Enhanced Charged Higgs Signal at the LHC

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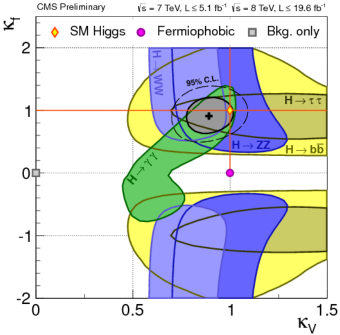
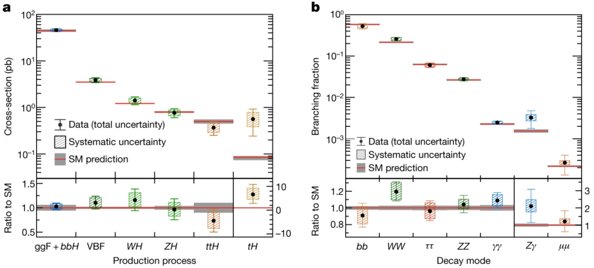
Where do we stand?



- A CP-even Higgs boson ($m_h = 125$ GeV) was discovered in 2012.
- Where is new physics? Is there a second Higgs doublet?
- This 125 GeV Higgs boson looks almost like the Standard Higgs in the decoupling limit or the alignment limit.

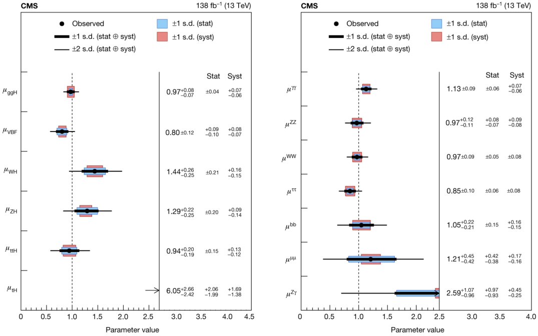
Where do we stand?



a, Cross-sections for different Higgs boson production processes are measured assuming standard model (SM) values for the decay branching fractions. **b**, Branching fractions for different Higgs boson decay modes are measured assuming SM values for the production cross-sections. The lower panels show the ratios of the measured values to their SM predictions. The vertical bar on each point denotes the 68% confidence interval. The *p* value for compatibility of the measurement and the SM prediction is 65% for **a** and 56% for **b**. Data are from ATLAS Run 2.

The ATLAS Collaboration. A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. Nature 607, 52–59 (2022).

Where do we stand?



Signal-strength parameters extracted for various production modes μ_i, assuming $\mathcal{B}^f = (\mathcal{B}^f)_{SM}$ (left), and decay channels μ^f, assuming $\sigma_i = (\sigma_i)_{SM}$ (right). The thick and thin black lines indicate the 1-s.d. and 2-s.d. confidence intervals, respectively, with the systematic (syst) and statistical (stat) components of the 1-s.d. interval indicated by the red and blue bands, respectively. The vertical dashed line at unity represents the values of μ_i and μ^f in the SM. The covariance matrices of the fitted signal-strength parameters are shown in Extended Data Fig. 5. The *P* values with respect to the SM prediction are 3.1% and 30.1% for the left plot and the right plot, respectively. The *P* value corresponds to the probability that a result deviates as much, or more, from the SM prediction as the observed one.

The CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. Nature 607, 60–68 (2022).

General Two Higgs Doublet Models

The Yukawa Lagrangian in a general two Higgs doublet model:

$$\begin{aligned}\mathcal{L}_Y = & \frac{-1}{\sqrt{2}} \sum_{\mathrm{F=U,D,L}} \bar{F} \Big\{ \left[\kappa^F s_{\beta-\alpha} + \rho^F c_{\beta-\alpha} \right] h^0 + \left[\kappa^F c_{\beta-\alpha} - \rho^F s_{\beta-\alpha} \right] H^0 \\ & - i\,\mathrm{sgn}(Q_F) \rho^F A^0 \Big\} P_R F - \bar{U} \left[V \rho^D P_R - \rho^{U\dagger} V P_L \right] D H^+ \\ & - \bar{\nu} \left[\rho^L P_R \right] L H^+ + \mathrm{H.c.}\end{aligned}$$

