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Probing for $t \to ch^0$ at the LHC

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The Higgs boson h and the top quark t are the two most massive and most recently discovered particles. If $t \to ch$ occurs at a couple of percent level, the observed ZZ^* and $\gamma\gamma$ signal events for the Higgs boson may have accompanying cbW activity coming from $t\bar{t}$ feeddown. A general two Higgs doublet model brings in new ct, cc and tt couplings that modify the light neutral Higgs h^0 properties, and $t \to ch^0$ can be searched for via $h^0 \to ZZ^*$, $\gamma\gamma$, WW^* and $b\bar{b}$ (even $\tau^+\tau^-$) modes in $t\bar{t}$ events. We show that existing data should be able to push $\mathcal{B}(t \to ch^0)$ down to below the percent level. Discovery would invalidate minimal SUSY, and imply flavor changing nuetral Higgs couplings.

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1. Introduction

The top was discovered only in 1995, while the Higgs (denoted as h^0) only 2012. These two are the heaviest particles we have found so far, and we believe that the top quark receives its mass through the Higgs boson. It is thus not only a curiosity, but in fact profound, if we were to discover the $t \to ch^0$ decay process. The reason is that Flavor-Changing-Neutral-Higgs (FCNH) couplings are forbidden fruit not only in SM, but in fact also in the two standard types of two Higgs Doublet Models (2HDM I & II) that satisfy the NFC (Natural Flavor Conservation) condition Ref. [1].

But the NFC condition was proposed almost 40 years ago, at a time when all fermions were lighter than several GeV, while facing rather stringent FCNC constraints. Given that the Higgs boson is the mass provider, while there is no natural restriction on the number of Higgs bosons, it seems natural to reopen the case for FCNH. In particular, the tch^0 coupling is obviously the front runner for such a candidate, since constraints are weakest for the top quark, while mass generation itself provides a great motivation. In this context, the search for $t \to ch^0$ and $h^0 \to t\bar{c}$ were suggested [2] even before the discovery of the top quark itself. We shall use 2HDM III [3] to denote the 2HDM without NFC, and let data determine the strength of FCNC couplings. Such a Higgs sector may be called for by the BaBar "Anomaly" [4], which we shall discuss in the next Section. With or without this, we shall discuss the tch^0 coupling of the observed neutral Higgs,

$$\rho_{ct} \cos(\beta - \alpha)\, \bar{c} t h^0 + \text{h.c.}, \tag{1.1}$$

which can induce $t \to ch^0$ decay. Besides the raw FCNH coupling ρ_{ct}, the $\cos(\beta - \alpha)$ factor gives the exotic Higgs admixture of the 126 GeV boson h^0.

The work reported here arose from a numerical study of the $t \to ch^0$ in the $h^0 \to b\bar{b}$ mode in $t\bar{t}$ pair production events at the LHC, where it was shown [5, 6] that with current data, the $b\bar{b}$ mode could push $\mathscr{B}(t \to ch^0)$ down to % level. We were then inspired [7] by the prowess of the $h^0 \to ZZ^*$ and $\gamma\gamma$ modes in discovering the Higgs boson itself. We will argue that, given the aid of the associated other top, even the WW^* final state becomes an interesting search mode [8].

The game changer from a little over a year ago is: we now know the mass for h^0. We therefore plot $\mathscr{B}(t \to ch^0)$ vs $\rho_{ct} \cos(\beta - \alpha)$ in Fig. 1 and ask "How large can $\rho_{ct} \cos(\beta - \alpha)$ be?", or "At what value of $\mathscr{B}(t \to ch^0)$, above which we should not have missed already?"

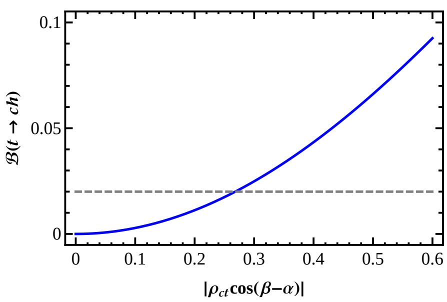

Figure 1: $\mathscr{B}(t \to ch^0)$ vs $\rho_{ct} \cos(\beta - \alpha)$, with dashed line at 2% to guide the eye.

