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Flavour structure of R-parity violating supersymmetry and the LHC

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We use flavour and GUT symmetries in order to study the structure and hierarchies of operators that violate R-parity. Different groups favour different search channels, and concrete statements on how to link future observations with specific symmetries of the underlying theory are obtained. We then proceed to discuss R-violating decays of neutralinos and charginos. Since both sparticles couple to all (s)fermions, these channels are optimal for the simultaneous study of all 45 couplings and for making comparative studies. We demonstrate the ability to understand whether more than one coupling dominates, and to map the experimental signatures to specific operator hierarchies, which can then be compared against theoretical models of flavour. The expectations for neutrino masses and for low energy lepton flavour violation are also addressed, providing additional correlations and input on the flavour structure of the theory. Within these schemes, light gravitinos can be naturally stable on cosmological scales, providing a very good candidate for dark matter. Moreover, due to the rapid decay of the next-to-lightest supersymmetric particle, these models are naturally compatible with Big Bang Nucleosynthesis.

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1. Introduction

After the first results of the LHC and the spectacular discovery of the Higgs particle [1], the expectations for signatures of new physics have not yet been fulfilled. This resulted in strong bounds on several Standard Model (SM) extensions, including the simplest realisations of supersymmetry, such as the MSSM (Minimal Supersymmetric Standard Model) [2]. On the other hand, there has been increasing interest in R-violating supersymmetry, where the very rich structure of Yukawa couplings generates additional possibilities. Indeed, supersymmetrizing the Standard Model allows for additional trilinear lepton or baryon number violating terms, namely:

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \tag{1.1}$$

where L (Q) are the left-handed lepton (quark) doublet superfields, and $\bar{E}$ $(\bar{D}, \bar{U})$ the corresponding left-handed singlets. SU(2) and SU(3) invariance imply that there are 45 R-violating couplings in all (27 λ'_{ijk}s and 9 each of λ_{ijk} and λ''_{ijk}) [3].

Very strict bounds on lepton and baryon-number violating operators arise from proton stability, but the assumption of conserved R-parity automatically rules out all of the terms in (1.1) [4]. However, alternative symmetries (baryon or lepton parities [5]) can also exclude the simultaneous presence of dangerous $LQ\bar{D}$ and $\bar{U}\bar{D}\bar{D}$ couplings. Experimental constraints from the non-observation of modifications to Standard Model rates, or from possible exotic processes [3] impose additional limits. Overall, the phenomenology to be expected out of such theories is very rich [3], since the LSP (Lightest Supersymmetric Particle) is no longer stable and the missing-energy signatures of the MSSM are substituted by multi-lepton or multi-jet events. Moreover, resonant single superparticle productions, which would be spectacular signatures, are also possible.

In general, the flavour structure of R-violating couplings is of particular relevance in defining the nature of the signals to be expected, and any information on this would be crucial for understanding the flavour structure of the fundamental theory. In this respect, the hierarchies amongst R-violating couplings can be linked to those in fermion masses, using models with family and/or GUT symmetries, as we have done for instance in [6], linking our findings with physics at HERA [7]. A large class of such models allows only the third generation fermions to be massive, while the remaining masses are generated by the spontaneous breaking of the family symmetry through the Froggatt-Nielsen mechanism [8]. In such a scheme, if R-parity is violated, couplings with different family charges are likely to appear with different powers of the family symmetry-breaking parameter, and thus with different magnitudes.

2. Predictions for R-violation from GUT and flavour symmetries

Most phenomenological analyses are assuming the dominance of a single R-violating operator. However, once a flavour structure is invoked (e.g., to explain fermion masses and mixings), the R-violating hierarchies are related to the flavour charges of the respective fields. Even more importantly, even if only one R-violating operator is to be postulated in the interaction basis, fermion mixing would, in general, induce non-zero values for others. This implies that it is natural to expect a range of hierarchies for R-violating operators, as was found for instance in [6], where two representative cases, namely Left-Right symmetric models and $SU(5)$, combined with family symmetries, were explored.

2.0.1 Left-Right-symmetric models

The simplest starting point is a single $U(1)$ family symmetry with the same charges for the left- and right-handed states (left-right symmetry, LR) as shown in Table 1, where, e.g., the choice $a_i = (-4,1,0)$ [9] gives an acceptable pattern for the mass matrices.

With these charge assignments the quark mass matrices (up to numerical factors and phases, which, in general, are expected to be of order unity) take the form

	Q_i	$\bar{U}_i$	$\bar{D}_i$	L_i	$\bar{E}_i$	H_2	H_1
$U(1)$	a_i	a_i	a_i	b_i	b_i	$-2a_3$	$-2a_3$

Table 1: *Assignments of* $U(1)$ *charges.*

$$M^{\text{up}} \sim \begin{pmatrix} \varepsilon^8 & \varepsilon^3 & \varepsilon^4 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^4 & \varepsilon & 1 \end{pmatrix}, \quad M^{\text{down}} \sim \begin{pmatrix} \bar{\varepsilon}^8 & \bar{\varepsilon}^3 & \bar{\varepsilon}^4 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon} \\ \bar{\varepsilon}^4 & \bar{\varepsilon} & 1 \end{pmatrix} \tag{2.1}$$

where $\bar{\varepsilon} \approx \sqrt{\varepsilon} \approx 0.2$.

