Electroweak Beautygenesis: From $b \to s$ CP Violation to the Cosmic Baryon Asymmetry
Tao Liu, Michael J. Ramsey-Musolf, and Jing Shu
DOI: 10.1103/PhysRevLett.108.221301
Electroweak Beautygenesis:  
From $b \to s$ CP-violation to the Cosmic Baryon Asymmetry  
Tao Liu,  
Michael J. Ramsey-Musolf, and Jing Shu  
1Department of Physics, University of California, Santa Barbara, CA 93106, USA  
2Department of Physics, University of Wisconsin, Madison, WI 53706, USA  
and Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125  
3Institute for the Physics and Mathematics of the Universe,  
University of Tokyo, Kashiwa, Chiba 277-8568, Japan  
4International School for Advanced Studies (SISSA), Via Bonomea 265, I-34136 Trieste, Italy  

We address the possibility that CP-violation in $B_s - \bar{B}_s$ mixing may help explain the origin of the cosmic baryon asymmetry.

The baryon asymmetry of the Universe (BAU) has been precisely measured by the WMAP collaboration. Combining its five year results with those from other CMB and large scale structure measurements gives $\Omega_b h^2 = 0.02265 \pm 0.00059$ [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: (1) baryon number violation; (2) C and CP violation; (3) 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. 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.

## Introduction

The baryon asymmetry of the Universe (BAU) has been precisely measured by the WMAP collaboration. Combining its five year results with those from other CMB and large scale structure measurements gives $\Omega_b h^2 = 0.02265 \pm 0.00059$ [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: (1) baryon number violation; (2) C and CP violation; (3) 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. 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.

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.

### Two Higgs Doublet Model

The Higgs sector in the general 2HDM is $(H_{u,d} \equiv$ Higgs doublets with their SM gauge charges being $(0, 2, \pm 1/2))$

\[
\mathcal{L} = \sum_{ij} v_i^u Q^i_H^u (\epsilon H_d^u)^j u_R \lambda_{ij} \epsilon H_d^u H_d^d d_R^j - y_{ij} Q^i_H^d H_u^u u_R^j + \epsilon_H^u d_R^j \]

(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

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

where $v_u, v_d$ are vacuum expectation values (VEVs) of the neutral Higgs fields with $v = \sqrt{v_u^2 + v_d^2}$ and $\tan \beta = v_u / v_d$. $v_u, v_d$ are functions of spacetime during the EWPT. Meanwhile, $H_{bs} = -\cos \beta H_u + \sin \beta H_d$, 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 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 $\lambda_{bs}$ is complex (with $\theta_{\lambda_{bs}} = \text{Arg}(\lambda_{bs})$) and $y_{bs}, y_{bb}$ and $\lambda_{bb}$ are real, and furthermore, assume $\lambda_{ii} = y_{ii}$ and $|\lambda_{bs}| = |y_{bs}|$. The mass matrix is then

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

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

The mass matrix can be diagonalized by a unitary transformation $U_L M_{bR} U_L^T = D$. 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

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

with $\text{Arg}(\xi_{bs}) = \theta_{\lambda_{bs}}/2$ for $y_{bs} > 0$ and $< 0$, respectively. It is just the phase $\theta$ (or $\lambda_{bs}$) that both introduces CP-violation in $b \to s$ transitions (via $\zeta_{bs}$) 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 $\tilde{z} = z + v_w t$. Here $v_w$ is the wall velocity; $\tilde{z} < 0$ and $> 0$ correspond to the unbroken and broken phases, respectively; and the boundary extends over $0 < \tilde{z} < L_w$. As pointed out in [19], the transport properties of particles during the EWPT is most appropriately treated using non-equilibrium quantum field theory. Working in its closed time path formulation (for pedagogical discussions, see [20]) and under the “VEV-insertion” approximation (see, e.g., Refs. [9, 19–21]), we compute the CP-violating source induced by the Higgs mediated process $b_L \to s_R \to b_L$. It is given by

$$S_{bL}^{\text{OP}} = -N_s^{\text{CF}} = \frac{N_s \Delta(\tilde{z})^2}{\pi^2} \int_0^\infty \frac{dk^2}{\omega_{bL} \omega_{sR}} \left( \frac{\tilde{E}_{sL}^* \tilde{E}_{sR} - k^2(n_F(\tilde{E}_{sR}) - n_F(\tilde{E}_{sL}))}{(\tilde{E}_{sR} - \tilde{E}_{bL})^2} \right) \int \left\{ \frac{\tilde{E}_{bL}^* \tilde{E}_{sR} - k^2(n_F(\tilde{E}_{sR}) + n_F(\tilde{E}_{bL}))}{(\tilde{E}_{sR} + \tilde{E}_{bL})^2} \right\} . \tag{5}$$

