Higgs-dilaton(radion) system confronting the LHC Higgs data

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Abstract

We consider the Higgs-dilaton(radion) system using the trace of energy-momentum tensor ($T^\mu_\mu$) with the full Standard Model (SM) gauge symmetry $G_{SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$, and find out that the resulting phenomenology for the Higgs-dilaton(radion) system is distinctly different from the earlier studies based on the $T^\mu_\mu$ with the unbroken subgroup $H_{SM} \equiv SU(3)_c \times U(1)_{em}$ of $G_{SM}$. After electroweak symmetry breaking (EWSB), the SM Higgs boson and dilaton(radion) will mix with each other, and there appear two Higgs-like scalar bosons and the Higgs-dilaton mixing changes the scalar phenomenology in interesting ways. The signal strengths for the $gg$-initiated channels could be modified significantly compared with the SM predictions due to the QCD scale anomaly and the Higgs-dilaton(radion) mixing, whereas anomaly contributions are almost negligible for other channels. We also discuss the self couplings and the signal strengths of the 126 GeV scalar boson in various channels and possible constraints from the extra light/heavy scalar boson. The Higgs-dilaton(radion) system considered in this work has a number of distinctive features that could be tested by the upcoming LHC running and at the ILC.

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I. INTRODUCTION

Scale symmetry has been an interesting subject both in formal quantum field theory and in particle physics phenomenology [1]. The most important example is the scale invariance (Weyl invariance or conformal invariance) in string theory, which is nothing but 2-dimensional quantum field theories for the string world sheet in target space-time of space-time dimensionality $d$. The condition of vanishing quantum scale anomaly constrains possible perturbative string theories to be defined only in $d = 26$ spacetime for bosonic string theory and $d = 10$ spacetime for superstring theory. However, implementing scale symmetry to particle physics has not been so successful compared with string theory for various reasons.

First of all, scale symmetry is always broken by quantum radiative corrections through renormalization effects. Even if we start from a theory with classical scale symmetry (namely, no dimensional parameters in $L_{\text{classical}}$), the corresponding quantum theory always involves hidden scales, the cutoff scale ($\Lambda$) in cutoff regularization or Pauli-Villa regularization, and the renormalization scale $\mu$ in dimensional regularization. In either case, scale symmetry is explicitly broken by quantum effects, and scale symmetry is anomalous. If the couplings do not run because of vanishing $\beta$ function, we would have truly scale invariant (or conformal symmetric) theory, and $N = 4$ super Yang-Mills theory is believed to be such an example.

Secondly scale symmetry may be spontaneously broken by some nonzero values of dimensionful order parameters due to some nonperturbative dynamics, very often involving some strong interaction. For example, we can consider massless QCD with classical scale invariance. In this case there could be nonzero gluon condensate $\langle G^{a}_{\mu\nu} G^{a}_{\mu\nu} \rangle \sim \Lambda_{G}^{4}$ and chiral condensate $\langle \bar{q}q \rangle \sim \Lambda_{\bar{q}q}^{3}$, where new scales $\Lambda_{G}$ and $\Lambda_{\bar{q}q}$ are generated dynamically and they would be roughly order of the confinement scale $\Lambda_{QCD}$. Since scale symmetry is spontaneously broken, there would appear massless Nambu-Goldstone (NG) boson, which is often called dilaton related with dilatation symmetry. If scale symmetry were not anomalously broken by renormalization effects, dilaton could be exactly massless. However scale symmetry is usually broken explicitly by renormalization effects, dilaton would acquire nonzero mass which is related with the size of quantum anomaly, in a similar way to the pion as a pseudo Nambu-Goldstone boson in ordinary QCD. If the dilaton mass is too large compared with the spontaneous scale symmetry breaking scale, it is not meaningful to talk about dilaton.
as a pseudo NG boson. On the other hand, if dilaton is light enough, then we can use the nonlinear realization of scale symmetry with built-in quantum scale anomaly. Whether dilaton can be light enough or not is a very difficult question to address. The answer would depend on the underlying theories with classical scale symmetry, without which we cannot say for sure about pseudo NG boson nature of dilaton.

Let us note that there have been longtime questions about generating the masses of (fundamental) particle only from quantum dynamics. A good example is getting proton mass from massless QCD. Since the contributions of current quark masses to proton mass are negligible, we can say that proton mass is mostly coming from quantum dynamics between (almost massless) quarks and gluons. Another well known example is radiative symmetry breaking à la Coleman-Weinberg mechanism [2]. In fact, a number of recent papers address generating particle masses along this direction. There are two different ways to getting mass scales from scale invariant classical theories: one from new strong dynamics in a hidden sector [3–5] and the other by CW mechanism [6–13]. If there are no mass parameters in classical Lagrangian, the theory would have classical scale symmetry. And all the mass scales would have been generated by quantum effects, either nonperturbatively or perturbatively.

