Contribution 10

Improved vacuum stability in scalar dark matter models

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Abstract
If the Higgs boson mass is 125 ± 1 GeV, the standard model cannot be a fundamental theory up to the GUT scale due to the vacuum stability arguments. We show that if the dark matter of the Universe consists of stable scalar particles, the vacuum stability constraints are modified and the theory can be valid up to a high scale. We argue that the present LHC data may favour such a scenario.

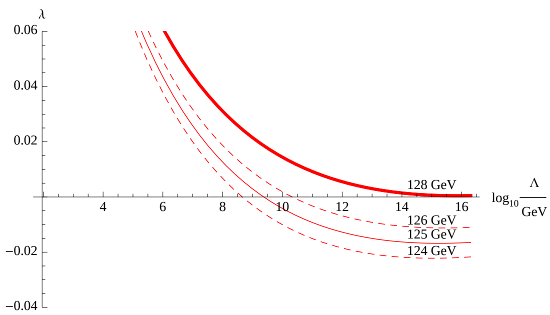
1 INTRODUCTION

The scalar potential of the standard model (SM) Higgs boson [290–293] is one of the best studied objects in particle physics. If the Higgs boson mass is $M_H \approx 125$ GeV as indicated by the recent experimental results by ATLAS [143] and CMS [144] experiments, the SM cannot be valid up to the Grand Unification (GUT) or Planck scales [272, 294]. For such a low Higgs boson mass its quartic self-coupling λ runs to negative values at energy scales much below the GUT scale, causing vacuum instability at higher scales Λ. This result is presented in the left panel of Fig. 1 in which the renormalization group equation running of the SM Higgs self-coupling is presented at the two loop level for different values of the Higgs mass. Consecuently, the SM alone cannot be valid up to the scales required by gauge coupling unification and proton decays arguments.

On the other hand, any realistic model of new physics beyond the SM must explain the existence of dark matter (DM) in the Universe. By far the simplest extension of the SM is obtained by adding a real [295–297] or complex [298, 299] singlet scalar field to the SM scalar potential. In addition to minimality, such a SM extension is motivated by GUT arguments [299]. In those models the DM and Higgs sectors are related via the Higgs portal and the scalar potentials are in general rather complicated. Due to new self-interactions in the scalar sector, the SM Higgs quartic coupling renormalization is modified, and one might expect that the triviality $\lambda(\Lambda) = 0$ may be achieved for much higher values of Λ.

In addition to the vacuum stability arguments, the scalar DM may also be motivated by the LHC data. In the light of recent XENON100 and LHC results, this possibility has been studied in Refs. [277, 300, 301]. It was argued in Ref. [301] that the LHC data may contain indications for Higgs boson invisible decays consistent with the direct DM searches in XENON100. Thus it is necessary to study the SM-like Higgs boson properties in every possible production and decay channel.

The aim of this note is to point out that, indeed, if the DM of the Universe consists of scalar singlets, the stability of scalar potential of the model may be guaranteed up to the GUT scale even for the Higgs boson mass 125 GeV. Thus, in this case, there is no reason to introduce any intermediate scale in the theory and the known physics can be considered to be fundamental



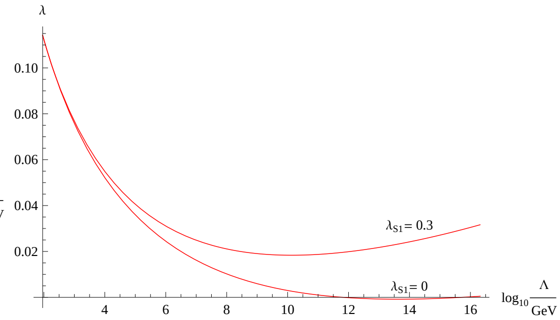


Figure 1: Left: running of the SM Higgs boson self-coupling λ for different Higgs boson masses at the two loop level. Right: running of the Higgs self-coupling in the complex singlet model for two different values of λ_{S1} at one loop level.

until Grand Unification takes over.

