PHYSICAL REVIEW D **86,** 034022 (2012)

Masses of a fourth generation with two Higgs doublets

Leo Bellantoni,[1,*] Jens Erler,[2,†] Jonathan J. Heckman,[3,‡] and Enrique Ramirez-Homs[4,§]

[1]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[2]*Departamento de Física Teórica, Instituto de Física, Universidad Nacional Autónoma de México, 04510 México D.F., México*
[3]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[4]*University of Texas, El Paso, Texas 79968, USA*

(Received 24 May 2012; published 24 August 2012)

We use sampling techniques to find robust constraints on the masses of a possible fourth sequential fermion generation from electroweak oblique variables. We find that in the case of a light (115 GeV) Higgs from a single electroweak symmetry breaking doublet, inverted mass hierarchies are possible for both quarks and leptons, but a mass splitting more than M_W in the quark sector is unlikely. We also find constraints in the case of a heavy (600 GeV) Higgs in a single doublet model. As recent data from the Large Hadron Collider hints at the existence of a resonance at 124.5 GeV and a single Higgs doublet at that mass is inconsistent with a fourth fermion generation, we examine a Type II two Higgs doublet model. In this model, there are ranges of parameter space where the Higgs sector can potentially counteract the effects of the fourth generation. Even so, we find that such scenarios produce qualitatively similar fermion mass distributions.

DOI: 10.1103/PhysRevD.86.034022 PACS numbers: 14.65.Jk

I. INTRODUCTION

Adding a sequential fourth generation of fermions (4G) is one of the simplest possible extensions to the Standard Model. Indeed, although the width of the Z limits the number of active light neutrinos to three, there can in principle be a fourth neutrino generation which is much heavier. Recent and extensive literature examines the impact of how 4G would reduce tensions in recent measurements in the b sector and create distinctive phenomena in kaon decays [1,2], as well as providing a potential scenario for the baryon asymmetry of the Universe [3]. As a more top-down motivation, simple string constructions often lead to toy models with an even number of generations. Of course, achieving three chiral generations is also possible in a wide class of examples, and some stringy models of flavor physics predict that more than three generations would be inconsistent with the measured three-generation quark mixing matrix [4]. More generally, one can view the 4G scenario as a simple template for scenarios of physics beyond the Standard Model in which states of some extra sector receive a mass proportional to the Higgs vev.

In light of these considerations, it is clearly of interest to study the viability of the 4G scenario. In addition to the possibility of direct detection of such states, the contributions of these additional states enter as loop corrections to various Standard Model processes. For example, a fourth generation tends to produce a positive contribution to both S and T, the oblique electroweak parameters. By contrast, in a single Higgs doublet model, increasing the mass of the Higgs generates a positive contribution to S and a negative contribution to T. Thus, while cancellation for the T parameter is possible, the contributions to the S parameter typically move in the same (positive) direction, though mass hierarchies in the fourth generation can reduce the size of this contribution. The extra generation also affects the phenomenology of the Higgs, leading to an increase in $\Gamma(h \to gg)$, and a decrease in $\Gamma(h \to \gamma\gamma)$.

Though less well studied, even simple extensions of the Higgs sector can counteract (or exacerbate) some of the effects of a chiral fourth generation with an appropriate tuning of parameters. For example, in two Higgs doublet models (2HDM), the contributions to S and T can have either sign (see e.g., Refs. [5–7]). General values of the Higgs mixing angles also allow for changes in $\Gamma(h \to gg)$ and $\Gamma(h \to \gamma\gamma)$, independently, relative to the 4G scenario.

In this paper we study the available parameter space for the 4G scenario and its extension to 2HDM models. The full parameter space of 4G is too large for easy visualization, but much of what we need to know to understand existing experimental results and to inform future searches can be expressed with two pairs of numbers: the two quark masses and the two lepton masses. We therefore seek, by sampling this four-parameter space and comparing the samples with constraints on electroweak oblique parameters, to determine the most likely mass spectrum for 4G, should it exist. Similar earlier analyses of this type may be found in Refs. [8–10], but new experimental data has appeared since these publications. Other similar studies have appeared recently [11–13].

*bellanto@fnal.gov
†erler@fisica.unam.mx
‡jheckman@ias.edu
§enraho@gmail.com

Exclusion limits on the mass of a Standard Model-like Higgs impose additional constraints on the 4G scenario. In 4G, the gluon fusion production cross section for the Higgs is markedly increased over the three-generation scenario. Both LHC collaborations [14] independently exclude, using a combination of channels, the range 120 GeV $< M_h <$ 600 GeV when there is a fourth generation. The LEP II lower limit of 114.4 GeV is independent of the number of fermion generations [15]. Because a fourth generation of fermions contributes to T roughly quadratically with $m(t_4)$ and $m(b_4)$, and because a large T corresponds to a large $m(h)$, values of $m(h)$ as high as 1 TeV are allowed by electroweak constraints [10,16] in 4G. However, studies of the stability and triviality bounds on $m(h)$ in 4G [17] prohibit $m(h) \gtrsim 700$ GeV unless there is also some other new phenomenon on a scale below 2 TeV.

Most recently, there are "hints" of a Higgs with a mass [18] of 124.5 ± 0.8 GeV from the LHC [19] and supporting evidence from the Tevatron [20]. The hint is strongest in the channel $gg \rightarrow h \rightarrow \gamma\gamma$, where the ATLAS experiment reports an excess above background of 2.8 standard deviations. The statistical significance of these results is not enough to declare discovery or even strong evidence for a Higgs, but it is strong enough to provoke discussion. This mass is within the bounds ruled out by the LHC when supposing a fourth fermion generation. To leading $\mathcal{O}(G_F m_f^2)$, it is possible to retain 4G if one supposes only the $\gamma\gamma$ channel's hint remains significant with the addition of more data, but including exact next-to-leading order electroweak corrections makes this difficult [21,22]. Consequently, the 4G hypothesis is valid only if (a) the hints turn out to be statistical fluctuations or (b) the hints are due to something beyond a single Higgs doublet, such as a two Higgs doublet model.

