Chiral heavy fermions in a two Higgs doublet model: 750 GeV resonance or not

Shaouly Bar-Shalom$^1$ and Amarjit Soni$^2$

$^1$Physics Department, Technion-Institute of Technology, Haifa 32000, Israel
$^2$Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

(Dated: January 6, 2018)

We revisit models where a heavy chiral 4th generation doublet of fermions is embedded in a class of two Higgs doublets models (2HDM) with a discrete $Z_2$ symmetry, which couples the “heavy” scalar doublet only to the 4th generation fermions and the “light” one to the Standard Model (SM) fermions - the so-called 4G2HDM introduced by us several years ago. We study the constraints imposed on the 4G2HDM from direct searches of heavy fermions, from precision electroweak data (PEWD) and from the measured production and decay signals of the 125 GeV scalar, which in the 4G2HDM corresponds to the lightest CP-even scalar $h$. We then show that the recently reported excess in the $\gamma\gamma$ spectrum around 750 GeV can be accommodated by the heavy CP-even scalar of the 4G2HDM, $H$, resulting in a unique choice of parameter space: negligible mixing ($\sin\alpha \lesssim O(10^{-3})$) between the two CP-even scalars $h, H$ and heavy 4th generation quark and lepton masses $m_{t', c'}, m_{u', c', b'} \lesssim 400$ GeV and $m_{u', c', b'} > 900$ GeV, respectively. Whether or not the 750 GeV $\gamma\gamma$ resonance is confirmed, interesting phenomenology emerges in $q'-H$iggs systems ($q' = t', b'$), that can be searched for at the LHC. For example, the heavy scalar states of the model, $S = H, A, H^\pm$, may have $BR(S \rightarrow q'q') \sim O(1)$, giving rise to observable $q'q'$ signals on resonance, followed by the flavor changing $q' \rightarrow u\bar{h}$ ($u = u, c$) and/or $b' \rightarrow dh$ ($d = d, s, b$). This leads to rather distinct signatures, with or without charged leptons, of the form $q'q' \rightarrow (nj + mb + EW)\gamma$ ($j$ and $b$ being light and b-quark jets, respectively), with $n + m + \ell = 6 - 8$ and unique kinematic features. These high jet-multiplicity signals appear to be very challenging and may need new search strategies for detection of such heavy chiral quarks. It is also shown that the flavor structure of the 4G2HDM can easily accommodate the interesting recent indications of a percent-level branching ratio in the lepton-flavor-violating (LFV) decay $h \rightarrow \tau\mu$ of the 125 GeV Higgs, if it is experimentally confirmed.

I. INTRODUCTION

The ongoing search for new physics (NP) is mostly inspired by the shortcomings of the SM in addressing some of the fundamental questions in modern particle physics, such as the hierarchy problem, the flavor patterns in the fermionic sector and dark matter. Some of these unresolved issues may be closely related and may have TeV-scale origins, thus inspiring the search for TeV-scale NP, both theoretically and experimentally. Indeed, two seemingly unrelated interesting measurements of both the ATLAS $^1[1, 2]$ and the CMS $^2[3, 4]$ collaborations at CERN, have been recently reported:

1. A possible $(2 - 4)\sigma$ (local) excess in the diphoton invariant mass distribution around 750 GeV, corresponding to a signal cross-section roughly in the range $\sigma(pp \rightarrow \gamma\gamma) \sim 3 - 13$ fb (1$\sigma$), see e.g., $^3[3, 4]$. The interpretation of this excess signal has a slight preference to a spin 0 resonance, produced via gluon-fusion and having a total width ranging from sub-GeV to 45 GeV, with a more significant signal obtained in the ATLAS analysis for a scalar with a total width $\Gamma \sim 45$ GeV $^1[1]$.\n
2. A possible $(1 - 2.5)\sigma$ excess in the measurement of the LFV decay $h \rightarrow \tau\mu$ of the 125 GeV light Higgs. In particular, the CMS collaboration finds $BR(h \rightarrow \tau\mu) = 0.84\%_{-0.37}\%$, while the ATLAS collaboration finds $BR(h \rightarrow \tau\mu) = (0.53 \pm 0.51)\%$ $^2[2]$.

Whether or not these two measurements are confirmed, it emphasizes the importance of the current efforts in the search for NP, since it provides an interesting manifestation/example of the exciting possibility that the building blocks of new TeV-scale physics may have rather non-conventional properties, potentially with important repercussions for both flavor and the hierarchy problems. For example, the new heavy scalar particle, $S$, responsible for the 750 GeV $\gamma\gamma$ excess, should have a rather narrow width and suppressed decay rates into “conventional” channels such as

---

$^*$Electronic address: shaouly@physics.technion.ac.il
$^1$Electronic address: adiersoni@gmail.com
Early attempts in this direction investigated the possibility of using the top-quark as the agent of dynamical EWSB via top-condensation corresponding LHC searches. In addition, such a heavy scalar $S$ is most likely related to the light 125 GeV scalar state and, therefore, might also be involved in flavor changing (FC) transitions in the fermionic sector. Such properties of the would be new 750 GeV resonating particle are, therefore, very challenging to accommodate in models beyond the SM, in particular, in supersymmetric models or in models that involve extra space-time dimensions, which seem to have a more fundamental origin and, therefore, likely linked to physics at higher energy scales. Nonetheless, we will show in this paper that a certain class of low-energy effective 2HDM frameworks with a 4th generation of heavy chiral fermions may be interesting candidates for such “exotic” TeV-scale NP.

In particular, since no evidence for such fundamentally structured theories has yet been seen, a frequently adopted phenomenological approach in studies of NP, is to construct TeV-scale models which require a UV completion and may, thus, be viewed as low energy effective frameworks for the underlying dynamics. Such models are useful as a guide for the exploration and model building of more fundamental theories and they often include new heavy fermionic and scalar states with sub-TeV masses. One of the simplest variants of an effective low-energy NP candidate, which dates back to the 1980’s [8], is the SM with an additional 4th generation of fermions; the so called SM4 (for useful reviews see e.g., [9]). Indeed, since three generations of chiral fermions have been observed in nature, it is natural to ask why not four generations of chiral fermions? It is quite interesting that this simple extension of the SM may address some of the theoretical challenges in particle physics, such as: electroweak symmetry breaking (EWSB) and the hierarchy problem [10], the CP-violation and the strength of the first-order phase transition needed to explain the origin of matter - anti matter asymmetry in the universe [11, 12], and flavor physics [13]. As is well known, the SM4 (i.e., with four generations of fermions and one Higgs doublet) is now excluded, since it cannot accommodate the measured SM-like properties of the 125 GeV scalar, see e.g., [14, 15], primarily due to an $O(10)$ enhancement in the gluon-fusion light Higgs production mechanism from diagrams with $t^\prime$ and $b^\prime$ in the loops [16]; see, however, W.-S. Hou in [17].

This fact, along with the rather stringent direct limits on the masses of such heavy quarks (to be discussed later), has led to a common belief that generic extensions to the SM with heavy chiral 4th generation fermions $t^\prime, b^\prime, \nu^\prime, \tau^\prime$ are excluded. However, as was suggested by us a few years ago [18] and will be demonstrated again here, this is not the case when the heavy 4th generation chiral sector is embedded in frameworks with an extended Higgs sector (see also [19]). Indeed, an extended Higgs sector in the context of 4th generation heavy fermions may come in handy for further addressing flavor problems [18] and the strength of the EW phase transition required for baryogenesis [12, 20]. In particular, we will consider in this paper a version of a 2HDM introduced by us in [18] - the so called 4G2HDM of type I, where a chiral 4th generation doublet of heavy fermions (quark and lepton) is added and is coupled only to one of the scalar doublets (the “heavy” doublet), while the SM 1st-3rd generations fermions are coupled only to the other doublet (the “light” doublet). We will show in this paper that this 4G2HDM is a well motivated and valid low-energy model, which is compatible with the 125 GeV signals (see also [21]), with PEWD and with the existing direct bounds on the heavy fermions, and at the same time can also accommodate the recent indications for a new 750 GeV scalar resonance in the $\gamma\gamma$ channel.

As was shown in [18], the price to pay when adding another heavy SM-like chiral fermion doublet is that such constructions posses a nearby threshold/cutoff at the several TeV scale, which is manifest (as Landau poles in the evolution of the Yukawa and Higgs potential couplings [18, 22]). Indeed, the large Yukawa couplings of the heavy chiral fermions can be thought of as a reflection of an underlying TeV-scale strong dynamics, so that the 4G2HDM framework should be viewed as a low energy (i.e., sub-TeV) effective model of an underlying strongly interacting sector. In particular, if the new heavy chiral fermions are viewed as the agents of EWSB (and are, therefore, linked to strong dynamics at the nearby TeV-scale, see e.g., [23, 24]), then more Higgs particles, which may be composites of these 4th generation fermions, are expected at the sub-TeV regime.[1] In such scenarios the resulting low-energy effective theory may contain more than a single composite Higgs field [18, 24, 26] and may thus resemble a two (or more) Higgs doublet framework (for other related studies of the phenomenology of multi-Higgs 4th generation models see e.g., [27]).

