Benchmark for LHC searches for low-mass custodial fiveplet scalars in the Georgi-Machacek model

Ameen Ismail^{1,*}, Ben Keeshan^{2,†}, Heather E. Logan^{2,‡} and Yongcheng Wu^{2,§}

¹*Department of Physics, LEPP, Cornell University, Ithaca, New York 14853, USA*

²*Ottawa-Carleton Institute for Physics, Carleton University,
1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada*

(Received 14 April 2020; accepted 5 April 2021; published 12 May 2021)

The Georgi-Machacek (GM) model is used to motivate and interpret LHC searches for doubly charged scalars decaying to vector bosons pairs. The doubly charged scalars are part of a degenerate fermiophobic custodial fiveplet with states $H_5^{\pm\pm}$, $H_5^\pm$, and H_5^0 and common mass m_5 . The GM model has been extensively studied at the LHC for $m_5 > 200$ GeV, but there is a largely unprobed region of parameter space from $120 \text{ GeV} < m_5 < 200 \text{ GeV}$ where light doubly charged scalars could exist. This region has been neglected by experimental searches due in part to the lack of a benchmark for $m_5 < 200$ GeV. In this paper we propose a new “low- m_5 ” benchmark for the GM model, defined for $m_5 \in (50, 550)$ GeV, and characterize its properties. We apply all existing experimental constraints and summarize the phenomenology of the surviving parameter space. We show that the benchmark populates almost the entirety of the relevant allowed parameter plane for m_5 below 200 GeV and satisfies the constraints from the 125 GeV Higgs boson signal strengths. We compute the 125 GeV Higgs boson’s couplings to fermion and vector boson pairs and show that they are always enhanced in the benchmark relative to those in the Standard Model. We also compute the most relevant production cross sections for H_5 at the LHC, including Drell-Yan production of H_5 pairs. The process $pp \rightarrow H \rightarrow H_5 H_5$ contributes in a small region of parameter space, but is small compared to the Drell-Yan production cross section. Finally we compute the branching ratios of $H_5^0 \rightarrow \gamma\gamma$ and $H_5^\pm \rightarrow W^\pm \gamma$. The width-to-mass ratio of each of the H_5 states is below 1% over the entire benchmark, so that the narrow-width approximation is well justified.

DOI: [10.1103/PhysRevD.103.095010](https://doi.org/10.1103/PhysRevD.103.095010)

I. INTRODUCTION

The Georgi-Machacek (GM) model [1,2] provides a prototype for models in which part of electroweak symmetry breaking is due to the vacuum expectation value (vev) of scalars in $SU(2)_L$ representations larger than the doublet (“exotic” scalars). These models have as a common feature the possibility that the Standard Model (SM)-like Higgs boson h can couple to W and Z boson pairs with a strength greater than that in the SM [1,3–6], due to enhancement factors arising from the $SU(2)_L \times U(1)_Y$ generators in the gauge-kinetic terms of the scalar Lagrangian. They include generalizations of the GM model

to higher isospin [4] and the scalar septet model [5,6]. These models also contain as a common feature singly and doubly charged Higgs bosons that couple at tree level to vector boson pairs and play a crucial role in the unitarization of longitudinal vector boson scattering amplitudes in these models [3]. In the GM model, these are the so-called custodial-fiveplet $H_5^{\pm\pm}$, $H_5^\pm$, and H_5^0 states, which have a common mass m_5 and are fermiophobic. Their coupling to vector boson pairs is parametrized by $s_H \equiv \sin \theta_H = 2\sqrt{2}v_\chi/v$, where v_χ is the vev of the isospin-triplet scalars in the GM model and v is the Higgs vev in the SM. In particular, s_H^2 is equal to the fraction of the W and Z boson squared masses that are generated by the triplet vevs. Assuming that the branching ratio of the H_5 to vector bosons is close to 1, the proportionality of the vector boson fusion production cross section of the H_5 states to s_H^2 allows LHC searches to directly constrain s_H as a function of m_5 [7–13].

The current LHC searches for the H_5 states in the GM model focus on H_5 masses of 200 GeV and above, for which the decays into vector boson pairs are on shell. Below this mass, there exists a largely unprobed region in

*ai279@cornell.edu

†BenKeeshan@cmail.carleton.ca

‡logan@physics.carleton.ca

§ycwu@physics.carleton.ca

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP³.

the parameter space with doubly charged Higgs bosons as light as 120 GeV still allowed. However, this open region of parameter space could easily be constrained by extending existing experimental searches to lower masses. For example, the ATLAS search for Drell-Yan production of $H^{++}H^{--}$ with decays to like-sign W bosons [13], if extended to masses below 200 GeV and using the full run 2 dataset, would probe this entire neglected low-mass region independent of s_H and could potentially entirely exclude H_5 masses below 200–300 GeV. (The only possible loophole to such an exclusion would be mass spectra engineered to make the Higgs-to-Higgs decays $H_5^{++} \rightarrow H_3^+ W^+$ and/or $H_5^{++} \rightarrow H_3^+ H_3^+$ dominate over the $H_5^{++} \rightarrow W^+ W^+$ decay mode. It is not yet known whether such a scenario can be achieved while satisfying all theoretical and experimental constraints.) To simplify the interpretation of the above searches, the LHC Higgs cross section working group developed the H5plane benchmark scenario for the GM model [14,15], defined for $m_5 \in [200, 2000]$ GeV. The H5plane benchmark takes as its two free parameters m_5 and s_H and the other parameters are fixed to ensure $\text{BR}(H_5 \rightarrow VV) = 1$ to a good approximation. However, for $m_5 < 200$ GeV, the H5plane benchmark is unable to cover a significant fraction of the region allowed in a general parameter scan.

In this paper we propose and study a new benchmark plane in the GM model that is valid in the low- m_5 region, defined in our case to be $m_5 \in (50, 550)$ GeV. The purpose of this benchmark is to facilitate experimental searches that extend to m_5 values below 200 GeV. This benchmark is designed to yield $\text{BR}(H_5 \rightarrow VV) = 1$ while avoiding constraints from the measurements of the 125 GeV Higgs boson signal strengths; in particular, the parameters are chosen to avoid large modifications to $h \rightarrow \gamma\gamma$ from loops of light $H_5^\pm$ and $H_5^{\pm\pm}$. We show that the low- m_5 benchmark successfully populates a large portion of the theoretically allowed region and almost the entire experimentally allowed region. We also show that the SM-like Higgs couplings to fermion and vector boson pairs, κ_f^h and κ_V^h , are always enhanced in the benchmark with κ_f^h as large as 1.19 and κ_V^h as large as 1.08. We compute the cross sections for Drell-Yan production of pairs of H_5 states as well as their single production cross sections via vector boson fusion (VBF). We also point out a small region of parameter space in which H_5 pairs can be produced via on shell decays of the heavier custodial-singlet scalar H , though the cross sections for this production mode are more than an order of magnitude smaller than those from Drell-Yan. We present the branching ratios of the loop suppressed decays of the H_5^0 and $H_5^\pm$, which become significant at low values of m_5 and highlight that the dominant exclusion in the $m_5 < 200$ GeV region comes from $H_5^0 \rightarrow \gamma\gamma$ which limits this branching ratio to be less than approximately 5%. Finally, we note that the H_5 width to mass ratios are below 1%,

which is sufficiently small to justify the narrow-width approximation.

