Constraints on R-parity violating supersymmetry from leptonic and semileptonic τ, B_d and B_s decays

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Abstract

We put constraints on several products of R-parity violating $\lambda\lambda'$ and $\lambda'\lambda'$ type couplings from leptonic and semileptonic τ, B_d and B_s decays. Most of them are one to two orders of magnitude better than the existing bounds, and almost free from theoretical uncertainties. A significant improvement of these bounds can be made in high luminosity tau-charm or B factories.

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1. Introduction

We live in a time when Standard Model (SM) has been vindicated in a number of experiments and at the same time has left us with a feeling that it is incomplete, which makes the search for physics beyond SM a holy grail for most of the particle physics community. We have absolutely no idea what the manifestation of the new physics will be; this forces us to consider all sorts of theoretically motivated new physics options. Since one does not have any experimental signal that definitely points to new physics, the best one can do is to constrain the parameter space of the new physics models. These constraints come mostly from experimental data (including astrophysical ones) but sometimes from theoretical considerations too [1].

As long as one does not produce the new particles directly, one has to look for their indirect effects in low-energy observables. All low-energy data are more or less consistent with the SM, taking into account the experimental and theoretical errors and uncertainties. Thus, one can look at those observables which may be explained by SM; the trick is to maximize the width of the window for new physics and put constraints on the parameter space of such models. Alternatively, one can look at those observables which are absolutely forbidden or highly suppressed in SM so that one does not expect any signal; here even one event will signal new physics and in the absence of any event, the parameter space for new physics may be constrained from the experimental upper bounds.

Among the new physics options that people consider, supersymmetry (SUSY), with all its variants, is the most popular one [1]. In the minimal and some non-minimal versions of SUSY, the action is so taken as to conserve the R quantum number defined as $R = (-1)^{3B+L+2S}$, where B, L and S stand for baryon number, lepton number and spin of the field respectively. This ensures $R = +1$ for all particles and $R = -1$ for all superparticles, and conservation of R imply that superparticles must occur in pair in all allowed Feynman vertices. However, R-parity is a discrete symmetry imposed by hand (to make the parameter space of the model more restricted and tractable) and one can write a R-parity violating superpotential of the form

$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c \tag{1}$$

which does not violate any gauge symmetry. The factors of $1/2$ take care of the fact that λ and λ'' couplings are antisymmetric in its first two indices. Such R-parity violating terms can be motivated from some of the grand unified theories [2]. In eq. (1) L, Q, U, D and E denote, respectively, $SU(2)_L$ doublet lepton and quark superfields, and $SU(2)_L$ singlet up, down and charged lepton superfields, and i, j, k are generation indices. Of course, B and L are both violated, and to forbid proton decay, one has to keep either L-violating λ and λ' terms or B-violating λ'' terms, but not both. There is also a bilinear R-parity violating term of the form $\epsilon_i L_i H_2$, which has a lot of interesting phenomenology [3], including possible leptonic flavor violation [4], but we will not consider that term in the present paper.

With 45 new couplings (and all of them can theoretically be complex) the phenomenology is immensely richer, but at the same time less predictive. There is, however, one major point to be noted: R-conserving SUSY can affect low-energy observables through loop effects and hence can hardly compete with SM effects (except in some of the cases where the SM process itself is loop-induced or, even better, forbidden); R-parity violating (RPV) SUSY, on the other hand, can show up in tree-level slepton or squark mediated processes which can successfully compete

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[1]For example, from the consideration of the stability of the scalar potential.

with the SM. This also ensures that for comparable coupling strength, RPV SUSY amplitudes are generally orders of magnitude higher than the R-conserving SUSY amplitudes.

The individual RPV couplings have been constrained from various low-energy processes [5], and upper limits on some of the product couplings, including their phases, have also been found [6, 7, 8, 9, 10, 11]. Often one finds that the product coupling is much more constrained than the direct product of the upper bounds of the individual couplings [2].

In this paper we find the upper limits on the products of some of the L-violating λ and λ' type couplings coming from rare τ, B_d and B_s decays. The leptonic flavour violating processes are forbidden in the SM, and the only contributing amplitude comes from RPV SUSY. The expected branching ratios (BR) of leptonic flavour conserving $\Delta B = 1$ processes within SM are so much below the experimental numbers (except $B \to K^{(*)}\ell^+\ell^-$) that one can safely ignore the SM effects, as well as the R-conserving SUSY effects, to put bounds on the RPV couplings. Most of these decay modes are also theoretically clean and free from any hadronic uncertainties which plague nonleptonic decays. (The exception is again the semileptonic process $B \to K^{(*)}\ell^+\ell^-$.)

There are three major sources of uncertainty, however. First, the decay constants of the neutral mesons, particularly that of η, B_d and B_s, are yet to be cleanly determined. Fortunately, the bounds where these decay constants are relevant just scale with their values; this will be discussed in the appropriate section. Second, the $B \to K/\pi$ formfactors allow a slight theoretical uncertainty. We use the BSW formfactors with oscillator parameter $\omega = 0.5$ GeV [12]. Lastly, the current masses of the light quarks cause the maximum uncertainty in $\lambda\lambda'$ type couplings; again, the bounds scale with the quark masses. The individual bounds in most of the cases are fairly weak and the bounds on the product couplings that we find are sometimes one to two orders of magnitude better than the existing ones. Some of these product couplings have been considered earlier [7, 8]; these we update with better experimental numbers. These updated numbers, too, are vastly improved. We have not discussed leptonic and semileptonic D^0 decays since the bounds are much weaker than those which one gets from $\mu \to e$ conversion [6]. This in turn implies that such decay signals of D^0, if observed in present and upcoming colliders, imply some new physics but not RPV SUSY.

When we say that these bounds are robust, we of course not only mean to alleviate the theoretical uncertainties of the SM. The fact that leptonic flavour-changing processes are absolutely forbidden in the SM imply that these bounds stand no matter what the phases of these RPV couplings may be. The same is true for all purely leptonic B decays, but not if there are competing SM amplitudes (as in $B \to K\ell^+\ell^-$), even if one takes the lowest possible SM number and saturates the experimental data by RPV contribution, which is the standard practice. The reason is simple: the two amplitudes are coherent and the bounds depend on the phase of the RPV couplings, while the standard prescription is true for incoherent amplitudes only. This we show explicitly for the $B \to K\ell^+\ell^-$ decays. One should note here that the most conservative bounds, not necessarily the true ones, come from such incoherent amplitude summation.