Before the Higgs boson was discovered, dilaton (denoted as $\phi$ in this paper) has been considered an alternative to the Higgs boson [14–18] from time to time, since dilation couplings to the SM fields is similar to the SM Higgs field at classical level, except that the overall coupling scale is given by the dilaton decay constant $f_{\phi}$ instead of the Higgs vacuum expectation value (VEV) $v$. At quantum level, dilaton has couplings to the gauge kinetic functions due to the quantum scale anomaly [19], a distinct property of dilaton which is not shared by the SM Higgs boson. The radion [20] in Randall-Sundrum (RS) model [21, 22] has the similar properties as the dilaton, in that it couples to the trace of energy-momentum tensor too just like the dilaton [20, 23, 25, 67].

The interest in dilaton physics has been renewed recently [26–38], since the LHC announced discovery of a new boson of mass around 126 GeV (which we call $H$ in this letter) [39, 48]. Radion-Higgs mixing scenarios have also been extensively studied in the light of the LHC results [49–54]. The current data still suffer from large uncertainties, but the observed new particle has properties that are consistent with the SM predictions, although there is a tendency that the $\gamma\gamma$ ($ZZ^*$) mode is enhanced over the SM predictions at ATLAS detector.
The other modes are consistent with the SM predictions, but within a large uncertainty.

The effective interaction Lagrangian for a dilaton \( \phi \) to the SM field can be derived by using nonlinear realization: \( \chi = e^{i\phi} \) [1]. With the trace of the energy momentum tensor, which is the divergence of dilatation current, the interaction terms which are linear in \( \phi \) cast into

\[
\mathcal{L}_{\text{int}} \simeq -\frac{\phi}{f_\phi} T^\mu_\mu = -\frac{\phi}{f_\phi} \left[ 2\mu^2_H H^\dagger H - 2m^2_W W^+ W^- - m^2_Z Z^\mu Z^\mu + \sum_f m_f \bar{f} f + \sum_G \beta_G G^\mu_\mu G^\mu_\mu \right].
\]

We argue that this form of dilaton interaction to the SM fields may not be proper, since only the unbroken subgroup of the SM gauge symmetry has been imposed on \( T^\mu_\mu \). If we imposed the full SM gauge symmetry on \( T^\mu_\mu \), the more proper form of the dilaton couplings to the SM should be described by Eq. (3) below.

The SM Lagrangian is written as

\[
\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}}(G) + \mathcal{L}_{\text{kin}}(f) + \mathcal{L}_{\text{kin}}(H) + \mathcal{L}_{\text{Yukawa}}(f, \bar{f}, H) - \mu^2_H H^\dagger H - \lambda (H^\dagger H)^2,
\]

where \( G, f \) and \( H \) denote the SM gauge fields, fermions and Higgs field in a schematic way. In this form, scale symmetry is explicitly broken by a single term, \( \mu^2_H H^\dagger H \) in the SM. Also quantum mechanical effects break scale symmetry anomalously. In the end, the trace of energy-momentum tensor of the SM, which measures the amount of scale symmetry breaking, is given by

\[
T^\mu_\mu(\text{SM}) = 2\mu^2_H H^\dagger H + \sum_G \beta_G G^\mu_\mu G^\mu_\mu.
\]

This form of \( T^\mu_\mu \) respects the full SM gauge symmetry \( G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \). This form is clearly different from the usual form, Eq. (1), which is constructed after EWSB and respects only the unbroken subgroup of the SM, \( H_{\text{SM}} = SU(3)_C \times U(1)_{\text{em}} \). We claim that one has to use the form before EWSB, since we do not know the scale of spontaneous scale symmetry breaking. If \( v_{\text{EW}} < f_\phi \), it would be more reasonable to impose the full SM gauge symmetry with Eq. (3) [68]. This point should be even more evident for the radion in the Randall-Sundrum scenario, since the existence of the radion \( \phi \) is independent of EWSB, and thus it should couple to the \( T^\mu_\mu \) of the SM fields with the full SM gauge symmetry \( G_{\text{SM}} \), Eq. (3), and not to the form with the unbroken subgroup \( H_{\text{SM}} \) of the SM.

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\[\text{(1)}\]

\[\text{(2)}\]

\[\text{(3)}\]

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It is the purpose of this paper to analyze the Higgs-dilaton system using the dilaton couplings to the SM fields which respects the full SM gauge interactions, and compare the results with the most recent LHC data on the Higgs boson. In Sec. II, we derive the effective Lagrangian for dilaton coupled to the SM fields, and derive the interactions between them. Then we perform phenomenological analysis in Sec. III, comparing theoretical predictions based on Eq. (3) with the LHC data on the Higgs boson, and derive the constraints on the mass of the 2nd scalar boson and the mixing angle, as well as the deviations of quartic and triple couplings of the Higgs bosons. The results are summarized in Sec. IV, and the β functions for dimensionless couplings in the SM are collected in Appendix for convenience.

