Electroweak baryogenesis via bottom transport

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We consider a scenario in which an extra bottom Yukawa coupling can drive electroweak baryogenesis in the general two-Higgs doublet model. It is found that the new bottom Yukawa coupling with $\mathcal{O}(0.1)$ in magnitude can generate the sufficient baryon asymmetry without conflicting existing data. We point out that future measurements of the bottom Yukawa coupling at High-Luminosity Large Hadron Collider and International Linear Collider, together with the CP asymmetry of $B \rightarrow X_s \gamma$ at SuperKEKB provide exquisite probes for this scenario.

Introduction. — Existence of the baryon asymmetry of the Universe (BAU) is firmly established by various cosmological observations such as the cosmic microwave background and big-bang nucleosynthesis \cite{1}. However, its origin is still unclear, which motivates one to search for physics beyond the Standard Model (SM).

A plethora of baryogenesis scenarios have been proposed so far. After the discovery of the Higgs boson at Large Hadron Collider (LHC) in 2012 \cite{2}, a significant attention has been paid in particular to electroweak baryogenesis (EWBG) \cite{3,4} for its close connection to Higgs physics. One of the necessary conditions for the successful EWBG is that electroweak phase transition (EWPT) is strongly first order, which requires an extra scalar particle with a mass of sub-TeV that couples to the Higgs boson. Furthermore, CP violation relevant to EWBG often arises from Higgs-Yukawa interactions. Therefore, the Higgs signal strengths are inevitably modified by the new physics (NP) effects.

Recently, the Higgs boson decay to bottom quarks has been observed at the LHC. Its signal strength relative to the SM expectation is $1.01 \pm 0.12$(stat.$) \pm 0.15$(syst.) at ATLAS \cite{5} and $\mu = 1.04 \pm 0.14$(stat.$) \pm 0.14$(syst.) at CMS \cite{6}, respectively. While the measured values are consistent with the SM, however, there still exist sufficient room for NP.

The NP effects in the bottom sector is of great importance for $B$ physics as well. In addition to the on-going LHcb experiment, Belle-II at KEK will start collecting data (phase 3) in early 2019 and accumulate it up to $50 \text{ ab}^{-1}$ by 2024. One of the goals is to search for CP violation beyond the Cabibbo-Kobayashi-Maskawa (CKM) framework \cite{7}. It is of broad interest whether such a CP violation can be related to the BAU.

In this Letter, we consider a scenario in which an additional bottom Yukawa coupling is responsible for the BAU and discuss its implications to collider phenomenology as well as $B$ physics, especially $B \rightarrow X_s \gamma$. We take the general two Higgs doublet model (G2HDM) \cite{8} as a benchmark model. For previous studies of EWBG in the model, see, e.g., Refs. \cite{9-14}. For instance, in Ref. \cite{13} a scenario in which BAU is sourced by new CP violation in the up-type Yukawa couplings is considered. This EWBG scenario is very efficient as long as an extra top Yukawa coupling is complex and $\mathcal{O}(0.1-1)$ in magnitude. In such a case, there is no strong motivation to consider additional CP violation in the down-type Yukawa couplings. In the current analysis, however, we explore the EWBG possibility assuming that the up-type Yukawa couplings do not provide any new CP violation. Therefore, the current analysis is complementary to the above top-driven scenario.

We point out that the extra bottom Yukawa coupling of $\mathcal{O}(0.1)$ in magnitude can offer the successful EWBG without upsetting existing experimental constraints. It is found that, except some corner of the parameter space, most EWBG-viable regions can fully be covered by Higgs signal strength measurements at High-Luminosity LHC (HL-LHC) and future colliders such as International Linear Collider (ILC). Besides, such scenario can also be tested by $B$ physics observables, especially the branching ratio and CP asymmetry of $B \rightarrow X_s \gamma$ at SuperKEKB.

