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Higgs data does not rule out a sequential fourth generation with an extended scalar sector

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Contrary to common perception, we show that the current Higgs data does not eliminate the possibility of a sequential fourth generation that get their masses through the same Higgs mechanism as the first three generations. The inability to fix the sign of the bottom-quark Yukawa coupling from the available data plays a crucial role in accommodating a chiral fourth generation which is consistent with the bounds on the Higgs signal strengths. We show that effects of such a fourth generation can remain completely hidden not only in the production of the Higgs boson through gluon fusion but also to its subsequent decay to $\gamma\gamma$ and $Z\gamma$. This, however, is feasible only if the scalar sector of the standard model is extended. We also provide a practical example illustrating how our general prescription can be embedded in a realistic model.

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I. INTRODUCTION

Since the first observation of a new resonance at the Large Hadron Collider (LHC) [1,2] in 2012, the particle physics community converged on the view that this is a standard model (SM)-like Higgs boson if not the SM Higgs boson itself. The fact that the LHC Higgs data is gradually drifting towards the SM expectations [3] has pushed many scenarios that go beyond the SM (BSM) to some contrived corner of the parameter space. For some BSM, the situation is even worse as they have nowhere to hide, because quantum effects coming from some of the heavy degrees of freedom do not decouple and hence leave observable imprints in the Higgs signal strengths. The SM extended by a chiral fourth generation (SM4) [4] constitutes such an example. The fourth generation quark masses, so heavy as to avoid the direct detection bound, are proportional to the corresponding Yukawa couplings and thus, their contributions to the $gg \to h$ production amplitude saturate to a constant value just as in the case of the top quark loop. Consequently, the gluon-gluon fusion (ggF) amplitude for the Higgs production increase roughly by a factor of 3 compared to the SM, enhancing the cross section by a factor of 9. This should have been reflected as a huge enhancement in the Higgs signal strengths, nothing like which has been observed, leading us to believe that the possibility of a sequential fourth generation is strongly disfavored from the existing data [5–9].

Efforts have been made to counter the enhanced production in the ggF channel by reducing the branching ratios (BRs) of the Higgs boson into different visible channels. This can be achieved, e.g., by adjusting the mass of the fourth generation neutrino ($m_{\nu'}$) so that the Higgs boson mainly decays invisibly into a pair of fourth generation neutrinos thereby increasing the total decay width of the Higgs boson [10–18]. However this possibility also fell out of favor after the arrival of the Higgs data [8]. Another way to avoid the enhancement in the ggF production channel is to assume that the heavy chiral fourth generation receives its masses from a different scalar other than the SM Higgs doublet.[1] This option has been considered in the framework of a two Higgs doublet model (2HDM) [21–24].

In this article, we ask a more ambitious question: Can we still accommodate an extra generation of fermions coupling to the SM Higgs *in an identical way* as the first three generations, without altering appreciably the Higgs signal strengths from their corresponding SM expectations? We will answer in the affirmative and provide a practical example of such a scenario. As we will explain, this is

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[1]Although, at the initial stage of the Higgs discovery when the data was not so precise, the possibility of the fourth generation coupling to the SM Higgs doublet could have been entertained in different BSM scenarios [19,20], these options became increasingly disfavored by the LHC Higgs data constantly evolving toward the SM expectations.

feasible because the Yukawa couplings of up- and down-type quarks can be so arranged as to make the extra contributions cancel out. Such a cancellation, quite remarkably, is also effective for loop-induced Higgs decays. However, a realization of this is not possible with only one scalar doublet,[2] so one needs to extend the scalar sector of the SM.

II. MAKING THE FOURTH GENERATION SURVIVE

The way to make a fourth generation survive is to note the subtle fact that the sign of the bottom quark Yukawa coupling is not determined from the present LHC data. The sign of the top quark Yukawa coupling has to be positive with respect to the WWh coupling (where h is the SM, or SM-like, Higgs boson with a mass of 125 GeV), which can be inferred from the interference in the $h \to \gamma\gamma$ amplitude. The mass being small, effect of the bottom quark loop is negligible as far as current precision is concerned.

