Chapter 4
R-parity Violation and Phenomenological Constraints

4.1 R-parity Violating Interactions

The R-parity violating (RPV) interactions are generated by the following superpotential:

$$W_{\not R} = \mu'_i \varepsilon_{ab} \hat{L}_i^a \hat{H}_u^b + \frac{1}{2}\lambda_{ijk}\varepsilon_{ab}\hat{L}_i^a \hat{L}_j^b (\hat{E}^c)_k + \lambda'_{ijk}\varepsilon_{ab}\hat{L}_i^a \hat{Q}_j^b (\hat{D}^c)_k + \frac{1}{2}\lambda''_{ijk}(\hat{U}^c)_i (\hat{D}^c)_j (\hat{D}^c)_k \ , \tag{4.1}$$

with $i, j, k = 1, 2, 3$ indicating the generation, and $a, b = 1, 2$ the $SU(2)_L$ indices. The sum is taken for each index. For the baryon number violating interactions (terms with λ''), the $SU(3)_c$ indices have been omitted. The lepton left-chiral superfields $\hat{L}$ and $\hat{E}^c$ are respectively the $SU(2)_L$ doublet and singlet. The quark superfields $\hat{Q}$, $\hat{U}^c$ and $\hat{D}^c$ denote respectively the quark $SU(2)_L$ doublet, up quark singlet and down quark singlet left-chiral superfields, and $\hat{H}_u$ the up type Higgs left-chiral superfield. The RPV superpotential gives rise to the following baryon or lepton number violating interactions (see Fig. 4.1).

$$\begin{aligned}
\mathscr{L}_{\not R} =& \mu'_i \left[\bar{\nu}_i P_L \left(\tilde{h}_u^0\right)^c - \bar{e}_i P_L \left(\tilde{h}_u^+\right)^c \right] + \text{h.c.} \\
& - \frac{1}{2}\lambda_{ijk} \left[\tilde{\nu}_i \bar{e}_k P_L e_j + \tilde{e}_{Lj} \bar{e}_k P_L \nu_i + \tilde{e}_{Rk}^\dagger \bar{\nu}_i^c P_L e_j - (i \leftrightarrow j) \right] + \text{h.c.} \\
& - \lambda'_{ijk} \Big[\tilde{\nu}_i \bar{d}_k P_L d_j + \tilde{d}_{Lj} \bar{d}_k P_L \nu_i + \tilde{d}_{Rk}^\dagger \bar{\nu}_i^c P_L d_j \\
& \qquad - \tilde{e}_{Li} \bar{d}_k P_L u_j - \tilde{u}_{Lj} \bar{d}_k P_L e_i - \tilde{d}_{Rk}^\dagger \bar{e}_i^c P_L u_j \Big] + \text{h.c.} \\
& - \frac{1}{2}\lambda''_{ijk} \left[\tilde{u}_{Ri}^\dagger \bar{d}_j P_L d_k^c + \tilde{d}_{Rj}^\dagger \bar{u}_i P_L d_k^c + \tilde{d}_{Rk}^\dagger \bar{u}_i P_L d_j^c \right] + \text{h.c.} \ ,
\end{aligned} \tag{4.2}$$

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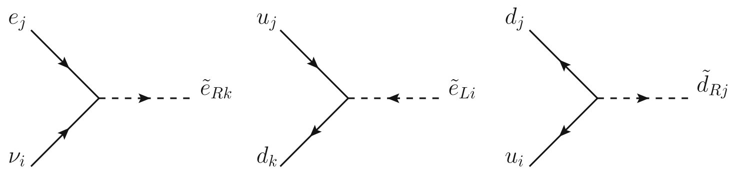

Fig. 4.1 Example of Yukawa interactions generated from R-parity violation. Arrows indicate the lepton or baryon number flow

where $P_L \equiv \frac{1}{2}(1-\gamma_5)$, and $\tilde{h}_u$ denotes the up type higgsino. The first three terms in Eq. (4.2) are lepton number violating and the last term is baryon number violating. There are also RPV scalar quartic interactions, but we do not consider them since these interactions have less effects on observable.

