Cancellations Between Two-Loop Contributions to the Electron Electric Dipole Moment with a *CP*-Violating Higgs Sector

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We present a class of cancellation conditions for suppressing the total contributions of Barr-Zee diagrams to the electron electric dipole moment (eEDM). Such a cancellation is of particular significance after the new eEDM upper limit was released by the ACME Collaboration, which strongly constrains the allowed magnitude of *CP* violation in Higgs couplings and hence the feasibility of electroweak baryogenesis (EWBG). Explicitly, if both the *CP*-odd Higgs-photon-photon (Z boson) and the *CP*-odd Higgs-electron-positron couplings are turned on, a cancellation may occur either between the contributions of a *CP*-mixing Higgs boson, with the other Higgs bosons being decoupled, or between the contributions of *CP*-even and *CP*-odd Higgs bosons. With a cancellation, large *CP* violation in the Higgs sector is still allowed, yielding successful EWBG. The reopened parameter regions would be probed by future neutron, mercury EDM measurements, and direct measurements of Higgs *CP* properties at the Large Hadron Collider Run II and future colliders.

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Introduction.—The baryon asymmetry in the Universe (BAU), currently expressed as the baryon-to-entropy density ratio [1,2], $n_b/s \approx (0.7-0.9)\times 10^{-10} \neq 0$, has puzzled physics researchers for more than half a century. Among various dynamical mechanisms to solve this puzzle, electroweak baryogenesis (EWBG) falls into the most popular class, because of its potential testability at the LHC and in other experiments. A generic feature of EWBG is that the *CP* phases employed to generate the BAU must enter the couplings between the Higgs sector and particles, which either exist in the standard model (SM) or are introduced in new physics, regardless of whether the *CP* phases are flavor diagonal, off diagonal [3], or flavor decoupled. Otherwise, these *CP* phases are decoupled from electroweak phase transition (EWPT), and the EWBG will never be implemented. Measurement of the Higgs *CP* proper-ties therefore provides essential information for solving the BAU puzzle.

Thus, the *CP* properties of the Higgs boson discovered in 2012 [4] have been extensively studied by both theorists [5–9] and experimental groups [10] since their discovery [4], by using a method of direct measurements at the LHC. Given the limited statistics, however, the sensitivity of the LHC at this stage is still low. Nevertheless, rapid progress has been made in indirect measurements. Using the polar molecule thorium monoxide (ThO), the ACME Collaboration recently reported an upper limit on the electron electric dipole moment (eEDM) at 90% confidence level, an order of magnitude stronger than the previous best limit [11]: $|d_e| < 8.7\times 10^{-29}e$cm. This limit severely constrains the allowed magnitude of *CP* phases in the Higgs couplings [6–9] via Barr-Zee diagrams, causing a tension between the observation and the *CP* phase required for successfully implementing EWBG (e.g., Ref. [12] where the expected projection of the eEDM bounds to the EWBG in the minimal supersymmetric standard model (MSSM) was studied).

In this Letter, we find that in these studies a crucial effect has been effectively ignored, which can dramatically change the conclusions. This is because, generally, both the *CP*-odd Higgs-photon-photon and the *CP*-odd Higgs-electron-positron couplings can be or tend to be turned on. These two couplings contribute to the eEDM separately and simultaneously. If a cancellation exists between their contributions (as shown subsequently in two contexts: the type-II two-Higgs Doublet Model (2HDM), in which the tree-level *CP* phase arises from the pure Higgs sector, and the MSSM where the tree-level *CP* phase arises from Higgs-superparticle interaction sectors), even if the magnitudes of the *CP* phases in Higgs couplings are high, the current ACME bound can be well satisfied. In such a case, EWBG can still be successfully implemented [13].

