Physics Letters B 734 (2014) 220–226

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Next to new minimal standard model

Naoyuki Haba [a,b], Kunio Kaneta [b,c,d,*], Ryo Takahashi [b]

[a] Graduate School of Science and Engineering, Shimane University, Matsue, Shimane 690-8504, Japan
[b] Department of Physics, Faculty of Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan
[c] Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8568, Japan
[d] Department of Physics, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

ARTICLE INFO

Article history:
Received 1 February 2014
Received in revised form 14 April 2014
Accepted 11 May 2014
Available online 15 May 2014
Editor: J. Hisano

ABSTRACT

We suggest a minimal extension of the standard model, which can explain current experimental data of the dark matter, small neutrino masses and baryon asymmetry of the universe, inflation, and dark energy, and achieve gauge coupling unification. The gauge coupling unification can explain the charge quantization, and be realized by introducing six new fields. We investigate the vacuum stability, coupling perturbativity, and correct dark matter abundance in this model by use of current experimental data.

1. Introduction

The standard model (SM) in particle physics has achieved great success in the last few decades. In particular, a recent discovery of the Higgs particle with the mass of 126 GeV at the CERN Large Hadron Collider (LHC) experiment [1] filled the last piece of the SM. So far the results from the LHC experiment are almost consistent with the SM, and no signatures of new physics such as the supersymmetry (SUSY) or extra-dimension(s) are discovered. However, there are some unsolved problems in the SM, for example, there is no candidate of dark matter (DM) in the SM, which are expected to be solved by the new physics beyond the SM.

The SUSY is an excellent candidate for the physics beyond the SM since it solves the gauge hierarchy problem and realizes the gauge coupling unification (GCU) as well as contains the DM candidate. But, the recent discovery of the Higgs with the 126 GeV mass and no signature of the SUSY may disfavor the SUSY at low energy. Actually, the magnitude of the fine-tuning in the gauge hierarchy problem is much less than that of the cosmological constant problem. So it should be meaningful to reconsider the minimum extension of the SM by forgetting about the gauge hierarchy problem. A model suggested in Ref. [2] was a minimal extension of the SM,[1] which is called new minimal SM (NMSM). In addition to the SM fields, the NMSM contains a gauge singlet scalar, two right-handed neutrinos, an inflaton, and the small cosmological constant, which can explain the DM, small neutrino masses and baryon asymmetry of the universe (BAU), inflation, and dark energy (DE), respectively. Although a favored parameter space in the NMSM for the vacuum stability, triviality bounds, and the correct DM abundance was shown in Ref. [2], experimental data was old. For example, the allowed region for the scalar singlet DM is also updated [4] by utilizing the results of the LHC searches for invisible Higgs decays, the thermal relic density of the DM, and DM searches via indirect and direct detections, recently. The parameter search must be investigated again with the current experimental data. This is one motivation of this paper.

It is worth noting that the GCU cannot be achieved in the NMSM. The charge quantization is one of the biggest problems in the SM, which should be solved in a grand unified theory (GUT). The GCU can be a sufficient condition of the GUT, and the great merit of the SUSY SM is just the realization of the GCU. Thus, here we suggest next to new minimal SM (NNMSM) in order to achieve the GCU by extending the NMSM. Our model includes new fields which are two adjoint fermions and four vector-like $SU(2)_L$ doublet fermions, in addition to the particle content of the NMSM. The model can achieve the GCU by adding those six fields, where the degrees of freedom are lower than minimal SUSY SM.[2]

We also revisit the stability and triviality bounds with the 126 GeV Higgs mass, the recent updated limits on the DM particle, and the latest experimental value of the top pole mass as 173.5 GeV. The vacuum stability and triviality bounds are quite sensitive to the Higgs and top masses. We will point out that there are parameter regions in which the stability and triviality bounds,

* Corresponding author.
[1] See also [3] and references therein for related works.

[2] The particle content of our model is similar to a low energy spectrum of the split SUSY scenario. On the other hand, we suggest a model by respecting the minimality, and the model can achieve the GCU by the lower degrees of freedom.

http://dx.doi.org/10.1016/j.physletb.2014.05.016

Table 1
Quantum numbers of additional particles ($i = 1, 2$).

	λ_3	λ_2	L'_i	$\overline{L'_i}$	S	N_i	φ
$SU(3)_C$	8	1	1	1	1	1	1
$SU(2)_L$	1	3	2	2	1	1	1
$U(1)_Y$	0	0	−1/2	1/2	0	0	0
Z_2	−	−	+	+	−	+	+

the correct abundance of DM, and the Higgs and top masses can be realized at the same time.

