Toward verification of electroweak baryogenesis by electric dipole moments

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We study general aspects of the CP-violating effects on the baryon asymmetry of the Universe (BAU) and electric dipole moments (EDMs) in models extended by an extra Higgs doublet and a singlet, together with electroweak-interacting fermions. In particular, the emphasis is on the structure of the CP-violating interactions and dependences of the BAU and EDMs on masses of the relevant particles. In a concrete model, we investigate a relationship between the BAU and the electron EDM for a typical parameter set. As long as the BAU-related CP violation predominantly exists, the electron EDM has a strong power in probing electroweak baryogenesis. However, once a BAU-unrelated CP violation comes into play, the direct correlation between the BAU and electron EDM can be lost. Even in such a case, we point out that verifiability of the scenario still remains with the help of Higgs physics.

I. INTRODUCTION

The particle content of the standard model (SM) has been completed by the discovery of the 125 GeV Higgs boson at the Large Hadron Collider (LHC) [1]. So far, there is no clear signal beyond the SM in laboratory experiments. Nevertheless, the cosmological problems such as the origin of the baryon asymmetry of the Universe (BAU) and identification of the cold dark matter still remain unsolved within the SM.

One of the mechanisms for generating the BAU is electroweak baryogenesis (EWBG) [2]. In this scenario, the BAU arises during the electroweak phase transition (EWPT), and its feasibility depends on properties of models at the GeV/TeV scales. From the viewpoint of the testability, EWBG is the first scenario that is verified or falsified by the ongoing and upcoming experiments, among others. As is well known, the SM has the two drawbacks that prevent it from generating the BAU: absence of both a strong first-order EWPT [3] and a sufficient amount of CP violation [4]. Supersymmetric (SUSY) models may naturally solve those issues simultaneously. For example, in the minimal SUSY SM model (MSSM), a light scalar top (stop) could induce the strong first-order EWPT, and the fermionic superpartners provide the substantial amount of CP violation. However, it turns out that the light stop scenario in the MSSM is not consistent with the LHC Run 1 data such as the Higgs signal strengths and the direct stop searches [5]. Given this fact, the colored particles may no longer the candidates for archiving the strong first-order EWPT. Therefore, whatever a UV theory might be, the possibility of EWBG can be investigated in the framework of an effective field theory of non-colored particles after integrating out irrelevant heavy degrees of freedom, i.e.,

\[ \text{UV theories} \supset \text{multi-Higgs + EW-interacting fermions}. \]  

Experiments that are most sensitive to the CP violation are measurements of the electric dipole moments (EDMs) of electron, neutron and atoms etc. Clarifying relationships between the BAU-related CP violations and the EDMs are indispensable for the test of the EWBG scenario. In some analyses in the literature, the CP-violating effect is incorporated by higher dimensional operators assuming only one Higgs doublet and by which the BAU is evaluated. In such a case, the CP-violating effects peculiar to the finite temperature, such as a resonant enhancement pointed out in Ref. [6], are missing, which drastically changes the correlation between the BAU and EDM.

In this Letter, we clarify similarities and differences between the BAU-related CP violation and the EDM-related one with particular emphasis on the structure of the interactions and the mass dependences of the relevant particles. As an illustration, we consider a framework in which the Higgs sector is augmented by an additional Higgs doublet and a singlet, and in addition, SU(2) doublet fermions and singlet fermion are introduced to accommodate CP violation for baryogenesis. In our setup, the structure of the CP-violating interactions are more generic than those in SUSY models. We evaluate the CP-violating source term for the BAU in the closed-time-path formalism and relate it with the electron EDM. The correlation between the two CP-violating quantities is elucidated as functions of the EW-interacting fermion masses.

As a specific example, we consider a next-to-MSSM-like model and work out the relationship between the BAU and electron EDM. It is found that the electron EDM is the useful probe of the baryogenesis favored region as long as the BAU-related CP violation predom-
in the diffusion equation of the Higgs bubble walls, which leads to a dominant CP-violating source term for the BAU.

in the model. However, there is a case in which a BAU-unrelated CP violation, if it exists, alters the intimate connection between the BAU and EDM, which makes it difficult to test EWBG via the electron EDM experiment only. Nevertheless, such a specific case is possible only in the case that the doublet-singlet Higgs boson mixing exists, which is needed for a tree-potential-driven strong first-order EWPT, and thus still testable in combination with Higgs physics.

