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# Natural electroweak symmetry breaking from scale invariant Higgs mechanism

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ABSTRACT

We construct a minimal viable extension of the standard model (SM) with classical scale symmetry. Its scalar sector contains a complex singlet in addition to the SM Higgs doublet. The scale-invariant and CP-symmetric Higgs potential generates radiative electroweak symmetry breaking à la Coleman–Weinberg, and gives a natural solution to the hierarchy problem, free from fine-tuning. Besides the 125 GeV SM-like Higgs particle, it predicts a new CP-even Higgs (serving as the pseudo-Nambu–Goldstone boson of scale symmetry breaking) and a CP-odd scalar singlet (providing the dark matter candidate) at weak scale. We systematically analyze experimental constraints from direct LHC Higgs searches and electroweak precision tests, as well as theoretical bounds from unitarity, triviality and vacuum stability. We demonstrate the viable parameter space, and discuss implications for new Higgs searches at the upcoming LHC runs and the on-going direct detections of dark matter.



## 1. Introduction

The LHC discovery of a 125 GeV Higgs-like particle [1,2] seems to provide the last missing piece of the standard model (SM) of particle physics, but the SM apparently fails to accommodate dark matter (DM) and neutrino masses. Higgs mechanism [3] is the cornerstone of the SM, which hypothesizes a single spin-0 Higgs doublet to realize spontaneous electroweak symmetry breaking (EWSB) and gives rise to a physical remnant — the Higgs boson. This generates [4] the observed masses for spin-1 weak bosons and all three families of spin-$\frac{1}{2}$ SM fermions via gauge and Yukawa interactions of the Higgs boson. However, the Higgs boson could not fix its own mass and an *ad hoc* negative mass term is input by hand at the weak scale. As such, it is customary to think that the Higgs mass will be destabilized against the Planck scale by quantum corrections unless large fine-tuned cancellation of the associated quadratical divergences is imposed [5]. Historically, seeking resolutions to this naturalness problem has been the major driving force behind numerous "beyond SM" extensions on the market, ranging from supersymmetry and compositeness to large or small extra dimensions, despite none of them has been seen so far at the LHC.

The naturalness theorem [6] asserts that the absence of large corrections can only be maintained through certain symmetry which protects the Higgs mass term. This means that the symmetry must increase when the Higgs mass approaches zero. It is important to note that the Higgs mass is the unique dimensionful parameter in the SM Lagrangian, and only causes soft breaking of the scale symmetry.[1] Such a scale symmetry will also be explicitly broken by the trace anomaly with dimension-4 operators at quantum level. But this only leads to logarithmic running of coupling constants and cannot generate quadratical divergence in the dimension-2 Higgs mass term [7]. Hence, the SM itself could be technically natural up to high scales[2] and free from fine-tuning in the Higgs mass renormalization due to the softly broken classical scale invariance [7,9].

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[1] After the SM is extended with singlet right-handed neutrinos, their dimension-3 heavy Majorana mass-term provides another soft breaking of scale invariance. Our present construction will naturally generate this Majorana mass term via spontaneous symmetry breaking at TeV scale.

[2] The SM Higgs sector with a 125 GeV Higgs boson is free from triviality bound, but suffers a vacuum stability bound at the scale $\mu \simeq 10^{12}$ GeV [8]. We will analyze both triviality and vacuum stability bounds for the present model.

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It is even more tempting to restore the full scale symmetry for the SM Lagrangian by setting a vanishing Higgs mass. This justifies the use of a scale-invariant regularization method for loop corrections, which automatically ensures the absence of quadratical divergence in the Higgs mass renormalization. (The simplest regulator respecting classical scale symmetry is the dimensional regularization [11].) Thus, such a scale-invariant SM Lagrangian or its scale-symmetric extensions will stabilize the weak scale up to a high ultraviolet (UV) cutoff $\Lambda_{\rm UV}$ provided [7]: (1) no intermediate scales[3] would mix with the weak scale; (2) no Landau poles (or instabilities) appear in the running couplings (or Higgs potential) over the energies up to $\Lambda_{\rm UV}$.

With such a fully scale-invariant SM Lagrangian, one can radiatively generate nonzero Higgs mass and spontaneous EWSB via Coleman–Weinberg mechanism [10]. In consequence, the weak scale is nicely induced at quantum level via dimensional transmutation. This further reduces one more free-parameter from the conventional SM. But, unfortunately such a minimal version has its Higgs potential unbounded from below at one-loop given the experimentally observed masses of top quark and weak gauge bosons. In addition, the radiatively induced Higgs mass is too low to even survive the LEP-II Higgs search bound $M_h > 114.4$ GeV (95% C.L.) [13]. Hence, the SM Higgs sector has to be properly extended and some interesting attempts appeared in recent years [14–16].

