

## Asymmetric di-Higgs signals of the next-to-minimal 2HDM with a U(1) symmetry

Sumit Banik<sup>1,2,\*</sup>, Andreas Crivellin<sup>1,2,†</sup>, Syuhei Iguro<sup>3,4,‡</sup> and Teppey Kitahara<sup>5,6,7,§</sup>

<sup>1</sup>Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH–8057 Zürich, Switzerland

<sup>2</sup>Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland

<sup>3</sup>Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), Engesserstraße 7, 76131 Karlsruhe, Germany


<sup>4</sup>Institute for Astroparticle Physics (IAP), KIT,

Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

<sup>5</sup>Institute for Advanced Research & Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya 464–8602, Japan

<sup>6</sup>KEK Theory Center, IPNS, KEK, Tsukuba 305–0801, Japan

<sup>7</sup>CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

 (Received 23 March 2023; accepted 31 July 2023; published 9 October 2023)

The two-Higgs-doublet model with a  $U(1)_H$  gauge symmetry (N2HDM- $U(1)$ ) has several advantages compared to the “standard”  $Z_2$  version (N2HDM- $Z_2$ ): It is purely based on gauge symmetries, involves only spontaneous symmetry breaking, and is more predictive because it contains one parameter less in the Higgs potential, which further ensures  $CP$  conservation, i.e., avoiding the stringent bounds from electric dipole moments. After pointing out that a second, so far unknown version of the N2HDM- $U(1)$  exists, we examine the phenomenological consequences for the Large Hadron Collider (LHC) of the differences in the scalar potentials. In particular, we find that while the N2HDM- $Z_2$  predicts suppressed branching ratios for decays into different Higgs bosons for the case of the small scalar mixing (as suggested by Higgs coupling measurements), both versions of the N2HDM- $U(1)$  allow for sizable rates. This is particularly relevant in light of the CMS excess in resonant Higgs-pair production at around 650 GeV of a Standard Model Higgs boson subsequently decaying to photons and a new scalar with a mass of  $\approx 90$  GeV subsequently decaying to bottom quarks (i.e., compatible with the CMS and ATLAS  $\gamma\gamma$  excesses at 95 GeV and  $\approx 670$  GeV). As we will show, this excess can be addressed within the N2HDM- $U(1)$  in case of a nonminimal Yukawa sector, predicting an interesting and unavoidable  $Z + b\bar{b}$  signal and motivating further asymmetric di-Higgs searches at the LHC.

DOI: [10.1103/PhysRevD.108.075011](https://doi.org/10.1103/PhysRevD.108.075011)

### I. INTRODUCTION

The discovery of the Brout-Englert-Higgs boson [1–6] by ATLAS [7] and CMS [8] established, for the first time, the existence of a fundamental scalar particle within the Standard Model (SM). This observation motivates the existence of more scalar particles and, in turn, the experimental search for them. While the 125 GeV Higgs ( $h$ ) boson has approximately SM-like properties [9–14], this

does not exclude the existence of additional scalar bosons, as long as their role in the breaking of the electroweak (EW) gauge symmetry and the mixing with the SM-like Higgs boson are sufficiently small.

In this context, strong constraints on new physics (NP) models are provided by the  $\rho$  parameter that relates the EW gauge couplings to the  $W$  and  $Z$  masses and is defined to be unity in the SM at tree level. This singles out models with  $SU(2)_L$ -singlet or  $SU(2)_L$ -doublet extensions of the SM Higgs sector whose vacuum expectation values (VEVs) conserve the custodial symmetry, such that the additional scalars only give loop-level effects in the  $\rho$  parameter.<sup>1</sup>

<sup>1</sup>Also larger  $SU(2)_L$  multiplets are possible in case their VEV is very small, or if a global custodial  $SU(2)$  symmetry protects the  $\rho$  parameter, which however entails larger and more complex Higgs sectors [15].

\*sumit.banik@psi.ch

†andreas.crivellin@cern.ch

‡igurosyuhei@gmail.com

§teppeik@kmi.nagoya-u.ac.jp

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 SCOAP<sup>3</sup>.

The most studied extensions of the SM scalar sector are the two-Higgs-doublet models (2HDMs) [16–19]. Here, usually a discrete  $Z_2$  symmetry is imposed to both solve the problem of flavor changing neutral currents [20,21] (resulting in four different versions with natural flavor conservation [22,23]) and to provide (accidental)  $CP$  conservation in the Higgs potential. However, for phenomenological reasons, i.e., to give VEV-independent masses to the additional scalars, the  $Z_2$  symmetry must be broken. In order to avoid domain wall problems caused by a spontaneous discrete symmetry breaking [24], the  $Z_2$  symmetry is usually softly broken by a dimension-two term [25]. This operator (in case of a nonvanishing and nonaligned  $\lambda_5$  term) in general gives rise to  $CP$  violation within the Higgs sector, with potentially dangerously significant effects in electric dipole moments [26].

Reference [27] proposed to solve these problems by replacing the discrete  $Z_2$  symmetry with a  $U(1)_H$  gauge symmetry, which can mimic the effect of the  $Z_2$  symmetry but forbids the explicit soft-breaking term. However, if the  $Z'$  boson originating from the  $U(1)_H$  gauge is required to be heavier than the EW scale, one has to supplement the model with an additional scalar charged under  $U(1)_H$ ; minimally, a complex scalar  $\phi$  that is a singlet under the SM gauge group. Because its  $CP$ -odd component becomes (in the vanishing scalar mixing limit) the longitudinal component of the  $Z'$ , the scalar potential effectively resembles the one of the next-to-minimal 2HDM (N2HDM) with a real scalar (see, e.g., Refs. [28–46]). In particular, the VEV of  $\phi$  gives rise to the  $m_{12}^2$  term that softly breaks the  $Z_2$  symmetry.

While in the N2HDM with two discrete  $Z_2$  symmetries (N2HDM- $Z_2$ ),<sup>2</sup> Higgs-boson-related collider observables have been studied in detail [47], including loop effects [48,49], and even automated codes exist [50–53],<sup>3</sup> studies of the N2HDM with a  $U(1)_H$  gauge symmetry [N2HDM- $U(1)$ ] have not focused on the collider phenomenology of the additional scalars but mostly considered dark matter [57–59], muon  $g-2$  [60], neutrino masses [61–66],  $b \rightarrow s\ell^+\ell^-$  anomalies [67,68],  $Z'$  searches [7,69,70], and Higgs signal strengths [71]. However, also the (effective) scalar potential of this N2HDM- $U(1)$  is different from the one of the usual N2HDM- $Z_2$ , which, in particular, leads to different Higgs self-interactions and, therefore, different decay rates for heavy scalars into light ones.

This aspect is now more relevant in light of the ongoing and intensified Large Hadron Collider (LHC) searches for new scalar bosons (see, e.g., Ref. [72] for a recent review). While no unequivocal evidence for a new particle has been observed, interesting hints for new scalars with masses

around 95 GeV [46,73–87], 151 GeV [88–92], and 670 GeV [76,93–95] have been reported.<sup>4</sup> In particular, the CMS excess for a  $\approx 650$  GeV scalar decaying into a  $\approx 90$  GeV one (i.e., compatible with the 95 GeV hints mentioned above due to the limited detector resolution for bottom jets) and a SM Higgs boson [76] needs multiple new Higgs bosons with a mass hierarchy [which is only possible if they are not within the same  $SU(2)_L$  multiplet while respecting perturbativity bounds]<sup>5,6</sup> Furthermore, as it is an asymmetric di-Higgs decay, it requires interactions among the three different scalars. Here, asymmetric decay means the decay of a heavy scalar into two different lighter scalars. While the rates of such asymmetric di-Higgs decays are in general small in the MSSM [100,101], 2HDMs [102] and also in the N2HDM- $Z_2$  [103], we will show that for the N2HDM- $U(1)$  they are naturally sizable.

## II. THE MODEL

As outlined in the Introduction, a  $Z_2$  symmetry is commonly used to construct the four versions of the 2HDMs with natural flavor conservation and, at the same time, constrain the scalar potential. In the N2HDM, even two  $Z_2$  symmetries are usually employed to prevent tree-level flavor changing neutral currents and eliminate most sources of  $CP$  violation. We want to use instead a single  $U(1)_H$  gauge symmetry under which at least two of the scalar fields are charged.