We can also add the general soft SUSY breaking lagrangian in the RPV sector:

$$\mathscr{L}_{\not{R}\text{soft}} = \mu'^2_{ui}\tilde{L}_i H_u + \tilde{m}^2_{di} H_d^\dagger \tilde{L}_i \\ + m_{\tilde{G}}\left[\frac{1}{2}A^{\lambda}_{ijk}\lambda_{ijk}\tilde{L}_i\tilde{L}_j\tilde{E}^c_k + A^{\lambda'}_{ijk}\lambda'_{ijk}\tilde{L}_i\tilde{Q}_i\tilde{D}^c_k + \frac{1}{2}A^{\lambda''}_{ijk}\lambda''_{ijk}\tilde{U}^c_i\tilde{D}^c_j\tilde{D}^c_k\right] \\ + \text{h.c.}\,, \tag{4.3}$$

where the field operators with tildes are the scalar component of the chiral-superfields. The $SU(2)_L$ and $SU(3)_c$ indices were omitted, but fields must be combined in a gauge invariant way.

As mentioned before, the motivation of eliminating the RPV interactions is mainly to prevent the proton decay in the theory. However, there is no definite reasons to forbid all RPV interactions. On the phenomenological ground, there is actually no reasons to prefer R-parity conserved models than RPV models. Furthermore, the RPV interactions can play roles in the grand unification. If we believe the grand unification, the quarks and leptons should be embedded in the same multiplets, and the conservation of R-parity seems to be incompatible. Many grand unified models which effectively give RPV interactions at low energy have been studied [1–6]. From the point of view of the grand unification, there is no preference between the R-parity conserving and RPV models, and all grand unification models do not have any generic prediction for the size of the RPV interactions. (In string theories, it is also possible to construct models with or without R-parity [7, 8]). We can say that the study of RPV interactions has potential to provide us with knowledge about the grand unification.

4.2 Bilinear R-parity Violation

The study of bilinear RPV interactions (mixing between lepton and Higgs) is interesting by itself. The bilinear RPV interactions can be rotated away by redefining the Higgs field as

$$\hat{H}'_{da} = \frac{\mu \hat{H}_{da} + \sum_i \varepsilon_{ba} \mu'_i \hat{L}_i^b}{\sqrt{\mu'^2 + \mu'^2_1 + \mu'^2_2 + \mu'^2_3}}, \tag{4.4}$$

where the massive parameter μ of the first term in the numerator is the coefficient of the mixing between up type and down type Higgs (the so-called μ-term of the superpotential). This redefinition also converts the Higgs-fermion-fermion (standard Yukawa) terms of the superpotential to the RPV superpotential (for example, $\varepsilon_{ab} \hat{Q}_i^a \hat{H}_u^b \hat{U}_j^c \to \varepsilon_{ab} \hat{Q}_i^a \hat{L}_k^b \hat{U}_j^c$). This is the reason why we often treat bilinear and trilinear RPV interactions separately. We must note that this rotation cannot get rid of the bilinear RPV soft breaking terms. In the case where these soft breaking terms are present, the sneutrinos also develop vacuum expectation value.

By using the above properties, it is possible to construct a scenario with R-parity which breaks spontaneously using the following superpotential [9]:

$$\hat{f} = \sum_{i,j=1,2,3} \Big[(\mathbf{f}_u)_{ij} \varepsilon_{ab} \hat{Q}_i^a \hat{H}_u^b \hat{U}_j^c + (\mathbf{f}_d)_{ij} \hat{Q}_i^a \hat{H}_{da} \hat{D}_j^c + (\mathbf{f}_e)_{ij} \hat{L}_i^a \hat{H}_{da} \hat{E}_j^c \\ + (\mathbf{f}_\nu)_{ij} \varepsilon_{ab} \hat{L}_i^a \hat{H}_u^b \hat{\nu}_j^c + (\mathbf{f})_{ij} \hat{\Phi} \hat{S}_i \hat{\nu}_j^c \Big] + (f_0 \hat{H}_u \hat{H}_d - \varepsilon^2) \hat{\Phi}, \tag{4.5}$$

