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125 GeV Higgs, type III seesaw and gauge–Higgs unification

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ABSTRACT

Recently, both the ATLAS and CMS experiments have observed an excess of events that could be the first evidence for a 125 GeV Higgs boson. This is a few GeV below the (absolute) vacuum stability bound on the Higgs mass in the Standard Model (SM), assuming a Planck mass ultraviolet (UV) cutoff. In this Letter, we study some implications of a 125 GeV Higgs boson for new physics in terms of the vacuum stability bound. We first consider the seesaw extension of the SM and find that in type III seesaw, the vacuum stability bound on the Higgs mass can be as low as 125 GeV for the seesaw scale around a TeV. Next we discuss some alternative new physics models which provide an effective ultraviolet cutoff lower than the Planck mass. An effective cutoff $\Lambda \simeq 10^{11}$ GeV leads to a vacuum stability bound on the Higgs mass of 125 GeV. In a gauge–Higgs unification scenario with five-dimensional flat spacetime, the so-called gauge–Higgs condition can yield a Higgs mass of 125 GeV, with the compactification scale of the extra-dimension being identified as the cutoff scale $\Lambda \simeq 10^{11}$ GeV. Identifying the compactification scale with the unification scale of the SM SU(2) gauge coupling and the top quark Yukawa coupling yields a Higgs mass of 121 ± 2 GeV.

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1. Introduction

The discovery of the Higgs boson is a major goal of the physics program at the Large Hadron Collider (LHC), in order to confirm the origin of the electroweak symmetry breaking and the mechanism of particle mass generation. The ATLAS [1] and CMS [2] experiments have reported an excess of events that could be the first evidence of the Higgs boson with a mass of around 125 GeV [3]. Recent analysis by the Tevatron experiments [3] supports the above observations.

A value of 125 GeV is quite interesting from the viewpoint of the vacuum stability bound on the Higgs boson mass [4]. In the SM, the Higgs boson mass is determined by the self-coupling of the Higgs doublet, so that we can analyze the high energy behavior of the self-coupling by using the renormalization group equations (RGEs). For a relatively light Higgs boson, the self-coupling becomes negative in its RGE running at some high energy, which implies an instability of the effective Higgs potential. If we require that the running self-coupling remains positive below a given cutoff scale, we obtain a lower bound on the Higgs boson mass, known as the (absolute) vacuum stability bound [5].

It would seem natural to adopt the reduced Planck mass as the cutoff scale, in which case the vacuum stability bound is found to be close to 129 GeV for a top quark mass of 173.2 GeV [6]. Taking into account the uncertainty on the top quark mass ($M_t = 173.2 \pm 0.9$ GeV),

$$m_H \geq 128.9 \text{ GeV} + 1.9 \text{ GeV} \left(\frac{M_t - 173.2 \text{ GeV}}{0.9 \text{ GeV}} \right). \quad (1)$$

If the observed excess of events around 125 GeV actually is evidence for the Higgs boson, we may entertain two possibilities for lowering the vacuum stability bound of 129 GeV. One possibility is that the RGE running of the quartic self-coupling is altered from the one in the SM, keeping the reduced Planck mass cutoff. This means that new particles are involved in the RGEs at energies below the reduced Planck mass. Another possibility is that the effective cutoff scale lies suitably below the reduced Planck scale, while all the RGEs of the SM remain unaltered. In general, one also could consider a combination of these two possibilities. In any case, new physics beyond the SM should play a crucial role to reconcile the discrepancy between 125 GeV and 129 GeV.

In this Letter, we study the implications of a 125 GeV Higgs boson for new physics from the viewpoint of the vacuum stability bound. We first consider a seesaw extension of the SM where the RGE running of the self-coupling is altered by the presence of new particles. We will see that the type of seesaw as well as the seesaw scale are restricted in order to realize a Higgs mass of 125 GeV,

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with the reduced Planck scale cutoff. For a different possibility, we will consider physics models which can provide an effective cutoff scale lower than the reduced Planck mass. As a very interesting example, we investigate gauge–Higgs unification in flat five-dimensional (5D) spacetime. In this model, the effective cutoff scale is identified as the compactification scale of the fifth dimension and a Higgs mass of 125 GeV determines the compactification scale. We find a Higgs mass prediction close to 125 GeV if the compactification scale is identified with the unification scale of the top quark Yukawa and SU(2) gauge couplings.