General analysis.—The relevant operators in an effective Lagrangian for a Higgs sector are $\mathcal{L}_{\rm eff} = m_f\sum_i h_i\bar{f}(c^i_f + i\tilde{c}^i_f\gamma^5)f/v + \alpha\sum_i h_i(c^i_\gamma F^{\mu\nu}V_{\mu\nu} + \tilde{c}^i_\gamma F^{\mu\nu}\tilde{V}_{\mu\nu})/\pi v$, where $F_{\mu\nu}$ is the field strength of a photon, with $\tilde{F}_{\mu\nu} \equiv (1/2)\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$, $V_{\mu\nu}$ is the field strength of a photon and Z boson, with $\tilde{V}_{\mu\nu}\equiv(1/2)\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$, and $\theta^i_f = \tan^{-1}(\tilde{c}^i_f/c^i_f)$ defines the *CP* phase of the Yukawa couplings. These operators can be inserted in the Barr-Zee diagrams. Integrating out the internal degrees of freedoms, we have $\mathcal{L}_{\rm eff} = -id_e\bar{e}\sigma^{\mu\nu}\gamma_5 e\partial_\mu A_\nu$ with its contribution to the eEDM expressed as

$$\frac{d_e}{e} = C\sum_i\left[-c_e^i\tilde{c}_\gamma^i\log\left(\frac{\tilde{\Lambda}_{\rm UV}^{i2}}{m_{h_i}^2}\right) + \tilde{c}_e^i c_\gamma^i\log\left(\frac{\Lambda_{\rm UV}^{i2}}{m_{h_i}^2}\right)\right]. \quad (1)$$

Here $C = \alpha m_e/4\pi^3 v^2$, $v = 246$ GeV is the normalized vacuum expectation value (VEV) of the Higgs fields, and $\Lambda_{\rm UV}^i$ ($\tilde{\Lambda}_{\rm UV}^i$) is the relevant scale for the $h_i F^{\mu\nu}V_{\mu\nu}$ ($h_i F^{\mu\nu}\tilde{V}_{\mu\nu}$) operator. Clearly, the Barr-Zee contributions depend on not only the CP-odd Higgs diphoton coupling $\tilde{c}_\gamma^i$ but also the CP-even c_γ^i if the Higgs bosons have a CP-odd coupling with electrons ($\tilde{c}_e^i \neq 0$).

The ACME measurement greatly improves the current bound on the eEDM, leading to $\sum_i[-c_e^i\tilde{c}_\gamma^i\log(\tilde{\Lambda}_{\rm UV}^{i2}/m_{h_i}^2) + \tilde{c}_e^i c_\gamma^i\log(\Lambda_{\rm UV}^{i2}/m_{h_i}^2)] < 0.14$. This strongly constrains the allowed CP violation in a single Higgs coupling, for example in the case with one (SM-like) Higgs coupling only and $\tilde{c}_e = 0$ [17]. However, if a cancellation occurs among these inference terms, CP symmetry is allowed to be significantly violated, without contradicting with the current eEDM bound. Using the type-II 2HDM and MSSM shows two cancellation mechanisms, both of which are mainly motivated by EWBG: (1) Cancellation occurs between the contributions of a CP-mixing Higgs boson, while the other Higgs bosons are decoupled (see the upper diagrams in Fig. 1); and (2) cancellation occurs between the contributions of CP-even and CP-odd Higgs bosons (see the bottom diagrams in Fig. 1).

Type II 2HDM.—For illustration, we consider the type-II 2HDM with a soft Z_2 symmetry ($\phi_1 \to -\phi_1$ and $\phi_2 \to \phi_2$) [18]. Its tree-level Higgs potential is obtained using

