

Top FCNC decays in the aligned two-Higgs doublet model

Gauhar Abbas*

IFIC, Universitat de València – CSIC, Apt. Correus 22085, E-46071 València, Spain

Alejandro Celis

*Ludwig-Maximilians-Universität München, Fakultät für Physik,
Arnold Sommerfeld Center for Theoretical Physics, 80333 München, Germany*

Xin-Qiang Li

*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE),
Central China Normal University, Wuhan, Hubei 430079, China, and
State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,
Chinese Academy of Sciences, Beijing 100190, China*

Jie Lu

Department of Physics, Shanghai University, Shanghai 200444, China

Antonio Pich

IFIC, Universitat de València – CSIC, Apt. Correus 22085, E-46071 València, Spain

We compute the flavour-changing top decays $t \rightarrow ch$ and $t \rightarrow cV$ ($V = \gamma, Z$) within the framework of the aligned two-Higgs-doublet models. By exploiting constraints from flavour physics and the measured Higgs properties, we investigate the parameter space of the model and its impact on the associated branching ratios. It is observed that the Higgs signal strength in the di-photon channel imposes important restrictions on the $t \rightarrow ch$ decay rate when the charged scalar of the model is light. We conclude that the rates of these flavour-changing top decays are beyond the expected sensitivity of the future high-luminosity phase of the LHC.

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*Speaker.

1. Introduction

The celebrated discovery of a new boson by the ATLAS [1] and CMS [2] collaborations marks a new era of particle physics. This new boson shows the same behaviour as the standard model (SM) Higgs boson so far. However, the SM does not forbid an extended scalar sector. Hence, the discovery of this new boson could be the beginning of an enlarged electro-weak symmetry breaking sector. The two-Higgs-doublet model (2HDM) is a simple example of this kind of set up where the SM is extended by adding a second scalar doublet. The most general version of this model is plagued by flavour-changing neutral-current (FCNC) interactions at tree-level. The usual solution is the hypothesis of natural flavour conservation (NFC). The large FCNCs are forbidden by imposing a Z_2 symmetry which allows only one doublet to couple with a given type of right-handed fermion [3, 4]. A more general solution to this issue is the assumption of Yukawa alignment in flavour space [5]. This leads to the so-called aligned two-Higgs-doublet model (A2HDM) where the two Yukawa matrices associated with the same type of right-handed fermion are aligned in flavour space, guaranteeing the absence of tree-level FCNCs automatically. It is remarkable that all different versions of the 2HDM with Z_2 symmetry represent particular limits of the A2HDM. The constraints from flavour and collider physics data on the A2HDM are derived in refs. [6, 7, 8, 9, 10, 11] and [12, 13, 14, 15, 16, 17, 18, 19], respectively.

In this article, we present our investigations on the flavour-changing top-quark decays $t \rightarrow ch$ and $t \rightarrow cV$ ($V = \gamma, Z$), within the framework of the CP-conserving A2HDM [20]. These decays are highly suppressed in the SM due to the GIM mechanism and occur only at the loop level. In the A2HDM, the charged Higgs contribution in the loops could enhance their branching ratios with respect to the SM predictions, making these processes an ideal place to look for physics beyond the SM.

The ATLAS and CMS collaborations have been searching for flavour-changing top decays and have provided bounds on the associated branching ratios [21, 22, 23, 24, 25]. In the future high luminosity running phase of the LHC, these bounds are expected to be improved by at least one order of magnitude [26, 27].

2. The Yukawa sector of A2HDM

In the A2HDM, the fermionic-scalar interactions are given by the following Lagrangian [5]

$$\begin{aligned} \mathcal{L}_Y = & -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} [\zeta_d V M_d P_R - \zeta_u M_u^\dagger V P_L] d + \zeta_l \bar{\nu} M_l P_R l \right\} \\ & - \frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0} \varphi_i^0 [\bar{f} M_f P_R f] + \text{h.c.}, \end{aligned} \quad (2.1)$$

where $P_{L,R} = (1 \mp \gamma_5)/2$ are the chirality projectors, $M_{f=u,d,l}$ are the diagonal fermion mass matrices, V is the Cabibbo–Kobayashi–Maskawa (CKM) matrix, and

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\mathcal{R}_{i3}) \zeta_{d,l}, \quad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\mathcal{R}_{i3}) \zeta_u^*. \quad (2.2)$$

The alignment parameters ζ_f ($f = u, d, l$) are family-universal complex quantities which introduce new sources of CP violation beyond the CKM matrix.

