$R$-parity Violation and Semileptonic Decays of $B$-meson

Ji-Ho Jang *, Yeong Gyun Kim †, and Jae Sik Lee ‡
Department of Physics, Korea Advanced Institute of Science and Technology
Taejon 305-701, Korea

Abstract

We investigate the effects of $R$-parity violation on the semileptonic decays of $B$-meson in the minimal supersymmetric standard model with explicit $R$-parity violation and discuss its physical implications. We find that the semileptonic decays of $B$-meson can be largely affected by $R$-parity violation.

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*E-mail: jhjang@chep6.kaist.ac.kr
†E-mail: ygkim@chep6.kaist.ac.kr
‡E-mail: jslee@chep6.kaist.ac.kr
One of the most important objects of future experiments is to find supersymmetry or a hint for it. In supersymmetric models, there are gauge invariant interactions which violate the baryon number $B$ and the lepton number $L$ generally. To prevent presence of these $B$ and $L$ violating interactions in supersymmetric models, an additional global symmetry is required. This requirement leads to the consideration of the so called $R$-parity. The $R$-parity is given by the relation $R_p = (-1)^{(3B + L + 2S)}$ where $S$ is the intrinsic spin of a field. Even though the requirement of $R_p$ conservation gives a theory consistent with present experimental searches, there is no good theoretical justification for this requirement. Therefore models with explicit $R_p$ violation ($R_p$) have been considered by many authors [1].

In models without $R_p$, the supersymmetric particles can decay into the ordinary particles alone. So the couplings which violate $R_p$ can be detected by using the usual particle detectors. If we discover a sign of $R_p$ in future experiments, it may provide us with some hints for supersymmetry. Among future experiments, the upcoming experiments on $B$-mesons (BaBar, BELLE, HERA B, CLEO, RUN II at FNAL) [2] motivate the study of the effects of $R_p$ on the decays of $B$-meson.

In this paper, we study the semileptonic decays of $B$-meson in the minimal supersymmetric standard model (MSSM) with $R_p$. We investigate how much $R_p$ affects the semileptonic decay rates within the present bounds and discuss its physical implications. We find that the semileptonic decays of $B$-meson can be largely affected by $R_p$.

In the MSSM the most general $R_p$ violating superpotential is given by

$$W_{R_p} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c E_k^c. \quad (1)$$

Here $i, j, k$ are generation indices and we assume that possible bilinear terms $\mu_i L_i H_2$ can be rotated away. $L_i$ and $Q_i$ are the $SU(2)$-doublet lepton and the quark superfields and $E_i^c, U_i^c, D_i^c$ are the singlet superfields respectively. $\lambda_{ijk}$ and $\lambda'_{ijk}$ are antisymmetric under the interchange of the first two and the last two generation indices respectively; $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda'_{ijk} = -\lambda''_{ikj}$. So the number of couplings is 45 (9 of the $\lambda$ type, 27 of the $\lambda'$ type and 9 of the $\lambda''$ type). Among these 45 couplings, 36 couplings are related with the lepton flavor violation. Usually, the constraints on the couplings with heavy fields are not as strong as those with light fields.

There are upper bounds on a single $R_p$ violating coupling from several different sources [3–7]. Among these, upper bounds from atomic parity violation and $eD$ asymmetry [3], $\nu_\mu$ deep-inelastic scattering [4], neutrinoless double beta decay [4], $\nu$ mass [4], $K^+, t$-quark decays [3][4][4], and $Z$ decay width [5] are strong. Neutrinoless double beta decay gives $\lambda_{111} < 4 \times 10^{-4}$. The bounds from $\nu$ mass are $\lambda_{133} < 10^{-3}$ and $\lambda'_{133} < 10^{-3}$. From $K^+$-meson decays one obtain $\lambda''_{1jk} < 0.012$ for $j = 1$ and $2$. Here all masses of scalar partners which mediate the processes are assumed to be 100 GeV. Extensive reviews of the updated limits on a single $R_p$ violating coupling can be found in [3][4].

There are more stringent bounds on some products of the $R_p$ violating couplings from the mixings of the neutral $K$- and $B$- mesons and rare leptonic decays of the $K_L$-meson, the muon and the tau [10], $B^0$ decays into two charged leptons [11], $b\bar{b}$ productions at LEP [12] and muon(ium) conversion, and $\tau$ and $\pi^0$ decays [3].

