Ruling out a fourth generation using limits on hadron collider Higgs signals

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We consider the impact of a 4th generation on Higgs to $\gamma\gamma$ and $WW, ZZ$ signals and demonstrate that the Tevatron and LHC have essentially eliminated the possibility of a 4th generation if the Higgs is SM-like and has mass below 200 GeV. We also show that the absence of enhanced Higgs signals in current data sets in the $\gamma\gamma$ and $WW, ZZ$ final states can strongly constrain the possibility of a 4th generation in two-Higgs-doublet models of type II, including the MSSM.

Although new physics has not yet been seen at the Tevatron or LHC, as the integrated luminosity, $L$, escalates increasingly interesting constraints on new physics emerge. This Letter focuses on the interconnection between limits on excesses in the $\gamma\gamma$ and $WW, ZZ$ mass spectra and the possible existence of a 4th generation and/or a sequential $W'$, assuming existence of: (1) a Standard Model (SM) Higgs boson; or (2) a two-doublet Higgs sector (including the special case of the Minimal Supersymmetric Standard Model, MSSM). Important results arise even though a Higgs boson has not yet been detected.

There are now significant constraints on Higgs to $\gamma\gamma$ and $WW$ signals coming from the current Tevatron and LHC data samples. A convenient review is Ref. [1]. In particular, no peak is observable in the $\gamma\gamma$ channel in the $L=131$ pb$^{-1}$ ATLAS data, and, indeed, the observed rate lies somewhat below the expected background. Similarly, both the LHC and, especially, the Tevatron restrict any excess in the $WW$ channel relative to the SM. We define the ratio $R_X^k = [\Gamma_{gg}^k BR(h \to X)]/[\Gamma_{gg}^{SM} BR(h_{SM} \to X)]$, where the denominator is always computed for 3 generations. Crude estimates from the ATLAS $\gamma\gamma$ spectrum plots of [1] are that $R_{\gamma\gamma} \lesssim 10$ for $M_{\gamma\gamma}$ in the 100 – 150 GeV range. As regards $R_{WW}$, currently the Tevatron CDF+D0 combination [2] provides the strongest limits: at 95% CL the Bayesian upper limits on $R_{WW}$ in the $m_h \in [100, 200]$ GeV window range between 2.54 and 0.64. Limits of this same order will eventually be achieved out to large $m_{WW}$ as $L$ increases.

These constraints motivate an examination of the possibilities for enhanced $R_{\gamma\gamma}$ and $R_{WW}$ values in the context of various models for the Higgs sector. Here, we consider implications for a 4th generation in the context of the Standard Model (SM) and two-Higgs-doublet models (2HDM) (including the MSSM) and for a sequential $W'$ in the SM case. The lepton and quark masses of the 4th generation will be set to 400 GeV and 1400 GeV will be chosen for the $W'$ mass, both only slightly above current experimental limits.

A plot showing $R_{\gamma\gamma}$ and $R_{WW}$ as a function of $m_h$ in the case of an $h$ with SM-like couplings and decays appears in Fig. 1. If a 4th generation is present, one observes large $R_{\gamma\gamma}$ ($\geq 4$) only for $m_h > 2m_{W'}$, where, in any case, prospects for probing $R_{\gamma\gamma} \leq 4$ must be regarded as uncertain due to the large size of the Higgs total width. Fortunately, the $WW$ channel is much more definitive. $R_{WW}$, also plotted in Fig. 1, is predicted to be $\geq 6.5$ for $m_h < 300$ GeV, falling to $\geq 4.8$ for $m_h \in [400, 500]$ GeV. This is in clear contradiction to the above quoted experimental limits from the Tevatron for the [110, 200] GeV mass range. Thus, the $WW$ channel already implies that having a light SM-like Higgs boson is inconsistent with the presence of a 4th generation. (See also the earlier analysis of [4] using less integrated luminosity.) The only escape would be if the Higgs boson has non-standard decays that deplete $BR(h \to WW)$ and $BR(h \to \gamma\gamma)$. Since models of this type abound [5], a definitive conclusion will require actual observation of a Higgs with the couplings and decays predicted in the SM.

Before leaving the SM, we note from Fig. 1 that inclusion of a heavy sequential $W'$ without a 4th genera-

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1 $R_{\gamma\gamma} \sim 1$ for $m_h \lesssim 130$ GeV because the increase in $\Gamma_{gg}$ is closely offset by a decrease in $BR(\gamma\gamma)$ resulting from the increased cancellation of the 4th generation fermion loops with the (opposite sign) $W$ loop.
tion gives \( R_{\gamma\gamma} \sim 4 - 5 \) for \( m_{h_{SM}} \lesssim 115 \) GeV, a value that can probably be excluded relatively soon. But, once \( m_{h_{SM}} \gtrsim 2m_W \), \( R_{\gamma\gamma} \) falls to \( \sim 3 \), a value requiring large \( L \) to either observe or exclude given that \( I_{10}^{h_{SM}} \) is large for such masses. If both a 4th generation and a sequential \( W' \) are present the predicted \( R_{\gamma\gamma} \sim 15 - 20 \) is probably already excluded for \( m_{h_{SM}} \lesssim 150 \) GeV (perhaps higher once the analysis is done) using the current data set. In contrast, \( R_{WW} \) is nearly unaffected by a possible \( W' \).

