

Probing the general 2HDM with flavor violation through $A \rightarrow ZH$

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We investigate the LHC discovery prospects for a second Higgs doublet through $A \rightarrow ZH$ weak decay. The latter is identified as the *smoking gun signature* of two Higgs doublet models (2HDMs) with first-order electroweak (EW) phase transition, a necessary condition for EW baryogenesis. In the general 2HDM (G2HDM) that has flavor-changing neutral Higgs couplings, H may decay dominantly via $t\bar{c} + \bar{t}c$ final states, giving rise to trilepton signals. By a phenomenological analysis, we show that $A \rightarrow ZH$ in $\ell^+\ell^-\bar{t}c$ or $\ell^+\ell^-\bar{t}c$ final states could be a promising probe of G2HDM at the LHC with flavor violation.

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I. INTRODUCTION

The existence of a second Higgs doublet introduces extra Higgs bosons beyond the one discovered at the LHC [1,2], and could provide the mechanism to explain the matter-antimatter asymmetry of the Universe. Its discovery would confirm the nonminimal structure of the Higgs sector and perhaps shed light on the mechanism behind the baryon asymmetry of the Universe (BAU).

We specifically advocate the general two Higgs doublet model (G2HDM), i.e. without the usual Z_2 symmetry. With two identical weak doublets, it allows for a second set of Yukawa couplings, other than fermion masses. Though it has not garnered much attention, this model has quite a few merits.

Quartic couplings at $\mathcal{O}(1)$ can provide [3] prerequisite first-order electroweak phase transition (FOEWPT), needed for electroweak baryogenesis (EWBG), while $\mathcal{O}(1)$ extra top Yukawa couplings ρ_{tc} and ρ_{tt} can *each* drive [4] EWBG to account for BAU, one of the biggest mysteries. [See also Refs. [5–26] for FOEWPT and EWBG in the two Higgs doublet model (2HDM).] Given this, one must confront the stringent electron electric dipole moment bounds of ACME [27] and JILA [28], where a spectacular cancellation mechanism [29] allows one to survive these bounds.

Without the Z_2 symmetry, G2HDM allows for flavor-changing neutral Higgs (FCNH) couplings, such as $t \rightarrow ch$ [30]. Interestingly, this decay still has not been seen, as it is suppressed by *alignment*, by a rather small h - H mixing between the two CP -even scalars. However, FCNH couplings can lead to *alignment enhanced* processes such

as $cg \rightarrow tH/tA \rightarrow t\bar{t}\bar{c}, t\bar{t}\bar{t}$ [31], while processes such as $cg \rightarrow bH^+$ [32] and $\bar{b}g \rightarrow \bar{c}H^+$ [33], along with $c\bar{b} \rightarrow H^+$ [34] resonant production, are not subject to Cabibbo-Kobayashi-Maskawa (CKM) suppression as in the 2HDM with Z_2 symmetry.

In this paper, we study the discovery prospects of $A \rightarrow ZH$ decay in $\ell^+\ell^-\bar{t}c$ or $\ell^+\ell^-\bar{t}c$ (henceforth, $\ell^+\ell^-\bar{t}c$) final states. This decay channel is identified as the smoking gun signature at the LHC of 2HDM scenarios with FOEWPT [13–16]. We propose a benchmark scenario and perform a detector level Monte Carlo analysis at the 14 TeV LHC. We show that searches for the $A \rightarrow ZH$ decay into the $\ell^+\ell^-\bar{t}c$ final state are promising: Run 2 data may already lead to discovery, thus providing a probe of G2HDM that has flavor-violating couplings.

II. G2HDM

In the Higgs basis where only one doublet gives mass, the most general CP -conserving scalar potential for two doublets Φ and Φ' is given by [35,36]

$$\begin{aligned} V(\Phi, \Phi') = & \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 |\Phi'|^2 - (\mu_{12}^2 \Phi^\dagger \Phi' + \text{H.c.}) \\ & + \frac{\eta_1}{2} |\Phi|^4 + \frac{\eta_2}{2} |\Phi'|^4 + \eta_3 |\Phi|^2 |\Phi'|^2 + \eta_4 |\Phi^\dagger \Phi'|^2 \\ & + \left[\frac{\eta_5}{2} (\Phi^\dagger \Phi')^2 + (\eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2) \Phi^\dagger \Phi' + \text{H.c.} \right], \end{aligned} \quad (1)$$

where all mass and quartic coupling parameters are chosen to be *real*, Φ generates the vacuum expectation value v for electroweak (EW) symmetry breaking through a first minimization condition of $\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2$, while $\langle \Phi' \rangle = 0$; hence, $\mu_{22}^2 > 0$. A second minimization condition $\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$ reduces the number of parameters to 9.

