Probing Supersymmetry-Induced *CP* Violation at *B* Factories

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In the minimal supersymmetric standard model, the μ parameter and the trilinear coupling A_t may be generically complex and can affect various observables at B factories. Imposing the electric dipole moment constraints, we find that there is no new large phase shift in the B^0-$\overline{B^0}$ mixing, CP violating dilepton asymmetry is smaller than 0.1%, and the direct CP violation in $B \to X_s \gamma$ can be as large as $\sim \pm 16\%$.

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In the minimal supersymmetric standard model (MSSM), there can be many new *CP* violating (CPV) phases beyond the Kobayashi-Maskawa (KM) phase in the standard model (SM). These supersymmetric (SUSY) CPV phases are constrained by the electron/neutron electric dipole moment (EDM) and have been considered very small [$\delta \lesssim 10^{-2}$ for $M_{\rm SUSY} \sim O(100)$ GeV] [1]. However, there is a logical possibility that various contributions to the electron/neutron EDM cancel out each other in a substantial part of the MSSM parameter space even if SUSY CPV phases are $\sim O(1)$ [2,3], or one can consider effective SUSY models where decouplings of the 1st/2nd generation sfermions are invoked to solve the SUSY flavor-changing neutral-current interactions (FCNC) and *CP* problems. Then one loop EDM constraints are automatically evaded in this scenario [4]. In such cases, these new SUSY phases may affect B and K physics in various manners. Closely related with this is the electroweak baryogenesis (EWBGEN) scenario in the MSSM. One of the fundamental problems in particle physics is to understand the baryon number asymmetry, $n_B/s = 4 \times 10^{-12}$, and a currently popular scenario is EWBGEN in the MSSM [5]. The EWBGEN is in fact possible in a certain region of the MSSM parameter space, especially for a light stop ($120 \lesssim m_{\tilde{t}_1} \lesssim 175$ GeV, dominantly $\tilde{t}_1 \simeq \tilde{t}_R$) with CP violating phases in μ and A_t parameters. Then one would expect that this light stop and new CP violating phases may lead to observable consequences to B physics.

The purpose of this Letter is to consider the possibility of observing effects of these new flavor conserving and CPV phases (ϕ_μ and ϕ_{A_t}) at B factories in the MSSM (including the EWBGEN scenario therein). More specifically, we consider the following observables: SUSY contributions to the B^0-$\overline{B^0}$ mixing, the dilepton CP asymmetry in the $B^0\overline{B^0}$ decays, and the direct CP asymmetry in $B \to X_s \gamma$. The B^0-$\overline{B^0}$ mixing is important for determination of three angles of the unitarity triangle. Also, the last two observables are vanishingly small in the standard model, and any appreciable amounts of these asymmetries would herald the existence of new CP violating phases beyond the KM phase in the SM. The question to be addressed in this Letter is how much these observables can be deviated from their SM values when μ and A_t parameters in the MSSM have new CPV phases.

In order to study B physics in the MSSM, we make the following assumptions [6]. First of all, the 1st and the 2nd family squarks are assumed to be degenerate and very heavy in order to solve the SUSY FCNC and CP problems [4]. Only the 3rd family squarks can be light enough to affect $B \to X_s \gamma$ and B^0-$\overline{B^0}$ mixing. We also ignore possible flavor changing squark mass matrix elements that could generate the gluino-mediated flavor-changing neutral-current process in addition to those effects we consider below. Recently, such effects were studied in the B^0-$\overline{B^0}$ mixing [7,8], the branching ratio of $B \to X_s \gamma$ [7] and CP violations therein [9,10], and $B \to X_s l^+ l^-$ [10], respectively. Ignoring such contributions, the only source of the FCNC in our model is the Cabibbo-Kobayashi-Maskawa (CKM) matrix, whereas there are new CPV phases coming from the phases of μ and A_t parameters in the flavor-preserving sector in addition to the KM phase $\delta_{\rm KM}$ in the flavor-changing sector. In this sense, this paper is complementary to the earlier works [7–10].

