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Dilepton decays and oscillation of B_s in split supersymmetry with R-parity violation

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We study B physics phenomenology in the scenario of split supersymmetry without R parity. By assuming the constraints of bilinear (trilinear) R-parity violating couplings, which are introduced to solve the problem of the atmospheric (solar) neutrino mass, we show that the decay branching ratios of $B_s \to \ell^+\ell^-$ and the mixing of $B_s - \bar{B}_s$ can be large. Explicitly, we find that $B(B_s \to \mu^+\mu^-) = O(10^{-7})$ and $\Delta m_{B_s} = O(10^{-9})$ GeV, which should be observed at future hadron colliders.

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It is believed that the standard model (SM) is not complete due to most phenomena being based on 19 input parameters [1]. It is expected that new physics should exist at some high energy scale Λ to smear the divergent mass of Higgs, induced from one-loop level. Otherwise, the principle of naturalness [2] breaks down while Λ goes to the scale which is much higher than that of electroweak. It is found that extending the SM to supersymmetry (SUSY) at the scale Λ of O(TeV) can solve not only the hierarchy problem, but also the problem of unified gauge coupling [3,4]. Furthermore, the predicted lightest neutralino in supersymmetric models could also provide the candidate of dark matter [3,5].

Apart from the above successes, models with SUSY still suffer some difficulties from phenomenological reasons, such as the problems on small CP violating phases, large flavor mixings, and proton decays, as well as they predict a too large cosmological constant. Inevitably, fine-tuning always appears in the low-energy physics. Recently, in order to explain the cosmological constant problem and preserve the beauty of the ordinary low-energy SUSY models, the scenario of split SUSY was suggested [6,7], in which the SUSY breaking scale is much higher than the electroweak scale. In this split SUSY scenario, except the SM Higgs which could be as light as the current experimental limit, the scalar particles are all ultraheavy. On the other hand, by the protection of approximate chiral symmetries, the masses of fermions, such as gauginos and Higgsinos, could be at the electroweak scale [6,8].

Based on the aspect of split SUSY, various interesting topics on particle physics phenomenology have been studied, including, for instance, physics at colliders [9], Higgs [10], phenomena of stable gluino [11], sparticles in cosmic rays [12], dark matter [13,14], grand unified theories [15], neutrino physics [16], and so on.

In this paper, we examine the implication of the split SUSY scenario on B physics at hadron colliders, such as BTeV and LHC. In particular, we explore the possibility of having large effects in the dilepton decays and oscillation in the B_s system with split SUSY. In the conventional SUSY models with R-parity invariance, it is known that the gaugino penguin and box diagrams have significant contributions to B processes, such as $B_{d(s)} - \bar{B}_{d(s)}$ mixings, $B \to X_s\gamma$ [17], $B \to K^*\ell^+\ell^-$ [18], and the time-dependent CP asymmetry of $B \to \phi K_S$ [19], etc. However, since the diagrams involved are associated with squarks in the internal loop, the results in the split SUSY will be highly suppressed by the masses of squarks, denoted by m_S. Hence, one suspects that the scenario of split SUSY with R parity could not induce interesting phenomena from low-energy physics.

In this study, we consider split SUSY in the framework of R-parity violation. It has been pointed out recently in Ref. [13] that the lightest neutralino in the R-parity violating model could still remain the candidate of dark matter. Although R-parity violation leads to the decay of neutralino, by the suppression of the high-scale SUSY breaking, the neutralino lifetime could exceed the age of our Universe. Moreover, by the combination of bilinear and trilinear couplings, it has been shown in Ref. [16] that the observed mass scales of atmospheric and solar neutrinos can be accommodated in the split SUSY scenario without R parity. In our analyses, we will assume that the neutrino mixing arises from the neutralino-neutrino mixing in our split SUSY scenario.