where $\hat{\Phi}$, $\hat{S}_i$ and $\hat{\nu}_i^c$ are the new chiral superfields with lepton numbers 0, −1 and +1, respectively, and they are all with baryon number 0. The mechanism goes as follows. First, the scalar potential gets vacuum expectation values in the directions of $\tilde{\nu}_{Ri}$, $\tilde{S}_i$, $\tilde{\Phi}$, h_u^0 and h_d^0. These vacuum expectation values break the lepton number, thus generating the effective bilinear RPV interaction (both the superpotential and the soft breaking lagrangian). This can also be redefined in a basis with the RPV trilinear superpotential and the vacuum expectation value of the sneutrinos. Note that this spontaneous breakdown of R-parity does not change the proton life time since the superpotential of Eq. (4.5) does not minimize to baryon number violating vacuum.

4.3 Phenomenological Constraints on Trilinear RPV Interactions

Many of the trilinear RPV interactions are constrained phenomenologically. We will review in detail the most important ones.

Constraints from the Non-Observation of the Proton Decay

The simultaneous presence of lepton and baryon number violating RPV interactions leads to proton decays (see Fig. 4.2). As the proton decay is not observed in experiments, the combination of λ'', λ or λ'', λ' are strongly constrained [10–12].

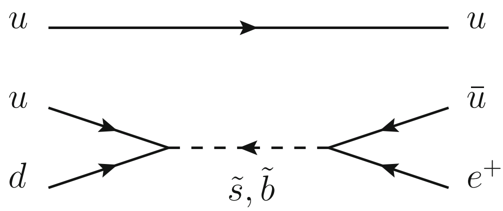

Fig. 4.2 Existence of both baryon and lepton number violating RPV interactions induces proton decay

Table 4.1 Upper limits on combinations of RPV couplings from double beta decay experiments

RPV couplings	λ'^2_{111}	$\lambda'_{112}\lambda'_{121}$	$\lambda'_{113}\lambda'_{131}$
Upper limits ($[m_{\text{SUSY}}]^3$)	7.7×10^{-6}	4.0×10^{-7}	1.7×10^{-8}

$[m_{\text{SUSY}}]^3$ is the mass of the SUSY particle (d squark involved in the decay) in unit of 100 GeV

Constraints from proton life time can be written as

$$|\lambda'_{ijk}\lambda''_{lmn}| < 10^{-26} \sim 10^{-11},$$
$$|\lambda_{ijk}\lambda''_{lmn}| < 10^{-11} \sim 10^{-3}, \tag{4.6}$$

which set very strong upper limits [10–16]. Due to this result, we often assume in theoretical analysis that baryon and lepton number violating RPV interactions do not co-exist.

Constraints from Lepton Number Violating Processes

The non-observation of the neutrinoless double beta decay sets also strong constraints on RPV couplings [13–21] (see Fig. 4.3).

The combinations of RPV couplings λ'^2_{111}, $\lambda'_{112}\lambda'_{121}$ and $\lambda'_{113}\lambda'_{131}$ are constrained as shown in Table 4.1.

The effective Majorana mass of the neutrino can also be generated by lepton number violating combination of RPV interactions [13–16, 22–24] (see Fig. 4.4). As the neutrino (Majorana) mass is constrained by observation, it is possible to limit

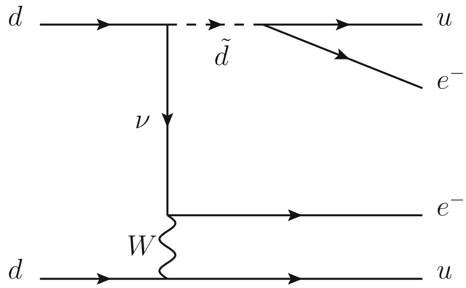

Fig. 4.3 Example of neutrinoless double beta decay amplitude induced from RPV interactions

