

Probing the General 2HDM with Flavor Violation Through $A \rightarrow ZH$ and $H^+ \rightarrow W^+H$

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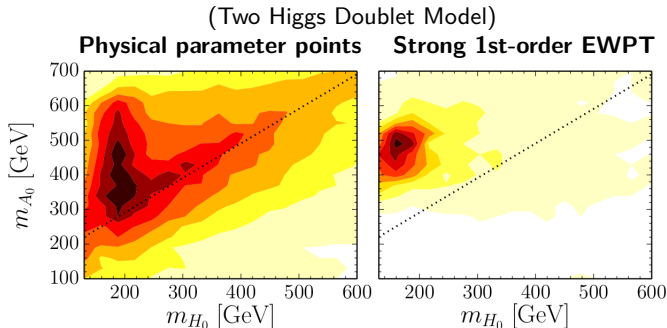
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Why $A \rightarrow ZH$ and/or $H^+ \rightarrow W^+H$?

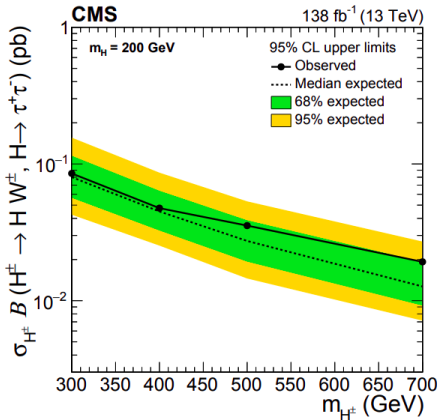
- ▶ SM: KM phase too small & EWPT not first-order \implies EWBG not viable
- ▶ Extended Higgs sector: new CPV & first-order EWPT \implies EWBG possible!



[Dorsch, Huber, Mimasu, No, PRL'14]

- ▶ Strong first order EWPT in 2HDM favors a rather heavy CP-odd scalar state A ($m_A > 300$ GeV) and a large mass splitting $m_A - m_H \gtrsim v$
- ▶ The decay $A \rightarrow ZH$ is kinematically allowed (*smoking-gun* signature)

CMS Searches for H^\pm

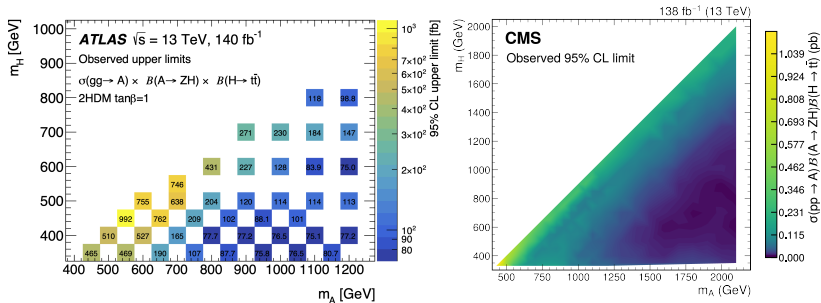


[CMS, JHEP'23]

- ▷ First limits on H^\pm production in the $H^\pm \rightarrow W^\pm H$ decay at the LHC.

LHC searches for $A \rightarrow ZH$

Both ATLAS¹ and CMS have recently searched for $A \rightarrow ZH \rightarrow \ell^+ \ell^- t\bar{t}$



[ATLAS, JHEP'24]

[CMS, PLB'25]

- ▶ ATLAS reported an excess in the region around $(m_A, m_H) = (650, 450)$ GeV with a local significance of 2.85 standard deviations [ATLAS, JHEP'24]
- ▶ ATLAS excess is not observed by CMS [CMS, PLB'25]

¹ATLAS has also searched for $A \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$.

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]

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

with

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

- ▶ The Z_2 symmetry is not imposed \implies FCNCs at tree-level
- ▶ Many parameters and extra processes arise
- ▶ EWBG, Absence of FCNCs (e.g. $t \rightarrow ch_{125}$), ... could be explained
- ▶ Sub-TeV H , A , and H^\pm may still exist

Higgs Couplings

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

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

- ▶ λ^f matrices: diagonal, fixed by fermion mass
- ▶ ρ^f matrices: (complex) non-diagonal lead to FCNCs
- ▶ Alignment ($c_\gamma \approx 0$) suppresses FCNCs for h but allows FCNCs for H and A
- ▶ ρ_{ij} are severely constrained by flavor physics [See, e.g., A. Crivellin *et al.*, PRD'13]
- ▶ ρ_{tc} and ρ_{tt} could still be large and can *each* drive EWBG
[See, e.g., Fuyuto, Hou, Seneha, PLB'18]
- ▶ The LHC offers the best way to test the model and constrain ρ_{tc} and ρ_{tt}

Limits on ρ_{tc}

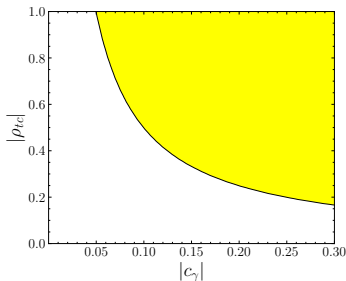
For $c_\gamma \neq 0$, LHC $t \rightarrow ch$ searches set significant constraint on ρ_{tc} .