BAU via bottom transport. — The Yukawa interactions of the G2HDM in the Higgs mass eigen-basis are cast into the form

$$-\mathcal{L}_Y = \bar{f}_L y_\phi^f f_R \phi + \bar{u} \left[ V \rho^d P_R - \rho^u \rho^d V P_L \right] d H^+ + \text{H.c.}$$

where $f = u, d, e$, $P_{L,R} = (1 \mp \gamma_5)/2$, $V$ is the CKM matrix, $H^+$ is charged scalar and $\phi = h, H, A$, with $h$ is identified as 125 GeV boson, and $H$ and $A$ are CP-even and CP-odd scalars respectively. $y_\phi^f$ are the $3 \times 3$ matrices defined, respectively, as

$$y_{hij}^f = \frac{\lambda_f^i}{\sqrt{2}} \delta_{ij} s_{\beta-\alpha} + \frac{\rho_f^i}{\sqrt{2}} c_{\beta-\alpha},$$

$$y_{Hij}^f = \frac{\lambda_f^i}{\sqrt{2}} \delta_{ij} c_{\beta-\alpha} - \frac{\rho_f^i}{\sqrt{2}} s_{\beta-\alpha},$$

$$y_{Aij}^f = \mp \frac{i \rho_f^i}{\sqrt{2}},$$

where $i, j$ are flavor indices, $\lambda_f^i = \sqrt{2} m_f^i/v \ (v = 246 \text{ GeV})$, $s_{\beta-\alpha} = \sin(\beta - \alpha)$ and $c_{\beta-\alpha} = \cos(\beta - \alpha)$.
with $\alpha$ being the mixing angle between $h$ and $H$ while $\beta$ is the ratio of the vacuum expectation values (VEVs) of the two Higgs doublets. The negative (positive) sign in Eq. (4) is for the up (down)-type fermions. The $3 \times 3$ matrices $\rho^f$ are in general complex and can break CP explicitly and/or induce the flavor-changing processes. Note that the Yukawa coupling for $h$ is reduced to the SM in the limit of $c_{\beta-\alpha} \to 0$ (alignment limit). In the current study, we consider the case in which $\rho_{1s}^t$, $\rho_{1s}^b$, and $\rho_{cs}^e$ are non-zero and set all other $\rho_{ij} = 0$ for simplicity. Furthermore, $\rho_{1s}^b$ is assumed to be real (for a complex $\rho_4$ case, see Ref. [13]). As discussed below, the nonzero $\rho_{ce}^e$ plays a pivotal role in realizing a cancellation mechanism in electric dipole moment (EDM) of electron [13]. Hereinafter, we omit the superscripts of $\rho$'s for notational simplicity.

As demonstrated in Refs. [10,13], with a specific ansatz for the Yukawa matrices in the gauge eigenstate (denoted as $Y_{1,2}$) $\rho_{bb}$ is given by
\[
\text{Im}(\rho_{bb}) = -\frac{1}{\lambda_b} \text{Im}[(Y_1)_{bs} (Y_2)_{bs}^*].
\] (5)

Therefore, $\rho_{bb}$ is correlated with the $b$-$s$ changing interactions in the symmetric phase, where the Higgs VEVs are zero. Since we consider the VEVs as the small perturbation in calculating the BAU (VEV insertion approximation [15]), the CP-violating source term arising from the $b$-$s$ transitions takes the form
\[
S_{\text{CPV}} = C_{\text{BAU}} \text{Im}[(Y_1)_{bs} (Y_2)_{bs}^*],
\] (6)

where $C_{\text{BAU}}$ denotes a dynamical factor for the scattering processes among the bottom/strange quarks and bubble wall (for the explicit form, see Refs. [12,13]). While this baryogenesis mechanism is the same as in Ref. [11], the correlation of Eq. (5) is unclear in [11], leading to different phenomenological consequences as shown below.

