Sub-TeV $H^+$ Boson Production as Probe of Extra Top Yukawa Couplings

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We suggest searching for the charged Higgs boson at the Large Hadron Collider (LHC) via $c g \rightarrow b H^+ \rightarrow b \bar{b} b$. In the general two Higgs Doublet Model, extra top Yukawa couplings $\rho_{tc}$ and $\rho_{tt}$ can drive the disappearance of antimatter from the Universe, while $\bar{c} b H$ and $\bar{b} H^+$ couple with strength $\rho_{tc} V_{tb}$ and $\rho_{tt} V_{tb}$, respectively. For $\rho_{tc}, \rho_{tt} \sim 0.5$ and $m_{H^+} \sim 300-500$ GeV, evidence could emerge from LHC Run 2 data at hand, and discovery by adding Run 3 data in the near future.

Introduction.— The discovery of the Higgs boson $h(125)$ at the LHC [1] suggests a weak scalar doublet, but there is no principle that precludes the existence of a second doublet. Having two Higgs doublets (2HDM), one has a charged $H^+$ boson plus the CP-even/odd scalar bosons $H, A$ [2]. We propose a novel process, $c g \rightarrow b H^+$ (see Fig. 1) followed by $H^+ \rightarrow t \bar{b}$, that may lead to the discovery of the exotic $H^+$ boson in the near future.

In the popular 2HDM type II (2HDM-II), up- and down-type quark masses arise from separate doublets [2], hence mass and Yukawa matrices are simultaneously diagonalized, just like in the Standard Model (SM). The model motivates an $H^+$ search at the LHC via the process $b g \rightarrow t H^+$ [3,4] which goes through the $\bar{b} b H^+$ coupling, while the $c g \rightarrow H^+$ process is suppressed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix element ratio $|V_{tb}/V_{ts}|^2 \sim 1.6 \times 10^{-3}$. But in the general 2HDM (g2HDM) with extra Yukawa couplings [5,6], $\bar{c} b H^+$ and $\bar{b} H^+$ couple with strength $\rho_{tc} V_{tb}$ and $\rho_{tt} V_{tb}$, respectively, and $c g \rightarrow b H^+$ is not CKM-suppressed.

The extra top Yukawa couplings [5] $\rho_{tc}$ and $\rho_{tt}$ are not well constrained. If both are $O(1)$, i.e. the top Yukawa coupling strength $\lambda_t$ in SM, they facilitate the production and decay in $c g \rightarrow b H^+ \rightarrow b \bar{b} b$ [5,7], with the signature of lepton plus missing energy and three $b$-jets. It is known [5] that $\rho_{tc}$ and $\rho_{tt}$ at $O(1)$ can each drive electroweak baryogenesis (EWBG), hence account for the disappearance of antimatter shortly after the Big Bang, one of the biggest mysteries. Perhaps equally interesting, when the ACME 2018 bound [9] on electron electric dipole moment (eEDM) seemed to rule out the $\rho_{tt}$ parameter space of Ref. [5], a second paper [10] brought in the extra electron Yukawa coupling, $\rho_{ee}$, and showed that a natural cancellation mechanism can survive the ACME18 bound, and with expanded parameter space for EWBG. This gives strong motivation for the $c g \rightarrow b H^+ \rightarrow b \bar{b} b$ search. The recent CMS hint of an “excess” [11] in $gg \rightarrow A \rightarrow t \bar{t}$ at $m_A \sim 400$ GeV could also arise from $\rho_{tt} \sim O(1)$ [12].

In this Letter, we first show that the $H, A$ and $H^+$ bosons in g2HDM can be sub-TeV in mass while satisfying all known constraints. This is in contrast with the absence of beyond SM (BSM) signatures so far at the LHC, with bounds often reaching multi-TeV in scale.