There is another point that we like to emphasize. Though it is true that observation of the SM-forbidden decays would be a definite signal of new physics, to show convincingly that it is RPV SUSY one needs to find some correlated signals (*e.g.*, enhancement of BRs) in different decay channels. We briefly discuss how this can be done for explicit RPV models (spontaneous RPV models have been discussed in [13], including bounds coming from mesonic and leptonic flavor violating decays). If one finds such correlated signals, it will be an almost definite RPV signal,

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[2]Constraints coming from Δm_K, Δm_B, $\mu \to 3e$, $\mu \to e$ conversion, etc. fall in this category.

without the direct observation of superparticles. Such signals occur from the fact that same four-Fermi operators lead to different final states. Among leptonic and semileptonic B decays, one may mention the correlated channels (i) $B_d \to e\mu$ and $B_d \to \pi e\mu$; (ii) $B_s \to \ell_i^+ \ell_j^-$ and $B_d \to K\ell_i^+ \ell_j^-$. More correlated channels are to be found in nonleptonic B decays, which will be discussed in a future paper [14]. In the absence of any correlated decay channel, the next best thing is to observe the decay distribution of the final state particles, since RPV SUSY has a different Lorentz structure from that of the SM. One may, for example, study the angular distribution of final state leptons in $B \to K\ell^+ \ell^-$ decays — the crucial fact is that tree-level RPV has a Lorentz structure of the form $(V - A) \otimes (V + A)$. We do not go into any detailed discussion of this issue in the present work.

We consider only nonzero L-violating λ and λ' type couplings. Though it is true that leptonic τ decays can be mediated by λ type couplings alone, the individual bounds on these couplings are much tighter than one may hope to get from such decays. Thus, $\tau \to 3$ lepton (there can be six different combinations) processes give a fairly weak bound ($\sim \mathcal{O}(1)$) on the relevant λ-type couplings. We do not consider such processes further; if they are observed in near future, their explanation must lie somewhere else. It is obvious that λ'' type couplings cannot mediate leptonic and semileptonic decays.

To construct four-Fermi operators from λ and λ' type couplings that mediate such semileptonic and leptonic τ and B decays, one needs to integrate out the squark or the slepton propagator. Both the couplings coming in the product may be complex; one is free to absorb the phase of one coupling in the sfermion propagator but the other remains, making the overall coupling responsible for the process a complex one in general. However, since all these processes are one-amplitude (there is no SM counterpart) no scope of CP-violation exists; one only observes the nonzero branching ratios. By the same argument, we can take all couplings to be real without any loss of generality. The only exception to this statement, *viz.* $B \to K^{(*)}\ell^+ \ell^-$, will be dealt in proper place.

The paper is arranged as follows. In the next section, we discuss the formalism for, and the bounds coming from, semileptonic τ decays. Section 3 discusses leptonic B_d and B_s decays, while section 4 is on semileptonic decays of these mesons. We summarize and conclude in section 5.

2. τ decays

All the processes that we consider involve terms in the RPV Hamiltonian with two leptons and two quarks as external fields. The Hamiltonian can be written as

$$
\begin{aligned}
\mathcal{H}_{\not{R}} &= -A_{jklm}(\overline{\ell_j}(1 + \gamma_5)\ell_k)(\overline{d_m}(1 - \gamma_5)d_l) + \frac{1}{2}B_{jklm}(\overline{\ell_j}\gamma^\mu(1 - \gamma_5)\ell_l)(\overline{d_m}\gamma_\mu(1 + \gamma_5)d_k) \\
&\quad -\frac{1}{2}C_{jklm}(\overline{\ell_j}\gamma^\mu(1 - \gamma_5)\ell_l)(\overline{u_k}\gamma_\mu(1 + \gamma_5)u_m) + h.c.
\end{aligned}
\tag{2}
$$

where

$$
A_{jklm} = \sum_{i=1}^{3} \frac{\lambda_{ijk}^* \lambda_{ilm}'}{4m_{\tilde{\nu}_i^2}}; \quad B_{jklm} = \sum_{i=1}^{3} \frac{\lambda_{jik}'^* \lambda_{lim}'}{4m_{\tilde{u}_{L_i}^2}}; \quad C_{jklm} = \sum_{i=1}^{3} \frac{\lambda_{jki}'^* \lambda_{lmi}'}{4m_{\tilde{d}_{R_i}^2}}.
\tag{3}
$$

To put bounds, we will assume only one of the A, B or C terms to be nonzero so that there is no interference effect between different RPV couplings. We will also take only one sfermion generation index i to be nonzero at a time.

Note that if the final state consists of two down-type quarks, both A and B terms may contribute, whereas for two up-type quarks, only the C term comes. For mesons like π^0, ρ^0 or η in the final state, all the three terms may be important.

One thing that we do not consider is the running of the RPV couplings between the sfermion scale and the low-energy scale. The corrections are electroweak in origin and can be safely neglected. The only QCD correction may occur between the two quark fields; for τ decays, this pair hadronizes, absorbing all such uncertainties in the decay constant. The same is true for leptonic B or D decays. For semileptonic meson decays the formfactors are supposed to take care of these short-distance corrections. However, this effect is important when we have four quarks as external fields and may contribute a multiplicative factor of ~ 2 to the effective Hamiltonian [15].

The generic process $\tau \to \ell + M$ is lepton-flavour violating and does not occur in the SM. Strong experimental upper limits exist on at least fourteen modes that we consider here: $\ell = e, \mu$ and $M = \pi, \rho, \eta, K^0, K^{0*}, \overline{K^{0*}}, \phi$. Such modes are fairly clean from a theoretical point of view. In RPV SUSY, all such processes can occur with squark or sneutrino propagator mediating the decay. Since the squark is very heavy, we do not consider any QCD effect that may take place between the squark and the final state quarks.