We calculate the BAU using closed-time-path formalism applied in Refs. [11,12,15,17]. After solving a diffusion equation for the baryon number density $(n_B)$, one finds
\[
n_B = \frac{-3 I_{B}^{(\text{sym})}}{2 D_q \lambda_{\pm}} \int_{-\infty}^{0} dz' n_L(z') e^{-\lambda_{\pm} z'},
\] (7)

with $\lambda_{\pm} = \left[ v_w \pm \sqrt{v_w^2 + 4 R D_q} \right] / 2 D_q$, $v_w$ denotes the bubble wall velocity, $D_q$ is the quark diffusion constant, $I_{B}^{(\text{sym})}$ is the $B$-changing rate via sphaleron in the symmetric phase, and $R = 15 I_{B}^{(\text{sym})} / 4$. For the calculation procedure of the left-handed fermion number density $(n_F)$ from the coupled diffusion equations for the top, bottom, strange and Higgs, readers are referred to Ref. [11].

One comment on an approximation adopted in Ref. [11] is that the CP-conserving source term induced by $(Y_{1,2})_{bs}$ is treated as the next-to-leading order due to the fact that it is smaller than the corresponding term induced by the top quark, and thus neglected. However, naively, the numerical impact of such a term may not be negligibly small. If so, the BAU based on Ref. [11] would be overestimated. In our numerical analysis, we regard the dropped term as the part of the theoretical uncertainties and defer the improvement of the BAU calculation to future work. For numerical estimate of $n_B$, we take $v_w = 0.4$, $D_q = 8.9/T$ and $I_{B}^{(\text{sym})} = 5.4 \times 10^{-6} T$ with $T$ being temperature.

We find the BAU-viable regions by requiring that $Y_B = n_B s$ should be greater than the observed value $Y_B^{\text{obs}} = 8.59 \times 10^{-11}$ [15], where $s$ denotes the entropy density.

The BAU can survive after the EWPT if the $B$-changing process is sufficiently suppressed. The rough criterion of the $B$ preservation is given $v_c / T_C > 1$, where $T_C$ denotes a critical temperature and $v_c$ is the Higgs VEV at $T_C$. In our numerical analysis, we calculate $v_c / T_C$ using a finite-temperature one-loop effective potential with thermal resummation.

**Experimental constraints.** — Before showing the numerical results, we first outline the experimental constraints relevant to our study. The $\rho_{bb}$ coupling is constrained by several existing measurements such as Higgs signal strengths, branching ratio of $B \to X_s \gamma$ ($B(B \to X_s \gamma)$), EDM and the asymmetry of the CP asymmetry between charged and neutral $B(B \to X_s \gamma)$ decay ($\Delta A_{CP}$).

First we consider constraints from Higgs signal strength measurements. The presence of non-zero $c_{\beta-\alpha}$ and $\rho_{bb}$ modify the $h$ boson couplings $g_{hf}$, as can be seen from Eq. (2). As a result $\rho_{bb}$ receives stringent constraint if $c_{\beta-\alpha}$ is non-zero. For our analysis we incorporate the Run-2 combined measurements of Higgs boson couplings by CMS [19]. The result is based on $\sqrt{s} = 13$ TeV $pp$ collision with $35.9$ fb$^{-1}$ (2016 data) and summarizes different signal strengths $\mu_i^f$ for a specific decay mode $i \to h \to f$. The signal strength $\mu_i^f$ is defined as
\[
\mu_i^f = \frac{\sigma_i B^f}{(\sigma_i)_{\text{SM}} (B^f)_{\text{SM}}} = \mu_i \mu_i^f,
\] (8)

where $\sigma_i$ is the production cross section for $i \to h$ and $B^f$ is the branching ratio for $h \to f$, with $i = ggF$, $VBF$, $Zh$, $Wh$, $ttH$ and $f = \gamma\gamma$, $ZZ$, $WW$, $\tau\tau$, $bb$, $\mu\mu$. We follow Refs. [8,20,22] for the expressions of different $\mu_i^f$. In particular, we take two production modes, gluon fusion ($ggF$) and vector boson fusion ($VBF$) in our analysis. We find that for the $ggF$ category, the sensitive decay modes are $\mu_{\gamma\gamma}^f$, $\mu_{ZZ}^f$, $\mu_{WW}^f$ and $\mu_{\tau\tau}^f$, while $\mu_{VBF}^f$, $\mu_{VBF}^{ggF}$ and $\mu_{VBF}^{VBF}$ for $VBF$; these can be found from Table 3 of Ref. [19]. Additionally, we also consider the recent observation of $h \to bb$ in $Vh$ production by ATLAS [5] and CMS [9]. In order to determine the constraint on $\rho_{bb}$, we combine all these measurements and refer them together as "Higgs signal
strength measurements”.