The purpose of this work is to revisit the 4G2HDM of [18], studying its compatibility with the updated measurements of the 125 GeV light Higgs signals and with PEWD. We will also confront our model with the 750 GeV $\gamma\gamma$ excess and study its compatibility with a sub-percent branching ratio of the light Higgs in the FC decay channel $h \rightarrow \tau\mu$. Indeed, many interesting and exotic constructions beyond the SM have been suggested as possible explanations of the 750

[1] Early attempts in this direction investigated the possibility of using the top-quark as the agent of dynamical EWSB via top-condensation [22]. These models, however, fail to reproduce the observed value of the top-quark mass. Moreover, as opposed to the case of condensates of the heavy 4th generation fermions, where the typical cutoff for the new strong interactions is of $O(1)$ TeV, the top-condensate models require a corresponding cutoff many orders of magnitude larger than $m_t$, i.e., of $O(10^{57})$ GeV, thus resulting in a severely fine-tuned picture of dynamical EWSB.
GeV $\gamma\gamma$ excess (too many to be cited here); in most cases involving new degrees of freedom beyond just the 750 GeV resonating particle. In particular, the relevance of 2HDM frameworks to the 750 GeV $\gamma\gamma$ excess has been intensively studied in the past several months, where it was shown that the simplest 2HDM extension to the SM, in which no additional heavy degrees of freedom are added (i.e., beyond the extended scalar sector), cannot accommodate the needed enhancement in $\sigma(pp \to H(750) \to \gamma\gamma)$, see e.g., [28]. Consequently, extended 2HDM models with TeV scale vector-like (VL) fermions have been suggested for addressing the 750 GeV resonance signal [29]. The upshot of these studies is that, the needed enhancement in the 1-loop production and decay channels $gg \to H(750)$ and $H(750) \to \gamma\gamma$, requires several copies of VL fermions and/or VL fermions with charges appreciably larger than those of the SM fermions, unless their Yukawa couplings are much larger than one. The 4G2HDM considered in this work is, therefore, conceptually simpler, relying on new heavy fermionic degrees of freedom with properties similar to the SM fermions in a model that already exists in the literature.

The paper is organized as follows: in section 2 we describe the type I 4G2HDM and we layout the physical parameters that are used in the numerical analysis. In section 3 we show our results and in section 4 we discuss their phenomenological consequences. In section 5 we discuss our results and summarize.

II. THE 4G2HDM: A 2HDM WITH 4TH GENERATION FERMIONS

Motivated by the idea that TeV-scale scalar degrees of freedom may emerge as composites associated with heavy fermions, we assume that the low-energy (sub-TeV) effective framework is parameterized by a 2HDM with a chiral SM-like 4th generation of heavy fermions. Specifically, the model is constructed following [18], such that one of the Higgs fields ($\phi_h$ - the “heavier” field) couples only to the new heavy 4th generation fermionic fields, while the second Higgs field ($\phi_l$ - the “lighter” field) is responsible for the mass generation of all other (lighter) fermions (i.e., the 1st-3rd generation SM fermions). In this model, named in [18] the 4G2HDM of type I (here we will refer to it simply as the 4G2HDM), the Yukawa interaction Lagrangian can be realized in terms of a $Z_2$-symmetry under which the fields transform as follows:

$$
\Phi_l \rightarrow -\Phi_l, \quad \Phi_h \rightarrow +\Phi_h, \quad F_L \rightarrow +F_L, \quad f_R \rightarrow -f_R \ (f = \text{SM fermions}), \quad f'_{f_R} \rightarrow +f'_{f_R} \ (f' = \text{4th gen. fermions}),
$$

where $F_L$ and $f_{f_R}$, $f'_{f_R}$ are the SU(2) fermion (quark or lepton) doublets and singlets, respectively, and $\Phi_{l,h}$ are the two Higgs doublets $\Phi_i = \left(\phi^+_i, \frac{v_i + \phi^0_i}{\sqrt{2}}\right), i = l,h$.

The Yukawa potential that respects the above $Z_2$-symmetry is:

$$
L_Y = -F_L \left(\Phi_i Y^l_i \cdot (I - \mathbb{I}) + \Phi_h Y^f_i \cdot \mathbb{I}\right) f_{u,R} - F_L \left(\tilde{\Phi}_l Y^l_i \cdot (I - \mathbb{I}) + \tilde{\Phi}_h Y^f_i \cdot \mathbb{I}\right) f'_{u,R} + h.c.,
$$

where $f_{u,R}$ and $f'_{u,R}$ are the up and down-type SU(2) fermion singlets (quark or lepton of all four generations), $I$ is the identity matrix and $\mathbb{I}$ is the diagonal $4 \times 4$ matrix $\mathbb{I} = \text{diag}(0, 0, 0, 1)$.

The scalar sector contains five massive states: a charged scalar $H^+$, a CP-odd state $A$, and two CP-even scalars $h, H$, so that $h$ is the lighter one, corresponding to the observed 125 GeV Higgs boson. These physical states are related to the components of the two SU(2) scalar doublets via:

$$
H = s_\alpha \text{Re} (\phi^0_h) + c_\alpha \text{Re} (\phi^0_l), \quad A = s_\beta \text{Im} (\phi^0_h) - c_\beta \text{Im} (\phi^0_l),
$$

$$
h = c_\alpha \text{Re} (\phi^0_h) - s_\alpha \text{Re} (\phi^0_l), \quad H^\pm = s_\beta \phi^+_h - c_\beta \phi^+_l,
$$

where $s_\alpha(c_\alpha) = \sin \alpha(\cos \alpha)$, $\alpha$ being the Higgs mixing angle in the CP-even sector and $s_\beta(c_\beta) = \sin \beta(\cos \beta)$, where $\tan \beta = v_h/v_l$ is the ratio between the VEV’s of the heavy and light Higgs fields.

The Yukawa Higgs-quark-quark interactions in the 4G2HDM are (similar terms can be written for the leptons) [18]:

$$
\mathcal{L}(h q_i q_j) = \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left[m_{q_i} s_\alpha s_\beta \delta_{ij} - \cos(\beta - \alpha) \cdot \left[m_{q_i} \Sigma^q_{ij} R + m_{q_j} \Sigma^q_{ji} L\right]\right] q_j h,
$$

$$
\mathcal{L}(H q_i q_j) = \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left[-m_{q_i} c_\alpha s_\beta \delta_{ij} + \sin(\beta - \alpha) \cdot \left[m_{q_i} \Sigma^q_{ij} R + m_{q_j} \Sigma^q_{ji} L\right]\right] q_j H,
$$

$$
\mathcal{L}(A q_i q_j) = \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left[m_{q_i} s_\beta^2 \gamma_5 \delta_{ij} - \left[m_{q_i} \Sigma^q_{ij} R - m_{q_j} \Sigma^q_{ji} L\right]\right] q_j A,
$$

$$
\mathcal{L}(H^+ u_i d_j) = \sqrt{2} \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left\{m_{d_j} s_\beta^2 \cdot V_{u_i,d_j} - m_{d_j} V_{ik} \Sigma^q_{kj} \right\} R + \left[-m_{u_i} s_\beta^2 \cdot V_{u_i,d_j} + m_{u_i} \Sigma^q_{ki} V_{kj}\right] L d_j H^+,
$$

$$
\mathcal{L}(H^+ u_i d_j) = \sqrt{2} \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left\{m_{d_j} s_\beta^2 \cdot V_{u_i,d_j} - m_{d_j} V_{ik} \Sigma^q_{kj} \right\} R + \left[-m_{u_i} s_\beta^2 \cdot V_{u_i,d_j} + m_{u_i} \Sigma^q_{ki} V_{kj}\right] L d_j H^+,
$$

$$
\mathcal{L}(H^+ u_i d_j) = \sqrt{2} \frac{g}{m_W \sin 2\beta} \tilde{q}_i \left\{m_{d_j} s_\beta^2 \cdot V_{u_i,d_j} - m_{d_j} V_{ik} \Sigma^q_{kj} \right\} R + \left[-m_{u_i} s_\beta^2 \cdot V_{u_i,d_j} + m_{u_i} \Sigma^q_{ki} V_{kj}\right] L d_j H^+.
$$
where \( V \) is the 4 \( \times \) 4 CKM matrix, \( q = d \) or \( u \) for down or up-quarks with \( I_d = -1 \) and \( I_u = +1 \), respectively, and \( R(L) = \frac{1}{2} \left( 1 + (-)^{I_q} \gamma_5 \right) \). Also, \( \Sigma^d \) and \( \Sigma^u \) are new mixing matrices where all FCNC effects of the 4G2HDM are encoded. They are obtained after diagonalizing the quark mass matrices and, therefore, depend on the rotation (unitary) matrices of the right-handed down and up-quarks \( D_R \) and \( U_R \), respectively. In particular, for \( I \equiv \text{diag} (0, 0, 0, 1) \) in Eq. \[2\] we have (see [18]):

\[
\begin{align*}
\Sigma^d_{ij} &= D^*_{R,4i} D_{R,4j}, \quad \Sigma^u_{ij} = U^*_{R,4i} U_{R,4j}.
\end{align*}
\]

