Scale invariant models without a light dilaton

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Abstract

In this work, we investigate the possibility of having a scale invariant (SI) standard model (SM) extension, where the light CP-even scalar with the pure radiative mass is the SM-like Higgs rather than the light dilaton. After deriving the required conditions for this scenario, we show that the radiative corrections that give rise to the Higgs mass can trigger the scalar mixing to experimentally allowed values. In addition, the heavy CP-even scalar is in a good agreement with all recent ATLAS and CMS measurements. We illustrate this scenario by considering the SI-scotogenic model as an example, while imposing all the theoretical and experimental constraints. We show some possible modifications of di-Higgs signatures at current/future with respect to the SM.

Keywords: classical scale invariance, dilaton, Higgs mass, heavy scalar resonance.

After the Higgs discovery [1, 2], many questions are still open within the standard model (SM), among them understanding the origin of the Higgs mass. It is well known that in the SM, the quadratic divergences appear in the radiative corrections to the Higgs mass, which cause the hierarchy problem. Among the popular to the hierarchy problem solutions is to set $\mu^2$ Higgs mass term in the Lagrangian to zero, which makes the SM scale invariant (SI) at the classical level. In this case, the electroweak symmetry breaking (EWSB) occurs via the so-called dimensional transmutation, where the scale invariance is broken at the quantum level [3]. The SI symmetry breaking is associated by a pseudo-Goldstone boson (PGB) that is strictly massless at tree-level and acquires its mass via radiative corrections. This light scalar is called the "dilaton". Many models that are SI extended in order to address, in addition to the hierarchy problem, some problems like the dark matter (DM) and the neutrino oscillation data [4, 5]. Here, we want to investigate the case where the light PGB is the observed 125 GeV SM-like Higgs rather than a light dilaton. In addition to the conditions for having a purely radiative Higgs mass (PRHM), we will discuss also the relevant theoretical and experimental constraints on this scenario. In order to illustrate our discussion, we consider a phenomenologically rich SI model [5] as an example, where we will show a full agreement with the recent measurements and give possible interesting predictions in current/future experiments.

The classical scale invariance symmetry enforces the action to be invariant under the conformal transformation $x^\mu \to \kappa^{-1}x^\mu, \Phi_i \to \kappa \Phi_i$, which implies the vanishing of the scalar quadratic terms in the Lagrangian density. Then, for a model with many scalar representations, the scalar potential is written in the general form

$$V = \sum_{i,j,k,l} \lambda_{ijkl} \Phi_i \Phi_j \Phi_k \Phi_l,$$

(1)

where the non-vanishing couplings $\lambda_{ijkl}$ are decided according to the symmetries that are assigned to the model.

Generally, most of the SI models in the literature include the SM Higgs doublet $H^T = \left(\chi^+, \left[h + i\chi^0\right]/\sqrt{2}\right)$, a real scalar singlet $\phi$ to assists the EWSB and other bosonic and fermionic representations in different multi-
and give masses to all the model fields. Then, we get two CP-even eigenstates $h_{1,2}$ ($m_1 < m_2$) via a rotation with the angle $\alpha$ in the basis $\{h, \phi\}$. Here, one of the eigenstates must match the SM-like Higgs with the measured mass $m_h = 125.18$ GeV. In the literature, the heavier eigenstate $h_2 = H$ corresponds to the SM-like Higgs and $h_1 = D$ is the dilaton scalar, which is strictly massless at tree-level and acquires its mass via the radiative corrections. We consider this to be the first case and the second one corresponds to a SM-like Higgs with a purely radiative mass, i.e., $h_1 = H$ and $h_2 = S$ would be a heavier scalar. The aim of this work is to investigate the second case of the PRHM scenario.

In order to achieve the EWSB, one has to consider the radiative corrections to the scalar potential. The one-loop scalar potential can be written in function of the CP-even scalar fields as

$$V^{1-\ell}(h, \phi) = \frac{1}{24} \left( \lambda_h + \delta \lambda \right) h^4 + \frac{1}{24} \left( \lambda_\phi + \delta \lambda \right) \phi^4 + \frac{1}{4} (\omega + \delta \omega) h^2 \phi^2 + \sum_i n_i G\left(m_i^2(h, \phi)\right),$$

where $\delta \lambda_h$, $\delta \lambda_\phi$, $\delta \omega$ are the counter-terms, $n_i$ and $m_i^2(h, \phi)$ are the field multiplicity and field dependant mass.

