Probing Top Changing Neutral Higgs Couplings at Colliders

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The $h(125)$ boson, discovered only in 2012, is lower than the top quark in mass, hence $t \rightarrow ch$ search commenced immediately thereafter, with current limits at the per mille level and improving. As the $t \rightarrow ch$ rate vanishes with the $h$-$H$ mixing angle $\cos \gamma \rightarrow 0$, we briefly review the collider probes of the top changing $tcH/tcA$ coupling $\rho_{tc}$ of the exotic CP-even/odd Higgs bosons $H/A$. Together with an extra top conserving $ttH/ttA$ coupling $\rho_{tt}$, one has an enhanced $cbH$ coupling alongside the familiar $tbH$ coupling, where $H^+$ is the charged Higgs boson. The main processes we advocate are $cg \rightarrow tH/A \rightarrow tt\bar{c}$, $t\bar{t}c$ (same-sign top and triple-top), and $cg \rightarrow bH^+ \rightarrow bb$. We also discuss some related processes such as $cg \rightarrow thh$, $tZH$ that depend on $\cos \gamma$ being nonzero, comment briefly on $gg \rightarrow H/A \rightarrow tt, t\bar{c}$ resonant production, and touch upon the $\rho_{tu}$ coupling.

Keywords: extra top Yukawa couplings; exotic Higgs bosons; $h$-$H$ mixing.

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1. Introduction

It was proposed in the early 1990s, before the top quark was even discovered, that\footnote{Hall and Weinberg also discussed $t \rightarrow ch$ under approximate $U(1)$ flavor symmetries.} “$t \rightarrow ch$ or $h \rightarrow tc$ decays could be quite prominent, if not the dominant, decay modes of the top quark and some neutral Higgs bosons” ($h$). The generic neutral Higgs boson $h$ (whether scalar or pseudoscalar) in the two Higgs doublet model (2HDM) context can have $\bar{q}_i q_j h$ couplings proportional\footnote{As much as this Cheng-Sher ansatz\cite{Cheng:1987rs} helped lead the way to identify $tch$ as plausibly the largest flavor changing neutral Higgs (FCNH) coupling, it was pointed out\cite{Hall:1990ih} that $\sqrt{m_i m_j}$ dependence need not be literal\cite{Buch:2012wr} but just “reflect fermion mass and mixing hierarchies”, i.e. the flavor enigma. This} to $\sqrt{m_i m_j}$, thereby evade effectively the low energy flavor changing neutral current (FCNC) constraints that so worried Glashow and Weinberg\footnote{As much as this Cheng-Sher ansatz\cite{Cheng:1987rs} helped lead the way to identify $tch$ as plausibly the largest flavor changing neutral Higgs (FCNH) coupling, it was pointed out\cite{Hall:1990ih} that $\sqrt{m_i m_j}$ dependence need not be literal\cite{Buch:2012wr} but just “reflect fermion mass and mixing hierarchies”, i.e. the flavor enigma. This}.
We will see that this process is still relevant, but we are getting ahead of ourselves.

With the top quark nowhere to be seen at the time, it was even suggested\(^5\) that \(m_t < M_W\) could still be possible, with \(t \rightarrow bW^*\) obscured by e.g. \(t \rightarrow ch\) (or \(bH^+\)). For a general review of 2HDMs, see Ref.\(^6\).

But the top quark was discovered via the \(t \rightarrow bW\) channel in 1995 at the Tevatron, while it took almost two more decades for the elusive \(h(125)\) boson to be discovered at the Large Hadron Collider (LHC). To set up notation, we note the remarkable emergent phenomenon from LHC Run 1 data, called “alignment”: the \(h(125)\) boson was found to resemble rather closely\(^7\) the Higgs boson of the Standard Model (SM). In the 2HDM framework, we denote \(h(125)\) as \(h\), while \(H/A\) and \(H^+\) are the exotic \(CP\)-even/odd and charged scalars, respectively.

After the top quark discovery\(^5\) in context of the push (in the 1990s!) for a 500 GeV \(e^+e^-\) linear collider and other future facilities, top FCNH was studied for \(e^+e^-\)\(^8\)\(\gamma\)\(^9\)\(\gamma\)\(^10\) and even\(^11\)\(\mu^+\mu^-\) colliders. One novel idea was that \(e^+e^- \rightarrow Z^* \rightarrow hA\) or \(HA\) pair production could\(^1\) give rise to \(tt\bar{c}\) final states\(^1\) i.e. same-sign top production. Exotic scalar production by vector boson fusion with “neutrino tags”, i.e. the \(e^+e^- \rightarrow t\bar{c}\nu_\ell\bar{\nu}_\ell\) process was also proposed\(^1\)\(^2\)\(^3\)\(^4\), but this channel may not be promising, as the exotic scalars probably do not couple much with vector bosons due to alignment. The same-sign top idea, however, was carried over to the LHC, with the direct production process\(^15\) of \(cq \rightarrow tA\) followed by \(A \rightarrow t\bar{c}\) decay, or \(cq \rightarrow tt\bar{c}\).

We will see that this process is still relevant, but we are getting ahead of ourselves.

Let us come back to the \(t \rightarrow ch\) decay process. In SM, \(t \rightarrow ch\) can only arise at the loop level\(^2\) hence very suppressed, i.e. a\(^24\)\(^25\) \(B(t \rightarrow ch) \sim 10^{-15}\) and even smaller for \(t \rightarrow uh\). This is definitely out of reach\(^1\) but it implies that any observation would indicate beyond SM (BSM) New Physics. Ref.\(^21\) also discussed 2HDM II, but since the authors corrected a sign error for the SM result after Ref.\(^22\) appeared, we do not quote their result. It was later found\(^24\)\(^25\) in 2HDM II that \(B(t \rightarrow ch) \sim 10^{-5}\) (or higher) can be reached, but this relies on large \(\tan \beta\) enhancement, as is the study\(^26\) of loop effects from a “2HDM for the top quark”\(^27\). A similar level can be reached in SUSY\(^28\) but it relies on flavor changing gluino couplings in a time far before the advent of the LHC. SUSY loop effects were of course followed up\(^29\) but became diminished\(^30\) after \(h(125)\) discovery. Other avenues explored are, to name a few, \(R\)-parity violation\(^31\) quark singlets\(^32\)\(^33\) warped extra dimensions\(^34\) mirror fermions\(^35\) composite Higgs\(^36\) and aligned 2HDM\(^37\) where the latter three are

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\(^1\)The conjugate process is always implied throughout the paper.

\(^2\)We do not discuss loop-induced \(t\bar{c}Z\) and \(t\bar{c}Y\) couplings as they are less promising in terms of rate. For an early exposition, we refer to Ref.\(^19\) and references therein. A subsequent review can be found in Ref.\(^20\) which covers different models and processes, including tree level effects.

\(^3\)The much larger\(^23\) \(B(t \rightarrow bW^*h) \simeq 2 \times 10^{-9}\) in SM is still out of reach.
post $h(125)$ discovery. None of these truly reach above $10^{-5}$, hence all fall short of a theoretical sensitivity estimate at $\sim 10^{-4}$ for the LHC.

In contrast to the above suppression of $t \rightarrow ch$ rates, the expectation in 2HDM III is wide open, as the process is tree level, which has also been studied via effective field theory (EFT)\textsuperscript{41–43} With the advent of the LHC, and with early indications of a light Higgs boson, a detailed study\textsuperscript{44} advocated $t \rightarrow ch$ followed by $h \rightarrow b\bar{b}$ as the discovery mode. By the time the paper was published, however, ATLAS and CMS had discovered the $h(125)$ boson. It was then pointed out that $B(t \rightarrow ch)$ at the percent level\textsuperscript{45} was still possible, and the search began in earnest.

Partially stimulated by the CMS hint\textsuperscript{46} for $h \rightarrow \tau\mu$ decay from 8 TeV data, variants of 2HDM III were discussed, but soon died out when the hint was not confirmed by 13 TeV data.\textsuperscript{8} The experimental pursuits, however, continued. There is actually a catch for $t \rightarrow ch$ search: the $tch$ coupling is suppressed by $h–H$ mixing, i.e. between the two $CP$-even bosons, hence nonobservation could be due to small mixing rather than small $tcH$ coupling. In this Brief Review, we focus on probing top changing neutral Higgs (TCNH) couplings at colliders via direct production processes. Rather than 2HDM III, we shall call the 2HDM with extra Yukawa couplings “general 2HDM” (g2HDM). In what follows, we give our theoretical framework in Sec. 2, then discuss $t \rightarrow ch$ search in Sec. 3. We turn to our main theme of direct production processes via TCNH coupling in Sec. 4, where Sec. 4.1 covers the $cg \rightarrow tH/A \rightarrow tt\bar{c}$, $tt\bar{t}$ processes, namely same-sign top with jet and the more exquisite triple-top, and Sec. 4.2 covers $cg \rightarrow bH^+ \rightarrow b\bar{b}$. In Sec. 5 we offer some discussion and cover a miscellany of topics, and present our summary and prospects in Sec. 6.

