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Vacuum stability with spontaneous violation of lepton number

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ABSTRACT

The vacuum of the Standard Model is known to be unstable for the measured values of the top and Higgs masses. Here we show how vacuum stability can be achieved naturally if lepton number is violated spontaneously at the TeV scale. More precise Higgs measurements in the next LHC run should provide a crucial test of our symmetry breaking scenario. In addition, these schemes typically lead to enhanced rates for processes involving lepton flavor violation.

1. Introduction

The vacuum of the Standard Model (SM) scalar potential is unstable since at high energies the Higgs effective quartic coupling is driven to negative values by the renormalization group flow [1,2]. Nevertheless, the SM cannot be a complete theory of Nature for various reasons, one of which is that neutrinos need to be massive in order to account for neutrino oscillation results [3].[1]

With only the SM fields, neutrino masses can arise in a model-independent way from a dimension 5 effective operator $\kappa LLHH$ which gives rise to a $\kappa \langle H \rangle^2$ neutrino mass after electroweak symmetry breaking [5]. This same operator unavoidably provides a correction to the Higgs self-coupling λ below the scale of the mechanism of neutrino mass generation through the diagram in Fig. 1. Although tiny[2] and negative, it suggests that the mechanism responsible for generating neutrino masses and lepton number violation is potentially relevant for the Higgs stability problem. The quantitative effect of neutrino masses on the stability of the scalar potential will, however, be dependent on the ultra-violet completion of the model.

After the historic Higgs boson discovery at CERN and the confirmation of the Brout–Englert–Higgs mechanism, it is natural to imagine that all symmetries in Nature are broken spontaneously by the vacuum expectation values of scalar fields. The charge neutrality of neutrinos suggests them to be Majorana fermions [6], and that the smallness of their mass is due to the feeble breaking of lepton number symmetry. Hence we need generalized electroweak breaking sectors leading to the double breaking of electroweak and lepton number symmetries.

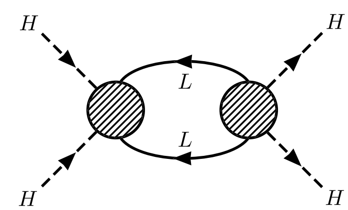

Fig. 1. Contribution of Weinberg's effective operator to the Higgs quartic interaction.

In this letter we examine the vacuum stability issue within the simplest of such extended scenarios,[3] showing how one can naturally obtain a fully consistent behavior of the scalar potential at all scales for lepton number broken spontaneously at the TeV scale. Note that within the simplest $\mathrm{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}$ gauge structure lepton number is a global symmetry whose spontaneous breaking implies the existence of a physical Goldstone boson, generically called majoron and denoted J, which must be a gauge singlet [8,9] in order to comply with LEP restrictions [10]. Its existence brings in new invisible Higgs boson decays [11]

$$H \to J\,J,$$

leading to potentially sizable rates for missing momentum signals at accelerators [12–14] including the current LHC [15]. Given the agreement of the ATLAS and CMS results with the SM scenario,

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[1] Planck scale physics could also play a role [4].

[2] The contribution to λ is suppressed by a factor $(m_\nu / \langle H \rangle)^2 / (4\pi)^2$.

[3] Extended Higgs scenarios without connection to neutrino mass generation schemes have been extensively discussed, see for example, Ref. [7] and references therein.

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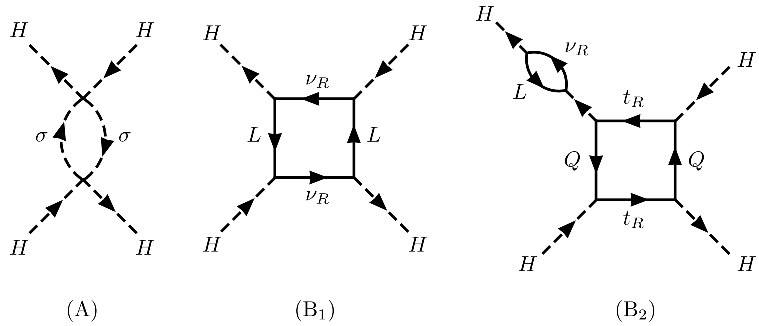

Fig. 2. In models with a complex singlet scalar σ, such as majoron type-I seesaw schemes, the positive contribution to the RGE of the Higgs quartic coupling (diagram A) is accompanied by the destabilizing effect of right-handed neutrinos through the 1-loop diagram B_1 and also through the two-loop diagram B_2.

one can place limits on the presence of such invisible Higgs decay channels. Current LHC data on Higgs boson physics still leaves room to be explored at the next run.

