Implications of Higgs Searches on the Four-Generation Standard Model

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(Received 21 June 2012; revised manuscript received 25 November 2012; published 25 February 2013)

Within the four-generation standard model, the Higgs couplings to gluons and to photons deviate in a significant way from the predictions of the three-generation standard model. As a consequence, large departures in several Higgs production and decay channels are expected. Recent Higgs search results, presented by ATLAS, CMS, and CDF, hint on the existence of a Higgs boson with a mass around 125 GeV. Using these results and assuming such a Higgs boson, we derive exclusion limits on the four-generation standard model. For $m_H = 125$ GeV, the model is excluded above 99.95% confidence level. For 124.5 GeV $\leq m_H \leq$ 127.5 GeV, an exclusion limit above 99% confidence level is found.

DOI: 10.1103/PhysRevLett.110.091801 PACS numbers: 14.65.Jk, 13.85.Rm, 14.80.Bn

The intriguing possibility of a four-generation standard model (SM4) has been studied intensively (see, e.g., Ref. [1] and references therein). Constraints on this scenario arise directly, via the search for production of fourth-generation quarks and leptons at colliders [2,3], and indirectly, through their effect on the oblique electroweak parameters [4–6] and on the Higgs boson production and decay partial widths [7,8]. Theoretical constraints are also present from vacuum stability and triviality bounds [5,9]. In the context of the Higgs observables, it has long been realized that the presence of a fourth generation drastically changes the Higgs branching fractions. In particular, the couplings to gluons and to photons are induced at the loop level and are therefore susceptible to the presence of (respectively, colored and electromagnetically charged) heavy new particles. As a consequence, precise measurements of the Higgs production rate and branching ratios can strongly constrain the existence of a fourth generation.

Recently, the ATLAS and CMS experiments have reported the discovery [10,11] of a light Higgs boson with a mass of about 125 GeV. Additionally, the CDF and D0 experiments have reported new results [12] which also hint for evidence of the Higgs boson. Several Higgs decay channels have been probed, including the $\gamma\gamma$ [13,14], ZZ^* [15,16], and WW^* [17,18] channels dominated by the gluon fusion production mode, $b\bar{b}$ in the associated production mode [12,19,20], and diphoton in association with the two-jets channel which has a large vector boson fusion production component [13,14]. The $\gamma\gamma$ and $b\bar{b}$ modes favor a slightly larger rate than predicted by the standard model (SM), while in the WW^* and ZZ^* channels are measured to have SM properties. As we show below, the discovery of the Higgs boson, with rates measured to be close to the standard model prediction, is sufficient to exclude the SM4.

Three ingredients are important in making such an exclusion possible. First, the fourth-generation top and bottom quarks would *enhance* the gluon fusion production rate of a light Higgs boson by a factor of $\mathcal{O}(10)$ [21]. Second, the partial decay width to diphotons can be *suppressed* by as much as a factor of $\mathcal{O}(100)$ [22]. Third, partial decay widths to final states which are dominated by tree-level amplitudes, such as $b\bar{b}$ and ZZ^*, receive smaller corrections to the SM prediction. The net result is therefore a significant enhancement in all gluon fusion produced channels, with the exception of the diphoton channel, which is significantly suppressed.

The data discussed above favor slightly enhanced rates, but not as high as predicted in the SM4. This situation has led the CMS Collaboration to rule out the SM4 for $m_h >$ 120 GeV at 95% C.L. and for $m_h > 125$ GeV at 99% C.L. [23]. The CMS analysis, however, assumes that the fourth-generation neutrino is heavy enough so that the additional invisible Higgs decay mode is forbidden, $m_N \gtrsim m_h/2$. The inclusion of such a channel dilutes all branching fractions uniformly and hence significantly weakens the CMS exclusion limit.

In this Letter, we relax the assumption on the mass of the fourth neutrino. Yet, we obtain significantly stronger exclusion limits and conclude that, in the presence of a light Higgs boson, the four-generation standard model is excluded [24].

The SM4 rates.—In the SM, the gluon fusion amplitude is dominated by the top-induced one-loop contribution. The SM4 introduces two new heavy quarks into the loop, for which the leading-order (LO) contribution is approximately independent of the actual masses. Consequently, the gluon fusion rate is enhanced by a factor of 9 at LO.

