Probing an additional bottom Yukawa coupling via $bg \rightarrow bA \rightarrow bZH$ signature

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The recent discovery of the bottom quark Yukawa coupling (hbb) of the 125 GeV scalar motivates one to search for extra bottom Yukawa coupling that may exist in nature. The two Higgs doublet model without a discrete Z_2 symmetry allows the possibility of additional bottom Yukawa coupling ρ_{bb} . We show that ρ_{bb} can be searched directly at the LHC via the $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ processes, where A and H are the CP -odd and CP -even scalars, respectively. We find that the $bg \rightarrow bA \rightarrow bZH$ process could be discovered with $\sim 300 \text{ fb}^{-1}$ integrated luminosity if $m_A \sim 300 \text{ GeV}$, while the latter process may emerge in the high luminosity LHC (HL-LHC) run. A discovery might touch upon the parameter space required for the electroweak baryogenesis.

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I. INTRODUCTION

The discovery of the 125 GeV scalar boson h [1] and its properties corroborate that the Standard Model (SM) is the correct effective theory at around the weak scale. Even though no clear evidence of new physics (NP) has been found, the Run-2 era of LHC witnessed one of the most intriguing *discoveries*; that is the bottom quark Yukawa coupling hbb [2,3]. The observation was announced simultaneously by the ATLAS and CMS collaborations. Both the experiments performed searches mainly in the process where h is produced in association with a Z or W boson, followed by the $h \rightarrow b\bar{b}$ decay. When combined with the results from the other searches of Run-1 and Run-2, the observed signal strengths relative to the SM expectation were reported to be $1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$ at ATLAS [2], while $1.04 \pm 0.14(\text{stat.}) \pm 0.14(\text{syst.})$ at CMS [3]. Although they are consistent with the SM prediction, both the measurements are quite accommodating for NP contribution. In the backdrop of these recent observations, it is timely to ask whether there exists any additional bottom Yukawa coupling in nature. In this article we explore the possibility of direct detection and identification of such an extra bottom Yukawa coupling at the LHC.

The context is the two Higgs doublet model (2HDM). In the absence of discrete Z_2 symmetry, which was invoked to ensure Natural Flavor Conservation (NFC) [4] to forbid flavor changing neutral Higgs couplings, both the doublets couple to

up- and down-type quarks. After the diagonalization of the fermion mass matrices two independent Yukawa matrices $\lambda_{ij}^F = (\sqrt{2}m_i^F/v)\delta_{ij}$ (with $v \simeq 246 \text{ GeV}$) and ρ_{ij}^F emerge, where F denotes up- and down-type quarks and leptons. The Yukawa matrices λ_{ij}^F are real and diagonal, whereas ρ_{ij}^F are in general nondiagonal and complex. Our focus of interest is the extra bottom Yukawa coupling ρ_{bb} . In this paper, we analyze the prospect of its direct detection at the LHC via the $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ processes (charge conjugate processes are implied) with b -tagging.

We investigate the discovery potential of ρ_{bb} via $pp \rightarrow bA + X \rightarrow bZH + X$ (X is inclusive activity) with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) and $H \rightarrow b\bar{b}$ (denoted as bZH process) at the 14 TeV LHC. In finding the discovery potential we assumed the extra top Yukawa coupling ρ_{tt} to be relatively small to avoid the direct search constraints from $gg \rightarrow A/H$. A sizable ρ_{bb} would also induce $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ which provides an additional probe for ρ_{bb} . We study this process via $pp \rightarrow b\bar{b}A + X \rightarrow b\bar{b}ZH + X$ followed by $Z \rightarrow \ell^+\ell^-$ and $H \rightarrow b\bar{b}$ (denoted as the $bbZH$ process). Recently, ρ_{bb} received additional significance as it can drive electroweak baryogenesis (EWBG) rather efficiently [5]. It was shown that $\mathcal{O}(0.1)$ imaginary ρ_{bb} [$\text{Im}(\rho_{bb})$] can successfully generate the observed Baryon Asymmetry of the Universe [5]. Although the information of the phase could not be captured in the bZH and $bbZH$ processes, however, a discovery might indicate ρ_{bb} driven EWBG.

The paper is organized as follows. We outlined the formalism in Sec. II, followed by discussion on the relevant constraints and available parameter space in Sec. III. Section IV is dedicated to the collider signatures of the bZH and $bbZH$ processes, respectively. We summarized our results with some discussions in Sec. V.

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II. FORMALISM

The most general CP -conserving two Higgs doublet potential is given in the general basis as [6,7]:

$$V(\Phi, \Phi') = m_{11}^2 |\Phi|^2 + m_{22}^2 |\Phi'|^2 - (m_{12}^2 \Phi^\dagger \Phi' + \text{H.c.}) \\ + \frac{\lambda_1}{2} |\Phi|^4 + \frac{\lambda_2}{2} |\Phi'|^4 + \lambda_3 |\Phi|^2 |\Phi'|^2 + \lambda_4 |\Phi^\dagger \Phi'|^2 \\ + \left[\frac{\lambda_5}{2} (\Phi^\dagger \Phi')^2 + (\lambda_6 |\Phi|^2 + \lambda_7 |\Phi'|^2) \Phi^\dagger \Phi' + \text{H.c.} \right], \quad (1)$$

where the parameters $m_{11}^2, m_{12}^2, m_{22}^2$ and λ_i s are all real. The vacuum expectation values of the doublets Φ and Φ' are given as $\langle \Phi \rangle = (0, v_1/\sqrt{2})^T$ and $\langle \Phi' \rangle = (0, v_2/\sqrt{2})^T$, respectively, such that $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$ and $\tan \beta = v_2/v_1$. With no Z_2 symmetry in place to distinguish between Φ and Φ' , $\tan \beta$ becomes unphysical. We move to the Higgs basis through basis rotation such that $\langle \Phi \rangle = (0, v/\sqrt{2})^T$ and $\langle \Phi' \rangle = (0, 0)^T$, where the parameters in the Higgs basis can be identified by the replacements $m_{ij}^2 \rightarrow \mu_{ij}^2$ and $\lambda_i \rightarrow \eta_i$.¹ The scalar potential minimization conditions lead to $\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2$ and $\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$, with $\mu_{22}^2 > 0$. The mixing angle $\beta - \alpha$ between the CP -even bosons h and H satisfies the relations [7]:

$$c_{\beta-\alpha}^2 = \frac{\eta_1 v^2 - m_h^2}{m_H^2 - m_h^2}, \quad \sin 2(\beta - \alpha) = -\frac{2\eta_6 v^2}{m_H^2 - m_h^2}, \quad (2)$$

with shorthand $\cos(\beta - \alpha) = c_{\beta-\alpha}$ and $\sin(\beta - \alpha) = s_{\beta-\alpha}$. In the alignment limit $c_{\beta-\alpha} = 0$, which leads to $\eta_1 v^2 = m_h^2$. The masses of the charged scalar $m_{H^\pm}$ and the neutral scalars A, h and H can be expressed as:

$$m_{H^\pm}^2 = \frac{1}{2}\eta_3 v^2 + \mu_{22}^2, \quad (3)$$

$$m_A^2 = \frac{1}{2}(\eta_3 + \eta_4 - \eta_5)v^2 + \mu_{22}^2, \quad (4)$$

$$m_{h,H}^2 = \frac{1}{2}[m_A^2 + (\eta_1 + \eta_5)v^2 \mp \sqrt{(m_A^2 + (\eta_5 - \eta_1)v^2)^2 + 4\eta_6^2 v^4}]. \quad (5)$$