We now consider the effect of the $U(1)$ symmetry on the pattern of allowed R-violating interactions [6, 10]. In this simple example, with all fermions of a given family having the same charge and with a left-right symmetry, the charges of the operators depend only on the combination (i,j,k) and are independent of the type, viz. $LL\bar{E}$, $LQ\bar{D}$ or $\bar{U}\bar{D}\bar{D}$, (see Table 2).

ijk	111	121	122	222	131
$U(1)$	$-12-w$	$-7-w$	$-2-w$	$3-w$	$-8-w$
ijk	133	333	223	233	123
$U(1)$	$-4-w$	$-w$	$2-w$	$1-w$	$-3-w$

Table 2: *Operator charges in a model (see text) with both family and Left-Right symmetry. Here* w *parametrises flavour-independent contributions [6].*

The parameter w accounts for the fact that the charge assignment is not unique in model constructions (although it is strongly constrained by phenomenological and theoretical arguments including anomaly cancellation, additional fields with a non-trivial flavour charge that couple to all operators, etc) [6].

The above flavour symmetries cannot ensure, by themselves, that rapid proton decay is avoided. This is done by imposing a baryon or a lepton parity. For instance, lepton-number violating operators can be eliminated by imposing a lepton triality [11], under which the fields transform as

$$Z_3 : (Q, \bar{U}, \bar{D}, L, \bar{E}, H_1, H_2) \to (1,1,1,a,a^2,1,1). \tag{2.2}$$

This allows only the baryon-number-violating operators and the mass terms, while forbidding lepton-number-violating ones. On the other hand, to forbid baryon-number violating operators, we would work instead with a baryon triality, such as in [5]:

$$Z_3 : (Q, \bar{U}, \bar{D}, L, \bar{E}, H_1, H_2) \to (1,a^2,a,a^2,a^2,a^2,a). \tag{2.3}$$

While w can be adjusted in order to ensure that all operators remain within the experimental bounds, there can be additional sources of suppression in the couplings (small $\tan\beta$, form of Kähler potential, or even extra fields and symmetries). If the couplings that correspond to higher flavours are bigger (have smaller flavour charge), similarly to those for fermion masses, then the operators that involve third-generation flavours would dominate also in this case.

The problem gets more complicated by taking into account mixing effects [6], in combination with bounds on both individual couplings as well as on products. The experimental bounds on R-violating couplings can help further. For instance, for $\Delta L \neq 0$ the strictest bounds are on $L_1 Q_1 \bar{D}_1$ from nuclear $\beta\beta$ decay and on $L_1 L_3 \bar{E}_3$ from bounds on Majorana neutrino masses [3], resulting to $|12+w| \geq 2$ and $|4+w| \geq 2$, which are easy to satisfy [6]. We also note that the magnitudes of the couplings in Table 2 are symmetric in the three indices ijk. This implies, for example, that the λ'_{121} and λ'_{112} couplings should have similar magnitudes. Then, constraints on the product $(L_1 Q_2 \bar{D}_1) \cdot (L_1 Q_1 \bar{D}_2)$, from bounds on Δm_K indicate that the relevant charge $|7+w|$ has to be large.

Overall, the various bounds plus the strong correlations between different couplings in LR-symmetric models, lead to a suppression of all couplings. Within this framework, therefore, single superparticle productions are suppressed and the best signal would be pair productions followed by R-violating decays. This is a strong statement, since it indicates that if single sparticle productions were to be observed, left-right symmetric models would be strongly disfavored.

2.0.2 $SU(5)$

Another interesting possibility is that the family symmetry commutes with an $SU(5)$ GUT, where the SM fermions are assigned to the representations of the group as follows:

$$\begin{aligned} Q_{(q,u^c,e^c)_i} &= Q_i^{10} \\ Q_{(l,d^c)_i} &= Q_i^{\bar{5}} \\ Q_{(\nu_R)_i} &= Q_i^{\nu_R} \end{aligned} \tag{2.4}$$

From the above it immediately follows that :
The up-quark mass matrix is symmetric (both left- and right-handed up quarks are in the 10, and thus have the same flavour charge).
The charged lepton mass matrix is the transpose of the down quark mass matrix.

In this case, a viable choice of charges obeying the restrictions of the symmetry (e.g., [12]) is:

$$\begin{aligned} Q_{1,2,3} = \bar{E}_{1,2,3} = 3,2,0 \\ \bar{D}_{1,2,3} = L_{1,2,3} = 1,0,0 \end{aligned} \tag{2.5}$$

leading to matrices that, apart from other features, lead to a maximal 2-3 lepton mixing, viz.

$$M^{\text{up}} \sim \begin{pmatrix} \bar{\varepsilon}^6 & \bar{\varepsilon}^5 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^5 & \bar{\varepsilon}^4 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \end{pmatrix}, \quad M^{\text{down}} \sim \begin{pmatrix} \bar{\varepsilon}^4 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon} & 1 & 1 \end{pmatrix}, \quad M^{\ell} \sim \begin{pmatrix} \bar{\varepsilon}^4 & \bar{\varepsilon}^3 & \bar{\varepsilon} \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \end{pmatrix}, \tag{2.6}$$

where $\bar{\varepsilon} \approx 0.2$.

