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Vanishing Higgs potential in minimal dark matter models

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ABSTRACT

We consider the Standard Model with a new particle which is charged under $SU(2)_L$ with the hypercharge being zero. Such a particle is known as one of the dark matter (DM) candidates. We examine the realization of the multiple point criticality principle (MPP) in this class of models. Namely, we investigate whether the one-loop effective Higgs potential $V_{\text{eff}}(\phi)$ and its derivative $dV_{\text{eff}}(\phi)/d\phi$ can become simultaneously zero at around the string/Planck scale, based on the one/two-loop renormalization group equations. As a result, we find that only the $SU(2)_L$ triplet extensions can realize the MPP. More concretely, in the case of the triplet Majorana fermion, the MPP is realized at the scale $\phi = \mathcal{O}(10^{16}\text{ GeV})$ if the top mass M_t is around 172 GeV. On the other hand, for the real triplet scalar, the MPP can be satisfied for $10^{16}\text{ GeV} \lesssim \phi \lesssim 10^{17}\text{ GeV}$ and $172\text{ GeV} \gtrsim M_t \gtrsim 171\text{ GeV}$, depending on the coupling between the Higgs and DM.

The discovery of the Higgs particle [1,2] is very meaningful for the Standard Model (SM). The experimental value of the Higgs mass suggests that the Higgs potential can be stable up to the Planck scale M_{pl} and also that both the Higgs self coupling λ and its beta function β_λ become very small around M_{pl}. This fact attracts much attention, and there are many works which try to find its physical meaning [3–29] and implications for cosmology [30–55].

In [3,4], the Higgs mass was predicted to be around 130 GeV by the requirement that $\lambda(\mu)$ and $\beta_\lambda(\mu)$ simultaneously become zero around M_{pl}.[1] Namely, the minimum of the Higgs potential $V(\phi)$ around M_{pl} vanishes. Such a requirement is called the multiple point criticality principle (MPP), and there have been many suggestions [39,46,56–62,64] that this principle might be closely related to physics at the Planck scale. One of the good points of the principle is its predictability: The low-energy effective couplings are fixed so that the minimum of the potential takes zero around M_{pl}. See [39,62–65] for examples of the prediction.

By taking the fact that the MPP is realized in the SM into consideration, a natural question is whether the MPP can be also realized in the models beyond the SM. It is meaningful to consider the MPP of these models because we can understand whether the SM is actually special among them. One of the interesting extensions is adding a new weakly interacting fermion χ or scalar X, which is an $n_{\chi(X)}$ representation of $SU(2)_L$ with the hypercharge $Y_{\chi(X)}$. Such extensions are phenomenologically well studied because they have dark matter (DM) candidates when $Y_{\chi(X)} = 0$ [66–68]. In this paper, we focus on $Y_{\chi(X)} = 0$, that is, Majorana fermions and real scalars. We examine the realization of the MPP of these models, based on the one/two-loop renormalization group equations (RGEs). We use the effective Higgs self coupling λ_{eff} and its beta function $\beta_{\lambda_{\text{eff}}}$ defined from the one-loop effective Higgs potential $V_{\text{eff}}(\phi)$. Their definitions and the two-loop RGEs when we add a new fermion are presented in Appendix A. In the case of the new scalar (fermion), we only have to consider $n_X = 3$ ($n_\chi = 3, 5$) since the scalar couplings ($SU(2)_L$ coupling g_2) rapidly blow(s) up when $n_X \geq 4$ [69] ($n_\chi \geq 7$ [66]), and the theory does not valid up to M_{pl}. For the septet and nonet fermion cases, we discuss this point in Appendix B.

In the following discussion, we regard the top mass M_t as a free parameter, and the Higgs mass is varied within [70]

$$M_h = 125.09 \pm 0.32\text{ GeV}. \tag{1}$$

As for the initial values of the $\overline{\text{MS}}$ SM couplings, we use the results of [19]. For illustration, the $Y_\chi \neq 0$ cases are also discussed in Appendix C.

First, we consider a new fermion. For $n_\chi = 3$ and 5, the mass M_χ is determined by the thermal relic abundance [67,68]:

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[1] It is interesting that the quadratic divergent bare Higgs mass also vanishes around this scale [13].