II. GENERAL ASPECTS OF CP-VIOLATING EFFECTS ON THE BAU AND EDMS

Before going to present our model, we here give a simple but rather generic argument about the relationship between the BAU-related CP violation and EDM. For illustrative purposes, we consider the framework in which two Higgs doublets and two species of EW-interacting fermions (denoted as \( \psi_{i,j} \)) are present. For definite, \( \psi_{i} \) is assumed to be Dirac fermion and \( \psi_{j} \) Majorana fermion. This setup applies to the bino-driven EWBG in the U(1)\( \beta \)-\( \beta \) and the singlino-driven EWBG in the U(1)\( \beta \)-\( \beta \) MSSM [8] and the Z'ino-driven EWBG in the U(1)\( \beta \)-\( \beta \) MSSM [9] in proper limits. We expect that the following discussion would hold in other cases by making an appropriate translation.

Let us parameterize the relevant interactions as

\[
\mathcal{L} = \frac{1}{\sqrt{2}} \bar{\psi}_i (c_{L,R} v_\alpha P_L + c_R v_b P_R) \psi_j + \text{h.c.},
\]

where \( v_{a,b} \) \((a, b = 1, 2)\) denote the Higgs vacuum expectation values (VEVs), and \( c_{L,R} \) are the complex parameters. With this Lagrangian, we evaluate the source terms in the diffusion equation of \( \psi_{i} \) in the closed-time-path formalism [9]. The vector current of \( \psi_{i} \) has the form

\[
\partial_\mu J_{\psi_i}^\mu = S_{\psi_i},
\]

where only the CP-violating source term is shown on the right-hand side. In a VEV insertion approximation [9], \( S_{\psi_i} \) to leading order is induced by the process shown in Fig. 1, which in turns is approximated by

\[
S_{\psi_i}(X) = \kappa_S \cdot 2m_i m_j \text{Im}(c_{L} c_{R}^\dagger) v^2(X) \dot{\beta}(X) \mathcal{I}^{ij}_f,
\]

where \( \kappa_S = +1 \) for \((a, b) = (2, 1)\), \( \kappa_S = -1 \) for \((a, b) = (1, 2)\) and \( \kappa_S = 0 \) for \((a, b) = (1, 1)\), \( (2, 2)\). \( m_{i,j} \) are the masses of \( \psi_{i,j} \), \( \dot{\beta}(X) \) is the time derivative of \( \beta(X) = \tan^{-1}(v_2(X)/v_1(X)) \), and \( \mathcal{I}^{ij}_f \) denotes a thermal function as will be given below. One can see that \( S_{\psi_i}(X) \) would vanish not only for \( \text{Im}(c_{L} c_{R}^\dagger) = 0 \) but also in the cases in which one of the following condition is fulfilled: \( v(X) = 0 \), \( \beta(X) = 0 \) and \( \mathcal{I}^{ij}_f = 0 \). Since the EWPT is of first order, the Higgs VEVs depend on a spacetime variable \( X \), and the profiles of which can be determined by static bubble configurations at a nucleation temperature. In most cases, the shapes of \( v(X) \) and \( \beta(X) \) would be approximated by kink-type configurations, so \( \dot{\beta}(X) \) is proportional to a variation of \( \beta(X) \) along the line connecting broken and symmetric phases. In the MSSM, \( \dot{\beta}(X) \) roughly scales as \( 1/m_A^2 \) [10], where \( m_A \) is the CP-odd Higgs boson mass, which implies that \( S_{\psi_i}(X) \) in Eq. 4 would completely disappear if the Higgs sector is composed of only one Higgs doublet, as already indicated in the case of \( \kappa_S = 0 \). From this argument, it is expected that the presence of the extra Higgs boson with a nonzero VEV may be essential for successful EWBG, regardless of the strong first-order EWPT realization. Here, it should be reminded that there is another type of the source term that is not suppressed in the large \( m_A \) limit, which may appear as a higher order correction to the approximation we have made here (see, e.g., Refs. [11, 12]). As long as the BAU is explained by a resonant enhancement, which is indeed the case in our analysis, such a source term would not play a central role.