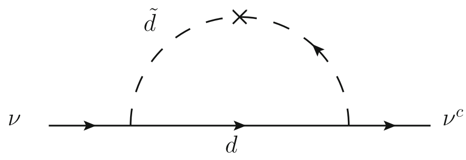

Fig. 4.4 RPV contribution to the Majorana mass of the neutrino

RPV couplings contributing to the process. This gives a relatively tight constraint on the RPV coupling λ'_{133}: $|\lambda'_{133}| < 3.5 \times 10^{-3}$.

Constraints from Precision Tests: Lepton Flavor Violating Process

Some combinations of RPV interactions are tightly constrained by lepton flavor violating processes. Here we present the example of the flavor changing radiative decay of charged lepton $l \to l'\gamma$ [13–16, 25] (see Fig. 4.5).

This process gives the following constraints on RPV interactions:

$$\begin{aligned}
|\lambda^*_{121}\lambda_{122}| &< 5.7 \times 10^{-5},\\
|\lambda^*_{131}\lambda_{132}| &< 5.7 \times 10^{-5},\\
|\lambda^*_{23k}\lambda_{131}| &< 1.1 \times 10^{-4},\\
|\lambda'^*_{2mk}\lambda'_{1mk}| &< 4.5 \times 10^{-4},\\
|\lambda'^*_{23n}\lambda'_{13n}| &< 7.7 \times 10^{-3},\\
|\lambda'^*_{233}\lambda'_{133}| &< 1.0 \times 10^{-2},\\
|\lambda'^*_{1jk}\lambda'_{3jk}| &< 1.2 \times 10^{-2},
\end{aligned} \tag{4.7}$$

where k $(= 1, 2, 3)$ and n $(= 1, 2)$ denote the generation of charged leptons.

Constraints from Precision Tests: Rare Hadron Decays

Hadron decays are very sensitive probe of RPV interactions since they receive contribution from the four-fermion interaction generated from R-parity violation [13–16,

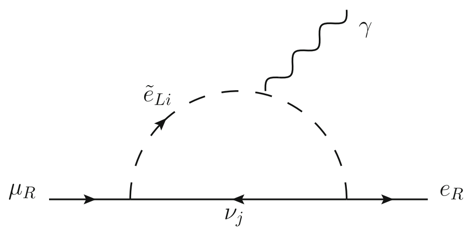

Fig. 4.5 $\mu \to e\gamma$ process within RPV interactions

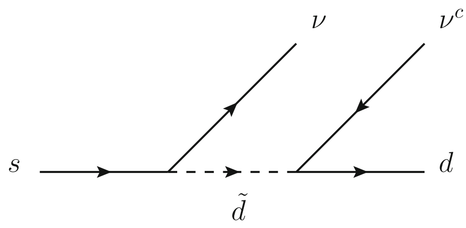

Fig. 4.6 RPV contribution to the $K \to \pi\nu\bar{\nu}$

26–31]. Here we will present the example of the semi-leptonic $K^+ \to \pi^+\nu\bar{\nu}$ decay. This K meson decay is induced by the following effective interaction (see Fig. 4.6)

$$\mathscr{L}_K = \frac{\lambda'^*_{ijk}\lambda'_{i'j'k}}{2m^2_{\tilde{d}_{Rk}}}\bar{d}_j\gamma^\mu P_L d_{j'}\,\bar{\nu}_i\gamma_\mu\nu_{i'} - \frac{\lambda'^*_{ijk}\lambda'_{i'jk'}}{2m^2_{\tilde{d}_{Lj}}}\bar{d}_k\gamma^\mu P_R d_{k'}\,\bar{\nu}_{i'}\gamma_\mu\nu_i + \text{h.c.}\,. \quad (4.8)$$