The Yukawa structure and couplings defined by Eqs. \[2\] is assumed to be copied to the leptonic sector, see [30]. In the following sections \[11\] and \[14\] for illustrative purposes (and without loss of generality), we will set \( \Sigma^d, \Sigma^u \rightarrow \text{diag}(0, 0, 0, 1) \) in both the quark and lepton sectors, so that FCNC effects (in particular, between the 4th generation fermions and the SM fermions) are “turned off”. In fact, from the phenomenological point of view, it is sufficient to assume that \( \Sigma^d_{44,43} \rightarrow 0 \) (i.e., forbidding the decay \( t' \rightarrow t h \)) and \( V^*_{4,4i} \rightarrow 0 \) (\( i = 1, 2, 3 \), thus forbidding the decays \( t' \rightarrow d_i W \) and \( b' \rightarrow u_i W \) with \( d_i = d, s, b \) and \( u_i = u, c, t \)) in order to accommodate relatively light \( t' \) and \( b' \) with masses as low as 350 GeV, since the existing stringent exclusion limits of \( m_{t'}, m_{b'} \gtrsim 700 \text{ GeV} \), are based on searches that assume 100% branching ratios of the 4th generation quarks into one of the channels: \( t' \rightarrow t h, t Z, d_i W \) and \( b' \rightarrow Z b, u_i W \) \([31, 32]\). We will, therefore, assume that the dominant \( t' \) and \( b' \) decays are into one of the FC channels \( t' \rightarrow u_i h \) and \( b' \rightarrow d_i h \) (\( u_i = u, c \) and \( d_i = d, s, b \)), due to small FCNC entries in \( \Sigma^d, \Sigma^u \) (which have no effect on the results presented in sections \[11\] and \[14\]), in which case small off-diagonal CKM entries \( |V_{4,4i}| \) and/or \( |V_{4,4j}| \) are also allowed as long as \( \text{BR}(t' \rightarrow d_i W), \text{BR}(b' \rightarrow u_i W) \lesssim 0.5 \) \([32]\). Such flavor structures, may have interesting phenomenological implications, as will be discussed in section \[14\].

The 2HDM scalar sector is parameterized by seven free parameters (after minimization of the potential), which, in the so called “physical basis”, can be chosen as the four physical Higgs masses (\( m_h, m_H, m_A, m_{H^0} \)), the two angles \( \beta \) and \( \alpha \) and one parameter from the scalar potential, which is needed in order to specify the scalar couplings, in particular, \( h H^+ H^- \) (which enters in the 1-loop \( h \rightarrow \gamma\gamma \) decay), \( H H^+ H^- \) (which enters the 1-loop \( H \rightarrow \gamma\gamma \) decay) and \( H h h \) (required for the decay \( H \rightarrow h h \)). In the physical basis, these scalar couplings can be written at tree-level as (see e.g., \([33]\)):

\[
\lambda_{Hhh} = -\frac{\cos(\alpha - \beta)}{2v} \left[ \sin 2\alpha \left( m^2_h + 2m^2_H \right) - 3\sin 2\alpha - 3\sin 2\beta \right] \frac{m^2_{t\ell}}{s_\beta c_\beta} ,
\]

\[
\lambda_{hH^+H^-} = -\frac{1}{2v} \left[ \cos(\alpha - 3\beta) + 3\cos(\alpha + \beta) \right] m^2_h - 4\sin 2\beta \sin(\alpha - \beta) m^2_{H^0} - 4\cos(\alpha + \beta) m^2_{H^\pm} \frac{m^2_{t\ell}}{s_\beta c_\beta} ,
\]

\[
\lambda_{H^+H^-} = -\frac{1}{2v} \left[ \sin(\alpha - 3\beta) + 3\sin(\alpha + \beta) \right] m^2_h + 4\sin 2\beta \cos(\alpha - \beta) m^2_{H^0} - 4\sin(\alpha + \beta) m^2_{H^\pm} \frac{m^2_{t\ell}}{s_\beta c_\beta} ,
\]

where \( m^2_{t\ell} \) is a mass-like term, \( m^2_{t\ell} \Phi^d \Phi_h + h.c. \), which softly breaks the above \( Z_2 \)-symmetry (i.e., \( \Phi_x \rightarrow -\Phi_x \), \( \Phi_h \rightarrow -\Phi_h \)), and which can be used to specify the above tree-level scalar couplings.

However, since the working assumption of the 4G2HDM is that the scalar sector may be strongly interacting at the near by few TeV scale, the scalar potential is expected to be subject to significant renormalization and threshold effects. Thus, the above scalar couplings are expected to deviate from their tree-level values, depending on the details of the UV completion and on the masses of the heavy degrees of freedom of this model, see e.g., \([33, 34]\). As an example, consider the 1-loop corrections to the \( H hh \) coupling \( \lambda_{Hhh} \), for \( |\alpha| \rightarrow \pi/2 \), in which case there is no mixing between the light and heavy Higgs fields (see Eq. \[3\]), as required in order to accommodate the 750 GeV \( \gamma\gamma \) excess in the 4G2HDM (see section \[14\]). In this limit, the Yukawa couplings of the 4th generation fermions to the light Higgs state \( h \) (i.e., \( t'h \) vanish (see Eq. \[4\] and Table \[IV\]) and we find that the dominant effect arises from the 1-loop triangle diagram with the charged Higgs exchange in the loop, giving a “renormalized” \( H hh \) coupling \( \lambda_{Hhh} \equiv a_{Hhh} \lambda_{Hhh} \), with:

\[
a_{Hhh} \approx 1 + \left( \frac{m^4_{t\ell}}{m^4_{H^\pm} v^2} \right) \frac{1 - 2c^2_\beta s^2_\alpha - 4c^2_\beta m^2_{H^\pm} - s^2_\alpha m^2_{H^\pm}}{2\pi^2(\sin 2\beta)^2} I (m_h, m_H, m_{H^\pm}) ,
\]

\[2\] Note that this is in contrast to “standard” frameworks such as the SM and the 2HDM’s of types I and II, where the right-handed mixing matrices \( U_R \) and \( D_R \) are non-physical, being “rotated away” in the diagonalization procedure of the quark masses.
where \( I(m_h, m_H, m_{H^+}) \) is the charged Higgs triangle loop integral, given by:

\[
I(m_h, m_H, m_{H^+}) = - \int_0^1 dx \int_0^1 dy \frac{1}{(x+y)(x+y-1)m_h^2 - xym_H^2 + m_{H^+}^2}.
\] (13)

In particular, one roughly finds \(|a_{Hhh}| \in \{0, 2\}\) when \(m_{H^+} \in \{500 \text{ GeV}, 1 \text{ TeV}\}\) and with \(m_H = 750 \text{ GeV}, m_h = 125 \text{ GeV}\) and \(m_{tH} \sim O(1 \text{ TeV})\). For example, \(a_{Hhh} \sim -0.15\) for \(m_{H^+} = m_H = 750 \text{ GeV}\) and \(m_{tH} = 1.2 \text{ TeV}\). In what follows we will, therefore, define the “renormalized” scalar couplings as: \(\bar{\lambda}_i \equiv a_i \lambda_i\), where \(\lambda_i\) are the corresponding tree-level couplings in Eqs. 9-11 and \(a_i\) will be treated as free-parameters in the fit that will be varied in the range \(|a_i| \in \{0, 2\}\).

### III. THE 125 GEV HIGGS SIGNALS AND PEWD

The measured signals of the 125 GeV Higgs particle, which in the 4G2HDM is the light Higgs \(h\), and PEWD impose stringent constraints on the free parameter space of the 4G2HDM. For the 125 GeV Higgs signals we use the measured values of the “signal strength” parameters, which are defined as the ratio between the measured rates and their SM expectation. In particular, for a specific production and decay channel \(i \rightarrow h \rightarrow f\), the signal strength is defined as:

\[
\mu_i^f \equiv \mu_i \cdot \mu_f^f,
\] (14)

with

\[
\mu_i = \frac{\sigma(i \rightarrow h)}{\sigma(i \rightarrow h)_{SM}} = k_i^2, \quad \mu_f^f = \frac{BR(h \rightarrow f)}{BR(h \rightarrow f)_{SM}} = \frac{k_f^2}{R_f},
\] (15)

where \(k_j\) is the 4G2HDM coupling involved in \(j \rightarrow h\) or \(h \rightarrow j\) production or decay processes, normalized by its SM value, and \(R_f\) is the ratio between the total width of \(h\) in the 4G2HDM and the total width of the SM 125 GeV Higgs. In particular,

\[
k_j \equiv \frac{k_j^{4G2HDM}}{k_j^{SM}} = R_T \equiv \Gamma_{4G2HDM}^{Total}/\Gamma_{SM}^{Total},
\] (16)

so that \(\mu_i^f = k_i^2 k_f^2 / R_f\).