We start with the scalar potential for the two  $SU(2)_L$  doublets  $H_1$  and  $H_2$  with hypercharge  $1/2$  (where according to the usual 2HDM conventions  $H_2$  contains most of the SM Higgs for the case of small mixing angles). If the  $U(1)_H$  charges of  $H_1$  and  $H_2$  are different, operators with an odd number of these fields are forbidden, leading to

$$\mathcal{V}_H = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1). \quad (1)$$

This potential is  $CP$  conserving as it does not contain the soft-breaking term  $m_{12}^2 H_1^\dagger H_2$  nor the term  $\frac{\lambda_5}{2} (H_1^\dagger H_2)^2$  contained in the 2HDM with the (softly broken)  $Z_2$  symmetry.

Next, we add a complex scalar SM singlet  $\phi$  that is charged under the  $U(1)_H$  gauge symmetry. Its

<sup>4</sup>In addition, anomalies in multilepton final states exist, which can also be explained by new scalars [88,96–99].

<sup>5</sup>Note that the di-Higgs excess is compatible with the 95 GeV and 670 GeV hints mentioned before due to the limited detector resolution for bottom jets, which effectively removes the look-elsewhere effect.

<sup>6</sup>The mass differences between the additional scalars are controlled by the couplings in the scalar potential if they come from the same multiplet. The large mass difference compared to the EW VEV requires the huge coupling and hence, violates the unitarity constraint.

<sup>2</sup>Under the first  $Z_2$  symmetry, only  $H_2$  is odd, while for the second  $Z_2$ , only the real scalar is odd.

<sup>3</sup>The program ewN2HDECAY [51] is based on HDECAY [54,55] and 2HDECY [56].

self-interactions, as well as the ones with two identical doublets,

$$\mathcal{V}_\phi = |\phi|^2 \left( m_\phi^2 + \frac{\lambda_\phi}{2} |\phi|^2 + \lambda_{\phi 1} |H_1|^2 + \lambda_{\phi 2} |H_2|^2 \right), \quad (2)$$

are allowed independently of the  $U(1)_H$  charges. In addition, there are two options for charge assignments under the  $U(1)_H$  symmetry (for  $Q_H(H_1) \neq Q_H(H_2)$ ):

(a) If  $|Q_H(\phi)| = |Q_H(H_1) - Q_H(H_2)|$ , one has the term,

$$\mathcal{V}_{\phi H}^a = \sqrt{2} \mu H_1^\dagger H_2 \phi + \text{H.c.}, \quad (3)$$

or  $\phi$  replaced by  $\phi^\dagger$ , depending on the sign on the  $U(1)_H$  charge.

(b) If  $|Q_H(\phi)| = |Q_H(H_1) - Q_H(H_2)|/2$ , the term,

$$\mathcal{V}_{\phi H}^b = \lambda_{\phi 12} (H_1^\dagger H_2) \phi^2 + \text{H.c.}, \quad (4)$$

is gauge invariant. Case (a) was already proposed in Ref. [27], while case (b) is novel, to the best of our knowledge.

Note that we have normalized the prefactors of these potentials in such a way, that once we decompose

$$\phi = (v_S + \hat{S} + i\eta_S)/\sqrt{2}, \quad (5)$$

$\eta_S$  (mostly) becomes the longitudinal mode of the  $Z'$  and the terms involving  $\hat{S}$  match the N2HDM- $Z_2$ . Here,  $v_S$  is the VEV of  $\phi$ , and one can choose it to be real and positive without loss of generality. Therefore, disregarding the  $Z'$  boson, which could be heavy or weakly coupled, the N2HDM- $U(1)$  resembles the N2HDM- $Z_2$  with the important differences that the  $m_{12}^2$  and  $\lambda_5$  terms are only effectively generated by  $v_S$  and  $Z'$  exchange, respectively, similar to the  $\mu$  term in the next-to-minimal supersymmetric Standard Model (NMSSM) [104–109]. Moreover, this guarantees the absence of  $CP$  violation in the scalar potential (even when the  $Z'$  is integrated out), while this, in general, is inevitable in both the N2HDM- $Z_2$  and NMSSM.

We know from Higgs signal strength measurements that the mixing among the SM-like Higgs boson and the other two  $CP$ -even scalars should be rather small. Therefore, we will label the  $CP$ -even mass eigenstates, contained in the absence of mixing within  $H_2$ ,  $H_1$ , and  $\phi$  as  $h$ ,  $H$ , and  $S$ , respectively.<sup>7</sup> Importantly, the mixing among  $H$ ,  $h$ , and  $S$  in the N2HDM- $U(1)$  is related to the masses  $m_H$ ,  $m_{H^\pm}$ , and  $m_A$  (where  $H^\pm$  and  $A$  denote the charged and  $CP$ -odd Higgs boson, respectively) because they all involve the effective  $m_{12}^2$  term originating from  $\mu$  or  $\lambda_{\phi 12}$ . This means that the effective  $m_{12}^2$  term automatically leads to  $H$ - $S$

<sup>7</sup>As we only consider the case of small mixing, we will label in the main text both the  $CP$ -even components of the doublets and the singlet, as well as the mass eigenstates by  $h$ ,  $H$ , and  $S$  and use them interchangeably. In the Appendix, the full mass matrices in the weak eigenbasis are given.

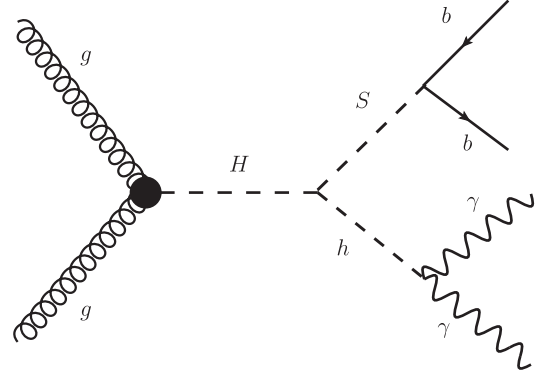


FIG. 1. Feynman diagram showing resonant asymmetric Higgs pair production. The discovery of this process, for which the CMS measurement constitutes a first hint, would be a smoking gun for the N2HMD- $U(1)$ . Here, the black circle denotes the loop-induced effective coupling to gluons. However, note that the heavy top limit cannot be used because  $m_t \ll m_H$ , and we use the expression for a dynamical top quark in our numerical analysis.

mixing as can be inferred from the  $CP$ -even mass matrix (in the large  $\tan\beta$  limit, i.e., assuming  $v_1$  to be small),

$$M_\rho^2 \approx \begin{pmatrix} -\mu v_S \tan\beta & \mu v_S & \mu v \\ \mu v_S & \lambda_2 v^2 & \lambda_{\phi 2} v v_S \\ \mu v & \lambda_{\phi 2} v v_S & \lambda_\phi v_S^2 \end{pmatrix}, \quad (6)$$

where  $\tan\beta = v_2/v_1$  and  $\langle H_i \rangle = v_i/\sqrt{2}$ . Note that the effects of  $\lambda_1$ ,  $\lambda_3$ ,  $\lambda_4$ , and  $\lambda_{\phi 1}$  on the  $CP$ -even Higgs masses become negligible in the large  $\tan\beta$  limit. The full expressions for the minimization, the mass matrices, etc., can be found in the Appendix.

Concerning the fermion Yukawa sector, the most natural choice is probably to assume that the SM fermions are uncharged under  $U(1)_H$ , or to assign equal charges to left-handed and right-handed fields (such as  $B - L$  or  $L_\mu - L_\tau$ ) in order to avoid gauge anomalies. In this setup, the doublet  $H_2$  would be  $U(1)_H$  neutral, while  $H_1$  carries some  $U(1)_H$  charge  $Q_H$ . This then leads to a type-I Yukawa sector, which also has the advantage of being quite unconstrained in the large  $\tan\beta$  and small  $\alpha$  (Higgs mixing angle) limit. However, also the other three types of 2HDMs with natural flavor conservation, as well as the generic type-III model,<sup>8</sup> can be obtained even in an anomaly free fashion if the fermion sector is extended [27].

### III. PHENOMENOLOGY

The N2HDM- $U(1)$  is in general more predictive than the N2HDM- $Z_2$  as it contains one parameter less and has no

<sup>8</sup>The type-III model has been comprehensively studied in Ref. [110] as it can (partially) explain the tensions in  $R(D^{(*)})$  [111,112].

sources of  $CP$  violation in the Higgs potential. However, what is the most striking difference regarding LHC observables between the different N2HDMs, even when the  $Z'$  predicted by the N2HDM- $U(1)$  is disregarded, as it might be heavy or weakly coupled?

