Can the Higgs Sector Trigger $CP$ Violation in the MSSM?

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Abstract

We reanalyze the possibility of $CP$ violation in the Higgs sector of the minimal supersymmetric standard model (MSSM). Contrary to the result of previous analysis, spontaneous $CP$ violation can not occur by only chargino and neutralino radiative corrections since the vacuum does not stable. Top and stop radiative corrections are crucially needed. However even with this correction there is no experimentally allowed region in $\tan \beta \geq 1$. This situation is not remedied even if the stop left-right mixing is included. We also analyze explicit $CP$ violation in the Higgs sector of the MSSM and show that the effect is too small to influence the phenomenology. We thus show that the Higgs sector can not, by itself, trigger $CP$ violation in the MSSM.

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1 Introduction

The minimal supersymmetric standard model (MSSM) is one of the strongest candidates for physics beyond the standard model (SM). Since the MSSM naturally contains two Higgs doublets, $CP$ could be violated in the Higgs sector both spontaneously and explicitly. The possibility of spontaneous $CP$ violation in the MSSM, which is caused by the non-trivial phase of vacuum expectation values (VEVs), was first discussed in Refs. [1][2]. They have shown the following:

(i) Spontaneous $CP$ violation is caused essentially by the chargino and the neutralino radiative corrections.

(ii) This scenario is excluded from the experiment since the "pseudoscalar" mass is of $O(\sqrt{\lambda} v)$ which is about 5 GeV.

In this paper we reconsider (i) and (ii), and results are the following:

(a) $CP$ violating vacuum discussed in Ref. [1] and [2] is not stable. It becomes stable when top and stop contributions are added, provided that the stop mass is larger than 180 GeV in the limit of small stop left-right mixing.

(b) Result (ii) was obtained in the case where there is no left-right mixing of stop. If the effect of the stop left-right mixing is included, Higgs masses depend on new parameters $A_t$ and $\mu$. Thus, there might be the experimental allowed region for spontaneous $CP$ violation scenario in the MSSM. Unfortunately, however, the numerical analysis shows that $CP$ violating vacuum is unstable in the parameter region of $A_t/m_t$ and/or $\mu/m_t \geq O(1/3)$, and the situation is almost same as the small left-right mixing limit case when $A_t/m_t$ and $\mu/m_t \leq O(1/3)$. We find that the result (ii) does not change even when we consider the possibility of left-right mixing.
(c) In this paper we consider only the region \( \tan \beta \geq \frac{1}{2} \). As for the experimental constraints, since spontaneous \( CP \) violation makes scalars and a pseudoscalar mix, it is not accurate to compare the lightest Higgs mass predicted in this scenario to the lower limit of pseudoscalar mass 24.3 GeV in Ref.[4] in which they assume that scalar and pseudoscalar do not mix. Therefore, we need to consider the precise experimental constraints from (A): \( Z \to h_1 h_2 \) and (B): \( Z \to h_i l^+ l^- \) \( (i = 1, 2) \).

(d) We also discuss briefly explicit \( CP \) violation in the Higgs sector of the MSSM in this paper. Since it is also caused by the radiative correction, its effect is too small to influence the phenomenology.

We therefore conclude that this scenario is excluded and the Higgs sector can not, by itself, trigger \( CP \) violation.

In Section 2, we discuss spontaneous \( CP \) violation. Section 3 gives summary and discussion. In Appendix, we show explicit \( CP \) violation in the Higgs sector.

