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Top-Higgs Associated Production involving A^0, H^0 with Mass at 300 GeV

George W.-S. Hou[*] [†]
National Taiwan University[‡]
E-mail: wshou@phys.ntu.edu.tw

We advocate two Higgs doublet model without Z_2 symmetry, and focus on the extra top Yukawa couplings ρ_{tt} and ρ_{tc}. We show that A^0 and H^0 bosons are still allowed at 300 GeV mass, where $cg \to tA^0$, tH^0 can lead to $tt\bar{c}$ same-sign top, or top-assisted di-Higgs th^0h^0 signatures, resp. As bonus material, we explore the constraint provided by current 4-top search, but advocate direct search for triple-top generated by $cg \to tH^0/A^0 \to tt\bar{t}$ for H^0, A^0 above $t\bar{t}$ threshold, and offer some insight on the mild but intriguing "excess" found by CMS in $gg \to A^0 \to t\bar{t}$ at 400 GeV.

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[*] Speaker.
[†] Work done in collaboration with Masaya Kohda and Tanmoy Modak.
[‡] Home institute.

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1. Introduction: 2HDM without Z_2

In 1977, Glashow and Weinberg gave [1] the "edict" of Natural Flavor Conservation (NFC): only one Yukawa matrix per mass matrix for two Higgs doublets. This eliminated the worries of Flavor Changing Neutral Higgs (FCNH) couplings. It arises automatically in supersymmetry, where one doublet couples to u-type quarks, the other couples to d-type quarks, which is two Higgs doublet model (2HDM), type II, usually implemented by a Z_2 symmetry.

Citing the Cheng-Sher pattern [2] of $\sqrt{m_i m_j}$ to control FCNH couplings, we pointed out [3] that $t \to ch^0$ or $h^0 \to t\bar{c}$, where h^0 is the lightest neutral scalar, are the best probes for such couplings. The paper also stressed that the Cheng-Sher pattern reflects the emergent fermion mass and mixing hierarchies, and called it Model III to distinguish from usual 2HDM I & II that invoke Z_2 symmetry. With observation of $h(125)$ in 2012, a second doublet is now highly plausible, and it is imperative that we undertake experimental search. Thinking back [4] towards the 1991 proposal for $t \to ch$ search, the ansatz of $\sqrt{m_i m_j}$ is seen as a "scaffold", and one should take the 2×2 Yukawa matrix of the top-charm sector seriously. For the four parameters, ρ_{ct} is constrained by flavor physics to be rather small [5], and ρ_{cc} should not be much larger than $\lambda_{cc} = \sqrt{2}m_c/v < 0.01$, where $v = 246$ GeV. The two remaining extra Yukawa couplings ρ_{tc} and ρ_{tt} can be $\mathcal{O}(1)$, where ρ_{tc} can induce $t \to ch^0$ decay, but modulated by the h^0–H^0 mixing angle $\cos(\beta-\alpha)$. From here we see that FCNH couplings for h^0 can be suppressed by h^0–H^0 mixing.

With emergent "alignment", that $\cos(\beta-\alpha)$ (called $\cos\gamma$ from now on) appears to be rather small because h^0 is rather close to the SM Higgs boson, we understand the non-observation so far of the $t \to ch^0$, $t \to uh^0$ and $h^0 \to \mu\tau$ decays are manifestations of alignment. A discussion synthesizing mass-mixing hierarchy and approximate alignment as replacement of NFC can be found in Ref. [6]. We shall refer to 2HDM without Z_2, i.e. with extra Yukawas, as g2HDM.

In our previous EPS-HEP proceedings [7], we emphasized that the extra Yukawa couplings ρ_{tt} and ρ_{tc}, naturally $\mathcal{O}(1)$ and complex, could drive [8] electroweak baryogenesis (EWBG). The ρ_{tt} coupling is the robust driver, but if it is less than a few %, then an $\mathcal{O}(1)$ ρ_{tc} with near maximal phase can be a backup option. The present report arose from our invited talk [9] at Moriond QCD 2018, where we used a diagram from our 1997 study of $cg \to tA^0$ [10] that gives same-sign top signature. Expecting this lighter A^0 case to be ruled out by LHC data, to our surprise, we found [11] the answer in the negative: an A^0 as light as 300 GeV is still viable! Replacing A^0 by H^0, the *CP* even exotic scalar, we explore the viable parameter space for top-assisted di-Higgs production [12] via $cg \to tH^0 \to th^0h^0$. As bonus material, we further discuss [13] the 4-top search constraint on triple-top, and mention an "excess" at 400 GeV [14] in scalar $t\bar{t}$ resonance search by CMS.