The CP -even scalars h, H , CP -odd scalar A , and the charged scalar $H^\pm$ couple to the fermions by [6]

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} \sum_{F=U,D,L} \bar{F}_{iL} [(\lambda_{ij}^F s_{\beta-\alpha} + \rho_{ij}^F c_{\beta-\alpha}) h \\ + (\lambda_{ij}^F c_{\beta-\alpha} - \rho_{ij}^F s_{\beta-\alpha}) H - i \text{sgn}(Q_F) \rho_{ij}^F A] F_{jR} \\ - \bar{U}_i [(V \rho^D)_{ij} P_R - (\rho^{U\dagger V})_{ij} P_L] D_j H^+ \\ - \bar{\nu}_i \rho_{ij}^L P_R L_j H^+ + \text{H.c.}, \quad (6)$$

¹The relations between the parameters in the two bases can be found out in Ref. [6].

where $i, j = 1, 2, 3$ are the generation indices that are summed over, $P_{L,R} = \frac{1 \mp \gamma_5}{2}$, V is the Cabibbo-Kobayashi-Maskawa matrix, λ_{ij}^F are real and diagonal, and ρ_{ij}^F are complex nondiagonal 3×3 matrices.

Our process of interest is $bg \rightarrow bA \rightarrow bZH$, where the production process is initiated by ρ_{bb} , and the decay $A \rightarrow ZH$ is conformed by

$$\frac{g_2}{2c_W} Z_\mu (c_{\beta-\alpha} (h \partial^\mu A - \partial^\mu h \cdot A) - s_{\beta-\alpha} (H \partial^\mu A - \partial^\mu H \cdot A)), \quad (7)$$

with g_2 is the $SU(2)_L$ gauge coupling and c_W is Weinberg's angle. A search can be performed in $bg \rightarrow bA \rightarrow b\bar{b}b$ mode, but the process suffers from the overwhelming QCD multi-jets backgrounds. For $m_{H^\pm} + m_W < m_A$ (m_W is the W boson mass) $bg \rightarrow bA \rightarrow bH^+W^-$ is possible, but if searched in $H^+ \rightarrow t\bar{b}$ (induced by ρ_{bb}) with $t \rightarrow b\ell^+\nu_\ell$ one loses the mass reconstruction capability of A , and, hence, controlling of the $t\bar{t}$ background. In general, backgrounds are even higher if searched in the hadronically decaying t mode. Notice that the ρ_{tt} coupling, which also can induce $H^+ \rightarrow t\bar{b}$ decay, obfuscates the role of ρ_{bb} . We remark that the $bg \rightarrow bA \rightarrow bZH$ process, which can only be induced via ρ_{bb} , offers a unique probe for the ρ_{bb} coupling.²

The process $bg \rightarrow bA \rightarrow bZh$ is indeed possible, however suppressed by the mixing angle $c_{\beta-\alpha}$. It should be clear from Eq. (7) that the decay $A \rightarrow ZH$ is proportional to $s_{\beta-\alpha}$. As a result, a discovery of the $bg \rightarrow bA \rightarrow bZH$ process is possible even in the approximate alignment (i.e., for small $c_{\beta-\alpha}$), which is observed at the LHC [9]. Further, ρ_{bb} can initiate $b\bar{b} \rightarrow A \rightarrow ZH$ and loop induced $gg \rightarrow A \rightarrow ZH$ [10]; however, the coupling information is lost in the pp collision. Besides, as ρ_{tt} can also get involved in the loop, the role of ρ_{bb} is obscured in $gg \rightarrow A \rightarrow ZH$. One can also have $gg \rightarrow A \rightarrow Zh$ (see e.g., Refs. [11,12] and references therein) and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}Zh$ (see e.g., Refs. [11–14]); however, again both processes are suppressed by the mixing angle $c_{\beta-\alpha}$.

III. ALLOWED PARAMETER SPACE

Having already set up the formalism we now focus on the relevant constraints and the available parameter space for our study. We first scrutinize the constraints on ρ_{bb} . For simplicity, we set all $\rho_{ij} = 0$ except for ρ_{bb} and ρ_{tt} in this section. We assume small ρ_{tt} in order to avoid direct search limits from $gg \rightarrow A/H$. In particular we choose $\rho_{tt} = 0.1$ for illustration. The most stringent constraints arise from the Higgs signal strength measurements, the branching

²In principle $qg \rightarrow bA \rightarrow bZH$ can replicate the same final state as in the $bg \rightarrow bA \rightarrow bZH$ process in the pp collision if ρ_{bq} or ρ_{qb} ($q = d$ and s) are sizable; however, they receive severe constraints from the B_q mixing [8].

ratio of $B \rightarrow X_s \gamma$ [$\mathcal{B}(B \rightarrow X_s \gamma)$], the asymmetry of the CP asymmetry between the charged and neutral $B \rightarrow X_s \gamma$ decays ($\Delta \mathcal{A}_{CP}$), electron electric dipole moment (EDM) measurement and the upper limit on the h decay width.

The couplings ρ_{ij} modify the h boson couplings to the fermions for moderate values of $c_{\beta-\alpha}$, as can be seen from Eq. (6). Therefore, ρ_{bb} receives meaningful constraint from the Higgs boson coupling measurements, unless $c_{\beta-\alpha}$ is vanishingly small. We utilized Run-2 ATLAS [15] and CMS [16] measurements which are based on 80 fb⁻¹ and 35.9 fb⁻¹ data, respectively. The results summarize the values of different signal strengths μ_i^f and corresponding errors to a particular decay mode $i \rightarrow h \rightarrow f$. Following the Refs. [15,16], we define a signal strength μ_i^f as:

$$\mu_i^f = \frac{\sigma_i \mathcal{B}^f}{(\sigma_i)_{SM} (\mathcal{B}^f)_{SM}} = \mu_i \mu^f, \quad (8)$$

