Non-renormalizable Yukawa Interactions and Higgs Physics

Z. Murdock, S. Nandi, and Santosh Kumar Rai

Department of Physics and Oklahoma Center for High Energy Physics,
Oklahoma State University, Stillwater, Oklahoma, 74078.

We explore a scenario in the Standard Model in which dimension four Yukawa couplings are either forbidden by a symmetry, or happen to be very tiny, and the Yukawa interactions are dominated by effective dimension six interactions. In this case, the Higgs interactions to the fermions are enhanced in a large way, whereas its interaction with the gauge bosons remains the same as in the Standard Model. In hadron colliders, Higgs boson production via gluon gluon fusion increases by a factor of nine. Higgs decay widths to fermion anti-fermion pairs also increase by the same factor, whereas the decay widths to photon photon and $\gamma Z$ are reduced. Current Tevatron exclusion range for the Higgs mass increases to $142-200$ GeV in our scenario, and new physics must appear at a scale below a TeV.

PACS numbers: 12.60.Fr,14.80.Bn

The Standard Model (SM) based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ is in excellent agreement with all the current experimental results. However, there are sectors of the SM which are still untested, such as the Higgs sector and the Yukawa sector. In the SM, we have only one Higgs doublet, and we allow the Higgs self interactions up to dimension four to maintain the renormalizability of the theory. In this case, the cubic ($h^3$) and the quartic ($h^4$) interactions of the remaining neutral scalar Higgs field, $h$, is determined in terms of the Higgs mass, $M_h$ and the known vacuum expectation value (VEV), $v$. Although we know $v$ experimentally to a very good accuracy, the Higgs mass is still unknown. Hence its presence, as well as the magnitude of its cubic and quartic self interactions are completely untested.

The other untested sector of the SM is the Yukawa sector. In the SM, we introduce dimension four Yukawa interactions which give masses to the fermions, and also generate the Yukawa interactions between the Higgs field $h$ and the fermions. The strength of these Yukawa interactions are completely determined in terms of the fermion masses and $v$. However, we do not have any experimental evidence for these interactions being the source of the fermion masses, and the presence of these dimension four Yukawa interactions. Another point to emphasize is that we do not know whether the Higgs boson is elementary or composite. Theories have been formulated in which the Higgs boson is a fermion anti-fermion composite; or more specifically a condensate of the third family quark and anti-quark [4]. Other possibilities for composite Higgs have also been advocated [2, 3]. Whether the Higgs boson is an elementary particle or composite, the operators of dimension higher than four suppressed by some scale, $M$ are expected. It has also been pointed out that the presence of dimension six operator in the Higgs potential allows us to have baryogenesis via sphaleron [3], still satisfying the current LEP limit on the Higgs mass.

In this letter, we propose an alternate scenario for the Yukawa sector, and explore how to test our predictions experimentally at the Tevatron and LHC. The effects of general dimension six operators in the Higgs sector have been considered and studied before [2]. Also other dimension six operators may appear in SM and a complete list of such operators is collected in Ref. [6]. We consider the case in which the usual dimension four Yukawa interactions are either forbidden by a symmetry, or the corresponding coupling happens to be too tiny to generate the observed values of the fermion masses. In this case, the dominant contribution to the fermion masses, as well as the interactions between the fermions and the Higgs boson will arise from the dimension six effective Yukawa interactions of the form $(f/M^2)\psi_L\psi_R H(H^\dagger H)$, where $M$ is the mass scale for the new physics through which such effective interactions are generated. As in the SM, fermion masses are still parameters in the theory, but the Yukawa couplings of the fermions to the Higgs boson are a factor of three larger than the SM. This enhances the production of the Higgs boson, as well as affect its decay branching ratios to various final states. This will have interesting consequences for Higgs signals at the Tevatron and LHC, as well as in the possible future lepton collider.

