Searching for resonant flavor-changing charged Higgs production at the LHC

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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]

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

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

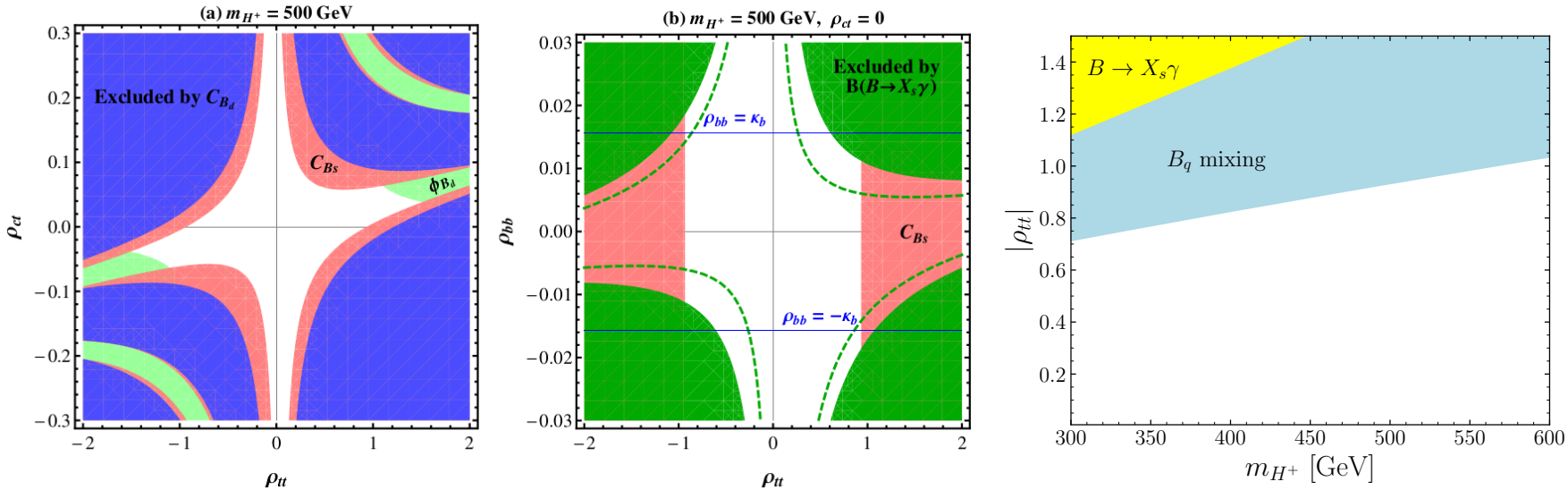
Higgs-fermion interactions can be described by [Davidson and Haber, PRD'05]

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

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

Flavor Constraints

- Flavor constraints on ρ_{tt} and ρ_{tc} are not particularly strong



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

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

$t \to ch$ Search Limits

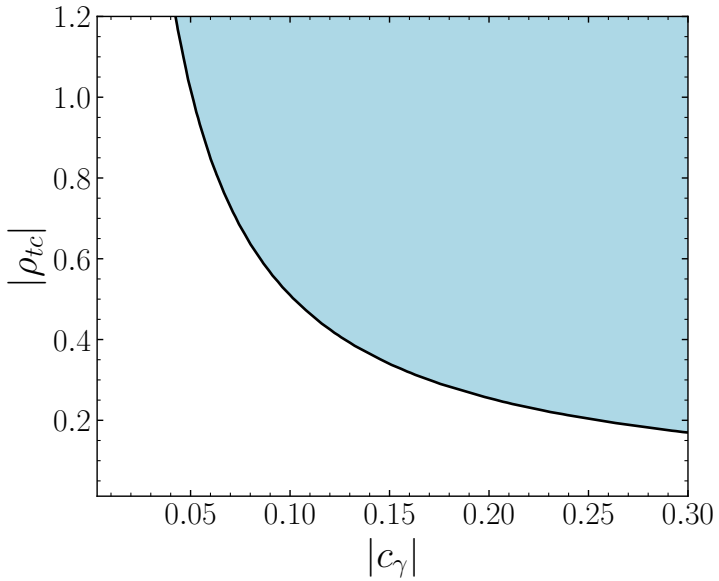
For $c_\gamma \neq 0$, LHC $t \to ch$ searches set significant constraint on ρ_{tc}.

