**R-parity-Violating Supersymmetric Yukawa Couplings: A Mini-review**

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I review the bounds on the $R$-parity-violating supersymmetric Yukawa couplings from the considerations of proton stability, $\bar{n}-n$ oscillation, $\nu_\mu$-Majorana mass, neutrino-less double $\beta$ decay, charged-current universality, $e-\mu-\tau$ universality, $\nu_\mu-\nu_e$ scattering, atomic parity violation, $\nu_\mu$ deep-inelastic scattering, $K^+$-decays, $\tau$-decays, $D$-decays and from the precision LEP electroweak observables. I also mention about the sparticle bounds at colliders when the assumption of $R$-parity-conservation is relaxed. Finally, I mention how $R$-parity-violating models have been invoked in an attempt to explain the reported excess in ALEPH 4-jet events.

1. INTRODUCTION

‘$R$-parity’ in supersymmetry (SUSY) refers to a discrete symmetry which follows from the conservation of lepton-number ($L$) and baryon-number ($B$) \[1\]. It is defined as $R = (-1)^{(3B+L+S)}$, where $S$ is the intrinsic spin of the field. $R$ is +1 for all standard model (SM) particles and −1 for all super-particles. However, $B$- and $L$-conservations are not ensured by gauge invariance and hence there is a *a priori* no reason to set these couplings to zero. It is, therefore, a phenomenological exercise to constrain these couplings from observed and unobserved phenomena in nature. Minimal SUSY requires the presence of two Higgs superfield doublets and one of their gauge quantum numbers are the same as those of the $SU(2)$-doublet lepton superfield. So, in the Yukawa superpotential, the latter can replace the former, if one sacrifices the assumption of $L$-conservation. If one sacrifices the assumption of $B$-conservation as well, no theoretical consideration prevents one to construct a Yukawa interaction involving three $SU(2)$-singlet quark superfields. These lead to *explicit* breaking of $R$-conserving interactions, which are parametrized in the superpotential (ignoring the bilinear $\mu L_i H_2$ term) as

\[
W_R = \lambda_{ijk} L_i L_j E^c_k + \lambda_{ij} L_i Q_j D^c_k + \lambda_{ijk}'' U^c_i D^c_j D^c_k ,
\]

where $L_i$ and $Q_i$ are the $SU(2)$-doublet lepton and quark superfields and $E^c_i, U^c_i, D^c_i$ are the singlet superfields; $\lambda_{ijk}$ is antisymmetric under the interchange of the first two $SU(2)$ indices, while $\lambda_{ijk}''$ is antisymmetric under the interchange of the last two. Thus, in total, there are 27 $\lambda$-type and 9 each of $\lambda'$- and $\lambda''$-type couplings, thereby adding 45 extra parameters in the minimal SUSY.

1.1. Cosmological implications

The requirement that GUT-scale baryogenesis does not get washed out imposes $\lambda'' < 10^{-7}$ \[2\]; however, these bounds are model dependent and can be evaded \[3\]. The $\lambda'$ couplings alone cannot wash out the initial baryon asymmetry. But, they can do so in association with a $B$-violating but $(B-L)$ conserving interaction, such as sphaleron-induced non-perturbative transitions. The latter processes conserve $\frac{1}{3}B - L_i$ for each lepton generation, and hence the conservation of any one lepton generation number is enough to retain the initial baryon asymmetry. We, therefore, assume that the $\lambda'$-type couplings involving any particular lepton family are smaller than $\sim 10^{-7}$ to avoid any cosmological bound on the remaining of them.

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2. LOW ENERGY PHENOMENOLOGY

2.1. Proton stability

Non-observation of proton decay places very strong bounds on the simultaneous presence of both $L$- and $B$-violating couplings; generically $\lambda^\prime\lambda^{\prime\prime} \leq 10^{-24}$. Specific cases have been considered in refs. 3, 4. Ref. 3 sets an upper limit of $10^{-9}$ ($10^{-11}$) for any product combination of $\lambda'$ and $\lambda^{\prime\prime}$ in the absence (presence) of squark flavour mixing.