2. Seesaw extended Standard Model

The seesaw mechanism is a simple and promising extension of the SM to incorporate the neutrino masses and flavor mixings observed in solar and atmospheric neutrino oscillations. There are three main seesaw extensions of the SM, type I [7], type II [8], and type III [9], in which singlet right-handed neutrinos, SU(2) triplet scalar, and SU(2) triplet right-handed neutrinos, respectively, are introduced. These new particles contribute to the RGEs at energies higher than the seesaw scale and as a result, the vacuum stability bound can be significantly altered. Some time ago, the important implications of the various seesaw models (type I [10,11], type II [12] and type III [11]) on the Higgs boson mass have been investigated with the Planck mass cutoff. In these papers, in addition to the vacuum stability bound, the perturbativity bound, given by the condition that the Higgs self-coupling remains perturbative below the Planck scale, has also been investigated. For both types I and III, it has been shown that the window for the Higgs boson mass between the vacuum stability and the perturbativity bounds becomes narrower and is eventually closed by the dramatic rise of the vacuum stability bound, as the neutrino Dirac Yukawa coupling becomes larger.

For lower values of the seesaw scale, the neutrino Dirac Yukawa coupling is small, and there is little effect from this coupling.¹ However, there is a remarkable difference between type I and type III because the right-handed neutrinos in type III are SU(2) triplets. As shown in [11], the vacuum stability bound becomes lower for decreasing seesaw scale. This is because the SU(2) triplet neutrinos change the RGE running of the SU(2) gauge coupling. In type II seesaw, the perturbativity bound receives a drastic reduction due to interactions between the Higgs doublet and the SU(2) triplet scalar. As a result, the window for the Higgs boson mass between the vacuum stability and the perturbativity bounds becomes narrower and is eventually closed by the dramatic fall of the perturbativity bound for larger values of the scalar couplings. The vacuum stability bound also receives a dramatic reduction when the seesaw scale is low. It has been shown in [12] that in type II seesaw, the Higgs stability bound becomes even lower than the LEP2 Higgs mass bound of 114.4 GeV [14] for a seesaw scale of around 1 TeV.

In the light of the recent LHC results suggesting a Higgs mass close to 125 GeV, types II and III seesaw models are interesting because in both cases, the vacuum stability bound can be lower than the SM prediction of 129 GeV. Since type II seesaw involves many free parameters, there is a wide range of parameter regions which yield a vacuum stability bound of 125 GeV. For this reason, in this Letter we consider type III seesaw in detail. In low scale type III seesaw compatible with a Higgs mass of 125 GeV, the neutrino Dirac Yukawa coupling is too small to play a role in the RGE run-

ning of the Higgs self-coupling. Therefore, the only free parameters involved in our analysis are the masses of the SU(2) triplet right-handed neutrinos. We analyze three cases with 1, 2 and 3 generations of the triplet neutrinos. Although at least 2 right-handed neutrinos are necessary to reproduce the neutrino oscillation data, we also analyze the 1 generation case for completeness.² For simplicity, we consider a degenerate mass spectrum for the triplet neutrinos. This assumption is reasonable if we consider thermal leptogenesis [15], where the CP-violating out-of-equilibrium decay of the right-handed neutrinos generates the lepton asymmetry in the universe. It is known that in order to generate a sufficient amount of baryon asymmetry, the seesaw scale should be higher than 10^{10} GeV [16], otherwise a certain enhancement mechanism of the CP-asymmetry parameter is necessary. As we will see in the following, the seesaw scale turns out to be much lower than the above bound and hence, the so-called resonant leptogenesis [17] is relevant to our case, where the CP-asymmetry parameter is enhanced by right-handed neutrinos that are almost degenerate in mass.