II. MODEL FOR THE HIGGS-DILATON (RADION) SYSTEM

A. Model Lagrangian

Let us assume that there is a scale invariant system where scale symmetry is spontaneously broken at some high energy scale \( f_\phi \), with the resulting Nambu-Goldstone boson which is called dilaton \( \phi \). In terms of \( \chi(x) \equiv e^{\phi(x)/f_\phi} \), the Lagrangian for the SM plus a dilaton would be written as

\[
\mathcal{L} = \mathcal{L}_{SM}(\mu_H = 0) + \frac{1}{2} f_\phi^2 \partial_\mu \chi \partial^\mu \chi - \mu_H^2 \chi^2 H^\dagger H - \frac{f_\phi^2 m_\phi^2}{4} \chi^4 \left\{ \log \chi - \frac{1}{4} \right\} ,
\]

\[
- \log \left( \frac{\chi}{S(x)} \right) \left\{ \beta_u (g_1) \mathcal{B}_{\mu\nu} B^{\mu\nu} + \beta_d (g_2) \mathcal{W}_{\mu\nu} W^{\mu\nu} + \beta_\lambda (g_3) \mathcal{G}_{\mu\nu} G^{\mu\nu} \right\} 
\]

\[
+ \log \left( \frac{\chi}{S(x)} \right) \{ \beta_u (Y_u) \bar{Q}_L \tilde{H} u_R + \beta_d (Y_u) \bar{Q}_L H d_R + \beta_l (Y_u) \bar{l}_L H e_R + H.c. \} 
\]

\[
+ \log \left( \frac{\chi}{S(x)} \right) \beta_\lambda (\lambda) \frac{1}{4} (HH^\dagger)^2 
\]

where \( S(x) \) is the conformal compensator, which is put to 1 at the end of calculation. Keeping the linear term in \( \phi \), we recover the Eq. (1) with \( T^\mu_\mu \) being given by Eq. (3). Note that the dilaton coupling to the SM fields in this work is different from other works in the literature. In most works, the dilaton is assumed to couple to the SM fields in the broken phase with unbroken local \( SU(3)_c \times U(1)_{em} \) symmetry. However if scale symmetry breaking occurs at high energy scale, it would be more reasonable to assume that the dilaton
couple to the SM Lagrangian as given in the above form with the full SM gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$ imposed.

The ground state of the potential for the classical Lagrangian is given by either $\langle H \rangle = 0, \langle \chi \rangle = 1$ for the unbroken EW phase, and $\langle H \rangle = (0, v/\sqrt{2})^T, \langle \phi \rangle = \bar{\phi}$ for EWSB into $U(1)_{em}$, ignoring the contributions from the vacuum expectation values of the scale anomaly, such as $\langle C_{\mu\nu}^a C^{a\mu\nu} \rangle$ etc.

The vanishing tadpole conditions for the correct vacua are given by

$$\lambda v^2 = \mu^2 e^{2\bar{\phi}/f_{\phi}}, \quad \mu^2 v^2 = f_{\phi} m_{\phi}^2 e^{2\bar{\phi}/f_{\phi}}. \quad (5)$$

We have used the $\mu^2 = -\mu_H^2 > 0$, for convenience. From these two conditions, one can derive

$$v^2 = \mu^2 \lambda e^{2\bar{\phi}/f_{\phi}} \quad \text{or} \quad \mu^4 = \lambda \bar{\phi} f_{\phi} m_{\phi}^2, \quad (6)$$

which solves for $\bar{\phi}$ for given $\mu^2, \lambda, f_{\phi}$ and $m_{\phi}^2$. Note that the Higgs VEV $v$ is fixed by the weak gauge boson masses $m_W$ and $m_Z$ to be 246 GeV.

We will consider the EWSB vacuum, and calculate the (mass)$^2$ matrix for the field fluctuation around the VEV: $H = (0, (v + h(x))/\sqrt{2})\hat{T}$ and $\bar{\phi} + \phi$. Note that rescaling of the quantum fluctuation $\phi$ around $\bar{\phi}$ is necessary, i.e. $\phi e^{i\bar{\phi}/f_{\phi}} \rightarrow \phi$. After rescaling the mass matrix should be

$$\mathcal{M}^2(h, \phi) = \begin{pmatrix} m_{hh}^2 & m_{h\phi}^2 \\ m_{\phi h}^2 & m_{\phi\phi}^2 \end{pmatrix} = \begin{pmatrix} 2\lambda v^2 & -2\lambda \bar{\phi} e^{-2\bar{\phi}/f_{\phi}} \\ -2\lambda \bar{\phi} e^{-2\bar{\phi}/f_{\phi}} & m_{\phi}^2 e^{2\bar{\phi}/f_{\phi}} \left(1 + 2\bar{\phi}/f_{\phi}\right) \end{pmatrix}$$

$$\equiv \begin{pmatrix} m_{hh}^2 & -m_{h\phi}^2 e^{-2\bar{\phi}/f_{\phi}} \\ -m_{\phi h}^2 e^{-2\bar{\phi}/f_{\phi}} & \tilde{m}_{\phi}^2 e^{2\bar{\phi}/f_{\phi}} \end{pmatrix}, \quad (8)$$

where we define

$$\tilde{m}_{\phi}^2 = m_{\phi}^2 \left(1 + 2\bar{\phi}/f_{\phi}\right). \quad (9)$$