$R_p$ couplings with heavy generation indices are only moderately constrained. This means that we could constrain $R_p$ couplings with heavy generation indices from $B$ meson decays...
and $R_p$ signals could be found in the upcoming experiments on $B$ mesons [2]. First examples on $R_p$ couplings from $B$ decays were given in Ref. [12].

In this paper we assume that the $B$ violating couplings $\lambda''$ are vanishing to avoid too fast proton decays. Especially in the models with a very light gravitino ($G$) or axino ($\tilde{a}$), $\lambda''$ have to be very small independently of $\lambda'$ from the proton decay $p \rightarrow K^+ G$ (or $K^+ \tilde{a}$); $\lambda_{112}'' < 10^{-15}$ [4]. One can construct a grand unified model which has only lepton number non-conserving trilinear operators in the low energy superpotential when $R_p$ is broken only by bilinear terms of the form $L_i H_2$ [13]. And usually it may be very difficult to discern signals of $B$-violating interactions above QCD backgrounds [3].

In the MSSM with $R_p$, the terms in the effective lagrangian relevant for the semileptonic $B$-meson decays are [16]

$$\mathcal{L}^{eff}(b \rightarrow q \ell \nu_l) = - V_{qb} \frac{4 G_F}{\sqrt{2}} \left[ (\bar{q} \gamma^\mu P_L b)(\bar{\ell} \gamma_\mu P_L \nu_l) - R_l (\bar{q} P_R b)(\bar{\ell} P_L \nu_l) \right],$$

(2)

where $P_{R,L} = \frac{1}{2}(1 \pm \gamma_5)$, $R_l = r^2 m_e m^Y_b$ and $r = \frac{\tan \beta}{m_{H^\mp}}$. An upper index $Y$ denotes the running quark mass, $\tan \beta$ is the ratio of the vacuum expectation values of the neutral Higgs fields and $m_{H^\pm}$ is the mass of the charged Higgs fields. The first term in Eq. (2) gives the standard model (SM) contribution and the second one gives that of the charged Higgs scalars. Neglecting the masses of the electron ($l = 1$) and the muon ($l = 2$), the contribution of the charged Higgs scalars is zero. The contribution of the charged Higgs scalars is not vanishing only when $l = 3$; $b \rightarrow q \tau \bar{\nu}_\tau$. We neglect a term proportional to $m^Y_e$ for $q = c$ since the term is suppressed by the mass ratio $m^Y_c/m^Y_b$ and does not have the possibly large $\tan^2 \beta$ factor.

In the MSSM without $R_p$, the exchange of the sleptons and the squarks leads to the additional four-fermion interactions which are relevant for the semileptonic decays of $B$-meson. Considering the fact that the CKM matrix $V$ is not an identity matrix, the $\lambda'$ terms of the Eq. (1) are reexpressed in terms of the the fermion mass eigenstates as follow

$$W_{\lambda'} = \lambda'_{ijk} \left( N_i D_j - \sum_p V^T_{jp} E_i U_p \right) D^c_k,$$

(3)

where $N_i$, $E_i$, $U_i$ and $D_i$ are the superfields with neutrinos, charged leptons, up- and down-type-quarks and $\lambda'$ have been redefined to absorb some field rotation effects. From Eq. (1) and Eq. (3) we obtain the effective interactions which are relevant for the semileptonic decays of $B$-meson as follows

$$\mathcal{L}^{eff}_{R_p}(b \rightarrow q \ell \nu_n) = - V_{qb} \frac{4 G_F}{\sqrt{2}} \left[ A^{q}_{ln} (\bar{q} \gamma^\mu P_L b)(\bar{\ell} \gamma_\mu P_L \nu_n) - B^{q}_{ln} (\bar{q} P_R b)(\bar{\ell} P_L \nu_n) \right],$$

(4)

where we assume the matrices of the soft mass terms are diagonal in the fermion mass basis.

Note that the operators in Eq. (4) take the same form as those of the MSSM with $R_p$. Comparing with the SM, the above effective lagrangian includes the interactions even when $l$ and $n$ are different from each other. The dimensionless coupling constants $A$ and $B$ depend on the species of quark, charged lepton and neutrino and are given by

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The interference contributions respectively. The explicit forms and relations between $\Gamma$ and the subindices $A_i$ are given in Ref. [16,18]. For $\lambda_{i3}$, $\lambda_{1i}$ and $\lambda_{2i}$, we should sum the above decay rates over neutrino species to compare with experimental data as follow.

\begin{align}
\mathcal{A}_{ln}^q &= \frac{\sqrt{2}}{4 G_F V_{qb}} \sum_{i,j=1}^{3} \frac{1}{2 m_{l_i}^2} V_{qj} \lambda_{i3i}^r \lambda_{lji}^r, \\
\mathcal{B}_{ln}^q &= \frac{\sqrt{2}}{4 G_F V_{qb}} \sum_{i,j=1}^{3} \frac{2}{m_{l_i}^2} V_{qj} \lambda_{iml}^r \lambda_{lji}^r, \quad (5)
\end{align}

where $q = u, c$ and $l$ and $n$ are the generation indices running from 1 to 3.