The structure of the paper is as follows. In Sec. II we present the specifics of the GM model. In Sec. III we introduce the low- m_5 benchmark. In Sec. IV we compare the low- m_5 benchmark to a general parameter scan and discuss the relevant experimental constraints. In Sec. V we discuss the phenomenological characteristics of the low- m_5 benchmark plane, focusing on the couplings of the 125 GeV Higgs boson, the H_5 production cross sections, and the dominant decays of the H_5 states. In Sec. VI we conclude.

II. GEORGI-MACHACEK MODEL

The scalar sector of the Georgi-Machacek model [1,2] consists of the usual complex doublet (ϕ^+, ϕ^0) with hypercharge¹ $Y=1$, a real triplet (ξ^+, ξ^0, ξ^-) with $Y=0$, and a complex triplet $(\chi^{++}, \chi^+, \chi^0)$ with $Y=2$. The doublet is responsible for the fermion masses as in the SM. In order to avoid stringent constraints on the electroweak ρ parameter, the model enforces a global $\text{SU}(2)_L \times \text{SU}(2)_R$ symmetry in the scalar potential that breaks to the diagonal subgroup, identified with the custodial $\text{SU}(2)$, upon electroweak symmetry breaking. In order to make the global $\text{SU}(2)_L \times \text{SU}(2)_R$ symmetry explicit, we write the doublet in the form of a bidoublet Φ and combine the triplets to form a bitriplet X :

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix}, \quad (1)$$

$$X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}. \quad (2)$$

The vevs are defined by $\langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} I_{2 \times 2}$ and $\langle X \rangle = v_\chi I_{3 \times 3}$, where $I_{n \times n}$ is the unit matrix and the W and Z boson masses constrain

$$v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246 \text{ GeV})^2, \quad (3)$$

where G_F is the Fermi constant. Note that the two triplet fields χ^0 and ξ^0 must obtain the same vev in order to preserve the custodial $\text{SU}(2)$ symmetry. Furthermore we will decompose the neutral fields into real and imaginary parts according to

¹We use $Q = T^3 + Y/2$.

$$\phi^0 \rightarrow \frac{v_\phi}{\sqrt{2}} + \frac{\phi^{0,r} + i\phi^{0,i}}{\sqrt{2}}, \quad \chi^0 \rightarrow v_\chi + \frac{\chi^{0,r} + i\chi^{0,i}}{\sqrt{2}}, \quad \xi^0 \rightarrow v_\chi + \xi^{0,r}, \quad (4)$$

where we note that ξ^0 is already a real field.

The most general gauge-invariant scalar potential involving these fields that preserves custodial SU(2) is given by [16]

$$V(\Phi, X) = \frac{\mu_2^2}{2} \text{Tr}(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2} \text{Tr}(X^\dagger X) + \lambda_1 [\text{Tr}(\Phi^\dagger \Phi)]^2 + \lambda_2 \text{Tr}(\Phi^\dagger \Phi) \text{Tr}(X^\dagger X) + \lambda_3 \text{Tr}(X^\dagger X X^\dagger X) + \lambda_4 [\text{Tr}(X^\dagger X)]^2 - \lambda_5 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^a) \text{Tr}(X^\dagger t^a X t^a) - M_1 \text{Tr}(\Phi^\dagger \tau^a \Phi \tau^a) (UXU^\dagger)_{ab} - M_2 \text{Tr}(X^\dagger t^a X t^a) (UXU^\dagger)_{ab}. \quad (5)$$

Here the SU(2) generators for the doublet representation are $\tau^a = \sigma^a/2$ with σ^a being the Pauli matrices, the generators for the triplet representation are

$$t^1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad t^2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad t^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad (6)$$

and the matrix U , which rotates X into the Cartesian basis, is given by [17]

$$U = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}. \quad (7)$$

We note that all the operators in Eq. (5) are manifestly Hermitian, so that the parameters in the scalar potential must all be real. Explicit CP violation is thus not possible in the Georgi-Machacek model.

In terms of the vevs, the scalar potential is given by

$$V(v_\phi, v_\chi) = \frac{\mu_2^2}{2} v_\phi^2 + 3 \frac{\mu_3^2}{2} v_\chi^2 + \lambda_1 v_\phi^4 + \frac{3}{2} (2\lambda_2 - \lambda_5) v_\phi^2 v_\chi^2 + 3(\lambda_3 + 3\lambda_4) v_\chi^4 - \frac{3}{4} M_1 v_\phi^2 v_\chi - 6M_2 v_\chi^3. \quad (8)$$

Minimizing this potential yields the following constraints:

$$0 = \frac{\partial V}{\partial v_\phi} = v_\phi \left[\mu_2^2 + 4\lambda_1 v_\phi^2 + 3(2\lambda_2 - \lambda_5) v_\chi^2 - \frac{3}{2} M_1 v_\chi \right], \quad (9)$$

$$0 = \frac{\partial V}{\partial v_\chi} = 3\mu_3^2 v_\chi + 3(2\lambda_2 - \lambda_5) v_\phi^2 v_\chi + 12(\lambda_3 + 3\lambda_4) v_\chi^3 - \frac{3}{4} M_1 v_\phi^2 - 18M_2 v_\chi^2. \quad (10)$$

Inserting $v_\phi^2 = v^2 - 8v_\chi^2$ [Eq. (3)] into Eq. (10) yields a cubic equation for v_χ in terms of v , μ_3^2 , λ_2 , λ_3 , λ_4 , λ_5 , M_1 , and M_2 . With v_χ (and hence v_ϕ) in hand, Eq. (9) can be used to eliminate μ_2^2 in terms of the parameters in the previous sentence together with λ_1 . We illustrate below how λ_1 can also be eliminated in favor of one of the custodial singlet Higgs masses m_h or m_H [see Eq. (22)].

The physical field content is as follows. When expanded around the minimum, the scalar potential gives rise to ten real physical fields together with three Goldstone bosons. The Goldstone bosons are given by

$$G^+ = c_H \phi^+ + s_H \frac{(\chi^+ + \xi^+)}{\sqrt{2}}, \quad G^0 = c_H \phi^{0,i} + s_H \chi^{0,i}, \quad (11)$$

where

$$c_H \equiv \cos \theta_H = \frac{v_\phi}{v}, \quad s_H \equiv \sin \theta_H = \frac{2\sqrt{2}v_\chi}{v}. \quad (12)$$

The physical fields can be organized by their transformation properties under the custodial SU(2) symmetry into a fiveplet, a triplet, and two singlets. The fiveplet and triplet states are given by

$$H_5^{++} = \chi^{++}, \quad H_5^+ = \frac{(\chi^+ - \xi^+)}{\sqrt{2}}, \quad H_5^0 = \sqrt{\frac{2}{3}} \xi^{0,r} - \sqrt{\frac{1}{3}} \chi^{0,r}, \quad H_3^+ = -s_H \phi^+ + c_H \frac{(\chi^+ + \xi^+)}{\sqrt{2}}, \quad H_3^0 = -s_H \phi^{0,i} + c_H \chi^{0,i}. \quad (13)$$