One can diagonalize this matrix by introducing two mass eigenstates $H_1$ and $H_2$ and the mixing angle $\alpha$ between the two states, with the following transformation:
\[ m_{H_1,2}^2 = \frac{m_h^2 + m_{\tilde{\phi}}^2 e^{2 \frac{\phi}{f_0}} \pm \sqrt{(m_h^2 - m_{\tilde{\phi}}^2 e^{2 \frac{\phi}{f_0}})^2 + 4e^{-4 \frac{\phi}{f_0} v^2} m_h^4}}{2}, \quad (10) \]

\[ \tan \alpha = \frac{-m_h^2 v e^{-2 \frac{\phi}{f_0}}}{m_{\tilde{\phi}}^2 e^{\frac{\phi}{f_0}} - m_{H_1}^2}. \quad (11) \]

Here we use the basis
\[ \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}. \quad (12) \]

Now the interaction Lagrangian between dilaton and the SM fields can be derived in terms of \( H_1 \) and \( H_2 \).

### B. Interaction Lagrangian for dilaton(radion) and the SM Fields

In this subsection, we derive the interaction Lagrangian between the dilaton(radion) and the SM fields both in the interaction and in the mass eigenstate basis.

Let us first discuss the interactions of the dilaton(radion) with the SM fermions and the SM Higgs boson with the full \( G_{SM} \):

\[ \mathcal{L}(f, \bar{f}, H_{i=1,2}) = -\frac{m_f}{v} \bar{f} f h = -\frac{m_f}{v} \bar{f} f (H_1 c_\alpha + H_2 s_\alpha), \quad (13) \]

with \( s_\alpha \equiv \sin \alpha \) and \( c_\alpha = \cos \alpha \). The first equality is in the interaction basis, whereas the second one is in the mass basis. Note that there is no direct coupling of the dilaton(radion) \( (\phi) \) to the SM chiral fermion at the classical level, namely when we ignore the quantum scale anomaly of Yukawa interactions. This is because we have imposed the full SM gauge symmetry, Eq. (3). On the other hand, earlier literature uses the following dilaton couplings to the SM fermions assuming the unbroken subgroup \( H_{SM} = SU(3)_C \times U(1)_Y \):

\[ \mathcal{L}(f, \bar{f}, \phi) = -\frac{m_f}{f_\phi} \bar{f} f \phi \ e^{-\phi/f_\phi}. \quad (14) \]

Note that there is no proper limit where the earlier result (14) based on \( T^\mu_\mu \) with unbroken subgroup of the SM gauge symmetry \( H_{SM} = SU(3)_C \times U(1)_{em} \) approaches our result (13) based on \( T^\mu_\mu \) with the full SM gauge symmetry \( G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \). This shows that it is very important to impose which gauge symmetry on the fundamental Lagrangian.
It should be the full SM gauge symmetry $G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$ rather than its unbroken subgroup $H_{\text{SM}} = SU(3)_C \times U(1)_\text{em}$ that has been widely used in earlier literature, when we consider new physics at EW scale and the new physics scale is not known \cite{69}.

The same argument applies to other interactions of the dilaton(radion) with the SM gauge bosons or the SM Higgs boson. We list them below for completeness:

\begin{equation}
L(g, g, H_{i=1,2}) = - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \frac{\beta_3(g_3)}{2g_3} G_{\mu\nu} G^{\mu\nu} \phi
= - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \frac{\beta_3(g_3)}{2g_3} G_{\mu\nu} G^{\mu\nu} (-H_1 s_\alpha + H_2 c_\alpha).
\end{equation}

\begin{equation}
L(W, W, H_{i=1,2}) = \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} h - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \frac{\beta_2(g_2)}{2g_2} W_{\mu\nu} W^{\mu\nu} \phi
= \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} (H_1 c_\alpha + H_2 s_\alpha)
- \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \frac{\beta_2(g_2)}{2g_2} W_{\mu\nu} W^{\mu\nu} (-H_1 s_\alpha + H_2 c_\alpha).
\end{equation}

