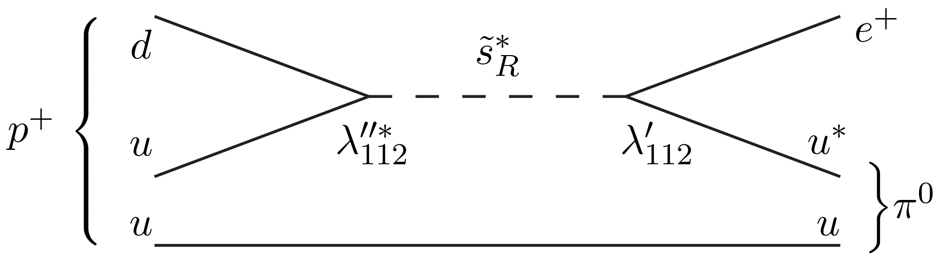
LFV physics at the TeV scale: R-parity violating Susy

R-parity = discrete symmetry defined as:

$$R_P \;=\; (-1)^{3B+L+2S} \;=\; \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for superpartners} \end{cases}$$

Introduced in the MSSM in order to avoid fast proton decay from supersymmetric baryon and lepton number violating interactions:

$$W_{RPV} \;=\; \frac{1}{2}\,\lambda_{ijk}\,L_i L_j \bar{e} \;+\; \lambda'_{ijk} L_i Q_j \bar{d}_k \;+\; \frac{1}{2}\,\lambda''_{ijk}\bar{u}_i \bar{d}_j \bar{d}_k \;+\; \mu_i H_u L_i$$



$$\Longrightarrow \quad |\lambda'\lambda''| \;\lesssim\; 10^{-25}\left(\frac{m_{\tilde{d}_R}}{1\,\mathrm{TeV}}\right)^2$$

Consequences of R-parity: proton stability; superpartners produced in pairs; stable LSP (dark matter, missing energy signals at colliders)

However, R-parity is not unavoidable: forbidding the λ'' couplings is enough to ensure proton stability

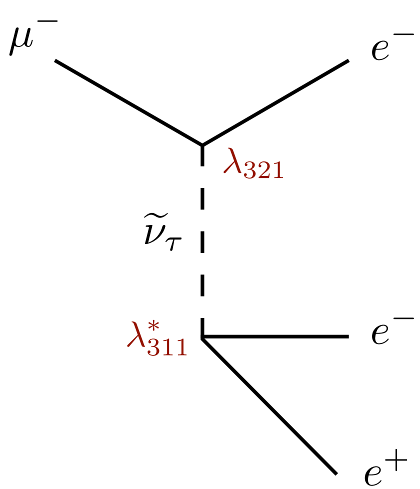
→ scenario where R-parity is violated by the lepton number violating couplings λ and λ' only (and possibly also μ_i)

→ rich phenomenology at colliders, depending on the size of λ and λ' (LSP decays and displaced vertices / RPV sparticle decays, single sparticle production...)

→ possibility of generating neutrino masses

- tree-level neutrino mass from μ_i-induced neutrino/higgsino mixing
- 1-loop neutrino masses induced by λ and λ' (need $\lambda, \lambda' \sim 10^{-4} - 10^{-3}$)

→ LFV decays of charged leptons ($l \to l' l' l''$ at tree level)



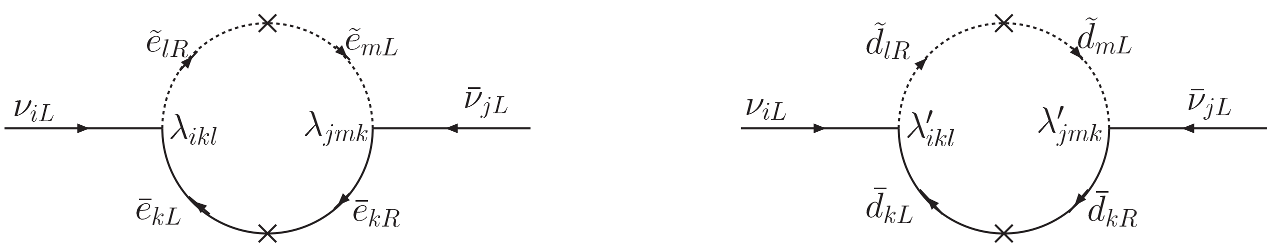
$$|\lambda_{321}\lambda^*_{311}|, \; |\lambda^*_{i12}\lambda_{i11}| \; < \; 7 \times 10^{-7} \left(\frac{m_{\tilde{\nu}}}{100\,\mathrm{GeV}}\right)^2$$

