Probing for Extra Top Yukawa Couplings in Light of $t\bar{t}h^{(125)}$ Observation

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The observation of $t\bar{t}h^{(125)}$ production at the Large Hadron Collider (LHC) is the first direct measurement of the top Yukawa coupling. It opens the window on an extra top Yukawa coupling, $\rho_{t\bar{t}h}$, from a second Higgs doublet, without a $Z_2$ symmetry to forbid flavor changing neutral Higgs couplings. We show that $t\bar{t}h$ and Higgs property measurements at the High Luminosity LHC can constrain the Re $\rho_{t\bar{t}h}$-Im $\rho_{t\bar{t}h}$ parameter space that could drive electroweak baryogenesis, but the $\Gamma_h$ width measurement must be considerably improved beyond current projections.

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Introduction — The CMS and ATLAS experiments announced [1, 2] recently the observation of $pp \rightarrow t\bar{t}h^0$ production at the Large Hadron Collider (LHC), where $h^0$ is the 125 GeV scalar boson discovered not so long ago. The observed production strengths are consistent with the Standard Model (SM) expectation, and constitute the landmark direct detection of the Higgs boson to the top quark, the top Yukawa coupling $\lambda_t$. While indirect evidence have long existed, we now have direct experimental proof that $\lambda_t \approx 1$, as prescribed by $\lambda_t = \sqrt{2m_t/v}$ in the SM, where $v$ is the vacuum expectation value of the Higgs doublet field.

Let us recap the experimental observations. Using 35.9 fb$^{-1}$ data collected in 2016 at 13 TeV collision energy and covering the $h \rightarrow WW^{*}$, $ZZ^{*}$, $\gamma\gamma$, $\tau^{+}\tau^{-}$, and $b\bar{b}$ final states, together with Run 1 data taken at 7 and 8 TeV, CMS [4] observes the relative strength

$$\mu_{t\bar{t}h} = 1.26^{+0.31}_{-0.26}, \quad \text{(Run 2 + Run 1, CMS)}$$

with respect to SM, amounting to 5.2$\sigma$ significance. The expected significance for SM is 4.2$\sigma$. ATLAS had published earlier [2] a Run 2 result based on 36.1 fb$^{-1}$ collected in 2016 and covering the same Higgs decay final states, finding 4.2$\sigma$ evidence. As a contribution to the LHCP conference held recently in Bologna, ATLAS updated the $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ^{*} \rightarrow 4\ell$ modes to a total of 79.8 fb$^{-1}$ data at 13 TeV. Together with the other 3 modes based on 36.1 fb$^{-1}$, ATLAS observes [2]

$$\mu_{t\bar{t}h} = 1.32^{+0.28}_{-0.26}, \quad \text{(Run 2 Update, ATLAS)}$$

at 5.8$\sigma$ significance (4.9$\sigma$), while combining further with Run 1 data, the significance becomes 6.3$\sigma$ (5.1$\sigma$). We have put the SM expectation in parenthesis.

Thus, both ATLAS and CMS have observed $t\bar{t}h$ production. We note that both experiments had earlier hints for $t\bar{t}h$ production with strength stronger than SM, which improve the combined significance quoted above.

Since Yukawa couplings are the source of $CP$ violation (CPV) in SM, with direct measurement of top Yukawa coupling attained, it opens up the question whether there are additional Yukawa couplings. As there is nothing against the existence of a second doublet, the two Higgs doublet model (2HDM) is in fact one of the most plausible beyond-SM (BSM) possibilities, where one should “naturally” have a second set of Yukawa couplings. However, due to the perceived curse of flavor changing neutral Higgs (FCNH) couplings, Glashow and Weinberg famously eliminated all such extra couplings by demanding “natural” flavor conservation (NFC) [3]: each type of fermion charge receives mass from a separate doublet, has been the most popular, as it arises with supersymmetry.