Signal	Observed (expected) 95% CL upper limits $\mathcal{B}(t \rightarrow Hq)$	$ C_{u\phi}^{qt,tq} $
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	$\mathcal{B}(t \rightarrow Hu)$	$\mathcal{B}(t \rightarrow Hc)$
	observed (expected)	observed (expected)
$H \rightarrow b\bar{b}$ [24]	0.079 (0.11)%	0.094 (0.086)%
$H \rightarrow \gamma\gamma$ [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)%

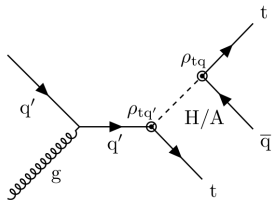
[CMS, PRD'25]



- ▶ $|\rho_{tc}| \gtrsim 0.5$ 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 ρ_{tc}

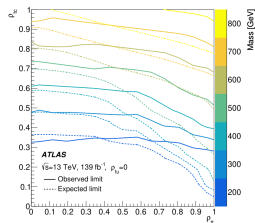
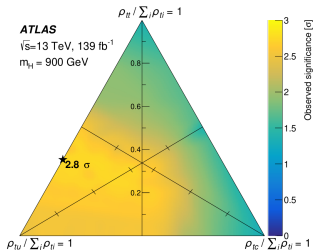
In G2HDM, one could have same-sign top and/or triple top final states via $cg \rightarrow tH/tA \rightarrow tt\bar{c}/tt\bar{t}$.



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)

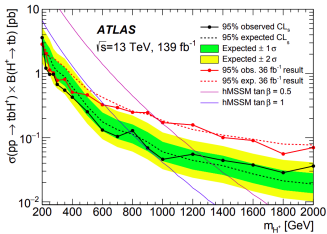
[CMS, PLB'24]



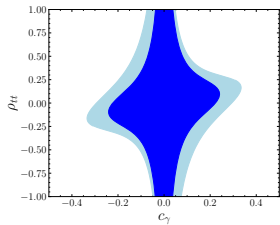
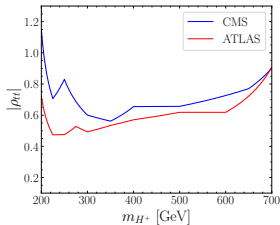
[ATLAS, JHEP'23]

Limits on ρ_{tt}

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



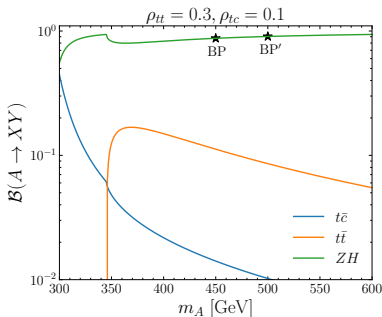
[ATLAS, JHEP'21]



- ▶ Limits are interpreted assuming $\mathcal{B}(H^+ \rightarrow \bar{t}b) = 100\%$ [Hou and MK, PRD'24]
- ▶ Constraints from ATLAS $H^+ \rightarrow W^+h$ search are very weak [ATLAS, JHEP'25]
- ▶ Agreement with the Higgs signal measurements using HiggsSignals (Runs 1 & 2; light blue) and HL-LHC projections (dark blue).

