Reconstructing the general 2HDM charged Higgs boson at the LHC

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Based on W.-S. Hou and M. Krab, PRD-L'24

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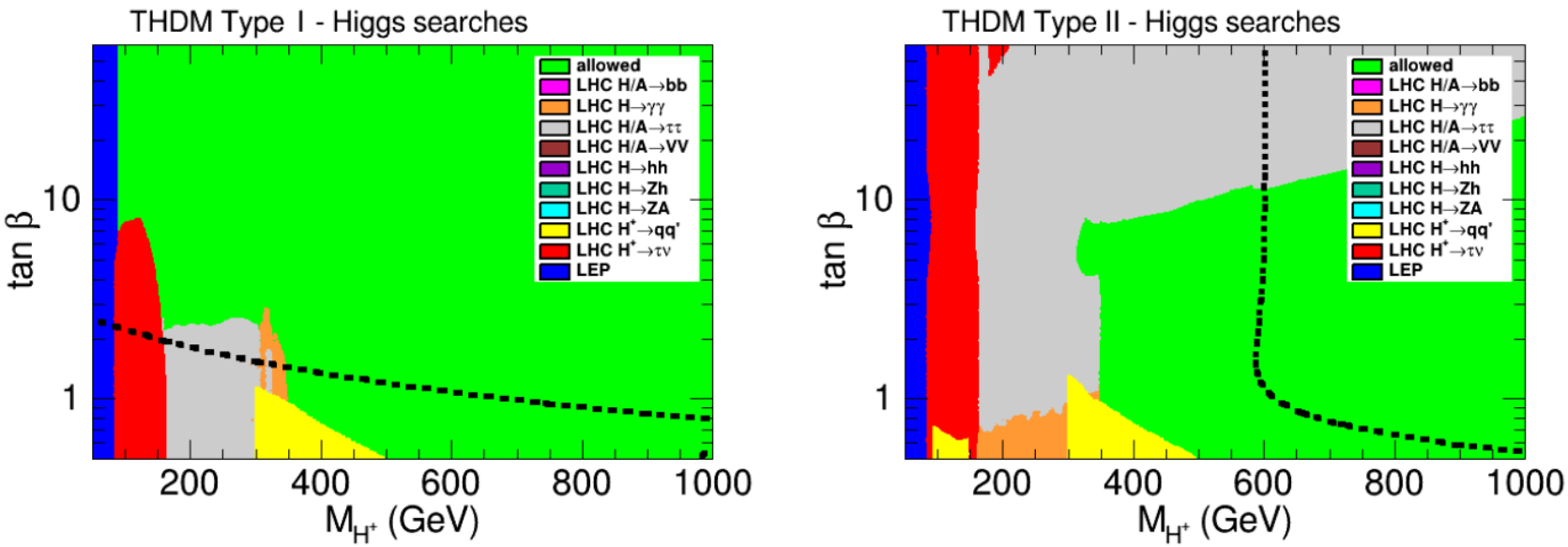
Introduction

- Searches for heavy charged Higgs bosons are getting complicated due to the large associated backgrounds.
- Also flavor observables like $b \to s\gamma$ put stringent bounds on the mass of the charged Higgs boson.



A. Arbey *et al.*, EPJC'18

- We suggest searching for H^+ with flavor-changing (FC) couplings

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: 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

