New Physics Scale from Higgs Observables with Effective Dimension-6 Operators

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No matter what the scale of new physics is, deviations from the Standard Model (SM) for the Higgs observables will indicate the existence of such a scale. We consider effective six dimensional operators, and their effects on the Higgs productions and decays to estimate this new scale. We analyze and identify the parameter space consistent with known properties of the Higgs boson using recent Run II results from ATLAS and CMS experiments corresponding to \( \sim 37 \, \text{fb}^{-1} \) of data. We then calculate the \( t\bar{t}h \) productions, as well as double Higgs production at the LHC using the effective couplings, and show that these can be much different than those predicted by the Standard Model, for a wide region of allowed parameter space. These predictions can be tested in the current or the future runs of the LHC. We find that the data are consistent with the existence of a new physics scale as low as 500 GeV for a significant region of parameter space of this six dimensional model with new physics effects at the LHC. We also find that for some region of the parameter space, di-Higgs production can be much larger than that predicted by the Standard Model, giving rise to the prospect of its observation even in the current run II of the LHC.

I. INTRODUCTION

There have been several major discoveries in the past few decades culminating with the observation of the Higgs boson in 2012 [1, 2]. This is a tremendous success of the SM. However, as most of us agree, SM can not be the whole story. The Higgs production in various modes and its decays into various final states so far agrees with the SM. But uncertainties with the SM predictions still remain in some of the observables of these measurements. This encourages us to venture into the possibility of a new physics scale that might be estimated from the uncertainty in these measurements. Also, using this approach, we might be able to make predictions which can be tested at the LHC. With this aim in mind, we consider the effect of a selected set of dimension six operators relevant for the Higgs Physics, in addition to the contribution from the SM. The dimension six operators related to the Higgs physics can be introduced both in the strong sector, as well as in the electroweak sector. Such operators will make extra contributions for the Higgs productions, as well as for its various decay modes. In the most general case, for the effective dimension six operators, there are many operators, and involve large number of parameters. In order to reduce the number of parameters, we only consider a selected set of such operators in the gauge sector (both strong and electroweak (EW)), as well as in the Yukawa sector. In particular, we include only those operators which are responsible for larger effects, and do not affect the constraints from the EW precision tests in a significant way.

The effective field theory provides a model independent framework for interpreting precision measurements connecting to specific UV models systematically [3]. Constraints on these operators have been derived from electroweak (EW) precision measurements [4–6]. Higgs sector measurements [7–10] and from the triple gauge couplings [11, 12]. Using EW data, global fits incorporating various searches have been performed in [13]. Subsequently fits have been performed including Higgs sector constraints [14–17]. In this context, di-Higgs production also has been studied here [18–21]. When the Standard Model is considered as an effective low-energy theory, higher dimensional interaction terms appear in the Lagrangian. Dimension-six terms have been enumerated [22, 23] and there are 15 + 19 + 25 = 59 independent operators (barring flavour structure and Hermitian conjugations). However, many of these operators affect processes that are well measured, e.g. flavor physics or electroweak precision observables set strong constraints on subsets of those operators. Some of them are also not relevant for the Higgs physics observables, which is the main emphasis of this work. Here, we focus on the effective operators that focus on the Higgs physics, and nothing else. This in the spirit of reference [24]. At the LHC, SM Higgs boson (h) can be produced significantly via gluon gluon fusion (ggF), vector boson fusion (VBF), associated production with W and Z bosons (Vh) or in association with tt (t\( t \bar{t}h \)). Due to insertion of the dimension-6 terms, SM Higgs production as well as decay branching ratios can be largely affected in these production modes. (1) In the single Higgs production, the most important is the coupling of the gluon pairs to the Higgs boson. Here we have the contribution from the SM dimension-4 operators contributing via the top quark loop. There may exist effective dimension 6 operator (contact interaction) emerging from new physics contributing to this production. (2) The Yukawa coupling of the top quark to the Higgs boson is most important in single Higgs production. Here also, there may exist dimension-6 operator (in addition to the dimension 4 present in the SM) emerging again from the new physics. This will also affect the \( t\bar{t}h \) production, as well as the double Higgs productions, which are of great importance in the upcoming LHC runs. (3) In the production of the Higgs boson in association with W or Z, the important contribution of dimension-6 operator will be the \( hZZ \) or \( hWW \) couplings, which will further effect the decays of the Higgs to WW* and ZZ*. Thus, in addition to the contribution from the usual SM, the contribution of the effective dimension six opera-