- $P_{L,R} \equiv (1 \mp \gamma_5)/2$, $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$, $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$,
- α is the mixing angle between neutral Higgs scalars,
- $\tan\beta \equiv v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets,
- Q_F is the fermion charge,
- κ matrices are diagonal and fixed by fermion masses to $\kappa^F = \sqrt{2} m_F / v$ with $v \approx 246$ GeV,
- ρ matrices contain both diagonal and off-diagonal elements with free parameters.

2HDMC

- A computer code that evaluates decay widths for h^0, H^0, A^0, and $H^\pm$ including higher-order QCD corrections, theoretical constraints and much more, by D. Eriksson, J. Rathsman, and O. Stål[1].
- For neutral Higgs bosons, QCD corrections are evaluated with $m_f(M_\phi)$ for $h^0, H^0, A^0 \to f\bar{f}$.
- FCNH decays are evaluated with $\rho_{qq'}$ such as $H^0 \to tc$ and $A^0 \to tc$.
- For charged Higgs decays into quarks, QCD corrections are calculated with $\rho_{qq'}$ scaled by running mass $m_q(M_{H^+})$, such as $H^\pm \to bc, tb$.

[1] https://2hdmc.hepforge.org/;
2HDMC - Two-Higgs-Doublet Model Calculator, D. Eriksson, J. Rathsman, O. Stål Comput. Phys. Commun. 181:189-205 (2010); Comput. Phys. Commun. 181:833-834 (2010); [arXiv:0902.0851]

MadGraph with 2HDM

- *The general Two-Higgs-Doublet Model*, by Claude Duhr, Michel Herquet, and Celine Degrande[2].
- 2HDM_UFO: leading order.
- 2HDM_NLO: QCD corrections with virtual and real gluons.
- For neutral Higgs bosons, to compare with 2HDMC for Higgs decays, we need 2HDM_NLO and scale $m(\mathrm{pole})$ to $m(Q = M_H)$.

[2] https://feynrules.irmp.ucl.ac.be/wiki/2HDM;
Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle, Celine Degrande, Comput. Phys. Commun. 197 (2015) 239-262.

Yukawa Interactions of Charged Higgs Boson

To study the interaction of $H^+\bar{c}b$, we follow the Lagrangian [3]:

$$\mathcal{L}_Y = -\bar{U}\left[V\rho^D P_R - \rho^{U\dagger} V P_L\right] D H^+ - \bar{\nu}\left[\rho^L P_R\right] L H^+ + \mathrm{H.c.} \qquad (1)$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$. For simplicity, let us choose ρ as real parameters.
The coupling of $H^+\bar{c}b$ can be simplified as

$$\begin{aligned}\mathcal{L}_{H^+\bar{c}b} =& -\bar{c}\left(V_{cd}\rho_{db} + V_{cs}\rho_{sb} + V_{cb}\rho_{bb}\right) P_R b\, H^+ \\ &+ \left(\rho^*_{uc} V_{ub} + \rho^*_{cc} V_{cb} + \rho^*_{tc} V_{tb}\right) P_L b\, H^+ + \mathrm{H.c.} \\ \simeq& + \bar{c}\left[\rho^*_{tc} V_{tb} P_L\right] b\, H^+ \mathrm{H.c.}\end{aligned}$$

The coupling $\lambda_{H^+\bar{c}b} \propto \rho_{tc} V_{tb}$ is not suppressed by V_{cb}.
We propose that the process $cg \to bH^+$ followed by $H^+ \to \bar{b}c$ might be a promising discovery channel for the charged Higgs boson (H^+).

[3] S. Davidson and H. E. Haber, Phys. Rev. D **72** (2005), 035004;
F. Mahmoudi and O. Stal, Phys. Rev. D **81** (2010), 035016.