Let us now define the Higgs coupling modification factors relative to the SM as follows:

$$\kappa_x = \frac{g_{xxh}}{(g_{xxh})_{\rm SM}}, \tag{1}$$

where, $x = W, Z$ and other massive fermions, and g_{xxh} is the generic coupling. For the SM, all $\kappa_x = 1$, which is of course completely consistent with the LHC data. However, as the tree-level two-body decays of h cannot shed any light on the phase of the coupling, one may also entertain an alternative scenario, namely,

$$\kappa_V = 1 \quad (V = W, Z) \tag{2a}$$

$$\kappa_u = 1 \quad \text{(for up type quarks)} \tag{2b}$$

$$\kappa_d = -1 \quad \text{(for down type quarks and charged leptons)}. \tag{2c}$$

In what follows, we will refer to this possibility as the *wrong sign limit*.

The modification factor for the $gg \to h$ production cross section in the presence of fourth generation quarks is given by

$$R_{gg} = \frac{|\kappa_t F_{1/2}(\tau_t) + \sum_{f=t',b'} \kappa_f F_{1/2}(\tau_f)|^2}{|F_{1/2}(\tau_t)|^2} \tag{3}$$

where, using $\tau_x \equiv (2m_x/m_h)^2$, the expression for $F_{1/2}$ is given by [25]

$$F_{1/2}(\tau_x) = -2\tau_x[1 + (1 - \tau_x) f(\tau_x)]. \tag{4}$$

Since we are concerned with heavy fermions, we can take $\tau_x > 1$ for $x = (t, t', b')$, and then

$$f(\tau) = [\sin^{-1}(\sqrt{1/\tau})]^2. \tag{5}$$

For chiral fermions much heavier than $m_h = 125$ GeV, the loop function $F_{1/2}$ saturates to a constant value [25] and the new physics (NP) contribution becomes proportional to $(\kappa_{t'} + \kappa_{b'})$. Clearly, in the SM-like limit $(\kappa_{t'} = \kappa_{b'} = 1)$, $R_{gg} = 9$, which dealt a killer blow to the sequential fourth generation within the SM. But, more importantly, in the wrong sign limit, the NP contributions coming from the t' and b' loops are of opposite sign and hence there exists the possibility that they may cancel each other. Strictly speaking, the cancellation is perfect in the limit $m_{t'} = m_{b'}$, but even if there is a mass splitting, it is still exact for all intents and purposes as long as t' and b' are much heavier than h. Thus, there is no enhancement in Higgs production through gluon-gluon fusion.

At this point, one might suspect that such a perfect cancellation might not occur for the $h \to \gamma\gamma$ decay. But we should remember that, for anomaly cancellation [26,27], one needs to include an extra chiral generation of leptons too. The fourth generation charged lepton, τ', also contributes to the diphoton decay. Consequently, the NP contribution to the $h \to \gamma\gamma$ amplitude, in the heavy mass limit, is proportional to

$$\kappa_{\gamma\gamma} = \sum_{f=t',b',\tau'} Q_f^2 N_c^f \kappa_f, \tag{6}$$

where, Q_f is the electric charge of the fermion f, and $N_c = 3$ for quarks and 1 for leptons. One can easily check that $\kappa_{\gamma\gamma} = 0$ in the wrong sign limit. Thus a heavy chiral extra generation can remain perfectly hidden from the LHC Higgs data in this limit. In passing, we note that, the quantity

$$\kappa_{Z\gamma} = \sum_{f=t',b',\tau'} Q_f T_3^f N_c^f \kappa_f, \tag{7}$$

where T_3^f denotes the isospin projection of f_L, also vanishes in the wrong sign limit leaving no trace of extra generations in the $h \to Z\gamma$ decay as well. The mechanism, obviously, works even for two or more such heavy generations as well.