Let us first look at the implications for the $LL\bar{E}$ operators. Since the charges of $L_{2,3}$ are the same, couplings such as $L_i L_2 \bar{E}_k$ and $L_i L_3 \bar{E}_k$ would be expected to be of similar magnitude. In short, the $U(1)$ assignments of Eq. (2.5) lead to operator charges as listed in Table 3.

Similarly for $LQ\bar{D}$, where now we have the connection $\lambda'_{ijk} = \lambda_{ijk}$ arising directly from the way we accommodate the fields in the GUT representation. We also note that, since the $U(1)$ charges

ijk	121,131	231	122,132	232	123,133	233
$U(1)$	$4-w$	$3-w$	$3-w$	$2-w$	$1-w$	$-w$

Table 3: *$LL\bar{E}$ charges in SU(5) enhanced by a U(1) flavour symmetry.*

of $L_{2,3}$ are the same, the respective operators are linked, reducing the number of independent couplings. Further reduction of the independent couplings occurs, since the $U(1)$ charges of $\bar{D}_{2,3}$ are the same. This leaves us with the results of Table 4. Finally, for the baryon-number violating operators, we find the results given in Table 5.

ijk'	111	112,113	121	122,123	131	132,133
$U(1)$	$5-w$	$4-w$	$4-w$	$3-w$	$2-w$	$1-w$
ijk'	211,311	212,213,312	221,321	222,223,322,323	231	232,233,332,333
$U(1)$	$4-w$	$3-w$	$3-w$	$2-w$	$1-w$	$-w$

Table 4: *$LQ\bar{D}$ charges in SU(5) enhanced by a U(1) flavour symmetry.*

ijk''	112,113	123	212,213	223	312,313	323
$U(1)$	$4-w$	$3-w$	$3-w$	$2-w$	$1-w$	$-w$

Table 5: *$\bar{U}\bar{D}\bar{D}$ charges in SU(5) enhanced by a U(1) flavour symmetry.*

Overall, we see that in SU(5) we can have larger hierarchies between the R-violating operators, and the correlations are weaker. Single sparticle productions are now allowed, and, being very sensitive to the flavour structure of R-violating operators, they give important feedback on the symmetries of the theory. Various interesting possibilities arise, namely:

- For $w = 0$, the $L_2L_3\bar{E}_3$ coupling is as large as the largest of the $LQ\bar{D}$ couplings and therefore the prospects of accurately identifying this coupling are improved. Moreover, the leading subdominant $LL\bar{E}$ operators, namely $L_1L_3\bar{E}_3$ and $L_1L_2\bar{E}_3$, carry a lot of tau flavour.
- $w = 1$ would imply a simultaneous dominance of the $L_1L_2\bar{E}_3$ and $L_1L_3\bar{E}_3$ couplings.
- $w = 2$ leads to a dominant $L_2L_3\bar{E}_2$ coupling.
- $w = 3$ results in a simultaneous dominance of the $L_2L_3\bar{E}_1$, $L_1L_2\bar{E}_2$ and $L_1L_3\bar{E}_2$ couplings.

A similar situation (but for different respective flavours) would occur for the remaining operators.

3. Neutralino and Chargino Decays at the LHC

From the above discussion, we see that, despite some very concrete statements (such as to which groups single sparticle productions can arise), testing the verious models against observations is hard, due to the large number of possibilities. However, it also becomes clear that the pair production of superpartners and their subsequent cascade decays via an unstable neutralino or chargino have a great advantage, since the latter (by coupling to all quarks and leptons) could decay via any of the 45 trilinear operators, thereby allowing a *comparative* and *simultaneous* study of all couplings. Through a detailed, correlated study of these decay chains, one may also investigate whether more than one R-violating couplings are of substantial size, “map” their magnitudes and hierarchies, and compare against theoretical models [10].

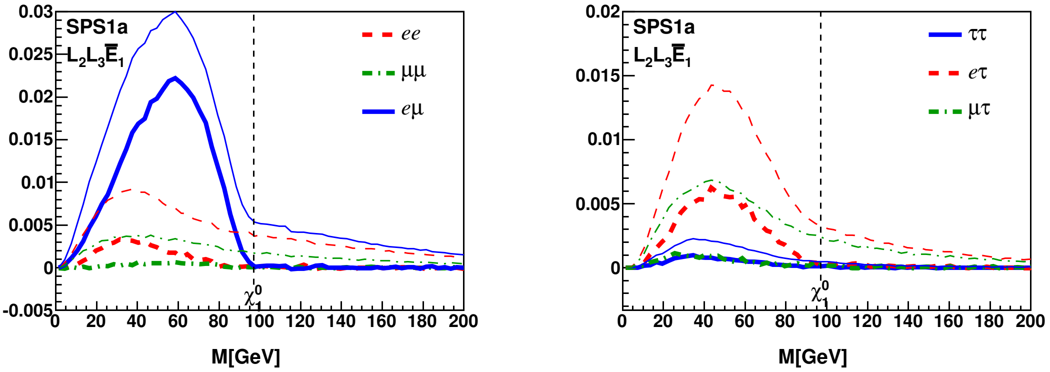


Figure 1: Di-lepton invariant masses for $L_2L_3\bar{E}_1$ at SPS1a, where the neutralino mass is 97.0 GeV. Thin curves: without same-sign subtraction. Thick curves: $M(\ell\ell')$ distributions after same-sign subtraction. Here, "τ" refers to a hadronic tau.

