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Charming Top Decays with a Flavor Changing Neutral Higgs Boson at Hadron Colliders

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We investigate the prospects for discovering a top quark decaying into one light Higgs boson (h^0) along with a charm quark in top quark pair production at the CERN Large Hadron Collider (LHC) and future hadron colliers. A general two Higgs doublet model is adopted to study the signature of flavor changing neutral Higgs (FCNH) interactions with $t \to ch^0$, followed by $h^0 \to WW^* \to \ell^+\ell^-, \ell = e, \mu$. We study the discovery potential for the FCNH signal and physics background from dominant processes with realistic acceptance cuts and tagging efficiencies. Promising results are found for the LHC running at 13 TeV or 14 TeV collision energies as well as future pp colliders at 27 TeV or 100 TeV.

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1. Introduction

In the Standard Model (SM) there is one Higgs doublet that generates masses for vector bosons and fermions. There are no tree-level flavor changing neutral currents (FCNC) mediated by gauge bosons or by Higgs boson. The fact that the Higgs boson (h^0) is lighter than the top quark ($m_t > M_h$) makes it possible for the top quark to decay into the Higgs boson along with a charm quark kinematically. At the one loop level, the branching fraction of $t \to ch^0$ is approximately 3×10^{-15} [2]. If this decay mode is detected, it would indicate new physics beyond the Standard Model.

A general two Higgs doublet model (2HDM) usually contains flavor changing neutral Higgs (FCNH) interactions if there is no discrete symmetry to turn off tree-level FCNC [3, 4]. In 1991, it was pointed out that top-charm FCNH coupling could be prominent [5] if the couplings of fermions and the Higgs boson are comparable to the geometric mean of their mass [6]. A special two Higgs doublet model for the top quark (T2HDM) [7] might provide a reasonable explanation why the top quark is much more massive than other elementary fermions. In the T2HDM, top quark is the only elementary fermion acquiring its mass from a special Higgs doublet (ϕ_2) with a large vacuum expectation value ($v_2 \gg v_1$). Since the up and charm quarks couple to another Higgs doublet (ϕ_1), there are FCNH interactions among the up-type quarks.

In a general 2HDM, there are five physical Higgs bosons: two CP-even scalars h^0 (lighter) and H^0 (heavier), a CP-odd pseudoscalar (A^0), and a pair of singly charged Higgs bosons ($H^\pm$). To study FCNH interactions in a general 2HDM, we employ the following Lagrangian with Higgs bosons and fermions ($F = U, D, L$) [8, 9],

$$\mathscr{L}_Y = \frac{-1}{\sqrt{2}}\bar{F}\left[(\kappa^F s_{\beta-\alpha} + \rho^F c_{\beta-\alpha})h^0 + (\kappa^F c_{\beta-\alpha} - \rho^F s_{\beta-\alpha})H^0 - i\,\mathrm{sgn}(Q_F)\rho^F A^0\right] P_R F + \mathrm{H.c.}, \tag{1.1}$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$, $c_{\beta-\alpha} = \cos(\beta-\alpha)$, $s_{\beta-\alpha} = \sin(\beta-\alpha)$, $\alpha =$ mixing angle between neutral Higgs scalars, $\tan\beta \equiv v_2/v_1$, Q_F is the fermion charge, and κ matrices are diagonal ($\kappa^F = \sqrt{2}m_F/v$) with $v \simeq 246$ GeV, while ρ matrices have diagonal and off-diagonal elements.

Most ATLAS and CMS measurements of the Higgs boson (h^0) are consistent with SM expectations [10, 11, 12]. In a general 2HDM, let us consider the light Higgs scalar (h^0) as the SM Higgs boson in the alignment limit [13, 14]. In the past few years, several theoretical studies have been completed for the charming top FCNH decay $t \to ch^0$ with (a) $h^0 \to b\bar{b}$ [15, 16], (b) $h^0 \to ZZ^*$ [17], (c) $h^0 \to \gamma\gamma$ [18], and (d) Higgs decays into multileptons [19]. Recently, the ATLAS collaboration has placed tight limits on the FCNH branching fraction for $t \to ch^0$ and the Yukawa coupling λ_{tch} with Higgs boson decaying into multileptons [20]: $\mathscr{B}(t \to ch^0) \leq 0.11\%$, and $\lambda_{tch} \leq 0.064$, for the effective Lagrangian

$$\mathscr{L}_{\mathrm{eff}} = -\frac{\lambda_{tch}}{\sqrt{2}}\bar{c}th^0 + \mathrm{H.c.}. \tag{1.2}$$