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In the Higgs basis, the CP -odd scalar A and the charged Higgs $H^\pm$ are mass eigenstates. The CP -even mass eigenstates h and H are obtained by diagonalizing the mass-squared matrix through a rotation characterized by the angle γ , denoted as $\beta - \alpha$ in 2HDM with Z_2 symmetry convention, which satisfies $s_\gamma c_\gamma = \eta_6 v^2 / (m_H^2 - m_h^2)$ [35,36], with $c_\gamma \equiv \cos \gamma$ ($s_\gamma \equiv \sin \gamma$). The emergent alignment phenomenon, that h closely resembles the SM Higgs boson [37], implies a rather small h - H mixing angle c_γ .

The general Yukawa couplings are [35,36]

$$\begin{aligned} \mathcal{L}_Y = & -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda_{ij}^f \sin \gamma + \rho_{ij}^f \cos \gamma) h \\ & + (\lambda_{ij}^f \cos \gamma + \rho_{ij}^f \sin \gamma) H - i \text{sgn}(Q_f) \rho_{ij}^f A] R f_j \\ & - \bar{u}_i [(V \rho^d)_{ij} R - (\rho^{u+})_{ij} L] d_j H^+ \\ & - \bar{\nu}_i \rho_{ij}^\ell R \ell_j H^+ + \text{H.c.}, \end{aligned} \quad (2)$$

where $i, j = 1, 2, 3$ are the generation indices, $\lambda_{ij}^f \equiv \delta_{ij} \sqrt{2} m_i^f / v$, $\text{sgn}(Q_f) = +1(-1)$ for $f = u$ ($f = d, \ell$), $L, R = (1 \mp \gamma_5)/2$, and V is the CKM matrix. The λ_{ij}^f matrices are real and diagonal, while ρ_{ij}^f are in general complex and nondiagonal. Here, we consider a CP -conserving model and take the ρ_{ij}^f matrices as real but not necessarily Hermitian.

In the alignment limit of $c_\gamma \rightarrow 0$, h couples diagonally as the SM Higgs boson, while H interacts through the extra Yukawa couplings ρ_{ij}^f . Thus, besides mass-mixing hierarchy protection [30] of FCNH couplings, alignment provides [36] further safeguard, such as for $t \rightarrow ch$, without relying on natural flavor conservation [38]. So, enforcing the Z_2 symmetry may be overkill. The H^+ and A couplings are independent of γ .

In what follows, we drop the superscript f and set all $\rho_{ij} = 0$ for simplicity, except ρ_{tt} and ρ_{tc} . We will return to the effect of turning on other ρ_{ij} later in the paper. We set $c_\gamma = 0$, and fix $m_h = 125$ GeV. In Fig. 1, we plot the branching ratios of $A \rightarrow t\bar{c} + \bar{t}c, t\bar{t}, ZH$ for $m_H = 200$ GeV, $\rho_{tt} = 0.3$, and $\rho_{tc} = 0.1$. We assume $m_{H^+} \simeq m_A$ (custodial symmetry), which is required by EW precision observables, implying that the decay $A \rightarrow W^- H^+$ is kinematically forbidden. We will return to $m_{H^+} \simeq m_H$ (twisted custodial [39]), where $A \rightarrow W^- H^+$ could be of similar magnitude to $A \rightarrow ZH$ later. We observe that $A \rightarrow ZH$ largely dominates over $A \rightarrow t\bar{c} + \bar{t}c$ and $A \rightarrow t\bar{t}$. Note that $A \rightarrow t\bar{c} + \bar{t}c$ dominates A decays for $m_A - m_H < m_Z$. The decay $A \rightarrow Zh$ is suppressed by c_γ . The subsequent decay of $H \rightarrow t\bar{c} + \bar{t}c$ is dominant, while $H \rightarrow W^+ W^-$ and $H \rightarrow ZZ$ decays are c_γ suppressed. Above the $t\bar{t}$ threshold, $H \rightarrow t\bar{t}$ opens up and could be the dominant decay channel. We note that a large $m_A - m_H$ splitting is still

