Implications on Supersymmetry-Breaking Mediation Mechanisms from Observing $B_s \to \mu^+\mu^-$ and the Muon $g-2$

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We consider $B_s \to \mu^+\mu^-$ and the muon $(g-2)_\mu$ in various supersymmetry-breaking mediation mechanisms. If the decay $B_s \to \mu^+\mu^-$ is observed at Tevatron Run II with a branching ratio larger than $\sim 2\times 10^{-8}$, the noscale supergravity (including the gaugino mediation), the gauge mediation scenario with a small number of messenger fields and low messenger scale, and a class of anomaly mediation scenarios will be excluded, even if they can accommodate a large muon $(g-2)_\mu$. On the other hand, the minimal supergravity scenario and similar mechanisms derived from string models can accommodate this observation.

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The minimal supersymmetric standard model (MSSM) is one of the leading candidates for the physics beyond the standard model (SM). Its detailed phenomenology depends on soft supersymmetry(SUSY)-breaking terms which contain 105 new parameters (including CP violating phases) compared to the SM. There are some interesting suggestions that have been put forward over the past two decades: gravity mediation (SUGRA), gauge mediation (GMSB), anomaly mediation (AMSB), and gaugino mediation ($\tilde{g}$MSB), etc. Each mechanism predicts specific forms of soft SUSY-breaking parameters at some messenger scale. It is most important to determine the soft parameters from various different experiments and compare the resulting soft SUSY-breaking parameters with those predicted in the aforementioned SUSY-breaking mediation mechanisms. This process will provide invaluable information on the origin of SUSY breaking, which may be intrinsically rooted in very high energy regimes such as intermediate, grand unified theory (GUT), or Planck scales.

In this Letter, we consider the low energy processes $(g-2)_\mu$, $B \to X_s\gamma$, and $B_s \to \mu^+\mu^-$ for theoretically well motivated SUSY-breaking mediation mechanisms: no-scale scenario [1] including $\tilde{g}$MSB [2], GMSB [3], and the minimal AMSB [4] and some variations [5–7]. It turns out there are qualitative differences among some correlations for different SUSY-breaking mediation mechanisms. Especially the branching ratio for $B_s \to \mu^+\mu^-$ turns out sensitive to the SUSY-breaking mediation mechanisms, irrespective of the muon anomalous magnetic moment $a_\mu^{\rm SUSY}$ as long as $10\times 10^{-10} \lesssim a_\mu^{\rm SUSY} \lesssim 40\times 10^{-10}$. If $B_s \to \mu^+\mu^-$ is observed at Tevatron Run II with a branching ratio larger than $\sim 2\times 10^{-8}$, the GMSB with a small number of messenger fields with low messenger scale and a class of AMSB scenarios will be excluded. Only supergravity or GMSB with high messenger scale and large number of messenger fields and the deflected AMSB would survive.

The SUSY contributions to a_μ come from the chargino-sneutrino and the neutralino-smuon loop, the former of which is dominant in most parameter space. Schematically, the result can be written as [8]

$$a_\mu^{\rm SUSY} = \frac{\tan\beta}{48\pi}\frac{m_\mu^2}{M_{\rm SUSY}^2}(5\alpha_2 + \alpha_1) \qquad (1)$$

in the limit where all the superparticles have the same mass $M_{\rm SUSY}$. In particular, $\mu > 0$ implies $a_\mu^{\rm SUSY} > 0$ in our convention. The deviation between the new Brookhaven National Laboratory data [9] and the most recently updated SM prediction [10] based on the $\sigma(e^+e^- \to \text{hadrons})$ data is $(33.9 \pm 11.2)\times 10^{-10}$. On the other hand, the deviation becomes smaller if the hadronic tau decays are used. Therefore, we do not use a_μ as a constraint except for $a_\mu > 0$ and give predictions for it in this Letter.