→ LFV decays of the LSP (from bilinear RPV):

$$\begin{array}{rcl} \tilde{\chi}_1^0 & \rightarrow & W^\pm l^\mp, \; Z\nu \\ \tilde{\chi}_1^0 & \rightarrow & l^\pm q\bar{q}', \; q\bar{q}\nu, \; l^+ l^- \nu \end{array}$$

Neutrino masses from R-parity violation

1) no bilinear R-parity violation (μ_i = 0 and no bilinear RPV soft terms $B_i \epsilon_i \tilde{L}_i H_u$ and $\widetilde{m}^2_{di} H_d^\dagger \tilde{L}_i$)



Neutrino masses at one loop, right ballpark for $\lambda, \lambda' \sim 10^{-4} - 10^{-3}$ but large number of parameters (9 + 27). Can expand:

$$M^\nu_{ij}|_\lambda \simeq \frac{1}{8\pi^2} \left\{ \lambda_{i33}\lambda_{j33} \frac{m_\tau^2}{\tilde{m}} + (\lambda_{i23}\lambda_{j32} + \lambda_{i32}\lambda_{j23}) \frac{m_\mu m_\tau}{\tilde{m}} + \lambda_{i22}\lambda_{j22} \frac{m_\mu^2}{\tilde{m}} \right\} + \cdots$$

$$M^\nu_{ij}|_{\lambda'} \simeq \frac{3}{8\pi^2} \left\{ \lambda'_{i33}\lambda'_{j33} \frac{m_b^2}{\tilde{m}} + (\lambda'_{i23}\lambda'_{j32} + \lambda'_{i32}\lambda'_{j23}) \frac{m_s m_b}{\tilde{m}} + \lambda'_{i22}\lambda'_{j22} \frac{m_s^2}{\tilde{m}} \right\} + \cdots$$

Enough freedom in the RPV couplings to reproduce the observed neutrino masses and lepton mixing and simultaneously evade the strong bounds from LFV processes

Not really a consistent framework though: trilinear RPV couplings induce bilinear RPV at the quantum level

2) bilinear R-parity violation present

Tree-level neutrino mass from higgsino-neutrino mixing (here $v_i = 0$):

$$M^{\nu}_{tree} \simeq -m\, M_{\chi}^{-1}\, m^T = -\frac{m_{\nu_{tree}}}{\sum_i \mu_i^2} \begin{pmatrix} \mu_1^2 & \mu_1\mu_2 & \mu_1\mu_3 \\ \mu_1\mu_2 & \mu_2^2 & \mu_2\mu_3 \\ \mu_1\mu_3 & \mu_2\mu_3 & \mu_3^2 \end{pmatrix}$$

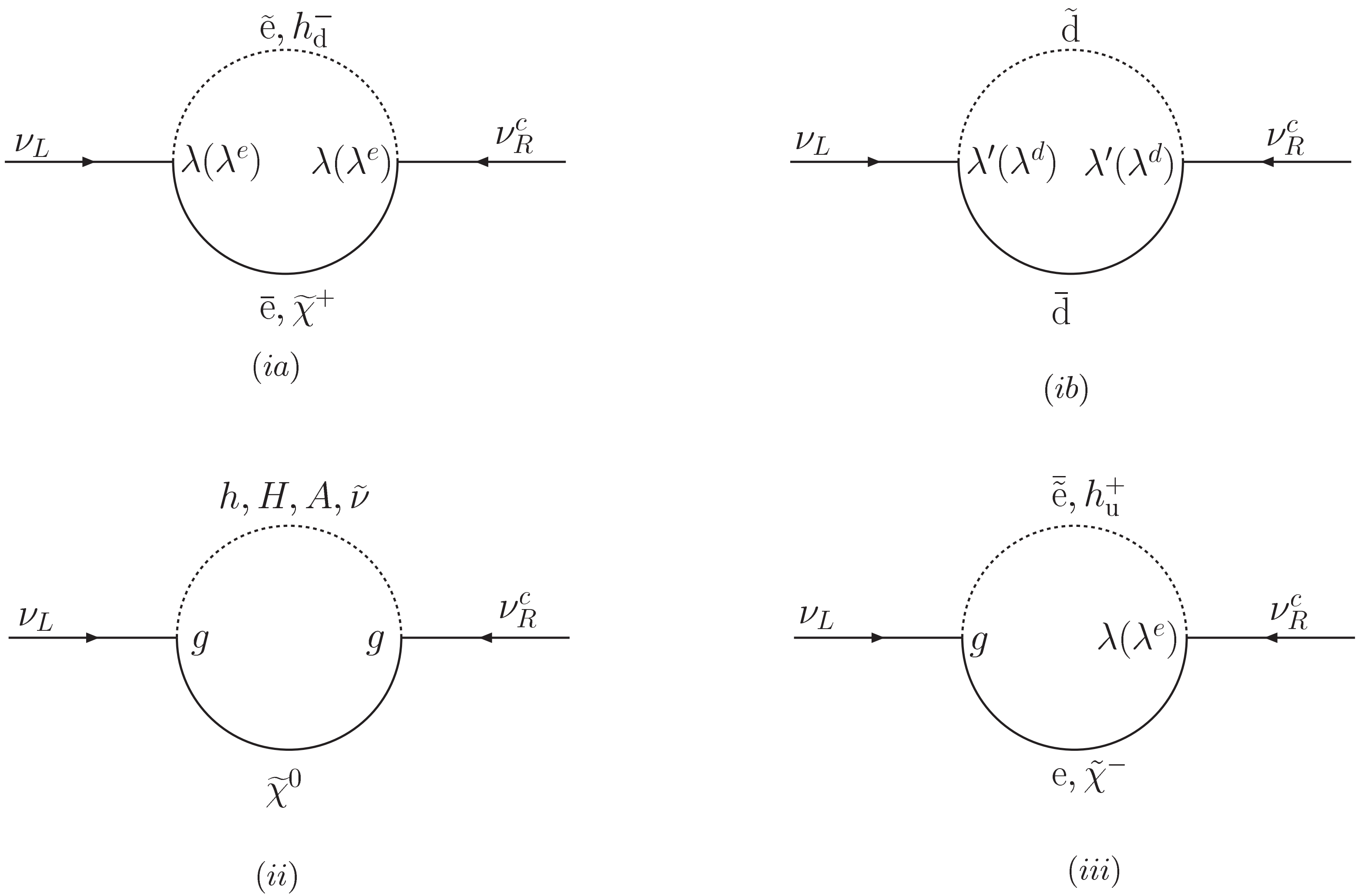
$$m_{\nu_{tree}} \simeq \frac{M_Z^2\, \cos^2\beta\, (M_1 c_W^2 + M_2 s_W^2)\, \mu \cos\xi}{M_1\, M_2\, \mu \cos\xi - M_Z^2\, \sin 2\beta\, (M_1 c_W^2 + M_2 s_W^2)}\, \tan^2\xi$$

