Physics Letters B 732 (2014) 320–324

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Effects of a real singlet scalar on Veltman condition

Canan Nurhan Karahan, Beste Korutlu *

Department of Physics, İzmir Institute of Technology, IZTECH, TR35430, İzmir, Turkey

ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 28 March 2014
Accepted 31 March 2014
Available online 8 April 2014
Editor: M. Cvetič

Keywords:
Veltman condition
Real singlet scalar
Vector-like fermions
Naturalness

ABSTRACT

We revisit the fine-tuning problem in the Standard Model (SM) and show the modification in the Veltman condition by virtue of a minimally-extended particle spectrum with one real SM gauge singlet scalar field. We demand the new scalar to interact with the SM fields through Higgs portal only, and the new singlet to acquire a vacuum expectation value, resulting in a mixing with the CP-even neutral component of the Higgs doublet in the SM. The experimental bounds on the mixing angle are determined by the observed best-fit signal strength σ/σ_{SM}. While, the one-loop radiative corrections to the Higgs mass squared, computed with an ultraviolet cut-off scale Λ, come with a negative coefficient, the quantum corrections to the singlet mass squared acquire both positive and negative values depending on the parameter space chosen, which if positive might be eliminated by introducing singlet or doublet vector-like fermions. However, based upon the fact that there is mixing between the scalars, when transformed into the physical states, the tree-level coupling of the Higgs field to the vector-like fermions worsens the Higgs mass hierarchy problem. Therefore, the common attempt to introduce vector-like fermions to cancel the divergences in the new scalar mass might not be a solution, if there is mixing between the scalars.

1. Introduction

The discovery of the fundamental particle of mass $m_h = 125.9 \pm 0.4$ GeV at the Large Hadron Collider (LHC) [1,2], highly likely to be the Higgs boson of the Standard Model (SM), settles the experimental validation for the long sought missing piece of the SM. The absence of any new physics signals by the first 20 fb^{-1} of data from LHC operating at 8 TeV, on the other hand, casts doubts on the relevance of our notion of the naturalness problem. At this very moment of the shutdown of LHC, after a glimpse of what may be the Higgs boson, understanding the hierarchy problem seems crucial. In an effective field theory approach with an ultraviolet cut-off Λ, the Higgs self-energy receives quadratically divergent corrections from loop diagrams such that

$$m_h^2 = \left(m_h^2\right)_{\text{bare}} + \mathcal{O}\left(\lambda_H, g_i^2\right)\Lambda^2, \tag{1}$$

where $m_h = \sqrt{2\lambda_H}\upsilon_H$ is the physical Higgs mass, λ_H is the Higgs self-coupling, and g_i are the renormalized couplings of the SM. Hence, the natural scale for the Higgs mass is $\mathcal{O}(\Lambda)$, and it is unnatural for it to be less than the ultraviolet cut-off of the theory, which could be as high as the Planck Scale ($M_{\text{Pl}} \sim 10^{19}$ GeV).

Originally studied by Veltman [3], the SM one-loop condition of the quadratic divergences reads

$$\delta m_h^2 = \frac{\Lambda^2}{16\pi^2}\left(6\lambda_H + \frac{9}{4}g^2 + \frac{3}{4}g'^2 - 6g_t^2\right), \tag{2}$$

where g and g' are the $SU(2)_L$ and $U(1)_Y$ gauge couplings of the SM, respectively, and $g_t = \sqrt{2}m_t/\upsilon_H$ ($\upsilon_H = 246$ GeV is the vacuum expectation value (VEV) of the Higgs field) is the top quark Yukawa coupling. Since the contributions to the Veltman condition (VC) by other fermions are considerably small compared to the one by top quark, they are not taken into account. The VC demands that the quadratically divergent terms above add up either to zero, or to a very small value by virtue of some symmetry of the model. Now that we know all the masses, based on the requirement that $|\delta m_h^2|/m_h^2 \leqslant 1$, the VC is in conflict with the experimental data for $\Lambda > 780$ GeV. There have been various attempts to protect Higgs mass from destabilizing by introducing a new set of particles and interactions. Chief among them is Supersymmetry, which solves the gauge hierarchy problem introducing supersymmetric partners of the SM particles with masses around TeV (see [4] for a review on supersymmetry and [5] as a recent work on the VC in a High-Scale Supersymmetric model). So far, however, no compelling sign of experimental evidence for supersymmetry has been found in the searches at the Large Hadron Collider (LHC) [6]. Other possible solutions are Little Higgs Models [7], Large and/or Warped Extra

