11 UV complete Model With a Composite Higgs Sector for Baryogenesis, DM, and Neutrino masses

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Abstract. We propose a UV complete model based on SUSY $SU(2)_H$ gauge theory with confinement. New Z_2 discrete symmetry and Z_2-odd right-handed neutrino superfields are also introduced to the model. Its low-energy effective theory can provide solutions for Baryogenesis, DM candidate, and origin of neutrino masses. Below a confinement scale, the Higgs sector is described in terms of mesonic superfields of fundamental $SU(2)_H$ doublets. We also discuss how to test the scenario by the future collider experiments in a benchmark scenario.

Povzetek. Avtor predlaga model za konfinirane kvarke, ki temelji na supersimetrični umeritveni teoriji $SU(2)_H$, dopolnjeni z diskretno simetrijo Z_2. Tudi za nevtrinska superpolja uporabi Z_2 diskretno simetrijo. V limiti nizkih energij lahko model ponudi odgovore za nastanek barionov, kandidate za temno snov in pojasni izvor nevtrinskih mas. Na energijski skali pod kromodinamskim faznim prehodom opiše Higgsove skalarje z mezonskimi superpolji osnovnega dubleta $SU(2)_H$. Obravnava tudi možnosti preverbe modela na bodočih poskusih na pospeševalnikih.

Keywords: New Physics, Composite Higgs sector, SUSY

11.1 Introduction

A Higgs boson was discovered in 2012 at LHC experiments, and it has been confirmed that its properties are consistent with the Higgs boson in the Standard Model (SM). However, it is not the end of the story. The SM has still serous problems. For example, there is no successful mechanism of Baryogenesis, there is no candidate of the Dark Matter (DM), there is no natural explanation of tiny neutrino masses, and so on. On the other hand, we have not fully understood the Higgs sector yet. There are still several fundamental questions. For example, how many Higgs bosons are there?, Whether is the Higgs boson a elementary scalar or a composite state? What is the origin of the negative mass squared of the Higgs boson? and so on. In many models, extension of the SM for explaining unsolved problems, such as Baryogenesis, DM, neutrino masses, etc lead to an

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extended Higgs sector. Thus, we can say that the Higgs sector will be a probe of new physics.

In this talk, we consider a SUSY model[1,2] with additional $SU(2)_H$ gauge symmetry to the SM gauge group and three matter fields (and three anti-matter fields) which are fundamental representations under the $SU(2)_H$. In the low energy effective theory of this model, the Higgs sector is described by mesonic fields of those six fields. We then show that this effective theory can provide enough enhancement of the first order electroweak phase transition (1stOPT) which is required by successful electroweak baryogenesis scenario[3], DM candidates, and mechanism to generate tiny neutrino masses through radiative corrections.

11.2 Model

In SUSY $SU(N_c)$ gauge theory with $N_c + 1$ flavour fields, confinement occurs at some scale[6]. The simplest example is $N_c = 2$ case. Utilising this setup, we propose a model with $SU(2)_H$ symmetry with three flavour fields which are fundamental representations of $SU(2)_H$. There should also be three anti-matter fields for each fundamental representation matter fields. We described these six fields as $T_i (i = 1, \cdots, 6)$. This setup is almost same as one in the minimal SUSY fat Higgs model[7]. In the minimal SUSY fat Higgs model, two doublets and one singlet mesonic fields are light in the low energy effective theory by introducing additional fields. In our model, in contrast, all the mesonic fields appears in the low energy effective theory.

We here introduce a right-handed neutrino (RHN) which is singlet under $SU(2)_H$ as well as the SM gauge symmetry. The model also has an unbroken discrete symmetry Z_2 in order to forbid tree level contributions to neutrino masses. The RHN has an odd charge under the Z_2 parity. We show the charge assignment of T_i and the RHN N_R^c under the SM gauge symmetry, $SU(2)_H$, and the Z_2 parity in Table 11.1-(I). The fifteen mesonic fields below a certain scale Λ_H which are canonically normalized as $H_{ij} \simeq \frac{1}{4\pi\Lambda_H} T_i T_j (i \neq j)$ are listed in the Table 11.1-(II).