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, CMS-TOP-22-002

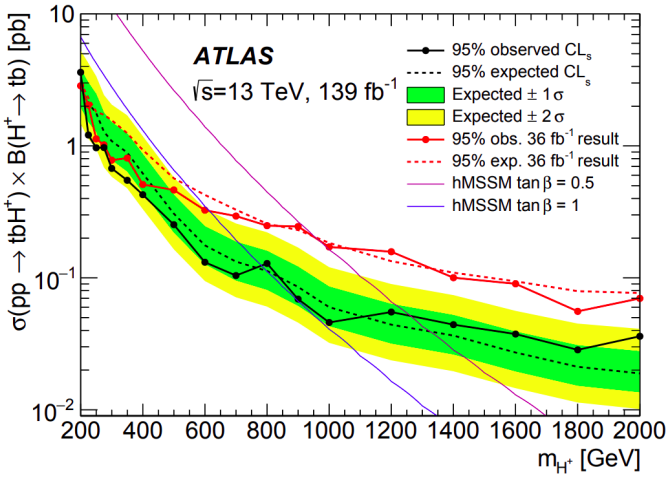


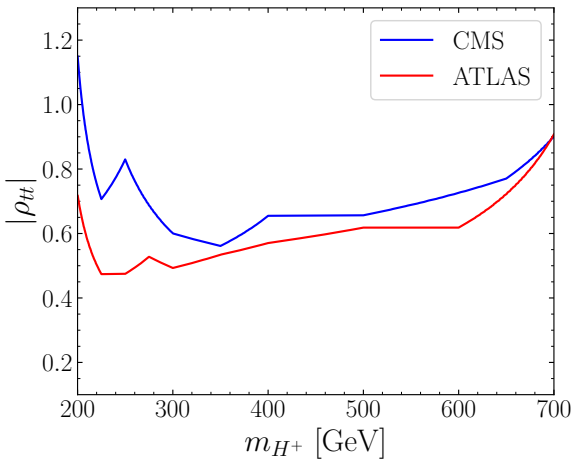
Hou and MK, PRD'24

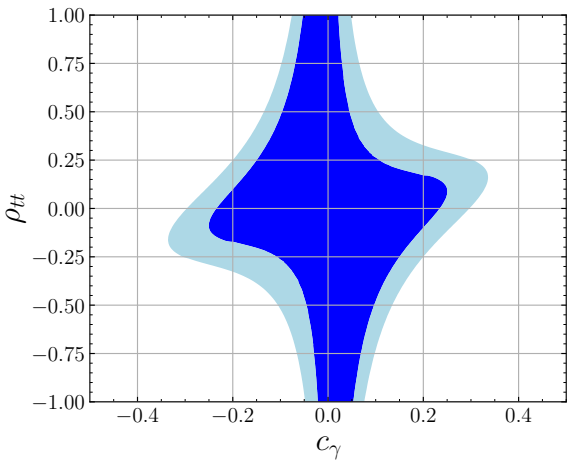
- $|\rho_{tc}| \gtrsim 0.5$ is excluded at 95% CL for $c_\gamma = 0.1$
- The limit diminishes for $c_\gamma < 0.1$ and vanishes for $c_\gamma = 0$ (alignment)

Constraints on ρ_{tt}

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





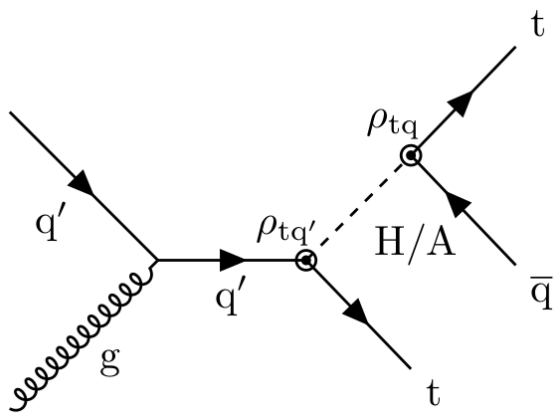


ATLAS, JHEP'21

- 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 weak [ATLAS, JHEP'25]
- Constraints from the SM-like Higgs boson properties are checked using the `HiggsSignals` module of `HiggsTools`