Within each custodial multiplet, the masses are degenerate at tree level. Using Eqs. (9)–(10) to eliminate μ_2^2 and μ_3^2 , the fiveplet and triplet masses can be written as

$$\begin{aligned}
m_5^2 &= \frac{M_1}{4v_\chi} v_\phi^2 + 12M_2 v_\chi + \frac{3}{2} \lambda_5 v_\phi^2 + 8\lambda_3 v_\chi^2, \\
m_3^2 &= \frac{M_1}{4v_\chi} (v_\phi^2 + 8v_\chi^2) + \frac{\lambda_5}{2} (v_\phi^2 + 8v_\chi^2) = \left(\frac{M_1}{4v_\chi} + \frac{\lambda_5}{2} \right) v^2.
\end{aligned} \tag{14}$$

Note that the ratio M_1/v_χ is finite in the limit $v_\chi \rightarrow 0$, as can be seen from Eq. (10), which yields

$$\frac{M_1}{v_\chi} = \frac{4}{v_\phi^2} [\mu_3^2 + (2\lambda_2 - \lambda_5) v_\phi^2 + 4(\lambda_3 + 3\lambda_4) v_\chi^2 - 6M_2 v_\chi]. \tag{15}$$

The two custodial SU(2) singlets are given in the gauge basis by

$$\phi^{0,r}, \quad H_1^{0r} \equiv \sqrt{\frac{1}{3}} \xi^{0,r} + \sqrt{\frac{2}{3}} \chi^{0,r}. \tag{16}$$

These states mix by an angle α to form the two custodial-singlet mass eigenstates h and H , defined such that $m_h < m_H$:

$$h = c_\alpha \phi^{0,r} - s_\alpha H_1^{0r}, \quad H = s_\alpha \phi^{0,r} + c_\alpha H_1^{0r}, \tag{17}$$

where we define $c_\alpha = \cos \alpha$, $s_\alpha = \sin \alpha$. The mixing is controlled by the 2×2 mass-squared matrix

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}, \tag{18}$$

where

$$\begin{aligned}
\mathcal{M}_{11}^2 &= 8\lambda_1 v_\phi^2, \\
\mathcal{M}_{12}^2 &= \frac{\sqrt{3}}{2} v_\phi [-M_1 + 4(2\lambda_2 - \lambda_5) v_\chi], \\
\mathcal{M}_{22}^2 &= \frac{M_1 v_\phi^2}{4v_\chi} - 6M_2 v_\chi + 8(\lambda_3 + 3\lambda_4) v_\chi^2.
\end{aligned} \tag{19}$$

The mixing angle is fixed by

$$\begin{aligned}
\sin 2\alpha &= \frac{2\mathcal{M}_{12}^2}{m_H^2 - m_h^2}, \\
\cos 2\alpha &= \frac{\mathcal{M}_{22}^2 - \mathcal{M}_{11}^2}{m_H^2 - m_h^2},
\end{aligned} \tag{20}$$

with the masses given by

$$m_{h,H}^2 = \frac{1}{2} \left[\mathcal{M}_{11}^2 + \mathcal{M}_{22}^2 \mp \sqrt{(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2)^2 + 4(\mathcal{M}_{12}^2)^2} \right]. \tag{21}$$

It is convenient to use the measured mass of the observed SM-like Higgs boson as an input parameter. The coupling λ_1 can be eliminated in favor of this mass by inverting Eq. (21):

$$\lambda_1 = \frac{1}{8v_\phi^2} \left[m_h^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{22}^2 - m_h^2} \right]. \tag{22}$$

Note that in deriving this expression for λ_1 , the distinction between m_h and m_H is lost. This means that, depending on the values of μ_3^2 and the other parameters, this (unique) solution for λ_1 will correspond to either the lighter or the heavier custodial singlet having a mass equal to the observed SM-like Higgs mass.

III. LOW- m_5 BENCHMARK

The low- m_5 benchmark plane, parametrized in terms of m_5 (for values between 50 and 550 GeV) and s_H , is designed as a complementary benchmark scenario to the H5plane benchmark which covers the m_5 range of [200, 2000] GeV. Its primary purpose is to facilitate the extension of current LHC searches to m_5 mass ranges below 200 GeV. In particular, since the Drell-Yan production cross section of $H^{++}H^{--}$ is independent of s_H , the ATLAS search for Drell-Yan production of $H^{++}H^{--}$ with decays to like-sign W bosons [13] has the potential to exclude the entire parameter space below approximately 200 GeV if extended to masses below 200 GeV. The low- m_5 benchmark is specified in Table I, in a form that is compatible with the inputs of version 1.4 and higher of the GM model calculator GMCALC [18].

In order to establish a benchmark *plane* with only two variable parameters, choices have to be made to fix the five

TABLE I. Specification of the low- m_5 benchmark for the Georgi-Machacek model. This set of input parameters can be accessed in GMCALC [18] by using INPUTSET = 6.

Fixed inputs	Variable parameters	Dependent parameters
$G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2}$	$m_5 \in (50, 550) \text{ GeV}$	$\lambda_2 = 0.08(m_5/100 \text{ GeV})$
$m_h = 125 \text{ GeV}$	$s_H \in (0, 1)$	$\lambda_5 = -0.32(m_5/100 \text{ GeV}) = -4\lambda_2$
$\lambda_3 = -1.5$		
$\lambda_4 = 1.5 = -\lambda_3$		
$M_2 = 10 \text{ GeV}$		

otherwise-free parameters of the GM model. These choices are dictated by the intended purpose of the benchmark, together with convenience of implementation. The low- m_5 benchmark specifies the nine parameters of the GM model Lagrangian in terms of m_h , G_F , m_5 , s_H , λ_2 , λ_3 , λ_4 , λ_5 , and M_2 (this set of input parameters is implemented as `INPUTSET = 6` in the `GM CALC` code). $m_h = 125$ GeV and G_F are fixed to their measured values.

The other fixed (or dependent) parameters of the benchmark are chosen to meet the following design considerations:

- (i) The couplings of h are sufficiently close to their SM values to avoid the benchmark being excluded by LHC measurements of h signal strengths. The main hazard here is that $h \rightarrow \gamma\gamma$ could be significantly modified by light H_5^+ and H_5^{++} scalars running in the loop, in addition to (heavier) H_3^+ in the loop. This possibility is conveniently avoided by the choice $\lambda_5 = -4\lambda_2$, for which the hH_5H_5 coupling strengths, given by

$$g_{h55} = -8\sqrt{3}(\lambda_3 + \lambda_4)s_\alpha v_\chi + (4\lambda_2 + \lambda_5)c_\alpha v_\phi \quad (23)$$

$$- 2\sqrt{3}M_2 s_\alpha,$$

go to zero in the limit $s_H \rightarrow 0$ (in which s_α also goes to zero). This strong cancellation is not strictly necessary (λ_2 can be varied by up to a factor of 2 relative to this choice before Higgs signal strength measurements begin to seriously constrain the parameter space), but it is convenient and does not affect the H_5 production and decay phenomenology that the benchmark is designed to capture.