Depending on the scenario, a variety of supersymmetric particles could be produced in proton-proton collisions, mostly squarks and gluinos, but also charginos and neutralinos. The squarks and gluinos will typically decay to quarks, leptons and gauginos (the final state depends on the flavour structure of the R-violating operator and the sparticle spectrum). Gauginos will then decay to the LSP, typically the lightest neutralino. The lightest chargino may also have observable decays, provided its mass is close to the one of the lightest neutralino.

3.1 R-violating Neutralino Decays

Our analysis [10] has been performed for some of the SPS points in [13] (in order to allow for direct comparisons between the MSSM results), using the Monte Carlo generator PYTHIA 8 [14].

We shall first consider the couplings $L_iL_j\bar{E}_k$, which typically lead to decays of the LSP to two charged leptons and a neutrino, for example

$$\tilde{\chi}_1^0 \xrightarrow[L_1L_2\bar{E}_1]{} e^+\mu^-\nu_e, \quad e^-\mu^+\bar{\nu}_e, \quad e^+e^-\nu_\mu, \quad e^+e^-\bar{\nu}_\mu. \tag{3.1}$$

While isolated leptons in the final state would also arise in R-conserving scenarios from decays higher up in the cascade chain, differences in kinematic distributions allow us to statistically disentangle the composition of the final state. We assume that $\lambda_{ijk} = 10^{-4}$, however, the actual strength of the R-violating coupling does not lead to qualitative differences in the predictions, as long as:
(i) it is strong enough for the neutralino decays to be inside the detector
(ii) it is not sufficiently large for sparticles to decay directly via the R-violating operators.

The large lepton multiplicity of the final state from $LL\bar{E}$ operators makes these operators relatively easy to handle. Suppressing the background is more or less trivial, since we only require a large number of isolated hard leptons. The only slight complication arises due to the presence of neutrinos in the final state of the decay. The way around this is to calculate the theoretically expected invariant mass distributions for the charged leptons of the final state; this can be done for lepton pairs that come directly from the neutralino, as well as for lepton pairs where one or both leptons come from a decaying tau [10].

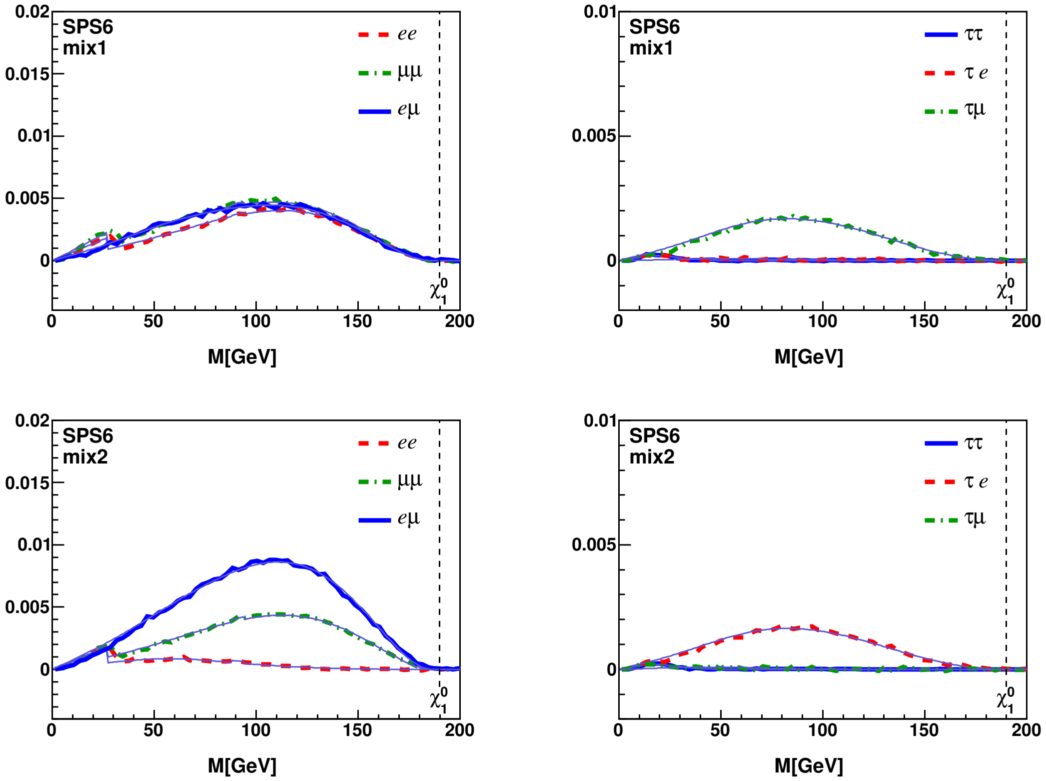


Figure 2: Di-lepton invariant masses for mix1 (upper panels) and mix2 (lower panels) at SPS6.