LHC Searches for G2HDM

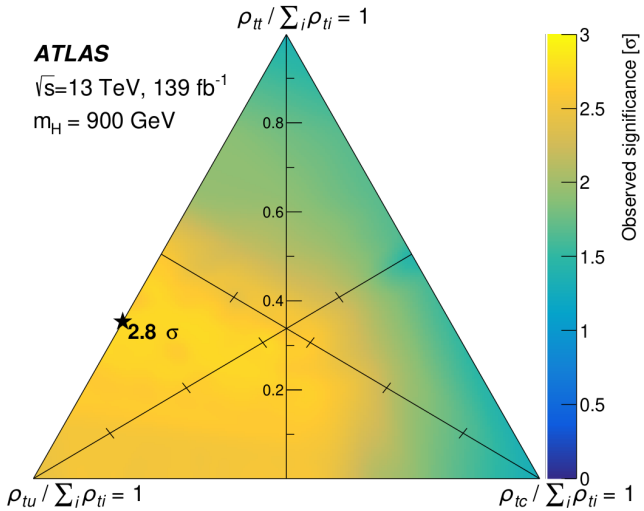
With $t \to ch$ alignment-suppressed, it is natural to pursue $cg \to tH/tA \to tt\bar{c}/tt\bar{t}$ (same-sign top/triple top), which is controlled by $s_\gamma \simeq 1$.

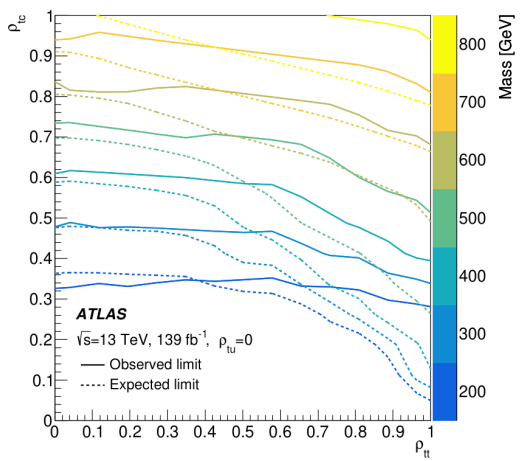


Observed (expected) mass limit [GeV]

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

CMS, PLB'24

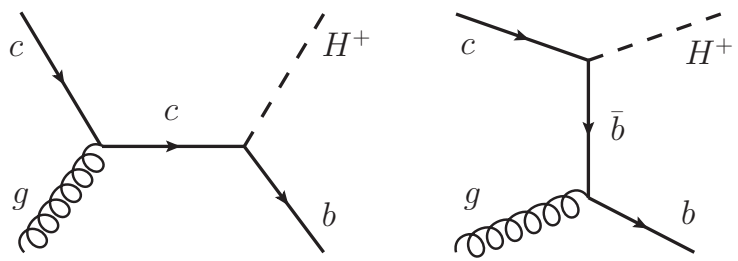




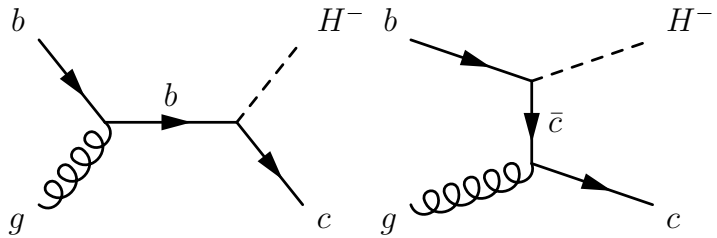
ATLAS, JHEP'23

New H^+ Production Modes

In G2HDM, where $\bar{c}bH^+$ couples with strength $\rho_{tc}V_{tb}$, $cg \to bH^+$ and $bg \to cH^-$ are not subject to CKM suppression as in the usual 2HDM-II.

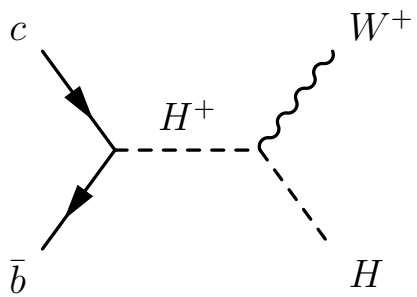


Ghosh, Hou, Modak, PRL'20 and WIP



Hou and MK, PRD'24(L)

$c\bar{b} \to H^+ \to W^+H$, which goes through the same $\bar{c}bH^+$ coupling of $\rho_{tc}V_{tb}$, could be a promising discovery channel for H^+.