We then show that $\rho_{tc}, \rho_{tt}$ at $O(1)$ is allowed by current $b g \rightarrow t H^+$ and other search bounds. Full Run 2 data could already give evidence for $c g \rightarrow b H^+ \rightarrow b \bar{b}$, and discovery is possible by adding Run 3 data.

Dimension-4 Higgs Couplings.— Besides gauge couplings, Higgs bosons uniquely possess two additional sets of dimension-4 couplings: Higgs quartic and Yukawa interactions. In the Higgs basis, one can write the most general CP-conserving potential [13,14] in g2HDM as

\[
V(\Phi, \Phi') = \mu^2_1 |\Phi|^2 + \mu^2_2 |\Phi'|^2 - (\mu^2_3 \Phi \Phi' + h.c.) + \frac{1}{2} \eta_1 |\Phi|^4 + \frac{1}{2} \eta_2 |\Phi'|^4 + \eta_3 |\Phi|^2 |\Phi'|^2 + \eta_4 |\Phi|^4 |\Phi'|^2 + \left[ \frac{1}{2} \eta_5 (\Phi \Phi')^2 + (\eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2) \Phi' \Phi' + h.c. \right],
\]

where all quartic couplings $\eta_i$ are real, $\Phi$ induces spontaneous symmetry breaking by the vacuum expectation value $v$, i.e. $\mu^2_1 = -\frac{1}{2} \eta_1 v^2 < 0$, while $\langle \Phi' \rangle = 0$ hence $\mu^2_2 > 0$. The minimization condition $\mu^2_3 = \frac{1}{2} \eta_6 v^2$ reduces the parameter count to nine. From Eq. (1) one finds $m^2_\Phi(0) = \eta_1 v^2$, $m^2_{H^+} = \mu^2_2 + \frac{1}{2} \eta_3 v^2$ and $m^2_{H(0)} = m^2_{H^+} + \frac{1}{2} (\eta_1 + \eta_5) v^2$. Finally, $\eta_6$ mixes $h(0)$ and $H(0)$ into $h$ and $H$. The emergent alignment phenomenon, that $h$ resembles the Higgs boson of the SM so well [15–17], implies that the $h-H$ mixing angle $c_\gamma \equiv \cos \gamma$ (denoted usually as $-\cos(\beta-\alpha)$) is rather small.

The Yukawa couplings to quarks are [13,14]

\[
\mathcal{L} = -\frac{1}{\sqrt{2}} \sum_{f=u,d} \bar{f}_i \left[ -\lambda^f_i \delta_{ij} s_\gamma + \rho^f_i c_\gamma \right] h
+ (\lambda^f_i \delta_{ij} c_\gamma + \rho^f_i s_\gamma) H - i \text{sgn}(Q_f) \rho^f_i A \right] R f_j
-\bar{u}_i \left[ (V \rho^d)_{ij} R - (\rho^d)^{ij} L \right] d_j H^+ + h.c.,
\]

where $\lambda^f_i = \sqrt{2} m^f_i / v$, $L, R = (1 \mp \gamma_5) / 2$ and $s_\gamma \equiv \sin \gamma$. Note that the $A, H^+$ couplings are independent of $c_\gamma$,

\[\text{FIG. 1. Feynman diagrams for } cg \rightarrow b H^+.\]
while in the alignment limit of $c_γ \to 0$, $h$ couples diagonally and $H$ carries the extra Yukawa couplings $\rho_{ij}^H$. Thus, besides mass-mixing hierarchy protection [18–20] of flavor changing neutral Higgs (FCNH) couplings, alignment provides [13] further safeguard, without the need of Natural Flavor Conservation [21]. The importance of $\rho_{tt}$ and $\rho_{tc}$ was emphasized [5] already at the $h(125)$ discovery, and was subsequently shown [8] to possibly drive EWBG.

