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Non-renormalizable Yukawa interactions and Higgs physics

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ABSTRACT

We explore a scenario in the Standard Model in which dimension-four Yukawa couplings are forbidden by a symmetry, 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–antifermion pairs also increase by the same factor, whereas the decay widths to photon–photon and γZ are reduced. Current Tevatron exclusion range for the Higgs mass increases to $\sim$ 146–222 GeV in our scenario, and new physics must appear at a scale below a TeV.

1. Introduction

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–antifermion composite; or more specifically a condensate of the third family quark and antiquark [1]. 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 [4], 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 [5,6]. Also other dimension-six operators may appear in SM and a complete list of such operators is collected in Ref. [7]. We consider the case in which the usual dimension-four Yukawa interactions are forbidden by a symmetry. 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 $(f/M^2)\bar{\psi}_L\psi_R H(H^\dagger H)$, 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.

2. Formalism

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 electroweak (EW)

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Table 1
Charge assignments in the model for the scalar fields H, F_1 and F_2, the SM quark fields q_{iL}, u_{iR}, d_{iR}, and the heavy vector-like quarks.

Field	$U(1)_Y$	$U(1)_{F_1}$	$U(1)_{F_2}$
q_{iL}	1/6	−1	0
u_{iR}	2/3	1	0
d_{iR}	−1/3	−3	0
D_{1R}	−1/3	1	0
D_{1L}	−1/3	0	0
D_{2R}	−1/3	−1	0
D_{2L}	−1/3	−1	1
Q_{1L}	1/6	1	0
Q_{1R}	1/6	1	1
Q_{2L}	1/6	−3	0
Q_{2R}	1/6	−3	1
U_{1R}	2/3	−1	0
U_{1L}	2/3	−2	0
U_{2R}	2/3	−3	0
U_{2L}	2/3	−3	1
H	1/2	0	0
F_1	0	1	0
F_2	0	0	1

quark doublets by $q_{Li} \equiv (u,d)^T_{Li}$, and the right-handed EW quark singlets by u_{Ri} and d_{Ri}, where the index i ($i = 1, 2, 3$) represent three fermion families. Then the usual dimension-four Yukawa interactions of the fermions with the Higgs boson are given by

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}_L f_u u_R \tilde{H} + \bar{q}_L f_d d_R H + \bar{l}_L f_l e_R H \qquad (1)$$

where the fermion fields represent three families, and f_d, f_u and f_l represent three corresponding Yukawa coupling matrices for the dimension-four Yukawa interaction. Along the lines of our previous works [8], we have generated models in which the dimension-four Yukawa interactions are forbidden by symmetry. Such models include additional global flavor symmetries which are spontaneously broken by the VEVs of the flavon scalars. These global symmetries are also broken softly in the flavon potential. The model also include additional heavy vector-like quarks and leptons at some scale M. The SM quarks carry quantum numbers under these new flavor symmetries while the SM Higgs do not. As a result, dimension-four Yukawa interaction are forbidden, and the effective Yukawa interactions are generated at the dimension-six level.

An explicit example realizing this scenario is discussed below.

2.1. The model

We present a model in which the usual dimension-four Yukawa interaction among the SM fermions are forbidden by a symmetry, and the effective Yukawa interactions arise at the dimension 6 level. We extend the SM gauge symmetry by adding two flavor symmetries, $U(1)_{F1}$ and $U(1)_{F2}$. These global symmetries are spontaneously broken by the VEVs of the flavon scalars, F_1 and F_2. These are also broken softly in the flavon potential so that we do not have any unwanted massless Goldstone bosons. The model also include additional vector-like quarks, Q_i, D_i and U_i, $i = 1, 2$.

The charge assignments of the particles are given in Table 1. With this charge assignments the dimension-four Yukawa interaction, allowed by the symmetries, are given by

$$\begin{aligned} L_1 = {} & f_1 \overline{Q}_{2L} d_{iR} H + f_2 \overline{Q}_{2L} U_{2R} \tilde{H} + f_3 \overline{U}_{1L} U_{2R} F_1 \\ & + f_4 \overline{U}_{1L} U_{1R} F_1^\dagger + f_5 \bar{q}_{iL} U_{1R} \tilde{H} + f_6 \overline{Q}_{1L} u_{iR} \tilde{H} \\ & + f_7 \overline{Q}_{1L} D_{1R} \tilde{H} + f_8 \overline{D}_{1L} D_{2R} F_1 + f_9 \overline{D}_{1L} D_{1R} F_1^\dagger \\ & + f_{10} \bar{q}_{iL} D_{2R} H + \text{h.c.} \end{aligned} \qquad (2)$$