We now turn our attention to $B(B \to X_{s}\gamma)$ constraint. $B(B \to X_{s}\gamma)$ receives contribution from charged Higgs and top quark loop, which modifies the leading order (LO) Wilson coefficient $C_{7,8}^{(0)}$ at the matching scale $\mu$. At the matching scale $\mu = m_{W}$ the LO Wilson coefficients are defined as

$$
C_{7,8}^{(0)}(m_{W}) = F_{7,8}^{(1)}(x_{t}) + \delta C_{7,8}^{(0)}(\mu_{W}),
$$

where $x_{t} = (m_{t}(m_{W})/m_{W})^{2}$, $m_{t}(m_{W})$ MS running mass of top at $m_{W}$, and $F_{7,8}^{(1)}(x_{t})$ can be found in the Ref. [24] (see also Ref. [23]). The second term in Eq. [9] arise from the charged Higgs contribution, which is, at LO, expressed as [25]

$$
\delta C_{7,8}^{(0)}(m_{W}) \simeq \frac{\rho_{H}^{2}}{3A_{t}} F_{7,8}^{(1)}(y_{H^{+}}) - \frac{\rho_{H}\rho_{bb}}{\lambda_{s}} F_{7,8}^{(2)}(y_{H^{+}}),
$$

with $y_{H^{+}} = (m_{t}(m_{W})/m_{H^{+}})^{2}$, while the expression for $F_{7,8}^{(2)}(y_{H^{+}})$ are given in Ref. [23]. In order to find constraint on $\rho_{bb}$, we follow the prescription of Ref. [26] and define

$$
R_{\text{exp}} = \frac{B(B \to X_{s}\gamma)_{\text{exp}}}{B(B \to X_{s}\gamma)_{\text{SM}}},
$$

The current world average of $B(B \to X_{s}\gamma)_{\text{exp}}$ extrapolated to photon energy cut $E_{0} = 1.6$ GeV is $(3.32 \pm 0.15) \times 10^{-4}$ [27], while the next-to-next-to LO prediction in SM for the same photon energy cut is $B(B \to X_{s}\gamma)_{\text{SM}} = (3.36 \pm 0.23) \times 10^{-4}$ [28]. We then demand $R_{\text{theory}} = B(B \to X_{s}\gamma)_{\text{G2HDM}}/B(B \to X_{s}\gamma)_{\text{SM}}$ based on our LO calculation. We take the matching scale and low-energy scale as $m_{W}$ and $m_{b}(m_{b})$ respectively, and demand $R_{\text{theory}}$ does not exceed 2$\sigma$ error of $R_{\text{exp}}$.

Recently, ACME Collaboration put a new constraint on photon EDM $|d_{e}| < 1.1 \times 10^{-29}$ e cm [29], which is the most sensitive constraint on $\text{Im}(\rho_{bb})$. As widely studied, the two-loop Barr-Zee diagrams [30] are the leading contributions to $d_{e}$ in the 2HDM [31]. It is found that our $\rho_{bb}$-EWBG scenario would be virtually excluded by the new $d_{e}$ bound unless the cancellation mechanism or the alignment limit are invoked [32]. In this case, we assume the former, where a non-zero $\rho_{ee}$ cancels out the contributions from $\rho_{bb}$.