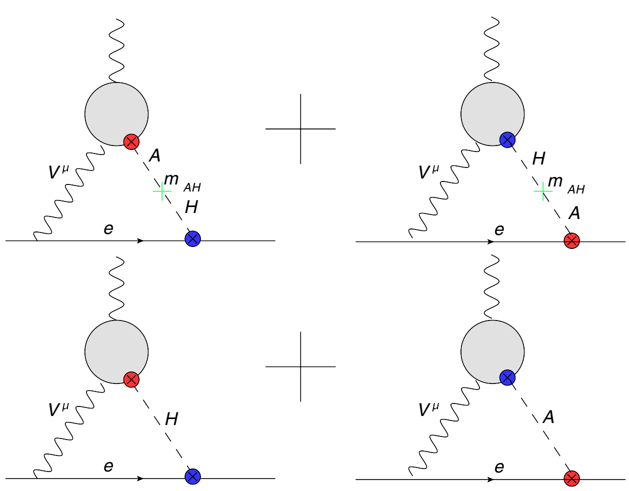

FIG. 1 (color online). Two cancellation mechanisms of the Bar-Zee contributions to the eEDM.

$$\begin{aligned} V = {}& \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \\ & + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{H.c.}] \\ & - \frac{1}{2}\{m_{11}^2(\phi_1^\dagger\phi_1) + [m_{12}^2(\phi_1^\dagger\phi_2) + \text{H.c.}] + m_{22}^2(\phi_2^\dagger\phi_2)\}, \end{aligned} \quad (2)$$

where m_{12} and λ_5 are complex parameters. Their relative phase $\text{Arg}(\lambda_5 m_{12}^{4*})$ leads to CP violation in the Higgs sector. We apply the convention that both Higgs doublets $\phi_{1,2}$ carry a hypercharge of one unit and that the general Higgs VEVs are $\langle\phi_1\rangle = (0, v_1)^T$, $\langle\phi_2\rangle = (0, v_2 e^{i\xi})^T$ with $\sin^2\beta = |v_2|^2/(|v_1|^2 + |v_2|^2)$, $v_1 = v\cos\beta/\sqrt{2}$, and $|v_2| = v\sin\beta/\sqrt{2}$. Subsequently, the unitary matrix R, defined to diagonalize the Higgs mass matrix M, $R\mathcal{M}R^{\rm T} = \text{diag}(M_{h_1}^2, M_{h_2}^2, M_{h_3}^2)$, in the mass eigenstate (h_1, h_2, h_3), can be easily determined using $R = (-s_\alpha c_{\alpha_b}, c_\alpha c_{\alpha_b}, s_{\alpha_b}; s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c}, -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c}, c_{\alpha_b} s_{\alpha_c}; s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c}, s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c}, c_{\alpha_b} c_{\alpha_c})$, where $c_i = \cos\alpha_i$, $s_i = \sin\alpha_i$. Here, α, α_b, and α_c are mixing angles between two CP-even Higgs, the light CP-even and the CP-odd Higgs, and the heavy CP-even and the CP-odd Higgs, respectively. The angular range, beyond which R is repeated, can be expressed as $0 < \alpha \leq \pi$, $-\pi < \alpha_b \leq \pi$, and $-\pi/2 < \alpha_c \leq \pi/2$.

The tree-level h_1 couplings rescaled by the SM values are obtained using $c_t = \cos\alpha\cos\alpha_b/\sin\beta$, $c_b = c_e = -\sin\alpha\cos\alpha_b/\cos\beta$, $\tilde{c}_t = -\cot\beta\sin\alpha_b$, $\tilde{c}_b = \tilde{c}_e = -\tan\beta\sin\alpha_b$, and $a_V = \cos\alpha_b\sin(\beta - \alpha)$. Here, h_1 is SM-like and a_V represents the h_1WW and h_1ZZ couplings. The CP phase of the top Yukawa coupling θ_t is obtained using $\tan\theta_t = -\cos\beta\tan\alpha_b/\cos\alpha$. These tree-level effective couplings further contribute to c_γ and $\tilde{c}_\gamma$ at loop level $c_\gamma^t = Q_f^2 c_f/2 = 2c_t/9$, $\tilde{c}_\gamma^t = -3Q_f^2\tilde{c}_f/4 = -\tilde{c}_t/3$, $c_\gamma^W = -7a_V/8$, yielding a relation $(c_\gamma^{t,W}\tilde{c}_e/\tilde{c}_\gamma^t c_e) \sim h(\alpha, \tan\beta)$ insensitive to α_b. Cancelling the two terms in Eq. (1) requires $c_\gamma^{t,W}\tilde{c}_e \sim \tilde{c}_\gamma^t c_e$, and therefore yields a band $h(\alpha, \tan\beta) \sim 1$ at the $\tan\beta - \alpha$ plane which is allowed by the current ACME bounds. This feature is illustrated in Fig. 2.

