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Rare Weak Decays and Direct Lepton Number Violating Signals in a Minimal R-Parity Violating Model of Neutrino Mass

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Within the framework of R-parity violating minimal supergravity model, at least three relatively large lepton-number violating λ' type trilinear couplings at the GUT scale, not directly related to neutrino physics, can naturally generate via renormalization group (RG) evolution and/or CKM rotation the highly suppressed bilinear and trilinear parameters at the weak scale required to explain the neutrino oscillation data. The structure of the RG equations and the CKM matrix restrict the choices of the three input couplings to only eight possible combinations, each with its own distinctive experimental signature. The relatively large input couplings may lead to spectacular low energy signatures like rare weak decays of the τ lepton and K mesons, direct lepton number violating decays of several sparticles, and unconventional decay modes (and reduced lifetime) of the lightest neutralino, assumed to be the lightest supersymmetric particle (LSP), all with sizable branching ratios. Several low background signals at the Tevatron and LHC have been suggested and their sizes are estimated to be at the observable level. From the particle content of the signal and the relative rate of different final states the input couplings at the GUT scale, *i.e.*, the origin of neutrino masses and mixing angles, can be identified.

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I. INTRODUCTION

The discovery of neutrino oscillations [1] has established beyond doubt that there are at least two massive neutrinos. However, their masses are much smaller than the masses of the other known fermions. Discovering the origin of these small masses is perhaps the most challenging task for current high energy physics.

The see-saw mechanism which can be naturally accomodated in any grand unified theory (GUT) is one of the most popular explanations of small ν masses [2]. Unfortunately the simplest version of this theory, a GUT with a grand desert, has very few predictions for low energy physics apart from ν masses and mixing angles. In particular the low energy spectrum of such a theory is practically identical with that of the Standard Model (SM).

Supersymmetry (SUSY) is the most elegant extension of the SM which solves the naturalness problem that is inevitable in any non-supersymmetric GUT [3]. There is a version of the minimal supersymmetric extension of the SM (MSSM) which conserves lepton number L and baryon number B due to an additional discrete symmetry called R-parity and defined in such a way that all particles have R$=1$ and all sparticles have R$=-1$. This theory is referred to as the R-parity conserving (RPC) SUSY. However, there are other interesting variations of the MSSM with appropriate discrete symmetries which violate either baryon number or lepton number [4] but not both (so proton decay does not occur). These variants are known as the R-parity violating (RPV) SUSY. In the most general version of this theory there are bilinear and trilinear RPV terms [4] in addition to the usual RPC terms.

One of the most interesting features of the L-violating version of the RPV SUSY is that it can naturally explain the experimentally measured ν masses and mixing angles [5]. More important, as demanded by the naturalness argument, this model is entirely governed by TeV scale physics. Thus the particle spectrum consists of superpartners, *i.e.*, the sparticles, of the particles of the SM, having masses in the TeV scale. The production and detection of these sparticles at the ongoing Tevatron run II and the upcoming Large Hadron Collider (LHC) or the International Linear Collider (ILC) accelerator experiments can directly test the RPV models of ν mass.

In the RPC SUSY the lightest supersymmetric particle (LSP) is stable. In contrast RPV SUSY allows the LSP to decay, through the RPV couplings, to lepton number violating channels. The multiplicity of particles in any event involving sparticle production is, therefore, much larger

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on the average. The other characteristic signatures [4] of RPV SUSY are single production of sparticles, direct decays of sparticles via lepton number violating channels, and in particular the decay of the lighter top squark [4, 6–9].

In addition to the above direct tests, indirect signatures of RPV or RPC SUSY can be obtained through rare weak processes such as highly suppressed K, B, D, or τ decays or decays forbidden in the SM [4, 10, 11]. The standard signal is an abnormal enhancement of the branching ratio (BR) and/or significant change of CP asymmetries compared to the SM expectations [12]. Moreover the observed $K^0 - \overline{K}^0$ and $B^0 - \overline{B}^0$ mixings put strong constraints on RPV parameters [13–15] as we shall see later. It should be emphasized that RPC SUSY can contribute to these processes only at the loop level, while RPV SUSY can contribute at the tree level. The latter contributions can, therefore, be potentially large and predict significant deviation of various observables from the corresponding predictions in the SM.

No evidence of RPV or RPC SUSY has so far been found either through direct or indirect methods. This leads to bounds on the parameter space of RPV SUSY [4, 16]. Particularly interesting are the bounds on the trilinear RPV couplings which control the size of various direct or indirect signatures. Some of these bounds, derived before the advent of the highly constrained neutrino oscillation data [1] or of precise cosmological observations [17], were remarkably weak and the corresponding RPV couplings could be as large as allowed by the perturbative nature of the theory! The magnitudes of direct or indirect signatures of RPV SUSY based on these bounds were, therefore, overestimated.

Many authors have revisited the bounds in the light of the neutrino data [18–20]. A major problem of the most general RPV model is that the number of free parameters are even larger than the almost unmanagably big parameter space of the RPC MSSM. In order to make the analysis tractable additional simplifying assumptions restricting the parameter space of the RPV sector were employed.

One approach is to consider a few selected benchmark scenarios of ν oscillation. Each scenario consists of a minimal set of RPV bilinear and trilinear couplings at the weak scale, the number of parameters being just enough to cope with the oscillation data [18]. Upper bounds on the parameters belonging to each set were then obtained by a global analysis of the ν oscillation data.

In this paper we shall focus on the scenario with three bilinear κ_i and three L-violating trilinear λ'_{i33} couplings (the leptonic index i will run from 1 to 3 in the entire paper). While the bilinears generate a tree-level mass matrix for the neutrinos, the trilinears generate such a matrix at the one loop level. The upper bounds on the λ' couplings turn out to be rather strong ($\sim 10^{-4}$) [18]. As a result the contributions of these couplings to most low energy processes except LSP decay are negligible. One notable exception is the direct RPV decay of the lighter top squark [8, 9] if it happens to be the next to lightest supersymmetric particle (NLSP), a theoretically well-motivated scenario. This is so because the competing RPC decays of the top squark NLSP are also naturally suppressed (see Section V for the details). Of course other RPV phenomena at observable levels can be accommodated in *ad hoc* models by arbitrarily adding other relatively large couplings not directly related to ν phenomenology. Such phenomena, however, are not correlated in any way with the ν sector and, hence, can throw no light on the origin of ν masses and mixing angles.

Another attractive approach is to assume that the fundamental theory at some high scale, say the GUT scale M_G, has a small number of parameters, of RPV or RPC type. A larger set of parameters required by low energy phenomenology, including ν oscillation, can be generated at the weak scale via the renormalization group (RG) evolution of these parameters. One popular way is to consider the usual boundary conditions at M_G of the minimal supergravity (mSUGRA) model along with three bilinear RPV parameters only [21]. However, these models have very little predictive power beyond LSP decay which has been studied in detail [22].

Subsequently the full set of both bilinear and trilinear RPV couplings were also included in the analysis [23]. A recent work [20] have obtained strong bounds on λ' couplings from the WMAP [17] constraints on the sum of ν masses. They extended the conventional mSUGRA boundary conditions at M_G minimally by adding only one non-zero λ' couping.

It should be noted that the conventional GUTs do not include gravity. Thus any GUT may be regarded as an effective theory embedded in a more fundamental theory of gravity. It is quite conceivable that this theory will lead to non-renormalizable opoerators at M_G suppressed by a heavy mass scale [24]. When the GUT symmetry is broken down and some heavy Higgs fields develop vacuum expectation values (VEV), bilinear and/or trilinear RPV interactions are generated at M_G. The magnitudes of these parameters depend, among other things, on these VEVs. Due to our rather limited knowledge of the high scale physics at the moment the magnitudes of the induced RPV parameters cannot be computed from first principles. However, it is quite possible that only a small subsets of these parameters have numerically significant magnitudes. At the moment a meaningful question would be to ask what is the smallest set of RPV parameters which can account for low energy phenomenology including neutrino physics. The magnitudes of these parameters can be restricted by low energy data.

In the model of ref. [20] the single λ' coupling at M_G induce RPV bilinears at the weak scale via RG evolution. This in turn induces one tree level ν mass at the weak scale incompatible with the WMAP bound unless the input λ' coupling is very tightly bounded from above. It turns out that almost all the 27 λ' couplings have tiny upper bounds [20] so that the predictions for the indirect signatures of RPV and/or the direct RPV decays of the sparticles, except for the LSP, are not at observable levels attainable in the foreseeable future.

However, a single λ'-type coupling cannot generate the full 3×3 neutrino mass matrix at the weak scale with contributions from both tree and one loop amplitudes, which could in principle be of the same order of magnitude. Thus the stringent bounds of [20], though highly suggestive, should not be regarded as a general conclusion following from the RPV models of m_ν.

In this paper we propose a novel mechanism with a minimal set of relatively large λ' couplings, *not directly related* to ν masses, as inputs at M_G. Thanks to flavor violating effects like non-diagonal Yukawa coupling matrices, this minimal set at M_G can induce, via RG evolution, several new non-zero λ' couplings in the weak or flavor basis at the weak scale with naturally suppressed magnitudes. The couplings in the physical or mass basis are obtained by applying appropriate Cabibbo-Kobayashi-Maskawa (CKM) rotations. In addition several RPV bilinear terms are generated, even though they are zero at M_G according to the chosen boundary conditions. While some of the naturally suppressed induced RPV parameters can take care of the ν oscillation data, some relatively large λ' couplings corresponding to the inputs at M_G exist at the weak scale with spectacular testable consequences for low energy physics.

It should, however, be emphasized that the choices of the minimal input sets are indeed very much restricted. This will be explained in Section III by analyzing the structures of the RG equations and the CKM matrix and by taking into account the experimental constraints currently available.

As an illustrative example we focus on the benchmark scenario consisting of three bilinear parameters κ_i, and three trilinear couplings λ'_{i33} [18] at the weak scale. We find that the set of input couplings for inducing this benchmark scenario should be of the form λ'_{ij3}, $i = 1, 2, 3$ and $j = 1, 2$. Any three of these six input couplings bearing different lepton indices provide the minimal set we wish to find out.

For the purpose of illustration we have focussed on a particular benchmark scenario of ν oscillation. One can in principle start with other appropriately chosen minimal set of input parameters (*e.g.*, three λ type couplings) at M_G having relatively large magnitudes and induce the the desired benchmark scenario (*i.e.*, κ_i and λ_{i33}, [18]) at the weak scale if CKM like flavor violation in the lepton sector is taken into account. Of course ν phenomenology alone cannot distinguish between various benchmark scenarios, but the phenomenology of the input couplings, which we shall discuss next, automatically points to the underlying model of ν oscillations.

The magnitudes of the input couplings can in principle be determined by the data on ν masses and mixing angles [1]. Unfortunately the detailed predictions for the ν sector depend also on the parameters of the RPC sector (see below for the details). Practically no information on these parameters are available at the moment.

We hope that sufficient information will soon be available on the RPC sector from the measurement of sparticle masses and BRs at Tevatron run II and LHC. Moreover, ν data will become more precise in course of time. Only then a complete phenomenological fit of the model parameters to the oscillation data can be possible. For the time being, in order to estimate the size of the signals predicted by our model, mainly for the purpose of illustration, we have restricted the input couplings in a rough way. We require that the magnitudes of the input couplings at M_G be such that the induced parameters at the weak scale related to the neutrino sector satisfy the upper bounds derived in [18] from oscillation data. More discussions on this point can be found in Sections II and V.

The main thrust of this paper is to identify the minimal sets of input couplings at M_G which are still allowed to be relatively large in spite of the severe constraints from ν oscillation data. We then examine the interesting rare weak decays and collider signatures, including direct RPV decays of sparticles other than the LSP or the top squark, which are allowed to be at the observable level in our model.

In general the elements of the Yukawa coupling matrices in the up and the down quark sector, denoted by Y_u and Y_d respectively, cannot be determined from the quark masses and the measured magnitudes of the elements of the CKM elements. On the other hand, these matrices appear explicitly in the RG equations. Quite often additional simplifying assumptions on the structures of the quark mass matrices are introduced so that the elements of Y_u and Y_d are calculable from the observables.