III. A PRACTICAL EXAMPLE

The reader, at this point, might wonder whether the conspiracy of couplings given in Eq. (2) can be realized in a gauge theoretic model. The wrong sign limit is not achievable in the SM itself with only one scalar doublet,

[2]One can make all the Yukawa couplings positive by suitable chiral rotations for a single scalar doublet coupling to all the fermions.

because of the uniform proportionality between the fermion masses and their Yukawa couplings. Also, one may note that the cancellation of the bad high-energy behavior for the $f\bar{f} \to W_L W_L$ scattering amplitude is sensitive to the relative sign between the WWh and $f\bar{f}h$ couplings [28]. Consequently, in the wrong sign limit, the amplitude at high energies for $d\bar{d} \to W_L W_L$ (where d represents a generic down-type quark or a charged lepton) will grow and eventually violate the partial-wave unitarity, if only one Higgs doublet is present in the theory. Hence, we must extend the scalar sector.

As an example, let us consider the Type-II two Higgs doublet model (2HDM)[29] where an additional Z_2 symmetry is employed so that one of the doublets (ϕ_2) couples only to the $T_3 = +\frac{1}{2}$ fermions and the other doublet (ϕ_1) couples only to the $T_3 = -\frac{1}{2}$ fermions, thereby ensuring the absence of any flavor changing neutral current (FCNC) mediated by neutral scalars. We follow the convention of Ref. [29] for the parameters of the potential as well as the couplings of the scalars to the fermions and gauge bosons, but extend this popular framework by adding one complete extra chiral generation of leptons and quarks. Note that we have introduced a right-handed neutrino for the fourth generation, and made it heavy enough to have no significant impact in collider as well as astrophysical experiments. We assume that $(B-L)$ symmetry remains exact in the Lagrangian and thus consider the neutrinos as Dirac particles. The lightest CP-even scalar (h) in the spectrum of the physical particles is then identified with the 125 GeV resonance observed at the LHC. Denoting the ratio of the vacuum expectation values (VEVs) of the two scalar doublets by $\tan\beta = v_2/v_1$, we can write the Higgs coupling modification factors as [29]

$$\kappa_V = \sin(\beta-\alpha), \quad (V = W, Z) \tag{8a}$$

$$\kappa_u = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha), \quad \text{(for up type quarks)} \tag{8b}$$

$$\kappa_d = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha), \quad \text{(for down type quarks and charged leptons)} \tag{8c}$$

where α is the mixing angle that takes us from the Lagrangian basis to the physical basis in the CP-even scalar sector. Evidently, the condition

$$\cos(\beta-\alpha) = \frac{2}{\tan\beta}, \quad \text{with,} \quad \tan\beta \gg 2 \tag{9}$$

leads to the desired wrong sign limit of Eq. (2) [30–34]. We also note that by demanding only $\kappa_u = -\kappa_d = 1$, one obtains from Eqs. (8b) and (8c) the condition,

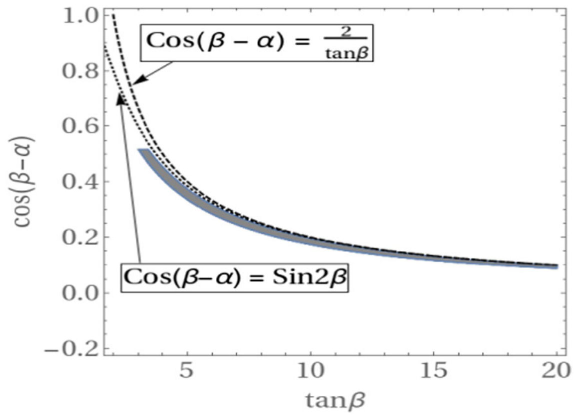

FIG. 1. The gray shaded region, based on the benchmark given in Eq. (11), is allowed at 95% CL from the current data for Higgs signal strengths [3], and ΔS, ΔT for the benchmark of Eq. (11). The dashed and dotted lines represent the contours for $\cos(\beta-\alpha) = 2/\tan\beta$ and $\cos(\beta-\alpha) = \sin 2\beta$ respectively.

$$\cos(\beta-\alpha) = \sin 2\beta \tag{10}$$

which reduces to Eq. (9) in the large $\tan\beta$ limit.

