Bino-driven electroweak baryogenesis with highly suppressed Electric Dipole Moments

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Abstract

It is conventional wisdom that successful electroweak baryogenesis in the Minimal Supersymmetric extension of the Standard Model (MSSM) is in tension with the non-observation of electric dipole moments (EDMs), since the level of CP-violation responsible for electroweak baryogenesis is believed to generate unavoidably large EDMs. We show that CP-violation in the bino-Higgsino sector of the MSSM can account for successful electroweak baryogenesis without inducing large EDMs. This observation weakens the correlation between electroweak baryogenesis and EDMs, and makes the bino-driven electroweak baryogenesis scenario the least constrained by EDM limits. Taking this observation together with the requirement of a strongly first-order electroweak phase transition, we argue that a bino-driven scenario with a light stop is the most phenomenologically viable MSSM electroweak baryogenesis scenario.

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I. INTRODUCTION

Explaining the origin of the observed baryon asymmetry of the Universe (BAU) [1] is one of the most compelling problems at the interface of cosmology, particle physics and nuclear physics. Among baryogenesis scenarios, electroweak baryogenesis (EWB) [2] is particularly subject to current and planned experimental scrutiny, given its essential dependence on new physics at the electroweak scale. It is well known that the standard model (SM) cannot explain the observed BAU[3], even though it contains in principle all the necessary ingredients for successful baryogenesis [4]. In particular, the SM Higgs sector does not generate a first-order electroweak phase transition, while the CP-violating interactions of the SM would not generate sufficiently large particle-antiparticle asymmetries at electroweak temperatures even if there was a strong first order SM phase transition. Therefore, successful EWB requires new physics at the electroweak scale.

The Minimal Supersymmetric extension to the Standard Model (MSSM), a theoretical framework that successfully addresses the naturalness problem of the SM, can also encompass a viable EWB mechanism for the generation of the BAU [5, 6, 7]. It has been shown that the phase transition in MSSM can be strongly first-order with a light, mainly right-handed, scalar top (stop) [8, 9]. Moreover, the MSSM provides additional CP-violating sources that may generate sufficiently large CP-violating asymmetries in the context of EWB. In general, however, the non-observation of permanent electric dipole moments (EDMs) places severe constraints on new electroweak scale CP-violating interactions such as those of the MSSM. Specifically, the current experimental bounds on the EDM of the electron, neutron, and the Mercury atom (^{199}Hg) are comparatively tight and constraining: $|d_e| < 1.6 \times 10^{-27}e$ cm (90% C.L.) [10], $|d_n| < 2.9 \times 10^{-26}e$ cm (90% C.L.) [11], and $|d_A(^{199}\text{Hg})| < 2.1 \times 10^{-28}e$ cm (95% C.L.) [12] (For recent reviews of EDM searches and their implications for MSSM, see, *e.g.* Refs. [13, 14, 15]). These results imply that complex CP-violating phases in the MSSM that generate one-loop EDMs must be tiny compared to naïve expectations, leading to the so-called supersymmetric "CP problem". The next generation of experiments on EDM searches will improve the current sensitivity by two or more orders of magnitude [16], and null results would only exacerbate the puzzle.

Solutions to the supersymmetric CP problem, as well as to the supersymmetric flavor problem, have inspired numerous theoretical studies and the formulation of specific frameworks where those issues are alleviated, such as "more minimal" SUSY [17] and "split-SUSY" [18]. For instance, in the latter scenario one-loop EDM contributions are suppressed by the mass scale of the relevant scalar fermions. However, it has been realized that two-loop EDM contributions survive, and that they play, both in the split-SUSY scenarios and in others where sfermions are heavy, a dominant role in constraining CP-violation in the MSSM [19, 20, 21, 22, 23].

On general grounds, one would expect that any large CP-violating source in the MSSM that is able to generate the BAU during the electroweak phase transition might also induce large two-loop EDMs. In what follows, we show that there exists an important exception to this expectation, namely, CP-violating interactions involving the relative phase between the supersymmetric Higgs-Higgsino mass term μ and the soft supersymmetry-breaking masses M_1 of the bino and b of the Higgsino. We show that this phase, $\phi_1 \equiv \text{Arg}(\mu M_1 b^*)$, is essentially unconstrained by EDM measurements even at the two-loop level and that the associated CP-violating interactions may generate the observed BAU during the supersymmetric electroweak phase transition. On the other hand, the phase $\phi_2 \equiv \text{Arg}(\mu M_2 b^*)$, involving the