In the first part of our analysis, summarized in the above paragraphs, we have assumed that the quark mass matrices have a particular texture such that the CKM matrix is identical to the mixing matrix in the up quark sector [20, 25]. If on the other hand a scenario with mixing restricted to the down quark sector is considered, the magnitudes of the input couplings at M_G are very severely restricted by the bounds of [18] and can hardly lead to any observable low energy phenomenology apart from the LSP decay. This feature of the second scenario has also been noted in [20], though their conclusion was based on a model with a single neutrino mass.

We then take a more phenomenological approach and assume that some RPV bilinears as well as λ' couplings in the weak basis, not directly related to ν physics, are generated at low energies with relatively large magnitudes by some high scale physics which is not necessarily of supergravity type. Starting from a limited number of input coupling sets at the weak scale, which are different in general from the ones obtained in the first scenario, the parameters required to explain the oscillation data can in principle be generated through CKM rotations. However, such rotations will generate other parameters as well. Using the currently available constraints on the elements of the CKM matrix [26] and those on the product RPV couplings arising from $K^0 - \overline{K}^0$ and $B^0 - \overline{B}^0$

mixing, we find that the input couplings are so severely restricted that neither the rare decays nor the direct lepton number violating decays of sparticles (other than the decay of the top squark or the LSP) triggered by them will be observable. However, both the top squark and the LSP decays will have distinctive features characteristic of the second scenario which will be discussed in detail.

The plan of the paper is as follows. In Section II we establish the notation, and discuss briefly the methodology of solving the relevant RG equations and determination of the physical RPV couplings from the ones in the weak basis generated by RG evolution in Scenario I (mixing restricted to the up quark sector). In Section III we identify the relatively large input trilinear RPV couplings at M_G in Scenario I which can induce at the weak scale the naturally suppressed parameters for neutrino oscillations and other interesting couplings via RG evolution and CKM rotation. In Section IV we discuss the testable predictions of our model for rare decays. In Section V the RPV decays of the top squark, the LSP, and other sparticles, and their collider signatures have been analyzed. In Section VI the phenomenological model at the weak scale in Scenario II (mixing restricted to the down quark sector) and its observable consequences are examined. Our conclusions are summarized in the last Section.

II. RG EVOLUTION AND CKM ROTATION OF THE RPV COUPLINGS

With an eye on the neutrino phenomenology, we confine ourselves to L-violating couplings only. There are three such terms in the superpotential:

$$W_{\not{L}} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \kappa_i L_i H_2 \qquad (1)$$

where L, E, Q, D and H_2 stand for doublet lepton, singlet charged lepton, doublet quark, singlet down-type quark, and the second Higgs doublet (that gives mass to the top quark) superfields, and $i, j, k = 1, 2, 3$ are generation indices. The first term is antisymmetric in i and j.

Regarding the RG evolution of the RPV couplings, we follow [20] and refer the reader to this paper for the details. The anomalous dimensions of the standard Yukawa couplings as well as of the RPV couplings, and the β-functions, including that of the bilinear terms μ and κ_i, are given in the appendix of [20], and we will not repeat them here.

For the benchmark scenarios at the weak scale we are interested in, it is sufficient to consider only the λ'_{ijk} type couplings at M_G. It is obvious from the RG equations that λ_{ijk}s are never generated from λ'_{ijk}s through RG equations and vice versa. However, even if the bilinear couplings κ_i are zero at the GUT scale, they will be generated at the weak scale mainly through a term in the RG equation that depends on the trilinear λ'_{ijk} couplings.

The first part of the procedure is to find the RPV parameters at the weak scale. This is done through a modified version of the code ISAJET v7.69 [27] to which we have added the RG equations for the RPV parameters. The steps are outlined below in brief.

- The gauge and Yukawa couplings are specified at the weak scale. We assume that the leptonic Yukawa matrix is diagonal. As discussed in the introduction some simplifying assumptions must be made about the structures of the Yukawa coupling matrices Y_u and Y_d in the quark sector so that their elements, which appear in the RG equations, can be directly determined from the quark masses and mixing angles. The quark Yukawa matrices at the weak scale are assumed to be real and symmetric so that the rotation matrices in left and right sectors are the same. In the most general case The Cabibbo-Kobayashi-Maskawa (CKM) matrix V is given by $V = U_L^\dagger D_L$ where U_L and D_L are the rotation matrices for left-handed quark fields. Following earlier works [20, 25] we consider two scenarios:
Scenario I: $U_L = U_R = V^\dagger$, $D_L = D_R = 1$;
Scenario II: $D_L = D_R = V$, $U_L = U_R = 1$.

  Subject to the above assumptions the entries of the Yukawa matrices can be computed from

$$\begin{aligned} (I) \quad & \mathbf{m}_d(M_Z) = [\mathbf{m}_d]_{\rm diag}(M_Z)\,, \\ & \mathbf{m}_u(M_Z) = V^*_{CKM}\cdot[\mathbf{m}_u]_{\rm diag}(M_Z)\cdot V^T_{CKM}\cdot \\ (II) \quad & \mathbf{m}_d(M_Z) = V^*_{CKM}\cdot[\mathbf{m}_d]_{\rm diag}(M_Z)\cdot V^T_{CKM}\,, \\ & \mathbf{m}_u(M_Z) = [\mathbf{m}_u]_{\rm diag}(M_Z)\,. \end{aligned} \qquad (2)$$

  For simplicity, we neglect u and d quark masses. One can also neglect the second generation quark masses, and all lepton masses except that of τ. The magnitude of the entries of the CKM matrix are taken from Particle Data Group 2004 [26], based on the unitarity of the matrix:

$$V_{CKM} = \begin{pmatrix} 0.9739-0.9751 & 0.221-0.227 & 0.0029-0.0045 \\ 0.221-0.227 & 0.9730-0.9744 & 0.039-0.044 \\ 0.0048-0.014 & 0.037-0.043 & 0.999-0.9992 \end{pmatrix}. \qquad (3)$$

For numerical calculations we consider the central value of each element, except V_{ub} and V_{td}.

- At the GUT scale the elements of Y_u and Y_d can be computed from the low energy inputs (eqs. (2) and (3)) via the RG equations following an iterative procedure [20]. The elements so computed will govern the RG evolutions of the RPV parameters. The numerical values of $Y_u(M_G)$ and $Y_d(M_G)$ in Scenario I will be presented in Section III.

  Scenario II will be discussed in Section VI.

- The mSUGRA parameter space is specified by m_0, the common scalar mass, $m_{1/2}$, the common gaugino mass, $\tan\beta$, the common trilinear term A_0, and $sgn(\mu)$. We run all the gauge and Yukawa couplings upwards until g_1 and g_2 meet; that is taken to be the unification point. The strong coupling g_3 is unified by hand at that point. It is checked whether $g_3(M_Z)$ in turn goes outside the experimental range; it does not. The mSUGRA parameters used for the computation of various signals will be presented in Section V.

- At the GUT scale, all mSUGRA parameters are specified. We also specify some λ' type RPV couplings to be nonzero at M_G. As we have mentioned earlier and shall further clarify in the next section, we need to specify at least three nonzero λ's each with a different lepton index at the GUT scale and in the *weak* eigenbasis of the quark fields in order to successfully reproduce the ν phenomenology at the weak scale.

- We run down to the weak scale, taking all threshold effects into account. It is ensured that the electroweak symmetry is radiatively broken determining thereby the magnitude of μ. We also perform some sample checks on the scalar directions of the superpotenial at various energy scales so that no dangerous directions with unbounded or charge-color breaking minima are encountered. Of course, this is not a serious objection if we live in a false vacuum, but the solution is not aesthetically pleasing.

- The above running of the input RPV couplings induce other trilinear and bilinear couplings at the weak scale including κ_i and λ'_{i33} required for the neutrino sector.

- One notes the crucial role the quark mixing matrices play: without them, no λ'_{ijk} which is zero at the GUT scale can acquire a nonzero value at the weak scale. This can easily be checked from the RG equations as given in [20]. Thus, with the CKM matrix, our minimal set of 3 λ' couplings at the GUT scale can generate all 27 couplings to be nonzero at the weak scale. These couplings are in the *weak* eigenbasis and should be rotated by the proper quark mixing matrix to get the physical couplings in the *mass* eigenbasis. How this is done is shown in the next section.

- The RG evolution of the input λ' couplings are by and large independent of the RPC sector of the mSUGRA parameters apart from $\tan\beta$ which relates the quark masses and the Yukawa couplings (eq. 2). The magnitudes of the κ_is at the weak scale, however, also depend on the higgsino mass parameter μ of the RPC sector. Usually the magnitude of this parameter is fixed by the radiative electroweak symmetry breaking condition [28]. This magnitude depends, among other things, on the assumption of a common soft breaking scalar mass m_0 at M_G. There are ample reasons to believe that even within the supergravity framework the soft breaking masses for the Higgs sector and the sfermion sector may be significantly different [29, 30] at M_G. In such nonuniversal models the magnitude of μ may be quite different from that in the mSUGRA model. This in turn introduces sizable uncertainties in the magnitudes of the bilinear RPV parameters. Moreover, both the tree level and one loop neutrino mass matrices depend on the mSUGRA input parameters which are poorly known at the moment.

- We have studied the variation of λ'_{ijk} and κ_i with $\tan\beta$. If $\tan\beta$ is changed from 5 to 20, the couplings which are important in the study here, *viz.*, λ'_{i13}, λ'_{i23} and λ'_{i33}, change by less than 10%. Hence our estimates of the sizes of various collider signals (Section V) remain practically unaffected. However, $(Y_d)_{ij}$ at M_G changes significantly, and as a result there is an appreciable change in κ_i. Thus if one attempts to fit the ν oscillation data precisely, $\tan\beta$ dependence must be taken into account.

- We do not attempt a detailed RPV parameter fitting using the ν oscillation data for reasons discussed in the last paragraph. We, however, ensure that the input RPV parameters have the right ballpark values by satisfying the following criteria:

  (i) The bilinear couplings κ_is at the weak scale, related to the elements of the tree level neutrino mass matrix, should not violate the upper limits ($\sim 10^{-4}$ GeV) [18];

  (ii) The magnitude of the trilinear couplings λ'_{i33}, which are responsible for the one loop neutrino mass matrices, should also be bounded from above ($< 1.5 \times 10^{-4}$), so that the neutrino mass squared splittings and the mixing angles are reproduced.

  Strictly speaking the bounds of [18] were derived for a common SUSY scale $M_{SUSY} = 100$ GeV for all masses and mass parameters and should be modified when an mSUGRA mass spectrum is considered. But since we are mainly interested in right ballpark values only, we ignore possible changes in the bounds, which are not expected to be very drastic. Moreover, the bounds of [18] were derived in a basis in which the sneutrino VEVs vanish, whereas after the RG evolution from the GUT scale to the weak scale we arrive at non-zero values of the above VEVs in general. In principle a rotation in the H_d-slepton space should be applied to make these VEVs zero. However, such rotations are expected to change the couplings by factors which are order one. We neglect such effects in our order of magnitude estimates.

(iii) In the mass eigenbasis, all the existing constraints on the individual couplings and their products [4, 16] from non-neutrino physics should be satisfied;

(iv) Clearly the ν oscillation data cannot be explained if all the induced parameters (κ_i and λ'_{i33}) have magnitudes much smaller than the above upper bounds. In order to estimate roughly the magnitudes of the input couplings, we have assumed that the magnitudes of the above parameters should be of the same order of magnitude of the upper limits mentioned in (i) and (ii). In a forthcoming paper [31], based on numerical calculation of the eigenvalues and eigenvectors of the neutrino mass matrix (including both tree level and one loop contributions) and comparison of the results with the measured ν mass squared differences and mixing angles, it will be shown that the above assumption is fairly realistic (also see Section V).