* Corresponding author.
E-mail addresses: cananduzturk@iyte.edu.tr (C.N. Karahan), bestekorutlu@iyte.edu.tr (B. Korutlu).

http://dx.doi.org/10.1016/j.physletb.2014.03.063

Dimensions [8]. There exists also a very different perspective, motivated by anthropic considerations [9], arguing that the notion of the naturalness of the weak scale should be abandoned.

In the present work, we show the effect of extending the scalar sector of the SM minimally, by introducing a real gauge singlet scalar field that only couples with the Higgs doublet, on the VC. The phenomenology of singlet scalars has been extensively studied by [10] as a hidden sector, by [11,12] as a dark matter candidate, and their effect on the stability condition has been previously discussed in [13,14]. We discuss also the radiative corrections for real singlet scalar, and as opposed to what has been found in the literature, we show that even a small mixing angle might yield interesting results, and that introducing singlet or doublet vector fermions might not be a valid scenario for both scalars in the model (Higgs boson and singlet scalar) in the presence of mixing between the two.

2. The model

We consider the simplest extension of the SM by introducing a real singlet scalar field S. We impose an additional $\mathbb{Z}_2$ symmetry under which S is odd. The most general, renormalizable, symmetric Lagrangian density reads,

$$\mathcal{L}_{HS} = (D_\mu H)^\dagger D^\mu H + \frac{1}{2}\partial_\mu S \partial^\mu S - V_{HS}, \tag{3}$$

where

$$V_{HS} = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda}{2} H^\dagger H S^2, \tag{4}$$

is the potential, and H is the SM Higgs doublet. The potential is bounded from below for $\lambda_H > 0$ and $\lambda_S > 0$, and the minimum of the potential breaks the electroweak symmetry spontaneously via non-zero vacuum expectation value (VEV) of the Higgs doublet, $\langle H \rangle = \upsilon_H/\sqrt{2}$, generating masses for the SM particles. Depending on whether the real singlet scalar develops a VEV or not, the VC takes different forms. In the subsequent analysis, we focus on the former. However, in explaining the details of our model, we will follow a pedagogical strategy, and include also the details of the model where S is not developing a VEV.

2.1. Singlet VEV vanishes

If the real singlet scalar does not acquire a VEV, minimum of the potential occurs at

$$\upsilon_H^2 = -\frac{\mu_H^2}{\lambda_H}, \qquad \upsilon_S^2 = 0. \tag{5}$$

Using the parametrization of the Higgs field above the vacuum as

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} H_3 + iH_4 \\ \upsilon_H + H_1 + iH_2 \end{pmatrix}, \tag{6}$$

the mass squared values of $H_1 \equiv h$ (the CP-even neutral component of the Higgs doublet) and the S fields (for later convenience, we use σ for the corresponding physical real singlet scalar) are obtained as

$$m_h^2 = 2\lambda_H \upsilon_H^2, \qquad m_\sigma^2 = \mu_S^2 + \frac{\lambda}{2}\upsilon_H^2. \tag{7}$$

In this scenario, with $\upsilon_S = 0$, there is no mixing between the Higgs and the new scalar field. Therefore, they appear naturally in their mass eigenstates. Moreover, as it can be seen in Eq. (4), despite there is no mixing, the quartic interaction term $\frac{\lambda}{4}\sigma^2 h^2$ between the σ and h fields still exists as long as $\lambda \neq 0$.