A decade after the Glashow-Weinberg NFC condition, the emerging quark mass-mixing hierarchy led to the critique [3] that NFC may be overkill. As the top quark is the heaviest fermion, the best probe may be $t \rightarrow c + h$ [6] for FCNH $tch$ coupling. With the observation of $h^{(125)}$ in 2012, it was stressed [7] that the 2 $\times$ 2 extra Yukawa couplings $\rho_{cc}$, $\rho_{ct}$, $\rho_{tc}$, and $\rho_{tt}$ of the exotic doublet should be taken seriously, and the issue is experimental: we have to demonstrate their nonexistence, rather than assume NFC and throw them away.

The $tch$ coupling in 2HDM without NFC is

$$\mathcal{L}_{tch} = -\frac{1}{\sqrt{2}}\tilde{L}_L(-\lambda_t \sin\gamma + \rho_{t\bar{t}h} \cos\gamma) t_R h + h.c.,$$

while the $tch$ coupling is $(\rho_{ct})$ is already constrained by flavor physics to be small [2, 6].

$$\mathcal{L}_{tch} = -\frac{1}{\sqrt{2}}\rho_{t\bar{t}h} \cos\gamma \tilde{L}_L c_R h,$$

where $\cos^2\gamma \ll 1$ is the alignment phenomenon observed at the LHC [6], the fact that the observed $h$ boson is rather close to the SM Higgs boson. In 2HDM-II, the mixing angle of the two CP-even scalars, $\cos\gamma$, is usually expressed as $\cos(\alpha - \beta)$, but without the NFC condition, or the $Z_2$ symmetry to implement it, $\tan\beta$ is
unphysical, hence we use the different notation \[11\]. It was recently noted that \(\lambda_i \Im \rho_{tt} \) can easily drive \[12\] the baryon asymmetry of our Universe (BAU), which needs \(O(1)\) Higgs quartic couplings of the 2HDM for the first order electroweak phase transition. The latter can relatively easily accommodate \[11\] the observed approximate alignment phenomenon. These add to the attraction of 2HDM without the NFC condition.

So far, the \(t \to ch\) decay has not been observed, with limits approaching \(10^{-3}\) \[13\]. We assume it is suppressed by \(\rho_{tc}\), but take the maximum \(\cos \gamma\) value allowed by data. The point is, even if the admixture of \(\rho_{tt}\) into the \(tt\) coupling is suppressed by approximate alignment, i.e. \(\cos \gamma\), interference with the leading SM \(\lambda_t\) effect provides a sensitive probe in \(tt\) production. In the following, we illustrate the new, direct probe of \(\rho_{tt}\) with central values as marked, allowing 5% and 10% uncertainties. We have taken \(\cos \gamma = 0.3\) and \(\sin \gamma < 0\).

\[\begin{align*}
\mu_{ggF} &\equiv \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\text{SM}}} \\
&\simeq (1.05 - 0.08i) [-\sin \gamma + \cos \gamma \Re(\rho_{tt})/\lambda_t] \\
&\quad - 0.05 + 0.08i)^2 + 2.57[\cos \gamma \Im(\rho_{tt})/\lambda_t]^2.
\end{align*}\] (5)

through triangle loop diagram, where the absorptive, i.e. explicit \(i\) terms arise from light quark loops. The \((\Re \rho_{tt})^2\) effect is suppressed by \((\cos \gamma)^2\), or alignment, where we shall take the value of \(\cos \gamma = 0.3\) (corresponding to \(-\sin \gamma = 0.954\)) that may still be allowed by data \[8\]. Of interest is the \(\sin \gamma \cos \gamma\) interference term between the SM and extra Yukawa coupling, which allows better sensitivity to \(\Re \rho_{tt}\). Although the \((\Im \rho_{tt})^2\) term is also suppressed by \((\cos \gamma)^2\), but because the imaginary part of the extra Yukawa coupling leads to a \(\gamma_5\) coupling, the term receives a numerical factor of order 2.6 (see e.g. Ref. \[16\] for discussion of pseudoscalar coupling), making \(gg \to h\) sensitive to larger values of \((\Im \rho_{tt})^2\).

