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D- and τ-Decays: Placing New Bounds on R-Parity–Violating Supersymmetric Couplings

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ABSTRACT

D- and τ-decays are used to place bounds on some R-parity–violating λ'-type Yukawa interactions. Some of these bounds are competitive with the existing ones, some are improved while some are new.

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Of the ideas that take us beyond the standard model (SM), supersymmetry is perhaps the most extensively discussed. As the name suggests, the Minimal Supersymmetric Standard Model (MSSM) is obtained by the naive supersymmetrization of both the SM particle content and the couplings [1]. Furthermore, an additional Higgs supermultiplet has to be included both for anomaly cancellation as well as for fermion mass generation. A new feature arises at this juncture. Since the $SU(2)$-doublet lepton superfields have the same gauge quantum numbers as one of the higgs supermultiplets, the latter can be replaced by the former in any or all of the Yukawa interaction terms. One may also write trilinear terms involving the $SU(2)$–singlet quark supermultiplets. The additional pieces in the superpotential may thus be parametrized as [2]

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \ , \tag{1}$$

where L_i and Q_i are the $SU(2)$-doublet lepton and quark superfields and E_i^c, U_i^c, D_i^c are the singlet superfields. Clearly λ_{ijk} is antisymmetric under the interchange of the first two indices, while λ''_{ijk} is antisymmetric under the interchange of the last two.

It is obvious that the presence of such terms can alter phenomenology to a great degree. For example, while the first two terms in eq.(1) violate lepton number, the last one violates baryon number. The simultaneous presence of both sets can, therefore, lead to a catastrophically high rate for proton decay. This and other such issues have provoked the introduction of a discrete symmetry known as "matter parity" or equivalently, "R–parity". Representable as $R = (-1)^{3B+L+2S}$, where B, L, S are the baryon number, lepton number and the intrinsic spin of the field respectively, R has a value of $+1$ for all SM particles and -1 for all their superpartners. This symmetry rules out each of the terms in eq.(1), with the additional consequence that the lightest superpartner (LSP) must be stable.

While an exact R-parity is a sufficient condition for the suppression of certain unobserved processes, the theoretical motivation for such a symmetry is not clear. This makes the question of establishing phenomenological bounds on R-violating couplings an interesting one. This issue is of paramount importance in the context of the search for supersymmetric particles in the forthcoming colliders. Even a tiny R-parity–violating ($\not R_p$) coupling can totally change the expected signatures.

The constraints imposed by the non–observance of proton decay can be circumvented by assuming that all of λ''_{ijk} are zero. Such a scenario might be motivated within certain theoretical frameworks [3], and we implicitly assume the same in the rest of this note. This assumption also renders simpler the problem of preservation of GUT–scale baryogenesis [4]. Although the presence of the other $\not R_p$ terms can also affect the baryon asymmetry of the universe, Dreiner and Ross [5] have argued that such bounds are highly model-dependent and can hence be evaded. For example, in cases where at least one L-violating coupling involving a particular lepton family is small enough ($\lesssim 10^{-7}$) so as to (almost) conserve the corresponding lepton flavour over cosmological time scales, such bounds are no longer effective.

In what follows, we focus our attention only on the λ'-type L-violating Yukawa interactions. Bounds on individual λ'-type couplings have been derived from limits on the Majorana mass of ν_e, by demanding charge–current universality in various decays and also from analyses of atomic parity violation, forward–backward asymmetry in e^+e^- collisions, deep inelastic scattering *etc.* A comprehensive study can be found in refs.[6]. However, while many of the λ'-type couplings are constrained to be $\lesssim 0.1$ for a common sfermion mass ($\tilde{m}$) of 100 GeV, the existing low–energy bounds on some of them are still relatively weak. Additionally, LEP data on the $Zl\bar{l}$ couplings have been used to derive some bounds on λ'_{i3k} (~ 0.5 for $\tilde{m} = 100$ GeV) [7].