Hou and MK, PRD'25(L)

Signal vs. Background

Signal: $pp \to H^+(+j) \to W^+H \to \ell^+\nu t(\to \ell^+\nu b)\bar{c} \to \ell^+\nu\ell^+\nu b\bar{c}$

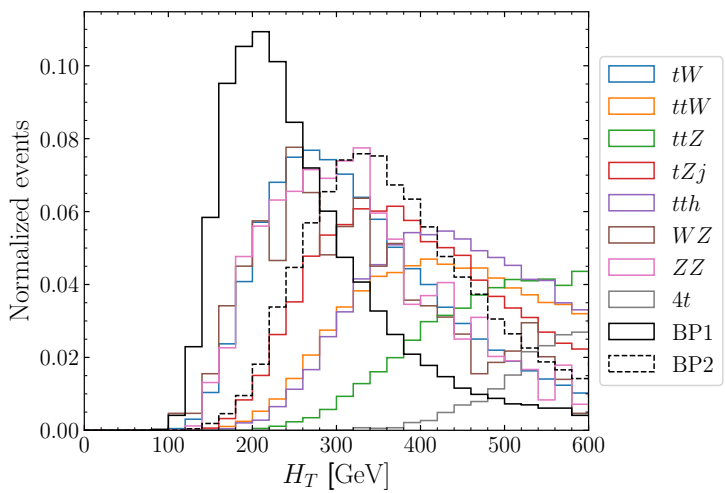
BKG: $t\bar{t}W+j$, $t\bar{t}Z+j$, $tW+j$, $WZ+j$, tZj, $ZZ+j$, $t\bar{t}h$, $4t$

BP	η_2	η_3	η_4	η_5	η_7	m_H	m_A	m_{H^+}	μ_{22}^2/v^2
1	1.40	2.00	-0.82	-0.82	-0.55	**200**	300	**300**	0.49
2	2.88	4.75	-2.64	-2.64	0.16	**300**	500	**500**	1.75

Table: For BP1, $\rho_{tc} = \rho_{tt} = 0.1$, while for BP2, $\rho_{tc} = 0.3$, $\rho_{tt} = 0.5$.

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

- $N_j \geq 2$ with $P_T^j \geq 20$ GeV
- At least one b-tagged ($N_b \geq 1$)
- SS2ℓ ($N_\ell = 2$), $P_T^{\ell_{1(2)}} \geq 25(20)$ GeV
- $\Delta R_{\ell\ell}, \Delta R_{\ell j} > 0.4$, $E_T^{\text{miss}} > 35$ GeV
- p_T sum of all jets and the two SS leptons $H_T < 400$ GeV