Benchmark Scenario

- ▶ We consider $m_H = 200$ GeV, and $m_A = m_{H^\pm} \in [300, 600]$ GeV



- ▶ We choose $m_A = 450$ (500) GeV as a representative benchmark point, denoted BP (BP'), where $B(A \rightarrow ZH) \simeq 87$ (90)%

Collider Study

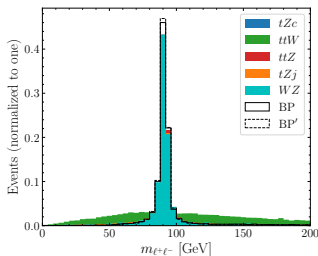
Signal: $pp \rightarrow A \rightarrow ZH \rightarrow \ell^+ \ell^- t\bar{c} \rightarrow \ell^+ \ell^- W^+ b\bar{c} \rightarrow \ell\ell\ell + b\bar{c} + E_T^{\text{miss}}$

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

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
$t\bar{t}t$	< 0.001



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

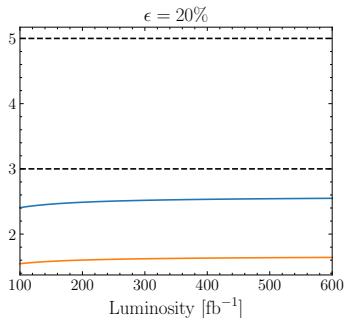
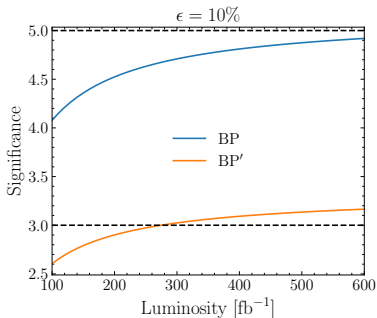
[Hou and MK, PRD'25]

Signal Significance

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

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

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.



Complementary H^+ Signal

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

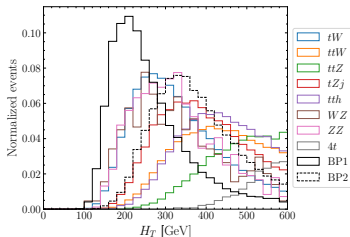
BKG: $t\bar{t}W + j, t\bar{t}Z + j, tW + j, WZ + j, tZj, ZZ + j, t\bar{t}h, 4t$

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, $\rho_{tc} = 0.3, \rho_{tt} = 0.5$.

Event selection:

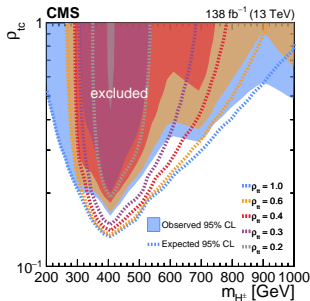
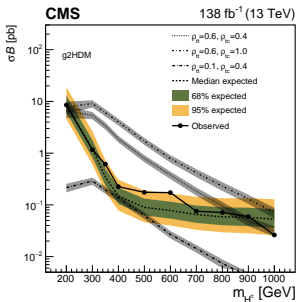
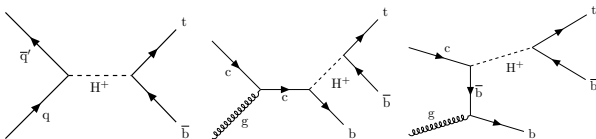
- ▶ $N_j \geq 2$ with $p_T^j \geq 20$ GeV
- ▶ At least one b -tagged ($N_b \geq 1$)
- ▶ $SS2\ell$ ($N_\ell = 2$), $p_T^{\ell_{1(2)}} \geq 25(20)$ GeV
- ▶ $\Delta R_{\ell\ell}, \Delta R_{\ell j} > 0.4, E_T^{\text{miss}} > 35$ GeV
- ▶ p_T sum of all jets and the two SS leptons $H_T < 400$ GeV



Significance ($L = 300 \text{ fb}^{-1}, \epsilon_B = 20\%$): BP1 (BP2) yields $\mathcal{Z} \simeq 3.8\sigma$ (4.5σ).

[Hou and MK, PRD'25]

A Hint of H^+ ?

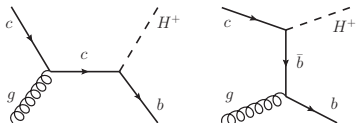


[CMS, arXiv:2512.24471]

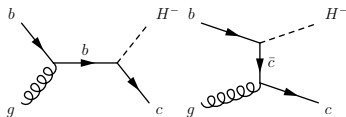
- ▷ An excess is observed at $m_{H^+} = 600 \text{ GeV}$ with a local significance of 2.4σ

New H^+ Production Modes

In general 2HDM with extra Yukawa couplings, $\bar{c}bH^+$ couples with strength $\rho_{tc}V_{tb}$, and $cg \rightarrow bH^+$ and $bg \rightarrow cH^-$ are not CKM suppressed.