To answer this, let us consider the limit of vanishing mixing among the neutral  $CP$ -even scalars, in which  $h$  is purely SM-like,  $H$  only couples to  $W^\pm H^\mp$  and  $ZA$ , and  $S$  is sterile. Now,  $\mu$  ( $\lambda_{\phi_{12}}$ ) in Eq. (3) [Eq. (4)] has to be nonvanishing to give masses to  $H$ ,  $A$ , and  $H^\pm$  that are above the EW scale, i.e.,

$$m_H^2 \approx m_A^2 \approx m_{H^\pm}^2 \approx -\mu v_S \tan \beta, \quad (7)$$

assuming  $\lambda_4$  to be small. This then, at the same time, suppresses  $H$ - $h$  and  $H$ - $S$  mixings, and from Eq. (6), we see that  $h$ - $S$  mixing can be avoided, for large  $\tan \beta$  with  $\lambda_{\phi_2} = 0$ . This means that for  $m_H \gg v$ , the only unsuppressed decay of  $H$ , in the absence of Yukawa coupling of  $H_1$ , is  $H \rightarrow Sh$  for case (a), and in addition,  $H \rightarrow SS$  for case of (b), if  $m_H \gg m_S$  and  $m_{H^\pm} \approx m_H$ . Therefore, in the large  $\tan \beta$  limit, the N2HDM- $U(1)$  predicts sizable branching ratios for  $H \rightarrow Sh$  [and also  $H \rightarrow SS$  in case (b)]. As this decay in the N2HDM- $Z_2$  is suppressed by small mixing angles, the discovery of an asymmetric di-Higgs signal would be a smoking gun for the N2HDM- $U(1)$ .<sup>9</sup>

Let us now illustrate this observation more quantitatively in the context of the hint for the  $\approx 650$  GeV boson decaying into a  $\approx 90$  GeV scalar and the SM Higgs boson with a global (local) significance of  $2.8\sigma$  ( $3.8\sigma$ ) [76]. Here, the  $\approx 90$  GeV resonance decays into  $b\bar{b}$  and the SM Higgs boson into  $\gamma\gamma$ . Because the detector resolution for bottom jets is not so good, this  $\approx 90$  GeV excess could be compatible with the  $\gamma\gamma$  [74],  $\tau\bar{\tau}$  [75], and the LEP  $ZH$  measurement [73] pointing towards a mass of  $\approx 95$  GeV, as well as with the  $\gamma\gamma$  [94] and  $ZZ$  excesses [93] at around  $\approx 670$  GeV. This makes this asymmetric di-Higgs signal particularly interesting and effectively eliminates the look-elsewhere effect of the CMS di-Higgs analysis.

The cross section for the  $pp \rightarrow b\bar{b}\gamma\gamma$  excess is  $\approx 0.35_{-0.13}^{+0.17}$  fb according to the CMS analysis [76]. However, the CMS analysis of  $pp \rightarrow b\bar{b}\tau\bar{\tau}$  [115] finds an upper limit on the corresponding cross section of  $\approx 4$  fb for  $\approx 650$  GeV boson search with  $m_{bb} \approx 90$  GeV. With  $\text{BR}(h \rightarrow \tau\bar{\tau})/\text{BR}(h \rightarrow \gamma\gamma) \approx 20$ , one can obtain  $\approx 0.2$  fb as the upper bound on  $pp \rightarrow b\bar{b}\gamma\gamma$ , and this translates into the limit  $\sigma(pp \rightarrow (650) \rightarrow (95)h) \times \text{BR}((95) \rightarrow b\bar{b}) \lesssim 90$  fb, taking into account that  $\text{BR}(h \rightarrow \gamma\gamma) \approx 0.23\%$ . Therefore, the  $b\bar{b}\gamma\gamma$  excess cannot be fully explained, but it is still possible to account for it within  $2\sigma$ , and we will aim at

<sup>9</sup>This resembles the situation in the NMSSM where also sizable asymmetric Higgs decays are possible [113,114].

$$\sigma(pp \rightarrow (650) \rightarrow (95)h) \times \text{BR}((95) \rightarrow b\bar{b}) \approx 70 \text{ fb}. \quad (8)$$

There are two options within the N2HDM- $U(1)$ : one can A) identify the  $\approx 95$  GeV state with  $H$  and the  $\approx 650$  GeV one with  $S$  ( $pp \rightarrow S \rightarrow Hh$ ) or B) vice versa ( $pp \rightarrow H \rightarrow Sh$ ). However, in case A), the  $\mu$  term is naturally small because  $H$  is light, such that also the branching ratio is suppressed, unless one chooses very small mixing angles among the  $CP$ -even scalars. Let us, therefore, consider option B), i.e.,  $pp \rightarrow H \rightarrow Sh$  (shown in Fig. 1) in the following, again in the limit of small mixing and large  $\tan \beta$ . To obtain a sufficient production cross section of  $H$  we will consider the case of a non-minimal flavor structure and assume that  $H$  has a (effective) coupling to top quarks originating from the Lagrangian term  $-\tilde{Y}_t \bar{Q}_L \tilde{H}_1 t_R$ .<sup>10</sup> This coupling then also leads to unsuppressed decays of  $H \rightarrow t\bar{t}$  (and  $A \rightarrow t\bar{t}$ ).

For the numerical analysis, we use that a SM Higgs boson with a mass of  $\approx 650$  GeV would have a gluon fusion production cross section of  $\approx 1.35$  pb at NNLO [118–123]. This means that a coupling to top quarks is needed, that is around one quarter of the one of the SM Higgs boson, i.e.,  $\tilde{Y}_t \approx Y_t/4/(\sqrt{\text{BR}(H \rightarrow Sh)}\sqrt{\text{BR}(S \rightarrow b\bar{b})})$ . Therefore, assuming that  $S$  decays SM-like<sup>11</sup> [ $\text{BR}(S \rightarrow b\bar{b}) \approx 0.8$ ] results with Eq. (8) in  $\sigma(pp \rightarrow H) \approx 84 \text{ fb}/\text{BR}(H \rightarrow Sh)$ . Based on the Goldstone boson equivalence theorem [124,125], we also expect  $\text{BR}(A \rightarrow SZ) \approx \text{BR}(H \rightarrow Sh)$  leading to  $pp \rightarrow A \rightarrow ZS \rightarrow Zb\bar{b}$  (and also  $pp \rightarrow A \rightarrow Zh \rightarrow Zb\bar{b}$ ) with cross sections around  $1.5 \times 70 \text{ fb}$ ,<sup>12</sup> searched for by ATLAS [127–129] and CMS [130,131]. Note that in fact, Ref. [131] finds a mild excess within the relevant region.

Furthermore, we can predict the cross section of  $H \rightarrow t\bar{t}$  and  $A \rightarrow t\bar{t}$ , as well as  $pp \rightarrow t\bar{t}H \rightarrow t\bar{t}t\bar{t}$  and  $pp \rightarrow t\bar{t}A \rightarrow t\bar{t}t\bar{t}$  as a function of  $\tan \beta$  and  $v_S$  (assuming  $\lambda_{\phi_2} = 0$  as well as  $m_H \approx m_A$ ) and compare this to the limits on the resonant  $t\bar{t}$  production of CMS [132] and ATLAS [133] as well as to  $t\bar{t}t\bar{t}$  production measured by CMS [134] and ATLAS [135]. This is illustrated in Fig. 2, where we show the predicted cross section for  $pp \rightarrow A \rightarrow t\bar{t}$  in units of pb as a function of  $\tan \beta$  and  $v_S$ . The red region is excluded by the  $pp \rightarrow t\bar{t}t\bar{t}$  search of ATLAS and the gray region by the requirement of

<sup>10</sup>This coupling can be induced at tree level by vectorlike quarks mixing with SM ones via coupling to  $S$ . Alternatively, an effective coupling to gluons could be loop induced by colored new heavy fermions or scalars. In fact, CMS observed an excess in di-di-jet searches [116] that point towards new colored particles at the TeV scale [117].

<sup>11</sup>This procedure is justified since the other couplings of  $S$  are given by the mixing with the other scalars and hence aligned to the SM-like coupling structure.

<sup>12</sup>Note that at this energy, the gluon-fusion-production cross section for a pseudoscalar via top-quark loops is  $\approx 1.5$  times the one of a  $CP$ -even scalar with the same mass and coupling (see, e.g., Refs. [101,126]).