where $\sin^2\xi = \sum_i \mu_i^2/\mu^2$, and more generally ξ is the angle between the 4-vectors (μ, μ_i) and (v_d, v_i) . ξ is zero if universal soft terms, or if RPV soft terms satisfy "alignment" conditions

$$\sin\xi \lesssim 10^{-6}\sqrt{1+\tan^2\beta}\,\sqrt{m_{\nu_{tree}}/0.05\,\mathrm{eV}}$$

A single neutrino massive at tree-level (with flavour composition determined by the μ_i). All neutrinos massive at the loop level.

1-loop contributions to the neutrino mass matrix from bilinear and trilinear RPV parameters:



Need 2 RPV vertices or mass insertions. Bilinear RPV parameters can do the job alone [even only bilinear RPV soft terms, see Abada, Losada]

A particulary predictive scenario: bilinear R-parity breaking

(only $\epsilon_i L_i H_u$ present in WRP, and the corresponding soft terms $B_i \epsilon_i \tilde{L}_i H_u$ in the scalar potential)

Parameters: $\epsilon_i, \Lambda_i \ (i = 1, 2, 3)$

where $B_i \ \rightarrow \ v_i \equiv \langle \tilde{\nu}_i \rangle$ (sneutrino vevs) $\rightarrow \ \Lambda_i \equiv \mu v_i + v_d \epsilon_i$

⇒ neutrino masses generated at tree + 1-loop level, with in particular

$$\tan^2 \theta_{23} \simeq \left(\frac{\Lambda_2}{\Lambda_3} \right)^2 \qquad \sin^2 \theta_{13} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2 + \Lambda_3^2}} \qquad \tan^2 \theta_{12} \sim \left| \frac{\epsilon_1}{\epsilon_2} \right|$$

→ the BR's of the LFV decays of the LSP are correlated with the measured oscillation parameters, e.g. [Mukhopadhyaya, Roy Vissani – Hirsch, Porod, Romao, Valle]

$$\frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \mu^\pm W^\mp)}{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \tau^\pm W^\mp)} \simeq \frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \mu^\pm \bar{q} q')}{\mathrm{BR}\,(\tilde{\chi}_1^0 \rightarrow \tau^\pm \bar{q} q')} \simeq \tan^2 \theta_{23}$$

