Searching for additional bottom Yukawa coupling via $bg \rightarrow bA \rightarrow bZH$ signature

Tamnoy Modak
Department of Physics, National Taiwan University, Taipei 10617, Taiwan

The recent discovery of the bottom quark Yukawa coupling ($bb\bar{b}$) of the 125 GeV scalar motivates one to search for extra bottom Yukawa coupling that may exist in the nature. The two Higgs doublet model without a discrete $Z_2$ symmetry allows the possibility of additional bottom Yukawa coupling $\rho_{bb}$. We show that $\rho_{bb}$ can be searched directly at the LHC via $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow bbA \rightarrow bbZH$ 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 $\sim 300$ fb$^{-1}$ integrated luminosity if $m_A \sim 300$ GeV, while the latter process may emerge in the high luminosity LHC (HL-LHC) data. A discovery might touch upon the parameter space required for the electroweak baryogenesis.

I. INTRODUCTION

The discovery of the 125 GeV scalar boson $h$ and its properties corroborate that the Standard Model (SM) is the correct effective theory at around weak scale. Although, no clear evidence of new physics (NP) has been found, the Run-2 era of LHC witnessed one of the most intriguing discovery, that is the bottom quark Yukawa coupling $bb\bar{b}$ [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 and followed by the $h \rightarrow bb$ decay. When combined with the results from other searches in the Run-1 and Run-2 with the $h \rightarrow bb$ decay, the observed signal strengths relative to the SM expectation were reported to be $1.01 \pm 0.12 \text{(stat.)} +0.16^{+0.19}_{-0.15} \text{(syst.)}$ 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 the nature. In this article we explore the possibility of direct detection and identification of such 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, 5] of Glashow and Weinberg 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 $\lambda^F_{ij} = (\sqrt{2}m^{ij}_F/v)\delta_{ij}$ (with $v \approx 246$ GeV) and $\rho^F_{ij}$ emerge, where $F$ denotes up- and down-type quarks and, leptons. The Yukawa matrices $\lambda^F_{ij}$ are real and diagonal, while as, $\rho^F_{ij}$ are in general non-diagonal and complex. Our focus of interest is the the extra bottom Yukawa coupling $\rho_{bb}$. In this paper, we analyze the prospect its direct detection at the LHC via $bg \rightarrow bA \rightarrow bZH$ and $gg \rightarrow bbA \rightarrow bbZH$ processes (charge conjugate processes are implied) with $b$-tagging.

We investigate the discovery potential of $\rho_{bb}$ via $pp \rightarrow bA + X \rightarrow bZH + X$ ($X$ is inclusive activity) with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) and $H \rightarrow bb$ (denoted as $bZH$ process) at the 14 TeV LHC. In finding the discovery potential we assumed the extra top Yukawa coupling $\rho_{tt}$ to be relatively small to avoid the direct search constraints from $gg \rightarrow A/H$. A sizable $\rho_{bb}$ would also induce $gg \rightarrow bbA \rightarrow bbZH$ which provides additional probe for $\rho_{bb}$. We study this process via $pp \rightarrow bbA + X \rightarrow bbZH + X$ followed by $Z \rightarrow \ell^+\ell^-$ and $H \rightarrow bb$ (denoted as $bbZH$ process). Recently, $\rho_{bb}$ received additional significance as it can drive electroweak baryogenesis (EWBG) rather efficiently [5]. It was shown that $O(0.1)$ imaginary $\rho_{bb}$ (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 $\rho_{bb}$ driven EWBG.

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

II. FORMALISM

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

$$V(\Phi, \Phi') = m^2_{11}|\Phi|^2 + m^2_{22}|\Phi'|^2 - (m^2_{12}\Phi^\dagger \Phi' + h.c.)$$

$$+ \frac{\lambda_1}{2}|\Phi|^4 + \frac{\lambda_2}{2}|\Phi'|^4 + \lambda_3|\Phi|^2|\Phi'|^2 + \lambda_4|\Phi^\dagger \Phi'|^2$$

$$+ \left[ \frac{\lambda_5}{2}|\Phi^\dagger \Phi'|^2 + (\lambda_6|\Phi|^2 + \lambda_7|\Phi'|^2)|\Phi^\dagger \Phi'| + h.c. \right],$$

(1)

where the parameters $m^2_{11}, m^2_{22}, m^2_{12}$ and $\lambda_{1-8}$ are all real. The vacuum expectation values of the doublets $\Phi$ and $\Phi'$ 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 $\Phi$ and $\Phi'$, $\tan \beta$ 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 $m_{ij}^2 \to \mu_{ij}^2$ and $\lambda_i \to \eta_i$. The scalar potential minimization conditions lead to $\mu_{ij}^2 = -\frac{1}{2} \eta_i v^2$ 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

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

(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:

$$m_{H^\pm}^2 = \frac{1}{2} \eta_6 v^2 + \mu_{22}^2,$$

(3)

$$m_A^2 = \frac{1}{2} (\eta_4 + \eta_5 - \eta_6) v^2 + \mu_{22}^2,$$

(4)

$$m_{h, H}^2 = \frac{1}{2} \left[ m_A^2 + (\eta_4 + \eta_5) v^2 \right]$$

$$\pm \sqrt{\left( m_A^2 + (\eta_5 - \eta_4) v^2 \right)^2 + 4 \eta_6 v^4}. \quad (5)$$

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

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} \sum_{F=U,D,L} \tilde{F}_{iL} \left[ (\lambda_{ij}^F s_{\beta - \alpha} + \rho_{ij}^F c_{\beta - \alpha}) h ight.$

$$+ (\lambda_{ij}^F c_{\beta - \alpha} - \rho_{ij}^F s_{\beta - \alpha}) H - i \text{sgn}(Q_F) \rho_{ij}^F A \right] F_{jR}$$

$$- U_i \left[ (V^{ij}_D)_{ij} P_R - (\rho^{ij}_D V^{ij}_D)_{ij} P_L \right] D_j H^+$$

$$- \tilde{\nu}_i \rho_{ij}^L P_R L_j H^+ + \text{h.c.},$$

(6)

where $i, j = 1, 2, 3$ are the generation indices that are summed over, $\nu$ and $\rho$ are real and diagonal and $\lambda_{ij}^F$ are complex non-diagonal 3 x 3 matrices.