From the numerical values of [17], we find

\begin{align}
\mathcal{A}_{ln}^u &= \sum_{i=1}^{3} \lambda_{i3i}^r \left\{ 422 \lambda_{11i}^r \left( \frac{V_{ud}/0.9751}{V_{ub}/0.0035} \right) + 96 \lambda_{12i}^r \left( \frac{V_{us}/0.2215}{V_{ub}/0.0035} \right) + 1.52 \lambda_{133}^r \right\} \left( \frac{100 \text{ GeV}}{m_{l_i}} \right)^2, \\
\mathcal{B}_{ln}^u &= \sum_{i=1}^{3} \lambda_{iml}^r \left\{ 1689 \lambda_{113}^r \left( \frac{V_{ud}/0.9751}{V_{ub}/0.0035} \right) + 384 \lambda_{123}^r \left( \frac{V_{us}/0.2215}{V_{ub}/0.0035} \right) + 6.1 \lambda_{133}^r \right\} \left( \frac{100 \text{ GeV}}{m_{l_i}} \right)^2, \\
\mathcal{A}_{ln}^c &= \sum_{i=1}^{3} \lambda_{i3i}^r \left\{ 8.2 \lambda_{11i}^r \left( \frac{V_{cd}/0.221}{V_{cb}/0.041} \right) + 36 \lambda_{12i}^r \left( \frac{V_{cs}/0.9743}{V_{cb}/0.041} \right) + 1.52 \lambda_{133}^r \right\} \left( \frac{100 \text{ GeV}}{m_{l_i}} \right)^2, \\
\mathcal{B}_{ln}^c &= \sum_{i=1}^{3} \lambda_{iml}^r \left\{ 32.7 \lambda_{113}^r \left( \frac{V_{cd}/0.221}{V_{cb}/0.041} \right) + 144 \lambda_{123}^r \left( \frac{V_{cs}/0.9743}{V_{cb}/0.041} \right) + 6.1 \lambda_{133}^r \right\} \left( \frac{100 \text{ GeV}}{m_{l_i}} \right)^2. \quad (6)
\end{align}

Note the large numerical factors coming from the big differences between the values of the CKM matrix elements.

When the species of the charged lepton and the neutrino are same, the decay rate of the process $b \to qe_l \nu_l$ is

\begin{align}
\Gamma_l^q &= \frac{|V_{qb}|^2 G_F^2 m_b^5}{192 \pi^3} \left\{ 1 + \mathcal{A}_{ll}^q |\Gamma_W + \frac{1}{4} |\mathcal{B}_{ll}^q |^2 \Gamma_H - 2 \text{Re} \left[ (R_l + \mathcal{B}_{ll}^q ) (1 + \mathcal{A}_{ll}^q ) \right] \frac{m_{e_l}}{m_b} \Gamma_I \right\}. \quad (7)
\end{align}

And for the different species of the charged lepton and the neutrino, the decay rate of the process $b \to qe_l \nu_n$ is

\begin{align}
\Gamma_{ln}^q |_{l \neq n} &= \frac{|V_{qb}|^2 G_F^2 m_b^5}{192 \pi^3} \left\{ |\mathcal{A}_{ln}^q |^2 |\Gamma_W + \frac{1}{4} |\mathcal{B}_{ln}^q |^2 \Gamma_H - 2 \text{Re} \left( \mathcal{B}_{ln}^q \mathcal{A}_{ln}^q \right) \frac{m_{e_l}}{m_b} \Gamma_I \right\}. \quad (8)
\end{align}

The subindices $W, H$ and $I$ of $\Gamma$ denote the $W$ mediated (SM), charged Higgs mediated and interference contributions respectively. The explicit forms and relations between $\Gamma_W, \Gamma_H$ and $\Gamma_I$ are given in Ref. [17,18]. For $l = 1$ and 2, $R_l$ and the interference term are vanishing assuming the electron and the muon are massless.

