.03	0.89	1.44	1.57	2.57
λ_Δ	0.22	0.13	1.60	0.14	0.67	0.25	0.38
λ'_H	-19.8	-2.47	-3.77	-3.51	-17.80	-3.65	-2.75
$\lambda_{H\Phi}$	-1.22	-2.24	-0.31	-1.45	0.003	-0.38	-1.85
$\lambda_{H\Delta}$	0.054	-0.36	-0.17	-0.15	-0.316	0.15	-0.99
$\lambda_{\Phi\Delta}$	2.12	0.95	3.63	0.08	2.08	1.44	1.97
$\lambda'_{H\Phi}$	3.73	9.73	2.16	5.52	1.46	5.49	6.35
v_Δ (TeV)	2.41	3.08	3.27	0.43	1.52	1.21	2.85
v_Φ (TeV)	52.11	40.05	46.39	65.79	51.91	39.32	40.88
$M_{H\Delta}$ (GeV)	2209	2776	1465	897	-2293	2656	956.7
$M_{\Phi\Delta}$ (GeV)	3.85	4.88	4.85	0.08	1.80	2.31	3.90
$\lambda_{h_1 h_1 h_1}$	0.31	0.71	0.55	-0.84	0.84	0.75	0.58
$\lambda_{h_2 h_1 h_1}$	-1.90	1.65	2.61	2.46	-3.32	5.04	6.54
κ_{qqh_1}	0.88	0.89	0.90	-0.92	0.93	0.91	0.89
κ_{qqh_2}	-0.47	0.46	0.44	0.40	-0.37	0.41	0.44
$\kappa_{q^H q^H h_1}$	-2.6×10^{-5}	-4.6×10^{-5}	-1.4×10^{-4}	-1×10^{-5}	3.7×10^{-5}	-3.1×10^{-5}	5.8×10^{-5}
$\kappa_{q^H q^H h_2}$	-5.7×10^{-5}	1.5×10^{-4}	3.0×10^{-4}	5.6×10^{-6}	9.2×10^{-5}	8.2×10^{-5}	1.5×10^{-4}
$\frac{\sigma(gg \rightarrow h_1 h_1)}{\sigma_{\text{SM}}}$	32.4	16.1	7.9	3.3	2.1	2.1	2.0

the LHC with $\sqrt{s} = 13$ TeV. In Fig. 6(a), it is obvious that the normalized invariant mass distributions for $\gamma\gamma b\bar{b}$, divided by the bin size $1200/120 = 10$ GeV, peak at the corresponding mass of the heavy scalar h_2 , while the peak around 400 GeV is for the SM. We will discuss this SM peak further in the next subsection. The peaks decrease as the mass of h_2 increases, due to the fact that when the mass of h_2 increases the nonresonant process becomes more relevant to the total production cross section. One can also observe that the normalized distributions of the opening angles of the two photons and of the pair of b jets divided by the bin size $2\pi/100$ in Figs. 6(b) and 6(c), respectively, become narrower when the mass of h_2 increases. This is

TABLE III. Branching ratios of the two-body decays of h_2 for the seven benchmark points.

Benchmark point	A	B	C	D	E	F	G
$h_2 \rightarrow h_1 h_1$	0.564	0.261	0.245	0.167	0.175	0.198	0.181
$h_2 \rightarrow W^+ W^-$	0.301	0.454	0.420	0.465	0.471	0.469	0.489
$h_2 \rightarrow ZZ$	0.134	0.211	0.201	0.224	0.230	0.230	0.241
$h_2 \rightarrow t\bar{t}$	0	0.073	0.133	0.143	0.122	0.102	0.088
$h_2 \rightarrow b\bar{b}$	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0

expected because when the parent decaying particle h_2 becomes heavier, the two daughter h_1 Higgs bosons will be more boosted, implying that the opening angles $\Delta R_{\gamma\gamma}$ and ΔR_{bb} would be smaller.

As mentioned above, the invariant mass distribution of the Higgs boson pair peaks at about 400 GeV in the case of the SM, even though there is no new resonance. A natural question arises: could we tell whether there exists a new scalar resonance S if the observed total cross section does not deviate much from the SM prediction? To answer this question, we will temporarily leave the G2HDM and do some shape comparisons in a hypothetical scenario defined below.