In this article, we focus on the discovery potential of the LHC in the search for the FCNH top decay $t \to ch^0$ followed by $h^0 \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$. We evaluate production rates for the signal and the physics background with optimized acceptance cuts to effectively reduce the background with realistic b-tagging and mistagging efficiencies. Promising results are presented for the LHC with $\sqrt{s} = 13$ TeV and $\sqrt{s} = 14$ TeV as well as for future hadron colliders at $\sqrt{s} = 27$ TeV and 100 TeV, for high luminosities (HL) [21] of $L = 300$ fb^{-1} and 3000 fb^{-1}.

2. The Higgs Signal and Physics Background

In this section we present the cross section for the FCNH Higgs signal in pp collisions ($pp \to t\bar{t} \to tch^0 \to bjjc\ell\ell\nu\bar{\nu} + X, \ell = e,\mu$) as well as for the dominant physics background processes.

2.1 The Higgs Signal in Top Decay

Applying the Lagrangian in Eq. [1] with general Yukawa interactions for the light Higgs boson and fermions, we obtain the decay width of $t \to ch^0$

$$\Gamma_{t\to ch^0} = \frac{c^2_{\beta-\alpha} m_t}{32\pi}\left[(1+r_c^2-r_h^2)\frac{(|\rho_{ct}|^2+|\rho_{tc}|^2)}{2} + r_c(\rho^*_{tc}\rho^*_{ct}+\rho_{tc}\rho_{ct})\right]\lambda^{1/2}(1,r_c^2,r_h^2) \tag{2.1}$$

where $c_{\beta-\alpha} = \cos(\beta-\alpha)$, $r_h = M_h/m_t$, $r_c = m_c/m_t$, and $\lambda(x,y,z) = x^2+y^2+z^2-2xy-2xz-2yz$.

For simplicity, we may adopt the following effective Lagrangian to study FCNH Yukawa interactions for the light CP-even Higgs boson (h^0) with the top quark (t) and the charm quark (c)

$$\mathscr{L} = -g_{tch}\bar{c}th^0 + \text{H.c.}, \tag{2.2}$$

where

$$g_{tch} = \frac{1}{\sqrt{2}}\tilde{\rho}_{tc}\cos(\beta-\alpha) = \frac{1}{\sqrt{2}}\lambda_{tch}, \quad \text{and} \quad \tilde{\rho}_{tc} = \sqrt{\frac{|\rho_{tc}|^2+|\rho_{ct}|^2}{2}}. \tag{2.3}$$

The decay width for $t \to ch^0$ [5] becomes

$$\Gamma(t\to c\phi^0) = \frac{|g_{tch}|^2}{16\pi}\times(m_t)\times[1+r_c^2-r_h^2]\times\sqrt{1-(r_h+r_c)^2}\sqrt{1-(r_h-r_c)^2}. \tag{2.4}$$

Let us assume that the total decay width of the top quark is

$$\Gamma_t = \Gamma(t\to bW)+\Gamma(t\to ch^0). \tag{2.5}$$

Then the branching fraction of $t \to ch^0$ becomes

$$\mathscr{B}(t\to ch^0) = \frac{\Gamma(t\to ch^0)}{\Gamma_t}. \tag{2.6}$$

We employ the programs MadGraph [23, 24] to evaluate the exact matrix element for the FCNH signal in top decays from gluon fusion and quark-antiquark annihilation,

$$\begin{aligned} gg, q\bar{q} &\to t\bar{t} \to t\bar{c}h^0 \to bjj\bar{c}\ell^+\ell^-\nu\bar{\nu}, \quad \text{and}, \\ gg, q\bar{q} &\to \bar{t}t \to \bar{t}ch^0 \to \bar{b}jjc\ell^+\ell^-\nu\bar{\nu}, \end{aligned} \tag{2.7}$$

where $\ell = e$ or μ. The cross section of the Higgs signal in FCNH top decays at the LHC and future hadron colliders for $pp \to t\bar{t} \to tch^0 \to bjjc\ell^+\ell^-\nu\bar{\nu} + X$ is evaluated with the parton distribution functions of CT14LO [25, 26] with a common value $Q = M_{t\bar{t}} =$ the invariant mass of $t\bar{t}$, for the renormalization scale (μ_R) and the factorization scale (μ_F). This choice of scale leads to a K factor of approximately 1.8 for top quark pair production. We have used the computer program Top++ [27] to evaluate higher order corrections.