The direct CP asymmetry $A_{CP}$ [32] of $B \to X_{s}\gamma$ also offers a very sensitive probe for $\text{Im}(\rho_{bb})$. However, it has been proposed [33] that $A_{CP}$, i.e. the asymmetry of the CP asymmetry for the charged and neutral $B \to X_{s}\gamma$ decay is even more powerful for probing CP violating effects. $A_{CP}$ is defined as [33]

$$
\Delta A_{CP} = A_{B \to X_{s}\gamma} - A_{B^{0} \to X_{s}\gamma} \approx 4\pi^{2}\alpha_{s} m_{b} \text{Im}(C_{8}/C_{7}),
$$

where $\tilde{\Lambda}_{78}$ is a hadronic parameter, $\alpha_{s}$ is the strong coupling constant at $\overline{m}_{b}(m_{b})$. Recently, Belle experiment reported $\Delta A_{CP} = (3.0 \pm 2.0 \pm 0.7)$% [34], where the first uncertainty is statistical and the second one is systematic. In order to find the excluded region for $\rho_{bb}$, we utilize Eq. (12), and allow 2$\sigma$ error on the measured value of $\Delta A_{CP}$. In finding the constraint, we have utilized the LO Wilson coefficients as in Eq. [9] as first approximation. The hadronic parameter $\tilde{\Lambda}_{78}$ is expected to be $\sim \Lambda_{QCD}$, and estimated to be in the range of 17 MeV $< \tilde{\Lambda}_{78} < 190$ MeV [33]. In our analysis we take the average value of $\tilde{\Lambda}_{78} = 89$ MeV as a reference value. We remark that this constraint heavily depends on the value of $\tilde{\Lambda}_{78}$ and becomes weaker for the smaller values of $\tilde{\Lambda}_{78}$.

Results. — For illustration we set $c_{\beta-\alpha} = 0.1$ and assume that $m_{H} = m_{A} = m_{H^{\pm}} = 600$ GeV, however the impact of other choices will be discussed later part of this letter. Furthermore, we take $\tan \beta = 1$ and $M = 400$ GeV, where $M$ is a mixing mass parameter of the two Higgs doublet in a generic basis. With this choice, we have $T_{C} = 112.4$ and $\nu(T_{C}) = 191.3$ GeV. For the input parameters for the $Y_{B}$ calculation, we take the parameters employed in Refs. [12, 13]. One comment we should make here is that $Y_{B}$ is linearly proportional to a variation of $\beta$ during the EWPT ($\Delta \beta$). Since its numerical value is unknown in the current model, we take $|\Delta \beta| = 0.015$ as a reference value.

In Fig. 1 the BAU-viable regions are shown with the current experimental constraints discussed above. We take $\rho_{H} = \lambda_{t}$ (left panel) and 0.1 (right panel), respectively. The regions of $|\text{Im}(\rho_{bb})| \geq 0.058$ give $Y_{B}/Y_{b}^{\text{obs}} > 1$, which are indicated by the blue solid contours. Note that the regions of $\text{Re}(\rho_{bb}) \geq 0$ and $\text{Im}(\rho_{bb}) \geq 0$ correspond to $\Delta \beta \geq 0$, respectively. The shaded regions in gray (purple) are ruled out by the Higgs signal strength measurements ($B(B \to X_{s}\gamma)$) at the 2$\sigma$ level, while the 2$\sigma$ exclusion limits of $\Delta A_{CP}$ are indicated by the red dash-dotted curves. In our analysis, we symmetrized the errors in the Higgs signal strength measurements for simplicity. One can see that the EWBG-viable regions are rather limited by these current experimental constraints. For $\rho_{H} = \lambda_{t}$, the regions conforming $\text{Im}(\rho_{bb}) \geq 0.058$ are excluded by $\Delta A_{CP}$ measurement (Fig. [1] left)), however, negative $\text{Im}(\rho_{bb})$ can still sustain $Y_{B}/Y_{b}^{\text{obs}} > 1$, but $|\text{Im}(\rho_{bb})|$ cannot be $\geq 0.1$. If $\rho_{H} = 0.1$, on the other hand, $|\text{Im}(\rho_{bb})|$ can reach around 0.2 and the EWBG-viable regions are expanded (Fig. [1] right). Note that $\Delta A_{CP}$ does not give any useful bounds in this case. We note in passing that if we do not assume the cancellation mechanism for $d_{e}$, the current bound would exclude the