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

$$\frac{g_2}{2 c_W} Z \left[ c_{\beta - \alpha} (h \partial^\mu A - \partial^\mu h \cdot A) ight.$$

$$- s_{\beta - \alpha} (H \partial^\mu A - \partial^\mu H \cdot A) \left], \quad (7)\right.$$ with $g_2$ is the $SU(2)_L$ gauge coupling and $c_W$ is Weinberg’s angle. A search can be performed in $bg \to bA \to bbb$ mode, although, the process suffers from the overwhelming QCD multijets background. For $m_{H^\pm} + m_W < m_A$ ($m_W$ is the W boson mass) $bg \to bA \to bH^+W^-$ is possible, but if searched in $H^+ \to t\bar{t}$ (induced by $\rho_{tt}$) with $t \to b^+\nu\ell$ 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 $\rho_{tt}$ coupling, which also can induce $H^+ \to t\bar{t}$ decay, obfuscates the role of $\rho_{bb}$. We remark that the $bg \to bA \to bZH$ process, which can only be induced via $\rho_{bb}$, offers a unique probe for the $\rho_{bb}$ coupling.

The process $bg \to bA \to bZH$ is indeed possible, however, suppressed by the mixing angle $c_{\beta - \alpha}$. It should be clear from Eq. (7) that the decay $A \to ZH$ is proportional to $s_{\beta - \alpha}$. As a result, a discovery is plausible even in the approximate alignment (i.e. for small $c_{\beta - \alpha}$), which is observed at the LHC. Further, $\rho_{bb}$ can initiate $bb \to A \to ZH$ and loop induced $gg \to A \to ZH$ [10], however, the coupling information is lost in the pp collision. Besides, as $\rho_{tt}$ can also get involved in the loop, the role of $\rho_{bb}$ is obscured in $gg \to A \to ZH$. One can also have $gg \to A \to Zh$ (see e.g. Refs. [11, 12] and references therein) and $gg \to b\bar{b}A \to b\bar{b}Zh$ (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 $\rho_{bb}$. For simplicity, we set all $\rho_{ij} = 0$ except for $\rho_{bb}$ and $\rho_{tt}$ in this section. We assume small $\rho_{tt}$ in order to avoid direct search limits from $gg \to A/H$. In particular we choose $\rho_{tt} = 0.1$ for illustration. The most stringent constraints arise from the Higgs signal strength measurements, the branching ratio of $B \to X_s \gamma$ ($B(B \to X_s \gamma)$), the asymmetry of the CP asymmetry between the charged and neutral $B \to X_s \gamma$ decays ($\Delta A_{CP}$), electron electric dipole moment (EDM) measurement and the upper limit on the $h$ decay width.

The couplings $\rho_{ij}$ modify the h boson couplings to the fermions for moderate values of $c_{\beta - \alpha}$, as can be seen from Eq. (6). Therefore, $\rho_{bb}$ 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 $\mu_i$ and corresponding errors to a particular decay mode $i \to h \to j$. Following the Refs. [15, 16], we define a signal strength

---

1 The relations between the parameters in the two bases can be found out in Ref. [8].

2 In principle $gg \to bA \to bZH$ can replicate the same final state as in $bg \to bA \to bZH$ process in the $pp$ collision if $\rho_{bb}$ or $\rho_{bb}$ ($q = d$ and $s$) are sizable, however, they receive severe constraints from the $B_q$ mixing [5].
FIG. 1. The constraints on $\rho_b$ from Higgs signal strength measurements of ATLAS (red shaded region), Higgs signal strength measurements of CMS (green shaded region), $B(D \rightarrow X_5 \gamma)$ (blue shaded region) and $\Delta A_{CP}$ (red dotted line). The figures are generated with $c_{3-\alpha} = 0.05$ and $\rho_t = 0.1$, for $m_{H^\pm} = 350$ GeV (left panel) and 450 GeV (right panel). See text for further details.

$\mu_i$ as:

$$\mu_i^f = \frac{\sigma_i^f}{\sigma_i^{SM}(B^f)} = \mu_i \mu_i^f,$$

where $\sigma_i$ is denoted as the production cross section of $i \rightarrow H$ and $B^f$ is the branching ratio for $h \rightarrow f$. The production modes considered are $i = ggF$ (gluon-fusion), $VBF$ (vector-boson-fusion), $Zh$, $Wh$, $ttb$, and the branching ratios are $f = \gamma \gamma, ZZ, WW, \tau \tau, bb, \mu \mu$. For simplicity we utilized the LO $\mu_i^f$ 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 $\mu_i^{ggF}$, $\mu_i^{WW}$, $\mu_i^{\gamma \gamma}$, and $\mu_i^{t \bar{t}b}$, while in the $VBF$ category $\mu_i^{VBF}$, $\mu_i^{\gamma \gamma}$, and $\mu_i^{BBF}$; we refer them together as “Higgs signal strength measurements”. In addition, we further considered the recent observation of the $h \rightarrow bb$ in the $Vh$ production by ATLAS [2] and CMS [3]. 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 $c_{3-\alpha} = 0.5$.