where σ_i is denoted as the production cross section of $i \rightarrow h$ and $\mathcal{B}^f$ is the branching ratio for $h \rightarrow f$. The production modes considered are $i = ggF$ (gluon-fusion), VBF (vector-boson-fusion), Zh , Wh , tth , and the branching ratios are $f = \gamma\gamma, ZZ, WW, \tau\tau, bb, \mu\mu$. For simplicity we utilized the LO μ_i^f in our analysis and followed Refs. [17–20] for their explicit expressions. In particular, we focused on two different production modes, the ggF and the VBF , in our analysis. We find that for the ggF category, the most relevant signal strengths for our analysis are μ_{ggF}^{ZZ} , μ_{ggF}^{WW} , $\mu_{ggF}^{\gamma\gamma}$ and $\mu_{ggF}^{\tau\tau}$, while in the VBF category μ_{VBF}^{WW} , $\mu_{VBF}^{\gamma\gamma}$ and $\mu_{VBF}^{\tau\tau}$. In addition, we further considered the recent observation of the $h \rightarrow b\bar{b}$ in the Vh production by ATLAS [2] and CMS [3]. We referred to them together as ‘‘Higgs signal strength measurements’’. The parameter space excluded by the Higgs signal strength measurements are shown by the red (ATLAS) and green (CMS) shaded regions in Fig. 1 for

$m_{H^\pm} = 350$ GeV (left) and 450 GeV (right). In generating Fig. 1, we allowed 2σ errors on each signal strength measurements and assumed $c_{\beta-\alpha} = 0.5$.

The branching ratio measurement of $B \rightarrow X_s \gamma$ provides another stringent constraint on ρ_{bb} . The coupling ρ_{bb} enters in the $\mathcal{B}(B \rightarrow X_s \gamma)$ via charged Higgs and top quark loop. At the matching scale $\mu = m_W$, the modified leading order (LO) Wilson coefficients $C_{7,8}^{(0)}$ are defined as:

$$C_{7,8}^{(0)}(m_W) = F_{7,8}^{(1)}(x_t) + \delta C_{7,8}^{(0)}(\mu_W), \quad (9)$$

with, $\bar{m}_t(m_W)$ is the $\overline{MS}$ running mass of top quark at m_W , $x_t = (\bar{m}_t(m_W)/m_W)^2$, while the expression for $F_{7,8}^{(1)}(x)$ can be found out in the Refs. [21,22]. The second term in Eq. (9), which originates from the charged Higgs contribution, expressed at LO as [23]:

$$\delta C_{7,8}^{(0)}(m_W) \simeq \frac{|\rho_{tt}|^2}{3\lambda_t^2} F_{7,8}^{(1)}(y_{H^+}) - \frac{\rho_{tt}\rho_{bb}}{\lambda_t\lambda_b} F_{7,8}^{(2)}(y_{H^+}), \quad (10)$$

where $y_{H^+} = (\bar{m}_t(m_W)/m_{H^+})^2$. Here we have followed Ref. [21] for the expression of $F_{7,8}^{(2)}(y_{H^+})$. The current world average of $\mathcal{B}(B \rightarrow X_s \gamma)_{\text{exp}}$, which is extrapolated to the photon energy cut $E_0 = 1.6$ GeV is found to be $(3.32 \pm 0.15) \times 10^{-4}$ [24]. The SM prediction of $\mathcal{B}(B \rightarrow X_s \gamma)$ at next-to-next-to LO (NNLO) for the same photon energy cut is $(3.36 \pm 0.23) \times 10^{-4}$ [25]. In order to find the constraint on ρ_{bb} , we adopted the prescription of Ref. [26] and defined

$$R_{\text{exp}} = \frac{\mathcal{B}(B \rightarrow X_s \gamma)_{\text{exp}}}{\mathcal{B}(B \rightarrow X_s \gamma)_{SM}}. \quad (11)$$

Based on our LO calculation we further defined

FIG. 1. The constraints on ρ_{bb} from Higgs signal strength measurements of ATLAS (red shaded region), Higgs signal strength measurements of CMS (green shaded region), $\mathcal{B}(B \rightarrow X_s \gamma)$ (purple shaded region) and $\Delta \mathcal{A}_{CP}$ (red dotted line). The figures are generated with $c_{\beta-\alpha} = 0.05$ and $\rho_{tt} = 0.1$, for $m_{H^\pm} = 350$ GeV (left panel) and 450 GeV (right panel). See text for further details.

$$R_{\text{theory}} = \frac{\mathcal{B}(B \rightarrow X_s \gamma)_{\text{G2HDM}}}{\mathcal{B}(B \rightarrow X_s \gamma)_{\text{SM}}}, \quad (12)$$

and took m_W and $\bar{m}_b(m_b)$ as the matching scale and low-energy scales, respectively. We finally demanded R_{theory} should not exceed 2σ error of R_{exp} . The excluded regions are displayed by the purple shaded regions in Fig. 1.

The direct CP asymmetry $\mathcal{A}_{CP}$ [27] of $B \rightarrow X_s \gamma$ is sensitive to $\text{Im}(\rho_{bb})$. However, it has been proposed [28] that $\Delta\mathcal{A}_{CP}$, defined as the asymmetry of the CP asymmetry between the charged and neutral $B \rightarrow X_s \gamma$ decay, provides an even more powerful probe for the CP -violating effects. The $\Delta\mathcal{A}_{CP}$ is defined as [28]:

$$\Delta\mathcal{A}_{CP} = \mathcal{A}_{B^- \rightarrow X_s^- \gamma} - \mathcal{A}_{B^0 \rightarrow X_s^0 \gamma} \approx 4\pi^2 \alpha_s \frac{\tilde{\Lambda}_{78}}{m_b} \text{Im}\left(\frac{C_8}{C_7}\right), \quad (13)$$

where α_s is the strong coupling constant calculated at $\bar{m}_b(m_b)$ and $\tilde{\Lambda}_{78}$ is a hadronic parameter. It is expected that hadronic parameter $\tilde{\Lambda}_{78} \sim \Lambda_{\text{QCD}}$ and estimated to be in the range of $17 \text{ MeV} < \tilde{\Lambda}_{78} < 190 \text{ MeV}$ [28]. We take the average value of $\tilde{\Lambda}_{78} = 89 \text{ MeV}$ as a reference value for illustration. A recent Belle measurement reported $\Delta\mathcal{A}_{CP} = (+3.69 \pm 2.65 \pm 0.76)\%$ [29], where the first and second uncertainties are statistical and systematic, respectively. Utilizing Eq. (13) and allowing 2σ error on the Belle measurement of $\Delta\mathcal{A}_{CP}$ we find the red dotted lines (the regions above are excluded) in Fig. 1 for $m_{H^\pm} = 350 \text{ GeV}$ and 450 GeV . As a first approximation we have utilized the LO Wilson coefficients as in Eq. (9) in our analysis. We stress that the constraint heavily depends on the value of $\tilde{\Lambda}_{78}$ and becomes stronger for the larger values of $\tilde{\Lambda}_{78}$.

