Electroweak Beautygenesis: From $b \rightarrow s$ CP Violation to the Cosmic Baryon Asymmetry

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We address the possibility that CP violation in B_s-$\bar{B}_s$ mixing may help explain the origin of the cosmic baryon asymmetry. We propose a new baryogenesis mechanism—"electroweak beautygenesis"—explicitly showing that these two CP-violating phenomena can be sourced by a common CP phase. As an illustration, we work in the two-Higgs-doublet model. Because the relevant CP phase is flavor off diagonal, this mechanism is less severely constrained by null results of electric dipole moment searches than other scenarios. We show how measurements of flavor observables by the D0, CDF, and LHCb collaborations test this scenario.

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Introduction.—The baryon asymmetry of the Universe (BAU) has been precisely measured by the WMAP collaboration. Combining its 5 yr results with those from other CMB and large scale structure measurements gives $\Omega_b h^2 = 0.022\,65 \pm 0.000\,59$ [1], which is in excellent agreement with the 95% C.L. range 0.017–0.024 obtained from big bang nucleosynthesis [2]. The implied ratio of baryon density n_B to entropy s is $n_B/s = (8.82 \pm 0.23) \times 10^{-11}$.

To generate the observed BAU, three Sakharov criteria [3] must be satisfied in the early Universe: (i) baryon number violation; (ii) C and CP violation; (iii) a departure from thermal equilibrium (or CPT violation). These requirements are not unconquerable, though doing so requires physics beyond the standard model (SM) of particle physics. Indeed, there exist a number of possibilities, though none have been conclusively established. One of the most popular—standard thermal leptogenesis—provides a theoretically attractive solution, yet it is generally difficult to test experimentally. It is, therefore, worth considering scenarios that may be more directly tested laboratory experiments.

A particularly interesting and largely unexplored possibility involves CP violation that enters the B_s meson system. The relevant phases are generically flavor off-diagonal, making them less susceptible to constraints from searches for permanent electric dipole moments (EDMs) that challenge other baryogenesis scenarios (for an illustration in the minimal supersymmetric standard model (MSSM), see, e.g. [4]). Moreover, recent measurements in B factories and at the Tevatron exhibit indications of CP violation that differ by a few standard deviations from the SM predictions [5,6], though even more recent results from the LHCb collaboration favor smaller effects [7]. From a theoretical perspective if the CP phase(s) encoding the CP violation in B_s system can successfully drive the generation of the BAU and can be probed experimentally, our understanding of the BAU problem will be considerably advanced.

In this Letter, we report on an initial effort addressing this question. We propose a new mechanism in the framework of electroweak baryogenesis (EWBG), explicitly showing that the CP-violating phenomena characterized by different energy scales (B_s observables and BAU) can be sourced by a common CP phase. We then explore the capability of this common CP phase to directly drive the BAU creation, given the observations of the B_s CP-violating effects in different laboratory experiments. As an illustration, we will work in a two-Higgs-doublet model (2HDM). In this context, if a sufficiently strong, first-order electroweak phase transition (EWPT) occurs in the early Universe, the CP phase associated with the tree-level, Higgs-b-s interaction at the phase boundary can induce CP-asymmetries that ultimately induce the BAU. While EWBG in the 2HDM has been discussed extensively in the past [8], including two recent studies using the 2HDM that have addressed the possible connection between the BAU and B_s observables [9] (see also [10]), we emphasize that the mechanism discussed below is the only one thus far to explore the feasibility of baryogenesis directly driven by the $b \rightarrow s$ CP violation. Given the novel features that are generically absent elsewhere and the crucial role played by "beauty" quarks, we denote this mechanism "electroweak beautygenesis" (EWBTG).

In what follows, we concentrate on the issue of CP violation and do not treat the question of the first-order EWPT in the 2HDM. Following Ref. [9], we instead refer the reader to more general studies that may indicate its feasibility [8]. We note, however, that these analyses are typically gauge dependent and therefore open to question. Rather than delve into these subtleties of perturbative treatments of the EWPT, we also refer the readers to a recent and more extensive discussion [11].