Let us now discuss how far the ν data can be useful in constraining the RPV scenarios under consideration. First take Scenario I. In the mass eigenbasis, eq. (1) reads

$$W_{\not L} = \tilde{\lambda}'_{ijk} N_i D_j D^c_k + \overline{\lambda}'_{imk} E_i U_m D^c_p, \tag{4}$$

with

$$\tilde{\lambda}'_{ijk} = \lambda'_{ijk}, \quad \overline{\lambda}'_{imk} = \lambda'_{ijk} V^*_{jm}. \tag{5}$$

In eq. (4) N_i and E_i are respectively the neutral and charged components of the SU(2) doublet lepton superfield L_i. Thus, in the ν-sector, new couplings must be generated from the inputs at M_G through RG evolution alone; CKM rotations do not play any role. However, both RG evolution and CKM rotations may combine to generate at the weak scale interesting couplings in the mass basis involving charged lepton fields (see Sections IV and V for the consequences). Also see Section VI for Scenario II.

III. CHOICE OF THE INPUT RPV PARAMETERS AT M_G

Our goal is to find the minimal set of trilinear RPV couplings at M_G capable of reproducing at the weak scale the benchmark scenario [18] for ν oscillation under consideration.

Substituting for the anomalous dimension matrices in the RGE's of the trilinear couplings, eq. (A23) of [20], it is obvious that in order to generate a particular λ'_{ijk} at the weak scale we need a nonzero λ'_{imn} (with the same lepton index) at M_G. Thus at least three λ'-type couplings each bearing a different lepton index are required as inputs at M_G. The same conclusion follows if we examine the RG equations of the κ_is, and require these parameters to be non-zero at the weak scale for all values of i.

Of course, one option is to consider three couplings λ'_{i33} as the inputs at the GUT scale. However, the magnitudes of these inputs will be so small due to neutrino constraints that no new couplings having magnitudes appropriate for observable signals at the weak scale will be induced. Thus the only collider signals will be LSP decays [32] and top squark decays [8, 9] triggered by the three λ'_{i33}-type couplings themselves. These have, however, been studied in detail and we shall not consider this option further in this paper.

Thus the desired minimal set of input parameters at M_G may contain any three of the 24 λ'_{ijk}-type couplings (with $j = k = 3$ excluded) each with a different lepton index. First of all we reject λ'_{111} because from neutrinoless double β decay we get a very strong upper bound on this ($< O(10^{-5})$).

The Yukawa matrices Y_u and Y_d at M_G are needed to study the RG equations of the RPV parameters. Following [20] the elements of the matrix $Y_u(M_G)$ are determined from the quark masses and mixing angles. Their magnitudes in Scenario I (eq. (2)) are found to be

$$Y_u(M_G) = \begin{pmatrix} 1.67\times10^{-4} & 7.4\times10^{-4} & 8.4\times10^{-5} \\ 7.36\times10^{-4} & 3.5\times10^{-3} & 2.3\times10^{-2} \\ -9.8\times10^{-6} & 2.3\times10^{-3} & 5.7\times10^{-1} \end{pmatrix}, \tag{6}$$

where we have used $m_u = m_d \sim 0.0$, $m_s = 0.199$ GeV, $m_c = 1.35$ GeV, $m_b = 4.83$ GeV and $m_t = 175$ GeV. The off-diagonal elements of Y_d at M_G are generated through mixing in the up sector as seen from the equations given below. Starting from a diagonal Y_d at the weak scale we have

$$16\pi^2 \frac{d}{dt}(Y_d)_{22} = (Y_d)_{22}\left[-\left(\frac{7}{15}g_1^2+3g_2^2+\frac{16}{3}g_3^2\right)+|(Y_u)_{2n}|^2+6(Y_d)_{22}^2+3(Y_d)_{33}^2+(Y_e)_{33}^2\right],$$
$$16\pi^2 \frac{d}{dt}(Y_d)_{33} = (Y_d)_{33}\left[-\left(\frac{7}{15}g_1^2+3g_2^2+\frac{16}{3}g_3^2\right)+|(Y_u)_{3n}|^2+3(Y_d)_{22}^2+6(Y_d)_{33}^2+(Y_e)_{33}^2\right]. \quad (7)$$

For the off-diagonal elements of Y_d the equations are

$$16\pi^2 \frac{d}{dt}(Y_d)_{ij} = (Y_d)_{jj} \times (Y_u)_{in} \times (Y_u)_{jn}. \quad (8)$$

These three equations generate the elements of $Y_d(M_G)$. The only numerically significant elements are $(Y_d)_{13} = 9.5 \times 10^{-6}$, $(Y_d)_{22} = 3.5 \times 10^{-3}$, $(Y_d)_{23} = 2.5 \times 10^{-4}$, $(Y_d)_{32} = 1.73 \times 10^{-5}$, and $(Y_d)_{33} = 5.64 \times 10^{-2}$; all other elements of Y_d are negligible.

The procedure to identify the phenomenologically interesting minimal input sets is now outlined below.

- As discussed in the last section, we require λ'_{i33} and κ_i to be of the same order of magnitude of their upper bounds, 1.5×10^{-4} and 1.2×10^{-4} GeV respectively at the weak scale.

- If we consider the λ'_{211} and λ'_{311} couplings as inputs at M_G then from the RG equation

$$16\pi^2 \frac{d}{dt}\lambda'_{i33} = -3 \times (Y_d)_{33}(Y_d)_{11}\lambda'_{i11} \quad (9)$$

  it follows that the evolution of λ'_{i33} is controlled by the $(Y_d)_{11}$ which is too small to give λ'_{i33} with the desired order of magnitude. That is why we ignore λ'_{211} and λ'_{311} as possible inputs.

- If we numerically integrate the RG equations for λ'_{i33} and κ_i using any of λ'_{i21}, λ'_{i31} or λ'_{i12} as inputs, we find that the last condition can be satified only if the input couplings are very large and grossly violate the existing upper bounds [4, 16] from non-neutrino phenomenology. This can be understood by the following qualitative argument.

  Suppose we integrate the RGE's of κ_i using the crude approximation that all couplings other than κ_i are constants having their respective values at M_G at all scales. We obtain

$$\kappa_i{}^W = -1.25(\mu)^G((Y_d)_{nm})^G(\lambda'_{inm})^G. \quad (10)$$

  where the superscripts W and G refer to the weak scale and the GUT scale respectively. The constant 1.25 contains the large logarithm involving $M_G = 2 \times 10^{16}$ GeV, $M_Z = 91.1$ GeV and other multiplicative constants appearing in the RG equation [20]. Substituting the values of $(\mu)^G$ and $((Y_d)_{nm})^G$ and using κ_i as restricted above, we estimate the values of λ'_{inm} (with $n = m = 3$ excluded) at M_G. We find that due to small values of the corresponding elements of $Y_d(M_G)$, the parameters λ'_{i31}, λ'_{i12} and λ'_{i21} become too large. On the other hand λ'_{i22} at M_G is required to be too small to be of any phenomenological interest, due to the relatively large value of $((Y_d)_{22})^G$.

- The remaining choices are λ'_{il3} $(l = 1, 2)$ and λ'_{i32}. Using eq. (10) we can estimate the values of the couplings λ'_{il3} and λ'_{i32}, which induces κ_i^W in the right ballpark. Integrating the RG equation for λ'_{i33} using the same approximation as above, we find

$$\lambda'_{i33}{}^W \sim 2.09\lambda'_{i32}{}^G \times (Y_d)_{33}{}^G \times (Y_d)_{32}{}^G. \quad (11)$$

  When the estimated values of $\lambda'_{i32}{}^G$ are substituted, $\lambda'_{i33}{}^W$ turns out to be $O(10^{-7})$ which is too small to be of any interest in neutrino physics. On the other hand, if the elements $(\lambda'_{il3})^G$ are nonzero at M_G, a rough estimate of λ'_{i33} at the weak scale is

$$\lambda'_{i33}{}^W \sim 0.42\lambda'_{il3}{}^G \times (Y_u)_{3n}{}^G \times (Y_u)_{ln}{}^G. \quad (12)$$

  Compairing magnitudes of the elements of the matrices Y_u and Y_d at M_G, we conclude that the estimated values of λ'_{il3} naturally reproduce values of λ'_{i33} correct to the order of magnitude estimate that is favored by ν data.

So, at the end of the day, we have only six couplings, λ'_{i13} and λ'_{i23}, out of which any three with different lepton indices constitute a minimal set of inputs at M_G. From the numerical solutions of the RG equations we find that $|\lambda'_{i13}| \leq 0.13$ and $|\lambda'_{i23}| \leq 0.26 \times 10^{-2}$ can induce κ_i and λ'_{i33} with the correct order of magnitude at the weak scale.

IV. RARE WEAK DECAYS

In order to study the rare weak decays in Scenario I, we start with a set of three λ'-type couplings in the weak basis as inputs at the GUT scale (Section III). For successful explanation of ν phenomenology, these three couplings should have different lepton indices. After running down to the weak scale, as has been outlined in Section II, we get nonzero values for all λ'-type couplings, but they are still in the weak basis. For the interaction involving ν fields no further CKM rotation is required to get the interactions in the mass basis. For the charged lepton interactions, on the other hand, we rotate the fields to the mass basis (eqs. (4) and (5)) using the CKM elements given in eq. (3). The initial values of the three nonzero couplings at M_G are so chosen that at the weak scale all $|\lambda'_{i33}| \leq 1.5 \times 10^{-4}$. We start with the largest possible values thus allowed, and check whether any individual induced coupling $\overline{\lambda}'_{imk}$ at the weak scale and in the mass basis is in conflict with the already existing experimental upper bound[4, 16]. If that is the case, we scale down the input couplings accordingly. Otherwise we check whether any product of two such $\overline{\lambda}'$ couplings violates the corresponding bound, and if that is so, we scale down the input couplings further. This iterative process is continued till all couplings at the weak scale (and their products too) are consistent with the experimental limits. We next study a few specific choices of inputs at M_G.

Case 1: $\lambda'_{i13} \neq 0$

For this case, to start with, $|\lambda'_{i13}(M_G)|$ could be at most 0.13 due to oscillation constraints alone. Their magnitudes increase about threefold at the weak scale. However, even the individual bounds on λ'_{113} and λ'_{213} are tighter provided the squarks are not too heavy. The first one is $0.02(m_{\tilde{b}_R}/100)$ and the second one is $0.06(m_{\tilde{b}_R}/100)$ [4, 16] where $m_{\tilde{f}}$ is the generic sfermion mass. The bound on λ'_{113} comes from charge current universality (CCU) (as well as atomic parity violation (APV)) and that on λ'_{213} comes from the measured ratio $R_\pi \equiv \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ [4, 16]. After taking this scaling down into account, the RG induced couplings $|\lambda'_{i33}|$ relevant for the ν sector now have acceptable order of magnitude values.

The charged lepton couplings $|\lambda'_{i13}|$ in the weak basis change to the $\overline{\lambda}'$ couplings in the mass basis due to CKM rotation. The new couplings thus generated violate the upper bounds on the products $|\overline{\lambda}'_{313}\ \overline{\lambda}'_{333}|(100/m_{\tilde{l}})^2 < 2.0 \times 10^{-3}$ coming from $B^0 - \overline{B}^0$ mixing and $|\overline{\lambda}'_{313}\ \overline{\lambda}'_{323}|(100/m_{\tilde{l}})^2 < 2.7 \times 10^{-3}$ from $K^0 - \overline{K}^0$ mixing [15] unless the input values are further scaled down (for the relevent formulae see eq.(21) of [15]). Only *these* constraints, and not the ones from ν oscillation, control the ultimate upper limits of the input values of the λ's at the GUT scale. Our final choice is $\lambda'_{113}(100/m_{\tilde{b}_R}) < 0.0064$, $\lambda'_{213}(100/m_{\tilde{b}_R}) < 0.0194$, and $\lambda'_{313}(100/m_{\tilde{l}}) < 0.0386$.

Such a set of couplings generate several novel channels for rare τ decays, *e.g.*, $\tau \to \mu\rho$, which is forbidden in the SM. The decay amplitudes can be found in eq. (11) of [15]. The BR scales with $m_{\tilde{b}_R}^{-4}$. In Table (I) we show the maximum theoretical expectations vis-a-vis the experimental upper bounds [26] for a number of lepton flavor violating channels, with inputs $m_{\tilde{b}_R}$ = 300 GeV and $m_{\tilde{l}}$ = 100 GeV. It is interesting to note that the theoretical limits turn out to be only one order of magnitude (or even less) smaller than the experimental data in many cases.