Even more enhanced signals from the Higgs bosons of the 2HDM are possible. In the context of the 2HDM (a convenient summary appears in the HHG [3]), the masses of the light and heavy CP-even Higgs bosons, \( h \) and \( H \), of the CP-odd Higgs boson, \( A \), and of the charged Higgs boson \( H^\pm \) are the value of \( \tan \beta \) (the ratio of VEVs for the two doublets) and the CP-even Higgs sector mixing angle \( \alpha \) can all be taken as independent parameters, whose values will determine the \( \lambda_i \) of the general 2HDM Higgs potential. Thus, it is appropriate to present results for each neutral Higgs boson as a function of its mass for various \( \tan \beta \) values.

As reviewed in [6], in the 2HDM there are only two possible models for the fermion couplings that naturally avoid flavor-changing neutral currents (FCNC), Model I and Model II. As a brief reminder, we provide the summary of Table I of the couplings of the \( h \), \( H \) and \( A \) in the two cases, relative to SM normalizations. In both Model I and Model II the \( WW, ZZ \) couplings of the \( h \) and \( H \) are given by \( \sin(\beta - \alpha) \) and \( \cos(\beta - \alpha) \), respectively, relative to the SM values. And, very importantly, there is no coupling of the \( A \) to \( WW, ZZ \) at tree level. If the \( \lambda_i \) of the Higgs potential are kept fully perturbative, the decoupling limit, in which \( m_H \to m_A \) and \( \sin^2(\beta - \alpha) \to 1 \), sets in fairly quickly as \( m_A \) increases.

In this Letter, we focus on the 2HDM-II coupling possibility, and the CP-odd \( A \), for which only \( \gamma\gamma \) decays are relevant. \( R_{A_{\gamma\gamma}}^A \) is plotted as a function of \( m_A \) in Fig. 2 for the 3 generation case. Enhanced \( \gamma\gamma \) signals, \( R_{A_{\gamma\gamma}}^A > 1 \), are only possible for low \( \tan \beta \) values. Although not shown, enhanced signals are possible for \( \tan \beta < 1 \) also in Model I. Note that \( R_{A_{\gamma\gamma}}^A \) is not influenced by possible sequential \( W' \)s since they do not couple to the \( A \).

The impact of a fourth generation on the two-doublet results depends strongly on whether or not the model is Model I or Model II. In particular, a 4th generation does not affect \( R_{\gamma\gamma}^A \) in the case of Model-I. This is because the \( t' \) and \( b' \) of the 4th generation couple to the \( A \) with opposite signs but equal coefficients — see Table I. In contrast, the results for a Model-II \( A \) are changed dramatically: the 4th family case is illustrated in Fig. 3. Regardless of \( \tan \beta \), one predicts large \( R_{\gamma\gamma}^A \), the smallest values occurring at low \( m_A \) for moderate \( \tan \beta \in [1, 5] \), for which \( R_{A_{\gamma\gamma}}^A \sim 10 \) for \( m_A \in [30, 150] \) GeV. Of course, this is precisely the range of \( \tan \beta \) that is preferred in order that the Yukawa coupling of the \( t' \) is perturbative. \( R_{A_{\gamma\gamma}}^A \) increases dramatically for \( m_A > 2m_W \) because of the drop in \( BR(h_{SM} \to \gamma\gamma) \). The enhanced values of \( R_{A_{\gamma\gamma}}^A \) are least likely to be depleted by \( A \) decays to non-SM final states, most particularly \( A \to hZ, H^\pm W^\mp \), when \( m_A \) is not large.