The branching ratio measurement of $B(D \rightarrow X_5 \gamma)$ provide another stringent constraint on $\rho_b$. The coupling $\rho_b$ enters in the $B(D \rightarrow X_5 \gamma)$ 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

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

with, $m_t(m_W)$ is the MS running mass of top quark at $m_W$, $x_t = (m_t(m_W)/m_W)^2$, 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

$$\delta C_{7,8}^{(0)}(m_W) \simeq \frac{\rho_H^2}{3\lambda_t^2} F_{7,8}^{(1)}(y_{H^+}) - \frac{\rho_H \rho_b}{\lambda_t \lambda_b} F_{7,8}^{(2)}(y_{H^+}),$$

where $y_{H^+} = (m_t(m_W)/m_{H^+})^2$. Here we have followed Ref. [23], for the expression of $F_{7,8}^{(2)}(y_{H^+})$. The current world average of $B(D \rightarrow X_5 \gamma)$ 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 $B(D \rightarrow X_5 \gamma)$ 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 $\rho_b$, we adopted the prescription of Ref. [24] and defined

$$R_{exp} = \frac{B(D \rightarrow X_5 \gamma)_{exp}}{B(D \rightarrow X_5 \gamma)_{SM}},$$

Based on our LO calculation we further defined

$$R_{theory} = \frac{B(D \rightarrow X_5 \gamma)_{G2HDM}}{B(D \rightarrow X_5 \gamma)_{SM}},$$

and took $m_W$ and $m_t$ as the matching scale and low-energy scales respectively. We finally demanded $R_{theory}$ should not exceed $2\sigma$ error of $R_{exp}$. The excluded regions are displayed by the blue shaded regions in Fig. 1.

The direct CP asymmetry $A_{CP}$ [27] of $B \rightarrow X_5 \gamma$ is sensitive to $\text{Im}(\rho_b)$. However, it has been proposed [28] that $A_{CP}$, defined as the asymmetry of the CP asymmetry between the charged and neutral $B \rightarrow X_5 \gamma$ decay provides even more powerful probe for the CP violating effects. The $\Delta A_{CP}$ is defined as [28]

$$\Delta A_{CP} = A_{B \rightarrow X_5 \gamma} - A_{B^0 \rightarrow X_5 \gamma} \approx 4\pi^2 \alpha_s \frac{\lambda_t}{m_b} \text{Im}(\frac{C_b}{C_7}),$$

with $C_b/C_7$.
where, $\alpha_s$ is the strong coupling constant calculated at $\overline{m}_b(m_b)$ and $\Lambda_7$ is a hadronic parameter. It is expected that hadronic parameter $\Lambda_7 \sim \Lambda_{QCD}$ and estimated to be in the range of $17$ MeV $< \Lambda_7 < 190$ MeV [28]. We take the average value of $\Lambda_7 = 89$ MeV as a reference value for illustration. A recent Belle measurement report $\Delta A_{CP} = (+3.69 \pm 2.65 \pm 0.76)$% [29], where the first and second uncertainties are statistical and systematic respectively. Using Eq. (13) and allowing $2\sigma$ error on the Belle measurement of $\Delta A_{CP}$ we find the red dotted lines (the regions above are excluded) in Fig. 1 for $m_{H^\pm} = 350$ GeV and $450$ GeV. As a first approximation we have utilized the LO Wilson coefficients as in Eq. (1) in our analysis. We stress that the constraint heavily depends on the value of $\Lambda_7$ and becomes stronger for the larger values of $\Lambda_7$.

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 is 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 cm [32], which excludes even the nominal value (i.e. $|\text{Im}(\rho_{bb})| \lesssim 0.058$) required for $\rho_{bb}$ driven EWBG [3]. The constraint could be relaxed by either turning on $\rho_{ee}$, or even could vanish in the alignment limit. In the former scenario non-zero $\rho_{ee}$ and $\rho_{bb}$ induce other Barr-Zee diagrams with opposite sign, where as in the the latter case all the contributions to the EDM are simply decoupled. In particular, Ref. [3] finds for $\text{Re}(\rho_{ee}) = 0$, $\mathcal{O}(0.1) \text{Im}(\rho_{bb})$ is still allowed if $0.06 \lesssim \text{Im}(\rho_{ee})/(\lambda \lambda_{bb}) \lesssim 0.3$.

The current upper limit of the $b$ boson decay width, which is extracted to be $< 0.013$ GeV (95% CL) [33], can provide some limit on $|\rho_{bb}|$ if $c_{\beta-\alpha} \neq 0$. Besides, the presence of the additional scalars modify the Zb vertex [34] at one-loop and in principle can constrain the $\rho_{bb}$ 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 depend primarily on the value of $c_{\beta-\alpha}$ and vanish in the alignment limit. Same is true for the constraint from the electron EDM, which also disappears in the alignment limit. On the other hand, bounds from $B(B \to X_s\gamma)$ and $\Delta A_{CP}$ alleviate if $\rho_{tt}$ is small, and/or $H^\pm$ is heavy. It is clear from Fig. 1 that $|\rho_{bb}| \sim 0.1$ is still allowed, however, $c_{\beta-\alpha}$ and $\rho_{tt}$ 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 which can also constrain $\rho_{bb}$, 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. The quartic couplings $\eta_1, \eta_3-6$ can be expressed in terms of $m_h, m_A, m_H, m_{H^\pm}, \mu_{22}$ and mixing angle $\beta-\alpha$, all normalized to $v$.

