Some novel contributions to radiative B decays in supersymmetry without R parity

Otto C. W. Kong and Rishikesh D. Vaidya
Department of Physics, National Central University, Chung-Li, Taiwan 32054
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We present a systematic analysis at the leading log order of the influence of combination of bilinear and trilinear R parity violating couplings on the decay $b \to s + \gamma$. Such contributions have never been explored in the context of $b \to s + \gamma$ decay. We show that influence of charged-slepton-Higgs mixing mediated loops can dominate the SM and MSSM contributions and hence can provide strong bounds on the combination of bilinear-trilinear R parity violating couplings. Such contributions also are enhanced by large $\tan\beta$. With substantially extended basis of operators (28 operators), we provide illustrative analytical formulas of the major contributions to complement our complete numerical results which demonstrate the importance of QCD running effects.

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I. INTRODUCTION

The minimal supersymmetric standard model (MSSM) has been the most popular candidate theory for physics beyond the standard model (SM) for the last couple of decades. With the recent accumulation of evidence for neutrino oscillations, it is clear that the lepton number conserving MSSM has to be amended. The simplest option is then to give up imposing R parity and hence admit all gauge invariant terms in a (generic) supersymmetric SM. Other alternatives include incorporating any particular neutrino sector model such as the seesaw mechanism with extra gauge singlet superfields. We focus on the first option [1,2]. The model has the special merit that the parameters that give rise to neutrino masses and mixings also have interesting phenomenological consequence in the quark and charged lepton sectors. Here in this letter, we report on some of the novel contributions to the $b \to s + \gamma$ decay from the model.

Within the SM, the flavor sector still needs more scrutiny from theory as well as experiments. In particular, flavor changing neutral current processes are widely considered to be the window of the physics beyond SM. Among the processes, $B \to X_s + \gamma$ is a particularly attractive candidate. The most up-to-date SM prediction [3] gives

$$\mathrm{Br}[B \to X_s + \gamma_{(E_\gamma > 1.6\ \mathrm{GeV})}]_{\mathrm{SM}} = (3.57 \pm 0.30) \times 10^{-4}, \tag{1}$$

while the experimental number (world-average) is [4]

$$\mathrm{Br}[B \to X_s + \gamma_{(E_\gamma > 1.6\ \mathrm{GeV})}]_{\mathrm{EXP}} = (3.34 \pm 0.38) \times 10^{-4}. \tag{2}$$

It clearly leaves not much room for new physics contributions. Hence, it can be used to obtain stringent constraints on flavor parameters of various new physics models.

This channel is indeed very well studied in the most popular theory of beyond SM physics, namely, the minimal supersymmetric standard model [5–7]. There have been some studies on the process within the general framework of R parity violation [8–10]. Reference [8], fails to consider the additional 18 four-quark operators which, in fact, give the dominant contribution in most of the cases. The more recent work of Ref. [9] has considered a complete operator basis. However, we find their formula for Wilson coefficient incomplete. In fact, the particular type of contributions—namely, one from a combination of a bilinear and a trilinear R parity violating (RPV) parameters, we focus on here—has not been studied in any detail before. Reference [10] deals with the CP asymmetries for $B \to X_s + \gamma$ and has a detailed treatment of operator basis and QCD running with the full anomalous dimension matrix.

It is not possible for us to give much analytical details of our study here in this short paper. We only will outline the major features of the full analysis given in a parallel report [11], to which interested readers are referred. We adopt an optimal phenomenological parametrization of the full model Lagrangian, dubbed the single-vacuum expectation value parametrization, first explicitly advocated in Refs. [12]. It is essentially about choosing a basis for Higgs and lepton superfields in which all the "sneutrino" vacuum expectation values vanish. The formulation gives the simplest expressions for all the mass matrices of the fermions and scalars without *a priori* assumption on the admissible form of R parity violation. In particular, all the RPV effects to the fermion mass matrices are characterized by the three bilinear parameter μ_i's. Working under the formulation, it has been pointed out in Ref. [13] that there are interesting contributions to the down squark and charged slepton mass matrices of the form $(\mu_i^* \lambda'_{ijk})$ and $(\mu_i^* \lambda_{ijk})$. These give explicit indications of the existence of bilinear-trilinear type contributions to fermion dipole moments at 1-loop order, including the transitional moment term to be identified with the $b \to s + \gamma$ decay. Detailed analytical and numerical studies have been performed on the case of neutron electric dipole moment [14] and $\mu \to e + \gamma$ [15]. Here, we report on the more difficult calculation of $B \to X_s + \gamma$. Background details on the model and the various mass matrices are given in Ref. [1]. Based on the latter results, we implement our (1-loop) calculations using mass eigenstate expressions [11], hence free from the commonly adopted mass-insertion approximation. While a trilinear RPV parameter gives a coupling, a bilinear parameter now contributes only through mass mixing matrix elements characterizing the effective couplings of the mass eigenstate running inside the loop. The μ_i's are involved in fermion, as well as scalar mixings [1]. There are also the corresponding soft bilinear B_i parameters involved only in scalar mixings [1]. Combinations of μ_i's and B_i's with the trilinear λ'_{ijk} parameters are our major focus.