2. BaBar "Anomaly", 2HDM III and tch^0 Coupling

The B factories have reported numerous "anomalies", most of which have disappeared, or otherwise not more than 2σ level. But more than a year ago, from a detailed study of $B \to D\tau\nu$ and $D^*\tau\nu$ decays, normalized to $B \to D^{(*)}\ell\nu$ counterparts, the BaBar experiment reported that the resulting $R(D)$ and $R(D^*)$ ratios differed from SM expectations, with a combined significance of 3.4σ. More astounding is that the two measured values, interpreted under 2HDM II (version from minimal SUSY), gave disparate $\tan\beta/m_{H^+}$ values, which would exclude 2HDM II at greater than 99.8% level [4], for any value of m_{H^+}. Furthermore, value of $\tan\beta/m_{H^+}$ for either case would over-enhance $B \to \tau\nu$, which is more or less in agreement now with SM expectation.

Ref. [3] then pointed out that in 2HDM III, i.e. removing the NFC condition, one could possibly explain the BaBar result. One needs a new *c*-*t* coupling (and a separate *u*-*t* coupling to address $B \to \tau\nu$) that enters the H^+ coupling, absent if NFC is enforced, to be of order 1, while for the lepton side, Ref. [3] continued to assume the usual 2HDM-II coupling, i.e. $\rho_{\tau\tau} = -\tan\beta\sqrt{2}m_\tau/v$, where v is the weak scale.

To explain this, using the notation of Ref. [9], the Yukawa couplings for 2HDM III are,

$$-\frac{1}{\sqrt{2}}\sum_{f=}^{u,d,\ell}\bar{f}\left[\left(\kappa^f s_{\beta-\alpha}+\rho^f c_{\beta-\alpha}\right)h^0 + \left(\kappa^f c_{\beta-\alpha}-\rho^f s_{\beta-\alpha}\right)H^0 - i\,\mathrm{sgn}(Q_f)\rho^f\gamma_5 A^0\right]f$$
$$- \left[\bar{u}\left(V\rho^d R-\rho^u V L\right)dH^+ + \bar{\nu}\rho^\ell R\ell H^+ + \mathrm{h.c.}\right], \quad (2.1)$$

where we have kept $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$ and $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$ in the 2HDM II notation. It should be clear that, except for the first h^0 term, the rest arise from the exotic, presumably heavy doublet. The diagonal κ terms are related to mass generation, while ρ can have off-diagonal terms as allowed by data. The superscript f can be dropped once we consider elements of ρ. It is the combined effect of ρ_{ct} and $\rho_{\tau\tau}$, both entering through the H^+ couplings, that can account [3] for $B \to D^{(*)}\tau\nu$. But stringent constraints from down quark sector imply that only ρ_{bb} needs to be considered, which can combine with the CKM matrix V to induce $b \to c\tau\nu$ also.

Ref. [3] tacitly assumed the decoupling limit, or $\sin(\beta-\alpha) \to 1$ and $\cos(\beta-\alpha) \to 0$, hence h^0 is just the SM Higgs boson. To have $t \to ch^0$, we need nondecoupling, then $\cos(\beta-\alpha)$ gives the exotic component of h^0, hence Eq. (1.1). As we will see in the next section, not only ρ_{bb} but also $\rho_{\tau\tau}$ are constrained by data to be small. However, considering ρ_{ct} together with the diagonal elements ρ_{tt} and ρ_{cc}, a finite $t \to ch^0$ is still allowed, independent of the link with $B \to D^{(*)}\tau\nu$.

3. B Physics and $H \to \tau\tau$ Constraints

It is well known that $b \to s\gamma$ provide stringent constraints to many BSM models. Since $\rho_{ct} \sim 1$ is rather large, one has to be careful. We now show that, if one takes $\rho_{ct} \sim 1$, the well-known $b \to s\gamma$ process constrains ρ_{bb} to be rather tiny. This was noted recently [10] in a different way.

In the notation of Ref. [11], the H^+ loop gives the correction

$$\delta C_{7,8} \simeq \frac{1}{3}\left(\rho_{tt}+\frac{V_{cs}^*}{V_{ts}^*}\rho_{ct}\right)\left(\rho_{tt}^*+\frac{V_{cb}}{V_{tb}}\rho_{ct}^*\right)\frac{F_{7,8}^{(1)}(y)}{2m_t^2/v^2} - \left(\rho_{tt}+\frac{V_{cs}^*}{V_{ts}^*}\rho_{ct}\right)\rho_{bb}\frac{F_{7,8}^{(2)}(y)}{2m_t m_b/v^2}, \quad (3.1)$$