We start by introducing the interactions of R-parity violating terms. In terms of the notations in Ref. [16], the bilinear and trilinear terms for the lepton number violation in the superpotential can be written as [16,20,21]

$$W = \mu H_1 H_2 + \epsilon_i \mu L_i H_2 + \lambda'_{ijk} L_i Q_j D^c_k + \lambda_{ijk} L_i L_j E^c_k, \tag{1}$$

and the relevant scalar potential is given by

$$V = BH_1H_2 + B_iL_iH_2 + m^2_{L_iH_1} L_i H_1^\dagger + \text{h.c.} \tag{2}$$

Note that, for simplicity, we have neglected the baryon

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number violating effects and used the same notations for superfields and ordinary fields. In split SUSY, the soft parameters B, B_i, and $m^2_{L_iH_1}$ could be the order of m^2_S. It is known that m_S is in the range of 10^9–10^{13} GeV [6–8]. From Eqs. (1) and (2), the bilinear R-parity violating terms can make the vacuum expectation values (VEVs) of sneutrino fields be nonzero [22]. In terms of a set of tadpole equations [23], which are the conditions for obtaining the stable potential, these VEVs are given by $\tilde{\nu}_i = |\langle H_2^0\rangle B_i + \langle H_1^0\rangle m^2_{L_iH_1}|/m^2_{L_i}$, where we have neglected the small contributions of D terms for simplicity. By the couplings of slepton-lepton-gaugino, neutrinos and charged leptons will mix with neutralinos and charginos. Consequently, they induce neutrino masses at tree and loop levels, respectively. It has been shown [16] that, to explain the atmospheric neutrino mass scale $\sqrt{\Delta m^2_{\mathrm{atom}}} \sim 0.05$ eV, the involving parameters, associated with bilinear couplings and defined by $\xi_i = \tilde{\nu}_i/\langle H_1^0\rangle - \epsilon_i = m^2_{L_iH_1}/m^2_{L_i} + B_i/m^2_{L_i}\tan\beta - \epsilon_i$ with $\tan\beta = \langle H_2^0\rangle/\langle H_1^0\rangle$, are limited to $10^{-6}/\cos\beta$ at tree level. In order to obtain the mass scale of solar neutrino, $\sqrt{\Delta m^2_{\mathrm{sol}}} \sim 9$ meV, one has to go to one-loop level, induced by the same bilinear couplings. However, the results are suppressed by $\eta_i m_Z^2/m^2_{L_i}$ with $\eta_i = \xi_i - B_i/B$ [16,20]. To solve the solar neutrino mass problem, it is concluded [16] that the trilinear R-parity violating couplings λ'_{i23} and λ'_{i32} need to be of order 1.

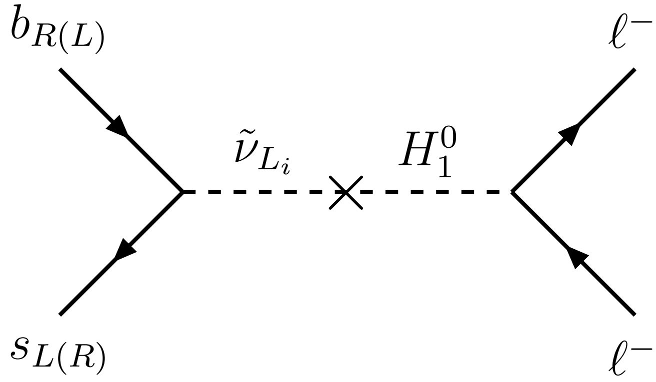

FIG. 1. Tree contribution to $B_s \to \ell^+\ell^-$ with the cross representing the mixings between sleptons and Higgs.