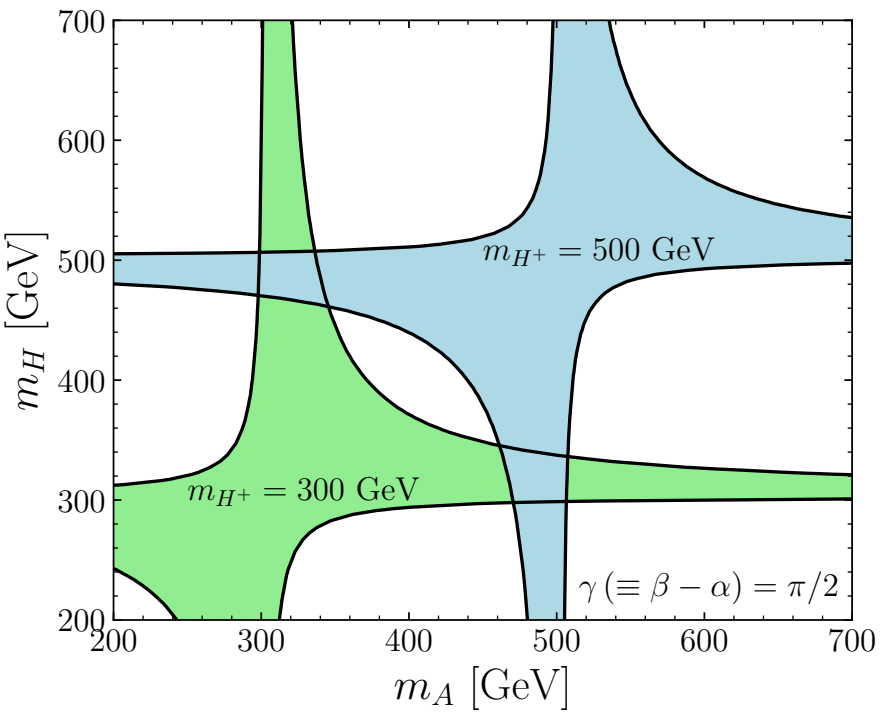
  Fuyuto, Hou, Seneha, PLB'18
- For simplicity, we set all $\rho_{ij} = 0$ except ρ_{tc} and ρ_{tt}

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:

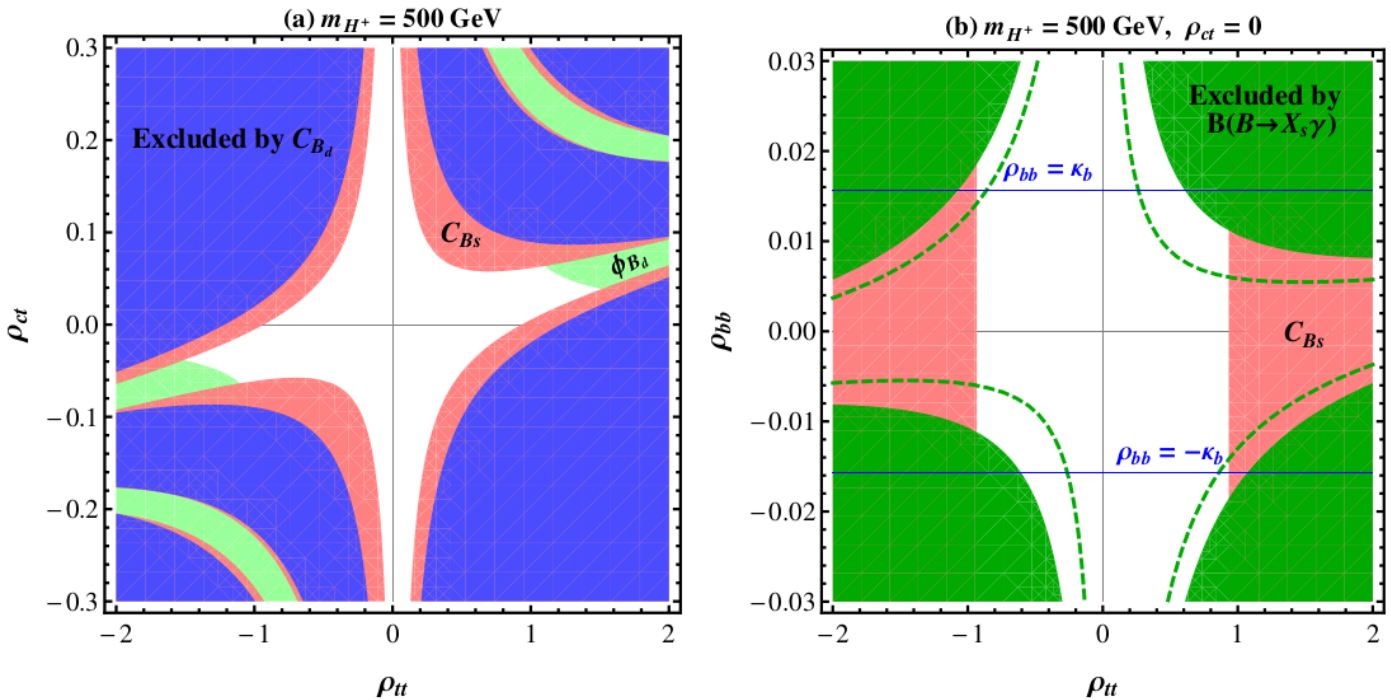
$$S = 0.05 \pm 0.08, \quad T = 0.09 \pm 0.07, \quad \rho_{ST} = 0.92, \quad \text{[PDG]}$$