Here, the function $G(r_i) = \frac{r_i}{64\pi^2} \left( \log \frac{r_i}{\Lambda^2} - c_i \right)$ is defined a la the $\overline{DR}$ scheme ($c_i = 3/2$) and $\Lambda = m_h = 125.18$ GeV is the renormalization scale. Here, we choose a renormalization scheme, where the minimum $\{h = v, \phi = x\}$ is still the vacuum at one-loop level; and one of the eigenmasses $m_{1,2}$ at one-loop must correspond to the measured Higgs mass value $m_h$. In other words, the counter-terms should be derived from the conditions $\frac{\partial V^{1-\ell}}{\partial h}\bigg|_{h=v,\phi=x} = \frac{\partial V^{1-\ell}}{\partial \phi}\bigg|_{h=v,\phi=x} = 0$ and $m_{1,2}^{2(1-\ell)} = m_{1,2}^2$.

Using the tapole conditions, the one-loop scalar squared mass matrix in the basis $\{h, \phi\}$, can be written in function of $\delta \omega$, as

$$M^2 = m_h^2 \left( A - \delta \omega v^2/m_h^2, C + \delta \omega v x/m_h^2 \right),$$

with the dimensionless parameters

$$A = \frac{x^2}{v^2 + x^2} + \frac{1}{m_h^2} \sum_i n_i \left[ \left( \partial_{h,h} m_i^2 - \frac{3}{2} \partial_{h} m_i^2 \right) G'(m_i^2) + \left( \partial_{h} m_i^2 \right)^2 G''(m_i^2) \right]_{h=v,\phi=x},$$

$$B = \frac{v^2}{v^2 + x^2} + \frac{1}{m_h^2} \sum_i n_i \left[ \left( \partial_{\phi,\phi} m_i^2 - \frac{3}{2} \partial_{\phi} m_i^2 \right) G'(m_i^2) + \left( \partial_{\phi} m_i^2 \right)^2 G''(m_i^2) \right]_{h=v,\phi=x},$$

$$C = -\frac{v x}{v^2 + x^2} + \frac{1}{m_h^2} \sum_i n_i \left[ \left( \partial_{h,\phi} m_i^2 \right) G'(m_i^2) + \left( \partial_{h} m_i^2 \right) \left( \partial_{\phi} m_i^2 \right) G''(m_i^2) \right]_{h=v,\phi=x},$$

where $m_i^2 \equiv m_i^2(h, \phi)$ are the field dependant squared masses, $G'(r) = \partial G(r)/\partial r$, $G''(r) = \partial^2 G(r)/\partial r^2$, $\partial_x = \frac{\partial}{\partial x}$ and $\partial_{x,y} = \frac{\partial^2}{\partial x \partial y}$. In order to derive the value of the counter-term $\delta \omega$, we require the measured Higgs mass to match one of the eigenmasses, i.e., $2m_h^2 - M_{11}^2 - M_{22}^2 = \pm \left\{ (M_{32}^2 - M_{11}^2)^2 + 4(M_{22}^2)^2 \right\}^{1/2}$. Both equations give the same value for $\delta \omega$.

$$\delta \omega = -\frac{m_h^2 (AB - C^2 - A - B + 1)}{v^2 + x^2 - Av^2 - Bx^2 - 2Cvx}.$$

Depending on the model free parameters (the singlet VEV $x$ and the fields couplings to the real scalar singlet and Higgs doublet), the light CP-even eigenmass could match the measured Higgs mass only if $M_{11}^2 + M_{22}^2 > 2m_h^2$, which is the required condition to have a PRHM scenario. It can be translated into