wino supersymmetry-breaking mass M_2, induces large two-loop EDMs for sub-TeV super-partner masses and, thus, must be kept small in order to be consistent with experimental limits. Assuming SUSY is discovered at the Large Hadron Collider, successful EWB could still occur in the MSSM if it is driven by CP-violating bino-Higgsino interactions (rather than wino-Higgsino interactions) in the presence of a light nearly right-handed stop. This "bino-driven" (or "neutralino-driven") EWB scenario (where $|M_1| \sim |\mu|$) requires a non-universality of the bino and wino phases relative to μ ($\phi_1 \neq \phi_2$). We argue below that, while not generic, this situation occurs in well-motivated models of supersymmetry breaking.

A number of recent studies, including Ref. [19, 20, 24, 25], have addressed the interplay between EWB and EDMs in the MSSM. While some of them [19, 20, 24] concentrate on the chargino-driven EWB scenario only, Ref. [25], although dealing with both chargino-driven and bino-driven EWB, assumed the same value for the bino and the wino relative phases. To our knowledge, the scenario of bino-driven EWB with highly suppressed EDMs introduced here has not been discussed previously. As a further motivation to investigate this framework, we recently completed and presented in [23] the complete calculation of the two-loop chargino-neutralino contributions to EDMs, which play a vital role in the interplay between EWB and EDMs. The results of this calculation enable us to draw reliable conclusions on how the bino phase contributes to the EDMs, and therefore to provide a solid test ground for the scenario of bino-driven EWB with highly suppressed EDMs.

Our study is organized as follows: In section II we describe the specific pattern of masses and phases that characterizes bino-driven EWB, and motivate why we expect highly suppressed EDMs, followed by our numerical results. We then devote section III to our summary and conclusions.

II. A SCENARIO OF SUCCESSFUL EWB WITH HIGHLY SUPPRESSED EDMS

A. EWB requirements on MSSM parameters

The requirement of a strongly first-order electroweak phase transition is satisfied, in the context of the MSSM, in the light stop scenario [8],where the mass of the lighter, mostly right-handed, stop is less than 125 GeV, according to the most recent analysis using renormalization group improved effective potentials [9]. The masses of the first-two generations of squarks and sleptons are kept heavier than a few TeV to avoid the supersymmetric flavor and CP problems [17]. The heavier stop (mainly left-handed) also needs to be heavier than a few TeV to satisfy the current Higgs mass bound, and to suppress contributions to electroweak precision observables [26]. In addition, the gluino mass should be larger than about 500 GeV in order not to suppress the improvement on the first order character of the electroweak phase transition [9].

In contrast, Higgsinos, binos and winos must remain light to trigger the needed CP-violating currents. Theoretical studies show that, for specific mass patterns, the CP asymmetry in MSSM EWB can be resonantly enhanced [6, 7]. Unless the relevant particle masses are extremely light, the resonant enhancement of CP-violating sources is required to reproduce the observed BAU. This leads to two scenarios. In the first one, the resonant enhancement occurs because the Higgsino mass scale is close to either the bino or the wino soft supersymmetry breaking masses, $|\mu| \approx |M_1|$ or $|\mu| \approx |M_2|$, corresponding to the so-called bino-driven and wino-driven EWB scenarios, respectively. In the second one, instead, the resonant enhancement occurs because the soft supersymmetry breaking masses of the

right-handed and of the left-handed stops are close to each other, $m_{\tilde{t}_R}^2 \approx m_{\tilde{t}_L}^2$. The latter resonant condition is, however, inconsistent with the simultaneous requirements of a light right-handed stop, as required by a strongly first-order phase transition, and of a heavy left-handed stop, as needed by the current Higgs mass limit and precision electroweak data. Therefore, on general grounds we regard the first scenario only, either involving bino- or wino-driven EWB, or even both, as being the phenomenologically viable and relevant one.