Absolute stability of the scalar potential is attainable as a result of the presence of the Majoron, which is part of a complex scalar singlet. Indeed, it is well known that generically the quartic coupling which controls the mixing between a scalar singlet and the Higgs doublet contributes positively to the value of the Higgs quartic coupling (which we shall call λ_2) at high energies [16–24] – see diagram A in Fig. 2. On the other hand, new fermions coupling to the Higgs field H, such as right-handed neutrinos [16,18,25], tend to destabilize λ_2 not only through the 1-loop effect depicted in diagram B_1 of Fig. 2, but also in what is effectively a two-loop effect (diagram B_2): through their Yukawa interaction with H, the new fermions soften the fall of the top Yukawa coupling at higher energies, which in turn contributes negatively to λ_2.[4] The model we consider below is a low-scale version of the standard type I majoron seesaw mechanism, such as the inverse seesaw type [26,27]. We stress however that, even though our renormalization group equations (RGEs) are the same as those characterizing standard case, the values of the Dirac-type neutrino Yukawa couplings are typically much higher in our inverse seesaw scenario.

2. Electroweak breaking with spontaneous lepton number violation

The simplest scalar sector capable of driving the double breaking of electroweak and lepton number symmetry consists of the SM doublet H plus a complex singlet σ, leading to the following Higgs potential [11]

$$V(\sigma, H) = \mu_1^2 |\sigma|^2 + \mu_2^2 H^\dagger H + \lambda_1 |\sigma|^4 + \lambda_2 \left(H^\dagger H\right)^2 + \lambda_{12} \left(H^\dagger H\right) |\sigma|^2 \, . \tag{1}$$

In addition to the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge invariance, $V(\sigma, H)$ has a global U(1) symmetry which will be associated to lepton number within specific model realizations. The potential is bounded from below provided that λ_1, λ_2 and $\lambda_{12} + 2\sqrt{\lambda_1\lambda_2}$ are positive; these are less constraining conditions than those required for the existence of a consistent electroweak and lepton number breaking vacuum where both H and σ acquire non-zero vacuum expectation values ($\equiv \frac{v_H}{\sqrt{2}}$ and $\frac{v_\sigma}{\sqrt{2}}$). For that to happen, λ_1, λ_2 and $4\lambda_1\lambda_2 - \lambda_{12}^2$ need to be all positive.[5] Three of the degrees of freedom in H are absorbed by the massive electroweak gauge bosons, as usual. On the other hand, the imaginary part of σ becomes the Nambu–Goldstone boson associated to the breaking of the global lepton number symmetry, therefore it remains massless. As for the real oscillating parts of H^0 and σ, these lead to two CP-even mass eigenstates H_1 and H_2, with a mixing angle α which can be constrained from LHC data [15,28–30]. We take the lighter state H_2 to be the 125 GeV Higgs particle recently discovered by the CMS and ATLAS Collaborations.

Using the renormalization group equations (given in the appendix) we evolved the three quartic couplings of the model imposing the vacuum stability conditions mentioned previously. Given that such equations rely on perturbation theory, the calculations were taken to be trustable only in those cases where the running couplings do not exceed $\sqrt{4\pi}$.[6]

3. Neutrino mass generation

In order to assign to the U(1) symmetry present in Eq. (1) the role of lepton number we must couple the new scalar singlet to leptonic fields. This can be done in a variety of ways. Here we focus on low-scale generation of neutrino mass [32]. For definitiveness we choose to generate neutrino masses through the inverse seesaw mechanism [33] with spontaneous lepton number violation [27].

The fermion content of the Standard Model is augmented by right-handed neutrinos ν_R (with lepton number $+1$) and left-handed gauge singlets S (also with lepton number $+1$) such that the mass term $\nu_R^c S$ as well as the interactions $SS\sigma$ and $H\nu_R^c L$ are allowed if σ carries -2 units of lepton number[7]:

$$-\mathscr{L}_\nu = Y_\nu H \nu_R^c L + M \nu_R^c S + Y_S SS\sigma + \text{h.c.} \tag{2}$$

The effective neutrino mass, in the one family approximation, is given by the expression

$$m_\nu = Y_S \langle\sigma\rangle \left(\frac{Y_\nu \langle H^0\rangle}{M}\right)^2 , \tag{3}$$

[4] Even though it does not happen in our case, one should keep in mind that fermions alone could in principle stabilize the Higgs potential by increasing the value of the gauge couplings at higher energies, which in turn have a positive effect on the Higgs quartic coupling.

[5] However, this last condition need not hold for arbitrarily large energy scales. Indeed, it is enough to consider $4\lambda_1\lambda_2 - \lambda_{12}^2 > 0$ for energies up to $\Lambda \approx \text{Max}\left(\sqrt{2\frac{|\mu_1^2|}{\lambda_{12}}}, \sqrt{\frac{|\mu_2^2|}{\lambda_2}}\right)$ – see [18,23] for details.

[6] Since all the new particles present in the low-scale seesaw model under consideration have yet to be observed, leading order calculations suffice. For our plots we have used the values $\alpha_S \approx 0.1185$ and $y_t \approx 0.96$ at the m_Z scale – more precise values with higher order corrections can be found in [31]. Small changes to these input values (for example a change of 0.03 in the top Yukawa y_t) do not affect substantially our plots.

[7] We ignore for simplicity the extra term $\nu_R^c \nu_R^c \sigma^*$ which is, in principle, also allowed.