The rest of this paper is organized as follows. In Sec. II we treat the 4G single Higgs doublet case. We give results for $m(h) = 115$ GeV (the "baseline" scenario) and for $m(h) = 600$ GeV (the "high mass" scenario). The baseline scenario is appropriate for the case considered in Ref. [21,22]; the difference in our results between $m(h) = 115$ GeV and 124.5 GeV is small. In Sec. III we extend the analysis to consider a Type II model with its parameters adjusted to match the 124.5 GeV hint. Section IV provides a summary.

II. SINGLE HIGGS DOUBLET SCENARIOS

A. Method

We have updated constraints on the oblique electroweak [23] parameters S, T and U, as found by the Global Analysis of Particle Properties (GAPP) [24] using data available in October 2011. In our sampling procedure, each sample is assigned a weight corresponding to the probability density function $p = p(S, T, U)$ for these three parameters. We employ the one-loop contributions to the oblique parameters, assuming small mixing with the extra family, as in Ref. [8]. See Ref. [25] for some recent discussion of the more general case of potentially large mixing effects.

The sampling distribution in this type of analysis plays the role of a Bayesian prior; we are taking the probability p of a specific value for S, T and U given an assumed set of four fermion masses, and weighting it in our result as the probability density created by our sampling of the fermion spectrum. We interpret the result as a probability density function for the fermion mass spectrum, but that interpretation is only valid in the context of that assumed sampling distribution. The peril in this process—the validity of the assumed prior—thus has the advantage of requiring explicit description.

We draw 5×10^7 uniformly distributed samples in the fermion mass spectrum with lower bounds set by direct experimental constraints described below. The upper bound is limited by unitarity arguments [26] to 500 GeV, but this is a rough bound, and we raise it to 700 GeV for clarity in the resulting figures.

The lower bound on the sampled $m(\nu_4)$ mass range is, in our baseline scenario, $m(\nu_4) = 90.3$ GeV from LEP II [27]. This limit is the weakest of the limits obtained under the assumption of ν_4 decay to each of the three known charged leptons; if $m(\nu_4) > m(\tau_4)$, then we would obtain a stronger limit. The lower bound on the sampled $m(\tau_4)$ range is 100.8 GeV; again, this is the weakest limit obtained in all the possible decay scenarios. These results are therefore robust against all assumptions about the lepton mass hierarchies. On the other hand, lepton mixing parameters are important considerations in searches for the leptons of 4G at the LHC which have been discussed [28] but have not yet been carried out.

Obtaining robust lower bounds on 4G quark masses and mixing angles is a little more complicated. Dramatic results [29] from the LHC are indeed available [30], and new ones are appearing constantly. The CMS collaboration has searched for

(i) $b_4\bar{b}_4 \rightarrow tW^-\bar{t}W^+ \rightarrow (bW^+W^-)(\bar{b}W^-W^+)$ with same-charge leptons and trileptons in a 4.6 fb^{-1} sample [31], obtaining a limit of 600 GeV.

(ii) both t_4 and b_4 using a simplified model with a range of final states, all containing two b quarks, in 1.1 fb^{-1} of data [32]. All of the diagrams considered have $b_4 \rightarrow tW$ or $t_4 \rightarrow bW$. Lower limits of 480–540 GeV were obtained.

(iii) pair-produced t_4 in the "lepton with jets" channel, wherein a decay to bW having the same signature as a $t\bar{t}$ event but with a different primary quark mass is sought. The analysis reconstructed $m(t_4)$ in each event. A 560 GeV lower limit was found using only 4.6 fb^{-1} of data [33].

(iv) pair-produced t_4 in the "dilepton" channel, wherein also a decay to bW having a top-quark signature but different mass is sought. A weaker constraint than that which was obtained in the "lepton with jets" analysis, 422 GeV, was found using 1.1 fb^{-1} of data [34].

The ATLAS collaboration has searched for

(i) pair-produced $b_4 \to tW$ in 34 pb^{-1} of data [35], as part of an inclusive search for exotic production of the same-charge dilepton signature.

(ii) pair-produced t_4 or b_4 decaying to Wq, where $q = u$, d, s, or b, appearing with opposite-charge dileptons and missing transverse momentum in 37 pb^{-1} of data [36]. An approximate event reconstruction is done. The resulting limit is $m(t_4) = m(b_4) > 270$ GeV.

(iii) $b_4\bar{b}_4 \to tW^-\bar{t}W^+ \to (bW^+W^-)(\bar{b}W^-W^+)$ with one lepton, at least six jets, and large missing momentum transverse to the beamline on a 1.0 fb^{-1} sample, obtaining [37] a limit of 480 GeV.

(iv) pair-produced t_4 or b_4 appearing with same-charge dileptons, large missing transverse momentum, and at least two jets in 1.0 fb^{-1} of data [38]. A limit of $m(b_4) > 450$ GeV was obtained.

See Ref. [39] for recent searches of more exotic fermions.

These search results, while impressive, are all built upon specific decay, i.e., CKM mixing angle, assumptions. With the exception of Ref. [36], mixing of the fourth generation into anything other than the third generation is not considered. Furthermore, $t_4 \to b_4 W^*$ (or in an inverted hierarchy, $b_4 \to t_4 W^*$) will be an additional contribution to b_4 (or t_4) production which will not necessarily appear in any specific signature as a result of the W^* products; the contribution from this channel can be significant if the mass splitting is small.

Additionally, there are constraints on the possible mixing parameters. For example, the mixing parameters for the quark sector may be constrained [2,40] with data from neutral mesons, the $b \to s\gamma$ transition, existing constraints on the three-generation quark mixing matrix and limits on $\mathrm{Br}(B_S \to \mu^+\mu^-)$. Reference [40] concludes that large mixings of the fourth generation with the three known generations are not ruled out, but Refs. [41,42], which consider constraints from corrections to the $Z \to b\bar{b}$ vertex from a fourth generation, conclude that these mixings could be comparable to Cabibbo mixing. The quark mixing matrix can also be constrained with precision electroweak data and $D^0 - \bar{D}^0$ mixing [43]. In any case, however, there is the possibility that 4G fermions could decay to either third- or lower-generation fermions with varying branching ratios.

