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

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Based on W.-S. Hou and M. Krab, arXiv:2409.18474

Extended Higgs Sector subgroup meeting

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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

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

with

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

- ▷ 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

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

- λ^f matrices: diagonal, fixed by fermion mass
- ρ^f matrices: non-diagonal (and in general complex) 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
- Extra top couplings ρ_{tc} and ρ_{tt} could be $\mathcal{O}(1)$ and can each drive EWBG

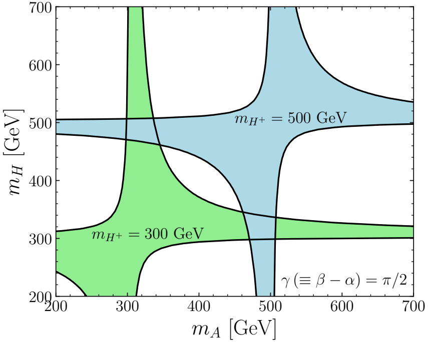
  Fuyuto, Hou, Seneha, PLB'18
- For simplicity, we set all $\rho_{ij} = 0$ except ρ_{tc} and ρ_{tt}

Constraints on G2DHM

G2HDM parameter space is subject to the following constraints:

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

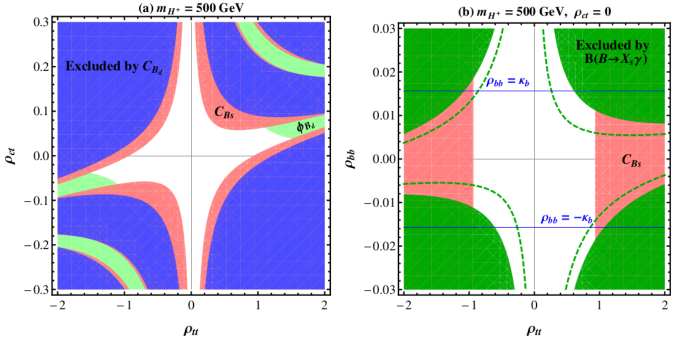
$$S = 0.05 \pm 0.08, \quad T = 0.09 \pm 0.07, \quad \rho_{ST} = 0.92, \quad \text{[PDG]}$$



- Flavor physics and direct searches (next slides)

Flavor constraints

Because of a $|V_{cq}/V_{tq}|$ $(q = d, s)$ (m_t/m_b) enhancement factor, ρ_{ct} (ρ_{bb}) is severely constrained by B_q–$\bar{B}_q$ $(b \to s\gamma)$.



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

- ▷ Constraints on ρ_{tc} are weak due to small m_c. 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 sizable ($\lesssim \mathcal{O}(1)$) under current data

Limit from $t \to ch$ searches

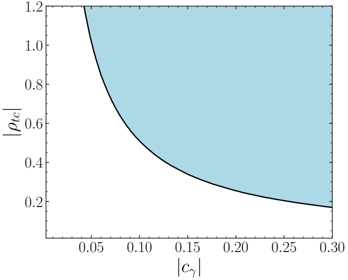
For $c_\gamma \neq 0$, LHC $t \to ch$ searches set significant constraint on ρ_{tc}.

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, arXiv:2407.15172

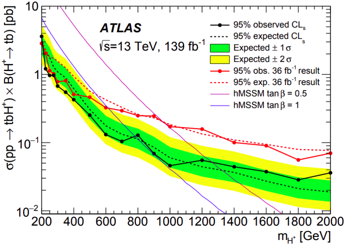


Hou and MK, PRD-L'24

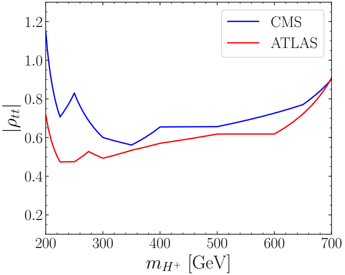
- ▷ $|\rho_{tc}| \gtrsim 0.5$ is excluded at 95% CL for $c_\gamma = 0.1$
- ▷ The limit diminishes for $c_\gamma < 0.1$ and vanishes for $c_\gamma = 0$ (alignment)

Limit from $H^+ \to t\bar{b}$ searches

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



ATLAS, JHEP'21

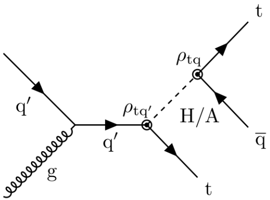


Hou and MK, PRD-L'24

- Limits are interpreted assuming $\mathcal{B}(H^+ \to t\bar{b}) = 100\%$
- Constraints from LHC searches for $pp \to H/A \to t\bar{t}$ and $pp \to t\bar{t}H/A \to t\bar{t}t\bar{t}$ are relatively weaker
- ρ_{tt} is safe from constraints from SM Higgs properties $(s_\gamma = 1)$

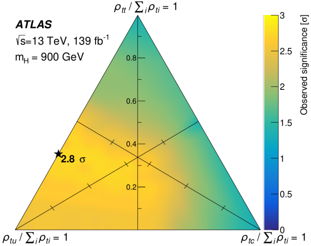
Search for G2HDM neutral Higgs bosons

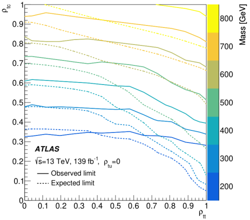
With $t \to ch$ alignment-suppressed, it is natural to pursue $cg \to tH/tA \to tt\bar{c}/tt\bar{t}$ (same-sign top/triple top), which is controlled by $s_\gamma \simeq 1$.