\begin{equation}
L(Z, Z, H_{i=1,2}) = \frac{m_Z^2}{v} Z_\mu Z^\mu h - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \left\{ \frac{s_W^2 \beta_2(g_2)}{2g_2} + \frac{c_W^2 \beta_1(g_1)}{2g_1} \right\} Z_{\mu\nu} Z^{\mu\nu} \phi
= \frac{m_Z^2}{v} Z_\mu Z^\mu (H_1 c_\alpha + H_2 s_\alpha)
- \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \left\{ \frac{s_W^2 \beta_2(g_2)}{2g_2} + \frac{c_W^2 \beta_1(g_1)}{2g_1} \right\} Z_{\mu\nu} Z^{\mu\nu} (-H_1 s_\alpha + H_2 c_\alpha).
\end{equation}

\begin{equation}
L(\gamma, \gamma, H_{i=1,2}) = - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \left\{ \frac{s_W^2 \beta_2(g_2)}{2g_2} + \frac{c_W^2 \beta_1(g_1)}{2g_1} \right\} F_{\mu\nu} F^{\mu\nu} \phi
= - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} \left\{ \frac{s_W^2 \beta_2(g_2)}{2g_2} + \frac{c_W^2 \beta_1(g_1)}{2g_1} \right\} F_{\mu\nu} F^{\mu\nu} (-H_1 s_\alpha + H_2 c_\alpha).
\end{equation}

\begin{equation}
L(\gamma, Z, H_{i=1,2}) = - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} 2s_Wc_W \left\{ \frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1} \right\} Z_{\mu\nu} F^{\mu\nu} \phi
= - \frac{e^{-\tilde{\phi}/f_\phi}}{f_\phi} 2s_Wc_W \left\{ \frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1} \right\} Z_{\mu\nu} F^{\mu\nu} (-H_1 s_\alpha + H_2 c_\alpha).
\end{equation}

The $\beta$ functions for the SM gauge groups are listed in the Appendix A for convenience. The SM Higgs field $h$ will interact with gluons or photons in just as in the standard model case, and we have to add these to the above interaction Lagrangian.

The offshoot of our approach is that the dilaton $\phi$ mixes with the SM Higgs boson $h$, and couples to the SM fields through quantum scale anomaly in addition to the classical scale symmetry breaking term, i.e. $\mu_H^2 H^\dagger H$. Since the dilaton $\phi$ and the SM Higgs boson $h$ mix with each other to make two scalar bosons $H_1$ and $H_2$, their couplings to the SM fermions
will be reduced by a universal amount due to the mixing effects \[55\], while their couplings to the SM gauge bosons, especially to gluons, could be further modified by quantum scale anomalies. This observation has a very tantalizing implication for Higgs signals at the LHC, which will be elaborated in the following. Since there are two scalar bosons, we take one of them to be 126 GeV resonance that was observed recently at the LHC. Since the dilaton (radion) $\phi$ coupling to the trace anomaly of the SM fields (Eq. (3)) are distinctly different from the interactions between the SM fields and other singlet scalar bosons appearing in various extensions of the SM \[55\], phenomenological consequences of the Higgs-dilaton mixing are analyzed separately in this paper.

III. IMPLICATIONS ON THE LHC HIGGS DATA

A. Analysis Strategy

Compared with the SM Higgs boson, the Higgs-dilaton system considered in this paper has only two more parameters ($m_\phi$ and $f_\phi$), which makes phenomenological analysis feasible. Two scalars $\phi$ and $h$ mix with each other after EWSB, leading to two mass eigenstates $H_1$ and $H_2$. Fixing one Higgs boson mass to be 126 GeV, all other parameters in the Lagrangian such as the other Higgs boson mass, the mixing angle $\alpha$, triple and quartic couplings of $H_1$ and $H_2$ are all expressed as functions of $m_\phi$ and $f_\phi$. Likewise, their decay widths and branching ratios are completely fixed as functions of $m_\phi$ and $f_\phi$.

As mentioned in the previous section, the interactions of the Higgs boson to the SM particles are modified in two different ways compared with the SM, via mixing with dilaton and the quantum scale anomalies. Note that the modification due to quantum scale anomalies are very small that their effects are negligible in most cases, except for the gluon-gluon and $\gamma\gamma$ couplings to the Higgs boson through scale anomaly associated with $SU(3)_C \times U(1)_{em}$ gauge interaction. Therefore the branching ratios of physical Higgs bosons decaying into the SM fermions are suppressed relative to those of the SM Higgs boson by mixing angle, whereas those into the SM gauge bosons could be modified through quantum scale anomaly.

