The $tZH$ and $tZ\ell$ production in 2HDM: Prospects for discovery at the LHC

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We study the discovery potential of the $cq \rightarrow tA \rightarrow tZH$ process at the LHC, where $A$ and $H$ are CP-odd and even exotic scalars, respectively. The context is the general Two Higgs Doublet Model, where $cq \rightarrow tA$ is induced by the flavor changing neutral Higgs coupling $\rho_{tc}$. We find that the process $cq \rightarrow tA \rightarrow tZH$ can be discovered for $m_A \sim 400$ GeV, but would likely require high luminosity running of the LHC. Such a discovery would shed light on the mechanism behind the observed Baryon Asymmetry of the Universe. We also study $cq \rightarrow tA \rightarrow tZ\ell$, where $h$ is the observed 125 GeV scalar, but find it out of reach at the LHC.

I. INTRODUCTION

The discovery of the Higgs boson [1] $h(125)$ at the Large Hadron Collider (LHC) confirms the Standard Model (SM) as the correct theory at the electroweak scale. As all fermions come in three copies, additional scalars might well exist in Nature. In particular, given that $h$ belongs to a weak doublet, extra scalar doublets ought to be searched for. However, the apparent absence of New Physics (NP) so far at the LHC and the emergent "approximate alignment", i.e. the $h$ boson is found to resemble rather closely the SM Higgs boson, suggest that the extra scalars might be rather heavy. In this so-called decoupling limit [2], where the exotic scalars are multi-TeV in mass, discovery becomes rather difficult even for the High Luminosity LHC (HL-LHC).

By adding just one scalar doublet $\Phi'$, the two Higgs doublet model (2HDM) [3] is one of the simplest extensions of SM. We are interested in sub-TeV exotic scalars $A$, $H$, and $H^\mp$. The most popular 2HDMs, of interest already before the $h$ boson discovery, are those with a $Z_2$ symmetry imposed [3]. The $Z_2$ symmetry enforces the up- and down-type quarks to couple to just one scalar doublet, thereby ensuring Natural Flavor Conservation (NFC) [4] and forbids all flavor changing neutral Higgs (FCNH) couplings. But this removes the possibility of any additional Yukawa coupling.

Our context is the general 2HDM (g2HDM), without imposing $Z_2$ symmetry. Indeed, approximate alignment can be accommodated [5] [6] without taking the decoupling limit, even with $O(1)$ extra Higgs quartic couplings, clearing the way for sub-TeV $A$, $H$, and $H^\mp$. In the absence of $Z_2$ symmetry, both doublets couple to $u$- and $d$-type quarks, and two separate Yukawa matrices $\lambda_{ij}^c = (\sqrt{2} m_{ij}^q / v) \delta_{ij}$ (with $v \approx 246$ GeV) and $\rho_{ij}^c$ emerge after diagonalization of the fermion mass matrices. Here, $F$ denotes $u$- and $d$-type quarks and $e$-type leptons, with the fermion mass and mixing structure and approximate alignment together replacing the NFC condition [5]. The $\lambda$ matrices are real and diagonal, but the $\rho$ matrices are in general non-diagonal and complex. It was pointed out recently that $O(1)$ $\rho_{tt}$ and $\rho_{tc}$ can drive electroweak baryogenesis (EWBG) rather efficiently [7] [8].

If $\rho_{tt}$ and $\rho_{tc}$ are $O(1)$, one might discover the exotic scalars via the $cq \rightarrow tA/H \rightarrow ttt$ process with clean same-sign top signature [9] [10] (see also Refs. [11] [13]), and also with $A/H \rightarrow ttt$, i.e. the triple-top process [9]. Induced by only $\rho_{tc}$, the same-sign top process might emerge already with full Run-2 data. On the other hand, the more exquisite triple-top process, which depends on both $\rho_{tt}$ and $\rho_{tc}$ couplings, may require the inclusion of Run 3 data to show any indication. But if $\rho_{tt}$ is negligibly small, the triple-top discovery would not be possible. In this paper we consider the case where $\rho_{tt}$ is $O(1)$ but $\rho_{tc}$ is tiny, where another novel discovery mode would be $cq \rightarrow tA \rightarrow tZH$ (charge conjugate process always implied) for $m_A > m_Z + m_t$. With no dilution from $A \rightarrow t\bar{t}$, the process can provide an additional discovery mode that is complementary to Refs. [9] [10], and provide additional information on $\rho_{tc}$ driven EWBG.

The $cq \rightarrow tA \rightarrow tZH$ process can be searched for in the inclusive $pp \rightarrow tA + X \rightarrow tZH + X$ process, with $Z \rightarrow \ell^+\ell^-$, $H \rightarrow t\bar{t} + t\bar{t}$, and at least one top decaying semileptonically. We call this the $tZH$ process, the observation of which has another intriguing impact. It has been shown that the $A \rightarrow ZH$ decay can provide a smoking gun signature for the strongly first order electroweak phase transition (EWPT) which might have occurred in the early Universe [14] [16]. A strongly first order EWPT is needed for the out of equilibrium condition that is required for successful EWBG [17]. Realizing the importance [13], indeed both ATLAS and CMS have pursued $gg \rightarrow A \rightarrow ZH$ search [19] [20]. However, if $\rho_{tt}$ is tiny, $gg \rightarrow A$ vanishes, and the $tZH$ process will be a unique probe of the strongly first order EWPT mechanism, as well as the $\rho_{tc}$ driven EWBG scenario.