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\[ \sigma_{\text{ggF}} = 43.92 \, \text{pb}, \sigma_{\text{VBF}} = 3.748 \, \text{pb}, \sigma_{\text{Vh}} = 1.38 \, \text{pb}, \sigma_{\text{Zh}} = 0.869 \, \text{pb}, \sigma_{\text{t\( t \bar{t}h \)}} = 58.58 \, \text{fb}.\]
The paper is organized as follows: In Sec. II, we discuss the formalism and analyze the dimension-6 operators. Thereafter in Sec. III, we perform the numerical simulations for collider signatures. Finally we conclude.

II. FORMALISM

Our gauge symmetry is the same as the SM. We are introducing a selected set of additional dimension six operators which can affect the Higgs observables in a major way. These operators are all invariant under the SM gauge symmetry.

• EW Yukawa sector:

\[
\mathcal{L}^{(6)}_{Yuk} \supset \frac{y_t^{(6)}}{M^2} (\bar{t}_L, b_L) t_R H (H^\dagger H) + \frac{y_b^{(6)}}{M^2} (\bar{b}_L, \bar{b}_L) b_R H (H^\dagger H) \\
+ \frac{y_t^{(6)}}{M^2} (\nu, \tau_L) \tau_R H (H^\dagger H) + \text{h.c.}
\]

We have included the dimension-6 terms for third generation fermions only. For simplicity, we have included only the flavor diagonal dimension six Yukawa couplings. Similarly, we can extend it for first and second generation fermions also. But, since we are interested in new physics affecting Higgs rates in a major way, we ignore the negligible effects originating from dimension-6 Yukawa terms for first and second generation fermions. We will also ignore the dimension six operator for the \( \tau \) lepton. The Higgs branching ratio to \( \tau \) pair is very small 6%, and its inclusion does not affect the phenomenology we are concentrating.

• Strong sector:

\[
\mathcal{L}^{(6)}_{\text{Strong}} \supset \frac{g^{(6)}}{M^2} G^{\mu\nu} G_{\mu\nu} (H^\dagger H)
\]

This operator will contribute to the Higgs production, as well as its decay to two gluons. \( g^{(6)} \) is an unknown parameter, and \( M \) is the new physics scale. This operator (the contact term) will significantly contribute, in addition to the SM contribution via the top quark loop, in single Higgs production via gluon gluon fusion process.

• EW gauge sector:

\[
\mathcal{L}^{(6)}_{\text{EW gauge}} \supset \frac{y_\tau^{(6)}}{M^2} (D^\mu H)^\dagger (D_\mu H) (H^\dagger H)
\]

where the coupling \( y_\tau^{(6)} \) is an arbitrary coefficient. There are several other dimension six operators which we neglect. The reason is that they do not contribute in a significant way to the processes we are emphasizing on this work, and some of them, if the coefficients are not very small, may mess up the EW precision test. We discuss briefly the effect of this operator above for the processes of interest. This operator contributes to the decays of \( h \to WW^* \) and \( ZZ^* \) as well as to the production through VBF and associated Higgs production with W or Z boson.

• Scalar Potential:

\[
\mathcal{L}^{(6)}_{\text{Scalar}} \supset \frac{\lambda^{(6)}}{M^2} (H^\dagger H)^3
\]

This operator will modify the Higgs trilinear coupling, and hence, contribute significantly to the di-Higgs production.

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2 For simplicity we focus on CP-conserving operators, CP-violating ones can be included in a straightforward way. We omit the operator \( |H^\dagger D^\mu H|^2 \), since it violates the custodial symmetry and is strongly constrained by LEP data. Its inclusion has no impact on our analysis.
Note that in Eq.3, when we put the VEV of the Higgs boson, this operator modifies [57] the Higgs kinetic term \( \frac{1}{2} \partial^\mu h \partial^\mu h \) to \( (1 + \frac{y_i^6}{2\lambda_i^6}) \frac{1}{2} \partial^\mu h \partial^\mu h \).