To demonstrate our proposition explicitly, we try to find the allowed region in the $\tan\beta$-$\cos(\beta-\alpha)$ plane so that the Higgs signal strengths into different production and decay channels remain within the experimental limits [3].[3] We display our result in Fig. 1. This plot shows the allowed parameter space in terms of the two free parameters of the model, namely, $\cos(\beta-\alpha)$ and $\tan\beta$, for the benchmark point

$$\begin{aligned} m_{t'} &= 550~\text{GeV}, & m_{b'} &= 510~\text{GeV}, \\ m_{\tau'} &= 400~\text{GeV}, & m_{\nu'} &= 200~\text{GeV}, \\ m_H &= 400~\text{GeV}, & m_A &= 810~\text{GeV}, \\ m_{H^+} &= 600~\text{GeV}. \end{aligned} \tag{11}$$

For the parameter space displayed in Fig. 1, the BSM effects to the oblique parameters S and T, taking into account both fermionic [4,36] and scalar [37,38] contributions, are within the experimental limits given by [39][4]

$$\Delta S = 0.05 \pm 0.10, \qquad \Delta T = 0.08 \pm 0.12. \tag{12}$$

In the limit $\tan\beta \gg 2$ or equivalently $\cos(\beta-\alpha) \to 0$, one gets (see Fig. 2)

[3]For $h \to \gamma\gamma$, we have also taken into account the effect of the charged scalar. However, as has been argued in Ref. [35], the charged scalar can be made to decouple by suitable tuning of the soft breaking mass parameter in scalar potential.

[4]If one takes the 1σ confidence limit on ΔS and ΔT, the bound on $\tan\beta$ gets modified slightly along the dotted line in Fig. 1 to $\tan\beta \gtrsim 4$.

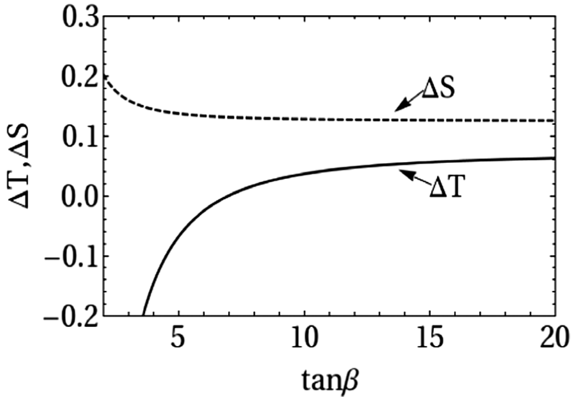

FIG. 2. Variation of the NP contributions to the S and T parameters with $\tan\beta$ assuming the validity of Eq. (8). This plot has been obtained for the benchmark values of Eq. (11).

$$\Delta S \approx 0.12, \qquad \Delta T \approx 0.07. \tag{13}$$

We have checked that all theoretical constraints on the potential, e.g., perturbative unitarity and stability, are satisfied for such a benchmark point. One may wonder whether such a benchmark point would not be in conflict with the direct search limits from the LHC. We discuss later how such bounds can possibly be evaded. At the same time higher mass values for the fourth generation fermions satisfying the ΔS and ΔT constraints would have been equally good for us.

As explained earlier, the mass splitting between the quarks does not affect the cancellation as the production amplitude in the ggF channel becomes insensitive to the precise mass values at the heavy mass limit; the same applies for the leptons while computing the $h \to \gamma\gamma$ amplitude.

Note that a large splitting between m_H and m_A contributes to the electroweak T-parameter with a negative sign [29,40–42]. This fact can be used to allow for much larger mass splittings between the components of fourth generation fermion doublets compared to that in the case of SM4 [4]. For the benchmark of Eq. (11) we find from Fig. 1 that the model automatically tends to the wrong sign limit, vindicating our assertion. We have also checked that the nature of the plot does not crucially depend on our choice of the benchmark as long as all the nonstandard masses are considerably heavier than 125 GeV.