In Table I we list the latest combined ATLAS and CMS six parameter fit from RUN1 \[35\], of the measured values for \(\mu_\gamma^\gamma\), \(\mu_\gamma^g\), \(\mu_g^g\), \(\mu_{WW}^\tau\), \(\mu_{WW}^\gamma\), \(\mu_{WW}^W\), \(\mu_{WW}^Z\) and \(\mu_{WW}^\gamma\), where \(\mu_V\) stands for Higgs production via vector-boson fusion (VBF) or in association with a vector-boson (VH)\[3\]. We also write in Table I the model predictions for the various signal strengths in terms of the normalized couplings defined above.

| measured value | model prediction / couplings |
|---------------|-----------------------------|
| \(\mu_\gamma^\gamma\) | \(1.33^{+0.24}_{-0.23}\) |
| \(\mu_\gamma^g\) | \(1.29^{+0.29}_{-0.25}\) |
| \(\mu_g^g\) | \(1.08^{+0.22}_{-0.19}\) |
| \(\mu_{WW}^\tau\) | \(0.65^{+0.37}_{-0.28}\) |
| \(\mu_{WW}^\gamma\) | \(1.07^{+0.25}_{-0.28}\) |
| \(\mu_{WW}^W\) | \(1.06^{+0.25}_{-0.27}\) |

TABLE I: Measured values \[35\] and model predictions in terms of normalized couplings (see text) of the various production and decay channels for the 125 GeV Higgs, using the signal strength prescription. Note that while \(k_V\), \(k_g\) and \(k_\gamma\) are ratios of tree-level couplings, \(k_0\) and \(k_{\gamma}\) are the normalized (with respect to the SM) 1-loop 4G2HDM couplings \(hgg\) and \(h\gamma\gamma\), respectively, calculated using the formula in \[36\]. Also, in our 4G2HDM \(k_V = k_g = k_{\gamma}\).

---

\[3\] We neglect Higgs production via \(pp \rightarrow tth\) which, although included in the fit, is 2-3 orders of magnitudes smaller than the gluon-fusion channel.
For the PEWD constraints on the 4G2HDM, we update our study in [18]. In particular, the effects of any new physics can be divided into those which do and which do not couple directly to the ordinary SM fermions. For the former, the leading effect in the 4G2HDM comes from the decay $Z \rightarrow b \bar{b}$, which is mainly sensitive to the $H^+t'b$ and $W^+t'b$ couplings through one-loop exchanges of $H^+$ and $W^+$, as was analyzed in detail in [18]. These contributions to $Z \rightarrow b \bar{b}$ are, however, absent in the currently studied versions of the 4G2HDM, since our working assumption here is that $V_{tb} \rightarrow 0$ and $\Sigma_{d,u} \rightarrow \text{diag}(0,0,0,1)$, so that the $H^+t'b$ and $W^+t'b$ vertices vanish or are negligibly small (see previous section).

The effects which do not involve direct couplings to the ordinary fermions, can be analyzed in the formalism of the oblique parameters $S, T$ and $U$ [37]. The contribution of a 2HDM with a 4th generation of chiral fermions to the oblique parameters were studied in [18]. This includes the pure 1-loop Higgs exchanges to the gauge-bosons 2-point functions and the 1-loop exchanges of $t'$ and $b'$ which shift the $T$ parameter and which involve the new SM4-like diagonal coupling $W't'b'$ (here also the contributions involving the off-diagonal couplings $W't'b'$ and $Wtb'$ are absent since we assume $V_{tb}, V_{tb} \rightarrow 0$, see also [38]). These are calculated with respect to the SM values and are bounded by a global fit to PEWD [39]:

$$\Delta S = S - S_{SM} = 0.06 \pm 0.09,$$

$$\Delta T = T - T_{SM} = 0.1 \pm 0.07,$$

with a correlation coefficient of $\rho = +0.91$. These values are obtained for $\Delta U = 0$ (the $U$ parameter is often set to zero since it can be neglected in most new physics models and, in particular in our 4G2HDM) and with the SM reference values $M_{H,SM} = 125$ GeV and $m_{H,SM} = 173$ GeV. We, thus, consider below the constraints from the 2-dimensional ellipse in the $S - T$ plane which, for a given confidence level (CL), is defined by:

$$\frac{(S - S_{exp})}{T - T_{exp}} = \frac{1}{\sigma_S \sigma_T} \begin{pmatrix} \sigma_S^2 & \sigma_S\sigma_T \\ \sigma_S\sigma_T & \sigma_T^2 \end{pmatrix} \begin{pmatrix} S - S_{exp} \\ T - T_{exp} \end{pmatrix} = -2\ln(1 - CL),$$

(17)

where $S_{exp} = 0.06$ and $T_{exp} = 0.1$ are the best fitted (central) values, $\sigma_S = 0.09, \sigma_T = 0.07$ are the corresponding standard deviations and $\rho = 0.91$ is the (strong) correlation factor between $S$ and $T$.

We thus perform a random (“blind”) scan of the relevant parameter space, imposing compatibility at 95% CL of the 4G2HDM with the measured 125 GeV Higgs signals listed above and with the best fitted values of $S$ and $T$ using Eqs. (17) and (18). In particular, we fix $m_H = 750$ GeV (for compatibility with the recent 750 GeV $\gamma \gamma$ signal, see next section) and scan the rest of the parameters over the following ranges:

$$\alpha \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right], \quad \tan\beta \in [0.4, 10], \quad \alpha_i \in [-2, 2] \quad (i = hH^+H^-, HH^+H^-, Hhh),$$

$$m_{\nu,\tau}^2 \in [-(2 \text{ TeV})^2, (2 \text{ TeV})^2], \quad m_{A,H^+} \in [300 \text{ GeV}, 1.5 \text{ TeV}],$$

$$m_{\nu',\tau'} \in [350 \text{ GeV}, 500 \text{ GeV}], \quad m_{\nu',\tau'} \in [200 \text{ GeV}, 1200 \text{ GeV}].$$

(19)

We find two types of possible 4G2HDM “solutions”:

- case 1: $\tan\beta \leq 0.5$, $\sin\alpha \rightarrow -1$ and $m_{\nu,\tau}^2 > 0$.
- case 2: $\tan\beta \geq 2$, $\sin\alpha \sim 0.1 - 0.45$ and any $m_{\nu,\tau}^2$ in the entire range scanned.

In both cases above, $m_A, m_{H^+}$ and the 4th generation fermion masses can have values spanning over the entire scan ranges. In Fig. 1 we plot the resulting distributions of the relevant parameter space in the $S - T$, $\tan\beta - \sin\alpha$ and $\Delta m_{\nu} - \Delta m_{\tau}$ planes, where $\Delta m_{\nu} \equiv m_{\nu} - m_{\nu'}$ and $\Delta m_{\tau} \equiv m_{\tau} - m_{\tau'}$. We also show in Fig. 1 the resulting predicted 125 GeV Higgs signal strengths for the two cases above, which, as can seen, have different characteristics.

We next discuss the compatibility of the above two 4G2HDM solutions with the recently observed 750 GeV $\gamma \gamma$ excess.

IV. THE 4G2HDM AND THE 750 GEV $\gamma \gamma$ RESONANCE

We search here for the portion of parameter space of the two 4G2HDM cases found in the previous section, that survive once the 4G2HDM is also required to accommodate the 750 GeV $\gamma \gamma$ excess, which is being interpreted here
as the decay of one or both of the heavy neutral Higgs (i.e., assumed to have masses $\sim 750$ GeV) $H \to \gamma\gamma$ and/or $A \to \gamma\gamma$.

Given the exploratory nature of our study, we will simplify our analysis at this point, assuming that the scalar spectrum have the characteristics of the so-called decoupling limit (see e.g., [40]). In particular, we assume that it is split into 2 typical scales: $m_{\text{light}} \sim 125$ GeV, corresponding to the observed light Higgs and $m_{\text{heavy}} \sim 750$ GeV around which the three heavy Higgs masses lie, i.e., $m_H, m_A, m_{H^+} \sim 750$ GeV. Even though we find a wider range of allowed masses for the non-resonant heavy scalar states (i.e., for $m_A$ and $m_{H^+}$, see below) that can accommodate the 750 GeV signal, the choice $m_H, m_A, m_{H^+} \sim 750$ GeV will suffice for conveying our point: that the 750 GeV resonance in the $\gamma\gamma$ channel can be accommodated by one of the heavy scalars of the 4G2HDM without any conflict with other existing relevant data. Indeed, if this measurement will be eventually confirmed, then it will be instructive to study the 4G2HDM within a wider range of the relevant parameter space.