(Throughout our analysis, we use the convention \( H = \begin{pmatrix} 0 & v^+ \\ v & 0 \end{pmatrix} \) in unitary gauge). Hence, we need to redefine the Higgs field by dividing out with the factor \( N = \left(1 + \frac{y_i^6}{2\lambda_i^6}\right)^{1/2} \) to get the canonically normalized form for the kinetic term \( \frac{1}{2} \partial^\mu h \partial^\mu h \). This modifies the usual couplings of the Higgs field to the gauge bosons, the fermions and the Higgs bosons as given below.

\[
\begin{align*}
\kappa_V &= \frac{1}{N^2} + \frac{\mu^4}{M^2 N^4}, \\
\kappa_t &= \frac{1}{N} \sqrt{\frac{m_t^2}{M^2 N^2}}, \\
\kappa_b &= \frac{1}{N} \sqrt{\frac{m_b^2}{M N^2}}, \\
\kappa_\tau &= \frac{1}{N} \sqrt{\frac{m_\tau^2}{M N^2}}, \\
\kappa_y &= \frac{1}{N} \left(1.034 \kappa_t + 1.036 \kappa_b + \frac{4\eta y_i^6}{\sqrt{\alpha_i} N^4}ight), \\
\kappa_{hhi} &= \frac{1}{N^2} \mu^4 y_i^4 M^2 N^2, \\
\kappa_{\gamma\gamma} &= \frac{\kappa_t F_{1/2}(m_b) + \kappa_y F_1(m_b)}{F_{1/2}(m_b) + F_1(m_b)}, \\
\kappa_{Z\gamma} &= \frac{2 \cos^4 \theta_W}{\cos^2 \theta_W (1 - \frac{3}{2} \sin^2 \theta_W)} \frac{\kappa_t F_{1/2}(m_b) + \kappa_y F_1(m_b)}{F_{1/2}(m_b) + F_1(m_b)}.
\end{align*}
\]

Loop functions used in this paper are defined as follows:

\[
\begin{align*}
F_1(x) &= -x^2 \left[ 2x^{-2} + 3x^{-1} + 3(2x^{-1} - 1)f(x^{-1}) \right], \\
F_{1/2}(x) &= 2x^2 \left[ x^{-1} + (x^{-1} - 1)f(x^{-1}) \right], \\
e_i &= -0.032 + 0.035 i 15
\end{align*}
\]

For a Higgs mass below the kinematic threshold of the loop particle, \( m_h < 2 m_{\text{loop}} \), we have

\[
f(x) = \arcsin^2 \sqrt{x}
\]

where \( x_i \equiv 4m_{\text{loop}}^4 / m_h^4 \) (\( i = t, W \)).

We now calculate the partial decay widths for various SM Higgs decay modes:

\[
\begin{align*}
\Gamma_{h \rightarrow \gamma \gamma} &= \kappa_\gamma^2 \Gamma_{h \rightarrow \gamma \gamma}, \\
\Gamma_{h \rightarrow WW^*} &= \kappa_T^2 \Gamma_{h \rightarrow WW^*}, \\
\Gamma_{h \rightarrow ZZ^*} &= \kappa_T^2 \Gamma_{h \rightarrow ZZ^*}, \\
\Gamma_{h \rightarrow b b} &= \kappa_b^2 \Gamma_{h \rightarrow b b}, \\
\Gamma_{h \rightarrow \tau \tau} &= \kappa_T^2 \Gamma_{h \rightarrow \tau \tau}, \\
\Gamma_{h \rightarrow g g} &= \kappa_g^2 \Gamma_{h \rightarrow g g}, \\
\Gamma_{h \rightarrow Z \gamma} &= \kappa_{Z \gamma} \Gamma_{h \rightarrow Z \gamma},
\end{align*}
\]

where the partial decay widths in the SM can be found in [33].

### III. COLLIDER PHENOMENOLOGY

In this section, we study the collider phenomenology of the Higgs sector. In particular, we discuss the possibility if the effective dimension-6 operators within this framework can explain the significant deviation in \( t \bar{t} h \) production cross section, as recently indicated by CMS [25] and ATLAS collaboration [26], along with the other Higgs boson properties. We also want to investigate if the di-Higgs production may be observable at the current or future runs of the LHC.

