

## New Bounds on R-parity Violating Couplings

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We use information from rare nonleptonic decays of heavy-quark mesons to put new bounds on the magnitudes of certain product combinations of baryon nonconserving R-parity violating couplings in supersymmetric models. Product combinations of lepton *and* baryon nonconserving R-parity violating couplings are also considered in the light of existing bounds on nucleon decay. Contrary to popular impression, a few such combinations are shown to remain essentially unconstrained.

Though the minimal supersymmetric standard model (MSSM) [1] is a leading candidate for new physics beyond the standard model, the conservation of R-parity,  $R_p$ , which is assumed in the model has no real theoretical justification. This has motivated many authors [2] to consider alternatives in which  $R_p$  is explicitly broken. In such models, sparticles can decay into non-supersymmetric particles alone, leading to novel signatures in search experiments and unusual decay processes.

The most general  $R_p$ -violating superpotential that one can write with the MSSM superfields, in the usual notation, is

$$W = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \quad (1)$$

Here,  $i, j, k$  are generation indices and we have rotated away a term of the form  $\mu_{ij} L_i H_j$ . Since the  $\lambda_{ijk}$  term is symmetric under exchange of  $i$  and  $j$ , and antisymmetric in color, it must be antisymmetric in flavor, thus we have  $\lambda_{ijk} = -\lambda_{jik}$ . Similarly,  $\lambda''_{ijk} = -\lambda_{ikj}$ . The number of couplings is then 36 lepton nonconserving couplings (9 of the  $\lambda$  type and 27 of the  $\lambda'$  type) and 9 baryon nonconserving couplings (all of the  $\lambda''$  type) in total.

It is generally thought that  $\lambda, \lambda'$  type couplings cannot coexist with  $\lambda''$  type couplings since both baryon and lepton number violations would lead to too rapid a proton decay. For this reason, previous authors have considered either lepton nonconserving *or* baryon nonconserving couplings, but not both. We will first make this assumption and consider the baryon number violating  $\lambda''$  couplings alone, since most of the earlier effort has been focused on  $\lambda$  and  $\lambda'$  couplings [3]. Later, we will examine proton decay in the presence of all three types of couplings. Severe constraints on  $R_p$ -violating couplings can be obtained by requiring that the cosmological baryon asymmetry not be washed out[4], but it is possible to evade these bounds [5].

Our philosophy throughout will be that we expect the couplings involving third generation fields to be the largest. There are two reasons for this. The only other Yukawa

couplings in the model (the Yukawa couplings of the quarks to the Higgs fields) exhibit a very strongly hierarchical generational structure and thus one would expect the R-parity violating couplings to do so as well. Second, many models result in the scalar top being the lightest of the squarks, and thus processes involving the scalar top may not be as suppressed by large propagators. We will thus concentrate on couplings involving higher generations, but will keep our bounds as general as possible.

We can write the 9 different  $\lambda''$  couplings as  $\lambda''_{tbs}, \lambda''_{tbd}, \lambda''_{tsd}, \lambda''_{cbs}, \lambda''_{cbd}, \lambda''_{csd}, \lambda''_{ubs}, \lambda''_{ubd}$  and  $\lambda''_{usd}$ . Let us first recount the existing constraints on these couplings. Brahmachari and Roy [6] showed that the requirement of perturbative unification typically places a bound of between 1.10 and 1.25 on many of the couplings. This was generalized to all the couplings by Goity and Sher [7]. The latter also showed, following earlier work [8, 9], that  $|\lambda''_{usd}|$  can be strongly bounded by the nonobservation of double nucleon decay into two kaons (such as  $^{16}O \rightarrow ^{14}C K^+ K^+$ , which would have been seen in water Cerenkov detectors), and  $|\lambda''_{ubd}|$  can be strongly bounded by the nonobservation of neutron-antineutron oscillations. Their bounds, for squark masses of 300 GeV, were  $|\lambda''_{ubd}| < 5 \times 10^{-3}$  and  $|\lambda''_{usd}| < 10^{-6}$ . In the work of Barbieri and Masiero [9], some bounds on products of couplings were obtained by considering  $K-\bar{K}$  mixing; these bounds will be discussed shortly. Finally, bounds from the  $\bar{b}b$  induced vertex correction to the decay of the  $Z$  into two charged leptons have recently been obtained [10]; though potentially interesting, with present data they are not significantly better than the bound from perturbative unification.