In this work, we construct the minimal viable extension of the SM with classical scale symmetry. Its Higgs sector contains a Higgs doublet and a complex gauge-singlet scalar. The Higgs potential is scale-invariant, as well as CP-conserving. The model predicts two CP-even Higgs boson and one CP-odd scalar at weak scale. Among the two CP-even states, one provides the observed 125 GeV Higgs boson and another serves as a pseudo-Nambu–Goldstone boson from scale symmetry breaking. The CP-odd scalar is a potential dark matter candidate. We will demonstrate that including the complex singlet scalar not only helps to lift the radiative mass of the Higgs boson to coincide with the current LHC Higgs data [1,2], but also nicely generate the Majorana mass term for right-handed neutrinos from scale-invariant Yukawa interaction. We systematically analyze experimental and theoretical constraints on the parameter space of our model. These include experimental bounds from the direct LHC Higgs measurements and the indirect electroweak precision tests, as well as the theoretical constraints from unitarity, triviality and vacuum stability. Finally, we note that our approach also differs from the previous studies [14–16] (à la Coleman–Weinberg) invoking extra scalars or certain hidden gauge groups. Those extended gauge groups include the $U(1)_X$ (sometimes $U(1)_{B-L}$), or the left-right gauge group, or the vector dark $SU(2)_D$, or certain strongly interacting hidden sector. An extensive analysis of a complex singlet scalar with the global $U(1)$ (or $Z_4$) symmetry and maximal CP-violation was given in [15], which differs from our CP-symmetric and scale-invariant Higgs sector (without extra global or local symmetry). Our model also differs from [16] which considered two real scalar singlets with an extra $Z_2$ to ensure stability of the $Z_2$-odd singlet as DM. In contrast, our model builds the imaginary component of the complex singlet as DM and its stability is automatically protected by CP invariance; we further include right-handed neutrinos for light neutrino mass-generations via TeV scale seesaw.

This Letter is organized as follows. Section 2 sets up the model construction for our classically scale-invariant Higgs potential. Then, we present the full one-loop corrections, identify the physical states, and derive their mass spectrum and couplings. In Section 3 we study both experimental and theoretical constraints on the parameter space of the model. Section 3.5 presents our results and discusses the physical implications. Finally, we conclude in Section 4.

## 2. Model structure and radiative electroweak symmetry breaking

In this section, we construct the minimal viable extension of the SM with classical scale-invariance. It only contains an extra gauge-singlet complex scalar $S$ in addition to the conventional Higgs doublet $H$. Our extended Higgs sector is CP invariant (similar to the SM) and respects the classical scale symmetry. This will naturally induce radiative EWSB and predict two new scalar states in addition to the observed 125 GeV light Higgs boson. This minimal construction maximally preserves all the original SM symmetries, and further incorporates three right-handed neutrinos for mass-generation of light neutrinos via TeV scale seesaw.

### 2.1. The model structure

In our construction, the extended Higgs sector consists of the SM Higgs doublet $H$ and a complex singlet scalar $S$, so its Lagrangian is,

$$\mathcal{L}_S = \left(D^\mu H\right)^\dagger D_\mu H + \partial^\mu S^* \partial_\mu S - V^{(0)}(H,S), \tag{2.1}$$

where the Higgs doublet $H$ is expressed in component form,

$$H = \begin{pmatrix} \pi^+ \\ \frac{1}{\sqrt{2}}(v_\phi + \phi^0 + \mathrm{i}\pi^0) \end{pmatrix}, \tag{2.2}$$

and $D^\mu$ is the covariant derivative under SM gauge group. In (2.2), $\phi$ is the SM-like Higgs field, with the vacuum expectation value (VEV), $v_\phi \simeq 246$ GeV, to be determined from radiative EWSB. The gauge-singlet scalar field $S$ has the following component form,

$$S = \frac{1}{\sqrt{2}}\left(v_\eta + \eta^0 + \mathrm{i}\chi^0\right), \tag{2.3}$$

where $\eta$ has $J^P = 0^+$. Thus, under either C or CP operation it transforms as, $S \to S^*$. This means that $\eta$ and $\chi$ belong to the CP-even and CP-odd fields, respectively.

Then, we can write down the most general scale-invariant and CP-symmetric Higgs potential with the Higgs doublet $H$ and complex singlet $S$,

$$\begin{aligned} V^{(0)}(H,S) = {} & \frac{\lambda_1}{6}\left(H^\dagger H\right)^2 + \frac{\lambda_2}{6}|S|^4 + \lambda_3\left(H^\dagger H\right)|S|^2 \\ & + \frac{\lambda_4}{2}\left(H^\dagger H\right)\left(S^2 + S^{*2}\right) + \frac{\lambda_5}{12}\left(S^2 + S^{*2}\right)|S|^2 \\ & + \frac{\lambda_6}{12}\left(S^4 + S^{*4}\right), \end{aligned} \tag{2.4}$$

which contains six dimensionless real coupling constants $\{\lambda_j\}$. Here the cubic couplings and mass terms are forbidden by the scale-invariance. In the above potential, the general mixing between Higgs doublet and singlet is represented by the third and fourth terms via the quartic couplings $\lambda_3$ and $\lambda_4$. For practical

[3] Our present model will extend the scale-invariant SM Lagrangian with a complex Higgs singlet and three right handed neutrinos at TeV scale. Hence, it is a technically natural *effective field theory* (EFT), all the way up to its UV cutoff (above which a more complete theory arises and is assumed to properly retain classical scale symmetry). We do not concern detailed Planck-scale dynamics [12], given the lack of a full theory of quantum gravity. This EFT is also free from little hierarchy problem because it invokes no extra heavy state at intermediate scales. We thank Nima Arkani-Hamed for discussing this point.