It is also straightforward to study cases with more than one operators being relevant. For instance, let us look at two cases where two operators are comparable, namely,

$$\begin{array}{ll} \mathrm{mix1}: & L_1L_2\bar{E}_1 = L_2L_3\bar{E}_2 = 10^{-4} \\ \mathrm{mix2}: & L_1L_2\bar{E}_2 = L_2L_3\bar{E}_1 = 10^{-4} \end{array} \tag{3.2}$$

These combinations are chosen such that the total flavour content of mix1 and mix2 is the same at the operator level.

The corresponding invariant mass distributions (Fig. 2) are clearly different, indicating that different mixing possibilities are distinguishable and can be directly linked to flavour symmetries that favor dominance of the specific operators.

For $LQ\bar{D}$ operators, the neutralino normally decays to a lepton or neutrino plus two jets. Due to the smaller number of leptons as compared to the $LL\bar{E}$ operators, we have to suppress backgrounds by requiring two same-sign leptons; this suppresses our signal, but since lepton pairs from $t\bar{t}$ events usually have opposite charge, it practically removes the background. The channel with a charged lepton plus two jets is also promising, due to the fact the we can observe everything and therefore we expect to see a peak in the appropriate invariant mass distribution. When, however, the lepton is a tau, the loss of energy due to the neutrino(s) in the decay of the tau, to some extent smears out the peak. Moreover, if the operator has b quarks from a $\bar{D}_3$ component, b tagging and same-sign subtraction reduce the combinatorial background in the invariant mass distributions. With such b quarks present, operators with tau leptons can also be handled. When, however, the b quarks arises from a 3rd generation Q operator we encounter the most difficult case of all. This is because the channel that includes a charged lepton in the decay also includes a top quark and therefore will be suppressed by the top mass.

The $\bar{U}\bar{D}\bar{D}$ operators are clearly the most difficult to observe, since the neutralino typically decays to three jets. We might therefore be left with just a lot of jets, which are very difficult to separate from the QCD background (although interesting possibilities do exist [15]). $\bar{U}_3\bar{D}\bar{D}$ is a special operator: if the neutralino is lighter than the top quark, the neutralino has no simple decay channels and may leave the detector, resulting to a fake MSSM scenario. The other possibility, that the neutralino is in fact heavier than the top, would lead to neutralino decays to a top (or anti-top) plus two jets [10].

3.2 R-violating Chargino Decays

Direct RPV chargino decays can take place in scenarios with a wino or higgsino effective LSP, where the lightest chargino and neutralino have a small mass difference Δm. In order to investigate the properties of these scenarios, we employed a bayesian scan over the MSSM parameter space, taking into account all relevant constraints [16]. We performed our main scan with logarithmic priors, checking that the central conclusions remain unchanged with linear priors.

In addition to concrete experimental signatures related to RPV chargino decays, differences between a wino and a higgsino LSP also exist: the first is somewhat preferred in the region of small Δm, while the second has a larger RPC branching ratio to leptons, which, if a long-lived chargino is discovered, can be used to probe the gaugino sector of the theory. This can be the case for substantial patches of the supersymmetric parameter space, even in the MSSm, which is the most conservative scenario. In extensions of the theory, the parameter space where such signatures could arise would be enhanced. The scan uses `MultiNest 2.17` [17] to explore the parameter space described above. For each point, the sparticle spectrum is calculated by `SoftSusy 3.3.5` [18]. Higgs masses are calculated using `FeynHiggs 2.9.4` [19] and electroweak precision observables using `SoftSusy` and `MicrOMEGAS 2.4.5` [20]. In addition, the relevant constraints from LEP data on the chargino mass and the LHC Higgs mass measurement are included.

For $LL\bar{E}$ operators, in addition to signals similar to those of the neutralinos, discussed above, spectacular signatures, such as three charged-lepton resonances, with explicit lepton number violation in the final state, can be expected. The results are shown in Fig. 3 for an indicative benchmark point (`RPV_C3` in [16]). In addition, similarly to neutralino decays, there are interesting features in the di-lepton invariant mass distributions, where employing same-sign subtraction practically removes the combinatorial background, thus revealing features that would otherwise be invisible.

For $LQ\bar{D}$ operators, the expected physics is mostly similar to RPV neutralino decays. However, for $LQ_3\bar{D}$, there is a distinct difference between RPV neutralino and chargino decays, since the first involves neutrinos plus jets or a charged lepton and a top quark, while the latter involves charged leptons plus jets or neutrinos and top quarks. For charginos therefore, a signal with both a lepton and a b-tag and potential charge identification has enhanced detectability.

