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

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Based on Phys.Rev.D 111 (2025) 11

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Scalars 2025: Higgs bosons and cosmology

September 24, 2025

# General Two-Higgs Doublet Model

In the Higgs basis, the general *CP*-conserving 2HDM scalar potential is given by

[Davidson and Haber, PRD'05; Hou and Kikuchi, EPL'18]

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

with

$$\Phi = \begin{pmatrix} G^+ \\ (v + h_1 + iG^0)/\sqrt{2} \end{pmatrix}, \qquad \Phi' = \begin{pmatrix} H^+ \\ (h_2 + iA)/\sqrt{2} \end{pmatrix}. \tag{2}$$

- The usual $Z_2$ symmetry is dropped $\Longrightarrow$ FCNC at tree-level
- Many parameters and extra processes arise
- EWBG, Absence of FCNC (e.g. $t \to ch_{125}$), ... could be explained
- Sub-TeV $H$, $A$, $H^\pm$ bosons may still exist

# General Yukawa Interaction

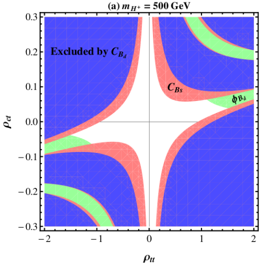
Higgs-fermion interactions can be described by [Davidson and Haber, PRD'05]

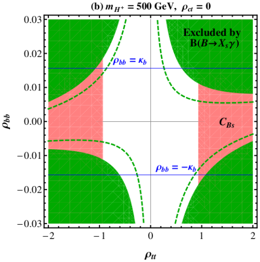
$$\begin{aligned}\mathcal{L}_Y &= -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[ (\lambda^f_{ij} s_\gamma + \rho^f_{ij} c_\gamma)\, h \\ &\quad + (\lambda^f_{ij} c_\gamma - \rho^f_{ij} s_\gamma) H - i\,\mathrm{sgn}(Q_f)\, \rho^f_{ij}\, A \Big] P_R\, f_j \\ &\quad - \bar{u}_i \big[ (V\rho^d)_{ij} P_R - (\rho^{u\dagger} V)_{ij} P_L \big] d_j H^+ \\ &\quad - \bar{\nu}_i\, \rho^\ell_{ij} P_R\, \ell_j H^+ + \mathrm{H.c.}. \end{aligned} \tag{3}$$

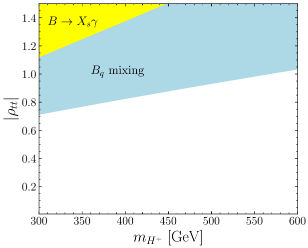
- $\lambda^f$ matrices: diagonal, fixed by fermion mass
- $\rho^f$ matrices: (complex) non-diagonal lead to FCNC
- Alignment ($c_\gamma \approx 0$) suppresses FCNC for $h$ but allows FCNC for $H$ and $A$
- $\rho_{ij}$ are severely constrained by flavor physics

# Flavor Constraints

- Flavor constraints on $\rho_{tt}$ and $\rho_{tc}$ are not particularly strong




B. Altunkaynak *et al.*, PLB'15

- Constraints on $\rho_{tc}$ are weak. An upper bound on $\rho_{tc}$ was found to be $|\rho_{tc}| \lesssim 1.3$ $(1.7)$ for $m_{H^+} = 300$ $(500)$ GeV [A. Crivellin *et al.*, PRD'13]
- $\rho_{tc}$ and $\rho_{tt}$ can still be large and (each) drive EWBG

  [See, e.g., Fuyuto, Hou, Seneha, PLB'18]
- The LHC offers the best way to test and constrain $\rho_{tc}$ and $\rho_{tt}$

# $t \to ch$ Search Limits

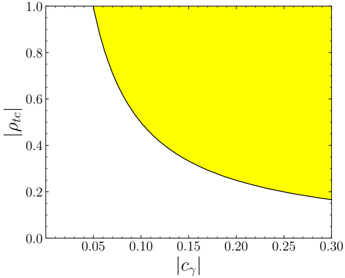
For $c_\gamma \neq 0$, LHC $t \to ch$ searches set significant constraint on $\rho_{tc}$.

| Signal | Observed (expected) 95% CL upper limits $\mathcal{B}(t \to Hq)$ | $\lvert C_{u\phi}^{qt,tq} \rvert$ |
|---|---|---|
| $tHu$ | $2.8\,(3.0) \times 10^{-4}$ | 0.71 (0.73) |
| $tHc$ | $3.3\,(3.8) \times 10^{-4}$ | 0.76 (0.82) |

