16

R-parity violation

We have already seen that, unlike the SM, the field content of the MSSM allows gauge-invariant, renormalizable interactions (8.8a) and (8.8b) that violate the conservation of lepton and baryon number, respectively. Within the MSSM these were forbidden by imposing an additional global symmetry that leads to the conservation of a multiplicative quantum number, R-parity, given by,[1]

$$R = (-1)^{3(B-L)-2s}. \tag{16.1}$$

Here B is baryon number, L is lepton number, and s is the spin of the component field. All the SM particles have $R = +1$, while all superpartners have $R = -1$. Imposing the conservation of R-parity has several phenomenological implications: most importantly, superpartners must ultimately decay to the lightest R-odd particle (the LSP), which must be absolutely stable. Since upper limits on the abundance of exotic isotopes exclude stable electrically charged or colored particles at the weak scale, it follows that LSPs produced in SUSY events would escape detection in collider experiments. The resulting $E_T^{\rm miss}$ signals are the hallmark of all models that we have considered up to now. There is, however, no good theoretical argument for excluding renormalizable R-parity-violating operators from the superpotential. However, once excluded, these will not be generated by radiative corrections. If R-parity is not a good quantum number, the arguments that led us to a weakly interacting LSP no longer apply, and the phenomenology may be radically different: except when the effects of R-parity violation are small, even the distinction between

[1] Continuous R-symmetries (which are symmetries under which the various components of a superfield do not transform the same way because θ also transforms non-trivially) were introduced by A. Salam and J. Strathdee, *Nucl. Phys.* **B87**, 85 (1975) and P. Fayet, *Nucl. Phys.* **B90**, 104 (1975) to accommodate conservation of lepton number in supersymmetric models. However, these R-symmetries cannot be exact, because they are broken both by gaugino mass terms, as well as by the bilinear μ term in the superpotential. The usually defined R-parity is a linear combination of a discrete parity subgroup of this continuous R-symmetry and other discrete symmetries of the model. To our knowledge, the formula (16.1) was first given by G. Farrar and P. Fayet, *Phys. Lett.* **B76**, 575 (1978).

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

a particle and a sparticle disappears. An examination of this interesting possibility forms the subject of this chapter.

We begin by rewriting the R-parity-violating superpotential that we introduced in Chapter 8. For later convenience, we reorganize it in terms of trilinear and bilinear terms (rather than baryon- and lepton-number-violating pieces) in the R-parity-violating part of the superpotential, and write it as,

$$\hat{f}_{\not{R}} = \hat{f}_{\mathrm{TRV}} + \hat{f}_{\mathrm{BRV}}, \tag{16.2a}$$

with

$$\hat{f}_{\mathrm{TRV}} = \sum_{i,j,k} \left[\lambda_{ijk}\epsilon_{ab}\hat{L}_i^a \hat{L}_j^b \hat{E}_k^c + \lambda'_{ijk}\epsilon_{ab}\hat{L}_i^a \hat{Q}_j^b \hat{D}_k^c + \lambda''_{ijk}\epsilon_{lmn}\hat{U}_i^{cl}\hat{D}_j^{cm}\hat{D}_k^{cn} \right], \tag{16.2b}$$

and

$$\hat{f}_{\mathrm{BRV}} = \sum_i \mu'_i \epsilon_{ab}\hat{L}_i^a \hat{H}_u^b. \tag{16.2c}$$

Here, $i, \ j$, and k are generation indices running from 1–3, $a, \ b$ are $SU(2)_\mathrm{L}$ indices, while $l, \ m$, and n are color indices. The first two terms in (16.2b) lead to lepton-number-violating interactions, while the last term leads to baryon-number-violating interactions. Collectively, these terms give rise to explicit *trilinear* R-parity violation (TRV) in the superpotential. Likewise, the operators in (16.2c) violate lepton number conservation and lead to *bilinear* R-parity violation (BRV).[2] We will see later that these provide a parametrization of spontaneous R-parity-violating models. Note that the $SU(2)_\mathrm{L}$ and $SU(3)_\mathrm{C}$ gauge symmetries require that the couplings λ_{ijk} (λ''_{ijk}) are antisymmetric in the indices i and j (j and k), so that there are $9 + 27 + 9 = 45$ new dimensionless complex parameters and three new dimensionful complex parameters in the general R-parity-violating superpotential. In addition, there are also corresponding soft SUSY breaking parameters in the most general parametrization of the model.

The bilinear term in the superpotential can be rotated away by working with the linear combination,

$$\hat{H}'_{da} = \frac{\mu \hat{H}_{da} + \sum_i \epsilon_{ba}\mu'_i \hat{L}_i^b}{\sqrt{\mu^2 + \mu_1'^2 + \mu_2'^2 + \mu_3'^2}},$$

[2] It is worth noting that in GUT theories based on higher symmetries (where $U(1)_{B-L}$ is part of the gauge symmetry), e.g. $SO(10)$, some or all of R-parity-violating couplings may not be allowed. As long as the fields that break the gauge symmetry are inert under $(-1)^{3(B-L)}$, R-parity will remain unbroken. Thus, depending on how the larger gauge symmetry is broken, none, some, or all of the R-parity-violating operators in (16.2b) and (16.2c) above would appear in the weak scale SUSY Lagrangian.

together with three other orthogonal combinations $\hat{L}'_i$. Eliminating $\hat{H}_{da}$ in favor of $\hat{H}'_{da}$ and $\hat{L}'_i$ in the R-parity-conserving part of the superpotential results in trilinear R-parity-violating superpotential operators. This field redefinition, which was chosen to eliminate the bilinear $\hat{H}_u\hat{L}_i$ terms from the superpotential, *does not* simultaneously get rid of the corresponding soft SUSY breaking terms,

$$\mathcal{L}_{\text{soft}} \ni \sum_i b_i \epsilon_{ab} \tilde{L}'^a_i H^b_u + \quad \text{h.c.} \tag{16.3}$$

which must be retained in a general analysis. Their existence implies that, in general, the "sneutrinos" will develop VEVs along with the neutral component of H_u.

Our discussion shows that one must be careful when deriving and interpreting limits on R-parity-violating parameters, since these would depend upon the basis that we are working in. We must either carefully and completely specify the basis,[3] or work with "basis-independent" quantities when performing a general analysis.[4] In practice, it is traditional to assume that just one of the many R-parity-violating operators dominates (in a chosen basis), and to examine its effect upon the phenomenology. It is then convenient to consider separately the phenomenological analysis of models with trilinear R-parity violation and bilinear R-parity violation since trilinear and bilinear superpotential terms may well have very different theoretical origins.

Exercise *Consider the MSSM but for a single matter generation. Assume that R-parity conservation is violated only by a bilinear term in the superpotential. Redefine the fields so that R-parity violation in the superpotential appears only as trilinear operators. You will find that the up quark and lepton superpotential Yukawa couplings are basis-independent, while the down quark superpotential Yukawa coupling is altered by the field redefinition. Verify that the down quark mass is basis-independent, as it must be.*

Since there is now no distinction between particles and sparticles, the lepton, the charged gaugino and the charged higgsino can all mix. Work out the charged fermion mass matrix. Check that, though one of the mass eigenvalues is proportional to the lepton Yukawa coupling, the ratio of this eigenvalue to the lepton Yukawa coupling depends on SUSY parameters. In other words, the usual tree-level relation between the fermion mass and its Yukawa coupling is altered.