- 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

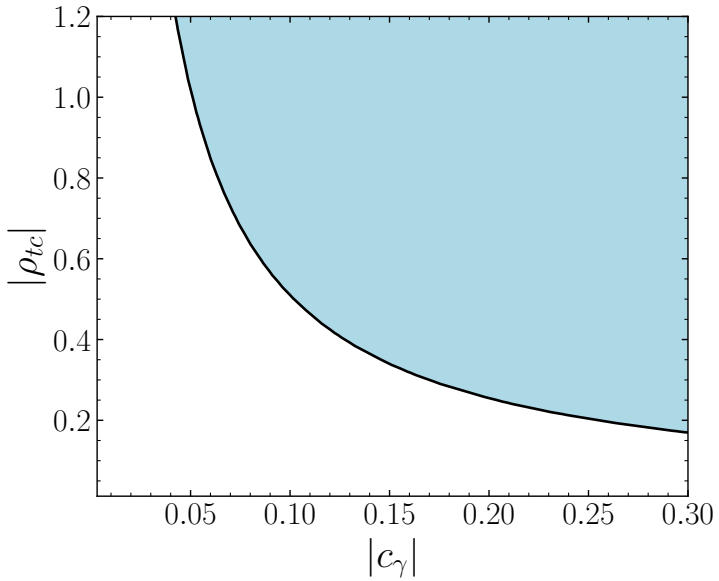
For $c_\gamma \neq 0$, LHC $t \to ch$ searches set significant constraint on ρ_{tc}.