ATLAS, EPJC'24

| Analysis | $\mathcal{B}(\mathrm{t} \to \mathrm{Hu})$ observed (expected) | $\mathcal{B}(\mathrm{t} \to \mathrm{Hc})$ observed (expected) |
|---|---|---|
| $\mathrm{H} \to \mathrm{b\bar{b}}$ [24] | 0.079 (0.11)% | 0.094 (0.086)% |
| $\mathrm{H} \to \gamma\gamma$ [25] | 0.019 (0.031)% | 0.073 (0.051)% |
| Leptonic (this analysis) | 0.072 (0.059)% | 0.043 (0.062)% |
| Combination | 0.019 (0.027)% | 0.037 (0.035)% |

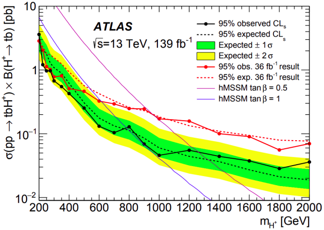
CMS, PRD'25



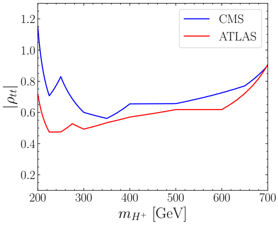

- $|\rho_{tc}| \gtrsim 0.5$ is excluded at 95% CL for $c_\gamma = 0.1$
- The limit diminishes for $c_\gamma < 0.1$ and vanishes for $c_\gamma = 0$ (alignment)

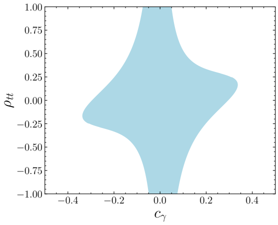
# Limits on $\rho_{tt}$

- LHC direct searches for $pp \to \bar{t}bH^+ \to \bar{t}bt\bar{b}$ strongly constrain $\rho_{tt}$




ATLAS, JHEP'21

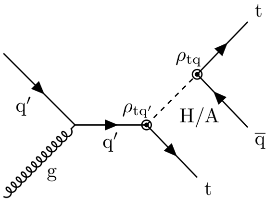



- Limits are interpreted assuming $\mathcal{B}(H^+ \to t\bar{b}) = 100\%$ [Hou and MK, PRD'24]
- Constraints from ATLAS $H^+ \to W^+h$ search are very weak [ATLAS, JHEP'25]
- Constraints from the SM-like Higgs boson properties are checked using the `HiggsSignals` module of `HiggsTools`

# LHC Searches for G2HDM

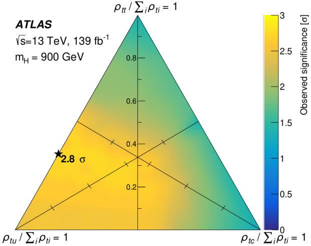
With $t \to ch$ alignment-suppressed, it is natural to pursue $cg \to tH/tA \to tt\bar{c}/tt\bar{t}$ (same-sign top/triple top), which is controlled by $s_\gamma \simeq 1$.

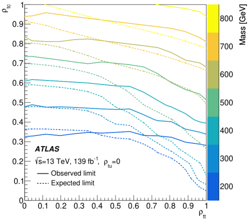



Observed (expected) mass limit [GeV]

| | without interference | with interference | with interference |
|---|---|---|---|
| | $m_A$ or $m_H$ | $m_A$ | $m_H$ |
| $\rho_{\rm tu}$ | | | |
| 0.4 | 920 (920) | 1000 (1000) | 950 (950) |
| 1.0 | 1000 (1000) | 1000 (1000) | 950 (950) |
| $\rho_{\rm tc}$ | | | |
| 0.4 | no limit | 340 (370) | 290 (320) |
| 1.0 | 770 (680) | 810 (670) | 760 (620) |

CMS, PLB'24



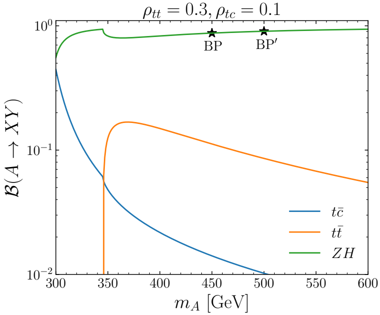




ATLAS, JHEP'23

# Benchmark Scenario

- Strong first-order EWPT in 2HDM, as needed for EWBG, favors a scenario with $m_{H^+} \approx m_A \approx 400$–$500$ GeV and $m_A - m_H \gtrsim 200$ GeV

  Dorsch *et al.*, PRL'14; Basler *et al.*, JHEP'17
- $A \to ZH$ is identified as the smoking-gun signature of 2HDM with FOEWPT
- We consider $m_H = 200$ GeV, and $m_A = m_{H^+} \in [300, 600]$ GeV.



