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Phenomenological constraints on light mixed sneutrino dark matter scenarios

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ABSTRACT

In supersymmetric models with Dirac neutrinos, the lightest sneutrino can be a good thermal dark matter candidate when the soft sneutrino trilinear parameter is large. In this paper, we focus on scenarios where the mass of the mixed sneutrino LSP is of the order of GeV so the sneutrino dark matter is still viable complying with the limits by current and near future direct detection experiments. We investigate phenomenological constraints in the parameter space of the models, as well as the vacuum stability bound. Finally, we show that the allowed regions can be explored by measuring Higgs boson properties at future collider experiments.

1. Introduction

On July 4th, 2012, the ATLAS and CMS Collaborations of the CERN Large Hadron Collider (LHC) announced the discovery of a new particle with a mass of 125 GeV [1]. The spin and parity properties of the new particle as well as its couplings to Standard Model (SM) particles have been investigated, and proven to be consistent with the prediction of the SM. The SM has been established as a low energy effective theory that explains phenomena at energy scales below $\mathcal{O}(100)$ GeV.

Although the SM is extraordinarily successful, there are still unresolved problems. The observation of neutrino oscillations reveals that neutrinos must have finite masses and contradicts the SM, where the neutrinos are massless [2]. Cosmological observations precisely determine the energy density of dark matter (DM) in the universe while there is no candidate particle that can fulfill the dark matter abundance in the SM [3,4]. From the theoretical viewpoint, in order to explain the observed Higgs boson mass in the framework of the SM an unnaturally huge fine-tuning between its bare mass squared and contributions from radiative corrections is required. We are obliged to construct a more fundamental theory beyond the SM to tackle these difficulties.

The problems mentioned above are solvable in supersymmetric (SUSY) extensions with right-handed neutrino chiral supermultiplets [5–20]. The couplings of the right-handed neutrinos to the left-handed counterparts provide a source of the observed neutrino masses, which are either Dirac- or Majorana-type. The hierarchy problem is avoided by introducing SUSY: The quadratically divergent SM contributions to the Higgs boson mass squared are canceled out by those from diagrams involving superparticles whose spins differ from their SM counterparts by half a unit. It is intriguing that a viable candidate for dark matter other than conventional ones is automatically introduced as a by-product in this framework: The lightest sneutrino which is mainly made of the right-handed component. When such a sneutrino is the lightest SUSY particle (LSP), the observed dark matter abundance can be explained while satisfying other experimental constraints, in sharp contrast to left-handed sneutrino LSP scenarios which are excluded by the data of direct detection of dark matter. In particular, SUSY scenarios with Dirac neutrinos and large SUSY breaking sneutrino trilinear parameters can provide a viable left–right mixed sneutrino dark matter candidate [8,10,11,14,15,18–20]. Sneutrino trilinear parameters of the order of other soft SUSY breaking masses can be naturally realized in models where F-term SUSY breaking is responsible for the smallness of the neutrino Yukawa couplings and induce large mixings between the left- and right-handed sneutrino states [6]. Due to the large sneutrino trilinear coupling, the lightest mixed sneutrino behaves as a weakly interacting massive particle (WIMP) and its thermal relic abundance falls in the cos-

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mological dark matter abundance. So far, such mixed sneutrino WIMP scenarios have been screened in the light of experimental results. If the mixed sneutrino mass is of the order of 100 GeV, its thermal relic abundance can account for the observed dark matter abundance without contradicting experimental constraints. On the other hand, when the mass of the mixed sneutrino is smaller than half the mass of the discovered Higgs boson, its invisible decay rate is significantly enhanced. It has been shown that such a light sneutrino dark matter scenario is excluded in the light of the LHC results if the gaugino mass universality is imposed [18].