---

[3] M. Bisset, O. Kong, C. Macesanu and L. Orr, *Phys. Rev.* **D62**, 035001 (2000).
[4] S. Davidson, *Phys. Lett.* **B439**, 63 (1998), and references therein.

16.1 Explicit (trilinear) R-parity violation

Here we consider that R-parity is explicitly broken only by dimensionless couplings in the superpotential. We assume, in addition, that there are no soft SUSY breaking bilinears so that we may consistently take all sneutrino VEVs to be zero. The scenario is thus parametrized by 45 additional complex superpotential couplings, together with corresponding trilinear soft SUSY breaking parameters that do not enter our discussion below.

16.1.1 The TRV Lagrangian

Before we can proceed to explore phenomenological implications of the TRV terms in the superpotential, we must first extract the corresponding interactions from $\hat{f}_{\rm TRV}$. From the master formula (6.44), two sets of terms come from the superpotential:

$$\mathcal{L} \ni -\sum_i \left|\frac{\partial \hat{f}}{\partial \hat{\mathcal{S}}_i}\right|^2_{\hat{\mathcal{S}}=\mathcal{S}} - \frac{1}{2}\sum_{i,j}\left[\left(\frac{\partial^2 \hat{f}}{\partial \hat{\mathcal{S}}_i \partial \hat{\mathcal{S}}_j}\right)_{\hat{\mathcal{S}}=\mathcal{S}} \bar{\psi}_i \frac{1-\gamma_5}{2}\psi_j + \quad \text{h.c.}\right]. \quad (16.4)$$

The first of these leads to new quartic scalar interactions which, while interesting, are not likely to lead to readily observable effects, at least when the scalar fields have no VEVs. We focus, therefore, on the R-parity-violating interactions of matter fermions, starting with the first term of (16.2b):

$$\hat{f} \ni \lambda_{ijk}\left(\hat{\nu}_i \hat{e}_j - \hat{e}_i \hat{\nu}_j\right)\hat{E}^c_k. \quad (16.5)$$

Although the two terms in (16.5) above are identical, for later convenience we will write the contributions from each of these separately. The first of these yields,

$$\mathcal{L} \ni -\frac{1}{2}\cdot 2\cdot\left[\tilde{e}^\dagger_{\mathrm{R}k}\bar{\psi}_{\nu_i} P_{\mathrm{L}}\psi_{e_j} + \tilde{e}_{\mathrm{L}j}\bar{\psi}_{\nu_i}P_{\mathrm{L}}\psi_{E^c_k} + \tilde{\nu}_i\bar{\psi}_{ej}P_{\mathrm{L}}\psi_{E^c_k}\right] + \quad \text{h.c.}, \quad (16.6)$$

where we remind the reader that the ψs are all Majorana spinors, whose chiral components make up the Dirac spinor for the massive fermions, as in (8.3). Using this, together with

$$e^c = P_{\mathrm{L}}\psi_{E^c} + P_{\mathrm{R}}\psi_e,$$

and the corresponding equations for the Dirac conjugates, it is straightforward to work out the resulting contributions to the Lagrangian. We find,

$$\begin{aligned}\mathcal{L}_\lambda = -\lambda_{ijk}\Big[&\tilde{e}^\dagger_{\mathrm{R}k}\bar{\nu^c_i}P_{\mathrm{L}}e_j + \tilde{e}_{\mathrm{L}j}\bar{e}_k P_{\mathrm{L}}\nu_i + \tilde{\nu}_i\bar{e}_k P_{\mathrm{L}}e_j - \tilde{e}^\dagger_{\mathrm{R}k}\bar{e^c_i}P_{\mathrm{L}}\nu_j\\ &- \tilde{e}_{\mathrm{L}i}\bar{e}_k P_{\mathrm{L}}\nu_j - \tilde{\nu}_j\bar{e}_k P_{\mathrm{L}}e_i\Big] + \quad \text{h.c.},\end{aligned} \quad (16.7a)$$

where the last three terms arise from the second term in (16.5). We will leave it as an exercise for the reader to check that the contribution of these last three terms of

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

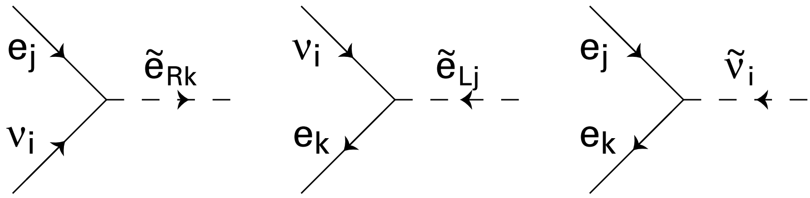

Figure 16.1 R-parity-violating interactions arising from the λ_{ijk} coupling in the superpotential. The arrows denote lepton number flow.

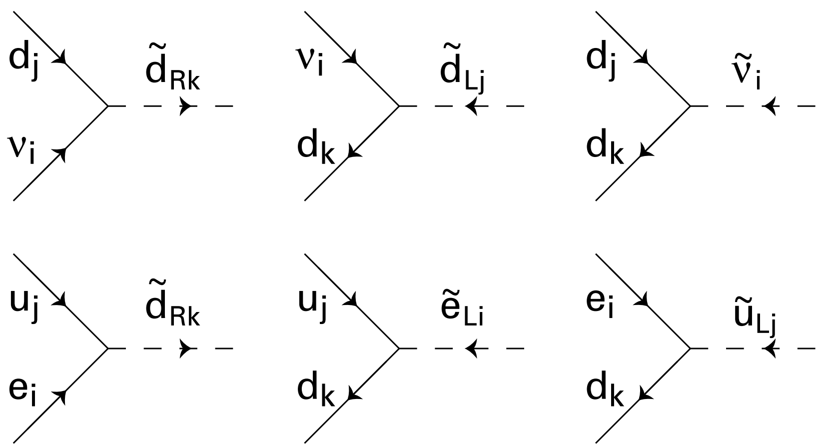

Figure 16.2 R-parity-violating interactions arising from λ'_{ijk} term in the superpotential. The arrows denote flow of B and L number.

$\mathcal{L}_\lambda$ is exactly the same as that of the first three. The new L-violating vertices are shown in Fig. 16.1.

We see that the *conjugate* fields ν_i^c and e_i^c appear in the R-parity-violating Lagrangian. We have already encountered this complication before, for instance in our evaluation of the amplitude (12.3b) for the process $d\bar{u} \to \widetilde{W}_i \widetilde{Z}_j$, so that their presence does not pose a new problem. We use the field expansion (3.33) for the conjugate fields in our calculation of any matrix elements that we need for the exploration of the phenomenological implications of these new interactions.