Even if the 1st/2nd generation squarks are very heavy and degenerate, there is another important EDM constraint considered by Chang, Keung, and Pilaftsis (CKP) for large $\tan\beta$ [11]. This constraint comes from the two loop diagrams involving stop/sbottom loops and is independent of the masses of the 1st/2nd generation squarks.

$$\left(\frac{d_f}{e}\right)_{\rm CKP} = Q_f \frac{3\alpha_{\rm em}}{64\pi^2} \frac{R_f m_f}{M_A^2} \sum_{q=t,b} \xi_q Q_q^2 F\left(\frac{M_{\tilde{q}_1}^2}{M_A^2}, \frac{M_{\tilde{q}_2}^2}{M_A^2}\right), \tag{1}$$

where $R_f = \cot\beta$ ($\tan\beta$) for $I_{3f} = 1/2$ ($-1/2$), and

$$\xi_t = \frac{\sin 2\theta_{\tilde{t}} m_t \,{\rm Im}(\mu e^{i\delta_t})}{\sin^2\beta v^2}, \qquad \xi_b = \frac{\sin 2\theta_{\tilde{b}} m_b \,{\rm Im}(A_b e^{-i\delta_b})}{\sin\beta \cos\beta v^2}, \tag{2}$$

with $\delta_q = \arg(A_q - R_q u^*)$, and $F(x,y)$ is a two-loop function given in Ref. [11]. Therefore, this CKP EDM constraint cannot be simply evaded by making the 1st/2nd generation squarks very heavy, and it turns out that this

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puts a very strong constraint on the possible new phase shift in the B^0-$\overline{B^0}$ mixing.

In the MSSM, the chargino mass matrix is given by

$$M_{\chi^\pm} = \begin{pmatrix} M_2 & \sqrt{2}\, m_W \sin\beta \\ \sqrt{2}\, m_W \cos\beta & \mu \end{pmatrix}. \tag{3}$$

In principle, both M_2 and μ may be complex, but one can perform a phase redefinition in order to render that the M_2 is real [3]. In such a basis, there appears one new phase $\arg(\mu)$ as a new source of CPV. The stop mass matrix is given by

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t(A_t^* - \mu/\tan\beta) \\ m_t(A_t - \mu^*/\tan\beta) & m_U^2 + m_t^2 + D_R \end{pmatrix}, \tag{4}$$

where $D_L = (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta m_Z^2$ and $D_R = \frac{2}{3}\sin^2\theta_W \cos 2\beta m_Z^2$. There are two new phases in this matrix, $\arg(\mu)$ and $\arg(A_t)$ in the basis where M_2 is real.

