A TeV scale model for neutrino mass, dark matter and baryon asymmetry

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We discuss a TeV scale model which would explain neutrino oscillation, dark matter, and baryon asymmetry of the Universe simultaneously by the dynamics of the extended Higgs sector and TeV-scale right-handed neutrinos with imposed an exact $Z_2$ symmetry. Tiny neutrino masses are generated at the three loop level, a singlet scalar field is a candidate of dark matter, and a strong first order phase transition is realized for successful electroweak baryogenesis. The model provides various discriminative predictions, so that it is testable at the current and future experiments.

1 Introduction

Today, we know that a new model beyond the standard model (SM) must be considered to understand the phenomena such as tiny neutrino masses and their mixing, the nature of dark matter (DM) and baryon asymmetry of the Universe.

In this talk, we discuss a model which would explain these problems simultaneously by an extended Higgs sector with TeV-scale right-handed (RH) neutrinos1. Tiny neutrino masses are generated at the three loop level due to an exact discrete symmetry, by which tree-level Yukawa couplings of neutrinos are prohibited. The lightest neutral odd state under the discrete symmetry is a candidate of DM. Baryon number can also be generated at the electroweak phase transition (EWPT) by additional CP violating phases in the Higgs sector2. In this framework, a successful model can be made without contradiction of the current data.

Original idea of generating tiny neutrino masses via the radiative effect has been proposed by Zee3. The extension with a TeV-scale RH neutrino has been discussed in Ref.4, where neutrino masses are generated at the three-loop level due to the exact $Z_2$ parity, and the $Z_2$-odd RH neutrino is a candidate of DM. This has been extended with two RH neutrinos to describe the neutrino data5. Several models with adding baryogenesis have been considered in Ref.6. The following advantages would be in the present model: (a) all mass scales are at most at the TeV scale without large hierarchy, (b) physics for generating neutrino masses is connected with that for DM and baryogenesis, (c) the model parameters are strongly constrained by the current data, so that the model provides testable and discriminative prediction at future experiments.

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We introduce two scalar isospin doublets with hypercharge 1/2 ($\Phi_1$ and $\Phi_2$), a real scalar singlet ($\eta$) and two generation isospin-singlet RH neutrinos ($N^\alpha_R$ with $\alpha = 1, 2$). We impose an exact $Z_2$ symmetry to generate tiny neutrino masses at the three-loop level, which we refer as $Z_2$. We assign $Z_2$-odd charge to $S^\pm$, $\eta$ and $N^\alpha_R$, while ordinary gauge fields, quarks and leptons and Higgs doublets are $Z_2$ even. In order to avoid the flavor changing neutral current, we impose another (softly-broken) discrete symmetry ($\tilde{Z}_2$). We assign $\tilde{Z}_2$ charges such that only $\Phi_1$ couples to leptons whereas $\Phi_2$ does to quarks, as summarized in Table 1. The Yukawa coupling in our model, which we refer to as the type-X, is different from that in the minimal supersymmetric SM (MSSM).

As $Z_2$ is exact, the even and odd fields cannot mix. Mass matrices for the $Z_2$ even scalars are diagonalized as in the usual THDM by the mixing angles $\alpha$ and $\beta$, where $\alpha$ diagonalizes the CP-even states, and $\tan \beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$. The $Z_2$ even physical states are two CP-even ($h$ and $H$), a CP-odd ($A$) and charged ($H^\pm$) states. We here define $h$ and $H$ such that $h$ is always the SM-like Higgs boson when $\sin(\beta - \alpha) = 1$.

2 Model

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3 Neutrino Mass, Dark Matter, 1st Order Phase Transition

The LH neutrino mass matrix $M_{ij}$ is generated by the three-loop diagrams in Fig. 1. To reproduce the neutrino data under the natural requirement on the coupling constant $h^\alpha_e \sim \mathcal{O}(1)$ in Fig. 1 and the $\mu \to e\gamma$ results, we find that $m_{N^\alpha_R} \sim \mathcal{O}(1)$ TeV, $m_{H^\pm} \lesssim \mathcal{O}(100)$ GeV, $\kappa \tan \beta \gtrsim \mathcal{O}(10)$, and $m_{S^\pm}$ being several times 100 GeV. On the other hand, the LEP direct search results indicate $m_{H^\pm}$ (and $m_{S^\pm}$) $\gtrsim 100$ GeV. In addition, with the LEP precision data for the $\rho$ parameter, the preferred values turn out to be $m_{H^\pm} \sim m_H$ (or $m_A$) $\sim 100$ GeV for $\sin(\beta - \alpha) \simeq 1$. Thanks to the Type-X Yukawa coupling, such a light $H^\pm$ is not excluded by the $b \to s\gamma$ data. Since we cannot avoid to include the hierarchy among $y_i^{\text{SM}}$, we only require $h^\alpha_{L_i}y_i \sim \mathcal{O}(y_e) \sim 10^{-5}$ for values of $h^\alpha_{L_i}$.

The lightest $Z_2$-odd particle is stable and can be a candidate of DM if it is neutral. In our model, $N^0_R$ must be heavy, so that the DM candidate is identified as $\eta$. When $\eta$ is lighter
than the W boson, \( \eta \) dominantly annihilates into \( b \bar{b} \) and \( \tau^+\tau^- \) via tree-level \( s \)-channel Higgs (\( h \) and \( H \)) exchange diagrams, and into \( \gamma\gamma \) via one-loop diagrams. From their summed thermal averaged annihilation rate \( \langle \sigma v \rangle \), the relic mass density \( \Omega h^2 \) is evaluated. Fig. 2(Left) shows \( \Omega h^2 \) as a function of \( m_\eta \). The data (\( \Omega_{\text{DM}}h^2 \approx 0.11 \)) indicate that \( m_\eta \) is around 40-65 GeV.