IV. CAVEAT EMPTOR

Lower bounds on the fourth generation quark masses ($m_{q'} \gtrsim 700$ GeV) have been placed from the direct searches at the LHC [43,44]. These bounds, however, crucially depend on the assumption that the lighter of the fourth generation quarks (q') decays into a light quark from the first three generations accompanied by a W-boson. But these decay modes can become subdominant if $V_{i4}, V_{4i} \approx 0$, ($i = 1, 2, 3$) in the 4×4 CKM matrix. In this case, q' becomes quasistable and, in our toy model in the framework of a Type II 2HDM, it mainly decays through the loop-induced neutral currents. In BSM scenarios with tree level FCNC, where $t' \to th$ is the dominant decay mode for t', the bound on the fourth generation mass can be relaxed up to $m_{t'} > 350$ GeV [45]. The bound of $m_{t'} \sim 850$ GeV for t' decaying through neutral-current channels, as recently found by the ATLAS collaboration [46], can be evaded if there are some exotic channels present. In addition to the direct searches, there are also constraints arising from tree-level unitarity of the scattering amplitudes for $2 \to 2$ processes of the type $\bar{f}_1 f_2 \to \bar{f}_3 f_4$ (f_i denotes a generic fermion). The unitarity bound for a fourth generation quark is $m_{q'} \lesssim 550$ GeV [36,47] whereas that for a leptonic fourth generation is $m_{\ell'} \lesssim 1.2$ TeV [47]. All these considerations together justifies our choice of the benchmark in Eq. (11).

In the moderate $\tan\beta$ region as shown in Fig. 1, one should take into account the bound coming from the decay $H \to \tau^+\tau^-$ [48]. For $\tan\beta \sim 10$, $\mathrm{BR}(H \to \tau^+\tau^-) \sim \mathcal{O}(10^{-2})$ for a type II 2HDM. In fact, the ATLAS bound, when translated to the MSSM case, gives $m_{H/A} \gtrsim 250$ GeV for $\tan\beta \sim 10$ [48]. This constraint can be diluted further if we allow H to decay invisibly into a pair of fourth generation neutrinos.

At this point, let us note that there should be some new dynamics not much above the scale of the new fermion masses. Such new dynamics will, in all probability, alter the bounds arising from tree-unitarity. The justification for such new dynamics comes from the fact that the presence of extra heavy chiral fermions will usually give large negative contributions to the evolution of the scalar quartic couplings [4]. This can potentially render the vacuum unstable very quickly after the effects of heavy fourth generation set in. This problem can possibly be diluted by considering a metastable vacuum instead of an absolutely stable one [4] and/or adding extra singlets to the scalar potential, which can give positive contribution to the concerned renormalization group equations.

In passing, we also note that, while such a fourth generation can remain hidden in single production of the Higgs boson, it should show up if one considers the double Higgs production, $gg \to hh$, because the new amplitudes will then add up instead of cancelling each other. Thus, a significant enhancement of the $gg \to hh$ rate may be taken as a possible signature of such an extension of the SM. Nonobservation of such an enhancement will similarly help to rule the model out.

V. SUMMARY

To summarize, we have presented a general recipe for resurrecting one, or more, sequential fermion generations in the precision Higgs era ushered by the LHC. Admittedly, we did not provide a complete model which solves *all* the problems faced by a heavy chiral generation. Nevertheless, we have demonstrated how, in a toy scenario based on a type II 2HDM, the sequential fourth generation can overcome its biggest threat, *viz*, the consistency of LHC Higgs data with the SM expectations. Thus our toy model can be taken as a constituent part of a more elaborate framework which can address all the other issues related to such extra chiral generations like the loss of unitarity or the stability of the electroweak vacuum way above the TeV scale. In anticipation that it will be long before the LHC starts probing the sign of the bottom quark Yukawa coupling [49], a sequential fourth generation can remain hidden in the wrong sign limit for many years to come. Hopefully this unconventional possibility can rekindle the interest in the study of extra fermionic generations.