$cg \to bH^{\pm} \to bbc$

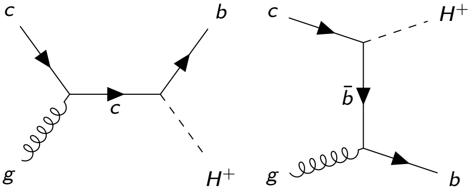
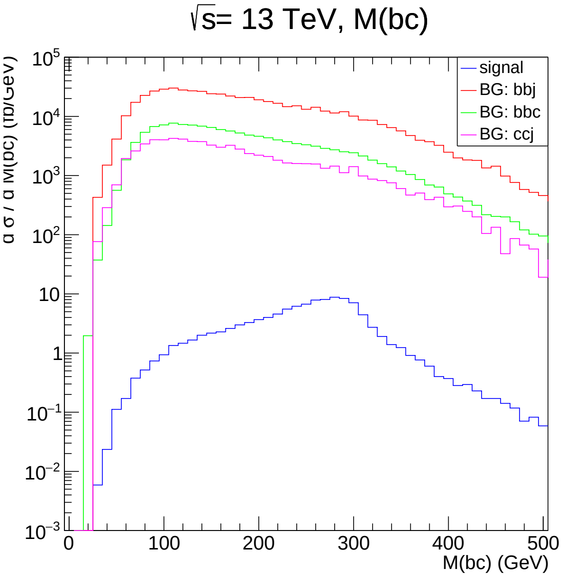


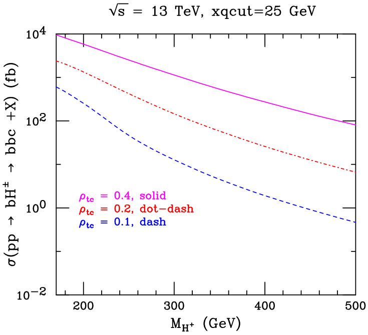
Figure: Leading-order Feynman diagrams for $cg \to bH^+$.

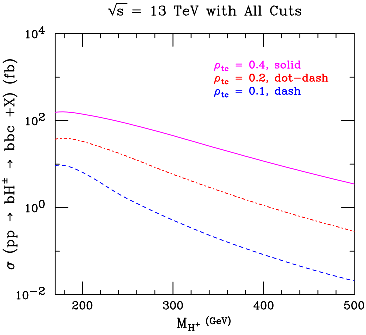
D. K. Ghosh, W. S. Hou and T. Modak, Phys. Rev. Lett. **125** (2020) no.22, 221801.