Since the species of the neutrinos cannot be distinguished by experiments and the $R_p$ interactions allow the different kinds of the charged lepton and the neutrino as decay products, we should sum the above decay rates over neutrino species to compare with experimental data as follow

\begin{align}
\Gamma_l^q &= \sum_{n=1}^{3} \Gamma_{ln}^q. \quad (9)
\end{align}
For the process $b \rightarrow e \bar{v} X_u$, the ratio of the decay rate in the MSSM without $R_p$ to that in the SM is given by

$$\mathcal{R}_1^u \equiv \frac{\Gamma_1^u(R_p)}{\Gamma_1^u(SM)} = \left[ 1 + |\mathcal{A}_{111}^u|^2 + |\mathcal{A}_{12}^u|^2 + |\mathcal{A}_{13}^u|^2 \right] + 0.28 \left[ |\mathcal{B}_{21}^u|^2 + |\mathcal{B}_{22}^u|^2 + |\mathcal{B}_{23}^u|^2 \right]. \quad (10)$$

We will call the above ratio a $R_p$-ratio. This ratio is always bigger than 1 assuming $\mathcal{A}_{111}^u$ is real and positive. Generally the above ratio could be smaller than 1. We will consider this possibility when we deal with the processes $b \rightarrow (e^-, \mu^-) \bar{v} X_c$ which are closely related to the semileptonic branching ratio of $B$-meson. For the process $b \rightarrow \mu \bar{v} X_u$, the $R_p$-ratio is given by

$$\mathcal{R}_2^u \equiv \frac{\Gamma_2^u(R_p)}{\Gamma_2^u(SM)} = \left[ |\mathcal{A}_{12}^u|^2 + |1 + \mathcal{A}_{22}^u|^2 + |\mathcal{A}_{23}^u|^2 \right] + 0.28 \left[ |\mathcal{B}_{21}^u|^2 + |\mathcal{B}_{22}^u|^2 + |\mathcal{B}_{23}^u|^2 \right]. \quad (11)$$

The above two ratios could be largely affected by $R_p$ within the present bounds on $\lambda \lambda'$ and $\lambda' \lambda'$. From the measurements of the ratio $|V_{ub}/V_{cb}|$ [19]

$$|V_{ub}/V_{cb}| = 0.06 - 0.10, \quad (12)$$

we can see that about 100% of the SM rate is allowed in the process $b \rightarrow u e^- (\mu^-) \bar{v}$ as a new physics contribution. In Table [1], we list the combinations of couplings whose present upper limits allow $\mathcal{R}_{(1,2)}^u$ to have values greater than 2, assuming only one product of $R_p$-violating couplings is nonzero and $\mathcal{A}_{111}^u$ is real and positive. For example, the bound $\lambda'_{132} \lambda'_{112} < 4.8 \times 10^{-3}$ can allow the ratio $\mathcal{R}_{1}^u$ to have the value of 9. From Table [1] we can see that this large enhancement comes from the big differences between the values of the CKM matrix elements. This means that the experimental determination of the ratio $|V_{ub}/V_{cb}|$ could be greatly affected by $R_p$.

There are no important contributions of $B_{(1,2)}^u$ to $\mathcal{R}_{(1,2)}^u$ taking into account the constraints coming from $B^0$-meson decays into two charged leptons [11]. For example, let’s assume that only $\lambda_{132} \lambda'_{113}$ which contributes $B_{23}^u$ is not vanishing. The upper bound on the product is $1.2 \times 10^{-3}$ without considering the process $B^0 \rightarrow \mu^+ \tau^\mp$. This upper bound gives $\mathcal{R}_2^u < 2.2$. But the product is more strongly constrained by the measurement of the process $B^0 \rightarrow \mu^+ \tau^\mp : \lambda_{132} \lambda'_{113} < 6.0 \times 10^{-4}$. This gives $\mathcal{R}_2^u < 1.3$. The maximum values of $\mathcal{R}_1^u$ and $\mathcal{R}_2^u$ allowed by $B_{(1,2)}^u$ are 1.1 and 1.3 respectively.