In this Letter, we note that many additional and interesting bounds on the  $\lambda''$  couplings can be obtained by considering rare two-body nonleptonic decays of heavy-quark mesons. We shall mostly consider B decays, but also, in some cases, D decays. Let us begin by considering the implications for  $\lambda''$  couplings from such processes.. Since lepton number is assumed to be conserved, only  $\Delta B = 0$  and  $\Delta B = 2$  decays can occur.

Thus any bounds will be on the products of two  $\lambda''$  couplings. Furthermore, since any B-decay will change the number of “b-flavors” by one unit, bounds from there will apply to products of the form  $\lambda_{u_i bs}\lambda_{u_j sd}$  or  $\lambda_{u_i bd}\lambda_{u_j sd}$ . We first consider  $\Delta B = 0$  (baryon number conserving) decays which actually give the best bounds and later comment on the  $\Delta B = 2$  processes.

In our calculation of two-body nonleptonic decays of heavy-quark mesons, we follow the computational method of Carlson and Milana [11] which is based upon the formalism of Brodsky and Lepage [12]. First, we neglect all light meson masses ( $\pi$ 's, K's). Then we make use of the fact that the relative momentum between the quark and the antiquark for each of the  $q\bar{q}$  pairs within the decaying meson and within each of the final state mesons is low. The large quark momentum transfers, needed to move a quark from one meson to another or to produce a  $q\bar{q}$  pair which enter different mesons, can be caused either by single-gluon exchange or through the emission of a virtual squark. However, both are needed in each diagram for the correct distribution of relative momentum, so we consider diagrams that involve both. Alternatively, one could consider the full meson wave functions [13] with the tail of the wave functions being crucial; if properly done, this should be equivalent to the previous calculation since at high enough relative momentum the tail is indeed given by 1-gluon exchange.

First, take the decay  $B^+ \rightarrow \bar{K}^0 K^+$  (or equivalently,  $B^- \rightarrow K^0 K^-$ ). This has an extremely small rate in the Standard Model, being penguin-suppressed and also reduced by the small CKM element  $V_{ub}$  in the amplitude. The dominant diagrams contributing to this process for nonzero  $\lambda''$  couplings are shown in Fig. 1. In each of these diagrams, the gluon is spacelike and the squark (of charge 2/3) is timelike. This generates from the gluon propagator an overall enhancement factor of  $m_B/(m_B - m_b) \simeq 10$  in the amplitude,  $m_B$  and  $m_b$  being the B-meson and b-quark masses respectively. (This factor is just the inverse of the fraction of the B-momentum assigned to the light quark.) One can draw

similar diagrams interchanging the squark and gluon internal lines and appropriately relabeling the quark lines. Each of these latter diagrams would have a timelike gluon and a spacelike squark (now of charge  $-1/3$ ). For these, however, the overall factor of  $m_B/(m_B - m_b)$  does not materialize so that contributions from these diagrams are significantly subdominant and can be neglected. It is of interest to point out that the decay  $B^o \rightarrow K^+K^-$  can proceed only through these latter diagrams, with the squark having charge  $2/3$ , and therefore yields a significantly weaker bound on the same product of  $\lambda''$  couplings than does  $B^+ \rightarrow \bar{K}^oK^+$ , in spite of stronger experimental limits on the branching ratio.