From Eq. (2) one finds that the leading $cbH^+$ and $tbH^+$ couplings are $\rho_{tc}V_{tb}$ and $\rho_{tt}V_{tb}$, respectively [22], where there is no CKM-suppression of the former [23] as in 2HDM-II. In this Letter, we take $m_{H^+} > m_t$ [24] and focus on the $cg \toZH^+ \to tb\ell$ process at the LHC. Note that the $gg \to cbH^+$ process discussed in Ref. [7] bears some similarity, but Fig. 1(left) was not mentioned explicitly, and a detailed collider study was not performed, hence the promise was not sufficiently demonstrated.

**Constraints on Higgs Parameters.**—Higgs quartics need to satisfy positivity, perturbativity, and tree-level unitarity, which we implement via 2HDMC [25]. We express [13,14] $\eta_1, \eta_3, \ldots, \eta_6$ in terms of $\mu_2, m_h, m_A, m_{H^+}$ (all normalized to $v$) and $\cos \gamma$, plus $\eta_2, \eta_7$ that do not enter Higgs masses. Since $H^+$ Yukawa couplings do not depend on $c_γ$, which is known to be small, we set $c_γ = 0$ for simplicity while fixing $m_h \cong 125 \text{ GeV}$, hence $\eta_1 = 0$ and $\eta_2 = m_h^2/v^2$. Thus, e.g. $t \to ch$ does not constrain $\rho_{tc}$. In the common Higgs basis, we identify $\eta_7$ with the input parameters $\Lambda_{1,7}$ to 2HDMC.

For fixed $m_{H^+}$, we randomly generate the parameters in the ranges $|\eta_2, \ldots, |\eta_7| \leq 3$ (positivity requires $\eta_2 > 0$), $\mu_2 \in [0, 1] \text{ TeV}$, and $m_{A,H} \in [m_{H^+} - m_W, 650 \text{ GeV}]$ to forbid $H^+ \to AW^+,HW^+$. We then use 2HDMC for scanning, where the electroweak oblique parameter constraints (including correlations) are imposed, e.g. the 2σ range of $-0.17 < T < 0.35$ [25], which restricts $m_{H^+}$ the scalar masses hence the $\eta$s. Scan points satisfying these constraints are plotted in Fig. 2 in the $m_{H^+} - m_A$ plane for $m_{H^+} = 300, 500 \text{ GeV}$, illustrating that finite parameter space exist. We choose a benchmark for each $m_{H^+}$ value and list the parameters in Table I. More details of our scanning procedure is given in Ref. [29].

**Flavor Constraints.**—Flavor constraints on $\rho_{tt}$ and $\rho_{tc}$ are not particularly strong [5,30]. For $m_{H^+} \leq 500 \text{ GeV}$, $B_q$ mixings ($q = d, s$) provide the most stringent constraint. An $H^+$ effect from $\rho_{tt}$ to the $M_{12}^q$ amplitude is enhanced by $|V_{cq}/V_{tq}| \sim 25$, hence $\rho_{ct}$ can be turned off [30]. Assuming all $\rho_{ij}$ vanish except $\rho_{tt}$, we have $M_{12}^q/M_{12}^{SM} = C_{B_q}$, with negligible phase. Allowing 2σ error on $C_{B_d} = 1.05 \pm 0.11$ and $C_{B_s} = 1.11 \pm 0.09$ [31], we find the blue shaded exclusion region (extending to upper-right) in Fig. 3 where the left (right) panel is for BP1 (BP2). The constraint from $H^+$ effects via charm loops [32] gives $\rho_{tc} \lesssim 1(1.7)$ for BP1 (BP2).

$B \to X_s \gamma$ puts a strong constraint on $m_{H^+}$ in 2HDM-II, but weakens for 2HDM due to extra Yukawa couplings. In fact, an $m_t/m_h$ enhancement factor constrains $\rho_{tt}$ more strongly [30] than $\rho_{tt}$. Taking $\rho_{tt}$ as small, the constraint on $\rho_{tt}$ falls outside the range of Fig. 3. The $B \to X_s \gamma$ constraint on $\rho_{tc}$ via charm loop is weaker than $B_q$ mixing [30]. Note that flavor constraints would grow weaker for $m_{H^+}$, heavier than our benchmarks.