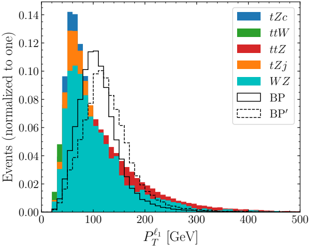

- We choose $m_A = 450\,(500)$ GeV as a benchmark point, denoted BP (BP′), where $\mathcal{B}(A \to ZH) \simeq 87\,(90)\%$.

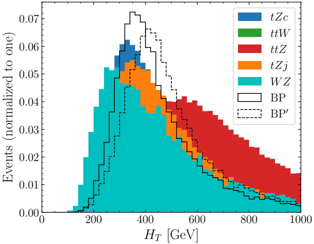
# Signal vs. Background

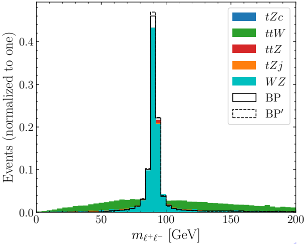
Signal: $gg \to A \to ZH \to \ell^+\ell^- t\bar{c} \to \ell^+\ell^-\ell^+\nu b\bar{c}$

BKG: $WZ + j$, $tZj$, $t\bar{t}Z + j$, $t\bar{t}W + j$, $tZc$, $WWZ$, $WZZ$, $t\bar{t}h$, $t\bar{t}t\bar{t}$

Simulation: `MadGraph5_aMC@NLO` ($\sqrt{s} = 14$ TeV) + `Pythia` + `Delphes`



# Signal vs. Background

For event selection, we require the presence of

- at least 2 jets ($N_j \geq 2$), with $P_T^j \geq 20$ GeV and $|\eta_j| < 2.5$,
- with at least one of them $b$-tagged ($N_b \geq 1$),
- exactly 3 leptons ($N_\ell = 3$), with $P_T^{\ell_1,\ell_2,\ell_3} \geq 80, 30, 20$ GeV,
- $E_T^{\text{miss}} > 20$ GeV, $280 < H_T < 500$ GeV (to maximize the significance),
- and $70 < m_{\ell^+\ell^-} < 110$ GeV ($Z$-pole).

| 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 |
| $t\bar{t}t\bar{t}$ | $< 0.001$ |

Significance ($\mathcal{Z}$): For $\mathcal{L} = 140$ fb$^{-1}$, $\mathcal{Z} \simeq 7.9\sigma$ ($5.0\sigma$) for BP (BP′). Assuming $\epsilon_B = 10\%$, BP (BP′) yields $\mathcal{Z} \simeq 4.4\sigma$ ($2.8\sigma$).

# Conclusion

- Exotic Higgs bosons are actively searched for at the LHC
- However, it might be difficult to detect at the LHC using conventional production and/or decay channels
- Exotic decays, like $A \to ZH$ and $H^+ \to W^+H$, can provide crucial probes
- Searches for $A \to ZH$ or $H \to ZA$ in the $\ell^+\ell^- t\bar{c}$ final state could probe the G2HDM with flavor-violating couplings
- Complementary searches for $H^+ \to W^+H/A$ in the $\ell^+\nu t\bar{c}$ final state can probe the G2HDM further [Hou and MK, PRD'25]
- In case $m_H \approx m_A \approx m_{H^+}$, which can also yield a FOEWPT [Bernon, Bian, Jiang, JHEP'18], $pp \to bH^+ \to bt\bar{b}, bc\bar{b}$ signals are proposed [Ghosh, Hou, Modak, PRL'20; Fang, Hou, Kao, MK, arXiv:2510.XXXXX]
- Observation would point to a very different 2HDM and perhaps shed light on the mechanism behind the BAU

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# Other Constraints

G2HDM is also subject to the following constraints:

- Unitarity, perturbativity and vacuum stability
- EW precision constraints through oblique parameters $S$, $T$ and $U$ using the following fit result:

$$S = -0.05 \pm 0.07, \quad T = 0.00 \pm 0.06, \quad \rho_{ST} = 0.93 \qquad \text{[PDG]}$$