When the Higgs meets the Top: Search for $t \to ch^0$ at the LHC

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The newly discovered “Higgs” boson $h^0$, being lighter than the top quark $t$, opens up new probes for flavor and mass generation. In the general two Higgs doublet model, new $ct$, $cc$ and $tt$ Yukawa couplings could modify $h^0$ properties. If $t \to ch^0$ occurs at the percent level, the observed $ZZ^*$ and $\gamma\gamma$ signal events may have accompanying $cbW$ activity coming from $tt$ feeddown. We suggest that $t \to ch^0$ can be searched for via $h^0 \to ZZ^*, \gamma\gamma, WW^*$ and $bb$, perhaps even $\tau^+\tau^-$ modes in $tt$ events. Existing data might be able to reveal some clues for $t \to ch^0$ signature, or push the branching ratio $B(t \to ch^0)$ down to below the percent level.

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1. INTRODUCTION AND MOTIVATION

With the landmark discovery \cite{1,2} of a 126 GeV boson in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC), efforts have shifted towards Higgs property studies, to either confirm that this is indeed the Higgs boson of the Standard Model (SM), or to find deviations indicating that it may not be the Higgs boson. With the Higgs boson as the “mass giver”, it is natural to ask whether it reveals any special effects associated with the heaviness of the top quark. A related question is: Considering all available data, what is the analogous parameters in the Cheng-Sher ansatz that cannot be argued against. Note that it was within the Cheng-Sher ansatz that $t \to ch^0$ (or $h^0 \to tc$) decay was first proposed \cite{3} as the leading effect.

To account for the BaBar anomaly, the FCNH coupling $\rho_{ct}$ of the exotic heavy Higgs doublet need to be of order 1 in strength \cite{10}. For our purpose, keeping notation of the usual 2HDM-II \cite{13}, the observed boson $h^0$ may contain a small admixture $\cos(\beta - \alpha)$ of the exotic neutral Higgs, hence the $tch^0$ coupling \cite{14}

$$\rho_{ct} \cos(\beta - \alpha) \, cth^0 + h.c., \quad (1)$$

which can induce $t \to ch^0$ decay. In Fig. 1 we illustrate the branching ratio $B(t \to ch^0)$ vs $\rho_{ct} \cos(\beta - \alpha)$. The question is: Considering all available data, what is the allowed $B(t \to ch^0)$, or equivalently, $\rho_{ct} \cos(\beta - \alpha)$ value? What are the signatures to pursue?

We note that, if we take $\rho_{ct} \sim 1$, which is not quite explored because it is suppressed by $\cos(\beta - \alpha)$ for couplings involving $h^0$ (but not suppressed for couplings involving the heavy exotic Higgs bosons $H^0, A^0$ and $H^\pm$), then the analogous parameters $\rho_{ct}, \rho_{cc}, \rho_{hb}$ and $\rho_{\tau\tau}$ will enter the Higgs property study program, as we shall elucidate. An existing study of multi-lepton final states finds a bound \cite{1} of $B(t \to ch^0) < 2.7\%$. But this should be taken with some caution, as it assumed SM branching ratios for $h^0 \to WW^*, ZZ^* and \tau\tau$ final states. The study took an effective field theory approach to isolate the $tch^0$ coupling, hence is not a full theory.

FIG. 1. $B(t \to ch^0)$ vs $\rho_{ct} \cos(\beta - \alpha)$, with 2% indicated.
II. BABAR ANOMALY, $h^0 \to \tau\tau$, AND $b \to s\gamma$

The BaBar experiment measured the ratios $\mathcal{R}(D^{(*)}) = \Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}\nu)$, finding them both larger than SM expectations, with a combined significance of $3.4\sigma$. In 2HDM-II, this implied $\tan\beta/m_{H^+} = 0.44 \pm 0.02$ GeV$^{-1}$ and $0.75 \pm 0.04$ GeV$^{-1}$ from $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, respectively. The impressive precision is because many uncertainties, both from measurement and from theory, cancel. The two numbers are incompatible with each other, hence “excites” the type II 2HDM charged Higgs boson with a $99.8\%$ confidence level for any value of $\tan\beta/m_{H^+}$ [8]. Either $\tan\beta/m_{H^+}$ value, however, would over-enhance $B \to \tau\nu$, which is found in agreement (in order of magnitude) with SM expectation, spurring further trouble.

