GENUINE EXTRA YUKAWAS FROM EXTRA HIGGS, IMPLICATIONS

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With a second Higgs doublet, extra Yukawa couplings ρij generally exist. Baryon Asymmetry of the Universe (BAU) can be accounted for by ρtt ∼ O(1), with first order electroweak phase transition (EWPT) arising from O(1) Higgs quartic couplings. The latter can explain why the observed h(125) boson so resembles the Standard Model (SM) Higgs: with coupling η6 ∼ O(1) for two-doublet mixing, the H–h mixing angle cos γ ∼ −η6v2/(m2H − m2h) is suppressed by the CP-even boson mass splitting m2H − m2h > few v2. The approximate alignment, together with the fermion mass-mixing pattern, controls FCNC Higgs effects at low energy. The picture can be probed by pp → tt, tt, i.e. same-sign top and triple-top processes at the LHC.

1 Introduction: Whither Extra Yukawas?

Though accounting for all observed CP violation (CPV), the unique phase in CKM matrix falls far short of BAU. Considering the origin of this phase, could there be extra Yukawa couplings? In general, a second Higgs doublet (2HDM) — quite plausible — should imply extra Yukawas, but these were killed by the Natural Flavor Conservation (NFC) condition: as u- and d-type quark masses each arise from a single doublet, the Yukawa couplings are basically the same as in SM. It was later noted that the fermion mass-mixing pattern could soften the need for NFC, and the best probe may be t → ch or h → tc, as the top quark is the heaviest fermion.

With the case for 2HDM elevated by the discovery of 125 GeV boson in 2012, we emphasized the need to probe the 2 × 2 extra Yukawa couplings ρij (i, j = c, t). It also became understood that the flavor changing neutral Higgs (FCNH) couplings of the form

ρtc cos(β − α) tLcRh,

are modulated by H–h mixing, where H is the second CP-even Higgs boson. The two doublets Φ1 and Φ2 give rise to Yukawa matrices Y1 and Y2. The combination YSM = Y1v1 + Y2v2 is diagonalized as usual, but the orthogonal combination gives rise to Yukawa matrix ρ that cannot be simultaneous diagonalized. In the limit that cos(β − α) is small, called alignment limit, couplings of h are diagonal, just as the SM Higgs, while H couples with the Yukawa matrix ρ. As Yukawa couplings, ρij should be complex,

ρij ≡ |ρij|eibij.

In place of NFC, we see that alignment (cos(β − α) → 0) removes FCNH couplings for h, while the mass-mixing pattern, shared by Y1,2, further suppresses ρij involving light(er) quarks.

2 Bonus 1: EWBG from Extra Top Yukawa ρtt

Given that YSM for u-type quarks is dominated by Yukawa coupling λt ∼ 1, together with the observed quark mass-mixing pattern, it is rather plausible that the orthogonal combination to
$Y_{SB}$ should also have a dominant $O(1)$ eigenvalue, with phase arbitrary. This motivates us\(^5\) to consider its possible role in baryogenesis. It is known that\(^6\) thermal loops involving extra Higgs bosons with $O(1)$ Higgs quartic couplings can give rise to 1st order EWPT. It is of interest to explore whether $\text{Im} \rho_{tt}$ could then lead to electroweak baryogenesis (EWBG).

The main issue is to generate sufficient $Y_B \equiv n_B/s$ (ratio of baryon and entropy densities) at the observed level of $Y_B^{\text{obs}} \sim 0.86 \times 10^{-10}$ or higher. Putting aside the complicated transport problem,\(^5\) which requires an actual 1st order EWPT, this boils down to producing enough left-handed top density at the expanding bubble wall of broken phase that accumulates inside the bubble, i.e. our Universe. This depends on CPV top interactions at the bubble wall, which boils down further to the CPV source term that arises from the extra top Yukawas,\(^5\)

$$\text{Im}[(Y_1)_{ij}(Y_2)^*_{ij}] = \text{Im}[(V_L^u V_{\text{diag}}^u V_R^u)^*_{ij}(V_L^u \rho V_{\text{diag}}^u V_R^u)^*_{ij}],$$

where $V_L^u, V_R^u$ forms the biunitary transform that diagonalizes $Y_{SB}$ to $Y_{\text{diag}}$ for $u$-type quarks.

Flavor constraints from $B_d$ and $B_s$ mixing and chiral enhancement in $b \to s \gamma$ demand\(^5,7\) $\rho_{ct}$ to be rather small, while $\rho_{cc} \sim O(\lambda_c)$ $\ll 1$ without fine tuning, hence the two main parameters are $\rho_{tt}$ and $\rho_{ct}$. Scanning over $|\rho_{ct}|$, $\phi_{tt}$ and $\phi_{ct}$, we find robust and large parameter space for EWBG. Fig. 1[left] plots $Y_B/Y_B^{\text{obs}}$ vs $|\rho_{tt}| \in (0.01, 1)$, with higher $0.5 \leq |\rho_{ct}| \leq 1.0$ (lower $0.1 \leq |\rho_{ct}| \leq 0.5$) plotted as green + (purple -). Little difference is seen between the two plots, hence $\rho_{tt}$ is the driver. However, for $|\rho_{tt}| < 0.05$ or so, the green +'s that populate $Y_B/Y_B^{\text{obs}} > 1$ suggest $\rho_{ct} > 0.5$, with phase $\phi_{ct}$ near maximal, could be a backup to $\rho_{tt}$ for EWBG. In making this plot, the simplifying assumption of $m_H = m_A = m_{H^+} = 500$ GeV is taken. Much higher values would either run into issues of perturbativity, or damping by decoupling.