As far as λ'_{i2k} are concerned, constraints exist for only some of them and these are not very stringent either. Derived mainly from three classes of experiments : (i) ν_μ-induced deep inelastic scattering, (ii) forward–backward asymmetry in e^+e^- collisions and (iii) atomic parity violation and eD asymmetry, the bounds range between 0.22–0.45 (for $\tilde{m} = 100$ GeV) at the 1σ level. It has been suggested in ref.[8] though that the presence of λ'_{1jk} would induce, at the one–loop level, a Majorana mass for ν_e. The upper bound on the latter could then be used to place stringent limits on λ'_{1jk} (and similarly on λ_{1jk} too). Such arguments, if correct, would also hold, to a lesser extent, for λ_{2jk} and λ'_{2jk} as well. However, a look at the Lagrangian in eqns.(1,2), shows that this constraint is applicable *only* for $j = k$, and *not* for the general case as suggested in ref.[8]. The only relevant bound from ν_e mass on λ'_{i2k} is then that on λ'_{122} which is now constrained to be $\lesssim 0.04$ (at 1σ) for $\tilde{m} = 100$ GeV. Bounds on λ'_{31k} and λ'_{32k} are, as yet, non-existent.

In this short note we attempt to improve the above situation. On the one hand, experimental data on the observed decays of D-mesons are utilized to place bounds on λ'_{i2k}, on the other, τ-decays are used to constrain λ'_{31k}. While some of these are new too, the others are at least comparable to those existing in the literature, and, in most cases, supplant them.

To keep the discussion simple, we shall confine ourselves to semi-leptonic decays, and there too to final states containing only a single meson. From eq.(1), the relevant part of the Lagrangian can be written (in terms of the component fields) as

$$\begin{aligned}\mathcal{L}_{\lambda'} \;=\; \lambda'_{ijk}\Big[&\overline{d_{kR}}\nu_{iL}\tilde{d}_{jL} + \overline{d_{kR}}d_{jL}\tilde{\nu}_{iL} + \overline{(\nu_{iL})^c}d_{jL}\tilde{d}^*_{kR} \\ &-\overline{d_{kR}}e_{iL}\tilde{u}_{jL} - \overline{d_{kR}}u_{jL}\tilde{e}_{iL} - \overline{(e_{iL})^c}u_{jL}\tilde{d}^*_{kR}\Big] + \text{h.c.}\end{aligned} \tag{2}$$

As is evident, the above $R\!\!\!/_p$ couplings manifest themselves only when the two non–spectator quarks form an $SU(2)_L$ doublet. As an explicit example, we discuss the particular decay D^+ $(c\bar{d}) \to \bar{K}^0(s\bar{d})$ $\mu^+\nu_\mu$. The presence of the above interaction introduces an additional quark level diagram (involving the exchange of a squark, say $\tilde{b}_R$ as a particular case) having the current structure

$$\frac{\lambda'^2_{223}}{m^2_{\tilde{b}_R}}\,\overline{(\mu_L)^c}c_L\;\;\overline{s_L}(\nu_{\mu L})^c\,. \tag{3}$$

A Fierz reordering in eq.(3) takes it back to the SM current structure and, adding the two contributions, the effective current looks like

$$\frac{1}{8}\left[\frac{g^2}{m_W^2}V_{cs}+\frac{\lambda'^2_{223}}{m^2_{\tilde{b}_R}}\right]\ \overline{\nu_\mu}\gamma_\rho(1-\gamma_5)\mu\ \ \bar{s}\gamma^\rho(1-\gamma_5)c\ . \tag{4}$$

It is easy to see that at the quark level, all the decays (whether of mesons or of the τ) meeting the above-mentioned criteria can be described by an effective four–fermion interaction similar to that in eq.(4). There now remains to calculate the branching fractions and compare these to the experimental results. However, there exists a small complication in the case of D-decays. The hadronic matrix elements involved in these decays can be parametrized in terms of a few form factors (two for $D \to Kl\nu$ and four for $D \to K^* l\nu$). Although these may be calculated to some degree of accuracy in various models [9], the theoretical errors involved are still somewhat large. The straightforward approach of using each decay channel separately should thus be avoided till these form factors are known better, say from calculations on the lattice [10]. A better method, in this case, is to compare the partial widths into electron and muon channel respectively (keeping the mesons the same). Since the lepton masses are negligible compared to the scale of the problem, we may safely ignore the q^2–evolution of the form factors. These no longer appear in the ratio of the experimental widths which thus gives a direct bound on the relative deviation due to the $\not{R}_p$ interaction. Although the process of combining observables involves compounding different experimental errors, this is more than offset by the deliverance from the theoretical uncertainties. One should also bear in mind the possibility that the sizes of the $\not{R}_p$ couplings in the electronic and the muonic sector are similar and hence the effects might cancel each other. However, the data on FCNC processes already constrain the products of different couplings to be very small. We shall then work under the (reasonable) assumption that at most one of these couplings is non–zero. For τ-decays, no such considerations are necessary. As the pion decay constant f_π is relatively well-measured, we may compare the theoretical expression for the decay $\tau \to \pi\nu_\tau$ with the experimentally determined partial width to obtain our bounds on λ'_{31k}.