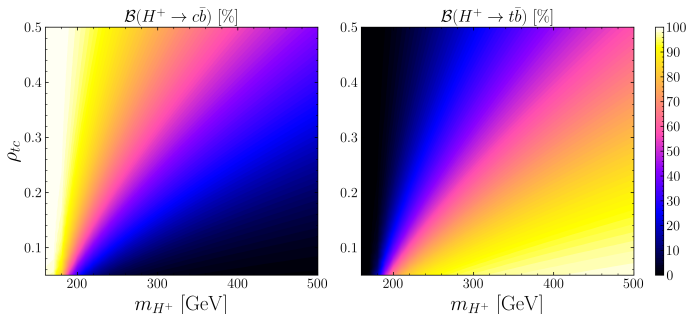


Ghosh, Hou, Modak, PRL'20



Hou and MK, PRD'24

H^+ decay ($m_H \sim m_A \sim m_{H^+}$, $c_\gamma = 0$, $\rho_{tt} = 0.2 \times (m_{H^+}/150)$ [Hou et al., PLB'19])

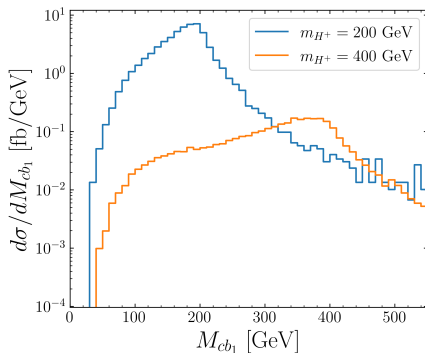


Event Generation

Signal: $pp \rightarrow bH^+ \rightarrow bc\bar{b}$

BKG: $pp \rightarrow b\bar{b}j$, $pp \rightarrow b\bar{b}c$, $pp \rightarrow c\bar{c}j$

Using the default ATLAS Delphes card, we incorporate charm-tagging efficiencies based on CMS results,² with $\epsilon_c = 0.22$, $\epsilon_{b \rightarrow c} = 0.01$, and $\epsilon_{j \rightarrow c} = 0.001$, where $j = u, d, s, g$. For b -tagging, we use the efficiency parametrization defined in the Delphes card.



[Fang, Hou, Kao, MK, arXiv:2511.19604]

²A. Tumasyan *et al.* [CMS], JINST **17** (2022) no.03, P03014.

Event Selection

For event selection, we adopt the following requirements:

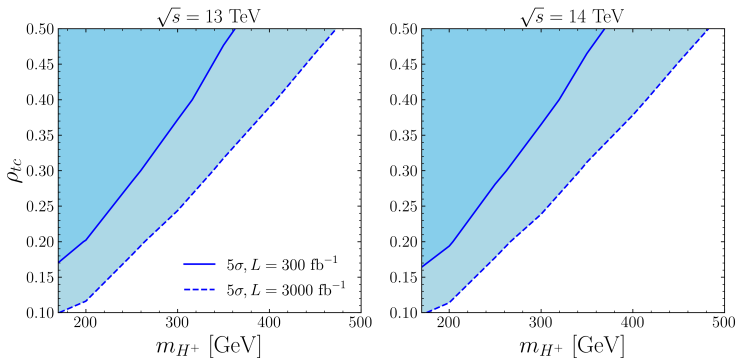
- ▷ one c -jet with $p_T^c \geq 25$ GeV and $|\eta_c| < 2.5$,
- ▷ two b -jets with $p_T^b \geq 25$ GeV and $|\eta_b| < 2.5$,
- ▷ $p_T^{b_1} > 50$ GeV, $p_T^c > 70$ GeV,
- ▷ $\Delta R_{cb_1} > 2.0$,
- ▷ $|M_{cb_1} - m_{H^+}| \leq 0.20 \times m_{H^+}$.

\sqrt{s} (TeV)	$m_{H^+} = 200$ GeV (fb)	$b\bar{b}j$ (fb)	$c\bar{c}j$ (fb)	Total (fb)
13	353.4	8.052×10^4	7343	8.786×10^4
13.6	394.0	8.407×10^4	7851	9.192×10^4
14	406.3	8.988×10^4	8741	9.862×10^4
\sqrt{s} (TeV)	$m_{H^+} = 300$ GeV (fb)	$b\bar{b}j$ (fb)	$c\bar{c}j$ (fb)	Total (fb)
13	103.2	8.332×10^4	7692	9.102×10^4
13.6	109.4	9.009×10^4	8223	9.831×10^4
14	116.1	9.723×10^4	9178	1.064×10^5
\sqrt{s} (TeV)	$m_{H^+} = 400$ GeV (fb)	$b\bar{b}j$ (fb)	$c\bar{c}j$ (fb)	Total (fb)
13	25.61	6.323×10^4	5634	6.887×10^4
13.6	27.64	6.927×10^4	5762	7.503×10^4
14	29.37	7.129×10^4	7025	7.832×10^4

K -factors are included in CS. $\rho_{tc} = 0.4$.