For a given ($m_\phi, f_\phi$), we calculate the signal strength of each scalar boson into a specific final state:

$$\mu_i(f.s.) = \frac{\sigma_{H(production)} \times B(H_i \rightarrow f.s.)}{\sigma_{H(production)}_{SM} \times B(H_i \rightarrow f.s.)_{SM}},$$

(20)
| Decay | Production | $\mu_i$ |
|-------|------------|--------|
| $\gamma\gamma$ | Combined | ATLAS $^{39}$ : $1.65^{+0.35}_{-0.3}$ |
| | | CMS $^{44}$ : $0.78^{+0.26}_{-0.28}$ |
| | $ggF$ | ATLAS $^{39}$ : $1.6^{+0.36}_{-0.42}$ |
| | $VBF$ | ATLAS $^{39}$ : $1.7^{+0.89}_{-0.94}$ |
| $ZZ^*$ | Combined | ATLAS $^{40}$ : $1.7^{+0.5}_{-0.4}$ |
| | | CMS $^{45}$ : $0.9^{+0.8}_{-0.25}$ |
| | $ggF$ | ATLAS $^{40}$ : $1.8^{+0.5}_{-0.8}$ |
| | | CMS $^{45}$ : $0.8^{+0.36}_{+0.46}$ |
| | $VBF(VH)$ | ATLAS $^{40}$ : $1.2^{+1.4}_{-3.8}$ |
| | | CMS $^{45}$ : $1.7^{+2.1}_{-2.2}$ |
| $WW^*$ | Combined | ATLAS $^{41}$ : $1.01^{+0.31}_{-0.31}$ |
| | | CMS $^{46}$ : $0.72^{+0.31}_{-0.18}$ |
| $bb$ | VH | ATLAS $^{42}$ : $0.2^{+0.7}_{-0.7}$ |
| | | CMS $^{47}$ : $1.0^{+0.5}_{-0.5}$ |
| $\tau\tau$ | Combined | ATLAS $^{43}$ : $1.4^{+0.4}_{-0.4}$ |
| | | CMS $^{48}$ : $1.1^{+0.4}_{-0.4}$ |

TABLE I: Signal strengths reported by ATLAS and CMS.

where ‘f.s.’ means a specific ‘final states’, $WW^*$, $ZZ^*$, $\gamma\gamma$, $f\bar{f}$ etc.. The subscript $i = 1, 2$ represents two scalar bosons in the mass eigenstates, and the ‘production’ denotes the production mechanisms such as gluon-gluon fusion ($ggF$), vector boson fusion ($VBF$), Higgs production associated with vector boson $(VH)$, and top quark pair production associated with Higgs boson $(ttH)$.

In case of decays of two physical scalar bosons, the dominant effect of dilaton results in the coupling suppression via the mixing between $h$ and $\phi$. On the other hand, in their production parts, there are further modifications on the $ggF$ generated by quantum scale anomaly associated with color $SU(3)_C$ gauge fields. This kind of modification by scale
anomaly is small in other production channels, i.e., VBF, VH and ttH. Consequently, we can expect that the ggF initiated processes can be significantly modified by quantum scale anomaly but other channels are suppressed just by the mixing angle.

B. Confronting the LHC Higgs data and predictions for the Higgs self-couplings and the mass of the extra boson

We perform the analyses for two distinct cases. First one is the case that the heavy mode $H_2$ is identified as observed 126 GeV boson, and the other is that the light mode $H_1$ as observed 126 GeV boson. The CMS and ATLAS collaborations reported the results based on five- and seven-different channels, respectively [39–48]. The most recent CMS results are consistent with the SM even including the diphoton decay channel [44], which was larger than the SM value in the previous analysis [56]. The enhancement in diphoton mode is still there in the ATLAS report, and also in the $ZZ^*$ mode with less significance.

Considering the current situation of conflicting data on $H \rightarrow \gamma\gamma$, we consider two separate cases reported by CMS and ATLAS collaborations. For each case, we perform the $\chi^2$ analysis and select the parameter sets within the 3$\sigma$ range around the each $\chi^2$ minimum [57].

1. Case I: 126 GeV $H_2$ and extra light $H_1$: $m_{H_1} < m_{H_2} = 126$ GeV

Let us start with the case that heavier $H_2$ is the observed 126 GeV boson. As mentioned in the previous section, we put the constraints of 3$\sigma$ range around the minimum $\chi^2$. In addition to that, we also consider the experimental constraint for the light scalar particle that is determined by the LEP experiment [58].

Considering these three constraints, the allowed parameter region is shown in Fig.1 in the $(m_{H_1}, \sin \alpha)$ plane. The colored columns denote the signal strengths. As noted in Sec. III A, the dilaton production from gluon fusion ($gg \rightarrow \phi$) can be enhanced due to the QCD scale anomaly and thus can compete with the SM Higgs production from gluon fusion ($gg \rightarrow h$). Therefore the Higgs signal strengths depend mainly on the production channels rather than the decay channels, and we present the $\gamma\gamma$ channel only in Fig. 1. One can see that the ggF initiated process can be modified significantly compared to the SM value. On the other hand, the VBF initiated one is suppressed by the mixing angle only, so that its signal
strength is always smaller that one. Also note that the allowed region for the mixing angle \( \alpha \) is highly constrained around \( \alpha \sim -\frac{\pi}{2} \). This means that the observed 126 GeV boson is largely SM-like and the extra light mode is dilaton-like, namely \( H_2 \simeq h \) and \( H_1 \simeq \phi \). Even though the mixing angle is close to \(-\pi/2\) and \( H_2 \simeq h \), rather large modification is possible from the mixing with the dilaton through the tuning of the input parameters \( m_\phi \) and \( f_\phi \).