2. Theoretical Framework

It is useful to trace the theory development since the early days of the $t \rightarrow ch$ proposal. The Cheng-Sher treatment, while evoking the mass-mixing hierarchy to evade low energy FCNC constraints, was somewhat vague regarding the Higgs bosons. The scenario does remove the usual but ad hoc $Z_2$ symmetry that enforces the NFC condition of Glashow and Weinberg, and more systematic works clarified the situation, both for the Higgs potential, and the Yukawa couplings.

We write the most general $CP$-conserving two Higgs doublet (without $Z_2$) potential in the Higgs basis as\textsuperscript{51–52}

$$
V(\Phi, \Phi') = \mu_1^2 \Phi^2 + \mu_2^2 \Phi'^2 - (\mu_{12}^2 \Phi\Phi' + h.c.) + \frac{\eta_1}{2} \Phi^4 + \frac{\eta_2}{2} \Phi'^4 + \eta_3 \Phi^2 \Phi'^2 + \eta_4 \Phi\Phi'^2 + \left\{ \frac{\eta_5}{2} (\Phi\Phi')^2 + \left[ \eta_6 \Phi^2 + \eta_7 \Phi'^2 \right] \Phi\Phi' + h.c. \right\},
$$

(1)

where $\langle \Phi \rangle \neq 0$ by\textsuperscript{51} $\mu_{11}^2 = -\frac{1}{2} \eta_1 v^2$, while $\langle \Phi' \rangle = 0$ hence $\mu_{22}^2 > 0$. A second minimization condition, $\mu_{12} = \frac{1}{2} \eta_6 v^2$, removes the soft $\mu_{12}^2$ term, reducing the total number

\textsuperscript{e}We note that, without a $Z_2$ symmetry, the usual notion of $\tan \beta = v_1/v_2$ is unphysical.\textsuperscript{51} Note also that the $\eta_6$ and $\eta_7$ terms in Eq. (1) would be absent in 2HDMs with $Z_2$ symmetry.
of parameters to nine, with η₆ the sole parameter for h-H mixing, namely

\[ M_{\text{even}}^2 = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & m_A^2 + \eta_5 v^2 \end{bmatrix}, \]  

(2)

for the CP-even Higgs mass matrix, where \( m_A^2 = \mu_{11}^2 + \frac{1}{2} (\eta_3 + \eta_4 - \eta_5) v^2 \). As mentioned, the emergent “alignment” phenomenon from LHC Run 1, that the h boson resembles rather closely the Higgs boson of SM, implies that the h–H mixing angle \( \cos \gamma \) (which we denote as \( c_{\gamma} \), and similarly \( s_{\gamma} = \sin \gamma \)) is rather small. We note the approximate relation near alignment,

\[ c_{\gamma} \approx \frac{\eta_6 v^2}{m_H^2 - m_h^2}, \]  

(3)

as \( s_{\gamma} \to 1 \) more rapidly than \( c_{\gamma} \to 0 \). Thus, it is quite intuitive that \( \Phi \) serves as the “mass-giver” with \( \mu_{11} < 0 \), while \( \Phi' \) is the exotic doublet with an inertial mass parameter \( \mu_{22} > 0 \), and the “soft” \( \mu_{12}^2 \) term is eliminated. This is in contrast to the usual 2HDM I and II with \( Z_2 \) symmetry, where both \( m_{11}^2, m_{22}^2 < 0 \), with the \( m_{12}^2 \) term playing the dual role of h–H mixing and inertial mass.

If one now takes the known \( v \equiv 246 \) GeV as the sole scale parameter, then the traditional, elementary notion of “naturalness” dictates that all dimensionless quantities in \( V(\Phi, \Phi') \), namely all \( \eta_i \)s and \( \mu_{ii}^2/v^2 \) in Eq. (1), ought to be \( \mathcal{O}(1) \). It was shown explicitly in Ref. [52] (see Fig. 1 of the reference) that this “naturalness” can be maintained without running into conflict with alignment, i.e. \( c_{\gamma} \) in Eq. (3) can be small with large parameter space. Although \( \eta_1 < \eta_6 \) seems needed, both can be \( \mathcal{O}(1) \), and the dynamical mixing parameter \( \eta_6 \) actually helps push \( \eta_1 v^2 \) down to the physical \( m_H^2 \) by level repulsion, hence \( \mu_{11}^2/v^2 \) is indeed also \( \mathcal{O}(1) \)! This is in contrast even with SM, where the usual \( \sqrt{\mu^2} \approx 87 \) GeV is a factor \( \sim 2\sqrt{2} \) lower than \( v \), which is borderline on being “natural”. Ref. [52] then asserts that, on top of mass-mixing hierarchy suppression in general the unforeseen emergent phenomenon of alignment, i.e. small \( c_{\gamma} \), further suppresses the FCNH couplings of the lighter \( h \). Thus, the combined effect of mass-mixing hierarchy and alignment can replace the brutal NFC condition, and one should therefore really view the usual \( Z_2 \) symmetry for what it is: \textit{ad hoc}.

Though not spelled out in great detail in Ref. [52] the naturalness argument of \( \mathcal{O}(1) \) parameters in \( V(\Phi, \Phi') \), together with alignment, implies the mass range

\[ m_H, m_A, m_{H^+} \in (300, 600) \text{ GeV}, \]  

(4)

which seems just right for the LHC to probe. The point is, at the upper mass range and beyond, either one has \( \eta_1 > \mathcal{O}(1) \) (strong couplings), or \( \mu_{22}^2/v^2 > \mathcal{O}(1) \) (decoupling) would set in. The former heads toward nonperturbativity, making estimates unreliable, while the latter would damp dynamical effects of interest. For the lower mass range, given that \( m_H^2 \) is raised by level repulsion, for \( m_H < 300 \) GeV or so

\footnote{The same level repulsion due to \( \eta_6 \) pushes \( m_A^2 + \eta_5 v^2 \) up to \( m_H^2 \) and helps maintain alignment.}
would bring \( m_A^2 + \eta_2 v^2 \) closer to \( \eta_1 v^2 \), and even a weak \( \eta_6 \) could more easily generate \( c_{\gamma} \), and alignment becomes harder to sustain. It should be clear that the sub-TeV range of Eq. (4) is just right for the LHC to probe in the next two decades.

Having accounted for the mass range of the exotic Higgs bosons, which is quite relevant for the LHC, we now write down\(^{51, 53}\) the Yukawa couplings:

\[
\begin{align*}
-1 & \sqrt{2} \sum_{f = u, d, \ell} \bar{f}_i \left[ \left( -\lambda_f^i \delta_{ij} s_\gamma + \rho_f^{ij} c_\gamma \right) h + \left( \lambda_f^i \delta_{ij} c_\gamma + \rho_f^{ij} s_\gamma \right) H - i \text{sgn}(Q_f) \rho_f^{ij} A \right] R f_j \\
& \quad - \bar{u}_i \left[ (V \rho_f^{i})_{ij} R - (\rho^u V)_j L \right] d_j H^+ - \bar{\nu}_i \rho_f^{ij} R \ell_j H^+ + \text{h.c.},
\end{align*}
\]

where the generation indices \( i, j \) are summed over, \( L, R = (1 \mp \gamma_5)/2 \) are projection operators, and \( V \) is the Cabibbo-Kobayashi-Maskawa matrix, with the corresponding matrix in lepton sector taken as unity.\(^{13}\) The \( \lambda_f^i \) matrices have been diagonalized as usual with elements \( \lambda_f^i = \sqrt{2} m_f^i / v \), but the extra Yukawa matrices, \( \rho_f^{ij} \), cannot be diagonalized simultaneously in principle. As has been said, however, the mass-mixing structure that Nature has revealed to us, together with the decoupling of \( h \) from \( \rho_f^{ij} \) matrices in the alignment limit (\( c_{\gamma} \to 0 \)), seem sufficient to shield FCNH couplings from our view, which could be the “flavor” design of Nature.