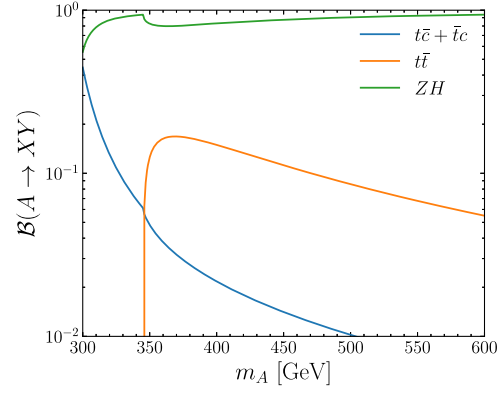


FIG. 1. Branching ratios of the CP -odd scalar A as a function of m_A for $m_H = 200$ GeV, $\rho_{tt} = 0.3$, and $\rho_{tc} = 0.1$.

possible, such that FOEWPT is realized while the $t\bar{t}$ channel remains open; see, e.g., Refs. [13–16] and references therein.

III. CONSTRAINTS ON G2HDM

The model is subject to theoretical and experimental constraints. Higgs quartic couplings in Eq. (1) are required to fulfill positivity, tree-level unitarity, and perturbativity constraints, which are implemented in 2HDMC-1.8.0 [40]. G2HDM parameter space is further required to fulfill EW precision constraints through the oblique parameters S , T , and U [41] using the Particle Data Group values [42]. The code 2HDMC calculates the theoretical predictions for these observables. We refer to Ref. [33] for details on the parameter space scan of the G2HDM and constraints.

Flavor constraints on extra top Yukawa couplings ρ_{tt} and ρ_{tc} are relatively mild [43,44], where it is found that [43,44] B_q mixing ($q = d, s$) strongly constrains ρ_{ct} due to the CKM $|V_{cq}/V_{tq}| \sim 25$ enhancement factor; hence, ρ_{ct} must be tiny. Therefore, ρ_{ct} is turned off here. Following Ref. [44], we estimate the modifications to the $B_q - \bar{B}_q$ mixing amplitude and use the UTfit results [45], $C_{B_d} = 1.09 \pm 0.09$ and $C_{B_s} = 1.10 \pm 0.06$, where $C_{B_q} \equiv M_{12}^q / M_{12}^{q|\text{SM}}$, while the phase ϕ_{B_q} is neglected in our study. We find the light blue region (extending to upper left) shown in Fig. 2 excluded at 2σ level. The B_q mixing constraint on ρ_{tc} is weaker [43]. Reinterpreting the limits from Ref. [43], we find the bound $|\rho_{tc}| \lesssim 1.7$ for $m_{H^+} = 500$ GeV.

The $B \rightarrow X_s \gamma$ constraint on m_{H^+} in G2HDM is not particularly strong [43,44]. Reference [44] finds that ρ_{bb} is more constrained than ρ_{tt} due to an enhancement factor of m_t/m_b ; hence, ρ_{bb} must be small. Setting $\rho_{bb} = 0$, we find the yellow exclusion region depicted in Fig. 2. The $B \rightarrow X_s \gamma$ constraint on ρ_{tc} is much weaker due to the small charm quark mass and the absence of any enhancement factor [44].

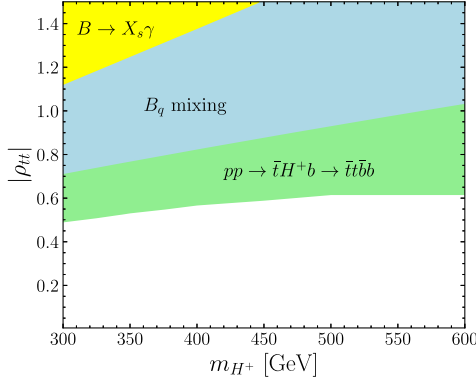


FIG. 2. Exclusion regions from $B \rightarrow X_s \gamma$, B_q mixing, and ATLAS $pp \rightarrow \bar{t}H^+b \rightarrow \bar{t}t\bar{b}b$ search in the m_{H^+} - $|\rho_{tt}|$ plane.