We, thus, re-scan the 4G2HDM parameter space corresponding to two 4G2HDM cases found in the previous section, where now $m_H, m_A$ and $m_{H^+}$ are varied within a 30 GeV mass range around 750 GeV, i.e., $m_{H,A,H^+} \in 750 \pm 30$ GeV. The scan is performed with the following additional “filters”/requirements (i.e., in addition to the requirement of compatibility with PEWD and with the measured 125 GeV Higgs signals, as outlined in the previous section):

- Reproducing the 750 GeV $\gamma\gamma$ excess within the range $3 \, \text{fb} < \sigma(pp \to H/A \to \gamma\gamma) < 13 \, \text{fb}$. We find that the (by far) dominant $H$ and/or $A$ production mechanism is the gluon-fusion one $gg \to H/A$, so that all the relevant cross-sections $\sigma(pp \to H/A \to f)$ are calculated in the narrow width approximation via:

$$
\sigma(pp \to H/A \to f) = \frac{C_{gg}}{8m_{H/A}^2} \Gamma(H/A \to gg) BR(H/A \to f),
$$

where $\sqrt{s} = 8$ or 13 TeV and $C_{gg}$ is the gluon luminosity:

$$
C_{gg} = \frac{\pi^2}{8} \int_{m_{H/A}^2/s}^1 \frac{dx}{x} g(x) g \left( \frac{m_{H/A}^2}{sx} \right),
$$

giving $C_{gg} \sim 2140(175)$ at $\sqrt{s} = 13(8)$ TeV, see [41].

- The resonating scalar which produces the 750 GeV $\gamma\gamma$ excess is required to have a width smaller than 45 GeV, i.e., $\Gamma_{H/A} < 45$ GeV.

- We impose the existing experimental bounds on the production and decays of the heavy neutral scalars $H$ and $A$, as obtained at the 8 and 13 TeV LHC runs (in particular when applied to $m_H, m_A \sim 750$ GeV) in all other channels which are relevant to our study: $pp \to W^+W^-, ZZ, tt, \tau\tau, bb, hh, hZ$. In particular, we use the 95% CL bounds in Table [II] quoted in [4].
TABLE II: Upper bounds at 95% CL on $\sigma(pp \rightarrow S \rightarrow f)$ for various final states $f$, produced through a narrow resonance with $m_S \sim 750$ GeV and $\Gamma_S/m_S \sim O(10^{-2})$, as applied to our scan with $S = H, A$. The bound on $\sigma(pp \rightarrow H/A \rightarrow jj)$ is relevant for $j =$ gluon. Table taken from [7].

| final state | $\sigma$ at $\sqrt{s} = 8$ TeV | $\sigma$ at $\sqrt{s} = 13$ TeV |
|------------|--------------------------------|--------------------------------|
| $pp \rightarrow H \rightarrow W^+ W^-$ | $< 40$ fb | $< 300$ fb |
| $pp \rightarrow H \rightarrow ZZ$ | $< 12$ fb | $< 200$ fb |
| $pp \rightarrow H \rightarrow hh$ | $< 39$ fb | $< 120$ fb |
| $pp \rightarrow A \rightarrow hZ$ | $< 19$ fb | $< 116$ fb |
| $pp \rightarrow H/A \rightarrow hh$ | $< 450$ fb | |
| $pp \rightarrow H/A \rightarrow bb$ | $< 1$ pb | |
| $pp \rightarrow H/A \rightarrow jj$ | $< 2.5$ pb | |
| $pp \rightarrow H/A \rightarrow \tau\tau$ | $< 12$ fb | $< 60$ fb |

FIG. 2: Scatter plots of the 4G2HDM parameter space that is compatible with the 125 GeV signals, with PEWD, with $\sigma(pp \rightarrow H \rightarrow \gamma\gamma) = 3–13$ fb, with $\Gamma_H \leq 45$ GeV and with all 8 and 13 TeV LHC bounds on the cross-section $\sigma(pp \rightarrow H/A \rightarrow f)$ in all final states $f$ relevant to the $H$ and $A$ decays, see Table III. The scatter plots are given for the mass splitting spectrum of the heavy fermions (left), the correlation between the soft breaking mass parameter $m_{lh}$ and the renormalization factor of the scalar couplings $a_i = \bar{\lambda}_i/\lambda_i$, $i = Hhh, hH^+H^-, HH^+H^-$ (middle), and the resulting allowed ranges of the 125 GeV light Higgs signal strengths in all the measured channels (right).

Applying the above filters, we find that:

1. Only the CP-even scalar state $H$ (with $m_H = 750$ GeV), can accommodate the 750 GeV $\gamma\gamma$ resonance, since $\sigma(pp \rightarrow A \rightarrow \gamma\gamma) \lesssim O(0.01)$ fb, which is 2-3 orders of magnitudes smaller than the measured $\gamma\gamma$ excess, see also Table IV.

2. Only a “shrinked” version of the 4G2HDM case 1 survives out of the two cases that were found to be compatible with PEWD and the 125 GeV light Higgs signals. In particular, the surviving 4G2HDM models have (see Fig. 2): $\tan\beta \leq 0.5$, $\alpha \rightarrow -\pi/2$ and $m_{lh} > 600$ GeV, having some correlation with the renormalization factors of the scalar couplings $a_i = \bar{\lambda}_i/\lambda_i$, $i = Hhh, hH^+H^-, HH^+H^-$.  

3. The resulting heavy fermions mass ranges are narrowed to: 350 GeV $\lesssim m_{\ell h}, m_{\ell h}' \lesssim 390$ GeV, where the lower limit is from direct searches (see section III), and 900 GeV $\lesssim m_{\ell h}, m_{\ell h}' \lesssim 1200$ GeV, where the upper limit is a rough estimate of the perturbativity bound on heavy chiral leptons.

In Fig. 2 we show three scatter plots of the resulting 4G2HDM parameter space, corresponding to the mass spectrum of the heavy fermions, the correlation between the soft breaking mass parameter $m_{lh}$ and the renormalization factor of the scalar couplings $a_i = \bar{\lambda}_i/\lambda_i$, $i = Hhh, hH^+H^-, HH^+H^-$, and the resulting allowed ranges of the 125 GeV light Higgs signal strengths in all the measured channels. We see that, while $|m_{\ell h}' - m_{\ell h}| \lesssim 30$ GeV, the mass splitting of the heavy leptons is typically $|m_{\ell h'} - m_{\ell h}| \sim m_{\ell h}$. We also see that smaller values of $m_{lh}$ typically require larger values of the renormalization factors of the scalar vertices $a_i$, e.g., $a_{Hhh} \sim 1$ for $m_{lh} \sim 700$ GeV.

It is interesting to note that the resulting mass spectrum of the heavy chiral quarks, which is required to accommodate the 750 GeV $\gamma\gamma$ resonance, is rather narrow and roughly centered around $m_H/2$, i.e., $m_{\ell h}, m_{\ell h}' \sim 350–390$ GeV.
This may hint back to the possibility that the the heavy scalars are composites primarily of the heavy chiral quarks, in which case the 4G2HDM might indeed be interpreted as a low energy effective framework for some TeV-scale strongly interacting theory. Such an effective low energy 2HDM, with features similar to the 4G2HDM discussed here, was introduced in [22], where it was shown that, using the Nambu-Jona-Lasinio (NJL) mechanism [23], it is possible to construct an effective sub-TeV 2HDM hybrid framework, in which the 125 GeV light Higgs is mostly a fundamental scalar, while the heavy Higgs states are components of a composite field of the form \( \Phi \), which is responsible for EW symmetry breaking and for the dynamical mass generation of the heavy quarks [4].

V. PHENOMENOLOGY OF THE 4G2HDM

Inspired by the indications of the 750 GeV \( \gamma \gamma \) resonance and following the analysis of the previous section, we briefly consider here some of the distinct phenomenological consequences of the 4G2HDM with characteristics similar to those required to accommodate such a heavy scalar resonance.

In particular, we will assume below that \( \tan \beta \approx 0.5 \) and \( \sin \alpha \approx -1 \), in which case the light 125 GeV Higgs of the 4G2HDM, \( h \), does not couple to \( f^\ast f' \), while the heavy CP-even Higgs, \( H \), does not couple to a pair of SM fermions (see Eqs. [4] and Table III). Also, the 4th generation heavy fermions are assumed to have masses in the ranges \( 350 \text{ GeV} < \mu_f, \mu_{f'} < 400 \text{ GeV} \) and \( 900 \text{ GeV} < m_{f''}, m_{f'} < 1200 \text{ GeV} \), and the dominant decay channels of the heavy quarks are \( t' \to uh \) (\( u = u, c \)) and \( b' \to dh \) (\( d = d, s, b \)), with corresponding branching ratios \( \sim 0.5 \), due to small off diagonal-entries \( \Sigma_{ii}^u \) (\( i = 1, 2 \)) and/or \( \Sigma_{ii}^d \) (\( i = 1, 2, 3 \)) (see Table III and discussion in section III).

