Implications of Higgs Searches on the Four Generation Standard Model

Eric Kuflik,1,‡ Yosef Nir,2,‡ and Tomer Volansky1,§

1Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel
2Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76000, Israel

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 at 99.9% confidence level. For \( 124 \) GeV \( \leq m_H \leq 127 \) GeV, an exclusion limit above 95% confidence level is found.

INTRODUCTION

The intriguing possibility of a four generation Standard Model (SM4) has been studied intensively (see e.g. [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 [4,5] and on the Higgs boson production and decay partial widths [6,7]. In the context of the latter set of 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, CMS, CDF and D0 experiments have reported new results [9,15] which hint on the existence of a light Higgs boson with a mass of order 125 GeV. Several Higgs decay channels have been probed, including the \( \gamma\gamma \), \( ZZ^* \) and \( WW^* \) channels dominated by the gluon fusion production mode, \( b\bar{b} \) in the associated production mode, and diphoton in association with two jets channel which has a large vector boson fusion (VBF) production component. These results favor a somewhat large rate in all but the \( WW^* \) channel, where no significant excess is found. In this letter we analyze these results under the assumption that a Higgs signal has been observed. As we show below, under such an assumption, the SM4 is excluded.

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 \( O(10) \) [17]. Second, the partial decay width to diphotons can be suppressed by as much as a factor of \( O(100) \) [18]. 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 Standard Model (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 favors 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% CL and for \( m_h > 125 \) GeV at 99% CL [19]. 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 note 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 [20].

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 modify also the LO contributions to the Higgs partial widths to digluons and diphotons. The latter is 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 9. On the other hand, \( h \to \gamma\gamma \), which is dominated by \( W \)-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.\cite{Denner:1991qz}, and partially implemented in HDECAY\cite{Djouadi:1997yw} and Prophecy4f\cite{Djouadi:2005ji}. 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 $WW^\ast$ and $ZZ^\ast$. 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.\cite{Denner:1991qz}, the cancelation between the LO and NLO correction is 90.8%.

HDECAY approximates the relative NLO corrections of $h \to \gamma\gamma$ to about 1% accuracy. However due to the very large cancelation, this may result in an $O(1)$ inaccuracy in the actual width at NLO. Additional sources of theoretical error/uncertainty arise in the NNLO corrections which may be as large as 100%. 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

Recently, the CMS, ATLAS, CDF and D0 experiments have reported results of Higgs searches in various channels\cite{CMS:2012gk,ATLAS:2012aa,CDF:2012au}. Three of the experiments report an excess of events which hint of the existence of a Higgs boson around 125 GeV. The excess is mostly apparent in four channels: inclusive diphoton, diphoton in association with two jets, fully leptonic $ZZ^\ast$, and associated production of Higgs decaying to $bb$. On the other hand, there is no apparent signal in Higgs decay to $WW^\ast$.

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.\cite{ATLAS:2012aa}, 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, $\mu_i$, is derived (or, when possible, directly taken from the reported results) as a function of the Higgs mass, by maximizing the corresponding likelihood functions. $\mu_i$ can then be compared with the corresponding SM4 value $R_i$. While the combination has not been presented by the collaborations and should be used with caution, the results are expected to be conservative. For $m_h$ between 120 GeV and 130 GeV, all $\mu_i$ and the corresponding standard deviations $\sigma_i$ are given by the ATLAS and CMS collaborations, with the exception of the diphoton plus dijet channel, in which $\mu$ and $\sigma$ are only provided for $m_h = 125$ GeV by CMS; ATLAS did not report results for the diphoton plus dijet channel. The full mass range was calculated in\cite{ATLAS:2012aa}. We do not use the $\gamma\gamma jj$ results of the more recent multivariate analysis\cite{ATLAS:2012aa}, since the relative efficiencies for different production modes are not stated.

RESULTS

In Fig.\cite{Carena:2012ew} 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.\cite{Carena:2012ew} where perturbativity reaches its limit. Additionally, our scan includes only sets of parameters that are within the 95% CL ellipse of the S and T oblique parameters\cite{Carena:2012ew,Alves:2012aa,Denner:1991qz}.

The constraints are made by minimizing the $\chi^2$,

$$\chi^2 = \sum_{\text{channels}} \frac{(R_i - \hat{\mu}_i)^2}{\sigma_i^2}.$$ (1)

The sum runs over the five measured channels: inclusive diphoton, diphoton in association with two jets, $ZZ^\ast$, $WW^\ast$, and $bb$ in association with a vector-boson. We assume that individual likelihoods follow a gaussian distribution, when calculating the $\chi^2$ cumulative distribution functions.

On the left box of Fig.\cite{Carena:2012ew} we show the exclusion limit as a function of $m_{N_i}$, 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 $m_h \geq 125$ GeV is excluded at above 99.9% (99.7%) CL, for all values of the fourth generation neutrino mass.
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. **Right**: the exclusion limit as a function of $m_h$, with all fourth generation masses varied.

