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Extra Yukawas: Searching for New Scalars via Triple-Top Signature

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The study of top quark is one of the major program at LHC. Essentially being a top factory, LHC provides a unique opportunity to study multi-top productions. In the Standard Model (SM), the single-top, $t\bar{t}$ and four-top production cross sections are very large and well over pb level, while the triple-top is few fb. Any enhancement in triple-top production would be intriguing. This may be realized in the Two-Higgs-Doublet-Model (2HDM) without a discrete Z_2 symmetry, where both the doublets couple to the up- and down-type quarks. After diagonalization of the fermion mass matrices, two different Yukawas κ_f and ρ_f emerge, where κ_f is diagonal and real, however, ρ_f is in general non-diagonal and complex. Extra Yukawas ρ_{tt} and ρ_{tc} with $\mathcal{O}(1)$ magnitude can enhance the cross section of triple-top process to pb level. In this proceeding we discuss the discovery potential of new scalars via two novel signatures: $cg \to tH^0/tA^0 \to tt\bar{c}$ (same-sign top) and $cg \to tH^0/tA^0 \to tt\bar{t}$ (triple-top) at LHC. Discovery may shed light on the Baryon Asymmetry of the Universe.

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1. Introduction

The discovery [1] of the 125 GeV scalar (h^0) has opened up the search for additional scalar doublet that may exist in nature. The SM like nature of 125 GeV scalar indicates the approximate-alignment phenomena. This might imply that the second doublet is heavy i.e. the approximate-alignment from decoupling. However, approximate-alignment may emerge without decoupling [2, 3, 4], allowing sub-TeV second doublet. This brings the search for pseudo-scalar A^0 and CP-even scalar H^0 well within the reach of LHC. Approximate-alignment without decoupling can also be realized in the 2HDM without discrete Z_2 symmetry [5]. The 2HDM without discrete Z_2 symmetry opens up the possibility of extra Yukawas such as ρ_{tc} and ρ_{tt}. It was recently discussed [6] that ρ_{tt} and ρ_{tc} with $\mathcal{O}(1)$ magnitude and complex phase can drive electroweak baryogenesis (EWBG) efficiently. Together, ρ_{tc} and ρ_{tt} induce two clean processes $cg \to tA^0/tH^0 \to tt\bar{c}$ and $cg \to tA^0/tH^0 \to tt\bar{t}$ at LHC. Focusing in the range 350 GeV $\leq m_{A^0}(m_{H^0}) \leq$ 700 GeV, we discuss the discovery potential of $pp \to tA^0/tH^0 + X \to tt\bar{c} + X$ and $pp \to tA^0/tH^0 + X \to tt\bar{t} + X$ followed by leptonic decays of all top quarks. The discovery of any of these two processes would help us understand mechanism behind EWBG.

2. Framework and Results

For our study, the relevant extra Yukawa couplings for the up-type quarks are [7],

$$\frac{\rho_{ij}}{\sqrt{2}} \bar{u}_{iL}(H^0 + iA^0)u_{jR} + \text{h.c.}, \tag{2.1}$$

where, ρ_{ij} non-diagonal complex matrix, but plausibly [5] shares the same "flavor organization" features of SM, i.e. trickling down of off-diagonal elements as reflected in the observed quark masses and mixings. Therefore, we expect ρ_{tt} and ρ_{tc} to be $\mathcal{O}(\kappa_t)$, where $\kappa_t \sim \sqrt{2}m_t/v$ ($v \approx$ 246 GeV) is the top Yukawa in SM. Similarly, ρ_{bb} and $\rho_{\tau\tau}$ (and $\rho_{\tau\mu}$) most likely be $\sim \kappa_b$ and $\sim \kappa_\tau$ respectively. Note that $\rho_{ct} \simeq 0$ is demanded by B physics constraints [8, 9]. Here, we took $\cos\gamma \to 0$ for simplicity, where $\cos\gamma$ [5] is the mixing angle between the CP-even scalars h^0 and H^0 (analogous to $\cos(\beta - \alpha)$ in 2HDM II).