To start this effort, we first numerically analyze the effects of dimension-6 terms on the \( t \bar{t} h \) production as well as the signal strengths of Higgs boson decay modes for \( h \rightarrow \gamma \gamma, WW, ZZ, b \bar{b}, \tau \bar{\tau}, Z \gamma \). Then, we identify a parameter space which is consistent with both the recent ATLAS and CMS results on the LHC (Run-1 and Run-2 (37 fb\(^{-1}\)) data). Then remaining within the allowed parameter space, we analyze the possible signals, such as the enhanced di-Higgs boson production that may be observable at the current or future run of the LHC. The relevant parameter space of this model is spanned by the three new dimension-6 Yukawa terms, dimension-6 term from electroweak gauge sector, dimension-6 term from strong sector, dimension-6 term from scalar potential and the mass (8) of the new physics scale:

\[
\begin{align*}
\{ y_t^6, y_b^6, y_\tau^6, g^6, \lambda^6, M \}
\end{align*}
\]

(9)

In the LHC Higgs observable analysis \[^3\] [34], the searches for Higgs boson at ATLAS and CMS can give strong bounds on these free parameters. The signal strength \( \mu \), defined as the ratio of the measured Higgs boson rate to its SM prediction, is used to characterize the Higgs boson yields and it is given by:

\[
\mu_f = \frac{\sigma^{(i)} \cdot \Gamma_{h \rightarrow f}}{(\sigma^{SM}) \cdot (\Gamma_{h \rightarrow f}^{SM})} = \mu_f \cdot \mu_f.
\]

(12)

Here \( \sigma^{(i)} = ggF, VBF, Wh, Zh, t\bar{t}h \) and \( BR_f(\Gamma = ZZ^*, WW^*, \tau \bar{\tau}, b \bar{b}, \mu \bar{\mu} \ldots) \) are respectively the SM Higgs production cross section for different production mechanism (\( i \rightarrow h \)) and the branching fraction for different decay modes of SM Higgs \( (h \rightarrow f) \).

The ATLAS and CMS run 1 data are combined and analyzed using the signal strength formalism and the results are presented in [34]. Recently, ATLAS and CMS collaborations have updated the results [28] on Higgs searches based on 37 fb\(^{-1}\) data at 13 TeV LHC. The individuals analyze a specific Higgs boson decay mode, with categories related to the various production processes and they are \( h \rightarrow \gamma \gamma [36-39], h \rightarrow ZZ^+ [40-43], h \rightarrow WW^+ [44-46], h \rightarrow \tau \bar{\tau} [47, 48], h \rightarrow b \bar{b} [49, 50], h \rightarrow Z \gamma [51, 52] \). Throughout our study, we have used the most updated ATLAS and CMS reported results on 125 GeV Higgs boson searches to impose constraints on signal strengths for various decay modes at 95% confidence level and which is summarized in Table I.

For our analysis, we adopt the following strategy.

[^3]: In our analysis, we employ the center value of the Higgs boson mass \( m_h = 125.09 \) GeV [34] and the center value of the combination of Tevatron and LHC measurements of the top quark mass \( m_t = 173.34 \) in GeV [55].
(1) First, we introduce dimension-6 operator in the Yukawa sector and try to explore whether any new physics effect (enhanced/suppressed couplings of Higgs to fermions) can be achieved satisfying all Higgs physics constraints and try to identify the six dimensional parameter space where these effects can arise.

(2) Then we introduce dimension-6 operator in the EW gauge sector and discuss its effect following the previous effects from the Yukawa sector.

(3) After that we introduce dimension-6 term in strong sector and analyze both individual and combined effects of all of these dimension-6 operators and discuss the new physics effects.

(4) Then, we introduce dimension-6 operator in the scalar potential and analyze its effect in di-Higgs production.

(5) Finally, we discuss about two correlated new physics signatures: enhanced (or suppressed) $tth$ and enhanced $hh$ production.

Since the gauge structure of the SM has been very well established from the precision measurements, as mentioned above, we first concentrate on the Yukawa sector, in particular, the effects coming from the six dimensional Yukawa couplings for the third generation fermions. The top and bottom Yukawas ($y_t^{(6)}$ and $y_b^{(6)}$) play key roles in Higgs observable. The top Yukawa dictates the production of SM Higgs mostly, whereas the bottom Yukawa guides the branching ratio for different decay modes of SM Higgs $h$. Since the partial decay width for $h \rightarrow bb$ mostly contributes $\sim 58\%$ to the total Higgs decay width, any slight deviation in bottom Yukawa will change the total decay width and hence the branching ratio to other decay modes. We analyze the full parameter space of extra Yukawa terms and new physics scale affecting the SM Higgs physics and impose constraints from the signal strength limits [cf. Table I] for various decay modes ($\gamma \gamma, \tau \tau, bb, ZZ^*, WW^*$) at $95\%$ confidence level. The effect is displayed in Fig.1. The white shaded region simultaneously satisfies all the experimental constraints. Since $y_t^{(6)}$ has no significant contribution to the total decay width of SM Higgs compared to $y_b^{(6)}$, as mentioned before, we have ignored $y_t^{(6)}$ for our analysis regarding the effect of dimension six operators. It does not affect the phenomenology we are concentrating.