In the following discussions, we will take that $\lambda'_{i23,i32}$ as well as the ratios of the bilinear couplings and m^2_S, i.e., $m^2_{L_iH_1}/m^2_S$ and B_i/m^2_S, are order of unity. It is interesting to investigate if there are some observable physics phenomena beside those discussed in Ref. [16]. Since $\lambda'_{i23,i32} \sim 1$, it is natural for us to think of physics involving the flavor changing natural current (FCNC) of $b \to s$ transition. Indeed, we find that $B_s \to \ell^+\ell^-$ can occur at tree level as shown in Fig. 1, which may not be suppressed. In the SM, it is known that $B_s \to \ell^+\ell^-$ decays arise from the electroweak penguin and box diagrams. The decay branching ratio (BR) of $B_s \to \mu^+\mu^-$ is found to be $(3.8 \pm 1.0) \times 10^{-9}$ [24], which is much less than the current experimental upper limit of 5.0×10^{-7} [25]. From the relationship $B(B_s \to \tau^+\tau^-)/B(B_s \to \mu^+\mu^-) = \bar{m}_\tau^2/\bar{m}_\mu^2$ with $\bar{m}_\ell = m_\ell(1 - 4m_\ell^2/m_{B_s}^2)^{1/2}$ [26], the corresponding tau mode can also be studied. It was demonstrated that $B(B_s \to \mu^+\mu^-) = O(10^{-7})$ could be achieved in ordinary SUSY models [27]. However, it is easy to check that these contributions are suppressed in the split SUSY scenario. Since in the split SUSY approach, except the SM-like Higgs denoted by h^0 is light, all scalars are extremely heavy. Therefore, we may simplify the calculations by using $-h^0\sin\alpha(h^0\cos\alpha)$ instead of the Higgs $H_1^0(H_2^0)$, where the angle α describes the mixing of two neutral Higgses [28]. In terms of the interactions in Eqs. (1) and (2), the decay amplitude for $B_s \to \ell^+\ell^-$ is given by

$$A = \langle \ell^+\ell^-|H_{\mathrm{eff}}|\bar{B}_s\rangle = \frac{-i}{2m_h^2}\left(\frac{g m_\ell}{2m_W}\frac{\sin\alpha}{\cos\beta}\right)\frac{f_{B_s}m_{B_s}^2}{(m_b + m_s)}\frac{m^2_{L_iH_1}(\lambda'^*_{i23} - \lambda'_{i32})}{m^2_{\tilde{\nu}_i}}\bar{\ell}\ell, \tag{3}$$

where m_h, m_W, m_b, m_s, m_ℓ, m_{B_s} stand for the masses of Higgs, W boson, b quark, s quark, lepton, and B_s, respectively. As mentioned early, except the SM-like Higgs, the masses of sfermions, scalar, and pseudoscalar bosons are much higher than the electroweak scale. Therefore, the contributions from other scalar particles will be neglected. In Eq. (3), the second factor and $m^2_{L_iH_1}$ are from the coupling of the SM Higgs to the lepton and the mixings between sleptons and Higgs, respectively. In the equation, we have also used the identity $\langle 0|\bar{s}\gamma_5 b|\bar{B}_s\rangle \approx -if_{B_s}m^2_{B_s}/(m_b + m_s)$. Since the trilinear couplings in sleptons and quarks involve two possible chiralities, there is a cancellation in Eq. (3). Note that, if $\lambda'^*_{i23} = \lambda'_{i32}$, our mechanism vanishes automatically. By squaring the decay amplitude and including the phase space factor, the decay rate is derived to be

$$\Gamma = \frac{m_{B_s}}{16\pi}\frac{G_F m_\ell^2}{\sqrt{2}}\left(\frac{f_{B_s}m_{B_s}}{m_h^2}\frac{\sin\alpha}{\cos\beta}|\mathcal{N}_i|\right)^2\left[1 - \left(\frac{2m_\ell}{m_{B_s}}\right)^2\right]^{3/2} \tag{4}$$

with $\mathcal{N}_i = m^2_{L_iH_1}(\lambda'^*_{i23} - \lambda'_{i32})/m^2_{\tilde{\nu}_i}$. We note that the decay rate is proportional to m_ℓ^2, which is the same as that in the SM.

Besides $B_s \to \ell^+\ell^-$ decays, we find that the same mechanism can also generate other FCNC processes, such as the $B_s - \bar{B}_s$ mixing, induced by the W-exchange box diagrams in the SM. We note that its SM value is $(1.19 \pm 0.24) \times 10^{-11}$ GeV [29], while the current experimental limit is larger than 9.48×10^{-12} GeV [30]. In SUSY models with R parity, the main effects are also from the box diagrams but with gluinos and charginos instead of W boson in the loops [17]. Unfortunately, the resultants are associated with $1/m_S^2$, which are obviously highly suppressed in split SUSY. However, if we insert one more mixing of sneutrinos and Higgses in the Higgs propagator of Fig. 1, the $B_s - \bar{B}_s$ oscillation could be induced at tree level, too, as shown in Fig. 2. Consequently, the effective Hamiltonian is obtained as