LHC indirect and direct measurement set limits on ρ_{tt} , but these are weaker [46] due to c_γ suppression [see Eq. (2)]. We further check these constraints using the new version of the code HiggsSignals [47], which incorporates the latest ATLAS and CMS Run 2 measurements, via HiggsTools [48]. ATLAS [49] and CMS [50] direct searches for $pp \rightarrow \bar{t}H^+(b)$ followed by $H^+ \rightarrow t\bar{b}$ (charge conjugate process implied) constrain ρ_{tt} as well. These searches set significant limits on $\sigma[pp \rightarrow \bar{t}H^+(b)] \times \mathcal{B}(H^+ \rightarrow t\bar{b})$. We reinterpret ATLAS limits [49] assuming $\mathcal{B}(H^+ \rightarrow t\bar{b}) = 100\%$ and obtain the light green exclusion region (extending upward) shown in Fig. 2. CMS limits [50] are also reinterpreted and found to be weaker; thus, only the ATLAS bounds are shown.

ATLAS [51] has performed searches for exotic Higgs bosons with flavor-violating couplings in final states with multiple leptons and b -tagged jets. The search results are interpreted in terms of a G2HDM with extra top Yukawa couplings ρ_{tt} , ρ_{tc} , and ρ_{tu} . An additional scalar boson with masses m_H between 200 and 620 GeV and couplings $\rho_{tt} = 0.4$, $\rho_{tc} = 0.2$, and $\rho_{tu} = 0.2$ is excluded at 95% confidence level (CL). CMS [52] searches for same-sign top associated production with a jet, via the $pp \rightarrow tH/A \rightarrow tt\bar{c}$ and $pp \rightarrow tH/A \rightarrow tt\bar{u}$ processes, set limits on ρ_{tc} and ρ_{tu} . In the absence of interference between H and A , and setting $\rho_{tc} = 1.0$, H or A with masses below approximately 770 GeV is excluded at 95% CL. Including interference effects extends the exclusion to $m_A = 810$ GeV at 95% CL. For our conservative choice of $\rho_{tc} = 0.1$, no limits are set. For nonzero c_γ , LHC $t \rightarrow qh$ ($q = u, c$) searches [53,54] set further limits on ρ_{tc} and ρ_{tu} . For $c_\gamma = 0.1$, we find that $|\rho_{tc}| \gtrsim 0.5$ ($|\rho_{tu}| \gtrsim 0.38$) is excluded at 95% CL. The limit decreases for $c_\gamma < 0.1$ and disappears for $c_\gamma = 0$, which we assume in our analysis. Note that D - $\bar{D}$ mixing and $B \rightarrow \tau\nu$ observables impose strong bounds on ρ_{tu} [43], requiring it to be very small; we set it to zero in our study.

Before discussing LHC search for $A \rightarrow ZH$ in $\ell^+\ell^-tc$ final state at 14 TeV, we point out that the chosen

benchmark model ($m_H = 200$ GeV, $|\rho_{tt}| = 0.3$, and $|\rho_{tc}| = 0.1$) evades all the constraints mentioned above.

IV. LHC SEARCH FOR $A \rightarrow ZH$

We now discuss the LHC search prospects for the $A \rightarrow ZH \rightarrow \ell^+\ell^-tc$ channel, which leads to a final state consisting of three leptons plus at least two jets, with at least one b -tagged and one non- b -tagged, and missing transverse energy. We use the simple *cut and count* method and assume 14 TeV collision energy. We choose $m_A = 450(500)$ GeV as a benchmark point, denoted BP (BP'), where $\mathcal{B}(A \rightarrow ZH) \simeq 87(90)\%$. This benchmark could also be used to search for charged Higgs bosons via $H^+ \rightarrow W^+H$ [34]. Our signal can be searched for via $pp \rightarrow A \rightarrow ZH \rightarrow \ell^+\ell^-(t\bar{c} + \bar{t}c) + X$, with $t \rightarrow \ell^+\nu b$, where $\ell = e$ or μ . The dominant SM backgrounds are WZ , tZj , $t\bar{t}Z$, $t\bar{t}W$, and tZc , with WWZ , WZZ , $t\bar{t}h$, and $t\bar{t}t$ are subdominant. Other backgrounds such as $tttj$ and $tttW$ are minor.