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[1] 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).
[2] 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).
[3] G. Aad *et al.* (ATLAS, CMS Collaborations), 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, J. High Energy Phys. 08 (2016) 045.
[4] G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. P. Tait, Four generations and Higgs physics, Phys. Rev. D **76**, 075016 (2007).
[5] O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, Impact of a Higgs Boson at a Mass of 126 GeV on the Standard Model with Three and Four Fermion Generations, Phys. Rev. Lett. **109**, 241802 (2012).
[6] A. Djouadi and A. Lenz, Sealing the fate of a fourth generation of fermions, Phys. Lett. B **715**, 310 (2012).
[7] M. I. Vysotsky, in *Proceedings, Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons (HQ 2013), JINR, Dubna, Russia, 2013* (2014), p. 311 [arXiv:1312.0474].
[8] E. Kuflik, Y. Nir, and T. Volansky, Implications of Higgs Searches on the Four Generation Standard Model, Phys. Rev. Lett. **110**, 091801 (2013).
[9] A. Lenz, Constraints on a fourth generation of fermions from Higgs Boson searches, Adv. High Energy Phys. 13 (**2013**) 910275.
[10] V. A. Khoze, Comment on an invisible Higgs boson and 50 GeV neutrino, arXiv:hep-ph/0105069.
[11] K. Belotsky, D. Fargion, M. Khlopov, R. Konoplich, and K. Shibaev, Invisible Higgs boson decay into massive neutrinos of fourth generation, Phys. Rev. D **68**, 054027 (2003).
[12] S. A. Cetin, T. Cuhadar-Donszelmann, M. Sahin, S. Sultansoy, and G. Unel, Impact of the relatively light fourth family neutrino on the Higgs boson search, Phys. Lett. B **710**, 328 (2012).
[13] C. Englert, J. Jaeckel, E. Re, and M. Spannowsky, Evasive Higgs maneuvers at the LHC, Phys. Rev. D **85**, 035008 (2012).
[14] T. Cuhadar-Donszelmann, M. Karagoz, V. E. Ozcan, S. Sultansoy, and G. Unel, Fourth Family Neutrinos and the Higgs Boson, J. High Energy Phys. 10 (2008) 074.
[15] L. M. Carpenter and A. Rajaraman, Revisiting constraints on fourth generation neutrino masses, Phys. Rev. D **82**, 114019 (2010).
[16] W.-Y. Keung and P. Schwaller, Long lived fourth generation and the Higgs, J. High Energy Phys. 06 (2011) 054.
[17] A. Aparici, J. Herrero-Garcia, N. Rius, and A. Santamaria, On the nature of the fourth generation neutrino and its implications, J. High Energy Phys. 07 (2012) 030.
[18] M. Geller, S. Bar-Shalom, G. Eilam, and A. Soni, The 125 GeV Higgs in the context of four generations with 2 Higgs doublets, Phys. Rev. D **86**, 115008 (2012).
[19] L. Bellantoni, J. Erler, J. J. Heckman, and E. Ramirez-Homs, Masses of a fourth generation with two Higgs doublets, Phys. Rev. D **86**, 034022 (2012).
[20] S. Banerjee, M. Frank, and S. K. Rai, Higgs data confronts sequential fourth generation fermions in the Higgs triplet model, Phys. Rev. D **89**, 075005 (2014).
[21] S. Bar-Shalom, S. Nandi, and A. Soni, Two Higgs doublets with 4th generation fermions—models for TeV-scale compositeness, Phys. Rev. D **84**, 053009 (2011).
[22] S. Bar-Shalom, M. Geller, S. Nandi, and A. Soni, Two Higgs doublets, a 4th generation and a 125 GeV Higgs: A review., Adv. High Energy Phys. **2013**, 672972 (2013).
[23] X.-G. He and G. Valencia, An extended scalar sector to address the tension between a fourth generation and Higgs searches at the LHC, Phys. Lett. B **707**, 381 (2012).
[24] S. Chamorro-Solano, A. Moyotl, and M. A. Pérez, Lepton flavor changing Higgs boson decays in a two Higgs doublet model with a fourth generation of fermions, arXiv:1707.00100.
[25] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, The Higgs Hunter's Guide, Front. Phys. **80**, 1 (2000).
[26] S. L. Adler, Axial vector vertex in spinor electrodynamics, Phys. Rev. **177**, 2426 (1969).
[27] J. S. Bell and R. Jackiw, A PCAC puzzle: $\pi^0 \to \gamma\gamma$ in the sigma model, Nuovo Cimento A **60A**, 47 (1969).

