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Constraining a lighter exotic scalar via same-sign top

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ABSTRACT

It was shown recently that, in two Higgs doublet models without Z_2 symmetry, extra Yukawa couplings such as ρ_{tc}, ρ_{tt} can fuel enough CP violation for electroweak baryogenesis (EWBG). We revisit an old proposal where a pseudoscalar A^0 has mass between $t\bar{c}$ and $t\bar{t}$ thresholds. With ρ_{tt} small, it evades $gg \to A^0 \to h^0(125)Z$ constraints, where approximate alignment also helps. We find this scenario with relatively light A^0 is not yet ruled out, and $cg \to tA^0 \to tt\bar{c}$ can probe sizable ρ_{tc} at the LHC, giving access to the second mechanism of EWBG provided by such models.

1. Introduction

The absence of clear signs of New Physics (NP) at the Large Hadron Collider (LHC) motivates one to think in less conventional ways. In searching for extra Higgs bosons, it is common to assume a two-Higgs doublet model (2HDM) with a softly-broken Z_2 symmetry that implements the Natural Flavor Conservation (NFC) condition [1]. Such Z_2 symmetries ensure that each type of charged fermions couples to a single Higgs doublet, which thereby excludes the possible existence of extra Yukawa matrices. However, given that we still do not understand the origin of the Yukawa sector, the Z_2 assumption may appear too strong. With a first doublet established since 2012 [2], it seems imperative that we should use experimental *data* to constrain possible extra Yukawa couplings.

The 2HDM without the Z_2 symmetries offers extra Yukawa couplings that induce flavor-changing neutral Higgs (FCNH) interactions at tree level. In particular, the Yukawa matrix element ρ_{tc}, the tcS^0 ($S^0 = H^0, A^0$) coupling, may be large because it involves the heaviest quark, top. The $S^0 \to t\bar{c}, \bar{t}c$ width may well exceed $S^0 \to b\bar{b}$, and could be the dominant decay mode for m_{S^0} lying between the $t\bar{c}$ and $t\bar{t}$ thresholds. Through the $cg \to tS^0 \to tt\bar{c}$ process, one may have same-sign top-quark pair production at the LHC.

Such processes were first studied for the pseudoscalar boson A^0 about two decades ago [3], in the scenario that $m_{A^0} < m_{H^+} + M_W$, $m_{h^0/H^0} + M_Z$. Assuming the Higgs sector is CP-conserving, two-body A^0 decays are then limited to fermionic final states at tree level. Invoking the Cheng–Sher ansatz [4] to allow for sizable tcA^0 coupling, $A^0 \to t\bar{c}$ would be the dominant decay for m_{A^0} between the $t\bar{c}$ and $t\bar{t}$ thresholds. For 200 GeV $\lesssim m_{A^0} \lesssim 2m_t$, it was advocated that $cg \to tA^0 \to tt\bar{c}$ [5] is a promising process to probe for the tcA^0 coupling.

The case for sizable ρ_{tc} was strengthened recently from cosmological concerns. It was shown [10] that in 2HDM without Z_2 symmetry, top/charm transport can generate enough CP violation (CPV) for successful electroweak baryogenesis (EWBG) [11] during the electroweak phase transition (EWPT), which can be of strong first order if Higgs quartic couplings are $\mathcal{O}(1)$ [12]. The extra flavor-diagonal complex Yukawa coupling ρ_{tt} is more efficient in generating the CPV, but an $\mathcal{O}(1)$ ρ_{tc} with a large phase can still realize EWBG even if ρ_{tt} is rather small.

With the advent of LHC data and the renewed motivation, we revisit the study of Ref. [3]. With the discovered [13] 125 GeV boson h^0 [14] being quite consistent with the Higgs boson of the Standard Model (SM) [15], the scenario needs some update. In particular, assuming $m_{A^0} < m_{h^0} + M_Z$ would preclude most of the mass range of interest, hence must be dropped. This opens up the $A^0 \to h^0 Z$ decay, which is suppressed by proximity to the alignment limit [16], as implied [17] by LHC data. To simplify our analysis, we focus on A^0 and assume it to be considerably lighter than H^0 and H^+, which is stronger than the original assumption of $m_{A^0} < m_{H^+} + M_W$, $m_{H^0} + M_Z$ of Ref. [3]. We discuss possible effects of $cg \to tH^0 \to tt\bar{c}$ near the end of this paper.

In this paper, we assume both top quarks decay semileptonically in $cg \to tA^0 \to tt\bar{c}$, leading to the signature of same-sign dilepton with jets and missing energy (SS2ℓ). We take an agnostic view on the FCNH coupling ρ_{tc}, treating it as a free parameter. We survey existing LHC data pertaining to the SS2ℓ signature to constrain ρ_{tc}, then study the discovery/exclusion potential at the LHC.