$$2 - A - B + \delta \omega (v^2 + x^2)/m_h^2 < 0.$$
Numerically, the counter-terms $\delta \omega$, $\delta \lambda_h$ and/or $\delta \lambda_\phi$ may acquire large values, especially for large singlet VEV $x$, non-negligible dimensionless couplings and/or large fields multiplicities. To avoid such naturalness, one has to impose the perturbativity constraints on the one-loop quartic couplings $\lambda_{H_h^\ell}^{1-\ell}$, $|\omega^{1-\ell}| < 4 \pi$, where these one-loop couplings are defined as the $4^{th}$ derivatives of the effective potential (3) at the vacuum $\{h = v, \phi = x\}$. Here, there is no need to impose such vacuum stability conditions $\lambda_{H_h^\ell}^{1-\ell}$. $3\omega^{1-\ell} + \{\lambda_{H_h^\ell}^{1-\ell} \lambda_{\phi}^{1-\ell}\}^{1/2} > 0$, using the one-loop couplings, since the leading term in the effective potential (3) is $q^4 \log q$ rather than $q^4$. Therefore, the one-loop conditions of the vacuum stability come from the coefficients positivity of the term $q^4 \log q$, with $q$ is any direction in the plane $\{h, \phi\}$.

In the PRHM scenario, the cosine and sine of the scalar mixing angle at tree-level are given by $(\epsilon_a^{\text{tree-level}} = v/(v^2 + x^2)^{1/2}, s_a^{\text{tree-level}} = x/(v^2 + x^2)^{1/2})$, which are in a clear contradiction with the recent measurements. Both ATLAS and CMS measurements at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV reported the total Higgs signal strength modifier to be $\mu_{\text{tot}} = \epsilon_a^2 \times (1 - B_{\text{BSM}}) \geq 0.89$ at $95\%$ CL [6], which implies that $s_a^2 \leq 0.11$ in the absence of invisible and undetermined Higgs decay ($B_{\text{BSM}} = 0$). This can be translated at tree-level into the contradictory bound on the singlet VEV $x \leq 86.6$ GeV. If one writes $s_a = (1 + \Delta_{\sin a})s_a^{\text{tree-level}}$, then the radiative corrections must be negative and large in absolute value: $\Delta_{\sin a} \leq -1 + 0.331662479 (1 + v^2/x^2)^{1/2}$, in order to have a viable PRHM scenario. Therefore the radiative corrections (described by the fields multiplicities and couplings to the Higgs doublet and the real singlet) must push the light CP-even scalar mass to match $m_H$, and give large negative contribution to the mixing sine at the same time to have a SM-like Higgs in the PRHM scenario.

The new heavy CP-even scalar $S$ is a subject of constraints from many negative searches at the LHC. Since the CP-even field of the Higgs doublet can be written as $h = H c_s + S s_s$, then the scalar S has the same SM-like Higgs couplings to the SM fermions and gauge bosons scaled either by $s_s$, or $s_s^2$. Therefore, it decays to SM final states, di-Higgs final state or via other invisible or undetermined channels according to the model field content. This allows different search types: the first one is for the heavy CP-even resonance in the channels of pair of leptons, jets or gauge bosons $pp \to S \to \ell\ell, jj, VV$. The second search type is via a resonant di-Higgs production $pp \to S \to HH$. For the first type, we consider the recent ATLAS analysis at 13 TeV with 139 fb$^{-1}$ $pp \to S \to \tau\tau$ [7], and $pp \to S \to ZZ$ via the channels $\ell\ell\ell\ell$ and $\ell\ell\gamma\gamma$ [8], in addition to the CMS analysis at 13 TeV with 137 fb$^{-1}$ $pp \to S \to WW$ [9]. For the second type, we consider the recent ATLAS combination [10], that includes the analyses at 13 TeV with 139 fb$^{-1}$ via the channels $HH \to b\bar{b}\tau\tau$ [11], $HH \to b\bar{b}b\bar{b}$ [12] and $HH \to b\bar{b}\gamma\gamma$ [13].