**Collider Constraints.**—To focus on our signal process, we set all $\rho_{ij} = 0$ except $\rho_{tt}$ and $\rho_{tc}$ for simplicity.

For finite $\rho_{tt}$, one can have $bg \to t(b)H^+ \to t\bar{t}$ (charge conjugate process implied). Searches at 13 TeV provide model independent bounds on $\sigma(pp \to t(b)H^+)B(H^+ \to \ell b)$, for $m_{H^+} = 200 \text{ GeV}$ to 2 (3) TeV for ATLAS [3] (CMS [4]). Using the Monte Carlo (MC) event generator MadGraph5\_aMC@NLO [34] with default NN23LO1 parton distribution function (PDF) [35] and effective model implemented in FeynRules 2.0 [36], we calculate $\sigma(pp \to t(b)H^+)B(H^+ \to \ell b)$ at leading order (LO) for a reference $|\rho_{tt}|$, then rescale by $|\rho_{tt}|^2 B(H^+ \to \ell b)$ to get the upper limits. For $m_{H^+} = 300, 500 \text{ GeV}$ and with $\rho_{tc} = 0$ (hence $B(H^+ \to \ell b) \sim 100\%$), we plot the extracted ATLAS (CMS) 95% C.L. bounds on $\rho_{tt}$ as the red (purple) shaded regions in Fig. 5. The ATLAS/CMS limit is more/less stringent than $B_q$ mixing for BP1 ($m_{H^+} = 300 \text{ GeV}$), while opposite for BP2 ($m_{H^+} = 500 \text{ GeV}$). The exclusion bands are overlaid to illustrate this.

Heavy Higgs searches via $gg \to H/A \to \ell\ell$ can constrain $\rho_{tt}$. ATLAS [37] searched at 8 TeV for $m_{A/H} > 500 \text{ GeV}$; with 36 fb$^{-1}$ at 13 TeV, CMS constrains the “coupling modifier” [11] for $m_{A/H} = 400–750 \text{ GeV}$ for various $\Gamma_{A/H}/m_{A/H}$ values. Both ranges are above BP1, while for BP2 the bounds are weaker than results shown.

| $\eta_2$ | $\eta_3$ | $\eta_4$ | $\eta_5$ | $\eta_7$ | $m_{H^+}$ | $m_A$ | $m_H$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| BP1   | 1.40  | 0.62  | 0.83  | 1.06  | 0.79  | 1.18  | 300   |
| 272   | 372   |
| BP2   | 0.71  | 0.69  | 1.52  | 0.93  | 0.24  | 3.78  | 500   |
| 569   | 517   |

**TABLE I.** Benchmark points BP1 and BP2, with $\eta_6 = 0$ hence $\eta_7 \cong 0.258$. Higgs masses are in GeV.

**FIG. 2.** Scan points in $m_{H^+}-m_A$ plane that pass positivity, perturbativity, unitarity and oblique parameter constraints.
in Fig. 3(right). The CMS “excess” at $m_A \sim 400$ GeV [1] is discussed later.