II. THE EFFECTIVE HAMILTONIAN APPROACH

The partonic transition $b \to s + \gamma$ is described by the magnetic penguin diagram. Under the effective Hamiltonian approach, the corresponding Wilson coefficients of the standard $\mathcal{Q}_7$ operator has many RPV contributions at the scale M_W. For example, we separate the contributions from different types of diagrams as $C_7 = C_7^W + C_7^{\tilde{g}} + C_7^{\chi^-} + C_7^{\chi^0} + C_7^{\phi^-} + C_7^{\phi^0}$. The neutral scalar loop contribution $C_7^{\phi^0}$, as an illustrative case, is proportional to

$$\frac{\mathcal{Q}_d}{M^2_{S_m}}\left[\tilde{\mathcal{N}}^R_{nmj}\tilde{\mathcal{N}}^{L^*}_{nmi}\frac{m_{d_n}}{m_{d_j}}F_3\left(\frac{m^2_{d_n}}{M^2_{S_m}}\right) + \tilde{\mathcal{N}}^L_{nmj}\tilde{\mathcal{N}}^{L^*}_{nmi}F_1\left(\frac{m^2_{d_n}}{M^2_{S_m}}\right)\right],$$

where the effective vertex couplings $\tilde{\mathcal{N}}^{L^*}_{nmi}$ and $\tilde{\mathcal{N}}^{R^*}_{nmi}$ for the mass eigenstates each contains the a λ'-coupling contribution [11].

Apart from the eight SM operators with additional contributions, we actually have to consider many more operators with admissible nonzero Wilson coefficients at M_W resulting from the RPV couplings. These are the chirality-flip counterparts $\tilde{\mathcal{Q}}_7$ and $\tilde{\mathcal{Q}}_8$ of the standard (chromo)magnetic penguins $\mathcal{Q}_7$ and $\mathcal{Q}_8$, and a whole list of 18 new relevant four-quark operators of current-current type to be given as

$$\mathcal{Q}_{9-11} = (\bar{s}_{L\alpha}\gamma^\mu b_{L\beta})(\bar{q}_{R\beta}\gamma_\mu q_{R\alpha}), \qquad q = d, s, b; \quad (3)$$

$$\tilde{\mathcal{Q}}_{3,4} = (\bar{s}_{R\alpha}\gamma^\mu b_{R\alpha,\beta})\sum_{i=u,c,d,s,b}(\bar{q}_{Ri\beta}\gamma^\mu q_{Ri\beta,\alpha}); \quad (4)$$

$$\tilde{\mathcal{Q}}_{5,6} = (\bar{s}_{R\alpha}\gamma^\mu b_{R\alpha,\beta})\sum_{i=u,c,d,s,b}(\bar{q}_{Li\beta}\gamma^\mu q_{Li\beta,\alpha}); \quad (5)$$

$$\tilde{\mathcal{Q}}_{9-13} = (\bar{s}_{R\alpha}\gamma^\mu b_{R\beta})(\bar{q}_{L\beta}\gamma_\mu q_{L\alpha}), \qquad q = d, s, b, u, c; \quad (6)$$

and six more operators from λ'' couplings [11] we skip here for brevity. The interplay among the full set of 28 operators is what makes the analysis complicated. The effect of the QCD corrections proved to be very significant even for the RPV parts.