An exactly similar calculation to the one above gives rise to the R-parity-violating Lagrangian from the second term of (16.2b). We find that this second set of lepton-number-violating interactions is given by,

$$\mathcal{L}_{\lambda'} = -\lambda'_{ijk}\Big[\tilde{d}^\dagger_{\mathrm{R}k}\bar{\nu_i^c}P_{\mathrm{L}}d_j + \tilde{d}_{\mathrm{L}j}\bar{d}_k P_{\mathrm{L}}\nu_i + \tilde{\nu}_i\bar{d}_k P_{\mathrm{L}}d_j - \tilde{d}^\dagger_{\mathrm{R}k}\bar{e_i^c}P_{\mathrm{L}}u_j - \tilde{e}_{\mathrm{L}i}\bar{d}_k P_{\mathrm{L}}u_j - \tilde{u}_{\mathrm{L}j}\bar{d}_k P_{\mathrm{L}}e_i\Big] + \quad \text{h.c.} \tag{16.7b}$$

The corresponding vertices are shown in Fig. 16.2.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

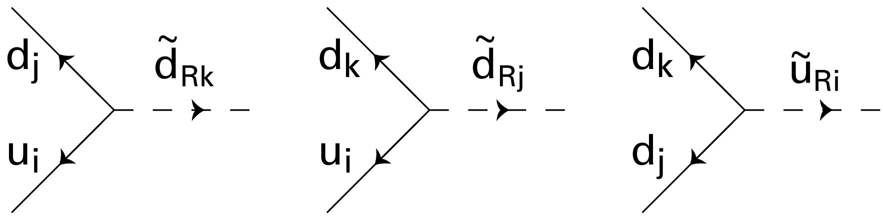

Figure 16.3 R-parity-violating interactions arising from λ''_{ijk} term in the superpotential. The arrows denote flow of B number.

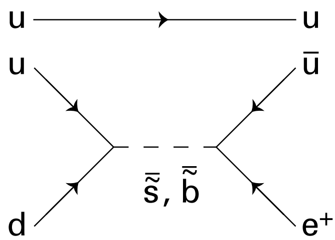

Figure 16.4 R-parity-violating decay of the proton via the λ'_{11k} and λ''_{11k} couplings.

Finally, the B-violating superpotential couplings in the third term of (16.2b) give the interactions,

$$\mathcal{L}_{\lambda''} = -\lambda''_{ijk} \left[\tilde{d}^{\dagger}_{\mathrm{R}k} \bar{u}_i P_{\mathrm{L}} d^c_j + \tilde{d}^{\dagger}_{\mathrm{R}j} \bar{u}_i P_{\mathrm{L}} d^c_k + \tilde{u}^{\dagger}_{\mathrm{R}i} \bar{d}_j P_{\mathrm{L}} d^c_k \right] + \quad \text{h.c.} \qquad (16.8)$$

The corresponding vertices are shown in Fig. 16.3.

16.1.2 Experimental constraints

Low energy bounds

The new B- and L-violating interactions can lead to non-standard contributions to a wide variety of physical phenomena. Since the R-violation arises from superpotential Yukawa couplings, we expect strong constraints on various couplings from flavor-violating processes. If both λ' as well as λ'' type couplings are present, these interactions can mediate proton decay via the diagrams depicted in Fig. 16.4.

A naive estimate of the proton decay rate gives,

$$\Gamma(p \to \pi^0 e^+) \sim \sigma(ud \to \bar{u} e^+) |\psi(0)|^2 \sim \frac{|\lambda'_{11k}|^2 |\lambda''_{11k}|^2}{m^4_{\tilde{d}k}} \frac{m_p^2}{128\pi} \frac{1}{\pi a^3}, \qquad (16.9)$$

where $k = 2$ or 3. Here, we have taken the squared wave function factor, which is a measure that the two quarks come together to annihilate by the baryon and lepton number-violating process, to be given by $1/\pi a^3$, where $a \sim 1$ fm is the size

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

Table 16.1 *Sample upper limits on products of R-parity-violating couplings for $M_{\rm SUSY} = 100$ GeV, assuming that just one such product is not zero. Except for those from proton decay, these limits all scale inversely as $M^2_{\rm SUSY}$.*

Combinations	Limits	Sources	Combinations	Limits	Sources
$\lambda'_{11k}\lambda''_{11k}$	10^{-26}	Proton decay	$\lambda'_{ijk}\lambda''_{lmn}$	10^{-11}	Proton decay
$\lambda_{1j1}\lambda_{1j2}$	7×10^{-7}	$\mu \to 3e$	$\lambda_{231}\lambda_{131}$	7×10^{-7}	$\mu \to 3e$
$\lambda'_{i1k}\lambda'_{j2k}$	5×10^{-5}	$K^+ \to \pi^+\nu\nu$	$\lambda'_{i12}\lambda'_{i21}$	1×10^{-9}	Δm_K
$\lambda'_{i13}\lambda'_{i31}$	8×10^{-8}	Δm_B	$\lambda'_{1k1}\lambda'_{2k2}$	8×10^{-7}	$K_{\rm L} \to \mu e$
$\lambda'_{1k1}\lambda'_{2k1}$	5×10^{-8}	μTi $\to e$Ti	$\lambda'_{11j}\lambda'_{21j}$	8.5×10^{-8}	μTi $\to e$Ti

of the proton. The Super-Kamiokande bound $\tau(p \to \pi e^+) > 5 \times 10^{33}$ years then implies that,

$$|\lambda'_{11k}\lambda''_{11k}| \lesssim 8 \times 10^{-27} \times \left(\frac{m_{\tilde{d}k}}{100\ \text{GeV}}\right)^2 . \tag{16.10}$$

We see that unconstrained R-parity violation leads to catastrophic p-decay rates. This extremely severe bound on the product of couplings strongly suggests that one or the other (or both) of these couplings is zero. It should be remembered that not all combinations of B- and L-violating interactions are as tightly constrained,[5] and, further, that the limit depends on the basis in which the couplings are written. Nevertheless, it is usually assumed that even if R-parity is not a good quantum number, one of B or L is conserved, which is sufficient to prevent proton decay. Non-observation of $n - \bar{n}$ oscillations or $\Delta B = 2$ "double nucleon decay" of atomic nuclei leads to limits on baryon number violating couplings that do not depend on concomitant lepton number violation.[6] It is clear that if R-violating couplings exist, then they must only occur in a restricted set of all the possible new interactions. As we have already noted, it is often assumed that just one of the 45 new couplings is dominant. This allows for tractable phenomenological analyses, and usually leads to the most conservative limits on the couplings. A summary of some of the most important restrictions on products of R-violating couplings, along with their sources, is shown in Table 16.1.[7] Here, and in subsequent tables, we have assumed that the couplings are all real. If the couplings are complex, yet new limits may be possible. For instance, the determination of ϵ_K restricts $Im\ \lambda'_{i12}\lambda'^{*}_{i21} < 8 \times 10^{-12}$ for $M_{\rm SUSY} = 100$ GeV. Upper limits on the electric dipole moments of the electron

[5] See C. Carlson, P. Roy and M. Sher, *Phys. Lett.* **B357**, 99 (1995).
[6] See J. L. Goity and M. Sher, *Phys. Lett.* **B346**, 69 (1995); *ibid* **B385**, 500 (1996) (erratum).
[7] These and the following restrictions on R-violating couplings have been adapted from G. Bhattacharyya, hep-ph/9709395 and B. Allanach *et al.*, hep-ph/9906224, where the sources for these limits, as well as others not listed here, can be found.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