The behavior of the thermal function \( \mathcal{I}^{ij}_f \) is somewhat complicated, and in some specific region it is strongly governed by the finite temperature physics. The explicit form of \( \mathcal{I}^{ij}_f \) is [6]

\[
\mathcal{I}^{ij}_f = \int_k \frac{k^2}{\omega_{ji} \omega_i} \left[ \left\{ (1 - 2\text{Re}(n_i)) \text{I}_{ji} + (i \leftrightarrow j) \right\} - 2(\text{Im}(n_j) + \text{Im}(n_i)) G_{ji} \right],
\]

where \( \int_k = \int_0^\infty dk/(4\pi^2) \), \( n_i = 1/(e^{(\omega_{ji}-\omega_{ij})/T} + 1) \), \( \omega_i = \sqrt{k^2 + m_i^2} \), with \( \Gamma_i \) being the thermal widths of \( \psi_i \). Here, \( I_{ij} \) and \( G_{ij} \) are respectively expressed by

\[
I_{ij} = \Gamma + \left[ \frac{\omega^+}{(\omega^2 + \Gamma_+^2)^2} + \frac{\omega^-}{(\omega^2 + \Gamma_-^2)^2} \right],
\]

\[
G_{ij} = \frac{1}{2} \left[ \frac{\omega^2 - \Gamma_+^2}{(\omega^2 + \Gamma_+^2)^2} - \frac{\omega^2 - \Gamma_-^2}{(\omega^2 + \Gamma_-^2)^2} \right],
\]

where \( \omega_{\pm} = \omega_i \pm \omega_j \) and \( \Gamma_+ = \Gamma_i + \Gamma_j \). One can see that \( \mathcal{I}^{ij}_f \) vanishes if \( \Gamma_i = \Gamma_j = 0 \). Since \( \Gamma_{ij} \approx g T \), where \( g \) represents a typical coupling in a model and \( T \) a temperature, \( S_{\psi_i}(X) \) first emerges to order of \( \mathcal{O}(g^4) \) assuming \( |c_L| = |c_R| \approx g \).

As is well known, \( S_{\psi_i} \) has a resonant enhancement at \( m_i = m_j \), the behavior of which comes from \( G_{ij} \). Since
\[ \omega_{ij} \gg \Gamma_{ij}, \text{one may approximate } G_{ij} \text{ as} \]
\[ G_{ij} \approx -\frac{1}{2} \frac{\omega^2 - \Gamma_i^2}{(\omega_i^+)^2} + O \left( \frac{1}{\omega_i^+} \right). \quad (8) \]

One can see that \( G_{ij} \) has a peak at \( \omega_+ = 0 \), which can yield the dominant source for the BAU.

We now study the impact of \( \text{Im}(c_L c_H^\ast) \) on the EDM. Since the new fermions have the EW charges, the following interactions exist:
\[ \mathcal{L} = \frac{g_2}{\sqrt{2}} \left( \bar{\psi}_i^+ \gamma^\mu \psi_i W^+_{\mu} + \bar{\psi_i} \gamma^\mu \psi^+_i W^-_{\mu} \right) - e \bar{\psi_i} \gamma^\mu \psi_i^+ A_{\mu}, \quad (9) \]

where \( \psi^\pm \) denote electrically charged members in the SU(2)_L multiplet fermion. We assume that \( \psi_i \) is the neutral member of the same multiplet. In this case, the WW-mediated Barr-Zee diagram is induced, as shown in Fig. 2. The EDM of a fermion \( f \) using the mass insertion method is given in Eq. (10)
\[ \frac{d^{WW}_f}{e} = -\frac{\alpha_{em}}{64\pi^2 s_W} \frac{m_r m_{\psi^+} v e}{m_W^2} \text{Im}(c_L c_H^\ast) F^{WW} \]
\[ = C^{WW}_{\text{EDM}} \text{Im}(c_L c_H^\ast). \quad (10) \]

where the negative (positive) sign is the case that \( f \) is up-type (down-type) fermion, \( F^{WW} = (f^{WW}(r_i, r_+) - f^{WW}(r_i, r_-))/(m_i^2 - m_j^2) \) with \( r_i = m_f^2/m_W^2, r_j = m_f^2/m_W^2 \) and \( r_+ = m_f^2/m_W^2 \). The explicit form of \( f^{WW} \) is given in Ref. 14. We emphasize that unlike \( S_{\psi_i}(X) \) in Eq. (4), Eq. (10) does not vanish for \((a, b) = (1, 1)\) or \((2, 2)\) in addition, \( d^{WW}_f/e \) is not enhanced at \( m_i = m_j \), which are the prominent differences between the two CP-violating quantities. One may find that \( d^{WW}_f/e \propto m_f/m_j \) for \( m_i \gg m_j \) and \( d^{WW}_j/e \propto m_f/m_i \) for \( m_j \gg m_i \), which signifies another distinct feature of the EDM as discussed below. In what follows, we confine ourself to the cases of \((a, b) = (2, 1)\) and \((1, 2)\).