The superpotential of the Higgs sector below Λ_H is given by

$$\begin{aligned} W_{\text{eff}} =& \lambda N \left(H_u H_d + v_0^2\right) \\ &+ \lambda N_\Phi \left(\Phi_u \Phi_d + v_\Phi^2\right) \\ &+ \lambda N_\Omega \left(\Omega_+ \Omega_- - \zeta\eta + v_\Omega^2\right) \\ &+ \lambda \left\{\zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega_+ H_d \Phi_d - \Omega_- H_u \Phi_u - N N_\Phi N_\Omega\right\} . \end{aligned} \quad (11.1)$$

(I)

Superfield	$SU(2)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	1	2	0	+1
T_3	2	1	1	+1/2	+1
T_4	2	1	1	−1/2	+1
T_5	2	1	1	+1/2	−1
T_6	2	1	1	−1/2	−1
N_R^c	1	1	1	0	−1

(II)

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
$H_d \equiv \begin{pmatrix} H_{14} \\ H_{24} \end{pmatrix}$	1	2	−1/2	+1
$H_u \equiv \begin{pmatrix} H_{13} \\ H_{23} \end{pmatrix}$	1	2	+1/2	+1
$\Phi_d \equiv \begin{pmatrix} H_{15} \\ H_{25} \end{pmatrix}$	1	2	−1/2	−1
$\Phi_u \equiv \begin{pmatrix} H_{16} \\ H_{26} \end{pmatrix}$	1	2	+1/2	−1
$\Omega_- \equiv H_{46}$	1	1	−1	−1
$\Omega_+ \equiv H_{35}$	1	1	+1	−1
$N \equiv H_{56}, N_\Phi \equiv H_{34}, N_\Omega = H_{12}$	1	1	0	+1
$\zeta \equiv H_{36}, \eta \equiv H_{45}$	1	1	0	−1

Table 11.1. (I) The charge assignment of the $SU(2)_H$ doublets T_i and the RHN N_R^c under the SM gauge group $(SU(3)_c \times SU(2)_L \times U(1)_Y$ and the Z_2 parity. (II) The field content of the extended Higgs sector in the low energy effective theory below the scale Λ_H.

By the Naive Dimensional Analysis, $\lambda \simeq 4\pi$ is naively expected at the confinement scale Λ_H. The relevant soft SUSY breaking Lagrangian terms are given by

$$\begin{aligned}
\mathcal{L}_H = &- m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - m_{\Phi_u}^2 \Phi_u^\dagger \Phi_u - m_{\Phi_d}^2 \Phi_d^\dagger \Phi_d \\
&- m_N^2 N^* N - m_{N_\Phi}^2 N_\Phi^* N_\Phi - m_{N_\Omega}^2 N_\Omega^* N_\Omega - m_{\Omega_+}^2 \Omega_+^* \Omega_+ - m_{\Omega_-}^2 \Omega_-^* \Omega_- \\
&- m_\zeta^2 \zeta^* \zeta - m_\eta^2 \eta^* \eta - \left\{ m_{\zeta\eta}^2 \eta^* \zeta + \frac{B_\zeta^2}{2} \zeta^2 + \frac{B_\eta^2}{2} \eta^2 + \text{h.c.} \right\} \\
&- \left\{ C \lambda v_0^2 N + C_\Phi \lambda v_\Phi^2 N_\Phi + C_\Omega \lambda v_\Omega^2 N_\Omega + \text{h.c.} \right\} \\
&- \{ B\mu H_u H_d + B_\Phi \mu_\Phi \Phi_u \Phi_d + B_\Omega \mu_\Omega (\Omega_+ \Omega_- + \zeta\eta) + \text{h.c.} \} \\
&- \lambda \big\{ A_N H_u H_d N + A_{N_\Phi} \Phi_u \Phi_d N_\Phi + A_{N_\Omega} (\Omega_+ \Omega_- - \eta\zeta) N_\Omega + A_\zeta H_d \Phi_u \zeta \\
&\qquad + A_\eta H_u \Phi_d \eta + A_{\Omega_-} H_u \Phi_u \Omega_- + A_{\Omega_+} H_d \Phi_d \Omega_+ + \text{h.c.} \big\} \,. \qquad (11.2)
\end{aligned}$$

