Model-Independent Description and Large Hadron Collider Implications of Suppressed Two-Photon Decay of a Light Higgs Boson

Daniel Phalen, Brooks Thomas, James D. Wells
Michigan Center for Theoretical Physics (MCTP)
Department of Physics, University of Michigan, Ann Arbor, MI 48109

For a Standard Model Higgs boson with mass between 115 GeV and 150 GeV, the two-photon decay mode is important for discovery at the Large Hadron Collider (LHC). We describe the interactions of a light Higgs boson in a more model-independent fashion, and consider the parameter space where there is no two-photon decay mode. We argue from generalities that analysis of the $tth$ discovery mode outside its normally thought of range of applicability is especially needed under these circumstances. We demonstrate the general conclusion with a specific example of parameters of a type I two-Higgs doublet theory, motivated by ideas in strongly coupled model building. We then specify a complete set of branching fractions and discuss the implications for the LHC.

Introduction. The Standard Model (SM) explanation for Electroweak Symmetry breaking (EWSB) – that one condensing Higgs boson doublet carries all burdens of elementary particle mass generation – remains speculative. Experimental results are consistent with this simple explanation, albeit for an increasingly shrinking window of Higgs boson mass. Precision electroweak data suggest that the Higgs boson must be less than $\sim 200$ GeV [1], otherwise the virtual effects of the Higgs boson cause theory predictions to be incompatible with the data. Direct searches at LEP II indicate that the Higgs boson mass must be greater than 114 GeV [2].

Despite these passive successes of the SM Higgs boson, well-known theoretical concerns involving naturalness and the hierarchy problem suggest that the simple SM explanation is not complete. There have been an extraordinary number of interesting ideas that have surfaced for a more palatable description of EWSB and elementary particle mass generation, and each of them affects Higgs boson collider observables. The effect could be small, as in supersymmetry with very heavy superpartners and a SM-like lightest Higgs boson, or large, as in strongly coupled theories of EWSB [3].

In this letter, we examine an enlargement of the Higgs sector. It resembles the Standard Model in that it contains one light Higgs boson, but differs from the SM in the strengths of this particle’s interactions with other fields. There is a compelling reason for doing this sort of analysis: soon data from the LHC, a $\sqrt{s}=14$ TeV, will teach us a great deal more about the theoretical nuances of EWSB. We begin our analysis by introducing a basic, model-independent parameterization of the couplings of the light Higgs boson to SM particles. We then examine how modifications to these couplings can dramatically affect the collider observables most relevant to Higgs searches. In particular, we focus on the process $gg \rightarrow h \rightarrow \gamma\gamma$, which is one of the most promising channels for the discovery of a light Higgs boson at the LHC, and demonstrate how such modifications to the Higgs couplings affect the potential for discovery.

Shutting off two-photon decays. Higgs boson decays to two photons provide one of the most important detection channels for a SM Higgs boson in the mass range $115 \text{ GeV} \lesssim m_h \lesssim 150$ GeV. Here, we wish to discuss the possibility that the two-photon decay branching fraction of the Higgs boson is significantly reduced compared to that of the SM. This can occur for many reasons. In certain regions of parameter space within supersymmetry, for example, this is possible when the partial width to the dominant mode, such as $h \rightarrow b\bar{b}$, is significantly enhanced such that $B(h \rightarrow \gamma\gamma) = \Gamma(h \rightarrow \gamma\gamma)/\Gamma_{\text{tot}} \rightarrow 0$ because $\Gamma_{\text{tot}}$ is so large [4]. However, a rather extreme shift in couplings is needed in general to suppress the $h \rightarrow \gamma\gamma$ branching fraction to an insignificant level this way. A less extreme way that nature could reduce the $h \rightarrow \gamma\gamma$ branching fraction is by simultaneously altering the various couplings that enter the effective $h\gamma\gamma$ vertex such that a cancelation occurs. We will focus primarily on this second possibility.