The most stringent constraint on $\text{Im}(\rho_{bb})$ comes from the electron EDM (d_e) measurements. The two-loop Barr-Zee diagrams [30], which are studied widely in the context of 2HDM [31], are the leading contributions to d_e . A recent result from ACME Collaboration finds $|d_e| < 1.1 \times 10^{-29} e \text{ cm}$ [32], which excludes even the nominal value (i.e., $|\text{Im}(\rho_{bb})| \lesssim 0.058$) required for ρ_{bb} driven EWBG [5]. The constraint could be relaxed by either turning on ρ_{ee} , or even could vanish in the alignment limit. In the former scenario nonzero ρ_{ee} and ρ_{bb} induce other Barr-Zee diagrams with the opposite sign, whereas in the latter case all the contributions to the EDM are simply decoupled. In particular, Ref. [5] finds for $\text{Re}(\rho_{ee}) = 0$, $\mathcal{O}(0.1) \text{ Im}(\rho_{bb})$ is still allowed if $0.06 \lesssim \text{Im}(\rho_{ee})/(\lambda_e \lambda_b) \lesssim 0.3$.

The current upper limit of the h boson decay width, which is extracted to be $< 0.013 \text{ GeV}$ (95% CL) [33], can provide some limit on $|\rho_{bb}|$ if $c_{\beta-\alpha} \neq 0$. Besides, the presence of the additional scalars modifies the Zbb vertex [34] at one-loop and in principle can constrain the ρ_{bb} coupling. However, we found these limits to be weaker and lie beyond the plotted ranges in Fig. 1.

Let us understand Fig. 1. In generating Fig. 1 we set $c_{\beta-\alpha} = 0.05$ and $\rho_{tt} = 0.1$ for illustration. The constraint from the Higgs signal strength measurements depends primarily on the value of $c_{\beta-\alpha}$ and vanishes in the alignment limit. The same is true for the constraint from the electron EDM, which also disappears in the alignment limit. On the other hand, bounds from $\mathcal{B}(B \rightarrow X_s \gamma)$ and $\Delta\mathcal{A}_{CP}$ alleviate for small ρ_{tt} , and/or for heavier $H^\pm$. It is clear from Fig. 1 that $|\rho_{bb}| \sim 0.1$ is still allowed; however, $c_{\beta-\alpha}$ and ρ_{tt} should not be very large. In the following we would assume the alignment limit and set $\rho_{tt} = 0$ for the sake of simplicity; however, their impacts will be discussed in the latter part of the paper. In passing we remark that there exist several direct searches at the LHC which can also constrain ρ_{bb} , even for $c_{\beta-\alpha} = 0$ and $\rho_{tt} = 0$. We defer a detailed discussion of them for the next section.

For the dynamical parameters in Eq. (1), one needs to satisfy the perturbativity, positivity and tree-level unitarity conditions for which we utilized 2HDMC [35]. The quartic couplings η_1, η_{3-6} can be expressed in terms of $m_h, m_A, m_{H^\pm}, m_{22}$ and the mixing angle $\beta - \alpha$, all normalized to v [7]:

$$\eta_1 = \frac{m_h^2 s_{\beta-\alpha}^2 + m_{H^\pm}^2 c_{\beta-\alpha}^2}{v^2}, \quad (14)$$

$$\eta_3 = \frac{2(m_{H^\pm}^2 - \mu_{22}^2)}{v^2}, \quad (15)$$

$$\eta_4 = \frac{m_h^2 c_{\beta-\alpha}^2 + m_{H^\pm}^2 s_{\beta-\alpha}^2 - 2m_{H^\pm}^2 + m_A^2}{v^2}, \quad (16)$$

$$\eta_5 = \frac{m_{H^\pm}^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - m_A^2}{v^2}, \quad (17)$$

$$\eta_6 = \frac{(m_h^2 - m_{H^\pm}^2) s_{\beta-\alpha} c_{\beta-\alpha}}{v^2}. \quad (18)$$

The mixing angle $\beta - \alpha$ and the quartic couplings η_2 and η_7 are not related to masses. Hence, we take $v, m_h, m_A, m_{H^\pm}, c_{\beta-\alpha}, \eta_2, \eta_7$ and μ_{22} as the phenomenological parameters. However, in order to save computation time, we randomly generated these parameters in the following ranges: $\mu_{22} \in [0, 700] \text{ GeV}$, $m_A \in [300, 500] \text{ GeV}$, $m_{H^\pm} \in [300, 800] \text{ GeV}$, $\eta_2 \in [0, 3]$, $\eta_7 \in [-3, 3]$, $m_H \in [200, m_A - m_Z] \text{ GeV}$, and $c_{\beta-\alpha} = 0$ while satisfying $m_h = 125 \text{ GeV}$. Further, we demanded $m_A < m_{H^\pm} + m_W$ to forbid the $A \rightarrow H^\pm W^\mp$ decay for simplicity. In general, heavier m_A is possible; however, the discovery potential would alleviate due to the rapid fall in the parton luminosity. These randomly generated parameters are then passed to 2HDMC, which uses the input parameters [35] $m_{H^\pm}$ and Λ_{1-7} in the Higgs basis, and with v as the implicit parameter while scanning. We identify Λ_{1-7} with η_{1-7} and take $-\pi/2 \leq \beta - \alpha \leq \pi/2$ to match the convention of 2HDMC. We further conservatively require all $|\eta_i| \leq 3$; however, $\eta_2 > 0$ is demanded by the

 FIG. 2. The scanned points plotted in the $|\eta_3 + \eta_4 - \eta_5|$ vs m_A (left) and μ_{22}^2/v^2 vs m_A (right) plane.

positivity of the potential in Eq. (1), in addition to other involved conditions in 2HDMC.

We further imposed the stringent oblique T parameter [36] constraint, which restricts the scalar masses m_H , m_A and $m_{H^\pm}$ [37,38], and hence η_i s. Utilizing the expression given in Ref. [37] the points that passed unitarity, perturbativity and positivity conditions from 2HDMC were further required to satisfy the T parameter constraint within the 2σ error [39]. These points are denoted as “scanned points”. Finally the scanned points are plotted as gray dots in Fig. 2 in the $|\eta_3 + \eta_4 - \eta_5|$ vs m_A and μ_{22}^2/v^2 vs m_A plane. Figure 2 implies that finite parameter space exists for $300 \text{ GeV} \lesssim m_A \lesssim 500 \text{ GeV}$.³

IV. COLLIDER SIGNATURES

In this section we analyze the discovery potential of the $pp \rightarrow bA + X \rightarrow bZH + X$ and $pp \rightarrow b\bar{b}A + X \rightarrow b\bar{b}ZH + X$ processes, followed by the $H \rightarrow b\bar{b}$ and $Z \rightarrow \ell^+\ell^-$ decays. In general $Z \rightarrow \nu\bar{\nu}$ and $Z \rightarrow \tau^+\tau^-$ are possible; however, we found these modes to be not as promising. In order to illustrate the discovery potential we took three benchmark points (BPs) from the scanned points in Fig. 2, which are summarized in Table I. As discussed earlier, the phase information of ρ_{bb} is lost in the $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ processes. Therefore, the only meaningful quantity in this section is the absolute value of ρ_{bb} ($|\rho_{bb}|$). Unless otherwise specified we would only consider $|\rho_{bb}|$ from here on.