In the PRHM scenario, the triple scalar couplings $\lambda_{HHH}$ and $\lambda_{HHS}$ are strictly vanishing at tree-level. Therefore, any process that it sensitive to these scalar triple couplings (like $pp \to HH@\text{LHC14}$ and $e^-e^+ \to ZHH@\text{ILC500}$ as examples) would be fully triggered by radiative effects. Since the radiative contributions to the scalar mixing ($\Delta s_s$) are expected to be large and negative, one has consider a more precise estimation for these triple couplings $\lambda_{HHH}$ and $\lambda_{HHS}$. By considering the one-loop scalar mixing, these couplings should be defined as the third derivatives of the one-loop effective potential (3) following [14], which leads to a significantly improved values of the (re-summed) couplings. In this setup, each of these processes $pp \to HH@\text{LHC14}$ and $e^-e^+ \to ZHH@\text{ILC500}$ occurs via Feynman diagrams with the triple scalar couplings ($\lambda_{HHH,HHS}$) and also via other diagrams without $\lambda_{HHH,HHS}$. Then, the cross section can be divided as: (1) a contribution that involves only $\lambda_{HHH,HHS}$ ($\sigma_\lambda$) diagrams, (2) a pure gauge couplings contribution ($\sigma_G$); and (3) the interference contribution ($\sigma_{GL}$). This makes the cross section of both processes modified as

$$R(f) = \frac{\sigma(f) - \sigma_{SM}(f)}{\sigma_{SM}(f)} = \frac{\xi_1\sigma_G + \xi_2\sigma_\lambda + \xi_3\sigma_{GL}}{\sigma_G + \sigma_\lambda + \sigma_{GL}} - 1,$$

(8)

with $f \equiv pp \to HH@\text{LHC14}$ and $e^-e^+ \to ZHH@\text{ILC500}$. For the process $f \equiv pp \to HH@\text{LHC14}$, we have $\sigma_G \equiv \sigma_G(c) = 70.1$ fb, $\sigma_\lambda \equiv \sigma_\lambda(c) = 9.66$ fb and $\sigma_{GL} \equiv \sigma_{GL(c)} = -49.9$ fb are the box, triangle and interference contributions to the total cross section, respectively [15]. Using MadGraph [16], we find $\sigma_G = 0.0837$ fb, $\sigma_\lambda = 0.01565$ fb and $\sigma_{GL} = 0.05685$ fb for the process $e^-e^+ \to ZHH@\text{ILC500}$. The coefficients $\xi_i$ are given at the
deriving the field dependant masses through the relevant parts of the SI Lagrangian density

\[ \xi_1 = c_a, \quad \xi_2 = |P|^2, \quad \xi_3 = c_a^2 R (P), \quad \mathcal{P} = c_a \frac{\lambda_{HHH}}{\lambda_{hh}} s - m_h^2 + i m_h \Gamma_h \]

with \( \Gamma_h = 4.2 \text{MeV} \) is the measured Higgs total decay width, \( \Gamma_5 \) is the estimated heavy scalar total decay width and \( \lambda_{hh} \) is the SM Higgs triple coupling that is estimated as in [18].

In order to illustrate this discussion, we consider a phenomenologically rich SI model, the SI-scotogenic model [5], where the SM is extended by one inert doublet scalar, \( S \), three singlet Majorana fermions \( N_i \), and one real neutral singlet scalar \( \phi \). The model is assigned by a global \( Z_2 \) symmetry \( \{ S, N_i \} \rightarrow \{ S, -N_i \} \), where all other fields being \( Z_2 \)-even. This global symmetry makes the lightest \( Z_2 \)-odd field \( N_2 \) as a stable DM candidate. One can easily construct the effective potential (3) for this model by deriving the field dependant masses through the relevant parts of the SI Lagrangian density

\[ -\mathcal{L} \supset = \frac{1}{2} y_i \phi N_i^2 N_i + \frac{1}{6} \lambda_h (|\mathcal{H}|^2)^2 + \frac{\lambda_\phi}{24} \phi^2 + \frac{\lambda_5}{2} |S|^4 + \frac{\omega_1}{2} |\mathcal{H}|^2 \phi^2 + \frac{\omega_2}{2} \phi^2 |S|^2 + \lambda_3 |\mathcal{H}|^2 |S|^2 + \lambda_4 |\mathcal{H}^\dagger S|^2 + \frac{\lambda_5}{2} (\mathcal{H}^\dagger S|^2) + \text{h.c.}, \]

where \( \mathcal{H}^\dagger \equiv (\chi^+, |h + i \phi^0|/\sqrt{2}) \) denotes SM Higgs doublet.