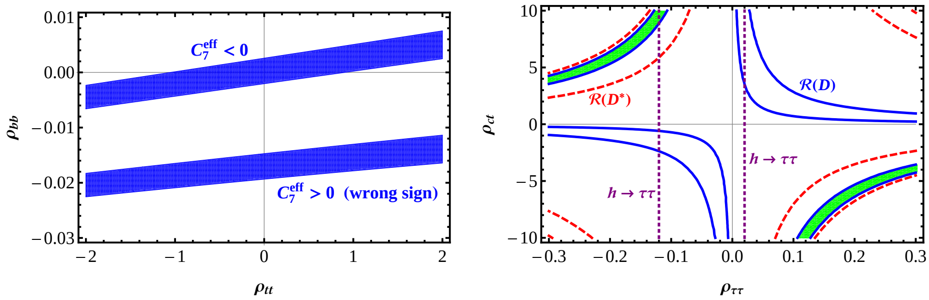

Figure 2: (left) Constraint on ρ_{bb} from $b \to s\gamma$, assuming $\rho_{ct} = 1$, $\rho_{cc} = 0.2$ [12]; (right) allowed $\rho_{\tau\tau}$–ρ_{ct} region for 2HDM-III to solve the $B \to D^{(*)}\tau\nu$ anomaly. In both cases, we take $m_{H^+} = 700$ GeV For the second plot, $\rho_{bb} = 0$ is assumed. The shaded-green area is the combined result from $\mathscr{R}(D)$ (solid-blue lines) and $\mathscr{R}(D^*)$ (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. (4).

evaluated at matching scale $\mu_W \sim M_W$, where $y = m_t^2/M_{H^+}^2$ and $F_{7,8}^{(1,2)}(y)$ are given in Ref. [11]. The effect through ρ_{bb} is enhanced by m_t/m_b as well as quark mixing elements, Together, these act as lever arms, such that even a tiny ρ_{bb} could affect $b \to s\gamma$. We illustrate ρ_{bb} vs ρ_{tt} in the left plot of Fig. 2, where we take $\rho_{ct} = +1$, $m_{H^+} = 700$ GeV, and constrain $\mathscr{B}(B \to X_s\gamma)$ to be within 50% of SM expectation. The "wrong-sign" $C_7^{\rm eff}$ case has been included for comparison. Assuming $C_7^{\rm eff}$ does not change sign, $|\rho_{bb}|$ is constrained to be considerably less than 0.01.

Ref. [3] treated the lepton part of $b \to c\tau\nu$ the same as for 2HDM II, which in our notation means $\rho_{\tau\tau} \sim 1$ also. Since we are concerned with $t \to ch^0$, hence nondecoupling of the light SM Higgs from the exotic Higgs doublet, we need to check against $h^0 \to \tau\tau$ data. Currently, combining CMS and ATLAS, there is some hint for this process. But it certainly is not greatly enhanced, as would be the case if $\rho_{\tau\tau} \sim 1$. For illustration, we take $h^0 \to \tau\tau$ to be within a factor of 2 of SM,

$$|s_{\beta-\alpha} + (\rho_{\tau\tau}v/\sqrt{2}m_\tau)c_{\beta-\alpha}| \lesssim \sqrt{2}. \tag{3.2}$$

and plot in Fig. 2 the range for $\rho_{\tau\tau}$–ρ_{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. [3], 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. (4), then $-0.12 < \rho_{\tau\tau} < 0.02$ would push ρ_{ct} to become very large.

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 ρ_{ct}. We note that further analysis [13] of q^2 ($\tau\nu$ pair mass) dependence of $B \to D\tau\nu$ by BaBar favors New Physics from spin-1 particles. Hence, with great regret, we shall detach from the BaBar anomaly, although it motivated the possibility of $\rho_{ct} \sim 1$. We now focus on probing tch^0 coupling directly at the LHC.

4. $t \to ch^0$ Search at the LHC

It should be stressed that the juicy $t \to ch^0$ entry in the PDG is waiting to be filled. So, how large can $\mathscr{B}(t \to ch^0)$ be? If $\rho_{ct} \sim 1$, what constraint do we have on $\cos(\beta - \alpha)$? A sizable rate could affect top quark measurements. We will skip the argument [7], but using the currently best measured $\sigma_{t\bar{t}}$ in dilepton final states and comparing with NNLO results, one infers that $\mathscr{B}(t \to ch^0)$ cannot be more than a few %, thereby our line of 2% in Fig. 1. We now illustrate that, even a 2% value, because of the large $t\bar{t}$ cross section, the observed ZZ^* events for Higgs discovery could contain "contamination" of $t\bar{t}$ feeddown through $t \to ch^0$ decay! This concept was already explored in Ref. [8] for $h^0 \to WW^*$ case, exploiting a SUSY-based CMS analysis of multileptons with 2011 data. The advantage is it also takes in $h^0 \to ZZ^*$ and $\tau\tau$ events also. A bound of 2.7% was found, but the analysis assumed SM branching fractions, and has no mass resolution.