The fourth-generation top and bottom also modify the LO contributions to the Higgs partial widths to digluons and diphotons. The latter are also affected by the fourth-generation charged lepton. Similarly to the gluon fusion production cross section, the $h \to gg$ width is increased by a factor of 9. On the other hand, $h \to \gamma\gamma$, which is dominated by the W-boson loop, is suppressed as the additional fermions interfere destructively with the W-boson contribution. At LO this amounts to decreasing the diphoton width by a factor of about 5 relative to the SM; it is also mostly independent of fermion masses. Finally, the other leading partial widths, which are all allowed at tree level, remain unchanged at LO.

At next-to-leading-order (NLO), the large Yukawa couplings for heavy fermions can contribute significantly to all widths. Complete NLO widths have been calculated by Denner *et al.* [22], and partially implemented in HDECAY [25] and PROPHECY4F [26]. For very heavy fermion masses, up to the perturbative limit, the corrections to the decay rates to fermions and heavy gauge bosons can be as large as a factor of 2 and tend to increase the widths to fermions and decrease the widths to $WW^\star$ and $ZZ^\star$. The NLO corrections to $h \to gg$ are less significant.

The LO value of the $h \to \gamma\gamma$ width is already accidentally small due to the destructive interference between the W-boson and fermion loops. As a consequence, the NLO corrections are relatively large, and the two-loop matrix elements can lead to another significant *cancellation* in the amplitude. For instance, for $m_h = 130$ GeV and for fermion masses given in the "extreme scenario" of Ref. [22], the cancellation between the LO and NLO correction is 90.8%.

One should not view this as a breakdown of the perturbative expansion. The NLO corrections give a large effect only because of large, accidental cancellations. The next-to-next-to-leading-order (NNLO) correction is still smaller than the NLO correction and will have a significant effect only if the cancellation becomes more pronounced. Since this will lower the predicted $h \to \gamma\gamma$ width relative to the observed width, the constraints obtained from using the $h \to \gamma\gamma$ measurement will be strengthened when there is a cancellation. Alternatively, the NNLO correction can enhance the $h \to \gamma\gamma$ width relative to the NLO prediction by, at most, an $\mathcal{O}(1)$ amount. We address this possibility below by allowing enhancement by a factor of 2 in the width relative to the NLO calculation.

HDECAY approximates the relative NLO corrections of $h \to \gamma\gamma$ to about 1% accuracy. However, due to the very large cancellation, this may result in an $\mathcal{O}(1)$ inaccuracy in the actual width at NLO. Additional sources of theoretical error or uncertainty arise in the NNLO corrections. As discussed below, for light fourth-generation fermion masses, where the Higgs constraints are the *weakest*, these uncertainties are expected to be low. For all cases, we calculate the widths at $m_h = 120$, 125, and 130 GeV and interpolate the widths for intermediate Higgs masses.

Higgs searches at colliders.—The CMS, ATLAS, CDF, and D0 experiments have reported results of Higgs searches in various channels. The ATLAS and CMS Collaborations report an excess of events significant enough to claim discovery of a Higgs boson around 125 GeV. The excess is mostly apparent in five channels: inclusive diphoton, diphoton in association with two jets, fully leptonic ZZ^*, fully leptonic WW^*, and associated production of a Higgs boson decaying to $b\bar{b}$.

The gluon fusion production (which is expected to be the dominant source of Higgs bosons at the LHC) and the diphoton decay are particularly sensitive to the presence of additional sequential quarks and leptons. Hence measurements of these rates provide an excellent opportunity to revisit the limits on the SM4. The excess observed indicates a cross section that is somewhat larger than the SM prediction. While this cannot (and at present should not) be taken as a hint for new physics, it can be used to put strong constraints on the SM4.

In order to efficiently constrain the SM4, it is crucial to consider each Higgs search channel separately. In Ref. [27], a combination of the ATLAS and CMS results is presented for the five channels mentioned above. For each channel i, the best fit value for the signal strength, $\hat{\mu}_i$, defined as the rate (cross section times branching ratio) normalized to the standard model, is found. $\hat{\mu}_i$ can then be compared with the corresponding SM4 value R_i. For m_h between 124 and 128 GeV, all $\hat{\mu}_i$ and the corresponding standard deviations σ_i are given by the ATLAS and CMS Collaborations, with the exception of the diphoton plus dijet channel, in which $\hat{\mu}$ and σ are only provided for $m_h = 125$ GeV by CMS and $m_h = 126.5$ GeV by ATLAS; following the procedure outlined in Ref. [28], we calculate the observed rate at ATLAS for $m_h = 125$ GeV.