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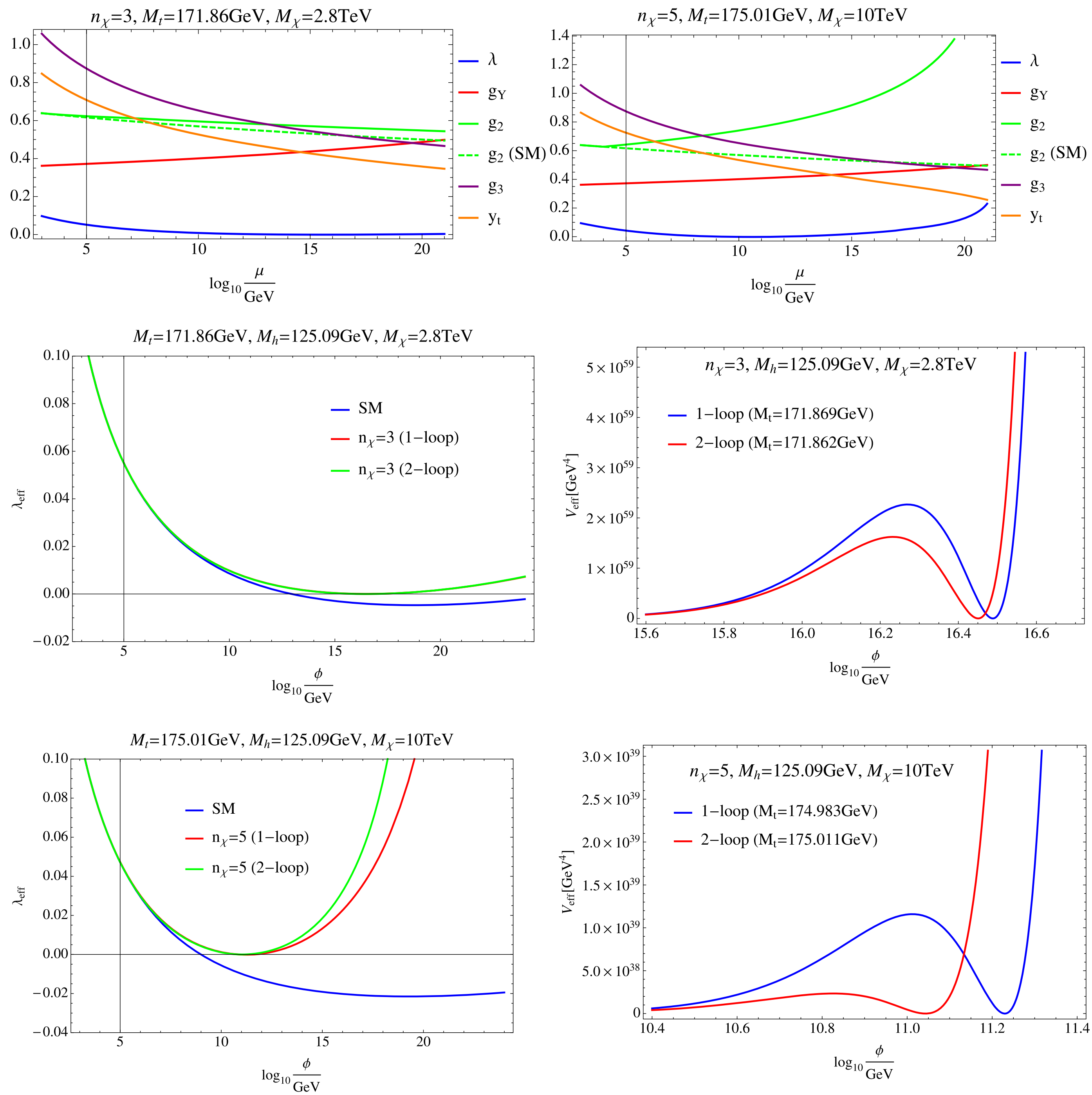

Fig. 1. Upper left (right): the runnings of the SM parameters when $n_\chi = 3$ (5). Here, the dashed green lines represent the SM running of g_2. Middle (Lower): the running of the effective Higgs self coupling λ_{eff} (left) and the one-loop effective Higgs potential $V_{\text{eff}}(\phi)$ (right) in the case of $n_\chi = 3$ (5). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

$$M_\chi \simeq \begin{cases} 2.8\ \text{TeV} & (\text{for } n_\chi = 3), \\ 10\ \text{TeV} & (\text{for } n_\chi = 5). \end{cases} \tag{2}$$

As a result, M_t and Λ_{MPP} are uniquely predicted because there is no additional free parameter. The results are

$$\begin{aligned} &171.7\ \text{GeV} \leq M_t \leq 172.0\ \text{GeV}\,, \\ &2.5 \times 10^{16}\ \text{GeV} \leq \Lambda_{\text{MPP}} \leq 3.2 \times 10^{16}\ \text{GeV (for } n_\chi = 3), \\ &174.8\ \text{GeV} \leq M_t \leq 175.2\ \text{GeV}\,, \\ &1.1 \times 10^{11}\ \text{GeV} \leq \Lambda_{\text{MPP}} \leq 1.2 \times 10^{11}\ \text{GeV (for } n_\chi = 5), \end{aligned} \tag{3}$$

depending on 124.77 GeV $\leq M_h \leq$ 125.41 GeV.[2] The upper panels of Fig. 1 show the runnings of the SM parameters where $M_h = 125.09$ GeV, and M_t is correspondingly fixed so that the MPP is realized. Here, we also show the SM running of g_2 by the dashed green line for comparison. Furthermore, in the middle and

[2] These values of M_t are consistent with the recent analyses: $M_t = 173.34 \pm 0.76$ GeV [71] and $M_t = 172.38 \pm 0.10 \pm 0.65$ GeV [72] at 2σ level. However, the relation between these masses and the pole mass is not clear. In the following calculation of the bare Higgs mass, we use more conservative value of M_t determined by the $t\bar{t}$ total cross section [73].