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Higgs inflation in a radiative seesaw model

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ABSTRACT

We investigate a simple model to explain inflation, neutrino masses and dark matter simultaneously. This is based on the so-called radiative seesaw model proposed by E. Ma in order to explain neutrino masses and dark matter by introducing a Z_2-odd isospin doublet scalar field and Z_2-odd right-handed neutrinos. We study the possibility that the Higgs boson as well as neutral components of the Z_2-odd scalar doublet field can satisfy conditions from slow-roll inflation and vacuum stability up to the inflation scale. We find that a part of parameter regions where these scalar fields can play a role of an inflaton is compatible with the current data from neutrino experiments and those of the dark matter abundance as well as the direct search results. A phenomenological consequence of this scenario results in a specific mass spectrum of scalar bosons, which can be tested at the LHC, the International Linear Collider and the Compact Linear Collider.

1. Introduction

The new particle with the mass of 126 GeV which has been found at the LHC [1,2] is showing various properties that the Higgs boson must have. It is likely that the particle is the Higgs boson. If this is the case, the Standard Model (SM) of elementary particles is confirmed its correctness not only in the gauge interaction sector but also in the sector of electroweak symmetry breaking. By the discovery of the Higgs boson, all the particle contents in the SM are completed. This means that we are standing on the new stage to search for new physics beyond the SM. There are several empirical reasons why we consider the new physics. Phenomena such as neutrino oscillation [3–8], existence of dark matter [9] and baryon asymmetry of the Universe [9–11] cannot be explained in the SM. Cosmic inflation at the very early era of the Universe [12], which is a promising candidate to solve cosmological problems such as the horizon problem and the flatness problem, also requires the additional scalar boson, the inflaton.

The determination of the Higgs boson mass at the LHC opens the door to directly explore the physics at very high scales. Assuming the SM with one Higgs doublet, the vacuum stability argument indicates that the model can be well defined only below the energy scale where the running coupling of the Higgs self-coupling becomes zero. For the Higgs boson mass to be 126 GeV with the top quark mass to be 173.1 GeV and the coupling for the strong force to be $\alpha_s = 0.1184$, the critical energy scale is estimated to be around 10^{10} GeV by the NNLO calculation, although the uncertainty due to the values of the top quark mass and α_s is not small [13]. The vacuum seems to be metastable when we assume that the model holds up to the Planck scale. This kind of analysis gives a strong constraint on the scenario of the Higgs inflation [14] where the Higgs boson works as an inflaton, because the inflation occurs at the energy scale where the vacuum stability is not guaranteed in the SM. Recently, a viable model for the Higgs inflation has been proposed, in which the Higgs sector is extended including an additional scalar doublet field [15].

In order to generate tiny masses of neutrinos, various kinds of models have been proposed. The simplest scenario is so-called the seesaw mechanism, where the tiny neutrino masses are generated at the tree level by introducing very heavy particles, such as right-handed neutrinos [16], a complex triplet scalar field [17], or a complex triplet fermion field [18]. The radiative seesaw scenario is an alternative way to explain tiny neutrino masses, where they are radiatively induced at the one loop level or at the three loop level by introducing Z_2-odd scalar fields and Z_2-odd right-handed neutrinos [19–21]. An interesting characteristic feature in these radiative seesaw models is that dark matter candidates automatically enter into the model because of the Z_2 parity.

In this Letter, we discuss a simple model to explain inflation, neutrino masses and dark matter simultaneously, which is based on the simplest radiative seesaw model [20]. Both the Higgs boson and neutral components of the Z_2-odd scalar doublet can satisfy conditions for slow-roll inflation [22] and vacuum stability up to the inflation scale. We find that a part of the parameter region

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Table 1
Particle contents and their quantum charges.

	Q_L	u_R	d_R	L_L	ℓ_R	Φ_1	Φ_2	ν_R
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_I$	**2**	**1**	**1**	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$	0
Z_2	1	1	1	1	1	1	-1	-1

where these scalar fields can play a role of the inflaton is compatible with the current data from neutrino experiments and those of the dark matter abundance as well as the direct search results [23]. A phenomenological consequence of scenario results in a specific mass spectrum of scalar fields, which can be tested at the LHC, the International Linear Collider (ILC) [24] and the Compact Linear Collider (CLIC) [25].

2. Lagrangian

We consider the model, which is invariant under the unbroken discrete Z_2 symmetry, with the Z_2-odd scalar doublet field Φ_2 and right-handed neutrino ν_R to the SM with the SM Higgs doublet field Φ_1 [20]. Quantum charges of particles in the model are shown in Table 1. Dirac Yukawa couplings of neutrinos are forbidden by the Z_2 symmetry. The Yukawa interaction for leptons is given by

$$\mathcal{L}_{Yukawa} = Y_\ell \overline{L_L}\Phi_1 \ell_R + Y_\nu \overline{L_L}\Phi_2^c \nu_R + h.c., \tag{1}$$

where the superscript c denotes the charge conjugation. The scalar potential is given by [15]

$$\begin{aligned} V = {} & \frac{M_P^2 R}{2} + \left(\xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2\right)R \\ & + \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 \\ & + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ & + \left[\frac{1}{2}\lambda_5\left(\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right)\right], \end{aligned} \tag{2}$$

where M_P is the Planck scale ($M_P \simeq 10^{19}$ GeV), and R is the Ricci scalar.