There exist several direct search limits from ATLAS and CMS that may restrict the parameter space of ρ_{bb} , even for $c_{\beta-\alpha} = 0$ and $\rho_{tt} = 0$. We find that the searches of the heavy Higgs boson, in particular Refs. [41–44] are the relevant ones for our study. The most stringent bound arises from the CMS search for a heavy Higgs boson production in association with least one additional b quark and decaying into $b\bar{b}$ pair [41]. The search is performed with 13 TeV 35.7 fb⁻¹ data. It sets model-independent 95% CL

upper limits on the $\sigma(pp \rightarrow bA/H + X) \cdot \mathcal{B}(A/H \rightarrow b\bar{b})$ for m_A/m_H ranging from 300 to 1300 GeV. Utilizing this result we have extracted [45] 95% CL $\sigma(pp \rightarrow bA/H + X) \cdot \mathcal{B}(A/H \rightarrow b\bar{b})$ upper limit for BPI, BPII and BPIII. We then calculated the production cross sections ($pp \rightarrow bA/H + X$) at the leading order (LO) for the three BPs for a reference $|\rho_{bb}|$ value using Monte Carlo event generator MADGRAPH5_AMC@NLO [47] with the default NN23LO1 parton distribution function (PDF) set [48]. Since CMS does not veto additional activity in the event, we also included contributions from $gg \rightarrow b\bar{b}A/H$ along with $bg \rightarrow bA/H$ in the cross-section estimation. The cross sections are then rescaled by $|\rho_{bb}|^2 \times \mathcal{B}(A/H \rightarrow b\bar{b})$ to get the corresponding 95% CL upper limits on $|\rho_{bb}|$. The upper limits for the BPI is $|\rho_{bb}| \lesssim 0.5$, whereas $|\rho_{bb}| \lesssim 0.26$ and $|\rho_{bb}| \lesssim 0.24$ for BPII and BPIII, respectively. A similar search has been performed by ATLAS [42]; however, the limits are somewhat weaker than that of Ref. [41]. The limits extracted from Ref. [43], which searches for a light scalar decaying into a $b\bar{b}$ pair, are weaker except for BPI, which we found also to be $|\rho_{bb}| \lesssim 0.5$ (at 95% CL). Moreover, the ATLAS search for $H^\pm$ in association with a t quark and a b quark with $H^+/H^- \rightarrow t\bar{b}/\bar{t}b$ decay [44] is relevant, but the constraints are milder for all three BPs. The effective model is implemented in the FEYNRULES 2.0 [49].

We choose $|\rho_{bb}| = 0.1$ as a representative value for illustration in this section. Since our working assumptions are an alignment limit with all $\rho_{ij} = 0$ except ρ_{bb} , the total decay width of A is nicely approximated as the sum of the partial widths of $A \rightarrow b\bar{b}$ and $A \rightarrow ZH$, while H only decays to $b\bar{b}$. The corresponding branching ratios of A for the three BPs are given in Table II, whereas $\mathcal{B}(H \rightarrow b\bar{b}) \approx 100\%$ for all three BPs. Note, nonzero ρ_{bb} induces $A/H \rightarrow \gamma\gamma$ and $A/H \rightarrow gg$ decays at one loop. These branching ratios are negligibly small, and hence neglected.

A. The bZH process

There exist several SM backgrounds for the bZH process. The dominant backgrounds are $t\bar{t}$ + jets, Drell-Yan + jets (DY + jets), Wt + jets, $t\bar{t}Z$ + jets, $t\bar{t}h$, tZ + jets,

³See also Ref. [40] for more on the parameter counting and scanning strategy.

TABLE I. Parameter values for the three benchmark points. See text for details.

BP	η_1	η_2	η_3	η_4	η_5	η_6	η_7	$m_{H^\pm}$ (GeV)	m_A (GeV)	m_H (GeV)	$\frac{\mu_{32}^2}{v^2}$
I	0.258	1.151	2.78	-1.557	-0.831	0	-0.236	335	301	200	0.46
II	0.258	2.155	2.496	-0.625	-1.885	0	0.375	349	400	214	0.76
III	0.258	2.63	2.142	-0.333	-2.436	0	-0.134	426	495	312	1.92

with subdominant contributions arise from four-top ($4t$), $t\bar{t}W$, tWh , tWZ and WZ + jets. Backgrounds from WW + jets and ZZ + jets are negligibly small and hence not included. The signal and background event samples are generated at LO, utilizing MADGRAPH5_AMC@NLO for pp collisions at $\sqrt{s} = 14$ TeV with the PDF set NN23LO1 and then interfaced with PYTHIA 6.4 [50] for showering and hadronization. We adopted the MLM matching scheme [51] for matrix element and parton shower merging. The event samples are finally fed into fast detector simulator DELPHES 3.4.0 [52] for detector effects. Here we have incorporated the default ATLAS based detector card available within the DELPHES framework. We do not include backgrounds from the fake and nonprompt sources. Such backgrounds are not properly modeled in Monte Carlo simulations and require data to estimate such contributions.

The LO $t\bar{t}$ + jets and Wt + jets cross sections are normalized to NNLO + NNLL cross sections by factors 1.84 [53] and 1.35 [54], respectively. The DY + jets background cross section is adjusted to the NNLO QCD + NLO EW one by a factor 1.2, which is obtained utilizing FEWZ 3.1 [55]. The $t\bar{t}Z$, $t\bar{t}Z$ + jets, $t\bar{t}h$, $4t$ and $t\bar{t}W^-$ ($t\bar{t}W^+$) cross sections at LO are normalized to NLO ones by the K -factors 1.56 [56], 1.44 [47], 1.27 [57], 2.04 [47] and 1.35 (1.27) [58], respectively, while tWh and tWZ are kept at LO. Further, the W^-Z + jets background is normalized to NNLO cross section by factor 2.07 [59]. For simplicity, we assumed the QCD correction factors for the tZj and W^+Z + jets to be the same as their respective charge conjugate processes. The signal cross sections are kept at LO.

