SUSY CP violations in $K$ and $B$ systems

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Abstract

I report our recent works on the effects of CP violating phases in SUSY models on $B$ and $K$ phenomenology.

I. INTRODUCTION

In the minimal supersymmetric standard model (MSSM), there arise many new CP violating (CPV) phases beyond the KM phase in the standard model (SM). These SUSY CPV phases generically lead to too large electron/neutron electric dipole moment (EDM) and $\epsilon_K$. There are basically three different ways to evade this SUSY CP problem: (i) vanishing (or very small) SUSY CP phases, (ii) decoupling scenario (effective or more minimal MSSM $\equiv$ MMSSM), and (iii) cancellation mechanism. In each case, these new SUSY CP phases could affect $B$ and $K$ physics in vastly different manners.

In this talk, we report our three recent works related with this subject. The topics covered here are divided into two parts. In the first part, we consider a possibility of observing effects of the $\mu$ and $A_t$ phases which are flavor conserving at $B$ factories in the MMSSM (including the electroweak baryogenesis scenario therein). In the second part of the talk, I demonstrate that fully supersymmetric CP violations in the kaon system are possible, on the contrary to the conventional folklore. Both $\epsilon_K$ and $\text{Re}(\epsilon'/\epsilon_K)$ can be accounted for in terms of a single CP violating complex number $(\delta^d_{12})_{LL}$ (to be defined below) within the double mass insertion approximation (MIA).

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II. EFFECTS OF $\mu$ AND $A_T$ PHASES ON $B$ PHYSICS IN THE MORE MINIMAL SUPERSYMMETRIC STANDARD MODEL (MMSSM)

In the MMSSM (decoupling scenario), the 1st and the 2nd family squarks are assumed to be very heavy and almost degenerate in order to solve the SUSY FCNC/CP problems. Only the third family squarks can be light enough to affect $B \to X_s \gamma$ and $B^0 - \bar{B}^0$ mixing. We also ignore possible flavor changing squark mass matrix elements that could generate gluino-mediated flavor changing neutral current (FCNC) process in addition to those effects we consider below. Recently, such effects were studied in the $B^0 - \bar{B}^0$ mixing, the branching ratio of $B \to X_s \gamma$ and CP violations therein, and $B \to X_s l^+ l^-$, respectively. Ignoring such contributions, the only source of the FCNC in our model is the CKM matrix, whereas there are new CPV phases coming from the phases of $\mu$ and $A_t$ parameters in the flavor preserving sector in addition to the KM phase $\delta_{KM}$ in the flavor changing sector. (We choose to work in the basis where the wino mass parameter $M_2$ is real.) In this sense, this paper is complementary to the earlier works.

Even if the 1st/2nd generation squarks are very heavy and degenerate, there is another important edm constraints considered by Chang, Keung and Pilaftsis (CKP) for large $\tan \beta$. This constraint comes from the two loop diagrams involving stop/sbottom loops, and is independent of the masses of the 1st/2nd generation squarks. Therefore, this CKP edm constraints can not be simply evaded by making the 1st/2nd generation squarks very heavy, and it turns out that this puts a very strong constraint on the possible new phase shift in the $B^0 - \bar{B}^0$ mixing.

The $B^0 - \bar{B}^0$ 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 gluino and neutralino contributions are negligible in our model. It turns out that the chargino exchange contributions to $B^0 - \bar{B}^0$ mixing can be generically complex relative to the SM contributions, and can generate a new phase shift in the $B^0 - \bar{B}^0$ mixing relative to the SM value. This effect can be in fact significant for large $\tan \beta$ case. In Fig. 1 (a), we plot $2\theta_d \equiv \text{Arg} \left( M^{\text{FULL}}_{12}/M^{\text{SM}}_{12} \right)$ as a function of $\tan \beta$. The open squares (the crosses) denote those which (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 $|2\theta_d| \leq 1^\circ$. 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 still measure directly three angles of the unitarity triangle even in the presence of new CP violating phases, $\phi_{A_t}$ and $\phi_\mu$. The above $B^0 - \bar{B}^0$ mixing is also related with the dilepton asymmetry which is proportional to $\text{Re}(\epsilon_B)$. Neglecting the small SM contribution which is about $\sim 10^{-3}$, we found that $|A_{ll}| \leq 0.1\%$ in our mode, which is well below the current data, $A_{ll} = (0.8 \pm 2.8 \pm 1.2)\%$. 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, assuming the MSSM is realized in nature.
FIG. 1. Correlations between (a) $\tan \beta$ vs. $2|\theta_d|$, and (b) $\text{Br}(B \to X_s\gamma)$ vs. $A_{12}^{\text{FULL}}/A_{12}^{\text{SM}}$. The squares (the crosses) denote those which (do not) satisfy the CKP edm constraints.