Invariant Mass Distributions

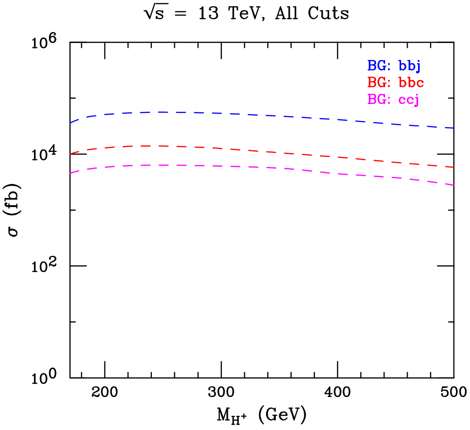


Cross Section versus M_{H^+}

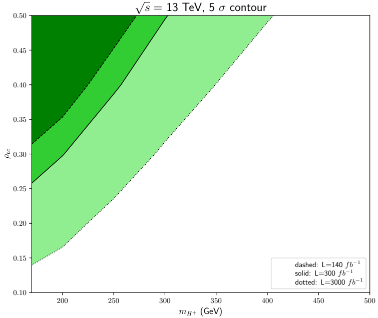


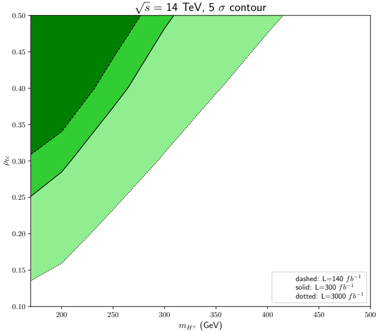


Physics Background



5 σ discovery contours for $cg \to bH^{\pm}$



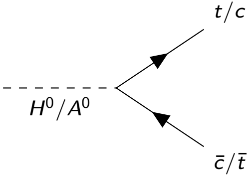


Summary for Enhanced Charged Higgs Signal

- In a general two Higgs doublet model, $H^{\pm} \to bc$ does not have V_{cb} suppression.
- The cross section of $cg \to bH^{\pm} \to bbc$ in G2HDM can be significantly larger than that in models with Type II Yukawa couplings with $1/V_{cb}^2$ enhancement.
- This discovery channel offers great promise to search for BSM new physics.
- Its cross section is proportional to ρ_{tc}^4 and might provide a good opportunity to measure ρ_{tc}.

Charming Higgs Bosons with Top Quarks

- With strong constraint $\mathcal{B}(t \to ch^0) \leq 3.7 \times 10^{-4}$, placed by ATLAS Collaboration[4] and CMS Collaboration[5]
  - $\lambda_{tch} \leq 0.036$, with $\lambda_{tch} \propto 1.92 \times \sqrt{\mathcal{B}(t \to ch^0)}$
  - $|\lambda_{tch}| \propto \tilde{\rho}_{tc} \cos(\beta - \alpha)$, where $\tilde{\rho}_{tc} \approx \sqrt{(|\rho_{tc}|^2 + |\rho_{ct}|^2)/2}$
- $H^0/A^0 \to t\bar{c} + \bar{t}c$



$$\frac{\lambda_{tcH}}{\sqrt{2}}\bar{c}tH^0, \quad i\frac{\lambda_{tcA}}{\sqrt{2}}\bar{c}tA^0$$
$$|\lambda_{tcH}| \propto \tilde{\rho}_{tc} \sin(\beta - \alpha), \quad |\lambda_{tcA}| \propto \tilde{\rho}_{tc}\,.$$

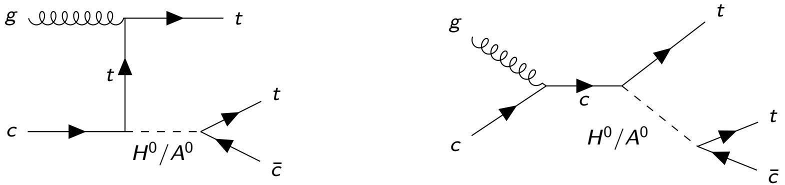
- In the alignment (decoupling) limit, $\cos(\beta - \alpha) \to 0$, $\sin(\beta - \alpha) \approx 1$, $|\lambda_{tcH}|$ and $|\lambda_{tcA}|$ are not suppressed

[4] G. Aad *et al.* [ATLAS], Eur. Phys. J. C **84**, no.7, 757 (2024).

[5] A. Hayrapetyan *et al.* [CMS], [arXiv:2407.15172 [hep-ex]

Charming Higgs Bosons with Top Quarks

- $pp \to t\phi^0 \to t(tc)$, where $\phi^0 = H^0$ or A^0



- All Top: $ttc \to bjjcb\ell\nu$
  - dominant physics background: (ttj) $pp \to t\bar{t}j \to b\bar{b}jjj\ell\nu$
- Same Sign Top: $ttc \to bbc\ell^\pm\ell^\pm\nu\nu$ where $\ell = e$ or μ
  - dominant physics background: (ttw) $pp \to t\bar{t}w^\pm \to b\bar{b}jj\ell^\pm\ell^\pm\nu$
  - other background: (ttz) $pp \to t\bar{t}z \to b\bar{b}jj\ell^\pm\ell^\pm\ell^\mp$