It has long been known that the $B \to X_s\gamma$ branching ratio puts a severe constraint on many new physics scenarios including weak scale SUSY models. The magnetic dipole coefficient $C_{7\gamma}$ for this decay gets contributions from SM, charged Higgs, and SUSY particles in the loop. The charged Higgs contributions always add up to the SM contributions, thereby increasing the rate. On the other hand, the last (mainly by the stop-chargino loop) can interfere with the SM and the charged Higgs contributions either in a constructive or destructive manner depending on the sign of μ. Since the SM predictionis in good agreement with the data [11], there is very little room for new physics contributions. Note that the positive $a_\mu^{\rm SUSY}$ picks up $\mu > 0$ in our convention, and the stop-chargino loop interferes destructively with the SM and the charged Higgs contribution in $B \to X_s\gamma$ decay. In turn, this prefers a positive $\mu M_{\tilde{g}}$ in many SUSY-breaking scenarios except for the AMSB scenario in which $\mu M_{\tilde{g}} < 0$ [12]. In the AMSB scenario, this leads to the constructive interference between the stop-chargino loop and the SM contributions to $B \to X_s \gamma$, thereby increasing the rate even more. Therefore, the AMSB scenario is strongly constrained if $a_\mu^{\rm SUSY} > 0$.

Another important effect is the nonholomorphic SUSY QCD corrections to the $hb\bar{b}$ couplings in the large $\tan\beta$ limit: the Hall-Rattazzi-Sarid effect [13]. Also, the stop-chargino loop could be quite important for large A_t and y_t couplings. One can summarize these effects as the following relation between the bottom quark mass and the bottom Yukawa coupling y_b:

$$m_b = y_b \frac{\sqrt{2} M_W \cos\beta}{g} (1 + \Delta_b), \qquad (2)$$

where the explicit form of Δ_b can be found in Ref. [14]. In the large $\tan\beta$ limit, the SUSY loop correction Δ_b which is proportional to $\mu M_{\tilde{g}} \tan\beta$ can be large as well with either sign, depending on the signs of the μ parameter and the gluino mass parameter $M_{\tilde{g}}$. In particular, the bottom Yukawa coupling y_b becomes too large and nonperturbative when $\mu > 0$ in the AMSB scenario, since the sign of Δ_b would be negative. This puts additional constraint on $\tan\beta \lesssim 35$ for the positive μ in the AMSB scenario.

The decay $B_s \to \mu^+\mu^-$ has a very small branching ratio in the SM [$(3.7 \pm 1.2) \times 10^{-9}$] [15]. But it can occur with much higher branching ratio in SUSY models when $\tan\beta$ is large, because the Higgs exchange contributions can be significant for large $\tan\beta$ [16,17]. The branching ratio for $B_s \to \mu^+\mu^-$ is proportional to $\tan^6\beta$ for large $\tan\beta$. Thus, this decay may be observable at the Tevatron Run II down to the level of 2×10^{-8} and could be complementary to the direct search for SUSY particles at the Tevatron Run II in the large $\tan\beta$ region.

In the following, we consider three aforementioned SUSY-breaking mediation mechanisms. Each scenario gives definite predictions for the soft terms at some messenger scale. We use renormalization group equations in order to get soft parameters at the electroweak scale, impose the radiative electroweak symmetry breaking (REWSB) condition, and then obtain particle spectra and mixing angles. Then we impose the direct search limits on Higgs and SUSY particles. The most stringent limits turns out to be the neutral Higgs mass bound ($m_h^{\rm SM} > 113.5$ GeV) and $m_{\tilde{\tau}} > 71$ GeV. For the GMSB scenario, the lightest supersymmetric particle (LSP) is always very light gravitinos, and we impose $m_{\rm NLSP}^{\rm GMSB} >$ 100 GeV, which is stronger than other experimental bounds on SUSY particle masses. In order to be as model independent as possible, we do not assume that the LSP is color and/or charge neutral (except for the GMSB scenario where the gravitino is the LSP), nor do we impose the color-charge breaking minima or the unbounded from below constraints, since one can always find ways out. Also we impose the $B \to X_s \gamma$ branching ratio as a constraint with a conservative bound (at 95% C.L.) considering theoretical uncertainties related with QCD corrections: $2.0 \times 10^{-4} < B(B \to X_s \gamma) < 4.5 \times 10^{-4}$ [11].