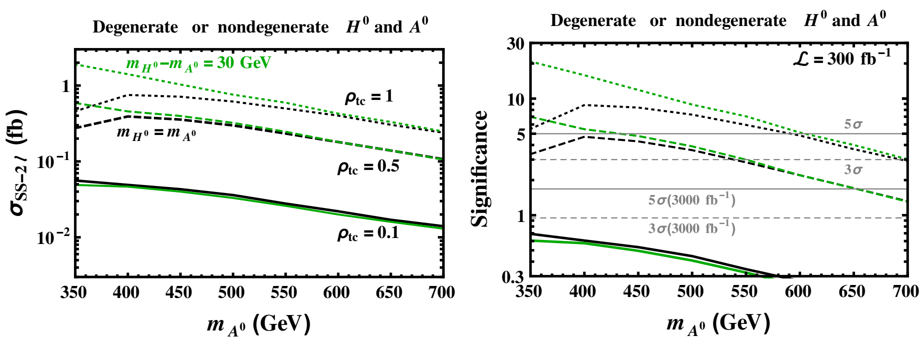

Figure 1: Signal cross sections (left) and discovery potential (right) of SS2ℓ for $m_{H^0} = m_{A^0}$ (black) and $m_{H^0} - m_{A^0} = 30$ GeV (light green), with $\rho_{tc} = 1,\ 0.5,\ 0.1$, setting $\rho_{tt} = 1$. The CM energy and integrated luminosity chosen for the analysis are $\sqrt{s} = 14$ TeV and 300 fb^{-1} respectively.

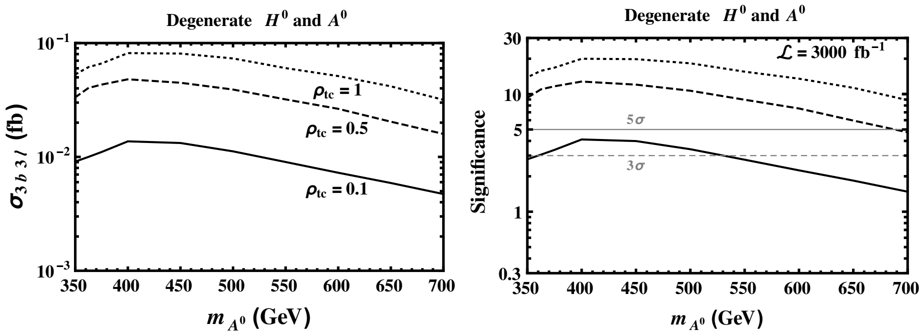

Figure 2: The signal cross sections (left) and discovery potential (right) of $3b3\ell$ process for $m_{A^0} = m_{H^0}$ with $\rho_{tc} = 1,\ 0.5,\ 0.1$, setting $\rho_{tt} = 1$ at 14 TeV LHC. The integrated luminosity is chosen to be 3000 fb^{-1}.