We scan over the MSSM parameter space as indicated below (including that relevant to the EWBGEN scenario in the MSSM): 80 GeV $< |\mu| <$ 1 TeV, 80 GeV $< M_2 <$ 1 TeV, 60 GeV $< M_A <$ 1 TeV, $2 < \tan\beta < 70$, $(130\ \text{GeV})^2 < M_Q^2 < (1\ \text{TeV})^2$, $-(80\ \text{GeV})^2 < M_U^2 < (500\ \text{GeV})^2$, $0 < \phi_\mu, \phi_{A_t} < 2\pi$, $0 < |A_t| < 1.5$ TeV. We have imposed the following experimental constraints: $M_{\tilde{t}_1} > 80$ GeV independent of the mixing angle $\theta_{\tilde{t}}$, $M_{\tilde{\chi}^\pm} > 83$ GeV, $\mathcal{B}(B \to X_{sg}) < 6.8\%$ [12], and $0.77 \le R_\gamma \le 1.15$ [13], where R_γ is defined as $R_\gamma = \mathcal{B}(B \to X_s\gamma)^{\text{expt}}/\mathcal{B}(B \to X_s\gamma)^{\text{SM}}$ and $\mathcal{B}(B \to X_s\gamma)^{\text{SM}} = (3.29 \pm 0.44) \times 10^{-4}$. It has to be emphasized that this parameter space is larger than that in the constrained MSSM (CMSSM) where the universality of soft terms at the grand unified theory (GUT) scale is assumed. Especially, we allow m_U^2 to be negative as well as positive, which is preferred in the EWBGEN scenario [5]. Since we do not impose any further requirement on the soft terms (such as radiative electroweak symmetry breaking, absence of color charge breaking minima, etc.), our results of the maximal deviations of B^0-$\overline{B^0}$ mixing and $A_{CP}^{b\to s\gamma}$ from the SM predictions are conservative upper bounds within the MSSM. If more theoretical conditions are imposed, the maximal deviations will be smaller. In the numerical analysis, we used the following numbers for the input parameters: $\overline{m_c}[m_c(pole)] = 1.25$ GeV, $\overline{m_b}[m_b(pole)] = 4.3$ GeV, $\overline{m_t}[m_t(pole)] = 165$ GeV [these are running masses in the modified minimal subtraction ($\overline{\text{MS}}$) scheme], and $|V_{cb}| = 0.0410$, $|V_{tb}| = 1$, $|V_{ts}| = 0.0400$, and $\delta_{\text{KM}} = \gamma(\phi_3) = 90°$ for the CKM matrix elements.

The B^0-$\overline{B^0}$ mixing is generated by the box diagrams with $u_i - W^\pm(H^\pm)$ and $\tilde{u}_i - \chi^\pm$ running around the loops in addition to the SM contribution. The resulting effective Hamiltonian is given by

$$H_{\text{eff}}^{\Delta B=2} = -\frac{G_F^2 M_W^2}{(2\pi)^2} \sum_{i=1}^{3} C_i O_i\,, \tag{5}$$

where $O_1 = \overline{d}_L^\alpha \gamma_\mu b_L^\alpha \overline{d}_L^\beta \gamma^\mu b_L^\beta$, $O_2 = \overline{d}_L^\alpha b_R^\alpha \overline{d}_L^\beta b_R^\beta$, and $O_3 = \overline{d}_L^\alpha b_R^\beta \overline{d}_L^\beta b_R^\alpha$. The Wilson coefficients C_i's at the electroweak scale ($\mu_0 \sim M_W \sim M_{\tilde{t}}$) can be written schematically as [14]

$$\begin{aligned} C_1(\mu_0) &= (V_{td}^* V_{tb})^2 [F_V^W(3;3) + F_V^H(3;3) + A_V^C], \\ C_2(\mu_0) &= (V_{td}^* V_{tb})^2 F_S^H(3;3), \\ C_3(\mu_0) &= (V_{td}^* V_{tb})^2 A_S^C, \end{aligned} \tag{6}$$

where the superscripts W, H, and C denote the $W^\pm$, $H^\pm$, and chargino contributions, respectively, and

$$A_V^C = \sum_{i,j,k,l}^{1,2} \frac{1}{4} G_{(3,k)}^i G_{(3,k)}^{j*} G_{(3,l)}^{i*} G_{(3,l)}^j Y_1(r_k, r_l, s_i, s_j),$$

$$A_S^C = \sum_{i,j,k,l}^{1,2} H_{(3,k)}^i G_{(3,k)}^{j*} G_{(3,l)}^{i*} H_{(3,l)}^j Y_2(r_k, r_l, s_i, s_j).$$