For the numerical computation we use the following experimental inputs [11]

$$\begin{aligned}
a)&\quad \frac{Br(D^+\to \bar{K}^0\mu^+\nu_\mu)}{Br(D^+\to \bar{K}^0 e^+\nu_e)} &=&\ 1.06^{+0.48}_{-0.34}\ ;\\
b)&\quad \frac{Br(D^+\to \bar{K}^{0*}\mu^+\nu_\mu)}{Br(D^+\to \bar{K}^{0*} e^+\nu_e)} &=&\ 0.94\pm 0.16\ ;\\
c)&\quad \frac{Br(D^0\to K^-\mu^+\nu_\mu)}{Br(D^+\to K^- e^+\nu_e)} &=&\ 0.84\pm 0.12\ ;
\end{aligned} \tag{5}$$

and

$$d)\quad Br(\tau^-\to\pi^-\nu_\tau)=0.117\pm0.004,\qquad f_\pi=(130.7\pm0.1\pm0.36)\ \mathrm{MeV}. \tag{6}$$

The constraints that we derive are summarized in Table 1. The bounds on λ'_{121} and λ'_{123} are already quite competitive[1] with the ones existing in the literature. These are going to improve even further once the D-branching fractions are known to a better accuracy. On the other hand, for λ'_{221}, our numbers are already better than the existing constraints. On the five couplings, $\lambda'_{222}, \lambda'_{223}$ and all λ'_{31k}, our method places phenomenological bounds for the first time.

$\{ijk\}$	Existing bounds	Our bounds	
		(1σ)	(2σ)
121, 123	0.26 (1σ)	$0.30^{a)}$, $0.28^{b)}$, $0.31^{c)}$	$0.45^{a)}$, $0.36^{b)}$, $0.38^{c)}$
221 222, 223	0.22 (2σ)	$0.42^{a)}$, $0.18^{b)}$ $0.42^{a)}$, $0.18^{b)}$	$0.58^{a)}$, $0.30^{b)}$, $0.17^{c)}$ $0.58^{a)}$, $0.30^{b)}$, $0.17^{c)}$
$31k$		$0.14^{d)}$	$0.18^{d)}$

Table 1: The upper bounds on the λ'–type $\not{R}_p$ couplings (for $\tilde{m} = 100$ GeV) obtained from our analyses of D- and τ-decays. The specific processes are labelled by the superscripts, a) to d), exactly as they correspond to the experimental inputs shown in eqs.(5–6). At the 1σ level, there are no bounds on λ'_{22k} from process (c). The existing bounds are quoted from ref.[6].

To summarise, we use the data on D- and τ-decays to constrain some of the λ'-type $\not{R}_p$ couplings within the MSSM. D-decays constrain λ'_{12k} and λ'_{22k}, while τ-decay constrains λ'_{31k}. Bounds obtained on λ'_{121} and λ'_{123} are *at par* with the existing ones, while those obtained on λ'_{221} are already *better*. Further improvements can be expected from two sources : (i) an increase in the experimental accuracies, and/or (ii) a better determination of form factors involved in D-decays enabling us to use each decay channel as an independent input rather than use only their ratios. The most significant constraints that we have derived are those on λ'_{222}, λ'_{223} and λ'_{31k}. All of these bounds are *new* from the phenomenological standpoint. With this analysis, only one set of lepton–number violating $\not{R}_p$ couplings, namely λ'_{32k} remains relatively unconstrained. This gap would, most likely, be difficult to fill from low–energy experiments, with rare D-decays perhaps being the best hope!

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[1] We also obtain similar numbers for λ'_{122}, but the latter is already constrained tightly from the upper bound on ν_e Majorana mass.

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