The branching ratio of the purely RPV $K^+ \to \pi^+\nu\bar{\nu}$ decay is given by [28–31]

$$B_{\text{RPV}}(K^+ \to \pi^+\nu\bar{\nu}) = \frac{r_+ B(K^+ \to \pi^0 e^+\nu_e)}{16|V_{us}|^2 G_F^2}\left|\frac{\lambda'^*_{i2n}\lambda'_{j1n}}{m^2_{\tilde{d}_{Rn}}} - \frac{\lambda'^*_{in1}\lambda'_{jn2}}{m^2_{\tilde{d}_{Ln}}}\right|^2, \quad (4.9)$$

where $r_+ = 0.901$ is the isospin correction factor. The branching ratio of the K decay into isospin partner is given by $B(K^+ \to \pi^0 e^+\nu_e) = (5.07 \pm 0.04) \times 10^{-2}$. The above RPV branching ratio should not excess the discrepancy between experimental data [32–35] and the standard model prediction [36]. Recently, experiment has observed the rare $K^+ \to \pi^+\nu\bar{\nu}$ decay, and the result is consistent with the standard model prediction. The RPV contribution is therefore constrained and should not excess the error of $B_{\text{exp}} - B_{\text{SM}}$, the difference between experimental value and the standard model contribution. We do not consider the interference between RPV and standard model contributions. The experimental value of the branching ratio of the decay $K^+ \to \pi^+\nu\bar{\nu}$ is [32–35]

$$B_{\text{exp}}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}. \quad (4.10)$$

The theoretical estimation of the standard model contribution is [36]

$$B_{\text{SM}}(K^+ \to \pi^+\nu\bar{\nu}) = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}, \quad (4.11)$$

where the first error is related to the uncertainty of the input parameters and the second one to the theoretical uncertainty. We obtain then the following inequality for the bilinear of RPV couplings:

$$4.1 \times \left| \frac{\lambda'^*_{i2n}\lambda'_{j1n}}{[m_{\tilde{d}_{Rn}}]^2} - \frac{\lambda'^*_{in1}\lambda'_{jn2}}{[m_{\tilde{d}_{Ln}}]^2} \right|^2 < 2.2 \times 10^{-10}, \tag{4.12}$$

where the expression with $[\cdots]$ denotes the mass of the sparticle in unit of 100 GeV. The right-hand side of the above equation is the error of $B_{\rm exp} - B_{\rm SM}$. This gives then the following bounds to the RPV couplings:

$$|\lambda'^*_{i2n}\lambda'_{j1n}| < 7.3 \times 10^{-6}[m_{\tilde{d}_{Rn}}]^2 , \qquad |\lambda'^*_{in1}\lambda'_{jn2}| < 7.3 \times 10^{-6}[m_{\tilde{d}_{Ln}}]^2, \tag{4.13}$$

where the dominance of the single bilinear of RPV couplings was assumed. Note that we have not considered the interference of the RPV amplitudes with standard model and R-parity conserving supersymmetric contributions.

This limit can be used to constrain RPV interactions with other flavors via flavor mixing. The change from the current basis to the mass basis yields the change $\bar{d}_k d_{k'} \to \bar{d}'_k d'_{k'} \simeq V_{k'1} V^*_{k2} \bar{s} d + \cdots$ for the quark bilinear in the effective lagrangian. We then obtain the following upper limits

$$\begin{aligned} |\lambda'_{imk}| &< 5.7 \times 10^{-3}[m_{\tilde{d}_{Rk}}], \\ |\lambda'_{i3k}| &< 0.14\,[m_{\tilde{d}_{Rk}}], \end{aligned} \tag{4.14}$$

where $i, k = 1, 2, 3$ and $m = 1, 2$.