We omit here the details involved in the evaluation of the various effective Wilson coefficients for the decay rate of $b \to s + \gamma$ and give only the numerical results from our leading log order analysis [11]:

$$\begin{aligned} C_7^{\rm eff}(m_b) &= -0.351C_2^{\rm eff}(M_W) + 0.665C_7^{\rm eff}(M_W) \\ &\quad + 0.093C_8^{\rm eff}(M_W) - 0.198C_9^{\rm eff}(M_W) \\ &\quad - 0.198C_{10}^{\rm eff}(M_W) - 0.178C_{11}^{\rm eff}(M_W), \\ \tilde{C}_7^{\rm eff}(m_b) &= 0.381\tilde{C}_1^{\rm eff}(M_W) + 0.665\tilde{C}_7^{\rm eff}(M_W) \\ &\quad + 0.093\tilde{C}_8^{\rm eff}(M_W) - 0.198\tilde{C}_9^{\rm eff}(M_W) \\ &\quad - 0.198\tilde{C}_{10}^{\rm eff}(M_W) - 0.178\tilde{C}_{11}^{\rm eff}(M_W) \\ &\quad + 0.510\tilde{C}_{12}^{\rm eff}(M_W) + 0.510\tilde{C}_{13}^{\rm eff}(M_W) \\ &\quad + 0.381\tilde{C}_{14}^{\rm eff}(M_W) - 0.213\tilde{C}_{16}^{\rm eff}(M_W). \end{aligned} \quad (7)$$

The branching fraction for $\mathrm{Br}(b \to s + \gamma)$ is expressed through the semileptonic decay $b \to u|ce\bar{\nu}$ so that the large bottom mass dependence ($\sim m_b^5$) and uncertainties in CKM elements cancel out;

$$\mathrm{Br}\,(b \to s + \gamma) = \frac{\Gamma(b \to s + \gamma)}{\Gamma(b \to u|ce\bar{\nu}_e)}\mathrm{Br}_{\rm exp}(b \to u|ce\bar{\nu}_e), \quad (8)$$

where $\mathrm{Br}_{\rm exp}(b \to u|ce\bar{\nu}_e) = 10.5\%$ and

$$\Gamma(b \to s\gamma) = \frac{\alpha m_b^5}{64\pi^4}(|C_7^{\rm eff}(\mu_b)|^2 + |\tilde{C}_7^{\rm eff}(\mu_b)|^2). \quad (9)$$

Note that we have also to include RPV contributions to the semileptonic rate for consistency [11].

III. ANALYTICAL APPRAISAL OF THE RESULTS

There are three kinds of bilinear RPV parameters, μ_i, B_i, and $\tilde{m}^2_{L_{0i}}$ related by the tadpole equation constraints [1,13]. Without loss of generality, we choose μ_i and B_i to be independent. The influence of a $|B_i|$ (or $|\mu_i|$), in conjunction with $|\lambda'_{ijk}|$ is felt through the lepton number violating mass mixings in (s)leptonic propagators of tree and penguin diagrams. $|B_i|$ insertions may have much stronger influence than the $|\mu_i|$ as the former case is inversely proportional to light slepton mass squared whereas the latter ones come with the inverse of heavier squark mass squared. We focus our discussion here on the $|B_i|$ insertions to provide an analytical appraisal of the numerical results. The case for μ_i can be appreciated in a similar fashion [16].

There are two kinds of B_i–λ' combinations that contribute to $b \to s + \gamma$ at 1-loop: (a) $B_i^*\lambda'_{ij2}$ and (b) $B_i\lambda'^*_{ij3}$. These involve quark-scalar loop diagrams. Case (a) leads to the $b_L \to s_R$ transition (where SM and MSSM contribution is extremely suppressed) whereas case (b) leads to SM-like $b_R \to s_L$ transition. For the purpose of illustration, we will assume a degenerate slepton spectrum and take the sleptonic index $i = 3$ as a representative. The $j = 3[2]$ contributions for case (a) [(b)] with both sneutrino-Higgs mixings and charged-slepton-Higgs mixings are easy to appreciate. For the j values, the charged loop contributions are still possible by invoking CKM mixings. Consider the contribution of case (a) with $|B_3^*\lambda'_{332}|$ to the Wilson coefficient $\tilde{C}_7$, for instance. Through the extraction of the bilinear mass mixing effect under a perturbative diagonalization of the mass matrices [1], we obtain