In this setup, the lightest Higgs boson h_1 leads to a leading-order contribution to the eEDM [19–21] via the Barr-Zee diagrams [22]. These quantities depend on three free parameters: α, α_b, and β. For simplicity, we will work within the limit $\beta = \alpha + \pi/2$, where the free parameters are reduced to β and α_b, with $\tan\theta_t = -\cot\beta\tan\alpha_b$; the 125 GeV Higgs boson is SM-like if there is no CP violation. The overall contribution to the eEDM is $[d_e/e]^{h_1\gamma\gamma} = (\sqrt{2}\alpha G_F m_e/32\pi^3)[f'(z_t, \tan\beta) - g'(z_W, \tan\beta)]\sin\alpha_b\cos\alpha_b$, where $f'(z,x) = -(8/3)[xf(z) + g(z)/(x)]$, $g'(z,x) = [3f(z) + 5g(z)]x$, $z_t = m_t^2/m_{h_1}^2$, $z_W = m_W^2/m_{h_1}^2$ and the loop functions $f(z)$ and $g(z)$ are given in Ref. [22].

TABLE I. The LHC data used for the fitting.

	$\gamma\gamma$	WW^*	ZZ^*
ATLAS	1.17 ± 0.27 [24]	$0.99^{+0.31}_{-0.28}$ [25]	$1.44^{+0.40}_{-0.33}$ [26]
CMS	$1.14^{+0.26}_{-0.23}$ [27]	$0.72^{+0.20}_{-0.18}$ [28]	$0.93^{+0.29}_{-0.25}$ [29]
	bb	$\tau\tau$	
ATLAS	0.52 ± 0.40 [30]	$1.4^{+0.5}_{-0.4}$ [31]	
CMS	1.15 ± 0.62 [32]	0.78 ± 0.27 [33]	

Numerically, we have $f(z_t) = 1.0$ and $g(z_t) = 1.4$. The contributions from a neutral Higgs with a Z gauge boson and a charged Higgs with a W gauge boson as the propagators are much smaller; therefore, we neglect them in the calculation [23].

The results of fitting the inclusive LHC data published in 2014, summer (see Table I) and the ACME result [11] are presented in Fig. 2. As indicated by the upper panel, the eEDM cancellation occurs in a wide range for both $\tan\beta$ and α generally. In the alignment limit, the cancellation condition $h(\alpha, \tan\beta) \sim 1$ is reduced to $\tan\beta \sim 1$ (see both the upper and lower panels). This is because a relatively low $\tan\beta$ can prevent an excessively high large signal rate of $h \to bb$, and hence an over-suppressed $h \to \gamma\gamma$ rate (Table I). The bottom panel also shows that CP violation with $|\tan\alpha_b| \sim |\tan\theta_t| > 0.1$ is allowed in the cancellation region, where the most stringent constraints are from the nEDM. Indeed, comparing to the ACME bound for top Yukawa coupling $|\tilde{c}_t| \lesssim \mathcal{O}(10^{-2})$ which is suggested by Ref. [6], the allowed range of CP violation in the Higgs sector is greatly broadened due to cancellation, yielding successful EWBG.

MSSM.—Although the MSSM is of the type-II 2HDM, there is no tree-level CP violation in the Higgs sector either explicitly or spontaneously, because of a vanishing λ_5 term in Eq. (2). Therefore, the CP phases used for EWBG mostly arise in the tree-level superparticle sectors, such as the chargino, neutrolino, sfermion sectors.