Similar analysis holds for the B meson decays [37–40]. The effective lagrangian of Eq. (4.8) involving b quark generates the following purely RPV decay $B^+ \to X_s \nu_j \bar{\nu}_i$, and can be expressed as follows [37]

$$\frac{B_{\rm RPV}(B^+ \to X_s \nu_j \bar{\nu}_i)}{B(B^+ \to X_c e^+ \nu_e)} = \frac{1}{8G_F^2 |V_{cb}|^2 f_{PS}(m_c^2/m_b^2)} \sum_k \left\{ \left| \frac{\lambda'_{i2k}\lambda'^*_{j3k}}{2m^2_{\tilde{d}_{Rk}}} \right|^2 + \left| \frac{\lambda'_{ik2}\lambda'^*_{jk3}}{2m^2_{\tilde{d}_{Lk}}} \right|^2 \right\}, \tag{4.15}$$

where $f_{PS}(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x^2$ is the phase space factor. By using the quark masses $m_c = 1.29^{+0.05}_{-0.11}$ GeV and $m_b = 4.19^{+0.18}_{-0.06}$ GeV [39, 40], we obtain $f_{PS}(m_c^2/m_b^2) \approx 0.5$. The notations X_s and X_c denote the strange and charmed hadronic final states respectively. From the review of Particle data group, we have [39, 40]

$$B(B^+ \to K^+ \nu\bar{\nu}) < 1.3 \times 10^{-5}, \tag{4.16}$$

$$B(B^+ \to K^*(892)^+ \nu\bar{\nu}) < 8 \times 10^{-5} , \tag{4.17}$$

$$B(B^+ \to X_c e^+ \nu_e) = (10.8 \pm 0.4) \times 10^{-2}, \tag{4.18}$$

From the upper two inequalities, we have $B(B^+ \to X_s \nu\bar{\nu}) < 1 \times 10^{-4}$. The standard model prediction is $B_{\rm SM}(B^+ \to X_s \nu\bar{\nu}) < 5 \times 10^{-5}$ [37]. By neglecting the standard model contribution, we obtain the following bound to the RPV interactions:

$$|\lambda'_{i2k}\lambda'^{*}_{j3k}| < 5.8 \times 10^{-4}[m_{\tilde{d}_{Rk}}]^2 , \qquad |\lambda'_{ik2}\lambda'^{*}_{jk3}| < 5.8 \times 10^{-4}[m_{\tilde{d}_{Lk}}]^2. \quad (4.19)$$

As for the $K \to \pi\nu\bar{\nu}$ decay, the change from the current basis to the mass basis can set limits to other combination of RPV couplings. The mixing between s and b quarks gives the following bound

$$|\lambda'_{i3k}| < 0.12[m_{\tilde{d}_{Rk}}]. \quad (4.20)$$

where $i, k = 1, 2, 3$.

Constraints from Precision Tests: Electric Dipole Moments

The electric dipole moments of neutron, YbF molecule, ^{205}Tl and ^{199}Hg atoms can set severe constraints on the CP phases between RPV couplings. This topic is the main subject of this thesis and will be discussed in detail in Part III.

Constraints from Precision Tests: Universalities

The universality of the gauge coupling is an important tool to rule out the interactions of new physics. If the universality of the weak coupling holds, the contribution from the RPV must be embedded in the uncertainty of the standard model. This can be applied to the RPV interactions by noticing that the weak decay of leptons (or hadrons) can be mimicked by RPV amplitude with the same Lorentz structure [41, 42].

Let us examine the decays of leptons. The lepton number violating RPV interaction λ_{ijk} also contributes to the process. In Fig. 4.7, an example of the RPV muon decay process is shown. This contribution can interfere with the muon beta decay, and leads to the following redefinition of the Fermi weak coupling constant for the muon decay

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_W^2}\left[1 + \frac{m_W^2}{g_2^2 m_{\tilde{e}_{R_k}}^2}|\lambda_{21k}|^2\right]. \quad (4.21)$$

