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An origin for small neutrino masses in the NMSSM

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Abstract: We consider the Next to Minimal Supersymmetric Standard Model (NMSSM) which provides a natural solution to the so-called μ problem by introducing a new gauge-singlet superfield S. We realize that a mechanism of neutrino mass suppression arises, based on the R-parity violating bilinear terms $\mu_i L_i H_u$ mixing neutrinos and higgsinos, offering thus an original approach to the neutrino mass problem (connected to the solution for the μ problem). We generate realistic (Majorana) neutrino mass values without requiring any strong hierarchy amongst the fundamental parameters, in contrast with the alternative models. In particular, the ratio $|\mu_i/\mu|$ can reach $\sim 10^{-1}$, unlike in the MSSM where it has to be much smaller than unity. We check that the obtained parameters also satisfy the collider constraints and internal consistencies of the NMSSM. The price to pay for this new cancellation-type mechanism of neutrino mass reduction is a certain fine tuning, which get significantly improved in some regions of parameter space. Besides, we discuss the feasibility of our scenario when the R-parity violating bilinear terms have a common origin with the μ term, namely when those are generated via a VEV of the S scalar component from the couplings $\lambda_i S L_i H_u$. Finally, we make comments on some specific phenomenology of the NMSSM in the presence of R-parity violating bilinear terms.

Keywords: Supersymmetry Phenomenology, Supersymmetric gauge theory, Extended Supersymmetry, Neutrino Physics.

Contents

1. Introduction

The most severe theoretical drawback of the Standard Model (SM) is probably the gauge hierarchy problem (see for example [1]). In well defined supersymmetric extensions of the SM, the property of cancellation of quadratic divergences allows to address this problem. With regard to the field content, the most economical candidate for such a realistic extension is the Minimal Supersymmetric Standard Model (MSSM). Nevertheless, within the MSSM, there are two unexplained hierarchies.

The first one is intrinsic to supersymmetric models: it is named as the μ problem [2]. It arises from the presence of a mass (μ) term for the Higgs fields in the superpotential. The only two natural values for this μ parameter are either zero or the Planck energy scale. While the former value is excluded by experiments as it gives rise to the unacceptable existence of an axion, the latter one reintroduces the gauge hierarchy problem.

The other hierarchy with an unknown origin is the one existing between the small neutrino masses and the electroweak symmetry breaking scale ($\sim$ 100GeV). Indeed, during last years, neutrino oscillation experiments have confirmed that neutrinos are massive. Furthermore, the additional results, extracted from tritium beta decay experiments and cosmological data, indicate that the values of absolute neutrino masses are typically smaller than the eV scale.

In this paper, we propose a supersymmetric scenario which has the virtue of addressing simultaneously both of these hierarchy questions: the μ value naturalness *and* the neutrino mass smallness. A nice feature of our scenario is that the mechanisms generating the two hierarchy origins are connected, since they involve the same additional gauge-singlet superfield, providing thus a common source to the solutions of these two independent problems.

Our framework is the Next to Minimal Supersymmetric Standard Model (NMSSM) [3]. [1] The NMSSM provides an elegant solution to the μ problem through the introduction of a new gauge-singlet superfield S entering the scale invariant superpotential. The scalar component of S acquires naturally a Vacuum Expectation Value (VEV) of the order of the supersymmetry breaking scale, generating an effective μ parameter of order of the electroweak scale. Another appealing feature of the NMSSM is to soften the "little fine tuning problem" of the MSSM [5, 6]. The introduction of suitable non-renormalizable operators [7] can avoid the possibility of a cosmological domain wall problem [8] (see also [9] for a different approach to this problem). There exist different explanations for a μ value of order of the electroweak scale, but those arise in extended frameworks.

In supersymmetric extensions of the SM, there exist coupling terms violating the so-called R-parity symmetry [10, 11] which acts on fields like $(-1)^{3B+L+2S}$, B, L and S being respectively the Baryon number, Lepton number and Spin. From a purely theoretical point of view, these terms must be considered, even if some phenomenological limits apply on the R-parity violating ($\not R_p$) coupling constants [12 − 16]. As a matter of fact, these terms are supersymmetric, gauge invariant and some of them are renormalizable. Moreover, from the points of view of scenarios with discrete gauge symmetries [18, 19], Grand Unified Theories (GUT) [20]-[21] as well as string theories [26], there exists no fundamental argument against the violation of the R-parity symmetry [12]. In the present work, we consider the 'bilinear' R-parity violating term H_uL appearing in the superpotential, H_u and L being respectively the up Higgs and lepton doublet superfields. The existence/influence of the other $\not R_p$ terms will also be discussed. This bilinear interaction has been recently considered within the NMSSM context [17]. In particular, this type of interaction, which breaks the lepton number, mixes the higgsino and neutrinos together so that the neutrino field picks up a Majorana mass [27] (the generation of such a neutrino mass requires two units of L violation). Hence, no additional right handed neutrino has to be introduced in order to generate a non-vanishing neutrino mass term.

In our scenario, the smallness of absolute neutrino mass scale, with respect to electroweak scale, finds an origin in the following sense: the neutrino field acquires a mass of the eV order without requiring any high hierarchy among the fundamental parameters, namely between the NMSSM parameters (λ or μ, as we will see later) and the $\not R_p$ coupling constants (λ_i or μ_i, respectively). The price that one must pay here in order to suppress the neutrino mass is a certain fine tuning on some NMSSM parameters. However, this fine tuning can be greatly softened in specific regions of parameter space, since several NMSSM parameters enter the effective neutrino mass expression and some of them through power-law dependence.

There exist mainly two supersymmetric alternatives to our scenario: two other kinds of model [28, 29] have been suggested in order to address simultaneously the hierarchy ques-

[1]The phenomenology of the NMSSM was studied, for instance, in [4].

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tions of the μ naturalness *and* the neutrino lightness. We will compare the characteristics and numerical aspects of these two models with those of our scenario.

In next section, we study the simplest version of our scenario, taking into account the constraints on NMSSM parameter space issued from collider physics. For that purpose, we use the NMHDECAY program [30]. In section 3, we discuss a version where the bilinear $\not{R}_p$ terms are generated via the spontaneous breaking of a symmetry. Finally, we conclude in section 4.

2. Scenario I

2.1 Neutralino masses

• **Superpotential:** The superpotential of the NMSSM contains two characteristic terms in addition of the Yukawa couplings:

$$W_{NMSSM} = Y^u_{ij} Q_i H_u U^c_j + Y^d_{ij} Q_i H_d D^c_j + Y^\ell_{ij} L_i H_d E^c_j + \lambda S H_u H_d + \frac{1}{3}\kappa S^3, \tag{2.1}$$

$Y^{u,d,\ell}_{ij}$ being the Yukawa coupling constants (i, j, k are flavor indexes), λ and κ dimensionless coupling constants and Q_i, L_i, U^c_i, D^c_i, E^c_i, H_u, H_d, S respectively the superfields for the quark doublets, lepton doublets, up-type anti-quarks, down-type anti-quarks, anti-leptons, up Higgs, down Higgs, extra singlet under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. The $SU(2)_L$ product of the two Higgs doublets $H^T_d = (H^0_d, H^-_d)$ and $H^T_u = (H^+_u, H^0_u)$ is defined as,

$$H_u H_d = H^+_u H^-_d - H^0_u H^0_d. \tag{2.2}$$

The absence of terms $H_u H_d$ as well as S^2 and tadpoles is insured by a suitable discrete symmetry. An effective μ term, $\lambda\langle s\rangle H_u H_d$, is generated via a VEV for the scalar component s of the singlet superfield S.

In addition to the above NMSSM superpotential, we first consider the bilinear $\not{R}_p$ interactions:

$$W_I = W_{NMSSM} + \mu_i L_i H_u, \tag{2.3}$$

where μ_i are dimension-one $\not{R}_p$ parameters. The presence of the other renormalizable $\not{R}_p$ interactions, namely the trilinear $\not{R}_p$ interactions such as $\lambda_{i,j,k} L_i L_j E^c_k$, depends on the symmetries of the superpotential that one assumes. It is desirable that the superpotential symmetries forbid the trilinear $\not{R}_p$ interactions violating either the lepton or baryon number, or both (as does the R-parity symmetry for example), in order to guarantee the proton stability [31]. In other words, the whole superpotential symmetry should be either a Generalized Lepton (GLP), Baryon (GBP) or Matter (GMP) Parity. In case where some trilinear $\not{R}_p$ interactions are effectively present in the theory with significant coupling constant values, those can possibly induce direct contributions to neutrino masses through one-loop level diagrams involving squarks or sleptons [20, 32]. [2] The trilinear $\not{R}_p$ interactions also

[2]The trilinear $\not{R}_p$ couplings can also induce effective masses for neutrinos propagating in matter, via tree level squark or slepton exchanges, but the SNO results forbid these contributions to be dominant [33].

induce $L_i H_u$ interactions via the renormalization group equations, and the effective μ_i parameters generated in that way are naturally suppressed for small trilinear $\not{R}_p$ coupling constant values [34].

• **Soft terms:** In the soft supersymmetry-breaking part of the Lagrangian, there exist also $\not{R}_p$ terms [17]. In the presence of bilinear $\not{R}_p$ soft terms, the electroweak symmetry breaking can lead to a non-vanishing VEV for sneutrinos, denoted $\langle\tilde{\nu}_i\rangle$ and corresponding to a possible spontaneous breaking of R-parity. These VEV produce new mixings between the neutrinos and neutralinos, contributing then to Majorana neutrino masses.

However, the H_d and L_i superfields, having identical quantum numbers, can be redefined by an SU(4) rotation on $(H_d, L_i)^T$. Under this transformation, the $\not{R}_p$ parameters are modified. It is always possible to find a basis in which either $\langle\tilde{\nu}_i\rangle = 0$ or $\mu_i = 0$. Nevertheless, generally $\langle\tilde{\nu}_i\rangle$ and μ_i do not vanish simultaneously [16]. In the present framework, we will consider a basis where $\langle\tilde{\nu}_i\rangle = 0$ and $\mu_i \neq 0$.