$$\tilde{C}_7^{\phi^-} \approx \frac{-|V_{\rm CKM}^{tb}|^2|B_3^*\lambda'_{332}|}{M_s^2} \times \left\{ y_b \tan\beta \left[F_2\left(\frac{m_t^2}{M_{\tilde{\ell}}^2}\right) + \mathcal{Q}_u F_1\left(\frac{m_t^2}{M_{\tilde{\ell}}^2}\right)\right] + \frac{y_t m_t}{m_b}\left[F_4\left(\frac{m_t^2}{M_{\tilde{\ell}}^2}\right) + \mathcal{Q}_u F_3\left(\frac{m_t^2}{M_{\tilde{\ell}}^2}\right)\right]\right\}, \qquad (10)$$

$$\tilde{C}_7^{\phi^0} \approx \frac{-2\mathcal{Q}_d y_b |B_3^*\lambda'_{332}|\tan\beta}{M_s^2 M_S^2} F_1\left(\frac{m_b^2}{M_S^2}\right), \qquad (11)$$

for the charged and neutral scalar loop, respectively. In the above equations, proportionality to $\tan\beta$ shows the importance of these contributions in the large $\tan\beta$ limit. The M_s^2, $M_{\tilde{\ell}}^2$, M_S^2, are all scalar (slepton/Higgs) mass parameters. The term proportional to y_t above has chirality flip into the loop. Thinking in terms of the electroweak states, it is easy to appreciate that the loop diagram giving a corresponding term for $\tilde{C}_7^{\phi^0}$ (cf. involving $\tilde{\mathcal{N}}^L_{nm3}\tilde{\mathcal{N}}^{R^*}_{nm2}$) requires a Majorana-like scalar mass insertion, which has to arrive from other RPV couplings [1]. In the limit of perfect mass degeneracy between the scalar and pseudoscalar part (with no mixing) of multiplet, it vanishes. Dropping this smaller contribution, together with the difference among the Inami-Lim loop functions and the fact that the charged loop has more places to attach the photon (with also larger charge values) adding up, we expect the $\tilde{C}_7^{\phi^-}$ to be larger than $\tilde{C}_7^{\phi^0}$.

IV. NUMERICAL RESULTS

The basic strategy for the implementation of our numerical study is to choose model parameters in such a way that in the limit that the RPV parameters vanish, the resulting MSSM gives the decay rate well within the experimental limit [7]. The otherwise arbitrariness in the choice mostly does not have much of an effect on the qualitative dependence of the results on a specific combination of RPV parameters. Note that we always keep R parity conserving flavor violating squark and slepton mixings vanishing, to focus on the RPV effects. We take nonvanishing values for relevant combinations of a bilinear and a trilinear RPV parameters one at a time and stick to real values only. Our model choice is (with all mass dimensions given in GeV): squark masses 300, down-type Higgs mass 300, $\mu_0 = -300$ sleptons mass 150 and gaugino mass $M_2 = 200$ (with $M_1 = 0.5M_2$ and $M_3 = 3.5M_2$), $\tan\beta = 37$ and A parameter 300. The mass for H_u and soft bilinear parameter B_0 are determined by electroweak symmetry breaking conditions which are modified in the presence of RPV parameters [1,13].

TABLE I. Bounds for the products of bilinear and trilinear RPV couplings.