Two-Higgs-doublet model.—The Higgs sector in the general 2HDM is [$H_{u,d}$ are Higgs doublets with their SM gauge charges being (0, 2, $\pm 1/2$)]

$$\mathcal{L} = \lambda_{ij}^u \bar{Q}^i (\epsilon H_d^\dagger) u_R^j - \lambda_{ij}^d \bar{Q}^i H_d d_R^j - y_{ij}^u \bar{Q}^i H_u u_R^j + y_{ij}^d \bar{Q}^i (\epsilon H_u^\dagger) d_R^j + \text{H.c.} \tag{1}$$

In a supersymmetric embedding, the first term can arise at loop level [12]. For experimental relevance, we focus on the two-flavor b-s system. The study can be extended to a three-flavor system without requiring essential changes in this mechanism. The mass matrix is

$$m_{ij} = y_{ij} v_u + \lambda_{ij} v_d = (y_{ij} \sin\beta + \lambda_{ij} \cos\beta) v, \tag{2}$$

where $v_{u,d}$ are vacuum expectation values (VEVs) of the neutral Higgs fields with $v = \sqrt{v_u^2 + v_d^2}$ and $\tan\beta = v_u/v_d$. $v_{u,d}$ are functions of spacetime during the EWPT. Meanwhile, $H_{bs} = -\cos\beta H_u + \sin\beta H_d^\dagger$, a linear combination of Higgs mass eigenstates, will introduce flavor-changing neutral current (FCNC) effects at zero temperature.

Since we are investigating the feasibility that a common phase can source the BAU and account for the B_s CP-violating observables, we will work in a simplified but sufficiently representative scenario, deferring a more comprehensive treatment to future work where the following scenario would arise in one region of parameter space. First, we take $\tan\beta = 1$ at zero temperature, emphasizing that $\tan\beta$ is not a constant during an EWPT. Second, we assume $y_{sb} = \lambda_{sb} = m_{sb} = 0$. In the limit of y_{ss}, $\lambda_{ss} \to 0$, there is one CP-violating phase after appropriate field redefinitions. Without loss of generality, we assume that λ_{bs} is complex (with $\theta_{\lambda_{bs}} = \text{Arg}(\lambda_{bs})$) and y_{bs}, y_{bb} and λ_{bb} are real, and furthermore, assume $\lambda_{ii} = y_{ii}$ and $|\lambda_{bs}| = |y_{bs}|$. The mass matrix is then

$$\begin{pmatrix} \pm 2\xi_{ss} & 0 \\ \xi_{bs}(\pm 1 + e^{i\theta_{\lambda_{bs}}}) & \pm 2\xi_{bb} \end{pmatrix} v, \tag{3}$$

here $\xi_{ij} = |\lambda_{ij}|/\sqrt{2}$ and the "$\pm$" signs are due to y_{ss}, y_{bs} and $y_{bb} >$ or <0. Denoting m_{bs} as $m_{bs} = \Delta \exp(i\theta)$, we have $\Delta = 2\xi_{bs} |\cos(\theta_{\lambda_{bs}}/2)| v$, $\theta = \theta_{\lambda_{bs}}/2$ for $y_{bs} > 0$, and $\Delta = 2\xi_{bs} |\sin(\theta_{\lambda_{bs}}/2)| v$, $\theta = (\theta_{\lambda_{bs}} + \pi)/2$ for $y_{bs} < 0$.

The mass matrix can be diagonalized by a unitary transformation $U_L^\dagger M U_R = D$. In the small m_{ss} limit, U_L is trivial and U_R is parametrized by a rotation angle $\alpha_R = -\arctan(\Delta/m_{bb})$. The coupling of H_{bs} and b_L, s_R quarks in the mass eigenstate basis is given by

$$\zeta_{bs} = \xi_{bs}[\mp 1 + \exp(i\theta_{\lambda_{bs}})] \cos\alpha_R. \tag{4}$$

with $\text{Arg}(\zeta_{bs}) = \theta \pm \pi/2$ for $y_{bs} > 0$ and <0, respectively. It is just the phase θ (or $\theta_{\lambda_{bs}}$) that both introduces CP-violation in $b \to s$ transitions (via ζ_{bs}) and source the generation of baryon asymmetry (via m_{bs}).