Our model is based on the SM gauge symmetry, $SU(3)_C \times SU(2)_L \times U(1)_Y$. We denote the left handed (EW) quark doublets by $q_L \equiv (u, d)^T_L$, and the right handed EW quark singlets by $u_R$ and $d_R$, where the index $i$ $(i = 1, 2, 3)$ represent three fermion families. Then the Yukawa interactions of the fermions with the Higgs boson up to dimension six are given by

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}_L f_u u_R \bar{H} + \bar{q}_L f_d d_R H + \bar{e}_L f_e e_R H + \frac{1}{M^2} (\bar{q}_L y_u u_R \bar{H} + \bar{q}_L y_d d_R H + \bar{e}_L y_e e_R H)(H^\dagger H) + \text{h.c.},$$

(1)

where the fermion fields represent three families, and $f_u, f_d$ and $f_e$ represent three corresponding Yukawa coupling matrices for the dimension four Yukawa interaction while $y_u, y_d$ and $y_e$ represent three corresponding Yukawa
coupling matrices for the dimension six Yukawa interactions. $M$ is the mass scale for a new physics which generates these dimension six interactions.

Our proposed scenario is the case in which the dimension four Yukawa couplings, $f_d, f_u$ and $f_l$ are either forbidden by a symmetry, or happen to be very tiny to generate the observed fermion masses, and this sector is dominated by dimension six interactions given above. Thus, choosing the couplings $f$ to be zero, for the fermion mass and the Yukawa coupling matrices, we obtain

$$M_{\text{New}} = \frac{1}{2\sqrt{2}M^2} y_d(v^3),$$

$$Y_{\text{New}} = \frac{1}{2\sqrt{2}M^2} y_d(3v^2),$$

and similar expressions for the up quark and lepton sectors. In contrast, in the usual SM, where we do not include the effective dimension six interactions, we have

$$M_{\text{SM}} = \frac{1}{\sqrt{2}} f_d(v),$$

$$Y_{\text{SM}} = \frac{1}{\sqrt{2}} f_d.$$ (3)

In our scenario, one can see from Eq. 2 that the mass matrices and the corresponding Yukawa coupling matrices are proportional. Hence as in the usual SM, we do not have any Higgs mediated flavor changing neutral current interactions. The important point to note is that in our scenario (for simplicity, we call it the new model), the Yukawa couplings of the Higgs boson to the fermions are three times larger than those in the SM, whereas the gauge interaction of the Higgs boson remains the same. This will make important differences for Higgs production, and its decay branching ratios as we discuss below.

In the low Higgs mass range ($M_h \leq 125$ GeV), the Higgs boson dominantly decays to $b\bar{b}$ in the SM. This mode is even more dominant in the new model, since the $h b\bar{b}$ coupling is enhanced by a factor of three compared to the SM. In the SM, the $b\bar{b}$ to $WW$ crossover takes place at $M_h \sim 135$ GeV (see fig. 1a), while in our model, this crossover happens at $M_h \sim 155$ GeV, (see fig. 1b). Also, as can be seen from these figures, the $\gamma\gamma$ branching fraction in our model is suppressed by about a factor of ten compared to the SM. The reason is that in the $h \to \gamma\gamma$ decay, the contribution comes from the $W$ loop and the top quark loop, and the two contributions are of opposite sign. In our model, because the $ht\bar{t}$ coupling is enhanced by a factor of three, there is a strong cancelation between the top loop and the $W$ loop contributions, resulting in the large suppression in the $\gamma\gamma$ mode. Note that in our model, Higgs couplings to the gauge bosons $WW$ and $ZZ$ are unaltered, hence these branching ratios get suppressed compared to the SM as long as $h b\bar{b}$ is dominant. For heavy Higgs mass range, $M_h \geq 155$ GeV, the WW mode starts to dominate, and hence the branching ratio to this mode is very similar to the SM. The same is true for the $ZZ$ mode. The branching ratio for the $ZZ$ mode is also essentially the same as the SM for larger mass ranges ($M_h \geq 185$ GeV).