Product coupling	Upper bound at M_W	Process	Predicted BR	Expt. limit
$\lambda'_{313}\lambda'_{113}$	2.4×10^{-3}	$\tau \to e\pi$	8.5×10^{-8}	3.7×10^{-6}
		$\tau \to e\eta$	7.8×10^{-8}	8.2×10^{-6}
		$\tau \to e\rho$	1.5×10^{-7}	2.0×10^{-6}
$\lambda'_{313}\lambda'_{213}$	7.2×10^{-3}	$\tau \to \mu\pi$	7.8×10^{-7}	4.0×10^{-6}
		$\tau \to \mu\eta$	7.2×10^{-7}	9.6×10^{-6}
		$\tau \to \mu\rho$	1.4×10^{-6}	6.3×10^{-6}

TABLE I: RPV mediated rare decays of the τ lepton with possibly large BRs. Since λ'_{i13} is the input coupling set, there is hardly any difference between λ' and $\overline{\lambda}'$ for these couplings.

The trilinear couplings of νs with two down-type quarks do not feel any effect of the CKM rotation, and the nonzero values are solely generated by RG evolution. Unfortunately we do not have much interesting phenomenology here: the decay $K^+ \to \pi^+\nu\overline{\nu}$ turns out to have a very tiny contribution, orders of magnitude smaller than the SM prediction.

Case 2: $\lambda'_{i23} \neq 0$

In this case the bounds are controlled by ν phenomenology only: none of the three λ'_{i23} can be more than 2.6×10^{-3} at M_G. This yields unobservably tiny contributions in all rare weak processes.

Case 3: $\lambda'_{123} \neq 0, \lambda'_{213}, \lambda'_{313} \neq 0$

Following the identical iterations as in Case 1, our optimum choice for GUT scale inputs come out to be $\lambda'_{123} = 0.0026$, $\lambda'_{213} = 0.0194$, and $\lambda'_{313} = 0.0386$. With this, all low-energy constraints on product couplings are satisfied (including that on $K^0 - \overline{K}^0$ mixing and Δm_K), but this generates a large contribution to $K^+ \to \pi^+\nu\overline{\nu}$; in fact, with such a choice, the bound on $|\overline{\lambda}'_{313}\overline{\lambda}'_{323}|$, which is 3.5×10^{-4} for 300 GeV squarks [15], is violated by a factor of 3. Of course, one can scale down the input values at M_G, but this shows that RPV couplings that are severely restricted by ν phenomenology can still generate in a correlated way a large amplitude for the $K^+ \to \pi^+\nu\overline{\nu}$ decay, and this channel is worth watching out. However, the BRs of various lepton flavor violating τ and μ decay modes turn out to be much smaller than Case 1, of the order of 10^{-14} or less, and hence completely uninteresting.

V. LEPTON NUMBER VIOLATING DECAYS OF SPARTICLES

A. Benchmark points

As in the last section we shall consider three choices of relatively large trilinear couplings as inputs at the GUT scale:

Case (1) : $\lambda'_{i13} \neq 0$ at M_G,
Case (2) : $\lambda'_{i23} \neq 0$ at M_G,
Case (3) : any combination of three non-zero couplings

taken from Case 1 and Case 2.
In all three cases the chosen trilinear couplings must carry different lepton indices i. All the three choices can allow direct lepton number violating decays of the sparticles (sleptons, squarks and LSP) with appreciable BRs. More significantly the collider signals can reveal, both qualitatively and quantitatively, the GUT scale RPV physics related to the origin of ν masses.

From the upper bounds on the input couplings the precise magnitudes of the input couplings cannot be computed. However, it has been noted in [31] that the hierarchy $\lambda'_{i13} < \lambda'_{i23}, \lambda'_{i33}$ provides an interesting solution of the oscillation data. If we set the magnitudes of the three input couplings in Case 1 in the ratio of their upper bounds, the desired hierarchy is maintained. For the purpose of illustration we shall follow this procedure, namely, of setting the input RPV couplings at M_G at such values so as to reproduce, at M_W, the upper bounds of the respective couplings computed with a common mass of 100 GeV for all the sfermions. (Note that they may not be the actual upper bounds at the benchmarks chosen by us, but one needs a standard set, valid across the different benchmark points, to make quantitative comparisons.) In case (2) the signal is qualitatively different from case (1). Even here, for quantitative estimates we shall set all input couplings equal to their upper bounds (*i.e.*, at 100 GeV). Using λ' scaled up by the ratio $m_{\tilde{b}_R}/100$ (see Section IV) one obtains larger RPV signals. Our estimates are, therefore, conservative.

Sparticles have RPC decays as well. So the BR of the RPV decay of any sparticle depends on the parameters of both RPV and RPC sectors. Computing the BRs using the above prescription on the input couplings, we find that sizable BRs of direct RPV decays of sfermions are still allowed. However, for quantitative estimates, we show our numbers for some favorable benchmark points. for example, the LHC benchmark is at

$$\begin{aligned} &m_0 = 200 \text{ GeV}, \ m_{\frac{1}{2}} = 250 \text{ GeV}, \\ &A_0 = 0, \tan\beta = 10, sgn(\mu) = -1. \end{aligned} \tag{13}$$

From radiative electroweak symmetry breaking one gets $|\mu| = 345.44$ GeV. The SUSY soft parameters are at $M_1 = 107.1$ GeV and $M_2 = 210.4$ GeV, and the mass spectrum (in GeV) is
$m_{\tilde{e_L}} = m_{\tilde{\mu_L}} = 270.4$, $m_{\tilde{\tau}_1} = 220.9$, $m_{\tilde{\tau}_2} = 271.9$, $m_{\tilde{u_L}} = 576.7$, $m_{\tilde{d_L}} = 582.1$, $m_{\tilde{b_1}} = 526.3$, $m_{\tilde{b_2}} = 554.7$, $m_{\tilde{\chi}_1^0} = 106.4$, $m_{\tilde{\chi}_2^0} = 199.7$, $m_{\tilde{\chi}_3^0} = 350.4$, $m_{\tilde{\chi}_4^0} = 361.8$, $m_{\tilde{\chi}_1^+} = 200.0$, $m_{\tilde{\chi}_2^+} = 365.1$, $m_{\tilde{g}} = 634.7$.

We have used three representative benchmark points for the Tevatron.

Choice (1): Signals for gaugino pair production

$$\begin{aligned} &m_0 = 200 \text{ GeV}, \ m_{\frac{1}{2}} = 145 \text{ GeV}, \\ &A_0 = -540, \ \tan\beta = 11, \ sgn(\mu) = -1. \end{aligned} \tag{14}$$

Radiative electroweak symmetry breaking yields $|\mu| = -318.9$ GeV, and SUSY soft parameters are $M_1 = 61.4$ GeV , $M_2 = 121.9$ GeV. The SUSY mass spectrum (in GeV) is
$m_{\tilde{e_L}} = m_{\tilde{\mu_L}} = 229.7$, $m_{\tilde{\tau}_1} = 198.9$, $m_{\tilde{\tau}_2} = 230.7$, $m_{\tilde{u_L}} = 381.3$, $m_{\tilde{d_L}} = 389.4$, $m_{\tilde{b_1}} = 313.8$, $m_{\tilde{b_2}} = 367.8$, $m_{\tilde{t_1}} = 153.1$, $m_{\tilde{t_2}} = 406.4$, $m_{\tilde{\chi}_1^0} = 61.3$, $m_{\tilde{\chi}_2^0} = 117.6$, $m_{\tilde{\chi}_1^+} = 117.6$, $m_{\tilde{\chi}_2^+} = 337.3$, $m_{\tilde{g}} = 390.4$.

This choice is motivated by the fact that the electroweak gaugino masses are slightly above the kinematic reach of LEP and should be observable at the Tevatron.

Choice (2): Signals from top squark pair production

Here we use two benchmark points, namely,

$$\begin{aligned} (\mathbf{2a}): \quad &m_0 = 140 \text{ GeV}, \ m_{\frac{1}{2}} = 180 \text{ GeV}, \\ &A_0 = -631, \ \tan\beta = 11, \ sgn(\mu) = -1, \end{aligned} \tag{15}$$

and

$$\begin{aligned} (\mathbf{2b}): \quad &m_0 = 140 \text{ GeV}, \ m_{\frac{1}{2}} = 180 \text{ GeV}, \\ &A_0 = -630, \ \tan\beta = 6, \ sgn(\mu) = 1. \end{aligned} \tag{16}$$

For choice (2a) we have $|\mu| = -381.1$ GeV, $M_1 = 76.5$ GeV, and $M_2 = 151.32$ GeV. The mass spectrum (in GeV) is
$m_{\tilde{e_L}} = m_{\tilde{\mu_L}} = 195.1$, $m_{\tilde{\tau}_1} = 136.1$, $m_{\tilde{\tau}_2} = 200.4$, $m_{\tilde{u_L}} = 423.2$, $m_{\tilde{d_L}} = 430.6$, $m_{\tilde{b_1}} = 346.7$, $m_{\tilde{b_2}} = 407.7$, $m_{\tilde{t_1}} = 135.5$, $m_{\tilde{t_2}} = 456.9$, $m_{\tilde{\chi}_1^0} = 74.3$, $m_{\tilde{\chi}_2^0} = 140.9$, $m_{\tilde{\chi}_1^+} = 140.8$, $m_{\tilde{\chi}_2^+} = 398.0$, $m_{\tilde{g}} = 468.5$.

The above choice is motivated by the requirement that the top squark be the NLSP. For choice (2b), $\tan\beta$ is smaller so that the RPC loop decay is somewhat suppressed and the RPV decay with smaller couplings, as in Case (2), can compete with the RPC decay [9]. For this case $|\mu| = 385.4$ GeV, $M_1 = 76.5$ GeV, and $M_2 = 151.3$ GeV. The mass spectrum (in GeV) is
$m_{\tilde{e_L}} = m_{\tilde{\mu_L}} = 194.8$, $m_{\tilde{\tau}_1} = 152.0$, $m_{\tilde{\tau}_2} = 198.3$, $m_{\tilde{u_L}} = 423.2$, $m_{\tilde{d_L}} = 430.4$, $m_{\tilde{b_1}} = 354.1$, $m_{\tilde{b_2}} = 410.7$, $m_{\tilde{t_1}} = 128.4$, $m_{\tilde{t_2}} = 462.2$, $m_{\tilde{\chi}_1^0} = 73.4$, $m_{\tilde{\chi}_2^0} = 138.8$, $m_{\tilde{\chi}_1^+} = 138.4$, $m_{\tilde{\chi}_2^+} = 402.9$, $m_{\tilde{g}} = 468.7$.

All production cross-sections and BRs in this section have been calculated using the software CalcHep [33].

B. Lightest neutralino decay

We begin our discussions with RPV decays of the LSP, assumed to be $\tilde{\chi_1}^0$. These decays govern all RPV signals at the colliders except for the ones arising from direct RPV decays of sfermions. If there are only λ'_{i33}-type couplings, *i.e.*, only those required by ν physics, then the main LSP decay modes are $\tilde{\chi_1}^0 \to \nu_i b\bar{b}$ (assuming $m_t > m_{\tilde{\chi_1}^0}$). As has been discussed in [9] the lepton number violating nature of this decay is not obvious due to the missing νs. Moreover, this decay can be faked by RPC decays like $\tilde{\chi_2}^0 \to \tilde{\chi_1}^0 b\bar{b}$. This is especially so if the masses of $\tilde{\chi_1}^0$ and $\tilde{\chi_2}^0$ do not follow the hypothesis of gaugino mass unification at M_G and the LSP is allowed to be much lighter than the $\tilde{\chi}_2{}^0$. It should also be noted that the above decay may be the main decay channel of $\tilde{\chi}_2{}^0$ if the lighter b-squark happens to be significantly lighter than the other sfermions due to strong mixing effects at large tan β.

In our model the LSP decay pattern is totally different because of the presence of the relatively large λ'_{i13} and/or λ'_{i23} couplings. The dominant decay modes are $\tilde{\chi}_1{}^0 \to (l_i u/\nu_i d)\bar{b}$ (Case 1) or $\tilde{\chi}_1{}^0 \to (l_i c/\nu_i s)\bar{b}$ (Case 2). In Case 3 some lepton flavors will be accompanied by u/d jets while the others will come in association with c/s jets. Thus the nature of the heavy flavor jets accompanying the charged lepton in the final state would be the qualitative feature that can distinguish one choice of GUT scale physics from another.