For the process $b \rightarrow \tau \bar{v} X_u$, the $R_p$-ratio is given by

$$\mathcal{R}_3^u \equiv \frac{\Gamma_3^u(R_p)}{\Gamma_3^u(SM)} = \left[ |\mathcal{A}_{31}^u|^2 + |\mathcal{A}_{32}^u|^2 + |1 + \mathcal{A}_{33}^u|^2 \right] + 0.31 \left[ |\mathcal{B}_{31}^u|^2 + |\mathcal{B}_{32}^u|^2 + |R_3 + \mathcal{B}_{33}^u|^2 \right]$$

$$- 0.34 \text{Re} \left[ A_{31}^{u*} B_{31}^u + A_{32}^{u*} B_{32}^u + (1 + A_{33}^{u*})(R_3 + B_{33}^u) \right] \left( \frac{m_\tau/1.8 \text{ GeV}}{m_b/4.8 \text{ GeV}} \right). \quad (13)$$

This process could be largely affected by $R_p$ (see Table [1]). There is no experimental evidence for this process at present.

For the process $b \rightarrow e \bar{v} X_c$, the $R_p$-ratio is given by
\[ \mathcal{R}_1^c \equiv \frac{\Gamma_1^c(R_p)}{\Gamma_1^c(SM)} = \left[ 1 + |A_{11}^c|^2 + |A_{12}^c|^2 + |A_{13}^c|^2 \right] + 0.28 \left[ |B_{11}^c|^2 + |B_{12}^c|^2 + |B_{13}^c|^2 \right]. \] (14)

From the measurements of the semileptonic branching ratio \( B_{SL} \) we can see that about 5% of the SM rate is allowed in the process \( b \to c e^- \bar{\nu} \) as a new physics contribution. In Table II, we list the combinations of couplings whose present upper limits allow \( \mathcal{R}_1^c \) to have values greater than 1.1 assuming only one product of \( R_p \)-violating couplings is nonzero and \( A_{il}^c \) is real and positive.

For the process \( b \to \mu \bar{\nu} X_c \) the \( R_p \)-ratio is given by

\[ \mathcal{R}_2^c \equiv \frac{\Gamma_2^c(R_p)}{\Gamma_2^c(SM)} = \left[ |A_{21}^c|^2 + |1 + A_{22}^c|^2 + |A_{23}^c|^2 \right] + 0.28 \left[ |B_{21}^c|^2 + |B_{22}^c|^2 + |B_{23}^c|^2 \right]. \] (16)

We list the combinations of couplings similar to the case of \( b \to e \bar{\nu} X_c \) in Table I. We also observe that the contributions of \( B_{(1,2)n}^c \) are negligible taking into account the constraints coming from \( B^0 \)-meson decays into two charged leptons.

From the considerations of the processes \( b \to e(\mu)\bar{\nu}X_{u,c} \), we can see that the contributions of the \( \lambda \)-type couplings to the semileptonic decays of \( B \)-meson would be negligible comparing with those of the \( \lambda' \)-type couplings within present bounds.

If we loose the assumption that \( A_{11}^c \) and \( A_{22}^c \) are real and positive, \( R_p \) can decrease the semileptonic branching ratio. For example, let's assume that only \( \lambda_{132}^c \lambda_{122}^c \) which contributes to \( A_{11}^c \) is nonzero. Since the upper bound on the magnitude of this combination is 4.8 \( \times 10^{-3} \), it can decrease \( \mathcal{R}_1^c \) by 0.3. In fact we obtain

\[ 0.7 < \mathcal{R}_1^c < 1.5, \]
\[ 0.7 < \mathcal{R}_2^c < 1.7. \] (17)

This implies that it is possible to explain the gap between the measured and the expected values for the semileptonic branching ratio of \( B \)-meson by \( R_p \).

\( R_p \) could results in the lepton non-universality. The semileptonic branching ratios \( b \to e\nu X \) and \( b \to \mu\nu X \) measured by the L3 Collaborations [21] are

\[ B(b \to e\nu X) = (10.89 \pm 0.55) \%, \]
\[ B(b \to \mu\nu X) = (10.82 \pm 0.61) \%. \] (18)

Considering this lepton universality measurements under the assumption that \( R_p \) does not contribute to these two semileptonic branching ratios simultaneously, we can derive 1\( \sigma \) bounds on single and some products of \( R_p \) couplings slightly stronger than previous ones, see Table II.