A method for producing experimental limits that are mixing-angle independent [44] and that allows for the contributions of both 4G quarks to any particular signature was applied to the results of CDF searches [45], resulting in lower limits of ~280 GeV for $m(b_4)$ and ~290 GeV for $m(\tau_4)$. We use these lower but mixing-independent values here while strongly advocating the application of these techniques to the more recent LHC results. Such an analysis could soon sharply constrain or even rule out the 4G hypothesis.

B. Results

Figures 1 and 2 show the lepton and quark mass spectra in our baseline and high $m(h)$ scenarios. In these and similar figures, the color for each bin represents a probability density integrated over the bin, and normalized so as to give unit probability when summed over the entire plot. For the baseline (high mass) case, $|m(t_4) - m(b_4)| < M_W$ in over 99% (90%) of our samples; transitions between 4G quarks will produce off-shell W bosons. The lepton mass splitting is less than M_W with probability 69% (24%). Normal mass hierarchies are more likely than not, but by no means certain; in the lepton sector the probability of a normal mass hierarchy is 70% (93%), and in the quark sector, it is 59% (69%).

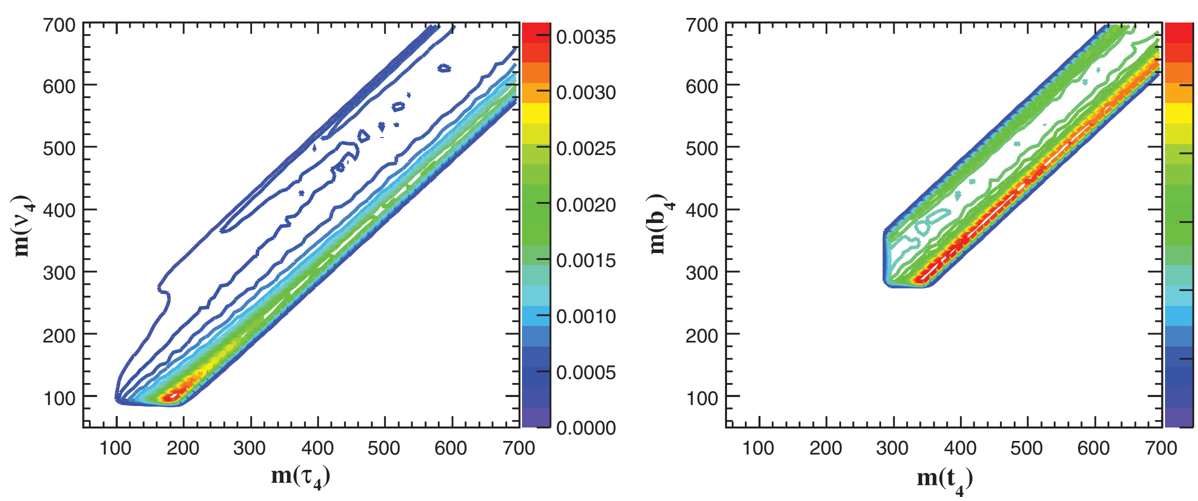

FIG. 1 (color). Contour plots of the probability densities in the 4G baseline scenario. Left: $m(\nu_4)$ vs $m(\tau_4)$; Right: $m(b_4)$ vs $m(t_4)$. All scales are in GeV; probability densities have been normalized, and each bin is 10 GeV × 10 GeV.

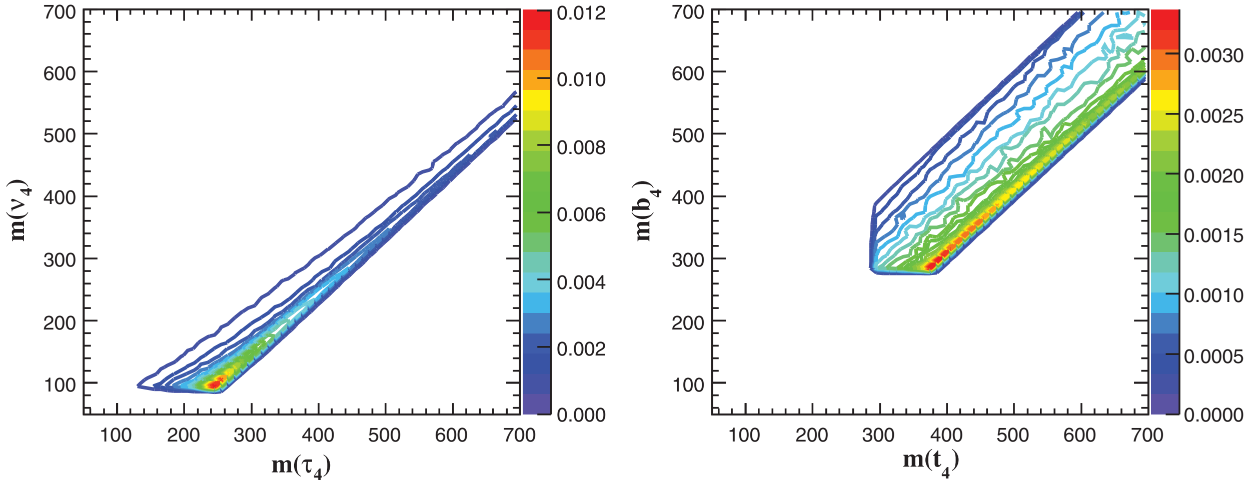

FIG. 2 (color). Contour plots of the probability densities in the 4G scenario with $m(h) = 600$ GeV. Left: $m(\nu_4)$ vs $m(\tau_4)$; Right: $m(b_4)$ vs $m(t_4)$. All scales are in GeV; probability densities have been normalized, and each bin is 10 GeV × 10 GeV.