It should be stressed that, not only the \( \rho_f^{ij} \) matrices cannot be simultaneously diagonalized with the \( \lambda_f^i \) matrices, they are in principle complex, \(^{14}\) \( \rho_{tt} \) expected to be the largest elements. In fact, \( \rho_{tt} \) being \( O(1) \) and complex is the most plausible, as it is the companion to the diagonal \( \lambda_t \approx 1 \), which has been recently affirmed\(^{55, 56}\) by experiment. Exploiting this, it was shown that electroweak baryogenesis (EWBG) can be achieved\(^{57}\) with the \( CP \) violating (CPV) strength,

\[
\lambda_t \text{Im} \rho_{tt} = O(1),
\]

as the driver. Interestingly, the “naturalness” condition of \( O(1) \) dimensionless parameters in the Higgs potential is precisely what is needed to allow a first order phase transition, a prerequisite for EWBG. On the other hand, with the recent order of magnitude improvement of the limit on the electron electric dipole moment (eEDM) by ACME18\(^{59}\) the EWBG study has been updated\(^{60}\) by adding the previously ignored \( \rho_{ee} \) as a complex parameter. It is found that, so long that

\[
\rho_{ee} / \rho_{tt} \propto \lambda_e / \lambda_t,
\]

holds, which rhymes with the mass-mixing hierarchy, eEDM could be suppressed by two orders of magnitude or even more, and there can be an ACME (or other competing experiment) discovery in the not so distant future.

It can now be said that g2HDM touches “the Heavens and the Earth”! We now turn to see how extra Yukawa couplings can be explored at the LHC. We retrace in Sec. 3 the saga of the ongoing \( t \rightarrow ch \) search, then on to our main theme of direct production processes via TCNH couplings in Sec. 4.

\(^8\)Similar formulas were given in Ref.\(^{54}\) but this reference assumed the \( \rho_f^{ij} \)s are diagonal.

\(^h\)This holds true as the active neutrinos are rather degenerate at vanishingly small masses.
3. Prelude: $t \to ch$ search

We have already given a brief survey of theory work on $t \to ch$ in the Introduction. But with $h(125)$ found lighter than top, one enters a different era. The search for $t \to ch$ decay commenced immediately with the $h(125)$ discovery. Even if NFC is operative in Nature, it is a no-lose situation for pursuing the experimental search. It is in fact an obligation.

It should be clear that $B(t \to ch)$ cannot be overly large, otherwise even Tevatron $t\bar{t}$ studies might have uncovered it. At the LHC, a multi-lepton analysis using CMS 7 TeV results gave a bound at 2.7% already in 2012. It was cautioned, however, that one needs to take possible modifications of $h$ properties into account. It was then stressed that the $h(125)$ discovery events in $ZZ^*$ final states themselves could contain information on $B(t \to ch)$ because of its sizable branching fraction and exceptional cleanliness. For example, one should look for accompanying jets enriched with $b$s, if the events actually cascaded down from $t\bar{t}$ production. The conclusion was that 2011-2012 data should be able to reach the 1% level. This carried with it some sense of excitement, as discovery was possible. Indeed, the experimental measurements were already under way.

By 2013 summer conferences, ATLAS reported a result on $t \to ch$ search via $h \to \gamma\gamma$ with 20 fb$^{-1}$ data at 8 TeV. The published limit of 0.79% in 2014 at 95% C.L. indeed broke the 1% floor. Using same amount of data and combining $\gamma\gamma$ and multi-lepton results, CMS found a better limit at 0.56%.

We refrain from accounting for further developments, as it is well documented in PDG, but comment that $t \to ch$ search via the dominant $h \to bb$ decay has yet to deliver its full promise, and should be explored further. The current best limit on $t \to ch$ search at 95% C.L. is from ATLAS,

\begin{equation}
B(t \to ch) < 1.1 \times 10^{-3}, \quad \text{(ATLAS 36 fb}^{-1}, \ 2019) \tag{8}
\end{equation}

which combines the $h \to bb$, $\tau\tau$ modes with earlier $h \to WW$, $ZZ$, and $\gamma\gamma$ Run 2 results. The two photon mode gave a limit at $2.2 \times 10^{-3}$, but remarkably, the limit from the $\tau\tau$ mode at $1.9 \times 10^{-3}$ is better. As this is only a fraction of Run 2 data, the bound would continue to improve in the near future, while CMS should certainly be watched also.

Although experiments continue to set constraints on the effective $\lambda_{tch}$ Yukawa coupling, Ref. pointed out that the coupling in fact should be

\begin{equation}
\lambda_{tch} = \rho_{tc} c_\gamma, \tag{9}
\end{equation}

in g2HDM, where $\rho_{tc}$ is a TCNH coupling from the extra Yukawa matrix $\rho^u$, defined in Eq. 5. Since we know that $c_\gamma \equiv \cos \gamma$ (denoted usually as $\cos(\beta - \alpha)$ in 2HDMs with $Z_2$) has to be small, the nonobservation so far can be accounted for, without

\footnote{We will keep to $tch$ couplings in our main text, and comment on search for $tuh$ couplings, where constraint is slightly weaker, in Sec. 5.}
requiring $\rho_{tc}$ to be small, even though discovery can still happen at any time.\footnote{Note that we have dropped $\rho_{ct}$ in Eq. (9), as it has to be rather small\footnote{because its effect in $B_d$ and $B_s$ mixing is CKM enhanced.} because its effect in $B_d$ and $B_s$ mixing is CKM enhanced.}

4. Probing Extra Top Yukawa Couplings in Production Processes

From the emergent “alignment” phenomenon\footnote{we learned that Nature has further designs\footnote{for suppressing FCNH effects at low energy: small $c_\gamma$, or alignment in the Higgs sector. This is reflected in Eq. (9), which can be read off from Eq. (5). It applies also to $h \rightarrow \tau\mu$, where there was once a hint\footnote{from CMS Run 1 data, but not supported by Run 2 data (see footnote j below). To probe the TCNH coupling $\rho_{tc}$ without $c_\gamma$ suppression, one has to access the direct production of the $H$, $A$ and $H^+$ bosons, where the mass range in Eq. (7) that follows from naturalness ($O(1)$ parameters) seems tailor-made for the LHC. We turn to such processes, namely\footnote{58} $cg \rightarrow tH,tA$ and\footnote{59} $cg \rightarrow bH^+$, in this main section.} $cg \rightarrow tH,tA$ and $cg \rightarrow bH^+$, in this main section.}

The existence of the extra diagonal Yukawa coupling $\rho_{tt}$ means $H$, $A$ can be produced by gluon-gluon fusion. We relegate resonance production, namely $gg \rightarrow H,A \rightarrow t\bar{t},t\bar{c}$ and $\tau\mu$ to Sec. 5, as they face various and different challenges.

4.1. Top-associated $H/A$ Production: $cg \rightarrow tH/tA \rightarrow tt\bar{c}, tt\bar{t}$

We first consider $cg \rightarrow tH,tA$ production via the TCNH $\rho_{tc}$ coupling (see Fig. 1), with subsequent decay of $H,A$ to $t\bar{c}$ and $t\bar{t}$ final states, which depends on $H,A$ masses and the strength of the extra diagonal $\rho_{tt}$ coupling.

To compute the decay rates and parton cross sections, we simplify and take the alignment limit of $c_\gamma = 0$. The extra Yukawa couplings for $u$-type quarks are,

$$\frac{\rho_{ti}}{\sqrt{2}} \bar{u}_iL (H + iA) u_jR + h.c., \quad (c_\gamma = 0) \tag{10}$$

where $\rho_{ij}$ should share the “flavor organization” attributes of SM, i.e. trickling down off-diagonal elements. For sake of discussion, we keep only $\rho_{tc}$ and $\rho_{tt}$ finite ($\rho_{ct}$ is constrained small\footnote{by $B$ physics} by $B$ physics) and set all other $\rho_{ij}$s to zero, including those of down and lepton sectors, for the remainder of this section. For $S = H$, $A$, we

\begin{align*}
\text{Fig. 1. The } cg \rightarrow tS (S = H,A) \text{ process.}
\end{align*}
Fig. 2. Cross sections $\sigma_{pp \to tS}$ and $\sigma_{pp \to t\bar{t}S}$ for $\rho_{tt} = 1$ and $\rho_{tc} = 0.1$ (solid), $0.5$ (dashed) and $1$ (dots) at $\sqrt{s} = 14$ TeV.

Fig. 3. $\mathcal{B}(H/A \to t\bar{t}, t\bar{c})$ for $\rho_{tt} = 1$ and $\rho_{tc} = 0.1$ (solid), $0.5$ (dashed) and $1$ (dots).

display $\sigma_{cg \to tS}$ at parton level in Fig. 2 for $m_S \in (350, 700)$ GeV. The $H, A$ decay branching fractions are given in Fig. 3.

We will see that $cg \to tS \to tt\bar{c}$, or same-sign top pair (SS2$t$) production, is already quite promising with $300 \text{ fb}^{-1}$ if $S$ is in the lower range of Eq. (4). For the higher mass range, i.e. $S$ considerably above the $2m_t \gtrsim 350$ GeV threshold, the $tt\bar{t}$ (3$t$) signature holds more promise in cutting down background at the High Luminosity LHC (HL-LHC). Note that the 3$t$ cross section in SM is at $\mathcal{O}(\text{fb})$, while $g2\text{HDM}$ could enhance this by a factor of several hundred (cf. Fig. 2). Although both CMS and ATLAS have zoomed in on $tt\bar{t}$ (i.e. 4$t$) search with full Run 2 data, neither experiments have initiated studies targeting 3$t$ so far. We give in Fig. 2 also the $t\bar{t}S$ cross section, where $t\bar{t}A$ is larger than $t\bar{t}H$. While almost two orders below $tS$ for $\rho_{tc} \simeq 1$, it can feed our signatures, and would dominate over $tS$ for low $\rho_{tc}$.