Employing FCNH parameters in 2HDM-III to account for the BaBar “anomaly”, a new $c\ell$ coupling (and $u\ell$ for $B \to \tau\nu$), heretofore forbidden by the NFC condition [11], needs to be of order 1. For the lepton sector, Ref. [10] assumed the usual 2HDM-II coupling, i.e. $\rho_{\tau\nu} = -\tan\beta(2m_{\tau}/v)$, where $v$ is the weak scale.

We shall use the following notation for the Yukawa couplings of the 2HDM-III Higgs sector [16],

$$-\frac{1}{\sqrt{2}} \sum_{f=\ell,u,t} \bar{f} \left[ (\kappa f s_{\beta-\alpha} + \rho f c_{\beta-\alpha}) h^0 ight. \\
+ \left. (\rho f c_{\beta-\alpha} - \rho f s_{\beta-\alpha}) H^0 - i sgn(Q_f) \rho f \gamma_5 A^0 \right] f - \bar{\bar{u}} \left( V_{\rho}^\dagger R - V_{\rho}^\dagger V_L \right) dH^+ + \bar{\bar{v}} \rho f \bar{\bar{t}} H^+ + \text{h.c.} \right],$$

where $s_{\beta-\alpha}$ and $c_{\beta-\alpha}$ stand for $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$ in the 2HDM-II notation [12] for sake of comparison (even though $\beta$ is no longer physical). The diagonal $\kappa$ terms relate to mass generation, while the hermitian $\rho$ terms come from the second Higgs doublet, and can have off-diagonal terms allowed by data. It is the combined effect of $\tau\tau$ and $D^\tau$ couplings, that can account for $B \to D^{(*)}\tau\nu$. Stringent constraints from down quark sector imply that only $c_{\beta-\alpha} = 0.2$ in Eq. (3).

![FIG. 2. Allowed $\rho_{\tau\nu}$ region for 2HDM-III to solve the $B \to D^{(*)}\tau\nu$ anomaly, taking $m_{H^+} = 700$ GeV (and $\rho_{bb} = 0$). The shaded-green area is the combined result from $\mathcal{R}(D)$ (solid-blue lines) and $\mathcal{R}(D^*)$ (dashed-red lines), while the dotted-purple lines illustrate the $h^0 \to \tau\tau$ bound by taking $c_{\beta-\alpha} = 0.2$ in Eq. (3).](image)

![FIG. 3. Constraint on $\rho_{bb}$ from $b \to s\gamma$, assuming $\rho_{ct} = 1$, $\rho_{cc} = 0.2$ and $m_{H^+} = 700$ GeV.](image)

FIG. 2. Allowed $\rho_{\tau\nu}$ region for 2HDM-III to solve the $B \to D^{(*)}\tau\nu$ anomaly, taking $m_{H^+} = 700$ GeV (and $\rho_{bb} = 0$). The shaded-green area is the combined result from $\mathcal{R}(D)$ (solid-blue lines) and $\mathcal{R}(D^*)$ (dashed-red lines), while the dotted-purple lines illustrate the $h^0 \to \tau\tau$ bound by taking $c_{\beta-\alpha} = 0.2$ in Eq. (3).

With $\rho_{\tau\nu} \simeq -0.5$ [10], even a small $c_{\beta-\alpha}$ could upset this bound. To illustrate further, we plot in Fig. 2 the range for $\rho_{\tau\tau}-\rho_{ct}$ allowed by BaBar anomaly for the typical value of $m_{H^+} = 700$ GeV. The point $\rho_{\tau\tau} \simeq -0.5$, $\rho_{ct} \sim 1$ of Ref. [10], far outside the plot, would require $c_{\beta-\alpha}$ to be rather small. If we take $c_{\beta-\alpha} = 0.2$ (i.e. $s_{\beta-\alpha} \simeq 0.98$) in Eq. (3), then $-0.12 < \rho_{\tau\tau} < 0.02$ would push $\rho_{ct}$ to become very large, as seen from Fig. 2.