Here $n_F(x) = 1/(\exp(x) + 1)$ is the Fermi distribution; $\omega_{bL,sR} = \omega_{bL,sR} - i\Gamma_{bL,sR}$ are complex poles of the spectral function with $\omega_{bL,sR} = k^2 + m_{bL,sR}^2$ and $m_{bL,sR}$ and $\Gamma_{bL,sR}$ are thermal parameters. This source corresponds to the “A”-type terms in Eq. (58) of [20], after properly accounting for temperature-independent vacuum contributions that are removed via normal ordering [33]. The quantity $\theta(\tilde{z}) = d\theta(\tilde{z})/dt$ is given by

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

with $f(\tilde{z}) = (v_u \bar{v}_{uL} v_{uL}^*) e^{i\theta_{\lambda_{bs}}} \tilde{E}_{bL}^* \tilde{E}_{sR} \sim v_w v_{b}^2 \delta \beta / L_w$ being a function describing the relative variation of the Higgs VEVs across the bubble wall. Although analyses performed in the MSSM [22] indicate $\delta \beta \sim \mathcal{O}(10^{-2})$, a systematic analysis is absent in the 2HDM. Here, we shall simply adopt $\delta \beta = -0.05$ (if $y_{bs}$ is complex and $\lambda_{bs}$ is real, we need $\delta \beta > 0$ to keep the sign of $f(\tilde{z})$ unchanged). Note, $S_{bL}^{\text{OP}}$ is non-zero only within the moving bubble wall, where $\theta(\tilde{z}) \neq 0$.

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 $\{Q_{1,2,3}, U, D, C, S, T, B, H = H_u^+ + H_d^-, H_u^- - H_d^+\}$ 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

$$\begin{align*}
\partial^\mu Q_{3\mu} &= -\Gamma_{m_1} (\xi_T - \xi_{Q_1}) + \Gamma_{m_1} (\xi_T - \xi_T) + (\xi_{Q_1} - \xi_{Q_3}) + 2\Gamma_{ss} (\xi_T - 2\xi_{Q_3} + \xi_S + \xi_{bL}) + S_{bL}^{\text{OP}} \\
\partial^\mu T_{\mu} &= -\Gamma_{m_1} (\xi_T - \xi_{Q_3}) - \Gamma_{m_1} (\xi_T - \xi_T - \xi_{Q_1}) - \Gamma_{ss} (\xi_{Q_1} - 2\xi_{Q_3} + \xi_S + 8\Gamma_{bL}) \\
\partial^\mu \delta_{\mu} &= -S_{bL}^{\text{OP}}, \quad \text{(with } \delta = S - B) \end{align*}$$

with $Q_{3\mu} = -Q_{3\mu}^\dagger$. The wall is at $\tilde{z} = 0$, and $b_L, s_R$ are produced in the wall to maintain baryon asymmetry.
\[ \partial^\mu H_\mu = \Gamma_l (\xi_T - \xi_H - \xi_{Q_s}) - 2 \Gamma_h H . \]  

(7)

Here \( \partial^\mu = v_w \frac{d}{\partial z} - D_{q\bar{q}} \frac{d^2}{d^2z} \) in the planar bubble wall approximation with \( D_q \) 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 (\( \Gamma_l \)) and strong sphaleron (\( \Gamma_{ss} \)) processes; (ii) top relaxation processes (\( \Gamma_{m_t} \)), while we neglect the other Yukawa interactions since \( \Gamma_D \langle v^2 \rangle < 1 \); and (iii) Higgs relaxation processes (\( \Gamma_h \)) due to Higgs mass mixing, with typically \( \Gamma_h < \Gamma_{m_t} \) in this scenario.

