Physics Letters B 738 (2014) 178–186

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Radiative neutrino mass, dark matter and electroweak baryogenesis from the supersymmetric gauge theory with confinement

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A R T I C L E I N F O

Article history:
Received 23 May 2014
Received in revised form 30 July 2014
Accepted 1 September 2014
Available online 10 September 2014
Editor: J. Hisano

A B S T R A C T

We propose a simple model to explain neutrino mass, dark matter and baryogenesis based on the extended Higgs sector which appears in the low-energy effective theory of a supersymmetric gauge theory with confinement. We here consider the $SU(2)_H$ gauge symmetry with three flavours of fundamental representations which are charged under the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry and a new discrete Z_2 symmetry. We also introduce a Z_2-odd right-handed neutrino superfield in addition to the standard model matter superfields. The low-energy effective theory below the confinement scale contains the Higgs sector with fifteen composite superfields, some of which are Z_2-odd. When the confinement scale is of the order of ten TeV, electroweak phase transition can be sufficiently of first order, which is required for successful electroweak baryogenesis. The lightest Z_2-odd particle can be a new candidate for dark matter, in addition to the lightest R-parity odd particle. Neutrino masses and mixings can be explained by the quantum effects of Z_2-odd fields via the one-loop and three-loop diagrams. We find a benchmark scenario of the model, where all the constraints from the current neutrino, dark matter, lepton flavour violation and LHC data are satisfied. Predictions of the model are shortly discussed.

1. Introduction

The Higgs boson has been discovered at the LHC, and its measured properties are currently consistent with the standard model (SM) [1]. However, the minimal Higgs sector in the SM is just an assumption. We still do not know the essence of the Higgs boson and the structure of the Higgs sector. Is the Higgs boson really a scalar particle or otherwise a composite state? What is the fundamental physics behind the Higgs dynamics? What is the origin of vacuum condensation? How many Higgs fields are there? Answers for these questions directly correspond to the paradigm of the fundamental theory beyond the SM. At the same time, the possibility of various extended Higgs sectors provides us an idea that the Higgs sector would be strongly related to the phenomena such as tiny neutrino masses and mixing [2], the existence of dark matter (DM) [3] and the baryon asymmetry of the Universe (BAU) [3], none of which can be explained in the SM.

Among several possibilities for baryogenesis [4,5], there is a scenario so-called electroweak baryogenesis [5], where the BAU could be explained by the dynamics of the Higgs potential when the electroweak phase transition is of strongly first order. It is well-known that the electroweak baryogenesis cannot be realized within the SM. Hence, a non-minimal Higgs sector has to be introduced for the successful scenario of electroweak baryogenesis [6–8]. With the discovered Higgs boson mass to be 126 GeV, the condition of the strong first-order phase transition (1stOPT) requires at least one of the self-coupling constants in the Higgs potential to be relatively large. A phenomenological consequence of the theory with the strong 1stOPT is a significantly larger triple Higgs boson coupling than the SM prediction, by which the scenario of the electroweak baryogenesis can be tested at future collider experiments [9]. At the same time, such a large self-coupling constant in the Higgs potential tends to cause early brow-up of the running coupling constant, and the Landau pole [10] can appear at the scale much below the Planck scale [11]. In this case, the ultraviolet picture above the Landau pole should also be considered [12].

One possible explanation for tiny neutrino masses is based on the seesaw mechanism, where neutrino masses are explained at the tree level with introducing very heavy right-handed (RH) neutrinos [13], Higgs triplet fields [14] or fermion triplet fields [15]. An alternative idea is to generate tiny neutrino masses radiatively by introducing extended Higgs sectors at the TeV scale. Since the original model was proposed by A. Zee [16], many models [17–22]

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http://dx.doi.org/10.1016/j.physletb.2014.09.013
0370-2693/

have been proposed along this line. In a class of models where neutrino masses are generated radiatively at loop levels, an unbroken discrete Z_2 symmetry and RH neutrinos are introduced such that the RH neutrinos have the odd quantum number to make neutrino Yukawa coupling constants absent at the tree level [17–19,22]. The same symmetry also guarantees the stability of the lightest Z_2-odd particle, so that it can be a DM candidate. The model proposed by E. Ma (the Ma model) is the simplest model of this category [17] where the neutrino masses are generated at the one-loop level, and in the model proposed in Ref. [18,19] (the AKS model) they are generated at the three-loop level. Both models have DM candidates. Furthermore, in the AKS model, the strong 1stOPT is also realized. Although these models are phenomenologically acceptable, additional scalar particles are introduced in an *ad-hoc* way which seems rather artificial. Fundamental theories are desirable in which these phenomenological models are deduced in the low-energy effective theory.