In addition there are terms involving F_2 that will give mass to the vector-like quarks after F_2 receives a VEV:

$$\begin{aligned} L_2 = {} & f_{11} \overline{D}_{2L} D_{2R} F_2 + f_{12} \overline{Q}_{1L} Q_{1R} F_2^\dagger \\ & + f_{13} \overline{Q}_{2L} Q_{2R} F_2^\dagger + f_{14} \overline{U}_{2L} U_{2R} F_2. \end{aligned}$$

We assume all f_i to be of order 1. Now, if we integrate out the heavy fermions in the tree level diagram composed of the first 5 terms of Eq. (2),

$$\begin{aligned} & f_1 \overline{Q}_{2L} d_{iR} H + f_2 \overline{Q}_{2L} U_{2R} \tilde{H} + f_3 \overline{U}_{1L} U_{2R} F_1^\dagger + f_4 \overline{U}_{1L} U_{1R} F_1 \\ & \quad + f_5 \bar{q}_{iL} U_{1R} \tilde{H}, \end{aligned}$$

we produce a low energy effective coupling:

$$f_1 f_2 f_3 f_4 f_5 \frac{F_1^2}{M^2} \frac{H^\dagger H}{M^2} \bar{q}_{iL} d_{jR} H.$$

We can do the same for the up-type quarks, the result is:

$$f_6 f_7 f_8 f_9 f_{10} \frac{(F_1^\dagger)^2}{M^2} \frac{H^\dagger H}{M^2} \bar{q}_{iL} u_{jR} \tilde{H}.$$

After F_1 receives a VEV, $\langle F_1 \rangle = M$, we obtain the effective dimension-six Yukawa interactions. Models similar to this have been explored in detail in [8].

Dimension-six Yukawa interactions are given by

$$\mathcal{L}_{\text{Yukawa}} = \frac{1}{M^2} (\bar{q}_L y_u u_R \tilde{H} + \bar{q}_L y_d d_R H + \bar{l}_L y_L e_R H)(H^\dagger H) + \text{h.c.}, \qquad (3)$$

where y_d, y_u and y_l 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.

In our model, for the fermion mass and the Yukawa coupling matrices, we obtain

$$\begin{aligned} \mathcal{M}_{\text{New}} &= \frac{1}{2\sqrt{2}M^2} y_d (v^3), \\ \mathcal{Y}_{\text{New}} &= \frac{1}{2\sqrt{2}M^2} y_d (3v^2), \end{aligned} \qquad (4)$$

and similar expressions for the up quark and lepton sector. In contrast, in the usual SM, we have

$$\mathcal{M}_{\text{SM}} = \frac{1}{\sqrt{2}} f_d v, \qquad \mathcal{Y}_{\text{SM}} = \frac{1}{\sqrt{2}} f_d. \qquad (5)$$

In our scenario, one can see from Eq. (4) 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 will discuss shortly.

We now comment on the perturbativity in our scenario. The dimension-six Yukawa interaction between the SM fermion and the Higgs boson is given by Eq. (3). Using

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \qquad (6)$$

in the effective four-dimensional theory, for the Yukawa interaction of the top quark with the Higgs boson, h (Eq. (3)), we then obtain

$$\mathcal{L}_{\text{Yukawa}} = \frac{y_t}{2\sqrt{2}M^2} (v^3 + 3v^2 h + 3vh^2 + h^3) \bar{t}t. \qquad (7)$$