For the process \( b \to \tau \bar{\nu} X_c \), the \( R_p \)-ratio is given by

\[ \mathcal{R}_3^c \equiv \frac{\Gamma_3^c(R_p)}{\Gamma_3^c(SM)} = \left[ |A_{31}^c|^2 + |A_{32}^c|^2 + |1 + A_{33}^c|^2 \right] + 0.31 \left[ |B_{31}^c|^2 + |B_{32}^c|^2 + |B_{33}^c|^2 \right] \]
\[ \quad - 0.35 \left| A_{31}^c B_{31}^c + A_{32}^c B_{32}^c + (1 + A_{33}^c)(R_3 + B_{33}^c) \right| \left( \frac{m_\tau/1.8 \text{ GeV}}{m_6/4.8 \text{ GeV}} \right). \] (19)
Using the SM prediction for the branching ratio $B(\bar{B} \rightarrow \tau \bar{\nu} X) = 2.30 \pm 0.25\%$ [18] and the experimental results of the branching ratio, $2.68 \pm 0.28\%$ [20] and assuming $\frac{B(b \rightarrow \tau \bar{\nu} X(R_p))}{B(b \rightarrow \tau \bar{\nu} X(SM))} \approx \mathcal{R}_3^c$, we obtain

$$\mathcal{R}_3^c < 1.34 \ (1\sigma).$$

(20)

We find that all the constraints on the products of $R_p$ couplings coming from the measurement of the branching ratio of the process $\bar{B} \rightarrow \tau \bar{\nu} X$ are weaker than previous ones neglecting $R_3$. We list some competitive upper bounds on $R_p$ couplings from $\bar{B} \rightarrow \tau \bar{\nu} X$ in Table IV. One of them ($\lambda'_{333}$) was firstly given in Ref. [12].

To see the effects of $R_p$ on the determination of the upper bound on $r = \tan \beta/m_{H^\pm}$, we assume only $\mathcal{A}_{33}^c$ is not vanishing. The condition $\mathcal{R}_3^c < 1.34$ becomes

$$|1 + \mathcal{A}_{33}^c|^2 + 0.31 |R_3|^2 - 0.35 \text{Re}(R_3(1 + \mathcal{A}_{33}^{c*})) < 1.34.$$  

(21)

Assuming $\mathcal{A}_{33}^c$ is real and using the present bound $|\mathcal{A}_{33}^c| < 1.0 \times 10^{-1}$ and we find

$$r < 0.54 \ \text{GeV}^{-1} \text{ for } \mathcal{A}_{33}^c = -0.1,$$

$$r < 0.52 \ \text{GeV}^{-1} \text{ for } \mathcal{A}_{33}^c = 0,$$

$$r < 0.51 \ \text{GeV}^{-1} \text{ for } \mathcal{A}_{33}^c = 0.1.$$  

(22)

We obtain slight weak upper bounds on $r$ than that of Ref. [10] : $r < 0.51 \ \text{GeV}^{-1}$. We observe the effects of $R_p$ on the bound on $r$ are negligible.

In conclusion, we investigate the effects of $R_p$ on the semileptonic decays of $B$-meson in the MSSM with explicit $R$-parity violation. We find that $R_p$ has large effects on the experimental determination of the ratio $|\frac{V_{ub}}{V_{cb}}|$ and could decrease the semileptonic branching ratio. The effects of $\lambda$-type couplings are negligible compared with those of $\lambda'$-type couplings. Also are derived the bounds on single and some products of $R_p$ couplings slightly stronger than previous ones. We observe that the effects of $R_p$ on the bound on $\tan \beta/m_{H^\pm}$ are negligible.

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TABLE I. Maximally allowed $R_p$-ratios and the list of combinations whose present upper bounds are weak enough to allow the ratios to have the value greater than 2 for the processes $b \to e_\ell \bar{\nu} X_\mu$. We assume that only one combination is nonzero and $A_{ij}^R$ is real and positive. We use the magnitudes of the CKM matrix elements and the masses of the squarks and the sleptons as shown in Eq. (6).