Here $G_{(3,k)}^i$ and $H_{(3,k)}^i$ are the couplings of the kth stop and the ith chargino with left-handed and right-handed quarks, respectively:

$$\begin{aligned} G_{(3,k)}^i &= \sqrt{2}\, C_{R1i}^* S_{tk1} - \frac{C_{R2i}^* S_{tk2}}{\sin\beta} \frac{m_t}{M_W}, \\ H_{(3,k)}^i &= \frac{C_{L2i}^* S_{tk1}}{\cos\beta} \frac{m_b}{M_W}, \end{aligned} \tag{7}$$

and $C_{L,R}$ and S_t are unitary matrices that diagonalize the chargino and stop mass matrices. Explicit forms for functions $Y_{1,2}$ and F's can be found in Ref. [14], and $r_k = M_{\tilde{t}_k}^2/M_W^2$ and $s_i = M_{\tilde{\chi}_i^\pm}/M_W^2$. It should be noted that $C_2(\mu_0)$ was misidentified as $C_3^H(\mu_0)$ in Ref. [15]. The gluino and neutralino contributions are negligible in our model. The Wilson coefficients at the m_b scale are obtained by renormalization group running. The relevant formulas with next-to-leading order QCD corrections at $\mu = 2$ GeV are given in Ref. [16].

In our model $C_1(\mu_0)$ and $C_2(\mu_0)$ are real relative to the SM contribution. On the other hand, the chargino exchange contributions to $C_3(\mu_0)$ (namely, A_S^C) are generically complex relative to the SM contributions and can generate a new phase shift in the B^0-$\overline{B^0}$ mixing relative to the SM value. This effect can be in fact significant for large $\tan\beta(\simeq 1/\cos\beta)$, since $C_3(\mu_0)$ is proportional to $(m_b/M_W \cos\beta)^2$ [15]. However, the CKP EDM constraint puts a strong constraint for the large $\tan\beta$ case, which was not properly included in Ref. [15]. In Fig. 1(a), we plot $2\theta_d \equiv \arg(M_{12}^{\text{FULL}}/M_{12}^{\text{SM}})$ as a function of $\tan\beta$. The open squares (the crosses) denote those that do (do not) satisfy the CKP EDM constraints. It is clear that the CKP EDM constraint on $2\theta_d$ is in fact very important for large $\tan\beta$, and we have $|2\theta_d| \lesssim 1°$. If we ignored the CKP EDM constraint at all, then $|2\theta_d|$ could be as large as $\sim 4°$. This observation is important for the CKM phenomenology, since time-dependent CP asymmetries in neutral B decays into $J/\psi K_S$, $\pi\pi$, etc. would

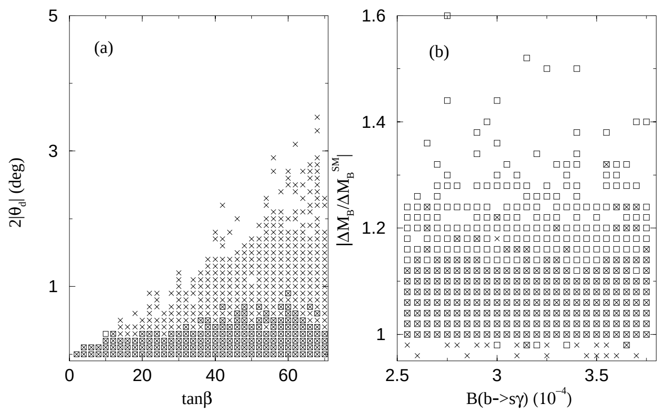

FIG. 1. Correlations between (a) $\tan\beta$ vs $2|\theta_d|$, and (b) $\mathcal{B}(B \to X_s\gamma)$ vs $A_{12}^{\rm FULL}/A_{12}^{\rm SM}$. The squares (crosses) denote those which do (do not) satisfy the CKP EDM constraints.

still measure directly three angles of the unitarity triangle even in the presence of new CP violating phases, ϕ_{A_t} and ϕ_μ. Our result is at variance with that obtained in Ref. [15] where the CKP EDM constraint was not properly included.