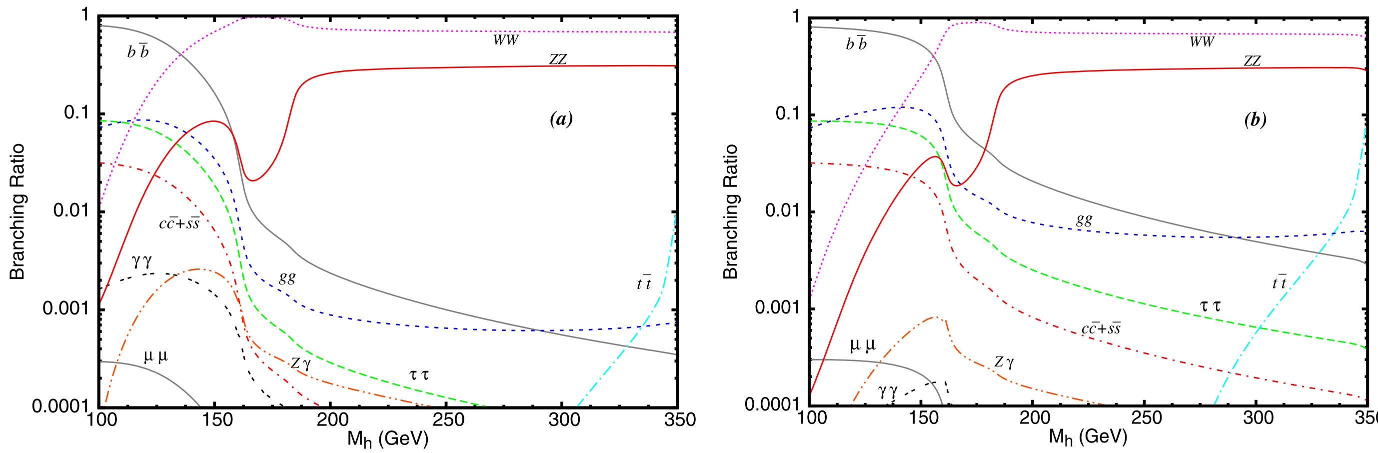

Fig. 1. Illustrating the branching ratios for Higgs decays in (a) SM and (b) new model as a function of its mass. We have used the package HDECAY [9] to calculate the Higgs decay modes.

Eq. (7) then gives

$$m_t = \frac{y_t}{2\sqrt{2}} \frac{v^3}{M^2},$$

$$y_{\bar{t}th} = \frac{y_t}{2\sqrt{2}} \frac{3v^2}{M^2}. \tag{8}$$

Using Eq. (8), we obtain

$$y_{\bar{t}th} = 3\frac{m_t}{v}. \tag{9}$$

Note that this $y_{\bar{t}th}$ is the Yukawa coupling that appears in the interaction of the top quark with the physical Higgs boson h and from Eq. (9) is less than 3. (y_t appearing in Eq. (7) is just a parameter in the six-dimensional Lagrangian). Thus our effective four-dimensional theory is perturbative.

3. Phenomenological implications

In the low Higgs mass range ($M_h \leqslant 125$ 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 $hb\bar{b}$ 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 cancellation 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 $hb\bar{b}$ is dominant. For heavy Higgs mass range, $M_h \geqslant 155$ 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 ($M_h \geqslant 185$ 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 Fermilab Tevatron. For the SM Higgs boson, recent combined analysis by the CDF and D0 Collaborations (using 6.7 fb^{-1} of data) has excluded the SM Higgs

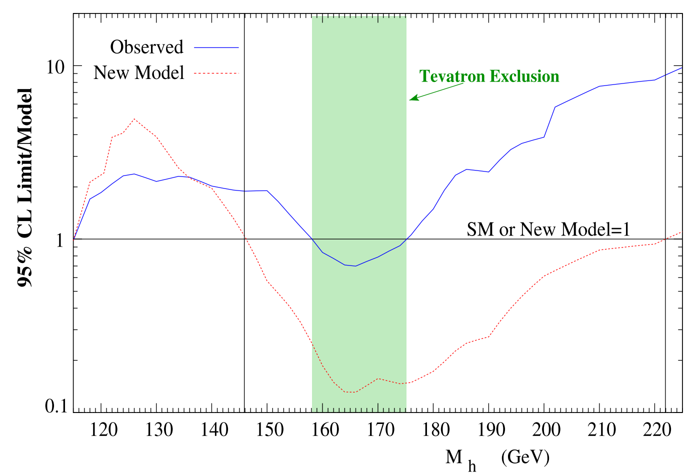

Fig. 2. Illustrating how the Tevatron bound on SM Higgs applies on the Higgs boson in our model.

mass range from 158 to 175 GeV at 95% confidence level (C.L.) [10, 11]. The dominant production mechanism for the Higgs boson is gluon–gluon fusion via the top quark loop. Since in our model, the coupling of the Higgs to the top quark is three times larger, the Higgs production cross sections will be nine times larger than the SM. Higgs production via the gauge interactions to Wh and Zh in our model remains the same as in the SM. Combined Tevatron analysis includes the Higgs signals for all channels, and the corresponding backgrounds. Their experimental curve for the observation of the Higgs signals at 95% C.L. over the SM expectation curve as a function of the Higgs mass is shown by the solid curve in Fig. 2 [11]. The corresponding SM expectation is shown by the horizontal line labeled "SM or New Model = 1". As shown by the Tevatron analysis (solid curve), the SM Higgs mass in the range of 158–175 GeV is excluded. To apply this combined CDF–D0 analysis as well as the LEP limits [12] to our model, we use the package *HiggsBounds* [13] which is a computer code that tests theoretical predictions of models with arbitrary Higgs sectors against the exclusion bounds obtained from the Higgs searches at LEP and the Tevatron. The dashed curve in Fig. 2 shows our results obtained using *HiggsBounds* for our model. The intersection of the dashed curve with the solid "SM or New Model = 1" line indicates an estimate of the Higgs mass range ($222 \text{ GeV} \gtrsim M_h \gtrsim 146$ GeV) that would be excluded by the present Tevatron analysis in our model.