By the vacuum expectation values (vev's) of Z_2-even singlet fields N, N_Φ and N_Ω, the mass parameters $\mu = \lambda \langle N \rangle$, $\mu_\Phi = \lambda \langle N_\Phi \rangle$ and $\mu_\Omega = \lambda \langle N_\Omega \rangle$ are induced. The

RHN has Yukawa couplings and the Majorana mass term given by

$$W_N = y_N^i N_R^c L_i \Phi_u + h_N^i N_R^c E_i^c \Omega_- + \frac{M_R}{2} N_R^c N_R^c + \frac{\kappa}{2} N N_R^c N_R^c \,. \tag{11.3}$$

11.3 Benchmark point and its phenomenology

For successful electroweak baryogenesis, the condition $\varphi_c/T_c > 1$ should be satisfied, which means that the 1stOPT is strong enough. Though new CP violation phases are required in order to reproduce the correct amount of Baryon asymmetry of the Universe, we here focus only on the 1stOPT. It is naively expected that we can introduce several CP phases relevant to Baryogenesis as in the case of MSSM[8]. In our model, the 1stOPT can be enhanced by the loop contributions of extra Z_2-odd scalar particles strongly enough.

Since our low energy effective theory keeps both Z_2-parity and R-parity unbroken, there are potentially three kinds of the DM candidates, *i.e.* the lightest particles with the parity assignments of $(-,+)$, $(+,-)$, and $(-,-)$. However, in the case that one of them is heavier than the sum of the masses of the others, the heaviest one decays into the other two particles so that the heaviest particle cannot be a DM.

In our model, tiny neutrino masses are generated via loop contributions shown in Fig. 11.1. There are one-loop and three-loop contributions. The one-loop and three-loop diagrams correspond to the SUSY versions of Ma model[4] and AKS[5], respectively. It is interesting that the one-loop diagrams are driven by the coupling y_N and the three-loop diagrams are controlled by another coupling h_N. Both one-loop and three-loop contributions can be significant if $h_N \gg y_N$. Therefore, two different mass squared differences can be generated even if only one RHN is introduced.

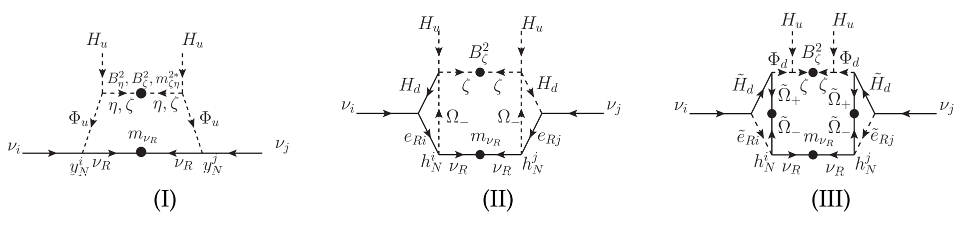

Fig. 11.1. (I) A one-loop diagram and (II) three-loop diagrams which contribute to the neutrino mass matrix. The figures are taken from [1]

A benchmark scenario is provided in Table 3 of Ref. [1] and some predictions are shown in Table 4 of the same reference, where the condition $\varphi_c/T_c > 1$ is satisfied, the neutrino masses and the mixing angles given by neutrino oscillation data can be reproduced, and the relic abundance of the DM can be explained with satisfying the constraints from the experiments such as LFV searches.