2.2. $n-\bar{n}$ oscillation

The contributions of the $\lambda''_{121}$- and $\lambda''_{131}$-induced interactions to $n-\bar{n}$ oscillation proceed through the process $(udd \rightarrow \bar{d}d \rightarrow \bar{d}d \rightarrow \bar{u}d)$. In ref. 4, the intergenerational mixing was not handled with sufficient care. In the updated analysis 5, the constraint on $\lambda''_{131}$ has been estimated to be $\leq 10^{-4} - 10^{-5}$ for $m = 100$ GeV, while that on $\lambda_{121}$ is shown to be weaker (diluted by a relative factor of $m_{12}^2/m_{13}^2$). It has, however, been shown in the same paper 6 that the best constraint on $\lambda''_{121}$ comes from the consideration of double nucleon decay into two kaons and the bound is estimated to be $\leq 10^{-6} - 10^{-7}$.

2.3. $\nu_e$-Majorana mass

$\lambda'$- and $\lambda''$-type couplings can induce a Majorana mass of $\nu_e$ by self-energy type diagrams. An approximate expression for the induced $\nu_e$-Majorana mass, for a generic coupling $\lambda$, is

$$\delta m_{\nu_e} \sim \frac{\lambda^2}{8\pi^2} \frac{1}{m^2} M_{\text{SUSY}}^2 m^2.$$  (2)

Assuming $M_{\text{SUSY}} = \tilde{m}$, the $\lambda_{133}$-induced interaction with $\tau\tau$ loops yields the constraint (1σ) $\lambda_{133} \leq 3 \times 10^{-3}$ for $m_\tau = 100$ GeV 7. On the other hand, the $\lambda''_{133}$-induced diagrams with $b\bar{b}$ loops leads to $\lambda''_{133} \leq 10^{-5}$ for $m_b = 100$ GeV 8.

2.4. Neutrinoless double beta decay

It is known for a long time that neutrinoless double beta decay ($\beta\beta_0$) is a sensitive probe of lepton-number-violating processes. In $R$-parity-violating scenario, the process $dd \rightarrow uuee^+e^-$ is mediated by $\tilde{e}$ and $\tilde{\tau}$ or by $\tilde{\nu}$ and $\tilde{\tau}$, yielding $\lambda_{111} \leq 10^{-4}$ 9. Recently, a new bound on the product coupling $\lambda_{111}\lambda_{131} \leq 3 \times 10^{-9}$ has been placed from the consideration of the diagrams involving the exchange of one $W$ boson and one scalar boson 10.

2.5. Charged-current universality

Universality of the lepton and quark couplings to the $W$-boson is violated by the presence of $\lambda'$- and $\lambda''$-type couplings. The scalar-mediated new interactions have the same $(V - A) \otimes (V - A)$ structure as the $W$-exchanged diagram. The experimental value of $V_{ud}$ is related to $V_{ud}^{\text{SM}}$ by

$$|V_{ud}^{\text{exp}}|^2 \simeq |V_{ud}^{\text{SM}}|^2 \left[ 1 + 2r_{1k}(d_R^k) - 2r_{12k}(\tilde{c}_R^k) \right],$$  (3)

where, $r_{ijk}(l) = (M_{ij}^2/g^2)(\lambda_{ijk}/m_{l}^2)$.  

$r_{ij}$ is defined using $\lambda''_{ijk}$ analogously as $r_{ijk}$. Assuming the presence of only one $R$-parity-violating coupling at a time, one obtains, for a common $\tilde{m} = 100$ GeV, $\lambda_{12k} \leq 0.04$ (1σ) and $\lambda_{11k} \leq 0.03$ (2σ), for each $k$. 11.