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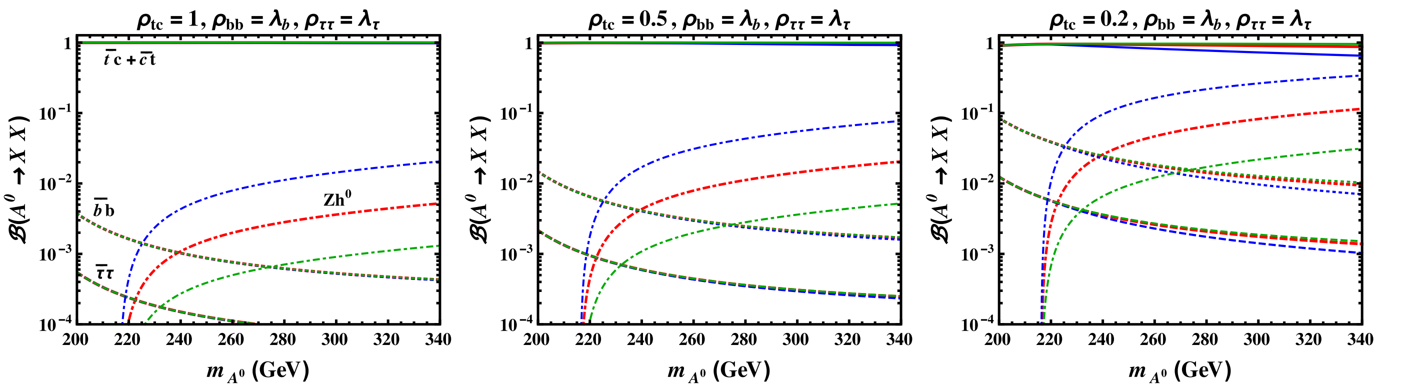

Fig. 1. For $\rho_{tc} = 1$ [left], 0.5 [middle] and 0.2 [right], branching ratios of A^0 decay to $t\bar{c} + \bar{t}c$ (solid), $b\bar{b}$ (dotted), $\tau^-\tau^+$ (dashed) and h^0Z (dot-dashed) with $c_\gamma = 0.2$ (blue), 0.1 (red) and 0.05 (green). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

It is intriguing that the light A^0 scenario of Ref. [3] is still allowed by existing data, and that future LHC data can probe ρ_{tc} values relevant for EWBG.

2. Framework and constraints

We assume the Higgs potential is CP-conserving [16]. Without a Z_2 symmetry, the coupling of A^0 to fermions is [18]

$$\frac{i}{\sqrt{2}} \sum_{F=U,D,L} \mathrm{sgn}(Q_F)\rho^F_{ij} \bar{F}_{iL} F_{jR} A^0 + \mathrm{h.c.}, \tag{1}$$

where $i, j = 1, 2, 3$ are generation indices, $\mathrm{sgn}(Q_F) = +1$ (-1) for $F = U$ $(F = D, L)$, and ρ^F are general 3×3 complex matrices. For the tcA^0 couplings of interest, $\rho^U_{23} \equiv \rho_{ct}$ and $\rho^U_{32} \equiv \rho_{tc}$. B physics sets stringent limits on ρ_{ct} [19], while ρ_{tc} is only mildly constrained [20], depending on m_{H^+}. In our study, we set $\rho_{ct} = 0$ and vary ρ_{tc} within $|\rho_{tc}| \lesssim 1$.

Other couplings can affect our study through the $A^0 \to t\bar{c}$ branching ratio: important ones are $\rho^D_{33} \equiv \rho_{bb}$ and $\rho^L_{33} \equiv \rho_{\tau\tau}$, where each may be as large as the corresponding SM Yukawa coupling $\lambda_f = \sqrt{2}m_f/v$ with $v \simeq 246$ GeV, leading to $A^0 \to b\bar{b}$, $\tau^+\tau^-$. A nonzero $\rho^U_{33} \equiv \rho_{tt}$ induces $A^0 \to t\bar{t}$, which is forbidden below the $t\bar{t}$ threshold, but can still generate $A^0 \to gg, \gamma\gamma$ via the triangle loop. Finally, $A^0 \to h^0Z$ can occur via the gauge coupling

$$\frac{g_2 \cos\gamma}{2\cos\theta_W} Z_\mu (h^0 \partial^\mu A^0 - A^0 \partial^\mu h^0), \tag{2}$$

where $\cos\gamma$ [21] is the CP-even scalar mixing, usually [16] denoted as $\cos(\alpha - \beta)$ in models with Z_2 symmetry.