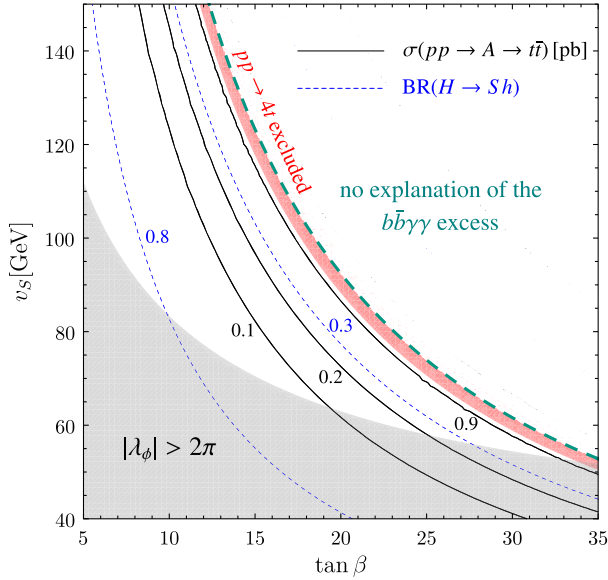


FIG. 2. Predictions for  $\sigma(pp \rightarrow A \rightarrow t\bar{t})$  [pb] as a function of  $\tan\beta$  and  $v_S$  in the N2HDM- $U(1)$  for case (a), assuming that the CMS excess  $b\bar{b}\gamma\gamma$  in Eq. (8) is explained. The gray region is excluded by the requirement of perturbative couplings, while the red region is excluded by the  $t\bar{t}t\bar{t}$  search [135], assuming  $m_A \approx m_H$ . Note that the  $b\bar{b}\gamma\gamma$  excess cannot be explained in the top-right region of the green dashed line.

positive eigenvalues of the mass matrix as well as perturbative couplings. Since  $\sigma(pp \rightarrow H \rightarrow Sh) \approx 84$  fb is required, when  $\text{BR}(S \rightarrow \gamma\gamma) \approx 0.15\%$  (again assuming that  $S$  has SM-like branching ratios), we obtain for the inclusive cross section  $\sigma(pp \rightarrow S + X \rightarrow \gamma\gamma + X) \approx 0.1$  fb, which is compatible with the current limits but insufficient to explain the  $\gamma\gamma$  excess at 95 GeV of  $\approx 50$  fb [74]. Therefore, direct production of  $S$  would be required in addition to explain the  $\gamma\gamma$  excess, e.g., via gluon fusion from the mixing of  $S$  with  $H$  or  $h$  [82]. We would like to emphasize again that although the current excesses are not fully explained in the minimal model, the asymmetric di-Higgs decay is a key prediction and further experimental analyses are encouraged.

#### IV. CONCLUSIONS

While Higgs physics in the N2HDM with two discrete  $Z_2$  symmetries (N2HDM- $Z_2$ ) has been studied in detail in the literature, this phenomenological aspect of the N2HDM with a  $U(1)_H$  gauge symmetry has received little to no attention so far. While both versions have desirable features such as natural flavor conservation, there are even several advantages of the N2HDM- $U(1)_H$  over the N2HDM- $Z_2$ :

- (i) Only one  $U(1)_H$  gauge symmetry is needed instead of two  $Z_2$  symmetries.
- (ii) Like the SM, the N2HDM- $U(1)_H$  is built on local gauge symmetries and spontaneous symmetry

breaking (i.e., unlike the N2HDM- $Z_2$  no soft-breaking is needed).

- (iii) The N2HDM- $U(1)_H$  symmetry is more predictive than the N2HDM- $Z_2$  because it contains one parameter less.

If the  $Z'$  boson is decoupled from phenomenology, either because it is heavy or weakly interacting, the scalar sector of the N2HDM- $U(1)_H$  is close to the one of the N2HDM- $Z_2$ ; however, there are important differences:

- (i) In the N2HDM- $U(1)$  no  $\lambda_5$  term is allowed, leading to  $CP$  conservation. This feature is even conserved when the  $Z'$  is integrated out because of an automatic phase alignment avoiding potentially dangerous effects in electric dipole moments.
- (ii) The  $m_{12}^2$  term is absent before spontaneous symmetry breaking and induced by the VEV of  $\phi$ , either from the term  $\mu H_1^\dagger H_2 \phi$  or  $\lambda_{\phi 12} (H_1^\dagger H_2) \phi^2$ , depending on the charge assignment. Please note that the latter option was, to the best of our knowledge, not proposed before in the literature.
- (iii) While in N2HDM- $Z_2$ , if  $H$  is heavy, only symmetric decays into Higgs pairs; i.e.,  $H \rightarrow SS$  and  $H \rightarrow hh$  are possible in the limit of zero mixing, in the N2HDM- $U(1)$ , one expects naturally large branching ratios for  $H \rightarrow Sh$ . Note that while in case (a), only asymmetric decays are unsuppressed, in case (b) also decays to identical scalars (e.g.,  $H \rightarrow SS$ ) can be sizable.

The last difference has important implications for the asymmetric  $\approx 650$  GeV excess in  $b\bar{b}\gamma\gamma$ . While even if  $H$  is equipped with a sufficiently high production cross section (e.g., from direct top-quark Yukawa couplings of  $H_1$ ), the N2HDM- $Z_2$  could not account for the preferred central value of the measurement as  $\text{BR}(H \rightarrow Sh)$  could not be sizable enough, taking into account the limits on the scalar mixing from Higgs coupling strength measurements at the LHC. However, the N2HDM- $U(1)$  can address this measurement, predicting signatures in  $pp \rightarrow H(A) \rightarrow t\bar{t}$ ,  $pp \rightarrow t\bar{t}H(A) \rightarrow 4t$ , and  $pp \rightarrow A \rightarrow SZ$ , not far away from the current experimental limits.

Finally, let us point out that  $Z$ - $Z'$  mixing, in general, present in this model, can naturally account for the higher than expected value of the  $W$  mass [136], as suggested by the measurement of the CDF-II Collaboration [137]. Together with the previous arguments this strongly motivates detailed studies of the N2HDM- $U(1)$  (including its Higgs sector) which, in our opinion, should be considered to be (at least) at the same level of interest as the standard N2HDM- $Z_2$  and therefore be examined with the same scrutiny theoretical and experimental in the future, motivating more asymmetric di-Higgs searches at the LHC.

#### ACKNOWLEDGMENTS

We are very grateful to Michael Spira for useful comments on the manuscript and to Bruce Mellado for useful

discussion. The work of A. C. is supported by a professorship grant from the Swiss National Science Foundation (Grant No. PP00P21\_76884). S. I. is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Grant No. 396021762-TRR 257. T. K. is supported by the Grant-in-Aid for Early-Career Scientists from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan, Grant No. 19K14706. This work is also supported by the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program, Grant No. JPJSCCA20200002.

*Note added.*—Recently, CMS presented updated results for low mass searches for new scalars decaying into  $\gamma\gamma$  [138], confirming the previous excess.

### APPENDIX: MINIMIZATION AND MASS MATRICES

In this appendix, we give the minimization conditions and mass matrices of both types, (a) and (b), of the N2HDM- $U(1)$ . We define  $H_1$ ,  $H_2$  and  $\phi$  as,

$$H_1 = \begin{pmatrix} w_1^+ \\ \frac{v_1 + \hat{H} + i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} w_2^+ \\ \frac{v_2 + \hat{h} + i\eta_2}{\sqrt{2}} \end{pmatrix},$$

$$\phi = \frac{v_S + \hat{S} + i\eta_S}{\sqrt{2}}. \quad (\text{A1})$$

#### 1. Case (a): $|\mathcal{Q}_H(\phi)| = |\mathcal{Q}_H(H_1) - \mathcal{Q}_H(H_2)|$

The minimization conditions are

$$m_{11}^2 + \frac{1}{2}\lambda_1 v_1^2 + \frac{1}{2}\lambda_{345} v_2^2 + \frac{1}{2}\lambda_{\phi 1} v_S^2 + \mu v_S \frac{v_2}{v_1} = 0,$$

$$m_{22}^2 + \frac{1}{2}\lambda_2 v_2^2 + \frac{1}{2}\lambda_{345} v_1^2 + \frac{1}{2}\lambda_{\phi 2} v_S^2 + \mu v_S \frac{v_1}{v_2} = 0,$$

$$m_S^2 + \frac{1}{2}\lambda_{\phi 1} v_1^2 + \frac{1}{2}\lambda_{\phi 2} v_2^2 + \frac{1}{2}\lambda_{\phi} v_S^2 + \mu \frac{v_1 v_2}{v_S} = 0, \quad (\text{A2})$$

where  $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5^{\text{eff}}$ , and  $\lambda_5^{\text{eff}} \neq 0$  is only generated if the  $Z'$  is integrated out. The scalar squared-mass matrices are