Product	Our bound	Wilson coefficient
$\left\lvert\frac{B_i\cdot\lambda'^*_{i23}}{\mu_0^2}\right\rvert$	5.0×10^{-5}	$C_{7,8}$, $\tilde{C}_{7,8}$, C_{11}, $\tilde{C}_{10}$, $\tilde{C}_{13}$
$\left\lvert\frac{B_i^*\cdot\lambda'_{i32}}{\mu_0^2}\right\rvert$	7.4×10^{-3}	$C_{7,8}$, $\tilde{C}_{7,8}$, C_{10}, $\tilde{C}_{11}$
$\left\lvert\frac{B_i\cdot\lambda'^*_{i33}}{\mu_0^2}\right\rvert$	2.3×10^{-3}	$C_{7,8}$, $\tilde{C}_{7,8}$
$\left\lvert\frac{B_i^*\cdot\lambda'_{i22}}{\mu_0^2}\right\rvert$	6.5×10^{-2}	$\tilde{C}_{7,8}$
$\left\lvert\frac{B_i\cdot\lambda'^*_{i13}}{\mu_0^2}\right\rvert$	8.0×10^{-2}	$C_{7,8}$
$\left\lvert\frac{B_i^*\cdot\lambda'_{i12}}{\mu_0^2}\right\rvert$	4.5×10^{-2}	$\tilde{C}_{7,8}$
$\left\lvert\frac{\mu_i^*\cdot\lambda'_{i23}}{\mu_0}\right\rvert$	2.2×10^{-3}	$C_{7,8}$
$\left\lvert\frac{\mu_i\cdot\lambda'^*_{i32}}{\mu_0}\right\rvert$	1.0×10^{-2}	$\tilde{C}_{7,8}$
$\left\lvert\frac{\mu_i\cdot\lambda'^*_{i33}}{\mu_0}\right\rvert$	8.0×10^{-2}	$C_{7,8}$

Under the scenario discussed, we impose the experimental number to obtain bounds for each combination of RPV parameters independently (given in Table I). We address here a couple of cases in a bit more detail. Consider, for instance, the case (b) combination $|B_3\lambda'^*_{323}|$. We obtain a bound of 5.0×10^{-5}, when normalized by a factor of μ_0^2.

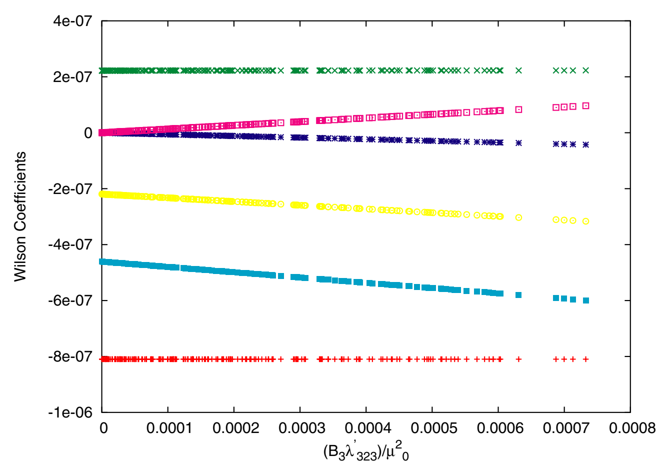

FIG. 1 (color online). Various Wilson coefficients versus $|B_3\lambda'_{323}|$. + sign stands for MSSM chargino contribution, × for the MSSM charged Higgs contribution, ⋆ for sneutrino contribution, all contributing to C_7. Empty square stands for $C_{11}(M_W)$, filled square for $C_7(M_W)$, and empty circle for $C_7(m_b)$.

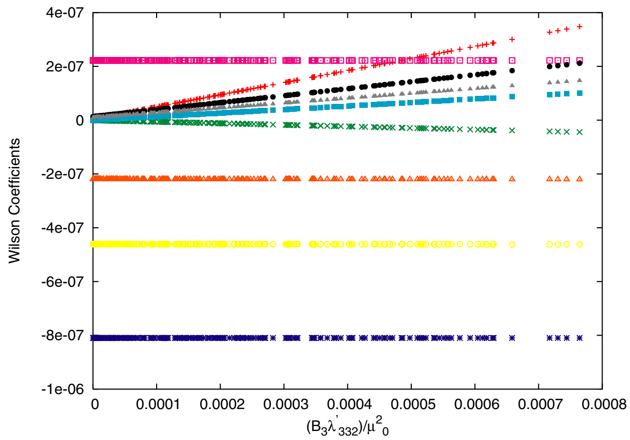

FIG. 2 (color online). Various Wilson coefficients versus $|B_3^* \lambda'_{332}|$. + sign stands for charged slepton contribution, × for sneutrino contribution, ⋆ for MSSM chargino contribution, all contributing to $\tilde{C}_7$. Empty square stands for MSSM charged Higgs contribution, filled square for $\tilde{C}_{11}(M_W)$, empty circle for $C_7(M_w)$, filled circle for $\tilde{C}_7(M_W)$, empty triangle for $C_7(m_b)$, and filled triangle for $\tilde{C}_7(m_b)$.