| Processes | Combinations | Upper Bound $\times$ CKM | Maximum of $R_p$-ratio |
|-----------|--------------|---------------------------|------------------------|
| $b \to e_\ell \bar{\nu} X_\mu$ | $\lambda'_{132} \lambda'_{112}$ | $4.8 \times 10^{-3} \times (V_{ud}/V_{ub})^{a,b}$ | 9.0 |
| | $\lambda'_{132} \lambda'_{122}$ | $4.8 \times 10^{-3} \times (V_{us}/V_{ub})^{a,b}$ | 2.1 |
| | $\lambda'_{232} \lambda'_{112}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 6.0 |
| | $\lambda'_{233} \lambda'_{113}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 6.0 |
| | $\lambda'_{332} \lambda'_{112}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 2.7 |
| | $\lambda'_{333} \lambda'_{113}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 2.7 |
| $b \to \mu \bar{\nu} X_\mu$ | $\lambda'_{131} \lambda'_{211}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{d,b}$ | 2.7 |
| | $\lambda'_{132} \lambda'_{212}$ | $4.8 \times 10^{-3} \times (V_{ud}/V_{ub})^{a,b}$ | 5.0 |
| | $\lambda'_{231} \lambda'_{211}$ | $2.6 \times 10^{-3} \times (V_{ud}/V_{ub})^{e,b}$ | 4.5 |
| | $\lambda'_{232} \lambda'_{212}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 10.4 |
| | $\lambda'_{233} \lambda'_{213}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 10.4 |
| | $\lambda'_{333} \lambda'_{211}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 2.3 |
| | $\lambda'_{333} \lambda'_{212}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 2.7 |
| | $\lambda'_{333} \lambda'_{213}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 2.7 |
| $b \to \tau \bar{\nu} X_\mu$ | $\lambda'_{331} \lambda'_{211}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{d,b}$ | 2.7 |
| | $\lambda'_{132} \lambda'_{312}$ | $4.8 \times 10^{-3} \times (V_{ud}/V_{ub})^{a,b}$ | 5.0 |
| | $\lambda'_{231} \lambda'_{311}$ | $2.6 \times 10^{-3} \times (V_{ud}/V_{ub})^{e,b}$ | 2.2 |
| | $\lambda'_{232} \lambda'_{312}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 5.8 |
| | $\lambda'_{233} \lambda'_{313}$ | $5.3 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 5.8 |
| | $\lambda'_{331} \lambda'_{311}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 5.3 |
| | $\lambda'_{332} \lambda'_{312}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 5.3 |
| | $\lambda'_{333} \lambda'_{313}$ | $3.1 \times 10^{-3} \times (V_{ud}/V_{ub})^{c,b}$ | 5.3 |

(a): $t$-decay (2σ) [3], (b): $K^+$-decay (90 % C.L.) [4][5], (c): $Z$ decay width (1σ) [6], (d): Atomic parity violation and $eD$ asymmetry (1σ) [7], (e): $\nu_\mu$ deep-inelastic scattering (2σ) [8].
TABLE II. Maximally allowed $R_p$-ratios and the list of combinations whose present upper bounds are weak enough to allow the ratios to have the value greater than 1.1 for the processes $b \rightarrow e \bar{\nu} X_c$. We assume that only one combination is nonzero and $A_f^c$ is real and positive. We use the magnitudes of the CKM matrix elements and the masses of the squarks and the sleptons as shown in Eq. (6).

| Processes       | Combinations | Upper Bound $\times$ CKM | Maximum of $R_p$-ratio |
|-----------------|--------------|---------------------------|------------------------|
| $b \rightarrow e \bar{\nu} X_c$ | $\lambda'_{131}\lambda'_{121}$ | $3.1 \times 10^{-3} \times (V_{cs}/V_{cb})^{a,b}$ | 1.2 |
|                 | $|\lambda'_{131}|^2$ | $6.8 \times 10^{-2} \times (V_{cb}/V_{cb})^{a}$ | 1.2 |
|                 | $\lambda'_{132}\lambda'_{122}$ | $4.8 \times 10^{-3} \times (V_{cs}/V_{cb})^{c,b}$ | 1.4 |
|                 | $|\lambda'_{132}|^2$ | $1.6 \times 10^{-1} \times (V_{cb}/V_{cb})^{c}$ | 1.5 |
| $b \rightarrow \mu \bar{\nu} X_c$ | $\lambda'_{231}\lambda'_{221}$ | $2.6 \times 10^{-3} \times (V_{cs}/V_{cb})^{d,b}$ | 1.2 |
|                 | $|\lambda'_{231}|^2$ | $4.8 \times 10^{-2} \times (V_{cb}/V_{cb})^{d}$ | 1.2 |
|                 | $\lambda'_{232}\lambda'_{222}$ | $5.3 \times 10^{-3} \times (V_{cs}/V_{cb})^{e,b}$ | 1.4 |
|                 | $|\lambda'_{232}|^2$ | $1.9 \times 10^{-1} \times (V_{cb}/V_{cb})^{e}$ | 1.7 |
|                 | $\lambda'_{233}\lambda'_{223}$ | $5.3 \times 10^{-3} \times (V_{cs}/V_{cb})^{e,b}$ | 1.4 |
|                 | $|\lambda'_{233}|^2$ | $1.9 \times 10^{-1} \times (V_{cb}/V_{cb})^{e}$ | 1.7 |

(a): Atomic parity violation and $eD$ asymmetry (1$\sigma$ ) [3], (b): $K^+$-decay (90% C.L.) [3][4][5], (c): $t$-decay (2$\sigma$ ) [3], (d): $\nu_\mu$ deep-inelastic scattering (2$\sigma$ ) [3], (e): $Z$ decay width (1$\sigma$ ) [7].