The \(h \to WW^*, ZZ^*\) rates are modified by the overall factor \(\sin^2 \gamma\) from the SM ones. As for \(h \to \gamma\gamma\) decay, which also arises from triangle loop, the rate is only mildly affected \[14, 15\] by \(\cos \gamma \rho_{tt}\)

\[\mu_{\gamma \gamma} \equiv \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} \simeq -(1.27 + 0.01i) \sin \gamma \\
- 0.28[-\sin \gamma + \cos \gamma \Re(\rho_{tt})/\lambda_t] + 0.01 - 0.01i)^2 \\
+ 0.18[\cos \gamma \Im(\rho_{tt})/\lambda_t]^2,\] (6)

because of \(W\) boson dominance in the loop.

Using the Run 1 combination of ATLAS and CMS results \[10\], constraints on real and imaginary parts of \(\rho_{tt}\) for \(\cos \gamma = 0.3\) with \(\sin \gamma < 0\) are shown in Fig. \[1\]. We use the ten-parameter fit to the three decay channels \(h \to \gamma\gamma, ZZ^*, WW^*\) with \(ggF+ttH\) or \(VBF+VH\) production, and individual \(2\sigma\) constraints from the six signal strengths are overlaid, resulting in the gray shaded regions. The right-hand side (r.h.s.) comes from the \(h \to WW^*\) decay mode, while l.h.s. comes from \(h \to ZZ^*\). The actual sensitivity to \(\Re \rho_{tt}\) and \(\Im \rho_{tt}\) is mainly driven by \(gg \to h\) production.

For the direct probe of \(tt\) coupling, we calculate the \(pp \to t\bar{t}h\) cross section at leading order (LO) by Monte Carlo event generator MadGraph5 aMC@NLO \[17\] with the parton distribution function set NN23LO1 \[18\]. In particular, we use the Higgs Characterisation model \[19\]
implemented in FeynRules 2.0 [20] framework, where model details can be found in Ref. [21]. We ignored contributions other than from $tth$ coupling. The signal strength for 13 TeV LHC can be approximated by

$$\mu_{tth} \approx \left( -\sin \gamma + \cos \gamma \Re(\rho_{t})/\lambda t \right)^2 + 0.45 [\cos \gamma \Im(\rho_{t})/\lambda t]^2, \quad (13 \text{ TeV})$$ (7)

with mild modification of the 0.45 coefficient to 0.46 for 14 TeV LHC. Thus, the $(\Re \rho_{t})^2$ and $(\Im \rho_{t})^2$ terms are suppressed by $|\cos \gamma|^2$, but the $\sin \gamma \cos \gamma$ interference term brings in better sensitivity to $\Re \rho_{t}$. We take the ATLAS Run 2 update of $\mu_{tth}$, Eq. (2), and display the $2\sigma$ allowed range in Fig. [left] as marked. Because of the mild excess, a positive $\Re \rho_{t}$ is preferred, but partially excluded by the indirect data. However, a broad range of $|\Im \rho_{t}|$ is allowed, extending beyond 1 if the $\Re \rho_{t}$ interference effect is destructive.

Thus, current data between indirect and direct probes of $\rho_{t}$ are quite consistent with electroweak baryogenesis [12] by 2HDM without NFC.

It is of interest, therefore, to project the reach for HL-LHC. This is shown as the blue and red lines in Fig. [right] for $\mu_{tth} = 0.81, 1.32$, corresponding to $-2\sigma$ and central value in Eq. (2), respectively. Considering the trend in measurements of $\mu_{tth}$, we do not display the $+2\sigma$ case. On the other hand, we take an optimistic 5% as the 1$\sigma$ uncertainty reach for ultimate HL-LHC sensitivity, based on current projections [22], and anticipating a combination of ATLAS and CMS data. However, we have left the indirect probes, the shaded region, unchanged from the Run 1 ATLAS-CMS combination, as it is rather hard to estimate the HL-LHC sensitivity reach. Although Run 2 analyses are available from ATLAS and CMS, the results so far [23] suggest correlations between the values of ggF (gluon-gluon fusion) and VBF (vector boson fusion) production, and in any case the two datasets are not yet combined. A full Run 2 combination is probably a couple of years away. We also note that, as data increases, separate production/decay channels would likely be disentangled.

But one can visualize a narrower “allowed white crescent” from the indirect measurements. Depending on the overlap with the $\mu_{tth}$ band, the allowed region could be a specific $\Re \rho_{t}$ with restricted $\Im \rho_{t}$ range, or more interestingly, a preference for relatively large values of $\Im \rho_{t}$. Either way, without probing CPV directly, this would provide insight on the origin of BAU.