2. $cg \to tA^0 \to tt\bar{c}$: allowed for $m_{A^0} \sim 300$ GeV

Without a Z_2 symmetry, the coupling of A^0 to fermions is (no $\cos\gamma$ suppression)

$$\frac{i}{\sqrt{2}} \sum_{F=u,d,e} \mathrm{sgn}(Q_F)\rho^F_{ij}\bar{F}_{iL}F_{jR}A^0 + \mathrm{h.c.}, \tag{2.1}$$

where $i, j = 1,2,3$ are generation indices, $\mathrm{sgn}(Q_F) = +1$ (-1) for $F = u$ $(F = d, e)$, and ρ^F are 3×3 complex matrices. In checking the original proposal for $cg \to tA^0$ production [10], we considered [11] a light A^0 in the range 200 GeV $< m_{A^0} <$ 340 GeV, i.e. below $t\bar{t}$ threshold, allowing

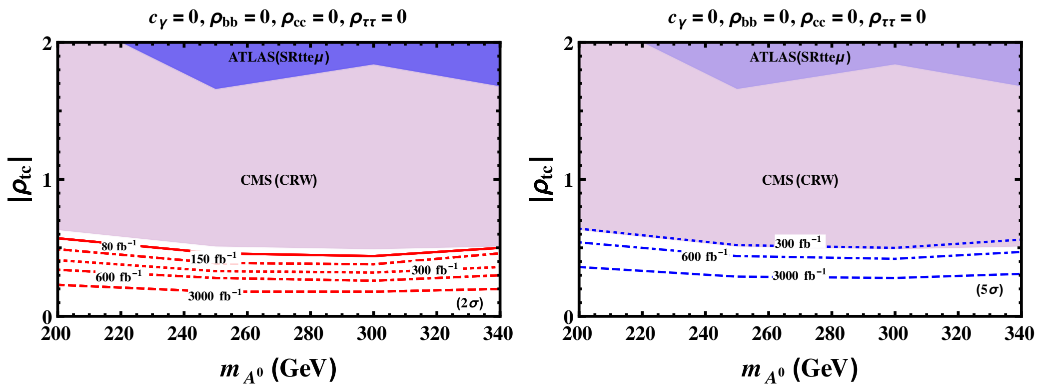

Figure 1: [left] 2σ exclusion and [right] 5σ discovery for $|\rho_{tc}|$ by SStt for various $\int \mathscr{L}dt$ at 14 TeV, with SRtteμ of ATLAS $cc \to tt$ search (blue/dark) and CRW of CMS $t\bar{t}t\bar{t}$ search (purple/light) overlaid.

$A^0 \to t\bar{c} + \bar{t}c$ to be dominant. However, to avoid the $A^0 \to Zh$ constraint from ATLAS [15] and CMS [16], we assume $|\rho_{tt}| \ll 1$ to suppress $gg \to A^0$, even though the AZh gauge coupling is $\cos\gamma$, or alignment, suppressed. This means our discussion can be extended somewhat to beyond the $t\bar{t}$ threshold. Note that one still has the ρ_{tc}-driven EWBG [8] even in this case. To simplify discussion, in the following numerics we set all $\rho_{ij}^F = 0$ except for ρ_{tc}, and assume the alignment limit where $c_\gamma = 0$, so that $\mathscr{B}(A^0 \to t\bar{c}) = 50\%$. The H^0, H^+ bosons are treated[1] as somewhat heavier.

Assuming $\rho_{tc} = 1$, the cross section for $cg \to tA^0$ at 14 TeV is 1 fb for m_{A^0} at 200 GeV, and 1.3 fb for 340 GeV after selection cuts. For the same-sign top plus jet (SStt) signature, i.e. same-sign di-lepton plus jets, the main background is $t\bar{t}W$ production. ATLAS has a dedicated $qq \to tt$ search [18] in various signal regions (SRs), where we find SRtteμ, or $e\mu$ final state from both tops decaying semileptonically, giving the best limit on ρ_{tc}. On the other hand, the most relevant constraint comes from the $t\bar{t}t\bar{t}$ search for CMS, which has been recently updated to 137 fb^{-1} [19], or full Run 2 data, from an earlier analysis [20] based on 2016 data. Based on the number of leptons, jets or b-tagged jets, CMS defines eight SRs plus two control regions (CRs) for background. We find CRW for $t\bar{t}W$ background gives the best limit. In the left panel of Fig. 1 we give the 2σ exclusion limits for various integrated luminosities, and the 5σ discovery reaches are given in the right panel. For comparison, we overlay the constraints from SRtteμ of ATLAS $cc \to tt$ search [18] from Run 1, and CRW ($t\bar{t}W$ control region) of 4-top search by CMS [19] with full Run 2 data. Note that this plot is an update of our published work [11] based on the earlier CMS PAS.