We assume that $\mu_1^2 < 0$ and $\mu_2^2 > 0$. Φ_1 obtains the vacuum expectation value (VEV) v $(=\sqrt{-2\mu_1^2/\lambda_1} \simeq 246$ GeV), while Φ_2 cannot get the VEV because of the unbroken Z_2 symmetry. The lightest Z_2-odd particle is stabilized by the Z_2 parity, and it can act as the dark matter as long as it is electrically neutral. The quartic coupling constants should satisfy the following constraints on the unbounded-from-below conditions at the tree level;

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0. \tag{3}$$

Three Nambu–Goldstone bosons in the Higgs doublet field Φ_1 are absorbed by the Z and W bosons by the Higgs mechanism.

Mass eigenstates of the scalar bosons are the SM-like Z_2-even Higgs scalar boson (h), the Z_2-odd CP-even scalar boson (H), the Z_2-odd CP-odd scalar boson (A) and Z_2-odd charged scalar bosons ($H^\pm$). Masses of these scalar bosons are given by [20]

$$\begin{aligned} m_h^2 &= \lambda_1 v^2, \\ m_H^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2, \\ m_A^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2, \\ m_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2. \end{aligned} \tag{4}$$

3. Constraint on the model from inflation and dark matter

3.1. Inflation

We consider the Higgs inflation scenario [14,15,26] in our model defined in the previous section. The scalar potential is given in the Einstein frame by

$$V_E \simeq \frac{\lambda_1 + \lambda_2 r^4 + 2(\lambda_3 + \lambda_4)r^2 + 2\lambda_5 r^2\cos(2\theta)}{8(\xi_2 r^2 + \xi_1)^2}\left(1 - e^{-2\phi/\sqrt{6}}\right)^2, \tag{5}$$

where ϕ, r and θ are defined as

$$\begin{aligned} &\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 \end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 e^{i\theta} \end{pmatrix}, \\ &\phi = \sqrt{\frac{3}{2}}\ln\left(1 + \frac{\xi_1 h_1^2}{M_P^2} + \frac{\xi_2 h_2^2}{M_P^2}\right), \qquad r = \frac{h_2}{h_1}, \end{aligned} \tag{6}$$

with taking a large field limit $\xi_1 h_1^2/M_P^2 + \xi_2 h_2^2/M_P^2 \gg 1$.

For stabilizing r as a finite value, we need to impose following conditions [15];

$$\begin{aligned} &\lambda_2\xi_1 - (\lambda_3 + \lambda_4)\xi_2 > 0, \\ &\lambda_1\xi_2 - (\lambda_3 + \lambda_4)\xi_1 > 0, \\ &\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2 > 0. \end{aligned} \tag{7}$$

Parameters in the scalar potential should satisfy the constraint from the power spectrum [9,15];

$$\xi_2\sqrt{\frac{2(\lambda_1 + a^2\lambda_2 - 2a(\lambda_3 + \lambda_4))}{\lambda_1\lambda_2 - (\lambda_3 + \lambda_4)^2}} \simeq 5 \times 10^4, \tag{8}$$

$$\frac{\lambda_5}{\xi_2}\frac{a\lambda_2 - (\lambda_3 + \lambda_4)}{\lambda_1 + a^2\lambda_2 - 2a(\lambda_3 + \lambda_4)} \lesssim 4 \times 10^{-12}, \tag{9}$$

where a is given as $a \equiv \xi_1/\xi_2$. When the scalar potential satisfies the conditions in Eqs. (7)–(9), the model could realize the inflation.

3.2. Dark matter

We assume that the CP-odd boson A is the lightest Z_2-odd particle. (By changing the sign of the coupling constant λ_5, the similar discussion can be applied with the CP-even boson H to be the lightest.) When λ_5 is very small such as $\mathcal{O}(10^{-7})$, A is difficult to act as the dark matter because the scattering process $AN \to HN$ opens, where N is a nucleon. The cross section is too large to be consistent with the current direct search results for dark matter [27–29]. In Ref. [15], the authors claim that both the Higgs boson and Z_2-odd neutral scalar bosons can work as the inflatons when the dark matter (H or A) has the mass of 600 GeV if $\lambda_5 \lesssim 10^{-7}$. However, as recently discussed in Ref. [28], the bound from direct search results are getting stronger, and such a dark matter is not allowed anymore in this model without a fine tuning among the scalar self-coupling constants. We here take $\lambda_5 \simeq 10^{-6}$ and

$$a\lambda_2 - (\lambda_3 + \lambda_4) \simeq 10^{-1} \tag{10}$$

at the inflation scale. With this choice, the process $AN \to HN$ can be avoided kinematically. Still masses of A and H are almost the same value. The coannihilation process $AH \to XX$ via the Z boson is important to explain the abundance of the dark matter where X is a particle in the SM, because the pair annihilation process $AA \to XX$ via the h boson is suppressed due to the constraint from the inflation. The cross section of $AH \to XX$ depends only on the