• **Mass matrix:** Therefore, within our framework, the neutralino mass terms read as,

$$\mathcal{L}^m_{\tilde{\chi}^0} = -\frac{1}{2}\Psi^{0^T}\mathcal{M}_{\tilde{\chi}^0}\Psi^0 + H.c. \tag{2.4}$$

in the basis defined by $\Psi^{0^T} \equiv (\tilde{B}^0, \tilde{W}^0_3, \tilde{h}^0_d, \tilde{h}^0_u, \tilde{s}, \nu_i)^T$, where $\tilde{h}^0_{u,d}$ $(\tilde{s})$ is the fermionic component of the superfield $H^0_{u,d}$ (S) and the ν_i denote the neutrinos. In eq. (2.4), the neutralino mass matrix is given by,

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} \mathcal{M}_{NMSSM} & \xi^T_{\not{R}_p} \\ \xi_{\not{R}_p} & \mathbf{0}_{3\times 3} \end{pmatrix} \tag{2.5}$$

where $\mathcal{M}_{NMSSM}$ is the neutralino mass matrix which holds in the NMSSM with conserved R-parity (s, c standing for sin, cos):

$$\mathcal{M}_{NMSSM} = \begin{pmatrix} M_1 & 0 & -M_Z\ s\theta_W\ c\beta & M_Z\ s\theta_W\ s\beta & 0 \\ 0 & M_2 & M_Z\ c\theta_W\ c\beta & -M_Z\ c\theta_W\ s\beta & 0 \\ -M_Z\ s\theta_W\ c\beta & M_Z\ c\theta_W\ c\beta & 0 & -\mu & -\lambda v_u \\ M_Z\ s\theta_W\ s\beta & -M_Z\ c\theta_W\ s\beta & -\mu & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa\langle s\rangle \end{pmatrix}, \tag{2.6}$$

$\xi_{\not{R}_p}$ is the $\not{R}_p$ part of the matrix mixing neutrinos and neutralinos,

$$\xi_{\not{R}_p} = \begin{pmatrix} 0 & 0 & 0 & \mu_1 & 0 \\ 0 & 0 & 0 & \mu_2 & 0 \\ 0 & 0 & 0 & \mu_3 & 0 \end{pmatrix} \tag{2.7}$$

M_1 (M_2) is the soft supersymmetry breaking mass of the bino (wino), M_Z the Z^0 boson mass, θ_W the electroweak angle, $\tan\beta = v_u/v_d = \langle h^0_u\rangle/\langle h^0_d\rangle$ ($h^0_{u,d}$ being the scalar component of $H^0_{u,d}$) and

$$\mu = \lambda\langle s\rangle. \tag{2.8}$$

• **Parameters:** In this scenario, the independent parameters in the neutralino sector can be chosen as being the following set of variables,

$$\lambda,\ \kappa,\ \tan\beta,\ \mu,\ M_1,\ M_2. \tag{2.9}$$

We take these variables as free parameters at the electroweak scale. We adopt the convention of signs in which $\lambda > 0$, $\tan\beta > 0$ (without loss of generality) whereas κ and μ can take positive or negative values. Finally, we assume that λ, κ and the soft supersymmetry breaking parameters are real.

2.2 Effective neutrino mass

• **Mass expression:** We restrict ourselves to the case $|\mu_i/\mu| < 10^{-1}$ and to some parameter values (in particular sufficiently large $M_{1,2}$) such that the neutrino-neutralino mixing terms remain much smaller than the neutralino masses. Hence, the effective neutrino mass matrix is given in a good approximation by the following formula, having a "see-saw" type structure,

$$m_\nu = -\xi_{\not R_p}\ \mathcal{M}^{-1}_{NMSSM}\ \xi^T_{\not R_p}\ . \tag{2.10}$$

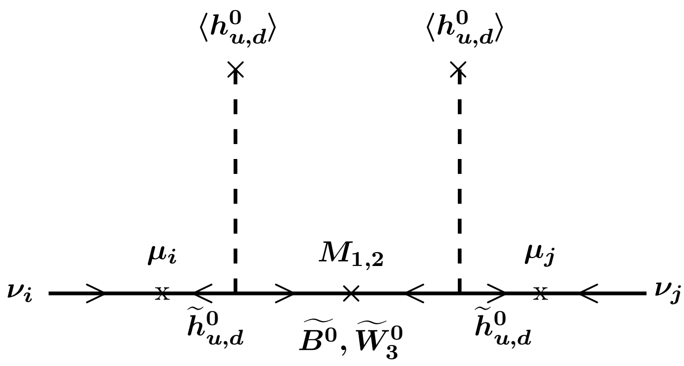
We have checked, through a comparison with an exact numerical diagonalization, that this block form expression represents systematically a good approximation for all the points of parameter space that we consider in this work. From eq. (2.6), eq. (2.7) and eq. (2.10), we deduce an analytic expression for the effective Majorana neutrino mass matrix:

$$m_{\nu ij} = \mu_i\mu_j \frac{M_1 M_2(2\kappa\mu/\lambda)}{Det(\mathcal{M}_{NMSSM})}\left(\frac{(\lambda v_u)^2}{2\kappa\mu/\lambda} + M_Z^2\left[\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right]\cos^2\beta\right), \tag{2.11}$$

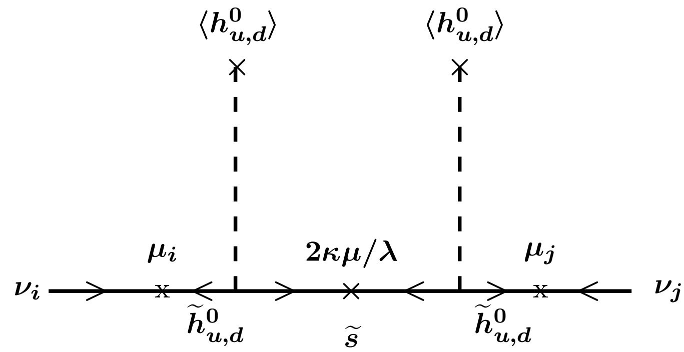
$Det(\mathcal{M}_{NMSSM})$ being the determinant of the matrix (2.6).

• **Origin of smallness:** We observe on neutrino mass matrix (2.11) that the overall factor can be significantly suppressed if the two terms in brackets compensate each other by taking opposite signs and approximately equal absolute values. This means that neutrino mass eigenvalues can be affected by an important suppression factor. This neutrino mass suppression has a different and new origin with respect to the other possible suppression coming from the smallness of ratio $|\mu_i/\mu|$ (c.f. eq. (2.11)). The smallness of $|\mu_i/\mu|$ constitutes an other (unexplained) mass hierarchy.

Let us understand this possible cancellation in eq. (2.11) from a diagramatic point of view. In figure (1), we present the two characteristic diagrams of neutralino mass contributions to Majorana neutrino mass terms. We see that the first term in brackets of neutrino mass expression (2.11) corresponds to the exchange of a gaugino shown in figure (1)(a). Indeed, this first term is of the type $\mu_i\mu_j(m^2/M)$, where m is the typical mass entering at the two vertex linked to a Higgs VEV and $M = M_{1,2}$ is the gaugino mass. The second term in brackets of formula (2.11) is associated to the exchange of the singlino $\tilde{s}$ shown in figure (1)(b): this term is also of the type $\mu_i\mu_j(m^2/M)$, where m is the typical mass at vertex with a Higgs VEV and now $M = 2\kappa\langle s\rangle = 2\kappa\mu/\lambda$ is the singlino mass (see eq. (2.6) and eq. (2.8)). In conclusion, an approximate cancellation between the two terms



(a)



(b)

Figure 1: (a) Feynman diagram for the typical contribution to the Majorana neutrino masses arising in the MSSM from mixing with neutralinos (see text for notations of fields and parameters). The effective mass affecting the two vertex is of type $m = \pm M_Z t(\theta_W) t(\beta)$, where $t(x)$ is equal to either $\sin x$ or $\cos x$. A cross indicates either a mass insertion or a VEV. The arrows show the flow of momentum for associated propagators. (b) Feynman diagram for the additional type of contribution to the Majorana neutrino masses arising in the NMSSM from mixing with neutralinos. The mass parameter at the two vertex is there $m = -\lambda v_{u,d}$.

in the brackets entering neutrino mass expression (2.11) would represent a compensation between the exchanges of a gaugino and a singlino.

The price of this neutrino mass suppression is a certain amount of fine tuning on some NMSSM parameter values. The λ parameter faces the most important fine tuning.

Nevertheless, this fine tuning is significantly reduced when $|\mu|$, $M_{1,2}$ and $\tan\beta$ increase. In next section, we discuss this aspect more precisely and quantitatively.

2.3 Numerical results

• **Flavors:** In the discussion of the main features of our scenario, we will concentrate on the case of one neutrino flavor, for simplification reasons. The treatment of the realistic three-flavor case requires the calculation of loop contributions to the neutrino mass matrix, via the Grossman-Haber diagrams [35] which kill the degeneracy in neutrino mass spectrum. Indeed, at the tree level, only one of the three neutrino eigenstates obtains a non-vanishing mass eigenvalue (from the mixing with neutralinos), a scheme which conflicts with present data as we know that solar and atmospheric neutrino data require at least two non-zero eigenvalues [36]. The possibility, that the combined tree and one-loop contributions could account for the observed data on three neutrino masses and three leptonic mixing angles, has been investigated extensively in the context of the MSSM [37]-[49]. Such a three-flavor global fit of all neutrino data at the loop level within the NMSSM is beyond the scope of our study. Nevertheless, we comment that, as in the MSSM, the soft supersymmetry breaking interactions (like $B_i h_u^0 \tilde{\nu}_i$) [35], the cancellations between contributions involving the Higgs sector modes [50] as well as the sneutrino mass splittings should play a crucial rôle in the computations for loop amplitudes of neutrino masses.

At one flavor, we see from eq. (2.11) that the neutrino mass can be written as,

$$m_\nu = \frac{\mu_1^2}{M_{SUSY}}, \tag{2.12}$$

where M_{SUSY} is an effective mass depending on the supersymmetry (breaking) parameters. In the three-flavor case, the only non-vanishing neutrino mass eigenvalue at tree level reads as,

$$m_\nu^{high} = \frac{\mu_1^2 + \mu_2^2 + \mu_3^2}{M_{SUSY}}. \tag{2.13}$$

At loop level, the two other neutrino mass eigenvalues receive loop contributions. We consider that the largest neutrino mass eigenvalue remains given by m_ν^{high} in eq. (2.13) to a good approximation. By consequence, the neutrino mass m_ν in eq. (2.12) that we will consider at one flavor, is approximately equal to the largest neutrino mass eigenvalue at three flavors, namely m_ν^{high} in eq. (2.13), for $\mu_{2,3}^2 \lesssim \mu_1^2$.