The correlation between $a_\mu^{\rm SUSY}$ and $B_s \to \mu^+\mu^-$ were recently studied in the minimal SUGRA scenario [16]. The result is that the positive large $a_\mu^{\rm SUSY}$ implies that $B(B_s \to \mu^+\mu^-)$ can be enhanced by a few orders of magnitude compared to the SM prediction and can be reached at the Tevatron Run II. The $\tilde{g}$MSB scenario, which finds a natural setting in the brane world scenarios, leads to the no-scale SUGRA type boundary condition for soft parameters, in which scalar mass and trilinear scalar terms all vanish at GUT scale, $B = m_{ij}^2 = A_{ijk} = 0$ and only gaugino masses are nonvanishing. Assuming the gaugino mass unification at GUT scale, we find that overall phenomenology of $\tilde{g}$MSB scenario (and the noscale scenario) in the $a_\mu^{\rm SUSY}$ and $B_s \to \mu^+\mu^-$ is similar to the mSUGRA scenario (see Ref. [18] for details including $B \to X_s l^+ l^-$). In the allowed parameter space, the $a_\mu^{\rm SUSY}$ can easily become up to $\sim 60 \times 10^{-10}$. But the branching ratio for $B_s \to \mu^+\mu^-$ is always smaller than 2×10^{-8} and becomes unobservable at the Tevatron Run II. The reason is that the large $\tan\beta$ region, where the branching ratio for $B_s \to \mu^+\mu^-$ can be much enhanced, is significantly constrained by stau or smuon mass bounds and the lower bound of $B \to X_s \gamma$. Therefore, if the $a_\mu^{\rm SUSY}$ turns out to be positive and the decay $B_s \to \mu^+\mu^-$ is observed at the Tevatron Run II, the $\tilde{g}$MSB scenario would be excluded.

In the gauge mediated SUSY breaking (GMSB), SUSY breaking in the hidden sector is assumed to be transmitted to the observable sector through SM gauge interactions of $N_{\rm mess}$ messenger superfields which lie in the vectorlike representation of the SM gauge group. The messenger fields couple to a gauge singlet superfield X, the vacuum expectation value of which (both in the scalar and the F components) will induce SUSY breaking in the messenger sector and, in turn, induce the soft SUSY-breaking parameters in the MSSM sector at the messenger scale $M_{\rm mess}$. Thus, GMSB scenarios are specified by the following set of parameters: M, N, Λ, $\tan\beta$, and $\mathrm{sgn}(\mu)$, where N is the number of messenger superfields, M is the messenger scale, and the Λ is SUSY-breaking scale, $\Lambda \approx \langle F_X \rangle / \langle X \rangle$. We scan these parameters over the following ranges: 10^4 GeV $\leq \Lambda \leq 2 \times 10^5$ GeV, $N_{\rm mess} =$ 1, 5, and $M_{\rm mess}$ from 10^6 to 10^{16} GeV, and impose direct search bounds on Higgs and SUSY particle masses. Note that the REWSB is hard to achieve for $\tan\beta > 50$ in this case.

In Fig. 1, we show the contour plots for the $a_\mu^{\rm SUSY}$ and $B(B_s \to \mu^+\mu^-)$ in the $(M_1, \tan\beta)$ plane for $N_{\rm mess} = 1$ and $M_{\rm mess} = 10^6$ GeV, where the parameter Λ has been traded into the bino mass parameter M_1. The left dark region is excluded by direct search limits on Higgs boson masses, and the gray region is excluded by the limit on the next lightest supersymmetric particle mass. Since the messenger scale (where the initial conditions for the renormalization group (RG) running for soft parameters

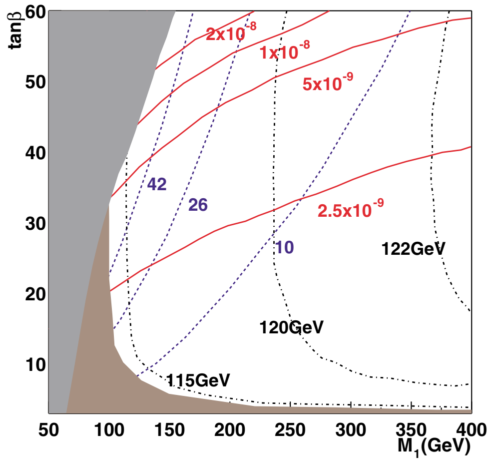

FIG. 1 (color online). The contour plots for $a_\mu^{\rm SUSY}$ in units of 10^{-10} (in the blue short dashed curves), the lightest neutral Higgs mass (in the black dash-dotted curves), and the Br $(B_s \to \mu^+\mu^-)$ (in the red solid curves) for the GMSB scenario in the $(M_1, \tan\beta)$ plane with $N = 1$ and $M = 10^6$ GeV.