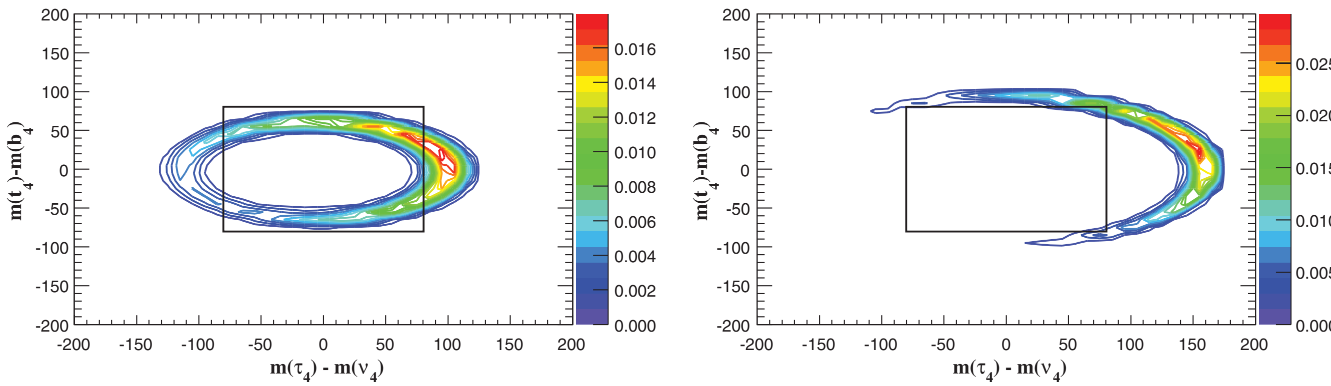

FIG. 3 (color). Contour plots of the probability densities for quark vs lepton mass splitting in the 4G scenario. Left: with $m(h) = 115$ GeV; Right: with $m(h) = 600$ GeV. The boxes mark the areas where the magnitude of the mass splittings is less than M_W. All scales are in GeV; probability densities have been normalized, and each bin is 10 GeV × 10 GeV.

Masses just over the existing limit for the leptons are heavily favored, and this tendency is greater in the high $m(h)$ scenario. Being able to predict this parameter relatively precisely makes it a valuable target for future searches.

In Fig. 3 we show the lepton and quark mass splittings. We see that, with perhaps a twofold ambiguity, the mass splittings in the two sectors are tightly related.

Carpenter and Rajaraman [46] revisited the LEP II results in a scenario with both left- and right-handed neutrinos. They conclude that $m(\nu_4)$ as low as 62.1 GeV is possible. Some recent studies [11,12,22] also consider low values of $m(\nu_4)$. We find that lowering the bound on $m(\nu_4)$ to 62.1 GeV does not produce much change relative to our baseline scenario. Figure 4 shows distributions that have the same probabilities of mass splittings less than M_W and the same probabilities of normal mass hierarchies as our baseline scenario to within about 2%.

III. TWO HIGGS DOUBLET SCENARIO

A. Method

Should the hints of a Higgs boson with $m(h) = 124.5$ GeV solidify with more data, the 4G hypothesis is only tenable if an extended electroweak symmetry breaking sector exists. As an example of such an extension we consider a second Higgs doublet [47] in conjunction with a fourth sequential fermion generation (2HD4G). Two identical complex scalar $SU(2)_L$ doublet fields Φ_1 and Φ_2, both of hypercharge $Y = 1$ are postulated. To forbid flavor-changing neutral currents, we select the Type II Yukawa coupling pattern, in which $Q = 2/3$ quarks couple to one doublet and $Q = -1/3$ quarks and charged leptons to the other. This restriction permits a $\mathbb{Z}_2$ symmetry to distinguish Φ_1 from Φ_2. We restrict consideration to the gauge-invariant, renormalizable and CP-conserving potential

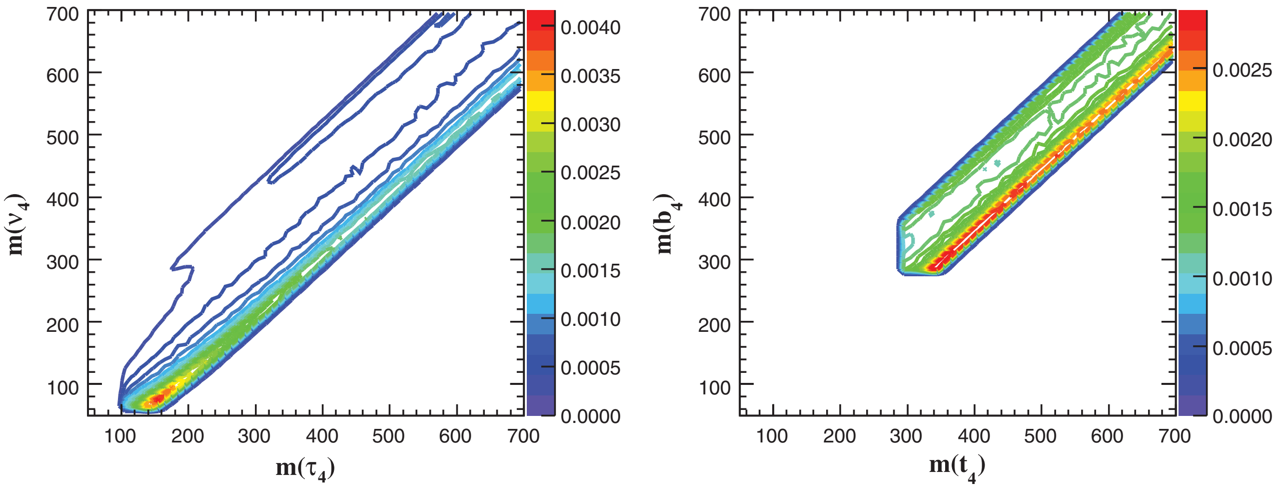

FIG. 4 (color). Contour plots of the probability densities in the 4G baseline when $m(\nu_4)$ is allowed to go as low as 60.1 GeV. Left: $m(\nu_4)$ vs $m(\tau_4)$; Right: $m(b_4)$ vs $m(t_4)$. All scales are in GeV; probability densities have been normalized, and each bin is $10\mathrm{GeV} \times 10\mathrm{GeV}$.