Next, we evaluate the signal strength $\mu_{tth} (= \kappa_t^2)$ for the production of SM Higgs associated with the top quark pair. Upper left segment of Fig. 1 shows the contour plot of $\mu_{tth}$ in $\{y_t^{(6)}, M\}$ plane for a fixed value of $y_b^{(6)} (= -0.1)$, whereas upper right segment shows the contour plot of $\mu_{tth}$ in $\{y_b^{(6)}, M\}$ plane for a fixed value of $M = 500$ GeV and bottom one of Fig. 1 shows the contour plot of $\mu_{tth}$ in $\{y_b^{(6)}, M\}$ plane for a fixed value of $y_t^{(6)} (= 2)$. Fig. 1 clearly indicates that within this framework, $tth$ can be produced up to 2 times of the SM predicted cross-section at the LHC satisfying all the current experimental constraints from 125 GeV Higgs boson searches while we allow a variation of $y_b^{(6)}$ between -3 to 3. On the other hand, $tth$ production rate can also be as low as 0.5 times weaker than the SM predicted value. This enhanced or suppressed $tth$ production can be the new physics signature and it can be tested at the LHC. We mention that, although SM Higgs $h$ is resonantly produced in gluon gluon fusion via triangular loop circulating by top quarks mainly, there is small effect ($\sim 7\%$) due to the bottom

| Decay channel | Production Mode | CMS | ATLAS |
|---------------|----------------|-----|-------|
| $\gamma\gamma$ | $ggF$ | $1.05^{+0.19}_{-0.19}$ | $0.80^{+0.19}_{-0.18}$ |
| $VBF$ | $0.6^{+0.6}_{-0.5}$ | $2.1^{+0.6}_{-0.6}$ |
| $Wb$ | $3.1^{+1.50}_{-1.30}$ | $0.7^{+0.8}_{-0.17}$ |
| $Zh$ | $0.0^{+0.0}_{-0.10}$ | $0.7^{+0.9}_{-0.18}$ |
| $ZZ^*$ | $ggF$ | $1.20^{+0.22}_{-0.21}$ | $1.11^{+0.22}_{-0.27}$ |
| $VBF$ | $0.05^{+0.03}_{-0.04}$ | $4.0^{+2.1}_{-1.5}$ |
| $Wh$ | $0.0^{+0.0}_{-0.0}$ | $< 3.8$ |
| $Zb$ | $0.0^{+0.0}_{-0.0}$ | $< 3.8$ |
| $W^+W^-$ | $ggF$ | $0.9^{+0.40}_{-0.30}$ | $1.02^{+0.20}_{-0.26}$ |
| $VBF$ | $1.4^{+0.8}_{-0.30}$ | $1.7^{+1.1}_{-0.9}$ |
| $Vh$ | $2.1^{+2.2}_{-1.4}$ | $3.2^{+2.7}_{-1.8}$ |
| $ggF + VBF + Vh$ | $1.05^{+0.26}_{-0.26}$ | $-$. |
| $bb$ | $Vh$ | $1.06^{+0.31}_{-0.29}$ | $0.9^{+0.28}_{-0.26}$ |
| $\tau^+\tau^-$ | $ggF$ | $1.05^{+0.49}_{-0.46}$ | $2.0^{+0.8}_{-0.7}$ |
| $VBF + Vh$ | $1.07^{+0.45}_{-0.43}$ | $1.24^{+0.58}_{-0.54}$ |
| $ggF + VBF + Vh$ | $1.06^{+0.25}_{-0.24}$ | $1.43^{+0.43}_{-0.37}$ |

*Results from 36 fb$^{-1}$ data from 13 TeV LHC is not still reported.