Same-sign top was advocated to appear with even 1 fb$^{-1}$ LHC data due to some Tevatron "anomaly", but this was quickly ruled out. Same-sign top production has also been advocated recently with flavor-changing $Z'$ as well as neutral scalar $\phi$ exchange.

This is in part because SM 4$t$ cross section at $\sim 12$ fb is an order of magnitude larger than 3$t$ in SM, hence can be measured sooner if SM holds true.

We do not include $t\bar{c}S$ in Fig. 2. However, it is included in our collider signal for the inclusive same-sign top (marked as SS2$t$) production discussed in Sec. 4.1.2.
4.1.1. Collider Constraints on $\rho_{tc}$

A small $c_t$ makes the $t \rightarrow ch$ constraint on $\rho_{tc}$ rather mute. But since the original proposal for $cg \rightarrow tH/tA \rightarrow tt\bar{c}$ search, both CMS\cite{22} and ATLAS\cite{23} have now searched for $4t$ production with full Run 2 data set of 137 fb$^{-1}$ at 13 TeV. Some of the Control Regions (CRs) of these $4t$ studies can probe into the $SS2t$ signature, which can be used to constrain $\rho_{tc}$ independent of $c_t$. The results of this and the following subsection therefore follow the more recent analysis of Ref.\cite{80} updating from Ref.\cite{68} for the $\rho_{tc}$ study.

Let us start with the CMS $4t$ search.\cite{23} With the baseline selection criterion of at least two same-sign leptons, we find the most stringent constraint on $\rho_{tc}$ arises from CRW\cite{23} the CR of $t\bar{t}W$. The CRW of the CMS $4t$ search\cite{23} is defined as containing two same-sign leptons plus two to five jets with two $b$-tagged.

The selection cuts are as follows. For leading (subleading) lepton transverse momentum, $p_T^{l_1}(l_2) > 25\,(20)$ GeV. For pseudorapidity, $\eta^c < 2.5$ while $\eta^{\mu,j} < 2.4$. The $p_T$ of (b-)jets should satisfy one of the following: (i) $p_T > 40$ GeV for both $b$-jets; (ii) $p_T > 20$ GeV for one $b$-jet, $20 < p_T < 40$ GeV for the second $b$-jet, and $p_T > 40$ GeV for the third jet; (iii) $20 < p_T < 40$ GeV for both $b$-jets, with two extra jets each satisfying $p_T > 40$ GeV. Defined as the scalar sum of $p_T$ of all jets, one requires $H_T > 300$ GeV, while $p_T^{\text{miss}} > 50$ GeV. To reduce the Drell-Yan background with a charge-misidentified ($Q$-flip) electron, events with same-sign electron pairs with $m_{ee} < 12$ GeV are rejected. Using these selection cuts, CMS reports 338 observed events in CRW, with $335 \pm 18$ events (SM backgrounds plus $4t$) expected\cite{23}.

To estimate our limits, we use MadGraph5\_aMC@NLO\cite{81} (denoted as MadGraph5\_aMC) to generate signal events for $\sqrt{s} = 13$ TeV at leading order (LO) with default parton distribution function (PDF) set NN23LO1 \cite{82} interface with PYTHIA 6.\cite{83} for showering and hadronization, and MLM matching\cite{84,85} prescription for matrix element (ME) and parton shower merging. The event samples are then fed into DELPHES 3.4.\cite{86} for fast detector simulation. We utilize the default $b$-tagging efficiency and light-jet rejection of DELPHES CMS-based detector card.

The jets are reconstructed via anti-$k_T$ algorithm with radius parameter $R = 0.6$, whereas the effective model is implemented in FeynRules\cite{87}.

The $pp \rightarrow tH/tA \rightarrow tt\bar{c}$ process with both top quarks decaying semileptonically (nonresonant $cg \rightarrow tt\bar{c}$, $t$-channel $H/A$ exchange $cc \rightarrow tt$ and $gg \rightarrow t\bar{c}A/H$ processes are included) contributes to CRW of the CMS $4t$ search. Setting all other $\rho_{ij} = 0$, we estimate the cross section for $\rho_{tc} = 1$ then scale by $\rho_{tc}^2$, assuming narrow $H/A$ widths with $\mathcal{B}(H/A \rightarrow t\bar{c} + \ell\bar{c}) = 100\%$. We then demand the sum of expected SM and $\rho_{tc}$-induced events agree with observed, where the $2\sigma$ excluded region from CRW is displayed in Fig. 4 [left] in purple, assuming Gaussian behavior for simplicity. To avoid cancellation\cite{88} between $H$ and $A$ mediated production processes, we have assumed a splitting of $m_A - m_H = 50$ GeV. This almost doubles the production rate, while if one of the exotic boson is much heavier than the other, the cross section drops by roughly one half. One can see the power of the $4t$ search, constraining $\rho_{tc}$

especially for $m_S$ not far above the $t\bar{t}$ threshold of 350 GeV, but tapers off rapidly for heavier Higgs bosons due to rapid fall in the parton luminosity.

ATLAS has also searched for 4f production\textsuperscript{27} with 139 fb$^{-1}$, but categorizing into different CRs and Signal Regions (SRs). Again the CR for $t\bar{t}W$, called CRttW2, is the most relevant. It is defined as at least two same-sign leptons ($e\mu$ or $\mu\mu$), plus at least four jets with at least two $b$-tagged, where $p_T > 28$ GeV with $\eta^{\ell} < 2.5$ and $\eta^{c} < 1.5$ for the same-sign leptons. All jets should satisfy $p_T > 25$ GeV and $\eta < 2.5$. For two $b$-jets, or three or more $b$-jets but with no more than 5 jets, the scalar $p_T$ sum over all jets and same-sign leptons (different from CMS), $H_T < 500$ GeV. Unlike CRW for CMS, ATLAS does not give the observed number of events in CRttW2, but provides a figure of comparison between data and prediction in the variable $\sum p_T^j$ (see Ref. \textsuperscript{77} for definition). We follow Ref. \textsuperscript{88} and digitize the figure to extract the number of expected and observed events in the CRttW2 from the $\sum p_T^j$ distribution. We find $378 \pm 10$ and $380$, respectively, where we simply add the errors in quadrature for the expected events from each $\sum p_T^j$ bin.

To extract the constraint, we follow the event selection as described and use now the ATLAS-based detector card of DELPHES. Assuming that the $\rho_{tc}$-induced events plus SM stay within $2\sigma$ of expected, the exclusion limits from ATLAS are the cyan shaded region in Fig. 4\textsuperscript{[left]}, which is weaker due to different selection cuts. From CMS 4f search, we find $\rho_{tc} \lesssim 0.37–0.44$ is still allowed for 200 GeV $\lesssim m_H \lesssim 400$ GeV, while larger values open up quickly for $m_H > 400$ GeV. We again illustrate for $m_H - m_A = 50$ GeV, as there is strong cancellation\textsuperscript{25} between $cg \to tH \to tt\bar{c}$ and $cg \to tA \to tt\bar{c}$ amplitudes for $H, A$ that are nearly degenerate in mass and width. Note also that SUSY and other exotic searches nowadays use rather strong cuts and do not give relevant constraints for our relatively low mass range.

Fig. 4\textsuperscript{[right]} is done in the same way as the left-hand plot, but with $\rho_{tc}$ replaced\textsuperscript{20} by $\rho_{tu}$, which we would discuss only in Sec. 5.
4.1.2. Same-sign Top: $cq \rightarrow tH/TA \rightarrow t\ell\bar{c}$

Although existing 4t searches with full LHC Run 2 data can constrain $\rho_{tc}$, they are not optimized for $cq \rightarrow tH/TA \rightarrow t\ell\bar{c}$ search. We advocate a dedicated study of a stand-alone $\rho_{tc}$ coupling with all other $\rho_{ij} = 0$.

The $pp \rightarrow tH/TA + X \rightarrow t\ell\bar{c} + X$ signature is defined as same-sign dilepton $(ee, e\mu, \mu\mu)$ plus at least three jets with at least two $b$-tagged and one non-$b$-tagged, and $E_T^{\text{miss}}$. The SM backgrounds are $t\ell Z$, $t\ell W$, $4t$, $t\ell h$, with $tZ+$ jets subdominant ($3t+j$ and $3t+W$ turn out negligible). The $t\ell$ and $Z/\gamma^*+$ jets processes, with sizable cross sections, would contribute if one lepton charge is misidentified ($Q$-flip), with probability taken as $0.02\times 2\times 10^{-4}$ in our analysis.