In our analysis, we consider the model free parameters to be lying in the ranges

\[ x < 10^6 \text{GeV}, \quad y_i^2, \quad |\lambda_i| < 4\pi, \quad M_{DM} < 3\text{ TeV} \]

where \( \lambda_i \) denotes all the quartic couplings in (10). In Fig. 1, we show many observables that represent either the relevant constraints on the model or some predictions for future colliders. In order to have an idea about the radiative corrections effects, we compare our SI-scotogenic results with a toy model, the SM is extended by a bosonic degree of freedom “i” with the multiplicity \( n_i \) and the field dependant mass \( m_i^2 = \frac{1}{2} (a_i h^2 + \beta_i \phi^2) \), in addition to the singlet scalar \( \phi \) to assist the radiative EWSB. The toy model parameters \( \{ n_i, a_i, \beta_i \} \) are constrained by a PRHM requirements and the heavy scalar with a mass \( m_H < m_S \leq 3 \text{ TeV} \).

One has to mention that for the upper range in Fig. 1, we used 10k benchmark points (BPs) and considered many theoretical and experimental constraints such as the vacuum stability, perturbativity, perturbative unitarity, electroweak precision tests, the di-photon Higgs decay, the Higgs invisible decay when applicable, the Higgs total decay width measurement [19, 20], the implications of the negative searches on neutralinos and charginos in supersymmetric models on the inert masses, the bounds on DM nucleon scattering cross section from DD experiments (Xenon 1T [21]); and the Higgs signal strength at the LHC \( \mu_{tot} \geq 0.89 \) [6]. For the lower range, we omitted the BPs that are excluded by the negative searches for a heavy resonance in the channels \( pp \rightarrow S \rightarrow \tau \tau \) [7], \( pp \rightarrow S \rightarrow ZZ \) [8] and \( pp \rightarrow S \rightarrow WW \) [9]; in addition to the negative searches on the resonant di-Higgs production \( pp \rightarrow S \rightarrow HH \) via the different channel \( HH \rightarrow b\bar{b}\tau\tau \) [11], \( HH \rightarrow b\bar{b}bb \) [12] and \( HH \rightarrow b\bar{b}gg \) [13]. These recent constraints exclude only 5.35% of the BPs used in the upper panels in Fig. 1. Indeed, there are other relevant constraints to this model such as neutrinos oscillation data, dark matter (DM) relic density and and the lepton flavor violating processes. These constraints are not considered here since we interested on the parameters and constraints that are relevant to the radiative effects on the Higgs sector.

From Fig. 1, one can reach many conclusions. A PRHM scenario is most likely possible, where the radiative corrections can give rise to the Higgs mass and simultaneously push the scalar mixing to be in agreement with the total Higgs strength bound [6]. For instance, for heavy scalar masses below 3 TeV, the one-loop quartic couplings \( \lambda_{ii}^{1-\ell} \) and \( \omega_{i}^{1-\ell} \) are not practically constrained by the perturbativity since they are lying in the ranges \( [0.07, 2.5] \) and \( [-1, 2] \), respectively. However, the singlet one-loop quartic coupling \( 10^{-5} < \lambda_{i}^{1-\ell} \leq 4\pi \), together with the previous requirements make the singlet scalar VEV lies in the range 600 GeV < \( x < 100 \) TeV. Here, the fact that the heavy scalar is barely constrained by the recent RUN-II measurements of ATLAS with 139 fb\(^{-1} \) [7, 8, 10], and CMS with 137 fb\(^{-1} \) [9], makes this scenario within the reach of the coming analysis.