**TABLE I:** Signal strength constraints from recently reported 13 TeV 36 fb$^{-1}$ LHC data along with references.

![FIG. 1: Top Left: Contour plot of $\mu_{tth}$ in $\{y_t^{(6)}, M\}$ plane; Top Right: Contour plot of $\mu_{tth}$ in $\{y_b^{(6)}, M\}$ plane and Bottom: Contour plot of $\mu_{tth}$ in $\{y_b^{(6)}, M\}$ plane. The yellow, cyan, green, red and purple shaded regions are excluded from the signal strength limits [cf. Table I] for various decay modes ($\gamma \gamma, \tau \tau, bb, ZZ^*, WW^*$) respectively at 95% confidence level. The white shaded region simultaneously satisfies all the experimental constraints. Boxed numbers indicate the $\mu_{tth}$ values.](image-url)
expected and as can be seen from Fig. 2 that as bottom Yukawa \( y_b^{(6)} \) gets larger value to enhance overall \( bbb \) coupling, \( y_b^{(6)} \) has to have larger value to satisfy the constraints from Higgs observables. This is due to the fact that, whenever \( y_b^{(6)} \) is large, the partial decay width for \( h \rightarrow b\bar{b} \) mode gets enhanced and hence, total decay width becomes larger suppressing branching ratio for \( h \rightarrow WW, ZZ \) decay modes. Since \( y_b^{(6)} \) has no impact on production via ggF process, \( y_b^{(6)} \) has to be larger to enhance the partial decay width for \( h \rightarrow WW, ZZ \) decay modes making branching ratio almost unaffected to satisfy the correct signal strength limits on ZZ, WW channels. From upper left segment of Fig. 2, we can see that if dimension-6 terms in Yukawa sector are not introduced and only the effect of \( y_b^{(6)} \) is considered, we can still get enhanced \( tth \) production rate which is almost 1.3 times of the SM predicted value. After inclusion of \( y_b^{(5)} \) and \( y_b^{(6)} \), this effect can be much larger and the signal strength for \( tth \) production can become as large as 2.4 and as low as 0.5. It is important to mention that whenever \( tth \) production is getting enhanced making single Higgs production rate via ggF process larger, overall branching ratios for \( h \rightarrow WW^* \) or \( h \rightarrow ZZ^* \) modes has to be suppressed to satisfy correct limits. This also indirectly suppresses the Higgs production in VBF, Wh and Zh processes. Our scenario predicts enhanced \( tth \) production and simultaneously suppressed production of SM Higgs boson in VBF, Wh or Zh processes and this can be tested in the upcoming runs of the LHC. However, there are still large uncertainties in these channels [cf. Table I], but CMS reported central values [cf. Table I] mostly favor this scenario according to the updated status.

Next, we introduce the dimension-6 term \( (g_t^{(6)}) \) in the strong sector and investigate its effect. Deviation in di-Higgs production compared to the SM can be one of the new physics effect due to this term. The di-Higgs boson production has drawn a lot of attentions since it is the golden channel to test the EW symmetry breaking mechanism. Since the SM Higgs boson (h) does not carry any color, they are produced in pair through the triangle loop and box loop in SM. The di-Higgs production rate in the SM is small mainly due to the large destructive interference between the triangle and box loop diagrams. At the LHC with a center of mass energy of 13 TeV, the production cross section is about 33.45 fb, which can not be measured owing to the small branching ratio of the Higgs boson decay and large SM backgrounds. The detailed study of SM di-Higgs production can be found in ref.[55]. However,
in new physics models, the di-Higgs production cross-section can significantly deviate from the SM value. Due to insertion of the dimension-6 term in strong sector, there will be additional diagrams contributing to the di-Higgs production in addition to the SM contribution and as shown in Fig. 3. Also, change in SM $tth$ and $hh$ couplings could give a significant deviation on di-Higgs production cross-section. These two effects could enhance the di-Higgs production and make it testable at the LHC. Therefore, it is important to study how large can the cross section of the double Higgs boson production be considering all the constraints from the single Higgs boson measurements. The $bb\gamma\gamma$ final state is particularly promising for this search, as it benefits from the clean diphoton signal due to high $m_{\gamma\gamma}$ resolution and the large branching fraction of the $h \to bb$ decay ($\sim 58\%$). We consider the signal strength relative to the SM expectation $\mu_{hh}$ as $\mu_{hh} = \frac{\sigma(pp \to hh)_{\text{exp}}}{\sigma(pp \to hh)_{\text{SM}}}$. 

