SUSY effects in RbRbR_b: revisited under current experimental constraints Postprint

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Abstract

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Full Text

Preamble

SUSY effects in Rb: revisited under current experimental constraints

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Abstract

In this note we revisit the SUSY effects in Rb under current experimental constraints including the LHC Higgs data, the B-physics measurements, the dark matter relic density and direct detection limits, as well as the precision electroweak data. We first perform a scan to figure out the currently allowed parameter space and then display the SUSY effects in Rb. We find that although the SUSY parameter space has been severely restrained by current experimental data, both the general MSSM and the natural-SUSY scenario can still alter Rb with a magnitude sizable enough to be observed at future Z-factories (ILC, CEPC, FCC-ee, Super Z-factory) which produce 10 -10^{12} Z-bosons.

To be specific, assuming a precise measurement Rb = 2.0 × 10 at FCC-ee, we can probe a right-handed stop up to 530 GeV through chargino-stop loops, probe a sbottom to 850 GeV through neutralino-sbottom loops and a charged

Higgs to 770 GeV through the Higgs-top quark loops for a large tan . The full one-loop SUSY correction to Rb can reach 1 × 10   in natural SUSY and 2 × 10   in the general MSSM.

Keywords: Supersymmetry, Rb
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INTRODUCTION

After the discovery of the 125 GeV Higgs boson [1, 2], the primary task of the LHC is to hunt for new physics beyond the Standard Model (SM). Among various extensions of the SM, low-energy supersymmetry (SUSY) is the most appealing candidate since it can solve the gauge hierarchy problem, naturally explain cosmic cold dark matter, and achieve gauge coupling unification. The search for SUSY has long been performed both directly and indirectly. On the one hand, colliders have directly searched for sparticle production. On the other hand, SUSY effects have been probed indirectly through precision measurements of low-energy observables.

Rb = $\Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{hadrons})$ is a famous observable that is sensitive to new physics beyond the SM [4]. So far the most precise experimental value Rb^exp = 0.21629 ± 0.00066 comes from LEP and SLC measurements [5], while the SM prediction is Rb^SM = 0.21579 [6]. Future Z-factories are expected to produce many more Z-bosons than the LEP experiment. For example, 10 , 10^{1} , and 10^{12} Z-bosons are expected to be produced at the International Linear Collider (ILC) [7], the Circular Electron-Positron Collider (CEPC) [8], the Future Circular Collider (FCC-ee) [9], and the Super Z-factory [10], respectively. This will allow for more precise measurement of Rb [11] and help pin down the involved new physics effects.

The SUSY effects in Rb were calculated and discussed many years ago [12–15]. In this work we revisit these effects for two reasons: (i) Current experiments, especially the LHC experiments, have severely restrained the SUSY parameter space. It is intriguing to figure out the possible magnitude of SUSY effects in the currently allowed parameter space; (ii) Given the possibility of future Z-factories like ILC, CEPC, or FCC-ee, more precise measurement of Rb will help reveal SUSY effects, although these effects may have already been restrained to be rather small by current experiments. To know whether SUSY effects are accessible in future measurements of Rb, we must determine their currently allowed values.

This work is organized as follows. In Sec. II, we describe SUSY effects in Rb. In Sec. III, we scan over the SUSY parameter space and display the SUSY effects in the allowed parameter space. Finally, we give our conclusion in Sec. IV.

II. SUSY CORRECTIONS TO Rb

Since the SUSY effects in Rb have been calculated in the literature [12, 13], here we only give a brief description. The dominant SUSY effects in Rb come from vertex corrections to Z → b̄b, as shown in Figs. 1-5. These corrections arise from gluino loops, chargino loops, neutralino loops, charged Higgs loops, and neutral Higgs loops.

The one-loop SUSY correction to Rb can be expressed as:

R_b^SUSY R_b^0 _b^2 [v_b(3 - _b^2) + 2a_b^2 _b^2] ^{2} × {[(3 - _b^2)v_b + 6a_b _b^2] v_b + [(3 - _b^2)a_b + 6v_b _b^2] a_b}

where v_b = 1/2 - (2/3)sin^2 _W and a_b = 1/2 are respectively the vector and axial-vector couplings of the tree-level Zb̄b interaction, _b = √(1 - 4m_b^2/m_Z^2) is the velocity of the bottom quark in Z → b̄b, and v_b and a_b are the corresponding corrections defined as [13, 16, 17]:

v_b = Σ_b^L(m_Z^2) + g_b^L + Σ_b^R(m_Z^2) + g_b^R a_b = Σ_b^L(m_Z^2) + g_b^L - Σ_b^R(m_Z^2) - g_b^R

Here g_b^ (= L, R) is given by:

g_b^ = Γ_f^ (m_Z^2) - Σ_b^ (m_Z^2)

where Γ_f^ (m_Z^2) denotes the vertex loop contributions and Σ_b^ (m_Z^2) is the counterterm from the bottom quark self-energy.