\footnote{We are grateful to Akimasa Ishikawa for pointing out the changed central value and errors of $\Delta A_{CP}$ in the latest version of Ref. [34].}
regions of $|\text{Im}(\rho_{bb})| \gtrsim 0.06$, excluding the most EWBG-viable regions. We further remark that the current constraints in Fig. 1 heavily depend on $c_{\beta-\alpha}$, $\rho_{tt}$ and $m_{H^\pm}$. For example, in the alignment limit, the constraint from Higgs signal strength measurements i.e. gray shaded region would vanish. This is clear from the expression of $y_{ij}^f$ (see Eq. (2)), where the terms proportional to $\rho_{ij}$ are modulated by $c_{\beta-\alpha}$. Moreover, $B(B \to X_s\gamma)$ and $\Delta A_{\text{CP}}$ do not depend on $c_{\beta-\alpha}$, the constraints from them will remain even for $c_{\beta-\alpha} = 0$. However, these two constraints vanish if $\rho_{tt} = 0$ and/or $m_{H^\pm}$ becomes too heavy. In such special case, i.e. when $\rho_{tt} = 0$ and $c_{\beta-\alpha} = 0$, constraint on $|\text{Im}(\rho_{bb})|$ could be milder.

Now we discuss future prospects. The future measurements of these observables from Belle-II, full HL-LHC dataset (3000 fb$^{-1}$) will also provide very sensitive probe. It will be nonetheless interesting to find out the parameter space for $\rho_{bb}$ assuming future projections of these constraints. In order to find the constraints from future projections, we adopt two different scenarios. In the first scenario (Scenario-1), we assume the central values of the future measurements for all these constraints are same as in SM, while in the second scenario (Scenario-2) the central values are assumed to remain same as in the current measurements. The parameter space for $\rho_{bb}$ with the projections in Scenario-1 are summarized in Fig. 2, while the projections with Scenario-2 are shown in Fig. 3.

Let us discuss the impact of these future projections in detail. The full HL-LHC dataset is expected to measure $\mu_{g\gamma}^{\gamma\gamma}$, $\mu_{gg}^{ZZ}$, $\mu_{gg}^{WW}$, $\mu_{VBF}^{\gamma\gamma}$ and $\mu_{VBF}^{WW}$ very precisely, leading to very stringent constraint on $\rho_{bb}$. For example, with an integrated luminosity of 3000 fb$^{-1}$, the projected relative uncertainties by ATLAS and CMS are $\sim 5\%$ for $\mu_{gg}^{\gamma\gamma}$, $\mu_{gg}^{ZZ}$, $\mu_{gg}^{WW}$, and $\sim 10\%$ for $\mu_{VBF}^{\gamma\gamma}$, $\mu_{VBF}^{WW}$, respectively. We find the $2\sigma$ orange dot-dashed contours in Figs. 2 and 3 assuming Scenario-1 and 2, respectively. In addition to these limits, ILC could measure the $bb$ coupling at 1.1% (1$\sigma$) accuracy (relative to its SM value) in the 250 GeV program (2 ab$^{-1}$ data). We show this projected limit (2$\sigma$ exclusion) by the black dotted contours in Figs. 2 and 3.

Belle-II will also provide stringent constraint. The projected $2\sigma$ exclusion form $B(B \to X_s\gamma)$ are shown in Figs. 2 and 3 by green solid contours, while projection for $\Delta A_{\text{CP}}$ is shown by red dashed contours. In finding these contours, we adopted similar strategy as in the HL-LHC projection of the Higgs signal strength measurements and take two different scenarios for central values. For $B(B \to X_s\gamma)$, we utilize the 3.2% relative uncertainty for Belle-II with 50 ab$^{-1}$ data [38], in our analysis. This projected uncertainty is for the leptonic-tag $B(B \to X_s\gamma)$ and is smaller than hadronic-tag or the combination of the both. On the other hand, projected Belle-II (50 ab$^{-1}$) absolute uncertainty for $\Delta A_{\text{CP}}$ is 0.3% [35].