Case 1: $\lambda'_{i13} \neq 0$

Here our choices are $\lambda'_{113} = 0.0064$, $\lambda'_{213} = 0.0194$, and $\lambda'_{313} = 0.0386$ at M_G (see Section IV), which we use for the purpose of illustration in our numerical computations. At the weak scale the magnitudes increase by about a factor of 3. For our model of quark mixing (Scenario I) the physical couplings for the decays involving νs are the same as the ones in the flavor basis. For the decays into charged leptons the couplings in the two bases are practically identical as they are related by diagonal elements of the CKM matrix.

These couplings generate several novel channels for $\tilde{\chi}_1{}^0$ decay, tabulated in Table II. We have also presented in this table the partial widths and the BRs of different modes. The BRs for other values of the couplings can be computed by simple scaling of the partial widths. It is to be noted that the lepton number violating nature of the underlying interaction is obvious from the decays involving charged leptons. Since, $\tilde{\chi}_1{}^0$ is a Majorana particle it can decay into leptons of both charges with equal BRs. Thus final states with like sign dileptons or dileptons of different flavors and no missing energy would be clean signals of sparticle pair production in this model. Moreover, the relative abundance of final states with different leptonic compositions will be a strong indication of the magnitudes of underlying input couplings at M_G.

Finally from the total width computable from Table II, we find that the LSP is going to decay inside the detector. Note that it is only a matter of proper scaling to get the partial widths with a different set of input couplings. However, for larger input couplings, the $\tilde{\chi}_1{}^0$ lifetiem will be correspondingly shorter and the displaced vertex may be missed.

It is interesting to note that in addition to the highly suppressed λ'_{i33} couplings, required for ν-physics, this choice of input couplings also induces at M_W $\overline{\lambda'}_{i23}$ couplings with reasonable magnitudes via CKM rotation, as shown in Table II. The decays triggered by these induced couplings into final states involving charged leptons and charm have small BRs, but they may still be observable in the clean environment of the ILC.

Case 2: $\lambda'_{i23} \neq 0$

$\tilde{\chi}_1{}^0$ decays through	Value at M_W	Decay channel	Partial width (GeV)	BR at LHC
λ'_{113}	0.02	$e^- u\bar{b}$	1.2×10^{-9}	8.8×10^{-3}
		$\overline{\nu_e} d\bar{b}$	1.4×10^{-9}	1.0×10^{-2}
λ'_{213}	0.064	$\mu^- u\bar{b}$	1.3×10^{-8}	9.0×10^{-2}
		$\overline{\nu_\mu} d\bar{b}$	1.4×10^{-8}	1.0×10^{-1}
λ'_{313}	0.12	$\tau^- u\bar{b}$	5.4×10^{-8}	3.8×10^{-1}
		$\overline{\nu_\tau} d\bar{b}$	5.3×10^{-8}	3.8×10^{-1}
$\overline{\lambda'}_{123}$	0.0045	$e^- c\bar{b}$	6.3×10^{-11}	4.5×10^{-4}
$\overline{\lambda'}_{223}$	0.014	$\mu^- c\bar{b}$	6.1×10^{-10}	4.3×10^{-3}
$\overline{\lambda'}_{323}$	0.03	$\tau^- c\bar{b}$	3.4×10^{-9}	2.4×10^{-2}

TABLE II: BRs of LSP decays at LHC, for Case (1) parameter set. The CP conjugate channels are implied. The last three couplings are generated by CKM rotation and can produce only charged leptons in the final state.

$\tilde{\chi}_1{}^0$ decays through	Value at M_W	Decay channel	Partial width (GeV)	BR at LHC
λ'_{123}	0.0082	$e^- c\bar{b}$	2.1×10^{-10}	1.5×10^{-1}
		$\overline{\nu_e} s\bar{b}$	2.3×10^{-10}	1.6×10^{-1}
λ'_{223}	0.0082	$\mu^- c\bar{b}$	2.1×10^{-10}	1.5×10^{-1}
		$\overline{\nu_\mu} s\bar{b}$	2.3×10^{-10}	1.6×10^{-1}
λ'_{323}	0.0082	$\tau^- c\bar{b}$	2.5×10^{-10}	1.8×10^{-1}
		$\overline{\nu_\tau} s\bar{b}$	2.5×10^{-10}	1.8×10^{-1}
$\overline{\lambda'}_{113}$	0.0018	$e^- u\bar{b}$	1.0×10^{-11}	7.1×10^{-3}
$\overline{\lambda'}_{213}$	0.0018	$\mu^- u\bar{b}$	1.0×10^{-11}	7.1×10^{-3}
$\overline{\lambda'}_{313}$	0.0017	$\tau^- u\bar{b}$	1.1×10^{-11}	7.7×10^{-3}

TABLE III: Same as Table II, but for Case (2) parameter set.

$\tilde{\chi}_1{}^0$ decays through	Value at M_W	Decay channel	Partial width (GeV)	BR at Tevatron
λ'_{113}	0.02 (0.02)	$e^- u\bar{b}$	2.2×10^{-10} (6.3×10^{-10})	1.0×10^{-2} (5.6×10^{-2})
		$\overline{\nu_e} d\bar{b}$	2.2×10^{-10} (1.1×10^{-9})	1.3×10^{-2} (9.8×10^{-2})
λ'_{213}	0.064 (0.027)	$\mu^- u\bar{b}$	1.9×10^{-9} (1.2×10^{-9})	9.1×10^{-2} (1.0×10^{-1})
		$\overline{\nu_\mu} d\bar{b}$	2.2×10^{-9} (2.0×10^{-9})	1.1×10^{-1} (1.7×10^{-1})
λ'_{313}	0.12 (0.03)	$\tau^- u\bar{b}$	8.0×10^{-9} (3.2×10^{-9})	3.9×10^{-1} (2.9×10^{-1})
		$\overline{\nu_\tau} d\bar{b}$	7.9×10^{-9} (2.9×10^{-9})	3.8×10^{-1} (2.6×10^{-1})
$\overline{\lambda'}_{123}$	0.0045 (0.0046)	$e^- c\bar{b}$	1.1×10^{-11} (3.3×10^{-11})	5.3×10^{-4} (3.0×10^{-3})
$\overline{\lambda'}_{223}$	0.014 (0.0061)	$\mu^- c\bar{b}$	1.1×10^{-10} (5.9×10^{-11})	5.0×10^{-3} (5.2×10^{-3})
$\overline{\lambda'}_{323}$	0.03 (0.0065)	$\tau^- c\bar{b}$	5.2×10^{-10} (1.7×10^{-10})	2.5×10^{-2} (1.5×10^{-2})

TABLE IV: Same as Table II, for Case (1) and Tevatron benchmark point 1 (point 2(a)).

$\tilde{\chi}_1{}^0$ decays through	Value at M_W	Decay channel	Partial width (GeV)	BR at Tevatron
λ'_{123}	0.0082	$e^- c\overline{b}$	3.6×10^{-11}	1.4×10^{-1}
			(9.1×10^{-11})	(8.8×10^{-2})
		$\overline{\nu_e} s\overline{b}$	5.0×10^{-11}	2.0×10^{-1}
			(2.2×10^{-10})	(2.1×10^{-1})
λ'_{223}	0.0082	$\mu^- c\overline{b}$	3.6×10^{-11}	1.4×10^{-1}
			(9.1×10^{-11})	(8.8×10^{-2})
		$\overline{\nu_\mu} s\overline{b}$	5.0×10^{-11}	2.0×10^{-1}
			(2.2×10^{-10})	(2.1×10^{-1})
λ'_{323}	0.0082	$\tau^- c\overline{b}$	3.5×10^{-11}	1.4×10^{-1}
			(1.3×10^{-10})	(1.2×10^{-1})
		$\overline{\nu_\tau} s\overline{b}$	4.2×10^{-11}	1.7×10^{-1}
			(2.6×10^{-10})	(2.5×10^{-1})
$\overline{\lambda}'_{113}$	0.0018	$e^- u\overline{b}$	1.7×10^{-12}	6.8×10^{-3}
			(4.4×10^{-12})	(4.3×10^{-3})
$\overline{\lambda}'_{213}$	0.0018	$\mu^- u\overline{b}$	1.7×10^{-12}	6.8×10^{-3}
			(4.4×10^{-12})	(4.3×10^{-3})
$\overline{\lambda}'_{313}$	0.0018	$\tau^- u\overline{b}$	1.6×10^{-12}	6.4×10^{-3}
			(6.2×10^{-12})	(6.0×10^{-3})

TABLE V: Same as Table II, for Case (2) and Tevatron benchmark point 1 (point (2b)).

In this case none of the three input couplings λ'_{i23} can be larger than 2.6×10^{-3} at M_G (see Section IV). The allowed LSP decay modes, shown in Table (III), are characterized by the presence of charm and strange particles in the final state. These jets will be isolated from the b jet and hopefully can be tagged. Moreover the strangeness quantum number of the strange particle directly emitted by the $\tilde{\chi}_1{}^0$ will be opposite to that emitted by the $\overline{b}$ (unless that hadronizes into a neutral B meson and oscillates). It is encouraging to note that the possibility of c-jet tagging and reconstruction of c-flavored hadrons are being discussed vigorously [34].

This particular set of input couplings will induce λ'_{i13} with much reduced strengths compared to the input values in case 1. Thus the dominant (rare) decay modes in this case would be the rare (dominant) decay modes of case 1. The magnitudes of the induced couplings are given in Table III.

Case 3

Here the three input couplings could be various combinations of the six couplings presented in Case 1 and Case 2 where each input coupling should bear a different lepton index. The decay modes will now be combinations of the ones presented in Tables II and III. Using the partial widths presented in these tables one can easily compute the desired BRs. Again the decay modes of the LSP and the relative population of different final states may lead to the underlying model.

In Tables IV and V, we have shown the LSP decay modes for the Tevatron benchmark points. Note that for Case 2, we have chosen benchmark 2(b), the reason of which has been explained earlier.

C. Direct RPV decays of the sleptons

With our choices of λ'_{113} and λ'_{213} in Case 1 the direct RPV decays of the left selectron $\tilde{e}_L$ and the left smuon $\tilde{\mu}_L$ have strongly suppressed BRs (see Table VI). Such decays may therefore occur only as rare modes. In sharp contrast the heavier τ slepton mass eigenstate, which is dominantly a left slepton, may have sizable BRs for direct lepton number violating channels. However, if we scale the input λ' couplings by $m_{\tilde{b}_R}/100$ for the LHC benchmark point, even $\tilde{e}_L$ and $\tilde{\mu}_L$ will have RPV BRs competitive with the RPC channels. In case 2 the direct RPV decays of all sleptons will only occur as rare modes.

D. Direct RPV decays of the squarks

There is a small but non-negligible parameter space within the mSUGRA framework where gluinos are heavier than all squarks. Our choice of mSUGRA parameters belongs to this parameter space. However, this condition may be satisfied by squarks belonging to the third generation in a larger region of the parameter space. In the mSUGRA model the b squark mass eigenstates can be lighter than the gluinos at large or even intermediate values of tanβ due to mixing effects. The more interesting case of the top squark will be discussed seperately.

Squarks lighter than the gluinos are more common if non-universal squark and/or gluino masses [30, 35] motivated by various intricacies of physics at M_G are allowed. Detailed phenomenology of RPC models with squarks lighter than the gluinos due to SUSY breaking SO(10) D-terms has been discussed in [36]. The RPV signals can be obtained from these by simply adding the LSP decay. Since the RG equations of the RPV λ'-type couplings are almost independent of the RPC parameters, our estimates of the magnitudes of these couplings remain by and large unaltered even in models beyond mSUGRA.

In the LHC benchmark point and in Case (1), squarks dominantly decay into electroweak gauginos. We present in Table VII the BRs of RPC decays, as well as those of RPV decays through λ'_{i13} couplings of $\tilde{u_L}$ and $\tilde{d_L}$. Only the decays into τ or ν_τ may have a few percent BR while the other modes are suppressed. Table VIII shows the channels for b squark decay. For the lighter mass eigenstate $\tilde{b}_1$ RPV modes have highly suppressed BRs, while the heavier mass eigenstate $\tilde{b}_2$ can decay into several RPV channels each having a few percent BR. It should be noted that the BRs of the RPV decays of $\tilde{b}_2$ will increase dramatically if $m_{\tilde{b}_2} < m_t + m_{\tilde{\chi}_2^-}$.