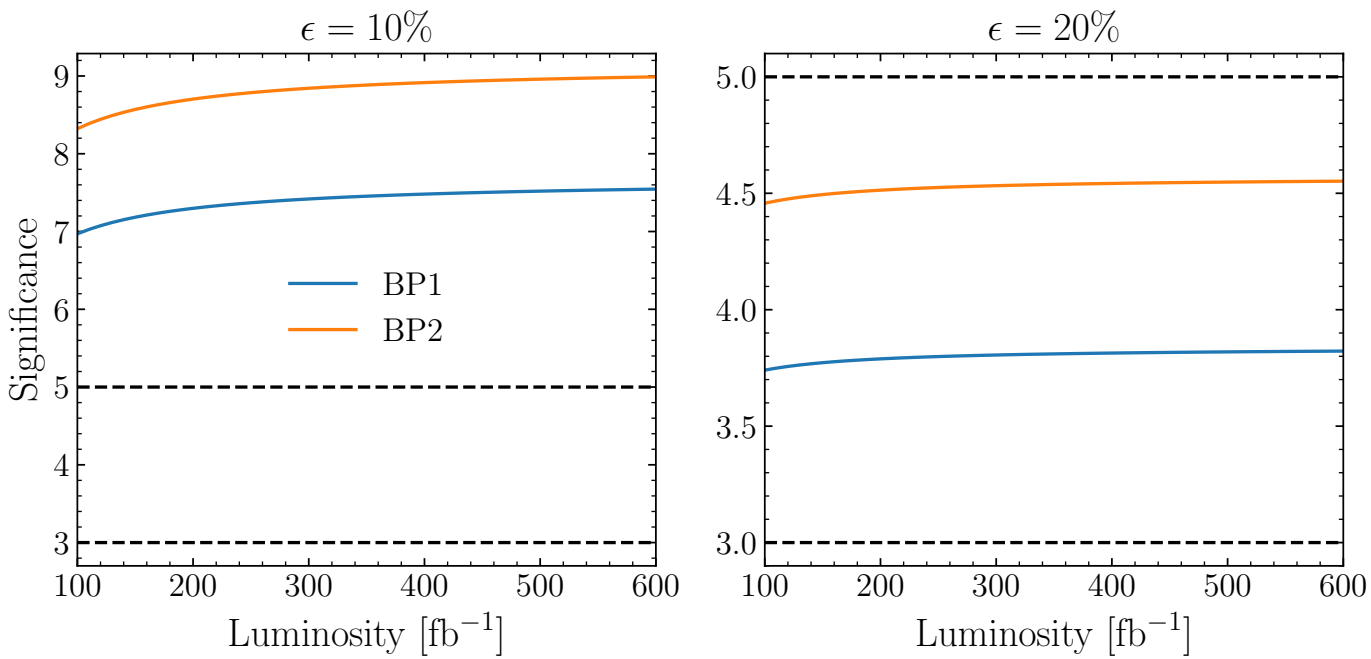


Significance

We estimate our signal sensitivity using [Kumar and Martin, PRD'15]

$$\mathcal{Z} = \sqrt{2\left[(S+B)\ln\left(\frac{(S+B)\left(B+\Delta_B^2\right)}{B^2+(S+B)\Delta_B^2}\right) - \frac{B^2}{\Delta_B^2} + \ln\left(1+\frac{\Delta_B^2 S}{B(B+\Delta_B^2)}\right)\right]},$$

with $\Delta_B = \epsilon B$, where S (B) is the number of signal (background) events, and ϵ refers to the systematic uncertainty in the background estimation.



Conclusion

- Charged Higgs bosons are actively searched for at the LHC
- However, it might be difficult to detect at the LHC via $bg \to tH^- \to t\bar{t}b$
- $cg \to bH^+ \to bt\bar{b}$ and $\bar{b}g \to \bar{c}H^+ \to \bar{c}t\bar{b}$ could be useful to probe H^+ further
- Resonant $c\bar{b} \to H^+$ production, followed by $H^+ \to W^+H$ could be promising
- Proposed benchmark scenario can also be used to search for $A \to ZH$ decay in the $\ell^+\ell^- tc$ final state (trilepton signal) [arXiv:2503.23133 (accepted by PRD)]