On the right box of Fig. [1] we show the exclusion limit as a function of the Higgs mass. Again we show the exclusions with and without the $\gamma\gamma jj$ mode. Since the CMS experiment does not provide the values of $\tilde{\mu}_{\gamma\gamma jj}$ for $m_h = 120 - 130$ GeV, we use the analysis of [24] where the best fit rates and errors are calculated. For $m_h > 123$ GeV, the SM4 is excluded above 90% CL. For $124$ GeV < $m_h < 127$ GeV, the SM4 is excluded above 95% CL.

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.

**DISCUSSION**

The Higgs boson is yet to be discovered. Nonetheless, evidence from three independent experiments, ATLAS, CMS and CDF, hint to its existence and pointing to a mass of about 125 GeV. Under the assumption that these measurements are not the result of a statistical fluctuation, stringent constraints on the low energy effective couplings of the Higgs boson to heavy quarks and vector bosons can be placed [23, 25–28].

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 $\sim 9$ while the diphoton decay rate is suppressed by a factor $\sim 100$. 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 ameliorate 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 99.9% CL.

**Acknowledgements**

The authors thank Gideon Bella, Ansgar Denner, Adam Falkowski, Zoltan Ligeti and Michael Spira for useful discussions. The work of EK and TV is supported in part by a grant from the Israel Science Foundation. The work of TV is further supported in part by the US-Israel Binational Science Foundation and the EU-FP7 Marie Curie, CIG fellowship. YN is the Amos de-Shalit chair of theoretical physics and is supported by the Israel Science Foundation and by the German-Israeli foundation for scientific research and development (GIF).

* ekuflik@gmail.com
† yosef.nir@weizmann.ac.il
1 tomerv@post.tau.ac.il

[1] B. Holdom et al., PMC Phys. A3, 4 (2009) [0904.4698].
[2] ATLAS Collaboration, G. Aad et al., JHEP 1204, 069 (2012) [1202.5520].
[3] ATLAS Collaboration, G. Aad et al., (2012), 1202.6540.
[4] M. E. Peskin and T. Takeuchi, Phys. Rev. D46, 381 (1992).
[5] G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. Tait, Phys. Rev. D76, 075016 (2007) [0706.3718].
[6] M. Hashimoto, Phys. Rev. D81, 075023 (2010) [1001.4335].
[7] G. Guo, B. Ren, and X.-G. He, (2011), 1112.3188.
[8] N. Chen and H.-J. He, JHEP 1204, 062 (2012) [1202.3072].
[9] ATLAS Collaboration, G. Aad et al., Phys. Lett. B710, 383 (2012) [1202.1415].
[10] ATLAS Collaboration, G. Aad et al., Phys. Rev. Lett. 108, 111803 (2012) [1202.1414].
[11] ATLAS Collaboration, G. Aad et al., Phys. Lett. B710, 49 (2012) [1202.1408].
[12] CMS Collaboration, S. Chatrchyan et al., Phys. Lett. B710, 403 (2012) [1202.1487].
[13] CMS Collaboration, S. Chatrchyan et al., (2012), 1202.1997.
[14] CMS Collaboration, S. Chatrchyan et al., Phys. Lett. B710, 26 (2012) [1202.1488].
[15] D0 Collaboration, (2012), Conference Note 6304-CONF.
[16] CMS Collaboration, (2012), CMS-PAS-HIG-12-001.
[17] H. Georgi, S. Glashow, M. Machacek, and D. V. Nanopoulos, Phys. Rev. Lett. 40, 692 (1978).
[18] A. Denner et al., (2011), 1111.6395.
[19] CMS Collaboration, (2012), CMS-PAS-HIG-12-008.
[20] The results of this note were presented previously on Jan. 26 at Stony Brook, on Feb. 29 at Seoul ("Top physics and electroweak symmetry breaking in the LHC era"
and on March 28 at a CERN workshop ("Implications of LHC results for TeV-scale physics")
[21] A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. 108, 56 (1998) [hep-ph/9704448].
[22] A. Bredenstein, A. Denner, S. Dittmaier, and M. Weber, p. 150 (2007), 0708.4123.
[23] D. Carmi, A. Falkowski, E. Kuflik, and T. Volansky, (2012), 1202.3144.
[24] M. Bank et al., (2011), 1107.0975.
[25] A. Azatov, R. Contino, and J. Galloway, JHEP 04, 127 (2012) [1202.3415].
[26] J. Espinosa, C. Grojean, M. Muhlleitner, and M. Trott, JHEP 05, 097 (2012) [1202.3697].
[27] P. P. Giardino, K. Kannike, M. Raidal, and A. Strumia, (2012), 1203.4254.
[28] J. Ellis and T. You, (2012), 1204.0464.