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A natural connection between neutrino mass generation and the lightness of a next-to-minimal supersymmetric Standard Model pseudoscalar

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Abstract. One of the attractive properties of the NMSSM is that it can accommodate a light pseudoscalar of order 10 GeV. However, such scenarios are constrained by several experimental results, especially those related to the fermionic decays of the pseudoscalar. In this work, extending the NMSSM field content by two gauge singlets, with lepton number +1 and −1, we generate neutrino masses via the inverse see-saw mechanism at one hand and on the other hand a very light pseudoscalar becomes experimentally viable by having dominant invisible decay channels which help it to evade the existing bounds.

Keywords. Neutrino mass; inverse see-saw; next-to-minimal supersymmetric Standard Model.

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The next-to-minimal supersymmetric Standard Model (NMSSM) provides a natural solution to the so-called μ problem through the vacuum expectation value (VEV) of a new gauge singlet superfield $\hat{S}$ in the superpotential [1,2]. This is the simplest supersymmetric generalization of the Standard Model (SM) that permits a scale invariant superpotential, thus the supersymmetry breaking scale is the only mass scale in the Lagrangian. One of the most appealing aspect of the NMSSM is related to the fact that it can admit a very light CP-odd Higgs boson ($m_{A_1} \sim$ 1–10 GeV) [1,2]. The main focus of this work is to improve the experimental viability of such a light pseudoscalar by attributing it a dominant invisible decay mode in a minimal extension of the NMSSM which contains a source of lepton number violation that also yields an acceptable neutrino mass [3].

In the NMSSM, the lightest CP-odd physical scalar A_1 can be decomposed as,

$$A_1 \equiv \cos\theta_A A_{\rm MSSM} + \sin\theta_A A_S\,, \quad (1)$$

where $A_{\rm MSSM}$ is the MSSM part of the CP-odd scalar, which arises solely from the NMSSM Higgs doublets and A_S is the part that arises from the new singlet superfield

$\hat{S}$. The detection of A_1 depends on its couplings to quarks and leptons through the prefactor $\cos\theta_A$. These couplings can be written as $\mathcal{L}_{A_1 f\bar{f}} = X_{u(d)}(gm_f/2M_W)\bar{f}\gamma_5 f A_1$ [4]. Here g is the $SU(2)$ gauge coupling, $X_d(X_u) = \cos\theta_A \tan\beta$ ($\cos\theta_A \cot\beta$) for down-type (up-type) fermions, $\tan\beta \equiv v_u/v_d$ with v_u and v_d denoting the up- and down-type Higgs VEVs.

The main interests behind a light pseudoscalar are the following (see for e.g. [3] and references therein):

(1) If A_1 is light, then h may dominantly decay into a pair of A_1, with each A_1 decaying into $f\bar{f}$, where f is the SM fermion. Therefore, the existing LEP-2 Higgs search strategy from $2b$ final states would fail as one should look for $4f$ final states. This allows a reduced value of m_h as low as 105 GeV which is in fact preferred by electroweak precision tests.
(2) If the lightest supersymmetric particle (LSP) happens to be very light (a few GeV), then a light A_1 can help to satisfy the observed dark matter relic abundance via s-channel LSP pair-annihilation processes.

Let us now briefly discuss the existing bounds on the mass of the light pseudoscalar. The constraints on X_d for m_{A_1} approximately in the range of 1–10 GeV have been summarized in [2,4,5]. Measurements of $\Delta M_{d,s}$, $\mathrm{Br}(\bar{B} \to X_s\gamma)$, $\mathrm{Br}(B^+ \to \tau^+\nu_\tau)$, $\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)$, $\mathrm{Br}(\bar{B}_s \to \mu^+\mu^-)$ and radiative Υ decays namely, $\Upsilon(nS) \to \gamma A_1$, with $A_1 \to \mu^+\mu^-(\tau^+\tau^-)$ or $\eta_b - A_1$ mixing may severely constrain mass and coupling of A_1. LEP (ALEPH and OPAL) results may also constrain A_1 in the same mass range. Different m_{A_1} windows which are sensitive to different processes are listed in table 1 in ref. [3]. The origin of all these constraints can be traced to the visible decay modes of A_1.

The situation may change appreciably if A_1 has dominant invisible decay modes. However there exists a strong constraint coming from the radiative Υ-decays which sets the upper limit on $\mathrm{Br}(\Upsilon(3S) \to \gamma A_1) \times \mathrm{Br}(A_1 \to \text{invisible})$ at $(0.7–31) \times 10^{-6}$ for m_{A_1} in the range of 3–7.8 GeV 90% CL [6].