In Figs. 7(a) and 7(b), we perform a standard deviation χ^2 test for the event distributions in $M_{\gamma\gamma b\bar{b}}$ and $\Delta R_{\gamma\gamma}$, respectively, at the high-luminosity LHC for the SM and a generic scalar resonance S with a mass of 400 GeV and a total production cross section that matches the SM prediction. The error is naively taken as the square root of the pseudodata bin content. It turns out that at the 13 TeV LHC with $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$, we cannot tell the difference between a new physics signal of the heavy scalar resonance with a mass of 400 GeV and the SM predictions in Higgs boson pair production. In particular, the deviations from the

FIG. 6. Normalized kinematic distributions of the $\gamma\gamma b\bar{b}$ channel for (a) the invariant mass $M_{\gamma\gamma b\bar{b}}$ of $\gamma\gamma b\bar{b}$, (b) the opening angle $\Delta R_{\gamma\gamma}$ of the two photons, and (c) the opening angle $\Delta R_{b\bar{b}}$ of the two b jets, in both the SM and G2HDM with $m_{h_2} = 300, 400, 500$, and 600 GeV at the $\sqrt{s} = 13$ TeV LHC.

SM predictions are about 1.31σ in the case of the $M_{\gamma\gamma b\bar{b}}$ kinematic distribution and only 0.03σ in the case of the $\Delta R_{\gamma\gamma}$ distribution.

However, the situation can be improved at a future hadron collider. For illustration, we present the corresponding integrated luminosity versus standard deviation χ^2 test for the generic 400 GeV scalar resonance and the SM one at a 100 TeV LHC. The result shown in Fig. 8 indicates that with an integrated luminosity $\mathcal{L}_{\text{int}} \sim 500 \text{ fb}^{-1}$ at a 100 TeV LHC, the signal for the 400 GeV scalar resonance can be distinguished from the SM at the 3σ level.

B. The $b\bar{b}b\bar{b}$ final-state channel

We now return to the G2HDM and select the benchmark points E, F, and G at which $m_{h_2} = 700, 800$, and 900 GeV, respectively, to study the kinematic distributions of the $b\bar{b}b\bar{b}$ final-state channel. In this case, we follow the event selections used in the ATLAS resolved analysis for the $b\bar{b}b\bar{b}$ final-state channel [50], which we summarize below:

- (1) To be specific, the events are required to contain at least four b jets with $p_T > 30$ GeV and $|\eta| < 2.5$.

FIG. 7. Standard deviation χ^2 test for pair production of the SM Higgs via a generic 400 GeV scalar resonance S versus the SM prediction at the 13 TeV LHC with an integrated luminosity of $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$.

- (2) Furthermore, we pair up these four b jets to reconstruct two 125 GeV Higgs boson candidates and then impose additional mass-dependent cuts for these two Higgs boson candidates as follows:

$$\left. \begin{aligned} \frac{360}{m_{4j}/\text{GeV}} - 0.5 < \Delta R_{jj}^{\text{lead}} < \frac{653}{m_{4j}/\text{GeV}} + 0.475 \\ \frac{235}{m_{4j}/\text{GeV}} < \Delta R_{jj}^{\text{subl}} < \frac{875}{m_{4j}/\text{GeV}} + 0.35 \end{aligned} \right\} \text{ if } m_{4j} < 1250 \text{ GeV},$$

$$\left. \begin{aligned} 0 < \Delta R_{jj}^{\text{lead}} < 1 \\ 0 < \Delta R_{jj}^{\text{subl}} < 1 \end{aligned} \right\} \text{ if } m_{4j} > 1250 \text{ GeV},$$

FIG. 8. The integrated luminosity versus standard deviation χ^2 test for pair production of the SM Higgs via a generic 400 GeV Higgs resonance S versus the SM prediction at the 100 TeV LHC. $\sigma = \sigma_{\text{SM}}$ means that we set the cross section for the process $gg \rightarrow S(400) \rightarrow h_1 h_1 \rightarrow \gamma\gamma\bar{b}b$ via the generic 400 GeV scalar resonance to be the same as the SM prediction.

where $\Delta R_{jj}^{\text{lead/subl}}$ is the opening angle of the two jets that the leading/subleading Higgs boson candidate decays into. Here, the leading Higgs boson candidate refers to the reconstructed Higgs boson that has the larger scalar sum of jet p_T .