In this paper, we explore the GeV-mass mixed sneutrino scenarios without gaugino mass universality. We show that when the lightest neutralino mass is of the order of the mixed sneutrino mass, the thermal relic abundance of the mixed sneutrino coincides with the observed dark matter abundance. It should be emphasized that the large sneutrino trilinear coupling makes our vacuum unstable. However, the vacuum stability bound in light mixed sneutrino WIMP scenarios has been neglected in earlier works. We compute the transition rate of our vacuum to a deeper one, and show that the vacuum stability bound is not severe. Although experimental constraints are very tight, there are some regions where mixed sneutrino WIMP scenarios are viable. We show that dark matter allowed regions can be examined by precisely measuring the invisible decay rate of the observed Higgs boson at future linear colliders.

The organization of this paper is as follows: In Section 2, the model of the mixed sneutrino dark matter is briefly reviewed. Experimental constraints on the model are summarized in Section 3. In Section 4, the vacuum stability bound in our model is discussed. Section 5 is devoted to a summary.

2. Model

Here, we briefly review the mixed sneutrino model with lepton number conservation, which is proposed in [6]. In this model, in addition to the usual matter content of the Minimal Supersymmetric Standard Model (MSSM), three generations of right-handed neutrinos ν_{Ri} (sneutrinos $\tilde{\nu}_{Ri}$) are introduced. Here, $i = 1, 2, 3$ denotes the generation. As a result, Dirac neutrino Yukawa interactions, soft right-handed sneutrino mass terms and soft trilinear couplings among the left-handed slepton doublet $\widetilde{\ell}_i$, $\widetilde{\nu}_{Ri}$ and the Higgs doublet with hypercharge $Y = 1/2$, h_u, which gives mass to the up-type quarks and Dirac neutrinos are added to the usual MSSM Lagrangian. The newly introduced soft terms are given by

$$\Delta\mathcal{L}_{\rm soft} = m^2_{\widetilde{N}_i}|\widetilde{\nu}_{Ri}|^2 + A_{\tilde{\nu}_i}\widetilde{\ell}_i\widetilde{\nu}^*_{Ri}h_u + \text{h.c.}\,, \tag{1}$$

where $m^2_{\widetilde{N}_i}$ are soft right-handed sneutrino mass parameters, and $A_{\widetilde{\nu}_i}$ are trilinear sneutrino A-parameters. In order to avoid lepton flavor violation, we have assumed that these soft parameters are diagonal in generation space. Majorana neutrino mass terms and the corresponding right-handed sneutrino bilinear terms are prohibited due to lepton number conservation.

Neglecting the contribution from the Dirac neutrino masses, the sneutrino mass matrix for one generation is written as

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\widetilde{L}} + \frac{1}{2}m_Z^2\cos 2\beta & \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\,v\sin\beta \\ \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\,v\sin\beta & m^2_{\widetilde{N}} \end{pmatrix}, \tag{2}$$

Table 1
Observables and experimental constraints.

Observable	Experimental result
Ωh^2	0.1196 ± 0.0062 (95% CL) [4]
$\sigma_{\rm N}^{\rm SI}$	$(m_{\rm DM},\ \sigma_{\rm N}^{\rm SI})$ constraints from LUX [21] and SuperCDMS [22]
$\sigma_{\rm ann}v$	$(m_{\rm DM},\ \sigma_{\rm ann}v)$ constraint from FermiLAT [23]
$\Delta\Gamma(Z \to \text{inv.})$	< 2.0 MeV (95% CL) [24]
${\rm Br}(h \to \text{inv.})$	< 0.29 (95% CL) [25]
$m_{\tilde{\tau}_R}$	> 90.6 GeV (95% CL) [26]
$m_{\widetilde{\chi}_1^\pm}$	> 420 GeV (95% CL) [26]
$m_{\tilde{g}}$	> 1.4 TeV (95% CL) [27,28]