The CP-violating sources in the bino- or wino-driven EWB scenario live in the chargino-neutralino sector. While numerous CP-violating phases appear in the most general MSSM parametrization, field redefinitions can be employed to rotate away all but two physical phases in the chargino-neutralino sector. We take these phases to be the $\phi_{1,2}$ introduced above. We will refer to ϕ_1 as the phase of the bino soft supersymmetry breaking mass, and to ϕ_2 as the phase of the wino mass, although they are indeed combinations of phases of the Higgsino mass μ, the gaugino mass $M_{1,2}$, and the soft Higgs mass term b. A large enough phase ϕ_1 or ϕ_2 is needed, in addition to the above-mentioned resonant condition on the masses, for successful EWB in the context of the bino-driven and wino-driven scenarios, respectively. In addition, the baryon asymmetry generated from MSSM EWB depends linearly on the relative variation of the two Higgs fields along the bubble walls, $\Delta\beta$, which receives significant suppression as the mass scale of CP-odd Higgs, m_A, increases [27].

B. Suppressed EDMs with viable MSSM EWB

The current most stringent EDM bounds are for the neutron, the Thallium atom (^{205}Tl), and the Mercury atom (^{199}Hg). In general, they receive contributions from operators associated with the lepton and quark EDMs, $d_{u,d,e}$; quark chromo-EDMs $\tilde{d}_{u,d}$; CP-odd 3-gluon Weinberg interaction, d^G [15, 28]; and CP-odd four-fermion interactions, C^{4f} (see e.g. [14] and [15] for recent reviews). As shown in Ref. [13, 15], the Thallium EDM is dominated by the electron EDM operator d_e, and possibly by the four-fermion operator C^{4f} if $\tan\beta > 30$; the neutron EDM mainly stems from the EDM and chromo-EDM operators of u and d

TABLE I: Summary of the phases entering in CP-odd operators, and of the conditions needed to suppress the operator without spoiling successful EWB. The symbol $\phi_{\tilde{f}}$ denotes generic CP-violating phases in the squark and slepton sector. $\phi_i \equiv \arg(\mu M_i b^*)$ indicate the physical phases in the chargino-neutralino, and in the gluino sector. Lastly, $m_{\tilde{f}_{1,2}}$ represents the (common) soft supersymmetry breaking masses of the first-two generations of sfermions.

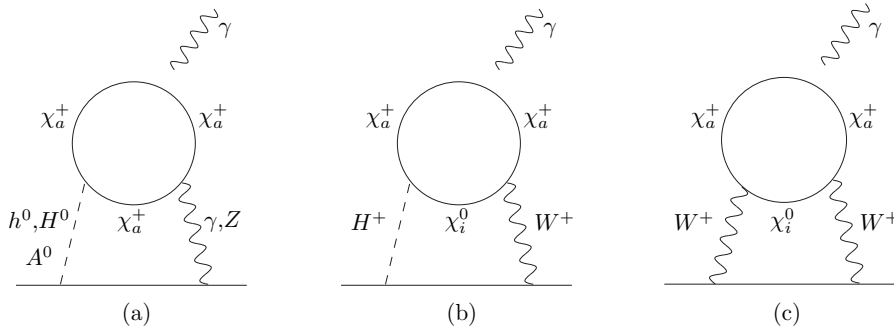| CP-odd operator	phases	suppression conditions without spoiling EWB
C^{4f}	$\phi_1,\ \phi_2,\ \phi_3,\ \phi_{\tilde{f}}$	$\tan\beta < 30$
d^G	$\phi_3,\ \phi_{\tilde{f}}$	$\sin\phi_{\tilde{f}} < 10^{-2},\ \sin\phi_3 < 10^{-2}$
$d_{u,d,e}^{1-\text{loop}}$	$\phi_1,\ \phi_2,\ \phi_3,\ \phi_{\tilde{f}}$	$m_{\tilde{f}_{1,2}} > 10$ TeV
$\tilde{d}_{u,d}^{1-\text{loop}}$	$\phi_1,\ \phi_2,\ \phi_3,\ \phi_{\tilde{f}}$	$m_{\tilde{f}_{1,2}} > 10$ TeV
$d_{u,d,e}^{2-\text{loop}}(\tilde{t},\tilde{b},\tilde{\tau})$	$\phi_{\tilde{f}}$	$\sin\phi_{\tilde{f}} < 10^{-2}$
$\tilde{d}_{u,d}^{2-\text{loop}}(\tilde{t},\tilde{b})$	$\phi_{\tilde{f}}$	$\sin\phi_{\tilde{f}} < 10^{-2}$
$d_{u,d,e}^{2-\text{loop}}(\chi^{\pm,0})$	$\phi_1,\ \phi_2$	$\sin\phi_2 < 10^{-2},\ \sin\phi_1 \sim \mathcal{O}(1)$

FIG. 1: The complete list of all chargino-neutralino two-loop diagrams contributing to EDMs of leptons and quarks. The external photon line is attached to the charged particles in each diagram in all possible ways. Mirror graphs are not displayed.

quarks, $d_{u,d}$ and $\tilde{d}_{u,d}$, and from the 3-gluon interaction d^G; lastly, the Mercury EDM is generated primarily by the chromo-EDM operators $\tilde{d}_{u,d}$.