Now we discuss Higgs production and the ensuing final state signals in our model and contrast those with the SM. First we consider the Higgs search at the Fer-
In the low Higgs mass range, the lower exclusion range increases slightly from $M_h > 109$ GeV in the SM to $M_h > 112$ GeV in our model. As the Tevatron luminosity accumulates further, its increased sensitivity to our model will help it study a bigger mass range of the Higgs boson than in the SM. Also, we note that for light Higgs ($M_h < 130$ GeV), the width of the Higgs boson in our model is larger by a factor of 9 compared to the SM. This can be tested in a possible future muon or $e^+e^-$ collider.

At the LHC, in the SM for large Higgs mass, $M_h > 150$ GeV, the most promising signals to observe the Higgs boson is via its dominant production through gluon gluon fusion (or $WW$ fusion), and then its subsequent decays to $WW$ or $ZZ$. In our model, since the dominant Higgs productions via gluon gluon fusion is nine times larger, the Higgs signals will be much stronger. The expectation for the Higgs signals in few of the relevant modes in our model is shown in fig. 2 (solid curve), and are compared with the SM expectations (dash-dotted curves) at the LHC for $\sqrt{s} = 7$ TeV. Note that the cross section times the branching ratio of $h \rightarrow WW$ in our model is larger than the SM by a factor of $\sim 3-9$ for the Higgs mass range of 150 – 200 GeV. The same is true for the $ZZ$ mode. For the low mass range of the Higgs boson, $M_h \sim 115 – 130$ GeV, the $\gamma\gamma$ mode is the most promising in the SM. In our model though, as shown in fig. 3, the signal for the $\gamma\gamma$ mode is reduced by a factor of $\sim 3-5$ compared to the SM. However, the signal in the $\tau\tau$ mode is enhanced almost by a factor of nine. Thus in our model, signal in the $\tau\tau$ mode may be observable at the LHC for the low Higgs mass range with good $\tau$ ID for the ATLAS and CMS detectors.

Inclusion of dimension six operators in the Yukawa sector also leads to enhancement in the other modes of Higgs production at colliders. The associated production of a Higgs boson with a heavy quark pair (e.g. $t\bar{t}h$) is enhanced by a factor of 9. The increased event rate would help in improving the sensitivity for the top-Yukawa coupling in this channel at LHC [11, 12].

In the low Higgs mass range, the lower exclusion range increases slightly from $M_h > 109$ GeV in the SM to $M_h > 112$ GeV in our model. As the Tevatron luminosity accumulates further, its increased sensitivity to our model will help it study a bigger mass range of the Higgs boson than in the SM. Also, we note that for light Higgs ($M_h < 130$ GeV), the width of the Higgs boson in our model is larger by a factor of 9 compared to the SM. This can be tested in a possible future muon or $e^+e^-$ collider.

At the LHC, in the SM for large Higgs mass, $M_h > 150$ GeV, the most promising signals to observe the Higgs boson is via its dominant production through gluon gluon fusion (or $WW$ fusion), and then its subsequent decays to $WW$ or $ZZ$. In our model, since the dominant Higgs productions via gluon gluon fusion is nine times larger, the Higgs signals will be much stronger. The expectation for the Higgs signals in few of the relevant modes in our model is shown in fig. 2 (solid curve), and are compared with the SM expectations (dash-dotted curves) at the LHC for $\sqrt{s} = 7$ TeV. Note that the cross section times the branching ratio of $h \rightarrow WW$ in our model is larger than the SM by a factor of $\sim 3-9$ for the Higgs mass range of 150 – 200 GeV. The same is true for the $ZZ$ mode. For the low mass range of the Higgs boson, $M_h \sim 115 – 130$ GeV, the $\gamma\gamma$ mode is the most promising in the SM. In our model though, as shown in fig. 3, the signal for the $\gamma\gamma$ mode is reduced by a factor of $\sim 3-5$ compared to the SM. However, the signal in the $\tau\tau$ mode is enhanced almost by a factor of nine. Thus in our model, signal in the $\tau\tau$ mode may be observable at the LHC for the low Higgs mass range with good $\tau$ ID for the ATLAS and CMS detectors.