Signal Significance

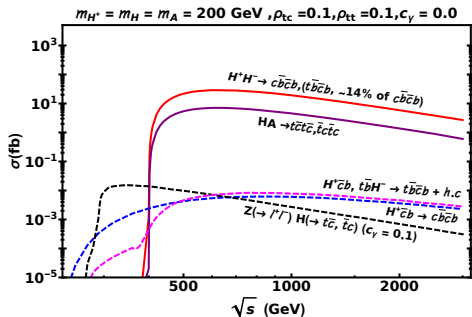
Significance calculated assuming $\epsilon_B = 0$.



Assuming $\epsilon_B = 5\%$, the significance decreases substantially...

But what if non-observation?!

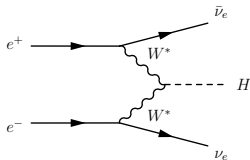
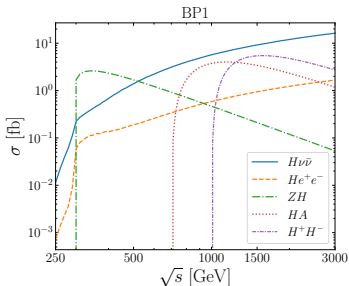
- ▶ This could happen if $\rho_{tc} \lesssim 0.1$ and $\rho_{tt} \lesssim 0.1$ suppressing Higgs production
- ▶ Would future e^+e^- colliders probe additional Higgs bosons?
- ▶ 500 GeV ILC would be able to probe m_{H^+} at $\mathcal{O}(200)$ GeV through $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}b$ [Hou, Jain, Modak, JHEP'22]
- ▶ H and A can also be searched for at ILC through $e^+e^- \rightarrow HA \rightarrow t\bar{c}t\bar{c}$ process³



³W.-S. Hou and G. L. Lin, Phys. Lett. B 379 (1996), 261-266.

Higgs production at future e^+e^- colliders

- ▶ In case $c_\gamma \neq 0$ and $|\rho_{tt}| \simeq 0.1$, while $\rho_{tc} \simeq 0$ (no FCNCs)
- ▶ $c_\gamma \neq 0$ would induce $H \rightarrow WW/ZZ$, $H \rightarrow hh$, $A \rightarrow Zh$, and $H^\pm \rightarrow W^\pm h$
- ▶ H^\pm can be searched for via $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}t\bar{b}, W^+SW^-S$ ($S = h, H, A$)⁴
- ▶ At high energy e^+e^- colliders, $e^+e^- \rightarrow H\nu\bar{\nu}$ has relatively large production cross section, and can offer a direct access to the mixing angle c_γ

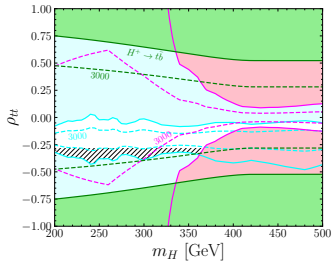
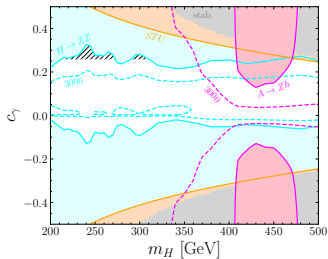
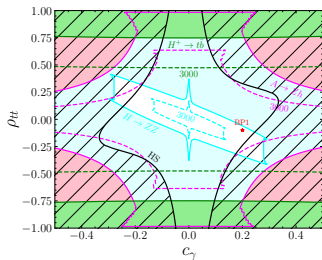


BP1: $m_H = 200$ GeV, $m_A = m_{H^\pm} = 500$ GeV, and $c_\gamma = 0.2$

⁴Or $e^+e^- \rightarrow H^\pm W^\mp S$. See, [Ouazghour, Arhrib, Cheung, Ghourmin, MK and Rahili, PRD'25](#).

Benchmark Scenario

We choose $m_A = m_{H^\pm} = 500$ GeV (to satisfy electroweak precision constraints), and scan $m_H \in [200, 500]$ GeV, $c_\gamma \in [-0.5, 0.5]$, and $\rho_{tt} \in [-1, 1]$ [Hou and MK, arXiv:2511.02420].