Table 16.2 *Upper limits (2σ) on the λ_{ijk} couplings of R-violating supersymmetry.*

ijk	λ_{ijk}	Sources
121	$0.049 \times (m_{\tilde{e}_R}/100\ \text{GeV})$	CC universality in μ-decay
122	$0.049 \times (m_{\tilde{\mu}_R}/100\ \text{GeV})$	CC universality in μ-decay
123	$0.049 \times (m_{\tilde{\tau}_R}/100\ \text{GeV})$	CC universality in μ-decay
131	$0.062 \times (m_{\tilde{e}_R}/100\ \text{GeV})$	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$
132	$0.062 \times (m_{\tilde{\mu}_R}/100\ \text{GeV})$	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$
133	$0.006 \times \sqrt{m_{\tilde{\tau}}/100\ \text{GeV}}$	ν_e mass
231	$0.070 \times (m_{\tilde{e}_R}/100\ \text{GeV})$	$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$
232	$0.070 \times (m_{\tilde{\mu}_R}/100\ \text{GeV})$	$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$
233	$0.070 \times (m_{\tilde{\tau}_R}/100\ \text{GeV})$	$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$

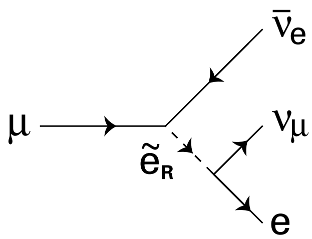

Figure 16.5 An example of an R-parity-violating contribution to β decay of the muon.

and the neutron also constrain the imaginary part of some other products at the 10^{-4} level.

In addition to these constraints, there is a variety of limits on individual R-parity-violating couplings. For example, the coupling λ_{121} leads to a new contribution to the standard decay of the muon, as shown in Fig. 16.5. Such contributions are strongly constrained by the observed universality of the charged current weak interactions.[8] Comparing muon decay with the β decay of quarks, one finds the limit $\lambda_{121} < 0.049 \times (m_{\tilde{e}_R}/100\ \text{GeV})$. This limit, together with corresponding limits on the λ_{ijk} couplings, along with their sources, is summarized in Table 16.2.

Constraints on the λ'_{ijk} couplings along with their sources are summarized in Table 16.3. While the limits on first generation λ's are rather strict, the corresponding bounds for third generation couplings are generally less severe. Also shown in parentheses are limits that result if we require perturbativity of the R-parity-violating couplings up to the GUT scale: if the couplings exceed these bounds at the weak scale, then they will diverge under renormalization group evolution before

[8] See V. Barger, G. F. Giudice and T. Han, *Phys. Rev.* **D40**, 2987 (1989).

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

Table 16.3 *Upper limits (2σ) on λ'_{ijk} couplings for R-violating SUSY. Bounds from requiring perturbativity up to the GUT scale are shown in parentheses.*

ijk	λ'_{ijk}	Sources
111	$5.2 \times 10^{-4} \times (m_{\tilde{e}}/100\ \text{GeV})^2 (m_{\widetilde{Z}_1}/100\ \text{GeV})^{1/2}$	$(\beta\beta)_{0\nu}$
112	$0.021 \times m_{\tilde{s}_R}/100$ GeV	CC univ.
113	$0.021 \times m_{\tilde{b}_R}/100$ GeV	CC univ.
121	$0.043 \times m_{\tilde{d}_R}/100$ GeV	CC univ.
122	$0.043 \times m_{\tilde{s}_R}/100$ GeV	CC univ.
123	$0.043 \times m_{\tilde{b}_R}/100$ GeV	CC univ.
131	$0.019 \times m_{\tilde{t}_L}/100$ GeV	APV
132	$0.28 \times m_{\tilde{t}_L}/100$ GeV (1.04)	A_{FB}
133	$1.4 \times 10^{-3}\sqrt{m_{\tilde{b}}/100\ \text{GeV}}$	ν_e-mass
211	$0.059 \times m_{\tilde{d}_R}/100$ GeV	$\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
212	$0.059 \times m_{\tilde{s}_R}/100$ GeV	$\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
213	$0.021 \times m_{\tilde{b}_R}/100$ GeV	$\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
221	$0.18 \times m_{\tilde{s}_R}/100$ GeV (1.12)	ν_μ DIS
222	$0.21 \times m_{\tilde{s}_R}/100$ GeV (1.12)	$D \to K\ell\nu$
223	$0.21 \times m_{\tilde{b}_R}/100$ GeV (1.12)	$D \to K\ell\nu$
231	$0.18 \times m_{\tilde{b}_L}/100$ GeV (1.12)	ν_μ DIS
232	0.56 (1.04)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$
233	$0.15\sqrt{m_{\tilde{b}}/100\ \text{GeV}}$	ν_μ-mass
311	$0.11 \times m_{\tilde{d}_R}/100$ GeV (1.12)	$\Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\nu)$
312	$0.11 \times m_{\tilde{s}_R}/100$ GeV (1.12)	$\Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\nu)$
313	$0.11 \times m_{\tilde{b}_R}/100$ GeV (1.12)	$\Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\nu)$
321	$0.52 \times m_{\tilde{d}_R}/100$ GeV (1.12)	$\Gamma(D_s \to \tau\nu_\tau)/\Gamma(D_s \to \mu\nu_\mu)$
322	$0.52 \times m_{\tilde{s}_R}/100$ GeV (1.12)	$\Gamma(D_s \to \tau\nu_\tau)/\Gamma(D_s \to \mu\nu_\mu)$
323	$0.52 \times m_{\tilde{b}_R}/100$ GeV (1.12)	$\Gamma(D_s \to \tau\nu_\tau)/\Gamma(D_s \to \mu\nu_\mu)$
331	0.45 (1.04)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$
332	0.45 (1.04)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$
333	0.45 (1.04)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$

the GUT scale is reached. If these couplings really become large before $Q = M_{\text{GUT}}$, they would be expected to make a substantial modification to the renormalization group flow, and to the successful prediction of the unification of gauge couplings. Of course, these latter limits are model dependent, since they are obtained assuming a desert between M_{SUSY} and M_{GUT}.

Finally, the limits of the B-violating couplings λ''_{ijk} are summarized in Table 16.4. Note that the bound on the first line is obtained under the assumption that the lifetime for the "double nucleon decay" $^{16}\text{O} \to ^{14}\text{C} + K^+K^+$ exceeds 10^{30} years.[9] While the bounds on first generation couplings can again be quite severe if

[9] This decay could presumably be detected in the Super-Kamiokande experiment which has obtained a limit exceeding 1.9×10^{33} on the decay $p \to K^+\nu$.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

Table 16.4 *Upper limits (2σ) on the λ''_{ijk} couplings in R-violating SUSY. The quantity Λ in the first line is some hadronic scale* ~ 300 *MeV. Most of the direct bounds listed are for* $M_{\text{SUSY}} = 100$ *GeV. Bounds from requiring perturbativity up to* M_{GUT} *are shown in parentheses.*

ijk	λ''_{ijk}	Sources
112	$10^{-15} \times (M_{\text{SUSY}}/\Lambda)^{5/2}$	Double nucleon decay
113	10^{-4}	$n - \bar{n}$ oscillation
123	(1.23)	Perturbativity
212	(1.25)	Perturbativity
213	(1.23)	Perturbativity
223	(1.23)	Perturbativity
312	0.50 (1.00)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$
313	0.50 (1.00)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$
323	0.50 (1.00)	$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \ell\bar{\ell})$

squarks are light, most of the second and third generation couplings have no real restriction other than from the requirement of perturbativity up to $Q = M_{\text{GUT}}$.