Assuming \( S_{Q_P}^L(\tilde{z}) < 0 = 0 \), we solve the Boltzmann equations for the net left-handed fermion density \( n_L = \sum_{i=\bar{q}}^3 Q_i \) analytically order-by-order in \( 1/\Gamma_{ss} \), with \( \Gamma_{ss} = 16 \alpha_s^2 \). The leading contribution arises at first order in this expansion. The baryon asymmetry \( \rho_B \) is then produced in weak sphaleron process, described by [23]

\[ \partial^\mu \rho_{B\mu} = -\Theta(-\tilde{z}) \Gamma_{us} \left( \frac{15}{4} \rho_B + 3 n_L \right) , \]

(8)

where \( \Gamma_{us} = 120 \alpha_s^5 \) is the weak sphaleron rate [24]. In the broken phase this gives \( (k_s = k_B \) is assumed)

\[ \rho_B = \frac{3 \Gamma_{us}}{v_w^2} \int_0^\infty \left[ r \frac{v_w^2}{\Gamma_s D} \left( 1 - \frac{D_q}{D} \right) \frac{S(\tilde{z})}{\kappa^+ e^{-\kappa^+ \tilde{z}}} \right] d\tilde{z} \]

(9)

with \( r = \frac{3}{2} \left[ 9 k_s^2 (k_Q + 2 k_h) \right] \) and \( \kappa^+ \approx \left( \sqrt{v_w^2 + 4 T^2} + v_w \right)/2 \). Here \( D, \Gamma \) and \( S \) are, respectively, the effective diffusion constant, decay rate and CP-violating source for the Higgs number density. \( D \) is defined in [20], while

\[ \Gamma = (9 k_t + 9 k_Q + k_B (\Gamma_{m_t} + 2 \Gamma_h))/X \]

\[ \tilde{S} = k_h (k_{Q_s} - 9 k_t + k_B) S_{Q_P}^L/X \]

\[ X = 9 k_Q k_t + k_B k_{Q_s} + 4 k_t k_B + k_H (9 k_t + 9 k_{Q_s} + k_B) . \]

(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 \( (\tilde{z} < 0) \), 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, \( H_{us} \) may be approximately a mass eigenstate, which we assume for illustration. Tree-level exchange of \( H_{us} \) in a WVE insertion leads to a \( B_s - \bar{B}_s \) mixing operator in the basis of quark mass eigenstates \( (\Lambda_{bs} \) is an effective new physics scale):

\[ \frac{\zeta_s^2}{\Lambda_{bs}^2} (\bar{b}_{LSR})(\bar{b}_{LSR}) , \]

with \( \Lambda_{bs} \simeq m_{B_{us}}^2/v \).

The RG running of this operator involves a mixture of scalar operator \( O_{SRR}^{bs} \equiv (\bar{b}_{PS}) (\bar{b}_{PS}) \) and tensor operators \( O_{TRR}^{bs} \equiv (\bar{b}_{PS} P_R) (\bar{b}_{PS} P_R) \) whose matrix elements are \( \langle B_s | O_{SRR}^{bs} | \bar{B}_s \rangle \approx 5 m_{B_{us}} f_{B_{us}}^2 B_{SRR}^{bs}/24 \) and \( \langle B_s | O_{TRR}^{bs} | \bar{B}_s \rangle \approx - m_{B_{us}} f_{B_{us}}^2 B_{TRR}^{bs}/24 \) [14]. Assuming \( m_{B_{us}}^2 \)

![FIG. 1: 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 \( k_Q = 2 k_T = 2 k_B = 6 \) [25], \( k_B = 4, \)

\( v_w = 0.4 \) [26], \( L = 2/T, D_q = 6/T \) and \( \Lambda_{bs} = 1 \) TeV.

<table>
<thead>
<tr>
<th>( \beta^{SM}_{s} )</th>
<th>( \beta^{TeV}_{s} )</th>
<th>( f_{B_{us}} \sqrt{B_{B_{us}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.019 ± 0.001</td>
<td>0.27 ± 0.15</td>
<td>(275 ± 13) MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \Delta m_{s}^{SM} )</th>
<th>( \Delta m_{s}^{TeV} )</th>
<th>( A_{b_s}^{LHCb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.30 ± 2.2 ps(^{-1} )</td>
<td>17.77 ± 0.12 ps(^{-1} )</td>
<td>(4.2 ± 1.4) \times 10^{-3}</td>
</tr>
</tbody>
</table>

| \( \frac{\Delta m_{s}^{SM} \Delta m_{s}^{TeV}}{|\Delta m_{s}^{SM}|} \) | \( A_{b_s}^{LHCb} \) |
|---------------------------------|------------------|
| 0.098 ± 0.024 ps\(^{-1} \) | 0.997 ± 0.031 ps\(^{-1} \) | (7.40 ± 1.93) \times 10^{-3} |