- (3) Then, an algorithm is applied to select the best pairing of b jets into two Higgs boson candidates as follows. A distance D_{h_1, h_1} [50] is defined as

$$D_{h_1, h_1} = \sqrt{(m_{2j}^{\text{lead}})^2 + (m_{2j}^{\text{subl}})^2} \times \left| \sin \left(\tan^{-1} \left(\frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}} \right) - \tan^{-1} \left(\frac{115}{120} \right) \right) \right|, \quad (31)$$

which is the distance of the reconstructed pairing's point $(m_{2j}^{\text{lead}}, m_{2j}^{\text{subl}})$ to the line connecting the two points (0 GeV, 0 GeV) and (120 GeV, 115 GeV) in

FIG. 9. Normalized kinematic distributions of the $b\bar{b}b\bar{b}$ channel for (a) the invariant mass M_{4b} of $b\bar{b}b\bar{b}$, (b) the opening angle ΔR_{bb}^{lead} of the two b jets associated with the leading Higgs boson candidate, and (c) the opening angle ΔR_{bb}^{subl} of the two b jets associated with the subleading Higgs boson candidate with $m_{h_2} = 700, 800$, and 900 GeV for the ATLAS detectors at $\sqrt{s} = 13$ TeV. The results for the SM are also shown for comparison.

the $m_{2j}^{lead} - m_{2j}^{subl}$ plane. Here, $m_{2j}^{lead/subl}$ is the mass of the leading/subleading Higgs boson candidate and the values of 120 and 115 GeV are basically the centers of the signal regions for m_{2j}^{lead} and m_{2j}^{subl} , respectively. Among the Higgs boson candidates, the pair that has the minimum distance D_{h_1, h_1} is defined to be the two Higgs bosons.

- (4) In addition, the two Higgs boson candidates are required to have transverse momenta p_T^{lead} and p_T^{subl} ,

opening angle $\Delta R(h_1, h_1)$, and pseudorapidity difference $|\Delta\eta_{h_1 h_1}|$ that satisfy the following mass-dependent cuts:

$$\begin{aligned}
 p_T^{lead} &> 0.5m_{4j} - 90 \text{ GeV}, \\
 p_T^{subl} &> 0.33m_{4j} - 70 \text{ GeV}, \\
 \Delta R(h_1, h_1) &> 1.5,
 \end{aligned}$$

and

$$|\Delta\eta_{h_1 h_1}| < \begin{cases} 1.1 & \text{if } m_{4j} < 850 \text{ GeV}, \\ 2 \times 10^{-3} (m_{4j}/\text{GeV}) - 0.6 & \text{if } m_{4j} > 850 \text{ GeV}. \end{cases}$$

(5) Finally, the mass of the Higgs boson candidates must lie within the signal region X_{h_1, h_1} defined by [50]

$$X_{h_1, h_1} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 115 \text{ GeV}}{0.1 m_{2j}^{\text{subl}}}\right)^2} < 1.6. \quad (32)$$

In Fig. 9, we present various normalized kinematic distributions of the $b\bar{b}b\bar{b}$ channel for (a) the invariant mass M_{4b} of $b\bar{b}b\bar{b}$, (b) the opening angle $\Delta R_{bb}^{\text{lead}}$ of the two b jets associated with the leading Higgs boson candidate, and (c) the opening angle $\Delta R_{bb}^{\text{subl}}$ of the two b jets associated with the subleading Higgs boson candidate, with $m_{h_2} = 700, 800, \text{ and } 900 \text{ GeV}$ for the ATLAS detectors at $\sqrt{s} = 13 \text{ TeV}$. For comparison, the results for the SM are also shown. We note that the three benchmark points (E, F, and G) selected to study this $b\bar{b}b\bar{b}$ final-state channel have the same production cross sections and are about twice the SM value (see Table II).

In Fig. 9(a), for the SM one can observe that the nonresonant contributions from both the box and triangle diagrams in the invariant mass distribution for $b\bar{b}b\bar{b}$ peak around 400 GeV. Recall that in the SM the box diagram is dominant while the triangle diagram interferes destructively with the box. On the other hand, for the benchmark points E, F, and G in the G2HDM with $m_{h_2} = 700, 800, \text{ and } 900 \text{ GeV}$, respectively, there are two peaks: besides the original ones around 400 GeV, there are peaks located around 700, 800, and 900 GeV, presumably due to the resonant contributions from on-shell h_2 decay in the triangle diagram. Thus, this invariant mass distribution in M_{4b} is useful to distinguish between these benchmark points in the G2HDM and the SM.