Let us now analyze the vacuum stability bound in type III seesaw extended SM. Although our analysis is basically the same as in [11], we consider three different generations for the triplet neutrinos. In addition, we have taken into account the two-loop RGE improved one-loop effective Higgs potential and the updated top quark pole mass. These improvements and update alter the resultant Higgs mass by about 4 GeV from the one obtained in [11], which is quite important when we discuss the discrepancy between the observed 125 GeV Higgs boson mass and the vacuum stability bound of 129 GeV. We introduce N generations of mass degenerate right-handed neutrinos which transform as $(\mathbf{3}, 0)$ under the electroweak gauge group SU(2) \times U(1)_Y:

$$\psi_i = \sum_a \frac{\sigma^a}{2} \psi_i^a = \frac{1}{2} \begin{pmatrix} \psi_i^0 & \sqrt{2}\psi_i^+ \\ \sqrt{2}\psi_i^- & -\psi_i^0 \end{pmatrix}. \quad (2)$$

The terms in the Lagrangian relevant for the seesaw mechanism are given by

$$\mathcal{L} \supset -y_{ij} \bar{\ell}_i \psi_j \Phi - M_R \text{tr}[\bar{\psi}_i^c \psi_i], \quad (3)$$

where ℓ_i is the i -th generation SM lepton doublet ($i = 1, 2, 3$), Φ is the SM Higgs doublet with a U(1)_Y charge $-1/2$, and M_R is the common mass for the triplet neutrinos. The light neutrino mass matrix obtained via type III seesaw mechanism is given by

$$\mathbf{M}_\nu = \frac{v^2}{8M_R} \mathbf{Y} \mathbf{Y}^T, \quad (4)$$

where $v = 246$ GeV is the vacuum expectation value of the Higgs doublet, and $\mathbf{Y} = y_{ij}$ is a $3 \times N$ Yukawa matrix. It is natural to expect the light neutrino mass scale to be $\mathcal{O}(\sqrt{\Delta m_{23}}) \sim 0.05$ eV, where $\Delta m_{23} = 2.43 \times 10^{-3}$ eV² [18] is given by the atmospheric neutrino oscillation data. Using the seesaw formula, we find $y_{ij} \ll 1$ for $M_R \ll 10^{15}$ GeV. This is the case we analyze here, and so the neutrino Dirac Yukawa coupling has essentially no effect on our results. In the following analysis, we employ RGEs at two-loop level.

For a renormalization scale $\mu < M_R$, the heavy neutrinos are decoupled, and there is no effect on the RGEs for the SM couplings. For the three SM gauge couplings g_i ($i = 1, 2, 3$), we have

¹ In a general parameterization, the neutrino Dirac Yukawa coupling can be large and affect the Higgs mass bounds [13], although fine-tuning of parameters is required to realize the neutrino oscillation data.

² One may consider a combination of type I and type III to reproduce the neutrino oscillation data. Since a light singlet neutrino has no effect on RGEs, our result with one triplet neutrino corresponds to this case.

$$\frac{dg_i}{d \ln \mu} = \frac{b_i}{16\pi^2} g_i^3 + \frac{g_i^3}{(16\pi^2)^2} \left(\sum_{j=1}^3 B_{ij} g_j^2 - C_i y_t^2 \right), \quad (5)$$

where

$$b_i = \left(\frac{41}{10}, -\frac{19}{6}, -7 \right), \quad B_{ij} = \begin{pmatrix} \frac{199}{50} & \frac{27}{10} & \frac{44}{5} \\ \frac{9}{10} & \frac{35}{6} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{pmatrix}, \quad (6)$$

$$C_i = \left(\frac{17}{10}, \frac{3}{2}, 2 \right),$$

and we have included the contribution from the top Yukawa coupling (y_t). We use the top quark pole mass $M_t = 173.2$ GeV [6] and the strong coupling constant at the Z-pole (M_Z) $\alpha_s = 0.1193$ [19]. For the top Yukawa coupling, we have

$$\frac{dy_t}{d \ln \mu} = y_t \left(\frac{1}{16\pi^2} \beta_t^{(1)} + \frac{1}{(16\pi^2)^2} \beta_t^{(2)} \right). \quad (7)$$

Here the one-loop contribution is

$$\beta_t^{(1)} = \frac{9}{2} y_t^2 - \left(\frac{17}{20} g_1^2 + \frac{9}{4} g_2^2 + 8g_3^2 \right), \quad (8)$$

while the two-loop contribution is given by [20]

$$\begin{aligned} \beta_t^{(2)} = & -12y_t^4 + \left(\frac{393}{80} g_1^2 + \frac{225}{16} g_2^2 + 36g_3^2 \right) y_t^2 \\ & + \frac{1187}{600} g_1^4 - \frac{9}{20} g_1^2 g_2^2 + \frac{19}{15} g_1^2 g_3^2 - \frac{23}{4} g_2^4 \\ & + 9g_2^2 g_3^2 - 108g_3^4 + \frac{3}{2} \lambda^2 - 6\lambda y_t^2. \end{aligned} \quad (9)$$