$$M_\rho^2 = \begin{pmatrix} \lambda_1 v_1^2 - \mu v_S \frac{v_2}{v_1} & \lambda_{345} v_1 v_2 + \mu v_S & \lambda_{\phi 1} v_1 v_S + \mu v_2 \\ \lambda_{345} v_1 v_2 + \mu v_S & \lambda_2 v_2^2 - \mu v_S \frac{v_1}{v_2} & \lambda_{\phi 2} v_2 v_S + \mu v_1 \\ \lambda_{\phi 1} v_1 v_S + \mu v_2 & \lambda_{\phi 2} v_2 v_S + \mu v_1 & \lambda_{\phi} v_S^2 - \mu \frac{v_1 v_2}{v_S} \end{pmatrix}, \quad (\text{A3})$$

$$M_\eta^2 = \begin{pmatrix} -\mu v_S \frac{v_2}{v_1} - \lambda_5^{\text{eff}} v_2^2 & \mu v_S + \lambda_5^{\text{eff}} v_1 v_2 & \mu v_2 \\ \mu v_S + \lambda_5^{\text{eff}} v_1 v_2 & -\mu v_S \frac{v_1}{v_2} - \lambda_5^{\text{eff}} v_1^2 & -\mu v_1 \\ \mu v_2 & -\mu v_1 & -\mu \frac{v_1 v_2}{v_S} \end{pmatrix}, \quad (\text{A4})$$

$$M_w^2 = \begin{pmatrix} -\mu v_S \frac{v_2}{v_1} - (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v_2^2}{2} & \mu v_S + (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v_1 v_2}{2} \\ \mu v_S + (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v_1 v_2}{2} & -\mu v_S \frac{v_1}{v_2} - (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v_1^2}{2} \end{pmatrix}, \quad (\text{A5})$$

which are defined via the bilinear potential terms

$$V_{m^2} = \frac{1}{2} \begin{pmatrix} \hat{H} & \hat{h} & \hat{S} \end{pmatrix} M_\rho^2 \begin{pmatrix} \hat{H} \\ \hat{h} \\ \hat{S} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \eta_1 & \eta_2 & \eta_S \end{pmatrix} M_\eta^2 \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_S \end{pmatrix} + (w_1^- \quad w_2^-) M_w^2 \begin{pmatrix} w_1^+ \\ w_2^+ \end{pmatrix}. \quad (\text{A6})$$

The eigenvalues of the  $CP$ -odd and charged-Higgs masses are then given by

$$M_A^2 = -\mu \left( \frac{v_S v^2}{v_1 v_2} + \frac{v_1 v_2}{v_S} \right) - \lambda_5^{\text{eff}} v^2, \quad (\text{A7})$$

$$M_{H^\pm}^2 = -\frac{\mu v_S v^2}{v_1 v_2} - (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v^2}{2}. \quad (\text{A8})$$

#### 2. Case (b): $|\mathcal{Q}_H(\phi)| = |\mathcal{Q}_H(H_1) - \mathcal{Q}_H(H_2)|/2$

The minimization conditions in this case are

$$m_{11}^2 + \frac{1}{2}\lambda_1 v_1^2 + \frac{1}{2}\lambda_{345} v_2^2 + \frac{1}{2}\lambda_{\phi 1} v_S^2 + \frac{1}{2} \frac{\lambda_{\phi 12} v_2 v_S^2}{v_1} = 0,$$

$$m_{22}^2 + \frac{1}{2}\lambda_2 v_2^2 + \frac{1}{2}\lambda_{345} v_1^2 + \frac{1}{2}\lambda_{\phi 2} v_S^2 + \frac{1}{2} \frac{\lambda_{\phi 12} v_1 v_S^2}{v_2} = 0,$$

$$m_S^2 + \frac{1}{2}\lambda_{\phi 1} v_1^2 + \frac{1}{2}\lambda_{\phi 2} v_2^2 + \frac{1}{2}\lambda_{\phi} v_S^2 + \lambda_{\phi 12} v_1 v_2 = 0, \quad (\text{A9})$$

and the squared-mass matrices are given by

$$M_\rho^2 = \begin{pmatrix} \lambda_1 v_1^2 - \frac{\lambda_{\phi 12} v_2 v_S^2}{2v_1} & \lambda_{345} v_1 v_2 + \frac{1}{2} \lambda_{\phi 12} v_S^2 & \lambda_{\phi 1} v_1 v_S + \lambda_{\phi 12} v_2 v_S \\ \lambda_{345} v_1 v_2 + \frac{1}{2} \lambda_{\phi 12} v_S^2 & \lambda_2 v_2^2 - \frac{\lambda_{\phi 12} v_1 v_S^2}{2v_2} & \lambda_{\phi 2} v_2 v_S + \lambda_{\phi 12} v_1 v_S \\ \lambda_{\phi 1} v_1 v_S + \lambda_{\phi 12} v_2 v_S & \lambda_{\phi 2} v_2 v_S + \lambda_{\phi 12} v_1 v_S & \lambda_\phi v_S^2 \end{pmatrix}, \quad (\text{A10})$$

$$M_\eta^2 = \begin{pmatrix} -\frac{\lambda_{\phi 12} v_2 v_S^2}{2v_1} - \lambda_5^{\text{eff}} v_2^2 & \frac{1}{2} \lambda_{\phi 12} v_S^2 + \lambda_5^{\text{eff}} v_1 v_2 & \lambda_{\phi 12} v_2 v_S \\ \frac{1}{2} \lambda_{\phi 12} v_S^2 + \lambda_5^{\text{eff}} v_1 v_2 & -\frac{\lambda_{\phi 12} v_1 v_S^2}{2v_2} - \lambda_5^{\text{eff}} v_1^2 & -\lambda_{\phi 12} v_1 v_S \\ \lambda_{\phi 12} v_2 v_S & -\lambda_{\phi 12} v_1 v_S & -2\lambda_{\phi 12} v_1 v_2 \end{pmatrix}, \quad (\text{A11})$$

$$M_w^2 = \frac{1}{2} \begin{pmatrix} -\frac{\lambda_{\phi 12} v_2 v_S^2}{v_1} - (\lambda_4 + \lambda_5^{\text{eff}}) v_2^2 & \lambda_{\phi 12} v_S^2 + (\lambda_4 + \lambda_5^{\text{eff}}) v_1 v_2 \\ \lambda_{\phi 12} v_S^2 + (\lambda_4 + \lambda_5^{\text{eff}}) v_1 v_2 & -\frac{\lambda_{\phi 12} v_1 v_S^2}{v_2} - (\lambda_4 + \lambda_5^{\text{eff}}) v_1^2 \end{pmatrix}. \quad (\text{A12})$$

The eigenvalues of the  $CP$ -odd and charged-Higgs masses are then given by

$$M_A^2 = -\lambda_{\phi 12} \left( \frac{v_S^2 v^2}{2v_1 v_2} + 2v_1 v_2 \right) - \lambda_5^{\text{eff}} v^2, \quad (\text{A13})$$

$$M_{H^\pm}^2 = -\frac{\lambda_{\phi 12} v_S^2 v^2}{2v_1 v_2} - (\lambda_4 + \lambda_5^{\text{eff}}) \frac{v^2}{2}. \quad (\text{A14})$$

- 
- [1] P. W. Higgs, Broken symmetries, massless particles and gauge fields, *Phys. Lett.* **12**, 132 (1964).
- [2] F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, *Phys. Rev. Lett.* **13**, 321 (1964).
- [3] P. W. Higgs, Broken Symmetries and the Masses of Gauge Bosons, *Phys. Rev. Lett.* **13**, 508 (1964).
- [4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global Conservation Laws and Massless Particles, *Phys. Rev. Lett.* **13**, 585 (1964).
- [5] P. W. Higgs, Spontaneous symmetry breakdown without massless bosons, *Phys. Rev.* **145**, 1156 (1966).
- [6] T. W. B. Kibble, Symmetry breaking in non-Abelian gauge theories, *Phys. Rev.* **155**, 1554 (1967).
- [7] G. Aad *et al.* (ATLAS Collaboration), Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* **716**, 1 (2012).
- [8] S. Chatrchyan *et al.* (CMS Collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* **716**, 30 (2012).
- [9] V. Khachatryan *et al.* (CMS Collaboration), Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV, *Phys. Rev. D* **92**, 012004 (2015).
- [10] G. Aad *et al.* (ATLAS Collaboration), Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector, *Eur. Phys. J. C* **75**, 476 (2015); **76**, 152(E) (2016).
- [11] V. Khachatryan *et al.* (CMS Collaboration), Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV, *Eur. Phys. J. C* **75**, 212 (2015).
- [12] G. Aad *et al.* (ATLAS Collaboration), Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at  $\sqrt{s} = 7$  and 8 TeV in the ATLAS experiment, *Eur. Phys. J. C* **76**, 6 (2016).
- [13] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, *Nature (London)* **607**, 60 (2022).
- [14] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, *Nature (London)* **607**, 52 (2022); **612**, E24(E) (2022).
- [15] M. S. Chanowitz and M. Golden, Higgs boson triplets With  $M(W) = M(Z) \cos \theta_w$ , *Phys. Lett.* **165B**, 105 (1985).
- [16] T. D. Lee, A theory of spontaneous T violation, *Phys. Rev. D* **8**, 1226 (1973).
- [17] J. F. Gunion and H. E. Haber, Higgs bosons in supersymmetric models. 2. Implications for phenomenology, *Nucl. Phys.* **B278**, 449 (1986); **B402**, 569(E) (1993).
- [18] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, *The Higgs Hunter's Guide* (CPC Press, Boca Raton, 2000), Vol. 80.
- [19] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, *Phys. Rep.* **516**, 1 (2012).