Electroweak beautygenesis.—Production of the BAU during a first-order EWPT involves a dynamic generation of CP-violating charge asymmetries through particle interactions in the wall of nucleated bubbles. Those charge asymmetries are converted, via left-handed fermions (n_L), into the baryon asymmetry through the electroweak sphaleron transitions. We ignore the wall curvature in our analysis so all relevant functions depend on the variable $\bar{z} = z + v_w t$. Here v_w is the wall velocity; $\bar{z} < 0$ and >0 correspond to the unbroken and broken phases, respectively; and the boundary extends over $0 < \bar{z} < L_w$. As pointed out in [13], the transport properties of particles during the EWPT is most appropriately treated using nonequilibrium quantum field theory. Working in its closed time path formulation (for pedagogical discussions, see [14]) and under the "VEV-insertion" approximation (see, e.g., Refs. [9,13–15]), we compute the CP-violating source induced by the Higgs mediated process $b_L \to s_R \to b_L$. It is given by

$$S_{b_L}^{\not{C}P} = -S_{s_R}^{\not{C}P} = \frac{N_c \Delta(\bar{z})^2}{\pi^2} \dot{\theta}(\bar{z}) \int_0^\infty \frac{dk k^2}{\omega_{b_L} \omega_{s_R}} \times \text{Im}\left\{ \frac{(\mathcal{E}_{b_L}^* \mathcal{E}_{s_R} - k^2)(n_F(\mathcal{E}_{s_R}) - n_F(\mathcal{E}_{b_L}^*))}{(\mathcal{E}_{s_R} - \mathcal{E}_{b_L}^*)^2} + \frac{(\mathcal{E}_{b_L} \mathcal{E}_{s_R} + k^2)(n_F(\mathcal{E}_{s_R}) + n_F(\mathcal{E}_{b_L}))}{(\mathcal{E}_{s_R} + \mathcal{E}_{b_L})^2} \right\}. \tag{5}$$

Here, $n_F(x) = 1/(\exp(x) + 1)$ is the Fermi distribution; $\mathcal{E}_{b_L,s_R} = \omega_{b_L,s_R} - i\Gamma_{b_L,s_R}$ are complex poles of the spectral function with $\omega_{b_L,s_R}^2 = k^2 + m_{b_L,s_R}^2$; and m_{b_L,s_R} and Γ_{b_L,s_R} are thermal parameters. This source corresponds to the "A"-type terms in Eq. (58) of [14], after properly accounting for temperature-independent vacuum contributions that are removed via normal ordering [16]. The quantity $\dot{\theta}(\bar{z}) = d\theta(\bar{z})/dt$ is given by

$$\dot{\theta}(\bar{z}) = \frac{-2f(\bar{z})}{\Delta(\bar{z})^2} \text{sgn}(y_{bs}) \xi_{bs}^2(\infty) \sin\theta_{\lambda_{bs}} \tag{6}$$

with $f(\bar{z}) = (\dot{v}_u(\bar{z}) v_d(\bar{z}) - v_u(\bar{z}) \dot{v}_d(\bar{z})) \sim v_w v^2 \delta\beta / L_w$ being a function describing the relative variation of the Higgs VEVs across the bubble wall. Although analyses performed in the MSSM [17] indicate $\delta\beta \sim \mathcal{O}(10^{-2})$, a systematic analysis is absent in the 2HDM. Here, we will simply adopt $\delta\beta = -0.05$ (if y_{bs} is complex and λ_{bs} is real, we need $\delta\beta > 0$ to keep the sign of $f(\bar{z})$ unchanged). Note, $S_{b_L}^{\not{C}P}$ is nonzero only within the moving bubble wall, where $\dot{\theta}(\bar{z}) \neq 0$.

In contrast to EWBG driven by flavor-diagonal sources, the transport of both the second and third family particles is sourced by CP-violating terms. We define the number densities $\{Q_{1,2,3}, U, D, C, S, T, B, H = H_u^+ + H_u^0 - H_d^- - H_d^0\}$ which correspond, respectively, to left-chiral quarks of different families, right-chiral up, down, charm, strange, top and beauty, and Higgs bosons. Since all light quarks (except b_L and s_R) are mainly produced by strong sphaleron processes and all quarks have similar diffusion constants, baryon number conservation on time-scales shorter than the inverse electroweak sphaleron rate implies the approximate constraints $Q_1 = Q_2 = -2U = -2D = -2C = -2B$ and $S + T + Q_3 = 0$. The set of Boltzmann equations is

$$\begin{aligned}\partial^\mu Q_{3\mu} &= \Gamma_{m_t}(\xi_T - \xi_{Q_3}) + \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) \\ &\quad + 2\Gamma_{ss}(\xi_T - 2\xi_{Q_3} + \xi_S + 8\xi_B) + S_{b_L}^{\not{C}P}\partial^\mu T_\mu \\ &= -\Gamma_{m_t}(\xi_T - \xi_{Q_3}) - \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) \\ &\quad - \Gamma_{ss}(\xi_T - 2\xi_{Q_3} + \xi_S + 8\xi_B)\partial^\mu \delta_\mu \\ &= -S_{b_L}^{\not{C}P},\end{aligned}$$