• **Neutrino mass constraints:** Let us summarize the existing experimental constraints on the largest neutrino mass eigenvalue m_ν^{high}. First, a three-flavor global fit analysis, including the results from solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K) experiments, leads to the following intervals at the 4σ level [36]: $6.8 \leq \Delta m_{21}^2 \leq 9.3 \quad [10^{-5}\text{eV}^2]$ and $1.1 \leq \Delta m_{31}^2 \leq 3.7 \quad [10^{-3}\text{eV}^2]$, $\Delta m_{21}^2 \equiv m_{\nu_2}^2 - m_{\nu_1}^2$ and $\Delta m_{31}^2 \equiv m_{\nu_3}^2 - m_{\nu_1}^2$ being the differences of squared neutrino mass eigenvalues. Hence, the largest neutrino mass eigenvalue is larger than about $\sqrt{3\ 10^{-3}\text{eV}^2}$, which can be written as,

$$0.05\text{eV} \lesssim m_\nu^{high}. \tag{2.14}$$

	κ	μ [GeV]	$\tan\beta$	M_1 [TeV]	M_2 [TeV]	μ_1 [GeV]	λ
A	0.05	-400	54	5	5	10 10^{-1}	$(9.0969-9.105)\ 10^{-3}$ $(1.43-2.8)\ 10^{-2}$
B	0.05	-300	50	1	1	10 10^{-1}	$(1.48759-1.48771)\ 10^{-2}$ $(1.613-2.31)\ 10^{-2}$
C	0.15	-300	30	5	5	10 10^{-1}	$(1.76374-1.764)\ 10^{-2}$ $(2.014-3.2)\ 10^{-2}$
D	0.2	-200	50	3	4	10 10^{-1}	$(1.3321-1.3323)\ 10^{-2}$ $(1.51-2.35)\ 10^{-2}$
E	-0.1	300	50	3	3	10 10^{-1}	$(1.29955-1.2999)\ 10^{-2}$ $(1.585-2.72)\ 10^{-2}$

Table 1: Sets (A,...,E) of values, for the parameters entering the whole neutralino mass matrix (2.5), which reproduce the correct neutrino mass. The two values of parameter λ correspond to the neutrino masses $m_\nu = 0.1\text{eV} - 1\text{eV}$ (m_ν being defined via eq. (2.11)), respectively. As the one-flavor case is considered here, the flavor index i of $R\!\!\!/_p$ parameter μ_i takes only the value $i=1$ (as in eq. (2.12)).

We now turn to the current upper experimental limits on absolute neutrino mass scales. We first consider the limits extracted from the tritium beta decay experiments [51 − 53] which are independent of the nature of neutrino mass (Majorana or Dirac). The data provided by the Mainz [52] and Troitsk [53] experiments give rise to the bounds (at 95% *C.L.*): $m_\beta \leq 2.2$ eV [Mainz] and $m_\beta \leq 2.5$ eV [Troitsk], where the effective mass m_β is defined by $m_\beta^2 = \sum_{i=1}^3 |U_{ei}|^2 m_{\nu_i}^2$, U_{ei} being the leptonic mixing matrix. This matrix is parameterized by the three mixing angles θ_{12}, θ_{23} and θ_{13} which are constrained to lie in the ranges [36]: $0.21 \leq \sin^2\theta_{12} \leq 0.41$, $0.30 \leq \sin^2\theta_{23} \leq 0.72$ and $\sin^2\theta_{13} \leq 0.073$. From the above constraints, we deduce that the largest neutrino mass eigenvalue is bounded from above typically by

$$m_\nu^{high} \lesssim 1\text{eV}. \tag{2.15}$$

Secondly, the cosmological data from WMAP and 2dFGRS galaxy survey [54] place the following bound (depending on cosmological priors): $\sum_{i=1}^3 m_{\nu_i} \lesssim 0.7\text{eV}$. This bound gives rise to an upper limit on the largest neutrino mass eigenvalue which is of the same order of magnitude as in eq. (2.15).

As we have discussed above, the largest neutrino mass eigenvalue m_ν^{high}, at three flavors, is approximately equal to the neutrino mass m_ν, at one flavor. One thus concludes from the typical bounds (2.14) and (2.15) that

$$0.1\text{eV} \lesssim m_\nu \lesssim 1\text{eV}. \tag{2.16}$$

• **Neutrino mass suppression:** In table 1, we present characteristic points of parameter space for which the neutrino mass (2.11) at one flavor, namely m_ν (c.f. eq. (2.12)),

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is equal to 0.1eV and 1eV, in order to cover the typical range of values allowed by experimental results (see eq. (2.16)).

In fact, for each of the sets of parameters shown in table 1, the λ value is determined as a function of the other parameters through the formula (2.11) for neutrino mass. In other terms, the relation (2.11) fixes one of the parameters (as the m_ν value is given) that we choose to be λ. The λ values are written with the accuracy necessary to obtain the wanted neutrino mass. This accuracy reflects two aspects: the fact that it is λ that we determine as a function of the other parameters, and, the fine tuning needed on λ (which will be discussed in more details in next table). As already said, λ is the quantity that suffers from the most important fine tuning.

Let us discuss the physical meaning of results presented in table 1. We remark that for the signs of parameters systematically chosen in this table (note the different sign configuration for last point E), the approximate cancellation between the two terms in brackets entering neutrino mass expression (2.11) is effective as these two terms possess opposite signs. The first possibility is that this cancellation is only partially responsible for the neutrino mass suppression relatively to the electroweak scale: this is the case for all the points in this table with $|\mu_1/\mu| \simeq 10^{-3}$ ($\mu_1 = 10^{-1}$GeV). In that case, the suppression of neutrino mass is also due to the hierarchy introduced between the $\not{R}_p$ parameter $|\mu_1|$ and the effective $|\mu|$ quantity (i.e. the smallness of $|\mu_1|$ reduces the neutrino-neutralino mixing and thus also suppresses the neutrino mass). The other possibility is that the above cancellation constitutes the main mechanism suppressing the neutrino mass: this happens when $|\mu_1/\mu| \simeq 10^{-1}$ ($\mu_1 = 10$GeV). Then, the fine tuning on λ is larger than in the previous possibility, as illustrates table 1 where the accuracy on λ is higher for $|\mu_1/\mu| \simeq 10^{-1}$ than for $|\mu_1/\mu| \simeq 10^{-3}$ (this relative fine tuning aspect is discussed more precisely and quantitatively in the later paragraph concerning table 2). Nevertheless, the necessary neutrino mass suppression is achieved here without introducing a strong hierarchy between $|\mu_1|$ and $|\mu|$.

This result, that the smallness of neutrino mass can be mainly due to a compensation between two contributions exchanging a gaugino and a singlino, is one of the major and new results of our paper.

• μ **naturalness:** Let us comment about the parameter values taken in table 1. Motivated by arguments of naturalness, one may wish to restrict to $\langle s \rangle < \mathcal{O}(10)$TeV, which translates (c.f. eq. (2.8)) into the condition $\mathcal{O}(|\mu|[\mathrm{GeV}] \times 10^{-4}) < \lambda$. The values obtained in table 1 verify $\lambda \sim |\mu|[\mathrm{GeV}] \times 10^{-4}$ and thus correspond to this approximative naturalness limit. Besides, the absence of Landau singularities, for λ, κ and the Yukawa coupling constants Y^b, Y^t below the GUT energy scale, imposes [55] the typical bounds on NMSSM parameters: $\lambda \lesssim 0.75$, $|\kappa| \lesssim 0.65$ and $1.7 \lesssim \tan\beta \lesssim 54$. All the parameter values in table 1 satisfy these bounds. Finally, the various values of μ in this table have been chosen such that $|\mu| \gtrsim 100$GeV, in order to safely respect the LEP bound on the lightest chargino mass: $m_{\tilde{\chi}_1^+} > 103.5$GeV [56].

In addition, we have checked that the parameter sets presented in table 1 belong well to some regions of the NMSSM parameter space which are compatible with the various theoretical consistencies and experimental constraints. For that purpose, we have

	$m_{\tilde{\chi}_1^0}$ [GeV]	$m_{\tilde{\chi}_5^0}$ [GeV]	$\mathcal{F}_\lambda$
A	399	5002	$(0.9 - 9.3)\ 10^{-4}$
	399	5002	$(2.5 - 3.2)\ 10^{-1}$
B	295	2017	$(0.9 - 9.0)\ 10^{-5}$
	294	1862 - 1303	$(0.7 - 2.4)\ 10^{-1}$
C	299	5103 - 5102	$(0.2 - 1.6)\ 10^{-4}$
	299	5002	$(1.1 - 2.8)\ 10^{-1}$
D	199	6006 - 6005	$(0.1 - 1.5)\ 10^{-4}$
	199	5310 - 4002	$(1.0 - 2.7)\ 10^{-1}$
E	299	4617 - 4616	$(0.3 - 2.7)\ 10^{-4}$
	298	3787 - 3003	$(1.5 - 3.0)\ 10^{-1}$

Table 2: Lowest $[m_{\tilde{\chi}_1^0}]$ and highest $[m_{\tilde{\chi}_5^0}]$ neutralino masses (among the six mass eigenvalues of matrix (2.5), except the neutrino mass eigenvalue m_ν) for the points A,. . . ,E of parameter space presented in table 1. Together with these masses, we also show the value of fine tuning function $\mathcal{F}_\lambda$ defined in the text for the λ parameter. The two values of ($m_{\tilde{\chi}_5^0}$ and) $\mathcal{F}_\lambda$ correspond respectively to the two λ values in table 1 (leading to $m_\nu = 0.1\text{eV} - 1\text{eV}$). For each point, the first and second lines are respectively associated to $\mu_1 = 10\text{GeV}$ and $\mu_1 = 10^{-1}\text{GeV}$, as in table 1.