As before, we generate signal and background events at LO via MadGraph5 aMC but for $\sqrt{s} = 14$ TeV and follow the same showering, hadronization, ME matching and parton shower merging, but adopt the default ATLAS-based detector card of DELPHES. The LO $t\ell W^- (t\ell W^+)$, $t\ell Z$, $4t$, $t\ell h$ and $tZ+$ jets cross sections are normalized to next-to-leading order (NLO) $K$ factors $1.35$ ($1.27$)$^{+2.04}_{-1.44}$, $1.56$ and $2.04$ respectively. We assume the same $K$ factor for $tZ+$ jets background for simplicity. The Q-flip $t\ell$+ jets and $Z/\gamma^*+$ jets backgrounds are corrected to NNLO cross sections by $1.2$ and $1.84$, respectively, where we use FEWZ 3.1 to obtain the latter factor for $Z/\gamma^*+$ jets.

To suppress backgrounds and optimize for $pp \rightarrow TA/tH+X \rightarrow t\ell\bar{c}+X$, we take a cut based analysis that differs from CRW of CMS 4t search. For leading (subleading) lepton, $p_T^{\ell_1 (\ell_2)} > 25$ (20) GeV, while $\eta^{\ell_1, \ell_2} < 2.5$. For all three jets, $p_T > 20$ GeV and $\eta < 2.5$, and we demand $E_T^{\text{miss}} > 30$ GeV. The separation $\Delta R$ between (i) a lepton and any jets ($\Delta R_{l,j}$), (ii) the two $b$-jets ($\Delta R_{bb}$), and (iii) any two leptons ($\Delta R_{\ell\ell}$) should all satisfy $\Delta R > 0.4$. Finally, with ATLAS definition of $H_T$, i.e. with $p_T$ of the two leading leptons included, we demand $H_T > 300$ GeV. The signal cross sections for select $m_H$ values are given in the first column of Table 1 together with the estimated background cross sections, where the $K$ factors from LO to NLO are shown in brackets. There are also “nonprompt” backgrounds. The CMS study of same-sign dilepton (SS2t) signature with slightly different cuts than ours, finds nonprompt background at $\sim 1.5$ times the $t\ell W$ background. These backgrounds are not properly modeled in our Monte Carlo simulations, and we simply add such backgrounds to the overall background at $1.5$ times $t\ell W$ after selection cuts. A realistic analysis by the experiments can handle this better.

To estimate the exclusion limit ($2\sigma$) and discovery potential ($5\sigma$), we utilize the test statistic $^{[29]}$

$$Z(nx) = \sqrt{-2 \ln \frac{L(nx)}{L(nn)}}, \quad (11)$$

where $L(nx) = e^{-x} x^n / n!$ is the likelihood function of Poisson probabilities with $n$ the observed number of events, and $x$ is either the number of events predicted by the background-only hypothesis $b$, or signal plus background hypothesis $s + b$. For
Table 1. The signal cross sections of the same-sign top SS2t after selection cuts for different $m_H$ (in parentheses) with $m_A = m_H + 50$ GeV for $\rho_{tc} = 1$ at 14 TeV LHC. Various backgrounds cross sections after selection cuts are presented in the third column, where numbers in brackets in second column are LO to NLO $K$ factors.

| Signal cross section in fb ($m_H$ in GeV) | Backgrounds | Cross section (fb) |
|-----------------------------------------|-------------|--------------------|
| 3.83 (200)                              | $t\bar{t}W$ [1.35 (1.27)] | 1.31               |
| 4.12 (300)                              | $t\bar{t}Z$ [1.56]     | 1.97               |
| 2.35 (400)                              | $4t$ [2.04]      | 0.092              |
| 1.14 (500)                              | $t\bar{t}h$ [1.27]   | 0.058              |
| 0.75 (600)                              | Q-flip [1.84/1.27] | 0.024              |
|                                        | $tZ$+jets [1.44]    | 0.007              |

exclusion $(s + b)$ hypothesis, we demand $Z(bs + b) \geq 2$ for $2\sigma$, while for discovery ($b$ hypothesis), we demand $Z(s + bb) \geq 5$ for $5\sigma$. The signal cross sections for the reference $\rho_{tc} = 1$ value after selection cuts are given in Table 1 for several $m_H$ values with $m_A - m_H = 50$ GeV, assuming $m_H > m_A$. Utilizing the signal and background cross sections in Table 1, we present in Fig. 4[left] the exclusion and discovery contours by scaling the signal cross section with $\rho_{tc}^2 B(A/H \rightarrow t\bar{t}c + \bar{t}c)$ in $m_H - \rho_{tc}$ plane for different luminosities. We set all $\rho_{ij} = 0$ in generating signal, which simply translates to $B(A/H \rightarrow t\bar{t}c + \bar{t}c) = 100\%$. We repeat a similar analysis with standalone $\rho_{tu}$ (all other $\rho_{ij} = 0$) replacing $\rho_{tc}$, i.e. for the $pp \rightarrow tA/tH + X \rightarrow tt\bar{u} + X$ process induced by the $ug \rightarrow tH/tA \rightarrow tt\bar{u}$ at parton level. The exclusion limits and discovery potential are plotted in Fig. 4[right]. In Fig. 4 we have simply interpolated the contours from $m_H$ values given in Table 1 and analogously for $\rho_{tu}$ case.

We see from Fig. 4[left] that CRW of CMS 4$t$ search is suitably powerful: with full Run 2 data, our target analysis can only probe the region of $\rho_{tc} \sim 0.34$–0.4, while adding full Run 3 data, the sensitivity extends to a broader region of parameter space, but so would the continued 4$t$ analysis. The $5\sigma$ discovery region for 3000 fb$^{-1}$ is somewhat better than the 300 fb$^{-1}$ exclusion limit, and one can follow up on any hint from full Run 2+3 data. To be watched is $\rho_{tc} \sim 1$, needed for the backup mechanism for EWBG for $m_{H,A}$ at the higher end of the mass range in Fig. 4[left]. The high significance found in Ref. 68 suggests it could already be relevant in LHC Run 2. Same-sign top pair search has the potential to reveal to us whether the $\rho_{tc} \sim 1$ mechanism for EWBG is allowed.

As noted, CMS has searched for SS2$t$ events using $\sim 36$ fb$^{-1}$ data at 13 TeV, which can constrain $\rho_{tc}$. It is found that the constraint is only $\rho_{tc} \geq 1$ for $S = H, A$ at 350 GeV, and tapers off to higher values, so does not affect our discussion above. The CMS update with full Run 2 data does not change this conclusion, as cuts have moved upward hence missing our target mass range.
4.1.3. Triple-Top: \( cg \to tH/A \to t\bar{t} \)

We would advocate, however, that “triple-top” search is more informative with a larger dataset. New physics triple-top search has been advocated in topcolor-assisted technicolor model, usual 2HDM with \( Z_2 \) symmetry and also using EFT approach with four-fermi operators involving triple-top. Our sub-TeV exotic Higgs bosons have dimension-4 couplings (Sec. 2) that render an EFT approach artificial.

As \( S \to t\bar{t} \) decay is needed for \( cg \to tS \) to contribute, it is less sensitive just above \( t\bar{t} \) threshold. With cross sections smaller due to more exquisite selection cuts, we give results for 3000 fb\(^{-1}\). Unlike Sec. 4.1.2 for SS2t, the result presented here have not been updated to take sufficient account of 4t constraint with full Run 2 data. In this subsection, we take \( \rho_{tt} = 1 \).

We denote our triple-top signature as 3\( \ell \)3b, which is defined as: at least three leptons, at least three jets with at least three tagged as b-jets, plus \( E_T^{\text{miss}} \). The selection cuts are: for the three leading leptons and b-jets, \( p_T > 25 \) GeV and \( p_T^b > 20 \) GeV, respectively; \( \eta, \Delta R \) and \( E_T^{\text{miss}} \) are the same as for SS2t; scalar sum, \( H_T \), of transverse momenta of all three leading leptons and b-jets should satisfy \( H_T > 320 \) GeV. To reduce \( t\bar{t}Z + \text{jets} \) background, we veto the mass range 76 GeV < \( m_{\ell\ell} \) < 95 GeV for same flavor, opposite charged lepton pairs, and if more than one pair is present, the veto is applied to the pair mass closest to \( m_Z \).