2 Reanalysis of Spontaneous \( CP \) Violation in the MSSM

The most general two Higgs doublet model potential[3] is given by

\[
V(H_1, H_2) = m_1^2|H_1|^2 + m_2^2|H_2|^2 - (m_{12}^2 H_1 H_2 + \text{h.c.}) + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\
+ \frac{1}{2}[\lambda_5 (H_1 H_2)^2 + \text{h.c.}] \\
+ \frac{1}{2}[\lambda_6 (H_1 H_2) |H_1|^2 + \text{h.c.}] + \frac{1}{2}[\lambda_7 (H_1 H_2) |H_1|^2 + \text{h.c.}].
\] (1)

Parameter space \( \tan \beta < 1 \) is strongly disfavored in low energy SUSY models[3] as pointed out in Ref.[2].
$H_1$ and $H_2$ are Higgs doublet fields denoted as

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix},$$

with

$$H_1 H_2 = H_1^0 H_2^0 - H_1^- H_2^+.$$  \hfill (3)

Quartic couplings $\lambda_i$s ($i = 1 \sim 4$) are written by gauge couplings in the MSSM as

$$\lambda_1 = \lambda_2 = \frac{1}{8} (g^2 + g'^2), \quad \lambda_3 = \frac{1}{4} (g^2 - g'^2), \quad \lambda_4 = -\frac{1}{2} g'^2,$$

where $g$ and $g'$ are gauge couplings of $SU(2)_L$ and $U(1)_Y$, respectively. Parameters $m_1$, $m_2$, and $m_{12}$ are arbitrary determined by supersymmetric Higgs mass $\mu$ and soft SUSY breaking parameters. Coupling $\lambda_5$ get non-zero positive value by radiative corrections of the chargino and the neutralino\cite{1}\cite{2}. The value of $\lambda_5$ is

$$\lambda_5 = \frac{g^4}{32 \pi^2} \sim 5 \times 10^{-4},$$

in the limit of small squark left-right mixings and SUSY breaking mass parameter $B$, and equal mass limit of charginos and neutralinos\cite{2}. Couplings $\lambda_6$ and $\lambda_7$ are expected to be the same order of $\lambda_5$. Parameters $m_{12}^2$ and $\lambda_{5 \sim 7}$ are all complex in general. In the case that the Higgs sector has $CP$ symmetry,

$$\text{Im}(\lambda_5^* m_{12}^4) = \text{Im}(\lambda_5^* \lambda_6^2) = \text{Im}(\lambda_5^* \lambda_7^2) = 0$$

are satisfied, and all these parameters can be real by the redefinition of Higgs fields. Then we can set all parameters to be real in spontaneous $CP$ violation scenario. As for the explicit $CP$ violation, Eq.(3) is not held as shown in Appendix. Eq.(3) shows that the Higgs potential of the MSSM is automatically $CP$ invariant in the tree level because $\lambda_{5 \sim 7}^{(\text{tree})} = 0$.

Assuming that the charged Higgs does not get VEV, we denote VEVs of neutral components as

$$\langle H_1^0 \rangle = v_1, \quad \langle H_2^0 \rangle = v_2 e^{i \phi},$$

where $v_1$ and $v_2$ are physical Higgs masses defined at the scale $\Lambda$.
where $v_1$ and $v_2$ are real and positive parameters which satisfy $v \equiv \sqrt{v_1^2 + v_2^2} = 174$ GeV. We define fields around this vacuum as

$$H_1^0 = v_1 + \frac{1}{\sqrt{2}}(S_1 + i \sin \beta A),$$
$$H_2^0 = v_2 e^{i\phi} + \frac{1}{\sqrt{2}} e^{i\phi} (S_2 + i \cos \beta A),$$

where $S_1$ and $S_2$ are scalar fields and $A$ is a pseudoscalar field, and $\tan \beta = v_2/v_1$.

The stationary condition of the phase

$$\frac{\partial V}{\partial \phi} \bigg|_{\phi = \phi_0} = 0$$

induces

$$\sin \phi = 0 \text{ or } \cos \phi = \frac{2m_{12}^2 - \lambda_6 v_1^2 - \lambda_7 v_2^2}{4\lambda_5 v_1 v_2}.$$ (10)