In order to distinguish the signal from the background processes, we have applied the following event selection criteria: Each event should contain two same flavor opposite sign leptons (e and μ), at least three jets where at least three of them are b -tagged. The minimum transverse momenta (p_T) of the leading and subleading leptons are required to be >28 GeV and >25 GeV, respectively, whereas the p_T of all three b -jets should be >20 GeV. The absolute value of the pseudorapidity ($|\eta|$) of the leptons

and all three b -jets are needed to be <2.5 . The jets are reconstructed by anti- k_T algorithm with radius parameter $R = 0.6$. The separations ΔR between any two b -jets, any two leptons, and any b -jet and lepton in an event are required to be >0.4 . In order to reduce the $t\bar{t}$ + jets background we vetoed events with missing transverse energy (E_T^{miss}) >35 GeV. The invariant mass of the two same flavor opposite charge leptons ($m_{\ell\ell}$) is required to be within the Z boson mass window, i.e., $76 < m_{\ell\ell} < 100$ GeV. To reduce backgrounds further, we finally demanded the invariant mass of the two same flavor opposite charge leptons and two leading b -jets ($m_{\ell\ell bb}$) to remain within $|m_A - m_{\ell\ell bb}| < 100$ GeV. The normalized $m_{\ell\ell}$ and $m_{\ell\ell bb}$ distributions before application of any selection cuts are presented in the Appendix. We adopted the η and p_T dependent b -tagging efficiency, and c - and light-jets misidentification efficiencies of DELPHES. The background cross sections of the three benchmark points after selection cuts are summarized in Table III, while the signal cross sections along with their corresponding significances with the integrated luminosity $\mathcal{L} = 300 \text{ fb}^{-1}$ are given in Table IV for $|\rho_{bb}| = 0.1$. We remark that in our exploratory study we have not optimized the selection cuts, such as $m_{\ell\ell}$ and $m_{\ell\ell bb}$, and kept them unchanged for all three benchmark points; however the impact of changing them will be discussed in the following.

The statistical significances in Table IV are determined by using $\mathcal{Z} = \sqrt{2[(S+B)\ln(1+S/B) - S]}$ [60], where S and B are the number of signal and background events after selection cuts. The achievable significances for BPI, BPII and BPIII are $\sim 6.6\sigma$, $\sim 4.0\sigma$ and $\sim 2.2\sigma$ with 300 fb^{-1} integrated luminosity. We find that even the collected Run-2 data ($\sim 150 \text{ fb}^{-1}$) would lead to $\sim 4.7\sigma$, $\sim 2.8\sigma$ significances for the BPI and BPII, respectively, whereas lower than 2σ for BPIII. As for the parameter space of EWBG, $|\text{Im}(\rho_{bb})|$ should be $\gtrsim 0.058$ [5], which leads to $\sim 12.1\sigma$, $\sim 4.5\sigma$ and $\sim 2.5\sigma$ significances for the BPI, BPII and BPIII with the full HL-LHC dataset (i.e., 3000 fb^{-1} integrated luminosity). This implies that the bZH process can fully probe the parameter space required for ρ_{bb} driven EWBG if $m_A \lesssim 300$ GeV, whereas evidence (3σ) could be found for $300 \text{ GeV} \lesssim m_A \lesssim 400$ GeV all three BPs. Here, we have kept the Z -pole invariant mass cut fixed to $76 \text{ GeV} < m_{\ell\ell} < 100$ GeV. The significances change negligibly up to $76 \text{ GeV} < m_{\ell\ell} < 110$ GeV for all three BPs, however, reduce if broadened further. On the other hand, we have kept the $m_{\ell\ell bb}$ cut fixed to $|m_A - m_{\ell\ell bb}| < 100$ GeV for all

TABLE II. The branching ratios of A for the three benchmark points given in Table I.

$ \rho_{bb} $	BP	ZH	$b\bar{b}$
0.1	I	0.618	0.382
	II	0.047	0.953
	III	0.05	0.95

TABLE III. The cross sections (in fb) for the different background contributions of the bZH process after selection cuts at $\sqrt{s} = 14$ TeV LHC. The subdominant backgrounds $4t$, $t\bar{t}W$, tWh , tWZ and $WZ + \text{jets}$ are added together and denoted as “Others” in the second to last column, while the last column conforms the total background (Total Bkg.) yield.

BP	$t\bar{t} + \text{jets}$	$DY + \text{jets}$	$Wt + \text{jets}$	$t\bar{t}Z$	$t\bar{t}h$	$tZ + \text{jets}$	Others	Total Bkg. (fb)
I	0.477	0.975	0.372	0.038	0.012	0.014	0.005	1.893
II	0.391	0.747	0.252	0.039	0.007	0.009	0.004	1.449
III	0.198	0.458	0.111	0.027	0.002	0.006	0.002	0.804

TABLE IV. The signal cross sections after selection cuts of the bZH process for the three benchmark points are presented in the third column for $|\rho_{bb}| = 0.1$. The corresponding significances are given in the fourth column.

BP	$ \rho_{bb} $	Signal (fb)	Significance ($\mathcal{Z}$) 300 fb $^{-1}$
I		0.548	6.6
II	0.1	0.286	4.0
III		0.119	2.2

three BPs. Significances do change with the change in the $|m_A - m_{\ell\ell bb}|$ cut, however mildly. We have checked that, e.g., if the cut $|m_A - m_{\ell\ell bb}|$ is set to < 80 GeV the significances enhance by $\sim 1\%$, $\sim 5\%$ and $\sim 3\%$ for BPI, BPII and BPIII, respectively, while they reduce by $\sim 2\%$, $\sim 3\%$ and $\sim 2\%$ if set to < 120 GeV. A narrower $m_{\ell\ell bb}$ cut than 80 GeV again reduces the significance for all three BPs.

Before closing, we remark that the scope for discovery of the bZh process (i.e., $pp \rightarrow bA + X \rightarrow bZh + X$ with $Z \rightarrow \ell^+ \ell^-$, $h \rightarrow b\bar{b}$) is limited if $c_{\beta-\alpha}$ is small. E.g., if $|\rho_{bb}| = 0.1$, $c_{\beta-\alpha} = 0.05$, $m_A = 388$ and $m_H = 236$,⁴ the significance lies below $\sim 1\sigma$, even for the full HL-LHC dataset.⁵ The significance improves substantially if $m_A < m_H + m_Z$ and/or ρ_{bb} is large. A larger $c_{\beta-\alpha}$ would also help; however in such cases the significance would be balanced by more severe bounds from Higgs signal strength measurements. For $c_{\beta-\alpha} \sim 0.05$, $H \rightarrow ZZ$, $H \rightarrow W^+ W^-$ would open up, but we do not find them to be very promising even for HL-LHC.