Dominant SM backgrounds are \( t\bar{t}Z + \text{jets} \) and 4t, with \( t\bar{t}W + \text{jets}, t\bar{t}h \) and \( tZ + \text{jets} \) subdominant (3t + j, 3t + W are less than subdominant). The \( t\bar{t} + \text{jets} \) process can contribute if a jet gets misidentified as a lepton, with probability taken as \( 10^{-4} \). We do not include nonprompt backgrounds as they are not properly modeled in Monte Carlo simulations. Unlike the SS2t signature, the three hard leptons plus high b-jet multiplicity, along with Z-pole veto and \( H_T \) cut may reduce such contributions significantly. The \( t\bar{t}Z + \text{jets}, 4t, t\bar{t}W + \text{jets}, t\bar{t}h \) and \( tZ + \text{jets} \) cross sections at LO are adjusted by the same factors as for SS2t, i.e. 1.56, 2.04, 1.35, 1.27 and 1.44 respectively, and likewise 1.84 for \( t\bar{t} + \text{jets} \) with jet faking lepton. Conjugate processes are assumed to have the same correction factors for simplicity.

With background cross sections given in Table 2, the signal cross sections after

| Backgrounds | Cross section (fb) |
|-------------|-------------------|
| \( t\bar{t}Z + \text{jets} \) (1.56) | 0.0205 (0.0026) |
| 4t (2.04) | 0.0232 (0.0209) |
| \( t\bar{t}W + \text{jets} \) (1.35) | 0.0017 (0.0015) |
| \( t\bar{t}h \) (1.27) | 0.0015 (0.0013) |
| \( tZ + \text{jets} \) (1.44) | 0.0002 (--) |
| \( t\bar{t} + \text{jets} \) (fake) | 0.0026 (0.0025) |
Fig. 5. [left] Cross sections (fb), and [right] significance (at 3000 fb$^{-1}$) for 3$\ell$3$b$ final state at $\sqrt{s} = 14$ TeV for $\rho_{tt} = 1$ and several $\rho_{tc}$ values after selection cuts.$^{65}$

selection cuts are plotted in Fig. 5[left] for $\rho_{tt} = 1$ and $\rho_{tc} = 0.1$, 0.5 and 1. For $\rho_{tc} = 1$ and 0.5, $B(A \rightarrow t\bar{t}) > B(H \rightarrow t\bar{t})$ (see Fig. 3) makes the cross section for $A$ higher than $H$, which also explains the slower turn on for $H$ with $m_H$. For $\rho_{tc} = 0.1$, the $t\bar{t}S$ process dominates, with higher cross section for $A$ (see Fig. 2). The discovery contours, estimated using Eq. (11) for 3000 fb$^{-1}$, are plotted in Fig. 5[right]. We find 5$\sigma$ discovery reach for $\rho_{tc} = 1$ covers the full range of Eq. (4) and even a bit beyond. For $\rho_{tc} = 0.5$, 5$\sigma$ reach is up to 520 (570) GeV for $H$ ($A$) while 3$\sigma$ evidence covers the full range of Eq. (4). With no interference between $A$ and $H$ induced contributions for triple-top, a small $A$-$H$ mass splitting makes little effect, hence$^{65}$ for degenerate $A$-$H$, one could make 5$\sigma$ discovery even beyond the full range of Eq. (4).

For lower masses with small splitting, the relative strength of triple-top and same-sign top at HL-LHC could in principle allow one to extract information on relative strength of $\rho_{tc}$ vs $\rho_{tt}$, assuming discovery.$^{65}$ This would throw light on whether EWBG is more driven by $\rho_{tt}$ or $\rho_{tc}$. Although we have elucidated the effect of exotic $H$ and $A$ scalars, mass reconstruction would not be easy, and further study would be needed, especially at HL-LHC.

We have assumed nearly degenerate heavy scalars, which need not be the case. Finite splittings could lead to $H \rightarrow AZ$, $H^\pm W^\mp$ (or reverse) decays, which would dilute our signatures but enrich the program. One charming aspect of extra $\rho_{tt}$ and $\rho_{tc}$ Yukawa couplings is their intrinsic complexity, which is why they can drive EWBG.$^{57}$ More studies are needed to probe these CPV phases. Our proposal is thus only a first step of a large program.

4.2. Bottom-associated $H^+$ Production: $cg \rightarrow bH^+ \rightarrow bt\bar{b}$

A novel process, $cg \rightarrow bH^+$ (see Fig. 6) followed by $H^+ \rightarrow t\bar{b}$, was proposed recently.$^{69}$ that may lead to the discovery of the exotic $H^+$ boson in the near future.

The usual 2HDM II motivates the study of the $bg \rightarrow tH^+$ process.$^{111,112}$ which goes through the $tbH^+$ coupling. In contrast, despite being phase space favored, the $cg \rightarrow bH^+$ process is suppressed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix element ratio $V_{cb}/V_{tb}^2 \sim 1.6 \times 10^{-3}$. But in g2HDM with extra Yukawa
Decoupling $c \bar{b} H^+$ and $\bar{t} b H^+$ couple with strength $\rho_{tc}V_{tb}$ and $\rho_{tt}V_{tb}$, respectively, and $c g \to b H^+$ is not CKM-suppressed. Although this fact can be read off from the $H^+$ coupling in Eq. (5), it is not quite “apparent”, and was realized after a study of $H^+$ effect in $B \to \mu \bar{\nu}$. We turn to the $c g \to b H^+$ process in this section. The process was noted by others, but were either mentioned without collider study, or without sufficient detail. For example, the $gg \to \bar{c} b H^+$ process was discussed in Ref. [79], but Fig. 6 was not explicitly mentioned, and in absence of a detailed collider study, the promise was not quite elucidated.

4.2.1. Constraints on Higgs and Flavor Parameters

We express the quartic couplings $\eta_1, \eta_3-6$ in terms of $\mu_{22}, m_{h,H,A,H^+}$ (which are all normalized to $v$) and $\cos \gamma$, plus $\eta_2, \eta_7$ that do not enter Higgs masses. As Yukawa couplings of $H^+$ do not depend on $c_\gamma$, which is known to be small, we set $c_\gamma = 0$ (thus, e.g. $t \to c h$ does not constrain $\rho_{tc}$) while fixing $m_h \cong 125$ GeV. Thus $\eta_6 = 0$ and $\eta_1 = m_h^2/v^2$, which simplifies the study considerably. In the Higgs basis, we identify $\eta_1-7$ with the input parameters $\Lambda_1-7$ to 2HDMC, which we utilize to check they satisfy positivity, perturbativity and tree-level unitarity.

For fixed $m_{H^+} = 300$ and 500 GeV, we randomly generate the parameters in the ranges $\eta_2, \eta_7 \leq 3$ (except $\eta_2 > 0$ by positivity), $\mu_{22} \in [0,1]$ TeV, and $m_{A,H} \in [m_{H^+} - m_W, 650$ GeV] to forbid $H^+ \to AW^+, HW^+$, again to simplify. The generated parameters are passed to 2HDMC for scanning, where we follow the scanning procedure discussed in Ref. [125]. We further impose the electroweak oblique parameter constraints, which restrict the scalar masses hence the $\eta_i$s. Scan points satisfying these constraints are plotted in Fig. 7 in the $m_{H^+}-m_A$ plane for $m_{H^+} = 300, 500$ GeV, which illustrates that finite parameter space exist. We choose a benchmark for each $m_{H^+}$ value and list the parameters in Table 3.

**Flavor Constraints**

With large parameter space for the Higgs sector demonstrated, we turn to flavor and collider constraints on $\rho_{tc}$ and $\rho_{tt}$. Flavor constraints are not very strong. For $m_{H^+} \lesssim 500$ GeV, $B_q$ mixings ($q = d, s$) provide the relevant constraint. In particular, and as mentioned before, $\rho_{ct}$ must be turned off because of a

The $c b H^+$ couplings in 2HDM III context has been studied in different decay channels and involving various flavor assumptions, where our list is only partial.
CKM-enhanced effect in $B_q$ mixings. Assuming all $\rho_{ij}$ vanish except $\rho_{tt}$, we define $M_{12}^f/M_{12}^{f,\text{SM}} = C_{B_q}$, with phase negligible. Allowing $2\sigma$ error on $C_{B_s} = 1.05 \pm 0.11$ and $C_{B_d} = 1.11 \pm 0.09$ from summer 2018 UTfit, we give the blue shaded exclusion region in Fig. 8 which extends to upper-right and the left (right) panel is for BP1 (BP2). The constraint from $H^+$ effects via charm loops is more forgiving.

$B \to X_s \gamma$ puts a strong constraint on $m_{H^+}$ in 2HDM II, but weakens for g2HDM due to extra Yukawa couplings. An $m_t/m_b$ enhancement factor actually constrains $\rho_{bb}$ more strongly than $\rho_{tt}$. Taking $\rho_{bb}$ as small, the constraint on $\rho_{tt}$ from $B \to X_s \gamma$ falls outside the range of Fig. 8, while the $B \to X_s \gamma$ constraint on $\rho_{tc}$ via charm loop is weaker than $B_q$ mixing.