For completeness, we also study the prospect for the $cq \rightarrow tA \rightarrow tZ\ell$ process. The process is also induced by $\rho_{tc}$, but would depend on $\cos \gamma$, the $h-H$ mixing angle. The process can be searched for via $pp \rightarrow tA + X \rightarrow tZH + X$, with $t \rightarrow \ell^+\nu\ell$, $Z \rightarrow \ell^+\ell^-$ and $h \rightarrow bb$, which we call the $tZH$ process. It provides another complementary probe of the $\rho_{tc}$ driven EWBG scenario, as well as the $c_\gamma$ mixing angle if $\rho_{tt}$ is rather small.

In the following, we first discuss the framework in Sec. II followed by the parameter space and discovery potential of the $tZH$ process in Sec. III, Sec. IV is dedicated to the $tZ\ell$ process, and we summarize our results with some discussion in Sec. V.
II. FRAMEWORK

The scalars \( h, H, A \) and \( H^+ \) couple to fermions by \[21\]

\[
\mathcal{L} = -\frac{1}{\sqrt{2}} \sum_{F=L,D,L'} F_i \left[ -\lambda_{ij}^F s_i + \rho_{ij}^F c_i \right] h
+ \left( \lambda_{ij}^F c_i + \rho_{ij}^F s_i \right) H - i \text{sgn}(Q_F) \rho_{ij}^F A \right] R F_j
- \bar{U}_i \left[ (V^{R^\dagger})_{ij} R \right. - \left. (\rho^{U^\dagger} V)_{ij} L \right] D_j H^+
- \bar{U}_i \rho_{ij}^F R L_i^+ H^+ + \text{H.c.},
\]

where \( L, R = (1 \mp \gamma_5)/2, i, j = 1, 2, 3 \) are generation indices, \( V \) is Cabibbo-Kobayashi-Maskawa matrix, \( c_0 = \cos \gamma \) is the \( h-H \) mixing angle between CP-even scalars, and \( U = (u, c, t), D = (d, s, b), L' = (e, \mu, \tau) \) and \( V = (\nu_e, \nu_\mu, \nu_\tau) \) are in vectors in flavor space. The matrices \( \lambda_{ij}^F, \rho_{ij}^F \) are real and diagonal, whereas \( \rho_{ij}^F \) are in general complex and non-diagonal.

In the Higgs basis, the most general CP-conserving two Higgs doublet potential can be written as \[5, 21\]

\[
V(\Phi, \Phi') = \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 |\Phi'|^2 - (\mu_{12}^2 \Phi^\dagger \Phi' + h.c.)
+ \eta_1 |\Phi|^4 + \eta_2 |\Phi'|^4 + \eta_3 |\Phi|^{2} |\Phi'|^{2} + \eta_4 |\Phi'|^{2} |\Phi|^2
+ \left[ \frac{\eta_6}{2} (\Phi^\dagger \Phi')^2 + (\eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2) \Phi^\dagger \Phi' + h.c. \right],
\]

where the vacuum expectation value \( v \) arises from the doublet \( \Phi \) via the minimization condition \( \mu_{11}^2 = -\frac{1}{2}\eta_1 v^2 \), while \( \langle \Phi' \rangle = 0 \) (hence \( \mu_{22}^2 > 0 \)), and \( \eta \)'s are quartic couplings. Here we follow the notation of Ref. \[5\]. A second minimization condition, \( \mu_{12}^2 = \frac{1}{2} \eta_6 v'^2 \), removes \( \mu_{12}^2 \), and the total number of parameters are reduced to nine \[5\].

Two relations \[5\] arise for the mixing angle \( \gamma \) when diagonalizing the mass-squared matrix for \( h, H \),

\[
c_\gamma^2 = \frac{\eta_6 v'^2 - m_h^2}{m_H^2 - m_h^2}, \quad \sin 2\gamma = \frac{2\eta_6 v'^2}{m_H^2 - m_h^2}.
\]

The alignment limit, \( c_\gamma \to 0 \), is reached for \( \eta_6 \to 0 \), hence \( m_h^2 \to \eta_6 v'^2 \), or via decoupling \[2\], i.e. \( m_{H^2}^2 \gg v'^2 \). But for small but not infinitesimal \( c_\gamma \), one has \( c_\gamma \simeq |\eta_6| v'^2/(m_H^2 - m_h^2) \). This is the so-called approximate alignment \[5\], i.e. small \( c_\gamma \) values can be attained with \( \eta_6, \eta_1 \gg m_h^2/v'^2 \). The scalar masses can be expressed in terms of the parameters in Eq. \[2\],

\[
m_{h,H}^2 = \frac{1}{2} \left[ m_A^2 + (\eta_1 + \eta_5) v'^2 \right. + \sqrt{(m_A^2 + (\eta_5 - \eta_1) v'^2)^2 + 4\eta_6^2 v'^4}\right],
\]

\[
m_A^2 = \frac{1}{2} (\eta_3 + \eta_4 - \eta_5) v'^2 + \mu_{22}^2,
\]

\[
m_{H^\pm}^2 = \frac{1}{2} \eta_3 v'^2 + \mu_{22}^2.
\]