Results.—In Fig. 1, we show the exclusion limits on the SM4, using the LHC and Tevatron Higgs measurements discussed above. The shaded regions show the results of a scan over SM4 spectra. All masses are required to be below the "extreme scenario" of Ref. [22] where perturbativity reaches its limit. Additionally, our scan includes only sets of parameters that are within the 95% C.L. ellipse of the S and T oblique parameters [5,6,22,29]. The electroweak precision constraints depend on both the absolute masses of the fermions and the mass splitting within the doublets. The scan lies within the range

$$\begin{aligned} m_T, m_B, m_E &\in \{100, 650\}\text{GeV}, \\ m_N &\in \{45, 600\}\text{GeV}, \\ m_T - m_B &\in \{-100, 50\}\text{GeV}, \\ m_N - m_E &\in \{-175, 200\}\text{GeV}. \end{aligned} \tag{1}$$

Several aspects of the SM4, additional to the analysis here, are considered in later works. For instance, a more detailed analysis of electroweak precision constraints can be found in Refs. [30–32], a discussion of the effects of quark mixing in Ref. [30], and direct limits from collider searches for fourth-generation quarks and leptons are studied in Ref. [32]. A detailed comparison of the Dirac and Majorana case is unique to our Letter. Wherever relevant, the results of Refs. [30–32] agree with ours.

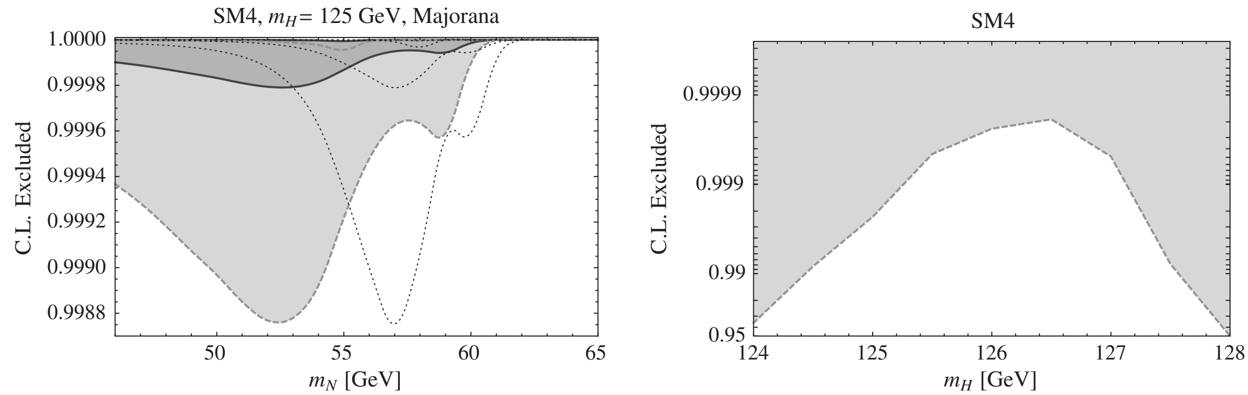

FIG. 1. Constraints on the SM4 derived from scanning over the fourth-generation fermion masses as described in the text. The darker region within the solid borders (light region within the dashed borders) shows the level of exclusion with (without) the $\gamma\gamma jj$ mode. Left: The exclusion limit as a function of the neutrino mass (the other fourth-generation fermion masses are scanned) for fixed $m_h = 125$ GeV. Also shown are the exclusions (dotted contour) for the case when the neutrino is purely left-handed Majorana. Right: The exclusion limit as a function of m_h, with all fourth-generation masses varied.

The constraints are made by minimizing the χ^2:

$$\chi^2 = \sum_{\text{channels}} \frac{(R_{\text{i}} - \hat{\mu}_{\text{i}})^2}{\sigma_{\text{i}}^2}. \qquad (2)$$

The sum runs over the five measured channels: inclusive diphoton, inclusive ZZ^*, inclusive WW^*, $b\bar{b}$ in association with a vector boson, and diphoton in association with two jets. Throughout it is assumed that individual likelihoods follow a Gaussian distribution, when calculating the χ^2 cumulative distribution functions.

In the left box in Fig. 1, we show the exclusion limit as a function of m_N, the fourth-generation neutrino mass, for fixed $m_h = 125$ GeV. The darker region shows the confidence level exclusion when including the $\gamma\gamma jj$ mode, while the lighter region shows the exclusion when omitting this mode. Since there are large systematic uncertainties in the gluon-fusion contribution to the dijet mode, we show constraints with this mode separately. When including (omitting) the $\gamma\gamma jj$ mode, the SM4 with $m_h = 125$ GeV is excluded at above 99.98% (99.8%) C.L., for all values of the fourth-generation neutrino mass.