The explicit CP violation in these sectors can break the CP symmetry in the Higgs sector at loop level, leading to CP-even and CP-odd mixing terms in the Higgs squared mass matrix. However, the Higgs CP mixture caused by this effect is small because of the loop suppression. For nonstandard Higgs bosons, the CP mixture is typically below 10%, consistent with Ref. [34], even if the CP phase arises from the stop sector. However, for the SM-like Higgs boson, the CP mixture is suppressed more by an additional $\tan\beta$ factor. Hence, the Higgs eigenstates are approximate CP eigenstates, with their couplings with electrons being either $|c_e| \gg |\tilde{c}_e|$ (for CP-even Higgs bosons) or $|c_e| \ll |\tilde{c}_e|$ (for CP-odd Higgs bosons). However, a relatively high $\tan\beta$ is favored in the MSSM, because the tree-level mass of the SM-like Higgs boson is larger in this case. This leads to $|c_e^h| \ll |c_e^{H,A}|$, and hence a small h contribution to the eEDM (mainly via the $c_e\tilde{c}_\gamma$ term). Thus, in the MSSM with

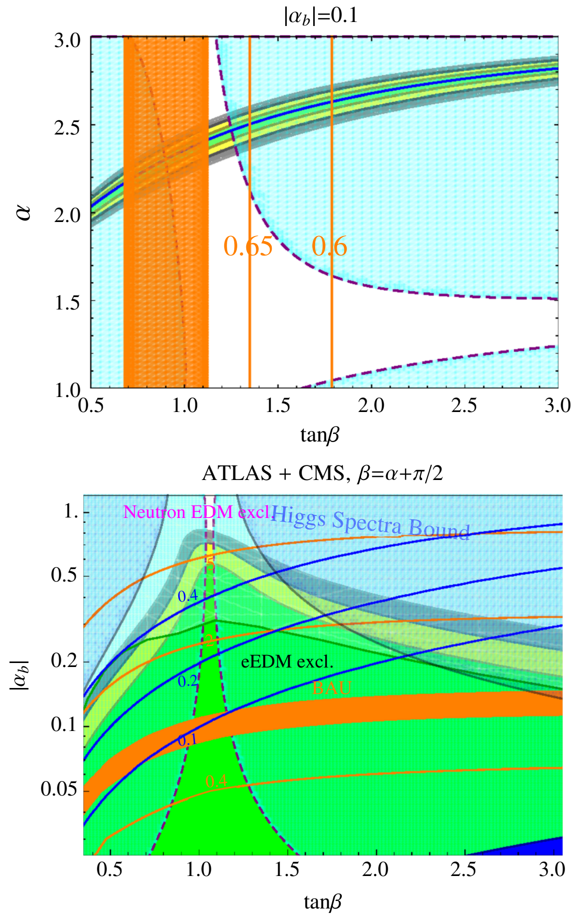

FIG. 2 (color online). The allowed parameter region for α (upper), $|\alpha_b|$ (bottom) versus $\tan\beta$. The grey, yellow, and green regions are the 1,2, and 3σ regions favored by the LHC Higgs global fits. The purple dashed lines and the green solid line represent the exclusion limits set by the eEDM and neutron EDM (nEDM) experiment at 90% C.L. In the upper panel, the blue curve represents the alignment limit. In the bottom panel, the light blue region has been excluded by the requirement of a Higgs mass spectrum $m_h = 125$ GeV, $m_{H^+} = 420$ GeV, $m_{H_2} = 400$ GeV, and $m_{H_3} = 450$ GeV. The blue solid contours represent the CP measure of the top Yukawa coupling $\tan\theta_t$. With no cancellation, only the blue region is allowed by the ACME constraint, yielding $|\tilde{c}_t| \lesssim \mathcal{O}(10^{-2})$ [6]. For both panels, the n_B/s contours are given in the color of orange, in a unit of 10^{-10}, whereas the orange band indicates where the right n_B/s can be achieved. To calculate the BAU, a wall velocity $v_w = 0.02$, a wall width $L_w = 5/T_c$, and a critical temperature $T_c = 100$ GeV are assumed for the bubble generation during the EWPT.

the EWBG mechanism implemented, the main contributions to the eEDM are made by nonstandard Higgs bosons unless they are highly decoupled.