Our result is most conveniently expressed as a ratio of  $\Gamma(B^+ \rightarrow \bar{K}^oK^+)$  to the partial width of another  $B^+$  decay channel (specifically  $B^+ \rightarrow K^+J/\psi$ ) that proceeds unsuppressed in the Standard Model. This description eliminates many of the uncertainties in the coefficient factors. We find, considering only t-squark contributions, that

$$\frac{\Gamma(B^+ \rightarrow \bar{K}^oK^+)}{\Gamma(B^+ \rightarrow K^+J/\psi)} = \left(1 - \frac{m_{J/\psi}^2}{m_B^2}\right)^{-1} \left(\frac{f_K}{f_{J/\psi}}\right)^2 \frac{|\lambda''_{tbs}\lambda''_{tsd}|^2(m_W/m_{\tilde{t}})^4}{(G_F m_W^2)^2 |V_{cb}|^2 |V_{cs}|^2} \times (9.8 \times 10^{-2}) \quad (2)$$

Here,  $m_{\tilde{t}}$  is the mass of the scalar top,  $m_{J/\psi}$  is the mass of the  $J/\psi$  meson,  $f_K$  and  $f_{J/\psi}$  are the decay constants of the  $K$  and  $J/\psi$ , which are related to their wave functions at the origin, and  $V_{cb}$  and  $V_{cs}$  are CKM elements. We shall use  $f_{J/\psi}/f_K \simeq 2.55$ . Using the experimental branching ratio for  $B^+ \rightarrow K^+J/\psi$ , namely [14]  $10.2 \times 10^{-4}$ , we have

$$\text{B.R.}(B^+ \rightarrow \bar{K}^oK^+) \simeq 1.97 |\lambda''_{tbs}\lambda''_{tsd}|^2 (m_W/m_{\tilde{t}})^4. \quad (3)$$

On using the recent experimental upper bound [15] of  $5 \times 10^{-5}$  on the branching ratio, and noting that one can replace the scalar top with a scalar charm or scalar up, we then have

$$\frac{|\lambda''_{qbs}\lambda''_{qsd}|m_W^2}{m_{\tilde{q}}^2} < 5 \times 10^{-3}, \quad (4)$$

for  $q = t, c, u$ . We have redone the computation of Eq. 2 using the methods of heavy quark symmetry and find a 15% downward revision in the upper bound<sup>1</sup>.

One can repeat the calculation for the decay  $B^+ \rightarrow \bar{K}^0 \pi^+$  (or equivalently  $B^- \rightarrow K^0 \pi^-$ ) in much the same way. The result (with only the t-squark contribution being considered) is

$$\text{B.R.}(B^+ \rightarrow \bar{K}^0 \pi^+) = 1.32 |\lambda''_{tbd} \lambda''_{tsd}|^2 (m_W/m_{\tilde{t}})^4. \quad (5)$$

Again, using the experimental upper bound [15] of  $5 \times 10^{-5}$  on the branching ratio, we have

$$\frac{|\lambda''_{qbd} \lambda''_{qsd}| m_W^2}{m_{\tilde{q}}^2} < 4.1 \times 10^{-3}, \quad (6)$$

for  $q = t, c, u$ .

Though these methods of calculation would be less reliable for two-body nonleptonic decays of  $D$ -mesons, we can use a similar approach there to get an order of magnitude estimate of the corresponding bounds. However, we find that the bounds are significantly higher than bounds obtained from  $D - \bar{D}$  mixing, discussed below.