In this work we further explore the possibility of invisible decay channels that would allow a light A_1 to escape detection even outside the range of 3–7.8 GeV. To achieve our purpose, we extend the NMSSM by two additional gauge singlets with non-vanishing lepton numbers, which provide a substantial invisible decay channel to A_1 along with the small masses for neutrinos through lepton number violating ($\Delta L = 2$) interaction.

Our superpotential is given by

$$W = W_{\mathrm{NMSSM}} + W' \,, \tag{2}$$

where

$$W_{\mathrm{NMSSM}} = f^d_{ij}\hat{H}_d\hat{Q}_i\hat{D}_j + f^u_{ij}\hat{H}_u\hat{Q}_i\hat{U}_j + f^e_{ij}\hat{H}_d\hat{L}_i\hat{E}_j + \lambda_H\hat{H}_d\hat{H}_u\hat{S} + \frac{\kappa}{3}\hat{S}^3,$$
$$W' = f^\nu_{ij}\hat{H}_u\hat{L}_i\hat{N}_j + (\lambda_N)_i\hat{S}\hat{N}_i\hat{X}_i + \frac{(\lambda_X)_i}{2}\hat{S}\hat{X}_i\hat{X}_i \,.$$

Here, $\hat{H}_d$ and $\hat{H}_u$ are the down- and up-type Higgs superfields, respectively; $\hat{Q}_i$ and $\hat{L}_i$ denote the $SU(2)$ doublet quark and lepton superfields, respectively; $\hat{U}_i$, $\hat{D}_i$ and $\hat{E}_i$ are

Table 1. Invisible branching ratios of the lightest NMSSM pseudoscalar for $m_D = 10$ GeV, $M_N = (5, 30)$ GeV and $\mu_X = 1$ eV.

	$\tan\beta = 20, \cos\theta_A = 0.1$		$\tan\beta = 3, \cos\theta_A = 0.1$	
M_N (GeV)	5	30	5	30
$\mathrm{Br}(A_1 \to \Psi_N\Psi_X)$	0.7	0.9	~1	~1

the $SU(2)$ singlet up- and down-type quark superfields and the charged lepton superfields, respectively and $\hat{S}$ is the singlet superfield already present in the minimal NMSSM. Besides, we have added two more gauge singlets $\hat{N}$ and $\hat{X}$, for each generation (with lepton numbers -1 and $+1$), in a way that implements the 'inverse see-saw' [7] mechanism in the minimal NMSSM framework. Considering only one generation, the neutrino masses after diagonalization turns out to be ($m_1 \ll m_{2,3}$)

$$m_1 = \frac{m_D^2 \mu_X}{m_D^2 + M_N^2}, \quad m_{2,3} = \mp\sqrt{M_N^2 + m_D^2} + \frac{M_N^2 \mu_X}{2(m_D^2 + M_N^2)}. \tag{3}$$

One of the main motivations of inverse see-saw is that here the lightness of the smallest eigenvalue m_1 can be attributed to the smallness of μ_X ($\mu_X \simeq m_1$). Having this small dimensionful term in the Lagrangian is technically natural in the sense of 't Hooft [8], as in the limit of vanishing μ_X one recovers the lepton number symmetry.

We now compute the branching ratios of A_1 into the invisible modes comprising of the Ψ_ν, Ψ_N and the Ψ_X states. The most dominant invisible decay mode of A_1 is $\Psi_N\Psi_X$ which depends on $\sin\theta_A$ and can be expressed as (normalized to the visible ones) [3]

$$\frac{\mathrm{Br}(A_1 \to \Psi_N\Psi_X)}{\mathrm{Br}(A_1 \to f\bar{f}) + \mathrm{Br}\,(A_1 \to c\bar{c})} \simeq \tan^2\theta_A \frac{M_N^2}{m_f^2 \tan^2\beta + m_c^2 \cot^2\beta} \frac{v^2}{v_S^2}, \tag{4}$$

where $f = \mu, \tau, b$ and

$$v = \sqrt{v_u^2 + v_d^2} \simeq 174 \text{ GeV}.$$

For numerical illustration, we choose two values of $\tan\beta$ (=3, 20), fix $\cos\theta_A = 0.1$ and consider two values for M_N (= 5, 30 GeV). Though for $\tan\beta = 20$, the resultant X_d (=2) is above its upper limit within minimal NMSSM, for $\tan\beta = 3$, X_d (= 0.3) is of course well within the allowed limit. In the present scenario, A_1 has a significant branching ratio into invisible modes which, in turn, considerably relax the upper bound on X_d (see table 1).

To conclude, the main lesson is that if $\cos\theta_A$ is small, A_1 has a dominant singlet component. Then for a reasonable part of the parameter space A_1 can have a sizable invisible branching ratio in this scenario and this would weaken many of the stringent constraints.

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