Overall, because many parameters enter, we view the true constraints from $B \to X_s \gamma$ on $H^+$ parameters, e.g. $m_{H^+}$, as still an open issue.

**Collider Constraints**

For collider constraints, we again set all $\rho_{ij} = 0$ except $\rho_{tt}$ and $\rho_{tc}$ for simplicity. For finite $\rho_{tt}$, one can have $b \to \bar{t}(b)H^+$ (our list is not exhaustive), followed by $H^+ \to t\bar{b}$. Searches at 13 TeV provide model independent bounds on $\sigma(pp \to \bar{t}(b)H^+)B(H^+ \to t\bar{b})$ for $m_{H^+} = 200$ GeV to 2 (3) TeV for ATLAS (CMS). Using MadGraph5_aMC@NLO as before with default PDF of NN23LO1 and effective model implemented in FeynRules, we calculate $\sigma(pp \to \bar{t}(b)H^+)(H^+ \to t\bar{b})$ at LO for a reference $|\rho_{tt}|$, then rescale by $|\rho_{tt}|^2 B(H^+ \to t\bar{b})$ to get the upper limits. For $m_{H^+} = 300, 500$ GeV and with $\rho_{tc} = 0$ (hence $B(H^+ \to t\bar{b}) \sim 100\%$), we plot the extracted ATLAS (CMS) 95% C.L. bounds on $\rho_{tt}$ as the red (purple) shaded regions in Fig. 8. The ATLAS/CMS limit is more/less stringent than $B_q$ mixing for BP1 while opposite for BP2, with the exclusion bands overlaid to illustrate this.

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**Table 3.** Benchmark point BP1 (BP2) for $m_{H^+} = 300$ (500) GeV, with $\eta_b = 0$ hence $\eta_t \approx 0.258$ (alignment limit). Higgs masses are in GeV.

| $\eta_2$ | $\eta_3$ | $\eta_4$ | $\eta_5$ | $\eta_7$ | $m_{H^+}/\mu^2$ | $m_{H^+}$ | $m_A$ | $m_H$ |
|---------|---------|---------|---------|---------|----------------|-----------|-------|-------|
| BP1     | 1.40    | 0.62    | 0.53    | 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   |

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**Fig. 7.** Scan points in $m_H - m_A$ plane for $c_\gamma = 0$ that pass positivity, perturbativity, unitarity and $T$ parameter constraints. See text for details.
Constraints on $\rho_{tt}$ from Refs.~\cite{137,138} $gg \rightarrow H/A \rightarrow t\bar{t}$ search are weaker than results shown in Fig.~8. We will return to the CMS “excess”\cite{138} at $m_A \sim 400$ GeV later.

The CMS 4$\ell$ search\cite{76} based on full Run 2 data constrains $\rho_{tc}$, as discussed in Sec.~4.1.1, but now we consider the constraint together with $\rho_{tt}$. With both $\rho_{tt}$ and $\rho_{tt}$ finite, the $cg \rightarrow tH/tA \rightarrow t\bar{t}l^+l^-$ process\cite{68} can feed the SR12 signal region of the CMS 4$\ell$ search if all three top quarks decay semileptonically. As $cg \rightarrow tH/tA \rightarrow t\bar{t}l^+l^-$ barely occurs for BP1 because of low $m_{A,H}$ values, this applies only to BP2. SR12 requires\cite{76} at least three leptons, four jets with at least three $b$-tagged, plus $p_T^{miss}$. We generate events with PYTHIA 6.4 for showering and hadronization, adopt MLM merging\cite{84,85} of matrix element and parton shower, then feed into Delphes 3.4.2 for CMS-based detector card, including $b$-tagging and $c$- and light-jet rejection. We find $\rho_{tt} \gtrsim 1$ is excluded if $\rho_{tc} \sim 0.8$ for BP2. However, finite $\rho_{tc}$ induces $H^+ \rightarrow c\bar{b}$ decay, which would dilute $B(H^+ \rightarrow \bar{t}b)$ and soften the $bg \rightarrow t\bar{t}H^+$ constraint. This is illustrated by the dash (dot) curves in Fig.~8(right) for $\rho_{tc} = 0.4$ (0.8).

As already discussed in Sec.~4.1.1, the $cg \rightarrow tH/tA \rightarrow t\bar{t}c$ process\cite{86} can feed the CRW control region of CMS 4$\ell$ study when both tops decay semileptonically. Following Refs.~\cite{139,140} we find $\rho_{tc} \gtrsim 0.4$ is excluded for BP1, which is stronger than the $B_q$ mixing bound, and with little dependence on $\rho_{tt}$. For BP2, CRW gives comparable limit as SR12. Thus, we give in Fig.~8(left) the softened $bg \rightarrow t\bar{t}H^+$ constraint only for $\rho_{tc} = 0.4$. Note that analogous searches with similar signature usually involve stronger cuts and therefore do not give relevant constraints.

4.2.2. Collider Signature for $cg \rightarrow bH^+ \rightarrow b\bar{t}b$

We now show that the $cg \rightarrow bH^+ \rightarrow b\bar{t}b$ process, or $pp \rightarrow bH^+ + X \rightarrow b\bar{t}b + X$, is quite promising\cite{69}. For illustration, we conservatively take $|\rho_{tc}| = 0.4$, $|\rho_{tt}| = 0.6$ for both BPs. Receiving no CKM suppression, the approximate $H^+ \rightarrow \bar{c}b$, $t\bar{b}$ branching ratios are 50%, 50% for BP1, and 36%, 64% for BP2. Assuming $t \rightarrow b\ell\nu_\ell$ ($\ell = e, \mu$), the signature is one charged lepton, $p_T^{miss}$, and three $b$-jets. The inclusive...
The inclusive \( \sigma(pp \rightarrow H^+) \) with up to two extra jets in the five flavor scheme for BP1 (BP2) at 14 TeV is 50.8 (6.5) pb using MadGraph5_aMC with NN23LO1 PDF set and default run card.
and beyond. Note that significance can still be high at higher masses for larger \( \rho_{tc} \), \( \rho_{tt} \), but the decoupling \( \mu_2^2 \) would generally become larger \( \mu_2^2 \approx 3.78 \) for BP2 in Table 3 which would start to damp the EWBG motivation. The \( cg \rightarrow bH^+ \) process, however, can certainly be pursued for heavier \( m_{H^+} \) at higher luminosities.

Our BPs here involve both \( \rho_{tc} \) and \( \rho_{tt} \), and can feed the SS2\( \ell \) signature. Following the same analysis of Refs. 65 and 149, we find BP1 may have \( \sim 3.5\sigma \) significance with full Run 2 data since finite \( \rho_{tt} \) plays no effect. But for BP2, the significance is below \( \sim 1\sigma \) due to dilution from \( A/H \rightarrow \bar{t}t \) 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 \( pp \rightarrow H^+[b\bar{t}]j \), \( H^+[s\bar{b}]t \) can contribute 15.2 (2.9) pb for BP1 (BP2), which is within the 2\( \sigma \) error of current t-channel single-top measurements. The situation is similar for Run 1 with s-channel single-top measurements. We have not included uncertainties from scale dependence and PDF, where the latter is sizable for processes initiated by heavy quarks. Using signal cross sections at LO can also bring in some uncertainties, e.g. higher order corrections to \( \sigma(bg \rightarrow tH^+) \) may amount to 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.

5. Discussion and Miscellany

With \( \rho_{tt} = O(\lambda_t) \sim 1 \), the heavy Higgs bosons \( H \) and \( A \) can be produced via gluon-gluon fusion (ggF), and \( gg \rightarrow H/A \rightarrow \bar{t}t \) can interfere with the large, QCD-induced \( gg \rightarrow t\bar{t} \) amplitude, which distorts the Breit-Wigner peak into a peak-dip structure\( ^{[118]} \) making experimental search more challenging. A first study by ATLAS with 8 TeV data starting from 500 GeV found\( ^{[137]} \) no significant deviation. Based on 2016 data, CMS reported\( ^{[135]} \) more recently an intriguing signal-like deviation in \( gg \rightarrow A \rightarrow \bar{t}t \), compatible with an \( A \) with mass \( \sim 400 \) GeV with global significance of 1.9\( \sigma \) (and 3.5\( \sigma \) local). It was shown\( ^{[119]} \) that \( \rho_{tt} = O(1) \) can account for this possible “excess”, but \( \rho_{tc} = O(1) \) is called upon to reign in \( B(A \rightarrow \bar{t}t) \). It was further pointed out that \( ^{[119]} \) for purely imaginary \( \rho_{tt} \) — which can robustly drive the EWBG — an \( H \) would mimic an \( A \) in production and decay, and CMS could well be peeking at the first of the exotic bosons, \( m_H \sim 400 \) GeV, with heavier, degenerate \( m_A \simeq m_{H^+} \gtrsim 550 \) GeV satisfying\( ^{[128]} \) custodial symmetry, hence more easily fulfill oblique parameter constraints.\( ^{[10]} \) This fits nicely in the range of Eq. 4, and having \( A-H^+ \) heavier\( ^{[8]} \) also fits the single-state analysis of CMS.\( ^{[133]} \) We eagerly await the unveiling of the full Run 2 data from both CMS and ATLAS.