2.2. Singlet VEV does not vanish

If the real singlet scalar acquires a non-zero VEV, the minimum of the potential occurs at

$$\upsilon_H^2 = \frac{4\lambda_S \mu_H^2 - 2\lambda \mu_S^2}{\lambda^2 - 4\lambda_H \lambda_S}, \qquad \upsilon_S^2 = \frac{4\lambda_H \mu_S^2 - 2\lambda \mu_H^2}{\lambda^2 - 4\lambda_H \lambda_S}. \tag{8}$$

Using the parametrization of the Higgs field above the vacuum as in Eq. (6), and for the real singlet scalar as $S = \upsilon_S + S$ we obtain the mass squared mixing matrix for the fields H_1 and S

$$M_{H_1,S}^2 = \begin{pmatrix} 2\lambda_H \upsilon_H^2 & \frac{\lambda}{2}\upsilon_H \upsilon_S \\ \frac{\lambda}{2}\upsilon_H \upsilon_S & 2\lambda_S \upsilon_S^2 \end{pmatrix}. \tag{9}$$

After diagonalization, the mass matrix yields the masses of the physical scalar h (Higgs field) and σ fields as follows:

$$m_h^2 = \upsilon_H^2 \left(\lambda_H + \lambda_S \upsilon_{SH}^2 + \sqrt{\left(\lambda_H - \lambda_S \upsilon_{SH}^2\right)^2 + \frac{\lambda^2}{4}\upsilon_{SH}^2} \right),$$

$$m_\sigma^2 = \upsilon_H^2 \left(\lambda_H + \lambda_S \upsilon_{SH}^2 - \sqrt{\left(\lambda_H - \lambda_S \upsilon_{SH}^2\right)^2 + \frac{\lambda^2}{4}\upsilon_{SH}^2} \right), \tag{10}$$

where $\upsilon_{SH} = \frac{\upsilon_S}{\upsilon_H}$. The mixing angle in terms of model parameters reads

$$\tan 2\theta = \frac{\lambda \upsilon_{SH}}{\lambda_S \upsilon_{SH}^2 - \lambda_H}. \tag{11}$$

As expected, the mixing angle θ is proportional to λ.

Below, we study in detail the latter case to analyze the contributions to the VC coming from the singlet sector.

3. Phenomenology

The presence of one real singlet scalar field S, with VEV υ_S, modifies the VC for the Higgs mass, not only due to its direct coupling to the SM Higgs doublet, but also its mixing with the neutral, CP-even component of the doublet, which allows tree-level interactions of the new scalar with the SM fields. We carry our calculations up to one-loop order.

The VC is modified with the addition of one real singlet scalar field as follows (see Appendix A for the vertex factors):

$$\begin{aligned} \delta m_h^2 = \frac{\Lambda^2}{16\pi^2} \Bigg[& \cos^4\theta \left(\frac{\lambda}{2} + 3\lambda_H \right) + \sin^4\theta \left(\frac{\lambda}{2} + 3\lambda_S \right) \\ & + \sin^2 2\theta \left(\frac{3\lambda_H}{4} + \frac{3\lambda_S}{4} + \frac{\lambda}{4} \right) + \sin^2\theta \left(\frac{3\lambda}{2} \right) \\ & + \cos^2\theta \left(3\lambda_H + \frac{9}{4}g^2 + \frac{3}{4}g'^2 - 6g_t^2 \right) \Bigg]. \end{aligned} \tag{12}$$

In the limit of no mixing (i.e., $\cos\theta \to 1$, $\sin\theta \to 0$) the modified VC reduces to the original one given in Eq. (2), except the term $\frac{\Lambda^2}{16\pi^2}\frac{\lambda}{2}$, which appears regardless of the mixing, and disappears if and only if $\lambda = 0$. The reason is that vanishing of mass mixing ($\theta \to 0$) does not guarantee vanishing of the quartic mixing ($\frac{\lambda}{2} H^\dagger H S^2$). The latter gives contribution to the VC even when $\theta \to 0$.

The mass of the physical field σ is also shifted via the quadratically divergent quantum corrections.

$$\begin{aligned} \delta m_\sigma^2 = \frac{\Lambda^2}{16\pi^2} \Bigg[& \cos^4\theta \left(\frac{\lambda}{2} + 3\lambda_S \right) + \sin^4\theta \left(\frac{\lambda}{2} + 3\lambda_H \right) \\ & + \sin^2 2\theta \left(\frac{3\lambda_H}{4} + \frac{3\lambda_S}{4} + \frac{\lambda}{4} \right) + \cos^2\theta \left(\frac{3}{2}\lambda \right) \\ & + \sin^2\theta \left(3\lambda_H + \frac{9}{4}g^2 + \frac{3}{4}g'^2 - 6g_t^2 \right) \Bigg]. \end{aligned} \tag{13}$$