The only uncertainty, albeit small, appears in the decay constants of the neutral mesons. Our values for the decay constants are (in GeV) [16]:

$$f_\pi = 0.132, \ f_\rho = 0.216, \ f_K = 0.161, \ f_{K^*} = 0.214, \ f_\phi = 0.237. \tag{4}$$

The decay constants for η (and η') are obtained from the decay constants of the octet and singlet mesons $f_8 = 1.34 f_\pi$ and $f_1 = 1.10 f_\pi$ by a rotation:

$$
\begin{aligned}
f_\eta^u &= f_\eta^d = f_8 \cos\theta/\sqrt{6} - f_1 \sin\theta/\sqrt{3}, \\
f_\eta^s &= -2 f_8 \cos\theta/\sqrt{6} - f_1 \sin\theta/\sqrt{3}, \\
f_{\eta'}^u &= f_8 \sin\theta/\sqrt{6} + f_1 \cos\theta/\sqrt{3}, \\
f_{\eta'}^s &= -2 f_8 \sin\theta/\sqrt{6} + f_1 \cos\theta/\sqrt{3},
\end{aligned}
\tag{5}
$$

where the angle θ is estimated to be about $-22°$. The current quark masses are taken to be $m_d = 10$ MeV and $m_s = 200$ MeV.

Following the standard practice, we assume only one product of RPV coupling to be nonzero at a time. This eliminates the need to consider their phases and signs; without any loss of generality, we can assume all products to be real and positive since only the square of the absolute magnitude of the product enters in the expression for the decay width. If the final state quarks are of charge $-1/3$, the mediating squark must be a 'left-handed' up-type one, and if the quarks of charge $+2/3$, the mediating squark is a 'right-handed' down-type one. Note that if two or more products are simultaneously nonzero, there can in principle be an interference effect for $M = \pi, \rho$ and η, and it becomes imperative to consider the signs and the phases of the product couplings. We neglect this complexity.

The experimental 90% CL upper limits on the BRs of various τ decay modes are taken from [17]:

$$
\begin{array}{ll}
Br(\tau \to e\pi) < 3.7 \times 10^{-6} & Br(\tau \to \mu\pi) < 4.0 \times 10^{-6} \\
Br(\tau \to e\eta) < 8.2 \times 10^{-6} & Br(\tau \to \mu\eta) < 9.6 \times 10^{-6} \\
Br(\tau \to eK^0) < 1.3 \times 10^{-3} & Br(\tau \to \mu K^0) < 1.0 \times 10^{-3}
\end{array}
$$

$$Br(\tau \to e\rho) < 2.0 \times 10^{-6} \qquad Br(\tau \to \mu\rho) < 6.3 \times 10^{-6}$$
$$Br(\tau \to e\phi) < 6.9 \times 10^{-6} \qquad Br(\tau \to \mu\phi) < 7.0 \times 10^{-6}$$
$$Br(\tau \to eK^{*0}) < 5.1 \times 10^{-6} \qquad Br(\tau \to \mu K^{*0}) < 7.5 \times 10^{-6}$$
$$Br(\tau \to e\overline{K^{*0}}) < 7.4 \times 10^{-6} \qquad Br(\tau \to \mu\overline{K^{*0}}) < 7.5 \times 10^{-6}. \tag{6}$$

The nonzero $\lambda\lambda'$ type couplings can mediate only $\tau \to \ell + P$ type decays where P is a generic pseudoscalar meson. That the production of vector mesons is forbidden is evident from the Lorentz structure of the corresponding four-fermi hamiltonian. The decay width can be written as

$$\Gamma(\tau \to \ell_i + P[\equiv \overline{q_j}q_k]) = \frac{(m_\tau^2 + m_{\ell_i}^2 - m_P^2)C(m_\tau, m_{\ell_i}, m_P)F_P}{128\pi m_\tau^3 \tilde{m}^4}|\lambda_{ni3}\lambda'_{njk}|^2 \tag{7}$$

where

$$C(m_1, m_2, m_3) = \sqrt{m_1^4 + m_2^4 + m_3^4 - 2m_1^2 m_2^2 - 2m_1^2 m_3^2 - 2m_2^2 m_3^2}, \tag{8}$$

$$F_P = \frac{m_P^4 f_P^2}{(m_{q_j} + m_{q_k})^2}, \tag{9}$$

and $\tilde{m}$ denote the slepton mass. Note that due to our definition of the decay constants, the above expression is to be multiplied by a factor of $1/2$ only if there is a π^0 in the final state. The combination $\lambda_{ni3}\lambda'_{njk}$ can be replaced by $\lambda_{n3i}\lambda'_{nkj}$ which will generate the same decay and hence the same bound applies to both these combinations.

$\lambda\lambda'$	Final state	Bound	Previous bound	$\lambda\lambda'$	Final state	Bound	Previous bound
(123)(111)	$\mu\eta$	5.3×10^{-4}	2.5×10^{-5}	(123)(121)	μK^0	4.1×10^{-2}	1.0×10^{-3}
(123)(122)	$\mu\eta$	1.0×10^{-2}	2.1×10^{-3}	(123)(211)	$e\eta$	4.9×10^{-4}	2.9×10^{-3}
(123)(221)	eK^0	4.7×10^{-2}	8.8×10^{-3}	(123)(222)	$e\eta$	9.3×10^{-3}	1.0×10^{-2}
(131)(111)	$e\eta$	4.9×10^{-4}	3.2×10^{-5}	(131)(112)	eK^0	4.7×10^{-2}	1.3×10^{-3}
(131)(122)	$e\eta$	9.3×10^{-3}	2.7×10^{-3}	(132)(111)	$\mu\eta$	5.3×10^{-4}	3.2×10^{-5}
(132)(112)	μK^0	4.1×10^{-2}	1.3×10^{-3}	(132)(122)	$\mu\eta$	1.0×10^{-2}	2.7×10^{-3}
(133)(311)	$e\eta$	4.9×10^{-4}	6.6×10^{-4}	(133)(321)	eK^0	4.7×10^{-2}	3.1×10^{-3}
(133)(322)	$e\eta$	9.3×10^{-3}	1.3×10^{-3}	(231)(211)	$e\eta$	4.9×10^{-4}	4.1×10^{-3}
(231)(212)	eK^0	4.7×10^{-2}	4.1×10^{-3}	(231)(222)	$e\eta$	9.3×10^{-3}	1.5×10^{-4}
(232)(211)	$\mu\eta$	5.3×10^{-4}	4.1×10^{-3}	(232)(212)	μK^0	4.1×10^{-2}	4.1×10^{-3}
(232)(222)	$\mu\eta$	1.0×10^{-2}	1.5×10^{-2}	(233)(311)	$\mu\eta$	5.3×10^{-4}	7.7×10^{-3}
(233)(321)	μK^0	4.1×10^{-2}	3.6×10^{-2}	(233)(322)	$\mu\eta$	1.0×10^{-2}	3.6×10^{-4}

Table 1: Bounds on $\lambda\lambda'$ type products from $\tau \to \ell + M$ decays.