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

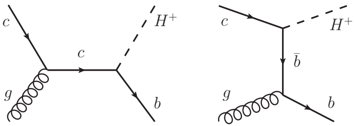




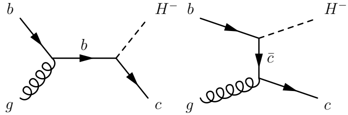
ATLAS, JHEP'23

Searching for H^+ with FC couplings

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

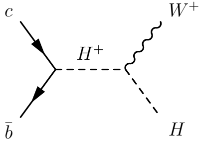


Ghosh, Hou, Modak, PRL'20



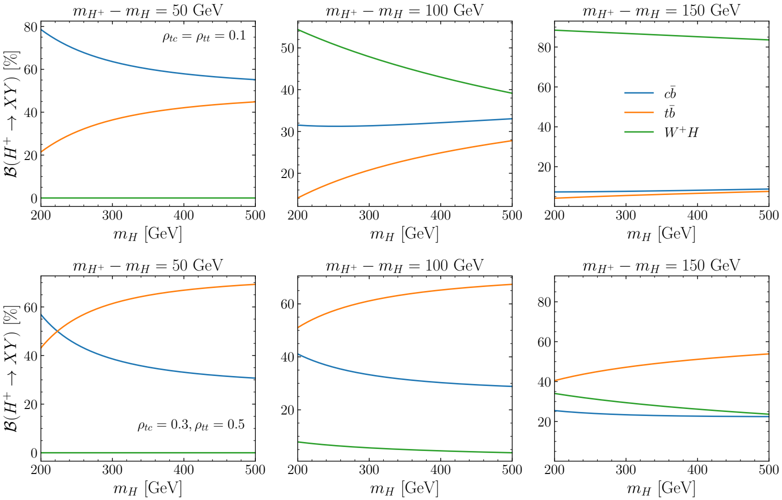
Hou and MK, PRD-L'24

$c\bar{b} \to H^+ \to W^+H$, which goes through the same $\bar{c}bH^+$ coupling of $\rho_{tc}V_{tb}$, is suggested as a new avenue for discovering H^+ at the LHC.



Hou and MK, arXiv:2409.18474

Charged Higgs decay



Signal vs. Background

Signal: $c\bar{b} \to H^+ \to W^+ H \to \ell^+ \nu t(\to \ell^+ \nu b)\bar{c} \to \ell^+ \ell^+ + \nu\nu + b\bar{c}$
BKG: $t\bar{t}V$ $(V = W, Z)$, tZj, $t\bar{t}h$, $4t$, tW, WZ, ZZ

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 two SS leptons $H_T < 400$ GeV

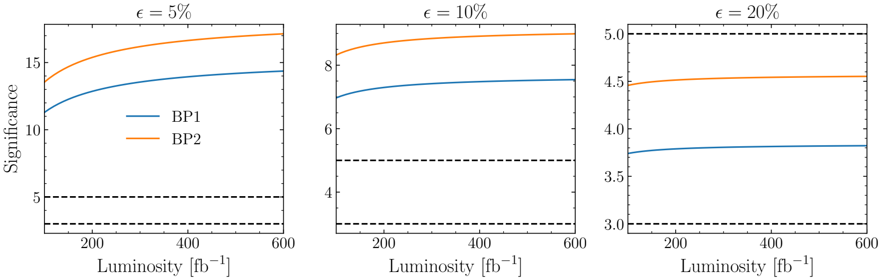
Background	Cross section
tW	1.61
$t\bar{t}W$	1.09
WZ	0.54
tZj	0.40
$t\bar{t}Z$	0.10
tth	0.05
ZZ	0.02
$4t$	0.0004
Q-flip	0.0018
Fake	0.0002

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 number of signal (background) events, and ϵ refers to systematic uncertainty in background estimation.



Conclusion

- Charged Higgs bosons are actively searched for at the LHC.
- However, it might be difficult to detect at the LHC via $bg \to tH^- \to t\bar{t}b$.
- In G2HDM, resonant $c\bar{b} \to H^+$ is induced by the FC top-charm coupling ρ_{tc} without CKM-suppression, and has a large cross section.
- Our proposed $c\bar{b} \to H^+ \to W^+ H(\to t\bar{c})$ signal, with its same sign dilepton signature, could be promising.

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