- (ii) m_5 is always less than m_3 , to avoid the decays $H_5 \rightarrow H_3 V$ or $H_5 \rightarrow H_3 H_3$. This choice is made to simplify the H_5 decay phenomenology in the benchmark and to emphasize the importance of the VV decay modes, which are in fact dominant over the majority of the parameter space of the unconstrained GM model. It also avoids exclusion of parts of the benchmark from direct searches for light H_3^+ scalars. This mass hierarchy is achieved through the choices of the signs and magnitudes of M_2 , λ_3 , and especially λ_5 .
- (iii) A sufficiently large portion of the m_5 - s_H plane is allowed by theoretical and indirect experimental constraints² within the benchmark for m_5 values below 200 GeV. This is the most challenging consideration to satisfy and dictates the specific choices for the values of M_2 , λ_3 , λ_4 , and λ_5 . These choices were largely obtained by trial and error

²Details of the theoretical and experimental constraints are given in the next section.

FIG. 1. The region of m_5 versus s_H that is populated by the low- m_5 benchmark (black) compared to a general scan over the full parameter space (red), imposing the same theoretical and indirect experimental constraints (S parameter and $B_s \rightarrow \mu\mu$). Because our general scan is less efficient for small m_5 values, we include a dedicated general scan restricted to $m_5 < 200$ GeV overlaid with a scan for $m_5 < 600$ GeV in order to generate a sufficient number of points below 200 GeV.

informed by knowledge of the theoretical constraints on the scalar potential.

The remaining underlying Lagrangian parameters are given by

$$M_1 = m_5^2 \frac{\sqrt{2}s_H}{c_H^2 v} - \frac{3}{\sqrt{2}} \lambda_5 v s_H - \frac{\sqrt{2}}{c_H^2} \lambda_3 v s_H^3 - \frac{6s_H}{c_H^2} M_2, \quad (24)$$

$$\mu_3^2 = \frac{2}{3} m_5^2 + M_1 \frac{v_\phi^2}{12v_\chi} - 2\lambda_2 v_\phi^2 - \frac{28}{3} \lambda_3 v_\chi^2 - 12\lambda_4 v_\chi^2 - 2M_2 v_\chi, \quad (25)$$

$$\lambda_1 = \frac{1}{8v_\phi^2} \left(m_h^2 + \frac{[\frac{\sqrt{3}}{2} v_\phi (-M_1 + 4(2\lambda_2 - \lambda_5) v_\chi)]^2}{M_1 \frac{v_\phi^2}{4v_\chi} - 6M_2 v_\chi + 8(\lambda_3 + 3\lambda_4) v_\chi^2 - m_h^2} \right), \quad (26)$$

$$\mu_2^2 = -4\lambda_1 v_\phi^2 - 3(2\lambda_2 - \lambda_5) v_\chi^2 + \frac{3}{2} M_1 v_\chi. \quad (27)$$

IV. POPULATED RANGE OF THE m_5 - s_H PLANE AND EXISTING CONSTRAINTS

We now examine the populated range of the m_5 - s_H plane in the low- m_5 benchmark and compare it to that of a general scan of the parameter space. The results are presented as scatter plots in the m_5 - s_H plane. For all the parameter scans shown here, we impose the theoretical constraints as implemented in `GM CALC` [18]—i.e., perturbative unitarity of quartic couplings [17], a scalar potential that is

FIG. 2. The excluded (colored) and allowed (black) points in the scan of the low-mass benchmark shown in Fig. 1. The black points are unconstrained, the dark blue points are excluded by the CMS run 2 direct search for like-sign dileptons [9], the orange points are excluded by the ATLAS run 2 direct search for $H_5^{\pm\pm}$ [13], the light blue points are excluded by the recast of the ATLAS run 1 diphoton resonance search [27], the yellow points are excluded by the recast of the ATLAS run 1 constraint on anomalous like-sign dimuon production [25], the teal points are excluded by the recast of the ATLAS run 1 VBF $\rightarrow W^+W^+ \rightarrow$ like-sign dileptons cross section measurement [23], and the red points are excluded by HiggsBounds 5.3.2.

bounded from below [16], and the absence of deeper alternative minima [16]. We also impose the indirect constraints, also implemented in GMCALC, from the S parameter and from B physics, the most stringent in the low- m_5 region being $B_s^0 \rightarrow \mu^+\mu^-$ (the constraint from $b \rightarrow s\gamma$ is very similar) [19]. We finally examine the direct experimental constraints on the low- m_5 region, applying direct search constraints, theory recasts and constraints from HiggsBounds 5.3.2 and HiggsSignals 2.2.3 [20], all of which have been implemented in or interfaced to GMCALC 1.5.0 [21]. A similar study of experimental constraints in a parameter scan of the GM model including roughly the same low mass region we are considering was previously carried out in Ref. [22].

In Fig. 1, we show the region of the available parameter space that is accessible in the low- m_5 benchmark compared to a general scan over the whole parameter space after imposing the theoretical and indirect experimental constraints previously described. The red points correspond to a general scan over the GM parameter space while the black points correspond to a scan over the benchmark. As can be seen, the low- m_5 benchmark populates a substantial region of parameter space for m_5 below 200 GeV, only failing to cover the full portion of the high s_H region. Because the benchmark is optimized to populate the low- m_5 region, at higher m_5 it does not cover the full range of s_H obtainable in a general scan, and fails the theoretical constraints entirely for $m_5 \gtrsim 550$ GeV. Nevertheless, the benchmark

provides enough viable parameter space to be used for searches that span m_5 values from around 60 GeV to of order 500 GeV—in particular, the full range where we expect a run 2 search for Drell-Yan production of $H_5^{++}H_5^{--}$ to be sensitive.

In Fig. 2 we show the benchmark scan and highlight the regions excluded by the various direct experimental constraints as a scatter plot in the m_5 - s_H plane. The black points are allowed. The exclusions come from the following sources: a CMS run 2 search for VBF $H^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow$ like-sign dileptons [9], which excludes s_H values above 0.2–0.3 for $m_5 > 200$ GeV (dark blue); an ATLAS run 2 search for Drell-Yan production of $H^{++}H^{--}$ with $H^{\pm\pm} \rightarrow W^\pm W^\pm$ [13] which excludes $200 \text{ GeV} < m_5 < 220$ GeV (orange); an ATLAS run 1 measurement of the VBF $\rightarrow W^+W^+ \rightarrow$ like-sign dileptons cross section [23] recast by theorists in Ref. [24], which excludes s_H values above 0.4–0.6 for m_5 between about 120 and 200 GeV (teal); an ATLAS run 1 search for anomalous like-sign dimuon production [25] recast by theorists in Refs. [4,26] to constrain Drell-Yan production of $H_5^{\pm\pm}$, which excludes m_5 values below 76 GeV independent of the value of s_H (yellow); an ATLAS run 1 diphoton resonance search [27] applied to Drell-Yan production of $H_5^0 H_5^\pm$ followed by $H_5^0 \rightarrow \gamma\gamma$, which excludes points mainly for m_5 between 80 and 120 GeV (light blue); and constraints coming from HiggsBounds 5.3.2 [20] (red), which exclude small regions around $s_H \sim 0.45$ – 0.65 and $m_5 \sim 110$ – 230 GeV from searches for $H \rightarrow ZZ$ and a sliver with $m_5 \simeq 55$ – 62 GeV and $s_H \lesssim 0.2$ from searches for $h \rightarrow H_5^0 H_5^0 \rightarrow 4\gamma$.