We perform straightforward loop calculations and confirm the expressions in [13]. The results can be expressed as:

Σ_b^ (p^2) = -C_g/(16 ^{2}) Σ_j | _ i j^b|^2 (B + B)(p_b, m_ i, m_ j)

Γ_b^ (q^2) = C_g/(16 ^{2}) Σ_{i,j} _ i j^{b*} $^{-\,i\,j}$Z × {m_ i m_ j C (p̄_b, p_b, m_ i, m_ k, m_ j) + q^2(C + C)(p̄_b, p_b, m_ i, m_ k, m_ j) - 2C (p̄_b, p_b, m_ i, m_ k, m_ j)}

where C_g = 4/3 for gluino loops and C_g = 1 for other loops, and B , B and C , C , C are Passarino-Veltman functions [18]. The notation (,) represents (b̃, g̃) for gluino loops, (t̃, ˜) for chargino loops, (b̃, ˜) for neutralino loops, (H , t) for charged Higgs loops, and (h/a/G , b) for neutral Higgs loops.

In addition to Rb, we also show SUSY effects in the forward-backward asymmetry A_b^FB in Z → b̄b decay:

A_b^{FB}SUSY (2v_b a_b)/(v_b^2 + a_b^2)^2 × (a_b v_b - v_b a_b)

Its experimental value is 0.0992 ± 0.0016 from LEP [5], while its SM prediction is 0.1032 ± 0.0004 [19]. In future Z-factories, this forward-backward asymmetry will be measured together with Rb, and both will jointly allow for revelation of SUSY effects.

III. NUMERICAL CALCULATIONS AND RESULTS

A. SUSY parameter space

To clarify our numerical calculations, we consider both the general MSSM and the natural-SUSY scenario [20]. From the natural-SUSY results (where the natural-SUSY parameter space is much smaller than the general MSSM), we can acquire more detailed characteristics of each type of loop, while from the general MSSM results we can obtain the more general size of SUSY loop effects.

For the natural-SUSY scenario, since only the higgsino masses and third-generation squark masses are assumed to be light while other sparticles are assumed to be rather heavy and thus decoupled from low-energy observables, in our scan we fix the soft-breaking mass parameters in the first two generation squark sector and the slepton sector at 5 TeV, and assume A_t = A_b. For the electroweak gaugino masses, inspired by the grand unification relation, we take M : M = 1 : 2 and fix M at 2 TeV. The gluino mass is fixed at 2 TeV since it is supposed to be not too far above the TeV scale in natural SUSY. Other parameters vary as follows:

1 < tan < 60, 100 GeV < < 200 GeV, 100 GeV < m_Q3, m_U3, m_D3 < 2 TeV.

For the general MSSM, assuming A_t = A_b and M : M : M = 1 : 2 : 6, we scan over the following parameter space:

1 < tan < 60, 100 GeV < < 1000 GeV, 100 GeV < m_Q3, m_U3, m_D3 < 2 TeV, 100 GeV < M < 20000 GeV.

In our scan we consider the following experimental constraints:

1. Constraints on the Higgs sector from LEP, Tevatron, and LHC experiments. We use the package HiggsBounds-4.0.0 [21] to implement these constraints.
2. Experimental constraints in B-physics. We require SUSY to satisfy various B-physics bounds at the 2 level with SUSY_FLAVOR v2.0 [22], which includes B → , B → , and so on [23].
3. Measurements of precision electroweak observables. The SUSY predictions for _l^eff, sin^2 _l^eff, and m_W are required to be within the 2 ranges of experimental values [5].
4. Dark matter constraints. We require the thermal relic density of neutralino dark matter to be below the 2 upper limit of the Planck value [24] and require the dark matter-nucleon spin-independent scattering cross section _SI to satisfy the 95% C.L. limits from LUX [25]. We also consider limits on the spin-dependent dark matter-nucleon cross section _SD from the XENON100 experiment [26]. The relic density, _SI, and _SD are calculated with the code MicrOmega v2.4 [27].