First, we turn off all the dimension 6 operators (in Yukawa sector or EW gauge sector) and explore the effect of $g^{(6)}$ only. This is shown in upper left segment of Fig. 4. We find that to satisfy the constraints from Higgs observables, either $g^{(6)}$ has to be very small $\sim 0$ or new physics scale has to be very large. For an example, $g^{(6)}$ can be as large as 0.06 and as low as -0.06 for the new physics scale, $M$, to be 2 TeV. Since $g^{(6)}$ is responsible for both single Higgs and di-Higgs boson production simultaneously, dimension-6 term ($g^{(6)}$) is highly constrained to give large di-Higgs production. For three of the benchmark points (BP1 and BP2), noted in upper left segment of Fig. 4, $\mu_{hh}$ and $\mu_{tth}$ is almost 1 and there is no significant deviation from SM prediction. Then, we add the contribution from dimension-6 Yukawa terms and we get a large region of the parameter space which is consistent with the Higgs observables and also gives significant deviation in $tth$ and $hh$ production. Due to the $g^{(6)}$ term, there will be two dominant processes for single Higgs production via ggF mode, one is due to the triangular loop circulated by top quark and the other one due to contact interaction term ($ggh$) and there will be large interference between these two diagrams. Upper right segment of Fig. 4 depicts the constraints in $\{y^{(6)}, g^{(6)}\}$ plane from the signal strength limits [cf. Table I] for various decay modes of SM Higgs at 95% confidence level. It is clear that when $y^{(6)}$ gets positive values, $g^{(6)}$ prefers negative values to compensate the overall enhancement effect in single Higgs production and vice versa. For two of the benchmark points (BP3 and BP4), the signal strength $\mu_{tth}$ becomes 2.0 and 0.7 and di-Higgs production cross-section becomes 64 fb and 41.8 fb respectively. Similarly, Lower left segment of Fig. 4 depicts the constraints in $\{y^{(6)}, g^{(6)}\}$ plane from the signal strength limits. Here we have fixed the value of $y_t^{(6)}$ (-1) and new physics scale $M$ (=500 GeV). In the survived parameter space, we choose three benchmark points (BP5 and BP6 as noted in this fig.) and calculate the $tth$ and $hh$ production rate. For benchmark points (BP5 and BP6), $\mu_{tth}$ equals 1.55 and di-Higgs production cross-sections are 31 fb and 81 fb respectively. Similarly, Lower Right segment of Fig. 4 shows the constraints from the signal strength limits in $\{y^{(6)}, g^{(6)}\}$ plane, where we have kept a fixed value of $y_t^{(6)}$ (-0.2) and new physics scale $M$ (=500 GeV). For two of the benchmark points (BP7 and BP8), signal strengths ($\mu_{tth}$) become 1.3 and 1.6 and di-Higgs production cross-sections become 221 fb and 52 fb respectively. As we already mentioned, since dimension 6 term in the strong sector, responsible for di-Higgs production, is not decoupled from the term responsible for the single Higgs production, di-Higgs production rate can not be enormously large, but it can be as large as 6 times of the SM predicted cross-section. Now, we try to emphasize on the determination of the mass scale where these dimension-6 operators are generated and which is consistent with the measurement of Higgs observable. We mention that the contribution of any effective operator is only sensitive to the ratio $g_{\text{effective}}/M^2$, and hence, new physics scale.
M is not observable without extra assumptions on the strength of the couplings $g^{(6)}(6),$ $g^{(6)}(6), \lambda^{(6)}.$ In order to set limit on the new physics scale M, we have assumed $g^{(6)}$ to be less than 3.5 to satisfy the perturbativity constraint. In Fig. 5, we have shown the limits on the mass scale M for different sets of the values of the effective six dimensional couplings. As we can see from Fig. 5, if all the dimension-6 couplings ($g^{(6)}$) are $\sim O(3)$, new physics scale (M) up to 14 TeV is ruled out by the LHC Run II data [cf. Table I] of the Higgs observables. Similarly, when all the dimension-6 couplings ($g^{(6)}$) are $\sim O(1)$ ($\sim O(0.5)$), new physics scale (M) has to be at least 8 TeV [5,7 TeV] to be consistent with the LHC Higgs results [cf. Table I] of Higgs searches.