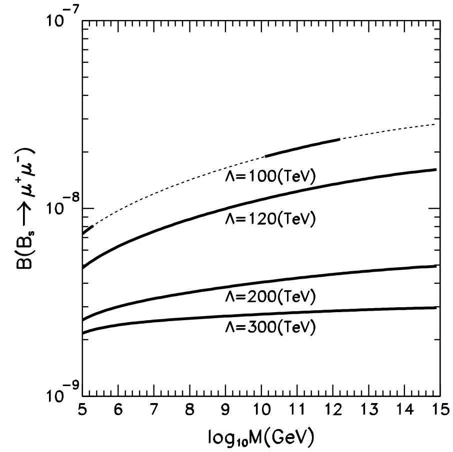

FIG. 2. The branching ratio for $B_s \to \mu^+\mu^-$ as a function of the messenger scale M in the GMSB with $N = 1$ for various Λ's with a fixed $\tan\beta = 50$. The dashed parts are excluded by the direct search limits on the Higgs and SUSY particle masses.

are given) is low, the flavor changing amplitude involving the gluino-squark is negligible and only the chargino-upsquark contribution is important to $B \to X_s\gamma$. Also, in the GMSB scenario with low messenger scale, the charged Higgs and stops are heavy and their effects on the $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$ are small. And the A_t is small since it can generated by only RG running, so that the stop mixing angle becomes small. These effects lead to very small branching ratio for $B_s \to \mu^+\mu^-$ ($\lesssim 10^{-8}$), making this decay unobservable at the Tevatron Run II. On the other hand, the $a_\mu^{\rm SUSY}$ can be as large as 60×10^{-10}. If we assume the messenger scale be as high as the GUT scale, the RG effects become strong and the stops get lighter. Also the A_t parameter becomes larger at the electroweak scale, and so is the stop mixing angle. Therefore, the chargino-stop loop contribution can overcompensate the SM and charged Higgs — top contributions to $B \to X_s\gamma$ and this constraint becomes more important compared to the lower messenger scale. Also the $B_s \to \mu^+\mu^-$ branching ratio can be enhanced (up to 2×10^{-8} for $\tan\beta = 50$, for example), because stops become lighter and larger $\tilde{t}_L - \tilde{t}_R$ mixing is possible. If the number of messenger fields is increased from $N = 1$ to 5, for example, the scalar fermion masses become smaller at the messenger scale, and stops get lighter in general. Therefore, the chargino-stop effects in $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$ get more important than the $N = 1$ case, and the $B_s \to \mu^+\mu^-$ branching ratio can be enhanced up to 2×10^{-7}.

In short, the overall features in the GMSB scenarios with high messenger scale look like the mSUGRA or the dilaton dominated case. Especially the branching ratio for the decay $B_s \to \mu^+\mu^-$ can be much more enhanced for large $\tan\beta$ in the GMSB scenario with high messenger scale (see also Fig. 2). Thus, if $a_\mu^{\rm SUSY} > 0$ and the decay $B_s \to \mu^+\mu^-$ is observed at the Tevatron Run II with the branching ratio larger than 2×10^{-8}, the GMSB scenario with $N = 1$ would be excluded up to $M_{\rm mess} \sim 10^{10}$ GeV and $\tan\beta \lesssim 50$.

In the AMSB scenario, the hidden sector SUSY breaking is assumed to be mediated to our world only through the auxiliary component of the supergravity multiplet (namely, superconformal anomaly). In this scenario, the gaugino masses are proportional to the one-loop beta function coefficient for the MSSM gauge groups, whereas the trilinear couplings and scalar masses are related with the anomalous dimensions and their derivatives with respect to the renormalization scale. Since the original AMSB model suffers from the tachyon problem in the slepton sector, we simply add a universal scalar mass m_0^2 to the scalar fermion mass parameters of the original AMSB model and assume that the aforementioned soft parameters make initial conditions at the GUT scale for the RG evolution. Thus, the minimal AMSB model is specified by the following four parameters: $\tan\beta$, ${\rm sgn}(\mu)$, m_0, $M_{\rm aux}$. We scan these parameters over the following ranges: 20 TeV $\leq m_{\rm aux} \leq$ 100 TeV, $0 \leq m_0 \leq 2$ TeV, $1.5 \leq \tan\beta \leq 60$, and ${\rm sgn}(\mu) > 0$.