2.6. $e-\mu-\tau$ universality

The ratio $R_\tau = \Gamma(\tau \rightarrow e\nu\nu)/\Gamma(\tau \rightarrow \mu\nu\nu)$, in the presence of $\lambda'$-type interaction takes the form

$$R_\tau = R_{\tau}^{\text{SM}} \left[ 1 + \frac{2}{V_{ud}} \left\{ r_{11k}(d_R^k) - r_{12k}(\tilde{c}_R^k) \right\} \right].$$  (5)

A comparison with experimental results yields, for a common mass $\tilde{m} = 100$ GeV and at 1σ, $\lambda_{11k} \leq 0.05$ and $\lambda_{21k} \leq 0.09$, for each $k$, assuming only one coupling at a time 11.

Similarly, from the consideration of $R_\tau = \Gamma(\tau \rightarrow e\nu\nu)/\Gamma(\tau \rightarrow \mu\nu\nu)$, one obtains, $\lambda_{13k} \leq 0.10$ and $\lambda_{23k} \leq 0.12$, for each $k$, at 1σ and for $\tilde{m} = 100$ GeV 11.

2.7. $\nu_\mu-e$ scattering

The neutrino-electron scattering cross section at low energies are given by

$$\sigma(\nu_\mu e) = \frac{G_{\nu}^2}{\pi} \left( g_L^2 + \frac{1}{3} g_R^2 \right),$$

$$\sigma(\bar{\nu}_e e) = \frac{G_{\nu}^2}{\pi} \left( \frac{1}{3} g_L^2 + g_R^2 \right);$$  (6)

where in the presence of $R$-parity-violating interactions ($x_{W} \equiv \sin^2 \theta_{W}$)

$$g_L = x_W - \frac{1}{2} - \left( \frac{1}{2} + x_W \right) r_{12k}(\tilde{c}_R^k),$$
The derived constraints (at 1σ) are λ_{12k} ≤ 0.34, λ_{121} ≤ 0.29 and λ_{231} ≤ 0.26 for ˜m = 100 GeV [13].

2.8. Atomic parity violation

The parity-violating part of the Hamiltonian of the electron-hadron interaction is

\[ H = \frac{G_F}{\sqrt{2}} (C_{11}\bar{e}r_\mu 5\gamma_i q_i + C_{21}\bar{e}r_\mu 5\gamma_i q_i), \]

where, \( i \) runs over the u- and d-quarks. For the definitions of the \( C_i \)'s in the SM, see any Review of Particle Properties (e.g., ref. [14]). The \( R \)-parity violating contributions are \( \Delta C \equiv C - C_{\text{SM}} \),

\[
\Delta C_1^u = -r_{11k}(d_R^k) + \left( \frac{1}{2} - \frac{2}{3}x_W \right)r_{12k}(e_R^k), \\
\Delta C_2^u = -r_{11k}(d_R^k) + \left( \frac{1}{2} - 2x_W \right)r_{12k}(e_R^k), \\
\Delta C_1^d = r_{1j1}(\bar{q}_L^j) - \left( \frac{1}{2} - \frac{2}{3}x_W \right)r_{12k}(e_R^k), \\
\Delta C_2^d = -r_{1j1}(\bar{q}_L^j) - \left( \frac{1}{2} - 2x_W \right)r_{12k}(e_R^k).
\]

Including the effects of radiative corrections, the 1σ bounds are \( \lambda_{11k}^u \leq 0.30, \lambda_{1j1}^d \leq 0.26 \) for ˜m = 100 GeV [13]. Bounds on λ_{12k} are much weaker than those obtained from charged-current universality.

2.9. \( \nu_\mu \) deep-inelastic scattering

The left- and the right-handed couplings of the d-quark in neutrino interactions are modified by the \( R \)-parity-violating couplings as

\[
g_L^d = \left( \frac{1}{2} + \frac{1}{3}x_W \right)(1 - r_{12k}(e_R^k) - r_{1j1}(\bar{q}_L^j)), \\
g_R^d = \frac{1}{3}x_W + r_{12j}(\bar{q}_L^j) - \frac{1}{3}x_Wr_{12k}(e_R^k).
\]

The derived limits, for ˜m = 100 GeV, are \( \lambda_{12k}^d \leq 0.11 \) (1σ) and \( \lambda_{1j1}^d \leq 0.22 \) (2σ) [13].