B. The $bbZH$ process

As for the $bbZH$ process, the SM backgrounds are essentially the same as in the preceding subsection, however with one extra b -jet in the final state. We have adopted a similar procedure for the signal and background events generation, and followed the event selection cuts as in the

bZH process, except the additional b -jet is required to have $p_T > 20$ GeV and $|\eta| < 2.5$. The separation ΔR between any two b -jets, any two leptons, and any b -jet and lepton should be > 0.4 . All other cuts are kept the same as in bZH . Finally, we applied the $m_{\ell\ell}$ and $m_{\ell\ell bb}$ selection cuts as before. The background and signal cross sections after the selection cuts are summarized in Table V and Table VI, respectively. We assumed the QCD correction factors for the different backgrounds as in the bZH process and kept the signal cross sections at LO. Therefore, we remark that there are slightly greater uncertainties involved in the background cross sections.

As can be seen from Table VI, the cross sections of the $bbZH$ process are suppressed due their to $2 \rightarrow 4$ body nature. Hence, the significances are provided only for 3000 fb $^{-1}$ integrated luminosity, which can reach up to $\sim 4.2\sigma$, $\sim 2.8\sigma$ and $\sim 1\sigma$ for the BPI, BPII and BPIII, respectively. Hence, a discovery is beyond the HL-LHC, that is, unless the ρ_{bb} is large. The significances can be higher if the upper limits of $|\rho_{bb}|$ for the corresponding BPs are saturated, which can rise up to $\sim 6.5\sigma$, $\sim 13.8\sigma$ and $\sim 4.5\sigma$ for BPI, BPII and BPIII, respectively, with the full HL-LHC data. The impacts of other choices of $m_{\ell\ell}$ are similar as in the bZH process. However, if the $|m_A - m_{\ell\ell bb}|$ cut is set to < 80 GeV (< 120 GeV), the significances enhance (reduce) by $\sim 2\%$ ($\sim 4\%$), $\sim 11\%$ ($\sim 5\%$) and $\sim 4\%$ ($\sim 2\%$) for BPI, BPII and BPIII, respectively. As in before, $pp \rightarrow b\bar{b}A + X \rightarrow b\bar{b}Zh + X$ is possible; however, the significances are even smaller than the bZh process.

V. DISCUSSION AND SUMMARY

Motivated by the recent observation of hbb coupling, we have investigated the possibility of probing extra bottom Yukawa coupling ρ_{bb} at the LHC. We first looked for the existing constraints on ρ_{bb} , mainly from the Higgs signal strength measurements, $\mathcal{B}(B \rightarrow X_s \gamma)$, $\Delta \mathcal{A}_{CP}$ of $B \rightarrow X_s \gamma$, electron EDM, as well as several direct searches at the LHC. We found that $\mathcal{O}(0.1) |\rho_{bb}|$ is allowed by the current data; however, $c_{\beta-\alpha}$ and ρ_{tt} should not be large. We remark that additional constraints can come from the $\mathcal{A}_{CP}$ and isospin violating asymmetry (Δ_{0+}) of $B \rightarrow K^* \gamma$ measurement by Belle [61], and could be comparable to the

⁴Corresponding parameters for this scanned point are: $\eta_1 = 0.259$, $\eta_2 = 0.838$, $\eta_3 = 1.633$, $\eta_4 = -0.044$, $\eta_5 = -1.569$, $\eta_6 = -0.033$, $m_{H^\pm} = 323$ and $\eta_7 = 0.130$.

⁵In evaluating the significance we assumed the same cut based analysis as in bZH , except the application of an additional $|m_h - m_{bb}| < 25$ GeV cut.

TABLE V. The cross sections (in fb) of the different backgrounds for the $bbZH$ process after selection cuts at $\sqrt{s} = 14$ TeV.

BP	$t\bar{t} + \text{jets}$	$DY + \text{jets}$	$Wt + \text{jets}$	$t\bar{t}Z$	$t\bar{t}h$	$tZ + \text{jets}$	Others	Total Bkg. (fb)
I	0.013	0.065	0.031	0.002	0.003	0.0005	0.0002	0.115
II	0.016	0.064	0.018	0.001	0.002	0.0003	0.0002	0.102
III	0.011	0.039	0.018	0.001	0.0008	0.0002	0.0002	0.071

inclusive one; however, they both suffer from sizable uncertainties in their theoretical predictions [62].

We have shown that $bg \rightarrow bA \rightarrow bZH$ with $Z \rightarrow \ell^+\ell^-$ and $H \rightarrow b\bar{b}$ offers an excellent probe for ρ_{bb} . Discovery seems plausible with 300 fb^{-1} integrated luminosity for $\mathcal{O}(0.1)\rho_{bb}$; however, m_A needs to be $\lesssim 300$ GeV. For $400 \text{ GeV} \lesssim m_A \lesssim 500 \text{ GeV}$ one may need the HL-LHC data. The process could be followed by $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$; however, we find that a discovery is unlikely even with the full HL-LHC dataset if $|\rho_{bb}| \simeq 0.1$. We focused on the scenario where $m_H + m_Z < m_A$. However, for $m_A + m_Z < m_H$ our study can be extended to the $bg \rightarrow bH \rightarrow bAZ$ (and $gg \rightarrow b\bar{b}H \rightarrow b\bar{b}ZA$) process where a complementary search strategy as in bZH (and $bbZH$) can be adopted. Note that ρ_{bb} also invokes $gg \rightarrow \bar{t}bH^+ \rightarrow \bar{t}b\bar{t}\bar{b}$, which we leave out for future study. We have not included QCD corrections for the signal and neglected systematic uncertainties in our analysis.

As a first estimate we have not included uncertainties arising from factorization scale (μ_F) and renormalization scale (μ_R) dependences in our LO cross section calculation. In general, the LO $bg \rightarrow bA/bH$ cross section has sizable scale uncertainties ($\sim 25\text{--}30\%$) in the mass range $m_{A/H} \sim 300\text{--}400$ GeV for bottom quark $p_T > 15\text{--}30$ GeV and $|\eta| < 2.5$ [63] (see also [64,65]). The uncertainties are much higher for $gg \rightarrow b\bar{b}A/H$. E.g., the scale uncertainties could be as large as $\sim 40\%$ at LO [66] depending on the choices of μ_R and μ_F . For both these processes the uncertainties are much smaller at NLO (or at NNLO) [63,66]. It was discussed in Ref. [67] that the LO cross sections estimated with LO PDF set CTEQ6L1 [68] have large factorization scale dependence. We remark that our LO cross sections, which are determined utilizing LO PDF set NN23LO1, may have a similar level of uncertainties. It is found that at $\mu_F \approx m_A$ (or m_H) the corrections are large negative ($\sim -70\%$) [67], while at $\mu_F \approx m_A/4$ (or $m_H/4$) the corrections are small, indicating $\mu_F \approx m_A/4$ is the

relevant factorization scale. In particular, the cross section uncertainties from renormalization and factorization scale choices are found to be small for $\mu_R = m_A$ and varied between $\mu_R = m_A/2$ to $\mu_R = 2m_A$, along with $\mu_F = m_A/4$ and varied between $\mu_F = m_A/8$ to $\mu_F = m_A/2$ [67]. Furthermore, we have not included PDF uncertainties, which could be substantial for the heavy quark initiated process, as discussed e.g., in Ref. [69]. A discussion on PDF choices and their uncertainties for LHC can be found out in Ref. [70]. These would induce some uncertainties in our results. A detailed estimation of such uncertainties we leave out for future.