2. Next to new minimal standard model

We suggest next to new minimal standard model (NNMSM) by extending the NMSM, which has the gauge singlet real scalar boson S, two right-handed neutrinos N_i, the inflaton φ, and the small cosmological constant Λ in addition to the SM. Our model introduces six new fields such as two adjoint fermions λ_a $(a = 2, 3)$ and four vector-like $SU(2)_L$-doublet fermions, L'_i and $\overline{L'_i}$ $(i = 1, 2)$, in addition to the particle contents of the NMSM. The quantum numbers of these particles are given in Table 1, where the quantum number of L'_i and $\overline{L'_i}$ is the same as that of the SM lepton doublet.[3] The gauge singlet scalar and two adjoint fermions have odd-parity under an additional Z_2-symmetry while other additional particles have even-parity. We will show the singlet scalar becomes DM as in the NMSM. Runnings of gauge couplings are changed from the SM due to new particles with the charges. The realization of the GCU is one of important results of this work as we will show later.

We consider the NNMSM as a renormalizable theory, and thus, the relevant Lagrangian of the NNMSM is given by

$$\mathcal{L}_{\rm NNMSM} = \mathcal{L}_{\rm SM} + \mathcal{L}_S + \mathcal{L}_N + \mathcal{L}_\varphi + \mathcal{L}_\Lambda + \mathcal{L}', \tag{1}$$

$$\mathcal{L}_{\rm SM} \supset -\lambda\left(|H|^2 - \frac{v^2}{2}\right)^2, \tag{2}$$

$$\mathcal{L}_S = -\frac{1}{2}\bar{m}_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{\lambda_S}{4!}S^4 + (\text{kinetic term}), \tag{3}$$

$$\mathcal{L}_N = -\left(\frac{M_i}{2}\overline{N_i^c}N_i + h_\nu^{i\alpha}\overline{N_i}L_\alpha\tilde{H} + c.c.\right) + (\text{kinetic term}), \tag{4}$$

$$\begin{aligned}\mathcal{L}_\varphi = &-B\varphi^4\left[\ln\left(\frac{\varphi^2}{\sigma^2}\right) - \frac{1}{2}\right] - \frac{B\sigma^4}{2} \\ &- \mu_1\varphi|H|^2 - \mu_2\varphi S^2 - \kappa_H\varphi^2|H|^2 - \kappa_S\varphi^2 S^2 \\ &- \left(y_N^{ij}\varphi\overline{N_i}N_j + y_3\varphi\overline{\lambda_3}\lambda_3 + y_2\varphi\overline{\lambda_2}\lambda_2 + y_{\varphi L'}^{ij}\varphi\overline{L'_i}L'_j + c.c.\right) \\ &+ (\text{kinetic term}),\end{aligned} \tag{5}$$

$$\mathcal{L}_\Lambda = \left(2.3\times10^{-3}\ \text{eV}\right)^4, \tag{6}$$

$$\begin{aligned}\mathcal{L}' = &\left[\left(y_L^{i\alpha}L'_i\tilde{H} + y_{\bar{L}}^{i\alpha}\overline{L'_i}^\dagger H^\dagger\right)E_\alpha \right.\\ &\left. + M_3\overline{\lambda_3}\lambda_3 + M_2\overline{\lambda_2}\lambda_2 + M_{L'_i}\overline{L'_i}L'_i + h.c.\right] \\ &+ (\text{kinetic terms}),\end{aligned} \tag{7}$$

with $\alpha = e, \mu, \tau$ and $\tilde{H} = i\sigma_2 H^*$ where $\mathcal{L}_{\rm SM}$ is the Lagrangian of the SM, which includes the Higgs potential. v is the vacuum expectation value (VEV) of the Higgs as $v = 246$ GeV. $\mathcal{L}_{S,N,\varphi,\Lambda}$ are Lagrangians for the dark matter, right-handed neutrinos, inflaton, and the cosmological constant, respectively. $\mathcal{L}_{\rm SM} + \mathcal{L}_{S,N,\Lambda}$ are the same as those of the NMSM.[4] $\mathcal{L}'$ is new Lagrangian in the NNMSM, where E is right-handed charged lepton in the SM. Mass matrix, M_L, is assumed to be diagonal, for simplicity.