For $\bar{U}\bar{D}\bar{D}$ operators we do not expect significant chargino RPV decays for positive Δm. For small (below pion mass) and negative mass differences, charginos below 500 GeV seem excluded by searches for long-lived charged particles. For heavier charginos, detection through RPV decays

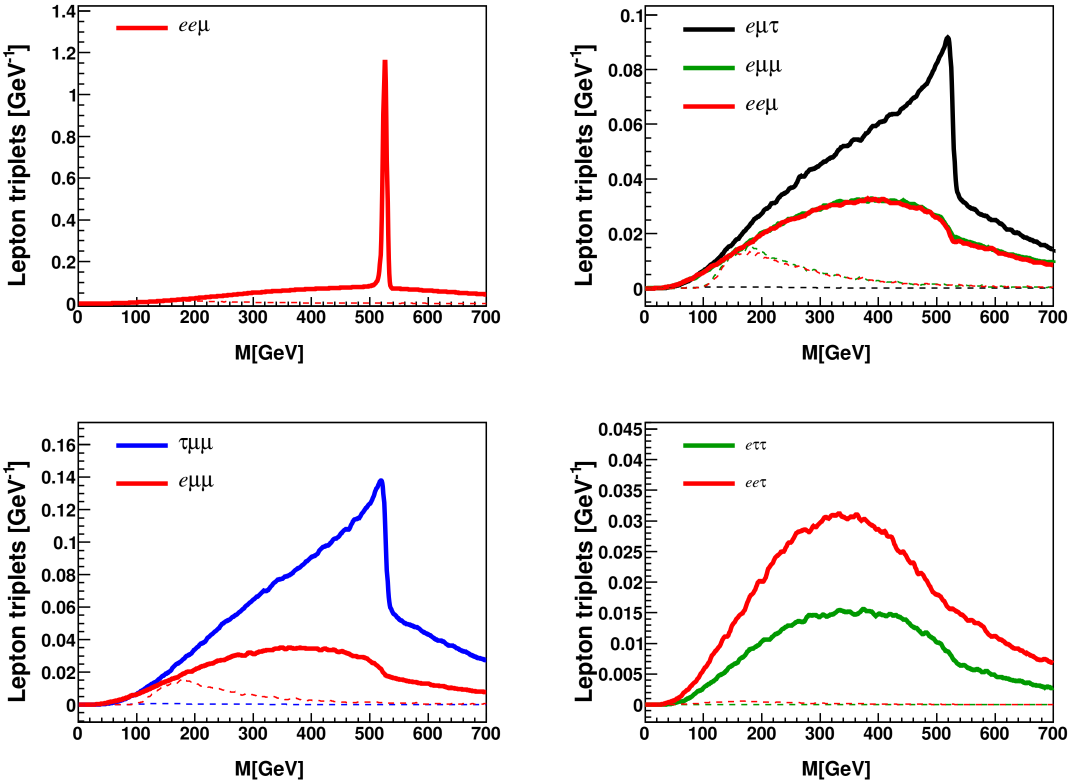


Figure 3: Various flavour combinations of tri-lepton invariant masses for the $L_1L_2\bar{E}_1$, $L_1L_2\bar{E}_3$, $L_2L_3\bar{E}_2$ and $L_1L_3\bar{E}_3$ couplings. The thin dashed lines give the dominant background, and the distributions are normalized to 1 fb^{-1} of integrated luminosity.

is very difficult, and requires the use of sophisticated jet clustering methods. Nevertheless, the operator $\bar{U}_3\bar{D}_j\bar{D}_k$ has a particularly interesting behaviour: while neutralino RPV decays will always contain a top quark, the chargino can decay to three jets including at least one b-jet. Furthermore, for the operators $\bar{U}_3\bar{D}_j\bar{D}_3$ one can also get bbj and ttj final states, opening the possibility to search for rare multi-top events and events with same sign top pairs.

In conclusion, direct neutralino (and depending on the parameter space) chargino R-violating decays are a powerful tool to simultaneously test the presence of all R-violating operators, and make the link with the underlying flavour and GUT symmetries.

4. Neutrino Masses and low energy LFV

Neutrino masses are generated at one-loop via squark (slepton) exchange for $LL\bar{E}$ ($LQ\bar{D}$) operators [21]. Under the assumption that the left-right sfermion soft mass-squared mixing terms are diagonal in the physical basis and proportional to the associated fermion mass ($m^2_{\tilde{f}LR} \propto m_f m_{\tilde{f}}$), the formula for the neutrino masses can be simplified to [21]