It should be clear that there is a lot of room for improving the SStt search, but the constraint from full Run 2 4-top search is pretty good. However, a dedicated search would be better. It is also interesting to note that $cg \to tA^0 \to tt\bar{c}$ might be discovered at 5σ level for ρ_{tc} around 0.6 with full Run 2 plus Run 3 data. The HL-LHC could push down to smaller ρ_{tc} values, although it may become less pertinent for EWBG. This highlights the value of a timely dedicated search.

We find it mildly surprising that a relatively light A^0 at or below $t\bar{t}$ threshold with FCNH coupling ρ_{tc} is not yet ruled out by LHC data. Direct search – which probes EWBG! – is encouraged.

[1]In this and the next section, we skip the discussion of near degenerate A^0 and H^0. See the original paper [17].

3. $cg \to tH^0 \to th^0h^0$: allowed for $m_{H^0} \sim 300$ GeV

If in fact the H^0 is the lighter exotic scalar, one should consider $cg \to tH^0$, again assuming $|\rho_{tt}| \ll 1$. Besides the discussion above, a new signature would be $H^0 \to h^0h^0$, leading to $cg \to tH \to thh$ [12], or top-assisted di-Higgs production. Given the general interest in di-Higgs search at the LHC, this sounds interesting in its own right.

The CP-even scalars h, H and CP-odd scalar A couple to fermions by

$$-\frac{1}{\sqrt{2}}\sum_{F=u,d,e}\bar{F}_{iL}\Big[\big(-\lambda^F_{ij}s_\gamma+\rho^F_{ij}c_\gamma\big)h+\big(\lambda^F_{ij}c_\gamma+\rho^F_{ij}s_\gamma\big)H-i\,\mathrm{sgn}(Q_F)\rho^F_{ij}A\Big]F_{jR}+\text{h.c.}, \quad (3.1)$$

where λ^F are the usual diagonal Yukawa matrices, and we take $c_\gamma = \cos\gamma$, $s_\gamma = \sin\gamma$ as shorthand. We see that in the alignment limit of $c_\gamma \to 0$, couplings of h become diagonal, i.e. approach SM Yukawa couplings, while H, A couple via extra ρ^F Yukawa matrices. We again exploit the ρ_{tc} coupling of H for its associated production with top.

To discuss Hhh coupling, we need to consider the Higgs potential, which we assume is CP-conserving (CP violation only through Yukawa). It can be written in the Higgs basis as [6]

$$\begin{aligned} V(\Phi,\Phi') = {} & \mu_{11}^2|\Phi|^2+\mu_{22}^2|\Phi'|^2-(\mu_{12}^2\Phi^\dagger\Phi'+h.c.)+\frac{\eta_1}{2}|\Phi|^4+\frac{\eta_2}{2}|\Phi'|^4+\eta_3|\Phi|^2|\Phi'|^2 \\ & +\eta_4|\Phi^\dagger\Phi'|^2+\left[\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2+\big(\eta_6|\Phi|^2+\eta_7|\Phi'|^2\big)\Phi^\dagger\Phi'+h.c.\right], \end{aligned} \quad (3.2)$$

where all parameters are real, v arises from the doublet Φ via $\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2$, while $\langle\Phi'\rangle = 0$, hence $\mu_{22}^2 > 0$. The "soft-breaking" parameter is eliminated by a second minimization condition, $\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$, which reduces the total number of parameters to nine [6], just one more compared to 2HDM II. For c_γ small but not infinitesimal, one has

$$c_\gamma \simeq \frac{-|\eta_6|v^2}{m_H^2-m_h^2}, \quad (3.3)$$

where another relation connects the proximity of m_h^2 to $\eta_1 v^2$. One finds approximate alignment i.e. small c_γ can be attained [6] without requiring η_6, η_1 to be small, which is an important check for the prerequisite of $\mathcal{O}(1)$ Higgs quartics for sake of first order electroweak phase transition [8].