Cosmological bounds

A very interesting bound on R-parity-violating couplings follows from considerations of GUT scale baryogenesis in the Big Bang cosmology. This bound arises from the requirement that any GUT scale matter–antimatter asymmetry that can develop in these models not be wiped out by R-parity-violating interactions.

It is known that within the SM there are non-perturbative effects from the so-called electroweak sphaleron interactions which violate separate B and L conservation but conserve $B - L$. Sphaleron effects will, therefore, tend to restore the matter–antimatter symmetry as the Universe cools to $T \sim M_{\text{weak}}$. However, any $B - L$ component of the matter–antimatter asymmetry that may have been generated at the high scale cannot be wiped out by these effects, and so will persist to the low scale.

Note that the R-parity-violating couplings in (16.2b) do not conserve $B - L$, so that if these remain in thermal equilibrium down to the weak scale, they would wash out any $B - L$ component of the matter–antimatter asymmetry. Together with sphaleron interactions that wash out the $B + L$ component, any matter–antimatter asymmetry that may have been generated at a high scale will be washed away, unless the R-parity-violating couplings are small enough so that these interactions fall out of equilibrium before the Universe cools to $T = M_{\text{weak}}$. This leads to a

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

generic upper limit on all TRV couplings:

$$\lambda_{ijk},\ \lambda'_{ijk},\ \lambda''_{ijk} < 5 \times 10^{-7}\,(M_{\rm SUSY}/1\ {\rm TeV})^{1/2}\,. \tag{16.11}$$

We will see in Section 16.1.4 that this limit implies that the LSP will be quasi-stable in that it essentially always decays outside any collider detector. Unless this LSP happens to be charged or colored, it would escape experimental detection exactly as in models where R is a good quantum number. Also, as discussed below, R-violating contributions to sparticle production and decay of heavier sparticles would be negligible, so that R-parity-violating couplings satisfying the bounds (16.11) would be irrelevant to any consideration of SUSY signals at colliders.

The bounds (16.11) clearly do not apply if baryogenesis occurs at the electroweak scale, instead of at the GUT or some intermediate scale. One suggestion (that has not been examined in detail) is that complex λ'' couplings generate the baryon asymmetry below the scale $M_{\rm SUSY} \sim M_{\rm weak}$. Electroweak scale baryogenesis is also possible within the MSSM, though this requires that $m_h \lesssim 115$–120 GeV, and $m_{\tilde{t}_R} < m_t$. It should, therefore, be possible to probe this scenario in collider experiments. If the particle content of the MSSM is extended by a singlet Higgs field and the gauge symmetry by an extra (anomaly free) $U(1)$, it appears possible to accommodate electroweak scale baryogenesis even if the top squark is heavy.

The observation that sphaleron interactions actually conserve $B/3 - L_i$ for each lepton flavor points out another loophole to the general argument that led to the stringent bounds on the TRV couplings, even if the matter–antimatter asymmetry is generated at $T \gg M_{\rm weak}$.[10] The conserved quantum numbers may equivalently be chosen to be $B - L$ and the two independent combinations of $L_i - L_j$. If a matter–antimatter asymmetry arises asymmetrically between the three lepton flavors, it will clearly be preserved by sphaleron and λ'' interactions even if these are in thermal equilibrium up to the electroweak scale. The surviving lepton number will be converted partially back into a baryon asymmetry at temperatures below the electroweak scale and, as long as L-violating couplings are negligible, the bounds on the λ'' couplings are essentially eliminated. Alternatively, if R-parity-violating couplings conserve baryon number, we can still maintain a GUT scale matter–antimatter asymmetry as long as the set of lepton number violating couplings that violate conservation of one of the lepton flavors falls out of thermal equilibrium sufficiently early – i.e. satisfies the bound (16.11), even if other L-violating couplings are large. In the case of R-parity violation via $\Delta L \neq 0$ couplings, the exact bounds depend on the details of the lepton flavor-violating couplings.

[10] See B. Campbell *et al.*, *Phys. Lett.* **B297**, 118 (1992), and H. Dreiner and G. Ross, *Nucl. Phys.* **B410**, 183 (1993) for further details.

The upshot of this discussion is that it is possible to construct scenarios consistent with high scale baryogenesis, and where R-parity-violating couplings have an important impact on collider signatures of supersymmetry.

16.1.3 s-channel sparticle production

If R-parity-violating couplings exist, then a novel feature of SUSY models is the possibility of resonance production of sparticles.[11] By examining the interactions in Figs. 16.1–16.3, it is easy to see the following processes can occur:

$$e^+e^- \to \tilde{\nu}_{Lj} \quad \text{(LEP2, NLC)}, \tag{16.12a}$$
$$e^-u_j \to \tilde{d}_{Rk} \quad \text{(HERA)}, \tag{16.12b}$$
$$e^-\bar{d}_k \to \bar{\tilde{u}}_{Lj} \quad \text{(HERA)}, \tag{16.12c}$$
$$\bar{u}_j d_k \to \tilde{e}_{Li} \quad \text{(Tevatron, LHC)}, \tag{16.12d}$$
$$d_j\bar{d}_k \to \tilde{\nu}_{Li} \quad \text{(Tevatron, LHC)}, \tag{16.12e}$$
$$\bar{u}_i\bar{d}_j \to \tilde{d}_{Rk} \quad \text{(Tevatron, LHC)}, \tag{16.12f}$$
$$\bar{d}_j\bar{d}_k \to \tilde{u}_{Ri} \quad \text{(Tevatron, LHC)}. \tag{16.12g}$$

At LEP2 or at an e^+e^- linear collider, it is thus possible to produce the $\tilde{\nu}_\mu$ or $\tilde{\nu}_\tau$ in the s-channel via the λ_{121} or λ_{131} couplings, respectively. Neglecting the sneutrino width, the production cross section is given by

$$\sigma(e^+e^- \to \tilde{\nu}_j) = \frac{\pi|\lambda_{1j1}|^2 s\delta(s - m^2_{\tilde{\nu}_j})}{4m^2_{\tilde{\nu}_j}}, \tag{16.13}$$

where $s = 4E^2_{\rm beam}$. Although the reaction rate may be suppressed by the magnitude of the R-violating Yukawa coupling, it is greatly enhanced compared to sneutrino pair production, provided the energy spread of the beam is smaller than the width of the sneutrino. Once the sneutrino is produced, it may decay via gauge couplings as $\tilde{\nu}_j \to \ell_j\widetilde{W}_1$ or $\nu_j\widetilde{Z}_i$, or via the R-violating coupling back into e^+e^-, if the coupling is large enough. Such reactions have been searched for at LEP2, where limits are usually placed in the $m_{\tilde{\nu}_j}$ vs. λ_{1j1} plane, and depend on the assumed decay modes.