If we parametrize the relative ratio of $M_{\rm SM}$ and $M_{\rm SUSY}$ as $M_{\rm SUSY}/M_{\rm SM} = he^{-i\theta}$, the dilepton asymmetry is given by

$$A_{ll} = \left(\frac{\Delta\Gamma}{\Delta M}\right)_{\rm SM} f(h,\theta) \equiv 4\,{\rm Re}(\epsilon_B)\,, \tag{8}$$

where $f(h,\theta) = h\sin\theta/(1 + 2h\cos\theta + h^2)$ and $(\Delta\Gamma/\Delta M)_{\rm SM} = (1.3 \pm 0.2) \times 10^{-2}$. We have neglected the small SM contribution. It is about $\sim 10^{-3}$ in the quark level calculation [17], but may be as large as $\sim 1\%$ if the delicate cancellation between the u and c quark contribution is not achieved [18]. Since the effects on θ_d are small in our model, we expect that the effects on A_{ll} will be similarly negligible [19]. However, we perform a search and confirm that this is indeed the case. Scanning over the available MSSM parameter space, we find $|f(h,\theta)| \lesssim 0.1$ so that $|A_{ll}| \lesssim 0.1\%$, which is well below the current data, $A_{ll} = (0.8 \pm 2.8 \pm 1.2)\%$ [20]. On the other hand, if any appreciable amount of the dilepton asymmetry is observed, it would indicate some new CPV phases in the off-diagonal down-squark mass matrix elements [8], assuming the MSSM is realized in nature.

On the contrary to the θ_d and A_{ll} discussed in the previous paragraphs, the magnitude of M_{12} is related with the mass difference of the mass eigenstates of the neutral B mesons: $\Delta m_B = 2|M_{12}| = (3.05 \pm 0.12) \times 10^{-13}$ GeV, and thus it will affect the determination of V_{td} from the B^0-$\overline{B^0}$ mixing. We have considered $|M_{12}^{\rm FULL}/M_{12}^{\rm SM}|$ and its correlation with $\mathcal{B}(B \to X_s\gamma)$ is shown in Fig. 1(b). The deviation from the SM can be as large as $\sim 60\%$, and the correlation behaves differently from the minimal supergravity case [21]. We repeated the same analyses for B_s^0-$\overline{B_s^0}$ mixing. There is no large new phase shift ($2|\theta_s|$) in this case either, but the modulus of $M_{12}(B_s)$ can be enhanced by up to 60% compared to the SM value.

The radiative decay of B mesons, $B \to X_s\gamma$, is described by the effective Hamiltonian including (chromo)magnetic dipole operators. Interference between $b \to s\gamma$ and $b \to sg$ (where the strong phase is generated by the charge loop via $b \to c\bar{c}s$ vertex) can induce direct CP violation in $B \to X_s\gamma$ [22], which is given by

$$\begin{aligned} A_{CP}^{b\to s\gamma} &\equiv \frac{\Gamma(B \to X_{\bar{s}} + \gamma) - \Gamma(\overline{B} \to X_s + \gamma)}{\Gamma(B \to X_{\bar{s}} + \gamma) + \Gamma(\overline{B} \to X_s + \gamma)} \\ &\simeq \frac{1}{|C_7|^2}\{1.23\,{\rm Im}[C_2C_7^*] - 9.52\,{\rm Im}[C_8C_7^*] \\ &\quad + 0.10\,{\rm Im}[C_2C_8^*]\} \quad (\text{in } \%)\,, \end{aligned} \tag{9}$$

adopting the notations in Ref. [22]. We have ignored the small contribution from the SM and assumed that the minimal photon energy cut is given by $E_\gamma \geq m_B(1 - \delta)/2$ ($\approx$1.8 GeV with $\delta = 0.3$). $A_{CP}^{b\to s\gamma}$ is not sensitive to possible long distance contributions and constitutes a sensitive probe of new physics that appears in the short distance Wilson coefficients $C_{7,8}$ [22].