\begin{align}
\eta_1 &= \frac{m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2}{v^2}, \\
\eta_3 &= \frac{2(m_H^2 - \mu_{22}^2)}{v^2}, \\
\eta_4 &= \frac{m_h^2 c_{\beta-\alpha}^2 + m_H^2 s_{\beta-\alpha}^2 - 2m_{H^\pm}^2 + m_A^2}{v^2}, \\
\eta_5 &= \frac{m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2 - m_A^2}{v^2}, \\
\eta_6 &= \frac{(m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha}}{v^2}.
\end{align}

The mixing angle $\beta-\alpha$ and the quartic couplings $\eta_2$ and $\eta_7$ are not related to masses. Hence, we take $v, m_h, m_A, m_H, m_{H^\pm}, c_{\beta-\alpha}, \eta_2, \eta_7$ and $\mu_{22}$ as the phenomenological parameters. However, in order to save computation time, we randomly generated these parameters in the following ranges: $\mu_{22} \in [0, 700]$ GeV, $m_A \in [300, 500]$ GeV, $m_{H^\pm} \in [300, 800]$ 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 $m_h = 125$ GeV. Further we demanded $m_A < m_{H^\pm} + m_W$ to forbid the $A \to H^+ W^-$ decay for simplicity. In general, heavier $m_A$ is possible, however the discovery potential would be alleviated due to the rapid fall in the parton luminosity. These randomly generated parameters are then passed to 2HDMC, which uses the input parameters $m_{H^\pm}$ and $A_{1-7}$ in the Higgs basis, and with $v$ as implicit parameter while scanning. We identify $A_{1-7}$ with $\eta_{1-7}$ 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 positivity of the potential in Eq. (1), in addition to other involved conditions in 2HDMC.

We further imposed the stringent oblique $T$ parameter constraint [34], which restricts the scalar masses $m_h, m_A, m_H$ and $m_{H^\pm}$, and hence $\eta_8$. Utilizing the expression given in Ref. [34], the points that passed unitarity, perturbativity and positivity conditions from 2HDMC, were further required to satisfy the $T$ parameter constraint within the $2\sigma$ error [39]. These points are denoted as “scanned points”. Finally the scanned points are plotted as gray dots in Fig. 2 in the $|\eta_2 + \eta_4 - \eta_6| vs m_A$ and $\mu_{22}^2/v^2$ vs $m_A$ plane. The Fig. 2 implies that finite parameter space exist for 300 GeV $\lesssim m_A \lesssim 500$ GeV.

\section*{IV. COLLIDER SIGNATURES}

In this section we analyze the discovery potential of $pp \to b + A \to bZ + X$ and $pp \to bbA \to bbZH + X$.

\footnote{See also Ref. [40] for more on the parameter counting and scanning strategy.}
processes, followed by $H \to b\bar{b}$ and $Z \to \ell^+\ell^-$ decays. In general $Z \to \nu\bar{\nu}$ and $Z \to \tau^+\tau^-$ 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 $\rho_b$ is lost in the $bg \to bA \to bZH$ and $gg \to b\bar{b}A \to b\bar{b}ZH$ processes. Therefore, the only meaningful quantity in this section is the absolute value of $\rho_b (|\rho_b|)$. Unless otherwise specified we would only consider $|\rho_b|$ from here on.

There exist several direct search limits from ATLAS and CMS that may restrict the parameter space of $\rho_b$, even for $c_{3H} = 0$ and $\rho_h = 0$. We find that the searches of heavy Higgs boson, in particular Refs. [11]-[14] 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 [11]. The search is performed with 13 TeV 35.7 fb$^{-1}$ data. It sets model-independent 95% CL upper limits on the $\sigma(pp \to bA/H + X) \cdot B(A/H \to b\bar{b})$ for $m_A/m_H$ ranging from 300 to 1300 GeV. Utilizing this result we have extracted [15] 95% CL $\sigma(pp \to bA/H + X) \cdot B(A/H \to b\bar{b})$ upper limit for BP1, BP2 and BP3. We then calculated the production cross sections ($pp \to bA/H + X$) at the leading order (LO) for the three BPs for a reference $|\rho_b|$ value using Monte Carlo event generator MadGraph5_aMC@NLO [17] with the default NN23LO1 parton distribution function (PDF) set [18]. Since, CMS does not veto additional activity in the event, we also included contributions from $gg \to b\bar{b}A/H$ along with $bg \to bA/H$ in the cross-section estimation. The cross sections are then rescaled by $|\rho_b|^2 \times B(A/H \to b\bar{b})$ to get the corresponding 95% CL upper limits on $|\rho_b|$. The upper limits for the BPI is $|\rho_b| \lesssim 0.5$, where as $|\rho_b| \lesssim 0.26$ and $|\rho_b| \lesssim 0.24$ for BPII and BPIII respectively. A similar search has been performed by ATLAS [12] however the limits are somewhat weaker than that of Ref. [11]. The limits extracted from Ref. [13], which searches for a light scalar decaying into $b\bar{b}$ pair, are weaker except for BPI. For BPI, we found the upper limit to be $|\rho_b| \lesssim 0.51$ (at 95% CL), which is roughly similar to the one from Ref. [11]. Moreover, ATLAS search for $H^\pm$ in association with a $t$ quark and a $b$ quark with $H^+H^- \to t\bar{b}/tb$ decay [14] is relevant, but the constraints are milder for all three BPs. The effective model is implemented in the FeynRules 2.0 [49].