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

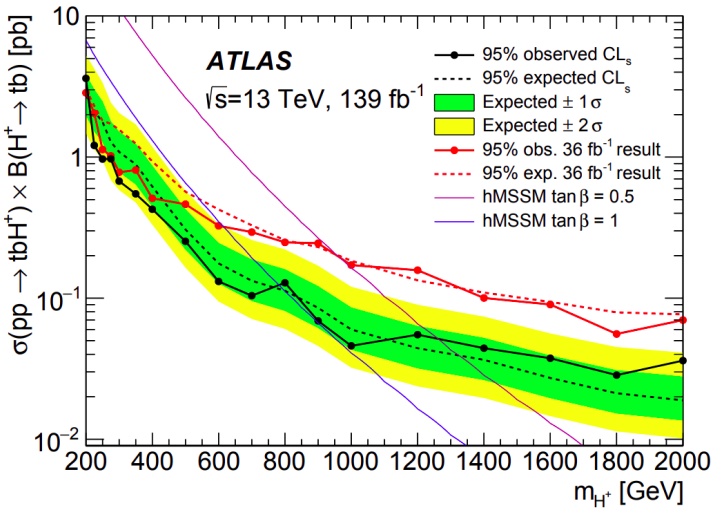


Hou and MK, PRD-L'24

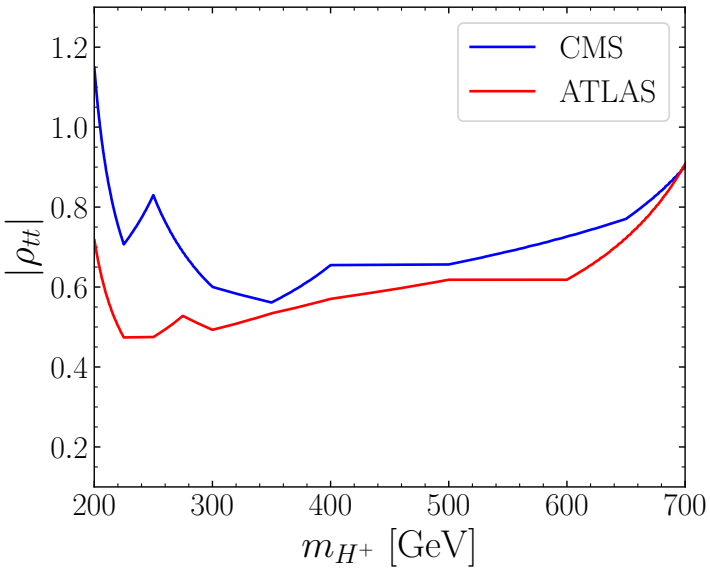
- $|\rho_{tc}| \gtrsim 0.5$ is excluded at 95% CL for $c_\gamma = 0.1$
- The limit diminishes for $c_\gamma < 0.1$ and vanishes for $c_\gamma = 0$ (alignment)

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

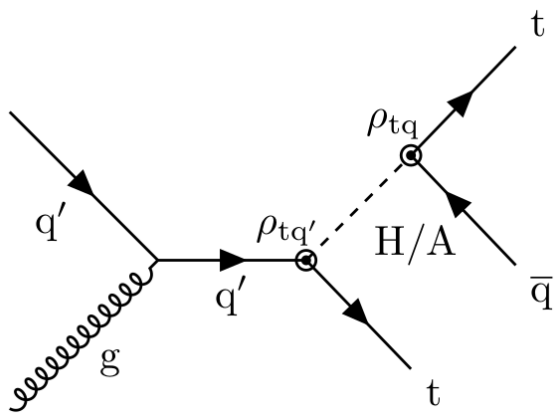


Hou and MK, PRD-L'24

- 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

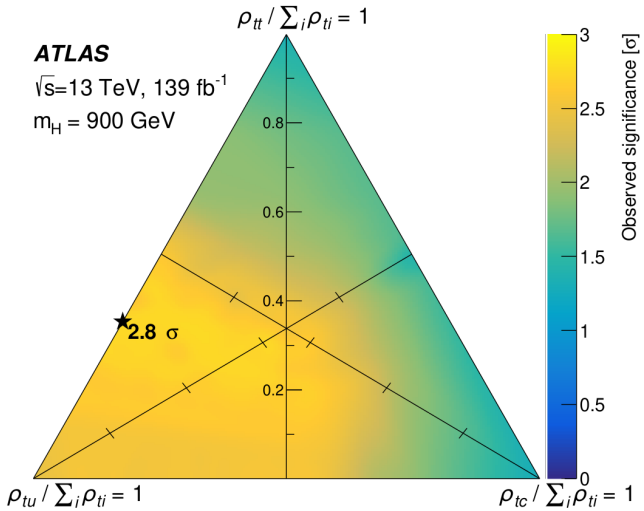
With $t \to ch$ alignment-suppressed, it is natural to pursue $cg \to tH/tA \to tt\bar{c}/tt\bar{t}$ (same-sign top/triple top), which is controlled by $s_\gamma \simeq 1$.