The CMS direct search for VBF $H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ is the dominant constraint in the region above $m_5 = 200$ GeV. The dominant constraints below $m_5 = 200$ GeV come from processes involving $H_5^0 \rightarrow \gamma\gamma$. The dominant exclusion is from Drell-Yan production of $H_5^0 H_5^\pm$ with the H_5^0 decaying to diphotons. Because the Drell-Yan cross section does not depend on s_H , the excluded region is almost independent of s_H [the tail extending to higher m_5 values at low s_H is due to the increase in $\text{BR}(H_5^0 \rightarrow \gamma\gamma)$ as the competing decays to WW and ZZ are suppressed]. This channel excludes m_5 between 65 and 120 GeV in the low- m_5 benchmark for any value of s_H . Although there is a run 2 version [28] of the run 1 search for anomalous like-sign dimuon production which one would expect to compete with the diphoton exclusion, it can not be recast for our purposes because, unlike the run 1 search, it does not consider invariant masses of the same-sign dileptons below 200 GeV. HiggsBounds exclusions from $h \rightarrow H_5^0 H_5^0 \rightarrow 4\gamma$ also exclude m_5 between 55–62 GeV for $s_H \lesssim 0.2$. The remaining parameter space below 65 GeV is excluded by the Drell-Yan production of $H_5^{++}H_5^{--}$ with decays to like-sign dimuons. The limits at higher s_H below $m_5 = 200$ GeV are almost entirely due to VBF production of

FIG. 3. The regions of the m_5 - s_H plane populated by the low- m_5 benchmark (black) and by a general scan (red) after all experimental constraints have been applied.

$H_5^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow$ like-sign dileptons. The HiggsBounds exclusions from production of H decaying to ZZ also exclude a portion of the high s_H , $m_5 \approx 200$ GeV region.

We also apply the constraints from the LHC measurements of the 125 GeV Higgs boson signal strength measurements using HiggsSignals 2.2.3 [20]. HiggsSignals performs a p -value test given a specified number of free model parameters. We treat each point as its own model, and hence compute the p value with zero free parameters. (Varying the number of free parameters in the HiggsSignals analysis between 0 and 2 did not have a significant effect on the p values.) HiggsSignals does not exclude any of the points of the low- m_5 benchmark; the returned p values vary between 0.54 and 0.75, with a p value of 0.7 over most of the parameter space. This is due in part to our choice of $\lambda_5 = -4\lambda_2$, which suppresses the tree-level hH_5H_5 couplings that contribute to the loop-induced $h \rightarrow \gamma\gamma$ decay.

In Fig. 3 we compare the coverage of the m_5 - s_H plane in the low- m_5 benchmark with that of the general scan after applying all the experimental constraints listed above. Once again, the red points correspond to a general scan, while the black points correspond to the low- m_5 benchmark. We can see that the low- m_5 benchmark can generate points covering the great majority of the allowed region. The survival of general scan points in regions excluded in the benchmark is a result of atypical suppression in the $\text{BR}(H_5^{++} \rightarrow W^+W^+)$ and $\text{BR}(H_5^0 \rightarrow \gamma\gamma)$ in the high and low m_5 region, respectively. The suppression in $\text{BR}(H_5^{++} \rightarrow W^+W^+)$ is caused by a non-negligible $\text{BR}(H_5^{++} \rightarrow H_3^+W^+)$ while the suppression in $\text{BR}(H_5^0 \rightarrow \gamma\gamma)$ is due to accidental cancellations between the gauge boson and charged scalar loop diagrams.

V. PHENOMENOLOGY

In this section we examine the properties of the low- m_5 benchmark. We focus on the phenomenological behavior of the H_5 states and the SM-like Higgs, h . The results are

presented as scatter plots or as contours in the m_5 - s_H plane. As above, for all the parameter scans shown here, we impose the theoretical constraints as implemented in GMCALC [18], the indirect constraints from the S parameter and from B physics, and direct experimental constraints as described in the previous section.

A. Couplings of h

The tree-level couplings of the 125 GeV Higgs boson h to fermion pairs and vector boson pairs are expressed in terms of model parameters by

$$\kappa_f^h = \frac{c_a}{c_H}, \quad \kappa_V^h = c_a c_H - \sqrt{\frac{8}{3}} s_a s_H, \quad (28)$$

where each κ is defined as the ratio of the corresponding h coupling to that of the SM Higgs boson. These couplings are shown in Figs. 4 and 5 in the low- m_5 benchmark, after applying all experimental constraints. Interestingly, in the benchmark both κ_f^h and κ_V^h are always greater than 1, so the SM-like Higgs couplings are always enhanced in the low- m_5 benchmark as compared to the SM (in a general scan each of these couplings can be either enhanced or suppressed relative to the SM).³ The κ_f^h enhancement can be as large as 19% while the κ_V^h enhancement can be as large as 8%.

In Fig. 4 we plot κ_f^h as a function of m_5 (left) and s_H (right) in the low- m_5 benchmark. For $m_5 < 200$ GeV, a wide range of values are accessible, varying from 1 to a maximum of 1.19 at $m_5 \simeq 124$ GeV, with the maximum enhancement falling steadily to 1.06 as m_5 increases to 200 GeV. For $m_5 > 220$ GeV, κ_f^h values vary from 1 to about 1.015. These two branches of the benchmark are easily distinguished in the scatter plot versus s_H as the two general trends, one a rough parabola corresponding to $m_5 < 200$ GeV and the other a linear trend at lower κ_f^h corresponding to $m_5 > 200$ GeV. The small gap in the allowed values around $\kappa_f^h \simeq 1.17$ is a result of the small parameter region excluded by searches for $H \rightarrow ZZ$ as implemented in HiggsBounds shown in red in Fig. 2.

In Fig. 5 we plot κ_V^h as a function of m_5 (left) and s_H (right) in the low- m_5 benchmark. For $m_5 < 200$ GeV,

³It is worth noting however that this statement applies only to the tree-level couplings. References [29,30] explored the effects of one-loop corrections to the SM Higgs couplings in the GM model and found a typical suppression of a few percent in the renormalized κ_f^h and κ_V^h couplings compared to their tree-level values. So we expect that at one-loop level it is possible to have κ_f^h and κ_V^h less than 1 in the low- m_5 benchmark, at least for s_H values below about 0.2 for which these couplings only differ from 1 by a few percent.

FIG. 4. Coupling modification factor κ_f^h for the SM-like Higgs h coupling to fermion pairs in the low- m_5 benchmark, as a function of m_5 (left) and s_H (right). The values range between 1 and 1.19.