What has been observed so far at the LHC for h^0 discovery in ZZ^* channel is

$$\sigma_{gg\to h^0} \cdot \frac{\Gamma_{h^0\to ZZ^*}}{\Gamma_{h^0}^{\rm SM}} \cdot \frac{\Gamma_{h^0}^{\rm SM}}{\Gamma_{h^0}} \simeq [\sigma \cdot \mathscr{B}]_{ZZ^*}^{\rm SM}, \tag{4.1}$$

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 15–20 $\ell\ell\ell'\ell'$ signal events consistent with full 2011-2012 data expectations, with little background. However, $\sigma_{t\bar{t}}$ is of order 220 pb at 8 TeV [14]. If one takes $\mathscr{B}_{ch} \simeq 2.7\%$, this amounts to ~ 12 pb into $t\bar{t} \to ch^0bW$, which should be compared with ~ 22 pb for gg-fusion production of a 126 GeV SM Higgs boson! Given the largely inclusive nature of the experimental search, we could have already observed $t \to ch^0$ via the ZZ^* mode, except that each of the three product factors in Eq. (4.1) could deviate from SM. For example, $\sigma_{gg\to h^0}$ may be smaller, or $\Gamma_{h^0} > \Gamma_{h^0}^{\rm SM}$ might dilute direct production.

We can now use Eq. (2.1) to discuss 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 (we are close to decoupling limit), its decay rate into WW^* and ZZ^* is proportional to $\sin^2(\beta-\alpha)$ and can hardly changed. Likewise, the $h^0 \to \gamma\gamma$ rate, dominated by W-loop, is also SM-like. For fermions, the mass generating κ terms are close to SM, while a small $\cos(\beta-\alpha)$ dilutes the effect of ρ-type couplings. The consistency of $h^0 \to \tau\tau$ with SM constrains $\rho_{\tau\tau}$ to be small, while ρ_{bb} is constrained by $b \to s\gamma$ to be tiny if $\rho_{ct} \sim 1$. Further diluted by $\cos(\beta-\alpha)$, the $b\bar{b}$ rate arises from κ_{bb} and is SM-like.

We are left with potential ρ_{cc} and ρ_{tt} effects. The $c\bar{c}$ mode is extremely hard to search for, hence there are no limits so far. With $\cos(\beta-\alpha) \sim 0.2$, $\rho_{cc} \sim 0.2$ [12] would bring $\Gamma_{c\bar{c}} \sim \Gamma_{b\bar{b}} \simeq \Gamma_{b\bar{b}}^{\rm SM}$, and the enhanced Γ_{h^0} would dilute the Higgs signal. This can be partially compensated for by ρ_{tt}, as this parameter should naturally be of order 1 if $\rho_{ct} \sim 1$, since $\kappa_{tt} \simeq 1$ also. With some suppression by $\cos(\beta-\alpha)$, nevertheless it could bring $\sigma_{gg\to h^0}$ up or down by a factor of ~ 2.

We summarize in Table I possible effects of our constrained 2HDM III (with $\rho_{ct} \sim 1$). While $\Gamma_{h^0\to ZZ^*}/\Gamma_{h^0}^{\rm SM}$ is similar to $\mathscr{B}_{ZZ*}^{\rm SM}$, $\sigma_{gg\to h^0}$ could change by a factor of 2 and Γ_{h^0} could be enhanced. We note that for enhanced $\sigma_{gg\to h^0}$, then dilution of $\mathscr{B}_{ZZ^*}$ would be necessary, implying enhanced $h^0 \to c\bar{c}$. However, if $\sigma_{gg\to h^0}$ is suppressed, or $\mathscr{B}_{ZZ*}$ is diluted, then more ZZ^* events may come from $t\bar{t}$ feeddown! We stress that these are the effects of the new parameters ρ_{cc}, ρ_{tt} and ρ_{ct}, and of course the Higgs mixing parameter $\cos(\beta-\alpha)$. It highlights a new sector to be probed at the LHC.

As already mentioned, the CMS and ATLAS search for the ZZ^* model in 4 lepton final state is done inclusively, without looking into any associated activity. Could there be any $t\bar{t} \to ch^0bW$ "contamination"? One should check whether there are some $\ell\ell\ell'\ell' + cbW$ events, with up to 4 jets.