In Table IV we list three benchmark points (BMP1,BMP2,BMP3) which have some distinct characteristics and which are compatible with PEWD, with the 125 GeV Higgs signals, with the 750 GeV \( \gamma \gamma \) signal and with the LHC bounds on all relevant 750 GeV Higgs resonance channels \( pp \to H/A \to f \) given in Table III. For definiteness, we have generated the benchmark points for the case of \( m_H = 750 \text{ GeV} \) and \( m_{A,H} \sim m_H \pm 50 \text{ GeV} \), but the discussion below has a more general scope, i.e., with regard to some of the possible phenomenological signatures of the 4G2HDM associated with the TeV-scale heavy scalars of the model and independent of whether the 750 GeV \( \gamma \gamma \) resonance is confirmed or not. The three benchmark points include cases where the 750 GeV Higgs total width ranges from a few GeV to \( \sim 45 \text{ GeV} \), having a resonance cross-section to \( \gamma \gamma \) between 4-12 fb. They also correspond to cases where \( BR(H/A \to q'q') \sim 1 \) and \( BR(H^+ \to q'q') \sim 1 \).

In particular, if \( m_H, m_{A,H} \sim m_{q'/2} \), then \( H/A \to q'q' \) is open and typically dominates, having a branching ratio of \( \mathcal{O}(1) \) (see Table IV). In that case, we find that within the 4G2HDM parameter space discussed here, the corresponding resonance cross-sections for \( q'q' \) production at the 13 TeV LHC are typically \( \sigma(pp \to H \to q'q') \sim \mathcal{O}(10) \) [pb] and \( \sigma(pp \to A \to q'q') \sim \mathcal{O}(0.1) \) [pb], (both \( H \) and \( A \) produced through gluon-fusion \( gg \to H/A \)), so that in the case of \( H \to q'q' \) (see Table IV), this is about an order of magnitude larger than the QCD (continuum) \( q'q' \) production rate. Therefore, if the 750 GeV \( \gamma \gamma \) resonance persists, one should also expect an observable resonance signal at least in the \( H \to q'q' \) channel.

Let us, therefore, briefly investigate the signal \( H \to q'q' \) under more general grounds, i.e., when \( m_H > m_{q'/2} \) but not necessarily \( m_H \sim 750 \text{ GeV} \). For example, in the case of \( H \to \bar{t}t' \), the \( t' \) will further decay either via

\[\text{Yukawa couplings in the } 4G2HDM \text{ with } \sin \alpha \sim -1\]

\[
\begin{array}{llll}
\hline
\text{Yukawa} & \text{Yukawa} & \text{Yukawa} & \text{Yukawa} \\
\text{couplings} & \text{couplings} & \text{couplings} & \text{couplings} \\
\hline
v \\
\cdot y(f \bar{f}) & v \cdot y(f' \bar{f}') & v \cdot y(f_i \bar{f}_j) & (i,j = 1-4, i \neq j) \\
\hline
h & \frac{-m_f}{\cos \beta} & 0 & \frac{\Sigma_{ij}^f}{\csc \beta} (m_f R + m_f L) \\
H & 0 & \frac{m_f}{\sin \beta} & \frac{\Sigma_{ij}^f}{\cos \beta} (m_f R + m_f L) \\
A & -i I_f m_f \tan \beta & i I_f m_f \cot \beta & i I_f \frac{\Sigma_{ij}^f}{\sin \beta \csc \beta} (m_f R - m_f L) \\
\hline
\end{array}
\]

TABLE III: Yukawa couplings of the neutral Higgs particles in the 4G2HDM with \( \sin \alpha \sim -1 \) and assuming \( \Sigma_{ij}^f \ll \Sigma_{44}^f = 1 \) for \( ij \neq 44 \), see section IV. In the first column \( f \) is a SM fermion of the 1st-3rd generations, while in the second column \( f' \) stands for a 4th generation fermion. In the 3rd column \( f_i \) correspond to any fermion of the \( i \)th generation. Also, \( I_f = 1(-1) \) for up(down) type fermions.
the FC channels $t' \to uh$ ($u = u$ or $c$) or via the 3-body decay $t' \to b'W \to dhW$ ($d = d, s, b$), where $b'W$ are either off-shell or on-shell (i.e., when $m_{t'} > m_{b'} + m_{W}$, see Fig. [I]). If the former case (i.e., $t' \to uh$) dominates, then the resulting resonance signal should be searched for in $pp \to pp' \to (jhW^+)_{j}(jhW^-)_{j'}$. In either case, the SM-like light Higgs ($h$) further decays into $bb$ or $WW$ with SM rates, giving rise to resonance signatures of the form $pp \to (nj + mb + tW)_{j}$, with $(n, m, \ell) = (2, 4, 0), (2, 0, 4), (2, 2, 2), (2, 2, 4), (2, 0, 6), (0, 2, 6), (0, 4, 4), (0, 6, 2)$ and with unique kinematic features that distinguishes them from more conventional signatures. Similar signals are also expected for $H \to b'b'$. We recognize that these type of signals are very challenging and may require new strategies, in particular, for reconstructing the parent $q'$s in such a high jet-multiplicity environment.

The decay pattern of the charged Higgs may also change in the 4G2HDM, in particular for the case when $m_{H^+} > m_{t'} + m_{W}$, for which the decay of $H^+$ into a pair of heavy 4th generation fermions can dominate (see BMP1 in Table [IV]). In particular, taking $m_{t'} \sim m_{t'} \equiv m_{t'}$ and assuming that $H^+$ is sufficiently heavier than $2m_{t'}$, so that we can ignore corrections of $O(4m_{t'}^2/m_{H^+}^2)$ in the phase-space factors, we have in the 4G2HDM:

$$R_{t'W/\ell b} \equiv \frac{\Gamma(H^+ \to t'b')}{\Gamma(H^+ \to \ell b)} \sim 2 \frac{m_{t'}^2}{m_{t'}^2} \cot^4 \beta,$$

$$R_{t'W/WH} \equiv \frac{\Gamma(H^+ \to t'b')}{\Gamma(H^+ \to Wb)} \sim 12 \frac{m_{t'}^2}{m_{H^+}^2} \left(\frac{\cot \beta}{\cos(\beta - \alpha)}\right)^2.$$ (22)

Thus, for $\alpha \sim -\pi/2$, $\tan \beta \sim 0.5$ (i.e., $\cos(\beta - \alpha) \sim -0.45$), $m_{t'} \sim 350$ GeV (i.e., values of the 4G2HDM parameter space that can accommodate the 750 GeV $\gamma\gamma$ signal) and taking $m_{H^+} \sim O(1)$ TeV, we obtain: $R_{t'W/\ell b} \sim O(100)$ and $R_{t'W/WH} \sim O(10)$, in which case $BR(H^+ \to t'b') \sim 1$ (e.g., as in the case of BMP2), leading to some interesting signatures of the heavy charged Higgs at the LHC. In particular, the dominant production channels of $H^+$ at the LHC are $gg/\gamma b \to H^+ b', H^+ W^- / H'^+ t$, with a typical cross-section of $\sim 100$ fb when $\tan \beta \sim 1$ [114]. The subsequent $H^+$ decay to a pair of 4th generation heavy fermions with $BR(H^+ \to t'b') \sim 1$ will, thus, lead to new $H^+$ signals, e.g., $pp \to t(t'b')_{H^+} \to (bW)_{j}(hh)_{j'}(j), v, v'$, again with the typical 4G2HDM heavy fermion high jet-multiplicity signatures of the form $pp \to nj + mb + tW$. This is in contrast to “standard” 2HDM frameworks where the heavy charged Higgs will dominantly decay to $Wh$ and/or $tb$ (see BMP1 and BMP3), leading to a lower multiplicity of jets in the final state.

As noted earlier, a wider range of solutions exist (which are not being discussed here) to all data and filters mentioned above (i.e., including the 750 GeV $\gamma\gamma$ resonance), in which lighter pseudoscalar $A$ and charged Higgs $H^+$ are allowed, with masses as low as 300 GeV. In such 4G2HDM scenarios, the heavy 4th generation quarks (and leptons) can have substantial decay rates in channels involving also the heavy Higgs species, i.e., $t' \to H^+ d, A u (d = d, s, b$ and $u = u, c)$ and $b' \to H^+ u, Ad (d = d, s, b$ and $u = u, c)$, followed by $H^+ \to W^+ b, \ell b$ and $A \to hZ, \ell \ell$. Indeed, such decay patterns can also lead to some un-explored collider signatures of the 4G2HDM. We leave the discussion of the phenomenology of such wider range of 4G2HDM scenarios to a later work.