The solution which has non-vanishing phase is derived from the second equation of Eq.(10) and we denote $\phi = \phi_0$ for this case. The necessary condition for spontaneous CP violation is

$$\langle V \rangle_{\langle H_1 \rangle = v_1} > \langle V \rangle_{\langle H_2 \rangle = v_2 e^{i\phi_0}}$$

for $\phi_0 \neq 0, \pi$, which derives

$$\lambda_5 > 0, \quad \left| \frac{2m_{12}^2 - \lambda_6 v_1^2 - \lambda_7 v_2^2}{4\lambda_5 v_1 v_2} \right| < 1.$$ (12)

It means that $m_{12}^2$ must be small of $O(\lambda_5 v^2)$ in order to get spontaneous CP violation. Eq.(12) is just a necessary and not the sufficient condition for spontaneous CP violation. We must not forget that there exist another stationary point with vanishing phase corresponding to the first equation of Eq.(10).

By the use of stationary conditions of VEVs

$$\frac{\partial V}{\partial v_i} \bigg|_{\phi = \phi_0} = 0 \quad (i = 1, 2),$$

(13)
we eliminate $m_1^2$ and $m_2^2$ as

$$
m_1^2 = \frac{g^2}{2}(v_2^2 - v_1^2) + \lambda_5 v_2^2 - \left(\frac{3\lambda_6 v_1 v_2}{2} + \frac{\lambda_7 v_3^2}{2v_1}\right) \cos \phi_0,
$$

(14)

$$
m_2^2 = \frac{g^2}{2}(v_1^2 - v_2^2) + \lambda_5 v_1^2 - \left(\frac{\lambda_6 v_1^3}{2v_2} + \frac{3\lambda_7 v_1 v_2}{2}\right) \cos \phi_0,
$$

(15)

where $g^2 \equiv (g^2 + g'^2)/2$. Now we can decide specific Higgs potential with definite values of $m_1^2$, $m_2^2$, and $m_{12}^2 = 2\lambda_5 v_1 v_2 \cos \phi_0 + (\lambda_6 v_1^2 + \lambda_7 v_2^2)/2$, which should have the stationary point at the non-trivial phase $\phi = \phi_0$. Expanding fields around this point as Eq.(8), mass spectra become

$$
M_{S_1 - S_1}^2 = g^2 v_1^2 + 2(\lambda_5 v_2^2 \cos^2 \phi_0 + \lambda_6 v_1 v_2 \cos \phi_0),
$$

(16)

$$
M_{S_2 - S_2}^2 = (g^2 + \Delta)v_2^2 + 2(\lambda_5 v_1^2 \cos^2 \phi_0 + \lambda_7 v_1 v_2 \cos \phi_0),
$$

(17)

$$
M_{S_1 - S_2}^2 = -\frac{g^2}{2}v_1 v_2 - 2\lambda_5 v_1 v_2 \sin^2 \phi_0 + \lambda_6 v_1^2 \cos \phi_0 + \lambda_7 v_2^2 \cos \phi_0,
$$

(18)

$$
M_{S_1 - A}^2 = -(2\lambda_5 \cos \phi_0 v_2 + \lambda_6 v_1) v \sin \phi_0,
$$

(19)

$$
M_{S_2 - A}^2 = -(2\lambda_5 \cos \phi_0 v_1 + \lambda_7 v_2) v \sin \phi_0,
$$

(20)

$$
M_{A - A}^2 = 2\lambda_5 v^2 \sin^2 \phi_0.
$$

(21)

$\Delta$ represents the top and stop effects

$$
\Delta \equiv \frac{3h_t^4}{4\pi^2} \ln \frac{m_t^2 + m_{\tilde{t}}^2}{m_t^2},
$$

(22)

where $m_t$ is the soft breaking stop mass parameter. Eq.(22) is derived from the one loop effective potential\[^{[3]}\] including only top and stop contributions, that is

$$
V_{\text{top}} = \frac{3}{16\pi^2} \left[(h_t^2|H_2|^2 + m_t^2)^2 \ln \left(\frac{h_t^2|H_2|^2 + m_t^2}{Q^2}\right) - h_t^4|H_2|^4 \ln \left(\frac{h_t^2|H_2|^2}{Q^2}\right)\right],
$$

(23)

where stop left-right mixing are neglected. The values of $M_{S_1 - A}^2$, $M_{S_2 - A}^2$ and $M_{A - A}^2$ are same as calculated by Pomarol\[^{[3]}\].