In the right box in Fig. 1, we show the exclusion limit as a function of the Higgs mass. Since the CMS and ATLAS experiments do not provide the values of $\hat{\mu}_{\gamma\gamma jj}$ for $m_h =$ 124–128 GeV, we show the exclusions without the $\gamma\gamma jj$ mode. Higgs masses outside this region are excluded by the measurement of the mass [10,11] above 99% confidence level. For 124 GeV $< m_h <$ 128 GeV the SM4 is excluded above 95% C.L., while for 125.5 GeV $< m_h <$ 127 GeV, the SM4 is excluded above 99.9% C.L. The constraints are expected to be much stronger when including the $\gamma\gamma jj$ mode for the full mass range.

The numerical scan shows robust exclusion over all of the parameter space. As mentioned above, care should be taken with these numerical codes as they only approximately calculate $\Gamma(h \to \gamma\gamma)$ at NLO, and NNLO corrections may be large for the heavier masses scan. Nonetheless, given these results, the constraints are expected to remain strong even if exact calculations could be performed. Indeed, we note that the weakest constraints are obtained when the fourth-generation masses are lightest. This is intuitive, since smaller Yukawa couplings imply smaller corrections and consequently a smaller cancellation in $h \to \gamma\gamma$ width. However, in precisely this region, the uncertainties in using the numerical code to calculate the width and the unknown NNLO corrections are both expected to be small. Thus, we do not expect these corrections to significantly alter the results obtained from the scan. Even while allowing for a 100% correction (doubling) of $\Gamma(h \to \gamma\gamma)$ for all points scanned, we find that the SM4 is still excluded at 99.94% C.L. (3.4σ) for $m_h = 125$ GeV.

Throughout this work we assumed that the fourth-generation neutrino is a Dirac fermion and receives mass only from its Yukawa coupling to the Higgs boson. These assumptions play a role in two points: (i) in the LO width of the Higgs boson into two neutrinos and (ii) in NLO (or NNLO) loop corrections to other partial decay widths. In particular, it affects the $h \to ZZ^*$ and $h \to WW^*$ widths at one loop and other modes at two loops. The constraints are weakest when there is a large invisible width, meaning the neutrino is lighter than 65 GeV, but in this case the neutrino Yukawa coupling is not too large and the loop corrections can be expected to be small. Neglecting the NLO effects (2), the constraints depend directly on the width, and only indirectly, via the width, on the neutrino mass and Yukawa coupling. Figure 1 shows that in the Dirac case the constraints are weakest for $m_N = 52.5$ GeV, corresponding to a partial width $\Gamma(h \to NN) = 0.036$ GeV. In fact, if the width were taken as a free parameter, one would find that this width also minimizes the constraints or, equivalently, minimizes the χ^2. Although the χ^2 will depend differently on the neutrino mass and Yukawa, the lower bound on the

χ^2 is given in the Dirac case. Thus the exclusions remain robust if the neutrino is Majorana. For completeness, we show the exclusions for a purely left-handed Majorana neutrino, indicated by the dotted curve in the left box in Fig. 1. Evidently, the minimum C.L. exclusion remains unchanged.

Discussion.—The ATLAS and CMS experiments discovered a Higgs-like boson with a mass of about 125 GeV and (together with the CDF and D0 experiments) place stringent constraints on its low energy effective couplings to heavy quarks and vector bosons [27,33–36]. The SM4 model analyzed by us provides a specific example of modified Higgs couplings, but the constraints obtained in the model-independent analyses mentioned above cannot be applied to it in a straightforward way. The general Higgs couplings analyses assume that widths are proportional to single couplings, which is not valid when loop-level corrections are large, as is the case with a heavy fourth generation. Moreover, the consideration of a specific model allows one to take into account additional relevant aspects, such as our inclusion of electroweak precision constraints.

A fourth generation would affect strongly the Higgs effective couplings to gluons and photons and consequently the corresponding Higgs partial decay widths. Concretely, the gluon fusion rate is enhanced by a factor ~ 9, while the diphoton decay rate is suppressed by a factor ~ 100. Consequently, several decay channels, such as ZZ^* and WW^*, which are dominantly produced via gluon fusion, are predicted to be enhanced, contradicting current measurements. It is possible to relieve the tension in these channels by allowing the fourth-generation neutrino to be light, thereby uniformly suppressing all branching fractions. However, the already suppressed diphoton channel is then far below its measured value.

The reasoning above allows one to strongly exclude the four-generation standard model. For a Higgs mass of 125 GeV, we find it to be excluded at the 99.95% C.L.