Thus, $h^0 \to \tau\tau$ data imply either one goes to the decoupling limit of $c_{\beta-\alpha} \to 0$, where $t \to ch^0$ vanishes, or one has to entertain nonperturbative values for $\rho_{ct}$ [12]. As further analysis [20] of $q^2 (\tau\tau)$ dependence of $B \to D\tau\nu$ favors New Physics from spin-1 particles, we will not strongly advocate the link to the BaBar anomaly, but use it to illustrate that $\rho_{ct}$ can be of order 1, and focus on probing $tch^0$ coupling directly at the LHC.

Before turning to the LHC, however, we explore one other piece of B physics: $b \to s\gamma$ (Fig. 3). We have already seen how $h^0 \to \tau\tau$ data pushes down $\rho_{\tau\tau}$. We now show that, if one takes $\rho_{ct} \sim 1$, the well-known $b \to s\gamma$ process constrains $\rho_{bb}$ to be rather tiny (noted recently in Ref. [21] in a different way).

In the notation of Ref. [22], the $H^+$ loop gives

$$\delta C_{7,8} \simeq 1/3 \left( \rho_{tt} + V_{ts}^* \rho_{ct} \right) \left( \rho_{ct} + V_{tb}^* \rho_{ct} \right) \frac{F_{7,8}^{(0)}(y)}{2m_t^2/v^2}$$

$$- \left( \rho_{tt} + V_{ts}^* \rho_{ct} \right) \rho_{bb} \frac{F_{7,8}^{(2)}(y)}{2m_b^2/v^2},$$

where $C_{7,8}$ to be considered; note that the superscript for $\rho$ can be dropped for flavor-specific elements. We shall only keep $\rho_{\tau\tau}$ from lepton sector, but it is $\rho_{ct}$, $\rho_{ct}$ and $\rho_{cc}$ from up quark sector that are of interest.

In the so-called “decoupling limit” [13, 14], $\cos(\beta-\alpha) \to 0$ and $\sin(\beta-\alpha) \to 1$, $h^0$ becomes just the Higgs boson of SM, while $H^0, A^0$ and $H^\pm$ form an exotic heavy scalar doublet with FCNH couplings. This limit was tacitly assumed in Ref. [10], which advocated $H^0, A^0 \to t\bar{c}$ search. But we entertain finite $c_{\beta-\alpha}$ values for sake of $t \to ch^0$ decay, hence would need to consider $h^0 \to \tau\tau$ data. The latter from vector boson fusion (VBF) production is within a factor of 2 [13] from SM expectations,
evaluated at matching scale $\mu_W \sim M_W$, where $y = m_t^2/M_{H^+}^2$ and $F_{t,s}^{(1,2)}(y)$ are given in Ref. 22. The effect through $\rho_{bb}$ is enhanced by $m_t/m_b$ as well as quark mixing elements, such that even a tiny $\rho_{bb}$ could affect $b \to s\gamma$. We illustrate $\rho_{bb}$ vs $\rho_{tt}$ in Fig. 3, where we take $\rho_{ct} = +1$, $m_{H^+} = 700$ GeV, and constrain $B(B \to X_s \gamma)$ to be within 50% of SM expectation. The “wrong-sign” $C_{7FF}$ case has been included for comparison. Assuming $C_{7FF}$ does not change sign, $|\rho_{bb}|$ is constrained to be considerably less than 0.01.

### III. PROBING $tch^0$ COUPLING AT LHC: GENERAL 2HDM-III

With $\rho_{tt}$ and $\rho_{bb}$ separately constrained to be small, we are still left with the up-sector exotic couplings, the FCNH $\rho_{ct}$, as well as the diagonal $\rho_{cc}$ and $\rho_{tt}$, which we turn to constrain with present data. How large can $B(t \to ch^0)$ be when $\rho_{ct} \sim 1$? I.e., what constraint do we have on $\cos(\beta - \alpha)$? We now take a direct search approach, namely, from knowledge of top quark physics.