These CP-violating operators are induced by various (physical) CP-violating phases in the MSSM, including $\phi_{1,2}$ in the chargino-neutralino sector; $\phi_3 \equiv \mathrm{Arg}(\mu M_3 b^*)$ in the gluino sector; and, lastly, in the sfermion-Higgs sector, $\mathrm{Arg}(\mu^* \tan\beta + A_f)$ and $\mathrm{Arg}(\mu^* \cot\beta + A_f)$ for down- and up-type sfermions, respectively, which we generally refer to as $\phi_{\tilde{f}}$, (where $y_f A_f$ is the coefficient of the supersymmetry-breaking triscalar interactions with y_f being the fermion f Yukawa coupling). We summarize in Table I the phases entering each CP-odd operator. We also list the conditions under which the corresponding CP-odd operator is suppressed without affecting EWB.

The Higgs-mediated CP-odd 4-fermion operators C^{4f} are only enhanced at large $\tan\beta$ due to their $\tan^3\beta$ dependence [29]. By restricting to the $\tan\beta < 30$ region (as also implied in the context of successful MSSM EWB by the recent study of Ref. [9]), we keep this contribution small, and the experimental bound on the Thallium EDM can be taken directly, in this regime, as a bound on d_e. (Incidentally, keeping $\tan\beta$ not too large also helps to suppress other EDM contributions.) The CP-odd 3-gluon operator d^G depends on the CP-violating phases in the sfermion sector, $\phi_{\tilde{f}}$, and in the gluino sector, ϕ_3, and it can be suppressed by restricting these phases to be less than 10^{-2} [15]. As discussed above, these phases are not crucial to successful EWB. With these operators suppressed, the remaining CP-odd operators are the EDMs of leptons and quarks, as well as the chromo-EDMs of quarks.

The lowest order contributions to EDM and chromo-EDM operators are induced at one-

TABLE II: Summary of mass scales and phases in the scenario of successful bino-driven EWB with highly suppressed EDMs. The light stop $\tilde{t}_1$ is predominantly right-handed, while the heavy stop $\tilde{t}_2$ is mainly left-handed. The other mass scales and phases are the same as in Table I. The final entry gives the range for $\tan\beta$.

$\sin\phi_1$	$\sin\phi_{2,3}$, $\sin\phi_{\tilde{f}}$	$|\mu| \approx |M_1|$, $|M_2|$, m_A	$|M_3|$	$m_{\tilde{f}_{1,2}}$, $m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$\tan\beta$
$\sim \mathcal{O}(1)$	$< \mathcal{O}(0.01)$	$\sim$ few 100 GeV	> 500 GeV	> 10 TeV	< 125 GeV	(3,30)

loop order [30]. They involve the first-two generations of sfermions, as well as neutralinos, charginos and gluinos. Without affecting EWB, these one-loop contributions are suppressed if the first-two generations of sfermions are heavier than 10 TeV [7, 17, 31]. However, the EDM constraints cannot be completely avoided by suppressing one-loop contributions. It is well known that the two-loop contributions of the Barr-Zee type [32] dominate over one-loop contributions when the latter are suppressed by heavy sfermion masses. Depending on the source of CP-violation, there are two types of two-loop contributions. In one of them, the CP-violation involves the third generation of sfermions [33]. Without affecting the EWB, these contributions to the two-loop EDM and chromo-EDM contributions can be held below the experimental bounds by suppressing the CP-violating phases in the sfermion sector, $\phi_{\tilde{f}}$, as already employed to suppress the 3-gluon operator d^G.

The second class of two-loop contributions involves the CP-violating phases $\phi_{1,2}$ in the chargino-neutralino sector. These are directly relevant to EWB, since $\phi_{1,2}$-dependent interactions also generate CP asymmetries during the electroweak phase transition. These phases contribute to the elementary fermion EDMs, but not to the chromo-EDMs. Moreover, both the CP-odd Higgs and the charged Higgs, whose mass depends on the parameter m_A, enter the chargino-neutralino two-loop EDM contributions. This provides yet another connection between this type of EDM contributions and EWB: a crucial dependence on the same mass parameter m_A.