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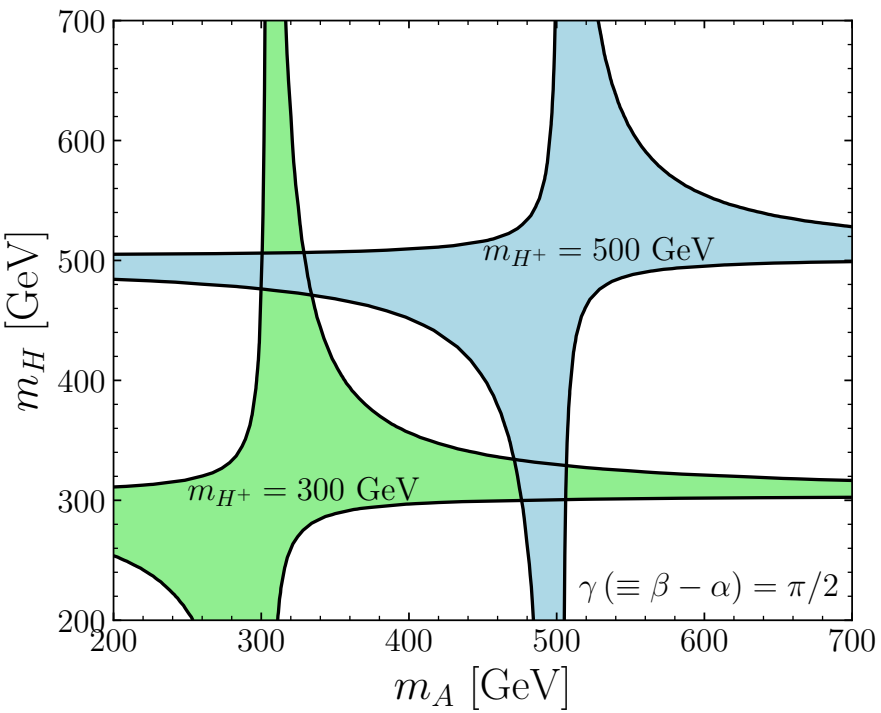
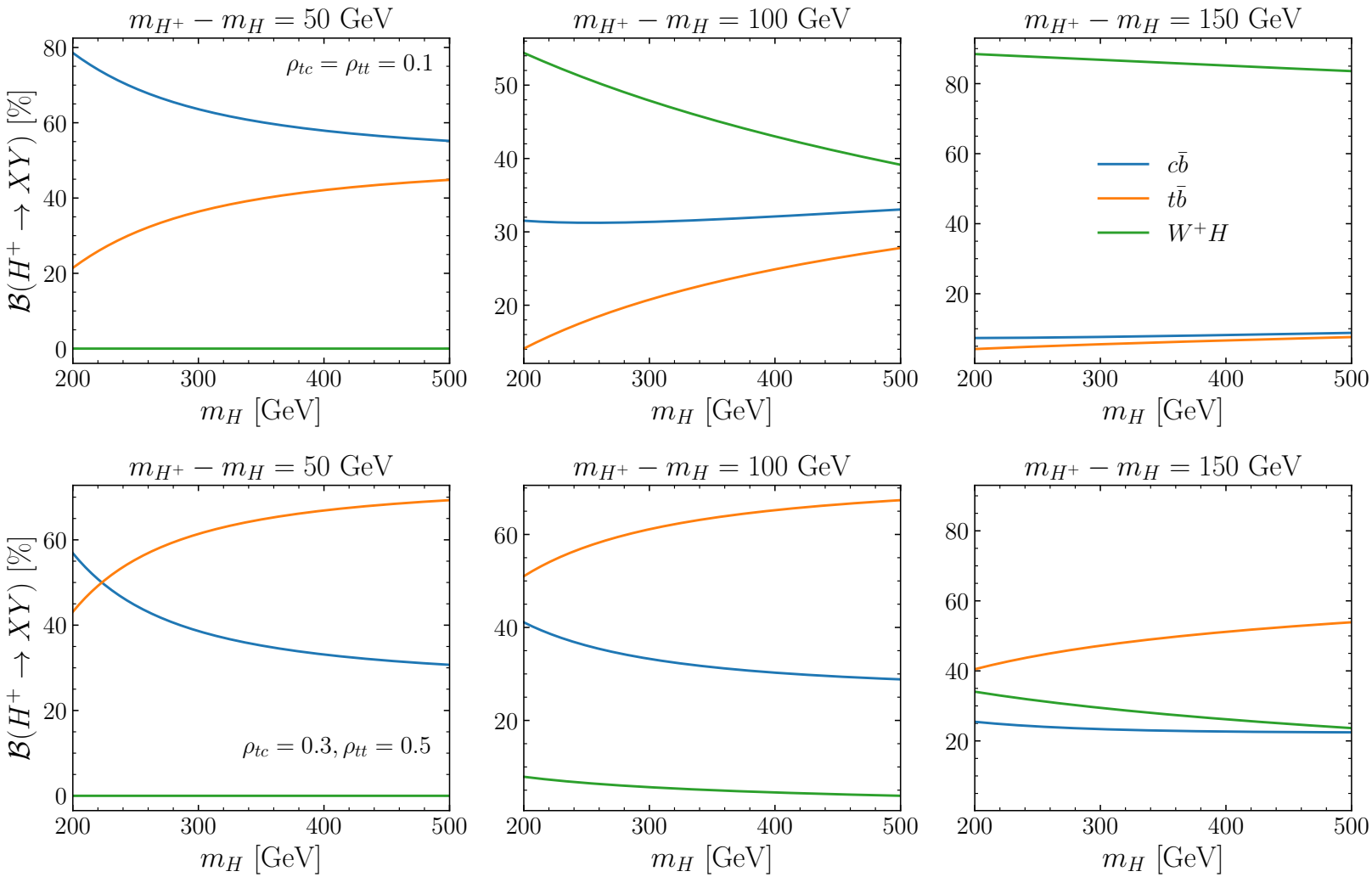
Other Constraints

G2HDM is also subject to the following theoretical and EW precision constraints:

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

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



Charged Higgs decay