Decays of Heavy Neutral Higgs Bosons

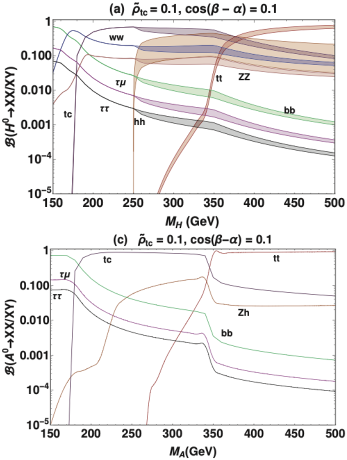
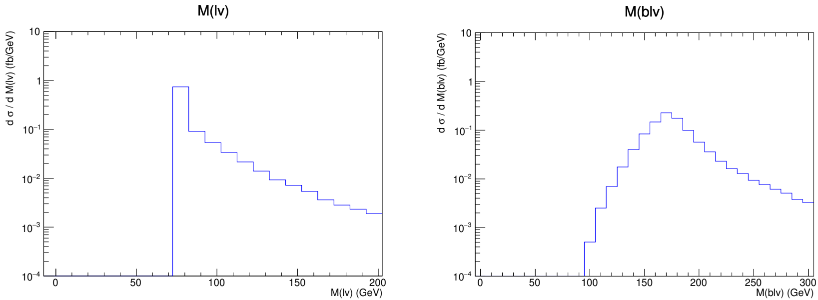


FIG. 1: Major two body decays of H^0 vs M_H for (a) $\tilde{\rho}_{tc} = 0.1$, and (b) $\tilde{\rho}_{tc} = 0.5$, with $\tilde{\rho}_{\tau\mu} = 0.01$, $\lambda_5 = 0$ and $1 \leq \tan\beta \leq 10$. The analogous case for A^0 is given in (c) and (d).

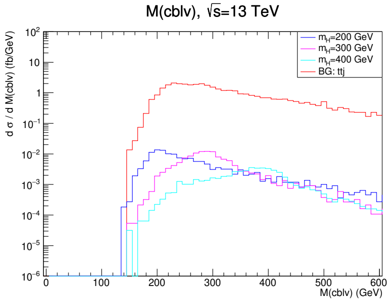
All Top final state ($bjjcb\ell\nu$)

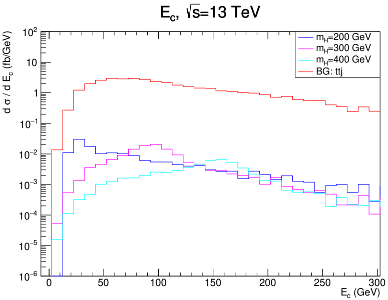
- Basic requirements
  - (i) five jets including two b-jet and one c-jet with $P_T(b,c,j) \geq 25$ GeV, $|\eta(b,c,j)| \leq 2.5$
  - (iii) a lepton with $p_T(\ell) \geq 20$ GeV, and $|\eta(\ell)| \leq 2.5$,
  - (iv) $\Delta R(cj, jj, bj, bc, \ell j, \ell b, \ell c) \geq 0.4$,
  - (v) missing transverse energy MET$= \not\!\!E_T \geq 25$ GeV,
- Reconstruct P_ν with m_w and m_t ($(P_\nu + P_\ell)^2 = m_W^2$, $(P_\nu + P_\ell + P_b)^2 = m_t^2$).



All Top final state ($bjjcb\ell\nu$)

- Reconstruct m_H with $c - jet$.
- Energy of the charm quark (E_c) in the rest frame of the Higgs Boson. The peak E_c^* is given by $E_c^* = \frac{m_H}{2}\left[1 + \frac{m_c^2}{m_H^2} - \frac{m_t^2}{m_H^2}\right]$.[6]
  $E_c^*(200) = 25.4$ GeV, $E_c^*(300) = 100.3$ GeV, $E_c^*(400) = 162.7$ GeV.