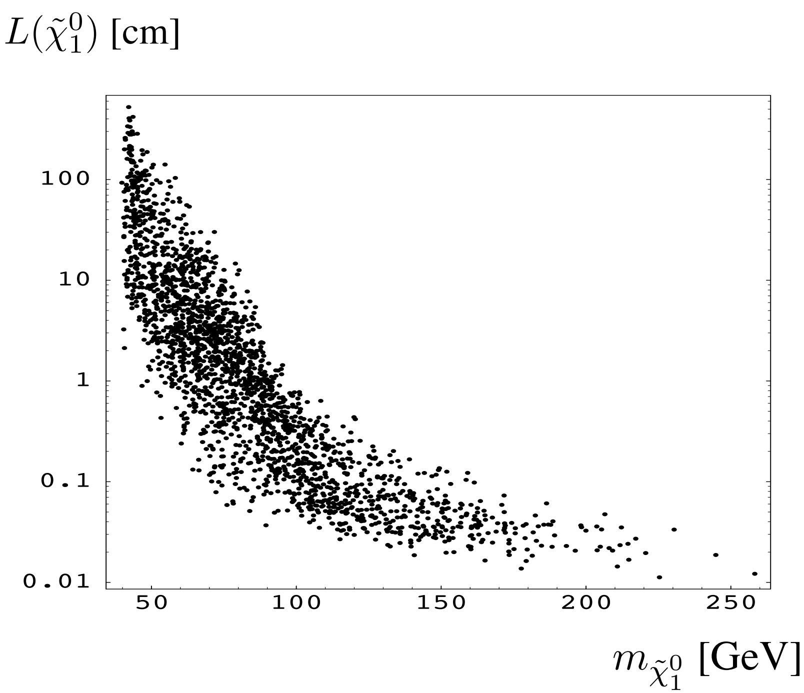
→ LFV in the charged lepton sector negligible

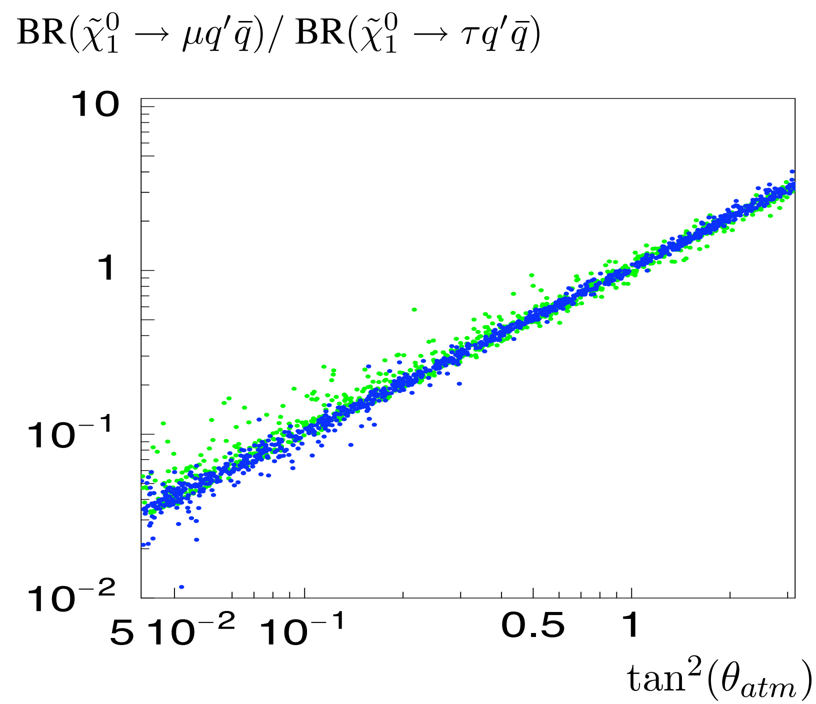
$$\mathrm{BR}\,(\mu \rightarrow e\gamma) < 10^{-17} \qquad\qquad \mathrm{BR}\,(\tau \rightarrow \mu\gamma, e\gamma) < 10^{-16}$$

Note: neutrino data requires small R-parity violating couplings

$\Rightarrow$ superpartner production and decays as in the MSSM with R-parity; only difference = LSP decay with a potentially measurable decay length, allowing to identify its decay products

Scan over the MSSM parameters: [Hirsch, Porod, Romao, Valle]





$$L(\tilde{\chi}_1^0) \sim (0.01 - 100)\,\mathrm{cm}$$

$$\frac{\mathrm{BR}\,(\tilde{\chi}_1^0 \to \mu^\pm q' \bar{q})}{\mathrm{BR}\,(\tilde{\chi}_1^0 \to \tau^\pm q' \bar{q})} \approx \tan^2\theta_{23}$$

Assume MSSM spectrum known within 10% : [Hirsch, Porod, Romao, Valle]

Parameters: $m_0 = 500\,\mathrm{GeV}, \quad M_2 = 120\,\mathrm{GeV}, \quad \mu = 500\,\mathrm{GeV}$
$A_0 = -500\,\mathrm{GeV}, \quad \tan\beta = 5$

Statistical error: $10^5\ \tilde{\chi}_1^0$