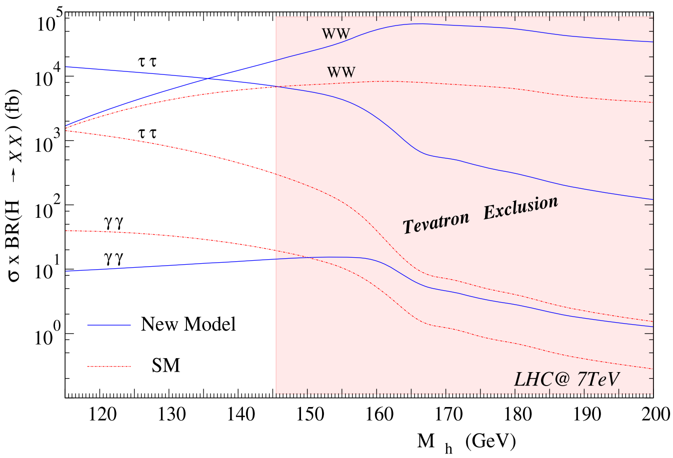

Fig. 3. Illustrating $\sigma \times BR$ for the SM Higgs and in our model for the decay modes $\tau\tau, \gamma\gamma$ and WW at LHC with a center-of-mass energy of 7 TeV.

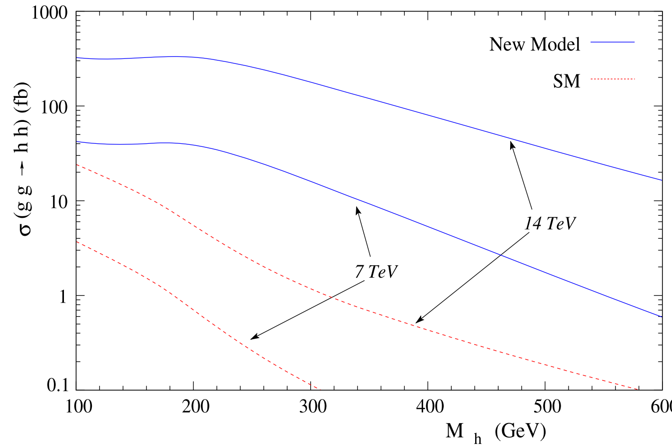

Fig. 4. Cross section for double Higgs production through gluon–gluon fusion for the SM Higgs (dashed) and for the Higgs in our model (solid) at LHC with a center-of-mass energy of 7 and 14 TeV.

In the low Higgs mass range, the lower exclusion range does not improve in comparison with the LEP constraints 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. 3 (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 $h \to WW$ in our model is larger than the SM by a factor of ~ 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 ~ 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 τ 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 [14,15].

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 [16–18]. 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-four 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 $\frac{6i\pi m_f \alpha_{EW}}{M_W^2}$ 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 Refs. [17,18]. To put our results in context we can rewrite the contributions in our model as

$$A_{\triangle}^{NP} = 5 \times A_{\triangle}^{SM} + 2 \times A_{\triangle}^{SM} \frac{\hat{s} - M_h^2}{M_h^2},$$
$$A_{\square}^{NP} = 9 \times A_{\square}^{SM}. \tag{10}$$

We plot the double Higgs production cross section[1] as a function of the Higgs mass in Fig. 4 for both the SM as well as our model. Although Eq. (10) shows a large enhancement in the individual contributions, there still is large cancellation 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 ~ 10 for low Higgs masses as shown in Fig. 4 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 ~ 300 fb at LHC with $\sqrt{s} = 14$ TeV and ~ 40 fb with $\sqrt{s} = 7$ TeV, respectively for $M_h \leqslant 220$ 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

$$V_{New} = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{1}{M^2} (H^\dagger H)^3. \tag{11}$$

Choosing λ to be zero, the condition for the global minima gives

$$M_h M = \sqrt{3} v^2. \tag{12}$$

Using the LEP bound for the Higgs mass, $M_h > 114$ GeV, from Eq. (11), we obtain $M \leqslant 1$ TeV. Note the interesting see-saw type relation between the M_h and M in Eq. (12). Thus if our point of view is correct, we expect the new physics to appear below the TeV scale.

[1] We use the public code available on M. Spira's webpage (http://people.web.psi.ch/spira/proglist.html).

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