The Hhh coupling is the coefficient of the $\lambda_{Hhh}Hh^2$ term derivable from Eq. (3.2),

$$\begin{aligned} \lambda_{Hhh} &= \frac{v}{2}\Big[3c_\gamma s_\gamma^2\eta_1+c_\gamma(3c_\gamma^2-2)\eta_{345}+3s_\gamma(1-3c_\gamma^2)\eta_6+3s_\gamma c_\gamma^2\eta_7\Big] \\ &\simeq \frac{c_\gamma}{2}v\left[3\frac{m_H^2}{v^2}-2\eta_{345}+3\mathrm{sgn}(s_\gamma)c_\gamma\eta_7+\mathcal{O}(c_\gamma^2)\right], \end{aligned} \quad (3.4)$$

where $\eta_{345} = \eta_3+\eta_4+\eta_5$, and the second step follows for small c_γ, which shows that $\lambda_{Hhh} \to 0$ as $c_\gamma \to 0$. To enhance $cg \to tH \to thh$, sizable λ_{Hhh} is needed, and $\eta_{345} < 0$ may be preferred so the first two terms add up. The Higgs quartic parameters η_1 and η_{3-6} can be expressed [6, 12] in terms of m_h, m_A, m_H, m_{H^+}, μ_{22}, all normalized to v, as well as the mixing angle γ, but η_2 and η_7 do not enter scalar masses. We do not go into the details [12] here, but with $v = 246$ GeV and $m_h = 125$ GeV fixed, in the following numerics, we scan over $\mu_{22} \in [0,700]$ GeV, $\eta_2 \in [0,3]$, $\eta_7 \in$

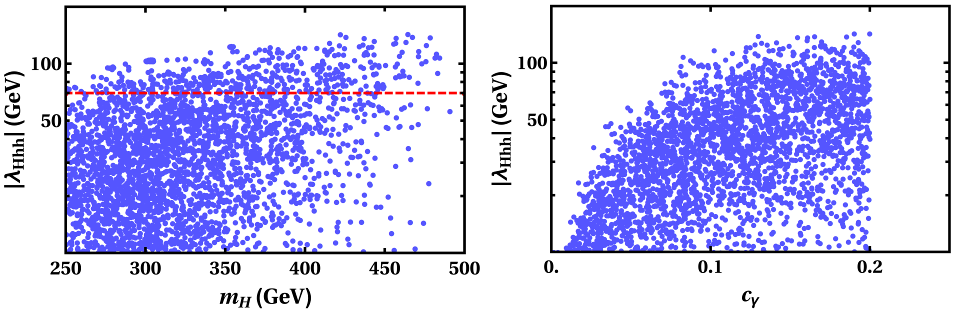

Figure 2: λ_{Hhh} vs m_H and c_γ plots for the scan points that pass perturbativity, tree-level unitarity and positivity through 2HDMC, where $|\eta_i| < 3$ is maintained. The T parameter constraint is also imposed.

	η_1	η_2	η_3	η_4	η_5	η_{345}	η_6	η_7	$m_{H^\pm}$ (GeV)	m_A (GeV)	m_H (GeV)	$\lvert\lambda_{Hhh}\rvert$ (GeV)	$\frac{\mu_{22}^2}{v^2}$
1	0.287	3.00	−0.188	2.04	−2.56	−0.704	−0.172	0.557	303	481	280	97	1.61
2	0.294	2.78	0.269	2.10	−2.95	−0.581	−0.21	0.633	340	518	304	104	1.77
3	0.309	2.98	−0.017	2.42	−2.73	−0.328	−0.301	0.881	363	536	354	123	2.18

Table 1: Parameter values for three benchmark points.

$[-3,3]$, $m_H \in [250,500]$ GeV, $m_{H^+} \in [300,600]$ GeV, $m_A \in [250,500]$ GeV with $m_H < m_A, m_{H^+}$, and γ values that satisfy $c_\gamma \in [0,0.2]$. We identify η_{1-7} with Λ_{1-7} of 2HDMC [21], which we use to enforce perturbativity (conservatively impose $|\eta_i| < 3$), tree unitarity and positivity.