The SM Higgs boson observables at the LHC involve tree-level interactions of the Higgs boson with $WW$, $ZZ$, and $ff$. A model-independent parameterization of these interactions suggests that we multiply each of the vertices by an $\eta$-factor of

$$g_h^{WW} \rightarrow \eta_W g_h^{WW}, \quad g_h^{ZZ} \rightarrow \eta_Z g_h^{ZZ}, \quad g_h^{ff} \rightarrow \eta_f g_h^{ff}$$

The relevant observables also rely crucially on the Higgs boson interacting at the loop level with $gg$ and $\gamma\gamma$, and to a lesser degree of importance $\gamma Z$. These interactions can be sensitive to new particles entering at one-loop order. Experimental data presently have little bearing on the question of how large an effect the new particles can have on the effective $hgg$ or $h\gamma\gamma$ vertices, and so we will parameterize their effects through effective operators. In general, deviations of the $h\gamma\gamma$ and $hgg$ couplings arise two ways: deviations of couplings of SM particles in the loops, and extra corrections due to exotic particles or effects contributing to the effective interactions. The former can be parameterized in terms of the $\eta$ coefficients described above; the latter can be parameterized by introducing new variables $\delta_g$ and $\delta_\gamma$. In the limit that the top quark is much heavier than the other SM fermions, the resulting...
operators are
\[
\left( \delta_7 + \eta_W F_1(\tau_W) + \eta_7 \frac{4}{3} F_{1/2}(\tau_i) \right) \frac{h}{v} \frac{\alpha}{8\pi} F_{\mu\nu} F_{\mu\nu} \tag{1}
\]
and
\[
\left( \delta_9 + \eta F_{1/2}(\tau_i) \right) \frac{h}{v} \frac{\alpha_s}{8\pi} G^{\mu\nu} G_{\mu\nu}, \tag{2}
\]
where \( v \approx 246 \text{ GeV} \) (SM Higgs VEV), \( \tau_i = 4m_i^2/m_h^2 \), and
\[
F_{1/2}(\tau) = -2\tau[1 + (1 - \tau)f(\tau)] \tag{3}
\]
\[
F_1(\tau) = 2 + 3\tau + 3\tau(2 - \tau)f(\tau) \tag{4}
\]
and
\[
f(\tau) = \begin{cases} 
\arcsin^2(1/\sqrt{\tau}) & \tau \geq 1 \\
\frac{1}{4}\left[\log(\eta_+/\eta_-) - i\pi\right]^2 & \tau < 1
\end{cases} \tag{5}
\]
with \( \eta_\pm = (1 \pm \sqrt{1 - \tau}) \). One should note that \( F_1(\tau_i) \) and \( F_{1/2}(\tau_i) \) can be complex if \( m_h > 2m_i \), as this corresponds to internal lines going on shell. Since any Higgs boson worth its name has the property \( \eta_W \neq 0 \), one can express the condition under which the effective \( h\gamma\gamma \) vertex vanishes as
\[
\left( \frac{\eta_7}{\eta_W} \right) = -\frac{3}{4} \left( \frac{1}{F_{1/2}(\tau_i)} \left( \frac{\delta_9}{\eta_W} \right) + \frac{F_1(\tau_W)}{F_{1/2}(\tau_i)} \right) \tag{6}
\]
In fig. 1 we plot the contours of \( \Gamma(h \to \gamma\gamma) = 0 \) in the \( \eta_7/\eta_W \) vs. \( \delta_7/\eta_W \) plane. The various lines of the plot correspond to various values of \( m_h \) within the range of Higgs boson masses that are considered applicable for discovery through their \( h \to \gamma\gamma \) decay channel.

Theory discussion. From experience in supersymmetry, exotic physics contributions to \( \delta_7 \) or \( \delta_9 \) can decouple very rapidly and have small effects \[^4\]. Possible exceptions to this statement include a radion in warped geometry that has large \( \delta_7 \) and \( \delta_9 \) contributions due to quantum breaking of conformal invariance \[^8\], or non-renormalizable operators with low-scale cutoff \[^8\]. If mixed with a condensing Higgs boson, the lightest mass eigenstate can have significant \( \delta_7 \) and \( \delta_9 \) contributions. Nevertheless, if we approximate that \( \delta_7 \) and \( \delta_9 \) are zero, we are left with the reasonable conclusion that the top quark coupling to the Higgs boson is greatly enhanced compared to its SM value. This is to be expected in the case where the \( h \to \gamma\gamma \) decay rate goes to zero, since the \( W \)-induced amplitude contribution is about six times larger than the top-quark induced amplitude contribution and of the opposite sign. Thus, one expects that a theory with reduction of the \( W \) coupling and simultaneous increase in the top-quark coupling has the potential to reduce and even zero out the \( h \to \gamma\gamma \) amplitude.