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2), \tag{1}$$

where all the parameters m_{ii} and λ_i are real. This system and its vacua preserve an additional $\mathbb{Z}_2$ symmetry. There are two CP-even neutral bosons, h and H $[m(h) < m(H)]$; a CP-odd neutral boson, A; and the charged bosons $H^\pm$ in this model.

This model is different from the similarly named "4G2HDM" model of Ref. [48]; however, Ref. [49] analyzed a similar model prior to the appearance of the 124.5 GeV hint. The presence of large fourth-generation Yukawas can lead to large radiative corrections which can potentially destabilize the form of the Higgs potential. Here we assume that the 2HDM effective potential is stabilized by some effect near the TeV scale, so that we can focus on the resulting effective theory below the TeV scale.

Though it is beyond the scope of this study, the combination of two Higgs doublets with a fourth sequential fermion generation creates a rich phenomenology for which constraints from the kaon and b sector could be derived. For example, the coupling constants $Z \to b\bar{b}$ vertex will obtain corrections which depend on $V_{t_4 b}$, $m(t_4)$, and (depending on chirality) either $\tan\beta$ or its inverse; these contributions can be constrained experimentally.

Two important parameters of this model are $\tan\beta$, the ratio of the vacuum expectation values of the two doublets and α, the angle which diagonalizes the mass-squared matrix of the CP-even bosons. Values of $\tan\beta$ less than 1 are disfavored experimentally assuming three fermion generations; more generally, $\tan\beta > 0.3$ results from the requirement that the top-quark Yukawa coupling not exceed the perturbative limit [47]. Requiring perturbativity of the fourth-generation Yukawa interactions can impose additional constraints. For the sake of generality, however, we do not impose this additional restriction in our scans. We sample $\tan\beta$ in a scale-independent way, i.e., the distribution of $\log(\tan\beta)$ is uniform. The angle α is scanned uniformly, but samples are weighted according to the value of α as described below; the masses of the 4G fermions and the bosons H, A and $H^\pm$ are selected with an initially uniform distribution. The mass of the lightest CP-even boson is set to 124.5 GeV. For further discussion on the phenomenology of two Higgs doublets with a fourth fermion generation, including the case where ν_4 is stable and contributes invisible decays to either h or A, see Ref. [50].

The 124.5 GeV hint is strongest in the channel $gg \to h \to \gamma\gamma$, where the ATLAS experiment reports an excess above background of 2.8 standard deviations. The second most significant hints are in the channels $gg \to h \to VV^*$, where the ATLAS results have a significance of 2.1 and 1.4 standard deviations for $V = W$, Z respectively. The combination of ATLAS and CMS data correspond to a $\gamma\gamma$ production rate about 1.4 ± 0.7 times the prediction of the Standard Model [51]; for VV^*, it is about $0.8^{+0.7}_{-0.4}$ times the Standard Model rate.

For each scanned value of α, we calculate $\sigma(gg \to h) \times \frac{\Gamma(h\to\gamma\gamma)}{\Gamma_{2HD4G}(\mathrm{tot})}$ and $\sigma(gg \to h)\frac{\Gamma(h\to VV^*)}{\Gamma_{2HD4G}(\mathrm{tot})}$ for the 2HD4G scenario and form a χ^2 of these values against these experimental values. We weight each sample according to that χ^2. We do not consider constraints from decays of the H, A and $H^\pm$ which are very parameter dependent in the 2HD4G scenario.

The dominant production mechanism at both the LHC and the Tevatron is gluon fusion through loop diagrams involving the colored states. In a 2HDM, this includes the contributions from both the t, b as well as t_4 and b_4. The Standard Model normalized cross section $\hat{\sigma} = \sigma_{2HD4G}/\sigma_{SM}$ of the gluon fusion production cross sections is

$$\hat{\sigma} = \frac{|\frac{c_\alpha}{s_\beta}(A_{1/2}(t) + A_{1/2}(t_4)) - \frac{s_\alpha}{c_\beta}(A_{1/2}(b) + A_{1/2}(b_4))|^2}{|A_{1/2}(t)|^2}, \quad (2)$$

where c_α and s_α denote $\cos\alpha$ and $\sin\alpha$ respectively, and $A_{1/2}(X)$ is the threshold correction of a spin-1/2 particle X to the $h \to gg$ vertex for a 124.5 GeV Higgs, with notation as in Ref. [52]. A similar expression holds for the Standard Model normalized decay rate $h \to \gamma\gamma$. In a 2HDM, this will include terms from loops containing W, t, b and τ and charged fourth-generation fermions, as well as a contribution from $H^\pm$, which all depend on the mixing angles. The total width of the Higgs in 2HD4G, including the mixing angle dependence, is fixed by similar considerations. Much as in Ref. [53], the overall normalization can be extracted from the recently updated values for the Standard Model 124.5 GeV Higgs partial widths [54] by including the mixing angle dependence and contribution from extra states in the various 2HD4G partial widths.

Constraints on two doublet models are readily available [55] through the package 2HDMC. We observe the constraints of tree-level unitarity [56], perturbativity (i.e., the magnitudes of all the quartic Higgs couplings must be less than 4π), and the absence of runaway directions, as implemented in 2HDMC. Contributions to the oblique electroweak parameters [57] are also provided as part of 2HDMC.