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

![Graph](image-url)

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

| BP | $\eta_1$ | $\eta_2$ | $\eta_3$ | $\eta_4$ | $\eta_5$ | $\eta_6$ | $m_{H^{\pm}}$ (GeV) | $m_A$ (GeV) | $m_H$ (GeV) | $\langle \mu^2_{22} / v^2 \rangle$ |
|----|--------|--------|--------|--------|--------|--------|-----------------|-------------|-----------|-----------------|
| I  | 0.258  | 1.151  | 2.78   | -1.557 | -0.831 | 0      | -0.236          | 335.47      | 300.84     | 200.24         | 0.46          |
| II | 0.258  | 2.155  | 2.496  | -0.625 | -1.885 | 0      | 0.375           | 349.48      | 400.43     | 214.46         | 0.76          |
| III| 0.258  | 2.63   | 2.142  | -0.333 | -2.436 | 0      | -0.134          | 425.92      | 495.19     | 312.12         | 1.92          |

TABLE I. Parameter values for the three benchmark points. See text for details.
| $|\rho_{bb}|$ | BP | $ZH$ | $\bar{b}b$ |
|---|---|---|---|
| 0.1 | I | 0.618 | 0.382 |
|   | II | 0.047 | 0.953 |
|   | III| 0.05  | 0.95  |

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

### A. The $bZH$ process

There exist several SM backgrounds for the $bZH$ process. The dominant backgrounds are $t\bar{t}+\text{jets}$, Drell-Yan+\text{jets} (DY+jets), $Wt+\text{jets}$, $tZ+\text{jets}$, $t\bar{t}h$, $tZ+\text{jets}$, with subdominant contributions arise from four-top (4$t$), $tW$, $tWh$, $tWZ$ and $WZ+\text{jets}$. Backgrounds from $WW+\text{jets}$ and $ZZ+\text{jets}$ 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 for showering and hadronization. We adopted MLM matching scheme for matrix element and parton shower merging. The event samples are finally fed into fast detector simulator Delphes 3.4.0 for detector effects (ATLAS based). We do not include backgrounds from the fake and non-prompt sources. Such backgrounds are not properly modeled in Monte Carlo simulations and requires data to estimate such contributions.

The LO $t\bar{t}+\text{jets}$ and $Wt+\text{jets}$ cross sections are normalized to NNLO+NNLL cross sections by factors 1.84 and 1.35 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. The $tZ$, $tZ+\text{jets}$, $t\bar{t}h$, $4t$ and $tW^-(tW^+)$ cross sections at LO are normalized to NLO ones by the $K$-factors 1.56 and 1.44 respectively, while $tW$ and $tWZ$ are kept at LO. Further, the $W^{-}Z+\text{jets}$ background is normalized to NNLO cross section by factor 2.07. For simplicity, we assumed the QCD correction factors for the $tZj$ and $W^{+}Z+\text{jets}$ 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 following event selection criteria: Each event should contain two same flavor opposite sign leptons ($e$ and $\mu$), at least three jets with 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, where as the $p_T$ of all three $b$-jets should be $> 20$ GeV. The absolute value of the pseudo-rapidity ($|\eta|$) 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 $\Delta R$ between any two $b$-jets, any two leptons and, any $b$-jet and lepton in an event are required be $> 0.4$. In order to reduce the $t\bar{t}+\text{jets}$ background we vetoed events with missing transverse energy ($E_T^{\text{miss}} > 35$ GeV). The invariant mass of the two leading 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 leading leptons and two leading $b$-jets ($m_{b\ell b\ell}$) to remain within $|m_A - m_{b\ell b\ell}| < 100$ GeV. We adopted the $\eta$ 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 I while the signal cross sections along with their corresponding significances with the integrated luminosity $L = 300$ 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 $m_{b\ell b\ell}$, and kept them unchanged for all three benchmark points for simplicity.

| BP | $t\bar{t}$+ jets | $DY$+ jets | $Wt$+ jets | $tZ$ | $t\bar{t}h$ | $tZ$+ 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 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 $4t$, $tW$, $tWh$, $tWZ$ and $WZ+\text{jets}$ are added together and denoted as “Others” in the second last column, while the last column conforms the total background (Total Bkg.) yield.

| $|\rho_{bb}|$ | Signal (fb) | Significance (Z) |
|---|---|---|
| I | 0.548 | 6.6 |
| II | 0.286 | 4.0 |
| III| 0.119 | 2.2 |

**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.

The statistical significances in Table IV are determined by using $Z = \sqrt{2(S + B)\ln(1 + S/B) - S}$, 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 ($\sim 150$ fb$^{-1}$ ) would lead to $\sim 4.7\sigma$, $\sim 2.8\sigma$ significances for the BPI and BPII respectively, whereas as lower than $2\sigma$ for BPIII. As for the parameter space of EWBG, $|\text{Im}(\rho_{bb})|$ should be $\gtrsim 0.058$, 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 $b\ell Zh$ process can fully probe the parameter space required for $\rho_{bb}$ driven EWBG if $m_A \lesssim 300$ GeV, where as a evidence (3$\sigma$) could be found for 300 GeV $\lesssim m_A \lesssim 400$ GeV.