Same-sign top.– The same-sign top process solely depends on the flavor changing neutral Higgs coupling ρ_{tc}. In order to demonstrate the discovery potential of $pp \to tA^0/tH^0 + X \to tt\bar{c} + X$ process, we look for leptonic decays of both the top quarks and select events with two same sign leptons (e and μ), at least three jets with at least two of them are b-tagged. We denote this final state as SS2ℓ. The SM background processes considered are: $t\bar{t}Z$, $t\bar{t}W$, $tZ+$ jets, $3t+j$, $3t+W$, $4t$, and $t\bar{t}h$. The $t\bar{t}$ and Z/γ^*+ jets processes may contribute if the charge of one of the leptons get misidentified. The largest background is non-prompt contribution [10], which is about 1.5 times of the second largest background $t\bar{t}W$ [1]. Note that, the $pp \to tA^0 + X \to tt\bar{c} + X$ and $pp \to tH^0 + X \to tt\bar{c} + X$ processes interfere destructively if masses and widths of H^0 and A^0 are degenerate. The cancellation effect alleviates when m_{H^0} and m_{A^0} and/or Γ_{H^0} and Γ_{A^0} become non-degenerate (see Refs. [11, 12] for details). In this scenario, the SS2ℓ cross section becomes the incoherent sum of $pp \to tA^0 + X \to tt\bar{c} + X$ and $pp \to tH^0 + X \to tt\bar{c} + X$ processes. In Fig. 1, we summarize the signal cross sections and discovery potential for $\rho_{tc} = 1,\ 0.5,$ and 0.1 setting $\rho_{tt} = 1$. In order to illustrate the impact of this cancellation effect, we chose two different mass hierarchies for H^0 and A^0: $m_{H^0} = m_{A^0}$ (black contours) and $m_{H^0} - m_{A^0} = 30$ GeV (green contours). As non-zero ρ_{tt} makes $\Gamma_{H^0} \neq \Gamma_{A^0}$, the cancellation between H^0 and A^0 cross sections are not exact. Hence the cross sections do not vanish for $m_{H^0} = m_{A^0}$ case, as can be seen from black lines in Fig. 1 (left). For $m_{H^0} - m_{A^0} = 30$ case both masses and widths become non-degenerate, resulting in green lines with larger cross sections. It is clear from Fig. 1 that discovery might happen for wide range of parameter space. E.g. if $\rho_{tc} = 1$ and 350 GeV $\lesssim m_{A^0} \lesssim$ 600 GeV discovery is possible with $\mathcal{L} = 300$ fb^{-1} dataset for the $m_{H^0} - m_{A^0} = 30$ scenario. We discovery contours for full HL-LHC data ($\mathcal{L} = 3000$ fb^{-1}) are also shown in the right panel of Fig. 1. We find if $\rho_{tc} = 0.1$, discovery is beyond even for full HL-LHC data.

Triple top.– The triple-top process $cg \to tA^0/tH^0 \to tt\bar{t}$ is more exquisite and depend on both ρ_{tc} and ρ_{tt} couplings. To determine the discovery probability $pp \to tA^0/tH^0 + X \to tt\bar{t} + X$, we focused on the final state where all three top quarks decay leptonically. The signature constitutes at least three leptons, at least three jets of which at least three are b-jets, and E_T^{miss} (denoted as $3b3\ell$). Although in the SM the triple-top cross section is about few fb [14], there exist several

[1] For the details of the cut based analysis, background cross sections and QCD correction factors see Ref. [11]. The correction factors for Z/γ^*+ jets processes can be found in Refs. [13].

other SM backgrounds which contribute to the overall background cross section. The dominant SM backgrounds are $t\bar{t}Z$+jets and $4t$, while $t\bar{t}Wb$, $tZjb$, $3t+W$, and $t\bar{t}h$ conform subdominant contributions. The $t\bar{t}$+jets process can contribute if a jet gets misidentified as a lepton. The details of the cut based analysis and QCD correction factors for different backgrounds can be found in Ref. [11]. The cross sections for $3b3\ell$ are smaller due to finer selection cuts than SS2ℓ, hence, we give results for 3000 fb^{-1}. Unlike the same-sign top, the A^0 and H^0 contributions do not cancel each other for triple-top. Hence, in Fig. 2, we only show the cross sections and discovery potential for $m_{H^0} = m_{A^0}$ (see Ref. [11] for other mass hierarchies). We can see from Fig. 2 [right] that 5σ (or higher) significance is possible if $m_{A^0} \lesssim 700$ GeV and even for $\rho_{tc} \gtrsim 0.5$. Unlike SS2ℓ, if $\rho_{tc} \sim 0.1$, one could still get some hint (at 3σ or higher) up to $m_{H^0} = m_{A^0} \sim 500$ GeV with 3000 fb^{-1} dataset. Hence, we advocate that the "triple-top" search is more exquisite and informative.

3. Summary

The 2HDM without a discrete Z_2 symmetry allows the possibility of extra Yukawas ρ_{tt} and ρ_{tc}. The ρ_{tt}, ρ_{tc} couplings induce two novel signatures at LHC: same-sign top ($cg \to tH^0/tA^0 \to tt\bar{c}$) and triple-top ($cg \to tH^0/tA^0 \to tt\bar{t}$). The former process may emerge in the early part of Run 3, while the triple-top process may require HL-LHC data. Discovery would enable us understand the origin of matter-antimatter asymmetry of the Universe. We also remark that the recent discovery of $t\bar{t}h$ provides additional probe for ρ_{tt} driven EWBG [15].

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