Inclusion of dimension six operators in the Yukawa sector also leads to enhancement in the other modes of Higgs production at colliders. The associated production of a Higgs boson with a heavy quark pair (e.g. $t\bar{t}h$) is enhanced by a factor of 9. The increased event rate would help in improving the sensitivity for the top-Yukawa coupling in this channel at LHC [11, 12].
Another important implication of our model is on double Higgs production at the LHC which can probe the triple Higgs vertex in SM. In the SM, double Higgs production at LHC proceeds through gluon gluon fusion at one-loop level through the top quark dominated triangle and box diagrams \[^{[13]}\]. Due to additional contributions coming from the terms involving the dimension six operators, there is an enhancement in all the vertices involving the Higgs boson in our model. The box contribution is enhanced by a factor of 9 in its amplitude because of two Yukawa vertices, while the triangle contribution is enhanced by a factor of 5, after combining the new Yukawa and triple Higgs vertices (arising from the Higgs potential where we neglect the dimension 4 operator). There is an additional contribution to the amplitude through a new interaction term (\(\bar{f}_L f_R h^2\)) with a coupling strength of \(\left(\frac{\hat{g}_m \lambda_{
abla,SM}}{M_h}\right)\) where \(m_f\) is the mass of the fermion which leads to a large enhancement of the double Higgs production cross section at LHC. The analytical formula for the double Higgs production in SM can be found in Ref.\(^{[14, 15]}\). To put our results in context we can rewrite the contributions in our model as

\[
A_{\Delta}^{NP} = 5 \times A_{\Delta}^{SM} + 2 \times A_{\Delta}^{SM} \frac{\hat{s} - M_h^2}{M_h^2}
\]

\[
A_{\Delta}^{NP} = 9 \times A_{\Delta}^{SM}
\]

We plot the double Higgs production cross section\(^1\) as a function of the Higgs mass in fig. \(\text{[H]}\) for both the SM as well as our model. Although Eq. \(\text{[H]}\) shows a large enhancement in the individual contributions, there still is large cancelation between the box and triangle contributions and so the enhancement in the cross section compared to the SM is only at the level of a factor of \(\sim 10\) for low Higgs masses as shown in fig. \(\text{[H]}\) which increases as we go higher in the Higgs mass. Nevertheless it is a substantial increase for the light Higgs mass range and gives a cross section of around \(\sim 300\) fb at LHC with \(\sqrt{s} = 14\) TeV and \(\sim 40\) fb with \(\sqrt{s} = 7\) TeV, respectively for \(M_h \leq 220\) GeV. This can give large enough event rates to study the double Higgs production at LHC.

Finally, let us comment on the scale of new physics, \(M\). Up to dimension six, we can write the Higgs potential as

\[
V_{\text{New}} = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{1}{M^2} (H^\dagger H)^3.
\]

Choosing \(\lambda = 0\) the condition for the global minima gives

\[
M_h M = \sqrt{3}\mu^2.
\]

\(^1\) We use the public code available on M. Spira’s webpage [http://people.web.psi.ch/spira/proglist.html]
[10] R. Barate et al. Phys. Lett. B 565, 61 (2003).
[11] W. Beenakker, S. Dittmaier, M. Kramer, B. Plumber, M. Spira and P. M. Zerwas, Phys. Rev. Lett. 87, 201805 (2001).
[12] F. Maltoni, D. L. Rainwater and S. Willenbrock, Phys. Rev. D 66, 034022 (2002).
[13] D. A. Dicus, C. Kao and S. S. D. Willenbrock, Phys. Rev. D 38, 1088 (1988).
[14] E. W. N. Glover and J. J. van der Bij, Nucl. Phys. B 309, 282 (1988).
[15] T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B 479, 46 (1996) [Erratum-ibid. B 531, 655 (1998)].