Before closing we remark that the scope for discovery of the $b\ell Zh$ process (i.e. $pp \to bA + X \to b\ell Zh + X$ with $Z \to \ell^+\ell^-$, $h \to bb$) is limited if $c_{\beta-\alpha}$ is small. E.g., if $|\rho_{bb}| = 0.1$, $c_{\beta-\alpha} = 0.05$, $m_A = 388.50$ and $m_H = 236.34$ $\text{GeV}$ the significance lies below $\sim 1\sigma$, even for the full HL-LHC dataset. The significance improves substantially if $m_A < m_H + m_Z$ and/or $\rho_{bb}$ 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 $c_{\beta-\alpha} \sim 0.05$, $H \to ZZ$, $H \to W^+W^-$ would open up, although we do not find them to be very promising even for HL-LHC.

### B. The $bb\ell Zh$ process

As for the $bb\ell Zh$ process, the SM backgrounds are essentially same as in the preceding subsection however with one extra $b$-jet in the final state. We have adopted similar procedure for the signal and background events generation and, followed the event selection cuts as in the $b\ell Zh$ process except the additional $b$-jet is required to have $p_T > 20$ GeV and $|\eta| < 2.5$. The separation $\Delta R$ between any two $b$-jets, any two leptons and, any $b$-jet and lepton should be $> 0.4$. All other cuts are kept same as in $b\ell Zh$. Finally, we applied the $m_4l$ and $m_{bb}\ell$ selection cuts as before. The background and signal cross sections after the selection cuts are summarized in Table $\text{V}$ and Table $\text{VI}$ respectively. We assumed the QCD correction factors for the different backgrounds as in the $b\ell Zh$ process and kept the signal cross sections at LO. Therefore, we remark that, there are slightly greater uncertainties involved in the background cross sections.

| BP | $t\bar{t}+$ jets | $DY+$ jets | $Wt+$ jets | $t\ell Z$ | $t\ell h$ | $t\bar{h}$ | $Z+$ 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  |

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

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

Table $\text{VI}$. Same Table as in Table $\text{V}$ however for the $bb\ell Zh$ process.

As can be seen from Table $\text{VI}$, the cross sections of the $bb\ell Zh$ process is suppressed due its to $2 \to 4$ 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 $\rho_{bb}$ 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 $\sim 4.5\sigma$, $\sim 13.8\sigma$ and $\sim 4.5\sigma$ for BPI, BPII and BPIII respectively with the full HL-LHC data. As before, $pp \to b\bar{b}A + X \to b\bar{b}Zh + X$ is possible, however, the significances are even smaller than the $b\ell Zh$ process.

### V. DISCUSSION AND SUMMARY

Motivated by the recent observation of $bbb$ coupling, we have investigated the possibility of probing extra bottom Yukawa coupling $\rho_{bb}$ at the LHC. We first looked for the existing constraints on $\rho_{bb}$, mainly from the Higgs signal strength measurements, $B(B \to X_s\gamma)$, $\Delta A_{\text{CP}}$ of $B \to X_s\gamma$, 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 $\rho_{tt}$ should not be large. We remark that additional constraints can come from the $A_{\text{CP}}$ and isospin violating asymmetry ($\Delta_a$) of $B \to K^{\ast}\gamma$ measurement by Belle [61], and could be comparable to the inclusive one, however, they both suffer from sizable uncertainties in their theoretical predictions [62].

We have shown that $bg \to bA \to b\ell Zh$ with $Z \to \ell^+\ell^-$ and $H \to bb$ offers excellent probe for $\rho_{bb}$. 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 GeV $\lesssim m_A \lesssim 500$ GeV one may need the HL-LHC.

---

4. Corresponding parameters for this scanned point are: $\eta_1 = 0.259$, $\eta_2 = 0.838$, $\eta_3 = 1.633$, $\eta_4 = -0.044$, $\eta_5 = -1.569$, $\eta_6 = -0.033$, $m_{H^\pm} = 323.56$ and $\eta_7 = 0.130$.

5. In evaluating the significance we assumed the same cut based analysis as in $b\ell Zh$, except the application of an additional $|m_h - m_{bb}| < 25$ GeV cut.
data. The process could be found by a discovery of $gg \to b\bar{b} A \to b\bar{b}ZH$, although we find that a discovery is unlikely even with the full HL-LHC dataset if $|\rho_b| \approx 0.1$. 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 $bg \to bH \to bAZ$ (and $gg \to bH \to bZA$) process where a complimentary search strategy as in $bZH$ (and $b\bar{b}ZH$) can be adopted. Note that, $\rho_b$ also invokes $gg \to bH^+ \to b\bar{b}b$, which we leave out for future study. We have not included QCD corrections for the signal and neglected systematic uncertainties in our analysis. These would induce some uncertainties in our results.

A discovery might indicate EWBG driven by $\rho_b$. 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 $\rho_b$. 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 $\Delta A_{CP}$ of $B \to X_{\gamma} \gamma$ at Belle-II, if $H^\pm$ is not too heavy.

In principle, $\rho_{bb}$, $\rho_{db}$, $\rho_{bs}$ and $\rho_{bb}$ 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 $\rho_c$ can mimic $bZ$ signature in $pp$ collision via $cg \to cA \to cZH$. However, such possibilities can be excluded with the simultaneous application of $c$- and $b$-tagging on the final state topology.