Signal and background samples are generated at leading order (LO) using MadGraph5_aMC@NLO [55]. These samples are passed to Pythia-8.2 [56] for parton showering and hadronization and then to Delphes-3.5.0 [57], with a default ATLAS card for detector simulation. We consider one additional jet for WZ , $t\bar{t}Z$, and $t\bar{t}W$ backgrounds using the MLM matching scheme [58]. The tZj , tZc , WWZ , WZZ , $t\bar{t}h$, and $t\bar{t}t$ backgrounds and signal samples are estimated without additional jets.

We rescale the LO cross sections for our signal and the dominant background WZ to their respective next-to-next-to-leading-order values using K factors of 2.14 (2.09) for BP (BP'), and 2.07 (2.02) for W^-Z (W^+Z) [59]. Note that the signal K -factor is computed using the code SusHi [60]. The LO tZj , $t\bar{t}Z$, $t\bar{t}W^-$ ($t\bar{t}W^+$), WWZ , WZZ , $t\bar{t}h$, and $t\bar{t}t$ backgrounds are adjusted to next-to-leading order by factors of 1.44 [55], 1.40 [61], 1.54 (1.51) [61], 1.74 [55], 1.85 [55], 1.26 [61], and 2.04 [55], respectively. The tZc background is assumed to have the same correction factor as tZj .

For event selection, we require the presence of exactly three charged leptons (samples with more than three leptons are vetoed), with $p_T^{\ell_1} > 80$, $p_T^{\ell_2} > 30$, and $p_T^{\ell_3} > 20$ GeV, and $|\eta_\ell| < 2.5$, together with at least two jets, of which there is at least one b -tagged and one non- b -tagged, with $P_T^j > 20$ GeV and $|\eta_j| < 2.5$, plus a missing transverse energy E_T^{miss} larger than 20 GeV. The scalar p_T sum of all jets and the three charged leptons (H_T) is required to be between 280 and 500 GeV. To further suppress the $t\bar{t}W$, $t\bar{t}h(\rightarrow WW^*)$, and $t\bar{t}t$ backgrounds, the invariant mass $m_{\ell^+\ell^-}$ of all possible same-flavor, opposite-sign $\ell^+\ell^-$ pairs must lie within the mass window $70 < m_{\ell^+\ell^-} < 110$ GeV. Note that the event selection cuts, particularly those on H_T and P_T^ℓ , are chosen to maximize

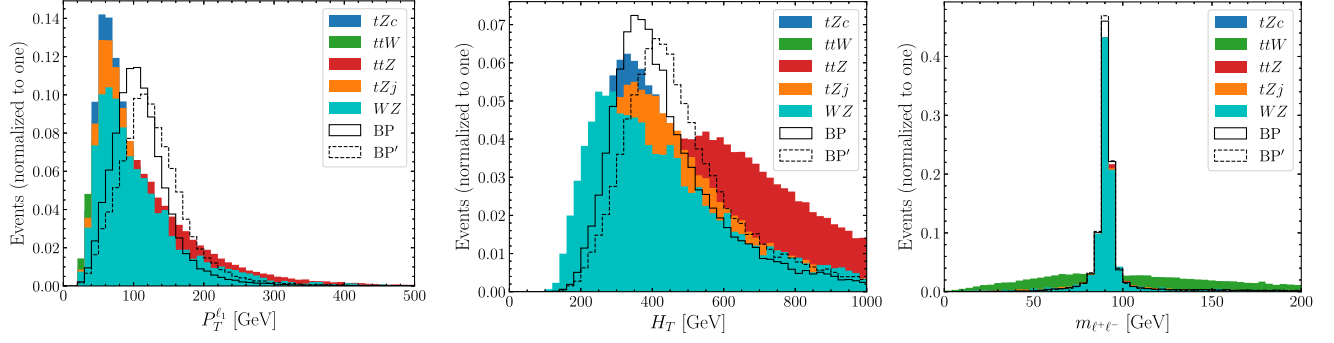


FIG. 3. $P_T^{\ell^1}$ (left), H_T (middle), and $m_{\ell^+\ell^-}$ (right) distributions for background and signal processes.

the signal significance. We also note that reconstructing the top quark (from the b -tagged jet, the missing energy, and the remaining lepton) could further suppress the dominant WZ background as well as the subdominant WWZ and WZZ backgrounds, which in turn would enhance the signal significance.