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performed a scan, by using the Fortran code NMHDECAY [30], in order to test the following parameter ranges: $0.009 < \lambda < 0.02$, $0.05 < |\kappa| < 0.2$, $30 < \tan\beta < 54$ and $100\text{GeV} < |\mu| < 400\text{GeV}$. This scan was done simultaneously with a scan over $-1\text{TeV} < A_\lambda < 1\text{TeV}$ and $-1\text{TeV} < A_\kappa < 1\text{TeV}$, where A_λ and A_κ are the trilinear soft supersymmetry breaking parameters (entering the NMSSM Lagrangian via the terms $\lambda A_\lambda s h_u h_d$ and $(1/3)\kappa A_\kappa s^3$) which do not affect the neutralino mass matrix (2.5). Precisely, the NMHDECAY program has allowed us to check that [30] *(i)* the physical minimum of the scalar potential is deeper than the local unphysical minima with $\langle h^0_{u,d}\rangle = 0$ and/or $\langle s\rangle = 0$ *(ii)* the running couplings λ, κ, Y^b and Y^t do not encounter a Landau singularity *(iii)* the experimental constraints from LEP in the neutralino, chargino and Higgs sectors are effectively satisfied.

The consistency of using the code NMHDECAY (which strictly speaking deals with the pure NMSSM) in our present scenario is justified by the following argument. The presence of the additional bilinear $\not{R}_p$ term $\mu_i L_i H_u$ in the superpotential (see eq. (2.3)), that we have supposed, does not automatically modifies the Higgs potential of the NMSSM at tree level. Indeed, the term $\mu_i^2 |h_u|^2$ in the Higgs potential, coming from the bilinear $\not{R}_p$ term, can be reabsorbed in a redefinition of the soft Higgs mass term $m^2_{h_u}|h_u|^2$.

• **Fine tuning:** The mechanism of neutrino mass suppression presented in section 2.2 requires a certain amount of fine tuning. In order to discuss quantitatively this fine tuning on the λ parameter (the most important fine tuning), we introduce the following ratio,

$$\mathcal{F}_\lambda = \left|\frac{\delta ln\lambda}{\delta ln m_\nu}\right| = \left|\frac{\delta\lambda/\lambda}{\delta m_\nu/m_\nu}\right|, \tag{2.17}$$

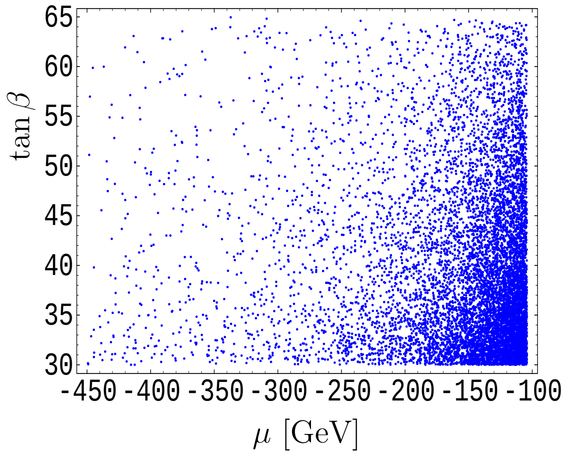

Figure 2: Points in the plan μ (in GeV) versus $\tan\beta$ producing a neutrino mass $m_\nu = 1$eV, for $\mu_1 = 1$GeV, $M_1 = 3$TeV, $M_2 = 4$TeV and values of λ and κ given by figure 3.

where δm_ν is the variation of neutrino mass associated to the variation $\delta\lambda$ of fundamental parameter λ, for any other parameter fixed to a certain value. The largest values of this quantity $\mathcal{F}_\lambda$ correspond to the smallest fine tuning. By using the neutrino mass expression (2.11), we have calculated analytically the quantity $\mathcal{F}_\lambda$ as a function of the fundamental parameters of the neutralino mass matrix.

In table 2, we give the values of this function $\mathcal{F}_\lambda$ for the points of parameter space presented in table 1 which generate acceptable neutrino masses through our cancellation mechanism. By comparing the points A and B of table 2, we observe, through the values of function $\mathcal{F}_\lambda$, that the fine tuning get smaller (larger $\mathcal{F}_\lambda$ value) as $M_{1,2}$ increases. Similarly, the comparison of parameter sets A and C (A and D) shows that the fine tuning is significantly improved for larger values of $\tan\beta$ ($|\mu|$). The point E, corresponding to different signs of κ and μ than for the other points, exhibits the weak dependence of fine tuning on the sign configurations. Finally, we remark that the fine tuning is smaller (larger $\mathcal{F}_\lambda$) for an higher neutrino mass (second $\mathcal{F}_\lambda$ values in table 2) as well as for a smaller $|\mu_i/\mu|$ ratio (second line for each point). The reason is that, in these two cases, the neutrino mass suppression mechanism, which is based on the compensation of two mass contributions, has to be less effective (i.e. it must suppresses less the absolute neutrino mass scale).

To finish the comments about table 2, we mention that, for each parameter set considered, the largest neutralino mass eigenvalue $m_{\tilde\chi^0_5}$ is of order of the TeV scale so that the gauge hierarchy problem remains addressed through the supersymmetry.

• **Scans:** In figure (2) and figure (3), we show points of the NMSSM parameter space generating a neutrino mass at one flavor (c.f. eq. (2.12)) equal to 1eV, for $\mu_1 = 1$GeV. This μ_1 value corresponds to $|\mu_1/\mu| \simeq 10^{-2}$, which means that, for the points presented in the two figures, the dominant effective suppression mechanism of neutrino mass is our cancellation mechanism (a ratio of $|\mu_i/\mu| \sim 10^{-6}$ is needed to obtain the entire neutrino mass reduction from the hierarchy between μ_i and μ, as we will discuss later).

The points in figure (2)-(3) have been obtained through a scan performed with the

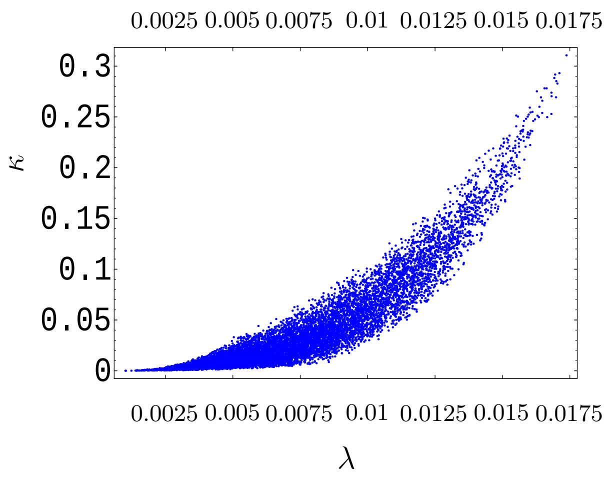

Figure 3: Points in the plan λ versus κ producing a neutrino mass $m_\nu = 1$eV, for $\mu_1 = 1$GeV, $M_1 = 3$TeV, $M_2 = 4$TeV and values of μ and $\tan\beta$ given by figure 2.

NMHDECAY program, so that they respect the experimental and theoretical constraints mentioned above.

These two figures show that an acceptable neutrino mass can be generated, via the considered cancellation model, in large regions of the NMSSM parameter space. Besides, figure (3) exhibits a correlation between the coupling constants λ and κ which is characteristic of the cancellation mechanism.

• **Lepton flavor violation:** In the present framework, we have shown that the experimental values of neutrino masses allow the ratio $|\mu_i/\mu|$ to be as large as $\sim 10^{-1}$. Such a possible enhancement of $|\mu_i/\mu|$ tends to increase the amplitudes of low energy lepton flavor violating processes like $\mu \to eee$ or $\mu \to e\gamma$. Indeed, these decay processes receive tree level contributions through the mixings of type $\mu_i \tilde{h}_u^+ \ell_i$. We obtain, via simple estimations (as done for instance in [44]), that the experimental upper limits [57] on the branching ratios of these decay processes are respected for $|\mu_i/\mu|$ values up to $\sim 10^{-2}$.

2.4 Comparison with the other models

Finally, we compare our scenario with existing alternative supersymmetric models. First, it has been suggested recently [29] that a gauge-singlet right handed neutrino N_i^c, added to the MSSM superfield content in order to generate Dirac neutrino masses (via $Y_{ij}^\nu L_i H_u N_j^c$), can also play the rôle of the NMSSM singlet S. Indeed, the scalar components of N_i^c (sneutrinos) can produce an effective μ term (via $\lambda^i N_i^c H_u H_d$) by acquiring a VEV. In this so-called new MSSM, the R-parity is broken explicitly via the cubic term for N_i^c ($(1/3)\kappa^{ijk} N_i^c N_j^c N_k^c$). The two other model-building differences of this new MSSM with our scenario are that, here, the added gauge-singlet N_i^c comes with a flavor index and has a right handed chirality (in contrast with S). Hence, in the new MSSM, there are three distinct origins to the neutrino mass: the mixing with gauginos/higgsinos, the Majorana neutrino mass proportional to κ^{ijk} and the Dirac neutrino mass involving the Yukawa coupling constants Y_{ij}^ν. These

Yukawa coupling constants must be of order 10^{-6} in order to obtain reasonable neutrino mass eigenvalues around 10^{-2}eV [29]. This means that a hierarchy of $\sim 10^{-6}$ has to be introduced between the Yukawa couplings of the neutrinos and the top quark ($Y^t \sim 1$). This has to be contrasted with our mechanism which can produce acceptable neutrino masses with only a little hierarchy of $|\mu_i/\mu| \sim 10^{-1}$. Concerning the μ problem, it was shown in [29] that the potential minimization conditions are similar to the ones in the NMSSM, with the substitution $N^c \leftrightarrow S$.

There exist another model [28] aimed at solving both the neutrino mass and μ term problems. Within this model, three gauge-singlets are added to the MSSM superfield content: a right handed neutrino N_i^c giving rise to Dirac neutrino masses, a singlet S addressing the μ naturalness "à la NMSSM", and, a singlet Φ_i which is essential in order to drive simultaneously a spontaneous breaking of the R-parity and electroweak symmetries in a phenomenologically consistent way. In this framework, it is not clear from the related literature [28] what must be the typical neutrino Yukawa coupling values in order to generate a physical neutrino mass scale around the eV.

We now compare our scenario, namely the NMSSM in the presence of the $\not R_p$ bilinear term $\mu_i L_i H_u$ (c.f. superpotential (2.3)), with the MSSM in the presence of this same bilinear term. The latter scenario, which suffers from the μ problem, was extensively studied in regard of the neutrino mass aspect [16].