The complete set of chargino-neutralino two-loop diagrams that contribute to quark and lepton EDMs in the MSSM are shown in Fig. 1. CP-violation stems from the chargino-neutralino loop, and is propagated to quarks and leptons through the exchange of gauge and Higgs boson pairs, including γh^0, γH^0, Zh^0, ZH^0, γA^0, ZA^0, and $WH^\pm$, or pure gauge boson pairs which can only be WW. Notice that it cannot be transmitted through the exchange of the neutral gauge boson pairs $\gamma\gamma$, γZ, and ZZ [21]. Obviously, the bino phase ϕ_1 can only possibly enter the $WH^\pm$ and WW contributions, since those are the only ones that involve neutralinos.

A subset of the contributions to the chargino-neutralino two-loop EDMs have been studied in the past [19, 20, 21, 22], and we recently presented the complete calculation in [23], making it possible to draw reliable conclusions on the correlation between EWB and EDMs at the two-loop level. Without assuming gaugino mass unification, we allow the phases ϕ_1 and ϕ_2 to be different. This is completely generic in the low-energy parametrization of softly broken supersymmetry in the MSSM, and in particular it occurs in some supersymmetry breaking models such as "mirage mediation" [34], wherein gaugino masses originate from more than one mediation mechanism, or "gaugino mediation" (see Ref. [35] and references therein).

The main result of the present analysis is that the EDM contribution induced by ϕ_1 is suppressed compared to ϕ_2 by a factor of ~ 0.02. This suppression is due to several effects:

1. While the wino phase ϕ_2 enters all two-loop contributions, the bino phase ϕ_1 can only possibly enter the $WH^\pm$ and WW contributions, which, as shown in Ref. [23], amounts to about 20% of the total 2-loop EDM chargino-neutralino contribution.

2. Wherever the bino enters in $WH^\pm$ and WW diagrams, its contribution is suppressed by a factor of $(g'/g)^2 = \tan^2\theta_W \sim 0.3$ compared to the corresponding wino contribution.

3. While the product of these two factors gives a suppression factor of 0.06, the further factor of 0.3 needed to explain the numerical result presumably stems from the fact that, in the $WH^\pm$ and WW contributions, the W boson directly couples to the wino,
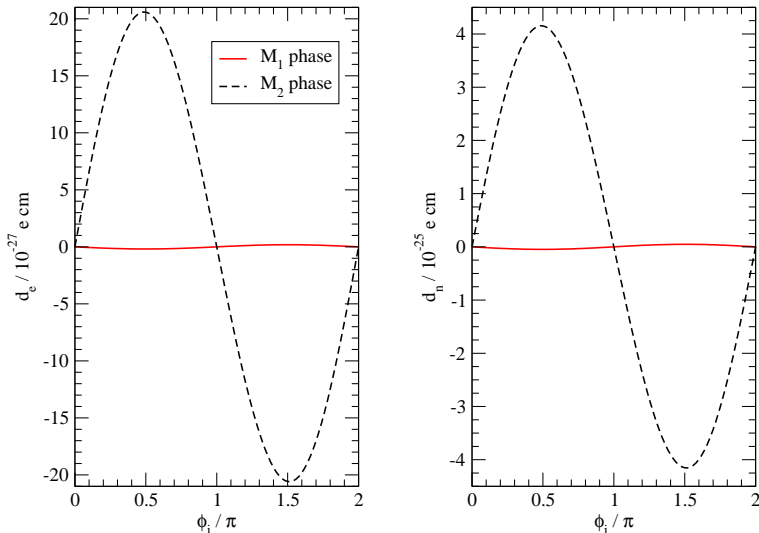
FIG. 2: The electron (left) and neutron (right) electric dipole moment as a function of the bino and wino phase.

but not to the bino, and the latter only enters through its coupling to the Higgs in $WH^{\pm}$, or through its mixing with Higgsino.

Since interactions involving ϕ_1 alone can generate enough baryon asymmetry in the bino-driven EWB scenario, the weak dependence of EDMs on ϕ_1 indicates the existence of a scenario for successful MSSM EWB consistent with highly suppressed EDMs: the bino-driven scenario with a light, mainly right-handed stop. This scenario is characterized by the specific pattern of MSSM masses and phases summarized in Tab. II.