**Simplified Effect of Light Fermions.**— But there is a catch. Analogous to Eq. (3), the 2HDM without NFC brings in extra Yukawa couplings that modify $hbb$, $h\tau\tau$ and $hcc$ couplings. While they give minor modifications to $gg \to h$ and $h \to \gamma\gamma$, the major impact is on the total $h$ width, $\Gamma_{h}$, which is not well measured yet.

As individual processes are also not yet well measured, rather than several couplings, we treat the partial width of $h \to$ light fermions as the single overall effect,

$$\frac{\Gamma_{all \, ff}}{\Gamma_{SM \, all \, ff}} = \frac{\Gamma_{bb} + \Gamma_{\tau\tau} + \Gamma_{cc} + \cdots}{\Gamma_{SM \, bb} + \Gamma_{SM \, \tau\tau} + \Gamma_{SM \, cc} + \cdots}$$ (8)

Taking branching ratio values [24] for $m_h = 125.09$ GeV, the total width is modified as

$$\frac{\Gamma_{h}}{\Gamma_{SM \, h}} \approx 0.67 \frac{\Gamma_{all \, ff}}{\Gamma_{SM \, all \, ff}} + 0.24 \sin^2 \gamma + 0.08 \mu_{ggF}.$$ (9)

Similar to Fig. [right], we display the effect of $\Gamma_{all \, ff} = 0.5 (1.5)\Gamma_{SM \, all \, ff}$ in Fig. [left] ([right]), where the “allowed white crescent” is moved leftward (rightward). We remark that 2HDM without NFC can relatively easily lead to $\Gamma_{h}$ that is narrower than in SM. We note in passing that the constraint on r.h.s. of Fig. [right] now arises from VBF production with $h \to WW^*$ decay. The $\mu_{tth} \sim 0.81$ band in Fig. [left] illustrates the situation where $\Re \rho_{t}$ is slightly negative, with $|\Im \rho_{t}|$ up to 1 fully allowed, while the $\mu_{tth} \sim 1.32$ band illustrates...
a tension between indirect and direct probes of \( \rho_t \). The \( \mu_{\text{th}} \sim 0.81 \) band in Fig. 2 (right) illustrates the situation where large \( \text{Im} \rho_t \) is indicated, while the \( \mu_{\text{th}} \sim 1.32 \) band illustrates constructive interference, but a broad range of \( \text{Im} \rho_t \) is allowed.

However, since the “white crescent” would become narrower with HL-LHC data, what Fig. 2 really shows is that a good measurement of \( \Gamma_h \) is needed. With current projections at 50% of \( \Gamma_h^{\text{SM}} \) for HL-LHC, we can only hope that \( \delta \Gamma_h \) can be much improved with actual data, otherwise we would not really know what is the overlap region, as 2HDM without NFC would shift all diagonal Yukawa couplings, in principle by same order as the corresponding SM Yukawa coupling, modulated by \( \cos \gamma \). More precise measurements of \( \mu_e \), \( \mu_{\tau \tau} \) and especially \( \mu_b \) may help. Another approach, for example, is VBF production followed by \( h \to VV^* \), which could probe \( \Gamma_h \) through branching ratio measurement, as the \( VV^* \) couplings are not much affected by \( \cos \gamma \rho_t \).

Discussion and Conclusion.— We stress that 2HDM without NFC offer new Yukawa couplings that could alter all \( fjh \) couplings from SM values, modulated by \( \cos \gamma \). This makes clear the importance of a complete program to measure \( \mu_{\text{th}}, \mu_{\tau \tau}, \mu_{\mu \mu} \), and even \( \mu_e \) if charm tagging could be vastly improved.