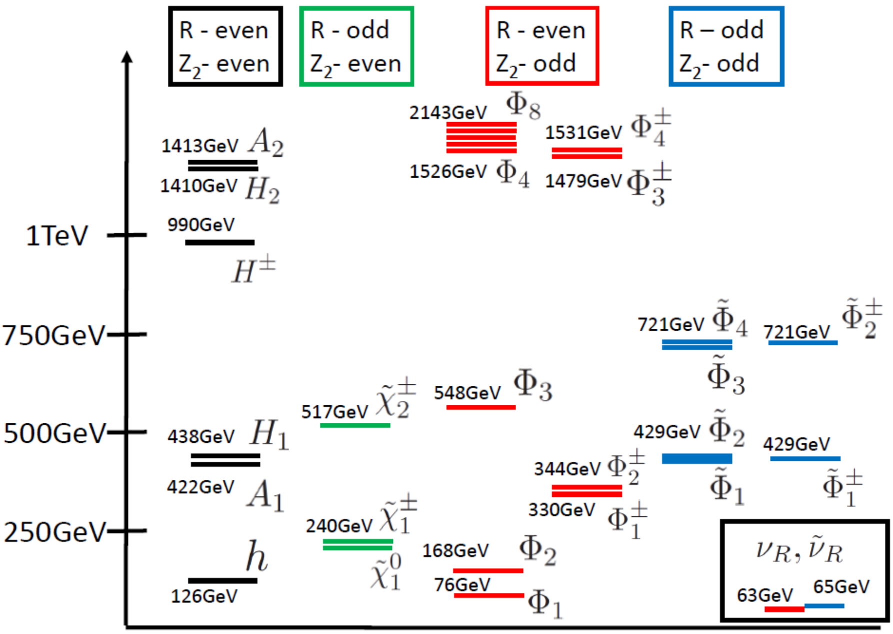

Fig. 11.2. The mass spectrum of the relevant particles in the bench mark scenario. The figure is taken from Ref.[1].

Though this point is already excluded by the direct detection experiment of the DM[9], we discuss phenomenological consequences of this benchmark scenario, because we can see some general features of our model in the scenario. In Fig. 11.2, the mass spectrum of the relevant particles in this benchmark scenario is shown. The Z_2-even part of the spectrum is similar to one in nMSSM. A significant size of mass splitting between the charged Higgs boson and the heavy Higgs bosons is required for obtaining the large mixing between doublet fields and a singlet field, which is necessary to reproduce the relic abundance of the DM. By looking at such a large splitting in the spectrum of extra Higgs bosons, the Z_2-even part of our scenario can be distinguished from the MSSM. In this benchmark scenario, φ_c/T_c is enhanced by the loop effect of Φ_u and Ω_-. The loop effect can also significantly affect the h-γ-γ coupling and the triple Higgs boson coupling as shown in Table 11.2. By using precise measurement of the SM-like Higgs boson couplings at future collider experiment such as ILC[10], our benchmark scenario can be distinguished from nMSSM too.

Couplings	hWW	hZZ	$h\bar{u}u$	$h\bar{d}d$	$h\bar{\ell}\ell$	$h\gamma\gamma$	hhh
$\kappa_{h\phi\phi} = g_{h\phi\phi}/g^{SM}_{h\phi\phi}$	0.990	0.990	0.990	0.978	0.978	0.88	1.2

Table 11.2. The deviations in the coupling constants from the SM values in the benchmark scenario defined in Ref. [1].

It is also interesting to discuss phenomenology in the Z_2-odd sector. By the direct search of inert doublet particles[11] and inert charged singlet searches[12] at ILC, it is expected to get a strong hint on the Z_2-odd sector of the scenario.

11.4 Conclusion

We have attempted to construct a simple model to solve the three problems such as baryogenesis, DM, and tiny neutrino mass, which cannot be explained in the SM. We have succeeded to find such a UV model based on SUSY $SU(2)_H$ gauge theory with confinement. In its low energy effective theory, we have shown that the 1stOPT is enhanced strongly enough for successful electroweak baryogenesis, multi-components DM scenario is realised, and tiny neutrino masses are generated via one-loop and three-loop diagrams. We have also introduced a benchmark scenario and we have discussed how to test it at future collider experiments. In this benchmark scenario, the spin-independent cross section of DM's are above the latest result of the DM direct detection experiments, so that we should look for a new benchmark scenario. In addition, we focus only on the 1stOPT for the baryogenesis. For complete analysis, new CP violation phases should be taken into account.

Recently, effects of CP violation in the singlet-doublet dark matter model is discussed and it is shown that the spin-independent cross section can be suppressed with a certain CP violation in the dark sector[13]. Therefore, it will be important to take CP phases in to account for evading the strong constraint from the direct detection of DMs as well as for complete analysis of the baryogenesis scenario.

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