- [20] S. L. Glashow and S. Weinberg, Natural conservation laws for neutral currents, *Phys. Rev. D* **15**, 1958 (1977).
- [21] E. A. Paschos, Diagonal neutral currents, *Phys. Rev. D* **15**, 1966 (1977).
- [22] V. D. Barger, J. L. Hewett, and R. J. N. Phillips, New constraints on the charged Higgs sector in two Higgs doublet models, *Phys. Rev. D* **41**, 3421 (1990).
- [23] M. Aoki, S. Kanemura, K. Tsumura, and K. Yagyu, Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology, *Phys. Rev. D* **80**, 015017 (2009).
- [24] Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun, Cosmological consequences of the spontaneous breakdown of discrete symmetry, *Zh. Eksp. Teor. Fiz.* **67**, 3 (1974).
- [25] R. A. Battye, A. Pilaftsis, and D. G. Viatic, Domain wall constraints on two-Higgs-doublet models with  $Z_2$  symmetry, *Phys. Rev. D* **102**, 123536 (2020).
- [26] T. Chupp, P. Fierlinger, M. Ramsey-Musolf, and J. Singh, Electric dipole moments of atoms, molecules, nuclei, and particles, *Rev. Mod. Phys.* **91**, 015001 (2019).
- [27] P. Ko, Y. Omura, and C. Yu, A resolution of the flavor problem of two Higgs doublet models with an extra  $U(1)_H$  symmetry for Higgs flavor, *Phys. Lett. B* **717**, 202 (2012).
- [28] X.-G. He, T. Li, X.-Q. Li, J. Tandean, and H.-C. Tsai, Constraints on scalar dark matter from direct experimental searches, *Phys. Rev. D* **79**, 023521 (2009).
- [29] B. Grzadkowski and P. Osland, Tempered two-Higgs-doublet model, *Phys. Rev. D* **82**, 125026 (2010).
- [30] H. E. Logan, Dark matter annihilation through a lepton-specific Higgs boson, *Phys. Rev. D* **83**, 035022 (2011).
- [31] M. S. Boucenna and S. Profumo, Direct and indirect singlet scalar dark matter detection in the lepton-specific two-Higgs-doublet model, *Phys. Rev. D* **84**, 055011 (2011).
- [32] X.-G. He, B. Ren, and J. Tandean, Hints of standard model Higgs boson at the LHC and light dark matter searches, *Phys. Rev. D* **85**, 093019 (2012).
- [33] Y. Bai, V. Barger, L. L. Everett, and G. Shaughnessy, Two-Higgs-doublet-portal dark-matter model: LHC data and Fermi-LAT 135 GeV line, *Phys. Rev. D* **88**, 015008 (2013).
- [34] X.-G. He and J. Tandean, Low-mass dark-matter hint from CDMS II, Higgs boson at the LHC, and darkon models, *Phys. Rev. D* **88**, 013020 (2013).
- [35] Y. Cai and T. Li, Singlet dark matter in a type II two Higgs doublet model, *Phys. Rev. D* **88**, 115004 (2013).
- [36] C.-Y. Chen, M. Freid, and M. Sher, Next-to-minimal two Higgs doublet model, *Phys. Rev. D* **89**, 075009 (2014).
- [37] J. Guo and Z. Kang, Higgs naturalness and dark matter stability by scale invariance, *Nucl. Phys.* **B898**, 415 (2015).
- [38] L. Wang and X.-F. Han, A simplified 2HDM with a scalar dark matter and the galactic center gamma-ray excess, *Phys. Lett. B* **739**, 416 (2014).
- [39] A. Drozd, B. Grzadkowski, J. F. Gunion, and Y. Jiang, Extending two-Higgs-doublet models by a singlet scalar field: The case for dark matter, *J. High Energy Phys.* **11** (2014) 105.
- [40] R. Campbell, S. Godfrey, H. E. Logan, A. D. Peterson, and A. Poulin, Implications of the observation of dark matter self-interactions for singlet scalar dark matter, *Phys. Rev. D* **92**, 055031 (2015); **101**, 039905(E) (2020).
- [41] A. Drozd, B. Grzadkowski, J. F. Gunion, and Y. Jiang, Isospin-violating dark-matter-nucleon scattering via two-Higgs-doublet-model portals, *J. Cosmol. Astropart. Phys.* **10** (2016) 040.
- [42] S. von Buddenbrock, N. Chakrabarty, A. S. Cornell, D. Kar, M. Kumar, T. Mandal, B. Mellado, B. Mukhopadhyaya, R. G. Reed, and X. Ruan, Phenomenological signatures of additional scalar bosons at the LHC, *Eur. Phys. J. C* **76**, 580 (2016).
- [43] A. Arhrib, R. Benbrik, M. El Kacimi, L. Rahili, and S. Semlali, Extended Higgs sector of 2HDM with real singlet facing LHC data, *Eur. Phys. J. C* **80**, 13 (2020).
- [44] I. Engeln, P. Ferreira, M. M. Mühlleitner, R. Santos, and J. Wittbrodt, The dark phases of the N2HDM, *J. High Energy Phys.* **08** (2020) 085.
- [45] D. Azevedo, P. Gabriel, M. Mühlleitner, K. Sakurai, and R. Santos, One-loop corrections to the Higgs boson invisible decay in the dark doublet phase of the N2HDM, *J. High Energy Phys.* **10** (2021) 044.
- [46] T. Biekötter, S. Heinemeyer, and G. Weiglein, Excesses in the low-mass Higgs-boson search and the  $W$ -boson mass measurement, *Eur. Phys. J. C* **83**, 450 (2023).
- [47] H. Abouabid, A. Arhrib, D. Azevedo, J. E. Falaki, P. M. Ferreira, M. Mühlleitner, and R. Santos, Benchmarking di-Higgs production in various extended Higgs sector models, *J. High Energy Phys.* **09** (2022) 011.
- [48] P. Drechsel, R. Gröber, S. Heinemeyer, M. M. Mühlleitner, H. Rzehak, and G. Weiglein, Higgs-boson masses and mixing matrices in the NMSSM: Analysis of on-shell calculations, *Eur. Phys. J. C* **77**, 366 (2017).
- [49] J. Baglio, T. N. Dao, and M. Mühlleitner, One-loop corrections to the two-body decays of the neutral Higgs bosons in the complex NMSSM, *Eur. Phys. J. C* **80**, 960 (2020).
- [50] I. Engeln, M. Mühlleitner, and J. Wittbrodt, N2HDECAY: Higgs boson decays in the different phases of the N2HDM, *Comput. Phys. Commun.* **234**, 256 (2019).
- [51] M. Krause and M. Mühlleitner, ewN2HDECAY: A program for the calculation of electroweak one-loop corrections to Higgs decays in the next-to-minimal two-Higgs-doublet model including state-of-the-art QCD corrections, *Comput. Phys. Commun.* **247**, 106924 (2020).
- [52] M. Mühlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, ScannerS: Parameter scans in extended scalar sectors, *Eur. Phys. J. C* **82**, 198 (2022).
- [53] H. Bahl, T. Biekötter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, and J. Wittbrodt, HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals, *Comput. Phys. Commun.* **291**, 108803 (2023).
- [54] A. Djouadi, J. Kalinowski, and M. Spira, HDECAY: A program for Higgs boson decays in the standard model and its supersymmetric extension, *Comput. Phys. Commun.* **108**, 56 (1998).
- [55] A. Djouadi, J. Kalinowski, M. Muehlleitner, and M. Spira, HDECAY: Twenty<sub>++</sub> years after, *Comput. Phys. Commun.* **238**, 214 (2019).