In solving the RGE for the top Yukawa coupling, its value at $\mu = M_t$ is determined from the relation between the pole mass and the running Yukawa coupling [21,22],

$$M_t \simeq m_t(M_t) \left(1 + \frac{4}{3} \frac{\alpha_3(M_t)}{\pi} + 11 \left(\frac{\alpha_3(M_t)}{\pi} \right)^2 - \left(\frac{m_t(M_t)}{2\pi v} \right)^2 \right), \quad (10)$$

with $y_t(M_t) = \sqrt{2} m_t(M_t) / v$. Here, the second and third terms in parentheses correspond to one- and two-loop QCD corrections, respectively, while the fourth term comes from the electroweak corrections at one-loop level.

The RGE for the Higgs self-coupling is given by [20],

$$\frac{d\lambda}{d \ln \mu} = \frac{1}{16\pi^2} \beta_\lambda^{(1)} + \frac{1}{(16\pi^2)^2} \beta_\lambda^{(2)}, \quad (11)$$

with

$$\begin{aligned} \beta_\lambda^{(1)} = & 12\lambda^2 - \left(\frac{9}{5} g_1^2 + 9g_2^2 \right) \lambda + \frac{9}{4} \left(\frac{3}{25} g_1^4 + \frac{2}{5} g_1^2 g_2^2 + g_2^4 \right) \\ & + 12y_t^2 \lambda - 12y_t^4, \end{aligned} \quad (12)$$

and

$$\begin{aligned} \beta_\lambda^{(2)} = & -78\lambda^3 + 18 \left(\frac{3}{5} g_1^2 + 3g_2^2 \right) \lambda^2 \\ & - \left(\frac{73}{8} g_2^4 - \frac{117}{20} g_1^2 g_2^2 - \frac{1887}{200} g_1^4 \right) \lambda - 3\lambda y_t^4 \\ & + \frac{305}{8} g_2^6 - \frac{289}{40} g_1^2 g_2^4 - \frac{1677}{200} g_1^4 g_2^2 - \frac{3411}{1000} g_1^6 \\ & - 64g_3^2 y_t^4 - \frac{16}{5} g_1^2 y_t^4 - \frac{9}{2} g_2^4 y_t^2 \end{aligned}$$

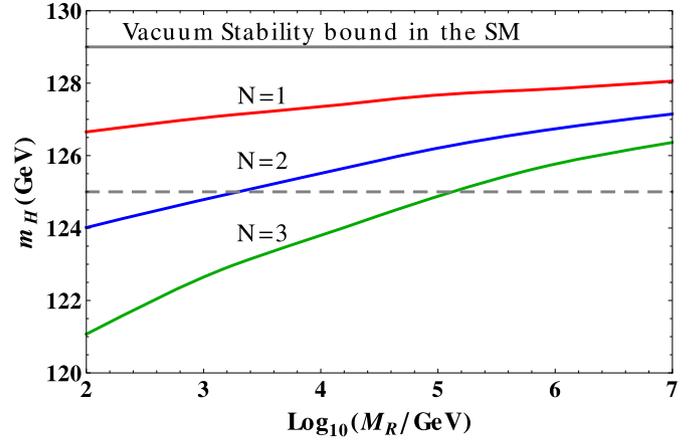


Fig. 1. The vacuum stability bound on the Higgs boson mass as a function of the triplet neutrino mass for $N = 1, 2$ and 3 generations, with reduced Planck mass cutoff. We have taken $M_t = 173.2$ GeV. The horizontal solid line denotes the vacuum stability bound in the SM while $m_H = 125$ GeV is shown as the dashed-line.

$$\begin{aligned} & + 10\lambda \left(\frac{17}{20} g_1^2 + \frac{9}{4} g_2^2 + 8g_3^2 \right) y_t^2 - \frac{3}{5} g_1^2 \left(\frac{57}{10} g_1^2 - 21g_2^2 \right) y_t^2 \\ & - 72\lambda^2 y_t^2 + 60y_t^6. \end{aligned} \quad (13)$$