2.10. \( K^+ \)-decays

Consideration of only one non-zero \( R \)-parity-violating coupling with indices related to the weak basis of fermions, automatically generates more than one non-zero coupling with different flavour structure in the mass basis. Consequently, flavour-changing-neutral-current processes are naturally induced. The Lagrangian governing \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) is given by

\[
L = -\frac{\lambda_{ijk}^2}{2m_{\nu_j}^2} V_{ij} V_{j2} (s_L \gamma^\mu d_L)(\bar{\nu}_L\gamma^\mu \nu_L), \quad (11)
\]

where \( V \) is the CKM matrix. The SM contribution is an order of magnitude lower than the experimental limit. Assuming that the new interaction dominates, one obtains, from the ratio of the \( \Gamma(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \) to \( \Gamma(K^+ \rightarrow \pi^0 \nu \bar{\nu}) \), the constraint \( \lambda_{ijk}^0 \leq 0.012 \) (90% CL), for \( m_{\nu_j} = 100 \) GeV and for \( j = 1 \) and 2 [13].

2.11. \( \tau \)-decays

The decay \( \tau^+ \rightarrow \bar{u}d\tau \) proceeds in the SM by a tree-level \( W \)-exchanged graph. The scalar-exchanged graph induced by \( \lambda_{11k}^\tau \) can be written in the same \( (V - A) \otimes (V - A) \) form by a Fierz rearrangement. Using the experimental input

\[
Br(\tau^+ \rightarrow \pi^- \nu_\tau) = 0.117 \pm 0.004, \quad (12)
\]

\[
f_\pi = (130.7 \pm 0.1 \pm 0.36) \text{ MeV},
\]

one obtains \( \lambda_{11k}^\tau \leq 0.16 \) (1σ) for \( m_{\nu_j} = 100 \) GeV [13].

2.12. \( D \)-decays

The tree-level process \( c \rightarrow se^{+}\nu_\tau \) is mediated by a \( W \) exchange in the SM and by a scalar boson exchange in \( X \)-induced interaction. By a Fierz transformation it is possible to write the latter in the same \( (V - A) \otimes (V - A) \) form as the former. Using the experimental input [14]:

\[
Br(D^+ \rightarrow \bar{K}^0s\mu^+\nu_\mu) = 0.94 \pm 0.16, \quad (13)
\]

one obtains, at 1σ, \( \lambda_{12k}^d \leq 0.29 \) and \( \lambda_{12k}^\tau \leq 0.18 \), for \( m_{\nu_j} = 100 \) GeV [13]. The form factors associated with the hadronic matrix elements cancel in the ratios, thus making the prediction free from the large theoretical uncertainties associated with those matrix elements.

3. LEP PRECISION MEASUREMENTS

The partial decay widths \( \Gamma_i \) of the Z boson into light fermions receive sizable triangle-loop
corrections when heavy chiral fermions float inside the loops. The $\lambda''_{ijk}$-induced vertex corrections involve new triangle diagrams contributing to $\Gamma_1$ with $Z, l^+$ and $l^-$ as external lines where $i = \text{lepton}$, $j = \text{quark}$, $k = \text{squark}$ indices or $i = \text{lepton}$, $j = \text{squark}$, $k = \text{quark}$ indices. Such couplings also add corrections to $\Gamma_{\text{had}}$ through triangle diagrams where the external lines are $Z, q, \bar{q}$ in a situation where, for example, $i = \text{lepton}$, $j = \text{quark}$ (squark) and $k = \text{quark}$ (squark). Since the heaviness of the chiral fermion in the loop is the crucial factor in determining the size of the new contributions, only $\lambda''_{ijk}$-type couplings involving internal top quark lines are constrained significantly by such processes [7]. Similarly, the $\lambda''$-induced corrections to the decay vertices $Z \to q\bar{q}$ also add sizable corrections to the hadronic partial widths [8]. Consequently, for $\tilde{m} = 100$ GeV and at 1σ, the following bounds emerge ($R_l = \Gamma_{\text{had}}/\Gamma_l$)^2.