We consider the mass range [3] of 200 GeV $< m_{A^0} <$ 340 GeV throughout this paper. Taking $\rho_{bb} = \lambda_b$ and $\rho_{\tau\tau} = \lambda_\tau$ for illustration, we present A^0 decay branching ratios in Fig. 1 for $\rho_{tc} = 1$ (left), 0.5 (middle) and 0.2 (right), with all other ρ^F_{ij} set to zero. In each panel, results for three different $c_\gamma \equiv \cos\gamma$ values are shown: 0.2 (blue), 0.1 (red) and 0.05 (green). We see that $A^0 \to t\bar{c}, \bar{t}c$ are the dominant decay modes in all the cases and $\mathcal{B}(A^0 \to t\bar{c} + \bar{t}c) \sim 1$ for $\rho_{tc} \gtrsim 0.5$. For $\rho_{tc} = 0.2$, other decay modes can become sizable, e.g. $\mathcal{B}(A^0 \to h^0Z) \gtrsim 0.2$ for $c_\gamma = 0.2$ and 270 GeV $\lesssim m_{A^0} <$ 340 GeV; however, $\mathcal{B}(A^0 \to t\bar{c} + \bar{t}c) > 60\%$ in all cases.

For nonzero ρ_{tt}, $gg \to A^0$ via the top loop makes $A^0 \to h^0Z$ search at the LHC relevant. In the A^0 mass range of interest and for $|\rho_{tt}| \sim \lambda_t \sim 1$, recent searches by ATLAS [22] and CMS [23], both using $h^0 \to b\bar{b}$ with ~ 36 fb^{-1} data at 13 TeV, are sensitive to $\mathcal{B}(A^0 \to h^0Z)$ at percent level. Furthermore, diphoton resonance search can also become relevant for $|\rho_{tt}| \sim \lambda_t$. For simplicity, we assume $|\rho_{tt}| \ll 1$ to suppress $gg \to A^0$. Note that one may still have the ρ_{tc}-driven EWBG [10] even in this case. In the following analyses, we set all $\rho^F_{ij} = 0$ except for ρ_{tc}, and assume the alignment limit where $c_\gamma = 0$, so that $\mathcal{B}(A^0 \to t\bar{c} + \bar{t}c) = 1$ always holds.

A nonzero ρ_{tc} induces $cg \to tA^0$, followed by $A^0 \to t\bar{c}, \bar{t}c$ in our setup. The $t\bar{t}c$ final state would be obscured by QCD production of $t\bar{t}$, but $ttc̄$ with semileptonically decaying top gives clean same-sign dilepton signature, and should provide an excellent probe for ρ_{tc}. Although there are no dedicated searches for a new boson in such a process, one may utilize existing results for NP searches in same-sign dilepton final states to constrain ρ_{tc}.

Surveying literature, we find two relevant experimental results. The first is the search by ATLAS [24] for $qq \to tt$ $(q = u$ or $c)$ mediated by t-channel scalar H exchange with tqH coupling, using 20.3 fb^{-1} data at 8 TeV. The other is the search for SM production of four top quarks ($t\bar{t}t\bar{t}$) by CMS [25], using 35.9 fb^{-1} data at 13 TeV. We note that searches for supersymmetry in similar event topologies typically require missing energies that are too large for our purpose. The requirement can be relaxed with R-parity violation, for example a search by ATLAS [26] for squark pair production in $pp \to \tilde{d}_R\tilde{d}_R \to \bar{t}\bar{t}\bar{b}\bar{b}$ or $\bar{t}\bar{t}\bar{s}\bar{s}$. The selection cuts, however, are still too strong to give meaningful constraints on ρ_{tc}.

The ATLAS $qq \to tt$ search [24], depending on lepton flavor, defines three signal regions (SRs), where we find SRtteμ ($e\mu$ final state from both tops decaying semileptonically) gives the best limit on ρ_{tc}. On the other hand, based on the number of leptons, jets or b-tagged jets, the CMS $t\bar{t}t\bar{t}$ search [25] defines eight SRs plus two control regions for background. We find CRW, the control region for $t\bar{t}W$ background, gives the best limit. Note that CMS has an earlier study [27] of $t\bar{t}t\bar{t}$ based on the same dataset, but Ref. [25] has better optimization to enhance signal sensitivity.

Let us take a closer look. The selection criteria for SRtteμ of the ATLAS $qq \to tt$ search [24] requires an event to contain a positively-charged $e\mu$ pair and two to four jets with at least one b-tagged. The transverse momenta, p_T, of both leptons should be > 25 GeV, the pseudo-rapidity, $|\eta|$, of electrons (muons) should be < 2.47 (2.5), while all jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. The azimuthal separation between the two leptons should be $\Delta\phi_{\ell\ell} > 2.5$. Finally, the missing p_T, or $p_T^{\rm miss}$, should be > 40 GeV, and the scalar sum, H_T, of all jet and lepton p_Ts is required to be > 450 GeV. With these selection cuts, ATLAS reports 5 observed events, with expected background at $7.5 \pm 1.3\,(\text{stat}) \pm 2.5\,(\text{syst})$.

CRW of the CMS $t\bar{t}t\bar{t}$ search [25] is defined to contain two same-sign leptons, two to five jets with two of them b-tagged. The selection cuts are as follows. Leading (subleading) lepton p_T