$$\mathcal{H}_{\text{eff}} = \frac{\lambda'^{*}_{i23}\lambda'_{j32}}{m_h^2} C_{ij}(\bar{s}P_R b)(\bar{s}P_L b) + \text{h.c.}, \qquad (5)$$

where

$$C_{ij} = \frac{1}{m^2_{\tilde{\nu}_i} m^2_{\tilde{\nu}_j}}[B_i B_j^* \cos^2\alpha + m^2_{L_iH_1} m^2_{L_jH_1} \sin^2\alpha]. \qquad (6)$$

It is interesting to note that, if $B_i = m^2_{L_iH_1}$, C_{ij} will be independent of the angle α. From Eq. (5), we see that the induced oscillation is associated with the multiple of $\lambda'^{*}_{i23}\lambda'_{j32}$. By considering the CP conserving case, the effective couplings are similar to those for the solar neutrino masses, presented by [16]

$$M^{\nu}_{ij} \sim \frac{3}{8\pi^2}\lambda'_{i23}\lambda'_{j32}\frac{m_b m_s}{m_S}. \qquad (7)$$

To estimate the hadronic matrix element, we employ the results of the vacuum insertion method, given by [17]

$$\langle \bar{B}_s | \bar{s}P_R b \bar{s} P_L b | B_s \rangle \approx \left[\frac{1}{24} + \frac{1}{4}\left(\frac{m_{B_s}}{m_b + m_s}\right)^2\right] m_{B_s} f^2_{B_s}. \qquad (8)$$

As a result, the mass difference for B_s and $\bar{B}_s$ is described by

$$\begin{aligned}\Delta m_{B_s} &= 2|M_{12}| \\ &= \frac{4}{m_h^2}|\text{Re}(\lambda'^{*}_{i23}\lambda'_{j32}C_{ij})|\left[\frac{1}{24} + \frac{1}{4}\right. \\ &\quad \left.\times\left(\frac{m_{B_s}}{m_b + m_s}\right)^2\right] m_{B_s} f^2_{B_s}. \end{aligned} \qquad (9)$$

Hence, it will be interesting to see if large contributions on BRs of $B_s \to \ell^+\ell^-$ and the B_s oscillation can be obtained in our split SUSY scenario.

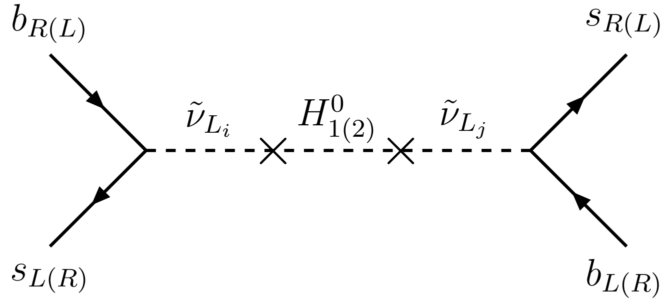

FIG. 2. Tree contribution to the mixing of $B_s - \bar{B}_s$ with the crosses representing the mixings between sleptons and Higgs.

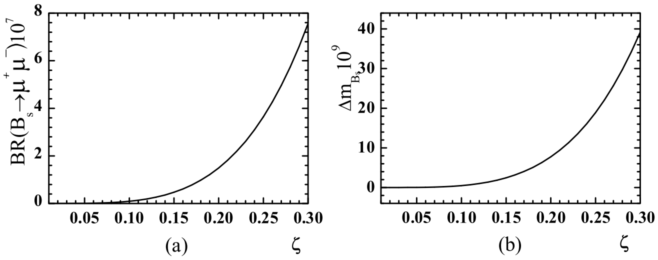

FIG. 3. (a) $\text{BR}(B_s \to \mu^+\mu^-)$ and (b) Δm_{B_s} as functions of ζ with $m_h = 150$ GeV.