B. Results

Figures 5 and 6 show the lepton and quark mass spectra in our two Higgs doublet scenario. The quark (lepton) mass splittings are less than M_W in 99% (65%) of our samples;

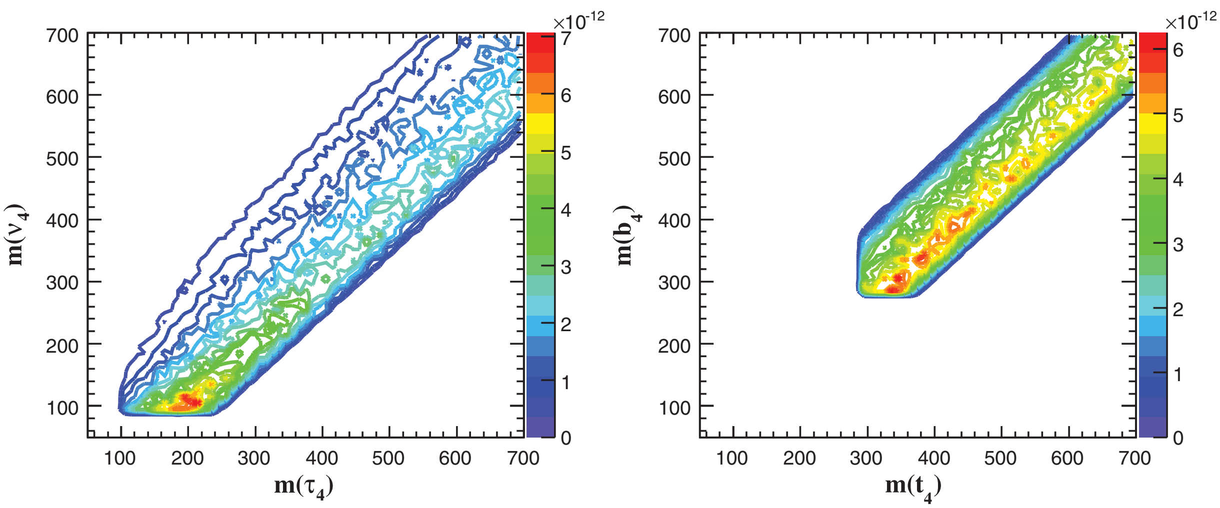

FIG. 5 (color). Contour plots of the probability densities in 2HD4G with the mass of the lightest CP-even state $m(h) = 124.5$ GeV. Left: $m(\nu_4)$ vs $m(\tau_4)$; Right: $m(b_4)$ vs $m(t_4)$. All scales are in GeV; probability densities have been normalized, and each bin is 10 GeV × 10 GeV.

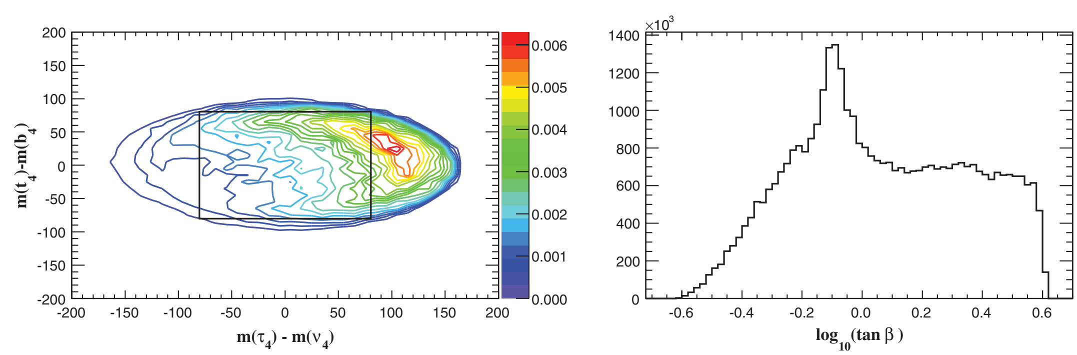

FIG. 6 (color). Left: Contour plots of the probability densities in 2HD4G with the mass of the lightest CP-even state $m(h) = 124.5$ GeV. Quark mass splitting vs lepton mass splitting. The box marks the area where the magnitude of the mass splittings is less than M_W. All scales are in GeV; probability densities have been normalized, and each bin is 10 GeV × 10 GeV. Right: The probability density function for $\log_{10}(\tan\beta)$ in 2HD4G with the mass of the lightest CP-even state $m(h) = 124.5$ GeV.

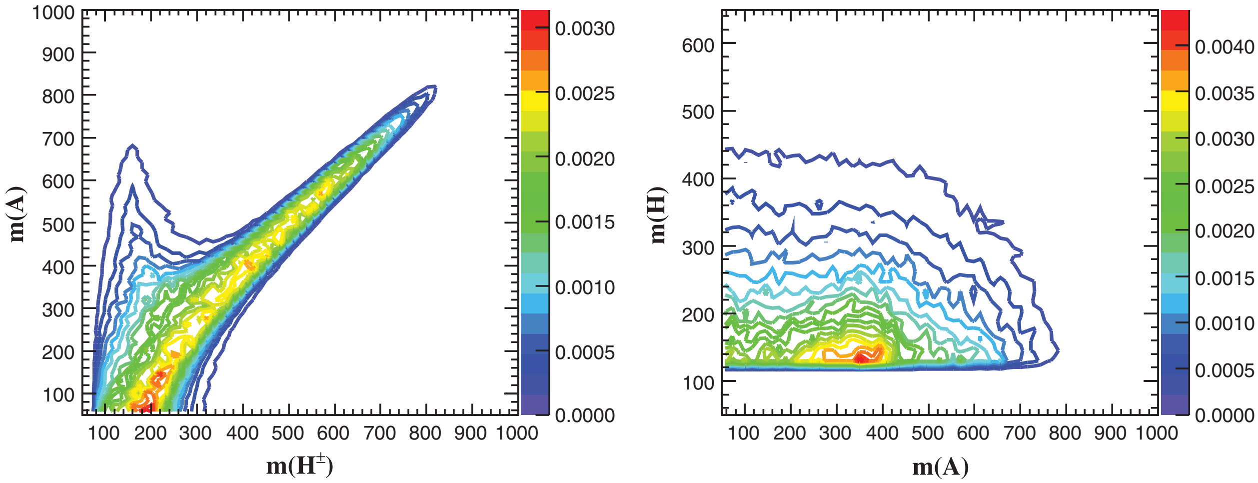

FIG. 7 (color). The probability density function for the masses of H, A and $H^{\pm}$ in 2HD4G with the mass of the lightest CP-even state $m(h) = 124.5$ GeV.

normal mass hierarchies in the quark (lepton) sector occur with a probability of 59% (72%).