E. Direct RPV decays of the lighter top squark

The lighter top squark mass eigenstate $\tilde{t}_1$ can naturally have a mass much smaller than that of the other squarks. This may happen due to two reasons. First, even if all squarks have the same mass m_0 at M_G, the

Type of Slepton	RPC Decay Channel	Partial Width (GeV)	Branching Ratio	RPV Decay Channel	Partial Width (GeV)	Branching Ratio
$\tilde{e}_L$	$\tilde{\chi_1}^0 e$	2.3×10^{-1}	2.5×10^{-1}			
	$\tilde{\chi_2}^0 e$	2.5×10^{-1}	2.7×10^{-1}	$\overline{u}b$	6.6×10^{-3}	7.2×10^{-3}
	$\tilde{\chi_1}^- \nu_e$	4.3×10^{-1}	4.7×10^{-1}	$\overline{c}b$	3.3×10^{-4}	3.6×10^{-4}
$\tilde{\mu_L}$	$\tilde{\chi_1}^0 \mu$	2.3×10^{-1}	2.4×10^{-1}			
	$\tilde{\chi_2}^0 \mu$	2.5×10^{-1}	2.5×10^{-1}	$\overline{u}b$	6.7×10^{-2}	6.8×10^{-2}
	$\tilde{\chi_1}^- \nu_\mu$	4.3×10^{-1}	4.4×10^{-1}	$\overline{c}b$	3.2×10^{-3}	3.3×10^{-3}
$\tilde{\tau_1}$	$\tilde{\chi_1}^0 \tau$	6.1×10^{-1}	9.7×10^{-1}	$\overline{u}b$	1.1×10^{-2}	1.7×10^{-2}
	$\tilde{\chi_2}^0 \tau$	2.6×10^{-3}	4.1×10^{-3}	$\overline{c}b$	6.6×10^{-4}	1.1×10^{-3}
	$\tilde{\chi_1}^- \nu_\tau$	4.6×10^{-3}	7.3×10^{-3}			
$\tilde{\tau_2}$	$\tilde{\chi_1}^0 \tau$	2.7×10^{-1}	2.4×10^{-1}	$\overline{u}b$	2.2×10^{-1}	2.0×10^{-1}
	$\tilde{\chi_2}^0 \tau$	2.2×10^{-1}	2.0×10^{-1}	$\overline{c}b$	1.4×10^{-2}	1.3×10^{-2}
	$\tilde{\chi_1}^- \nu_\tau$	3.7×10^{-1}	3.4×10^{-1}			

TABLE VI: BRs of RPC and RPV decay channels of sleptons in Case (1) with the LHC benchmark point.

Type of Squark	RPC Decay Channel	Partial Width (GeV)	Branching Ratio	RPV Decay Channel	Partial Width (GeV)	Branching Ratio
$\tilde{u_L}$	$\tilde{\chi_1}^0 u$	6.3×10^{-2}	1.1×10^{-2}	$e^+ b$	4.6×10^{-3}	8.1×10^{-4}
	$\tilde{\chi_2}^0 u$	1.7	3.1×10^{-1}			
	$\tilde{\chi_3}^0 u$	9.0×10^{-3}	1.6×10^{-3}	$\mu^+ b$	4.7×10^{-2}	8.3×10^{-3}
	$\tilde{\chi_4}^0 u$	8.1×10^{-2}	1.4×10^{-2}			
	$\tilde{\chi_1}^+ d$	3.5	6.2×10^{-1}	$\tau^+ b$	1.6×10^{-1}	2.9×10^{-2}
	$\tilde{\chi_2}^+ d$	7.3×10^{-2}	1.3×10^{-2}			
$\tilde{d_L}$	$\tilde{\chi_1}^0 d$	8.4×10^{-2}	1.5×10^{-2}	$\overline{\nu_e} b$	4.0×10^{-3}	7.2×10^{-4}
	$\tilde{\chi_2}^0 d$	1.7	3.1×10^{-1}			
	$\tilde{\chi_3}^0 d$	1.5×10^{-2}	2.7×10^{-3}	$\overline{\nu_\mu} b$	4.1×10^{-2}	7.5×10^{-3}
	$\tilde{\chi_4}^0 d$	1.1×10^{-1}	2.0×10^{-2}			
	$\tilde{\chi_1}^- u$	3.1	5.6×10^{-1}	$\overline{\nu_\tau} b$	1.4×10^{-1}	2.6×10^{-2}
	$\tilde{\chi_2}^- u$	2.9×10^{-1}	5.5×10^{-2}			

TABLE VII: BRs of RPC and RPV decay channels of up and down squarks in Case (1) with the LHC benchmark point.

mass parameters of $\tilde{t}_L$ and $\tilde{t}_R$ at the weak scale may be significantly smaller due to the influence of the large top quark Yukawa coupling in the RG equations. The mass of the lighter eigenstate may be further suppressed due to mixing effects in the $\tilde{t}_L$-$\tilde{t}_R$ mass matrix, with large off-diagonal entries. i It is quite conceivable that $\tilde{t}_1$ happens to be the next lightest supersymmetric particle (NLSP). If in addition the conditions $m_{\tilde{t}_1} < m_t + m_{\tilde{\chi_1}^0}$ and $m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi_1}^0}$ are satisfied, then the only possible RPC decay modes are
(i) the loop decay [37]: $\tilde{t}_1 \to c\tilde{\chi_1}^0$
or (ii) the four body decay [38]: $\tilde{t}_1 \to bf\overline{f}'\tilde{\chi_1}^0$, where f and f' are light fermions. Both the decays occur in higher order of perturbation theory and have naturally suppressed widths. If the couplings of the type λ'_{i3j} are nonzero and of the order of 10^{-1} or 10^{-2}, then the RPV two body decay

$$\tilde{t}_1 \to l_i^+ \overline{d_j} \tag{17}$$

overwhelm the RPC decays and occur with 100% BRs. However, If the underlying trilinear coupling is order 10^{-3} or smaller then the BR of each competing mode may have a sizable magnitude. In fact it was shown in [8] that the data from Tevatron Run I or the preliminary data from Run II are already sensitive to $\lambda'_{i3j} \sim 10^{-3}$-$10^{-4}$, although for rather small $m_{\tilde{t}_1}$. It was shown in [9] that a larger range of $m_{\tilde{t}_1}$ can be probed at Run II with integrated luminosity ~ 2 fb^{-1}.

If λ'_{i33}, *i.e.*, the couplings required by the ν sector, are the only ones with appreciable magnituds then the main decay channels of $\tilde{t}_1$ would be

$$\tilde{t}_1 \to l_i^+ \overline{b}. \tag{18}$$

In contrast our model allows other possibilities, particularly in Scenario II (Section VI), depending on the underlying model of CKM mixing and the input RPV couplings. First consider Scenario I. Here the three input couplings in the flavor basis at M_G are possible combinations of λ'_{i13} and λ'_{i23}. These input couplinngs can induce λ'_{i33} at the weak scale via the RG evolution as we have already discussed. However, the input couplings, depending on their magnitudes, may induce couplings of

Type of Squark	RPC Decay Channel	Partial Width (GeV)	Branching Ratio	RPV Decay Channel	Partial Width (GeV)	Branching Ratio
$\tilde{b}_1$	${\tilde{\chi}_1}^0 b$	1.7×10^{-1}	4.8×10^{-2}	$e^- u$	5.6×10^{-4}	1.6×10^{-4}
	${\tilde{\chi}_2}^0 b$	1.5	4.1×10^{-1}	μu	5.8×10^{-3}	1.6×10^{-3}
	${\tilde{\chi}_3}^0 b$	8.8×10^{-2}	2.5×10^{-2}	τu	2.0×10^{-2}	5.7×10^{-3}
	${\tilde{\chi}_4}^0 b$	8.2×10^{-2}	2.3×10^{-2}	$\overline{\nu_e} d$	4.8×10^{-4}	1.4×10^{-4}
	${\tilde{\chi}_1}^- t$	1.7	4.8×10^{-1}	$\overline{\nu_\mu} d$	4.9×10^{-3}	1.4×10^{-3}
	${\tilde{\chi}_2}^- t$	does not	occur	$\overline{\nu_\tau} d$	1.7×10^{-2}	4.8×10^{-3}
				ec	2.8×10^{-5}	7.9×10^{-6}
				μc	2.8×10^{-4}	7.9×10^{-5}
				τc	1.3×10^{-3}	3.6×10^{-4}
$\tilde{b}_2$	${\tilde{\chi}_1}^0 b$	2.0×10^{-1}	1.3×10^{-1}	eu	3.8×10^{-3}	2.4×10^{-3}
	${\tilde{\chi}_2}^0 b$	7.4×10^{-2}	4.7×10^{-2}	μu	3.9×10^{-2}	2.5×10^{-2}
	${\tilde{\chi}_3}^0 b$	1.8×10^{-1}	1.1×10^{-1}	τu	1.4×10^{-1}	8.8×10^{-2}
	${\tilde{\chi}_4}^0 b$	1.9×10^{-1}	1.2×10^{-1}	$\overline{\nu_e} d$	3.3×10^{-3}	2.1×10^{-3}
	${\tilde{\chi}_1}^- t$	9.0×10^{-2}	5.8×10^{-2}	$\overline{\nu_\mu} d$	3.4×10^{-2}	2.2×10^{-2}
	${\tilde{\chi}_2}^- t$	4.8×10^{-1}	3.1×10^{-1}	$\overline{\nu_\tau} d$	1.2×10^{-1}	7.6×10^{-2}
				ec	1.9×10^{-4}	1.2×10^{-4}
				μc	1.9×10^{-3}	1.2×10^{-3}
				τc	8.6×10^{-3}	5.5×10^{-3}

TABLE VIII: BRs of RPC and RPV decay channels of bottom squarks in Case (1) with the LHC benchmark point.

the type $\overline{\lambda}'_{i33}$ involving charged lepton interactions via the CKM rotation which could be much larger than the same couplings relevant for the ν sector via RG evolution only. This is a more likely situation for input couplings with possibly larger magnitudes as in Case 1.

These $\overline{\lambda}'_{i33}$ couplings trigger top squark decay. Maximum possible values of these couplings at the weak scale are:

$$\lambda'_{133} = 8.0\times10^{-4}, \;\; \lambda'_{233} = 2.4\times10^{-3}, \;\; \lambda'_{333} = 4.6\times10^{-3}. \tag{19}$$

The RPV decay modes will still be $\tilde{t}_1 \to l_i^+ \overline{b}$. The complete dominance of RPV decays, however, would strongly indicate the relatively large input couplings at the GUT scale.

For the purpose of illustrating the competition between RPC and RPV decay modes, we prefer to use somewhat scaled down values of the RPV couplings of Case (1) [otherwise the RPV decay modes will be overwhelmingly large]. The input values as well as the BRs are presented in Table IX. For Case (2), on the other hand, the upper limits of the input couplings λ'_{i23} are much smaller in magnitude ($\sim 10^{-3}$), and the CKM rotated $\overline{\lambda}'_{i33}$ couplings generated by them would be naturally $\sim 10^{-4}$ or smaller. Thus the possibility of competition among RPC and RPV is better in this case, see Table X. We use the Tevatron benchmark values, but let us emphasize that the stop signals will be much more prominent at the LHC.

In scenario II the situation is even more intriguing. For a discussion we refer the reader to Section VI.

Type of Squark	Decay Channel	RPV coupling and strength	Branching Ratio
$\tilde{t}_1$	$\tilde{t}_1 \to {\tilde{\chi}_1}^0 c$	——	15.5%
	$\tilde{t}_1 \to e^+ b$	$\overline{\lambda}'_{133}$: 8.0×10^{-4}	18.5%
	$\tilde{t}_1 \to \mu^+ b$	$\overline{\lambda}'_{233}$: 1.03×10^{-3}	30.7%
	$\tilde{t}_1 \to \tau^+ b$	$\overline{\lambda}'_{333}$: 1.1×10^{-3}	35.0%

TABLE IX: The lighter top squark BR into RPC and RPV channels. The input is as in Case (1), with couplings at the mass basis and at M_W. The benchmark point is that of Tevatron (2a).