It is worth making a comment on that the mass insertion method used in Eq. (10) not only makes it easy to see the relationship between the CP-violating source term and the EDM but also gives the numerically good approximation.

Eliminating \( \text{Im}(c_L c_H^\ast) \) in Eq. (11) using Eq. (10), one finds
\[ S_{\psi_i} = \frac{C_{\text{BAU}}}{C^{WW}_{\text{EDM}}} \left( \frac{d^{WW}_f}{e} \right). \quad (11) \]

In order to see the correlation between \( S_{\psi_i} \) and \( d^{WW}_f/e \) in more detail, we define
\[ \tilde{S}_{\psi_i} = \frac{C_{\text{BAU}}}{\bar{v}^2(X)\tilde{\beta}(X)C^{WW}_{\text{EDM}}} \left( \frac{d^{WW}_f}{e} \right)_{\text{exp}}. \quad (12) \]

In what follows, we consider the electron EDM as the experimental constraint, i.e., \( |d_e^{\text{exp}}| = 8.7 \times 10^{-29} e \cdot cm \). Here, we get rid of \( v^2(X)\tilde{\beta}(x) \) in \( C_{\text{BAU}} \) since it is rather model dependent.

In Fig. 3 \( \tilde{S}_{\psi_i} \) is plotted as a function of \( m_i \) with a fixed \( m_j \) or the other away around. As an example, we take \( \beta = 1 \), and the fixed mass is set to 500 GeV. As explained above \( C_{\text{BAU}} \) has a peak at \( m_i = m_j \). However, the decoupling behaviors in the large mass limits are substantially different from each other. For the varying \( m_j \) case, \( \tilde{S}_{\psi_i} \) becomes more or less flat in the large mass region while it grows for the varying \( m_i \) case. The latter is due to the rapid suppression of \( C^{WW}_{\text{EDM}} \) that scales as \( m_i/m_j^3 \) as mentioned above. Note that \( \text{Im}(c_L c_H^\ast) \gg 1 \) for \( m_i \lesssim 1 \) TeV since \( d^{WW}_f/e \) is fixed.

Now we move on to discuss a possibility that the aforementioned correlation between the CP-violating source

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1. Barr-Zee diagrams involving the heavy Higgs bosons are also generated. Here, we assume that those Higgs bosons are heavy enough not to alter the following discussion drastically. The case without this assumption will be given in [13].
term and the EDM is spoiled by contamination of BAU-unrelated CP violation. As delineated below, such a situation can arise when we address the issue of the strong first-order EWPT.

The SM Higgs sector has to be extended in such a way that the EWPT is of first order. There are two representative cases for achieving this:

- Thermal loop driven case
- Tree potential driven case

For example, the former corresponds to the SM, MSSM and a two Higgs doublet model (2HDM) and so on. In such cases, the cubic-like terms arising from the bosonic thermal loops play an essential role in inducing the first-order EWPT. In the latter case, on the other hand, a specific structure of a tree-level Higgs potential is the dominant source for generating a barrier separating the two degenerate minima at a critical temperature. One of the interesting possibilities is that no cancellation among those contributions becomes effective, it is possible for $d_f$ to be made highly suppressed but with the nonzero $d^W_{f}$, so the BAU-related CP violation is not constrained by a single EDM experiment in this case.

Nevertheless, one may probe such a parameter space with Higgs physics since the nonzero doublet-singlet Higgs mixing parameter and $g^{S,P}$ would lead to some deviations in the Higgs signal strengths. We will explicitly demonstrate this possibility in the next section.