Additional bounds were obtained by Barbieri and Masiero [9] from the contribution of  $K-\bar{K}$  mixing to the  $K_L-K_S$  mass difference. There are two main box diagrams towards this contribution, shown in Fig. 2. Assuming that one or the other of these diagrams is dominant, the results of Barbieri and Masiero lead to <sup>2</sup>

$$|\lambda''_{tbs} \lambda''_{tbd}| < \min \left( 6 \times 10^{-4} (m_{\tilde{t}}/m_W), 3 \times 10^{-4} (m_{\tilde{t}}/m_W)^2 \right) \quad (7)$$

$$|\lambda''_{cbs} \lambda''_{cbd}| < \min \left( 6 \times 10^{-4} (m_{\tilde{c}}/m_W), 2 \times 10^{-4} (m_{\tilde{c}}/m_W)^2 \right) \quad (8)$$

These authors did assume that the top quark was much lighter than scalar top, and that

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<sup>1</sup>This gives some idea of the theoretical uncertainty in the bound.

<sup>2</sup>We are considering bounds on the real part of the coupling constants only. Bounds on possible imaginary parts were also discussed by Barbieri and Masiero. If the couplings have significant imaginary parts, then in the bounds in this paper arising from  $K-\bar{K}$  and  $D-\bar{D}$  mixing,  $|\lambda_a \lambda_b|$  must be replaced by  $|\text{Re}(\lambda_a^* \lambda_b)|^{1/2}$ .

all squark masses are degenerate. The former assumption has been invalidated by recent data, so their bounds need to be revised.

These results can be generalized by noting that the exchanged quarks in Fig. 2a can be any two charge-2/3 quarks, and also that the exchanged quarks in Fig. 2b can consist of one  $c$ -quark and one  $t$ -quark ( $u$ -quark contributions are suppressed by a mass insertion in this diagram). We have calculated the possible contributions, assuming that all of the squark masses are equal except that of the scalar top, and using a mass of 175 GeV for the top quark with updated CKM angles.<sup>3</sup> In Fig 2a, we have also included (as did Barbieri and Masiero ) the contribution arising by replacing all of the particles in the box with their superpartners; we have not included the similar contribution from Fig. 2b due to the extra unknown parameters (it is unlikely that this contribution will almost exactly cancel the calculated contributions; thus our results will not be significantly affected by them). We require that these contributions not exceed the standard model contribution (which is uncertain by roughly a factor of two), and have plotted the upper bound for various products of couplings in Fig. 3. It is not hard to see that the contribution from  $B$ - $\bar{B}$  mixing to the  $B_L$ - $B_S$  mass difference will give bounds on the same couplings, but will be weaker.

Bounds from  $D$ - $\bar{D}$  mixing can also be considered. We find that one of the two box diagrams is suppressed by small CKM angles and the other gives

$$|\lambda''_{cbs}\lambda''_{ubs}| < 3.1 \times 10^{-3}(m_{\bar{s}}/m_W) \quad (9)$$

What about  $\Delta B = 2$  decays? One can envision the process of Figure 4, which will lead to the decay  $B \rightarrow \Sigma^+\Sigma^-$  or  $\Lambda\Lambda$  . However, a simple estimate of the rate gives branching ratios (assuming the B-violating couplings are unity and the scalar quark masses are near the  $W$  mass) of  $O(10^{-8})$ . The smallness of the rate is due in large part to two

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<sup>3</sup>In the limit of small top quark mass, our analytic result for the effective Hamiltonian is a factor of two smaller than that given by Barbieri and Masiero.

small CKM elements in the amplitude. Thus, such processes will not provide interesting bounds unless  $10^{10}$  B-decays are studied.