Type of Squark	Decay Channel	RPV coupling and strength	Branching Ratio
$\tilde{t}_1$	$\tilde{t}_1 \to {\tilde{\chi}_1}^0 c$	——	34.2%
	$\tilde{t}_1 \to e^+ b$	$\overline{\lambda}'_{133}$: 1.3×10^{-4}	21.8%
	$\tilde{t}_1 \to \mu^+ b$	$\overline{\lambda}'_{233}$: 1.3×10^{-4}	21.8%
	$\tilde{t}_1 \to \tau^+ b$	$\overline{\lambda}'_{333}$: 1.3×10^{-4}	21.8%

TABLE X: The same as Table IX, but with Case (2) input and Tevatron (2b) benchmark.

F. Some interesting signals with sizable number of events at the Tevatron and the LHC

Our aim is to propose some signals, in addition to LSP decays, which indicate the direct RPV decay of at least one sfermion. A signal arising from sfermion-antisfermion pair production followed by direct RPV decays of both is not suitable for this purpose because of obvious backgrounds. Slepton pair production, for example, would lead to final states with jets only (see Ta-

Channel number	Decay modes of stop pair	No. of events	Channel number	Decay modes of stop pair	No. of events
1.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to e^- \overline{b}$	3403	2.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \mu^- \overline{b}$	5647
3.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to e^- \overline{b}$	2985	4.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to e^+ b\overline{c}\,\overline{u}$	80
5.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{u}$	413	6.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{u}$	75
7.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{u}$	125	8.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{u}$	363
9.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{u}$	218	10.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{u}$	142

TABLE XI: Number of events coming from stop-antistop pair production at Tevatron for final states involving dileptons with (i) like sign and same flavor; (ii) like sign and different flavor; and (iii) unlike sign and different flavor. The dilepton signal is accompanied by two jets. The charge conjugated states are also included. The input parameters are of Case (1), Tevatron benchmark (2a), with $\tilde{m}_{t_1} = 135.5$ GeV. The stop pair production cross-section is 2.92 pb. We use the data of table IX and IV.

Channel number	Decay modes of stop pair	No. of events	Channel number	Decay modes of stop pair	No. of events
1.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to e^- \overline{b}$	3482	2.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \mu^- \overline{b}$	3482
3.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to e^- \overline{b}$	3482	4.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{c}$	240
5.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{c}$	328	6.	$\tilde{t_1} \to \tilde{\chi}_1{}^0 c \to \tau^+ b\overline{c}\,c$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{c}$	31
7.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{c}$	240	8.	$\tilde{t_1} \to \tilde{\chi}_1{}^0 c \to \mu^+ b\overline{c}\,c$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{c}$	17
9.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to e^+ b\overline{c}\,\overline{c}$	240	10.	$\tilde{t_1} \to \tilde{\chi}_1{}^0 c \to e^+ b\overline{c}\,c$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to e^+ b\overline{c}\,\overline{c}$	17
11.	$\tilde{t_1} \to \mu^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{c}$	328	12.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{c}$	328
13.	$\tilde{t_1} \to e^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \tau^+ b\overline{c}\,\overline{c}$	240	14.	$\tilde{t_1} \to \tau^+ b$ $\tilde{t_1}^* \to \tilde{\chi}_1{}^0 \overline{c} \to \mu^+ b\overline{c}\,\overline{c}$	240

TABLE XII: Same as Table XI, but for Case (2) and Tevatron benchmark (2b), where $\tilde{m}_{t_1} = 128.4$ GeV, and the stop pair production cross-section is 4.07 pb. We use the data of table X and V.

ble. VI) which will suffer from a huge QCD background. Squark-antisquark pairs decaying into isolated opposite sign dileptons (OSDs) of the same flavor and accompanied by $b\overline{b}$ jets may suffer from a large Drell-Yan background accompanied by QCD jets . However, final states with isolated like sign dilepton (LSD) pairs or dileptons carrying different flavors are expected to provide cleaner signals.

We discuss below some interesting signals arising from sparticle pair production and their subsequent decay. To estimate the number of events, we use an integrated luminosity of 10^5 pb^{-1} at LHC and 9000 pb^{-1} at Tevatron.

1. Signals from sfermion pair production

First we consider the dilepton plus dijet signals from direct RPV decays of the lighter top squark pair produced at the Tevatron. Even for the apparently unfavorable signal involving opposite sign dileptons (OSD) of the same flavor, the backgrounds can be suppressed by suitable cuts [8, 9]. We do not analyze this signal in this work. Rather, we analyze only those channels which result in either OSD of different flavor or LSD in the final state. We present in Tables XI and XII the number of events using the BRs in Tables II, III, IX, X. The number of events in several cases are quite encouraging. The reconstruction of the masses of the two top squarks when both decays directly to RPV channels was discussed in [9]. In some of the cases discussed, we need the reconstruction of the invariant masses of two sets: one with a lepton and a b-jet, and one with all other visible particles in the final state, such that the two reconstructed invariant masses agree with each other within certain tolerance limit. This establishes our signal.

Next we focus our attention on the final states

$l_i^{\pm} l_j^{\pm}\overline{b}\overline{b}(bb)+X$, where X is the unobserved junk at LHC arising from initial states not involving top squarks. One of the isolated leptons in the like sign dilepton (LSD) pair comes from the RPC decay of a sfermion followed by the RPV decay of the produced LSP, which is a Majorana fermion and decays into leptons of both flavors with equal BRs. The other one comes from the direct RPV decay of the second member of the produced fermion-antisfermion pair. Such final states may arise from several initial states listed in Tables XIII and XIV. The background to this signal is expected to be small due to the presence of the isolated LSDs without any accompanying missing energy. In principle the presence of the bb or $\overline{b}\overline{b}$ pair in the final state may also help to reduce the QCD background which always involve $b\overline{b}$. This is possible if lepton tagging and/or kaon tagging can distinguish between b and $\overline{b}$ with reasonable efficiency. One can hope that this will be achieved since the study of CP violation in B-decays is an important component of LHC physics. The direct lepton number violating decay of one of the sfermions can be identified by reconstructing the invariant mass as in the case of the decaying top squarks.

From Table. VII it is clear that the squarks may dominantly decay into τs via the RPV channel while decays to e and μ may be heavily suppressed. However, the BR of the muonic channel is still of the order of a few percent. Combining these informations one can estimate that a significant number of events of $\tau - \mu$ type (of all charge combinations) can be seen. We have also presented in Table XIII (see last two rows) $\tau^{\pm}\mu^{\pm}b\overline{b}$ events which are also expected to have small backgrounds. The signal size is already encouraging.

The production cross-section of slepton pairs is small at LHC. In spite of this, the signal may be important if the signal from the squarks are depleted due to the presence of gluinos lighter than the squarks. The LSD signal from τ slepton pair production has apparently a small size, but this may be enhanced using larger values of λ' which are still allowed (so this is in some sense a conservative estimate).

2. *Signals from gaugino pair production*

The $\tau^+\tau^+bb$ signals from gaugino pair production at LHC and Tevatron are presented in Table XV for Case(1) and in Table XVI for Case (2) input values. Sizable number of events are expected from $\tilde{\chi_2}^0\tilde{\chi_1}^+$ and $\tilde{\chi_1}^+\tilde{\chi_1}^-$ pairs involving LSDs of a particular flavor.

We conclude this section by reiterating that all the input λ's at M_G can in principle be determined by a fit to the oscillation data if at least a partial information about the RPC sector is available from collider experiments. This in turn will firmly predict the particle content of different final states as well as the relative abundance of various final states. The observation of these exciting signals will reveal the GUT scale physics lying at the origin of ν masses and mixing angles.

VI. MIXING IN THE DOWN QUARK SECTOR: PHENOMENOLOGY

Let us now discuss how far the neutrino data can be useful in constraining the RPV models in Scenario II with mixing in the down-quark sector, $V = D_L = D_R$, $U_L = U_R = \mathbf{1}$. In this case the off-diagonal elements of the Yukawa coupling matrix Y_d are much larger than those in Scenario I (mixing restricted to the up quark sector only). As a result any input λ'-type couplings would lead to rather large values of κ_i and λ'_{i33} via RG evolution, in conflict with the upper bounds in [18] unless the magnitudes of the input couplings are too small to be of any phenomenological interest. This conclusion agrees with that of [20] although the latter was arrived at in a model with a single neutrino mass.

However, this argument hinges crucially on the RG evolution from the GUT scale to the weak scale in the mSUGRA model. In practice, the origin of SUSY breaking is not known. It is quite possible that SUSY is broken at a much lower scale (as, *e.g.*, in the Gauge-mediated SUSY breaking models). For this type of models, not only the boundary conditions of the RG will be different but as a whole the evolution should have a less important role to play.

In view of the above uncertainties we take a more phenomenological point of view and assume that only a few relatively large λ' type couplings *in the weak basis*, not directly related to ν physics, and bilinear parameters κ_i are generated at the weak scale by some new physics at the high scale, the nature of which is unknown. We will see whether it is possible to generate the suppressed λ'_{i33} type couplings relevant for the ν sector via CKM rotation while the input couplings at the weak scale can still be sufficiently large to trigger interesting non-neutrino phenomenology.

In this case, the rotation to the mass eigenbasis is different from that in Scenario I. After rotation eq. (1) reads

$$W_{\not{L}} = \tilde{\lambda}'_{imp} N_i D_m D^c_p + \overline{\lambda}'_{ijp} E_i U_j D^c_p, \qquad (20)$$

where the fields are in the mass basis, and

$$\begin{aligned} \tilde{\lambda}'_{imp} &= \lambda'_{ijk} V_{jm} V^*_{kp}, \\ \overline{\lambda}'_{ijp} &= \lambda'_{ijk} V^*_{kp}. \end{aligned} \qquad (21)$$

Thus in contrast to Scenario I new couplings involving both neutral and charged lepton superfields can be induced by the input couplings via CKM rotations. The next task is to find out the possible minimal sets of input couplings at the weak scale which can serve our purpose.

Clearly, one can take $\lambda'_{i33} \neq 0$ as the input, each one with upper limits of 1.5×10^{-4} approximately [18]. However, the induced couplings in this case will be so small that no interesting phenomenology outside the neutrino sector apart from LSP decay [32] and top squark decay [9] is viable.

Before we investigate other options, let us note that $K^0 - \overline{K}^0$ mixing data predicts $|\lambda'_{i12}\lambda'_{i21}| < 10^{-9}$ [13, 15]

Channel number	Squark pair	σ (pb) at LHC	Decay mode of the squarks	No of events
1.	$\tilde{b_2}\tilde{b_2}^*$	0.54	$\tilde{b_2} \to \tau^- u$ $\tilde{b_2}^* \to \overline{b}\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{b}$	86
2.	$\tilde{b_2}\tilde{b_2}^*$		$\tilde{b_2} \to \tau^- u$ $\tilde{b_2}^* \to \overline{b}\tilde{\chi_2}^0 \to \overline{f} f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{b}\ \overline{f}\ f$	85
3.	$\tilde{b_1}\tilde{b_1}^*$	0.77	$\tilde{b_1} \to \tau^- u$ $\tilde{b_1}^* \to \overline{b}\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{b}\ \overline{f}\ f$	69
4.	$\tilde{u_L}\tilde{u_L}^*$	0.61	$\tilde{u_L}^* \to \tau^-\overline{b}$ $\tilde{u_L} \to u\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{b}\ \overline{f}\ f$	208
5.	$\tilde{b_2}\tilde{b_2}^*$		$\tilde{b_2}^* \to \mu^+\overline{u}$ $\tilde{b_2} \to \tau^- u$	237
6.	$\tilde{u_L}\tilde{u_L}^*$		$\tilde{u_L}^* \to \tau^-\overline{b}$ $\tilde{u_L} \to \mu^+ b$	32
7.	$\tilde{u_L}\tilde{u_L}$	1.02	$\tilde{u_L} \to \tau^+\overline{b}$ $\tilde{u_L} \to \mu^+ b$	49

TABLE XIII: Number of events arising from squark-antisquark pair production at LHC, with Case (1) input. Charge conjugate channels are included.