Next, in both Figs. 9(b) and 9(c) the $\Delta R_{bb}^{\text{lead/subl}}$ distributions tend to separate into two peaks—one at $\Delta R_{bb}^{\text{lead/subl}} \approx 1$ and another at $\Delta R_{bb}^{\text{lead/subl}} \approx 3$ —in both the G2HDM and SM. This behavior is somewhat expected in the G2HDM because of the different contributions from nonresonant and resonant processes to the total production cross section, keeping in mind that both the triangle and box diagrams in the SM are nonresonant. In particular, the peak at about 1 mainly comes from the h_2 resonance production in the G2HDM, while the box diagram is important in the case of the SM. On the other hand, the peak at about 3 represents the main contribution of the nonresonance triangle diagram for both the G2HDM and the SM. Therefore, one may be able to use the opening angle $\Delta R_{bb}^{\text{lead/subl}}$ to separate the nonresonant and resonant

contributions in the G2HDM. While the distributions look rather similar at $\Delta R_{bb}^{\text{lead/subl}} \approx 3$ in both the G2HDM and SM, they begin to differ at about 1 in both Figs. 9(b) and 9(c). Finally, we note that the $\Delta R_{bb}^{\text{lead}}$ distribution in Fig. 9(b) is more likely to have a peak located at about 1 due to its more energetic parent h_2 in the triangle diagram in the G2HDM.

VI. CONCLUSION

Exploring Higgs boson pair production at the LHC is an important way to probe for the Higgs boson self-coupling in the SM, in particular the trilinear term in the Higgs potential, which is a unique trace of electroweak symmetry breaking via the Higgs mechanism. It is also an interesting channel to search for new physics beyond the SM, especially for models that involve a new Higgs resonance decaying into a Higgs boson pair. We have studied this process in the G2HDM, a model which promotes the discrete Z_2 symmetry which ensures the stability of DM in the IHDM to a local gauge symmetry, by embedding the two Higgs doublets into the fundamental representation of the new $SU(2)_H$ gauge group. One interesting feature in the G2HDM is that the 125 GeV SM-like Higgs boson is in general a linear combination of the $SU(2)_L$ doublet and the $SU(2)_H$ doublet and triplet scalars, which may lead to deviations in the interactions of the Higgs boson with not only other particles but also itself, as compared with the SM couplings. In particular, the Higgs boson self-coupling could become negative, which will result in constructive interference between the box and triangle Feynman diagrams. Moreover, the existence of the heavy scalar bosons in the G2HDM, which will decay into two 125 GeV Higgs bosons, can significantly enhance the production cross section of Higgs boson pairs at the LHC.

We have taken into account the theoretical (VS + PU) and experimental (HP) constraints imposed upon the parameter space of the model. The DM constraints, including the DM relic density and direct detection searches, have also been imposed. We found that the Higgs boson trilinear coupling is stringently constrained by the DM relic density and direct searches. In particular, $\lambda_{h_1 h_1 h_1}$, the trilinear self-coupling of the 125 GeV Higgs in

the G2HDM normalized to its SM value (which could vary in the range $[-29, 32]$ before the DM constraints are applied) now varies in the range $[-1, 1.3]$. This results in a reduction of the double Higgs boson production cross section in the G2HDM from about 2 orders of magnitude enhancement before applying the DM constraints to just about 1 order of magnitude above the SM value. This range of $\lambda_{h_1 h_1 h_1}$ could be probed by the high-luminosity LHC (HL-LHC) with 3 ab^{-1} .

We have performed detailed simulations for the two final states of $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ from the decays of the Higgs boson pair by focusing on a few benchmark points of the parameter space in the G2HDM. All of these benchmark points satisfy the (VS + PU + HP + DM) constraints. The G2HDM demonstrates a representative case in which the kinematic distributions of the $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ final-state channels are significantly altered from the SM predictions at the $\sqrt{s} = 13 \text{ TeV}$ LHC. We also presented a standard

deviation χ^2 test for the signals of Higgs pair production via a generic scalar resonance. It turns out that it is impossible to distinguish a 400 GeV scalar resonant signal from the SM at the HL-LHC running at 13 TeV, if the total cross section of such a resonance is in close proximity to the one in the SM. However, at future machines with higher center-of-mass energies and luminosities it may be possible to observe this signal from a new scalar resonance.

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