The $P_T^{\ell^1}$, H_T , and $m_{\ell^+\ell^-}$ distributions, before any selection cuts (only default cuts during event generation in MadGraph5_aMC@NLO are applied), are shown in Fig. 3. Signal and background cross sections, after selection cuts, are given in Table I. Note that the $t\bar{t}$ + jets process can also contribute if a jet is misidentified as a lepton (fake). We adopt a conservative misidentification rate of $\epsilon_{\text{fake}} = 10^{-4}$ [62,63] and find the resulting cross section is below 0.001 after selection cuts. Thus, we neglect the fake contribution in our analysis.

Based on the results given in Table I, we determine the statistical significance for our signal with $\mathcal{Z} = \sqrt{2[(S+B)\ln(1+S/B) - S]}$ [64], where S (B) is the number of signal (background) events. For 140 fb^{-1} , the significance for $A \rightarrow ZH \rightarrow \ell^+\ell^-tc$ is $\sim 7.9\sigma$ ($\sim 5.0\sigma$) for BP (BP'). Thus, the available Run 2 data could lead to discovery. Assuming a conservative 10% systematic uncertainty in the background estimation, we find a significance of $\sim 4.4\sigma$ ($\sim 2.8\sigma$) for BP (BP').

TABLE I. Signal and background cross sections (in fb) at 14 TeV after selection cuts.

Process	Cross section
BP (BP')	0.87 (0.53)
WZ	0.81
tZj	0.36
$t\bar{t}Z$	0.17
$t\bar{t}W$	0.036
tZc	0.034
WWZ	0.008
WZZ	0.007
$t\bar{t}h$	0.002
$t\bar{t}t\bar{t}$	< 0.001

V. CONCLUSIONS

ATLAS [51] and CMS [52] have recently conducted searches for G2HDM Higgs bosons, marking a remarkable step by exploring new channels beyond the conventional ones. G2HDM is a quite robust model, as it can drive [4] EWBG that could explain the observed matter-antimatter asymmetry of the Universe. It is found that a strong FOEWPT in 2HDM, as needed for EWBG, favors a rather heavy CP -odd Higgs boson with $m_A > 300 \text{ GeV}$ and a large mass splitting $m_A - m_H \gtrsim v$ [13]. Hence, the decay $A \rightarrow ZH$ is identified as a smoking-gun signature of 2HDM scenarios with a strongly FOEWPT, and searches for $A \rightarrow ZH$ in $\ell^+\ell^-b\bar{b}$ and $\ell^+\ell^-W^+W^-$ final states are found promising [13]. In addition, $A \rightarrow ZH$ can also be explored in the $\ell^+\ell^-t\bar{t}$ and $\nu\nu b\bar{b}$ final states [16]. In this paper, we have shown that $A \rightarrow ZH$ in the $\ell^+\ell^-tc$ final state is very promising, and the current Run 2 data may be able to discover this exotic decay through the trilepton signal. Observation of this final state would be a smoking-gun for the G2HDM.

We have assumed a scenario where $m_A \simeq m_{H^+}$ (custodial), but one can, on other hand, consider the $m_H \simeq m_{H^+}$ case (twisted custodial [39]), with $m_{H^+} < m_A$. For example, let us consider $m_H = m_{H^+} = 200 \text{ GeV}$ and $m_A = 500 \text{ GeV}$ (with $|\rho_{tt}| = 0.3, |\rho_{tc}| = 0.1$). In this benchmark scenario, the CP -odd Higgs boson A would decay into W^-H^+ , with a branching ratio of $\sim 65\%$, which dilutes the $A \rightarrow ZH$ decay, thereby altering the expected number of events in $\ell^+\ell^-tc$ final state. In addition, the decay $H^+ \rightarrow c\bar{b}$ would be enhanced, suggesting $A \rightarrow W^-H^+ \rightarrow \ell^-\bar{\nu}c\bar{b}$ could serve as an alternative discovery channel. However, for Higgs masses above 200 GeV (e.g., $m_H \simeq m_{H^+} \simeq 300 \text{ GeV}$), the $H^+ \rightarrow t\bar{b}$ decay would dominate, making the $A \rightarrow W^-H^+ \rightarrow \ell^-\bar{\nu}t\bar{b}$ final state potentially more promising. It should be noted that our analysis can also be helpful to search for the $H \rightarrow ZA$ inverted scenario, which can also yield a FOEWPT (see, e.g., Refs. [14,15]; see also Ref. [65] for a recent study on distinguishing between the $A \rightarrow ZH$ and $H \rightarrow ZA$ signatures at the LHC).