TABLE III. Upper bounds on the magnitudes of $R_p$ couplings from the lepton universality in the semileptonic decays of $B$-meson. We use the magnitudes of the CKM matrix elements and the masses of the squarks and the sleptons as shown in Eq. (6).

| Processes       | Combinations Constrained | Upper Bound | Previous Bound |
|-----------------|--------------------------|-------------|----------------|
| $b \rightarrow e \bar{\nu} X_c$ | $\lambda'_{131}\lambda'_{121}$ | $1.1 \times 10^{-3}$ | $3.1 \times 10^{-3} \ a,b$ |
|                 | $\lambda'_{131}$ | $1.6 \times 10^{-1}$ | $2.6 \times 10^{-1} \ a$ |
|                 | $\lambda'_{132}\lambda'_{122}$ | $1.1 \times 10^{-3}$ | $4.8 \times 10^{-3} \ c,b$ |
|                 | $\lambda'_{132}$ | $1.6 \times 10^{-1}$ | $4.0 \times 10^{-1} \ c$ |
| $b \rightarrow \mu \bar{\nu} X_c$ | $\lambda'_{231}\lambda'_{221}$ | $1.1 \times 10^{-3}$ | $2.6 \times 10^{-3} \ d,b$ |
|                 | $\lambda'_{231}$ | $1.6 \times 10^{-1}$ | $2.2 \times 10^{-1} \ d$ |
|                 | $\lambda'_{232}\lambda'_{222}$ | $1.1 \times 10^{-3}$ | $5.3 \times 10^{-3} \ e,b$ |
|                 | $\lambda'_{232}$ | $1.6 \times 10^{-1}$ | $4.4 \times 10^{-1} \ e$ |
|                 | $\lambda'_{233}\lambda'_{223}$ | $1.1 \times 10^{-3}$ | $5.3 \times 10^{-3} \ e,b$ |
|                 | $\lambda'_{233}$ | $1.6 \times 10^{-1}$ | $4.4 \times 10^{-1} \ e$ |

(a): Atomic parity violation and $eD$ asymmetry (1$\sigma$ ) [3], (b): $K^+$-decay (90% C.L.) [3][4][5], (c): $t$-decay (2$\sigma$ ) [3], (d): $\nu_\mu$ deep-inelastic scattering (2$\sigma$ ) [3], (e): $Z$ decay width (1$\sigma$ ) [7].
TABLE IV. Upper bounds on the magnitudes of $H_R$ couplings from $\bar{B} \to \tau \bar{\nu} X$. We use the magnitudes of the CKM matrix elements and the masses of the squarks and the sleptons as shown in Eq. (6).

| Processes | Combinations Constrained | Upper Bound | Previous Bound |
|-----------|--------------------------|-------------|-----------------|
| $\bar{B} \to \tau \bar{\nu} X$ | $\lambda'_{331} \lambda'_{321}$ | $4.4 \times 10^{-3}$ | $3.1 \times 10^{-3}$ \(^a,b\) |
| | $\lambda'_{331}$ | $3.2 \times 10^{-1}$ | $2.6 \times 10^{-1}$ \(^a\) |
| | $\lambda'_{332} \lambda'_{322}$ | $4.4 \times 10^{-3}$ | $3.1 \times 10^{-3}$ \(^a,b\) |
| | $\lambda'_{332}$ | $3.2 \times 10^{-1}$ | $2.6 \times 10^{-1}$ \(^a\) |
| | $\lambda'_{333} \lambda'_{323}$ | $4.4 \times 10^{-3}$ | $3.1 \times 10^{-3}$ \(^a,b\) |
| | $\lambda'_{333}$ | $3.2 \times 10^{-1}$ \(^c\) | $2.6 \times 10^{-1}$ \(^a\) |

(a): $Z$ decay width (1σ) \(^7\), (b): $K^+$-decay (90% C.L.) \(^6,10\), (c): $\bar{B} \to \tau \bar{\nu} X$ \(^12\).