Next we show that if top and stop radiative corrections are not included, CP violating vacuum with non-vanishing phase can not be a global minimum. We expand
the determinant by small parameters $\lambda_{5\sim7}$ as

$$\text{Det}M_{ij}^2 = \text{Det}^{(0)}M_{ij}^2 + \text{Det}^{(1)}M_{ij}^2 + \text{Det}^{(2)}M_{ij}^2 + \ldots \ldots.$$  \hspace{1cm} (24)$$

As for the order $O(\lambda_{5\sim7}^0)$, $\text{Det}^{(0)}M_{ij}^2 = 0$. It is the result from so-called Georgi-Pais theorem[7], which says that the radiative symmetry breaking can be possible only when massless particle exists in the tree level. As for $O(\lambda_{5\sim7}^1)$,

$$\text{Det}^{(1)}M_{ij}^2 = 2\lambda_5 g^2 \Delta v^2 v_1^2 v_2^2 \sin^2 \phi_0.$$  \hspace{1cm} (25)$$

And for the next order $O(\lambda_{5\sim7}^2)$,

$$\text{Det}^{(2)}M_{ij}^2 = -g^2 [8\lambda_5^2 + (\lambda_6 + \lambda_7)^2] v^2 v_1^2 v_2^2 \sin^2 \phi_0.$$  \hspace{1cm} (26)$$

$\text{Det}^{(1)}M_{ij}^2$ is positive definite and $\text{Det}^{(2)}M_{ij}^2$ is negative definite. In order for $CP$ violating vacuum to be stable, where is a global minimum in fact, the relation

$$\text{Det}^{(1)}M_{ij}^2 > |\text{Det}^{(2)}M_{ij}^2|$$  \hspace{1cm} (27)$$

must be satisfied. For this inequality to be satisfied, top and stop contributions are essential, and stop mass must be larger than 178 GeV at $\tan \beta = 1$ (188 GeV at $\tan \beta = \infty$) when $m_t = 174$ GeV. Otherwise the determinant of this neutral Higgs mass matrix becomes negative. Without top and stop contributions, the stationary point which break $CP$ symmetry is not the true vacuum and $CP$ conserving point corresponding to the first equation of Eq.(10) becomes the true vacuum. For example, in the case of $\phi_0 = \pi/2$, we can really show

$$\langle V \rangle |_{(H_1)=v_1, (H_2)=v_2 e^{i\phi_0}} - \langle V \rangle |_{(H_1)=0, (H_2)=v_2} = \lambda_5 v_2^4 + O(\lambda_5^2) > 0 \quad (v_1^2 > v_2^2),$$  \hspace{1cm} (28)$$

$$\langle V \rangle |_{(H_1)=v_1, (H_2)=v_2 e^{i\phi_0}} - \langle V \rangle |_{(H_1)=0, (H_2)=v_2} = \lambda_5 v_1^4 + O(\lambda_5^2) > 0 \quad (v_2^2 > v_1^2),$$  \hspace{1cm} (29)$$

where we neglect $\lambda_6, \lambda_7$ for simplicity. We stress that spontaneous $CP$ violation can not occur only by one loop diagram of the chargino and the neutralino contrary to
Refs.\[1\][2]. Top and stop effects are essentially needed. However these effects do not influence to the $M_{A}^{2} - A$ component at all. Then the lightest Higgs mass has little dependence of $m_{\tilde{t}}$, and its mass becomes smaller than about 5.5 GeV.