The quantum corrections lead to some misalignment of the Yukawa coupling matrices. However the flavour structure of the A2HDM strongly constrains the possible FCNC effects. At one loop, the only FCNC local structures read [6]

$$\begin{aligned} \mathcal{L}_{\text{FCNC}} = & \frac{C}{4\pi^2 v^3} (1 + \zeta_u^* \zeta_d) \sum_j \varphi_j^0 \left\{ (\mathcal{R}_{j2} + i\mathcal{R}_{j3})(\zeta_d - \zeta_u) \left[\bar{d}_L V^\dagger M_u M_u^\dagger V M_d d_R \right] \right. \\ & \left. - (\mathcal{R}_{j2} - i\mathcal{R}_{j3})(\zeta_d^* - \zeta_u^*) \left[\bar{u}_L V M_d M_d^\dagger V^\dagger M_u u_R \right] \right\} + \text{h.c.}, \end{aligned} \quad (2.3)$$

which are absent in the 2HDMs with NFC. The renormalized coupling constant C is determined by the following equation [10]

$$C = C_R(\mu) + \frac{1}{2} \left\{ \frac{2\mu^{D-4}}{D-4} + \gamma_E - \ln(4\pi) \right\}, \quad (2.4)$$

where $\gamma_E \simeq 0.577$ is the Euler constant and μ is an arbitrary renormalization mass scale. The renormalized coupling satisfies

$$C_R(\mu) = C_R(\mu_0) - \ln(\mu/\mu_0). \quad (2.5)$$

Assuming Yukawa alignment to be exact at a given energy scale Λ_A , so that $C_R(\Lambda_A) = 0$, implies that $C_R(\mu) = \ln(\Lambda_A/\mu)$.

3. Flavour changing top decays: results

Now, we present our results of the flavour-changing top-quark decays $t \rightarrow ch$ and $t \rightarrow cV$ ($V = \gamma, Z$) [20]. We have computed them in the Feynman gauge and have checked the gauge independence by additionally performing all calculations in the unitary gauge. These decays have been computed in the CP-conserving A2HDM, which contains 12 free real parameters: μ_2 , λ_k ($k = 1, \dots, 7$), the three alignment constants ζ_f ($f = u, d, l$) and the counter-term coupling $C_R(\mu)$. Physical amplitudes are independent of the renormalization scale μ , due to eq. (2.5). We choose $\mu = M_W$ and some of the parameters of the scalar potential can be traded by the physical scalar masses and the angle $\tilde{\alpha}$ which relates physical scalars to unphysical ones. More details can be found in ref. [20].

The bounds on flavour-changing decays of the top quark are set by the ATLAS and CMS collaborations. The ATLAS collaboration provides $\text{Br}(t \rightarrow qZ) < 0.73\%$ at the 95% confidence level (CL), with 2.1 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [21], where the q in the final state denotes a sum over $q = u, c$. The CMS collaboration gives a better limit, $\text{Br}(t \rightarrow qZ) < 0.05\%$, with 24.7 fb^{-1} of data at $\sqrt{s} = 7 \& 8 \text{ TeV}$ [23]. The CMS collaboration sets a bound on $t \rightarrow c\gamma$ decay which is $\text{Br}(t \rightarrow c\gamma) < 0.182\%$, using 19.1 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$ [25]. The ATLAS collaboration provides $\text{Br}(t \rightarrow qh) < 0.79\%$, with 25 fb^{-1} of data at $\sqrt{s} = 7 \& 8 \text{ TeV}$ [22]. The limit set by the CMS collaboration is $\text{Br}(t \rightarrow qh) < 0.56\%$ using 19.5 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$ [24]. In the future high luminosity phase of the LHC, an improvement up to the 10^{-5} level for $\text{Br}(t \rightarrow cV)$ ($V = \gamma, Z$), and $10^{-4} - 10^{-5}$ for $\text{Br}(t \rightarrow ch)$ is expected [26, 27].