There should be an extra light scalar mode \( H_1 \) whose mass is constrained to be in the range \( m_{H_1} \sim [58, 104] \) GeV, which is a prediction of our model.

Since the model has only two more input parameters \((m_\phi, f_\phi)\), some observables are highly correlated, which make the generic signals of the model. In Fig. 2, we show two such correlations with the contours of \( m_{H_1} \) in different colours. The left plot shows a strong correlation between the ggF-initiated signal strengths \( WW^*(ZZ^*) \) and \( \gamma\gamma \) production process. The correlation is almost linear, since the scale anomaly contribution to the ggF initiated process is dominant. The slope of the correlation slightly deviates from one ‘1’ because of the small difference between the \( SU(2)_W \) and \( U(1)_{em} \) scale anomalies. The yellow and purple boxes are showing the 1\( \sigma \) observations by CMS and ATLAS. The right plot shows the correlation between the signal strengths of different initial states but the same final states, the diphoton channels. Though the correlation is not that strong as the left plot, the ATLAS data tends
FIG. 2: Left : Correlation between the signal strengths of ggF initiated $WW^*(ZZ^*)$ and $\gamma\gamma$ production. Blue dotted and red solid boxes mean the $1-\sigma$ allowed ranges for $WW^*$ and $ZZ^*$ each. Right : Correlation between ggF and VBF initiated diphoton production. $H_2$ is fixed as $m_{H_2} = 126$ GeV boson. The colored columns denote the mass of the lighter Higgs $H_1$.

to prefer the larger value of $m_{H_1}$ [70].

Triple and quartic couplings for the $H_2(m_{H_2} = 126$ GeV) are completely determined within this model, making distinct discriminators for this model. In the allowed parameter region, the predictions for triple and quartic couplings of the SM-like Higgs boson $H_2$ are shown in Fig.3. One can see that triple and quartic couplings are suppressed compared with the SM values, depending on the $H_1$ mass. Especially for the triple coupling it gives relative minus sign compared to the SM value, which would result in the constructive interference between the box diagram and the triangle diagram with the $s$–channel $H_2$ propagator, and thus increase the $H_2$ pair production in $gg \rightarrow H_2H_2$ [59]. In addition, we observe a strong correlation between triple and quartic couplings, which is presented in Fig.4. Along with the $H_1$ mass, the triple and quartic couplings are highly inter-related. This will be the strong distinctive signal for testing the model, which could be probed at the upcoming LHC run and at the ILC.
2. Case II: 126 GeV $H_1$ and extra heavy $H_2$: $m_{H_1} = 126$ GeV $< m_{H_2}$

Let us move to the other case where the observed 126 GeV boson is lighter one, $H_1$. In this case there is an extra heavy mode named $H_2$. As in Case I, we select the allowed parameter region by $3\sigma$ range from the $\chi^2$ minima for CMS and ALTAS results. In this case there are another experimental exclusion bounds on the Higgs-like heavy mode by CMS and
FIG. 5: Contour plots for the signal strengths for diphoton productions: ggF (left) and VBF (right) initiated processes. $H_1$ is fixed as $m_{H_1} = 126$ GeV boson.

ATALS with range upto $\sim 1000$ GeV $^{60-62}$.

In this case, the allowed range for the mixing angle $\alpha$ is severely restricted around the SM values, $\alpha \simeq 0$ (see Fig. 5).

For both cases the signal strengths are very close to 1, the SM values. This means that the experimental data strongly favor the SM case and the dilaton should be heavy enough to decouple from the theory. Compared to the SM, only the surviving region for the heavier scalar mass $m_{H_2}$ is relatively relaxed compared with the constraints on the SM-like Higgs boson, which can be expected because of the mixing between the SM Higgs boson $h$ and the dilation $\phi$ depending on the $(m_\phi, f_\phi)$ parameter values. As a result, other observables as triple and quartic couplings are also strongly restricted around the SM values.

As a result, unlike the Case I, it is not sufficient just to look into the observed $H_1(m_{H_1} = 126$ GeV) sector to discriminate the model from the SM, since the model is pointing to the almost exact SM values for it. The heavier scalar boson mass is constrained to be larger than $\sim 367$ GeV from the Higgs signal strengths of the observed 126 GeV boson and the heavier Higgs searches (see Fig. 5). This is a distinctive feature of our model compared with the SM. So the more detailed studies on the possible extra heavy scalar boson are necessary in the future 14 TeV LHC and tentative International Linear Collider (ILC) to test this.
model more completely.