In Fig. 3, we show the contour plots for the $a_\mu^{\rm SUSY}$ and $B(B_s \to \mu^+\mu^-)$ in the $(m_0, \tan\beta)$ plane for $M_{\rm aux} =$ 50 TeV. The low $\tan\beta$ region is excluded by the lower limit on the neutral Higgs boson, and the small m_0 region is excluded by the stau mass bound (the light dark region). In the case of the AMSB scenario with $\mu > 0$, the $B \to X_s\gamma$ constraint is even stronger compared to other scenarios (the shaded region in Fig. 3), and almost all the parameter space with large $\tan\beta > 30$ is excluded. Also stops are relatively heavy in this scenario mainly due to the universal addition of m_0^2. Therefore, the branching ratio for $B_s \to \mu^+\mu^-$ is smaller than 4×10^{-9}, and this process becomes unobservable at the Tevatron Run II. If

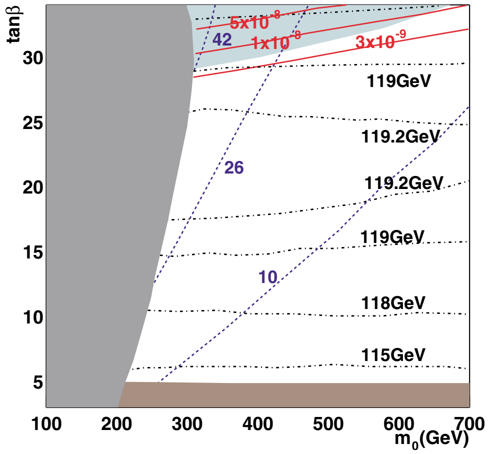

FIG. 3 (color online). The contour plots for $a_\mu^{\rm SUSY}$ in units of 10^{-10} (in the short dashed curves) and the Br $(B_s \to \mu^+\mu^-)$ (in the solid curves) in the $(m_0, \tan\beta)$ plane for $M_{\rm aux} = 50$ TeV.

the decay $B_s \to \mu^+\mu^-$ is observed at the Tevatron Run II, the minimal AMSB scenario would be excluded.

This general feature of the minimal AMSB scenario is still valid in the gaugino assisted AMSB scenario [5], where the scalar mass terms receive gauge-charge dependent positive contributions from the MSSM gauge multiplets living in the bulk, in addition to the pure anomaly mediation term. On the other hand, in the deflected AMSB scenario [6], the soft SUSY-breaking parameters are shifted from the pure AMSB case when heavy particles are integrated out and the tachyonic slepton problem is solved. Also the gluino mass parameter can flip the sign when the number of gauge charged messengers are increased. In this case, the $B \to X_s\gamma$ constraint becomes weaker and overall phenomenology is similar to the mSUGRA case (see Ref. [18] for more details). In case the Fayet-Iliopoulos term is employed to cure the tachyonic slepton problem, the allowed $\tan\beta$ is rather small [7] so that the branching ratio for $B_s \to \mu^+\mu^-$ cannot be enhanced to be observed at the Tevatron Run II.

In conclusion, we showed that there are qualitative differences in correlations among $(g-2)_\mu$, $B \to X_s\gamma$, and $B_s \to \mu^+\mu^-$ in various models for SUSY-breaking mediation mechanisms, even if all of them can accommodate the muon a_μ: $10 \times 10^{-10} \lesssim a_\mu^{\rm SUSY} \lesssim 40 \times 10^{-10}$. Especially, if the $B_s \to \mu^+\mu^-$ decay is observed at Tevatron Run II with the branching ratio greater than 2×10^{-8}, the GMSB with a low number of messenger fields N and a certain class of AMSB scenarios would be excluded. On the other hand, the minimal supergravity scenario and similar mechanisms derived from string models and the deflected AMSB scenario can accommodate this observation [18] without difficulty for large $\tan\beta$. Therefore, a search for $B_s \to \mu^+\mu^-$ decay at the Tevatron Run II would provide us with important informations on the SUSY-breaking mediation mechanisms, independent of information from a direct search for SUSY particles at high energy colliders.

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