It is generally assumed that the presence of both lepton nonconserving terms and baryon nonconserving terms leads to unacceptably rapid proton decay. However, if enough third generation fields are involved, proton decay can be sufficiently suppressed as to make some of the bounds very weak (or, in a few cases, nonexistent). To see this, suppose both  $\lambda$  and  $\lambda''$  terms exist. Consider the bound on the product  $|\lambda_{\mu\tau\tau}\lambda''_{usd}|$ . This will lead to proton decay through the diagram of Figure 5a. Although there is a suppression due to mixing angles and heavy squark propagators, the proton lifetime bound gives a strong bound of  $|\lambda_{\mu\tau\tau}\lambda''_{usd}| < 10^{-14}$ . This bound is independent of the final state leptons, and thus applies to all 9 of the  $\lambda$  couplings. Similar bounds can be obtained for all  $\lambda''$  couplings with at most one heavy field (which is then the scalar quark); we obtain  $|\lambda_{ijk}\lambda''_{ubd}| < 10^{-13}$ ,  $|\lambda_{ijk}\lambda''_{ubs}| < 10^{-12}$ ,  $|\lambda_{ijk}\lambda''_{csd}| < 10^{-13}$  and  $|\lambda_{ijk}\lambda''_{tsd}| < 10^{-12}$ . However, if the  $\lambda''$  coupling has two heavy fields, a loop is necessary, as shown in Figure 5b. This gives much weaker bounds; we obtain  $|\lambda_{ijk}\lambda''_{tbs}| < 10^{-2}$ ,  $|\lambda_{ijk}\lambda''_{tbd}| < 10^{-3}$ ,  $|\lambda_{ijk}\lambda''_{cbs}| < 10^{-3}$  and  $|\lambda_{ijk}\lambda''_{cbd}| < 10^{-2}$ . We thus see that the lack of observation of proton decay does NOT always give very strong bounds on the product of the lepton number violating and baryon number violating couplings.

Finally, we consider the product of  $\lambda'$  and  $\lambda''$  couplings. Here, there are  $27 \times 9$  possible products, of the form  $|\lambda'_{ijk}\lambda''_{abc}|$ . The diagrams that can lead to proton decay are shown in Fig. 6. For each of these, one can have a  $\tau$  or  $c, b, t$  quark on an external leg, in which case that leg must be virtual and decay through a  $W$ . We have examined all possible products of couplings and found that the vast majority are tightly bounded (product is less than  $10^{-6}$ ), but some are not. Rather than list the bounds for all 243 combinations, only the bounds which are greater than  $10^{-6}$  (for the product of the  $\lambda'$  and  $\lambda''$  couplings) will be given explicitly. It is found that all products with a  $\lambda''_{usd}$ ,  $\lambda''_{ubd}$  and



$\lambda''_{ubs}$  are smaller than  $10^{-9}$ . The same is true for  $\lambda''_{csd}$ ,  $\lambda''_{cbd}$  and  $\lambda''_{cbs}$ , *except* for  $|\lambda'_{tbl}\lambda''_{csd}|$  which is  $< 10^{-1}$ ,  $|\lambda'_{usl}\lambda''_{cbd}|$  which is  $< 10^{-2}$  and  $|\lambda'_{udl}\lambda''_{cbs}|$ , for which no bound better than the unitarity bound could be found. Here  $l$  is any lepton. For  $\lambda''_{tsd}$ , the only bound which is not very small is the combination  $|\lambda'_{cbl}\lambda''_{tsd}|$ , which is bounded only by unitarity. For  $\lambda''_{tbd}$  and  $\lambda''_{tbs}$ , we find  $|\lambda'_{ud(e,\mu)}\lambda''_{tbd}| < 10^{-2}$ ,  $|\lambda'_{us(e,\mu)}\lambda''_{tbs}| < 10^{-2}$ ,  $|\lambda'_{c(d,s)(e,\mu)}\lambda''_{tbd}| < 10^{-3}$ ,  $|\lambda'_{c(d,s)(e,\mu)}\lambda''_{tbs}| < 10^{-3}$ ,  $|\lambda'_{cd\tau}\lambda''_{tbd}| < 10^{-5}$ ,  $|\lambda'_{cs\tau}\lambda''_{tbs}| < 10^{-5}$ , whereas  $|\lambda'_{(u,c)d\tau}\lambda''_{tbs}|$  and  $|\lambda'_{(u,c)s\tau}\lambda''_{tbd}|$  are bounded only by unitarity. All other bounds are quite tiny. Thus, of the 243 combinations of couplings, thirty have bounds greater than  $10^{-6}$ , and eight are completely unconstrained by the lack of observation so far of proton decay.