Since this is a $b_R \to s_L$ transition, the RPV contribution interferes with the SM as well as the MSSM contribution. In Fig. 1 we have plotted the relevant Wilson coefficients. Over and above the loop contributions we see that there are contributions coming from four-quark operator with Wilson coefficients C_{11} ($\propto y_b$) which is stronger than the other two four-quark quark coefficients $\tilde{C}_{10,13} \propto y_s$ (not shown in the graph). Since the neutral scalar loop contribution is proportional to the loop function F_1 (which is order 0.01), it is suppressed compared to current-current contributions. Also here the charged scalar contribution comes only with chirality flip inside the loop and has a CKM suppression. So the current-current is dominant. It has a more subtle role to play when one writes the regularization scheme-independent $C_7^{\text{eff}} = C_7 - C_{11}$ at scale M_W. Because of dominant and negative sign chargino contribution ($A_t \mu_0 < 0$), the positive sign C_{11} interferes constructively with C_7 and enhances the rate.

The case (b) combination $|B_3 \lambda'_{332}|$ is a different story, as it leads to $b_L \to s_R$ transition and hence RPV does not interfere with SM or MSSM contribution. This leads to a bound of 7.3×10^{-3} after normalization by μ_0^2. In Fig. 2 we have again plotted the relevant Wilson coefficients. Unlike the previous case, here we see that the contributions from charged scalar loop dominates over both neutral scalar as well as current-current contributions. This is in accordance with our analytical expectations. Again, the current-current contribution due to $\tilde{C}_{11}$ has a very subtle role to play here. The regularization scheme-independent effective Wilson coefficient $\tilde{C}_7^{\text{eff}} = \tilde{C}_7 - \tilde{C}_{11}$ at the scale M_W. The negative sign leads to cancellations and hence weakens the bound.

The influence of $|\mu_i^* \lambda'_{ijk}|$ is less stronger than the B_i insertions. The μ_i insertions affect the MSSM chargino and the neutralino type of diagrams by mixing them with the charged and the neutral leptons. Since such contributions are suppressed by the heavier squark masses, the influence is not as strong as slepton loops. However there exist gluino mediated loop diagrams with a flavor violating chirality flip in the down-squark propagator ($\propto |\mu_i^* \lambda'_{ijk}|$) which gives non-negligible contributions and indeed leads to good bounds.

V. CONCLUSIONS

To conclude we have systematically studied the influence of the combination of bilinear-trilinear RPV parameters on the decay $b \to s + \gamma$ analytically as well as numerically. Such a study has not been attempted before. We demonstrate the plausible dominance of the RPV contributions over conventional SM and MSSM contributions in some parameter space regions. These contributions are enhanced by large $\tan\beta$. It is shown that charged-slepton-Higgs mixing mediated loop typically dominates over the sneutrino-Higgs mixing mediated loop. Our study has consistently incorporated all the QCD corrections at the leading log order, with a whole list of extra operators and their Wilson coefficients arising from RPV couplings. We have shown that, through the formulation of scheme-independent effective Wilson coefficients, the new current-current operators can considerably influence the decay rate. Under a typical and compatible model parameter choice, we obtain strong bounds on several combinations of RPV parameters. Bounds on such bilinear-trilinear parameter combinations were not available before. Various $b \to s + \gamma$ contributions over different parameter space regions may complicate the story and partial cancellation among them are a likely possibility. And our leading log calculation bears relatively large uncertainty. Nevertheless, the bounds show values of the RPV parameter combinations that will play a major role in endangering the compatibility of the theoretical $b \to s + \gamma$ result with the experimental limits. This interpretation of our results is quite robust.

Our analytical formulas include all RPV contributions at 1-loop level. Numerical study also has been performed on combinations of trilinear parameters [11]. We quote here a few exciting bounds under a similar sparticle spectrum. For instance $|\lambda'_{i33} \cdot \lambda'^*_{i23}|$ for $i = 2, 3$ should be less than 1.6×10^{-3} to be compared with rescaled existing bound of 2×10^{-2}.

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