The processes of interest are \( cg \to tA \to tZH \) and \( tZh \), where \( cg \to tA \) is induced by \( \rho_{ct} \), but the \( A \to ZH, Zh \) decays via the gauge couplings \[3, 22\]

\[
\frac{g_2}{2c_W} Z_\mu \left[ c_\gamma (h \tilde{\phi}^\mu A - A \partial^\mu h) - s_\gamma (H \tilde{\phi}^\mu A - A \partial^\mu H) \right], \quad (7)
\]

with \( c_W \) the Weinberg angle and \( g_2 \) the SU(2) gauge coupling. We see from Eq. \[7\] that \( A \to ZH \) is proportional to \( s_\gamma \), while \( Z \to ZH \) is proportional to \( c_\gamma \). The coupling \( \rho_{ct} \) can also generate \( cg \to tA \), but it is very stringently constrained by flavor physics \[23\]. We set \( \rho_{ct} \) to zero throughout the paper for simplicity.

For nonzero \( \rho_{ct} \), we remark that the discovery at LHC, if at all, would first occur through the process \( cg \to tA \to tt\bar{c} \) \[9\]. For \( m_A < 2m_t t \), if other \( \rho_{ij} \)'s are small, \( cg \to tA \to tZH \) could be the only process to emerge after \( cg \to tA \to tt\bar{c} \). For \( m_A > 2m_t t \), \( cg \to tA \to tt\bar{c} \) would in general be accompanied by the \( cg \to tA \to tt \) process \[9\], unless \( \rho_{tt} \) is negligibly small, which we shall assume. We shall focus on \( t \to b\ell^+\nu_\ell, H \to t\bar{c} + i\bar{c} \), and \( Z \to \ell^+\ell^- \) decays, with the top quark from H decay also decaying semileptonically. Thus, following a possible \( cg \to tA \to tt\bar{c} \) discovery, \( cg \to tA \to tZH \) could be the only process that might provide a complementary probe of the \( \rho_{ct} \) driven EWBG, even for approximate alignment (i.e. small \( c_\gamma \)). In the following, we assume \( \rho_{ct} \) is the only non-zero coupling and set all other couplings to zero. Their impact, however, will be discussed later in the paper.

The prospect for \( cg \to tA \to tZh \) closely depends on the mixing angle \( c_\gamma \), vanishing for \( c_\gamma \to 0 \). For large \( \rho_{tt} \), \( gg \to A \to Zh \) \[25\] probes \( c_\gamma \). For negligibly small \( \rho_{tt} \), the process \( cg \to tA \to tZh \) can provide unique probe of \( c_\gamma \). We shall focus on \( t \to b\ell^+\nu_\ell, h \to bb \) and \( Z \to \ell^+\ell^- \).

III. THE tZH PROCESS

In this section we analyze the discovery potential of the \( tZh \) process at the LHC. We first look at the relevant constraints on the parameter space, then find the discovery potential at \( \sqrt{s} = 14 \) TeV. For simplicity, we assume all \( \rho_{ij} = 0 \) except \( \rho_{ct} \). However, the impact of other \( \rho_{ij} \)'s will be discussed later in the paper. To simplify further, we set \( c_\gamma = 0 \) throughout this section.

A. Parameter Space

Let us find the available parameter space for the \( tZh \) process. We first focus on the mass spectrum of the extra scalars \( A, H \) and \( H^+ \). The process requires \( A \) heavier than \( H \) by at least \( m_Z \). To find whether such mass spectrum exists, the dynamical parameters in Eq. \[2\] need to satisfy positivity, perturbativity, and tree-level unitarity conditions, for which we utilize 2HDMC \[26\]. We first express the quartic couplings \( \eta_1, \eta_3 \) in terms of \[5, 21\].
\[ \eta_1 = \frac{m_h s_\gamma^2 + m_H^2 c_\gamma^2}{v^2}, \]
\[ \eta_3 = \frac{2(m_H^2 - \mu_2^2)}{v^2}, \]
\[ \eta_4 = \frac{m_h^2 c_\gamma^2 + m_H^2 s_\gamma^2 - 2m_{H^+}^2 + m_A^2}{v^2}, \]
\[ \eta_5 = \frac{m_H^2 s_\gamma^2 + m_A^2 c_\gamma^2 - m_A^2}{v^2}, \]
\[ \eta_6 = \frac{(m_h - m_H^2)(-s_\gamma^2)}{v^2}. \]

The quartic couplings \( \eta_2 \) and \( \eta_7 \) do not enter scalar masses, nor the mixing angle \( \gamma \). Therefore in our analysis we take \( v, m_h, m_H, m_A, m_{H^\pm}, \mu_2, \eta_2, \eta_7 \) as the phenomenological parameters.