A second point to note is that each one of these diagonal Yukawa coupling corrections are generally complex. For example, \( \text{Im} (\rho_t) \) contributes to the electron EDM through two-loop contributions. Under the assumption that the electron Yukawa coupling is SM-like (\( \rho_{ee} = 0 \)) and heavy scalar contributions are negligible, the recent ACME result \([22]\) would imply \( \left| \cos \gamma \text{Im} (\rho_t)/\lambda_t \right| < 0.01 \) \([12, 14]\). However, allowing for a complex, in particular imaginary, \( \rho_{ee} \) with strength similar to \( \lambda_e \) of SM, it can in principle induce cancellation \([12, 14]\) of the two-loop effect. We had tacitly assumed this in exploring \( tth \), and illustrates how the 2HDM without NFC could affect flavor physics. Note that, given that \( \lambda_i \cong 1 \) is already known, the dominant eigenvalue of the other combination of the two \( u \)-type Yukawa matrices, viz. \( \rho_{tt} \), is likely \( \mathcal{O}(\lambda_t) \) hence \( \mathcal{O}(1) \), and with phase arbitrary. Similar argument would hold for \( \rho_{bb} \) and \( \rho_{\tau \tau} \).

In contrast to usual effective Lagrangian discussions, the interaction terms reflected in Eqs. \([3, 4]\) are as fundamental as the Yukawa couplings in SM. On one hand, they are well hidden by approximate alignment, or the smallness of \( \cos \gamma \). Thus, the direct \( pp \to tth \) and other indirect probes would rapidly weaken for smaller \( \cos \gamma \). Furthermore, as outlined in Ref. \([11]\), the mass-mixing hierarchy, or some flavor-organization principle, could control FCNH involving lighter generations, and together with approximate alignment, can fully replace the NFC condition to explain the absence of low energy FCNH effects. But alignment need not \([11]\) imply decoupling, and the exotic Higgs sector could well be sub-TeV in mass. If alignment is effective, one would have to probe this exotic Higgs sector, for example via \( cg \to tH^0, tA^0 \) production, leading to novel \( tt\bar{c} \) (same-sign top) and \( tt\bar{t} \) (triple top) signatures \([25]\) at the LHC.

With the hope that alignment does not work too well, i.e. \( \cos \gamma \) is not overly small, what is the future outlook? First, \( \cos \gamma \) should be studied more generally, free of the \( Z_2 \) symmetry mindset (i.e. beyond Ref. \([9]\)). A measurement of, rather than constraint on, \( \cos \gamma \) would be astounding. Second, improved projections for HL-LHC is expected with a CERN Yellow Report that is under preparation for the European Particle Physics Strategy Update. But the projections must be continuously updated as experience is gained with larger datasets, including on \( \Gamma_h \) measurement. Third, we are at the juncture of ILC(250) \([29]\) or CLIC(380) \([30]\) decision. Although these machines are still far away, they provide great hope for much more precision in Higgs property measurements, which would provide better indirect constraints, including on \( \delta \Gamma_h \). However, \( tth \) production would require at least 500 GeV \( e^+e^- \) collision energy.

Thus, the high energy extension of LHC looks more promising for the nearer future on direct \( tth \) probe. There is no doubt that a 100 TeV machine \([31]\), though much farther away, would advance the \( tth \) and exotic Higgs frontiers by great stride. If the alignment phenomenon reflects \([11]\) \( O(1) \) Higgs quartic couplings within 2HDM, there is likely another layer of BSM physics at the 10 TeV scale to be explored. Finally, we have advocated simple probes of just measuring rates. More sophisticated angular or asymmetry analyses \([32]\) can probe the CPV nature of the \( tth \) coupling directly.

In conclusion, the observation of \( pp \to tth^0 \) at LHC is the first direct measurement of the top Yukawa coupling, and offers a window on the extra Yukawa coupling \( \rho_t \) from a second Higgs doublet where the NFC condition is not imposed. The large \( \lambda_i \cong 1 \) of SM provides the lever arm to probe \( \cos \gamma \rho_t \) through interference, where \( \cos \gamma \) is the \( CP \)-even Higgs mixing angle. The parameter space for electroweak baryogenesis offered by this 2HDM can be probed by \( CP \)-conserving \( tth^0 \) production rate and Higgs property measurements. The Achilles heel for this program at the HL-LHC is the knowledge of the \( h^0 \) width, \( \Gamma_{h^0} \), and ATLAS and CMS should put a premium on its improved measurement.

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