In order to show concrete numerical results for our scenario we choose, for definiteness, the following reference benchmark setup:

$$\mu = 200 \text{ GeV}, \quad |M_1| = 95 \text{ GeV}, \quad |M_2| = 190 \text{ GeV}, \quad \tan\beta = 10, \quad m_A = 300 \text{ GeV}. \quad (1)$$

This setup is consistent with (among other constraints) the limits from $b \to s\gamma$ [36]. In Fig. 2, we show the effect of a non-vanishing bino phase ϕ_1 (red lines) and wino phase ϕ_2 (black dashed) on the electron (left) and neutron (right) EDMs[1]. The figure indicates clearly that the size of the EDM contribution induced by ϕ_1 is suppressed by a factor of $0.01 - 0.02$ compared to that associated with ϕ_2 .

The significantly different impact on the size of the induced EDMs for ϕ_1 versus ϕ_2 makes the bino-driven EWB scenario much less constrained by EDM bounds than the wino-driven option. This is illustrated in detail in Fig. 3 and Fig. 4, where we compare bino-driven and wino-driven EWB by showing the predicted BAU, as well as curves of constant electron and neutron EDMs on the $(|M_1|,\phi_1)$ and $(|M_2|,\phi_2)$ planes, respectively. Again, for definiteness, we keep $|M_2| = 2|M_1|$ and set the other parameters to the values indicated in Eq. (1).

In Fig. 3 and Fig. 4, the green bands indicate the region compatible with the production of a baryon asymmetry $Y_B = 9.2 \times 10^{-11}$ at the 5-σ level (according to the results reported

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[1] The Mercury EDM is suppressed in the parameter space region of interest here, as it is generated primarily by the chromo-EDM operators, whose contributions from both one-loop and two-loop are suppressed.
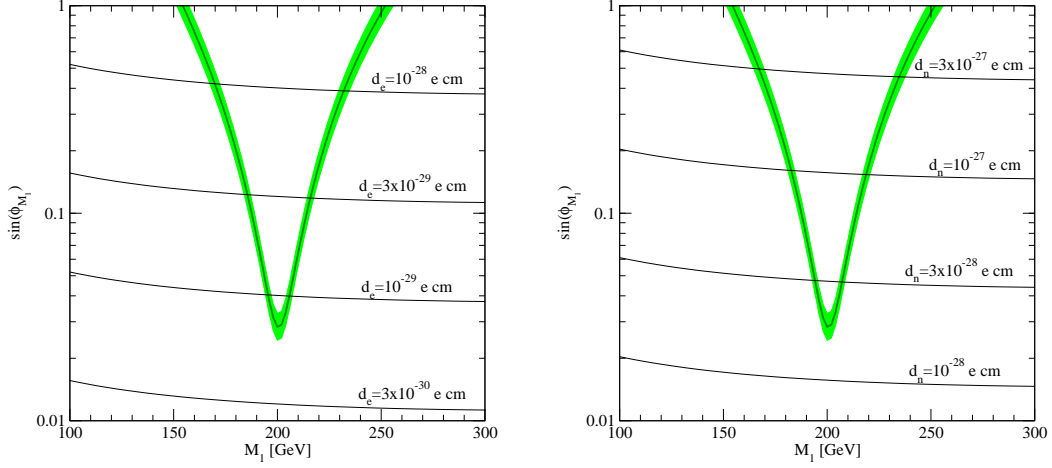
FIG. 3: The green band shows the region, in the $(M_1, \sin\phi_1)$ plane compatible with electroweak baryogenesis. We assume that $\sin\phi_2 = 0$. On the same plane, we indicate iso-level curves at constant values for the electron (left) and for the neutron (right) EDMs.
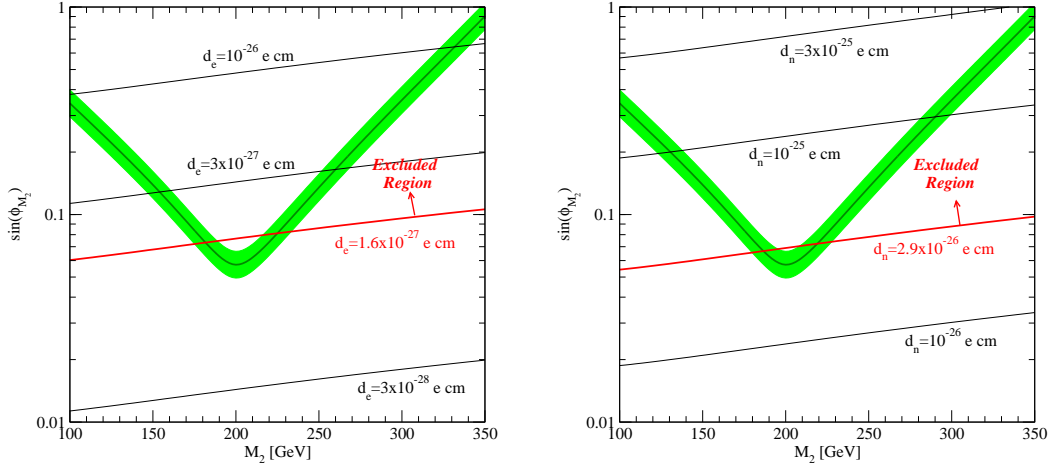