The CP-violating sources arising in the chargino sector is of particular interest because of its high efficiency in generating the BAU via EWBG. The charginos enter the $H\gamma\gamma$ and $A\gamma\gamma$ loops as new mediators, inducing nontrivial contributions to the eEDM via the $c_e\tilde{c}_\gamma$ and $\tilde{c}_e c_\gamma$ terms,

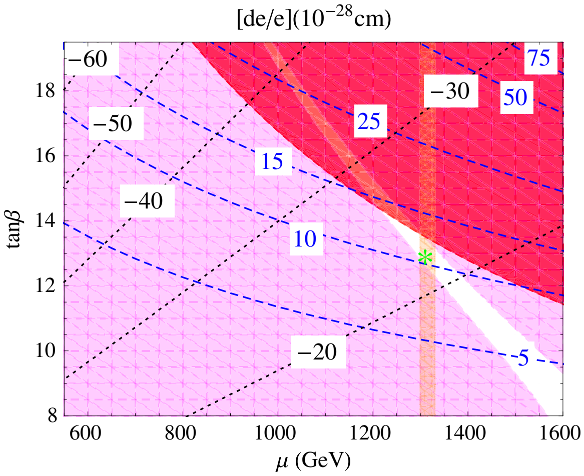

FIG. 3 (color online). Parameter region allowed by the current EDM bounds, and favored by the EWBG (orange band) in the $\mu - \tan\beta$ plane. The chargino and stau contributions to the eEDM are plotted with black dashed and blue dashed contours, respectively. The magenta and red regions were excluded in the ACME and Mercury experiments [50]. The bounds of nEDM are much weaker and fall outside of the figure. Here, we assumed that charged Higgs mass $m_{H^\pm} = 450$ GeV; trilinear softly SUSY-breaking parameters (except A_t) 1.5 TeV and $A_t = 2.5$ TeV; soft masses of gauginos $M_1 = 0.1$ TeV, $M_2 = 0.45$ TeV and $M_3 = 3.5$ TeV; soft masses of squarks and sleptons $0.1M_{Q_1,U_1,D_1} = 0.1M_{Q_2,U_2,D_2} = M_{Q_3,U_3,D_3} = 1.2$ TeV, and $0.1M_{L_1} = 0.1M_{L_2} = M_{L_3} = 0.15$ TeV, $0.05M_{E_1} = 0.05M_{E_2} = M_{E_3} = 0.35$ TeV, and CP phases $\mathrm{Arg}(\mu M_2^*) = \mathrm{Arg}(\mu A_f^*) = 90°$. The parameters v_w, L_w and T_c used to calculate the BAU are the same as those in the caption of Fig. 2.

respectively. Although these two contributions are comparable in magnitude, their signs are typically different. Given an additional minus sign for the term $c_e^i \tilde{c}_\gamma^i$ in Eq. (1), this scenario is strongly constrained by the ACME eEDM bound [6]. However, recall that charged particles such as staus enter the $A\gamma\gamma$ loop as well. If a nontrivial CP phase is turned on in the stau sector, new contributions to the eEDM would be introduced via the $\tilde{c}_e c_\gamma$ term. (Note that such a CP-violating coupling does not induce nontrivial contributions to the eEDM via the $H\gamma\gamma$ loop or the $c_e \tilde{c}_\gamma$ term, because staus are scalars.) This provides a potential cancellation, such that a CP phase in the Higgs-chargino couplings which is sufficiently large for implementing the EWBG mechanism, is still allowed.