The R-violating couplings λ_{122}, λ_{123}, λ_{132}, λ_{133}, and λ_{231} can also be probed at LEP2 and the NLC via the reactions

$$\gamma e^\pm \to \ell^\pm_k\tilde{\nu}_j, \quad \text{and} \tag{16.14a}$$
$$\gamma e^\pm \to \tilde{\ell}^\pm_j\nu_k, \tag{16.14b}$$

[11] The alert reader will object that the concept of sparticle is ill-defined when R-parity is not conserved because odd and even R states can now mix to form the mass eigenstates. By "sparticles" we are, in this chapter, referring to those mass eigenstates whose content is dominantly R-odd.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

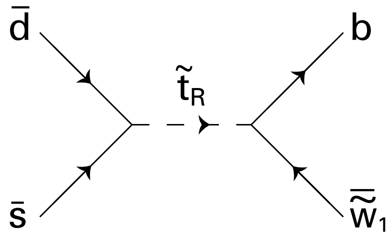

Figure 16.6 An example of resonance production of a top squark via R-parity-violating couplings at hadron colliders.

where the photon comes either from initial state radiation or from beamstrahlung. In this case, the production cross section has to be convoluted with a distribution function such as (12.18) that describes the density of photons in the electron or positron. Finally, a sparticle may be produced in association with a SM particle in e^+e^- collisions via t-channel exchange graphs; the resulting cross sections for these $2 \to 2$ processes are quite low because R-parity-violating couplings are typically smaller than gauge couplings.

The HERA ep collider at DESY is unique in that it allows for s-channel squark production via the λ'_{1j1} and λ'_{11k} couplings. If the R-violating couplings are large enough, and the produced squarks decay back into e and a jet, the analysis becomes very similar to the one for spin-0 leptoquark production. If the produced squarks decay instead into SUSY particles, then the signatures can be very different. Searches have been performed by the H1 and ZEUS collaborations. These searches exclude production of first generation squarks up to 240 GeV assuming that $\lambda' \gtrsim \sqrt{4\pi\alpha_{em}}$, although of course the limit depends strongly on the magnitude of this coupling. Note that for $M_{SUSY} = 240$ GeV, couplings of this size appear to be already excluded by the low energy constraints listed in Table 16.3.

Single squark production is also possible at the Tevatron and LHC colliders, mediated by the λ''_{ijk} couplings: see Fig. 16.6. These couplings are relatively unconstrained for production of second and third generation squarks. An analysis of single top squark production at the Fermilab Tevatron via $\bar{s}\bar{d} \to \tilde{t}_1$ followed by $\tilde{t}_1 \to b\widetilde{W}_1$ decay indicates $m_{\tilde{t}_1} \lesssim 200$–$300$ GeV can be probed with 2 fb^{-1} of integrated luminosity, if $\lambda''_{3jk} > 0.02$–0.06.[12]

16.1.4 $\not{R}$ decay of the LSP

If R-parity-violating couplings are small compared to gauge couplings, these do not alter sparticle mass patterns in any significant manner and the lightest neutralino

[12] E. Berger, B. W. Harris and Z. Sullivan, *Phys. Rev.* **D83**, 4472 (1999).

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

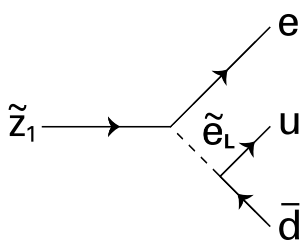

Figure 16.7 R-parity-violating decay of the lightest neutralino.

remains as the LSP in many models. However, these couplings render the LSP unstable. In this case, the LSP need not be electrically or color neutral, since if it is unstable, then cosmological bounds on stable relics from the Big Bang no longer apply. Thus, the $\tilde{g}$, $\widetilde{W}_1$, $\tilde{q}$, $\tilde{\ell}$ or $\tilde{\nu}$ states are viable LSP candidates, as long as these decay quickly enough so as not to disrupt nucleosynthesis in the early Universe.

In models such as mSUGRA, the $\widetilde{Z}_1$ is usually the LSP over most of parameter space, just as a consequence of the mSUGRA boundary conditions, and the RGEs. In this case, it is possible that R-violating couplings are so small that they do not affect sparticle production or decay reactions, except for the decay of the LSP, henceforth taken to be $\widetilde{Z}_1$. An example of $\widetilde{Z}_1 \to eu\bar{d}$ decay via $\tilde{e}_L$ exchange is shown in Fig. 16.7; two other diagrams involving $\tilde{d}_R$ and $\tilde{u}_L$ exchange also contribute. In addition, the λ'_{111} term will also mediate the decay $\widetilde{Z}_1 \to \nu_e d\bar{d}$.

We make an order of magnitude estimate of the decay length of $\widetilde{Z}_1$, assuming that it is a pure photino. In this case, the decay rate simplifies to

$$\Gamma(\widetilde{Z}_1 \to eu\bar{d}) \sim \frac{3\alpha\lambda'^2_{111}}{128\pi^2}\frac{m^5_{\widetilde{Z}_1}}{M^4_{\rm SUSY}}. \tag{16.15}$$

Roughly speaking, the decay takes place in the detector if $c\gamma\tau(\widetilde{Z}_1) \lesssim 1$ m, where γ is the Lorentz boost factor $\gamma = E_{\widetilde{Z}_1}/m_{\widetilde{Z}_1}$. This implies that

$$\lambda'_{111} > 1.4\times 10^{-6}\sqrt{\gamma}\left(\frac{M_{\rm SUSY}}{200\ {\rm GeV}}\right)^2\left(\frac{100\ {\rm GeV}}{m_{\widetilde{Z}_1}}\right)^{5/2}. \tag{16.16}$$

A similar calculation applies to decays mediated by other λ_{ijk}, λ'_{ijk} or λ''_{ijk} couplings. If the λs are much smaller than this limit, then the $\widetilde{Z}_1$ will generally escape the detector, leading to missing energy as in the MSSM with R-parity conservation.

For λ values comparable to the bound in Eq. (16.16), there may exist substantial decay gaps in collider detectors. If the LSP is not $\widetilde{Z}_1$ but a charged sparticle, its production will be signalled by highly ionizing tracks in the detector, followed by

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

B- or L-violating decays provided the R-parity-violating coupling responsible for the decay is large enough.

For a neutralino decaying via one of the λ_{ijk} couplings, the decay modes are

$$\widetilde{Z}_1 \to \bar{\nu}_i \bar{e}_j e_k \quad \text{and} \quad \nu_i e_j \bar{e}_k. \tag{16.17}$$

Since the λ_{ijk} are antisymmetric in ij, the $i \leftrightarrow j$ modes must be included as well. For instance, assuming λ_{121} is dominant, the decays $\widetilde{Z}_1 \to \bar{\nu}_e \bar{\mu} e$, $\nu_e \mu \bar{e}$, $\bar{\nu}_\mu \bar{e} e$, and $\nu_\mu e \bar{e}$ would each occur with a $\sim 25\%$ branching fraction provided that all the relevant sleptons have the same mass.

If instead the $\widetilde{Z}_1$ decays via the λ'_{ijk} coupling, then the decays are

$$\widetilde{Z}_1 \to e_i u_j \bar{d}_k \quad \text{and} \quad \bar{e}_i \bar{u}_j d_k, \quad \text{as well as} \tag{16.18a}$$

$$\widetilde{Z}_1 \to d_j \nu_i \bar{d}_k \quad \text{and} \quad \bar{d}_j \bar{\nu}_i d_k. \tag{16.18b}$$

The relative branching ratios between the modes containing charged leptons and those containing neutrinos are model dependent. Note that there are several possible R-violating $\widetilde{Z}_1$ decay modes for each λ'_{ijk} coupling. For instance, if λ'_{112} is dominant, then $\widetilde{Z}_1 \to eu\bar{s}$, $\bar{e}\bar{u}s$ with a branching fraction B, and $\widetilde{Z}_1 \to d\nu_e\bar{s}$, $\bar{d}\bar{\nu}_e s$ with a branching fraction $1 - B$.