\(^{[8]}\) Having \( m_A = 400 \) GeV while \( m_H \simeq m_{H^+} \gtrsim 550 \) GeV would correspond to “twisted” custodial symmetry\( ^{[127]} \) with more restricted parameter space.

\(^{[9]}\) We remark that, based on \( \sim 36 \) fb\(^{-1} \), a relatively stringent CMS bound\( ^{[22]} \) on \( m_{H^+} \) from \( pp \rightarrow t\bar{t}H^+ + X \) associated production followed by \( H^+ \rightarrow t\bar{b} \) would push \( m_{H^+} \) beyond 650 GeV. Full Run 2 data, including that from ATLAS, can tell whether this is a downward fluctuation.
But perhaps the excess would disappear with full Run 2 analysis, or some analysis difficulty may be encountered. There is then the $gg \to H/A \to t\bar{t}$ process, mediated by $\rho_{t\bar{t}}$ in production and $\rho_{tc}$ in decay. This could be promising, as it does not suffer from interference. However, there is worry that $tj$ ($j$ stands for a jet) mass resolution could wash the resonance away. Or one could pursue $H/A \to \tau\mu$ in the final state, which was shown to hold promise at the HL-LHC, but would likely suffer from suppressed $\mathcal{B}(H/A \to \tau\mu)$, as $\rho_{\tau\mu} = \mathcal{O}(\lambda_\tau) \sim 0.01$ would be our best guess. In principle, $H/A \to \tau\tau$ can also be searched for, but there is no "large tan$\beta$" enhancement mechanism as in 2HDM II, where again our best guess would be $\rho_{\tau\tau} = \mathcal{O}(\lambda_\tau)$ in g2HDM, that the second diagonal $\tau$ Yukawa coupling should go with the strength of $\lambda_\tau$ by the mass-mixing hierarchy argument. We note the prowess of ATLAS\textsuperscript{156} and CMS\textsuperscript{157} with simple final states containing $\tau$s.

This brings us back to our main proposed processes of $cg \to tH/A \to t\bar{t}\bar{c}, t\bar{t}c$ and $cg \to bH^+ \to b\bar{b}c$, but turning to the $\rho_{tu}$-induced process. Although $\rho_{tu} < \rho_{tc}$ is expected by way of mass-mixing argument, this is not based on direct experimental knowledge. In Sec. 4.1.1., we followed Ref. 80 to study the effect of CRW of CMS $4t$ analysis and CRttW2 of ATLAS $4t$ analysis on $\rho_{tu}$, and plotted the results in Fig. 4(right). The bounds from $4t$ analyses on $\rho_{tu}$ are indeed more stringent than on $\rho_{tc}$ of Fig. 4(left), but by far not as stringent by a $\sqrt{m_u/m_c}$ factor as implied roughly by the mass-mixing hierarchy. Furthermore, these bounds were studied keeping $\rho_{tu} \neq 0$ but setting all other $\rho_{ij} = 0$, with exclusion limits and discovery reach also plotted in Fig. 4(right). If $\rho_{tu}$ and $\rho_{tc}$ are both kept given that there are no good tools for separating $c$- and light $q$-jets, it would not be easy to gain on extracting information. We note, therefore, that the product $\rho_{tu}\rho_{\tau\mu}$ would be probed by the $B \to \mu\nu$ process at Belle II. If any deviation of $\mathcal{B}(B \to \mu\nu)/\mathcal{B}(B \to \tau\nu)$ from SM expectation is observed, it would imply that both $\rho_{tu}$ and $\rho_{\tau\mu}$ are nonvanishing, and more sophisticated analysis for having $\rho_{tu}$ and $\rho_{tc}$ both finite need to be developed, where Ref. 80 is only a start. The $\rho_{\tau\mu}$ coupling can also be probed via the $\tau \to \mu\gamma$ process at Belle II with the help of $\rho_{tu}$ via the two-loop mechanism. Thus, there is much synergies with the flavor frontier to look forward to, and with refined analyses at the (HL-)LHC, much progress can be anticipated.

Finally, let us comment on the implications of finite $c_\gamma$. For exotic Higgs in the mass range of Eq. (4), in general one would expect $h-H$ mixing, i.e. $c_\gamma$, to be finite. However, compared with the $\cos(\beta - \alpha)$ fit to Higgs property measurements at the LHC in 2HDM II (which is implied by SUSY), the many more parameters that can enter for production and decay of the $h$ boson, as we have illustrated only partially, implies that a similar fit to $c_\gamma$ (the equivalent to $\cos(\beta - \alpha)$) seems nowhere in sight. We can only argue that $c_\gamma$ has to be small to have $h$ resembling the Higgs boson of SM so well, but its value is not known.

With $c_\gamma$ small but nonzero, what could be the implications? The $H$ and $A$ (and $H^+$) would become mildly related to electroweak symmetry breaking, e.g. coupling to $W$ and $Z$ bosons. We mention here only a few collider possibilities. The first would be resonant di-Higgs production via the $cg \to tH \to thh$ process,
where a finite $c_\gamma$ induces an effective $\lambda_{Hhh}$ coupling. This can be searched for at the LHC via $pp \to tH + X \to thh + X$, and non-negligible discovery potential is found at the LHC for $m_H \lesssim 350$ GeV and $\rho_{tc} \gtrsim 0.5$. A second process would be $cg \to tA \to tZH$, where sufficient $m_A - m_H$ splitting is required to allow for $A \toZH$ decay. It further requires $\rho_{tt}$ to be small, otherwise $A \to t\bar{t}$ would in general be too strong. Under these conditions, it is found that discovery is possible at the HL-LHC for $m_A \sim 400$ GeV, hence $m_H \lesssim 300$ GeV, but $tZh$ production is not promising. A third example, discussed recently, targets the conclusive investigation of the $\rho_{tc}$ mechanism for EWBG (in the case that $\rho_{tt}$ turns out small), which can more easily survive the eEDM constraint as $\rho_{tc}$ does not enter the Barr-Zee two-loop mechanism. The $\rho_{tc}$ mechanism requires $\rho_{tc} \gtrsim 0.5$. The proposal is to utilize $cg \to bH^+ \to bW^+h$ for $c_\gamma \gtrsim 0.1$ to efficiently push the $\rho_{tc}$ bound (or discovery!) down to 0.2 or below at the HL-LHC. For small $c_\gamma \lesssim 0.12$, one counts on the $cg \to tH/A \to tt\bar{c}$ process, which depends rather weakly on $c_\gamma$, to push the exclusion (or discovery!) down to 0.25 or below. Combined, this two-prong search can draw a conclusion on the $\rho_{tc}$ mechanism.

6. Summary and Prospect

In the past few years, we have verified the Yukawa couplings of $t$, $b$ quarks and $\tau$, $\mu$ charged leptons, making extra Yukawa couplings involving a second Higgs doublet plausible and attractive. This general 2HDM with extra Yukawa couplings point to extra Higgs bosons $H$, $A$ and $H^+$ in the sub-TeV range, which is based on naturalness of the second set of dimension-4 couplings unique to the Higgs sector: Higgs quartic self-couplings. The exotic bosons are well hidden so far by fermion mass-mixing hierarchy and alignment, the smallness of $h - H$ mixing angle $c_\gamma$.

The search for $t \to ch$ (and concurrently for $h \to \tau\mu$) is ongoing. If it does not emerge with full Run 2 data, it would constrain the product of $\rho_{tc}c_\gamma$. But given that $c_\gamma$ is small, sizable $\rho_{tc}$ would still be allowed. In this brief review, we advocate the search for $cg \to tH/A \to tt\bar{c}$, $tt\bar{t}$ and $cg \to bH^+ \to b\bar{b}$ at the LHC, where production, unhampered by small $c_\gamma$, depends on sizable $\rho_{tc}$, while the $tt\bar{t}$ and $b\bar{b}$ final states require finite $\rho_{tt}$ for $H/A \to tt$ and $H^+ \to t\bar{b}$ decays. It would be interesting, therefore, to follow up with full Run 2 data on the $m_A \sim 400$ GeV excess seen by CMS in $tt$ resonance search. Both extra top Yukawa couplings $\rho_{tt}$ and $\rho_{tc}$ can drive electroweak baryogenesis, providing further impetus for search. LHC Run 2 data may already be promising, and Run 2+3 data would be even more revealing, while HL-LHC may hold the ultimate promise for discovery, which would open up a new chapter at the intersection of Higgs and flavor physics.

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