FIG. 5. Coupling modification factor κ_V^h for the SM-like Higgs h coupling to vector boson pairs in the low- m_5 benchmark, as a function of m_5 (left) and s_H (right). The values range between 1 and 1.08.

larger enhancements of κ_V^h are possible with values varying from 1 to a maximum of 1.08 at $m_5 \simeq 124$ GeV, with the maximum enhancement falling to below 1.04 at $m_5 \simeq 160$ GeV and then rising slightly as m_5 increases to 200 GeV. For $m_5 > 220$ GeV, κ_V^h values vary from 1 to above 1.04 with a maximum value increasing almost linearly with m_5 . In particular, for $m_5 > 220$ GeV, the allowed enhancements of κ_V^h are substantially larger than those of κ_f^h . The two branches of the benchmark are again distinguishable in the scatter plot versus s_H , with the branch at larger m_5 appearing at smaller s_H . Again, the small gap in the allowed values around $\kappa_V^h \simeq 1.07$ is a result of the small parameter region excluded by searches for $H \rightarrow ZZ$ as implemented in HiggsBounds shown in red in Fig. 2. Note that $\kappa_V^h > 1$ at tree level is a distinctive feature of the GM model that cannot occur in extended Higgs sectors containing only scalars in doublets or singlets of $SU(2)_L$.

As LHC measurements of h couplings become more precise we expect that they will begin to constrain the portion of the low- m_5 benchmark with large s_H values;

crucially, however, the full range of m_5 available in the benchmark is consistent with very SM-like couplings of h .

B. Production of H_5 at the LHC

We now discuss the major LHC production modes of the H_5 states in the low- m_5 benchmark. In Fig. 6 we show the H_5 production cross sections via Drell-Yan production of H_5 pairs and via VBF. The Drell-Yan production cross section is independent of s_H , making it particularly valuable to constrain the GM model at low s_H . The VBF cross section is proportional to s_H^2 ; we fix $s_H = 0.1$ in Fig. 6. We computed these cross sections at next-to-leading order (NLO) in QCD for 13 TeV pp collisions using MadGraph5_aMC@NLO [31] with the PDF4LHC15 NLO parton distribution functions [32]. VBF cross sections for production of the H_5 states at the LHC have previously been computed at next-to-next-to-leading order in QCD for $m_5 \geq 200$ GeV in Ref. [33]. Cross sections for $H_5^{\pm\pm}$ production in VBF, associated production with a W boson, and Drell-Yan production in pairs were also computed at

FIG. 6. Production cross sections for Drell-Yan production of pairs of H_5 states (left, independent of s_H) and VBF production of single H_5 states (right, for $s_H = 0.1$) at the 13 TeV LHC, computed at NLO in QCD using MadGraph5_aMC@NLO.

leading order for 14 and 100 TeV proton-proton collisions in Ref. [22].

The largest Drell-Yan production cross section corresponds to the $H_5^{++}H_5^{--}$ channel which falls from 545 fb at $m_5 = 120$ GeV to 86.3 fb at $m_5 = 200$ GeV while the smallest cross section corresponds to the $H_5^+H_5^-$ channel that falls from 138 fb at $m_5 = 120$ GeV to 21.6 fb at $m_5 = 200$ GeV. The largest VBF production cross section (calculated at $s_H = 0.1$) corresponds to the $H_5^{++}jj$ channel which falls from 40.4 fb at $m_5 = 120$ GeV to 23.3 fb at $m_5 = 200$ GeV while the smallest cross section corresponds to the H_5^-jj channel which falls from 18.8 fb at $m_5 = 120$ GeV to 9.85 fb at $m_5 = 200$ GeV.

Within the low- m_5 benchmark, there is a small region of parameter space in which the mass of the heavier custodial-singlet Higgs boson H satisfies $m_H > 2m_5$, kinematically

allowing the decays $H \rightarrow H_5H_5$. Production of H through, e.g., gluon fusion or VBF followed by decays to H_5 pairs will therefore enhance the total H_5 pair production rate in this region of the low- m_5 benchmark. As is shown below, this resonant contribution is always more than an order of magnitude smaller than the cross section from Drell-Yan production. This resonant contribution is very model dependent, and we advocate that it be omitted when setting bounds on $H_5^{++}H_5^{--}$ production via Drell-Yan in order to allow the limits to be interpreted in as model independent a way as possible. We determine the production cross sections of H using the recommended values for beyond-the-SM Higgs bosons from the LHC Higgs cross section working group [14] together with the appropriate κ_f^H and κ_V^H coupling factors. The expressions for the cross sections are given by

$$\sigma(pp \rightarrow H \rightarrow H_5^{++}H_5^{--}) = [(\kappa_f^H)^2 \sigma_{GGF}^H + (\kappa_V^H)^2 (\sigma_{VBF}^H + \sigma_{WH}^H + \sigma_{ZH}^H)] \times \text{BR}(H \rightarrow H_5^{++}H_5^{--}), \quad (29)$$

$$\sigma(pp \rightarrow H \rightarrow H_5^+H_5^-) = [(\kappa_f^H)^2 \sigma_{GGF}^H + (\kappa_V^H)^2 (\sigma_{VBF}^H + \sigma_{WH}^H + \sigma_{ZH}^H)] \times \text{BR}(H \rightarrow H_5^+H_5^-), \quad (30)$$

$$\sigma(pp \rightarrow H \rightarrow H_5^0H_5^0) = [(\kappa_f^H)^2 \sigma_{GGF}^H + (\kappa_V^H)^2 (\sigma_{VBF}^H + \sigma_{WH}^H + \sigma_{ZH}^H)] \times \text{BR}(H \rightarrow H_5^0H_5^0), \quad (31)$$

where all cross sections are evaluated at m_H (we use linear interpolation between values given in Ref. [14]), σ_{GGF}^H is the gluon-gluon fusion cross section evaluated at next-to-next-to-leading order + next-to-next-to-leading log in QCD (see Ref. [14]), and σ_{VBF}^H , σ_{WH}^H , and σ_{ZH}^H are the VBF and WH and ZH

associated production cross sections, respectively. Since $\text{BR}(H \rightarrow H_5^{++}H_5^{--}) = \text{BR}(H \rightarrow H_5^+H_5^-) = 2\text{BR}(H \rightarrow H_5^0H_5^0)$, the resonant production cross sections for $pp \rightarrow H \rightarrow H_5^{++}H_5^{--}$ and $pp \rightarrow H \rightarrow H_5^+H_5^-$ are equal and are twice as large as that of $pp \rightarrow H \rightarrow H_5^0H_5^0$.

FIG. 7. Contours of cross sections for the resonant processes $pp \rightarrow H \rightarrow H_5^{++}H_5^{--}$ (equal to $pp \rightarrow H \rightarrow H_5^+H_5^-$) (left) and $pp \rightarrow H \rightarrow H_5^0H_5^0$ (right) in the low- m_5 benchmark for the 13 TeV LHC. The shaded region has $m_H > 2m_5$ but is excluded by experimental searches. The region with contours above the dotted black line has $m_H > 2m_5$ and is still allowed. For $pp \rightarrow H \rightarrow H_5^{++}H_5^{--}$ and $pp \rightarrow H \rightarrow H_5^+H_5^-$, the minimum allowed cross section is 0.230 fb and the maximum allowed is 21.5 fb. For $pp \rightarrow H \rightarrow H_5^0H_5^0$ the minimum allowed cross section is 0.115 fb and the maximum allowed is 10.7 fb.