Away from the alignment limit, $A \rightarrow Zh$, $H \rightarrow W^+W^-$, and $H \rightarrow ZZ$ would be induced. For $c_\gamma = 0.1$, which agrees with standard model Higgs measurements at 2σ level by HiggsSignals, the decay $A \rightarrow Zh$ remains negligible. However, $H \rightarrow W^+W^-$ (ZZ) is important and has a branching ratio of $\sim 35\%$ ($\sim 16\%$), diluting $H \rightarrow t\bar{c} + \bar{t}c$. For nonzero c_γ , $A \rightarrow ZH \rightarrow \ell^+\ell^-tc$, and $A \rightarrow ZH \rightarrow \ell^+\ell^-W^+W^-$ would both lead to a trilepton signal, which is itself another G2HDM bonus. Note that $A \rightarrow ZH \rightarrow \ell^+\ell^-ZZ$ is also possible, but it would require much more data for potential discovery.

So far, we have only considered extra top Yukawa couplings ρ_{tt} and ρ_{tc} . Turning on $\rho_{bb}(\rho_{\tau\tau})$ would induce $H \rightarrow b\bar{b}(\tau^+\tau^-)$, and thus one can have $A \rightarrow ZH \rightarrow \ell^+\ell^-b\bar{b}$. However, flavor observables strongly constrain $\rho_{bb}(\rho_{\tau\tau})$, requiring $|\rho_{bb}| \lesssim \lambda_{bb}(|\rho_{\tau\tau}| \lesssim \lambda_{\tau\tau})$ [43,44]. For $\rho_{bb} \sim \rho_{\tau\tau} \sim 0.01$, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ are small, and their presence would slightly soften $H \rightarrow t\bar{c} + \bar{t}c$ but would not alter our conclusions. Note that nonzero ρ_{bb} and $\rho_{\tau\tau}$ would also induce $A \rightarrow b\bar{b}$ and $A \rightarrow \tau^+\tau^-$, but these decays are very small.

Other flavor-changing couplings, such as $\rho_{\mu\tau}$ and $\rho_{\tau\mu}$, come to mind; however, these couplings are severely constrained by lepton-flavor-violating $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decay. For $m_H = 500$ GeV ($\approx m_{H^\pm} \approx m_A$), $|\rho_{\mu\tau, \tau\mu}| \leq 3.7 \times 10^{-3}$ [43]. Hence, $\rho_{\mu\tau}$ and $\rho_{\tau\mu}$ must be very small. Note that this is only an example; other off-diagonal couplings are also strongly constrained. The $\rho_{\mu\tau}$ and $\rho_{\tau\mu}$ couplings are further constrained by flavor-violating Higgs boson $h \rightarrow \mu\tau$

decay searches [66]. These bounds disappear in the limit of $c_\gamma \rightarrow 0$ (alignment), which we assume to ensure agreement with Higgs signal measurements. Of course, nonzero $\rho_{\mu\tau}$ and/or $\rho_{\tau\mu}$ would induce $H/A \rightarrow \mu\tau$ but these decays are very small. The $H \rightarrow t\bar{c} + \bar{t}c$ and $A \rightarrow ZH$ decays can still be the dominant channels, and therefore our results remain unchanged. For the same reason, these flavor-changing couplings and even $\rho_{e\mu}$, $\rho_{\mu e}$, ρ_{bs} , or ρ_{bd} are turned off.

In summary, we suggest searching for $A \rightarrow ZH$ in the $\ell^+\ell^-tc$ final state, a smoking-gun signature for G2HDM. We proposed a benchmark scenario and carried out a signal-to-background analysis at the 14 TeV LHC and show that $A \rightarrow ZH$ is quite promising. Even current LHC Run 2 data may give potential discovery of this exotic decay into $\ell^+\ell^-tc$ final state, thus providing a probe of G2HDM with flavor violation.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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