Low values of $\tan\beta$ are likely in 2HD4G; in Fig. 6, $\tan\beta < 1$ in 46% of the final probability density function. Figure 7 shows the distribution of Higgs boson masses. There is a strong correlation between the masses $m(H^{\pm})$ and $m(A)$ largely but not entirely created by requiring VV^* as well as $\gamma\gamma$ production to be in agreement with experiment. It is amusing to note that the most likely values for the mass of the second CP-even boson are just over 124.5 GeV, and masses corresponding to a small excess in the 4ℓ channel at 240 GeV are not improbable.

While the extended Higgs sector does alter the results from the single Higgs double scenarios, the broad features of the mass-splitting structures and preference for low masses, particularly for ν_4, remain. These features are largely a result of the structure of the contributions to the electroweak oblique parameters from the fourth generation of sequential fermions. Similar results might be expected in almost any extension to the Higgs sector that is broadly consistent with a Standard Model-like Higgs.

IV. SUMMARY

While stringent limits on $m(t_4)$ and $m(b_4)$ have been found in specific decay modes by the LHC, completely ruling out the fourth generation hypothesis requires an analysis [45] that combines the results from a number of modes to obtain a result that is independent of quark mixing in the fourth generation.

We have used sampling methods to determine the probability densities of the masses of a possible fourth sequential generation of fermions in scenarios with one or two Higgs doublets. With a single Higgs doublet and a low (115 or 124.5 GeV) Higgs mass, fourth-generation mass splitting in the quark sector is less than M_W (see also Ref. [11]). Quark sector mass splittings less than M_W are favored but less certain if the Higgs mass is 600 GeV. A fourth generation is on the verge of being ruled out in the case of a single Higgs doublet [14], but a Type II two Higgs doublet model can be designed to reproduce the hints at 124.5 GeV from the LHC and the Tevatron. In that case, quark mass splittings less than M_W are still favored. In all of our scenarios, the most favored values for $m(\tau_4)$ are just above the experimental limit of 110.8 GeV, making searches for a fourth-generation charged lepton an interesting possibility.

ACKNOWLEDGMENTS

We gratefully thank the authors of 2HDMC in particular for developing a new version of their code. We also thank P. Kumar and P. Langacker for helpful discussions. J. J. H. thanks the Simons Center for Geometry and Physics for hospitality during the completion of this work. The work of L. B. and E. R.-H. is supported by DOE Contract No. DE-AC02-07CH11359; the work of J. E. is supported by CONACyT (México) Contracts No. 82291-F and No. 151234; the work of J. J. H. is supported by NSF Grant No. PHY-0969448 and by the c at the Institute for Advanced Study.

[1] See for example A. Soni, A. K. Alok, A. Giri, R. Mohanta, and S. Nandi, Phys. Rev. D **82**, 033009 (2010); V. Bashiry, N. Shirkhanghah, and K. Zeynali, Phys. Rev. D **80**, 015016 (2009); D. Choudhury and D. K. Ghosh, J. High Energy Phys. 02 (2011) 033; W-S. Hou, M. Nagashima, and A. Soddu, Phys. Rev. D **76**, 016004 (2007); B. Holdom, W.-S. Hou, T. Hurth, M. L. Mangano, S. Sultansoy, and G. Unel, PMC Phys. A **3**, 4 (2009); A. Mohanta and A. K. Giri, Phys. Rev. D **85**, 014008 (2012); A. Ahmed, I. Ahmed, M. J. Aslam, M. Junaid, M. A. Paracha, and A. Rehman, Phys. Rev. D **85**, 034018 (2012).

[2] A. J. Buras, B. Duling, T. Feldmann, T. Heidsieck, C. Promberger, and S. Recksiegel, J. High Energy Phys. 09 (2010) 106.

[3] W-S. Hou, Chin. J. Phys. (Taipei) **47**, 134 (2009).

[4] J. J. Heckman and C. Vafa, Nucl. Phys. **B837**, 137 (2010).

[5] J. J. Heckman, P. Kumar, C. Vafa, and B. Wecht, J. High Energy Phys. 01 (2012) 156.

[6] G. Funk, D. O'Neil, and R. M. Winters, Int. J. Mod. Phys. A **27**, 1250021 (2012).

[7] H. E. Haber and D. O'Neil, Phys. Rev. D **83**, 055017 (2011).

[8] H.-J. He, N. Polonsky, and S. Su, Phys. Rev. D **64**, 053004 (2001).

[9] G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. P. Tait, Phys. Rev. D **76**, 075016 (2007).

[10] M. Baak *et al.*, Eur. Phys. J. C **72**, 2003 (2012).

[11] A. Dighe, D. Ghosh, R. M. Godbole, and A. Prasath, Phys. Rev. D **85**, 114035 (2012).

[12] M. Buchkremer, J.-M. Gérard, and F. Maltoni, J. High Energy Phys. 06 (2012) 135.

[13] W. Bernreuther, P. Gonzalez, and M. Wiebusch, Eur. Phys. J. C **69**, 31 (2010).

[14] G. Aad *et al.* (ATLAS Collaboration), Report No. ATLAS-CONF-2011-135; S. Chatrchyan *et al.* (CMS Collaboration), Report No. CMS-PAS-HIG-11-011.

[15] *Working Group for Higgs Boson Searches*, [Phys. Lett. B 565, 61 (2003)].