2 VACUUM STABILITY IN SCALAR DARK MATTER MODELS

The natural question to ask is that what happens to the vacuum stability in models with extended scalar sector? Here we study the case of complex singlet scalar $S = (S_H + iS_A)/\sqrt{2}$, but the phenomenology in the real singlet case is similar. The vacuum stability of the real singlet model has been previously studied also in [302].

Denoting the SM Higgs boson with H_1, the most general Lagrangian invariant under the Z_2 transformations $H_1 \to H_1$, $S \to -S$ is given by

$$V = \mu_1^2 H_1^\dagger H_1 + \lambda_1 (H_1^\dagger H_1)^2 + \mu_S^2 S^\dagger S + \frac{\mu_S'^2}{2}\left[S^2 + (S^\dagger)^2\right] + \lambda_S (S^\dagger S)^2 + \frac{\lambda_S'}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda_S''}{2}(S^\dagger S)\left[S^2 + (S^\dagger)^2\right] + \lambda_{S1}(S^\dagger S)(H_1^\dagger H_1) + \frac{\lambda_{S1}'}{2}(H_1^\dagger H_1)\left[S^2 + (S^\dagger)^2\right]. \tag{1}$$

The vacuum stability conditions for the complex singlet model with a global $U(1)$ are given in [298]. However, those conditions are not applicable here because this model is far too simple compared to the general case (1). For the general model the full vacuum stability conditions are rather complicated and have been addressed previously in Ref. [303]. However, the conditions of [303] turn out to be too restrictive because they are derived by requiring the matrix of quartic couplings to be positive. This is required only if the coefficients of biquadratic terms are negative and, in general, cut out some of the allowed parameter space. The milder conditions arising from pure quartic terms of the potential (1) are

$$\lambda_1 \geq 0, \quad \lambda_S + \lambda_S' \geq |\lambda_S''|. \tag{2}$$

For simplicity we consider in addition only the case that the coefficents of the terms biquadratic in real fields (*e.g.* the coefficient of $S_H^2 S_A^2$) are all non-negative, giving

$$\lambda_S - 3\lambda_S' \geq 0, \quad \lambda_{S1} - |\lambda_{S1}'| \geq 0. \tag{3}$$

Doing this, we exclude a part of the points that would be allowed by the full vacuum stability conditions. However, this is sufficient for our purposes because our aim is to show that regions of the parameter space exist that lower the SM Higgs boson mass vacuum stability bound.

The one-loop renormalization group equations (RGEs) can be obtained from those in [303] by setting all couplings of the inert doublet to zero. The RGEs show that nonzero λ_{S1} or λ'_{S1} give a positive contribution to the β-function of λ_1, pushing the scale where $\lambda_1 \equiv \lambda = 0$ higher. For qualitative understanding of the model, we let $\lambda_S = \lambda'_S = \lambda''_S = \lambda'_{S1} = 0$.

In the right panel of Fig. 1 we plot the one loop level running for a 125 GeV Higgs boson quartic coupling for $\lambda_{S1} = 0$ (the SM case) and for $\lambda_{S1} = 0.3$. In the latter case, the minimum bound on the Higgs boson mass from the vacuum stability argument is lowered and the vacuum can be stable up to the GUT or Planck scale. This simple example demonstrates that the 125 GeV Higgs boson excess at the LHC may call for the extended scalar sector that simultaneously solves the vacuum stability and DM problems.

3 CONCLUSIONS

We have considered the implications of a $M_H \approx 125$ GeV Higgs boson for the vacuum stability in scalar DM models. In the SM the 125 GeV Higgs boson implies that the model cannot be consistent with the gauge coupling unification scale nor with the scale required by proton stability. We have shown here that in the case of non-SUSY scalar DM models the vacuum stability bounds are modified due to more complicated scalar potentials. Therefore, unlike the SM, the scalar DM models can be consistent models up to the GUT or Planck scales even if the present LHC excess at $M_H \approx 125$ GeV is be confirmed. If this is the case Nature has chosen, the Higgs boson interactions and possibly also its branching fractions at the LHC will be modified due to the coupling to DM.

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