Let us consider a generic basis in which $v_i = \langle \tilde{\nu}_i \rangle \neq 0$ and $\mu_i \neq 0$ simultaneously. Then, requiring a neutrino mass scale typically smaller than 1eV imposes the alignment [20, 58] of vectors $v_\alpha \equiv (v_d, v_i)$ and $\mu_\alpha \equiv (\mu, \mu_i)$ up to

$$\sin\zeta \lesssim 3\ 10^{-6}\ \sqrt{1+\tan^2\beta},$$

where the basis-independent angle ζ is defined by, [3]

$$\cos\zeta = \frac{\sum_\alpha v_\alpha \mu_\alpha}{\sqrt{(\sum_\alpha v_\alpha^2)(\sum_\alpha \mu_\alpha^2)}}.$$

Such an alignment arises naturally in the framework of horizontal symmetries, but it would then rely on the condition $|\mu_i| \ll |\mu|$, or more precisely $|\mu_i/\mu| < \mathcal{O}(10^{-5})$ in the first explicit realization proposed in [58]. Once more, this hierarchy is more dramatic than in our scenario, where a ratio $|\mu_i/\mu| \simeq 10^{-1}$ allows a sufficient neutrino mass suppression relatively to the electroweak energy scale.

Besides, in various accurate three-flavor analyzes [37]-[49], it was shown that the combined tree and loop MSSM contributions can accommodate the experimental measurements on neutrino masses and leptonic mixing angles. In particular, complete scans of the parameter space [41, 43, 46] have shown that the basis-independent quantities δ^i_μ and δ^i_B (see [40]) must be of order $|\delta^i_\mu| \sim 10^{-7}$ and $|\delta^i_B| \sim 10^{-5}$, assuming sparticle masses fixed at a common effective supersymmetry scale equal to 100GeV. In the basis where $v_i = 0$, these two quantities correspond respectively to the ratios $|\mu_i/\mu|$ and $|B_i/B|$ (μ_i and B_i can be negative), B being the soft supersymmetry breaking parameter entering the scalar

[3]For a general discussion on basis-independent parametrization, see [59].

potential via the interaction Bh_uh_d. So in this basis (that we have considered throughout the study of our scenario), the required ratio $|\mu_i/\mu| \sim 10^{-7}$ is much smaller than in our scenario where $|\mu_i/\mu|$ can reach $\sim 10^{-1}$, with respect to the correct order of magnitude for the neutrino mass scale. The trilinear $\not{R}_p$ terms, if included, do not change the order of magnitude of the ranges for δ^i_μ and δ^i_B, and, the $\not{R}_p$ trilinear coupling constants were found to be $\sim 10^{-4}$ to satisfy all constraints from neutrino data.

3. Scenario II

3.1 Neutralino masses

• **Superpotential:** We turn to a version of our scenario, proposed in section 2, where the bilinear $\not{R}_p$ interactions have the same origin as the μ term: those are now generated through the VEV of the scalar component of the S singlet superfield. Indeed, let us assume that the bilinear $\not{R}_p$ interactions of eq. (2.3) are forbidden by a symmetry (exactly like a symmetry is imposed within the NMSSM in order to kill the term $\mu H_u H_d$). Then the following supersymmetric and gauge invariant term, which is renormalizable, generates μ_i-like terms:

$$W_{II} = W_{NMSSM} + \lambda_i S L_i H_u, \tag{3.1}$$

where λ_i are new dimensionless coupling constants. This trilinear term, which has no analog in the MSSM, could be rotated away, by an SU(4) rotation on $(H_d, L_i)^T$, into the pure NMSSM term SH_uH_d. However, the trilinear term SL_iH_u would be regenerated via the renormalization group equations (in the presence of L violating couplings) [3–5]. We also note that no massless Goldstone boson (the problematic Majoron) appears when s acquires a VEV, since the lepton number is already explicitly broken by the trilinear term of eq. (3.1). This trilinear term also violates explicitly the R-parity symmetry, as the bilinear μ_i terms of superpotential (2.3). The existence of the other trilinear $\not{R}_p$ interactions depends on the superpotential symmetry. In order to protect the proton against its possible decay channels, this symmetry could be a GLP (killing $\lambda_{i,j,k} L_i L_j E^c_k$, $\lambda'_{i,j,k} L_i Q_j D^c_k$ and $\lambda_i S L_i H_u$), a GBP (killing $\lambda''_{i,j,k} U^c_i D^c_j D^c_k$) or a GMP (forbidding both L and B violating trilinear terms). It is desirable that all the global symmetries of the superpotential are discrete gauge symmetries [18, 19]. Under this hypothesis, by imposing the non-trivial conditions of linear anomaly (except the gravitational one) cancellation on the original Z_N cyclic local (R-)symmetries, the authors of [17] have shown that some residual symmetries of the three types, GLP, GBP or GMP, are possible within the NMSSM.

• **Mass matrix:** In this new framework, the Lagrangian containing the neutralino masses is the identical as (2.4) but with a different $\not{R}_p$ part of the mass matrix mixing neutrinos and neutralinos:

$$\xi'_{\not{R}_p} = \begin{pmatrix} 0 & 0 & 0 & \lambda_1\langle s\rangle & \lambda_1 v_u \\ 0 & 0 & 0 & \lambda_2\langle s\rangle & \lambda_2 v_u \\ 0 & 0 & 0 & \lambda_3\langle s\rangle & \lambda_3 v_u \end{pmatrix}. \tag{3.2}$$

Note the presence of the new mixings between $\tilde{s}$ and ν_i.

3.2 Effective neutrino mass

• **Mass expression:** Since we restrict to the situation $|\lambda_i/\lambda| < 10^{-1}$, the effective neutrino mass matrix is still given in a good approximation by the see-saw formula:

$$m_\nu = -\xi'_{\not R_p} \ \mathcal{M}^{-1}_{NMSSM} \ \xi'^{T}_{\not R_p} \ . \tag{3.3}$$

From eq. (2.6), eq. (3.2) and eq. (3.3), we derive analytically the following effective Majorana neutrino mass matrix,

$$m_{\nu ij} = \frac{\lambda_i}{\lambda}\frac{\lambda_j}{\lambda}\frac{M_1 M_2(2\kappa\mu/\lambda)}{Det(\mathcal{M}_{NMSSM})}\left(\frac{\lambda^2 v_u v_d}{2\kappa\mu/\lambda}+\frac{\mu}{2}\right)2\mu M_Z^2[\frac{\sin^2\theta_W}{M_1}+\frac{\cos^2\theta_W}{M_2}]\cos^2\beta. \tag{3.4}$$

In this scenario, we remark in eq. (3.4) that the specific ratio particularly relevant for the discussion becomes λ_i/λ instead of μ_i/μ (as in scenario I), since one has here (in terms of effective μ_i and μ parameters):

$$\frac{\mu_i}{\mu} = \frac{\lambda_i\langle s\rangle}{\lambda\langle s\rangle} = \frac{\lambda_i}{\lambda}.$$

• **Origin of smallness:** Once again, we see on the neutrino mass matrix (3.4) that there is a possible source of suppression from an approximate cancellation between the two terms in brackets. This neutrino mass suppression has a different source from the other suppression issued from the smallness of ratio $|\lambda_i/\lambda|$ (see eq. (3.4)). The smallness of this ratio allows to address the neutrino mass hierarchy problem by introducing an other hierarchy, namely the hierarchy between the fundamental parameters λ_i and λ.

This possible cancellation in eq. (3.4) can be understood from a diagramatic point of view, as before. Indeed, in the present framework, the Majorana neutrino mass still receives contributions from the previous exchanges of gauginos and singlino represented in diagrams (1), except that the μ_i mass insertions in these diagrams come now through the VEV of s and should be parameterized instead by $\lambda_i\langle s\rangle$. Furthermore, there is new possible exchange of singlino which we have drawn in figure (4). This contribution is due to the new trilinear $\not R_p$ term of superpotential (3.1). The above approximate cancellation between the two terms in brackets entering neutrino mass (3.4) would originate from a compensation between the two types of process contributing to neutrino mass: the exchange of gauginos (figure (1)(a)) and the exchanges of a singlino (figure (1)(b) and figure (4)).

This cancellation-like source of neutrino mass suppression requires some fine tuning on NMSSM parameters. It is, once more, λ that faces the strongest fine tuning. Nevertheless, this fine tuning on λ decreases greatly as $|\mu|$ and $|\kappa|$ (λ and $\tan\beta$) get smaller (larger).

3.3 Numerical results and discussion

• **Neutrino mass suppression:** In table 3, we show characteristic sets of parameters for which the neutrino mass (3.4) at one flavor is equal to 0.1eV and 1eV, covering the range of values motivated by experimental data (eq. (2.16)).

In table 3, the κ value is fixed by the other parameters via formula (3.4). Here, we have chosen to fix κ as it is direct to solve eq. ((3.4)) in term of this parameter.

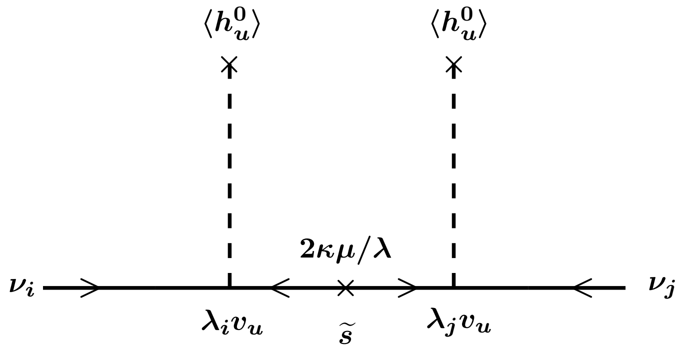

Figure 4: Feynman diagram for the contribution to Majorana neutrino mass which arises in the NMSSM through the trilinear coupling of eq. (3.1).

	λ	μ [GeV]	$\tan\beta$	M_1 [GeV]	M_2 [GeV]	λ_1	$-\kappa$
A	0.7	110	50	100	100	$7\ 10^{-2}$	$(1.71783 - 1.7177)\ 10^{-2}$
						$7\ 10^{-4}$	$(16.2 - 7)\ 10^{-3}$
B	0.7	300	50	50	500	$7\ 10^{-2}$	$(2.30954 - 2.3095)\ 10^{-3}$
						$7\ 10^{-4}$	$(2.26 - 1.8)\ 10^{-3}$
C	0.4	-110	30	100	100	$4\ 10^{-2}$	$(5.33839 - 5.3385)\ 10^{-3}$
						$4\ 10^{-4}$	$(5.41 - 6)\ 10^{-3}$

Table 3: Sets (A,B,C) of values, for the parameters entering the whole neutralino mass matrix, which reproduce the correct neutrino mass. The two values of parameter κ correspond to the neutrino masses $m_\nu = 0.1\text{eV} - 1\text{eV}$ (m_ν being defined via eq. (3.4)), respectively. As the one-flavor case is considered here, the flavor index i of $\not{R}_p$ coupling constant λ_i takes only the value $i = 1$.