Similarly, the Fermi constants for the decays of τ lepton to electron and to muon will be shifted by $(m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{31k}|^2$ and $(m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{32k}|^2$, respectively. The decay ratios $R_{\tau\mu} \equiv \Gamma(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)/\Gamma(\mu^- \to e^-\bar{\nu}_e\nu_\mu)$ and $R_\tau \equiv \Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau)/\Gamma(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$ will then be shifted by

$$R_{\tau\mu} = [R_{\tau\mu}]_{\rm SM}\left\{1 + 2[(m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{32k}|^2 - (m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{21k}|^2]\right\}, \quad (4.22)$$

$$R_\tau = [R_\tau]_{\rm SM}\left\{1 + 2[(m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{31k}|^2 - (m_W^2/g_2^2 m_{\tilde{e}_{R_k}}^2)|\lambda_{32k}|^2]\right\}. \quad (4.23)$$

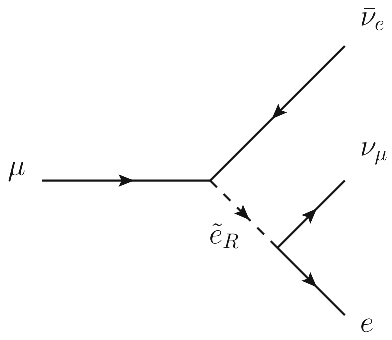

Fig. 4.7 Example of process with RPV interactions interfering to the SM weak process (example of muon decay)

The standard model prediction of these ratios are

$$[R_{\tau\mu}]_{\rm SM} = 1.309 \times 10^6,$$
$$[R_\tau]_{\rm SM} = 1.028. \tag{4.24}$$

These values were calculated by taking into account the radiative corrections and the running coupling [42]. The experimental values listed by the review of Particle data group are [39, 40]

$$[R_{\tau\mu}] = (1.315 \pm 0.006) \times 10^6,$$
$$[R_\tau] = 1.025 \pm 0.003. \tag{4.25}$$

The consistency between the experimental values and the standard model predictions implies that the RPV couplings must be within the experimental errors. The following constraints can then be given:

$$|\lambda_{21k}| < 0.05[m_{\tilde{e}_{Rk}}],$$
$$|\lambda_{31k}| < 0.03[m_{\tilde{e}_{Rk}}],$$
$$|\lambda_{32k}| < 0.05[m_{\tilde{e}_{Rk}}], \tag{4.26}$$

where $k = 1, 2, 3$. $[\cdots]$ denotes the mass of sparticles in unit of 100 GeV. Here we have also assumed the dominance of single RPV couplings.

Similar analysis holds for the decay ratios $\Gamma(\pi^- \to e^-\bar{\nu}_e)/\Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)$ and $\Gamma(\tau^- \to \pi^-\nu_\tau)/\Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)$, and also for the decay ratios $\Gamma(D^0 \to \mu^+\nu_\mu K^-)/\Gamma(D^0 \to e^+\nu_e K^-)$, $\Gamma(D^+ \to \mu^+\nu_\mu \bar{K}^0)/\Gamma(D^+ \to e^+\nu_e \bar{K}^0)$ and $\Gamma(D^+ \to \mu^+\nu_\mu \bar{K}^*(892)^0)/\Gamma(D^+ \to e^+\nu_e \bar{K}^*(892)^0)$. These processes receive contribution from lepton number violating RPV interactions λ'_{ijk}, so it is possible to constrain them. This method has the advantage to cancel the theoretical uncertainty due to the meson form factors, and the ratio can be fully calculated in the standard model. In these cases, the uncertainty of the CKM matrix elements V_{ud} and V_{cs} has to be taken into account. For detailed discussion, see Ref. [42].

RPV at Colliders

The RPV processes can also be observed in collider experiments [22, 41, 43, 44]. The first type of manifestation of the R-parity violation is the resonance of the sneutrino in *pp* collision, as shown in Fig. 4.8. The analysis of the data accumulated at the LHC provides a stringent constraint on the coupling λ'_{311}, if the τ sneutrino is the LSP. The non-observation of such resonance gives $\lambda'_{311} < 10^{-2}$ for $m_{\tilde{\nu}_\tau} = 1$ TeV and $\lambda'_{311} < 10^{-3}$ for $m_{\tilde{\nu}_\tau} = 100$ GeV [43, 44].