The Higgs boson pole mass m_H is determined through a one-loop effective potential improved by two-loop RGEs. The second derivative of the effective potential at the potential minimum leads to [23]

$$\begin{aligned} m_H^2 = & \lambda \zeta^2 v^2 + \frac{3}{64\pi^2} \zeta^2 v^2 \left\{ g_2^4 \left(\log \frac{g_2^2 \zeta^2 v^2}{4\mu^2} + \frac{2}{3} \right) \right. \\ & + \frac{1}{2} \left(g_2^2 + \frac{3}{5} g_1^2 \right)^2 \left[\log \frac{(g_2^2 + \frac{3}{5} g_1^2) \zeta^2 v^2}{4\mu^2} + \frac{2}{3} \right] \\ & \left. - 8y_t^4 \log \frac{y_t^2 \zeta^2 v^2}{2\mu^2} \right\}, \end{aligned} \quad (14)$$

where $\zeta = \exp(-\int_{M_Z}^{\mu} \frac{\gamma(\mu)}{\mu} d\mu)$, with the anomalous dimension γ of the Higgs doublet evaluated at two-loop level. All running parameters are evaluated at $\mu = m_H$, and the Higgs boson mass is determined as the root of this equation. We have checked that our results on the Higgs boson mass bounds for the SM case coincide with the ones obtained in recent analysis [5].

For the renormalization scale $\mu \geq M_R$, the SM RGEs should be modified to include contributions from the triplet neutrinos in type III seesaw, so that the effectively RGE evolution of the Higgs self-coupling is altered. For simplicity, we consider only one-loop corrections from the heavy neutrinos. As we have discussed above, the neutrino Dirac Yukawa coupling is very small and its effect in our analysis is negligible. Therefore, the presence of the triplet neutrinos only modifies the SU(2) gauge coupling beta function:

$$b_2 = -\frac{19}{6} \rightarrow -\frac{19}{6} + \frac{4}{3} N, \quad (15)$$

corresponding to N generations of triplet neutrinos.

In Fig. 1, we show the vacuum stability bound on the Higgs boson mass as a function of the triplet neutrino mass for $N = 1, 2$ and 3, respectively. Here we have used $M_t = 173.2$ GeV and the cutoff scale is taken to be the reduced Planck mass $M_P = 2.44 \times 10^{18}$ GeV. We see that the presence of triplet neutrinos lowers the resultant Higgs mass from the SM value $\simeq 129$ GeV. Note that at least two generations of triplet neutrinos are necessary to yield a Higgs mass of 125 GeV. Interestingly, two generation is also

Table 1

The seesaw scales which give the vacuum stability bound $m_H = 125$ GeV for varying M_t values and the reduced Planck mass cutoff.

$N = 2$	M_t (GeV)	172.3	173.2	174.1
	M_R (GeV)	3.2×10^6	1.6×10^3	–
$N = 3$	M_t (GeV)	172.3	173.2	174.1
	M_R (GeV)	1.0×10^8	1.6×10^5	3.2×10^3

the minimal number required to reproduce the neutrino oscillation data.

For $N = 2$ and 3, respectively, we list in Table 1 the values of M_R to give the Higgs mass of 125 GeV. Here we have varied the top quark pole mass in the range of $M_t = 173.2 \pm 0.9$ GeV. We see that a Higgs mass of 125 GeV is compatible with a seesaw scale in the TeV range, in which case the SU(2) triplet neutrinos may be found at the LHC [24].

3. Gauge–Higgs unification scenario

Another scenario for reducing the SM vacuum stability bound is to introduce some new physics which effectively lowers the UV cutoff scale below the reduced Planck mass. There are several models for achieving this. For example, in the Randall–Sundrum model [25], the UV cutoff of the SM (as an effective 4-dimensional theory) can be dramatically reduced to $\Lambda = \omega M_P$ by the ‘warp factor’ $\omega \ll 1$, without too much fine-tuning of the model parameters. Alternatively, in the presence of \mathcal{N} elementary particle species in an effective quantum field theory, the consistency of large-distance black hole physics imposes the following gravitational cutoff on the theory, $\Lambda = M_P / \sqrt{\mathcal{N}}$ [26]. Finally, if we introduce a non-minimal gravitational coupling, $\xi \Phi^\dagger \Phi \mathcal{R}$, it seems natural to adopt $\Lambda = M_P / \xi$ [27] for the effective gravitational cutoff scale. Here ξ is a dimensionless coupling constant, Φ is the SM Higgs doublet, and \mathcal{R} is the scalar curvature. In these scenarios, the SM is realized as an effective theory below the cutoff, so that the RGE of Higgs self-coupling remains the same.³ However, the cutoff can be considerably below the reduced Planck mass and as a result, the vacuum stability bound on the Higgs mass is reduced. The Higgs mass as a function of the effective cutoff Λ is depicted in Fig. 2. A Higgs mass $m_H = 125$ GeV can be realized with an effective cutoff $\Lambda \simeq 1.4 \times 10^{11}$ GeV, which corresponds to ω^{-1} , $\sqrt{\mathcal{N}}$, $\xi \simeq 10^7$.