Reducing \( W \) couplings is easy: arrange for several states or mechanisms to contribute to EWSB. Any individual Higgs boson state will have reduced couplings to \( W \) since couplings are proportional to the contribution that the Higgs boson makes to the mass of the \( W \) boson. As for the coupling to the top quark, increasing its value is not only possible, but can be expected when EWSB is shared among many sectors. If the top quark couples to only one Higgs boson \( H \) that does not fully generate the \( W \) masses, then the Yukawa coupling of the top quark to that Higgs has to have a larger value to generate the requisite top quark mass (i.e., \( m_t/(H) > m_t/(H_{sm}) \)).

The above considerations lead us naturally to think in terms of a type I two-Higgs doublet scenario \[^5\],[^8\]. In such a scenario, both (complex) doublets, which we denote \( \Phi_f \) and \( \Phi_{EW} \), obtain VEVs and contribute to EWSB and vector boson mass generation, but only one of the Higgs bosons, \( \Phi_f \), gives mass to the fermions. Among the eight degrees of freedom in \( \Phi_{EW} \) and \( \Phi_f \) three are eaten by \( W_L^\pm, Z_0^\pm \), two become charged Higgses \( H^\pm \), one becomes pseudo-scalar \( A^0 \), and two become scalars \( h^0, H^0 \), where \( h^0 \) is the lightest. Such a theory framework can be motivated by the dynamics of a strongly coupled sector \[^2\] which contributes to EWSB and to the vector boson masses. It is well-known that giving mass to the heavy fermions simultaneously is difficult, and so an additional scalar (or effective scalar) can be added to the theory that gives mass to the fermions (somewhat reminiscent of other approaches \[^4\]). Of course, this second sector will necessarily contribute to vector boson masses as well (one cannot hide EWSB from the vector bosons), and a complicated mixing among the two Higgs doublets ensues.

In our study we define a mixing angle \( \beta \) between the two Higgs VEVs, \( \tan \beta = (\langle \Phi_f \rangle)/(\langle \Phi_{EW} \rangle) \). A second angle, \( \alpha \), which parameterizes the mixing between the gauge and mass eigenstates of the CP-even Higgs, is defined by the relation
\[
\left( \begin{array}{c} H^0 \\ h^0 \end{array} \right) = \left( \begin{array}{cc} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{array} \right) \left( \begin{array}{c} \sqrt{2Re(\langle \Phi_{EW} \rangle)} \\ \sqrt{2Re(\langle \Phi_f \rangle)} \end{array} \right) \tag{7}
\]
The deviations in the couplings to SM fermions and vec-
The value of $\alpha$ is computed from the full potential of the theory is model-dependent, as are the masses of $H^\pm$ and $A^0$. The most stringent experimental constraint on these parameters comes from $b \to s \gamma$. The experimental limit is $BR(b \to s \gamma) = (3.3 \pm 0.4) \times 10^{-4}$ and in type I Higgs doublet models \cite{10},

$$
\Gamma(b \to s \gamma) = \frac{\alpha G_F m_{b}^2}{128 \pi^4} |A_W + \cot^2 \beta A_H(m_{H^\pm})|^2, \quad (9)
$$

where $A_W$ and $A_H$ are the respective loop functions for the SM and charged-Higgs-induced contributions. $A_H$ is a function of $m_{H^\pm}$ that has opposite sign to that of $A_W$. When $H^\pm$ is light, the charged Higgs contribution to $b \to s \gamma$ can be large and $\sin \beta$ is either constrained to be close to one, or $\sin \beta$ is tuned to a smaller value such that $A_W + \cot^2 \beta A_H \simeq -A_W$, thereby leading to an acceptable prediction. If $m_{H^\pm} > \text{few TeV}$, $A_H$ is effectively zero for any value of $\sin \beta \gtrsim 1/3$. In both of these cases (light or heavy $H^\pm$) a solution exists for our purposes, and the $H^\pm$ does not substantively affect the two-photon decay rate of the Higgs boson. We specify $\alpha$ to be small (in order to be precise in our discussion, we choose $\alpha = 0$), which is also nicely consistent with $m_{A^0}^2, m_{H^\pm}^2, m_{H^\pm}^2 \gg m_{t}^2$ and the model contains only one light Higgs boson. An extremely small $\alpha$ is by no means required, however, and we note that the results that carry forward will exhibit the same qualitative features when $|\alpha| \lesssim 1/2$.