One has to notice that the total decay width of the heavy scalar is much smaller than its mass for most of the viable parameters space, and therefore the narrow width approximation used to estimate \( \sigma(pp \rightarrow \)
Figure 1: In the upper range, the mixing ($s^2$) versus the singlet VEV $x$, where the palette shows the relative radiative contribution to mixing $\Delta \sin \alpha$ (left) and the heavy scalar mass (middle). The upper blue line corresponds to the tree-level value of the mixing $[s^2]_{\text{tree-level}} = x^2/(v^2 + x^2)$ and $\mu_{\text{tot}} = 0.89$ represents the experimental bound on the Higgs signal strength in the absence of non-SM Higgs decay modes. The orange, black and purple lines correspond to the cases $\{N_1 = 6, \alpha_1 = \beta_1 = 0.2\}$, $\{N_2 = 12, \alpha_2 = \beta_2 = 0.5\}$, $\{N_3 = 24, \alpha_3 = \beta_3 = 0.9\}$, respectively. In the top-right panel, we show the resonant di-Higgs production cross section via the heavy resonance $S$ at $\sqrt{s} = 13$ TeV, compared to the combination of the recent ATLAS measurements [10]. Here, the resonant di-Higgs production cross section estimation was based on the heavy Higgs production cross section values given in [22]. In the lower range, we show in the left panel the total decay width of the heavy resonance versus the ratio $\Gamma_S/m_S$, where the palette shows its di-Higgs branching ratio. In the middle and right panels, we show the relative enhancement (8) for the processes $pp \to HH@LHC$ and $e^-e^+ \to ZHH@ILC$500, where the palette shows the cross section values in fb.

$S \to HH$ is justified. In addition, the cross section of the non-resonant di-Higgs production at the LHC $pp \to HH@LHC14$ is reduced (by up to 75%) for the majority of the parameters space, while it is enhanced for few BPs by less than 10%. For the Z-associated di-Higgs production at the ILC $e^-e^+ \to ZHH@ILC500$, the cross section is mainly enhanced for heavy scalar masses below 500 GeV, and reduced for larger $m_S$ values. Here, the enhancement/suppression is maximal around $m_S \sim \sqrt{s} = 500$ GeV, where this is not a numerical mis-estimation of the cross section, since the propagators are Breit-Wigner approximated as given in (9). For completeness, one has to mention that the BPs in Fig. 1 are in agreement with other DM constraints such as the DD bounds and the relic density. Here, we enforced the relic density to be $\Omega_{N_1} h^2 > 0.12$ due to the annihilation channels $N_1 N_1 \to VV, HH, SS, SS, f\bar{f}$, where the contribution of the channel $N_1 N_1 \to f\bar{f}$ to the annihilation cross section would relax the relic density to match the measured value [23], $\Omega_{DM} h^2 = 0.120 \pm 0.001$ [24].

The idea of the Higgs as a PGB in a SI framework has been discussed in [25]. In addition to the EWSB details discussion, the authors had shown that the light CP-even mass could exceed the Higgs mass bound (then, $m_H > 114$ GeV). They considered two phenomenologically consistent models to validate this possibility. Although in SI models, it has been shown that the slow-roll inflation can be achieved by adding a extra VEVless singlet real scalar that is coupled to non-minimally to the gravity. This real field singlet inflationary model does not suffer from a unitarity breakdown at a scale below or comparable to the inflation scale [26]. Here, the singlet field that is responsible for inflation can be also a viable DM candidate. In a non SI model [27] that is similar to our illustrative example, where fermionic DM has been addressed and the EWSB is assisted by a real scalar singlet, it has been shown that the inflaton could either be the Higgs boson or the singlet scalar, and slow-roll inflation can be realized via a non-minimal coupling to gravity. This tells us that achieving a successful slow-roll inflation within the PRHM scenario deserves an extensive investigation to define the viable parameters space region.
In this work, we have shown that the PRHM scenario within the SI invariance approach is possible; and in a good agreement with all the ATLAS and CMS measurements. To avoid the constraints from the total Higgs signal strength modifier \cite{6}, one needs to consider the radiative corrections to the singlet-doublet scalar mixing. This leads to non-negligible values for the triple scalar couplings $\lambda_{HHH}$ and $\lambda_{HHS}$, and makes the PRHM scenario sensible to recent ATLAS measurement of $pp \to S \to HH$ \cite{10}. We considered the SI-scotogenic model \cite{5} as an illustrative example, where we have checked different experimental constraints and given some predictions about (Z-associated) di-Higgs production at (ILC500) LHC14. This PRHM scenario looks interesting since many physical observables are all triggered together by the radiative corrections effects. Therefore, some other aspects within this approach should be heavily investigated such as the electroweak phase transition (EWPT) strength, gravitational waves produced during the EWPT in addition to the different collider signatures that are relevant to the triple Higgs couplings.

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