Based on 137 fb$^{-1}$ at 13 TeV, the CMS 4t search [38] constrains $\rho_{tc}$ and $\rho_{tH}$. We first note that the direct limits from $\sigma(pp \to t\bar{t}A/t\bar{t}H)B(A/H \to t\bar{t})$ for $m_{A/H} \in [350, 650]$ GeV are again weaker than results shown in Fig. 3. With both $\rho_{tc}$ and $\rho_{tH}$ finite, the $cg \to tH/tA \to t\bar{t}t$ process [39] can feed the Signal Region, SR12, of the CMS 4t search if all three top quarks decay semileptonically. As $cg \to tH/tA \to t\bar{t}t$ barely occurs for BP1 because of low $m_{A,H}$ values, this applies only to BP2. SR12 requires [38] at least three leptons, four jets with at least three $b$-tagged, plus missing $p_T$. Following Ref. [12], we generate events and interface with PYTHIA 6.4 [40] for showering and hadronization, adopt MLM merging [41] of matrix element and parton shower, then feed into Delphes 3.4.2 [42] for CMS-based fast detector simulation, including $c$- and light-jet rejection. We find $\rho_{tH} \gtrsim 1$ is excluded if $\rho_{tc} \lesssim 0.8$ for BP2. Noting that $H^+ \to c\bar{b}$ decay from finite $\rho_{tc}$ would dilute $B(H^+ \to t\bar{b})$ and soften the $bg \to \bar{t}(b)H^+$ constraint, we illustrate this effect by the dashed (dot) curves in Fig. 3(right) for $\rho_{tc} = 0.4 (0.8)$.

The $cg \to tH/tA \to t\bar{t}c$ process [39] can feed the Control Region for $t\bar{t}W$ (CRW) background of CMS 4t study when both tops decay semileptonically. With CRW defined by same-sign dileptons ($e$ or $\mu$), $p_T^{miss}$, and up to five jets with at least two b-tagged, we follow Refs. [12, 43] and find $\rho_{tc} \gtrsim 0.4$ is excluded for BP1, which is stronger than the $B_q$ mixing bound, with little dependence on $\rho_{tH}$. For BP2, we find that CRW gives comparable limit as SR12. Thus, we illustrate in Fig. 3(left) the softened $bg \to \bar{t}(b)H^+$ constraint only for $\rho_{tc} = 0.4$.

We remark in passing that the ATLAS search for same-sign di-leptons and b-jets [44], or search for supersymmetry in similar event topologies [45], impose stronger cuts and in general do not give relevant constraints.

**Collider Signature for $cg \to bH^+ \to b\bar{b}$**. — We now show that the $cg \to bH^+ \to b\bar{b}$ process, or $pp \to bH^+ + X \to b\bar{b} + X$, is quite promising.

For illustration, we conservatively take $|\rho_{tc}| = 0.4$, $|\rho_{tH}| = 0.6$ for both BPs. Receiving no CKM suppression, the approximate $H^+ \to c\bar{b}$ branching ratios are 50%, 50% for BP1, and 36%, 64% for BP2. Assuming $t \to b\ell q$ ($\ell = e, \mu$), the signature is one charged lepton, $p_T^{miss}$, and three b-jets. Subdominant contributions such as PDF-suppressed $bg \to cH^+, tH^+ \to c\bar{b}\ell q$ with $c$-jet mistagged as b-jet, and $\rho_{tH}$-induced $bg \to tH^+ \to t\bar{b}b$ with one top decaying hadronically, are included as signal. There is also $c\bar{b} \to H^+ \to c\bar{b}, t\bar{b}$, but these suffer from QCD and top backgrounds. The dominant backgrounds for $cg \to bH^+$ arise from $t\bar{t}+jets$, $t$- and $s$-channel single-top ($t\bar{t}$), $Wt$-jets, with subdominant backgrounds from $tth$ and $t\bar{t}Z$. Minor contributions from Drell-Yan and $W+jets$, $4t$, $t\bar{t}W$, $tW\gamma$ are combined under “other”.

Signal and background samples are generated at LO for 14 TeV as before by MadGraph, interfaced with PYTHIA and fed into Delphes for fast detector simulation adopting default ATLAS-based detector card. The LO $t\bar{t}+jets$ background is normalized to NNLO by a factor 1.84 [37], and factors of 1.2 and 1.47 [49] for $t$- and $s$-channel single-top. The LO $Wt+jets$ background is normalized to NLO by a factor 1.35 [39], whereas the subdominant $tth, t\bar{t}Z$ receive factors of 1.27 [50], 1.56 [51]. The $DY+jets$ backgrounds are kept at LO. Correction factors for other charge conjugate processes are assumed to be the same, and the signal cross sections are kept at LO.