Unlike the $\theta_d$ and $A_d$ discussed in the previous paragraphs, the magnitude of $M_{12}$ can be affected a lot by the $\mu$ and $A_t$ phases, and it will affect the determination of $V_{td}$ from $\Delta m_{B_d}$. The deviation from the SM can be as large as $\sim 60\%$, [4] and the correlation behaves differently from the minimal supergravity case. [4]

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 charm loop via $b \to c\bar{c}s$ vertex) can induce direct CP violation in $B \to X_s\gamma$. [17] In our model, $A_{b \to s\gamma}^{\text{CP}}$ can be as large as $\sim \pm 16\%$ if chargino is light enough, even if we impose all the relevant edm constraints [3] (see Fig. 1 (b)).

The $\mu$ and $A_t$ phases can also affect $B \to X_s l^+ l^-$, whose branching ratio can be enhanced up to $\sim 85\%$ compared to the SM prediction in our model, [4] and the correlation between $\text{Br}(B \to X_s\gamma)$ and $\text{Br}(B \to X_s l^+ l^-)$ is distinctly different from the minimal supergravity scenario (CMSSM) (even with new CP violating phases) [18] in the presence of new CP violating phases in $C_{7,8,9}$ as demonstrated in model-independent analysis by Kim, Ko and Lee. [11] It is crucial to consider the direct CP asymmetry in $B \to X_s\gamma$ in the model independent determination of $C_{7,9,10}$, since these Wilson coefficients may be complex in general.

One can also consider the $K^0 - \bar{K}^0$ mixing in this model, and we find $\epsilon_K/\epsilon_K^{\text{SM}}$ can be as large as 1.4 for $\delta_{KM} = 90^\circ$. [4] This is a factor 2 larger deviation from the SM compared to the minimal supergravity case. [16] The dependence on the lighter stop is close to the case of the minimal supergravity case, but we can have a larger deviations. Such deviation is reasonably close to the experimental value, and will affect the CKM phenomenology at a certain level. This is the extent to which the new phases in $\mu$ and $A_t$ can affect the construction of the unitarity triangle through $\epsilon_K$.

**III. FULLY SUSY CP VIOLATION IN THE KAON SYSTEM**

In the MSSM with many new CPV phases, there is an intriguing possibility that the observed CP violation in $K_L \to \pi\pi$ is fully supersymmetric due to the complex parameters $\mu$ and $A_t$ in the soft SUSY breaking terms which also break CP softly, or CP violating
\[ \tilde{g} - q_i - \tilde{q}_j. \] Our study indicates that the supersymmetric \( \epsilon_K \) (namely, for \( \delta_{KM} = 0 \)) is less than \( \sim 2 \times 10^{-5} \), which is too small compared to the observed value: \( |\epsilon_K| = (2.280 \pm 0.019) \times 10^{-3} \). Details for this discussion can be found in Ref. [4].