Higgs Signal and Simulation

- ▶ The signal is $e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow W^+W^-\nu\bar{\nu}$, yielding the following final states:
 - i*) $\ell^+\ell^-\nu\bar{\nu}\nu\bar{\nu}$ (hereafter denoted as $\ell\ell + E_T^{\text{miss}}$)
 - ii*) $\ell^\pm jj\nu\bar{\nu}$ (hereafter $\ell jj + E_T^{\text{miss}}$)
 - iii*) $jjjj\nu\bar{\nu}$ (hereafter $4j + E_T^{\text{miss}}$)
- ▶ Among future e^+e^- colliders, we choose CLIC operating at $\sqrt{s} = 1.5$ TeV and use the default CLICdet_Stage2 Delphes card for fast detector simulation.
- ▶ Jets are clustered using the Valencia algorithm⁵ with a fixed jet number and a radius parameter of $R = 1$.
- ▶ The incoming electron and positron beams are assumed to be unpolarized. Including beam polarisation, however, would enhance the $e^+e^- \rightarrow H\nu\bar{\nu}$ production rate [H. Abramowicz *et al.*, EPJC'17].
- ▶ We consider $m_H = 200$ (250) GeV, $m_A = m_{H^\pm} = 500$ GeV, $c_\gamma = 0.2$, and $\rho_{tt} = -0.1$ as a representative benchmark point, denoted BP1 (BP2), for which the predominant decay channel of H is $H \rightarrow W^+W^-$, followed by $H \rightarrow ZZ$.

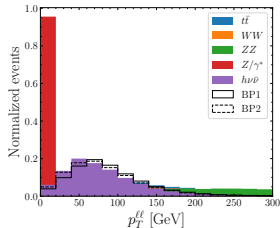
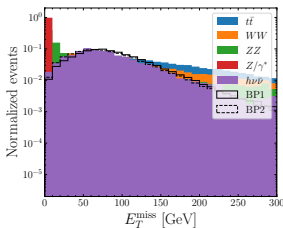
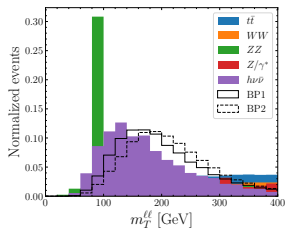
⁵Boronat, Fuster, Garcia, Ros and Vos, Phys. Lett. B **750** (2015), 95-99.

$\ell\ell + E_T^{\text{miss}}$ Final State

For event selection, we require

$\sqrt{s} = 1.5 \text{ TeV}$	BP1	BP2	tt	WW	ZZ	Z/γ^*	$h\nu\bar{\nu}$
Exactly two OS leptons	0.189	0.160	3.176	25.289	3.200	11013.7	1.089
$120 < m_T^{\ell\ell} < 260 \text{ GeV}$	0.124	0.104	0.469	1.362	0.669	0.304	0.618
$E_T^{\text{miss}} > 50 \text{ GeV}$	0.104	0.074	0.373	0.295	0.055	0.120	0.569
Jet veto	0.104	0.074	< 0.01	0.284	0.023	0.120	0.555
$p_T^{\ell\ell} > 30 \text{ GeV}$	0.104	0.074	< 0.01	0.263	0.023	0.101	0.553

BP1 (BP2) corresponds to $m_H = 200$ (250) GeV. Cross sections are in fb.

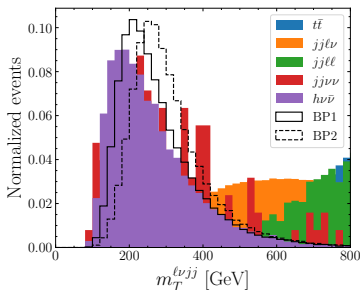
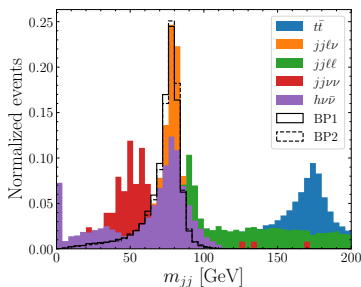


$\ell jj + E_T^{\text{miss}}$ Final State

For event selection, we require

$\sqrt{s} = 1.5$ TeV	BP1	BP2	$t\bar{t}$	$jj\ell\nu$	$jj\ell\ell$	$jj\nu\nu$	$h\nu\bar{\nu}$
$n_\ell = 1$ & $n_j = 2$	0.935	0.865	24.536	570.337	6.129	0.076	5.656
$E_T^{\text{miss}} > 30$ GeV	0.859	0.801	22.673	523.97	0.700	0.074	5.274
m_{jj} window	0.706	0.665	0.256	438.091	0.045	0.023	3.023
$m_T^{\ell\nu jj}$ window	0.294	0.350	< 0.01	4.216	—	0.005	1.422

BP1 (BP2) corresponds to $m_H = 200$ (250) GeV. Cross sections are in fb.