**Numerical results.** In fig. 2 we compute the decay branching fractions of a 140 GeV Higgs boson as a function of $\sin \beta$ relative to the SM decay branching fractions. In this, and subsequent calculations, SM quantities are obtained using HDECAY \cite{11}, and we allow $\sin \beta$ to vary from 1 down to $\sim 0.250$, below which point the perturbativity of the top quark Yukawa (given by $y_t = \sqrt{2} m_t / v \sin \beta$ in this model) becomes a concern. For low values of $\sin \beta$ the branching fraction to $b \bar{b}$ is enhanced significantly over that of $WW^*$. As $\sin \beta \to 1$, which recovers the SM result, $WW^*$ wins out.

More important than the branching fractions, however, is the total cross-section of $pp \to h \to \gamma \gamma$, since that is what is measured at the collider. The largest contribution to the production cross-section for this observable $\sigma_h(\gamma \gamma)$ is through gluon fusion, $gg \to h \to \gamma \gamma$. The amplitude for $gg \to h$ is the same as for $h \to gg$ up to simple co-factors at leading order. Thus, we make a good estimate of the relative size of the $pp \to h \to \gamma \gamma$ cross-section:

$$
\frac{\sigma_h(\gamma \gamma)}{\sigma_h(\gamma \gamma)_{SM}} = \frac{\Gamma_h(gg)}{\Gamma_h(gg)_{SM}} \frac{\Gamma_h(\gamma \gamma)}{\Gamma_h(\gamma \gamma)_{SM}} \left( \frac{\Gamma_h(\text{tot})}{\Gamma_h(\text{tot})_{SM}} \right)^{-1}, \quad (10)
$$

In fig. 3 we plot $\sigma(\gamma \gamma)/\sigma_h(\gamma \gamma)_{SM}$ as a function of $\sin \beta$ for $m_h = 140$ GeV (and we retain $\alpha = 0$). For $0.38 \lesssim \sin \beta \gtrsim 0.55$ we see that the total cross-section into two photons is more than an order of magnitude lower than the SM cross-section, thereby severely compromising the ability of the LHC to discover the light Higgs boson via that channel. However, as we suggested above, the $t\bar{t}h \to t\bar{t}bb$ cross-section is greatly enhanced by nearly an order of magnitude above the SM cross-section. Thus, it may still be possible to discover such a Higgs boson.

To investigate this, we compute the significance of discovery, with 30 fb$^{-1}$ of integrated luminosity, of the $h^0$ Higgs boson in this model by scaling the known significance values \cite{12} for discovering a SM Higgs boson in various channels using the ATLAS detector. In fig. 4 we assume that $\alpha = 0$ and as we vary the Higgs boson mass we select the value of $\sin \beta$ such that $\Gamma(h \to \gamma \gamma)$, and hence $\sigma(gg \to h \to \gamma \gamma)$, is zero. Any value of $\sin \beta$ in the neighborhood of this point will yield similar significance.
of discovery values for the channels displayed. The other significance values are modified from their SM values by the scaling of the Higgs couplings by $\eta_W, \eta_Z$ according to equation (8). Our scaling of the significance values are modified from their SM values by

\[ \Delta m_{\gamma\gamma}/m_{\gamma\gamma} \sim 1\% \quad [13] \]

of the relevant final states over the range of interest – see table [1].

Higgs boson discovery channels involving one or more couplings between the Higgs and EW gauge bosons (including all weak boson fusion processes) are suppressed by factors of $\eta_W, \eta_Z$ as well as by an increase in the total width of the Higgs due to an increase in Higgs decays to $\bar{b}b$, which dominate the total width in the mass range of interest—see table [4]. In contrast, the $t\bar{t}h$ channel significance is dramatically increased. As a result, while the usual channels in which one would look to discover a Higgs boson in the mass range $115 \text{ GeV} \lesssim m_h \lesssim 150 \text{ GeV}$ are suppressed below the $5\sigma$ level, there is still the opportunity to discover the Higgs boson in the $t\bar{t}h$ channel. The searches, of course, must extend themselves to Higgs boson mass values well above what is normally thought to be the relevant range for this signature.