The other way to constrain RPV interactions is to analyze the displaced vertices of the heavy particle decay. The typical process is the decay of the lightest neutralino as shown in Fig. 4.9. No significant result was found at the LHC, and it was concluded that the product between the production cross-section and the decay branching fraction of the neutralino is less than 5 pb for $m_{\tilde{q}} = 1.5$ TeV [43, 44].

Constraints from Cosmology

The non-conservation of R-parity leads to the decays of lightest sparticles (LSPs) (example of the decay is shown in Fig. 4.9) [13–16, 22]. This fact can disturb the current picture of the Universe in two ways, and we need to constrain RPV interactions in each case.

The first topic is the stability of the supersymmetric dark matters. The candidates of dark matter in supersymmetric models are the lightest neutralino or sneutrino. To

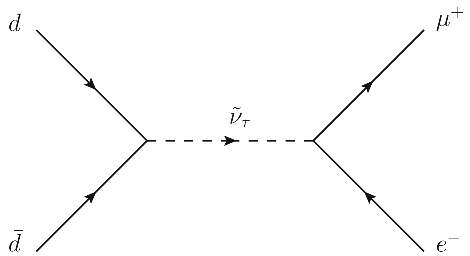

Fig. 4.8 Example of resonance process with RPV interactions in collider search

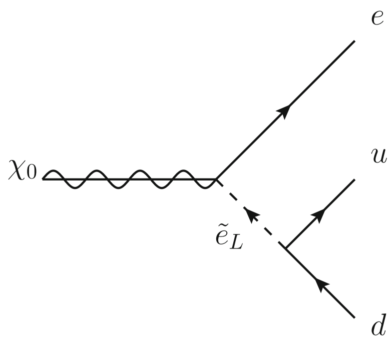

Fig. 4.9 Neutralino decay within RPV interactions

reconcile the scenario of supersymmetric dark matters with the existence of RPV interactions, the following constraint must hold:

$$|\lambda_{ijk}|, |\lambda'_{ijk}|, |\lambda''_{ijk}| < 10^{-21}, \tag{4.27}$$

for $m_{\rm SUSY} = O(100\,{\rm GeV})$, where $i, j, k = 1, 2, 3$. Of course these limits do not apply when the dark matter is not composed of supersymmetric particles.

If unstable LSPs with RPV interactions is larger than 10^{-20}, there is a second type of constraints. The LSP must actually decay before the nucleosynthesis to not disturb the nucleosynthesis [45]. The decay of LSPs before nucleosynthesis is translated to the following *lower* bounds

$$|\lambda_{ijk}|, |\lambda'_{ijk}|, |\lambda''_{ijk}| > 10^{-12}. \tag{4.28}$$

The other cosmological source of strong constraints on RPV interactions is the dilution of the baryon asymmetry [46–49]. The RPV interactions can dilute the baryon number asymmetry of the Universe when the expansion rate of the Universe is smaller than the decay rate of matter. The non-dilution of the matter imposes also constraints on RPV interactions as follows:

$$\begin{aligned} &|\lambda_{ijk}|, |\lambda'_{ijk}|, |\lambda''_{ijk}| < 1.6 \times 10^{-7}[m_{\tilde{f}}]^{1/2} \quad (T > m_{\tilde{f}}), \\ &|\lambda_{ijk}|, |\lambda'_{ijk}|, |\lambda''_{ijk}| < 1.6 \times 10^{-6}[m_{\tilde{f}}]^{1/2} \quad (T < m_{\tilde{f}}), \end{aligned} \tag{4.29}$$

where $[m_{\tilde{f}}]$ is the mass of sfermions in unit of 100 GeV. We must note that these bounds do not apply simultaneously to all RPV interactions. It is possible to protect the baryon number asymmetry by imposing the above constraints to a fixed generation.

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