In Fig. 7 we show the region of the m_5 - s_H plane in which $m_H > 2m_5$ in the low- m_5 benchmark (gray area and white area with contours above the dotted black line). The portion of this region shaded in gray is already excluded by existing searches. In the surviving allowed portion of this region, which spans approximately $120 \text{ GeV} < m_5 < 160 \text{ GeV}$ and s_H between 0.2 and 0.6, we show contours of the cross section for H_5 pairs through resonant production of H . The cross sections for resonant $H_5^{++}H_5^{--}$ and $H_5^+H_5^-$ ($H_5^0H_5^0$) production have a maximum of 21.5 fb (10.7 fb) at $m_5 \approx 120 \text{ GeV}$, which is more than an order of magnitude smaller than the 545 fb Drell-Yan production cross section of $H_5^{++}H_5^{--}$ at the same mass. It is also roughly an order of magnitude

smaller than the individual VBF production cross sections at this mass within the relevant range of s_H .

C. Decays of H_5

The low- m_5 benchmark plane is designed such that $m_5 < m_3$ and $m_5 < m_H$ over the entire benchmark. This means that the branching ratio of $H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ is 1. The decay of the $H_5^\pm$ is dominated by the $W^\pm Z$ channel for $m_5 > 170 \text{ GeV}$ (with a branching ratio of approximately 1) but for masses below this, the loop-induced decays to $W^\pm \gamma$ begin to compete. Similarly the decays of the H_5^0 are dominated by W^+W^- and ZZ above the appropriate thresholds but the loop-induced decays to $\gamma\gamma$ and $Z\gamma$ begin

FIG. 8. Contours of branching ratios of the loop-induced decays of $H_5^0 \rightarrow \gamma\gamma$ (left) and $H_5^+ \rightarrow W^+\gamma$ (right) in the low- m_5 benchmark. The region above and to the left of the dotted line is excluded by direct searches. The shaded gray area in the left panel is excluded by diphoton resonance searches applied to $H_5^0 \rightarrow \gamma\gamma$. For $m_5 < 200 \text{ GeV}$, the values of $\text{BR}(H_5^0 \rightarrow \gamma\gamma)$ in the low- m_5 benchmark range between 1.26×10^{-6} and 1.00, surpassing 99% for $m_5 \lesssim 80 \text{ GeV}$. The values of $\text{BR}(H_5^+ \rightarrow W^+\gamma)$ range between zero and 0.887 with the maximum at $m_5 \simeq 94 \text{ GeV}$.

to compete at low m_5 . In this section we show the branching ratios for the most phenomenologically interesting low-mass decays of the H_5^+ and H_5^0 to $W^+\gamma$ and $\gamma\gamma$, respectively. We compute these branching ratios using GMCALC, which implements doubly offshell decays of scalars to WW , ZZ , and WZ pairs below threshold as well as the loop-induced decays to $\gamma\gamma$, $Z\gamma$, and $W\gamma$ [34] (decays to $Z\gamma$ and $W\gamma$ with an off shell Z or W boson are not implemented). Throughout the low- m_5 benchmark plane, the maximum width-to-mass ratios of the H_5^0 , H_5^+ , and H_5^{++} are 6.4×10^{-3} , 6.5×10^{-3} , and 6.6×10^{-3} , respectively, so the narrow-width approximation is valid throughout the benchmark.

In Fig. 8 we show the branching ratios of $H_5^0 \rightarrow \gamma\gamma$ (left) and $H_5^+ \rightarrow W^+\gamma$ (right). The dotted line shows the boundary of the region allowed by experimental constraints; the region below and to the right of the dotted line is allowed (as is a tiny island at $m_5 \sim 120$ GeV and $s_H \sim 0.6$). To illustrate the impact of the diphoton resonance search on the $H_5^0 \rightarrow \gamma\gamma$ decay, the region excluded by this search is shaded in gray in the right panel of Fig. 8. Values of $\text{BR}(H_5^0 \rightarrow \gamma\gamma) \gtrsim 10\%$ are excluded since the exclusion curve closely follows the 10% BR contour. Values of $\text{BR}(H_5^+ \rightarrow W^+\gamma)$ as large as 2% are allowed for small values of s_H below 0.05 and m_5 in the range 125–160 GeV.

VI. CONCLUSIONS

In this paper we introduced the low- m_5 benchmark for the GM model, defined for $m_5 \in (50, 550)$ GeV. The benchmark highlights an unexcluded region of parameter space with light additional Higgs bosons, motivating and facilitating searches for H_5^{++} , H_5^+ , and H_5^0 at low masses below 200 GeV. By design, $m_3 > m_5$ throughout the benchmark plane so that $\text{BR}(H_5^{++} \rightarrow W^+W^+) = 1$, while simultaneously ensuring that the modification to $h \rightarrow \gamma\gamma$ by

loops of light charged scalars is suppressed. We examined the existing experimental constraints, which limit s_H to be strictly below 0.63 in the benchmark, and studied its phenomenology. Our numerical work has been done with a prerelease version of the public code GMCALC 1.5.0.

We showed that the 125 GeV Higgs boson's tree-level couplings to fermion and vector boson pairs are always enhanced in the low- m_5 benchmark, with enhancements as large as 19% and 8%, respectively, possible. Nevertheless, the 125 GeV Higgs boson satisfies the Higgs signal strength constraints throughout the entirety of the low- m_5 benchmark. We also showed that the benchmark-specific enhancement to the H_5 pair production cross sections by the process $pp \rightarrow H \rightarrow H_5 H_5$ is always at least an order of magnitude smaller than the Drell-Yan production of H_5 pairs. We anticipate that a dedicated experimental analysis of this Drell-Yan production at the LHC could exclude the entirety of the $m_5 < 200$ GeV region. Finally, we showed that $\text{BR}(H_5^0 \rightarrow \gamma\gamma)$ must be less than about 10% to satisfy constraints from diphoton resonance searches, which in turn forces $\text{BR}(H_5^+ \rightarrow W\gamma)$ to be less than about 2% in the benchmark. We also pointed out that the width-to-mass ratios of the H_5 states are below 1%, small enough to justify the narrow width approximation throughout the low- m_5 benchmark.

ACKNOWLEDGMENTS

We thank the members of the LHC Higgs cross section working group for encouraging us to create a benchmark valid for $m_5 < 200$ GeV. This work was supported by the Natural Sciences and Engineering Research Council of Canada. A. I. was also partially supported by a Cornell Presidential Life Science Fellowship. H. E. L. was also supported by the Grant H2020-MSCA-RISE-2014 No. 645722 (NonMinimalHiggs).