There is no allowed region in $\tan \beta \geq 1$ which satisfies following experimental constraints; (A): the branching ratio $B(Z \to h_{1}h_{2})$ should be less than $10^{-7}$\[4], (B): $B(Z \to h_{1}l^{+}l^{-})$ should be smaller than $1.3 \times 10^{-7}$\[4][8], where $h_{1}$ and $h_{2}$ are lightest and second lightest physical Higgs states, respectively. However in $\tan \beta < 1$, there is allowed region, for example,

$$\tan \beta = 0.2, \quad \phi_{0} = \pi/2, \quad m_{\tilde{t}} = 3 \text{ TeV}.$$ \hspace{1cm} (30)

But in this case, $h_{t}/4\pi^{2} \simeq 1.35$, so we can not trust the loop expansion of Eq.(23).

How does the situation change if the stop left-right mixing is included? Are there possibilities that there appears experimentally allowed region in $\tan \beta \geq 1$ by additional parameters $A_{t}$ and $\mu$ appeared in Eqs.(16)$\sim$(21)? Here $A_{t}$ is the SUSY breaking parameter of stop-stop-Higgs interaction. In order for $A_{t}$ and/or $\mu$ to have large effects on Higgs masses, they must be of $O(m_{\tilde{t}})$, since stop left-right mixing is proportional to $m_{t}A_{t}$ and $m_{t}\mu$. However it is shown that $CP$ violating vacuum becomes unstable in the parameter region of $A_{t}/m_{\tilde{t}}$ and/or $\mu/m_{\tilde{t}} \geq O(1/3)$ from the numerical analysis. And in the region of $A_{t}/m_{\tilde{t}}$ and $\mu/m_{\tilde{t}} \leq O(1/3)$, the situation is almost same as the limit case of small left-right mixing. In addition, the magnitude of $\lambda_{5}$, which is proportional to $M_{A}^{2} - A$, itself becomes small if stop left-right mixing exists. Thus, there is no experimentally allowed region even if parameters $A_{t}$ and $\mu$ take any values. Therefore we can conclude that spontaneous $CP$ violation in the MSSM is excluded from experimental constraints.
3 Summary and Discussion

We show that $CP$ violating vacuum can not be the true vacuum only by the chargino and the neutralino contributions. Top and stop contributions are crucially needed for spontaneous $CP$ violation in the MSSM. In the limit of small stop left-right mixing, the stop mass must be larger than about 180 GeV for the vacuum stability, however, there is no experimentally allowed region in $\tan \beta \geq 1$. If we include the stop left-right mixing, additional parameters $A_t$ and $\mu$ appear in Higgs masses. However numerical analysis shows that both $A_t$ and $\mu$ should be smaller than $O(m_\tilde{t}/3)$ for the vacuum stability, and the situation is not so changed as the limit case of small stop left-right mixing. Thus, there is no experimental allowed region for spontaneous $CP$ violation in the MSSM in $\tan \beta \geq 1$. In order to obtain experimentally consistent spontaneous $CP$ violation scenario in the SUSY model, we should extend the MSSM to, for example, the next-to-minimal supersymmetric standard model (NMSSM) which contains an additional gauge singlet field $N$. In Refs. [10] [11] [12], they discuss spontaneous $CP$ violation in the NMSSM. Especially for the NMSSM with the scale invariant superpotential, spontaneously $CP$ violation occurs radiatively, so we can not avoid Georgi-Pais theorem. However the large VEV of $N$ can lift up the lightest Higgs mass, which is relatively light compared to $\langle N \rangle$ in actual, and spontaneous $CP$ violation in the NMSSM can be consistent with the experimental constraints (A) and (B).

As for explicit $CP$ violation in the Higgs sector of the MSSM, the mixing with scalars and a pseudoscalar appears also at the loop level. In this case $m_{12}^2$ does not need to be small of $O(\lambda_5 v^2)$ as spontaneous $CP$ violation scenario. Angles of $CP$ mixings are negligibly small of $O(\lambda_{5-7})$ as shown in Appendix, which are too small to influence the phenomenology.
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A Explicit CP Violation

Once CP symmetry is violated explicitly at the Lagrangian level, Eq. (3) is not held in general. It is because $\lambda_5 \sim \ldots$ are derived from various different diagrams containing different CP phases such as Yukawa couplings, A terms, gaugino masses, and so on.