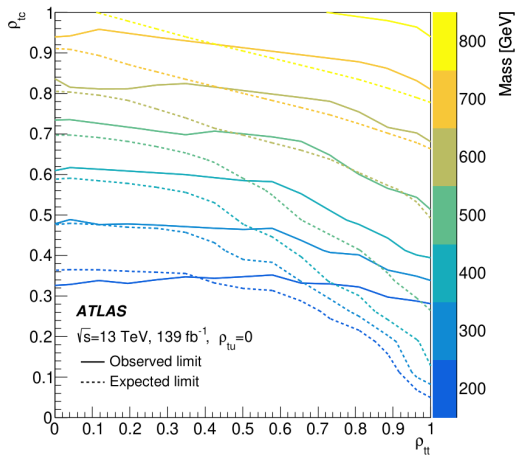


Observed (expected) mass limit [GeV]

	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; Jaffel's talk

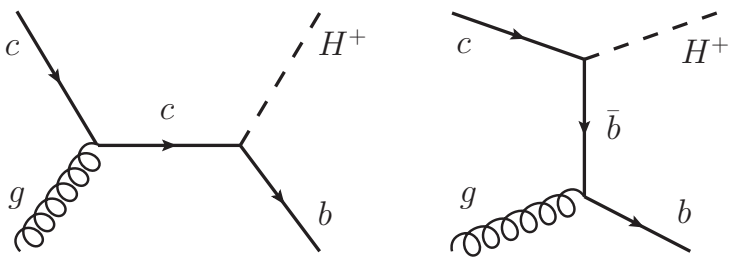




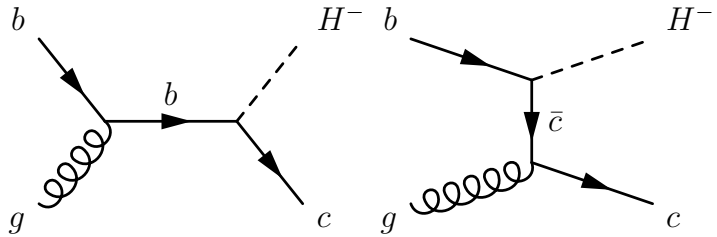
ATLAS, JHEP'23; Saka's talk

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.

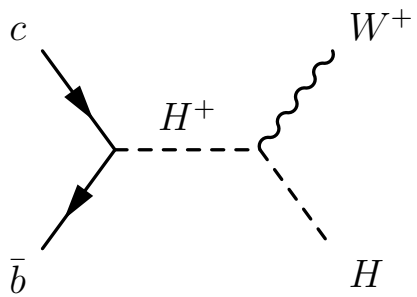


Ghosh, Hou, Modak, PRL'20



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.

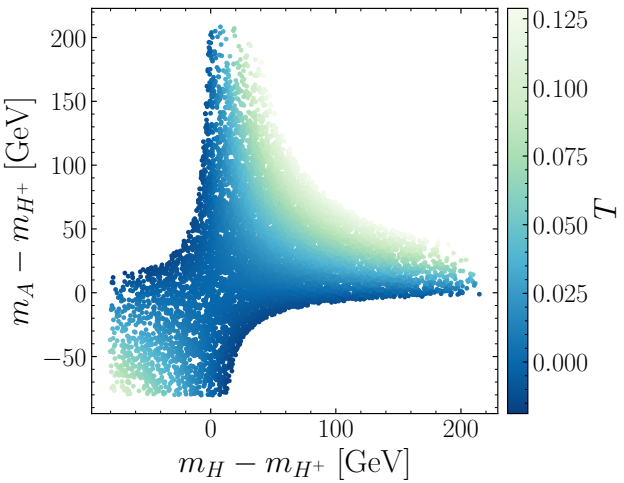


Hou and MK, arXiv:2409.18474

Signal vs. Background

Signal ($\rho_{tc} = 0.4$, $\rho_{tt} = 0.6$): $pp \to cH^- \to c\bar{t}b \to cW^-(\to \ell^-\bar{\nu}_\ell)\bar{b}b$

BKG: $t\bar{t}+$jets, $Wt+$jets, single top (tj), $t\bar{t}h$, $t\bar{t}Z$



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	0.62	0.53	1.06	−0.79	300	272	372	1.18
2	0.93	1.06	0.14	−0.36	−0.22	350	371	340	1.49
3	1.36	1.16	0.81	0.70	−0.36	400	404	454	2.06
4	0.61	1.83	1.30	−0.30	0.68	450	501	482	2.46
5	0.71	0.69	1.52	−0.93	0.24	500	569	517	3.78