Fig. 1[left] scanned through realistic Yukawa matrices, but a simplified texture can help elucidate the driving effect. Suppose $(Y_1)_{tc} \neq 0, (Y_2)_{tc} \neq 0$ and $(Y_1)_{tt} = (Y_2)_{tt} \neq 0$, while all other extra Yukawas vanish, i.e. altogether 3 complex parameters. If one assumes $\sqrt{2}Y_{SB}$ is the linear sum of $Y_1$ and $Y_2$, one can solve for $V_{L/R}^u$, while there is no need for $V_{L/R}^d$. One can then arrive at the combination of $Y_1$ and $Y_2$ that is orthogonal to $Y_{SB}$. In this way, one finds\(^5\)

$$\text{Im}[(Y_1)_{tc}(Y_2)^*_{tc}] = -\lambda_t \text{Im} \rho_{tt}, \quad \rho_{ct} = 0,$$

with $\rho_{ct}$ remaining basically a free parameter. We see from Eq. (4) that both doublets participate in the CPV source for EWBG in 2HDM, which is reminiscent to the Jarlskog invariant for SM. We can also see how 2HDM with extra Yukawas overcomes the suppression factors in the Jarlskog invariant, given that $\lambda_t, |\text{Im} \rho_{tt}|$ are both $O(1)$.
3 Bonus 2: Alignment from $O(1)$ Higgs Quartics

It is remarkable that the extra Yukawa coupling $\rho_\ell$ could account for BAU!

Note that such mechanism does not exist in 2HDM-I or 2HDM-II, the 2HDMs that satisfy NFC, since NFC means there are essentially no new Yukawa couplings, despite having a second Higgs doublet. We now show that the prerequisite for 1st order EWPT, that extra Higgs quartic couplings are $O(1)$, could be behind the observed approximate alignment.

The general CP-conserving Higgs potential of 2HDM is,

$$V(\Phi, \Phi^\dagger) = \mu_1^2|\Phi|^2 + \mu_2^2|\Phi|^2 - \left(\mu_3^2\Phi^\dagger\Phi + \text{h.c.}\right) + \frac{1}{2}\eta_1|\Phi|^4 + \frac{1}{2}\eta_2|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2 + \eta_4|\Phi|^2|\Phi'|^2 + \eta_5|\Phi|^2|\Phi'|^2 + \text{h.c.}$$

where we take Higgs basis, i.e. $\mu_1^2 < 0$ but $\mu_2^2 > 0$. With the two minimization conditions

$$\mu_1^2 = -\frac{1}{2}\eta_1v^2, \quad \mu_2^2 = \frac{1}{2}\eta_6v^2,$$

$\mu_1^2 < 0$ is exchanged for $v$, the usual “soft breaking parameter” $\mu_2^2$ is removed, and the quartic coupling $\eta_6$ is solely responsible for $\Phi - \Phi^\dagger$ mixing. The CP-even Higgs mass matrix

$$M_{\text{even}}^2 = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & \mu_2^2 + \frac{1}{2}(\eta_3 + \eta_4 + \eta_5)v^2 \end{bmatrix}, \quad R_\gamma = \begin{bmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{bmatrix},$$

is diagonalized by $R_\gamma$, i.e. $R_\gamma^T M_{\text{even}}^2 R_\gamma$ is diagonal with elements $m_H^2, m_h^2$. In Eq. (7), our $c_\gamma \equiv \cos \gamma$ corresponds to $\cos(\beta - \alpha)$ in the 2HDM-II notation, and is the relative angle (mod. $\pi/2$) between the Higgs basis and the neutral Higgs mass basis.

Rather than give the formula for $m_H^2$, we note the mixing angle $c_\gamma$ satisfies two relations,

$$c_\gamma^2 = \frac{\eta_1 v^2 - m_H^2}{m_H^2 - m_h^2}, \quad \sin 2\gamma = \frac{2\eta_6 v^2}{m_H^2 - m_h^2}.$$  

In alignment limit of $c_\gamma \to 0$, $s_\gamma \to -1$, one has $\eta_1 \to m_H^2/v^2 \approx 0.26$ in numerator of first term, where $m_H \approx 125$ GeV is used. For $c_\gamma$ small but nonvanishing, $m_H^2 - m_h^2 >$ several $v^2$ can weigh down $|\eta_1 v^2 - m_H^2| < v^2$. Since $s_\gamma \to -1$ holds better than $c_\gamma \to 0$, the second relation gives

$$c_\gamma \approx \frac{-\eta_6 v^2}{m_H^2 - m_h^2}.$$ (near alignment)  

Although the result exists in the literature, $|\eta_6| \ll 1$ is generally assumed, as it arises through loop effects in MSSM. But we see that $c_\gamma$ can be small for

$$|\eta_6| \sim O(1) \text{ (or smaller)}, \quad m_H^2 - m_h^2 > \text{several} \ v^2.$$ (10)

Note that a low $m_H^2/v^2 \approx 0.26$ is not required, i.e. $c_\gamma$ can be small even if $m_H \sim 300$ GeV.