Finally, we note that the stability and triviality bound place stringent constraints on the SM4 scenario [5,9], excluding it for a Higgs mass around 125 GeV. These bounds, however, can be ameliorated by simple extensions of the model, such as an extended Higgs sector or through couplings of the Higgs boson to scalar singlets. The bounds derived in this Letter are different in nature and are largely independent of such UV completions as long as the Higgs properties are not altered significantly.

The authors thank Gideon Bella, Ansgar Denner, Adam Falkowski, Zoltan Ligeti, and Michael Spira for useful discussions. The work of E. K. and T. V. is supported in part by a grant from the Israel Science Foundation. The work of T.V. is further supported in part by the U.S.-Israel Binational Science Foundation and the EU-FP7 Marie Curie, CIG fellowship. Y. N. is supported by the Israel Science Foundation and by the German-Israeli foundation for scientific research and development (GIF).

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[1] B. Holdom, WS. Hou, T. Hurth, M.L. Mangano, S. Sultansoy, and G. Ünel, PMC Phys. A **3**, 4 (2009).
[2] ATLAS Collaboration, J. High Energy Phys. 04 (2012) 069.
[3] ATLAS Collaboration, Phys. Rev. Lett. **109**, 032001 (2012).
[4] M.E. Peskin and T. Takeuchi, Phys. Rev. D **46**, 381 (1992).
[5] G.D. Kribs, T. Plehn, M. Spannowsky, and T.M.P. Tait, Phys. Rev. D **76**, 075016 (2007).
[6] M. Hashimoto, Phys. Rev. D **81**, 075023 (2010).
[7] G. Guo, B. Ren, and X.-G. He, arXiv:1112.3188.
[8] N. Chen and H.-J. He, J. High Energy Phys. 04 (2012) 062.
[9] A. Wingerter, Phys. Rev. D **84**, 095012 (2011).
[10] ATLAS Collaboration, Phys. Lett. B **716**, 1 (2012).
[11] CMS Collaboration, Report No. CMS-PAS-HIG-12-020, 2012.
[12] TEVNPH Tevatron New Phenomena and Higgs Working Group, CDF Collaboration, and D0 Collaboration, arXiv:1207.0449.
[13] ATLAS Collaboration, Report No. ATLAS-CONF-2012-091, 2012.
[14] CMS Collaboration, Report No. CMS-PAS-HIG-12-015, 2012.
[15] ATLAS Collaboration, Report No. ATLAS-CONF-2012-092, 2012.
[16] CMS Collaboration, Report No. CMS-PAS-HIG-12-016, 2012, 2012.
[17] ATLAS Collaboration, Report No. ATLAS-CONF-2012-098, 2012.
[18] CMS Collaboration, Report No. CMS-PAS-HIG-12-017, 2012.
[19] ATLAS Collaboration, arXiv:1207.0210.
[20] CMS Collaboration, Report No. CMS-PAS-HIG-12-019, 2012.
[21] H. Georgi, S. Glashow, M. Machacek, and D.V. Nanopoulos, Phys. Rev. Lett. **40**, 692 (1978).
[22] A. Denner *et al.*, arXiv:1111.6395.
[23] CMS Collaboration, Report No. CMS-PAS-HIG-12-008, 2012.
[24] The results of this Letter were presented previously on January 26 at Stony Brook, on February 29 at Seoul, and on March 28 at a CERN workshop.
[25] A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. **108**, 56 (1998).
[26] A. Bredenstein, A. Denner, S. Dittmaier, and M. Weber, arXiv:0708.4123.
[27] D. Carmi, A. Falkowski, E. Kuflik, and T. Volansky, arXiv:1202.3144.
[28] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky, and J. Zupan, arXiv:1207.1718.
[29] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, K. Mönig, M. Schott, and J. Stelzer, Eur. Phys. J. C **72**, 2003 (2012).
[30] O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, Phys. Rev. D **86**, 013011 (2012).

[31] O. Eberhardt, A. Lenz, A. Menzel, U. Nierste, and M. Wiebusch, Phys. Rev. D **86**, 074014 (2012).
[32] M. Buchkremer, J.-M. Gerard, and F. Maltoni, J. High Energy Phys. 06 (2012) 135.
[33] A. Azatov, R. Contino, and J. Galloway, J. High Energy Phys. 04 (2012) 127.
[34] J. Espinosa, C. Grojean, M. Muhlleitner, and M. Trott, J. High Energy Phys. 05 (2012) 097.
[35] P. P. Giardino, K. Kannike, M. Raidal, and A. Strumia, arXiv:1203.4254.
[36] J. Ellis and T. You, arXiv:1204.0464.