The final "scan points" within 2σ error of T parameter constraint are plotted in Fig. 2, where the horizontal dashed line drawn at $|\lambda_{Hhh}| \sim 70$ GeV is to illustrate that λ_{Hhh} can be sizable over a finite parameter region. Note that the condition $m_H < m_A$, m_{H^+} forbids the decays $H \to AZ$, $H^\pm W^\mp$. From the scan points, we select three favorable benchmark points[2] for $m_H \lesssim 350$ GeV, with λ_{Hhh} around or slightly above 100 GeV, as given in Table 1. All three benchmark points corresponds to $c_\gamma = 0.169$ ($s_\gamma = -0.986$), which is possible from Fig. 1[right]. They also correspond to $\rho_{tc} = 0.54$, with $\mathcal{B}(H \to hh)$ between 23% to 24%. Note that the ρ_{tc} and c_γ values are consistent with $t \to ch$ bounds. The $H \to t\bar{c} + \bar{t}c$ branching fraction is around 70%.

With these three benchmark points, we study the signature of $cg \to tH \to b\ell\nu + 4b$ [12]. Imposing lepton, missing E_T cuts and requiring at least 5 jets (with at least 4 b-tagged), the main

	$t\bar{t}$ (fb)	Single-t (fb)	$t\bar{t}h$ (fb)	$4t$ (fb)	$t\bar{t}W$ (fb)	$t\bar{t}Z$ (fb)	Others (fb)
1	6.70	1.01	1.01	0.016	0.022	0.234	0.007
2	7.42	1.01	1.12	0.019	0.022	0.262	0.008
3	7.94	1.52	1.14	0.024	0.020	0.268	0.008

Table 2: Background cross sections after selection cuts at $\sqrt{s} = 14$ TeV.

[2] A second set of benchmarks as well as more discussions are given in Ref. [12].

background cross sections are given in Table 2. For benchmark 1, 2, 3, we find signal cross sections of 0.396, 0.38, 0.288 fb, total background cross sections of 9.00, 9.86, 10.92 fb, and significance of 3.2, 2.9, 2.1 (7.2, 6.6, 4.8) for 600 (3000) fb^{-1}, respectively. We see that, though $H \to hh$ needs finite h-H mixing as well as $\mathcal{O}(1)$ extra Higgs quartics, as it now stands, the thh or top-assisted di-Higgs signature has non-negligible discovery potential at the LHC.

4. 4t on Triple-Top; and "Excess" in $A^0 \to t\bar{t}$ at 400 GeV?

In this section we present some "bonus" material from our more recent work [13] on 4-top constraints on g2HDM, and insight on some $t\bar{t}$ news.

One peculiarity of Nature is that, while SM single-top and $t\bar{t}$ enjoy the sizable cross sections at 14 TeV of roughly 0.2 and 0.6 nb, respectively, triple-top cross section at roughly 2 fb [22] is even smaller than 4-top production at just above 10 fb. As such, the ATLAS and CMS experiments have been pursuing 4-top search, where CMS has recently updated their previous result based on 36 fb^{-1} [20] to full Run 2 data of 137 fb^{-1} [19], clearly zooming in on 4-top cross section measurement (epitomized by the measured central value agreeing with theory projection). However, the search for triple-top has been bypassed.

We have focused so far on a lighter A or H, i.e. below $t\bar{t}$ threshold, which are actually spin-offs from our earlier triple-top work. For H and A above $t\bar{t}$ threshold, we proposed [17] two years ago the process $cg \to tH, tA \to tt\bar{c}, tt\bar{t}$, where the same-sign top signature arises from decay to $t\bar{c}$ via ρ_{tc}, while the triple-top signature arises from $H, A \to t\bar{t}$ decay via ρ_{tt}. Assuming ρ_{tc} (needed for production) and ρ_{tt} are $\mathcal{O}(1)$, the triple-top cross section can be larger than 4-top, extending even to pb. In the classic argument that a suppressed SM effect makes the New Physics search more compelling, we have urged all along a targeted, direct search for triple-top at the LHC.