The bounds are listed in table 1. Note that most of the numbers are at the same order of magnitude as the previous bounds coming from direct product of the individual couplings, though some have been improved[3]. We show only the best numbers; for example, the decay $\tau \to e + \pi^0$ puts a weaker bound on $\lambda_{231}\lambda'_{211}$ than that coming from $\tau \to e + \eta$, and hence is not shown separately. Here, and in all other cases, we take all squarks and sleptons to be degenerate at

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[3] Previous bounds indicate the numbers coming from direct product of individual bounds, or, in certain cases, bounds on the product coming from a different process. The bounds which are updated have not been considered as previous bounds.

100 GeV, and the bounds scale in a simple way: $(m_{\tilde{q},\tilde{\ell}}/100 \text{ GeV})^2$. For squarks of the first two generation this number is not allowed but used just as a benchmark value; for the lighter stop 100 GeV is still allowed, and light sbottom is of current phenomenological interest. Thus, as far as squark-mediated processes are concerned, the more realistic bounds for the first two generation of squarks should be the number quoted in our tables multiplied by a factor of ~ 10.

Though we have relied on published experimental numbers only to obtain the bounds, let us also quote the Belle numbers for the modes $\tau \to eK^0$ and $\tau \to \mu K^0$ [18]:

$$Br(\tau \to eK^0) < 1.8 \times 10^{-6}, \quad Br(\tau \to \mu K^0) < 1.8 \times 10^{-6}. \tag{10}$$

If we use the Belle data, all the eight $\lambda\lambda'$ type products in table 1 where the final state is either eK^0 or μK^0 have upper bounds of 1.7×10^{-3}, which is better or compatible to the previous numbers.

The generic couplings B and C (eq. 1) mediate the decay $\tau \to \ell + M$ where M can be either pseudoscalar or vector. The expression for the decay widths in these two cases are as follows:

$$\Gamma(\tau \to \ell_i + P[\equiv \overline{q_j}q_k]) = \frac{f_P^2 C(m_\tau, m_{\ell_i}, m_P)P_0(m_\tau, m_{\ell_i}, m_P)}{512\pi \tilde{m}^4 m_\tau^3}|\lambda'_{3nk}\lambda'_{inj}|^2$$

$$\Gamma(\tau \to \ell_i + V[\equiv \overline{q_j}q_k]) = \frac{f_V^2 C(m_\tau, m_{\ell_i}, m_V)V_0(m_\tau, m_{\ell_i}, m_V)}{512\pi \tilde{m}^4 m_\tau^3}|\lambda'_{3nk}\lambda'_{inj}|^2 \tag{11}$$

where $C(m_\tau, m_{\ell_i}, m_V)$ is defined in eq. (8) and

$$\begin{aligned}P_0(x,y,z) &= (x^2 - y^2)^2 - z^2(x^2 + y^2)\\ V_0(x,y,z) &= z^2(x^2 + y^2 - z^2) + (x^2 - y^2)^2 - z^4\end{aligned} \tag{12}$$

The combination $\lambda'_{3nk}\lambda'_{inj}$ appears if both q_j and q_k are down-type quarks. In this case the mediating squark is $\tilde{u}_{nL}$. If the final-state quarks are up-type, the combination that appears is $\lambda'_{3jn}\lambda'_{ikn}$, with rest of the formula remaining unchanged. Again, the expressions are to be multiplied by a factor of $1/2$ if one has π^0 or ρ^0 in the final state.

We list only the best bounds coming from these processes in table 2. Note that the best bounds always come from those decays where a vector meson is involved (if we do not consider the Belle data in eq. 10) in the final state; this is solely due to the better limits on the decay modes. Since some of the λ' type couplings have weak individual bounds, most of our bounds on the product couplings are one to two orders of magnitude improvement over the previous bounds.

Consideration of Belle data in eq. (10) shows that the couplings $\lambda'_{1i2}\lambda'_{3i1}$ and $\lambda'_{2i2}\lambda'_{3i1}$ both have upper bounds of 2.3×10^{-3} coming from $\tau \to eK^0$ and $\tau \to \mu K^0$ respectively, all other bounds remaining unchanged.

Let us, at this point, highlight certain features of the analysis:

- Mere observation of a single event in any of the decay modes will signal new physics.

- However, in a dedicated tau-charm factory, one may hope to observe more events in different channels if the RPV couplings are close to their present bounds obtained in tables 1 and 2.

- With only one nonzero $\lambda'\lambda'$ product, one should observe signals in different modes corresponding to the same quark-level subprocess: e.g., $\tau \to e\pi, e\eta, e\rho$ all should show some anomalous behaviour. This is another example of correlated channels and is important to establish the nature of the new physics. If no such signals are observed in the $\tau \to \mu + M$ channels, flavour-specific nature of the new physics will all the more be established.