To save computation time, we randomly generate these parameters in the following ranges: \( \eta_2 \in [0, 3], \eta_7 \in [-3, 3], \mu_2 \in [0, 1000] \text{ GeV}, m_A \in [300, 500] \text{ GeV}, m_H \in [200, m_A - m_Z] \text{ GeV}, m_{H^\pm} \in [300, 500] \text{ GeV} \), while satisfying \( m_h = 125 \text{ GeV} \). Note that since the \( cg \to tA \to tZH \) process depends only on \( s_\gamma \), for simplicity we take \( c_\gamma = 0 \) in this section. To simplify further, we demand \( m_A < m_{H^\pm} + m_W \) to forbid the \( A \to H^\pm W^\mp \) decay. We then pass the randomly generated parameters to 2HDMC for scanning, which uses \( m_{H^\pm} \) and \( \Lambda_{-7} \) as input parameters in the Higgs basis with \( v \) as an implicit parameter. To match the 2HDMC convention, we identify \( \eta_{1-7} \) as \( \Lambda_{1-7} \) and take \(-\pi/2 \leq \gamma \leq \pi/2\), and \( \eta_2 \) needs to be greater than zero as required by positivity, along with other more involved conditions in 2HDMC. In addition, we further conservatively demand all \( |\eta_i| \leq 3 \).

One also has to consider the stringent oblique \( T \) parameter \([27]\) constraint, which restricts the scalar masses \( m_A, m_H, \), and \( m_{H^+} \) \([28, 29]\), and therefore the quartic couplings \( \eta_i s \). We use the \( T \) parameter expression given in Ref. \([28]\) and check that the points that passed positivity, unitarity and perturbativity conditions in 2HDMC, also satisfy the \( T \) parameter constraint within 2\( \sigma \) error \([30]\). These final points together are called “scan points”, which are plotted as gray dots in Fig. 1 in the \( \mu_2^2/v^2 \) and \( |\eta_3 + \eta_4 - \eta_5| \) vs \( m_A \) planes. The figure illustrates that there exists finite parameter space for \( 300 \text{ GeV} \leq m_A \leq 500 \text{ GeV} \), which can facilitate \( A \to ZH \) decay. In general, heavier \( m_A \) are possible, but the discovery potential diminishes with the rapid fall-off in parton luminosity. From the scan points in Fig. 1 we choose three benchmark points (BPs) for our analysis, which are summarized in Table. I.

The coupling \( \rho_{tc} \) is constrained by both LHC search and flavor physics. As we assume \( c_\gamma = 0 \) throughout this section, the most stringent limit arises from CMS search for four-top production \([31]\), where the CRW region, i.e. Control Region for \( t\bar{t}W \) background, gives the most relevant constraint. For non-zero \( \rho_{tc} \), the process \( cg \to tH/tA \to t\bar{t}c \) with same-sign top (same sign leptons plus jets) contributes abundantly to the CRW region, resulting in stringent constraint on \( \rho_{tc} \). There is, however, a subtlety. The \( cg \to tH \to t\bar{t}c \) and \( cg \to tA \to t\bar{t}c \) processes cancel each other exactly by destructive interference, if the masses and widths of \( H \) and \( A \) are the same \([32, 33]\). This cancellation diminishes \([30]\) when the \( m_A - m_H \) mass splitting is larger than the respec-
We now analyze the discovery prospects for $c q \rightarrow t A \rightarrow t Z H$ at the LHC with $\sqrt{s} = 14$ TeV. The process can be searched for via $p p \rightarrow t A + X \rightarrow t ZH + X \rightarrow t Z(t\bar{c} + t\bar{c}) + X$, with $Z \rightarrow \ell^+ \ell^-$ and at least one of the final state top quarks decaying semileptonically. $Z \rightarrow \tau^+ \tau^-$, $\nu \bar{\nu}$ decays are also possible, but we do not find them as promising. The dominant backgrounds for the $t Z H$ process arise from $t\bar{t}Z$ and $WZ +jets$ processes, while $tWZ$, four-top quarks ($4t$), $t\bar{t}h$, $t\bar{t}W$ and $tZ + jets$ are subdominant. Minor contributions come from $3t + jets$ and $3t + W$jets.

In order to find the discovery potential of the three benchmark points, we generate background and signal event samples at LO by Monte Carlo event generator MadGraph5_aMC@NLO \cite{Alwall:2014hca} with the parton distribution function (PDF) set NN23LO1 \cite{Ball:2012cx} at $\sqrt{s} = 14$ TeV. The event samples are then interfaced with PYTHIA 6.4 \cite{Sjostrand:2006za} for showering and hadronization, and finally fed into Delphes 3.4.0 \cite{deFavereau:2013fsa} to incorporate detector effects. We have generated the matrix elements (ME) of signal and all backgrounds except for the $WZ + jets$ with up to one additional jet in the final state, followed by ME and parton shower merging with the MLM matching scheme \cite{Mangano:2006rw,Alwall:2007fs} to incorporate detector effects. We have not included backgrounds arising from the non-prompt and fake sources, as they are not properly modeled in Monte Carlo simulations, and usually require data to make estimates. Here we have incorporated default ATLAS-based detector card available within Delphes framework. The effective model is implemented in FeynRules \cite{Alloul:2013bka}.