Finally, we wish to comment on the flavor violating structure of the 4G2HDM and its compatibility with the recently reported indications of the LFV decay of the 125 GeV light Higgs $h \to \tau\mu$ [2, 3]. Writing the LFV couplings of $h$ in a general form:

$$\mathcal{L}(hf_if_j) = S_{ij} + P_{ij}\gamma_5,$$ (24)
one obtains:
\[
\Gamma(h \rightarrow f_i f_j + \bar{f}_j f_i) = \frac{m_h}{4\pi} \left(|S_{ij}|^2 + |P_{ij}|^2\right).
\] (25)

In our 4G2HDM we have for the case of the LFV decay \( h \rightarrow \tau\mu \) (neglecting terms of \( \mathcal{O}(m_\mu/m_\tau) \)), see Eq. (26):
\[
|S_{\tau\mu}| = |P_{\tau\mu}| \sim \frac{g}{4 m_W} f(\beta, \alpha) \xi_{\tau\mu},
\] (26)

where we have defined \( \Sigma_{32}^\ell = \Sigma_{23}^\ell \equiv \xi_{\tau\mu} \) (see Eq. (8)) and:
\[
f(\beta, \alpha) = \frac{\cos(\beta - \alpha)}{s_\beta c_\beta}.
\] (27)

Requiring now that \( BR(h \rightarrow \tau\mu) < 1\% \) we find:
\[
|f(\beta, \alpha)\xi_{\tau\mu}| \sim \mathcal{O}(0.1).
\] (28)

Thus, since for the values of \( \tan \beta \) and \( \alpha \) that were found to be compatible with all data considered in the previous sections, we find \( |f(\beta, \alpha)| \sim 1 - 5 \), and specifically \( f(\beta, \alpha) \sim 1 \) for \( \alpha \rightarrow -\pi/2 \) and \( \tan \beta \sim 0.5 \), as required in order to accommodate the 750 GeV \( \gamma\gamma \) resonance (see previous section), the 4G2HDM with \( |\xi_{\tau\mu}| < 0.1 \) can address the measured \( BR(h \rightarrow \tau\mu) < 1\% \) if it persists.

VI. SUMMARY

We have revisited a class of models beyond the SM, suggested by us a few years ago in \cite{18}, which put together an additional Higgs doublet with a heavy chiral 4th generation quark and lepton doublet and which have several important and attractive theoretical features. In particular, we focused on the so-called 4G2HDM of type I (in \cite{18}), in which a discrete \( Z_2 \) symmetry couples the “heavy” scalar doublet only to the heavy 4th generation fermions and the “light” one to the lighter SM fermions.

We have confronted this model with PEWD, with the measured 125 GeV light Higgs signals and also studied its compatibility with the recent indication of a 750 GeV \( \gamma\gamma \) resonance and with the current LHC bounds on heavy scalar resonances in other relevant channels. We found that the CP-even heavy Higgs state of the 4G2HDM with a mass \( \sim 750 \) GeV can accommodate the measured 750 GeV excess for a rather unique choice of the parameter space: \( \tan \beta \sim 0.5, \alpha \sim -\pi/2 \) (the Higgs mixing angle) and with heavy chiral fermion masses \( m_{t', b'} \lesssim 400 \) GeV and \( m_{\nu', \tau'} \gtrsim 900 \) GeV.

We have shown that the heavy chiral quarks (and leptons) of the 4G2HDM may have FCNC decays into the light 125 GeV Higgs plus a light-quark jet, \( q' \rightarrow j h \), with branching ratios of \( \mathcal{O}(1) \), thus leading to some un-explored signatures of \( q'q' \) production at the LHC and, therefore, being consistent with the current direct bounds on the masses of new heavy fermions. Indeed, new and rich phenomenology in \( q' \)- heavy Higgs systems is expected, including possible resonance production of \( q'q' \) pairs via either the heavy neutral or heavy charged Higgs particles of the 4G2HDM, which leads to high jet-multiplicity signatures, with or without charged leptons, of the form \( q'q' \rightarrow nj + mb + \ell W \), with \( n + m + \ell = 6 - 8 \) and unique kinematic features which are related to the resonating heavy scalar and the decay pattern of the heavy quarks. The reconstruction of the \( q'q' \) pairs in such high jet-multiplicity signals is very challenging and require more thought and possibly new search strategies.

We also show that the recent indication of a percent-level branching ratio in the LFV decay of the 125 GeV Higgs \( h \rightarrow \tau\mu \), if it persists, can be readily addressed within the distinct flavor structure of the 4G2HDM.

Acknowledgments: We thank Pier Paolo Giardino for useful conversations. The work of AS was supported in part by the US DOE contract #de-sc0012704.
[1] “Search for resonances to photon pairs in 3.2 fb\(^{-1}\) of pp collisions at \(\sqrt{s} = 13\) TeV with the ATLAS detector”, the ATLAS collaboration, Tech. Rep. ATLAS-CONF-2015-081, CERN, Geneva, Dec, 2015; M. Aaboud et al., the ATLAS collaboration, “Search for resonances in diphoton events at \(\sqrt{s} = 13\) TeV with the ATLAS detector”, arXiv:1606.03833 [hep-ex].

[2] “Search for lepton-flavor-violating decays of the Higgs and Z bosons with the ATLAS detector”, the ATLAS Collaboration, arXiv:1604.07730 [hep-ex].

[3] “Search for new physics in high mass diphoton events in proton-proton collisions at \(\sqrt{s} = 13\) TeV, the CMS Collaboration, CMS-PAS-EXO-15-004, CERN, Geneva, 2015; V. Khachatryan et al., the CMS collaboration, “Search for resonant production of high-mass photon pairs in proton-proton collisions at \(\sqrt{s} = 8\) and 13 TeV”, arXiv:1606.04193 [hep-ex].

[4] “Search for lepton-flavor-violating decays of the Higgs boson”, the CMS Collaboration, Phys.Lett. B749 (2015) 337.

[5] A. Falkowski, O. Slone, T. Volansky, JHEP 1602 (2016) 152.

[6] M. R. Buckley, Eur.Phys.J. C76 (2016) no.6, 345.

[7] A. Strumia, arXiv:1605.09401 [hep-ph].

[8] For older literature on the SM4, see: Proceedings of the First (February 1987) and the Second (February 1989) International Symposums on the fourth family of quarks and leptons, Santa Monica, CA, published in Annals of the New York Academy of Sciences, 517 (1987) & 578 (1989), edited by D. Cline and A. Soni.

[9] P.H. Frampton, P.Q. Hung, M. Sher, Phys.Rept. 330 (2000) 263. B. Holdom et al., talk presented at Beyond the 3rd SM generation at the LHC era workshop, Geneva, Switzerland, Sep 2008, arXiv:0904.4698 [hep-ph], published in PMC Phys. A3 (2009) 4.

[10] B. Holdom, Phys.Rev.Lett. 57 (1986) 2496, Erratum-ibid. 58 (1987) 177; W.A. Bardeen, C.T. Hill, M. Lindner, Phys.Rev. D41 (1990) 164; S.F. King, Phys.Lett. B234 (1990) 108; C. Hill, M. Luty, E.A. Paschos, Phys.Rev. D43 (1991) 3011; P.Q. Hung, G. Isidori, Phys.Lett. B402 (1997) 122; B. Holdom, JHEP 0608 (2006) 76; P.Q. Hung, C. Xiong, Nucl.Phys. B848 (2011) 288; Y. Mimura, W.S. Hou, H Kohyama, JHEP 1311 (2013) 048.

[11] M. Carena, A. Megevand, M. Quiros, C.E.M. Wagner, Nucl. Phys. B41 (1997) 122; S. Bar-Shalom, M. Geller, S. Nandi and A. Soni, Phys.Rev. D84 (2011) 114510; A.K. Alok, A. Dighe and D. London, Phys.Rev. D83 (2011) 073008; D. Choudhury, D. K. Ghosh, JHEP 1102 (2011) 033; R. Mohanta, A.K. Giri, Phys. Rev. D85 (2012) 014008 (2012); A. Ahmed et al., Phys. Rev. D85 (2012) 034018.

[12] A.TLAS Conference note 2011-135; S. Chatrchyan et al. [CMS Collaboration], Phys.Lett. B710 (2012) 26.