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$\lambda'\lambda'$	Final state	Bound	Previous bound	$\lambda'\lambda'$	Final state	Bound	Previous bound
(111)(311)	$e\rho$	2.5×10^{-3}	5.7×10^{-5}	(111)(312)	$e\overline{K^{0*}}$	3.5×10^{-3}	5.7×10^{-5}
(112)(311)	eK^{0*}	2.9×10^{-3}	2.3×10^{-3}	(112)(312)	$e\rho$	2.5×10^{-3}	2.3×10^{-3}
(113)(313)	$e\rho$	2.5×10^{-3}	2.3×10^{-3}	(121)(321)	$e\rho$	2.5×10^{-3}	22.4×10^{-3}
(121)(322)	$e\overline{K^{0*}}$	3.5×10^{-3}	22.4×10^{-3}	(122)(321)	eK^{0*}	2.9×10^{-3}	22.4×10^{-3}
(122)(322)	$e\phi$	3.3×10^{-3}	22.4×10^{-3}	(131)(331)	$e\rho$	2.5×10^{-3}	8.6×10^{-3}
(131)(332)	$e\overline{K^{0*}}$	3.5×10^{-3}	8.6×10^{-5}	(132)(331)	eK^{0*}	2.9×10^{-3}	0.126
(132)(332)	$e\phi$	3.3×10^{-3}	0.126	(211)(311)	$\mu\rho$	4.4×10^{-3}	6.5×10^{-3}
(211)(312)	$\mu\overline{K^{0*}}$	3.6×10^{-3}	6.5×10^{-3}	(212)(311)	μK^{0*}	3.6×10^{-3}	6.5×10^{-3}
(212)(312)	$\mu\phi$	3.3×10^{-3}	6.5×10^{-3}	(213)(313)	$\mu\rho$	4.4×10^{-3}	6.5×10^{-3}
(221)(321)	$\mu\rho$	4.4×10^{-3}	93.6×10^{-3}	(221)(322)	$\mu\overline{K^{0*}}$	3.6×10^{-3}	93.6×10^{-3}
(222)(321)	μK^{0*}	3.6×10^{-3}	0.109	(222)(322)	$\mu\phi$	3.3×10^{-3}	0.109
(231)(331)	$\mu\rho$	4.4×10^{-3}	81.0×10^{-3}	(231)(332)	$\mu\overline{K^{0*}}$	3.6×10^{-3}	81.0×10^{-3}
(232)(331)	μK^{0*}	3.6×10^{-3}	0.252	(232)(332)	$\mu\phi$	3.3×10^{-3}	0.252

Table 2: Bounds on $\lambda'\lambda'$ products from $\tau \to \ell + M$ processes. Only the best bounds are shown.

- If signals are observed in the pseudoscalar channels but not in the vector channels, that will probably indicate the presence of a $\lambda\lambda'$ type coupling. If the opposite happens, RPV explanation of new physics will be more difficult to sustain; probably one has to invoke cancellation between different RPV contributions.

- Finally, note that though the individual λ or λ' type couplings are L-violating, the overall four-fermi hamiltonian conserves L (it violates leptonic flavour). Thus, one cannot explain processes like $\tau^- \to \ell^+ M_1^- M_2^-$ with RPV.

3. Leptonic B_d and B_s decays

The leptonic flavour-violating decays $B_{d,s} \to \ell_i^{\pm}\ell_j^{\mp}$ $(i \neq j)$ are forbidden in the SM, and flavour-conserving decays $(i = j)$ are so suppressed (except for $\ell = \tau$ which we do not consider anyway) that we can take them to be almost forbidden to a very good extent. Thus, the entire amplitude, if nonzero, is solely due to new physics. In RPV models, both slepton-mediated $\lambda\lambda'$ type and squark-mediated $\lambda'\lambda'$ type interactions can cause such purely leptonic decays. As already stressed, the bounds are robust in the sense that they are free from any theoretical uncertainties (except for the decay constants of B_d and B_s), and do not depend on the phase of the RPV couplings.

The decay width of $B_{d,s} \to \ell_l^- \ell_m^+$ is given by

$$\Gamma(B_{q_i} \to \ell_l^- \ell_m^+) = \frac{f_{B_{q_i}}^2}{16\pi\tilde{m}^4 M_{B_{q_i}}^3} C(M_{B_{q_i}}, m_{\ell_l}, m_{\ell_m}) P_1(M_{B_{q_i}}, m_{\ell_l}, m_{\ell_m})|\lambda_{nlm}\lambda'_{ni3}|^2 \qquad (13)$$

or

$$\Gamma(B_{q_i} \to \ell_l^+ \ell_m^-) = \frac{f_{B_{q_i}}^2}{256\pi\tilde{m}^4 M_{B_{q_i}}^3} C(M_{B_{q_i}}, m_{\ell_l}, m_{\ell_m}) P_2(M_{B_{q_i}}, m_{\ell_l}, m_{\ell_m})|\lambda'_{lni}\lambda'_{mn3}|^2. \qquad (14)$$

Here P_1 and P_2 are given by

$$\begin{aligned}
P_1(x,y,z) &= x^4 - x^2y^2 - x^2z^2, \\
P_2(x,y,z) &= x^2(y^2+z^2) - (y^2-z^2)^2
\end{aligned} \tag{15}$$

and the C-function is defined in eq. (8). The generic slepton or squark mass is denoted by $\tilde{m}$. Note that the expression $\lambda_{nlm}\lambda'_{ni3}$ can be replaced by $\lambda_{nml}\lambda'_{n3i}$ in eq. (13) and $\lambda'_{lni}\lambda'_{mn3}$ can be replaced by $\lambda'_{ln3}\lambda'_{mni}$ in eq. (14). Since we consider only one combination to be present at a time, the same bound applies to all such combinations.