Let us comment on the results in table 3. κ is chosen negative so that the cancellation between the terms in brackets of expression (3.4) is effective. This cancellation can be only partially responsible for the neutrino mass reduction, as for points in the table with $|\lambda_1/\lambda| = 10^{-3}$ ($\lambda_1 = 4, 7\ 10^{-4}$). This cancellation can also be the principal mechanism that suppresses the neutrino mass, as for the points with $|\lambda_1/\lambda| = 10^{-1}$ ($\lambda_1 = 4, 7\ 10^{-2}$). Then the wanted neutrino mass suppression is reached without requiring any highly hierarchical pattern.

• **Fine tuning:** We quantify the fine tuning on λ with variable (2.17), now defined with the neutrino mass (3.4). On table 4, we give the values of this variable $\mathcal{F}_\lambda$ for the

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	$m_{\tilde{\chi}_1^0}$ [GeV]	$m_{\tilde{\chi}_5^0}$ [GeV]	$\mathcal{F}_\lambda$
A	34	193	$(0.2-1.9)\ 10^{-5}$
	33	193	$(2.1-196)\ 10^{-2}$
B	7	520	$(0.7-6.9)\ 10^{-6}$
	7	520	$(0.7-9.4)\ 10^{-2}$
C	18	180	$(0.4-4.1)\ 10^{-6}$
	18	180	$(0.4-3.3)\ 10^{-2}$

Table 4: Lowest $[m_{\tilde{\chi}_1^0}]$ and highest $[m_{\tilde{\chi}_5^0}]$ neutralino masses for the points A,B,C of parameter space presented in table 3. Together with these masses, we also give the value of fine tuning quantity $\mathcal{F}_\lambda$ defined in text for the λ parameter. The two values of $\mathcal{F}_\lambda$ correspond respectively to the two κ values in table 3 (leading to $m_\nu = 0.1\text{eV} - 1\text{eV}$). For each point, the first and second lines are respectively associated to $\lambda_1 = 4,7\ 10^{-2}$ and $\lambda_1 = 4,7\ 10^{-4}$, as in table 3.

points of parameter space shown in table 3 which reproduce the correct neutrino masses through the compensation mechanism. A comparison of points A and B in table 4 shows that the fine tuning on λ is smaller (larger $\mathcal{F}_\lambda$) if $|\mu|$ decreases. In the same way, by comparing parameters A and C, one observes that the fine tuning is significantly improved for larger values of λ or $\tan\beta$. table 4 also exhibits that the fine tuning is smaller for higher neutrino masses and smaller $|\lambda_1/\lambda|$ ratios.

• **Tachyons:** Unfortunately, it turns out that for any domain of the parameter space $\{\tan\beta, \mu, M_1, M_2\}$, the fact of requiring the neutrino mass (3.4) to be suppressed down to the eV scale, at least partially through our cancellation mechanism (namely for $|\lambda_i/\lambda| \gtrsim 10^{-6}$), imposes the ratio $|\kappa/\lambda|$ to be small, leading to the occurrence of unacceptable tachyons in the CP-even Higgs sector.

We have checked this feature of our scenario by using the code NMHDECAY [30] which applies on the pure NMSSM parameter space. However, this procedure is believed to be consistent since the additional trilinear $\not R_p$ interaction $\lambda_i S L_i H_u$ in the superpotential (see eq. (3.1)) is not expected to induce considerable modifications in the scalar potential of the NMSSM. As a matter of fact, we have systematically restricted ourselves to the case $|\lambda_i/\lambda| \leq 10^{-1}$ (c.f. eq. (2.1)).

In a situation where the $|\lambda_i/\lambda|$ ratio would be of order unity or even larger, giving rise to important changes in the NMSSM potential, it could happen that our cancellation mechanism for neutrino mass suppression would be active without implying necessarily the appearance of tachyons in the theory.

Another way out of this theoretical problem is to focus on the particular case $A_\kappa = 0$ in which no tachyons emerge from the CP-even sector. This possibility is conceivable as the trilinear soft supersymmetry breaking parameter A_κ, which was previously introduced in section 2.3, does not affect the neutralino mass matrix (2.5) on which is based our analysis.

• **Leptogenesis:** Anyway, within this second scenario, the suppression of neutrino mass scale can be insured by a small $|\lambda_i/\lambda|$ value, so that the tachyonic regions associated to

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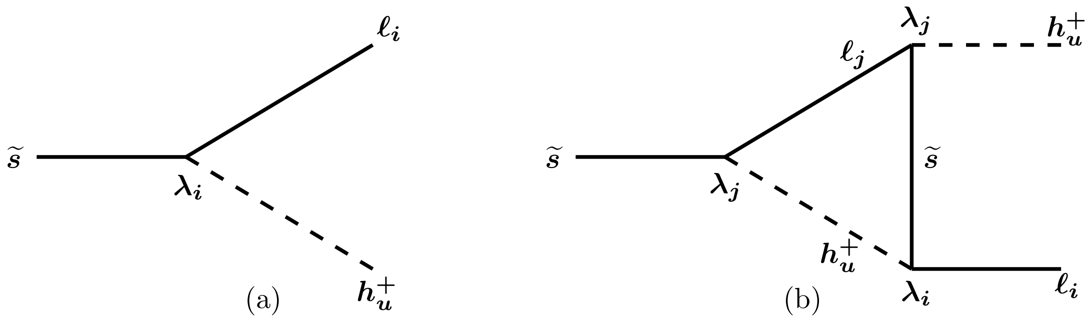

Figure 5: CP-asymmetry decay diagrams at tree (a) and loop (b) level in the NMSSM with $\not R_p$ trilinear couplings.

the cancellation mechanism are avoided. Then this scenario still possesses a new interesting phenomenological feature: the extra singlet of the NMSSM can produce, via decay channels involving $\not R_p$ trilinear couplings, a thermal leptogenesis. This leptogenesis can be converted into the baryonic sector through sphaleron induced processes, explaining then the baryon asymmetry of the universe. The lepton asymmetry arises through the out-of-equilibrium decay of the singlet in a L and CP-violating way, according to Sakharov's constraints [62]. Indeed, the CP-asymmetry may be generated from the interference between the tree level diagram of figure (5)(a) and one-loop diagrams such as the one drawn in figure (5)(b). Only the $\not R_p$ trilinear couplings of eq. (3.1) enter the two diagrams in figure (5). In that case, the CP-asymmetry

$$\epsilon = \frac{\Gamma(S \to \ell H) - \Gamma(S \to \bar{\ell} H)}{\Gamma(S \to \ell H) + \Gamma(S \to \bar{\ell} H)} \tag{3.5}$$

would be proportional to $\sum_j \lambda_i^2 \lambda_j^2 f$, where f is the loop function. There exist other types of diagrams, generating a CP-asymmetry, which involve the lepton Yukawa (Y_{ij}^{ℓ}) and $\not R_p$ trilinear (λ_i) coupling constants.

4. Conclusion

First, we have considered the NMSSM, which solves the μ problem, in the presence of bilinear $\not R_p$ interactions $\mu_i L_i H_u$ (scenario I). In this context, we have found that a cancellation mechanism arises for suppressing the Majorana neutrino mass, offering thus a possible interpretation to the smallness of neutrino mass compared to the electroweak scale. This mechanism, which relies on the existence of the gauge-singlet S introduced by the NMSSM, provides an approach to the neutrino mass problem which is interestingly connected to the solution for the μ problem.

More precisely, by using the NMHDECAY program, we have obtained various characteristic points of the NMSSM parameter space which satisfy the experimental constraints from collider physics, fulfill the theoretical consistency conditions (physical minimum, no Landau singularity,...) and simultaneously *generate* neutrino masses of order of the eV scale through our cancellation mechanism. By the verb 'generate', we mean here that small neutrino mass values are effectively produced without introducing a strong hierarchy between the fundamental parameters. Indeed, in the basis where $\langle\tilde{\nu}_i\rangle = 0$, the obtained parameters lead to neutrino masses $m_\nu \in [0.1, 1]$eV with $10^{-3} \lesssim |\mu_i/\mu| \lesssim 10^{-1}$ (the extreme values given here, for the ranges of neutrino mass and $|\mu_i/\mu|$ ratio, are not corresponding to each other).

For comparison, in the MSSM with a non-vanishing $\mu_i L_i H_u$ term, realistic neutrino masses are achieved for $|\mu_i/\mu| \sim 10^{-7}$ typically. In the new version of the MSSM suggested recently in [29], which constitutes an alternative to our scenario as it addresses both the μ value and neutrino mass problems, a stronger hierarchy of $\sim 10^{-6}$ is required between the the neutrino and top quark Yukawa coupling constants.

Nevertheless, our cancellation mechanism for neutrino mass suppression needs a certain fine tuning on some NMSSM parameters. For some of the obtained parameters mentioned above, that generate neutrino masses around the eV, the most important fine tuning reaches the acceptable level of $\sim 3\ 10^{-1}$ ($\sim 10^{-3}$) for $|\mu_i/\mu| \simeq 10^{-3}$ ($\simeq 10^{-1}$).

The continuation of this study [63] would be the combination of tree and one-loop contributions with three flavors in order to accommodate all the last data on neutrino masses and leptonic mixing angles.

Secondly, we have studied another attractive version of this model (scenario II), namely the NMSSM with $\not R_p$ μ_i-like interactions generated naturally by the VEV of the S scalar component, through the trilinear term $\lambda_i S L_i H_u$. There the same kind of cancellation mechanism can occur for the neutrino mass suppression. Based on this mechanism, we have easily found parameters which give rise to $m_\nu \in [0.1, 1]$eV for $10^{-3} \leq |\lambda_i/\lambda| \leq 10^{-1}$ corresponding to a quite soft hierarchy. The associated fine tuning can reach ~ 1 ($\sim 10^{-5}$) for $|\lambda_i/\lambda| = 10^{-3}$ ($= 10^{-1}$). However, here, the cancellation mechanism seems to imply the occurrence of tachyons in the CP-even sector, at least in the simplest form of the NMSSM. So one should think of some way out, like restricting to the particular situation where A_κ vanishes.