What drives alignment in 2HDM? For $\eta_1, \eta_3, \eta_5, \mu_2^2/v^2 \sim O(1)$, $[M_{\text{even}}^2]_{11}$ has four $O(v^2)$ terms while $[M_{\text{even}}^2]_{11}$ has only one, hence $m_H^2 - m_h^2 >$ several $v^2$ is likely. However, $\mu_2^2/v^2 > 1$ would damp the 1st order EWPT, hence sub-TeV exotic Higgs masses are preferred. Second, $\eta_6 \sim O(1)$ increases $m_H^2 - m_h^2$ by level repulsion, pushing $m_h^2/v^2$ down from $\eta_1 \sim O(1)$. Finally, tuning $\eta_6 < 1/4 \sim m_h^2/v^2$ would give extreme alignment ($c_\gamma \to 0$) hence $\eta_1 \to 0.26$. These observations are illustrated in Fig. 1[right] for allowed $\eta_1$ vs $\eta_6$ range, where custodial SU(2) is assumed to evade $\Delta T$ constraint, i.e. $m_A^2 = m_{H^+}^2 = \mu_2^2 + \eta_3 v^2/2$. We vary $\eta_4 = \eta_6 \in (0.5, 2)$, so $m_H$ could be up to 100 GeV higher. High values of $\eta_4$ are cut off by $\Delta T$ (via scalar–vector loop), and the two dashed lines mark $c_\gamma = 0.1$ and 0.2, which are quite close to alignment; even $c_\gamma = 0.3$, close to the bound from $\Delta T$, is still allowed by observed approximate alignment at LHC.
O(1) Higgs quartics could be behind approximate alignment, or small $c_{\gamma}$, regardless of whether a $Z_2$ symmetry is used to enforce NFC or not, as our discussion is general. But we have advocated that $\rho_{tt} \sim O(1)$ could explain BAU. It is then intriguing to comment that sizable $\rho_{tt}$ could possibly help “protect” alignment: with O(1) Higgs quartics, bosonic loops would reduce $\Gamma_{h \rightarrow ZZ^*}$, but the top loop can bring $\Gamma_{h \rightarrow ZZ^*}$ back to SM value for $\rho_{tt} c_{\gamma} > 0$, consistent with what is observed. This was our original motivation to understand the mechanism of alignment.

4 Same-sign Top and Triple-top Signatures: $pp \rightarrow tH/A \rightarrow tt\bar{c}, tt\bar{t}$

The process $cg \rightarrow tA$ was suggested long time ago as a direct probe of the $ctA$ FCNH coupling, restricting to $m_A < 2m_t$ such that $A \rightarrow t\bar{c}$ (and $t\bar{c}$) is at 100%. We recently studied the $cg \rightarrow tH/A$ associated production through the $\rho_{tc}$ coupling, followed by subsequent decay $H/A \rightarrow t\bar{c}, t\bar{c}$ and $t\bar{t}$ final states involving $\rho_{tc}$ and $\rho_{tt}$ couplings, advocating the signatures of same-sign top, $tt\bar{c}$, and triple-top, $tt\bar{t}$. The same-sign top signature involves same-sign dileptons, together with two $b$-jets, missing energy, and additional jets. We find that, for $\rho_{tc} \sim 1$, the second case for EWBG can be probed with 300 fb$^{-1}$, but signature does not improve for higher luminosity, unless background can be further controlled. Given that $\rho_{tt}$ is the favored driver for EWBG, triple-top search at HL-LHC may be more interesting, and possesses more exquisite signatures: three leptons, three $b$-jets, missing energy. The backdrop of SM cross section at only fb level makes the case strong, where full HL-LHC data can cover up to 700 GeV mass range for $\rho_{tt} \sim 1$, but $\rho_{tc}$ needs to be not much smaller than 0.5 for signal cross section.

5 Conclusion: $H^0$, $A^0$, $H^\pm$ in Our Time

With O(1) Higgs quartics for 1st order EWPT, the extra Yukawa $\rho_{tt}$ (or $\rho_{tc}$) $\sim O(1)$ in general 2HDM is remarkably efficient for EWBG. The O(1) Higgs quartics support approximate alignment, and together with quark mass-mixing hierarchy control low energy FCNH effect, without need for NFC. Having $H$, $A$ and $H^\pm$ sub-TeV in mass would be a boon to LHC search, the discovery of which in $tt\bar{c}$, $tt\bar{t}$ final states would touch upon Matter Asymmetry of the Universe.

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