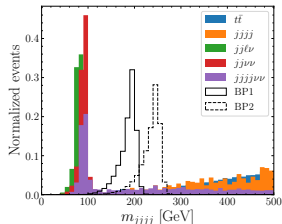
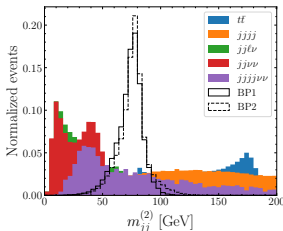
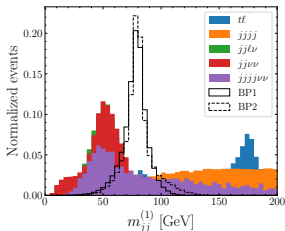


$4j + E_T^{\text{miss}}$ Final State

For event selection, we require

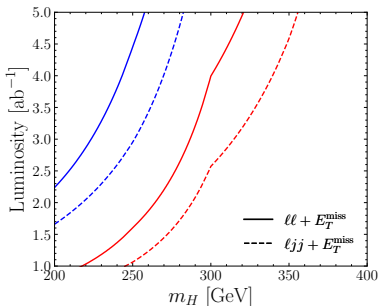
$\sqrt{s} = 1.5 \text{ TeV}$	BP1	BP2	$t\bar{t}$	$jjjj$	$jj\ell\nu$	$jj\nu\bar{\nu}$	$jjjj\nu\bar{\nu}$
$n_j = 4$	1.219	1.225	70.412	73.784	172.385	71.653	1.030
$E_T^{\text{miss}} > 30 \text{ GeV}$	1.136	1.136	52.189	31.616	153.86	71.471	1.001
$m_{jj}^{(1,2)}$ window	0.809	0.788	0.634	0.161	1.321	0.322	0.040
m_{jjjj} window	0.757	0.725	0.068	0.001	0.590	0.131	0.015
Lepton veto	0.756	0.724	0.006	0.001	0.497	0.131	0.015

BP1 (BP2) corresponds to $m_H = 200$ (250) GeV. Cross sections are in fb.



Signal Significance

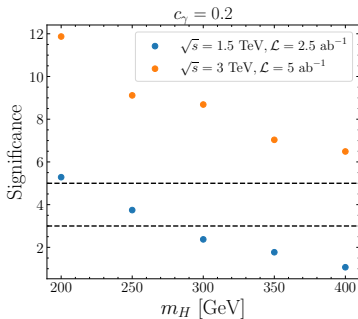
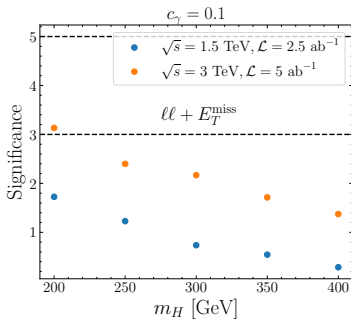
The signal significance is calculated using $\mathcal{Z} = \sqrt{2 \left[(N_S + N_B) \ln \left(1 + \frac{N_S}{N_B} \right) - N_S \right]}$



- ▶ The 3σ (red) and 5σ (blue) discovery contours are calculated for $c_\gamma = 0.2$
- ▶ The $4j + E_T^{\text{miss}}$ channel reaches a 5σ discovery with an integrated luminosity well below the expected CLIC luminosity of 2.5 ab⁻¹ at $\sqrt{s} = 1.5$ TeV (stage 2).

Signal Significance

- For $c_\gamma = 0.1$, the sensitivity of the $\ell\ell + E_T^{\text{miss}}$ and $\ell jj + E_T^{\text{miss}}$ channels is substantially reduced, however, $4j + E_T^{\text{miss}}$ channel would remain sensitive.



Effect of turning on ρ_{tc} (FCNCs):

- Assuming $\rho_{tc} = 0.1$ (to avoid $t \rightarrow ch$ limits), would induce $H \rightarrow t\bar{c}$ and soften $H \rightarrow WW$ decay but still the latter is predominant.
- Considering $\ell\ell + E_T^{\text{miss}}$ final state, and assuming $\sqrt{s} = 1.5 \text{ TeV}$ and $\mathcal{L} = 2.5 \text{ ab}^{-1}$, the expected significance is approximately 4.6σ for BP1. The significance for the $\rho_{tc} = 0$ case is about 5.3σ .