The dominant $t\bar{t}Z$ cross section at LO is normalized to the NLO by the $K$-factor 1.56 \cite{Liu:2013bpa}. The $WZ + jets$ background is adjusted to NNLO cross section by a factor 2.07 \cite{Kanazawa:2013sia}. Furthermore, the LO $t\bar{t}Z + jets$, $t\bar{t}h$, $4t$ and $t\bar{t}W^\pm (t\bar{t}W^\mp)$ cross sections are adjusted to NLO by $K$ factors 1.44 \cite{Liu:2013bpa}, 1.27 \cite{Liu:2013bpa}, 2.04 \cite{Liu:2013bpa} and 1.35 (1.27) \cite{Liu:2013bpa} respectively, while the cross sections for $3t + jets$, $3t + W$jets and $tWZ$ are kept at LO. For simplicity, the QCD correction factors for the $t\bar{t}Z_j$ and $W^\pm Z + jets$ processes are assumed to be the same as their respective charge conjugate processes. The signal cross sections for all three BPs are kept at LO.

Let us discuss the event selection criteria for the $t Z H$ process. Each event should contain at least three charged leptons ($e$ and $\mu$), at least three jets with at least two $b$-tagged, and missing transverse energy ($E_T^{miss}$). The
transverse momenta, $p_T$, of the leading charged lepton should be $> 25$ GeV, while the other two leptons should have $p_T > 20$ GeV. The minimum transverse energy $E_T^{\text{miss}}$ needs to be $> 35$ GeV. All three jets are required to have $p_T > 20$ GeV. The absolute value of pseudorapidity, $|\eta|$, of the three leading leptons and three jets (which includes two $b$-tagged jets) should be $< 2.5$. The separation $\Delta R$ between any two leptons, any two jets, and any jet and lepton should be $> 0.4$. The jets are reconstructed by utilizing anti-$k_T$ algorithm with radius parameter $R = 0.6$.

The invariant mass of the two opposite-charge, same-flavor leptons, $m_{\ell^+\ell^-}$, is required to be within the $Z$ boson mass window $76 < m_{\ell^+\ell^-} < 100$ GeV. As there are at least three charged leptons in the event, with two coming from $Z$ decay and one from one of the $t$ quark decays, there will be at least two combinations of $m_{\ell^+\ell^-}$. We identify the pair having the invariant mass $m_{\ell^+\ell^-}$ closest to $m_Z$ as the one coming from $Z$ decay, and then impose the $m_{\ell^+\ell^-}$ mass cut. We finally veto events for $E_T^{\text{miss}} > 150$ GeV, 250 GeV and 270 GeV for BPa, BPb and BPC, respectively. The $E_T^{\text{miss}}$ veto helps reduce the dominant $t\bar{t}Z$ background for all three BPs.

The normalized $m_{\ell^+\ell^-}$ and $E_T^{\text{miss}}$ distributions before any selection cuts (with minimal default cuts during event generation in MadGraph5_aMC@NLO) for the three BPs and backgrounds are plotted in Fig. 3.

In this exploratory study, for simplicity we have not optimized the selection cuts such as $m_{\ell^+\ell^-}$ and $E_T^{\text{miss}}$ for our BPs. The background cross sections after selection cuts are summarized in Table III for all three BPs. In Table IV we give signal cross sections and the corresponding significance for the integrated luminosities $\mathcal{L} = 600$ and 3000 fb$^{-1}$. The statistical significances in Table IV are determined by using $Z = \sqrt{2(S + B)\ln(1 + S/B) - S}$ [89], where $S$ and $B$ are the number of signal and background events after selection.

| BP  | $t\bar{t}Z$ | $WZ + \text{jets}$ | $tWZ$ | $4t$ | $t\bar{t}h$ | $t\bar{t}W$ | $tZ + \text{jets}$ | Others | Total Bkg. |
|-----|-------------|------------------|------|-----|-----------|-----------|-------------------|--------|-----------|
| $a$ | 0.655       | 0.077            | 0.025| 0.003 | 0.003     | 0.003     | 0.006             | 0.001  | 0.772     |
| $b$ | 0.902       | 0.11             | 0.035| 0.004 | 0.004     | 0.004     | 0.007             | 0.0002 | 1.066     |
| $c$ | 0.925       | 0.112            | 0.036| 0.005 | 0.004     | 0.004     | 0.007             | 0.0002 | 1.093     |

TABLE III. Background cross sections (in fb) for the $tZH$ process after selection cuts at $\sqrt{s} = 14$ TeV LHC. The subdominant $3\ell + \text{jets}$, $3\ell + W$ are added together as “Others” in the second last column, while the last column is the total background.