It would also be interesting to find an independent theoretical reason for the relation between the gaugino and singlino effective couplings, which is responsible for this new cancellation mechanism of neutrino mass suppression. In the same philosophy as for the see-saw mechanism, where the Dirac/Majorana mass hierarchy introduced finds a natural realization within the framework of the SO(10) GUT model for instance.

Let us finish by commenting on the specific and rich phenomenology of the NMSSM with additional $\not R_p$ μ_i-like interactions. We have discussed the fact that such a framework opens the possibility of new leptogenesis scenarios. This framework also leads to new decay channels for the Lightest Supersymmetric Particle (LSP). For instance, in the case where the LSP is the lightest neutralino, it can decays as $\tilde{\chi}^0_1 \to \nu_i Z^0$ and $\tilde{\chi}^0_1 \to l^\pm_j W^\mp$ via the $\not R_p$ μ_i-like mixings $\tilde{h}^0_u \nu_i$ or $\tilde{s}\nu_i$. The value of the LSP life time associated to these new decays [4] is fundamental in regard of the collider physics (if the LSP decays inside the detectors, the typical supersymmetric signatures are multi-jets/leptons instead of missing energy) as well as of the dark matter problem (the LSP remains a good WIMP candidate

[4]In our scenario, the $|\mu_i/\mu|$ ratio can reach values close to unity which tends to increase significantly the width of these new LSP decays, except if the $\tilde{\chi}^0_1$ is mainly composed by $\tilde{B}^0$, $\tilde{W}^0_3$ and/or $\tilde{h}^0_d$.

only if it is stable, relatively to the age of the universe).

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References

[1] L. Susskind, *Phys. Rep.* **104** (1984) 1881.

[2] J.E. Kim and H.P. Nilles, *The mu problem and the strong CP problem*, *Phys. Lett.* **B 138** (1984) 150.

[3] H.P. Nilles, M. Srednicki and D. Wyler, *Weak interaction breakdown induced by supergravity*, *Phys. Lett.* **B 120** (1983) 346;
J.M. Frère, D.R.T. Jones and S. Raby, *Fermion masses and induction of the weak scale by supergravity*, *Nucl. Phys.* **B 222** (1983) 11;
J.P. Derendinger and C.A. Savoy, *Quantum effects and* $\mathrm{SU}(2) \times \mathrm{U}(1)$ *breaking in supergravity gauge theories*, *Nucl. Phys.* **B 237** (1984) 307;
J.R. Ellis, J.F. Gunion, H.E. Haber, L. Roszkowski and F. Zwirner, *Higgs bosons in a nonminimal supersymmetric model*, *Phys. Rev.* **D 39** (1989) 844;
M. Drees, *Supersymmetric models with extended Higgs sector*, *Int. J. Mod. Phys.* **A 4** (1989) 3635;
U. Ellwanger, M. Rausch de Traubenberg and C.A. Savoy, *Particle spectrum in supersymmetric models with a gauge singlet*, *Phys. Lett.* **B 315** (1993) 331 [hep-ph/9307322];
S.F. King and P.L. White, *Resolving the constrained minimal and next-to-minimal supersymmetric standard models*, *Phys. Rev.* **D 52** (1995) 4183 [hep-ph/9505326];
F. Franke and H. Fraas, *Neutralinos and Higgs bosons in the next-to-minimal supersymmetric standard model*, *Int. J. Mod. Phys.* **A 12** (1997) 479 [hep-ph/9512366].

[4] U. Ellwanger, M. Rausch de Traubenberg and C.A. Savoy, *Higgs phenomenology of the supersymmetric model with a gauge singlet*, *Z. Physik* **C 67** (1995) 665 [hep-ph/9502206]; *Phenomenology of supersymmetric models with a singlet*, *Nucl. Phys.* **B 492** (1997) 21 [hep-ph/9611251];
U. Ellwanger and C. Hugonie, *Topologies of the (M+1)SSM with a singlino LSP at LEP2*, *Eur. Phys. J.* **C 13** (2000) 681 [hep-ph/9812427];
A. Dedes, C. Hugonie, S. Moretti and K. Tamvakis, *Phenomenology of a new minimal supersymmetric extension of the standard model*, *Phys. Rev.* **D 63** (2001) 055009 [hep-ph/0009125];
U. Ellwanger, J.F. Gunion and C. Hugonie, *Establishing a no-lose theorem for nmssm Higgs boson discovery at the LHC*, hep-ph/0111179;
U. Ellwanger, J.F. Gunion and C. Hugonie, *Difficult scenarios for nmssm Higgs discovery at the LHC*, *JHEP* **07** (2005) 041 [hep-ph/0503203];
U. Ellwanger and C. Hugonie, *Yukawa induced radiative corrections to the lightest Higgs boson mass in the nmssm*, *Phys. Lett.* **B 623** (2005) 93 [hep-ph/0504269];

JHEP08(2006)044

G. Belanger *et al.*, *JCAP* **0509** (2005) 001;
J.F. Gunion, D. Hooper and B. McElrath, *Light neutralino dark matter in the NMSSM*, *Phys. Rev.* **D 73** (2006) 015011 [hep-ph/0509024].

[5] M. Bastero-Gil, C. Hugonie, S.F. King, D.P. Roy and S. Vempati, *Does LEP prefer the NMSSM?*, *Phys. Lett.* **B 489** (2000) 359 [hep-ph/0006198].

[6] R. Dermisek and J.F. Gunion, *Escaping the large fine tuning and little hierarchy problems in the next to minimal supersymmetric model and $H \to aa$ Decay*, *Phys. Rev. Lett.* **95** (2005) 041801 [hep-ph/0502105].

[7] S.A. Abel, *Destabilising divergences in the NMSSM*, *Nucl. Phys.* **B 480** (1996) 55 [hep-ph/9609323];
C. Panagiotakopoulos and K. Tamvakis, *Stabilized nmssm without domain walls*, *Phys. Lett.* **B 446** (1999) 224 [hep-ph/9809475].

[8] S.A. Abel, S. Sarkar and P.L. White, *On the cosmological domain wall problem for the minimally extended supersymmetric standard model*, *Nucl. Phys.* **B 454** (1995) 663 [hep-ph/9506359].

[9] T. Han, P. Langacker and B. McElrath, *An nmssm without domain walls*, hep-ph/0402064; *The Higgs sector in a U(1)' extension of the MSSM*, *Phys. Rev.* **D 70** (2004) 115006 [hep-ph/0405244].

[10] G.R. Farrar and P. Fayet, *Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry*, *Phys. Lett.* **B 76** (1978) 575;
S. Weinberg, *Supersymmetry at ordinary energies. 1. masses and conservation laws*, *Phys. Rev.* **D 26** (1982) 287;
N. Sakai and T. Yanagida, *Proton decay in a class of supersymmetric grand unified models*, *Nucl. Phys.* **B 197** (1982) 533;
C.S. Aulakh and R.N. Mohapatra, *Neutrino as the supersymmetric partner of the majoron*, *Phys. Lett.* **B 119** (1982) 136.

[11] F.M. Borzumati, Y. Grossman, E. Nardi and Y. Nir, *Neutrino masses and mixing in supersymmetric models without r parity*, *Phys. Lett.* **B 384** (1996) 123 [hep-ph/9606251];
E. Nardi, *Renormalization group induced neutrino masses in supersymmetry without R-parity*, *Phys. Rev.* **D 55** (1997) 5772 [hep-ph/9610540];
H.P. Nilles and N. Polonsky, *Nucl. Phys. B* **499** (1997) 33.

[12] H.K. Dreiner, *Perspectives on supersymmetry*, G.L. Kane ed., World Scientific, hep-ph/9707435;
B.C. Allanach, A. Dedes and H.K. Dreiner, *Bounds on R-parity violating couplings at the weak scale and at the GUT scale*, *Phys. Rev.* **D 60** (1999) 075014 [hep-ph/9906209].

[13] G. Bhattacharyya, J.R. Ellis and K. Sridhar, *New lep constraints on some supersymmetric yukawa interactions that violate R-parity*, *Mod. Phys. Lett.* **A 10** (1995) 1583 [hep-ph/9503264];
G. Bhattacharyya and D. Choudhury, *D and tau decays: placing new bounds on r-parity violating supersymmetric coupling*, *Mod. Phys. Lett.* **A 10** (1995) 1699 [hep-ph/9503263];
G. Bhattacharyya, *R-parity-violating supersymmetric Yukawa couplings: a mini-review*, *Nucl. Phys.* **52A** *(Proc. Suppl.)* (1997) 83 [hep-ph/9608415]; *A brief review of R-parity-violating couplings*, hep-ph/9709395;
G. Bhattacharyya and A. Raychaudhuri, *New constraints on R-parity violation from K and B systems*, *Phys. Rev.* **D 57** (1998) 3837 [hep-ph/9712245].

JHEP08(2006)044

[14] R. Barbier et al., *Report of the group on the R-parity violation*, hep-ph/9810232.

[15] M. Chemtob, *Prog. Part. Nucl. Phys.* **54** (2005) 71.

[16] R. Barbier et al., *R-parity violating supersymmetry*, *Phys. Rept.* **420** (2005) 1 [hep-ph/0406039].

[17] M. Chemtob and P.N. Pandita, *Nonminimal supersymmetric standard model with lepton number violation*, *Phys. Rev.* **D 73** (2006) 055012 [hep-ph/0601159].

[18] L.E. Ibáñez and G.G. Ross, *Discrete gauge symmetry anomalies*, *Phys. Lett.* **B 260** (1991) 291; *Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model*, *Nucl. Phys.* **B 368** (1992) 3;
L.E. Ibáñez, *Grand unification with local supersymmetry*, *Nucl. Phys.* **B 218** (1983) 514.

[19] H. K. Dreiner *et al.*, *Phys. Rev. D* **73**0750072006.

[20] L.J. Hall and M. Suzuki, *Explicit r parity breaking in supersymmetric models*, *Nucl. Phys.* **B 231** (1984) 419.

[21] G.F. Giudice and R. Rattazzi, *R-parity violation and unification*, *Phys. Lett.* **B 406** (1997) 321 [hep-ph/9704339].