Skipping the details [13], we plot in Fig. 3 the constraints from CMS 4-top search, where SR8 is from 36 fb^{-1} [20], while SR12 is from 137 fb^{-1} [19], for two m_A values, treating it as the lighter exotic boson. One sees that the constraint has barely improved when the data has increase four-

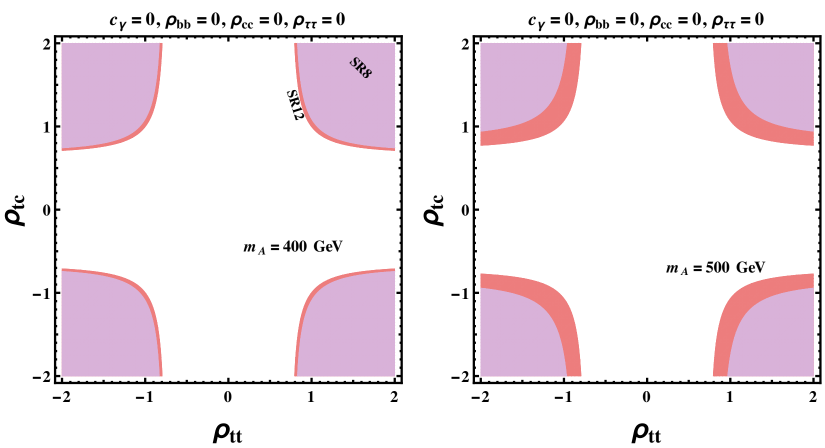

Figure 3: Constraints on ρ_{tc} and ρ_{tt} for A alone case [13], from SR8 (purple/light) of Ref. [20], and SR12 (red/dark) of Ref. [19], for [left] $m_A = 400$ GeV and [right] 500 GeV.

fold.[3] This is largely because for SR12 at 137 fb^{-1}, CMS has fixed to 4-jets, hence tuned towards 4-top measurement and giving less improvement on constraining triple-top!

An inadvertent encounter further strengthens our point. To understand the constraint from $gg \to A/H \to t\bar{t}$, we noticed [13] the mention of an "excess" (CMS wording) – but neither in Abstract, nor Introduction, nor in Summary – in CMS-PAS-HIG-17-027, though "deviation" appeared in abstract of arXiv version [14]. To quote roughly: "a signal-like excess for the pseudoscalar hypotheses (largest) at 400 GeV, $\Gamma/\Gamma_{\rm tot} = 4\%$, 3.5σ local (1.9σ look-elsewhere)", where we do not quote the CMS plots that illustrate the deviation. This study has traditionally been viewed by theorists as difficult [23], due to the peak-dip nature of interference with SM $t\bar{t}$ background.

Several points are worthy of note [13]:

- The 400 GeV "signal" for $A^0 \to t\bar{t}$ is consistent with $\rho_{tt} \lesssim 1.1$, $\rho_{tc} \lesssim 0.9$ (CMS did not give actual values of coupling modifiers), which is right on the border of the full Run-2 CMS constraint from 4-top (Fig. 3); and a dedicated 3-top search would provide further information. In our study, H and H^+ are at 500 and 550 GeV, respectively.

- It should be emphasized that 1.9σ global significance should be "below radar", but since ATLAS pioneered the $t\bar{t}$ scalar resonance search [24] with Run 1 data (although with $m_{t\bar{t}}$ starting at 500 GeV), it would be interesting to see an ATLAS update with Run 2 data, and needless to say, the full Run 2 result for both ATLAS and CMS.

- The "excess" of CMS, though for pseudoscalar A^0, could actually arise from scalar H^0, because with fully imaginary Yukawa coupling ρ_{tt}, the H^0 could mimic the A^0 in the triangle top loop of $gg \to H$ production (see Ref. [25] for a brief discussion, for H^0 admixture in h^0).

5. Conclusion

With one scalar doublet completed, a second doublet seems rather likely. With *No New Physics* seen so far, we should check our *Presumptions*. From this angle, we advocate 2HDM without Z_2, which permits extra Yukawa couplings such as ρ_{tt} and ρ_{tc}, and should be checked experimentally.

With $\rho_{tt} \to 0$ and ρ_{tc} driving EWBG, we find relatively light A^0 below $t\bar{t}$ threshold could give $tt\bar{c}$ signature of same-sign top, which is not yet ruled out; relatively light H^0 below $t\bar{t}$ threshold could give th^0h^0 or top-assisted di-Higgs signature. These signatures should be searched for.

Above $t\bar{t}$ threshold and with finite ρ_{tt}, while experiments are zooming in on 4-top, we continue to advocate direct search of 3-top. Stumbling on the "excess" in $A^0 \to t\bar{t}$ as reported by CMS, we note that this could arise from g2HDM, even from H^0 origin!

In conclusion, the exotic scalars of an extended Higgs sector may be sub-TeV in mass, and far richer and more *complex* than we are used to think.

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