Although one cannot generate enough CP violations in the kaon system through flavor preserving \( \mu \) and \( A_t \) phases in the MSSM, it is possible if one considers the flavor changing SUSY CPV phases. Let us work in the mass insertion approximation (MIA) and consider the flavor changing \( \tilde{g} - q_i - \tilde{q}_j \) in order to study these phenomena in a model independent manner. The folklore was that if one saturates the \( \epsilon_K \) with \( (\delta_{d12})_{LL} \), the corresponding \( \epsilon'/\epsilon_K \) is far less than the observed value. On the other hand, if one saturates \( \epsilon'/\epsilon_K \) with \( (\delta_{d12})_{LR} \), the resulting \( \epsilon_K \) is again too small compared to the data. Therefore one would need both \( |(\delta_{d12})_{LL}| \sim O(10^{-3}) \) and \( |(\delta_{d12})_{LR}| \sim O(10^{-5}) \), each of which has a \( \sim O(1) \) phase. Masiero and Murayama argued that such a large value of \( (\delta_{d12})_{LR} \) is not implausible in general MSSM, e.g., if the fundamental theory is a string theory. [19] In their model, the large \( (\delta_{d12})_{LR} \) is intimately related with the large \( (\delta_{d11})_{LR} \), so that their prediction on the neutron edm is very close to the current experimental limit.

Subsequently, we pointed out that a single complex number \( (\delta_{d12})_{LL} \sim O(10^{-2} - 10^{-3}) \) with an order \( \sim O(1) \) phase in fact can generate both \( \epsilon_K \) and \( \epsilon'/\epsilon_K \), if one goes beyond the single mass insertion approximation as often done in this field. [5] In our model, \( \epsilon_K \) is generated by \( (\delta_{d12})_{LL} \), whereas \( \epsilon'/\epsilon_K \) is generated by a flavor preserving \( \tilde{s}_R - \tilde{s}_L \) transition followed by flavor changing \( \tilde{s}_L - \tilde{d}_L \) transition.

![FIG. 2. Feynman diagram for \( \Delta S = 1 \) process.](image)

The former is proportional to \( m_s(A_s - \mu \tan \beta)/\tilde{m}^2 \) where \( \tilde{m} \) is the common squark mass in the MIA. This kind of the induced \( LR \) mixing is always present generically in any SUSY models.

If the KM phase were not zero, the CKMology should differ significantly from the SM case. For example, we cannot use the constraints coming from \( \epsilon_K \) or \( \Delta M_B \), since new physics would contribute to both \( \Delta S = 2 \) and \( \Delta B = 2 \) amplitudes. More detailed discussions on these points will be presented elsewhere. [20] Finally let us note that the recent observation on CP asymmetry in \( B^0 \to J/\psi K_S \) depends on different CP violating parameter \( (\delta_{d13})_{AB} \) where \( i = 1 \) or 2, and \( A, B = L \) or \( R \), and is independent of the kaon sector we considered here in the mass insertion approximation.
FIG. 3. $\epsilon'/\epsilon_K$ as a function of the modulus $r$ [(a) and (c)] and the phase $\varphi$ [(b) and (d)] of the parameter $(\delta_{12}^d)_{LL}$ with $A_s - \mu^* \tan \beta$ to be $-10 \, \text{TeV}$ [(a),(b)] and $-20 \, \text{TeV}$ [(c),(d)]. The common squark mass is chosen to be $\tilde{m} = 500 \, \text{GeV}$, and the solid, the dashed and the dotted curves correspond to $x = 0.3, \ 1.0, \ 2.0$, respectively.

IV. CONCLUSION

In conclusion, we first discussed the effects of $A_t$ and $\mu$ phases in the MMSSM on several observables in the $B$ meson system and on $\epsilon_K$. Our study includes the EW baryogenesis scenario in the MSSM. We demonstrated that the SUSY CP violating phases in $\mu$ and $A_t$ can affect the $B$ and $K$ physics a lot (especially direct CP asymmetry in $B \to X_s \gamma$), even if they are flavor conserving. We also argued that if we consider SUSY phases with flavor violation such as a flavor changing squark mixing $(\delta_{12}^d)_{LL}$, fully supersymmetric CP violation is possible for relatively large $\tan \beta$ (more specifically, $|\mu \tan \beta| \sim O(10) \, \text{TeV}$) in the double mass insertion approximation. The ongoing $B$ and $K$ factory experiments will test the KM paradigm for CP violation, and will shed light on the possible new sources of CP violations (which is necessary in the electroweak baryogenesis scenario), especially if the MSSM is the correct effective theory for nature at the electroweak scale.

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