(with $\delta = S - B$)

$$\partial^\mu H_\mu = \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) - 2\Gamma_h H. \qquad (7)$$

Here $\partial^\mu = v_w \frac{d}{d\bar{z}} - D_a \frac{d^2}{d\bar{z}^2}$ in the planar bubble wall approximation with D_a being a diffusion constant, and $\xi_a = n_a/k_a$ with n_a and k_a being the number density and the statistical factor of particle "a". Apart from the CP-violating sources, the interactions in Eq. (7) include (i) inelastic top Yukawa (Γ_t) and strong sphaleron (Γ_{ss}) processes; (ii) top relaxation processes (Γ_{m_t}), while we neglect the other Yukawa interactions since $\Gamma D_q/v_w^2 < 1$; and (iii) Higgs relaxation processes (Γ_h) due to Higgs mass mixing, with typically $\Gamma_h < \Gamma_{m_t}$ in this scenario.

Assuming $S_{b_L}^{\not{C}P}(\bar{z} < 0) = 0$, we solve the Boltzmann equations for the net left-handed fermion density $n_L = \sum_{i=1}^3 Q_i$ analytically order-by-order in $1/\Gamma_{ss}$, with $\Gamma_{ss} = 16\alpha_s^4 T$. The leading contribution arises at first-order in this expansion. The baryon asymmetry ρ_B is then produced in weak sphaleron process, described by [18]

$$\partial^\mu \rho_{B\mu} = -\Theta(-\bar{z})\Gamma_{ws}\left(\frac{15}{4}\rho_B + 3n_L\right), \qquad (8)$$

where $\Gamma_{ws} = 120\alpha_w^5 T$ is the weak sphaleron rate [19]. In the broken phase this gives ($k_S = k_B$ is assumed)

$$\rho_B = \frac{3\Gamma_{\rm ws}}{v_w^2}\int_0^\infty \left[r\frac{v_w^2}{\Gamma_{ss}\bar{D}}(1 - \frac{D_q}{\bar{D}})\frac{\bar{S}(\bar{z})}{\kappa^+}e^{-\kappa^+\bar{z}}\right]d\bar{z} \qquad (9)$$

with $r = -\frac{3}{2}[\frac{k_B(k_Q+2k_T)}{k_H(9k_T+9k_Q+k_B)}]$ and $\kappa^+ \simeq (\sqrt{v_w^2 + 4\bar{\Gamma}\bar{D}} + v_w)/2\bar{D}$. Here $\bar{D}$, $\bar{\Gamma}$ and $\bar{S}$ are, respectively, the effective diffusion constant, decay rate and CP-violating source for the Higgs number density. $\bar{D}$ is defined in [14], while

$$\begin{aligned}\bar{\Gamma} &= (9k_T + 9k_Q + k_B)(\Gamma_{m_t} + 2\Gamma_h)/X \\ \bar{S} &= k_H(k_{Q_3} - 7k_T + k_B)S_{b_L}^{\not{C}P}/X \\ X &= 9k_{Q_3}k_T + k_Bk_{Q_3} + 4k_Tk_B + k_H(9k_T + 9k_{Q_3} + k_B).\end{aligned} \qquad (10)$$

Note that while the weak sphaleron transitions are driven by the diffusion tail for n_L that extends ahead of the advancing wall in the unbroken phase ($\bar{z} < 0$), the solution in Eq. (9) contains an integral over the source in the broken phase that appears when matching the solutions to the Boltzmann equations at the phase boundary.