While determining the discovery potential we set all $\rho_{ij} = 0$ except $\rho_{bb}$ for the sake of simplicity. In general non-zero $\rho_{ij}$s suppress $B(A/H \to b\bar{b})$ and hence the discovery potential of the $bZH$ and $bbZH$. E.g., if $\rho_{tt} \sim 0.1$, we find that the statistical significances of the BPII and BPIII are reduced by $\sim 15\% - 20\%$ for both the processes. A larger $\rho_{tt}$ would alleviate the significances further if $m_A/m_H > 2m_t$. Besides, $\rho_{tt}$ is likely $O(\lambda_t)$ [7], although, the impact is negligibly small for both the processes in all three BPs. Here, we assumed the flavor changing neutral Higgs coupling $\rho_{tt}$ to be small, however, a $O(1)$ value is still allowed by the current data [61, 62] (see also Ref. [63]), and could potentially reduce the significances of both the processes.

We assumed small $\rho_{tt}$ in order to avoid strong constraints arising from the $gg \to A/H$ searches. Notwithstanding, $O(1)$ $\rho_{tt}$ with complex phase provides another robust mechanism for EWBG [67] (see also Ref. [68]), which can be probed by the conventional search programs such as $gg \to A/H \to tt$ or $gg \to A/HHtt \to tttt$ [69]. The former process suffers from large interference [70] with the overwhelming $gg \to tt$ background, however a recent ATLAS study [71] found some sensitivity. If both $\rho_{bb}$ and $\rho_{tt}$ are sizable $bg \to bA/H \to btt$ as well as $gg \to bbA/H \to btt$ [22] are possible and would provide complimentary information.

In summary, we have explored the possibility of discovering and identifying additional bottom Yukawa coupling that might exist in the nature via $bg \to bA \to bZH$ and $gg \to bA \to bZH$ 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 extend up to $\sim 500$ GeV but the full HL-LHC dataset would be required. The latter process could also be discovered at the HL-LHC, however $\rho_{bb}$ needs to be large. A discovery would not only confirm physics beyond the Standard Model, but may also indicate the EWBG driven by $\rho_{bb}$.

ACKNOWLEDGMENTS

We thank W.-S Hou, M. Kohda and E. Senaha for many fruitful discussions. We also thank U.K. Dey for comments. This research is supported by grant MOST-107-2811-M-002-3069.