FIG. 4: The green band shows the region, in the $(M_2, \sin\phi_2)$ plane compatible with electroweak baryogenesis. We assume that $\sin\phi_1 = 0$. On the same plane, we indicate iso-level curves at constant values for the electron (left) and for the neutron (right) EDMs. Parameter space points above the red lines are excluded by current experimental constraints on electron and neutron EDMs.

in Ref. [1]). We observe that as $|M_1|(|M_2|)$ approaches $|\mu| = 200$ GeV, the resonant enhancement becomes larger and larger, and thus the phase $\phi_1(\phi_2)$ needed to generate enough baryon asymmetry becomes smaller and smaller (no enhancement occurs in the two-loop EDMs if $|\mu| \sim |M_{1,2}|$). In turn, this makes it easier to evade the EDM bounds. However, for the reasons outlined above, one sees that, since the ϕ_1 contribution to EDMs is much smaller than that from ϕ_2, all the values of $\sin\phi_1$ are presently consistent with experimental EDM bounds, while the range of viable $\sin\phi_2$ values is constrained to a very limited parameter space (and likely ruled out when a more realistic Higgs profile is used). Future neutron and electron EDM searches with ~ 100 times better sensitivity than existing experiments would be needed to fully explore the CP-violating parameter space in the presently proposed

bino-driven EWB scenario.

We note that the BAU-allowed bands have been obtained from the work of Ref. [7], which included the effects of both resonantly-enhanced chiral relaxation and CP-violating sources in the bino-driven and wino-driven regimes for a simple, step-function wall profile. Had we employed a more realistic profile, leading to a somewhat smaller BAU (see, *e.g.*, Ref. [37]), the BAU-compatible regions in Figs. 3 and 4 would have moved to even larger values of the CP-violating phases corresponding to larger predicted magnitudes for the EDMs. In this respect, Figs. 3 and 4 give the most optimistic expectations for the wino-driven scenario, whose viability is clearly marginal. In contrast, the bino-driven scenario would be still be easily compatible with the observed BAU and present EDM limits when a more realistic profile is employed and the full set of transport equations are solved numerically, as in Ref. [37]. Consequently, we rely here on the simpler, schematic solution as it adequately addresses our primary point.

III. SUMMARY AND CONCLUSIONS

We have presented a novel possibility for reconciling present and prospective experimental limits on the EDMs of elementary particles with successful EWB in the MSSM. We pointed out that the most relevant CP violating phases for EWB are the bino phase ϕ_1 and the wino phase ϕ_2. We showed that, with its impact on EDMs suppressed by about two orders of magnitude compared to that of the wino phase ϕ_2, the bino phase ϕ_1 is only weakly constrained by the EDM bounds, and can be of order one. Since the bino phase by itself can generate the observed BAU in the bino-driven EWB scenario, our analysis revealed that bino-driven EWB is a scenario with the least tension with EDM constraints. This conclusion is unambiguously supported by the numerical results we presented. We leave the detailed study of the interplay between EWB and EDM over a larger cross section of the MSSM parameter space to a more comprehensive future study [31].

Besides the CP violation requirement, the other element needed in the MSSM for successful EWB is a strongly first-order phase transition, which leads to the additional requirement of a light stop [8, 9]. We therefore argue that bino-driven EWB with a non-universal gaugino-Higgsino CP-violating phase and with a light stop is the most promising scenario for successful EWB in the MSSM. Interestingly, we notice as a last comment that the specific mass spectrum and CP violating phases needed in this scenario will also be tested with colliders and explored in dark matter searches in the near future [25].

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