Events are selected with one lepton, at least three jets with three b-tagged, and $E_T^{miss} > 35$ GeV. Jets are reconstructed by anti-$k_t$ algorithm using radius parameter $R = 0.6$. The lepton $p_T$ should be $> 30$ GeV, with all three b-jet $p_T > 20$ GeV, and pseudo-rapidity ($|\eta|$) of lepton and b-jets $< 2.5$. The $\Delta R$ separation between a b-jet and the lepton, or any b-jet pair, should be $> 0.4$. The
Discussion and Summary.— The combined Run 2 and 3 data. Reanalyzing the signal and backgrounds for 13 TeV at 300 and 600 fb−1 with \( t\bar{t}A/tH \rightarrow t\bar{t}c \) decay and falling parton luminosity. Single-top studies may contain \( cg \rightarrow bH^+ \) events. For \( \rho_{tc} = 0.4 \) and \( \rho_{tt} = 0.6 \), we find the combined cross sections for \( pp \rightarrow H^+[b\bar{b}j], H^+[cb]\)t can contribute 15.2 (2.9) pb for BP1 (BP2), well within the 2\( \sigma \) error of current f-channel single-top [57, 58] measurements. The situation is similar for Run 1 with s-channel single-top.

We have not included uncertainties from scale dependence and PDF [59, 60], where the latter is sizable for processes initiated by heavy quarks. Using LO signal cross sections can also bring in some uncertainties, e.g. higher order corrections [49, 61] to \( \sigma(bg \rightarrow tH^+) \) may be 30–40% for \( m_{H^+} \sim 300–500 \) GeV. A detailed study of such uncertainties is left for the future, and is part of the reason why we adopt conservative \( \rho_{tc}, \rho_{tt} \) values.

Finally, our 300–500 GeV mass range is not just for its promise. Significance can still be high at higher masses for larger \( \rho_{tc}, \rho_{tt} \), but the decoupling \( \rho_{22}^2 \) would have to become larger [14] (as can be seen from \( \rho_{22}^2/\rho_{tt}^2 \simeq 3.78 \) for BP2 in Table I), which would start to damp the EWBG motivation. The \( cg \rightarrow bH^+ \) process can presumably be pursued for heavier \( m_{H^+} \) at higher luminosities.

In summary, extra top Yukawa couplings \( \rho_{tc} \) and \( \rho_{tt} \) enter \( cbH^+ \) and \( b\bar{b}H^+ \) couplings without CKM suppression, leading to the \( cg \rightarrow bH^+ \) signature of lepton plus missing energy and three b-jets. For conservative \( \rho_{tc}, \rho_{tt} \sim 0.5 \), evidence could already emerge with full LHC Run 2 data for \( m_{H^+} = 300–500 \) GeV, with discovery at 300 fb−1 and beyond, which would unequivocally point to physics beyond the Standard Model.

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Note Added After completion of this work, we noticed that the result for \( pp \rightarrow b\bar{b}H^+ \rightarrow b\bar{b} \) search by ATLAS has been updated with full Run 2 dataset [62]. We have checked that the chosen \( \rho_{tt} \) values for the BP’s are still allowed by current data.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
BP & \( ttjs \) & \( t_j \) & \( Wtjs \) & \( tth \) & \( ttZ \) & \( \text{other} \) & \( B_{\text{tot}} \) & \( \text{Sig} \) \\
\hline
BP1 & 1546 & 42 & 27 & 4.2 & 1.5 & 3.1 & 1627 & 11.4 \\
BP2 & 1000 & 27 & 16 & 2.9 & 1.2 & 1.9 & 1049 & 9.3 \\
\hline
\end{tabular}
\caption{Background and signal (Sig, for \( \rho_{tc} = 0.4, \rho_{tt} = 0.6 \)) cross sections (in fb) at 14 TeV after selection cuts.}
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