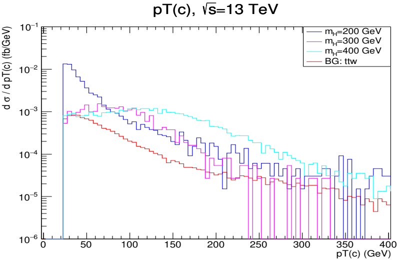


[6] T. Han, J. Jiang and M. Sher, Phys. Lett. B **516**, 337-344 (2001)

Same Sign Top final state[7, 8] ($bbc\ell^{\pm}\ell^{\pm}\nu\nu$)

- Basic requirements
  - (i) three jets including two b-jet and one c-jet with $P_T(b, c) \geq 25$ GeV, $|\eta(b, c, j)| \leq 2.5$
  - (ii) two lepton with $p_T(\ell) \geq 20$ GeV, and $|\eta(\ell)| \leq 2.5$,
  - (iii) $\Delta R(bc, \ell b, \ell c, \ell\ell) \geq 0.4$,
  - (iv) missing transverse energy MET$= \not{E}_T \geq 30$ GeV,

- For $m_H > 400$ GeV, $P_T(c)$ cuts can reduce background



[7] W. Hou, M. Kohda, T. Modak, Phys.Lett. B **786** (2018) 212-216

[8] CMS Collaboration, Phys. Lett. B **850** (2024) 138478

Statistical Significance

N_{SS} is calculated by:

$$N_{SS} = \sqrt{2 \times (N_S + N_B) \ln(1 + N_S/N_B) - 2 \times N_S}.$$

Here N_S and N_B are number of signal and background events, where $N_S = \sigma_s \times L$, $N_B = \sigma_b \times L$, and L is the luminosity of the LHC.[9]

[9] G. Cowan,K. Cranmer,E. Gross and O. Vitells, Eur. Phys. Jour. C **71** (2011) 1554.

Cross section & N_{SS}

- All Top state at $\sqrt{s} = 13$ TeV:

$\tilde{\rho}_{tc} = 0.4$	Signal	ttj	N_{SS}(L=1000 fb^{-1})
$m_H = 200$ GeV	0.2866 fb	14.80 fb	2.35
$m_H = 300$ GeV	0.3545 fb	31.62 fb	1.99
$m_H = 400$ GeV	0.1211 fb	18.17 fb	0.90

- Same Sign Top final state at $\sqrt{s} = 13$ TeV:

$\tilde{\rho}_{tc} = 0.4$	Signal	ttw	ttz	N_{SS}(L=1000 fb^{-1})
$m_H = 200$ GeV	0.2027 fb	0.0339 fb	0.0015 fb	22.41
$m_H = 300$ GeV	0.1791 fb	0.0339 fb	0.0015 fb	20.36
$m_H = 400$ GeV	0.0695 fb	0.0339 fb	0.0015 fb	9.43

5 σ Discovery Contours

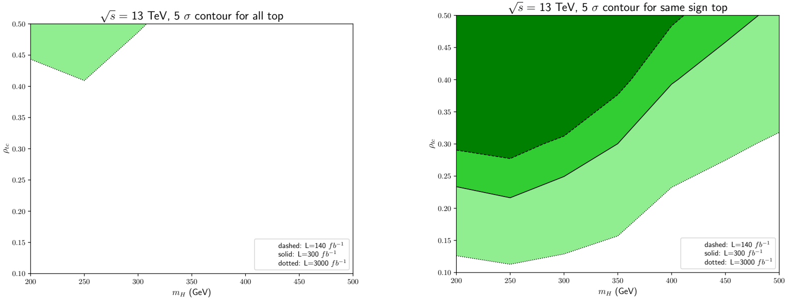
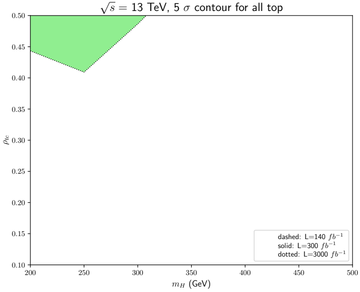


Figure: Discovery contours of $pp \to tH^0 \to ttc + X$ for All Tops (left) and Same Sign Tops (right).