The model satisfies the necessary conditions for baryogenesis. Especially, departure from thermal equilibrium can be realized by the strong first order EWPT. For sufficient sphaleron decoupling in the broken phase, it is required that \( \varphi_c/T_c \gtrsim 1 \), where \( \varphi_c \) (\( \neq 0 \)) and \( T_c \) are the critical values of \( \varphi \) and \( T \) at the EWPT. In Fig. 2(Right), the allowed region under this condition is shown. The condition is satisfied when \( m_{S^\pm} \gtrsim 350 \text{ GeV} \) for \( m_A \gtrsim 100 \text{ GeV} \), \( m_h \approx 120 \text{ GeV} \), \( m_H \approx m_{H^\pm} (\approx M) \approx 100 \text{ GeV} \) and \( \sin(\beta - \alpha) \approx 1 \).

4 Phenomenology

A scenario which can simultaneously solve the three issues under the data \( [10,11,12] \) would be

\[
\sin(\beta - \alpha) \approx 1, \quad \kappa \tan \beta \approx 30, \quad m_h = 120 \text{GeV}, \quad m_H \approx m_{H^\pm} \approx O(100) \text{GeV}, \\
m_A \gtrsim O(100) \text{GeV}, \quad m_{S^\pm} \approx 400 \text{GeV}, \quad m_\eta \approx m_W, \quad m_{N_1^R} \approx m_{N_2^R} \approx 3 \text{TeV}.
\]

This is realized without assuming unnatural hierarchy among the couplings. All the masses are between \( O(100) \) GeV and \( O(1) \) TeV. The discriminative phenomenological properties of this scenario are discussed in details in Refs. [1] and [5]. We shortly summarize them in the following.

The SM-like Higgs boson \( h \) decays into \( \eta \eta \) when \( m_\eta < m_h/2 \). The branching ratio is about 30% for \( m_\eta \approx 43 \text{ GeV} \) and \( \tan \beta = 10 \). This is related to the DM abundance, so that our DM scenario is testable at the CERN Large Hadron Collider (LHC) and the International Linear Collider (ILC) by searching the missing decay of \( h \). Furthermore, \( \eta \) is potentially detectable by direct DM searches [12], because \( \eta \) can scatter with nuclei via the scalar exchange [15].

Because of Type-X Yukawa interaction [7,8], \( H \) (or \( A \)) can predominantly decay into \( \tau^+\tau^- \) instead of \( b \bar{b} \) for \( \tan \beta \gtrsim 2 \); \( B(H(A) \rightarrow \tau^+\tau^-) \approx 100 \% \) and \( B(H(A) \rightarrow \mu^+\mu^-) \approx 0.3 \% \) for \( m_A = m_H = 130 \text{ GeV} \), \( \sin(\beta - \alpha) = 1 \) and \( \tan \beta = 10 \). At the LHC (30 fb\(^{-1}\)), the model can be distinguished from the MSSM Higgs sector by using \( gg \rightarrow A(H) \rightarrow \ell^+\ell^- \) and \( pp \rightarrow b\bar{b}A \rightarrow b\bar{b}\ell^+\ell^- \) except for the intermediate region of \( \tan \beta \), where \( \ell \) represents \( \mu \) and \( \tau \).

In addition, our scenario with light \( H^\pm \) and \( H \) (or \( A \)) can be directly tested at the LHC (300 fb\(^{-1}\)) via \( pp \rightarrow W^* \rightarrow HH^\pm \) and \( AH^\pm \) [16] and also \( pp \rightarrow HA \). The process \( e^+e^- \rightarrow HA \) at the ILC can also be used. Their signals are four lepton states \( \ell^-\ell^+\tau^\mp \nu \) and \( \ell^-\ell^+\tau^\mp \tau^- \) [59].
For successful baryogenesis, $S^\pm$ has to have the non-decoupling property that affects the $hhh$ coupling. The $hhh$ coupling should deviate from the SM value by more than about 20% (see Fig. 2), which would be tested at the ILC and its $\gamma\gamma$ option. $S^\pm$ can be produced in pair at the LHC and the ILC, and decay into $\tau^\pm\nu_\eta$. The signal would be a hard hadron pair with a large missing energy. In addition, the Majorana nature in the sub-diagram in Fig. 1 can be directly tested by the process $e^-e^- \to S^-S^-$ at the ILC $e^-e^-$ option due to $h_\alpha^e \sim O(1)$.

Finally, we comment on the case with the CP violating phases. Our model includes the THDM, so that the same discussion can be applied in evaluation of baryon number at the EWPT. The mass spectrum would be changed to some extent, but most of the features discussed above should be conserved with a little modification.

5 Summary

In this talk, we have discussed the model with the extended Higgs sector and TeV-scale RH neutrinos, which would explain neutrino mass and mixing, DM and baryon asymmetry by the TeV scale physics. It gives specific predictions on the collider phenomenology. In particular, the predictions on the Higgs physics are completely different from those in the MSSM, so that the model can be distinguished at the LHC and also at the ILC.

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