Finally, if $\widetilde{Z}_1$ decays via λ''_{ijk} couplings, the decay modes are

$$\widetilde{Z}_1 \to u_i d_j d_k \quad \text{and} \quad \bar{u}_i \bar{d}_j \bar{d}_k. \tag{16.19}$$

There are nine possibilities, since λ''_{ijk} is antisymmetric on the jk indices. For example, if λ''_{121} is dominant, then $\widetilde{Z}_1 \to uds$ or $\bar{u}\bar{d}\bar{s}$, each with a branching fraction of 50%.

Exercise *We have focussed on the case that the LSP is a neutralino. Assume instead that the LSP is one of the staus that decays to a pair of SM fermions via one of the λ or λ' couplings. Evaluate its decay rate and estimate the range of the R-violating coupling for which the stau may be detectable as an ionizing track in a collider detector. For what values of this coupling will the stau decay inside the detector? List its possible decay modes and calculate the corresponding branching fractions, assuming that just one of the couplings dominates the decay.*

16.1.5 Collider signatures

If R-parity-violating couplings are much smaller than the gauge couplings, the dominant sparticle pair production mechanisms will be the same as those discussed in Chapter 12: i.e. sparticle pair production rates will essentially be the same as in the

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

MSSM.[13] Moreover, heavier sparticles will dominantly decay to lighter sparticles via their gauge and MSSM superpotential couplings, so that their decay patterns will also be the same as in the MSSM. The difference is that the lightest sparticle will decay as discussed in the last section.

The decay of the LSP inside the experimental apparatus has very important implications for supersymmetric collider signatures.

- The E_T^{miss} signal that we have been considering as the hallmark of sparticle production may be greatly diminished. Except for gravitinos, which are relevant only in some special scenarios, neutrinos from the decay of the LSP or from other stages of SUSY cascades will be the only physics source of E_T^{miss} events. In the case that the LSP dominantly decays via $\widetilde{Z}_1 \to cds + \bar{c}\bar{d}\bar{s}$, we may expect that the observability of SUSY signals at hadron colliders will be considerably degraded, mostly due to the reduced E_T^{miss}, but also because the excess hadronic activity from LSP decays would also make it more difficult for any leptons produced in SUSY cascade decays to remain isolated.
- If the LSP dominantly decays leptonically into e or μ via λ-type couplings, then the rates for multilepton events from sparticle production would be greatly increased, and the SUSY reach at hadron colliders would be considerably larger than the projections in the last chapter.
- An unstable LSP that decays inside the detector will make it easier to completely reconstruct SUSY events, especially at an e^+e^- collider.
- If the LSP is relatively long-lived, it will decay with a displaced vertex which would serve as an additional handle for selecting the SUSY signal over SM background. Indeed, it may then be possible to determine the lifetime of the LSP, and directly obtain information about R-parity-violating couplings.
- If the LSP is charged and long-lived, it can be searched for by looking for heavily ionizing tracks of relatively slow-moving particles. If it is colored, it would bind with a quark or gluon to make a charged or neutral strongly interacting particle. A number of handles, some of which are quite spectacular, may be possible, but the signals are somewhat dependent on how this particle loses energy in traversing the material of the detector.[14]

In the difficult case where the LSP decays hadronically and without any displaced vertex, simulations within the mSUGRA framework extended by R-parity violation have shown that experiments at the Fermilab Tevatron may have no observable signal if gluinos are heavier than about 200 GeV and $m_{\tilde{q}} \gg m_{\tilde{g}}$.[15] On the other hand,

[13] We will, of course, have the "resonant $2 \to 1$" s-channel production mechanisms occuring with a rate that is directly dependent on the corresponding R-parity-violating coupling.
[14] See e.g. M. Drees and X. Tata, *Phys. Lett.* **B252**, 695 (1990).
[15] H. Baer, C. Kao and X. Tata, *Phys. Rev.* **D51**, 2180 (1995).

if the LSP decays dominantly via $\widetilde{Z}_1 \to \ell\ell\nu$ ($\ell = e, \mu$), there will be observable signals in the $\geq 4\ell$ channel even if $m_{\tilde{g}}$ exceeds 800 GeV with 10 fb^{-1} of integrated luminosity.

It is interesting to ask whether sparticles can remain hidden at the LHC in the case that $\widetilde{Z}_1 \to cds + \bar{c}\bar{d}\bar{s}$. A detailed study, again within the mSUGRA model extended to include the λ''_{212} coupling, has shown that the reach in the E_T^{miss} channel is indeed greatly degraded relative to that in the mSUGRA model.[16] Fortunately, the reach via multijet plus various $n_\ell \geq 1$ lepton channels introduced in the last chapter, where the leptons come from cascade decays, remains robust for squarks or gluinos up to just over 1 TeV.

At electron–positron colliders, we do not expect the decays of a neutralino LSP to significantly alter the mass reach for charged sparticles since this frequently extends most of the way to the kinematic limit. For the case of an unstable LSP it may in fact be easier to reconstruct SUSY events as we have already noted. R-parity-violating couplings may, however, greatly expand the model parameter space for which there is an observable signal at an e^+e^- collider because then $e^+e^- \to \widetilde{Z}_1\widetilde{Z}_1$ also leads to detectable signals.[17]

16.2 Spontaneous (bilinear) R-parity violation

Instead of adding TRV couplings to the superpotential, some authors have suggested that R-parity may be a symmetry of the Lagrangian, but not a symmetry of the ground state: i.e. R-parity conservation is broken spontaneously.

A model to exhibit the spontaneous violation of R-parity can be constructed by adding several new gauge singlet superfields ($\hat{\Phi}$, $\hat{\nu}_i^c$, $\hat{S}_i$) which carry lepton number (0, −1, 1), respectively, but no baryon number (i is a generation index) to the MSSM.[18] The superpotential of the model is given by,

$$\hat{f} = \sum_{i,j=1,2,3} \Big[(\mathbf{f}_u)_{ij}\epsilon_{ab}\hat{Q}_i^a \hat{H}_u^b \hat{U}_j^c + (\mathbf{f}_d)_{ij}\hat{Q}_i^a \hat{H}_{da}\hat{D}_j^c + (\mathbf{f}_e)_{ij}\hat{L}_i^a \hat{H}_{da}\hat{E}_j^c + (\mathbf{f}_\nu)_{ij}\epsilon_{ab}\hat{L}_i^a \hat{H}_u^b \hat{\nu}_j^c + (\mathbf{f})_{ij}\hat{\Phi}\hat{S}_i\hat{\nu}_j^c \Big] + (f_0 \hat{H}_u \hat{H}_d - \epsilon^2)\hat{\Phi}. \tag{16.20}$$

This superpotential which trivially conserves B, also conserves L, and hence also R-parity. Upon minimization, the corresponding scalar potential develops VEVs in the directions $\phi = \tilde{\nu}_{i\text{R}}$, $\tilde{S}_i$, $\tilde{\Phi}$, h_u^0, h_d^0 and $\tilde{\nu}_{i\text{L}}$. To illustrate the general idea, it is sufficient to only consider just one generation. The resulting Lagrangian, written

[16] H. Baer, C. Chen and X. Tata, *Phys. Rev.* **D55**, 1466 (1997).
[17] For a discussion of branching fractions and relative rates into various event topologies at an e^+e^- collider, see R. Godbole, P. Roy and X. Tata, *Nucl. Phys.* **B401**, 67 (1992).
[18] A. Masiero and J. W. F. Valle, *Phys. Lett.* **B251**, 273 (1990); for a review, see J. W. F. Valle, hep-ph/9603307 (1996).

in terms of the shifted fields, appears to violate lepton number, and hence R-parity conservation, but preserves B so that the proton is safe from decay. Since $U(1)_{\rm L}$ is spontaneously broken, there is a dominantly gauge singlet, massless Goldstone boson J, the Majoron, with very weak couplings to the Z boson. The Majoron may be eliminated by the Higgs mechanism if this model is embedded into one with a higher gauge symmetry.