-
- [1] H. Georgi and M. Machacek, Doubly charged Higgs bosons, *Nucl. Phys.* **B262**, 463 (1985).
 - [2] M. S. Chanowitz and M. Golden, Higgs boson triplets with $M(W) = M(Z) \cos \theta_W$, *Phys. Lett.* **165B**, 105 (1985).
 - [3] A. Falkowski, S. Rychkov, and A. Urbano, What if the Higgs couplings to W and Z bosons are larger than in the standard model?, *J. High Energy Phys.* **04** (2012) 073.
 - [4] H. E. Logan and V. Rantala, All the generalized Georgi-Machacek models, *Phys. Rev. D* **92**, 075011 (2015).
 - [5] J. Hisano and K. Tsumura, Higgs boson mixes with an SU(2) septet representation, *Phys. Rev. D* **87**, 053004 (2013).
 - [6] S. Kanemura, M. Kikuchi, and K. Yagyu, Probing exotic Higgs sectors from the precise measurement of Higgs boson couplings, *Phys. Rev. D* **88**, 015020 (2013).
 - [7] G. Aad *et al.* (ATLAS Collaboration), Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay $H^\pm \rightarrow W^\pm Z$ using pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Experiment, *Phys. Rev. Lett.* **114**, 231801 (2015).
 - [8] A. M. Sirunyan *et al.* (CMS Collaboration), Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a Pair of W and Z Bosons Using pp Collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **119**, 141802 (2017).

- [9] A. M. Sirunyan *et al.* (CMS Collaboration), Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **120**, 081801 (2018).
- [10] M. Aaboud *et al.* (ATLAS Collaboration), Search for resonant WZ production in the fully leptonic final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* **787**, 68 (2018).
- [11] CMS Collaboration, Measurement of electroweak WZ production and search for new physics in pp collisions at $\sqrt{s} = 13$ TeV, Report No. CMS-PAS-SMP-18-001.
- [12] M. Aaboud *et al.* (ATLAS Collaboration), Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Eur. Phys. J. C* **78**, 24 (2018).
- [13] M. Aaboud *et al.* (ATLAS Collaboration), Search for doubly charged scalar bosons decaying into same-sign W boson pairs with the ATLAS detector, *Eur. Phys. J. C* **79**, 58 (2019).
- [14] D. de Florian *et al.* (LHC Higgs Cross Section Working Group), Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, [arXiv:1610.07922](#).
- [15] H. E. Logan and M. B. Reimer, Characterizing a benchmark scenario for heavy Higgs boson searches in the Georgi-Machacek model, *Phys. Rev. D* **96**, 095029 (2017).
- [16] K. Hartling, K. Kumar, and H. E. Logan, The decoupling limit in the Georgi-Machacek model, *Phys. Rev. D* **90**, 015007 (2014).
- [17] M. Aoki and S. Kanemura, Unitarity bounds in the Higgs model including triplet fields with custodial symmetry, *Phys. Rev. D* **77**, 095009 (2008); Erratum, *Phys. Rev. D* **89**, 059902 (2014).
- [18] K. Hartling, K. Kumar, and H. E. Logan, GMCALC: A calculator for the Georgi-Machacek model, [arXiv:1412.7387](#).
- [19] K. Hartling, K. Kumar, and H. E. Logan, Indirect constraints on the Georgi-Machacek model and implications for Higgs boson couplings, *Phys. Rev. D* **91**, 015013 (2015).
- [20] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams, HiggsBounds: Confronting arbitrary Higgs sectors with exclusion bounds from LEP and the Tevatron, *Comput. Phys. Commun.* **181**, 138 (2010); HiggsBounds 2.0.0: Confronting neutral and charged Higgs sector predictions with exclusion bounds from LEP and the Tevatron, *Comput. Phys. Commun.* **182**, 2605 (2011); P. Bechtle, O. Brein, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein, and K. Williams, Recent developments in HiggsBounds and a preview of Higgs signals, *Proc. Sci.*, CHARGED2012 (2012) 024 [[arXiv:1301.2345](#)]; HiggsBounds – 4: Improved tests of extended Higgs sectors against exclusion bounds from LEP, the Tevatron and the LHC, *Eur. Phys. J. C* **74**, 2693 (2014); P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, and G. Weiglein, Applying exclusion likelihoods from LHC searches to extended Higgs sectors, *Eur. Phys. J. C* **75**, 421 (2015).
- [21] A. Ismail, H. E. Logan, and Y. Wu, Updated constraints on the Georgi-Machacek model from LHC Run 2, [arXiv:2003.02272](#).
- [22] C. W. Chiang, A. L. Kuo, and T. Yamada, Searches of exotic Higgs bosons in general mass spectra of the Georgi-Machacek model at the LHC, *J. High Energy Phys.* **01** (2016) 120.
- [23] G. Aad *et al.* (ATLAS Collaboration), Evidence for Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector, *Phys. Rev. Lett.* **113**, 141803 (2014).
- [24] C. W. Chiang, S. Kanemura, and K. Yagyu, Novel constraint on the parameter space of the Georgi-Machacek model with current LHC data, *Phys. Rev. D* **90**, 115025 (2014).
- [25] G. Aad *et al.* (ATLAS Collaboration), Search for anomalous production of prompt same-sign lepton pairs and pair-produced doubly charged Higgs bosons with $\sqrt{s} = 8$ TeV pp collisions using the ATLAS detector, *J. High Energy Phys.* **03** (2015) 041.
- [26] S. Kanemura, M. Kikuchi, H. Yokoya, and K. Yagyu, LHC Run-I constraint on the mass of doubly charged Higgs bosons in the same-sign diboson decay scenario, *Prog. Theor. Exp. Phys.* **2015**, 051B02 (2015).
- [27] G. Aad *et al.* (ATLAS Collaboration), Search for Scalar Diphoton Resonances in the Mass Range 65–600 GeV with the ATLAS Detector in pp Collision Data at $\sqrt{s} = 8$ TeV, *Phys. Rev. Lett.* **113**, 171801 (2014).
- [28] M. Aaboud *et al.* (ATLAS Collaboration), Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* **78**, 199 (2018).
- [29] C. W. Chiang, A. L. Kuo, and K. Yagyu, Radiative corrections to Higgs couplings with weak gauge bosons in custodial multi-Higgs models, *Phys. Lett. B* **774**, 119 (2017).
- [30] C. W. Chiang, A. L. Kuo, and K. Yagyu, One-loop renormalized Higgs boson vertices in the Georgi-Machacek model, *Phys. Rev. D* **98**, 013008 (2018).
- [31] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [32] J. Butterworth *et al.*, PDF4LHC recommendations for LHC Run II, *J. Phys. G* **43**, 023001 (2016).
- [33] M. Zaro and H. Logan, Recommendations for the interpretation of LHC searches for H_5^0 , $H_5^\pm$, and $H_5^{\pm\pm}$ in vector boson fusion with decays to vector boson pairs, Report No. LHCHSWG-2015-001.
- [34] C. Degrande, K. Hartling, and H. E. Logan, Scalar decays to $\gamma\gamma$, $Z\gamma$, and $W\gamma$ in the Georgi-Machacek model, *Phys. Rev. D* **96**, 075013 (2017); Erratum, *Phys. Rev. D* **98**, 019901 (2018).