Table IV. $tZH$ signal cross sections and significances after selection cuts for the three benchmark points.

| BP   | Signal (fb) | Significance ($Z$) 600 (3000) fb$^{-1}$ |
|------|-------------|------------------------------------------|
| $a$  | 0.055       | 1.5 (3.4)                                |
| $b$  | 0.115       | 2.7 (6.0)                                |
| $c$  | 0.092       | 2.1 (4.8)                                |

We find that the significances can reach up to $\sim 1.5\sigma$, $2.7\sigma$ and $2.1\sigma$ for BPa, BPb and BPC, respectively, for 600 fb$^{-1}$. With the full HL-LHC dataset (i.e. 3000 fb$^{-1}$ integrated luminosity) one can have $\sim 3.4\sigma$, $6\sigma$ and $4.8\sigma$ for the BPs, respectively. With moderate $S/B \sim 10\%$ for the three BPs, these significances illustrates that dis-

FIG. 3. The normalized $m_{\ell^+\ell^-}$ (left) and $E_T^{\text{miss}}$ (right) distributions for the signal and background processes.
covery is possible for $m_A \sim 400$ GeV, while evidence is possible for $m_A \sim 350$ GeV. The significance is lower for lighter $m_A$ should not be surprising, since $B(A \rightarrow ZH)$ is lower for BPa than BPb and BPc. For heavier $m_A$ in BPb and BPc, such enhancement in branching ratios can compensate lower $c_g \rightarrow tA$ production cross section due to fall in parton luminosity. Our results illustrate possible for $m_A$ to be $\sim 400$ GeV at Run 3 (300 fb$^{-1}$), but discovery would require the HL-LHC. The achievable significances depend mildly on the applied $E_T^{\text{miss}}$ veto. E.g., if we apply the same $E_T^{\text{miss}}$ veto that is chosen for BPa to BPb and BPc, the significances of the latter two BPs would drop by $\sim 10\%$ and $\sim 17\%$ respectively. However, rejecting events with $E_T^{\text{miss}} > 250$ GeV would enhance the significance for BPb by $\sim 18\%$ but reduce by $\sim 8\%$ for BPc, while keep the significance for BPb unchanged. We remark in our exploratory analysis we have not optimized $E_T^{\text{miss}}$ cut and leave out a more detailed analysis for future.

So far we have set all $\rho_{ij} = 0$ except $\rho_{tc}$. Before closing this subsection, let us briefly discuss the impact of other $\rho_{ij}$ couplings. If $\rho_{ij}$ follows similar flavor organization structure as in SM, $\rho_{tt}$ could be $O(\lambda_t)$, $\rho_{bb} \sim \lambda_b$, and $\rho_{tt} \sim \lambda_t$. In general, presence of other $\rho_{ij}$ opens up further decay modes of $A$ and $H$, which in turn dilutes $B(A \rightarrow ZH)$, and hence the discovery potential of the $tZH$ process. For example, if $\rho_{tt} = \lambda_t (0.5)$, the achievable significances for BPb and BPc with full HL-LHC dataset are reduced to $\sim 2.7\sigma (4.6\sigma)$ and $1.7\sigma (3.3\sigma)$ respectively, due to non-zero $B(A \rightarrow t(H)).$ The significance of BPa would remain unchanged as $m_A < 2m_t$. Impact of other $\rho_{ij}$ couplings are significantly milder than $\rho_{tt}$. For example, for $\rho_{bb} \sim \lambda_b$ and $\rho_{tt} \sim \lambda_t$, the significance in Table [IV] remain practically the same.

Complex $\rho_{tt}$ provides a generally more robust mechanism for EWBG [7, 8]. Having non-zero $\rho_{tt}$ motivates the conventional $gg \rightarrow H \rightarrow tt$ scalar resonance search, or $gg \rightarrow Htt \rightarrow tttt$ i.e. four-top search. The former process suffers from large interference [17] with the overwhelming $gg \rightarrow tt$ background, leading to a peak-dip signature that makes detection difficult, but recent searches by ATLAS [52] and CMS [53] find some sensitivity. See Ref. [32] for a recent discussion in g2HDM context. Presence of both $\rho_{tt}$ and $\rho_{tc}$ induce $gg \rightarrow A/H \rightarrow t\bar{t}$ [24] and $cg \rightarrow tA/tH \rightarrow ttt$ processes [8] which can also be observable at the LHC, but the former may suffer from $t+j$ mass resolution, which could be close to 200 GeV [54].