On the other hand, if we turn off dimension-6 term to be at least 8 TeV [5.7 TeV] to be consistent with the data [cf. Table I] of the Higgs observables. Similarly, when all the dimension-6 couplings, the new physics scale can be as low as 478 GeV making consistent with the SM, so in principle all the 6-dimensional couplings can be zero. In that case, it is not possible to say anything about the scale of new physics. However, the Higgs observables still have large errors, and hence gives the possibility of the existence of new physics. The questions we have addressed is whether in this effective coupling parameter space, there are regions which are allowed by the data, and allow low scale of new physics as well as giving some new physics signatures such as enhanced $tth$ and $hh$ predictions. For example, regarding the new physics scale, we want to mean that the new physics scale can be as low as 478 GeV making consistent with Higgs properties and also giving associated new physics signals like enhanced $tth$ or $hh$ predictions which can be testable at the current or upcoming run of LHC. Regarding the restriction on the effective couplings, since we consider the lowest order contributions, the higher order contributions will no longer be small, if the values of the couplings exceeds the perturbativity limit. This gives a reasonable justification to our assumption.

Next, we analyze the new physics contributions of the dimension-6 operator in the Higgs potential which contributes to the cubic Higgs coupling. Due to the addition of the effective dimension six operator in the Higgs potential, the effective triple Higgs coupling is modified significantly as shown in Eq. 22. As a result, this has the most major effect on the di-Higgs production in the LHC. We take two set of benchmark points which allow enhanced $tth$ production rate (1.5 times of the SM predicted value) at the LHC making consistent with the Higgs properties. It is quite interesting to see from Fig. 6 that we can get the signal strength $\mu_{hh}$ as big as 19 which means that the di-Higgs production cross-section can be as big as 636 fb which is 19 times of the SM predicted cross-section. We mention that the di-higgs production cross-section can be even larger than 636 fb for a certain region of parameter space as we can see from Fig. 6. But, ATLAS and CMS collaborations have analyzed and reported the new results on di-Higgs boson searches [28–32] looking at the different final states $(bb\gamma \gamma, bb\tau^+ \tau^- , bbbb$ and $bbW^+W^−)$, using 36 fb$^{-1}$ data from Run II of LHC at 13 TeV. Due to non-observation of any signal, the stringent limit of 636 fb on di-Higgs production cross section is reported [28–32]. The black meshed zone in Fig. 6 is excluded from this current di-Higgs searches. If LHC luminosity is upgraded to 3 ab$^{-1}$, SM like double Higgs production (33.45 fb) can be observed with 3.6σ significance [62]. On the other hand, in our scenario, the enhanced di-Higgs production can be even sensitive to the 50 fb$^{-1}$ LHC luminosity which is close to the data set currently analyzed. We think this a very interesting scenario which simultaneously provides a testable smoking gun signal for the di-Higgs production and enhanced $tth$ production at the LHC. The future hadron-hadron circular collider (FCC-hh) or the super proton-proton collider (SppC), designed to operate at the energy of 100 TeV, can easily probe most of the parameter space in our scenario through the $hh$ pair production [59–62]. As mentioned, the di-Higgs production in some sets of the six dimensional parameter space can be large enough to be observable...
even in this run of the LHC.

IV. CONCLUSION

In this work, we have made an investigation on the effect of the effective dimension six operators for the single Higgs productions, and the corresponding $\mu_{tth}$, as well as di-Higgs signals at the LHC. Since the number of the effective dimension six operators is too many, we have made a judicious choice of few operators which has the maximum impact for these observable. Using the experimental data at the LHC, we have analyzed in some detail the effects of these operators, how large or small the $\mu_{tth}$, and di-Higgs signals can be, and how small the new physics scale can be satisfying all the available experimental constraints. We find the the $\mu_{tth}$ signal can be as large as two times of that in the SM, while the di-higgs production cross section can be as large as 19 times of that in the SM at the 13 TeV LHC with a new physics scale, $M$ equal to 478 GeV. These predictions can be tested as more data accumulates at the current and the future runs at the LHC. The results presented here can be taken as an initial guide in the exploration of the enhanced $t\bar{t}h$ and $hh$ signal at the LHC via dimension-6 operators.

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