\[
\begin{align*}
\lambda''_{13k} & \leq 0.51 \leftarrow R^\text{exp}_{\mu} = 20.850 \pm 0.067, \\
\lambda''_{23k} & \leq 0.44 \leftarrow R^\text{exp}_{\mu} = 20.824 \pm 0.059, \\
\lambda''_{33k} & \leq 0.26 \leftarrow R^\text{exp}_{\mu} = 20.749 \pm 0.070, \\
\lambda''_{33k} & \leq 0.97 \leftarrow R^\text{exp}_{\mu} = 20.795 \pm 0.040.
\end{align*}
\]

^2While extracting limits on $\lambda''$, leptonic universality in $R_l$ is assumed since $\lambda''$-Yukawa’s do not involve any leptonic flavour.

The above experimental input are collected from the LEP Electro weak Working Group report [13].

4. DIRECT SEARCHES AT COLLIDERS

4.1. LEP1

In the $R$-parity-violating scenario, the LSP is unstable. The OPAL Collaboration at LEP [21] have assumed the photinos to be the LSP’s decaying via a $\lambda_{123}$-type coupling. They excluded at 95% C.L. $m_\tilde{\gamma} = 4–43$ GeV for $m_{\tilde{e}_L} < 42$ GeV, and $m_\tilde{\gamma} = 7–30$ GeV for $m_{\tilde{\tau}_L} < 100$ GeV.

The ALEPH Collaboration at LEP [22], dealing with a more general $\lambda$-type coupling and considering a general LSP rather than a pure photino, have updated the above exclusion zone and have also reported their negative results on other supersymmetric particles up to their kinematic limit ($< M_Z/2$).

A lighter photino ($\sim 2–3$ GeV) in conjunction with a $R$-parity-violating coupling provides a new semileptonic $B$-decay mode ($b \to c\ell\bar{\nu}$). Arranging such that the photino does not decay within the detector, the above channel adds incoherently to the standard semileptonic decay mode. However, the new mode, owing to the massive nature of the photino, arranges a different kinematic configuration compared to the standard channel where neutrino carries the missing energy. A kinematic exploration of the above has been car-
ried out in the context of LEP and CLEO \cite{22}.

4.2. LEP2

The $\tau$-number-violating operators were studied in the context of LEP2 in ref. \cite{3}. Like-sign di-tau events accompanied by jets without any missing $E_T$ were predicted as the most spectacular signals of such interactions.

Indirect effects of $R$-parity-violating couplings through deviations in the angular distributions of $e^+e^- \rightarrow f \bar{f}$ due to the induced sfermion-exchanged diagrams have been studied \cite{22} at LEP2 energies.

4.3. Fermilab Tevatron

The impact of the $\lambda'$-type couplings in $t$-quark decay at the Tevatron have been analysed in ref. \cite{15}. One of the consequences is the following: In the SM, the dominant decay mode is $t \rightarrow bW$. The $\lambda'_{3jk}$-type couplings will induce $t_L \rightarrow \tilde{l}^\dagger_R d_R$ (if kinematically allowed), followed by $\tilde{l}^\dagger_R \rightarrow t^+\tilde{\chi}^0$ (100\%) and $\tilde{\chi}^0 \rightarrow (\nu_i + b + d_k, \bar{\nu}_i + \bar{b} + \bar{d}_k)$ leading to final states with at least one $b$-quark, at least one $t$-quark and missing $E_T$. The characteristic features of this decay channel are that it spoils the lepton universality and for $k = 3$ produces additional $b$-quark events.