	$\mathscr{B}^{\rm SM}$	$\Gamma^{\rm SM}$	Γ	Comment
WW^*	21.5%	0.98	hard to change	$\sin(\beta-\alpha)\simeq 1$
ZZ^*	2.7%	0.12	hard to change	$\sin(\beta-\alpha)\simeq 1$
$\gamma\gamma$	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 $\sim\Gamma_{b\bar b}$	not measured
				$(\rho_{cc}\lesssim 0.2)$
gg	7.7%	0.35	up to fac. 2	$\rho_{tt}\sim 1$

Table 1: h^0 properties in 2HDM III with $\rho_{ct}\sim 1$. Widths are in MeV units, with $\Gamma^{\rm SM}_{h^0}\simeq 4.55$ MeV.

The CMS preliminary result with full 7 and 8 TeV data [15] 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 $\mathscr{B}(t\to ch^0)$, we assume $\sigma_{gg\to h^0}\cdot\mathscr{B}(h^0\to ZZ^*)$ takes SM value. By inserting the CMS data points, together with the background histograms provided in the same plot [15], and jet multiplicity distribution from top events, an upper limit on the top-Higgs contribution is estimated based on the standard CL$_{\rm s}$ method [16] used at the LHC. The resulting 95% confidence level limit on the relative signal strength between $t\to ch^0$ and inclusive Higgs production is around 31%, which can be converted to a limit of 6.5 pb on the effective cross section of $t\to ch^0$ at 8 TeV, or a branching ratio limit around 1.5%. A genuine analysis is best left to the experiments, as data is already at hand.

Intriguingly, ATLAS does have one $ee\mu\mu+4j$ event! This is an event that in fact passed VBF (vector boson fusion) selection, and is in Fig. 38 (in "extra") of ATLAS-CONF-2013-013 [17]. A question [18] can then be raised that, could some bias creep into even ZZ^*? That is, could there have been some inadvertent cut on jet activity? This highlights the need for a dedicated search. Short of that, we just place the single event in the $4j$ bin of CMS (keeping $3j$ bin empty) and refit with CL$_{\rm s}$. We find that the bound on $\mathscr{B}(t\to ch^0)$ is raised from 1.5% to 2.2%.

Our discussion of the ZZ^* mode highlights the need to broaden our scope for Higgs search. The $t\bar t$ feeddown can in fact make $t\to ch^0$ rather attractive for h^0 decay to:

– WW^*, where the study of Ref. [8] should be performed with full data;

– $b\bar b$, where Ref. [5] demonstrated that one can probe down to $\sim 1\%$;

– $\gamma\gamma$, where mass resolution offers incentive;

– $\tau\tau$.

Let us offer two comments. For $\gamma\gamma$ in the Higgs mass window, one should consider both $\gamma\gamma+4j$ and $\gamma\gamma+jj\ell\nu$. We note that, because of background concerns for the $h^0\to\gamma\gamma$ search period, these type of events may have been rejected by $\Delta\eta$ cuts, or VBF selection when extra jets exist. With b tagging and top mass in the backdrop, we would say that even the study of such background may be interesting. For the WW^* mode, the disadvantage is that one does not have mass reconstruction. However, it is a good search mode, i.e. for setting limits [19], as one can see from Ref. [8] for multilepton study. It clearly can be improved at both CMS and ATLAS.

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5. Conclusion

It is of great interest to search for the link between top and Higgs. With the intense effort of Higgs search in past two years, one can push the bound on $\mathscr{B}(t \to ch^0)$ to below % level in multiple channels. These can be done, with varying levels of difficulty, in the $h^0 \to ZZ^*$, $\gamma\gamma$, WW^* and $b\bar{b}$ channels. A combined study should reach considerably below 1%. It is quite amazing that this should be quickly achieved, compared to the years taken for the $t \to cZ$ study to reach below 10^{-3}.

What is truly attractive is that, if instead one makes a *discovery*, it would imply the existence of not only an extended Higgs sector, but one beyond the usual 2HDM II of minimal SUSY. One would have discovered the new phenomena of Flavor Changing Neutral Higgs, with an enlarged and enriched Higgs sector.

Epilogue. Immediately after the EPS HEP meeting, ATLAS reported [20] at Higgs Hunting 2013 a limit of $\mathscr{B}(t \to ch^0) < 0.83\%$ via the $\gamma\gamma$ channel, while CMS reported [21] at SUSY2013 the limit of $\mathscr{B}(t \to ch^0) < 0.31\%$ via the multilepton channel. This progress is simply astounding.

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[21] Talk by S. Somalwar, SUSY 2013, Trieste.