It is clear that the future measurements offer stern test for EWBG via bottom transport. For example, in Scenario-1, if $\rho_{tt} = \lambda_t$ (left panel of Fig. 2), constraints from HL-LHC (orange dot-dashed contours) and ILC-250 (black dotted contours) mutually exclude the regions required for $Y_B/Y_B^{\text{obs}}>1$. Additionally, in this scenario, red dashed contours from future $\Delta A_{\text{CP}}$ measurement lie below $|\text{Im}(\rho_{bb})| = 0.058$. However, if $\rho_{tt} \sim 0.1$, there exist regions where $|\text{Im}(\rho_{bb})| \gtrsim 0.058$. Situation becomes completely different for Scenario-2. In this scenario, HL-LHC, ILC-250 and $\Delta A_{\text{CP}}$ mutually exclude all of the regions that can support $Y_B/Y_B^{\text{obs}}>1$ both for $\rho_{tt} \sim \lambda_t$.
FIG. 2. Same as in Fig. 1 but future experimental sensitivities of HL-LHC (orange dash-dotted curves), ILC (black dotted curves) and Belle-II (green solid curve for $B(B → X_s \gamma)$ and red dotted curves for $\Delta A_{CP}$) are also overlaid. The central values for the future projection is assumed to be the same as in SM (Scenario-1).

FIG. 3. Same as in Fig. 2 but the central values for the future projection is assumed to be the same as in the current measurements (Scenario-2).

$\rho_{tt} \sim 0.1$. This can be seen easily from Fig. 3. However, we stress again that the excluded regions from future projections depend on the assumptions made on the parameters while generating Figs. 2 and 3. As discussed earlier, the constraints from HL-LHC Higgs signal strength measurements and ILC-250 vanish if $c_{\beta-\alpha} = 0$.

Besides, the constraints from $B(B → X_s \gamma)$ and $\Delta A_{CP}$ would also vanish if $\rho_{tt} = 0$ and $m_{H^\pm}$ becomes heavy. In such scenarios, there exist finite parameter space for $|\text{Im}(\rho_{bb})|$ to sustain $Y_B/Y_{B^{\text{obs}}} > 1$.

Discussions and conclusion.— The interpretation of the EWBG-viable regions need some caution. As discussed in Ref. [12], the BAU is subject to significant theoretical uncertainties (see also Ref. [4]). For example, we make use of the VEV insertion approximation that may lead to the overestimated BAU. Likewise, as mentioned above, ignorance of the CP-conserving term induced by the $(Y_{1,2})_{bs}$ could also yield the overestimated BAU. In addition to those computational issues, impreciseness of

2 Note that the other orange contour lies in the right hand side of the existing orange contour beyond the range shown in Fig. 3 [right]. Besides, the red dashed contours for the future $\Delta A_{CP}$ measurement lie far below $\text{Im}(\rho_{bb}) = 0$. Hence, HL-LHC, ILC-250 and future $\Delta A_{CP}$ mutually exclude the entire BAU-viable regions in Fig. 3 [right].
the input parameters are also the source of the theoretical uncertainties. In particular, if $\Delta \beta$ is found to be one-order magnitude smaller than the value we take here, the BAU would get smaller by one-order magnitude, eliminating the EWBG-viable regions. Therefore, improvement of the BAU calculation is crucially important for the test of the scenario. If $\rho_{bb}$ turns out to be deficient to drive the sufficient BAU in more refined calculation, the $\rho_{tt}/\rho_{bb}$-EWBG discussed in Ref. [13] would be the unique mechanism for baryogenesis in the G2HDM by virtue of their wider viable parameter space. Nonetheless, the definitive conclusion cannot be made until the refined BAU calculation is available.