Regarding mass bounds from LHC direct searches, in natural SUSY the higgsinos have very weak bounds because their pair production only gives missing energy and is rather difficult to detect (requiring a mono-jet or mono-Z in detection) [28], while for stops the right-handed one is weakly bounded (its mass can be as light as 210 GeV for higgsinos heavier than 190 GeV) [29]. When displaying numerical results, we will not show a sharp LHC bound on stop or higgsino mass (we only consider LEP bounds on stops and higgsinos). For each surviving sample we calculate the correction to Rb and display the numerical results in the following section.

B. Numerical results of Rb and A_b^FB

The results for natural SUSY and the general MSSM are displayed in Figs. 6–12 and Figs. 13–14, respectively. We first show the results of different loops and then show the combined results. Finally we compare the natural-SUSY results with the general MSSM results.

Regarding future precision of Rb measurement, the CEPC would produce 10^{1} Z-bosons and could probably measure Rb with an uncertainty of 1.7 × 10 [8, 11], while the FCC-ee could produce 10^{12} Z-bosons and give a much better Rb measurement at the 10 level [9]. In our figures, for illustration, we mark an uncertainty of 2 × 10 [9, 11]. The SUSY parameter space giving R_b^SUSY 2 × 10 corresponds to the observable region.

Some discussions about the results are in order:

(a) From Fig. 6 we see that chargino-stop loop effects are sizable only if t̃ is dominated by a right-handed stop. For a left-handed stop, its coupling with higgsino and bottom quark Y_b = g m_b/(√2 m_W cos) is suppressed (the lightest chargino ˜ ^± is dominated by higgsino component since the higgsino mass is much smaller than the gaugino masses M and M in natural SUSY). Only for very large tan can the coupling Y_b be comparable to the corresponding right-handed stop coupling Y_t = g m_t/(√2 m_W sin). Our numerical results show that tan is smaller than 35 (so that Y_b/Y_t < 1) for t̃ below 530 GeV (when tan is larger, t̃ must be heavier to satisfy experimental constraints). Note that, as commented in the preceding section, so far the right-handed stop mass in natural SUSY is weakly bounded by LHC experiments (its mass can be as light as 210 GeV for higgsinos heavier than 190 GeV) [29].

(b) As shown in Fig. 8, the gluino-sbottom loop effects are very small due to the heaviness of the gluino. The loop effects of neutralinos, charged and neutral Higgs bosons, as shown in Figs. 7, 9, and 10, are sensitive to tan and can be sizable for large tan . Our numerical results show that the neutralino loop can push the b̃ mass to 850 GeV when tan is around 32. If tan is about 23, through the charged Higgs loop, H̃ mass less than 770 GeV is excluded. The neutral Higgs loops impose an upper bound of 46 on the value of tan .

(c) From Figs. 11, 12, and 13 we see that SUSY effects in Rb and A_b^FB are correlated, as expected. Both observables can jointly probe SUSY effects. While chargino loop effects always enhance both quantities, the combined total effects of all loops can either enhance or reduce them. We also find that in the general MSSM without special naturalness requirements, both Rb and A_b^FB are allowed to vary in a larger region than in natural SUSY, especially when tan is small.

(d) From Figs. 6–13 we see that in some currently allowed parameter space, the effects of natural SUSY may be accessible in future Rb measurements. If Rb can be measured with an uncertainty of 2 × 10 , a large part of the SUSY parameter space can be covered.

(e) We find that for natural SUSY the most stringent limits are from B-physics, while for the general MSSM the most stringent limits are from dark matter-nucleon spin-independent scattering limits. The results are shown in Fig. 14. Other constraints, such as the dark matter-nucleon spin-dependent scattering cross section, also make impacts but are not as stringent as these two.

IV. CONCLUSION

We revisited SUSY effects in Rb under current experimental constraints including LHC Higgs data, B-physics measurements, dark matter relic density and direct detection limits, as well as precision electroweak data. We scanned over the SUSY parameter space and displayed the SUSY effects in Rb in the allowed parameter space.

We found that although the SUSY parameter space has been severely restrained by current experimental data, SUSY can still alter Rb with a magnitude sizable enough to be observed at future Z-factories (ILC, CEPC, FCC-ee). Assuming a precise measurement Rb = 2.0 × 10   at FCC-ee, we can probe the right-handed stop to 530 GeV through chargino-stop loops, probe the sbottom to 850 GeV through neutralino-sbottom loops, and probe the charged Higgs to 770 GeV through Higgs-top quark loops for large tan . The full one-loop SUSY correction to Rb can reach 1 × 10   in natural SUSY and 2 × 10   in the general MSSM.

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Note: Figure translations are in progress. See original paper for figures.