To estimate the numerical values, we take $f_{B_s} = 0.23$ GeV [31], $m_{B_s} = 5.37$ GeV, $m_b = 4.5$ GeV, $m_s = 0.13$ GeV, and $\tau_{B_s} = 1.46 \times 10^{-12}s$ [30]. In order to preserve the solar neutrino mass to be $\sim$9 meV, we set $\lambda'_{i23} = 0.9$ and $\lambda'_{j32} = -0.3$. As one of the CP-even Higgs bosons is very heavy, $\alpha \simeq \pi/2 + \beta$ and $\sin\alpha/\cos\beta = 1$. Therefore, in the split SUSY scenario, we see that the BR of $B_s \to \mu^+\mu^-$ is independent of the angles α and β due to Eq. (4). For simplicity, we set $\zeta = m_{L_iH_1}/m_{\tilde{\nu}_i} = \sqrt{|B_i|}/m_{\tilde{\nu}_i}$ so that in our numerical estimations $C_{ij} = \zeta^4$. To illustrate the specific values for $\text{BR}(B_s \to \mu^+\mu^-)$ and Δm_{B_s}, by using Eqs. (4) and (9) and choosing $m_h = 150$ GeV and $\zeta = 0.18$, we get

$$\begin{aligned}\text{BR}(B_s \to \mu^+\mu^-) &= 1.0 \times 10^{-7}, \\ \Delta m_{B_s} &= 4.8 \times 10^{-9}\ \text{GeV}.\end{aligned} \qquad (10)$$

We note that in Eq. (10) the decay BR of $B_s \to \mu^+\mu^-$ is close to the current experimental limit, while Δm_{B_s} is 2 orders of magnitude larger than the SM prediction. It is clear that our results on $\text{BR}(B_s \to \mu^+\mu^-)$ and Δm_{B_s} can be observed at hadron colliders, such as BTeV and LHC, which produce more than $10^8 B_s \bar{B}_s$. In Figs. 3 and 4, we present $\text{BR}(B_s \to \mu^+\mu^-)$ and Δm_{B_s} as functions of ζ with $m_h = 150$ GeV and m_h with $\zeta = 0.18$, respectively. Since we have taken $B_i = m^2_{L_iH_1}$, the values of Δm_{B_s} will not depend on angle α.

Finally, we remark that our mechanism could also be used to the B_d processes. By using $\lambda'_{i13,j31}$ instead of $\lambda'_{i23,j32}$, similar phenomena will occur in $B_d \to \ell^+\ell^-$ de-

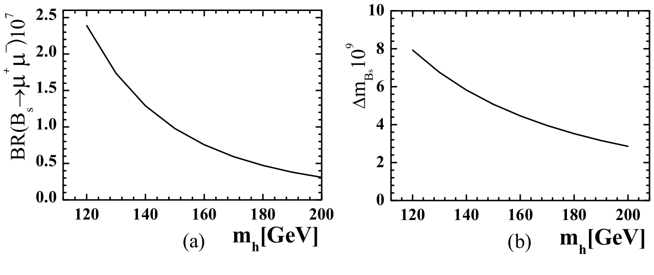

FIG. 4. (a) $\text{BR}(B_s \to \mu^+\mu^-)$ and (b) Δm_{B_s} as functions of m_h with $\zeta = 0.18$.

cays and the oscillation of B_d. However, since $m_d \ll m_s$, even with $\lambda'_{i13,j31}$ being order of unity, there are no interesting contributions to the solar neutrino masses. Moreover, the $B_d - \bar{B}_d$ mixing could be used as the constraint on the corresponding trilinear couplings. In addition, it is worth mentioning that the tree contribution of $b \to s\ell^+\ell^-$ in Fig. 1 could lead to large effects on physics in $B \to K^{(*)}\ell^+\ell^-$ [32] and $\Lambda_b \to \Lambda\ell^+\ell^-$ [33]. Similar conclusions could be applied to $\tau^\pm \to \mu^\pm\mu^+\mu^-$ as well. The study will be presented elsewhere [34].

In summary, we have studied the implications of split SUSY on the FCNC processes due to the $b \to s$ transition. It has been shown that, when the solar neutrino mass problem is solved in split SUSY scenario, we find that the mixing effects of sneutrino and Higgs could have large contributions to the BRs of $B_s \to \ell^+\ell^-$ and the $B_s - \bar{B}_s$ mixing.

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