We assume that the discovered 125 GeV Higgs boson corresponds to the lightest CP-even state. The coupling of it to the massive gauge vector bosons shows a SM-like strength which

implies $\cos \tilde{\alpha} \simeq 1$. The question about how large the enhancements of the flavour-changing top decay rates can be, compared with the SM predictions, is analyzed within the parameter space of the A2HDM with the following assumptions and constraints:

- The LHC and Tevatron's combined Higgs data set the limit $\cos \tilde{\alpha} > 0.9$ (68% CL) and $|y_f^h| \sim 1$ ($f = u, d, l$) [14, 18]. We choose $\cos \tilde{\alpha} = 1$ so that the alignment parameters are independent of the 125 GeV Higgs data [14, 18].
- The measurement of $\text{Br}(\bar{B} \rightarrow X_s \gamma)$ puts bounds on ζ_u and ζ_d [6, 7].
- The constraints from the $Z \rightarrow \bar{b}b$ decay and the $B_{s,d}^0 - \bar{B}_{s,d}^0$ mixings imply the alignment parameter $|\zeta_u| \leq 2$ [6]. The parameters $\zeta_{d,\ell}$ are taken $|\zeta_{d,\ell}| \leq 50$ as in ref. [7].
- The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have excluded $M_{H^\pm} \lesssim 80$ GeV (95% CL) in the framework of 2HDMs [29].
- Taking into account the limits provided by the ATLAS, CMS and Tevatron collaborations [32, 33, 34] on a light charged Higgs via the decay $t \rightarrow H^+ b$, a bound on the Yukawa combination $|\zeta_u \zeta_d|$ is derived which, although being weaker than the one from $\text{Br}(\bar{B} \rightarrow X_s \gamma)$, basically excludes one of the two possible strips allowed by the latter [18].
- We take into account the perturbativity bound on the quartic scalar couplings $|\lambda_{3,7}| \leq 4\pi$ [14]. The decay $h \rightarrow \gamma\gamma$ is sensitive to λ_3 and λ_7 through the charged Higgs contribution to this process [14, 18]. We include in our analysis the latest measurements of the Higgs signal strengths in the $h \rightarrow \gamma\gamma$ channel by CMS [28] and ATLAS [35].

Taking into account the above constraints, we scan the parameter space spanning over $\{\zeta_u, \zeta_d, \zeta_l, \lambda_3\}$. We obtain the upper bounds on $\text{Br}(t \rightarrow cV)$ ($V = \gamma, Z$) and $\text{Br}(t \rightarrow ch)$ for benchmark values of the charged Higgs mass shown in table 1 [20]. The direct searches of a charged Higgs at the LHC via top decays put stringent limits on the parameter ζ_d within the mass range $90 \text{ GeV} < M_{H^\pm} < 150 \text{ GeV}$, providing $|\zeta_d| \lesssim 10$. This means a very strong suppression of the decay rates. For $M_{H^\pm} < 90 \text{ GeV}$, the combined data of LHC and Tevatron provide a weaker bound, $|\zeta_d| \lesssim 25$. Thus, the processes $\text{Br}(t \rightarrow cV)$ are well beyond the reach of the high luminosity LHC for upper bounds obtained within the A2HDM [27]. Similar conclusions were obtained in refs. [36, 37] within the framework of 2HDMs with NFC.