In this Letter, we propose a simple model whose low-energy effective theory can explain neutrino mass, DM and baryogenesis. In this model, the supersymmetric (SUSY) extended Higgs sector appears in the low-energy effective theory of a SUSY gauge theory with confinement [23]. With an additional Z_2 symmetry, all the scalar fields introduced in the Ma model and the AKS model automatically appear, so that introducing a RH neutrino superfield with the odd quantum number, neutrino mass, DM and baryogenesis can be explained simultaneously by a hybrid mechanism of the Ma model and the AKS model in the framework of SUSY. Consequently there are three kinds of the DM candidates: i.e., one comes from the lightest R-parity odd SUSY particle, another is the lightest Z_2-odd particle, and the other has odd-parity under both the Z_2 symmetry and R-parity, and the other is the lightest Z_2-odd particle so that the DM scenario of our model is multi-component DM scenario.

We introduce the $SU(2)_H$ gauge symmetry with three flavours of fundamental representations [12,24], which are charged under the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry and a new discrete Z_2 symmetry. In addition to the SM matter superfields, we also introduce Z_2-odd RH neutrino superfields. Then the low-energy effective theory below the confinement scale contains the Higgs sector with fifteen composite superfields, some of which are Z_2-odd. Electroweak phase transition can be of sufficiently strong first-order, when the confinement scale is of the order of ten TeV [11,25]. In addition to the lightest R-parity odd particle, the lightest Z_2-odd particle can be a new candidate for DM. We can explain neutrino masses and mixings by the quantum effects of Z_2-odd fields via the one-loop and three-loop diagrams.

We find a benchmark scenario of the model, where all the constraints from the current neutrino [2], DM [3,26,27], lepton flavour violation (LFV) [28] and LHC data are satisfied. We also comment on predictions of the model.

2. The SUSY gauge theory with confinement and its low-energy effective theory

Our model is based on a SUSY model with the $SU(2)_H \times Z_2$ symmetry. We introduce six chiral superfields, T_i $(i = 1, \dots, 6)$, which are doublet under the $SU(2)_H$ gauge symmetry. The chiral superfields T_i's also have gauge quantum number under the SM gauge symmetry, $SU(3)_C \times SU(2)_L \times U(1)_Y$, and moreover quantum numbers of the Z_2 parity are assigned. In addition, a RH neutrino superfield N_R^c is also introduced. As similar to the setup proposed in Ref. [25], this is a singlet chiral superfield for both the $SU(2)_H$ and the SM gauge symmetry but it has an odd parity under the Z_2 symmetry. The SM charges and the Z_2 parity assignments on T_i's and N_R^c are shown in Table 1.

Table 1
The SM charges and the Z_2 parity assignment on the $SU(2)_H$ doublets T_i and the $SU(2)_H$ singlet RH neutrino N_R^c.

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

Table 2
The field contents of the Higgs sector below the confinement scale Λ_H.

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

As investigated in Ref. [23], in the SUSY $SU(2)_H$ gauge theory with three flavours (six doublet chiral superfields), the $SU(2)_H$ gauge coupling becomes strong at a confinement scale which is denoted by Λ_H, and below Λ_H the low-energy effective theory is described in terms of fifteen canonically normalized mesonic composite chiral superfields, $H_{ij} \simeq \frac{1}{4\pi\Lambda_H} T_i T_j$ $(i \neq j)$ by using the Naive Dimensional Analysis [29]. The fifteen superfields are summarized in Table 2. With these mesonic fields, the superpotential in the Higgs sector of the low-energy effective theory is written as

$$\begin{aligned} W_{\text{eff}} = {} & \lambda N\big(H_u H_d + v_0^2\big) + \lambda N_\Phi \big(\Phi_u \Phi_d + v_\Phi^2\big) \\ & + \lambda N_\Omega \big(\Omega_+ \Omega_- - \zeta\eta + v_\Omega^2\big) + \lambda\{\zeta H_d \Phi_u + \eta H_u \Phi_d \\ & - \Omega_+ H_d \Phi_d - \Omega_- H_u \Phi_u - N N_\Phi N_\Omega\}, \end{aligned} \tag{1}$$

where the Naive Dimensional Analysis suggests $\lambda \simeq 4\pi$ at the confinement scale Λ_H. The relevant soft SUSY breaking terms are given by

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

where 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 after the Z_2-even neutral fields N, N_Φ and