Many of the phenomenological effects of spontaneous R-parity violation can be incorporated into the MSSM by adding just the bilinear terms,

$$\hat{f} \ni \sum_i \mu'_i \epsilon_{ab} \hat{L}_i^a \hat{H}_u^b \tag{16.21a}$$

to the superpotential along with the corresponding soft SUSY breaking terms,

$$\mathcal{L}_{\rm soft} \ni \sum_i b_i \epsilon_{ab} \tilde{L}_i^a \tilde{H}_u^b + \quad \text{h.c.}, \tag{16.21b}$$

but no TRV couplings. As we have already discussed, it is possible to go to a basis where the superpotential bilinear R-violating (BRV) interactions are rotated away, resulting in trilinear couplings in the superpotential, with "sneutrinos" of this basis developing VEVs.

The BRV model as defined by (16.21a) and (16.21b) leads to several interesting consequences.[19] In the basis where lepton number is violated only by bilinear terms, there are many new sources of mixing that need to be included to deduce the phenomenological implications. This happens because in the absence of conservation of the lepton numbers L_i, there is no distinction between the three matter doublet superfields $\hat{L}_i$ and the doublet superfields $\hat{H}_d$ and $\hat{H}_u$.

- The neutralino fields now mix with the neutrino fields, leading to a 7×7 neutralino/neutrino mass matrix. One linear combination of *neutrino* fields develops a Majorana mass via tree-level mixing with Higgsinos, while the other combinations acquire masses upon including one-loop corrections if the corresponding lepton number is also not conserved. While it is possible to accommodate small neutrino masses, this evidently requires that the parameters be carefully adjusted to ensure that the tree-level neutrino masses are at the sub-eV level or smaller as required by phenomenology. It is, perhaps, worth emphasizing that neutrinos generically acquire Majorana masses in *all* R-parity-violating models where the corresponding lepton number is not conserved because there is no symmetry that precludes these masses from being radiatively generated. Indeed, it is exactly this

[19] Although we used the model with spontaneous R-violation as motivation for the BRV model, the two models are different. In the BRV model, L and R-parity are explicitly broken so that there is no Majoron. Many aspects of the phenomenology are similar because the Majoron is weakly coupled, and so is mainly relevant for neutrino physics since it allows for neutrino decays.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

that leads to the bound on λ_{133} and λ'_{133} in Tables 16.2 and 16.3, respectively. What is unique to the BRV model is that one of the neutrinos acquires an (albeit too large) mass even at the tree level.

- Likewise, charged gauginos and charged Higgsinos can now mix with the charged leptons, leading to a 5×5 mass matrix for charged fermions. As noted in the exercise at the start of this chapter, the SM relation between the Yukawa coupling and the corresponding "fermion mass" is modified.
- In the bosonic sector, the CP-even Higgs fields mix with the real components of the sneutrino fields, leading to a 5×5 mass matrix. The lightest Higgs scalar always has mass less than the corresponding lightest scalar in the MSSM.
- The imaginary components of the sneutrino fields mix with the CP-odd scalars, leading to a 5×5 mass matrix that includes the massless (would-be) neutral Goldstone boson which is subsequently eaten up by the Higgs mechanism.
- The fields $h_u^\pm$ and $h_d^\pm$ mix with the charged sleptons; including $\tilde{\ell}_L - \tilde{\ell}_R$ mixing effects, an 8×8 mass matrix is obtained that includes the (would-be) charged Goldstone boson.

In addition to low energy effects, e.g. in neutrinoless $\beta\beta$ decay, a variety of R-violating signals are possible at colliders. In particular, the LSP is unstable, and can decay for example into $\widetilde{Z}_1 \to \tau W^{(*)}$ or $\nu_\tau Z^{(*)}$, where the W and Z can be real or virtual. Decay gaps in $\widetilde{Z}_1$ decay are likely, and the LSP may appear to be quasi-stable in a collider detector. In models with a Majoron J, the lightest neutralino may also decay via $\widetilde{Z}_1 \to \nu J$.

The BRV model may also be embedded in the mSUGRA model framework. In this case, one assumes the MSSM augmented by the bilinear terms (16.21a) and (16.21b) is valid up to $Q = M_{\rm GUT}$ where, in addition to the usual mSUGRA boundary conditions (9.18b)–(9.18d), we assume that the three μ'_i unify to μ'_0, and the $B'_i \equiv b_i/\mu'_i$ unify with the usual Higgs sector B parameter. Compared to the mSUGRA model, there is then just one more GUT scale parameter in the theory. The RGEs of the MSSM must be supplemented with corresponding RGEs for the B'_is and the μ'_is.[20] The weak scale scalar potential of the model can now be minimized, exactly as we did in the mSUGRA model, although because there are now three additional field directions ${\rm Re}(\tilde{\nu}_{iL})$ that can potentially acquire VEVs the details are more complicated. The five minimization conditions for the potential fix these VEVs in terms of the potential parameters. Then, exactly as in the mSUGRA framework, one of the GUT scale parameters is fixed by the experimental value of M_Z, so that it would appear that the unified BRV model contains one more parameter than the mSUGRA framework. We should remember

[20] Renormalization group evolution does not generate trilinear superpotential couplings or soft parameters if these have been set to zero.

https://doi.org/10.1017/9781009289801.017 Published online by Cambridge University Press

however, that the mass of the heaviest neutrino (the other neutrinos are massless at tree level) must be in accord with atmospheric neutrino data, given its successful interpretation in terms of neutrino oscillations.[21] This would then mean that the model does not contain any additional free parameters. It has been argued that if the neutrino mass is constrained to be $\lesssim 1$ eV, many R-parity-violating effects are also suppressed within this constrained framework.[22] Even so, the "TRV" couplings in the superpotential induced upon rotating away the bilinear terms may be as big as $\sim 10^{-4}$ (depending on other parameters) of the original (R-conserving) superpotential coupling, in which case neutralino LSPs would still decay inside the detector.

[21] The charged fermion masses are all fixed by the corresponding Yukawa couplings exactly as in mSUGRA, and so do not enter our parameter counting. The neutrino which acquires a Majorana mass via mixing with the Higgsino, however, has no Yukawa couplings, so that its mass serves as a constraint on the other parameters, which must be fine-tuned to m_ν in the sub-eV range.

[22] See J. Ferrandis, *Phys. Rev.* **D60**, 095012 (1999).