<table>
<thead>
<tr>
<th>( \Delta m_{s}^{LHCb} )</th>
<th>( \Delta m_{s}^{LHCb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.725 ± 0.049 ps(^{-1} )</td>
<td>0.123 ± 0.030 ps(^{-1} )</td>
</tr>
</tbody>
</table>

**TABLE I: The theoretical input parameters [2, 15] and the experimental data from the Tevatron and LHCb.**

\[ \approx (m_b + m_s)^2 + \frac{B_{s}^{bs}}{B_{TRR}^{bs}} \approx B_{s}^{bs} = B_{B_{us}}, \]

we obtain \( M_{12} = \langle \bar{B}_s | \bar{h} | B_s \rangle = -\Delta^{2} f_{B_s}^{-1} m_{B_{us}} B_{s} \) (\( \bar{h} | SRR \rangle |24 \) and \( \bar{h} | SRR \rangle |24 \)), with \( \bar{h} | SRR \rangle \approx 1.87 \), \( \bar{h} | SRR \rangle \approx 0.01 \) [14].

Choosing \( \Gamma_t \) to be real and parametrizing \( M_{12}^s \) as [16]

\[ M_{12}^s = \langle M_{12}^{SM} \rangle \Lambda_{bs} \]

with \( \Lambda_{bs} = | \Lambda_{bs} | e^{i \Delta} \), we have

\[ \Delta \Gamma_s = \Delta \Gamma_s^{SM} \cos(\phi_s^{SM} + \phi_\Delta) , \]

\[ \Delta m_s = \Delta m_s^{SM} | \Delta_s | , \]

\[ a_{sL} = \frac{\Delta m_s^{SM} \sin(\phi_s^{SM} + \phi_\Delta)}{| \Delta_s |} , \]

\[ 2 \beta_s = 2 \beta_s^{SM} - \phi_\Delta \]

Here \( \Delta m_s \) and \( \Delta \Gamma_s \) are the mass and decay width difference between the heavy and light \( B_s \) mass eigenstates, \( a_{sL}^{SM} \) is the charge asymmetry in semileptonic \( B_s \) decays, and \( \beta_s \) 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. [18], while \( A_{b_s}^{LHCb} \) and \( \beta_s^{Exp} \), \( \Delta \Gamma^{Exp} \) are obtained by combining the DΦ and CDF measurements [5, 6]. We perform a \( \chi^2 \) fit to the four observables in Eq.(11), neglecting the correlation between \( \Delta \Gamma_s \) and \( \beta_s \) for simplicity. Assuming \( \Lambda_{bs} \) 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 $S_{\mu u}^{CP}$ is not sensitive to $A_{\mu}$ since the mediator of $B_s$ mixing is not directly involved in the interaction between bottom and strange quarks and the bubble wall at leading order.

**Discussion** The contours of constant $n_B/s$ in the $\sign(y_{bs})\xi_{bs} - \sin \beta_{\mu s}$ 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., [27]), 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 $\nu_w$ 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.

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 [28]) or a system with spontaneous CP-violation (for discussions on collider phenomenology and FCNC physics of these variants, e.g., see Ref. [31] 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 [29]), family non-universal $U(1)'$ model [30], and supersymmetric models, etc. to future work.

**Acknowledgements** We thank V. Cirigliano, J. Cline, S. Gori, C. Lee, S. Tulin and C. Wagner for helpful discussions; P. Draper for collaboration at the early stages of this project; and the Shanghai Jiao Tong University where part of this work was carried out. We are grateful to S. Tulin for pointing out an error in an earlier version of this work and for a critical reading of this manuscript. The work is partially supported by U.S. Department of Energy contracts DE-FG02-91ER40618 (TL) and DE-FG02-08ER41531 (MJRM); the Wisconsin Alumni Research Foundation (MJRM); and the World Premier International Research Center Initiative (WPI initiative) MEXT, Japan (JS), Grant-in-Aid for scientific research (Young Scientists (B) 21740169) from Japan Society for Promotion of Science (JS) and the ERC Advanced Grant no. 267985 “DaMESyFla” (JS).

**Notes added:** 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 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.

[33] We thank C. Lee for clarification of this point.