A discovery might indicate EWBG driven by ρ_{bb} . With the full HL-LHC dataset the bZH process can probe the entire parameter space required for the EWBG if $m_A \lesssim 300$ GeV. Although a discovery would be intriguing, however, it would not be sufficient to establish it to the EWBG without the information of the phase of ρ_{bb} . This would need further scrutiny and perhaps angular analysis of the bZH (or $bbZH$) process would be indicative. Information of the phase can also be extracted from the future measurement of $\Delta\mathcal{A}_{\text{CP}}$ of $B \rightarrow X_s\gamma$ at Belle-II, if $H^\pm$ is not too heavy.

In principle, ρ_{bd} , ρ_{db} , ρ_{bs} and ρ_{sb} all can replicate bZH and $bbZH$ signatures at the LHC; however, their impacts are inconsequential due to severe bounds from B_d and B_s mixings. If the charm quark gets misidentified as b -jet, a sizable ρ_{cc} can mimic the bZH signature in pp collision via $cg \rightarrow cA \rightarrow cZH$. However, such possibilities can be excluded with the simultaneous application of c - and b -tagging on the final state event topologies [71].

While determining the discovery potential we set all $\rho_{ij} = 0$ except for ρ_{bb} for the sake of simplicity. In general, nonzero ρ_{ijs} suppress $\mathcal{B}(A/H \rightarrow b\bar{b})$ and hence the discovery potential of the bZH and $bbZH$. It is plausible that ρ_{ij} couplings might share the same flavor organization patterns of the SM, i.e., trickling down off-diagonal elements as observed in the quark masses and mixings. If so, ρ_{ii} could be $\sim \lambda_i$, and similarly $\rho_{\tau\tau} \sim \lambda_\tau$ [7]. In demonstrating the discovery potential of the bZH and $bbZH$ processes, we have chosen $|\rho_{bb}| = 0.1$ for illustration; however, $|\rho_{bb}|$ could be $\sim \lambda_b$. For $|\rho_{bb}| = \lambda_b$, one has $\sim 3\sigma$ for BPI with the full HL-LHC data for the bZH process, whereas significances lie below 1σ for the BPII and BPIII. We remark that $\rho_{\tau\tau} \sim \lambda_\tau$ impacts negligibly on the discovery potential. Throughout we assumed the flavor

TABLE VI. Same table as in Table IV, however, for the $bbZH$ process.

BP	$ \rho_{bb} $	Signal (fb)	Significance ($\mathcal{Z}$) 3000 fb $^{-1}$
I		0.027	4.2
II	0.1	0.017	2.8
III		0.005	1.0

changing neutral Higgs coupling ρ_{tc} to be small; however, a $\mathcal{O}(1)$ value is still allowed by the current data [72,73] (see also Ref. [74]), and could potentially reduce the significances of both the processes.

We assumed small ρ_{tt} in order to avoid strong constraints arising from the $gg \rightarrow A/H$ searches. Notwithstanding, $\mathcal{O}(1)\rho_{tt}$ with a complex phase provides another robust mechanism for EWBG [75] (see also Ref. [76]), which can be probed by the conventional search programs such as $gg \rightarrow A/H \rightarrow t\bar{t}$ or $gg \rightarrow A/Ht\bar{t} \rightarrow t\bar{t}t\bar{t}$ [77]. The former process suffers from large interference [78] with the overwhelming $gg \rightarrow t\bar{t}$ background; however recent ATLAS [79] and CMS [80] studies found some sensitivity. We remark that ρ_{tt} could be $\sim \lambda_t$. Utilizing results from Refs. [44,81,82], Ref. [83] found $|\rho_{tt}| \gtrsim 0.8$ – 0.9 are excluded (at 95% CL) if $m_A/m_H \approx 400$ – 500 GeV, or $m_{H^\pm} \sim 300$ – 400 GeV. These are roughly the ballpark values of m_A and $m_{H^\pm}$ of the three BPs, as can be seen from Table I. Nonzero ρ_{tt} alleviates the discovery potential of both the bZH and $bbZH$ processes via $\mathcal{B}(A/H \rightarrow t\bar{t})$, for $m_A/m_H > 2m_t$. For example, taking $|\rho_{tt}| = 0.8$ as a yardstick and by a simple rescaling of the numbers in Table IV and Table VI, we find that the significances for BPII and BPIII drop by $\sim 60\%$ and $\sim 70\%$, respectively. Therefore, discovery of bZH is possible only for BPII (and BPI since m_A lies below $2m_t$ threshold), but would require full HL-LHC data. In such cases, discovery is not possible

for BPII and BPIII for the $bbZH$ process, even with full HL-LHC data. For sizable ρ_{bb} and ρ_{tt} , $bg \rightarrow bA/H \rightarrow b\bar{t}t$ as well as $gg \rightarrow b\bar{b}A/H \rightarrow b\bar{b}t\bar{t}$ [84] both are possible and would provide complementary information.

In summary, we have explored the possibility of discovery and identification of additional bottom Yukawa coupling that might exist in nature via the $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ processes at $\sqrt{s} = 14$ TeV LHC. We found that the former process could be discovered with 300 fb^{-1} integrated luminosity if $m_A \sim 300$ GeV, which could be extended up to ~ 500 GeV, but the full HL-LHC dataset would be required. The latter process could also be discovered at the HL-LHC; however ρ_{bb} needs to be large. A discovery would not only confirm physics beyond the Standard Model, but may also indicate the EWBG driven by ρ_{bb} .

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APPENDIX: INVARIANT MASS DISTRIBUTIONS

The normalized invariant mass distributions $m_{\ell\ell}$ and $m_{\ell\ell bb}$ for the signal and backgrounds of the bZH and

FIG. 3. The normalized $m_{\ell\ell}$ (left) and $m_{\ell\ell bb}$ (right) distributions of the three BPs together with different backgrounds for the bZH (upper panel) and $bbZH$ (lower panel) processes.

$bbZH$ processes are presented in Fig. 3. These figures are generated without any selection cuts. The events for the signal and background processes are generated with the

default cuts of MADGRAPH5_AMC@NLO with minimal modifications, followed by showering and hadronization via PYTHIA 6.4 and with the ATLAS based DELPHES card.

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