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
- ▶ Unlike conventional 2HDMs, in G2HDM with extra Yukawa couplings, $c\bar{b} \rightarrow H^+$, $cg \rightarrow bH^+$ and $bg \rightarrow cH^-$ are not CKM suppressed,
- ▶ and searches for H^+ via $pp \rightarrow bH^+ \rightarrow bt\bar{b}, bc\bar{b}$ could be promising!
- ▶ If kinematically allowed, $A \rightarrow ZH$ and $H^+ \rightarrow W^+H$ can provide crucial probes,
- ▶ and searches for $A \rightarrow ZH$ and $H^+ \rightarrow W^+H$ in the $\ell^+\ell^-t\bar{c}$ and $\ell^\pm\nu t\bar{c}$ final states could probe the G2HDM with flavor-violating couplings
- ▶ If QCD backgrounds limit LHC sensitivity, a future e^+e^- collider is essential...

Thank you!

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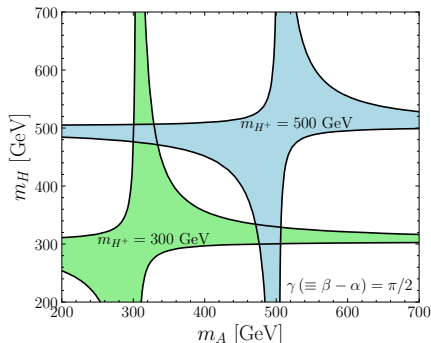
Thank you!

Other Constraints

G2HDM is also subject to the following constraints:

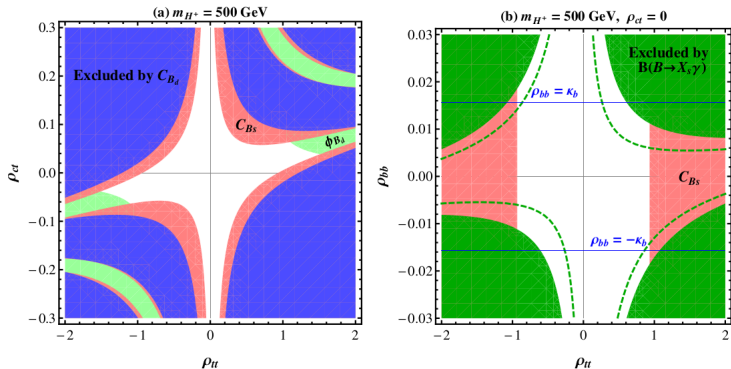
- ▶ Unitarity, perturbativity and vacuum stability
- ▶ EW precision constraints through oblique parameters S , T and U using the following fit result:

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



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]

Effect of Beam Polarization

Throughout the CLIC analysis presented here, the electron and positron beams have been assumed to be unpolarized. Since the signal process $e^+e^- \rightarrow H\nu\bar{\nu}$ proceeds dominantly through WW -fusion, it is expected to benefit significantly from beam polarization. For instance, with a polarization configuration of $(P_{e^-}, P_{e^+}) = (-80\%, +30\%)$, the WW -fusion cross section is enhanced by a factor of about 2.34 relative to the unpolarized case. Considering 80% of the integrated luminosity with $(P_{e^-}, P_{e^+}) = (-80\%, +30\%)$ and 20% with $(P_{e^-}, P_{e^+}) = (+80\%, +30\%)$, the enhancement factor is approximately 1.92.⁶ If the positron beam is unpolarized ($P_{e^+} = 0$), the enhancement is about 1.48.

⁶H. Abramowicz *et al.*, Eur. Phys. J. C **77** (2017) no.7, 475.

Mass Reconstruction

We define⁷ the transverse mass of the $\ell\nu jj$ system as

$$(m_T^{\ell\nu jj})^2 = \left(\sqrt{p_{T,\ell jj}^2 + m_{\ell jj}^2} + p_T^{\text{miss}} \right)^2 - \left(\vec{p}_{T,\ell jj} + \vec{p}_T^{\text{miss}} \right)^2. \quad (4)$$

and require it to satisfy $|m_T^{\ell\nu jj} - m_H| < 0.25 \times m_H$.

The four jets are paired into two hadronic W boson candidates by minimizing the χ^2 function

$$\chi^2 = \left(m_{jj}^{(1)} - m_W \right)^2 + \left(m_{jj}^{(2)} - m_W \right)^2, \quad (5)$$

with $m_{jj}^{(1,2)}$ denote the invariant masses of the two dijet systems.

⁷This definition, combining the two jets and the lepton into a single system while treating the missing momentum separately, leads to better mass reconstruction and signal-to-background ratio. An alternative definition in which the two W decays are treated separately yields almost similar results for the signal.