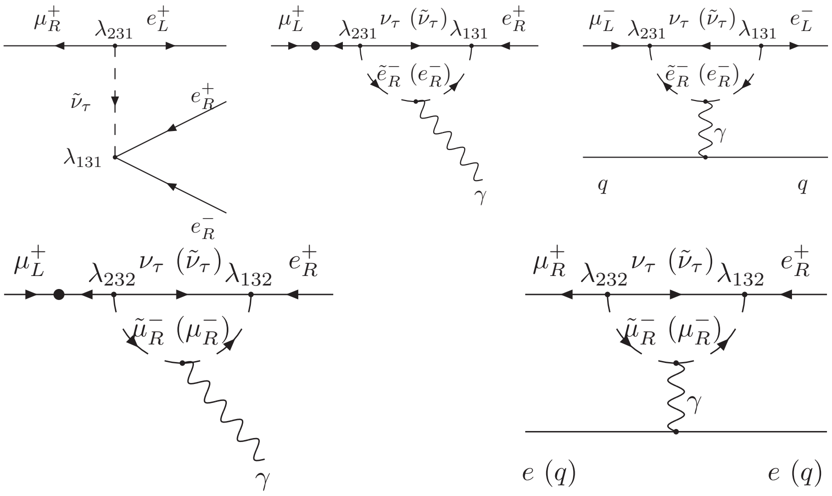
$$\begin{aligned} m_{\nu_{ii'}} &\simeq \frac{n_c \lambda_{ijk}\lambda_{ikj}}{16\pi^2} m_{f_j} m_{f_k} \left[\frac{f(m^2_{f_j}/m^2_{\tilde{f}_k})}{m_{\tilde{f}_k}} + \frac{f(m^2_{f_k}/m^2_{\tilde{f}_j})}{m_{\tilde{f}_j}} \right] \\ f(x) &= (x\ln x - x + 1)/(x-1)^2 \end{aligned} \tag{4.1}$$

Here, m_{f_i} is the fermion mass of the ith generation inside the loop, $m_{\tilde{f}_i}$ is the average of the $\tilde{f}_{Li}$ and $\tilde{f}_{Ri}$ squark masses, and n_c is a colour factor (3 for $LQ\bar{D}$ operators and 1 for $LL\bar{E}$ operators). This expression implies that the heavier the fermions in the loop, the stricter the bounds [3].

In addition, similar coupling magnitudes could lead to observable lepton flavour violation in channels such as $\mu \to e\gamma$, $\mu^+ \to e^+e^+e^-$ and $\mu - e$ conversion in nuclei. Complete expressions for the R-violating lepton flavour violating processes, at both tree-level and one-loop have beed derived in [22], also inluding polarisation effects.

Whether tree-level or one loop diagrams dominate in each mode depends on the flavour structure of the dominant R-violating operators. However, the current bounds on products of couplings from LFV processes [3], ought also to be considered. In particular:
(i) $\lambda_{131}\lambda_{231}$, $|\lambda_{121}\lambda_{122}|$ and $|\lambda_{131}\lambda_{132}|$ are constrained by $\mu \to 3e$.
(ii) $|\lambda_{132}\lambda_{232}|$, $|\lambda_{133}\lambda_{233}|$, and $|\lambda_{231}\lambda_{232}|$ are constrained by one-loop $\mu - e$ conversions.
(iii) $|\lambda'_{111}\lambda'_{211}|$, $|\lambda'_{112}\lambda'_{212}|$, $|\lambda'_{113}\lambda'_{213}|$ and $|\lambda'_{121}\lambda'_{221}|$ are constrained by tree-level $\mu - e$ conversions.
(iv) $|\lambda'_{122}\lambda'_{222}|$ and $|\lambda'_{123}\lambda'_{223}|$, are constrained by one-loop $\mu - e$ conversions.

We have several possibilities, as indicated in Figure 4, where we see that whether the LFV decays/conversions occur at tree or at loop level depends on the combinations of dominant R-violating operators [22]. The correlations of the LFV branching ratios for different combinations of dominant R-violating couplings are indicated in Table 1 [22], for $m_{\tilde{\nu},\tilde{l}_R} = 100$ GeV and $m_{\tilde{q}} = 300$ GeV. Cases (1), (2), (3) in the Table correspond to the three groups of diagrams in Fig. 4. For comparison, we also show a typical result obtained for the MSSM with heavy right-handed neutrinos and R-parity conservation.



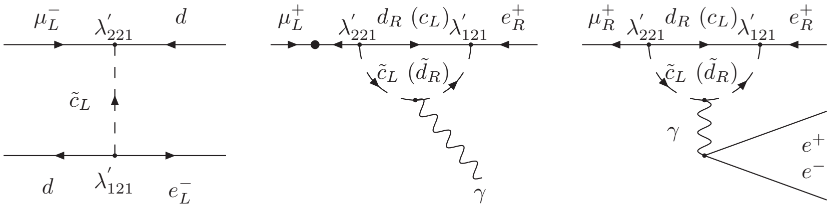


Figure 4: *Lowest order Feynman diagrams for lepton flavour violating processes induced by* $\lambda_{131}\lambda_{231}$, $\lambda_{132}\lambda_{232}$ *and* $\lambda'_{121}\lambda'_{221}$ *couplings respectively.*