The vacuum stability bound is the lower bound on the Higgs boson mass obtained with a fixed cutoff scale. Thus, Fig. 2 indicates that to achieve $m_H = 125$ GeV, the upper bound on the effective UV cutoff is $\Lambda \lesssim 1.4 \times 10^{11}$ GeV. It is therefore interesting to see if there exists models which can predict the Higgs boson mass once the effective UV cutoff is fixed. The gauge–Higgs unification scenario [29,30] provides a good example of one class of such models.

In the gauge–Higgs unification scenario, the SM Higgs doublet is identified as the extra-dimensional component of a higher-dimensional gauge field, so that the Higgs self-coupling is determined by the gauge invariance in higher dimensions. As has been shown in Ref. [31], the low energy effective theory of the gauge–Higgs unification scenario is equivalent to the SM with a certain boundary condition for the Higgs self-coupling imposed at the compactification scale of the extra-dimensions, the so-called ‘gauge–Higgs condition’. In particular, in the gauge–Higgs unification scenario in flat 5D spacetime, the gauge–Higgs condition re-

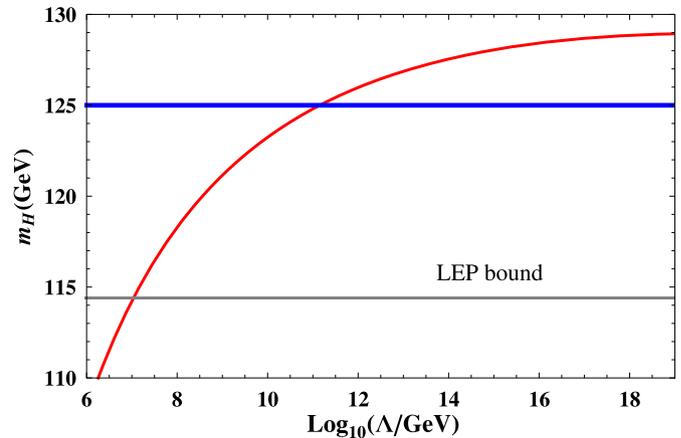


Fig. 2. The vacuum stability bound on the Higgs mass versus the effective cutoff scale Λ , for $M_t = 173.2$ GeV. A Higgs mass of 125 GeV corresponds to $\Lambda \simeq 1.4 \times 10^{11}$ GeV.

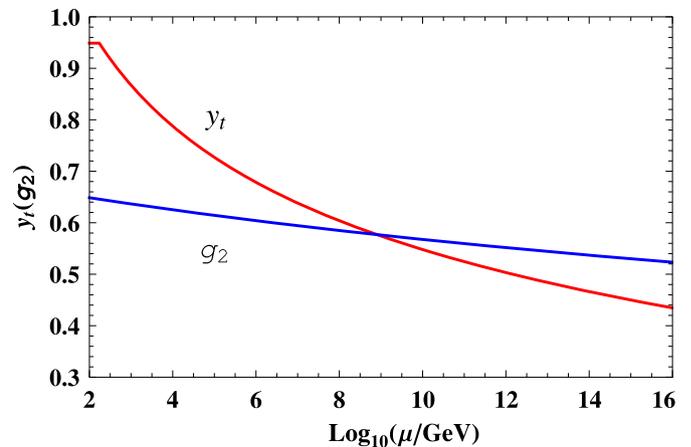


Fig. 3. RGE running of the SU(2) gauge coupling and top Yukawa coupling. They unify at 7.9×10^8 GeV, which is identified as the compactification scale.

quires a vanishing Higgs self-coupling at the cutoff scale Λ , which is identified as the compactification scale. Therefore, in a gauge–Higgs unification scenario, the vacuum stability bound on the SM Higgs boson mass is simply the Higgs mass prediction with the compactification scale Λ . Based on this identification, the SM Higgs boson mass has been calculated some time ago, in Ref. [32].