It is clear that $B_{ch} \equiv B(t \to ch^0)$ cannot be too large, for otherwise we should have seen deviations in $t\bar{t}$ measurements during the past two decades. The best measured $t\bar{t}$ production cross section is $\sigma_{tt} \approx 162$ pb by CMS 23 at $\sqrt{s} = 7$ TeV via dileptons, with an experimental error of 5%. On the theoretical side, studies are approaching NNLO (next-to-next-to-leading order) QCD corrections. Comparing the two calculations of Refs. 24 and 23, theoretical errors up to 10% appear allowed. However, a more recent full NNLO result 26 has reached much better theoretical control. In any case, given that $\sigma_{tt}$ would be diluted by $(1 - B_{ch})^2$, $B_{ch}$ of order several percent seems still allowed.

A multi-lepton analysis of Ref. 6, based on 7 TeV data from CMS 27, gives a slightly more stringent bound of 2.7%, or $|\sigma \cdot B|/pp \sim 2.7$ pb (at 7 TeV). We have commented that this study assumed SM branching ratios for $h^0$ decay, which should be taken with caution. However, it illustrates possible feeddown effects to observable Higgs boson decay modes, given the large $t\bar{t}$ production cross section at the LHC. Our chief suggestion is to inspect the clean $ZZ^* \to 4\ell$ samples of Higgs search data, which we now elaborate.

What has been observed so far at the LHC is

$$\sigma_{gg \to h^0} \cdot \frac{\Gamma_{h^0 \to ZZ^*}}{\Gamma_{h^0}} \cdot \frac{\Gamma_{h^0}}{\Gamma_{h^0}} \approx |\sigma \cdot B|_{ZZ^*},$$

where we assume $h^0$ is produced dominantly through gluon-gluon fusion. We have separated respective pieces where $h^0$ properties may deviate from SM. Both experiments find consistency with the expected 15–20 $\ell\ell\ell'$ signal events expected from full 2011-2012 data set. However, $\sigma_{gg}$ is of order 220 pb at 8 TeV 28. If one takes $B_{ch} \approx 2.7\%$, this amounts to $\sim 12$ pb into $t\bar{t} \to ch^0b\bar{w}$, which should be compared with $28 \sim 20$ pb for gg-fusion production of a 126 GeV SM Higgs boson! An excess could have appeared already in $ZZ^*$ mode, except that each of the three product factors in Eq. 5 could deviate from SM. For example, $\sigma_{gg \to h^0}$ may be smaller, or $\Gamma_{h^0} > \Gamma_{h^0}^{SM}$ might dilute direct production.

| TABLE I. Light Higgs $h^0$ properties in 2HDM-III with $\rho_{ct} \sim 1$. Widths are in MeV units, with $\Gamma_{h^0}^{SM} \approx 4.55$ MeV 23. |
|----------------+-----------------+--------------+-------------+-----------------|
| $B_{h^0}$     | $\Gamma_{h^0}$  | $\Gamma$    | Comment |
|----------------+-----------------+--------------+-------------+-----------------|
| $WW^*$         | 21.5% 0.98      | hard to change | $\sin(\beta - \alpha) \approx 1$ |
| $ZZ^*$         | 2.7% 0.12       | hard to change | $\sin(\beta - \alpha) \approx 1$ |
| $\gamma\gamma$ | 0.24% 0.011     | hard to change | $W$-loop dom. |
| $bb$           | 59.4% 2.70      | hard to change | $b \to s\gamma$ |
| $\tau\tau$    | 5.7% 0.26       | within fac. 2 | direct |
| $cc$           | 2.6% 0.12       | up to $\sim \Gamma_{bb}$ | not measured $(\rho_{ct} \lesssim 0.2)$ |
| $gg$           | 7.7% 0.35       | up to fac. 2  | $\rho_{tt} \sim 1$ |

Compared with Ref. 7, Eq. 2 allows us a more complete treatment of $h^0$-properties with $\rho_{ct} \sim 1$, hence understand what SM-like observation of $ZZ^*$ may imply. Our study also illustrates how 2HDM-III with FCNH could alter several Higgs properties, driving in the importance of their measurement.