$\lambda\lambda'$	Process	Bound $(\times 10^5)$	Previous bound	$\lambda\lambda'$	Process	Bound $(\times 10^5)$	Previous bound
(121)(113)	$B_d \to \mu^\pm e^\mp$	2.3	1.0×10^{-3}	(121)(123)	$B_s \to \mu^\pm e^\mp$	4.7	2.1×10^{-3}
(121)(131)	$B_d \to \mu^\pm e^\mp$	2.3	9.3×10^{-4}	(121)(132)	$B_s \to \mu^\pm e^\mp$	4.7	1.4×10^{-2}
(121)(213)	$B_d \to e^+ e^-$	1.7	2.9×10^{-3}	(121)(223)	$B_s \to e^+ e^-$	14	1.0×10^{-3}
(121)(231)	$B_d \to e^+ e^-$	1.7	8.8×10^{-3}	(121)(232)	$B_s \to e^+ e^-$	14	7.3×10^{-3}
(122)(113)	$B_d \to \mu^+ \mu^-$	1.5	5.4×10^{-3}	(122)(123)	$B_s \to \mu^+ \mu^-$	2.7	2.1×10^{-3}
(122)(131)	$B_d \to \mu^+ \mu^-$	1.5	9.3×10^{-4}	(122)(132)	$B_s \to \mu^+ \mu^-$	2.7	1.4×10^{-2}
(122)(213)	$B_d \to \mu^\pm e^\mp$	2.3	2.9×10^{-3}	(122)(223)	$B_s \to \mu^\pm e^\mp$	4.7	1.0×10^{-2}
(122)(231)	$B_d \to \mu^\pm e^\mp$	2.3	8.8×10^{-3}	(122)(232)	$B_s \to \mu^\pm e^\mp$	4.7	2.7×10^{-2}
(123)(113)	$B_d \to \mu^\pm \tau^\mp$	62	1.0×10^{-3}	(123)(131)	$B_d \to \mu^\pm \tau^\mp$	62	9.3×10^{-4}
(123)(213)	$B_d \to e^\pm \tau^\mp$	49	2.9×10^{-3}	(123)(231)	$B_d \to e^\pm \tau^\mp$	49	8.8×10^{-3}
(131)(113)	$B_d \to e^\pm \tau^\mp$	49	1.3×10^{-3}	(131)(131)	$B_d \to e^\pm \tau^\mp$	49	1.1×10^{-3}
(131)(313)	$B_d \to e^+ e^-$	1.7	6.8×10^{-3}	(131)(323)	$B_s \to e^+ e^-$	14	3.2×10^{-3}
(131)(331)	$B_d \to e^+ e^-$	1.7	2.8×10^{-2}	(131)(332)	$B_s \to e^+ e^-$	14	2.8×10^{-2}
(132)(113)	$B_d \to \mu^\pm \tau^\mp$	62	1.3×10^{-3}	(132)(131)	$B_d \to \mu^\pm \tau^\mp$	62	1.2×10^{-3}
(132)(313)	$B_d \to \mu^\pm e^\mp$	2.3	6.8×10^{-3}	(132)(323)	$B_s \to \mu^\pm e^\mp$	4.7	4.3×10^{-3}
(132)(331)	$B_d \to \mu^\pm e^\mp$	2.3	2.8×10^{-2}	(132)(332)	$B_s \to \mu^\pm e^\mp$	4.7	2.8×10^{-2}
(133)(313)	$B_d \to e^\pm \tau^\mp$	49	3.6×10^{-5}	(133)(331)	$B_d \to e^\pm \tau^\mp$	49	2.7×10^{-3}
(231)(213)	$B_d \to e^\pm \tau^\mp$	49	4.1×10^{-3}	(231)(231)	$B_d \to e^\pm \tau^\mp$	49	1.3×10^{-3}
(231)(313)	$B_d \to \mu^\pm e^\mp$	2.3	4.2×10^{-4}	(231)(323)	$B_s \to \mu^\pm e^\mp$	4.7	3.6×10^{-2}
(231)(331)	$B_d \to \mu^\pm e^\mp$	2.3	2.2×10^{-2}	(231)(332)	$B_s \to \mu^\pm e^\mp$	4.7	3.2×10^{-2}
(232)(213)	$B_d \to \mu^\pm \tau^\mp$	62	4.1×10^{-3}	(232)(231)	$B_d \to \mu^\pm \tau^\mp$	62	1.3×10^{-2}
(232)(313)	$B_d \to \mu^+ \mu^-$	1.5	1.3×10^{-2}	(232)(323)	$B_s \to \mu^+ \mu^-$	2.7	3.6×10^{-2}
(232)(331)	$B_d \to \mu^+ \mu^-$	1.5	3.5×10^{-3}	(232)(332)	$B_s \to \mu^+ \mu^-$	2.7	3.2×10^{-2}
(233)(313)	$B_d \to \mu^\pm \tau^\mp$	62	7.7×10^{-3}	(233)(331)	$B_d \to \mu^\pm \tau^\mp$	62	3.2×10^{-2}

Table 3: $\lambda\lambda'$ bounds from leptonic B_d and B_s decays.

We present our numbers for $\lambda\lambda'$ couplings in table 3 and $\lambda'\lambda'$ couplings in table 4. Our input parameters are the experimental 90% CL upper bounds on the BRs of the following modes [17, 19]

$$\begin{aligned}
Br(B_d \to e^+e^-) &< 8.3 \times 10^{-7}; & Br(B_d \to \mu^+\mu^-) &< 6.1 \times 10^{-7}; \\
Br(B_d \to e^\pm\mu^\mp) &< 1.5 \times 10^{-6}; & Br(B_d \to e^\pm\tau^\mp) &< 5.3 \times 10^{-4}; \\
Br(B_d \to \mu^\pm\tau^\mp) &< 8.3 \times 10^{-4}; & Br(B_s \to e^+e^-) &< 5.4 \times 10^{-5}; \\
Br(B_s \to \mu^+\mu^-) &< 2.0 \times 10^{-6}; & Br(B_s \to e^\pm\mu^\mp) &< 6.1 \times 10^{-6}.
\end{aligned} \tag{16}$$

Furthermore, we take the decay constants of both B_d and B_s to be 200 MeV; the bounds just scale as $(f_{B_{d,s}}/200\text{ MeV})^2$.

We also have Belle numbers for some of these modes [20]:

$$Br(B_d \to e^+e^-) < 6.3 \times 10^{-7}; \quad Br(B_d \to \mu^+\mu^-) < 2.8 \times 10^{-7}; \quad Br(B_d \to e^\pm\mu^\mp) < 9.4 \times 10^{-7}. \tag{17}$$

If one takes these bounds, which are yet to be published, into account, some of the numbers in tables 3 and 4 get modified. In table 3, the $\lambda\lambda'$ combinations coming from $B_d \to e^+e^-$ have upper bounds of 1.5×10^{-5} instead of 1.7×10^{-5}; those coming from $B_d \to \mu^+\mu^-$ and $B_d \to \mu^\pm e^\mp$ have upper bounds of 1.0×10^{-5} and 1.8×10^{-5} respectively. In table 4, the bounds on the $\lambda'\lambda'$ combinations coming from $B_d \to \mu^+\mu^-$ and $B_d \to \mu^\pm e^\mp$ are modified to 1.4×10^{-3} and 3.7×10^{-3} respectively. Obviously, these bounds scale as the square root of the upper bounds on respective branching fractions.