[1] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012); S. Chatrchyan et al. [CMS Collaboration], ibid. B 716, 30 (2012).
[2] M. Aaboud et al. [ATLAS Collaboration], Phys. Lett. B 786, 59 (2018).
[3] A. M. Sirunyan et al. [CMS Collaboration], Phys. Rev. Lett. 121, 121801 (2018).
[4] S.L. Glashow, S. Weinberg, Phys. Rev. D 15, 1958 (1977).
[5] T. Modak and E. Senaha, arXiv:1811.08058 [hep-ph].
[6] See, e.g., S. Davidson and H.E. Haber, Phys. Rev. D 72, 035004 (2005).
[7] W.-S. Hou and M. Kikuchi, Eur. Phys. Lett. 123, 11001 (2018).
[8] C. H. Chen and T. Nomura, Phys. Rev. D 98, 095007 (2018).
[9] D. Chowdhury and O. Eberhardt, JHEP 1805, 161 (2018). J. Haller, A. Hoecker, R. Kogler, K. Mijn, T. Peiffer and J. Stelzer, Eur. Phys. J. C 78, 675 (2018); For a non-exhaustive list, see e.g. B. Colella, F. Kling and S. Su, JHEP 1409, 161 (2014); G. C. Dorsch, S. J. Huber, K. Mimasu and J. M. No, Phys. Rev. Lett. 113, 211802 (2014); B. Hespel, F. Maltoni and E. Vryonidou, JHEP 1506, 065 (2015); V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 759, 369 (2016); M. Aaboud et al. [ATLAS Collaboration], Phys. Lett. B 783, 392 (2018); F. Kling, H. Li, A. Pyarelal, H. Song and S. Su, arXiv:1812.01633 [hep-ph].
[10] M. Aaboud et al. [ATLAS Collaboration], JHEP 1803, 174 (2018).
[11] A. M. Sirunyan et al. [CMS Collaboration], arXiv:1903.00941 [hep-ex].
[12] P. M. Ferreira, S. Liebler and J. Wittbrodt, Phys. Rev. D 97, no. 5, 055008 (2018).
[14] N. M. Coyle, B. Li and C. E. M. Wagner, Phys. Rev. D 97, 115028 (2018).
[15] The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2019-005.
[16] A. M. Sirunyan et al. [CMS Collaboration], arXiv:1809.10733 [hep-ex].
[17] A. Djouadi, Phys. Rept. 457, 1 (2008).
[18] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, Phys. Rept. 516, 1 (2012).
[19] D. Fontes, J. C. Romo and J. P. Silva, JHEP 1412, 043 (2014).
[20] W. S. Hou, M. Kohda and T. Modak, Phys. Rev. D 98, 075007 (2018).
[21] M. Ciuchini, G. Degrassi, P. Gambino and G. F. Giudice, Nucl. Phys. B 527, 21 (1998).
[22] K. G. Chetyrkin, M. Misiak and M. Munz, Phys. Lett. B 400, 206 (1997).
[23] B. Altunkaynak, W. S. Hou, C. Kao, M. Kohda and B. McCoy, Phys. Lett. B 751, 135 (2015).
[24] Y. Amhis et al. [HFLAV Collaboration], Eur. Phys. J. C 77, 895 (2017).
[25] M. Czakon, P. Fiedler, T. Huber, M. Misiak, B. McCoy, Phys. Lett. B 751, 400 (2017).
[26] A. Crivellin, A. Kokulu and C. Greub, Phys. Rev. D 87, 094012 (2013).
[27] A. L. Kagan and M. Neubert, Phys. Rev. D 58, 094012 (1998).
[28] M. Bennke, S. J. Lee, M. Neubert and G. Paz, Phys. Rev. Lett. 106, 141801 (2011).
[29] S. Watamuki et al., arXiv:1807.04230 [hep-ex].
[30] S. M. Barr and A. Zee, Phys. Rev. Lett. 65, 21 (1990).
[31] M. Jung and A. Pich, JHEP 1404, 076 (2014).
[32] V. Andreev et al. [ACME Collaboration], Nature 562, 355 (2018).
[33] M. Tanabashi et al. [Particle Data Group], Phys. Rev. D 98, 030001 (2018).
[34] H. E. Haber and H. E. Logan, Phys. Rev. D 62, 015011 (2000).
[35] D. Eriksson, J. Rathman and O. Stål, Comput. Phys. Commun. 181, 189 (2010).
[36] M. E. Peskin and T. Takeuchi, Phys. Rev. D 46, 381 (1992).
[37] H. E. Haber and O. Stål, Eur. Phys. J. C 75, 491 (2015).
[38] C. D. Froggatt, R. G. Moorhouse and I. G. Knowles, Phys. Rev. D 45, 2471 (1992).
[39] M. Baak and R. Kogler, arXiv:1306.0571 [hep-ph].
[40] W. S. Hou, M. Kohda and T. Modak, Phys. Rev. D 99, 055046 (2019).
[41] A. M. Sirunyan et al. [CMS Collaboration], JHEP 1808, 113 (2018).
[42] The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2019-010.
[43] CMS Collaboration, CMS-PAS-EXO-17-024.
[44] M. Aaboud et al. [ATLAS Collaboration], JHEP 1811, 085 (2018).
[45] To obtain the 95% CL $\sigma(pp \to bA/H + X) \cdot B(A/H \to b\bar{b})$ upper limit for the three benchmark points BP1, BP2 and BP3, we digitized the figure of Ref. [41]. The figure is available in http://cms-results.web.cern.ch/cms-results/.
[46] M. Kohda, T. Modak and A. Soffer, Phys. Rev. D 97, 115019 (2018).
[47] J. Alwall et al., JHEP 1407, 079 (2014).
[48] R.D. Ball et al. [NNPDF Collaboration], Nucl. Phys. B 877, 290 (2013).
[49] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr and B. Fuks, Comput. Phys. Commun. 185, 2250 (2014).
[50] T. Sjostrand, S. Mrenna and P. Skands, JHEP 0605, 026 (2006).
[51] J. Alwall et al., Eur. Phys. J. C 53, 473 (2008).
[52] J. de Favereau et al. [DELPHES 3 Collaboration], JHEP 1402, 057 (2014).
[53] ATLAS-CMS recommended predictions for top-quark-pair cross sections: https://twiki.cern.ch/twiki/bin/view/LHCPHysics/TopPairWWW
[54] N. Kidonakis, Phys. Rev. D 82, 054018 (2010).
[55] Y. Li and F. Petriello, Phys. Rev. D 86, 094034 (2012).
[56] J. Campbell, R.K. Ellis and R. Röntsch, Phys. Rev. D 87, 114006 (2013).
[57] SM Higgs production cross sections at $\sqrt{s} = 14$ TeV: https://twiki.cern.ch/twiki/bin/view/LHCPHysics/CERNYellowReportPageAt14TeV2010
[58] J.M. Campbell and R.K. Ellis, JHEP 1207, 052 (2012).
[59] M. Grazzini, S. Kallweit, D. Rathlev and M. Wiesemann, Phys. Lett. B 761, 179 (2016).
[60] G. Cowan, K. Cranmer, E. Gross and O. Vitells, Eur. Phys. J. C 71, 1554 (2011).
[61] T. Horiguchi et al. [Belle Collaboration], Phys. Rev. Lett. 119, no. 19, 191802 (2017).
[62] T. Hurth and M. Nakao, Ann. Rev. Nucl. Part. Sci. 60, 645 (2010).
[63] W. S. Hou, M. Kohda and T. Modak, Phys. Rev. D 98, 015002 (2018).
[64] M. Kohda, T. Modak and W. S. Hou, Phys. Lett. B 776, 379 (2018).
[65] W. S. Hou, M. Kohda and T. Modak, Phys. Lett. B 786, 212 (2018).
[66] W. Altmannshofer, B. Maddock and D. Tuckler, arXiv:1904.10956 [hep-ph].
[67] K. Fuyuto, W.-S. Hou, E. Senaha, Phys. Lett. B 776, 402 (2018).
[68] J. de Vries, M. Postma, J. van de Vis and G. White, JHEP 1801, 089 (2018).
[69] N. Craig, J. Hajer, Y. Y. Li, T. Liu and H. Zhang, JHEP 1701, 018 (2017).
[70] For a recent reference, see M. Carena and Z. Liu, JHEP 1611, 159 (2016), and references therein.
[71] M. Aaboud et al. [ATLAS Collaboration], Phys. Rev. Lett. 119, 191803 (2017).
[72] For recent discussions see e.g., A. Djouadi, L. Maiani, A. Polosa, J. Quevillon and V. Riquer, JHEP 1506, 168 (2015); N. Craig, F. D’Eramo, P. Draper, S. Thomas and H. Zhang, JHEP 1506, 137 (2015); J. Hajer, Y. Y. Li, T. Liu and J. F. H. Shiu, JHEP 1511, 124 (2015); S. Gori, I. W. Kim, N. R. Shah and K. M. Zurek, Phys. Rev. D 93, 075038 (2016).