With $h^0$ dominantly the SM Higgs boson, its $WW^*$ and $ZZ^*$ decay rates, proportional to $\sin^2(\beta - \alpha)$, are hardly changed. Likewise, the $h^0 \to \gamma\gamma$ rate, dominated by $W$-loop, is also SM-like. For fermions, the mass generating $\epsilon$ terms are close to SM, while a small $\cos(\beta - \alpha)$ (we are close to decoupling limit) dilutes the effect of $p$-type couplings. The consistency of $\Gamma_{h^0} \to \tau\tau$ with SM constraints $\rho_{tt}$ to be small, while $\rho_{bb}$ is constrained by $b \to s\gamma$ to be tiny if $\rho_{ct} \sim 1$. Further diluted by $\cos(\beta - \alpha)$, the $bb$ rate arises from $\kappa_{bb}$ and is SM-like.

We are left with potential $\rho_{cc}$ and $\rho_{tt}$ effects. The $c\bar{c}$ mode is extremely hard to search for, hence there are no limits so far. With $\cos(\beta - \alpha) \sim 0.2$, $\rho_{ct} \sim 0.2$ 30 would bring $\Gamma_{cc} \sim \Gamma_{bb} \approx \Gamma_{h^0}^{SM}$, and the enhanced $\Gamma_{h^0}$ would dilute the Higgs signal. This can be partially compensated for by $\rho_{tt}$, as this parameter should naturally be of order 1 if $\rho_{ct} \sim 1$, since $\kappa_{tt} \sim 1$ also. With some suppression by $\cos(\beta - \alpha)$, nevertheless it could bring $\sigma_{gg \to h^0}$ up or down by a factor of $\sim 2$.

We summarize in Table I possible effects of our constrained 2HDM-III (with $\rho_{ct} \sim 1$). While $\Gamma_{h^0} \to ZZ^*/\Gamma_{h^0}^{SM}$ is similar to $B_{ZZ^*}^{SM}$, $\sigma_{gg \to h^0}$ could change by a factor of 2 and $\Gamma_{h^0}$ could be enhanced. We comment:

- If $\rho_{cc}$ is small and $h^0$ branching ratios are SM-like (except for $gg$ mode), then the bound of $B(t \to ch^0) < 2.7\%$ from Ref. 7 would apply;
- For enhanced $\sigma_{gg \to h^0}$, then dilution of $B_{ZZ^*}$ would be necessary, implying enhanced $h^0 \to c\bar{c}$;
- If $\sigma_{gg \to h^0}$ is suppressed, or $B_{ZZ^*}$ is diluted, then more $ZZ^*$ events may come from $\ell\ell\ell'$ feeddown!

Given the clean signature of the $ZZ^*$ or $\ell\ell\ell'$ mode, the searches at CMS and ATLAS have been carried out.
in an inclusive way, i.e. simply reconstruct four charged leptons without looking into any associated byproducts. The experimental results can thus be used to constrain any other Higgs production process by looking into the extra activities in the events, which already have a clean peak around 126 GeV. There may well be some fraction of $\ell\ell\ell\ell + cW$ events, with up to 4 jets.

The CMS preliminary result with full 7 and 8 TeV data [31] shows 13, 8, and 4 events with 0, 1, and 2 jets, respectively, after selecting events with $m_{4\ell} \in (121.5, 130.5)$ GeV. There is no indication for higher associated jet activity. To extract a bound on $B(t \to h^0)$, we assume $\sigma_{gg\to h^0} \cdot B(h^0 \to ZZ^*)$ takes SM value. By inserting the CMS data points, together with the background histograms provided in the same plot [31], and jet multiplicity distribution from top events, an upper limit on the top-Higgs contribution is estimated based on the standard CL$_s$ method [32] used at the LHC. The resulting 95% confidence level limit on the relative signal strength between $t \to h^0$ and inclusive Higgs production is around 31%, which can be converted to a limit of 6.5 pb on the effective cross section of $t \to h^0$ at 8 TeV, or a branching ratio limit around 1.5%. This result is based on simple jet counting, with no simulation done.