The Wilson coefficients $C_{7,8}$ in the MSSM have been calculated by many groups [23], including the perturbative QCD corrections in certain MSSM parameter space [24]. In this Letter, we use the leading order expressions for C_i's which is sufficient for $A_{CP}^{b\to s\gamma}$. After scanning over the MSSM parameter space described in Eq. (3), we find that $A_{CP}^{b\to s\gamma}$ can be large as $\simeq \pm 16\%$ if chargino is light enough, even if we impose the EDM constraints. Its correlation with $\mathcal{B}(B \to X_s\gamma)$ and chargino mass is shown in Figs. 2(a) and 2(b), respectively. Our results are quantitatively different from other recent works [25,26], mainly due to the different treatments of soft terms. In the minimal supergravity scenario, this asymmetry is very small, because the A_t phase effect is very small in the electroweak scale [26]. If the universality assumption is

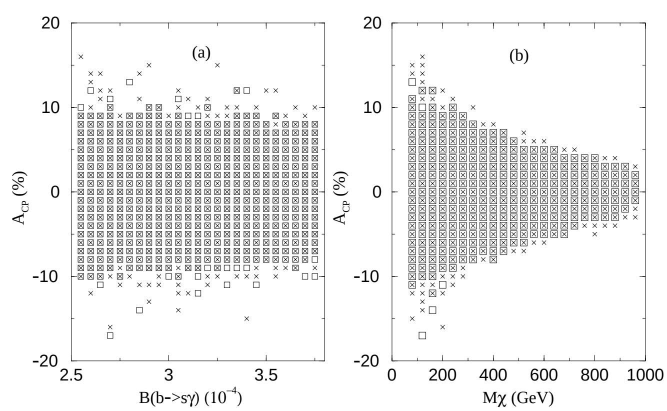

FIG. 2. Correlations of $A_{CP}^{b\to s\gamma}$ with (a) $\mathcal{B}(B \to X_s\gamma)$ and (b) the lighter chargino mass $M_{\chi^\pm}$. The squares (crosses) denote those which do (do not) satisfy the CKP EDM constraints.

relaxed, one can accommodate larger direct asymmetry without conflicting with the EDM constraints.

In conclusion, we studied consequences at B factories in the MSSM for the scenario where the first two generation sfermions are heavy, and there are CP violating phases in A_t and μ parameters. The main results can be summarized as follows. There is no appreciable new phase in the B^0-$\overline{B^0}$ mixing ($|2\theta_d| \lesssim 1°$), so that time-dependent CP asymmetries in neutral B decays (into $J/\psi K_S$, $\pi\pi$, etc.) still measure essentially three angles of the unitarity triangle even if there are new complex phases in μ and A_t parameters. The size of the B^0-$\overline{B^0}$ mixing can be enhanced up to $\sim$60% compared to the SM contribution, which will affect determination of V_{td} from Δm_B. There is no large shift in Re(ϵ_B), and dilepton CP asymmetry is rather small ($|A_{ll}| \lesssim 0.1\%$). Direct CP asymmetry in $B \to X_s\gamma$ can be as large as $\sim\pm16\%$ if the chargino is light enough.

These results would set the level of experimental sensitivity that one has to achieve in order to probe the SUSY-induced CP violations at B factories through B^0-$\overline{B^0}$ and $A_{CP}^{b\to s\gamma}$ mixing. Our results are conservative in a sense that we did not impose any conditions on the soft SUSY-breaking terms except that the resulting mass spectra for chargino, stop, and other sparticles satisfy the current lower bounds from the CERN LEP and the Fermilab Tevatron. Therefore, one would be able to find the effects of the phases of μ and A_t parameters by observing $A_{CP}^{b\to s\gamma}$ at B factories. Other effects of supersymmetric CP violating phases ϕ_μ and ϕ_{A_t} on $B \to X_s l^+ l^-$ and ϵ_K will be presented in a separate work [27].

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