As noted earlier, a rough estimate using the latest ATLAS plot shown in [10] suggests \( R_{\gamma\gamma} \lesssim 10 \) for \( M_{\gamma\gamma} \lesssim 150 \) GeV. This estimate assumes a narrow resonance. A plot of \( \Gamma_{tot}^A \) for \( m_A \lesssim 500 \) GeV is given as Fig. 4 for the 4 generation case. Since the \( t' \) and \( b' \) masses are larger than \( m_A/2 \), direct decays to 4th generation

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**TABLE I: Summary of 2HDM quark couplings in Model I and Model II.**

|       | Model I | Model II |
|-------|---------|----------|
|       | \( h \) | \( H \) | \( A \) |
| \( t\bar{t} \) | \( \cos \alpha \) | \( \sin \alpha \) | \( -i\gamma_5 \cot \beta \) | \( \cos \alpha \) | \( \sin \alpha \) | \( -i\gamma_5 \cot \beta \) |
| \( b\bar{b} \) | \( \cos \alpha \) | \( \sin \alpha \) | \( i\gamma_5 \cot \beta \) | \( -\sin \alpha \) | \( \cos \alpha \) | \( -i\gamma_5 \tan \beta \) |
quarks do not occur, but the 4th generation quarks do influence the loop-induced decays to $gg$ (and $\gamma\gamma$). For $m_A < 150$ GeV, the narrow width approximation only breaks down for $\tan\beta \geq 30$. At $m_A = 150$ GeV, $\Gamma_{\text{tot}} = 5$ GeV, 13 GeV for $\tan\beta = 30, 50$, respectively. For such total widths, limits would then be weaker than naively estimated using the narrow resonance assumption. However, we should note that $\tan\beta > 30$ is excluded by LHC data for $m_A \lesssim 170$ GeV \cite{12} using the $A \rightarrow \tau^+\tau^-$ decay mode and just $L = 35$ pb$^{-1}$ of data \cite{7}. These limits will improve very rapidly with increased $L$. Once $m_A > 2m_t$, the $A$ total width increases dramatically; a study of the feasibility of detecting a highly enhanced broad $\gamma\gamma$ signal above the continuum $\gamma\gamma$ background is needed to determine the level of sensitivity.

In passing, we note that $R_{\gamma\gamma}^h$ and $R_{\gamma\gamma}^H$ for the CP-even Higgs bosons are less robust as indicators of a 4th generation — in particular, they depend significantly on even Higgs bosons are less robust as indicators of a 4th generation. In this limit, it is $\Gamma_{\text{tot}} = 35$ pb$^{-1}$ of data \cite{7}. These limits will improve very rapidly with increased $L$. Once $m_A > 2m_t$, the $A$ total width increases dramatically; a study of the feasibility of detecting a highly enhanced broad $\gamma\gamma$ signal above the continuum $\gamma\gamma$ background is needed to determine the level of sensitivity.

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achieved. Meanwhile, for 4 generations $R_W^{hW} > 2.4$ is predicted for all $m_A \geq 200$ GeV and will eventually be excludable in the relevant $m_h \sim 400 - 500$ GeV mass range. If sparticles are light, then hopefully the LHC will detect them and $R_W^{hW}$ and $R_A^{A\gamma}$ predictions can be corrected for substantial $BR(h, A \rightarrow SUSY)$ values. In addition, predictions for $\Gamma_{gg} h, A \rightarrow SUSY$ will be larger in the presence of a 4th generation than without.

Finally, we note that if there is a $W'$, $R_W^{A\gamma}$ is not affected (because of the absence of a tree-level $AWW'$ coupling) while changes to $R_W^{hW}$ are very tiny. Further, $R_W^{hW}$ is only modestly influenced by sfermion loop contributions to $\Gamma_{gg}$ and sfermion loops are not present for either $gg \rightarrow A$ or $A \rightarrow \gamma\gamma$. Thus, $R_W^{A\gamma}$ and $R_W^{hW}$ are quite robust tests for the presence of a 4th generation and can potentially eliminate the possibility of 4 generations in the context of the MSSM even if no Higgs is observed. Of course, by the time sufficient $L$ is available to measure $R_W^{hW}$, out to large $m_h$, direct observation or exclusion of the 4th-generation quarks may have occurred.

Once a $\gamma\gamma$ or WW peak emerges (as will eventually happen if there is one or more light Higgs bosons) a multitude of possibilities will need to be analyzed. If no Higgs has been seen in any other mode, then there will be a plethora of Higgs sector choices that could explain the $\gamma\gamma$ or WW peak, both in the general 2HDM context and in the MSSM. In the MSSM context, if tan$\beta$ is known from general observations of superpartners, it will be important to see if there is a Higgs boson within some Higgs scenario that can explain the peak for the known tan$\beta$ value, either with or without a 4th generation and/or $W'$. To summarize, we have shown that great importance attaches to the most exhaustive possible search for peaks and enhancements in the $\gamma\gamma$, WW and ZZ mass spectra over the broadest possible range of $M_{\gamma\gamma}$, $m_{WW}$, and $m_{ZZ}$. Either detection of a peak or a simple limit on $R_{\gamma\gamma}$, $R_W^{hW}$ and $R_Z^{ZZ}$ as a function of $M_{\gamma\gamma}$, $M_{WW}$, and $M_{ZZ}$ will provide highly significant constraints and/or consistency checks both on the Higgs sector and on the possible existence of a 4th generation or $W'$.

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