- [56] M. Krause, M. Mühlleitner, and M. Spira, 2HDECAY: A program for the calculation of electroweak one-loop corrections to Higgs decays in the Two-Higgs-Doublet Model including state-of-the-art QCD corrections, *Comput. Phys. Commun.* **246**, 106852 (2020).
- [57] P. Ko, Y. Omura, and C. Yu, Dark matter and dark force in the type-I inert 2HDM with local  $U(1)_H$  gauge symmetry, *J. High Energy Phys.* **11** (2014) 054.
- [58] D. A. Camargo, M. D. Campos, T. B. de Melo, and F. S. Queiroz, A two Higgs doublet model for dark matter and neutrino masses, *Phys. Lett. B* **795**, 319 (2019).
- [59] T. Nomura and P. Sanyal, Lepton specific two-Higgs-doublet model based on a  $U(1)_X$  gauge symmetry with dark matter, *Phys. Rev. D* **100**, 115036 (2019).
- [60] T. Nomura and P. Sanyal, Explaining Atomki anomaly and muon  $g - 2$  in  $U(1)_X$  extended flavour violating two Higgs doublet model, *J. High Energy Phys.* **05** (2021) 232.
- [61] P. Ko, Y. Omura, and C. Yu, Multi-Higgs doublet models with local  $U(1)_H$  gauge symmetry and neutrino physics therein, *AIP Conf. Proc.* **1604**, 210 (2014).
- [62] T. Nomura and H. Okada, Hidden  $U(1)$  gauge symmetry realizing a neutrinophilic two-Higgs-doublet model with dark matter, *Phys. Rev. D* **97**, 075038 (2018).
- [63] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, Neutrino masses and mixings dynamically generated by a light dark sector, *Phys. Lett. B* **791**, 210 (2019).
- [64] D. A. Camargo, A. G. Dias, T. B. de Melo, and F. S. Queiroz, Neutrino masses in a two Higgs doublet model with a  $U(1)$  gauge symmetry, *J. High Energy Phys.* **04** (2019) 129.
- [65] H. Cai, T. Nomura, and H. Okada, A neutrino mass model with hidden  $U(1)$  gauge symmetry, *Nucl. Phys.* **B949**, 114802 (2019).
- [66] A. G. Dias, J. Leite, and D. S. V. Gonçalves, Axion-neutrino interplay in a gauged two-Higgs-doublet model, *Phys. Rev. D* **104**, 075014 (2021).
- [67] A. Crivellin, G. D'Ambrosio, and J. Heeck, Addressing the LHC flavor anomalies with horizontal gauge symmetries, *Phys. Rev. D* **91**, 075006 (2015).
- [68] L. Bian, S.-M. Choi, Y.-J. Kang, and H. M. Lee, A minimal flavored  $U(1)'$  for  $B$ -meson anomalies, *Phys. Rev. D* **96**, 075038 (2017).
- [69] D. A. Camargo, L. Delle Rose, S. Moretti, and F. S. Queiroz, Collider bounds on 2-Higgs doublet models with  $U(1)_X$  gauge symmetries, *Phys. Lett. B* **793**, 150 (2019).
- [70] J. A. Aguilar-Saavedra, F. R. Joaquim, and J. F. Seabra, Multiboson signals in the UN2HDM, *Eur. Phys. J. C* **82**, 1080 (2022).
- [71] P. Ko, Y. Omura, and C. Yu, Higgs phenomenology in Type-I 2HDM with  $U(1)_H$  Higgs gauge symmetry, *J. High Energy Phys.* **01** (2014) 016.
- [72] Y. G. Naryshkin, Search for new heavy Higgs bosons in ATLAS and CMS experiments at LHC (Mini-review), *Pis'ma Zh. Eksp. Teor. Fiz.* **113**, 221 (2021).
- [73] R. Barate *et al.*, (LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL Collaborations), Search for the standard model Higgs boson at LEP, *Phys. Lett. B* **565**, 61 (2003).
- [74] A. M. Sirunyan *et al.* (CMS Collaboration), Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at  $\sqrt{s} = 8$  and 13 TeV, *Phys. Lett. B* **793**, 320 (2019).
- [75] CMS Collaboration, Searches for additional Higgs bosons and vector leptoquarks in  $\tau\tau$  final states in proton-proton collisions at  $\sqrt{s} = 13$  TeV, <http://cds.cern.ch/record/2803739>.
- [76] CMS Collaboration, Search for a new resonance decaying to two scalars in the final state with two bottom quarks and two photons in proton-proton collisions at  $\sqrt{s} = 13$  TeV, <http://cds.cern.ch/record/2815230>.
- [77] J. Cao, X. Guo, Y. He, P. Wu, and Y. Zhang, Diphoton signal of the light Higgs boson in natural NMSSM, *Phys. Rev. D* **95**, 116001 (2017).
- [78] A. Crivellin, J. Heeck, and D. Müller, Large  $h \rightarrow bs$  in generic two-Higgs-doublet models, *Phys. Rev. D* **97**, 035008 (2018).
- [79] U. Haisch and A. Malinauskas, Let there be light from a second light Higgs doublet, *J. High Energy Phys.* **03** (2018) 135.
- [80] P. J. Fox and N. Weiner, Light signals from a lighter Higgs, *J. High Energy Phys.* **08** (2018) 025.
- [81] S. Heinemeyer, A Higgs boson below 125 GeV?!, *Int. J. Mod. Phys. A* **33**, 1844006 (2018).
- [82] T. Biekötter, M. Chakraborti, and S. Heinemeyer, A 96 GeV Higgs boson in the N2HDM, *Eur. Phys. J. C* **80**, 2 (2020).
- [83] J. Cao, X. Jia, Y. Yue, H. Zhou, and P. Zhu, 96 GeV diphoton excess in seesaw extensions of the natural NMSSM, *Phys. Rev. D* **101**, 055008 (2020).
- [84] T. Biekötter, S. Heinemeyer, and G. Weiglein, Mounting evidence for a 95 GeV Higgs boson, *J. High Energy Phys.* **08** (2022) 201.
- [85] S. Iguro, T. Kitahara, and Y. Omura, Scrutinizing the 95–100 GeV di-tau excess in the top associated process, *Eur. Phys. J. C* **82**, 1053 (2022).
- [86] S. Iguro, T. Kitahara, Y. Omura, and H. Zhang, Chasing the two-Higgs doublet model in the di-Higgs production, *Phys. Rev. D* **107**, 075017 (2023).
- [87] G. Coloretti, A. Crivellin, S. Bhattacharya, and B. Mellado, Searching for low-mass resonances decaying into  $W$  bosons, [arXiv:2302.07276](https://arxiv.org/abs/2302.07276).
- [88] S. von Buddenbrock, A. S. Cornell, A. Fadol, M. Kumar, B. Mellado, and X. Ruan, Multi-lepton signatures of additional scalar bosons beyond the standard model at the LHC, *J. Phys. G* **45**, 115003 (2018).
- [89] G. Aad *et al.* (ATLAS Collaboration), Search for dark matter in events with missing transverse momentum and a Higgs boson decaying into two photons in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *J. High Energy Phys.* **10** (2021) 013.
- [90] A. Crivellin, Y. Fang, O. Fischer, A. Kumar, M. Kumar, E. Malwa, B. Mellado, N. Rapheeha, X. Ruan, and Q. Sha, Accumulating evidence for the associate production of a neutral scalar with mass around 151 GeV, [arXiv:2109.02650](https://arxiv.org/abs/2109.02650).
- [91] F. Richard, A Georgi-Machacek interpretation of the associate production of a neutral scalar with mass around 151 GeV, in *Proceedings of the ILC Workshop on Potential Experiments* (2021), 12, [arXiv:2112.07982](https://arxiv.org/abs/2112.07982).