Interestingly, there is in fact one $\ell\ell\ell\ell + 4j$ event observed [33] by ATLAS for full 7 and 8 TeV data, although no jet-multiplicity plot is given. This event passed the VBF selection, but all 4 jets (in addition to the 4 leptons) are basically in the central rapidity region. As an exercise, we simply add 1 more event to the $N_{\text{jet}} = 4$ bin, and without changing anything else, we obtain an upper limit of 2.2%, instead of 1.5%. If we add 2 events to the $N_{\text{jet}} = 4$ bin, the upper limit becomes 2.8%.

It is clear that a genuine analysis is best left to the experiments, as data is already at hand. The ATLAS event reminds one to carefully check whether there is any bias towards lower number of jets, as VBF production is a measurement target. We remark that, except for our simplifying assumption of $\sigma_{gg\to h^0} \cdot B(h^0 \to ZZ^*)$ being SM-like, this is in fact a model-independent search for $t \to ch^0$ ($h^0 \to ZZ^*$) in $t\bar{t}$ events.

Our argument can be applied to the other mode, $\gamma\gamma$, that drives the Higgs boson discovery. But this mode is not so clean, and clearly carries a bias for VBF event selection of extra jets. However, for $\gamma\gamma + 4j$ events from $t\bar{t}$ feeddown, with $m_{\gamma\gamma}$ in the $m_{WW}$ window, the background should be completely different from the case when jet number is no more than 2, and should be rather promising. For the $h^0 \to WW^*$ final state, the multi-lepton analysis of Ref. [2] should be redone, while a specific $\tau\tau + 4j$ analysis can also be pushed. There is one final "steadfast" analysis that one could do, which is searching for $h^0 \to bb$ mode in $t\bar{t} \to ch^0 W \to c\bar{b}b + \ell\nu$. It has been shown [6] that, through heavy use of $b$-tagging and mass reconstruction, one should be able to push down to 1% sensitivity with 2011-2012 data. Here, $B(h^0 \to bb)$ might get diluted by $h^0 \to c\bar{c}$, which was not considered in Ref. [2], but perhaps the actual experimental analysis could do better than the theoretical study.

It is assuring that, if $h^0$ behaves SM-like except for inducing $t \to ch^0$ decay, we have multiple methods to probe $B(t \to h^0)$ down to the 1% level. The combined result of the above multi-channel analysis should reach the sub-percent level, which becomes comparable with $t \to cZ$ search [34]. If the ATLAS $4\ell + 4j$ event is any guide, we could even make a discovery.

IV. CONCLUSION

It is of great interest to search for the link between the top quark $t$ and the Higgs boson $h^0$. As we have illustrated with $t\bar{t} \to ch^0 bW \to 4l + n_j$, it is quite impressive that the intense efforts of Higgs search in the past two years could already push the limit on $t \to h^0$ down to the percent level. Actual experimental studies of $h^0$ production from $t\bar{t}$ feeddown, incorporating $h^0 \to ZZ^*$, $\gamma\gamma$, $WW^*$, $bb$ and $\tau\tau + 4j$ modes, should be able to push the limit to below the percent level. A discovery of the $t \to ch^0$ process with present data would not only imply the existence of an extended Higgs sector, but one beyond the usual 2HDM-II of minimal SUSY.

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Note Added After submission of this letter, Ref. [32] appeared in arXiv which also addresses the $tch^0$ coupling at the LHC. This study finds a far better sensitivity reach for the $tch^0$ coupling compared to our results, but we do not understand how it is achieved. In addition, after this letter was accepted, we learned about the ATLAS search for $4\ell + 4j$, with $h^0 \to \gamma\gamma$, in $t\bar{t}$ events, finding the limit $[30]$ of $B(t \to h^0) < 0.83\%$ at 95% C.L.

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