Could the unconstrained couplings be bounded by rare B decays? One can envision a diagram similar to Fig. 1 in which the upper vertex is a  $\lambda'$  vertex; this would lead to B decay into three quarks and a lepton, such as  $B \rightarrow p\tau$ . However, in all of the above 30 couplings, the scalar quark leaving the  $\lambda'$  vertex is different from that entering the  $\lambda''$  vertex, and thus a loop will be necessary, suppressing the rate. As originally noted by Thorndike and Poling[16], therefore, the bounds from proton decay will be better than those from B decay in all cases, unless branching ratios of  $10^{-8}$  or better are obtained.

It is interesting that the standard supersymmetric model can contain some baryon number and lepton number violating coupling constants which are of order unity, and which do not lead to excessively fast proton decay. Such couplings could be measured when squarks and sleptons are discovered, since they will lead to baryon and lepton number violating squark and slepton decays. These have been extensively discussed by Dreiner and Ross and by Dimopoulos, et al. [17], who analyze the impact of such decays on phenomenology.

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Figure 1: The dominant diagrams contributing to  $B^+ \rightarrow \bar{K}^0 K^+$ . The  $\tilde{t}$  refers to the scalar top quark, the  $g$  to the gluon.

Figure 2: Contribution of R-parity violating couplings to the  $K_L$ - $K_S$  mass difference.

Figure 3: Bounds on products of  $\lambda''$  couplings, plotted vs. the scalar bottom mass,  $m_s$ , arising from constraints from  $K$ - $\bar{K}$  mixing. The ratio of the scalar top mass to the scalar bottom mass is taken to be 0.5; all other scalar quark masses are degenerate with the scalar bottom mass. The bounds on  $|\lambda''_{tbd}\lambda''_{tbs}|$ ,  $|\lambda''_{tbs}\lambda''_{cbd}|$ ,  $|\lambda''_{cbd}\lambda''_{cbs}|$  are given by the solid, dashed, and dotted lines respectively. The bound on  $|\lambda''_{cbs}\lambda''_{cbd}\lambda''_{ubs}\lambda''_{ubd}|^{1/2}$  is  $\sqrt{2}$  lower than the dotted line; the bound on  $|\lambda''_{cbs}\lambda''_{cbd}\lambda''_{tbd}\lambda''_{tbs}|$  and  $|\lambda''_{ubd}\lambda''_{ubs}\lambda''_{tbd}\lambda''_{tbs}|$  are given by the products of the solid and dotted lines, the bound on  $|\lambda''_{ubd}\lambda''_{ubs}|$  is also the dotted line; and the bound on  $|\lambda''_{tbd}\lambda''_{cbs}|$  is larger than that of  $|\lambda''_{tbs}\lambda''_{cbd}|$  by a factor of roughly 1.7. If the scalar top mass is taken to be  $0.9m_s$ , then only the  $|\lambda''_{tbd}\lambda''_{tbs}|$  curve changes, increasing by roughly 50% over the entire range.

Figure 4: A typical contribution of R-parity violating couplings to the baryon number violating decay of the  $B^0$ , in this case yielding  $B^0 \rightarrow \Lambda\Lambda$ .

Figure 5: Diagram (a) shows a typical proton decay arising from the existence of both  $\lambda$  and  $\lambda''$  R-parity violating terms. In diagram (b), the contribution is given for the case in which the  $\lambda''$  term contains two heavy quarks.

Figure 6: Contributions to proton decay arising from the existence of both  $\lambda'$  and  $\lambda''$  R-parity violating terms. The tree-level diagram contributes if the  $\lambda'$  and  $\lambda''$  terms each have a single, identical heavy field; in other cases, either the loop diagrams contribute or one of the external lines is a heavy quark which must then emit a virtual  $W$  (or, in some cases, both must occur).