- [92] A. Fowlie, Comment on “Accumulating evidence for the associate production of a neutral scalar with mass around 151 GeV”, *Phys. Lett. B* **827**, 136936 (2022).
- [93] A. M. Sirunyan *et al.* (CMS Collaboration), Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **11** (2017) 047.
- [94] G. Aad *et al.* (ATLAS Collaboration), Search for resonances decaying into photon pairs in  $139 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *Phys. Lett. B* **822**, 136651 (2021).
- [95] M. Consoli and L. Cosmai, Experimental signals for a second resonance of the Higgs field, *Int. J. Mod. Phys. A* **37**, 2250091 (2022).
- [96] S. Buddenbrock, A. S. Cornell, Y. Fang, A. Fadol Mohammed, M. Kumar, B. Mellado, and K. G. Tomiwa, The emergence of multi-lepton anomalies at the LHC and their compatibility with new physics at the EW scale, *J. High Energy Phys.* **10** (2019) 157.
- [97] S. von Buddenbrock, R. Ruiz, and B. Mellado, Anatomy of inclusive  $t\bar{t}W$  production at hadron colliders, *Phys. Lett. B* **811**, 135964 (2020).
- [98] Y. Hernandez, M. Kumar, A. S. Cornell, S.-E. Dahbi, Y. Fang, B. Lieberman, B. Mellado, K. Monnagotla, X. Ruan, and S. Xin, The anomalous production of multi-lepton and its impact on the measurement of  $Wh$  production at the LHC, *Eur. Phys. J. C* **81**, 365 (2021).
- [99] O. Fischer *et al.*, Unveiling hidden physics at the LHC, *Eur. Phys. J. C* **82**, 665 (2022).
- [100] T. Plehn, M. Spira, and P. M. Zerwas, Pair production of neutral Higgs particles in gluon-gluon collisions, *Nucl. Phys.* **B479**, 46 (1996); **B531**, 655(E) (1998).
- [101] S. Dawson, S. Dittmaier, and M. Spira, Neutral Higgs boson pair production at hadron colliders: QCD corrections, *Phys. Rev. D* **58**, 115012 (1998).
- [102] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Ronca, and M. Spira, Full NLO QCD predictions for Higgs-pair production in the 2-Higgs-doublet model, [arXiv:2303.05409](https://arxiv.org/abs/2303.05409).
- [103] M. Mühlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, The N2HDM under theoretical and experimental scrutiny, *J. High Energy Phys.* **03** (2017) 094.
- [104] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, *Nucl. Phys.* **B90**, 104 (1975).
- [105] R. Barbieri, S. Ferrara, and C. A. Savoy, Gauge models with spontaneously broken local supersymmetry, *Phys. Lett.* **119B**, 343 (1982).
- [106] M. Dine, W. Fischler, and M. Srednicki, A simple solution to the strong  $CP$  problem with a harmless axion, *Phys. Lett.* **104B**, 199 (1981).
- [107] H. P. Nilles, M. Srednicki, and D. Wyler, Weak interaction breakdown induced by supergravity, *Phys. Lett.* **120B**, 346 (1983).
- [108] J. M. Frere, D. R. T. Jones, and S. Raby, Fermion masses and induction of the weak scale by supergravity, *Nucl. Phys.* **B222**, 11 (1983).
- [109] J. P. Derendinger and C. A. Savoy, Quantum effects and  $SU(2) \times U(1)$  breaking in supergravity gauge theories, *Nucl. Phys.* **B237**, 307 (1984).
- [110] A. Crivellin, A. Kokulu, and C. Greub, Flavor-phenomenology of two-Higgs-doublet models with generic Yukawa structure, *Phys. Rev. D* **87**, 094031 (2013).
- [111] A. Crivellin, C. Greub, and A. Kokulu, Explaining  $B \rightarrow D\tau\nu$ ,  $B \rightarrow D^*\tau\nu$  and  $B \rightarrow \tau\nu$  in a 2HDM of type III, *Phys. Rev. D* **86**, 054014 (2012).
- [112] M. Blanke, S. Iguro, and H. Zhang, Towards ruling out the charged Higgs interpretation of the  $R_{D^{(*)}}$  anomaly, *J. High Energy Phys.* **06** (2022) 043.
- [113] LHC-HXSWG3-NMSSM working group Collaboration, <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/NMSSMBenchmarkPoints>.
- [114] U. Ellwanger and C. Hugonie, Benchmark planes for Higgs-to-Higgs decays in the NMSSM, *Eur. Phys. J. C* **82**, 406 (2022).
- [115] A. Tumasyan *et al.* (CMS Collaboration), Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the  $\tau\tau b\bar{b}$  final state at 13 TeV, *J. High Energy Phys.* **11** (2021) 057.
- [116] CMS Collaboration, Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **07** (2023) 161.
- [117] A. Crivellin, C. A. Manzari, B. Mellado, S.-E. Dahbi, and A. K. Swain, Consistency and interpretation of the LHC (Di-)Di-Jet excesses, *Phys. Rev. D* **107**, 054045 (2023).
- [118] D. de Florian *et al.* (LHC Higgs Cross Section Working Group Collaborations), Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, [arXiv:1610.07922](https://arxiv.org/abs/1610.07922).
- [119] M. Spira, A. Djouadi, D. Graudenz, and P. M. Zerwas, Higgs boson production at the LHC, *Nucl. Phys.* **B453**, 17 (1995).
- [120] S. Liebler, S. Patel, and G. Weiglein, Phenomenology of on-shell Higgs production in the MSSM with complex parameters, *Eur. Phys. J. C* **77**, 305 (2017).
- [121] D. Graudenz, M. Spira, and P. M. Zerwas, QCD Corrections to Higgs Boson Production at Proton Proton Colliders, *Phys. Rev. Lett.* **70**, 1372 (1993).
- [122] C. Anastasiou, S. Beerli, S. Bucherer, A. Daleo, and Z. Kunszt, Two-loop amplitudes and master integrals for the production of a Higgs boson via a massive quark and a scalar-quark loop, *J. High Energy Phys.* **01** (2007) 082.
- [123] U. Aglietti, R. Bonciani, G. Degrossi, and A. Vicini, Analytic results for virtual QCD corrections to Higgs production and decay, *J. High Energy Phys.* **01** (2007) 021.
- [124] J. M. Cornwall, D. N. Levin, and G. Tiktopoulos, Derivation of gauge invariance from high-energy unitarity bounds on the  $s$  matrix, *Phys. Rev. D* **10**, 1145 (1974); **11**, 972(E) (1975).
- [125] C. E. Vayonakis, Born helicity amplitudes and cross-sections in non-Abelian gauge theories, *Lett. Nuovo Cimento Soc. Ital. Fis.* **17**, 383 (1976).
- [126] M. Spira, Higgs boson production and decay at hadron colliders, *Prog. Part. Nucl. Phys.* **95**, 98 (2017).
- [127] M. Aaboud *et al.* (ATLAS Collaboration), Searches for heavy  $ZZ$  and  $ZW$  resonances in the  $\ell\ell q\bar{q}$  and  $\nu\nu q\bar{q}$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *J. High Energy Phys.* **03** (2018) 009.
- [128] G. Aad *et al.* (ATLAS Collaboration), Search for a heavy Higgs boson decaying into a  $Z$  boson and another heavy

- Higgs boson in the  $\ell\ell bb$  and  $\ell\ell WW$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *Eur. Phys. J. C* **81**, 396 (2021).
- [129] ATLAS Collaboration, Combination of searches for heavy resonances using  $139 \text{ fb}^{-1}$  of proton–proton collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector, <http://cds.cern.ch/record/2809967>.
- [130] A. M. Sirunyan *et al.* (CMS Collaboration), Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **06** (2018) 127; **03** (2019) 128(E).
- [131] A. M. Sirunyan *et al.* (CMS Collaboration), Search for new neutral Higgs bosons through the  $H \rightarrow ZA \rightarrow \ell^+ \ell^- b\bar{b}$  process in pp collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **03** (2020) 055.
- [132] A. M. Sirunyan *et al.* (CMS Collaboration), Search for heavy Higgs bosons decaying to a top quark pair in proton-proton collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **04** (2020) 171; **03** (2022) 187(E).
- [133] G. Aad *et al.* (ATLAS Collaboration), Search for  $t\bar{t}$  resonances in fully hadronic final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, *J. High Energy Phys.* **10** (2020) 061.
- [134] A. M. Sirunyan *et al.* (CMS Collaboration), Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV, *Eur. Phys. J. C* **80**, 75 (2020).
- [135] ATLAS Collaboration, Search for  $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$  production in the multilepton final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, [arXiv: 2211.01136](https://arxiv.org/abs/2211.01136).
- [136] M. Algueró, J. Matias, A. Crivellin, and C. A. Manzari, Unified explanation of the anomalies in semileptonic B decays and the W mass, *Phys. Rev. D* **106**, 033005 (2022).
- [137] C. Hays (CDF Collaboration), High precision measurement of the W-boson mass with the CDF II detector, *Proc. Sci., ICHEP2022* (2022) 898.
- [138] CMS Collaboration, Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV, CERN, Geneva, Technical Report, 2023, <http://cds.cern.ch/record/2852907>.