IV. THE $tZH$ PROCESS

We now discuss the prospect of $tZH$ process, i.e. $pp \rightarrow tA+X \rightarrow tZH+X$, with $t \rightarrow b\ell^+\nu_\ell$, $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$), and $b \rightarrow b\ell$. The process depends heavily on the mixing angle $c_\gamma$, as well as $\rho_{tc}$. In addition to the constraint from CMS CRW region [31], it also receives constraint from ATLAS $B(t \rightarrow ch)$ [35]. Indeed, larger $c_\gamma$ enhances $B(A \rightarrow Zh)$, but $cg \rightarrow tA$ production is balanced by the stronger constraint on $\rho_{tc}$, as can be seen from Fig. 2. The process is further plagued by tiny $\mathcal{B}(Z \rightarrow \ell^+\ell^-)$. These make the $tZH$ process not as promising as $tZH$ even for HL-LHC, which we make clear in the following.

To find the discovery potential, we choose a benchmark point where $A$ is heavier than $m_t + m_Z$, and lighter than $m_H + m_Z$. Such a choice would forbid $A \rightarrow ZH$ decay and enhance $B(A \rightarrow Zh)$. Unlike the previous section, we also need $c_\gamma \neq 0$. We find such a benchmark point from 2HDM which passes the perturbativity, unitarity, positivity constraints, as well as the $T$ parameter constraint. The parameter values are: $\eta_1 = 0.428$, $\eta_2 = 2.88$, $\eta_3 = 0.795$, $\eta_4 = 2.916$, $\eta_5 = 2.334$, $\eta_6 = -0.897$, $\eta_7 = 2.76$, $m_{H^+} = 378$ GeV, $m_A = 401$ GeV, $m_H = 559$ GeV, $c_\gamma = 0.186$ and $\mu_{22}^2/v^2 = 1.96$. With this set of parameters, we find $\rho_{tc}$ values above 0.5 is excluded at 95% CL. This is extracted from $\mathcal{B}(t \rightarrow ch)$ [35], while the constraint from CMS CRW region [31] is a bit weaker. The branching ratios corresponding to this BP are $B(A \rightarrow Zh) \approx 0.1, B(A \rightarrow t\bar{t} + c\bar{c}) \approx 0.9$.

There exists several backgrounds for $tZH$ process. The dominant backgrounds are $tZ$, $4t$, $tth$, with subdominant backgrounds from $tZ+jets$, $tW$, $3t+jets$, $3t+W$jets and $tWZ$. To find the discovery potential, we follow the same procedure to generate signal and background events as in Sec. III. We keep signal cross section at LO, but for backgrounds we take the same QCD correction factors as in previous section. The details of the selection cuts, and signal and background cross sections after selection cuts, are presented in an Appendix.

The statistical significance at $\sim 1.1\sigma$ turns out to be rather small, even with full HL-LHC dataset. While significances would be lower for heavier $m_A$ due to fall in the parton luminosity, it does not improve much for lighter $m_A$. In the latter case, i.e. for lighter $m_A$, $B(A \rightarrow Zh)$ becomes lower, and the constraint on $\rho_{tc}$ becomes more stringent from CMS CRW region [31]. For $cg \rightarrow tA \rightarrow tZH$ search in $h \rightarrow W^+W^-$ and $Z \rightarrow b\ell$ modes, one loses the mass reconstruction capability of $m_Z$, $m_h$ and $m_A$, hence the control of background processes. Therefore, it is likely that the $tZH$ process would remain below sensitivity even for HL-LHC.

V. DISCUSSION AND SUMMARY

We have studied the discovery potential of $cg \rightarrow tA \rightarrow tZH$, $tZH$ processes at the LHC. The $tZH$ process can be discovered, albeit likely needing HL-LHC data. Discovery is possible for $m_A \sim 400$ GeV, with statistical significance reaching up to $\sim 6\sigma$ with full HL-LHC dataset. But $m_A$ cannot be much lighter or heavier than $\sim 400$ GeV. The discovery prospect for the $tZH$ process is rather limited, primarily due to the suppression from mixing angle $c_\gamma$ (alignment “protection”), and the constraint on $\rho_{tc}$ from $B(t \rightarrow ch)$. With significance only about $1\sigma$ at best with 3000 fb$^{-1}$, $tZH$ seems out of reach at the LHC. We note that the $cg \rightarrow tH \rightarrow tZA$ process is pos-
sible for $m_H > m_Z + m_A$, and can be searched for by a strategy similar to $tZH$. We also remark that $\rho_{tt}$ can induce $ug \rightarrow tA \rightarrow tZH$ process, with similar signature. Although $\rho_{tt}$ could become stringently constrained \cite{55}, the discovery potential is balanced by large valence-quark induced $ug \rightarrow tA$ production.

In general, the presence of $\rho_{tt}$ would reduce the discovery potential of $tZH$ because of $B(A \rightarrow t\ell)$, but it opens up other modes for $A \rightarrow ZH$ discovery, for example induce $A \rightarrow ZH$ signal via loop induced $gg \rightarrow A \rightarrow ZH$ \cite{18}. The same is true for $\rho_{bb}$, where $A \rightarrow ZH$ can be induced by $gb \rightarrow bA \rightarrow bZH$ \cite{56, 57} as well as $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}ZH$ \cite{56, 57}. One can also have $gg \rightarrow A \rightarrow Zh$ \cite{25} and $gg \rightarrow b\bar{b}A \rightarrow b\bar{b}Zh$ \cite{26, 58, 59}. But both processes are again suppressed by the mixing angle $c_{\gamma}$. In general, the impact of $\rho_{bb}$ is inconsequential for the $tZH$ process, but the presence of $\rho_{cc}$ would reduce the discovery potential for $\rho_{bb}$ induced $A \rightarrow ZH$ processes.