3 σ Discovery Contour



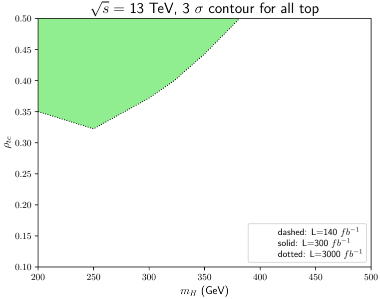
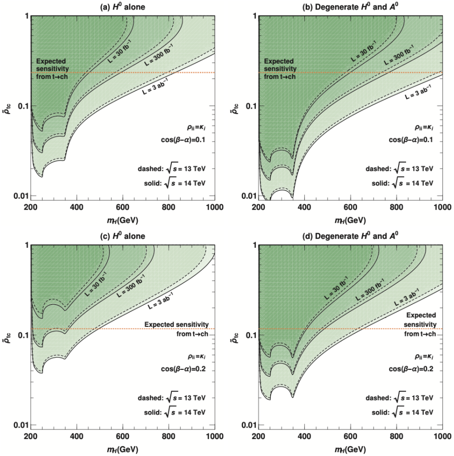


Figure: Discovery contours of $pp \to tH^0 \to ttc + X$ for all tops with 5σ (left) and 3σ (right).

Discovery Potential of $pp \to H^0 \to tc + X$



Flavor Changing Heavy Higgs Interactions at the LHC, B. Altunkaynak, W. S. Hou, C. Kao, M. Kohda and B. McCoy, Phys. Lett. B **751** (2015), 135-142.

Conclusions

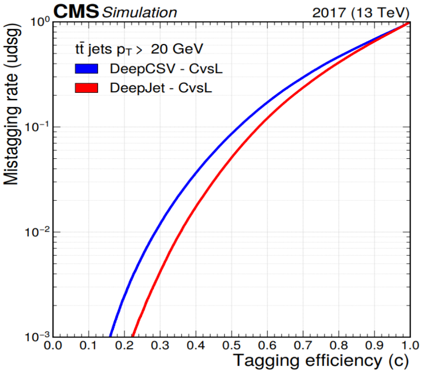
- It is of great interest to investigate the link between the most massive particle (top) and the mass giver (Higgs).
- In the decoupling limit, $\cos(\beta - \alpha) \to 0$ and $\sin(\beta - \alpha) \approx 1$.
- It is a win-win strategy to search for the FCNH top decay $t \to ch^0$ and the heavy Higgs decay $H^0, A^0 \to tc$ since $\lambda_{tch} \propto \tilde{\rho}_{tc} \cos(\beta - \alpha)$ and $\lambda_{Htc} \propto \tilde{\rho}_{tc} \sin(\beta - \alpha)$.
- Same sign top final state is almost background free. Combining with all top final state can help us improve the selection strategy and enhance the discovery potential for $pp \to tH^0 \to ttc + X$ at the LHC.
- The charged Higgs boson does not have CKM suppression for λ_{Hcb}. Thus $cg \to bH^\pm \to bbc$ is very promising to search for new physics.

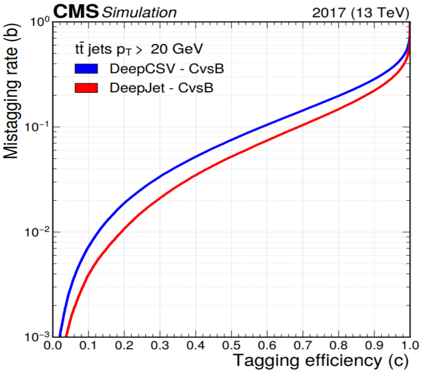
Collaborators

- *Enhanced Charged Higgs Signal at the LHC*:
  with Chenyu Fang, George W.-S. Hou, and Med Krab
- *Charming Higgs Bosons with Top Quarks at the LHC*:
  with Nicolas Bost, Chenyu Fang, and Phillip Gutierrez

Backup: C-Tagging

CMS c-tagging efficiency and missing tagging efficiencies [10].





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