**Conclusions.** Higgs decays to two photons provide one of the most important channels through which one might hope to discover a light ($115 \text{ GeV} \lesssim m_h \lesssim 150 \text{ GeV}$) SM Higgs boson at the LHC. However, nature allows a Higgs sector whose couplings differ from their SM values in such a way that $\Gamma(h \rightarrow \gamma\gamma)$ is suppressed into irrelevance. This possibility occurs readily in scenarios involving additional contributions to electroweak symmetry breaking from sources that do not contribute to the generation of fermion masses. The Higgs coupling to EW gauge bosons is decreased relative to the SM result as its contribution to EWSB is decreased, and its coupling to the fermions is consequently augmented, allowing for a cancelation in the coefficient of the effective $h\gamma\gamma$ vertex. This is well illustrated in type I two Higgs doublet models and in a variety of models where there exists a dynamical contribution to EWSB. If this is the case, one cannot rely on the usual channels (weak boson fusion, $h \rightarrow WW^{*}$, and $h \rightarrow \gamma\gamma$ itself) to discover a Higgs boson. Nevertheless, such a Higgs could still be detected through processes like $t\bar{t}h$, with $h$ decaying to $\bar{b}b$ or $\tau\tau$.

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**TABLE I:** In this table, we list the total width of the Higgs boson, evaluated when the $h\gamma\gamma$ effective coupling is adjusted to zero, for a variety of choices of the Higgs mass. The SM width is also shown for comparison.

| $m_h$ (GeV) | $\Gamma_{\text{tot}}(h)$ (MeV) | $\Gamma_{\text{tot}}^\gamma\gamma(h)$ (MeV) |
|------------|--------------------------------|----------------------------------|
| 110        | 12                             | 3.0                              |
| 130        | 16                             | 4.9                              |
| 150        | 23                             | 17                               |

**FIG. 4:** Significance of various light Higgs boson observables at the LHC with 30 fb$^{-1}$ of integrated luminosity. This plot is made for $\alpha = 0$ and $\sin \beta \simeq 0.45$ where $\Gamma(h \rightarrow \gamma\gamma) \to 0$ in the type I two-Higgs doublet model.

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[1] LEP Electroweak Working Group [LEP Collaborations], hep-ex/0511027.
[2] LEP Higgs Working Group [LEP Collaborations], hep-ex/0107030.
[3] C. T. Hill and E. H. Simmons, Phys. Rept. 381, 235 (2003) [Erratum-ibid. 390, 553 (2004)] [hep-ph/0203079].
[4] G. L. Kane et al., Phys. Rev. D 53, 213 (1996) [hep-ph/9508265].
[5] J. F. Gunion et al., *The Higgs Hunter’s Guide*, Addison-Wesley: Redwood City, CA, 1990.
[6] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 595, 250 (2001) [hep-ph/0002178]. C. Csaki, M. L. Graesser and G. D. Kribs, Phys. Rev. D 63, 065002 (2001) [hep-th/0008151]. D. Dominici et al., Nucl. Phys. B 671, 243 (2003) [hep-ph/0206192]. T. G. Rizzo, hep-ph/0207113.
[7] L. J. Hall and C. F. Kolda, Phys. Lett. B 459, 213 (1999) [hep-ph/9904236].
[8] H. E. Haber, G. L. Kane and T. Sterling, Nucl. Phys. B 161, 493 (1979).
[9] See, e.g., E. H. Simmons, Nucl. Phys. B 312, 253 (1989). C. T. Hill, Phys. Lett. B 345, 483 (1995) [hep-ph/9411426].
[10] V. D. Barger, J. L. Hewett and R. J. N. Phillips, Phys. Rev. D 41, 3421 (1990).
[11] A. Djouadi et al., hep-ph/0002258.
[12] S. Asai et al. (ATLAS Collaboration), Eur. Phys. J. C 3252, 19 (2004) [hep-ph/0402254].
[13] ATLAS Collaboration, “ATLAS detector and physics performance. Technical design report. Vol. 2,” CERN-LHCC-99-15 (1999).