Channel number	Slepton pair	σ (pb) at LHC	Decay mode of the sleptons	No of events
1.	$\tilde{\tau_2}^*\tilde{\tau_2}$	5.2×10^{-3}	$\tilde{\tau_2}^* \to u\overline{b}$ $\tilde{\tau_2} \to \tau^-\tilde{\chi_1}^0 \to \tau^-\ \tau^- u\overline{b}\ \overline{b}$	10
2.	$\tilde{\tau_2}^*\tilde{\tau_2}$		$\tilde{\tau_2}^* \to u\overline{b}$ $\tilde{\tau_2} \to \tau^-\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^-\ \tau^- u\overline{b}\ \overline{b}\ \overline{f} f$	8

TABLE XIV: Same as Table XIII, for stau pair production.

(we drop the tilde from now, but these couplings are in the mass basis). Thus, one should not start with nonzero λ'_{i11}, λ'_{i22}, λ'_{i12} or λ'_{i21} (in the weak basis) as inputs. From eq. (21), it is clear that one must start with such small values as to be devoid of all phenomenological interests. The limiting value of all these four sets is 1.4×10^{-4} at the weak scale [18]. This translates to $|\lambda'_{i33}| < 2.8 \times 10^{-9}$, 2.5×10^{-7}, and 2.6×10^{-8} (for both λ'_{i12} and λ'_{i21} sets) respectively. Considering the symmetric nature of the magnitude of the CKM elements, one can start with either (i) $\lambda'_{i13(i31)}$ or (ii) $\lambda'_{i23(i32)}$ to be nonzero. At first, the couplings are set to be nonzero at the weak scale with such a value as to produce the limiting value of 1.5×10^{-4} for λ'_{i33}, and then rescaled, if necessary, so as to conform with the Δm_K constraint (this is a similar iteration as was done in Section II).

Case (i): The maximum value of $\lambda'_{i23(i32)}$ to start with is 3.6×10^{-3}. After proper rotation, one obtains the couplings at the mass basis and finds $|\lambda'_{i12}\lambda'_{i21}| < 4.5 \times 10^{-10}$, so this choice is safe from the $K^0 - \overline{K}^0$ constraint.

Case (ii): The neutrino data constrains $\lambda'_{i13(i31)}$ to be less than 0.052, but one needs a scaling down by a factor of 9.7 to be in conformity with the $K^0 - \overline{K}^0$ constraints. For all these cases every other constraint on product couplings is satisfied.

However, with such small couplings, one does not hope to see an indirect non-neutrino signal of RPV. We mention again that for indirect signals of RPV, the individual couplings should be of the order of 10^{-2} and the product couplings of the order of 10^{-3}-10^{-4}. Such possibilities do not exist for the option we have just discussed; but again, this is a model-dependent statement and should not hold for other models of CKM mixing.

Thus we conclude that irrespective of the details of the high scale physics it is impossible to generate the λ'_{i33} couplings of the benchmark scenario from relatively large, phenomenologically interesting input couplings at the weak scale and in the weak basis if (i) quark mixing is primarily restricted to the down quark sector, and (ii) the Yukawa matrix is symmetric.

Still, these couplings can induce novel channels of decay for the lighter stop quark and the lightest neutralino which are quite distinct for those in Scenario I. Two possible phenomenological inputs couplings in the flavor basis at the weak scale are λ'_{i31} or λ'_{i32}. Since these couplings themselves can trigger top squark decays, the physical couplings in the mass basis does not suffer any further suppression due to CKM rotation. The absence of bottom jets in the final state distinguishes the top squark decay from that in Scenario I. These signals have also been discussed in refs [8, 9].

Channel number	Gaugino pair	σ (pb) at LHC (Tevatron)	Decay channel of the gauginos	No of events at LHC (Tevatron)
1.	$\tilde{\chi_1}^0\tilde{\chi_1}^0$	9.3×10^{-3}	$\tilde{\chi_1}^0 \to \tau^- u\ \overline{b}$ $\tilde{\chi_1}^0 \to \tau^- u\ \overline{b}$	62
2.	$\tilde{\chi_2}^0\tilde{\chi_2}^0$	2.1×10^{-2}	$\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{f}\ f$ $\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{f}\ f$	130
3.	$\tilde{\chi_2}^0\tilde{\chi_1}^+$	5.3×10^{-1} (2.8×10^{-1})	$\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{f}\ f$ $\tilde{\chi_1}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to \tau^- u\ \overline{b}\ \overline{f}_1\ f_2$	3350 (186)
4.	$\tilde{\chi_1}^+\tilde{\chi_1}^-$	4.7×10^{-1} (3.2×10^{-1})	$\tilde{\chi_1}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{f}_1\ f_2$ $\tilde{\chi_1}^- \to f_1\ \overline{f}_2\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ f_1\ \overline{f}_2$	3100 (214)
5.	$\tilde{\chi_2}^+\tilde{\chi_2}^-$	2.3×10^{-2}	$\tilde{\chi_2}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ \overline{f}_1\ f_2$ $\tilde{\chi_2}^- \to f_1\overline{f}_2\tilde{\chi_1}^0 \to \tau^- u\overline{b}\ f_1\ \overline{f}_2$	152

TABLE XV: Number of events from gaugino pair production for Case(1) input at LHC (Tevatron benchmark (1)) with the final state involving $\tau^-\tau^-\overline{b}\overline{b} + X$ (and charge conjugate channels).

Channel number	Gaugino pair	σ (pb) at LHC (Tevatron)	Decay channel of the gauginos	No of events at LHC (Tevatron)
1.	$\tilde{\chi_2}^0\tilde{\chi_2}^0$	2.1×10^{-2}	$\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}\ f$ $\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}\ f$	54
2.	$\tilde{\chi_2}^0\tilde{\chi_1}^+$	5.3×10^{-1} (2.9×10^{-1})	$\tilde{\chi_2}^0 \to \overline{f}\ f\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}\ f$ $\tilde{\chi_1}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}_1\ f_2$	1500 (73)
3.	$\tilde{\chi_1}^+\tilde{\chi_1}^-$	4.7×10^{-1} (3.2×10^{-1})	$\tilde{\chi_1}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}_1\ f_2$ $\tilde{\chi_1}^- \to f_1\ \overline{f}_2\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ f_1\ \overline{f}_2$	1318 (85)
4.	$\tilde{\chi_2}^+\tilde{\chi_2}^-$	2.3×10^{-2}	$\tilde{\chi_2}^+ \to \overline{f}_1\ f_2\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ \overline{f}_1\ f_2$ $\tilde{\chi_2}^- \to f_1\ \overline{f}_2\tilde{\chi_1}^0 \to l_i^- c\overline{b}\ f_1\ \overline{f}_2$	64

TABLE XVI: Same as Table XV, but for Case (2) input, and benchmark (1) for Tevatron.

VII. CONCLUSION

In conclusion we reiterate that three relatively large input couplings of λ'_{ijk} type in the flavor basis at M_G each bearing a different lepton index can generate at the weak scale via RG evolution several additional λ'-type couplings in the same basis (see Section III) with naturally suppressed magnitudes. This occurs due to the flavor violation inevitable in any model due to quark mixing. Also generated are three lepton number violating bilinear terms κ_i. These bilinears and three induced λ'_{i33} couplings can explain the ν oscillation data [18]. The upperbounds $\lambda'_{i33} < 1.5\times10^{-4}$ and $\kappa_i < 1.2\times10^{-4}$ obtained from neutrino data can be translated into upper bounds on the input couplings at M_G. In spite of the severe constraints from the ν sector these input couplings are allowed to be reasonably large. When evolved to the weak scale and then rotated to the mass basis the corresponding physical couplings can trigger several interesting signals, which are not expected in models where the couplings in the ν sector are the only ones with appreciable magnitude.

In order to illustrate these ideas we study the RG equations of the RPV mSUGRA model along with some models of the quark mixing matrix [20, 25]. In models with quark mixing occuring in the up sector (Scenario I) we find that a minimal set of any three couplings, chosen from the group λ'_{i13} and λ'_{i23}, each with a different lepton index can serve the purpose. For the input set λ'_{i13} (Case 1), the oscillation data as well as other low energy constraints [4, 16] lead to the upper bounds $\lambda'_{113} < 0.0064$, $\lambda'_{213} < 0.019$, $\lambda'_{313} < 0.039$ at M_G for $m_{\tilde{b}_R} = 100$ GeV (see Sections III and IV). Rare τ decays with BRs close to the current experimental bounds are allowed in this case (see Table I). For the input set λ'_{i23} (Case 2), the bounds on the input couplings are more stringent, and hence no interesting rare weak process can be mediated by such small couplings. For the mixed choice λ'_{123}, λ'_{213} and λ'_{313}, the rare decay $K \to \pi\nu\overline{\nu}$ with BR close to the current experimental upper limit are consistent with the bounds on the input couplings.

LSP decays with characteristic BRs occur for all choices of GUT scale inputs. For Case 1 LSP decays into a charged lepton accompanied by a b-jet and a light quark jet is the distinctive signal (Table II) . In Case 2 two heavy flavor jets (c and b) accompany the charged lepton (Table III). The relative abundance of the final states with different leptons can indicate the relative strengths of the inputs at M_G.

The lighter top squark decays in RPV channels can naturally compete with its RPC decays in models of ν mass provided this sparticle happens to be the NLSP

[8, 9]. In Case 1, due to the relatively large upper bounds on the input RPV couplings, RPV can overwhelm RPC decays in a large region of the parameter space. However, if the input couplings (in particular the one involving τ) are somewhat smaller than the upper bounds, competition between RPV and RPC modes may show up (Table VII). Competition among the RPV and RPC decays are more probable in Case 2 (Table VIII).

In Case 1 the upper bounds on the RPV couplings are consistent with direct RPV decays of other squarks and leptons with sizable BRs (Tables IV-VI). The above decays can lead to several low background signals both at the Tevatron and at the LHC. At Tevatron gaugino pair production followed by the LSP decay can lead to interesting signals (Tables XV and XVI).

Top squark pair production at Tevatron followed by direct RPV decays of both the sparticles into an OSD pair of same flavor and jets have been discussed in [8, 9]. In this paper we consider the signals with isolated LSD pairs and isolated dileptons of different flavors (Tables IX and X corresponding to Case 1 and Case 2, respectively). Both are expected to be low background signals and our numerical estimates indicate large number of events. Obviously a huge signal at LHC is anticipated.

Gaugino pair production followed by LSP decays can provide the signals similar to the ones discussed in the last paragraph. Even at the Tevatron a healthy size of the signal is expected in both Case 1 and 2 (Tables XIII and XIV). The prospect of observing these signals at the LHC is even better (Tables XV and XVI).

Interesting signals arising from sfermion-antisfermion pair production followed by the direct RPV decay of one and indirect RPV decay of the other can lead to signals with decent magnitudes at LHC (Tables XI and XII).

If, on the other hand, a model of the CKM matrix with mixing in the down quark sector (Scenario II) is considered, an mSUGRA type model with phennomenologically interesting, large input RPV couplings at M_G not directly related to the ν sector is not viable. If attention is paid to the ν constraint the input couplings at M_G are destined to be highly suppressed (Section VI)

We next consider a phenomenological model with relatively large weak scale RPV parameters in the flavor basis induced by some high scale physics, the nature of which is presently unknown. Even if the induced trilinear couplings are not directly related to the neutrino sector, the λ'_{i33} couplings can be generated in the mass basis via CKM rotations. One can start with either (i) $\lambda'_{i13(i31)}$ or (ii) $\lambda'_{i23(i32)}$ to be nonzero in the flavor basis at the weak scale. Unfortunately CKM rotations of these inputs not only generate the couplings required by the ν sector consistent with their upper limits, but also generate other dangerously large couplings leading to unaccetably large $K^0 - \overline{K}^0$ mixing amplitude. Consequently such inputs must have small magnitudes not interesting for rare weak decays or direct RPV decays of squarks or sleptons. However top squark and LSP decays occur with characteristics quite different from the ones discussed for Scenario I (Section VI).

VIII. ACKNOWLEDGEMENTS

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