$\lambda'\lambda'$	Process	Bound ($\times 10^3$)	Previous bound	$\lambda'\lambda'$	Process	Bound ($\times 10^3$)	Previous bound
(111)(213)	$B_d \to \mu^\pm e^\mp$	4.7	3×10^{-5}	(111)(313)	$B_d \to e^\pm\tau^\mp$	5.9	5.7×10^{-5}
(112)(213)	$B_s \to \mu^\pm e^\mp$	9.6	1.2×10^{-3}	(113)(211)	$B_d \to \mu^\pm e^\mp$	4.7	1.2×10^{-3}
(113)(212)	$B_s \to \mu^\pm e^\mp$	9.6	1.2×10^{-3}	(113)(311)	$B_d \to e^\pm\tau^\mp$	5.9	2.3×10^{-3}
(121)(223)	$B_d \to \mu^\pm e^\mp$	4.7	9.0×10^{-3}	(121)(323)	$B_d \to e^\pm\tau^\mp$	5.9	22.4×10^{-3}
(122)(223)	$B_s \to \mu^\pm e^\mp$	9.6	9.0×10^{-3}	(123)(221)	$B_d \to \mu^\pm e^\mp$	4.7	7.7×10^{-3}
(123)(222)	$B_s \to \mu^\pm e^\mp$	9.6	9.0×10^{-3}	(123)(321)	$B_d \to e^\pm\tau^\mp$	5.9	22.4×10^{-3}
(131)(233)	$B_d \to \mu^\pm e^\mp$	4.7	2.9×10^{-3}	(131)(333)	$B_d \to e^\pm\tau^\mp$	5.9	7.6×10^{-3}
(132)(233)	$B_s \to \mu^\pm e^\mp$	9.6	42×10^{-3}	(133)(231)	$B_d \to \mu^\pm e^\mp$	4.7	0.3×10^{-3}
(133)(232)	$B_s \to \mu^\pm e^\mp$	9.6	0.8×10^{-3}	(133)(331)	$B_d \to e^\pm\tau^\mp$	5.9	0.6×10^{-3}
(211)(213)	$B_d \to \mu^+\mu^-$	2.1	3.5×10^{-3}	(211)(313)	$B_d \to \mu^\pm\tau^\mp$	7.3	6.5×10^{-3}
(212)(213)	$B_s \to \mu^+\mu^-$	3.9	3.5×10^{-3}	(213)(311)	$B_d \to \mu^\pm\tau^\mp$	7.3	6.5×10^{-3}
(221)(223)	$B_d \to \mu^+\mu^-$	2.1	1.4×10^{-3}	(221)(323)	$B_d \to \mu^\pm\tau^\mp$	7.3	93.6×10^{-3}
(222)(223)	$B_s \to \mu^+\mu^-$	3.9	2.7×10^{-3}	(223)(321)	$B_d \to \mu^\pm\tau^\mp$	7.3	0.109
(231)(233)	$B_d \to \mu^+\mu^-$	2.1	27×10^{-3}	(231)(333)	$B_d \to \mu^\pm\tau^\mp$	7.3	81×10^{-3}
(232)(233)	$B_s \to \mu^+\mu^-$	3.9	84×10^{-3}	(233)(331)	$B_d \to \mu^\pm\tau^\mp$	7.3	67.5×10^{-3}

Table 4: $\lambda'\lambda'$ bounds from leptonic B_d and B_s decays.

The present e^+e^- B factories should improve these bounds by one order of magnitude at the end of their run, if such modes are not observed. The hadronic machines or high-luminosity e^+e^- machines like the projected SuperBaBar [21] should see a large number of such leptonic decays if the actual values of the couplings are anywhere near the present bounds. Since the same couplings cause both $B_d \to \ell_i\ell_j$ and $B \to \pi\ell_i\ell_j$ (the same is true for $B_s \to ell_i\ell_j$ and $B \to K\ell_i\ell_j$) decays, a simultaneous signal is expected.

4. Semileptonic decays: $B \to Ke^+e^-, B \to K\mu^+\mu^-, B \to Ke^\pm\mu^\mp, B \to \pi e^\pm\mu^\mp$

All three collaborations CLEO, BaBar and Belle have set upper limits on the BRs of the abovementioned semileptonic modes (and also modes with a vector meson in the final state) [22, 23, 24, 25]. In fact, the modes $B \to K\mu^+\mu^-$ (and $B \to Ke^+e^-$ at less than 3σ) have been observed by Belle [24]. The present status is as follows:

$$Br(B \to K\ell^+\ell^-) \quad < \quad 0.6 \times 10^{-6} \ (BaBar), \quad 1.49 \times 10^{-6} \ (CLEO) \ (\ell = e/\mu)$$

$$
\begin{aligned}
Br(B \to Ke^+e^-) &= (0.48^{+0.32+0.09}_{-0.24-0.11}) \times 10^{-6} \ (Belle) \\
Br(B \to K\mu^+\mu^-) &= (0.99^{+0.40+0.13}_{-0.32-0.14}) \times 10^{-6} \ (Belle) \\
Br(B \to he^\pm\mu^\mp) &< 1.6 \times 10^{-6} \ (CLEO), \ \ (h = K/\pi).
\end{aligned}
\tag{18}
$$

These numbers are at the same ballpark as the SM expectations. Unfortunately, the SM expectations are not precise; at least three different groups quoted three different numbers, which are all mutually compatible, but differ in their upper and lower limits [26, 27, 28]. For example, the predicted BR for the mode $B \to K\mu^+\mu^-$ is (i) $(0.57^{+0.16}_{-0.10}) \times 10^{-6}$ [26]; (ii) $(0.33 \pm 0.07) \times 10^{-6}$ [27]; (iii) $(0.42 \pm 0.09) \times 10^{-6}$ [28]. As we know, the bounds on new physics depend sensitively on the theoretical predictions. Moreover, the situation is complicated since we should not neglect the SM amplitudes (apart from the lepton flavour-violating cases).

We take a compromising approach: in table 5, we quote the bounds on the relevant RPV couplings assuming (i) that the SM expectation is at its lowest possible value predicted by [26]; (ii) that the experimental number is at its highest possible value; (iii) that the difference is saturated by RPV contribution; (iv) and, most important of all, that the total SM amplitude and the RPV amplitude add *incoherently*. This is certainly not true; for that, in table 6, we show how the bounds relevant for a particular decay mode (*viz.*, $B \to K\mu^+\mu^-$) change if (i) the RPV amplitude adds constructively to the SM one; (ii) the RPV amplitude adds destructively with the SM one (for this, we take the highest possible SM prediction and the lowest possible experimental number); and (iii) if we use the theoretical numbers in [27] or [28]. We draw the attention of the reader to the huge fluctuation of the RPV bounds. It is, however, heartening to note that the most conservative bounds come from incoherent amplitude summation, so that the bounds quoted in table 5 are robust as far as the phases in the RPV couplings are concerned. This analysis also shows that to get any meaningful signal of new physics from these modes, which is certainly feasible in not-too-distant future, one must minimize the theoretical as well as the experimental uncertainties. Another signal of new physics, which we do not investigate here, is the forward-backward asymmetry of the final state leptons.