CP-violation in the B_s-$\bar{B}_s$ mixing.—Depending on the details of the scalar potential, H_{bs} may be approximately a mass eigenstate, which we assume for illustration. Tree-level exchange of $H_{\rm bs}$ with a VEV insertion leads to a B_s-$\bar{B}_s$ mixing operator in the basis of quark mass eigenstates (Λ_{bs} is an effective new physics scale):

$$\frac{\zeta_{bs}^2}{\Lambda_{bs}^2}(\bar{b}_L s_R)(\bar{b}_L s_R), \quad \text{with} \quad \Lambda_{bs} \sim m_{H_{bs}}^2/v.$$

The RG running of this operator involves a mixture of scalar operator $O_{SRR}^{bs} \equiv (\bar{b}P_R s)(\bar{b}P_R s)$ and tensor operators $O_{TRR}^{bs} \equiv (\bar{b}\sigma^{\mu\nu}P_R s)(\bar{b}\sigma_{\mu\nu}P_R s)$ whose matrix elements are $\langle B_s|O_{SRR}^{bs}|\bar{B}_s\rangle \approx -5m_{B_s}f_{B_s}^2 B_{SRR}^{bs}/24$ and $\langle B_s|O_{TRR}^{bs}|\bar{B}_s\rangle \approx -m_{B_s}f_{B_s}^2 B_{TRR}^{bs}/2$ [20]. Assuming $m_{B_s}^2 \approx (m_b + m_s)^2$ and $B_{SRR}^{bs} \simeq B_{TRR}^{bs} = B_{B_s}$, we obtain $M_{12}^s \equiv \langle B_s|\mathcal{H}|\bar{B}_s\rangle = -\zeta_{bs}^2 f_{B_s}^2 m_{B_s} B_{B_s}(5\eta_{SRR}/24 + \eta_{TRR}/2)/\Lambda_{bs}^2$, with $\eta_{SRR} \approx 1.87$, $\eta_{TRR} \approx -0.01$ [20].

Choosing Γ_q to be real and parametrizing M_{12}^s as [21] $M_{12}^s \equiv (M_{12}^s)^{\rm SM}\Delta_s$ with $\Delta_s \equiv |\Delta_s|e^{i\phi_s^\Delta}$, we have

$$\begin{aligned}\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM}\cos(\phi_s^{\rm SM} + \phi_s^\Delta), &\quad \Delta m_s &= \Delta m_s^{\rm SM}|\Delta_s|, \\ a_{\rm SL}^s &= \frac{\Delta\Gamma_s^{\rm SM}}{\Delta m_s^{\rm SM}}\frac{\sin(\phi_s^{\rm SM} + \phi_s^\Delta)}{|\Delta_s|}, &\quad 2\beta_s &= 2\beta_s^{\rm SM} - \phi_s^\Delta.\end{aligned} \qquad (11)$$

Here Δm_s and $\Delta\Gamma_s$ are the mass and decay width difference between the heavy and light B_s mass eigenstates, a_{SL}^s is the charge asymmetry in semileptonic B_s decays, and β_s measures the time-dependent CP asymmetries in the hadronic B_s decay.

The theoretical inputs and experimental results are listed in the Table I. The decay constants and bag parameters are taken from Ref. [24], while A_{sl}^b, and $\beta_s^{\rm Exp}$, $\Delta\Gamma^{\rm Exp}$ are obtained by combining the D0 and CDF measurements [5,6]. We perform a χ^2 fit to the four observables in Eq. (11), neglecting the correlation between $\Delta\Gamma_s$ and β_s for simplicity. Assuming Λ_{bs} of 1 TeV, we scan over the remaining parameters, yielding the regions of 95% C. L. from the Tevatron and the LHCb results. We note that the CP-violating source term $S_{b_L}^{\not{C}P}$ is not sensitive to Λ_{bs} since the mediator of B_s mixing is not directly involved in the

TABLE I. The theoretical input parameters [2,22] and the experimental data from the Tevatron and LHCb.

$\beta_s^{\rm SM}$	$\beta_s^{\rm Tev}$ [5]	$f_{B_s}\sqrt{B_{B_s}}$
0.019 ± 0.001	0.27 ± 0.15	(275 ± 13) MeV
$(\Delta m_{B_s})^{\rm SM}$	$(\Delta m_{B_s})^{\rm Tev}$ [23]	$\phi_s^{\rm SM}$
$19.30 \pm 2.2\ {\rm ps}^{-1}$	$17.77 \pm 0.12\ {\rm ps}^{-1}$	$(4.2 \pm 1.4) \times 10^{-3}$
$(\Delta\Gamma_s)^{\rm SM}$	$(\Delta\Gamma_s)^{\rm Tev}$ [5]	A_{sl}^b [6]
$0.098 \pm 0.024\ {\rm ps}^{-1}$	$0.097 \pm 0.031\ {\rm ps}^{-1}$	$(-7.40 \pm 1.93) \times 10^{-3}$
$(\Delta m_{B_s})^{\rm LHCb}$ [7]	$(\Delta\Gamma_s)^{\rm LHCb}$ [7]	$\beta_s^{\rm LHCb}$ [7]
$17.725 \pm 0.049\ {\rm ps}^{-1}$	$0.123 \pm 0.030\ {\rm ps}^{-1}$	-0.015 ± 0.087

interaction between bottom and strange quarks and the bubble wall at leading order.