In the following, inspired by the 125 GeV Higgs, we recalculate the Higgs mass prediction in the 5D gauge–Higgs scenario. We have improved upon the previous analysis in [32] by taking into account the two-loop RGE improved one-loop effective Higgs potential in Eq. (14) and the updated top quark pole mass $M_t = 173.2 \pm 0.9$ GeV. As we have commented in the previous section, the improved analysis and the updated top quark pole mass alter the resultant Higgs mass by about 4 GeV. The precision at the level of a few GeV is important for the discussion of the vacuum stability bound. From the viewpoint of the gauge–Higgs unification scenario, the result shown in Fig. 2 indicates that a compactification scale of $\Lambda \simeq 1.4 \times 10^{11}$ GeV results in $m_H = 125$ GeV.

Since the gauge–Higgs unification scenario also provides unification of the gauge coupling and top quark Yukawa coupling at the compactification scale, we may identify the compactification scale with the unification scale of the SU(2) gauge coupling (g_2) and top Yukawa coupling (y_t) (see Fig. 3). In this way we predict the Higgs boson mass, as shown in Table 2 for varying top quark mass and the compactification scale.

³ To be precise, the non-minimal gravitational coupling slightly modifies the SM RGEs, but this effect on the vacuum stability bound is found to be negligible [28].

Table 2

Predicted Higgs boson mass for varying top quark pole mass, with the compactification scale determined by the unification of the SU(2) gauge coupling and top Yukawa coupling.

M_t (GeV)	g_2 - y_t unification scale (GeV)	Predicted m_H (GeV)
172.3	4.3×10^8	118.6
173.2	7.9×10^8	120.9
174.1	1.5×10^9	123.2

4. Conclusion

In conclusion, an excess of events around 125 GeV recently reported by the ATLAS and CMS experiments may be the first evidence for the SM Higgs boson. We have considered possible implications of a 125 GeV Higgs for new physics from the viewpoint of the vacuum stability bound on the SM Higgs mass with the reduced Planck mass cutoff. Since the (absolute) vacuum stability bound is close to 129 GeV, some new physics is needed to bring it down to 125 GeV. We first considered the seesaw extension of the SM which incorporates the observed neutrino masses and oscillations. In this case, the RGE of the SM Higgs self-coupling is modified for energies higher than the seesaw scale. In type II and type III seesaw, the 125 GeV mass can be achieved with the seesaw scale much lower than the conventional intermediate scale. With type III seesaw, the vacuum stability bound on the Higgs mass can be lowered to 125 GeV with 2 or 3 generations of SU(2) triplet neutrinos, with the seesaw scale as low as a TeV.

If there is no modification of the SM RGEs, it is necessary to introduce an effective ultraviolet cutoff $\Lambda \simeq 10^{11}$ GeV to yield a vacuum stability bound of $m_H = 125$ GeV. We have discussed various new physics models which provide such a low cutoff scale. In a gauge–Higgs unification scenario in 5D flat spacetime, the vacuum stability bound of $m_H = 125$ GeV is identified as a prediction of the Higgs mass under the gauge–Higgs condition imposed at the compactification scale $\Lambda \simeq 10^{11}$ GeV. If the compactification scale is identified with the unification scale of the SU(2) gauge coupling and top Yukawa coupling, the Higgs mass is predicted to lie close to 125 GeV.

Finally, while we have required absolute electroweak vacuum stability in this Letter, one may loosen the bound by considering meta-stability, which leads to a lower bound $m_H \gtrsim 110$ GeV on the Higgs mass. [See [33] for recent analysis in this context.] In this case, we may consider new physics effects which raise the bound to 125 GeV. As has been shown in [10,11], type I and type III seesaw with a seesaw scale $\gtrsim 10^{14}$ GeV will do this. However, the stability of a Minkowski vacuum has recently been suggested in terms of a consistent quantum field theory [34]. This argument is under debate [35,36], and it is still unclear whether the meta-stability bound on the Higgs boson mass is meaningful or not.

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