[28] G. Bhattacharyya, D. Das, and P. B. Pal, Modified Higgs couplings and unitarity violation, Phys. Rev. D **87**, 011702 (2013).

[29] 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).

[30] P. M. Ferreira, R. Guedes, J. F. Gunion, H. E. Haber, M. O. P. Sampaio, and R. Santos, in *Proceedings, 2nd Conference on Large Hadron Collider Physics Conference (LHCP 2014), New York, USA, 2014* (2014) [arXiv:1410.1926].

[31] D. Fontes, J. C. Romão, and J. P. Silva, A reappraisal of the wrong-sign $hb\bar{b}$ coupling and the study of $h \to Z\gamma$, Phys. Rev. D **90**, 015021 (2014).

[32] P. M. Ferreira, R. Guedes, M. O. P. Sampaio, and R. Santos, Wrong sign and symmetric limits and non-decoupling in 2HDMs, J. High Energy Phys. 12 (2014) 067.

[33] A. Biswas and A. Lahiri, Alignment, reverse alignment, and wrong sign Yukawa couplings in two Higgs doublet models, Phys. Rev. D **93**, 115017 (2016).

[34] P. M. Ferreira, J. F. Gunion, H. E. Haber, and R. Santos, Probing wrong-sign Yukawa couplings at the LHC and a future linear collider, Phys. Rev. D **89**, 115003 (2014).

[35] G. Bhattacharyya and D. Das, Nondecoupling of charged scalars in Higgs decay to two photons and symmetries of the scalar potential, Phys. Rev. D **91**, 015005 (2015).

[36] A. Dighe, D. Ghosh, R. M. Godbole, and A. Prasath, Large mass splittings for fourth generation fermions allowed by LHC Higgs exclusion, Phys. Rev. D **85**, 114035 (2012).

[37] W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, A precision constraint on multi-Higgs-doublet models, J. Phys. G **35**, 075001 (2008).

[38] W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, The oblique parameters in multi-Higgs-doublet models, Nucl. Phys. **B801**, 81 (2008).

[39] C. Patrignani *et al.* (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C **40**, 100001 (2016).

[40] G. Bhattacharyya, D. Das, P. B. Pal, and M. N. Rebelo, Scalar sector properties of two-Higgs-doublet models with a global U(1) symmetry, J. High Energy Phys. 10 (2013) 081.

[41] D. Das, New limits on $\tan\beta$ for 2HDMs with Z_2 symmetry, Int. J. Mod. Phys. A **30**, 1550158 (2015).

[42] G. Bhattacharyya and D. Das, Scalar sector of two-Higgs-doublet models: A minireview, Pramana **87**, 40 (2016).

[43] G. Aad *et al.* (ATLAS Collaboration), Search for pair production of a new heavy quark that decays into a W boson and a light quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Rev. D **92**, 112007 (2015).

[44] S. Chatrchyan *et al.* (CMS Collaboration), Combined search for the quarks of a sequential fourth generation, Phys. Rev. D **86**, 112003 (2012).

[45] M. Geller, S. Bar-Shalom, and G. Eilam, The need for new search strategies for fourth generation quarks at the LHC, Phys. Lett. B **715**, 121 (2012).

[46] ATLAS Collaboration, Report No. ATLAS-CONF-2017-015, 2017.

[47] M. S. Chanowitz, M. A. Furman, and I. Hinchliffe, Weak Interactions of Ultraheavy Fermions. 2., Nucl. Phys. **B153**, 402 (1979).

[48] M. Aaboud *et al.* (ATLAS Collaboration), Search for pair production of vector-like top quarks in events with one lepton, jets, and missing transverse momentum in $\sqrt{s} =$ 13Tev pp collisions with the ATLAS detector, J. High Energy Phys. 08 (2017) 052.

[49] T. Modak, J. C. Romão, S. Sadhukhan, J. P. Silva, and R. Srivastava, Constraining wrong-sign hbb couplings with $h \to \Upsilon\gamma$, Phys. Rev. D **94**, 075017 (2016).