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

- $N_j \geq 2$ & $N_j \leq 4$ with $P_T^j \geq 20$ GeV
- At least two b-tagged ($N_b \geq 2$)
- $N_\ell = 1$, $P_T^\ell \geq 30$, $E_T^{miss} > 20$ GeV
- $H_T > 300(400)$ GeV for BP1(2-5)
- $M_T^{H^+} \in [m_{H^+} - 50, m_{H^+} + 50]$

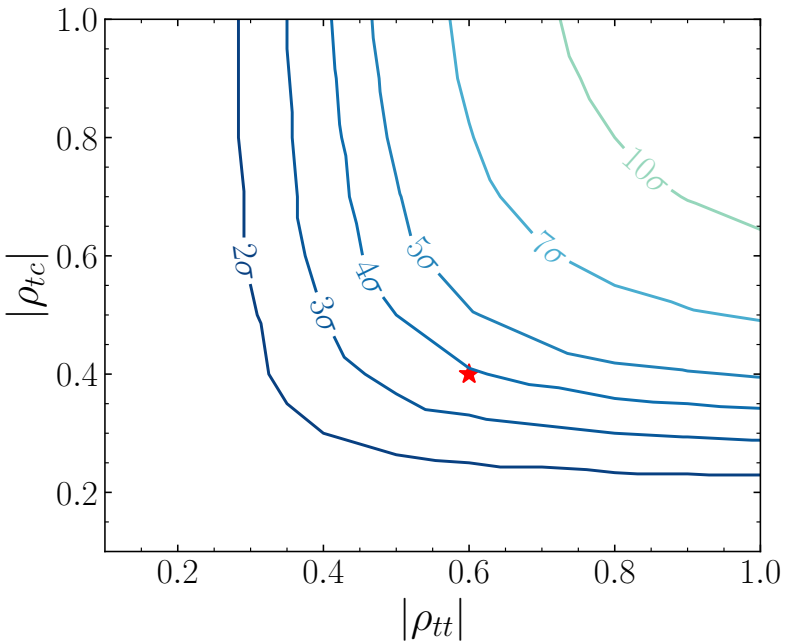
BP	$t\bar{t}+2j$	$Wt+2j$	$tj+1j$	$t\bar{t}h$	$t\bar{t}Z$	Signal
1	3143.2	699.2	228.1	1.5	0.9	14.9
2	2237.9	548.3	185.8	1.4	0.8	11.9
3	2782.1	816.5	222.5	1.9	1.1	13.8
4	2438.2	752.2	157.5	2.0	1.4	9.8
5	1894.8	605.5	108.1	1.7	1.0	6.4

Significance

We estimate our signal sensitivity using $\mathcal{Z} = \sqrt{2\left[(S+B)\ln(1+S/B) - S\right]}$

G. Cowan *et al.*, EPJC'11

BP	$\mathcal{Z}$ at 300 (600) fb^{-1}
1	4.0 (5.7)
2	3.8 (5.3)
3	3.9 (5.5)
4	2.9 (4.1)
5	2.2 (3.1)



- Evidence could emerge at 300 fb^{-1}, with discovery potential at 600 fb^{-1}.
- Larger ρ_{tc}, ρ_{tt} values could yield $\mathcal{Z} \sim 5\sigma$ (or even higher) at 300 fb^{-1}.

Conclusion

- Charged Higgs bosons are actively searched for at the LHC.
- However, it might be difficult to detect at the LHC via $bg \to tH^-$.
- In G2HDM, $bg \to cH^-$ is induced by the FC top-charm coupling ρ_{tc} without CKM-suppression, and has relatively large cross section.
- $bg \to cH^- \to c\bar{t}b$ is suggested, where the recoiling c could provide both a tag, and a discriminant to suppress the background.

Thank you!

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