So far, we have exclusively focused on the relationship between the CP-violating source term and the EDM. Here, we comment on the dependence of $\text{Im}(c_L c_R^*)$ on the baryon number density ($n_B$) briefly. Under some mild assumptions, one may have

$$n_B = \kappa_B \frac{S_{\text{CPV}}}{\sqrt{1 - S_{\text{CPV}}}}. \quad (15)$$

### Table I

| particles | $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ | $Z_2$ |
|-----------|-------------------------------------------------|------|
| $\Phi_1$  | (1, 2, 1/2)                                      | −    |
| $\Phi_2$  | (1, 2, 1/2)                                      | +    |
| $S$       | (1, 1, 0)                                        | −    |
| $\Phi_1$  | (1, 2, −1/2)                                     | −    |
| $\Phi_2$  | (1, 2, 1/2)                                      | +    |
| $S^0$     | (1, 1, 0)                                        | −    |

where $\kappa_B$ is a coefficient. $S_{\text{CPV}}$ is a CP-violating term arising from $S_{\psi}$ discussed above and $\Gamma_{\text{CPV}}$ a CP-conserving particle changing rate. For the latter, for example, the interactions in Eq. (2) induce

$$\Gamma_{\psi_i}(X) = \frac{1}{T} \left[ \left( |c_L|^2 v_0^2(X) + |c_R|^2 v_0^2(X) \right) F_{ji} ight. \nonumber$$

$$\left. + 2 \text{Re}(c_L c_R^*) v_1(X) v_2(X) m_i m_j \mathcal{R}_{ji} \right], \quad (16)$$

where $F_{ji}$ and $\mathcal{R}_{ji}$ are the thermal functions presented in Ref. [4]. As studied in Ref. [13], $\Gamma_{\psi_i}$ also has the resonant behavior at $m_i = m_j$, rendering $n_B$ smaller. It should be emphasized that a cancellation between the first and second terms in $\Gamma_{\psi_i}$ can happen depending on the choice of $\text{Arg}(c_L c_R^*)$ and $m_{i,j}$. Therefore, $n_B$ does not necessarily take its maximal value at $\text{Arg}(c_L c_R^*) = \pi/2$ or $-\pi/2$, which may relax the EDM constraint to some extent.

### III. A MODEL

Now, we define our model and give basic ingredients for calculating the BAU and the electron EDM. The particle content of the Higgs and the new EW-interacting fermion sectors in the model is shown in Table I. The total Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_{\text{2HDM}} + \frac{1}{2} \partial_{\mu} S \partial^{\mu} S - V_S - V_{\Phi S} + \mathcal{L}_{\Phi S} + \mathcal{L}_{\Phi \tilde{S}} + \mathcal{L}_{\Phi S},$$

$$\mathcal{L}_{\Phi S} = \sum_{i=1,2} \bar{\Phi} i \sigma^\mu \partial_{\mu} \Phi_i + \overline{S_0} i \sigma^\mu \partial_{\mu} S^0$$

$$- \epsilon_{ab} \left[ \sum_{j=1,2} \left( \bar{\Phi}^a_1 c_{1j} \Phi^b_j + \bar{\Phi}^a_2 c_{2j} (i \tau^2 \Phi^b_j) \right) S^0 \right. \nonumber$$

$$\left. + (\mu + \lambda S) \Phi^a_1 \Phi^b_2 + \text{h.c.} \right] \nonumber$$

$$+ \frac{1}{2} (\mu_S + \kappa S) \overline{S_0} S^0 + \text{h.c.}, \quad (17)$$

where $\Phi_{1,2}$ and $S^0$ are the two-component spinors, and $\epsilon_{12} = -\epsilon_{21} = +1$. As is the case in the MSSM, to avoid a lepton flavor violation, we impose a matter parity under which new EW-interacting fermions are odd.
and the SM fermions are even. Furthermore, as in the ordinary 2HDM, another $Z_2$ symmetry ($\Phi_1 \rightarrow -\Phi_1$ and $\Phi_2 \rightarrow \Phi_2$) is enforced to evade tree-level Higgs-mediated flavor-changing-neutral-current processes. Depending on $Z_2$ charge assignments for the fermions, four types of the Yukawa interactions are possible. However, the following analysis does not depend on those types since the top Yukawa coupling is the only relevant that is common to all the types.

The Higgs fields are parametrized as

$$\Phi_{1,2}(x) = \left( \begin{array}{c} \phi_1^+ \\ \phi_0^+ \\ \phi_i^+ (v_i + h_i(x) + i a_i(x)) \end{array} \right), \quad i = 1, 2,$$

where $v_1 = v \cos \beta$, $v_2 = v \sin \beta$ with $v = 246$ GeV.