The constraints from $B(B \to X_s \gamma)$ and $\Delta A_{CP}$ measurements can probe significant portion of the EWBG-viable parameter space. The $\Delta A_{CP}$ measurement with full Belle-II 50 ab$^{-1}$ dataset can probe $|\text{Im}(\rho_{bb})| \gtrsim 0.1$ in Scenario-1 or even can rule out entire BAU-viable region completely in Scenario-2, even for $\rho_{tt} \sim 0.1$. Although our assumptions on the central values for future measurements (i.e. Scenario-1 and Scenario-2) are very indicative, however, we stress that the program should be revisited after the actual future measurements. The recent measurements of $A_{CP}$ and isospin violating asymmetry ($\Delta \alpha_1$) of $B \to K^* \gamma$ decay by Belle [38] may also provide complementary probe for $\text{Im}(\rho_{bb})$, although the theoretical predictions of these observables in general suffer from sizable uncertainties [40]. The future updates from HFLAV for the global average of $B(B \to X_s \gamma)$ would also play a major role in constraining BAU-viable region, if $\rho_{tt}$ is not vanishingly small. In this regard, we remark that the $B_q \to \bar{B}_q (q = d, s)$ mixing [25] and the recent discovery of $t\bar{t}h$ [41] would provide independent probes [22] for $\rho_{tt}$.

The Higgs signal strength measurements at HL-LHC would be complementary in probing $\rho_{bb}$ regardless of the value of $\rho_{tt}$, however $c_{\beta-\alpha}$ should not be very small. It should be noted that $|\text{Im}(\rho_{bb})|$ cannot be too large for non-zero $c_{\beta-\alpha}$. The current limit on the boson total width $\Gamma_h < 0.013$ GeV (95% CL) [4] sets upper limit on $|\rho_{bb}|$ if $c_{\beta-\alpha} \neq 0$. Utilizing this limit we find that for $\text{Re}(\rho_{bb}) = 0$ and $c_{\beta-\alpha} = 0.1$, $|\text{Im}(\rho_{bb})| \lesssim 0.36$ at 95% CL. In determining the upper limit on $|\text{Im}(\rho_{bb})|$ we used LO decay width of $h$ for simplicity. We also remark, like Run 1 combination [43], a Run 2 combined fit of ATLAS and CMS Higgs signal strengths would be more indicative. Further, our study illustrates, ILC 250 GeV run might probe $\rho_{bb}$ better than HL-LHC. It is not surprising that ILC, even its 250 GeV program, presents better probe for NP in bottom Yukawa than HL-LHC.

Also, LHC might offer direct detection of $\rho_{bb}$ driven EWBG. A non-zero $\text{Im}(\rho_{bb})$ induces $gg \to \bar{b}bA(H) \to \bar{b}bZH(A)$ process if $m_A > m_H + m_Z$ ($m_H > m_A + m_Z$). This process provides unique probe for the EWBG, even for $c_{\beta-\alpha} = 0$ and/or $\rho_{tt} = 0$. Notwithstanding, if $c_{\beta-\alpha}$ is not too small direct detection program can cover $gg \to \bar{b}bA \to \bar{b}bZh$. A discovery would be intriguing. Furthermore, for moderate values of $\rho_{tt}$, $gg \to t\bar{t}A/t\bar{t}H \to t\bar{t}b\bar{b}$ with leptonic decays of at least one top and $A/H \to b\bar{b}$ could be interesting. These would be studied elsewhere.

In conclusion, motivated by recent discovery of Higgs boson decay to bottom quarks, we have analyzed the possibility of EWBG by extra bottom Yukawa $\rho_{bb}$ in the G2HDM. After satisfying all existing constraints, we found that indeed $\rho_{bb}$ can generate successful BAU, however, $|\text{Im}(\rho_{bb})|$ required to be $\gtrsim 0.058$. For a wide range of parameter space, future measurements from Belle-II, Higgs signal strengths at HL-LHC and ILC will provide exquisite probes for such scenario. If the additional scalar and pseudoscalar are in the sub-TeV range, the program can also be covered by direct searches at LHC.

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