There are several mass scales of new particles, i.e., masses of DM, right-handed neutrinos, adjoint fermions, and inflaton. For the minimal setup, we introduce two mass scales in addition to the EW (TeV) scale. One is the mass of the new particles, $M_{\rm NP}$, and all new fermions have the mass scale as $M_3 \simeq M_2 \simeq M_{L'_i} \simeq M_{\rm NP}$. The other is the scalar DM with the mass

$$m_S = \sqrt{\bar{m}_S^2 + kv^2/2}, \tag{8}$$

which is constrained by experiments and a realization of the correct abundance of the DM. Actually, there are other options for the setup of building the model, which will be shown later.

2.1. Gauge coupling unification

At first, we investigate the runnings of the gauge couplings in the NNMSM. Since we introduce two adjoint fermions λ_3 and λ_2, and four vector-like $SU(2)_L$-doublet fermions, L'_i and $\bar{L}_i$ $(i = 1, 2)$, listed in Table 1, the beta functions of the RGEs for the gauge couplings become

$$2\pi\frac{d\alpha_j^{-1}}{dt} = b_j^{\rm SM} + b'_j, \tag{9}$$

where $(b_1^{\rm SM}, b_2^{\rm SM}, b_3^{\rm SM}) = (41/10, -19/6, -7)$ for the SM, and $(b'_1, b'_2, b'_3) = (4/5, 8/3, 2)$ for new contributions in the NNMSM. $t \equiv \ln(\mu/1\ \text{GeV})$ and μ is the renormalization scale, and $\alpha_j \equiv g_j^2/(4\pi)$ $(j = 1, 2, 3)$ with $g_1 \equiv \sqrt{5/3}g'$. Since all masses of new particles are around the same scale, $\Lambda_{\rm EW} < M_{\rm NP} \simeq M_3 \simeq M_2 \simeq M_{L'_i}$, where $\Lambda_{\rm EW}$ is the EW scale, we should utilize the RGEs of Eq. (9) at high energy scale ($M_{\rm NP} \le \mu$) while the right-handed side of Eq. (9) must be $b_j^{\rm SM}$ at low energy scale ($\Lambda_{\rm EW} \le \mu < M_{\rm NP}$).

According to the numerical analyses, taking a free parameter $M_{\rm NP}$ as 1.40×10^3 TeV can realize the GCU with a good precision at 1-loop level as shown in Fig. 1.[5] We show the threshold of new particles with 1.40×10^3 TeV mass by a black solid line. The NNMSM suggests the GCU at

$$\Lambda_{\rm GCU} \simeq 2.45\times10^{15}\ \text{GeV} \tag{10}$$

with the unified coupling as

$$\alpha_{\rm GCU}^{-1} \simeq 36.1. \tag{11}$$

Suppose the minimal $SU(5)$ GUT at $\Lambda_{\rm GCU}$, the protons decay of $p \to \pi^0 e^+$ occurs by exchanging heavy gauge bosons of the GUT gauge group, and here we estimate a limit from the proton life time. A constraint from the proton decay experiments is $\tau(p \to \pi^0 e^+) > 8.2\times10^{33}$ years [6], and the partial decay width of proton for $p \to \pi^0 e^+$ is given by

$$\begin{aligned}\Gamma\left(p \to \pi^0 e^+\right) = \alpha_H^2\frac{m_p}{64\pi f_\pi^2}(1 + D + F)^2\left(\frac{4\pi\alpha_{\rm GCU}}{\Lambda_{\rm GCU}}A_R\right)^2 \\ \times\left(1 + \left(1 + |V_{ud}|^2\right)^2\right),\end{aligned} \tag{12}$$

[3] Other possibilities for particle contents are studied in Ref. [5].

[4] For the present cosmic acceleration, we simply assume that the origin of DE is the tiny cosmological constant, which is given in $\mathcal{L}_\Lambda$ of Eq. (6), so that the NNMSM predicts the equation of state parameter as $\omega = -1$, like the NMSM. We will not focus on the DE in this work anymore.

[5] In this analysis, we take the following values as [6], $\sin^2\theta_W(M_Z) = 0.231$, $\alpha_{\rm em}^{-1}(M_Z) = 128$, $\alpha_s(M_Z) = 0.118$, for the parameters in the EW theory, where θ_W is the Weinberg angle, $\alpha_{\rm em}$ is the fine structure constant, and α_s is the strong coupling, respectively.