In the following, we consider a rSM-like limit in which $\sin(\beta - \alpha) = 1$, where $\alpha$ denotes a mixing angle between two CP-even Higgs bosons ($h_{1,2}$). In this case, only one state (denoted as $h$) has the VEV and gives the masses of the gauge bosons and fermions. Since the strong first-order EWPT is assumed to be driven by the tree-Higgs potential, the heavy Higgs bosons do not necessarily have the so-called nondecoupling effect which is needed in the thermal loop driven strong first-order EWPT case [19].

The detailed comparison between the two cases will be given elsewhere [13].

Since we have the singlet Higgs boson in this model, $h$ mixes with $h_S$ through a mixing $\gamma$ as

$$\begin{pmatrix} h \\ h_S \end{pmatrix} = \begin{pmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}.$$

In our scenario, $H_1$ is the SM-like Higgs boson whose mass is 125 GeV, and $H_2$ is the singlet-like Higgs boson which is assumed to be heavier than $H_1$. Another CP-even Higgs boson originated from the Higgs doublet is denoted as $H_3$ which is heavier than $H_2$.

In response to $Z_2$ charges assignments of $\Phi_{1,2}$ and $S$, there are several types of the interactions among the new EW-interacting fermions and Higgs bosons [13]. Here, we focus on one of them as an example. The $Z_2$ charge assignment is listed in Table. 1

The relevant interactions among the EW-interacting fermions and Higgs bosons are

$$L^\text{int}_{hS} \ni \sum_{i=1,2} H_i \tilde{H}_i \left( g^e_{H,\tilde{H}} + i \gamma_5 g^p_{H,\tilde{H}} \right) \tilde{H}^+$$

where the fermions are expressed in terms of the four-component spinors. Each coupling is respectively given by

$$g^S_{H_i,\tilde{H}_i} = |\lambda| \cos \phi_{\lambda H} s_\gamma,$$

$$g^P_{H_i,\tilde{H}_i} = |\lambda| \sin \phi_{\lambda H} s_\gamma,$$

where we have defined $\lambda = |\lambda| e^{i \phi_5}$, $\mu = |\mu + \lambda v S| e^{i \phi_6}$, $\mu_S = |\mu_S| e^{i \phi_7}$ and $\phi_{\lambda H} = \phi_5 - \phi_6$. As discussed in the previous section, the interactions in the second line of Eq. (21) plays an essential role in generating the CP-violating term that fuels the BAU. For notational simplicity, we define $\phi = -(\phi_6 + \phi_7)$ hereafter.

IV. NUMERICAL ANALYSIS

Following a calculation method formulated and developed in Refs. [6, 18, 20], we estimate $n_B$ by

$$n_B = \frac{-3 \Gamma_B^{s}(s)}{2 \sqrt{v_w^2 + 4 R D_4}} \int_{-\infty}^{0} dz' n_L(z') e^{-\lambda - z'},$$

where $\lambda = \left( v_w - \sqrt{v_w^2 + 4 R D_4} \right)/(2 D_4)$, $\Gamma_B^{s}$ is a baryon number changing rate in the symmetric phase, $v_w$ is a velocity of the bubble wall, $D_4$ is a diffusion constant of the quarks, and $R$ is a relaxation term, which is $(15/4) \Gamma_B^{s}$ in our model. $n_L$ is the total number density of all the left-handed quarks and leptons [21, 22].

Since the EWPT is reduced to that in the rSM, we adopt S2 scenario investigated in Ref. [17] as a benchmark in which $m_{H_2} = 170$ GeV, $\cos \gamma \simeq 0.94$ and $v_C/T_C = 206.75$ GeV/111.76 GeV. In addition, we take $\tan \beta = 1, v_w = 0.4$, $\Gamma_H^s = 0.0257T$, $\Gamma_{\tilde{S}}^s = 0.003T$, and use an approximation, $\beta = v_w \Delta \beta/L_w$ taking $\Delta \beta = 0.015$. Under this assumption, $n_B$ does not depend on $L_w$. Moreover, the constant VEV but $v_C/2$ is used in calculating $n_B$, which may give a simple approximation of kink-type VEV [13]. For the heavy Higgs boson masses, we set 400 GeV, and for a softly broken mass, which is a mixing mass between $\Phi_1$ and $\Phi_2$, 250 GeV is taken. For the other parameters, we refer to the values adopted in Ref. [17]. In the following, the electron EDM is calculated in the mass eigenbasis of the neutral fermions rather than the mass insertion method, although the both are not much numerically different.