We have not discussed so far the uncertainties in our results. We have not included QCD correction factors for signal in both the $tZH$ and $tZH$ processes. In general, $c$-quark initiated processes have non-negligible systematic uncertainties such as from PDF, which we have not included in our analysis. Such uncertainties for $c$-quark initiated processes are discussed in Refs. \cite{60, 61}, while a detailed discussion of PDF choices and their uncertainties is beyond the scope of this paper. We have not discussed so far the uncertainties in our results. A detailed estimate of such uncertainties is beyond the scope of this paper.

While the presence of $\rho_{tt}$ reduces the discovery potential of the $tZH$ process $m_A > 2m_t$, it opens up the exquisite discovery mode $cg \rightarrow tA/tH \rightarrow t\ell\ell$. It is also worthy of mention the “excess” seen by CMS \cite{52} in $gg \rightarrow A \rightarrow t\ell$ search at $m_A \approx 400$ GeV. Such excess can be interpreted within g2HDM framework \cite{52}, if $\rho_{tt} \approx 1.1$ and $\rho_{cc} \approx 0.9$ with $m_{H^\pm} \gtrsim 530$ GeV and $m_{A} \gtrsim 500$ GeV. Note that, for $\rho_{tt} \sim 1$, the $tZH$ discovery (or $cg \rightarrow tH \rightarrow tA$ discovery) is not possible due to suppression from $B(A \rightarrow t\ell)$ ($B(H \rightarrow t\ell)$) decay. However, if this excess materializes into evidence or discovery by Run 3, $cg \rightarrow tA/tH \rightarrow t\ell\ell$ might emerge immediately followed by discovery of $cg \rightarrow tA/tH \rightarrow t\ell\ell$.

In Summary, motivated by electroweak baryogenesis, we analyzed the discovery potential of the $cg \rightarrow tA \rightarrow tZH$ process. Such process might be induced by extra Yukawa coupling $\rho_{cc}$ if one removes the discrete $Z_2$ symmetry from 2HDM. We find discovery is possible at the HL-LHC if $m_A \sim 400$ GeV, but $\rho_{tt}$ would need to be small. For completeness, we have also studied the $cg \rightarrow tA \rightarrow tZH$ process, but do not find it promising. Discovery of the $cg \rightarrow tA \rightarrow tZH$ process will not only shed light on the strongly first order electroweak phase transition, it may also help uncover the mechanism behind the observed Baryon Asymmetry of the Universe.

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**Appendix A: Event selection for the $tZH$ process**

We discuss the event selection criteria and the corresponding signal and backgrounds for the $tZH$ process. Events are required to have at least three leptons, and at least three $b$-jets with some missing transverse energy. The $p_T$ of the leading and other two subleading leptons are required to be $> 25, 20$ and $15$ GeV respectively, with pseudo-rapidity $|\eta| < 2.5$. The $p_T$ of all three $b$-jets are required to be $> 20$ GeV with $|\eta| < 2.5$. The $E_T^{miss}$ in each event should be $> 35$ GeV. We demand the separation $\Delta R$ between any two leptons, any two jets, and any jet and lepton to be $> 0.4$. We then apply the $m_{\ell\ell}$-cut: for each event there are at least two possible $m_{\ell\ell}$-combinations, and the $m_{\ell\ell}$-combination closest to $m_Z$ should be within $70$ GeV $< m_{\ell\ell} < 100$ GeV. Similarly, there are at least two possible $m_{bb}$ combinations in each event. We demanded the one that is closest to $m_h$ should be within $|m_{bb} - m_h| < 25$ GeV. Finally, we construct all possible $m_{\ell\ell bb}$ combinations from the three leading leptons and leading $b$-jets, and demand the $m_{\ell\ell bb}$ combination closest to $m_A$ should be within $|m_{\ell\ell bb} - m_A| < 100$ GeV. The cross sections of signal and background processes after selection cuts are summarized in Table \[V\].

| Signal (fb) | $tZH$ | $\ell\ell$ | $tt\ell$ | Others | Total Bkg. |
|------------|-------|-------------|---------|--------|-------------|
| 0.003 | 0.025 | 0.002 | 0.0004 | 0.0001 | 0.027 |

TABLE V. Signal and background cross sections (in fb) for the $tZH$ process after selection cuts at $\sqrt{s} = 14$ TeV LHC. The subdominant backgrounds are added together as “Others”, and the last column is the total background.

\[1\] G. Aad \textit{et al.} [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012); S. Chatrchyan \textit{et al.} [CMS Collaboration], \textit{ibid}. B 716, 30 (2012).

\[2\] J.F. Gunion and H.E. Haber, Phys. Rev. D 67, 075019 (2003).

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\[4\] S.L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).