IV. CONCLUSIONS

In this letter, we considered the SM coupled with some spontaneously broken scale symmetric sector with light dilaton (pseudo Nambu-Goldstone boson) (or the radion in the RS scenario) using the $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant form of the trace of the energy momentum tensor of the SM fields, Eq. (3). Our approach is different from others in that most earlier studies used the $T_{\mu}^{\mu}$ which is invariant under $SU(3)_C \times U(1)_{em}$ invariant form [Eq. (1)], not the form which is invariant under the full SM gauge symmetry.

The SM Higgs boson and the dilaton $\phi$ mix with each other after EWSB. Since the original dilaton is coupled to the SM fields only through the Higgs mass parameter $\mu_H^2$ term and the quantum scale anomalies, two scalar bosons after the mixing carry the nature of the original dilaton and the SM Higgs boson.

Considering the 3$\sigma$ ranges around the $\chi^2$ minima and experimental constraints on the extra light/heavy mode by LEP/LHC, the allowed region on the mixing angle and extra scalar mass is highly restricted. For the case of 126 GeV boson and extra light scalar particle, we can give robust prediction for the mass of the extra light scalar and mixing angle. Also the correlations between the various signal strengths could be the good distinctive signals of our model. The triple and quartic couplings and their correlation give the impressive testbed for the model, which can be further studied in the 14 TeV LHC and ILC.

On the other hand, if we identify the observed scalar particle with mass 126 GeV as light mode $H_1$, with the constraints upon the extra heavy SM-like scalar mode searched by CMS and ATLAS, the remaining parameter sets become severely confined around the SM expectations. This means that it is not enough to discriminate the model from the SM just by looking into the 126 GeV sector. In this case, the more detailed study on the extra heavy mode will be necessary to test the model completely.
Appendix A: The $\beta$ functions for the SM gauge group

The $\beta$-functions that contribute to scale anomalies are collected for convenience:

\[
\frac{dg_i}{dt} = \beta_{g_i} = -b_i \frac{g_i^3}{16\pi^2},
\]
\[
\frac{dY_u}{dt} = \beta_u = \frac{Y_u}{16\pi^2} \left( \frac{3}{2} \left( Y_u^\dagger Y_u - Y_d^\dagger Y_d \right) + Y_2(S) - \left( \frac{17}{20} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 \right) \right),
\]
\[
\frac{dY_d}{dt} = \beta_d = \frac{Y_d}{16\pi^2} \left( \frac{3}{2} \left( Y_d^\dagger Y_d - Y_u^\dagger Y_u \right) + Y_2(S) - \left( \frac{1}{4} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 \right) \right),
\]
\[
\frac{dY_e}{dt} = \beta_l = \frac{Y_e}{16\pi^2} \left( \frac{3}{2} Y_e^\dagger Y_e - \frac{9}{4} \left( g_1^2 + g_2^2 \right) \right),
\]

(A1)

where

\[
b_Y = \left( -\frac{2}{3} n_f - \frac{1}{10} \right) \frac{5}{3},
\]
\[
b_2 = -\frac{2}{3} n_f + \frac{22}{3} - \frac{1}{6},
\]
\[
b_3 = -\frac{2}{3} n_f + 11,
\]
\[Y_2(S) = \text{Tr}\{3Y_u^\dagger Y_u + 3Y_d^\dagger Y_d + Y_e^\dagger Y_e\}.\]

(A2)

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[67] For this reason, we will use the terminology “dilaton” for both dilaton in spontaneously broken scale symmetric theory and the radion in the RS scenario in this paper.

[68] This form of the trace of energy-momentum tensor was considered in Refs. 63 64. In these papers, the dilaton mass parameter was fixed by the scale symmetry breaking effect, i.e., non-zero value of divergence of dilatation current. In our case, dilaton mass is considered as free parameter and that can be justified when the tentative dark matter contributions are included, for instance.

[69] Similar observation was made in Ref. 66 in the context of singlet fermion dark matter model with Higgs portal. There it was shown that the effective Lagrangian approach gives us completely wrong answer in direct detection cross section for dark matter and nucleon and Higgs boson phenomenology. The same conclusion would apply even if one assumes that the interaction between the SM Higgs boson $h$ and the fermion DM $\psi$ is given by dim-4 operator $h\bar{\psi}\psi$, which in fact respect only the unbroken SM gauge group $H_{SM}$ and not the full gauge symmetry $G_{SM}$. When we construct the renormalizable model with the full SM gauge symmetry, we would recover the model presented in Ref. 66, and the model based on $H_{SM}$ would give wrong physics. More detail will be described elsewhere.

[70] Note that the CMS did not report the results depending on the initial production channels.