We first present the case where the electron EDM is induced by only the WW-mediated Barr-Zee diagram. In Fig. 1 contours of $Y_B/Y_B^{\text{obs}}$ and $|d_e|$ are shown in the ($m_{\tilde{S}}, m_{\tilde{S}}$) plane. We take $|\tilde{e}^p_{\tilde{S}}| = |\tilde{e}^p_{\tilde{S}}| = 0.42$, $\phi = 225^\circ$ and $|\lambda| = 0$. Here, $\phi$ is chosen in such a way that the cancellation in $\Gamma_{\text{CPC}}$ is effective. In this figure, the orange region is excluded by the current experimental limit of the electron EDM, $|d_e^{\text{expt}}| < 8.7 \times 10^{-28} e \cdot cm$, and the dashed line corresponds to $|d_e| = 1.0 \times 10^{-26} e \cdot cm$ which
and $m$ limit of the electron EDM, and the red dashed line corre-
region colored in red is excluded by the current experimen-
tural limit of the electron EDM, the dashed line indicates the
plane. The region colored in orange is excluded by the cur-
the electron EDM in the $(m_B, m_S)$ plane. The region colored in orange is excluded by the current experimen-
parameters are the same as in Fig. 4, but with
is reachable by the future experiments $^{22}$. The black solid and dashed lines represent $Y_B/Y_B^{obs} = 1$ and 0.1, respectively. We set $|e^{L}_B| = |e^{S}_B| = 0.42$ and $\phi = 225^\circ$.

![FIG. 4. The contours of $Y_B/Y_B^{obs}$ and $|d_e|$ in the $(m_B, m_S)$ plane. The region colored in orange is excluded by the current experimental limit of the electron EDM, and the red dashed line corre-](image)

is represented by the gray lines: $\mu_{\gamma} = 1.1, 1.0, 0.9$ and 0.8 from top to bottom. The whole region is still within the $2\sigma$ region of the current LHC data, $\mu_{\gamma} = 1.17 \pm 0.27$ (ATLAS) and $\mu_{\gamma} = 1.14_{-0.23}^{+0.26}$ (CMS). We remark that the the sensitivity of $\mu_{\gamma}$ is expected to be improved up to $O(5)\%$, and Higgs coupling to the gauge bosons ($\cos \gamma$ in the current setup) up to $O(0.1)\%$ at future colliders such as the high-luminosity LHC (HL-LHC) $^{25}$, International Linear Collider (ILC) $^{26}$ and TLEP $^{27}$. Therefore, the testability of EWBG in this scenario still persists.

**V. CONCLUSIONS**

We have studied the relationship between the CP-
violating source term for the BAU and the EDMs in the
framework where the extra Higgs doublet and the sin-
glet as well as the new EW-interacting fermions ($\psi_{i,j}$) are introduced. We scrutinized the ratio $\tilde{S}_\psi$ (defined by Eq. (12)) as functions of the EW-interacting fermion masses. In the region where new fermions are degenerate, $\tilde{S}_\psi$ is resonantly enhanced due to the thermal effect appearing in the source term. In the large mass limits of the fermions, on the other hand, $\tilde{S}_\psi$ gets milder or larger depending on the fermion species, and the behaviors of which are mostly governed by the property of the loop function of the EDM rather than that of the CP-violating source term for the BAU.

As a concrete example, we considered the next-to-
MSSM-like model and investigated the correlation be-
tween the BAU and the electron EDM for a typical par-
eter set. It is found that as long as the BAU-related CP violation predominantly exists, the current electron EDM places some constraints on the EWBG-favored re-
ion, and more importantly, it would probe the whole region if it is improved up to $1.0 \times 10^{-29} \, e \cdot cm$. How-
ever, once the BAU-unrelated CP violation comes into
action, the strong connection between the BAU and elec-
tron EDM is not guaranteed any more, which makes it
challenging to probe the parameter space with the elec-
tronic EDM only. Nevertheless, even in such a case, the scenario could be probed with the aid of Higgs physics.

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