Figure 3 depicts all low-energy experimental constraints calculated by CPsuperH [35–37]. We revised the CPsuperH codes used in the analysis in which we corrected several errors, incorporated the full renormalization group running effects, and updated several numerical inputs which are critical (for details, see the Supplemental Material [38]). As indicated in Fig. 3, the charginos have a negative contribution to the eEDM (black-dashed contours), by coupling with both A and H. The staus, by contrast, have a positive contribution to the eEDM

TABLE II. Benchmark in the MSSM, with the other parameters set as Fig. 3.

$R_{\gamma\gamma}$	$\tan\beta$	μ (TeV)	m_{H_1} (GeV)
0.84	12.8	1.31	125.4
$[d_e/e]$ (cm)	$[d_e/e](\tilde{\tau})$ (cm)	$[d_e/e](\tilde{\chi}^\pm)$ (cm)	$[d_e/e](\tilde{t})$ (cm)
4.2×10^{-29}	1.2×10^{-27}	-2.3×10^{-27}	0.8×10^{-27}
$[d_{Hg}/e]$ (cm)	$[d_n/e]$ (cm)	n_b/s	CP phases
3.0×10^{-29}	9.6×10^{-27}	0.85×10^{-10}	$\pi/2$

(blue-dashed contours), by mainly coupling with A. Both contributions are enhanced by $\tan\beta$ because of $\tilde{c}_e^A \propto \tan\beta$ and $c_e^H \propto 1/\cos\beta$. Their dependences on the μ parameter, however, are different. For charginos, the H/A-chragino-chargino couplings $g^P_{H\chi_i^\pm\chi_i^\pm} \approx i(C_R)_{i1}(C_L)^*_{i2}/2 - \mathrm{H.c.}$ and $g^S_{A\chi_i^\pm\chi_i^\pm} \approx -i(C_R)_{i1}(C_L)^*_{i2}/2 - \mathrm{H.c.}$, $i = 1, 2$ [37]. With $\mu > M_2$ assumed here, a low μ value increases the off diagonal term in the chargino mixing matrices, $(C_L)_{12}$ and $(C_R)_{21}$, and hence the overall eEDM contribution. Regarding the staus, a higher μ leads to a lighter $\tilde{\tau}_1$ because of a higher mixture term $\propto |\mu\tan\beta - A_\tau|$; therefore, their contribution to the eEDM increases for a higher μ value. Because of their cancellation, a blank region exists (Fig. 3), in which the total eEDM is below the current ACME bound. This region overlaps with the EWBG favored region, which was excluded by the ACME bound, if only the chargino contribution is considered. A benchmark point is presented in Table II.

Discussion and conclusion.—This Letter presents a class of cancellation conditions for suppressing the total contributions of Barr-Zee diagrams to the eEDM, which may occur either between the contributions of a CP-mixing Higgs boson, with the other Higgs bosons being decoupled, or between the contributions of CP-even and CP-odd Higgs bosons. For illustration, we consider two scenarios: the type-II 2HDM, in which the tree-level CP phase arises from the Higgs sector, and the MSSM, in which the tree-level CP phase arises from Higgs-superparticle interaction sectors. In the 2HDM, $\tan\beta \sim 1$ is favored by the LHC Higgs bounds, and the contributions of the Barr-Zee diagrams to the eEDM are mainly mediated by a CP-mixed SM-like Higgs boson. With a cancellation between them, a CP phase as large as $\mathcal{O}(0.1\text{–}1)$ is still allowed for the top Yukawa coupling, induced by the Higgs CP mixing. In the MSSM, a high $\tan\beta$ is favored by the LHC Higgs bounds, and the contributions of the Barr-Zee diagrams to the eEDM are mainly mediated by nonstandard CP-even and CP-odd neutral Higgs bosons (if they are not as heavy as a 10-TeV scale or higher). With a cancellation between them, a maximal CP phase in their couplings accompanied by superparticles such as charginos is still allowed. In summary, such a cancellation reopens parameter regions allowing sizable CP violation in the Higgs sector, which can yield successful EWBG and would be probed by the future neutron, mercury EDM measurements, and direct measurements of Higgs CP-properties at the Large Hadron Collider Run II and future colliders.

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