Strategies of setting squark and gluino mass limits from multilepton final states in the absence of $R$-parity-conservation have been discussed in ref. \cite{22}.

5. ALEPH 4-JET ANOMALY

On the basis of the LEP 1.5 run at $\sqrt{s} = 130 - 136$ GeV, the ALEPH Collaboration have reported \cite{27} an excess number of events in $e^+e^- \rightarrow$ 4 jets channel. They observed 16 events where the SM predicts 8.6. The excess 9 events have a 4-jet invariant mass $\Sigma M = 105$ GeV. There have been a few attempts to explain this anomaly by invoking the $R$-parity-violating couplings:

1. Refs.\cite{28,29} consider the pair production of sfermions by gauge interactions and their subsequent decays by $L$-violating (sneutrino decays \cite{28})- or $B$-violating (squark decays \cite{29})- couplings to quarks. Thus, although, notionally these lead to 4-jet final states, owing to small sfermion production cross section, enough number of events do not survive after the imposition of the ALEPH cuts.

2. Ref.\cite{30} considers, as the most optimistic option, the pair production of charginos ($e^+e^- \rightarrow \tilde{\chi}^+\tilde{\chi}^-$), followed by $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0_1 (LSP) + W^{\pm}$, and finally the $\lambda''$-induced decay $\tilde{\chi}^0_1 \rightarrow u_d d_k$ (and similar combinations) via virtual sfermion states. If the off-shell $W^*$'s decay hadronically, then there are 10 jets in the final states, which are required to merge into 4 somewhat fat jets. This has been claimed as a viable option. In the case of leptonic decay of one $W^*$, the final state leptons can escape detection by lying within the jets and after jet-merging a few 4-jet events still survive.

3. Ref.\cite{31} interprets the observed excess in 4-jet events as $e^+e^- \rightarrow \tilde{\chi}^+\tilde{\chi}^- \rightarrow d_j d_k \bar{d}_j \bar{d}_k \tau^+\tau^-$, where the chargino decays are induced by $\lambda'_{3jk}$-couplings. Thus, the final states contain 4 jets and 2 soft $\tau$'s which are experimentally reconstructed as 4 jets.

4. Ref.\cite{32} considers the pair production of charginos and finds the best solution to be $\tilde{\chi}^0_1 \rightarrow \tilde{t}_1 b \rightarrow dsb$ (the $\tilde{t}_1$ decay is induced by $\lambda''$), with the extremely soft $b$ evading detection as a result of the kinematic choice: $m_{\tilde{\chi}_1} \simeq 60$ GeV and $m_{\tilde{t}_1} \simeq 52$ GeV.

The main message that can be read from the above analyses is that the pair production cross section of charginos are significantly higher than those of the sfermions (and also higher than neutralino pair production cross section) and, therefore, even after paying the price of losing events while imposing the kinematic cuts during cascades following the decays of the charginos, required number of events still manage to survive resembling the 4-jet excess. But, most importantly, before speculating further, one should wait and see whether these anomalous events stand the test of time!!

\textsuperscript{3}Light photino with $R$-parity-violation has been employed \cite{24} to resolve the KARMEN anomaly.
6. CONCLUSION

In this talk, I have reviewed the existing bounds on the $R$-parity-violating couplings from low energy data and from LEP1 data. While the low energy data tend to constrain more the couplings involving the lighter generations, the LEP data are rather sensitive to couplings involving the third generation. The implications of $R$-parity-violation on direct searches at colliders are also mentioned. The excess 4-jet events at the LEP 1.5 run reported by the ALEPH Collaboration could find a natural explanation in the $R$-parity-violating atmosphere.

The effects of $R$-parity-violation in the context of GUT were discussed by F. Vissani and the RG-evolutions of those couplings with an emphasis on the fixed point solutions were discussed by V. Barger in this Conference.

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