We denote complex parameters $m^2_{12}$ and $\lambda_5 \sim \ldots$ as

$$m^2_{12} \equiv m^2_{12} e^{i \varphi_m}, \quad \lambda_5 \equiv \lambda_5 e^{i \varphi_5}, \quad \lambda_6 \equiv \lambda_6 e^{i \varphi_6}, \quad \lambda_7 \equiv \lambda_7 e^{i \varphi_7},$$

where $m^2_{12}$ and $\lambda_5 \sim \ldots$ on the right hand side are real and positive parameters. By the phase rotation of Higgs fields, we can always take $\varphi_m = 0$. The stationary condition of the phase Eq. (9) induces

$$2 m^2_{12} \sin \phi - 2 \lambda_5 v_1 v_2 \sin(\phi + 2 \varphi_5) - \lambda_6 v_1^2 \sin(\phi + \varphi_6) - \lambda_7 v_2^2 \sin(\phi + \varphi_7) = 0. \quad (32)$$

It means that $\phi = 0$ can be the minimum, and which we take here for simplicity.

Using Eq. (13) and (32), the mass matrix of the neutral Higgs becomes

$$M^2_{S_1 - S_1} = \frac{g^2}{2} v_1^2 + m^2_{12} v_2^2 + \frac{1}{2} \lambda_6 v_1 v_2 \cos \varphi_6 - \frac{1}{2} \lambda_7 v_2^2 \cos \varphi_7,$$

$$M^2_{S_2 - S_2} = (g^2 + \Delta) v_2^2 + m^2_{12} v_1^2 - \frac{1}{2} \lambda_6 v_1^2 \cos \varphi_6 + \frac{3}{2} \lambda_7 v_1 v_2 \cos \varphi_7,$$

$$M^2_{S_1 - S_2} = -m^2_{12} - (g^2 - \frac{\lambda_5}{2} \cos \varphi_5) v_1 v_2 + \frac{3}{2} (\lambda_6 v_1^2 \cos \varphi_6 + \lambda_7 v_2^2 \cos \varphi_7),$$

$$M^2_{S_1 - A} = \frac{v}{2 v_1} (\lambda_6 v_1^2 \sin \varphi_6 - \lambda_7 v_2^2 \sin \varphi_7),$$

$$M^2_{S_2 - A} = \frac{v}{2 v_2} (\lambda_6 v_1^2 \sin \varphi_6 - \lambda_7 v_2^2 \sin \varphi_7),$$

$$M^2_{A - A} = \frac{v^2}{2 v_1 v_2} (2 m^2_{12} - 4 \lambda_5 v_1 v_2 \cos \varphi_5 - \lambda_6 v_1^2 \cos \varphi_6 - \lambda_7 v_2^2 \cos \varphi_7). \quad (38)$$
The physical charged Higgs field is defined as \( C^+ \equiv \cos \beta H^+ + \sin \beta H^- \) and its mass is given by

\[
m_C^2 = m_W^2 + M_A^2 - A.
\]  
(39)

Mixings of scalars and a pseudoscalar are small of order \( O(\lambda_5 \sim v^2) \). It is because \( CP \) violation in the Higgs sector is not realized till radiative corrections are included. Contrary to spontaneous \( CP \) violation, the determinant of \( O(\lambda_5^0 \sim 7 v^2) \) becomes positive as

\[
\text{Det}^{(0)} M_{ij}^2 = \frac{g^2 m_1^4 v^2 (v_1^2 - v_2^2)^2}{v_1^2 v_2^2} > 0.
\]  
(40)

Angles of \( CP \) mixings in the Higgs sector are of \( O(\lambda_5^0 \sim v^2) \) from Eqs.(33) \( \sim \) (38). Then the effect of \( CP \) violation in the Higgs sector is negligibly small comparing to other sectors.
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