[16] J. Erler and P. Langacker, Phys. Rev. Lett. **105**, 031801 (2010).

[17] M. Hashimoto, Phys. Rev. D **81**, 075023 (2010); A. Wingerter, Phys. Rev. D **84**, 095012 (2011).

[18] J. Erler, arXiv:1201.0695.

[19] G. Aad *et al.* (ATLAS Collaboration), arXiv:1201.1408v3; S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **710**, 26 (2012).

[20] Tevatron New Phenomena and Higgs Working Group, CDF and D0 Collaborations, Report No. FERMILAB-CONF-12-065-E.

[21] G. Guo, B. Ren, and X.-G. He, arXiv:1112.3188; See also E. Kuflick, Y. Nir, and T. Volansky, arXiv:1204.1975.

[22] A. Djouadi and A. Lenz, arXiv:1204.1252; See also O. Eberhardt *et al.*, arXiv:1204.3872.

[23] M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. **65**, 964 (1990); Phys. Rev. D **46**, 381 (1992).

[24] J. Erler and P. Langacker in K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010); J. Erler, arXiv:hep-ph/0005084.

[25] O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, arXiv:1204.3872.

[26] M. S. Chanowitz, M. A. Furman, and I. Hinchliffe, Nucl. Phys. **B153**, 402 (1979); W. J. Marciano, G. Valencia, and S. Willenbrock, Phys. Rev. D **40**, 1725 (1989).

[27] P. Achard *et al.* (L3 Collaboration), Phys. Lett. B **517**, 75 (2001).

[28] L. M. Carpenter, A. Rajaraman, and D. Whiteson, arXiv:1010.1011.

[29] All limits are at the 95% confidence level.

[30] Sh. Rahatlou, on behalf of the (ATLAS, CDF, CMS and D0 Collaborations), in Proceedings of XXXI Physics In Collision, Vancouver, BC, Canada, 2011, Report No. CMS-CR-2011/306.

[31] L. Sonnenschein, on behalf of the (ATLAS and CMS Collaborations), in XLVII Rencontres de Moriond, QCD and High Energy Interactions, La Thuile, Italy, 2012.

[32] S. Chatrchyan *et al.* (CMS Collaboration), Report No. CMS-PAS-EXO-11-054.

[33] S. Chatrchyan *et al.* (CMS Collaboration), Reports No. CMS-PAS-EXO-11-051, No. CMS-PAS-EXO-11-099.

[34] S. Chatrchyan *et al.* (CMS Collaboration), Report No. CMS-PAS-EXO-11-050.

[35] G. Aad *et al.* (ATLAS Collaboration), J. High Energy Phys. 10 (2011) 107.

[36] G. Aad *et al.* (ATLAS Collaboration), Report No. ATLAS-CONF-2011-022.

[37] G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **109**, 032001 (2012).

[38] G. Aad *et al.* (ATLAS Collaboration), J. High Energy Phys. 04 (2012) 069.

[39] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **107**, 271802 (2011); G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **108**, 041805 (2012).

[40] O. Eberhardt, A. Lenz, and J. Rohrwild, Phys. Rev. D **82**, 095006 (2010); M. Bobrowski, A. Lenz, J. Riedl, and J. Rohrwild, Phys. Rev. D **79**, 113006 (2009).

[41] A. K. Alok, A. Dighe, and D. London, Phys. Rev. D **83**, 073008 (2011).

[42] M. S. Chanowitz, Phys. Rev. D **79**, 113008 (2009).

[43] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, Phys. Rev. D **76**, 095009 (2007).

[44] P. Q. Hung and M. Sher, Phys. Rev. D **77**, 037302 (2008) point out that for very small mixing angles, 4G quarks are charged massive particles, with signatures very different from those typically used in 4G searches.

[45] C. J. Flacco, D. Whiteson, T. M. P. Tait, and S. Bar-Shalom, Phys. Rev. Lett. **105**, 111801 (2010), arXiv:1101.4976; D. Whiteson (private communication).

[46] L. M. Carpenter and A. Rajaraman, Phys. Rev. D **82**, 114019 (2010).

[47] A recent review of two Higgs doublet models in general is G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Phys. Rep. **516**, 1 (2012).

[48] S. Bar-Shalom, S. Nandi, and A. Soni, Phys. Rev. D **84**, 053009 (2011); see also arXiv:1205.0575.

[49] M. Hashimoto, Phys. Rev. D **81**, 075023 (2010).

[50] N. Chen and H.-J. He, J. High Energy Phys. 04 (2012) 062.

[51] D. Carmi, A. Falkowski, E. Kuflik, and T. Volansky, arXiv:1202.3144.

[52] J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson, *The Higgs Hunter's Guide* (Perseus Publishing, Cambridge, MA, 1991).

[53] J. J. Heckman, P. Kumar, and B. Wecht, arXiv:1204.3640.

[54] V. Barger, M. Ishida, and W.-Y. Keung, Phys. Rev. Lett. **108**, 261801 (2012).

[55] D. Eriksson, J. Rathsman, and O. Stål, Comput. Phys. Commun. **181**, 189 (2010); see http://www.isv.uu.se/thep/MC/2HDMC.

[56] H. Huffel and G. Pocsik, Z. Phys. C **8**, 13 (1981); J. Maalampi, J. Sirkka, and I. Vilja, Phys. Lett. B **265**, 371 (1991); S. Kamemura, T. Kubota, and E. Takasugi, Phys. Lett. B **313**, 155 (1993); A. G. Akeroyd, A. Arhrib, and E.-M. Naimi, Phys. Lett. B **490**, 119 (2000); I. F. Ginzburg and I. P. Ivanov, Phys. Rev. D **72**, 115010 (2005); See also J. Hořijší and M. Kladiva, Eur. Phys. J. C **46**, 81 (2006).

[57] I. Maksymyk, C. P. Burgess, and D. London, Phys. Rev. D **50**, 529 (1994); W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, Nucl. Phys. **B801**, 81 (2008).