	$\frac{\mathrm{Br}(\mu\to e\gamma)}{\mathrm{Br}(\mu\to 3e)}$	$\frac{\mathrm{R}(\mu\to e \text{ in Ti})}{\mathrm{Br}(\mu\to 3e)}$
Case (1)		
$\lambda_{131}\lambda_{231}$	1×10^{-4}	2×10^{-3}
$\lambda_{121}\lambda_{122}$	8×10^{-4}	7×10^{-3}
$\lambda_{131}\lambda_{132}$	8×10^{-4}	5×10^{-3}
Case (2)		
$\lambda_{132}\lambda_{232}$	1.2	18
$\lambda_{133}\lambda_{233}$	3.7	18
$\lambda_{231}\lambda_{232}$	3.6	18
$\lambda'_{122}\lambda'_{222}$	1.4	18
$\lambda'_{123}\lambda'_{223}$	2.2	18
Case (3)		
$\lambda'_{111}\lambda'_{211}$	0.4	3×10^{2}
$\lambda'_{112}\lambda'_{212}$	0.5	8×10^{4}
$\lambda'_{113}\lambda'_{213}$	0.7	1×10^{5}
$\lambda'_{121}\lambda'_{221}$	1.1	2×10^{5}
MSSM with ν_R	1.6×10^{2}	0.92

Table 6: *Correlations of LFV branching ratios for different combinations of dominant R-violating couplings.*

5. Gravitino Dark Matter in R-violating supersymmetry

In addition to the consequences for collider searches, R-violation implies that gravitinos (which may have been thermally produced after a period of inflation) are also unstable. The various decay modes have been computed by [23–25] and are shown in Fig. 5. However, gravitino dark matter in the framework of R-violating supersymmetry is plausible [23–25], provided that the gravitino decays slowly enough for its lifetime to be larger than the age of the universe. This is an exciting possibility that allows for supersymmetric dark matter, even if the R-violating couplings are sufficiently large to lead to observable signatures at colliders [24].

Trilinear R-violating operators induce gravitino decays either via one-loop decays to neutrinos and photons, or via tree-level three-body decays to fermions [25]. In both cases, the very large suppression $1/M_p$ of the gravitino vertex, where M_p is the reduced Planck scale, plus additional suppression from loop factors and phase space, result in large gravitino lifetimes. For a wide set of parameters, the gravitino lifetime exceeds the age of the universe and is cosmologically stable.

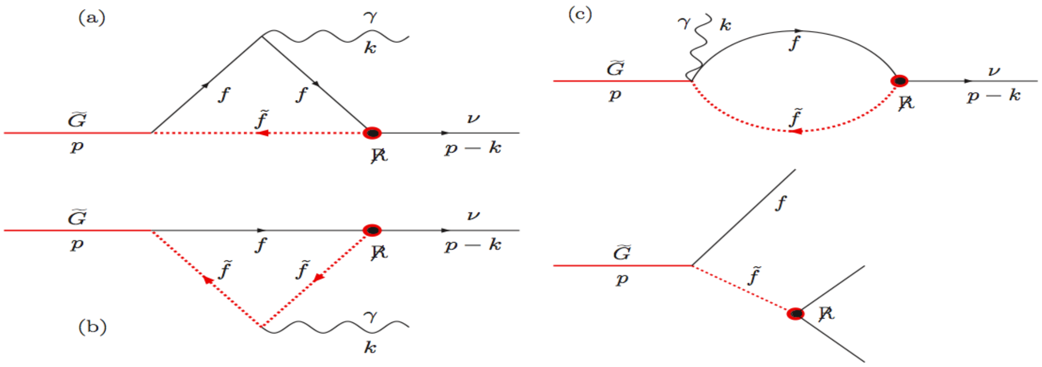


Figure 5: *Basic set of Feynman diagrams for radiative (diagrams a,b and c) and for three-body decays of gravitinos via R-parity violating couplings. Sfermions can carry any of the i, j or k indices.*

We found that the branching ratios for gravitino decays are very sensitive to the flavour structure of R-violating operators [11, 24]. For instance, dominance of the R-violating couplings of the heavier flavours would favour radiative over three body gravitino decays in scenarios with gravitino dark matter [11, 24].Interestingly enough, it turns out that the favoured values of these couplings are also in the range required to generate radiative neutrino masses and low energy lepton flavour violation (LFV).

In addition, the same R-violating couplings can be sufficiently large to lead to interesting R-violating signals in colliders. MSSM production of sparticle pairs followed by R-violating decays of neutralinos and possibly charginos, as discussed in previous sections, would be expected for most of the parameter space.This also implies rapid NSLP decays, mostly to three fermions, and natural consistency with the severe bounds of Big Bang Nucleosynthesis (BBN) This point is a big advantage with respect to R-conserving scenarios, where BBN bounds impose severe constraints in the supersymmetric parameter space, and result inevitably to fine-tuning. Here on the contrary, the problem does not exist at all.

6. Summary

We have shown that combining flavour and GUT symmetries, and linking the R-violating operators with those that generate fermion masses, is a powerful way to explore the possible hierarchies of lepton and baryon number violating trilinear couplings. Different signatures are expected to dominate for different groups, thus providing input on the structure of the underlying theory. Neutralino and chargino decays are optimal channels for a simultaneous study of all couplings, and the pattern of decays is closely correlated to unification, to the flavour structure of the theory and to the resulting supersymmetric parameter space. Low energy lepton flavour violation can be significant. The different symmetries and respective R-violating hierarchies result in different correlations between the expected rare processes, providing complementary input to that of the LHC. Gravitino dark matter can be generated in a natural way, in natural agreement with constraints from Big Bang Nucleosynthesis.

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