Discussion.—The contours of constant n_B/s in the ${\rm sgn}(y_{bs})\xi_{bs} - \sin\theta_{\lambda_{bs}}$ plane are indicated in Fig. 1. We observe that the regions favored by the LHCb (green) and the Tevatron studies without the di-muon asymmetry (yellow) at 95% C.L. overlap with the lines (0.88) that correspond to nearly the full BAU. For the Tevatron results with the di-muon asymmetry included, a smaller though still sizable portion of the BAU can be generated. The LHCb B_s hadronic decay results constrain the parameter space more tightly than do those from the Tevatron that do not include the di-muon asymmetry. Although tension exists between the LHCb- and Tevatron-favored regions, it appears feasible that a common CP-violating phase may be responsible for both generating at least a non-negligible portion of the BAU and accounting for observations in the B_s system.

A definitive statement awaits the resolution of both the experimental tensions as well as several theoretical issues, including the development of a VEV-resummed CP-violating source (for recent progress, see, e.g., [25]), analysis of the full numerical solutions to Eqs. (7), and completion of a gauge-invariant analysis of the EWPT in the 2HDM. Indeed, the results of this initial study are likely to indicate the maximum magnitude of the BAU that can be achieved in this scenario, given the generous assumptions we have made about various input parameters, including $\delta\beta$ and v_w and the use of an analytic rather than numerical solution of the Boltzmann equations. These open questions not withstanding, it is evident that a direct connection can be made between B_s observables and the BAU and that this connection can be tested or constrained by on-going experiments. Moreover, we expect that after future refinements are implemented, EWBTG may account for an interesting portion of the BAU in appropriate regions of parameter space.

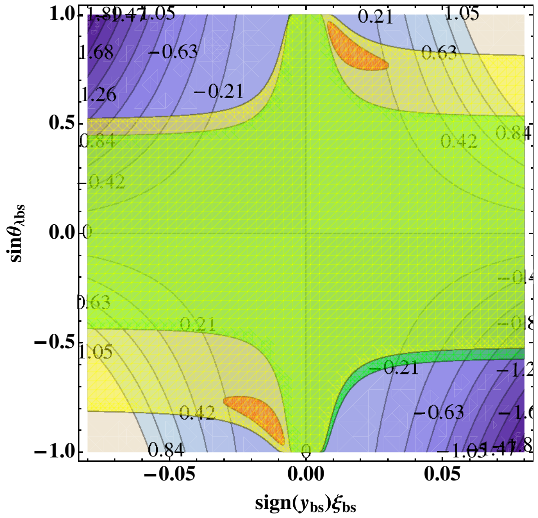

FIG. 1 (color online). Contours of n_B/s (in units of 10^{-10}). Orange, yellow and green contours indicate 95% C.L. Tevatron (with and without di-muon asymmetry) and LHCb constraints, respectively. We assume $k_{Q_3} = 2k_T = 2k_B = 6$ [30], $k_H = 4$, $v_w = 0.4$ [31], $L_w = 2/T$, $D_q = 6/T$ and $\Lambda_{bs} = 1$ TeV.

Though the foregoing discussion relied on the illustrative case of a two-flavor system of the 2HDM with a single phase, generalization to variants that make ancillary predictions, including three-flavor system as well as a system with minimal flavor violation with flavor-blind phases (e.g., see [26]) or a system with spontaneous CP violation (for discussions on collider phenomenology and FCNC physics of these variants, e.g., see Ref. [27] and references therein), would be straightforward. We leave the consideration of these possibilities, along with EWBTG in other models such as the four-family SM (e.g., see [28]), family nonuniversal $U(1)'$ model [29], and supersymmetric models, etc., to future work.

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While the current work was in the review process, the LHCb Collaboration announced new measurements of the CP violation in B_s mixing using 1 ${\rm fb}^{-1}$ data [32]. The new results have similar central values with smaller uncertainties. In this situation, one would require a larger $|\xi_{bs}|$ (see Fig. 1) to generate the correct baryon number density.

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