where $m^2_{\widetilde{L}}$ is the soft mass parameter for the left-handed slepton doublet. The sum of the squares of the vacuum expectation values and the ratio of the vacuum expectation values are given by $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$ and $\tan\beta = v_2/v_1$, respectively. Here, v_1 (v_2) is the vacuum expectation value of the Higgs doublet with hypercharge $Y = -1/2$ ($Y = 1/2$). In this model, the $A_{\tilde{\nu}}$ is not suppressed by the smallness of the corresponding neutrino Yukawa coupling, but is of the order of other soft parameters. This large $A_{\tilde{\nu}}$ parameter gives a large mixing between the left-handed and right-handed sneutrinos,

$$\tilde{\nu}_1 = \cos\theta_{\tilde{\nu}}\,\tilde{\nu}_R - \sin\theta_{\tilde{\nu}}\,\tilde{\nu}_L\,, \quad \tilde{\nu}_2 = \sin\theta_{\tilde{\nu}}\,\tilde{\nu}_R + \cos\theta_{\tilde{\nu}}\,\tilde{\nu}_L\,, \tag{3}$$

with $m_{\tilde{\nu}_1} < m_{\tilde{\nu}_2}$, and the sneutrino mixing angle $\theta_{\tilde{\nu}}$ is given by

$$\sin 2\theta_{\tilde{\nu}} = \left(\frac{\sqrt{2}A_{\tilde{\nu}}\,v\sin\beta}{m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1}}\right). \tag{4}$$

It should be emphasized that the couplings of the lighter sneutrino to the Z-boson, the Higgs boson and neutralinos are suppressed by a power of the small mixing angle $\theta_{\tilde{\nu}}$, compared to those of the MSSM left-handed sneutrinos. The smallness of the sneutrino interactions plays an important role in satisfying experimental constraints as discussed in the next section. The Feynman rules for such sneutrino interactions are given by

$$\begin{aligned} Z^\mu\tilde{\nu}_1^*(p')\tilde{\nu}_1(p)\ &: -i\frac{e}{\sin 2\theta_W}(p+p')^\mu\sin^2\theta_{\tilde{\nu}}\,, \\ h\tilde{\nu}_1^*\tilde{\nu}_1\ &: iem_Z\frac{\sin(\alpha+\beta)}{\sin 2\theta_W}\sin^2\theta_{\tilde{\nu}} \\ &\quad + i\frac{2\cos\alpha}{v\sin\beta}\sin^2\theta_{\tilde{\nu}}\cos^2\theta_{\tilde{\nu}}(m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1})\,, \\ \tilde{\nu}\overline{\nu_1}\widetilde{\chi}_i^0\ &: \frac{-ig}{2\sqrt{2}\sin 2\theta_W}(\cos\theta_W N_{i2} - \sin\theta_W N_{i1}) \\ &\quad \times\sin\theta_{\tilde{\nu}}(1-\gamma_5)\,, \end{aligned} \tag{5}$$

where e is the electric charge, g the $SU(2)_L$ coupling constant, m_Z the Z-boson mass and θ_W the Weinberg angle. As for SUSY parameters, α is the Higgs mixing angle, and the matrix N_{ij} diagonalizes the neutralino mass matrix.

In the rest of this paper, for simplicity, we focus on the cases where the lighter of the tau sneutrinos is a GeV-mass thermal WIMP candidate. We assume that the lighter sneutrinos of the first two generations are too heavy to affect experimental constraints on such GeV-mass tau sneutrino WIMP scenarios.

3. Experimental constraints

Thermal WIMP candidates have been extensively tested through many experiments. In particular, if the WIMP is lighter than half of the mass of the Higgs boson and interacts with the Higgs boson, such light WIMP models can be probed also through searches for the invisible decay of the Higgs boson. We list relevant experimental constraints imposed on light tau sneutrino WIMP scenarios in Table 1, and comment on the constraints below.

In general, dark matter candidates must be consistent with the upper limit of the dark matter relic density [4]. In our model, if the mass of the sneutrino WIMP is less than 10 GeV, sneutrinos tend