Now, we discuss especially the predictions of the decay rate $t \rightarrow ch$. This process could obtain a larger enhancement due to the intermediate charged Higgs contribution involving the cubic Higgs coupling $\lambda_{H^+H^-}^h$. The largest decay rate of $\text{Br}(t \rightarrow ch)$ occurs when the cubic scalar coupling $\lambda_{H^+H^-}^h$ saturates either the $h \rightarrow 2\gamma$ limits or the perturbativity bound [20]. The diagram which involves cubic Higgs coupling $\lambda_{H^+H^-}^h$ dominates the decay amplitude of this process. The contribution from this diagram is proportional to $\zeta_u \zeta_d \lambda_{H^+H^-}^h$ and $\zeta_d^2 \lambda_{H^+H^-}^h$. The first term $\zeta_u \zeta_d \lambda_{H^+H^-}^h$ is bounded to a small magnitude by $\text{Br}(\bar{B} \rightarrow X_s \gamma)$. However, as can be observed from the term $\zeta_d^2 \lambda_{H^+H^-}^h$, a large enhancement can occur for large $|\zeta_d|$ values. The limits from direct charged Higgs searches via top decays at the LHC allow such large values of $|\zeta_d|$ outside the window $90 \text{ GeV} < M_{H^\pm} < 160 \text{ GeV}$.

Prior to the Higgs discovery, it was found that a light charged Higgs could enhance considerably the decay rate of $t \rightarrow ch$ within the type-II 2HDM for large values of $\tan \beta$ and the cubic

Table 1: Upper bounds on $\text{Br}(t \rightarrow cV)$ ($V = \gamma, Z$) and $\text{Br}(t \rightarrow ch)$ in the CP-conserving A2HDM [20].

M_{H^\pm} [GeV]	$\text{Br}(t \rightarrow c\gamma)$	$\text{Br}(t \rightarrow cZ)$	$\text{Br}(t \rightarrow ch)$
100	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-13}$	$\lesssim 6 \times 10^{-9}$
200	$\lesssim 10^{-10}$	$\lesssim 3 \times 10^{-11}$	$\lesssim 3 \times 10^{-8}$
300	$\lesssim 10^{-11}$	$\lesssim 5 \times 10^{-12}$	$\lesssim 2 \times 10^{-8}$
400	$\lesssim 2 \times 10^{-12}$	$\lesssim 2 \times 10^{-12}$	$\lesssim 5 \times 10^{-9}$
500	$\lesssim 10^{-12}$	$\lesssim 10^{-12}$	$\lesssim 2 \times 10^{-9}$
Exp. limit	$< 1.8 \times 10^{-3}$ [25]	$< 5 \times 10^{-4}$ [23]	$< 5.6 \times 10^{-3}$ [24]

Higgs coupling $\lambda_{H^+H^-}^h$, and even touch the level of the expected sensitivity at the high luminosity LHC: $\text{Br}(t \rightarrow ch) \sim 10^{-5}$ [36, 37]. However, the current measurements of the 125 GeV Higgs signal strengths in the di-photon channel set a stringent limit on the size of the cubic Higgs coupling $\lambda_{H^+H^-}^h$ for a light charged Higgs. Therefore, the allowed enhancements of $\text{Br}(t \rightarrow ch)$ cannot be as large as previously speculated. After including constraints from the measurements of the 125 GeV Higgs properties, searches for a light charged Higgs via top decays, and the flavour physics, the largest decay rate is obtained for M_{H^\pm} being slightly below 90 GeV, $\text{Br}(t \rightarrow ch) \lesssim 2 \times 10^{-7}$ [20].

4. Conclusion

In this article, we have presented complete one-loop results for flavour-changing top decays ($t \rightarrow c\gamma$, $t \rightarrow cZ$, $t \rightarrow c\phi_j^0$), within the A2HDM where $\phi_j^0 = \{h, H, A\}$ represents any of the neutral scalar mass eigenstates [20]. These processes are highly suppressed in the SM which makes them out of the reach of the high-luminosity phase of the LHC. We have investigated the possible enhancements of the branching ratios of these decays within the A2HDM. We have taken into account constraints coming from the measurements of the 125 GeV Higgs properties, searches for a light charged Higgs via top decays, and the flavour physics. Assuming that the 125 GeV Higgs-like boson corresponds to the lightest CP-even state h of the CP-conserving A2HDM, we conclude that $t \rightarrow cV$ ($V = \gamma, Z$) and $t \rightarrow ch$ remain well below the expected sensitivity of the high luminosity LHC, across all of the parameter space considered [20].

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