$\lambda'\lambda'$	Final state	Bound	$\lambda'\lambda'$	Final state	Bound
(111)(213)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}	(113)(211)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}
(121)(223)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}	(123)(221)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}
(131)(233)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}	(133)(231)	$\pi\mu^\pm e^\mp$	5.0×10^{-4}
(112)(213)	$K\mu^\pm e^\mp$	3.3×10^{-4}	(113)(212)	$K\mu^\pm e^\mp$	3.3×10^{-4}
(122)(223)	$K\mu^\pm e^\mp$	3.3×10^{-4}	(123)(222)	$K\mu^\pm e^\mp$	3.3×10^{-4}
(132)(233)	$K\mu^\pm e^\mp$	3.3×10^{-4}	(133)(232)	$K\mu^\pm e^\mp$	3.3×10^{-4}
(212)(213)	$K\mu^+\mu^-$	9.7×10^{-5}	(222)(223)	$K\mu^+\mu^-$	9.7×10^{-5}
(232)(233)	$K\mu^+\mu^-$	9.7×10^{-5}	(112)(113)	Ke^+e^-	9.6×10^{-5}
(122)(123)	Ke^+e^-	9.6×10^{-5}	(132)(133)	Ke^+e^-	9.6×10^{-5}

Table 5: $\lambda'\lambda'$ bounds from semileptonic B_d decays.

For our analysis, we take the most stringent experimental numbers, *viz.*, the numbers quoted by BaBar for $B \to K\ell^+\ell^-$ ($\ell = e, \mu$) and the numbers quoted by CLEO for $B \to Ke\mu, \pi e\mu$. The SM prediction for the first two modes can be as low as 0.47×10^{-6} [26] and zero for the last two; with incoherent addition of SM and RPV amplitudes, one gets the bounds on $\lambda'\lambda'$ type products as shown in table 5. We do not show the $\lambda\lambda'$ bounds as they are at least one order of magnitude

weaker than those obtained from leptonic B_d and B_s decays, apart from being much less robust. We have also used the BSW formfactors [12] for $B \to K$ and $B \to \pi$ transitions and taken $F_0 = F_1$ with minimal loss of accuracy: $F_0^{B \to \pi}(0) = 0.39$ GeV, $F_0^{B \to K}(0) = 0.42$ GeV.

Though the bounds in table 5 appear to be better than those in table 4, we warn the reader that they depend sensitively to the experimental number as well as the scheme for theoretical prediction. This is evident from table 6. Thus, any future analysis with these product couplings should use the numbers quoted in table 4.

Is it possible to find other channels where one finds such RPV signals? If only one product coupling is nonzero, there are very few product couplings constrained here that may contribute to nonleptonic B decays. Such couplings are: (i) $\lambda'_{211}\lambda'_{213}$, mediating $b \to u\overline{u}d$ and $b \to d\overline{d}d$, and hence $B \to \pi\pi$ (this coupling also affects the B_d-$\overline{B_d}$ box diagram and thus the mixing-induced CP asymmetry coming from B_d decays); (ii) $\lambda'_{212}\lambda'_{213}$ and $\lambda'_{112}\lambda'_{113}$, mediating $b \to u\overline{u}s$ and $b \to d\overline{d}s$; (iii) $\lambda'_{221}\lambda'_{223}$, mediating $b \to c\overline{c}d$ and $b \to s\overline{s}d$; (iv) $\lambda'_{122}\lambda'_{123}$ and $\lambda'_{222}\lambda'_{223}$, giving rise to $b \to c\overline{c}s$ and $b \to s\overline{s}s$ (and hence $B_d \to J/\psi K_S$ and $B_d \to \phi K_S$). However, these processes are slepton mediated whereas the leptonic and semileptonic B decays discussed here are squark mediated, and hence the numbers quoted here should be scaled by $(m_{\tilde{q}}/m_{\tilde{\ell}})^2$. The conclusion is that one should look for any unusual change in CP asymmetry and/or branching fractions in the abovementioned channels to get a supporting evidence for RPV SUSY (though, their absence does not rule out the model).

	Ali *et al* [26]	Greub *et al* [27]	Melikhov *et al* [28]
BaBar	CC: 2.4×10^{-5}	CC: 9.5×10^{-5}	CC: 6.4×10^{-5}
	CD: 1.7×10^{-5}	CD: Not possible	CD: Not possible
	Inc: 9.7×10^{-5}	Inc: 2.1×10^{-4}	Inc: 1.7×10^{-4}
Belle	CC: 1.3×10^{-4}	CC: 2.4×10^{-4}	CC: 2.0×10^{-4}
	CD: 1.2×10^{-5}	CD: Not possible	CD: Not possible
	Inc: 2.6×10^{-4}	Inc: 3.9×10^{-4}	Inc: 3.3×10^{-4}

Table 6: Bounds on $|\lambda'_{2i2}\lambda'_{2i3}|$ from the decay $B \to K\mu^+\mu^-$ with different schemes for evaluating the SM branching ratio and two sets of experimental values from BaBar and Belle. CC and CD stand for complete constructive and destructive interference between SM and RPV amplitudes respectively, and Inc means incoherent amplitude sum. For two theoretical schemes, a complete destructive interference is ruled out from the data.

5. Summary and Conclusions

In this paper we found the bounds on $\lambda\lambda'$ and $\lambda'\lambda'$ type product couplings coming from leptonic and semileptonic τ and B decays. Most of our bounds are robust and one to two orders of magnitude better than the existing bounds. Some of the updated bounds also have major improvement.

The bounds are only on the magnitude of the product couplings. The phase is irrelevant apart from the semileptonic penguin decays of B_d mesons. For the latter the most conservative bounds come from incoherent amplitude summation but depend sensitively on the theoretical prediction for SM BRs.

After this work was communicated a paper came to the archive where some of these bounds

have been discussed [29].

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