[22] D.E. Brahm and L.J. Hall, *Low-energy lepton violation from supersymmetric flipped* SU(5), *Phys. Rev.* **D 40** (1989) 2449.

[23] K. Tamvakis, *Guts with exclusively* $\Delta_b = 1$, $Delta_l = 0$ *R-parity violation*, *Phys. Lett.* **B 382** (1996) 251 [hep-ph/9604343]; *Phys. Lett. B* 307 (1996) 251.

[24] A.Y. Smirnov and F. Vissani, *Large r-parity violating couplings and grand unification*, *Nucl. Phys.* **B 460** (1996) 37 [hep-ph/9506416].

[25] R. Barbieri, A. Strumia and Z. Berezhiani, *The high-*Q^2 *HERA anomaly and supersymmetric unification*, *Phys. Lett.* **B 407** (1997) 250 [hep-ph/9704275].

[26] M.C. Bento, L.J. Hall and G.G. Ross, *Generalized matter parities from the superstring*, *Nucl. Phys.* **B 292** (1987) 400;
N. Ganoulis, G. Lazarides and Q. Shafi, *Classification of three generation superstring models according to their discrete symmetries*, *Nucl. Phys.* **B 323** (1989) 374.

[27] C. S. Aulakh and R. N. Mohapatra, *Phys. Lett. B* 121 (1983) 14;
J.R. Ellis, G. Gelmini, C. Jarlskog, G.G. Ross and J.W.F. Valle, *Phenomenology of supersymmetry with broken R parity*, *Phys. Lett.* **B 150** (1985) 142;
G.G. Ross and J.W.F. Valle, *Supersymmetric models without R parity*, *Phys. Lett.* **B 151** (1985) 375.

[28] A. Masiero and J.W.F. Valle, *A model for spontaneous r parity breaking*, *Phys. Lett.* **B 251** (1990) 273;
J.C. Romaõ, F. de Campos and J.W.F. Valle, *New Higgs signatures in supersymmetry with spontaneous broken r parity*, *Phys. Lett.* **B 292** (1992) 329 [hep-ph/9207269];
M. Hirsch, J.C. Romao, J.W.F. Valle and A. Villanova del Moral, *Invisible Higgs boson decays in spontaneously broken R-parity*, *Phys. Rev.* **D 70** (2004) 073012 [hep-ph/0407269].

[29] D.E. Lopez-Fogliani and C. Muñoz, *Proposal for a new minimal supersymmetric standard model*, hep-ph/0508297.

JHEP08(2006)044

[30] U. Ellwanger, J.F. Gunion and C. Hugonie, *NMHDECAY: a fortran code for the Higgs masses, couplings and decay widths in the NMSSM*, *JHEP* **02** (2005) 066 [hep-ph/0406215]; U. Ellwanger and C. Hugonie, *NMHDECAY 2.0: an updated program for sparticle masses, Higgs masses, couplings and decay widths in the NMSSM*, hep-ph/0508022.

[31] H.K. Dreiner and G.G. Ross, *R-parity violation at hadron colliders*, *Nucl. Phys.* **B 365** (1991) 597.

[32] K.S. Babu and R.N. Mohapatra, *Supersymmetry and large transition magnetic moment of the neutrino*, *Phys. Rev. Lett.* **64** (1990) 1705.

[33] H.K. Dreiner and G. Moreau, *Status of a supersymmetric flavour violating solution to the solar neutrino puzzle with three generations*, *Phys. Rev.* **D 67** (2003) 055005 [hep-ph/0211354].

[34] B.C. Allanach, A. Dedes and H.K. Dreiner, *The r parity violating minimal supergravity model*, *Phys. Rev.* **D 69** (2004) 115002 [hep-ph/0309196].

[35] Y. Grossman and H.E. Haber, *Sneutrino mixing phenomena*, *Phys. Rev. Lett.* **78** (1997) 3438 [hep-ph/9702421]; *(S)neutrino properties in r-parity violating supersymmetry, I. CP-conserving phenomena*, *Phys. Rev.* **D 59** (1999) 093008 [hep-ph/9810536]; *Basis-independent analysis of the sneutrino sector in R-parity violating supersymmetry*, *Phys. Rev.* **D 63** (2001) 075011 [hep-ph/0005276].

[36] M. Maltoni, T. Schwetz, M.A. Tortola and J.W.F. Valle, *Status of global fits to neutrino oscillations*, *New J. ~Phys.* **6** (2004) 122 [hep-ph/0405172].

[37] R. Hempfling, *Neutrino masses and mixing angles in SUSY-gut theories with explicit R-parity breaking*, *Nucl. Phys.* **B 478** (1996) 3 [hep-ph/9511288].

[38] E.J. Chun and S.K. Kang, *One-loop corrected neutrino masses and mixing in supersymmetric standard model without R-parity*, *Phys. Rev.* **D 61** (2000) 075012 [hep-ph/9909429].

[39] M. Hirsch, M.A. Diaz, W. Porod, J.C. Romao and J.W.F. Valle, *Neutrino masses and mixings from supersymmetry with bilinear R-parity violation: a theory for solar and atmospheric neutrino oscillations*, *Phys. Rev.* **D 62** (2000) 113008 [hep-ph/0004115].

[40] S. Davidson and M. Losada, *Neutrino masses in the R_p violating MSSM*, *JHEP* **05** (2000) 021 [hep-ph/0005080].

[41] A. Abada and M. Losada, *Constraints on a general 3-generation neutrino mass matrix from neutrino data: application to the MSSM with R-parity violation*, *Nucl. Phys.* **B 585** (2000) 45 [hep-ph/9908352].

[42] S. Davidson, M. Losada and N. Rius, *Neutral Higgs sector of the MSSM without r(p)*, *Nucl. Phys.* **B 587** (2000) 118 [hep-ph/9911317].

[43] A. Abada and M. Losada, *Constraints on both bilinear and trilinear R-parity violating couplings from neutrino laboratories and astrophysics data*, *Phys. Lett.* **B 492** (2000) 310 [hep-ph/0007041].

[44] A. Abada, S. Davidson and M. Losada, *Neutrino masses and mixings in the MSSM with soft bilinear R_p violation*, *Phys. Rev.* **D 65** (2002) 075010 [hep-ph/0111332].

[45] S. Davidson and M. Losada, *Basis independent neutrino masses in the R_p violating MSSM*, *Phys. Rev.* **D 65** (2002) 075025 [hep-ph/0010325].

[46] A. Abada, G. Bhattacharyya and M. Losada, *A general analysis with trilinear and bilinear R-parity violating couplings in the light of recent SNO data*, *Phys. Rev.* **D 66** (2002) 071701 [hep-ph/0208009].

[47] F. Borzumati and J.S. Lee, *Novel constraints on $\Delta_l = 1$ interactions from neutrino masses*, *Phys. Rev.* **D 66** (2002) 115012 [hep-ph/0207184].

[48] E.J. Chun, D.-W. Jung and J.D. Park, *Bi-large neutrino mixing from bilinear R-parity violation with non-universality*, *Phys. Lett.* **B 557** (2003) 233 [hep-ph/0211310].

[49] M.A. Diaz, M. Hirsch, W. Porod, J.C. Romao and J.W.F. Valle, *Solar neutrino masses and mixing from bilinear R-parity broken supersymmetry: analytical versus numerical results*, *Phys. Rev.* **D 68** (2003) 013009 [hep-ph/0302021].

[50] Y. Grossman and S. Rakshit, *Neutrino masses in R-parity violating supersymmetric models*, *Phys. Rev.* **D 69** (2004) 093002 [hep-ph/0311310].

[51] Y. Farzan, O.L.G. Peres and A.Y. Smirnov, *Neutrino mass spectrum and future beta decay experiments*, *Nucl. Phys.* **B 612** (2001) 59 [hep-ph/0105105].

[52] J. Bonn et al., *The mainz neutrino mass experiment*, *Nucl. Phys.* **91** *(Proc. Suppl.)* (2001) 273.

[53] V.M. Lobashev et al., *Direct search for mass of neutrino and anomaly in the tritium beta-spectrum*, *Phys. Lett.* **B 460** (1999) 227; *Neutrino mass and anomaly in the tritium beta-spectrum. results of the 'troitsk nu mass' experiment*, *Nucl. Phys.* **77** *(Proc. Suppl.)* (1999) 327; *Direct search for neutrino mass and anomaly in the tritium beta-spectrum: status of 'troitsk neutrino mass' experiment*, *Nucl. Phys.* **91** *(Proc. Suppl.)* (2001) 280.

[54] S. Hannestad, *JCAP*0305 (2003) 003;
K. Ichikawa, M. Fukugita and M. Kawasaki, *Phys. Rev.* **D 71** (2005) 043001;
J. Lesgourgues and S. Pastor, *Massive neutrinos and cosmology*, *Phys. Rept.* **429** (2006) 307 [astro-ph/0603494].

[55] D.G. Cerdeno, C. Hugonie, D.E. Lopez-Fogliani, C. Muñoz and A.M. Teixeira, *Theoretical predictions for the direct detection of neutralino dark matter in the nmssm*, *JHEP* **12** (2004) 048 [hep-ph/0408102].

[56] LEP SUSY Working Group, LEPSUSYWG Note/02-04.1.

[57] Particle Data Group collaboration, S. Eidelman et al., *Review of particle physics*, *Phys. Lett.* **B 592** (2004) 1.

[58] T. Banks, Y. Grossman, E. Nardi and Y. Nir, *Supersymmetry without R-parity and without lepton number*, *Phys. Rev.* **D 52** (1995) 5319 [hep-ph/9505248].

[59] S. Davidson and J. R. Ellis, *Phys. Lett.* **B 39** (1997) 210; *Flavour-dependent and basis-independent measures of r violation*, *Phys. Rev.* **D 56** (1997) 4182 [hep-ph/9702247].

[60] B.A. Dobrescu and K.T. Matchev, *Light axion within the next-to-minimal supersymmetric standard model*, *JHEP* **09** (2000) 031 [hep-ph/0008192].

[61] R. Dermisek and J.F. Gunion, *Consistency of lep event excesses with an $H \to aa$ decay scenario and low-fine-tuning NMSSM models*, *Phys. Rev.* **D 73** (2006) 111701 [hep-ph/0510322].

[62] A. D. Sakharov, *JETP Lett.* **5** (1967) 24.

[63] In preparation, in collaboration with G. Bhattacharyya.