[13] O. Eberhardt et al., Phys.Rev. D86 (2012) 013011; A. Djonadi, A. Lenz, Phys.Lett. B715 (2012) 310; O. Eberhardt et al., Phys.Rev. D86 (2012) 074014; E. Kuflik, Y. Nir, T. Volanski, Phys.Rev.Lett. 110 (2013) no.9, 091801; M.S. Chanowitz, Phys.Rev. D88 (2013) no.1, 015012; M.I. Vysotsky, arXiv:1312.0474 [hep-ph]; G. Burdman, C.E.F. Haluch, JHEP 1112 (2011) 095; O. Eberhardt, A. Lenz and J. Rohrwild, Phys.Rev. D82 (2010) 035012; S. Nandi, A. Soni, Phys.Rev. D83 (2011) 114510; A.K. Alok, A. Dighe and D. London, Phys.Rev. D83 (2011) 073008; D. Choudhury, D. K. Ghosh, JHEP 1102 (2011) 033; R. Mohanta, A.K. Giri, Phys. Rev. D85 (2012) 014008 (2012); A. Ahmed et al., Phys. Rev. D85 (2012) 034018.

[14] G.D. Kribs, T. Plehn, M. Spannowsky, T.M.P. Tait, Phys.Rev. D76 (2007) 075016.

[15] W.-S. Hou, arXiv:1606.03732 [hep-ph].

[16] S. Bar-Shalom, S. Nandi, A. Soni, Phys.Rev. D84 (2011) 053009; S. Bar-Shalom, M. Geller, S. Nandi and A. Soni, Adv.High Energy Phys. 2013 (2013) 672972, arXiv:1208.3195 [hep-ph];

[17] S. Banerjee, M. Frank, S.K. Rai, Phys.Rev. D89 (2014) no.7, 075005.

[18] A. Katz, M. Perelstein, JHEP 1407 (2014) 107.

[19] M. Geller, S. Bar-Shalom, G. Eilam, A. Soni, Phys.Rev. D86 (2012) 115008.

[20] M. Geller, S. Bar-Shalom, A. Soni, Phys.Rev. D89 (2014) no.3, 035012.

[21] B. Holdom, Phys.Rev. Lett. 57 (1986) 2496, Erratum-ibid. 58 (1987) 177; W.J. Marciano, G. Valencia, S. Willenbrock, Phys.Rev. D40 (1989) 1725; S.F. King, Phys.Lett. B234 (1990) 108; P.Q. Hung, G. Isidori, Phys.Lett. B402 (1997) 122; B. Holdom, JHEP 0608 (2006) 76; Y. Mimura, W.S. Hou, H Kohyama, JHEP 1311 (2013) 048.

[22] M.A. Luty, Phys.Rev. D41 (1990) 2893; C. Hill, M. Luty, E.A. Paschos, Phys. Rev. D43, 3011 (1991); G. Burdman and L. da Rold, JHEP 0712 (2007) 86; P.Q. Hung, C. Xiong, Nucl.Phys. B848 (2011) 288; for an earlier discussion see also, “Dynamical symmetry breaking due to strong coupling Yukawa interaction” by M. Tanabashi, K. Yamawaki and K. Kondo, in Nagoya 1989, Proceedings, Dynamical symmetry breaking 28-36.

[23] V.A. Miransky, M. Tanabashi, K. Yamawaki, Phys.Lett. B221 (1989) 177; ibid., Mod.Phys.Lett. A4 (1989) 1043; W.A. Bardeen, C.T. Hill, M. Lindner, Phys.Rev. D41 (1990) 1647; see also Y. Nambu in e.g., EFI report #89-08, 1989 (unpublished).

[24] G. Burdman, L. da Rold, O. Eholi, R.D. Matheus, Phys.Rev. D79 (2009) 075026; M. Hashimoto and V.A. Miransky, Phys.Rev. D81 (2010) 055014; P.Q. Hung, C. Xiong, Nucl.Phys. B847 (2011) 160; P.Q. Hung, C. Xiong, Phys.Lett. B694 (2011) 438; G. Burdman, C.E.F. Haluch, JHEP 1112 (2011) 038; G. Burdman, L. da Lima, R.D. Matheus, Phys.Rev. D83 (2011) 035012. A.E.C. Hernandez, C.O. Dib, H.N. Neill, A.R. Zerwekh, JHEP 1202 (2012) 132; C.M. Ho, P.Q. Hung,
T.W. Kephart, JHEP 1206 (2012) 45; B. Holdom, Phys.Lett. B721 (2013) 290.

[27] M. Sher, Phys.Rev. D61 (2000) 057303; E. De Pree, G. Marshall, M. Sher, Phys.Rev. D80 (2009) 037301; W. Bernreuther, P. Gonzales, M. Wiebusch, Eur.Phys.J. C69 (2010) 31; John F. Gunion, arXiv:1105.3965 [hep-ph]; G. Burdman, C. Haluch, R. Matheus, JHEP 1112 (2011) 038; G. Burdman, L. Da Rold, JHEP 0712 (2007) 86; G. Burdman, L. Da Rold, O. Eboli, R.D. Matheus, Phys.Rev. D79 (2009) 075026; G. Burdman, L. de Lima, R.D. Matheus, Phys.Rev. D83 (2011) 035012; X.-G. He, G. Valencia, Phys.Lett. B707 (2012) 381; N. Chen, H. He, JHEP 1204 (2012) 062; A.E.C. Hernandez, C.O. Dib, H.N. Neill, A.R. Zerwekh, JHEP 1202 (2012) 132. H.-S. Lee, A. Soni, Phys.Rev.Lett. 110, (2013) no.2, 021802.

[28] R. S. Gupta et al., arXiv:1512.05332 [hep-ph].

[29] A. Angelescu, A. Djouadi and G. Moreau, Phys.Lett. B756 (2016) 126; W. Altmannshofer et al., Phys.Rev. D93 (2016) no.9, 095015; S. Di Chiara, L. Marzola, M. Raidal, Phys.Rev. D93 (2016) no.9, 095018; N. Bizot, S. Davidson, M. Frigerio, J.-L. Kneur, JHEP 1603 (2016) 073; D. Becirevic, E. Bertuzzo, O. Sumensari, R. Z. Funchal, Phys.Lett. B757 (2016) 261; A. Falkowski, O. Slone, T. Volansky, JHEP 1602 (2016) 152; M. Badziak, Phys.Lett. B759 (2016) 464; X.-F. Han, L. Wang, Phys.Rev. D93 (2016) no.5, 055027; E. Bertuzzo, P.A.N. Machado, M. Taeso, arXiv:1601.07508 [hep-ph]; D. Buttazzo, A. Grelo, D. Marzocca, Eur.Phys.J. C76 (2016) no.3, 116; B. Bellazzini, R. Franceschini, F. Sala, J. Serra, JHEP 1604 (2016) 072; S. Moretti, K. Yagyu, Phys.Rev. D93 (2016) no.5, 055043; W.-C. Huang, Y.-L. S. Tsai, T.-C. Yuan, Nucl.Phys. B909 (2016) 122; B. Holdom, M. Ratzlaff, arXiv:1605.08411 [hep-ph].

[30] S. Bar-Shalom, S. Nandi, A. Soni, Phys.Lett. B709 (2012) 207.

[31] The Review of Particle Physics (2015) K.A. Olive et al., (Particle Data Group), Chin.Phys. C38 (2014) 090001 and 2015 update.

[32] G. Aad et al., the ATLAS collaboration, Phys.Rev. D92 (2015) no.11, 112007.

[33] S. Kanemura, Y. Okada, E. Senaha, C.-P. Yuan, Phys.Rev. D70 (2004) 115002.

[34] See e.g., A. Arhrib, M.C. Peyranere, W. Hollik, S. Penaranda, Phys.Lett. B579 (2004) 361; P. Osland, P.N. Pandita and L. Selbuz, Phys.Rev. D78 (2008) 015003.

[35] ATLAS and CMS Collaboration, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV”, ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002.

[36] J.F. Gunion, H.E. Haber, G.Kane, S. Dawson, “The Higgs Hunter’s Guide”, Addison-Wesley (1990), see also Errata: SCIPP-92-58 (1992), arXiv:hep-ph/9302272.

[37] M.E. Peskin, T. Takeuchi, Phys.Rev.Lett. 65 (1990) 964; ibid., Phys.Rev. D46 (1992) 381.

[38] M.S. Chanowitz, Phys.Rev. D79 (2009) 113008; ibid. Phys.Rev. D82 (2010) 035018. J. Erler, P. Langacker, Phys.Rev.Lett. 105 (2010) 031801.

[39] M. Baak (CERN) et al., The Glüte Group Collaboration, Eur.Phys.J. C74 2014 3046.

[40] J.F. Gunion, H.E. Haber, Phys.Rev. D67 (2003) 075019.

[41] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur.Phys.J. C63 (2009) 189.

[42] Y. Nambu, G. Jona-Lasinio Phys.Rev. 122 (1961) 345.

[43] Y.-J. Zhang, B.-B. Zhou, J.-J. Sun, arXiv:1602.05539 [hep-ph].

[44] See e.g., A.G. Akeroyd et al., arXiv:1607.01320 [hep-ph].