In every event, we require that there should be one b jet and three light jets ($j = u,d,s,c$, or g in physics background). In addition, there are two leptons ($\ell = e$ or μ) and neutrinos, which will be lead to missing transverse energy ($\not{E}_T$). Unless explicitly specified, q generally denotes a quark (q) or an anti-quark ($\bar{q}$) and ℓ will represent a lepton (ℓ^-) or anti-lepton (ℓ^+).

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2.2 The Physics Background

The dominant physics background to the final state of $bjjc\ell^+\ell^-\nu\bar{\nu}$ comes from top quark pair production along with two light jets ($t\bar{t}jj$), $pp \to t\bar{t}jj \to b\bar{b}jjWW \to b\bar{b}jj\ell^+\ell^-\nu\bar{\nu}+X$, where every top quark decays into a $b-$quark as well as a W boson ($W \to \ell\nu$) and a b-jet is mis-identified as a c-jet. We have also considered backgrounds from (a) $t\bar{t}W$, (b) $b\bar{b}jjWW$ excluding contributions from $t\bar{t}jj$ and $t\bar{t}W$, (c) $c\bar{c}jjWW$ and (d) $jjjjWW$ where $j = u,d,s$, or g. The cross sections of physics background in pp collisions are evaluated with proper tagging and mistagging efficiencies. In our analysis, we adopt updated ATLAS tagging efficiencies [28, 29]: the b tagging efficiency is$\sim$ 70%, the probability that a c-jet is mistagged as a b-jet (ε_c) is approximately 14%, while the probability that any other jet is mistagged as a b-jet (ε_j) is 1%.

2.3 Mass Reconstruction

We search for the FCNH signal comes from top quark pair production with one top quark decaying into a charm quark and a Higgs boson ($t \to ch^0 \to cWW \to c\ell^+\nu\ell^-\bar{\nu}$) while the other decays hadronically ($t \to bW \to bjj$). In every event, there is one tagged b-jet and three light jets. Let us choose the pair of light jets that minimize $|M_{jj} - m_W|$ and $|M_{bjj} - m_t|$ as $j_1 j_2$ and label the other jet as $j_3 \simeq c$. That means, for a correctly reconstructed event, j_1 and j_2 are the products of a W decay such that their invariant mass distribution peaks at $M_{j_1 j_2} \simeq m_W$. For a background event, one b is likely coming from the top decay $t \to bW \to bjj$ while the other is either a mistagged c or a light quark jet coming from W decay, or a real b quark coming from the decay of $\bar{t}$.

To reconstruct the Higgs mass and top mass for $t \to ch^0 \to c\ell^+\ell^- + \not{E}_T$, we use cluster transverse mass $M_T(\ell\ell, \not{E}_T)$ and $M_T(c\ell\ell, \not{E}_T)$ [30, 31], defined below,

$$M_T^2(C, \not{E}_T) = \left(\sqrt{p_T^2(C) + M_C^2} + \not{E}_T \right)^2 - (\vec{p}_T(C) + \vec{\not{E}}_T)^2 \,, \tag{2.8}$$

where $C = \ell\ell$ or $C = c\ell\ell$, $p_T(\ell\ell)$ or $p_T(c\ell\ell)$ is the total transverse momentum of all the visible particles and $M_{\ell\ell}$ or $M_{c\ell\ell}$ is the invariant mass. In the cluster transverse mass distributions $d\sigma/dM_T(\ell\ell, \not{E}_T$ and $d\sigma/dM_T(c\ell\ell, \not{E}_T$ we can see broad peaks near M_h and m_t

$$M_T^*(\ell\ell, \not{E}_T) \sim M_h \,, \quad \text{and} \quad M_T^*(c\ell\ell, \not{E}_T) \sim m_t \,, \tag{2.9}$$

where M^* is the value of cluster transverse mass with a peak of the distribution. These distributions provide powerful selection tools to remove physics background while maintaining the Higgs signal.

3. Realistic Acceptance Cuts

To study the discovery potential of this charming FCNH signal from top decays at the LHC, we have applied $b-$tagging efficiencies and realistic basic cuts: (a) $p_T(b, j) > 25$ GeV, (b) $p_T(\ell_1, \ell_2) > 25, 15$ GeV, (c) $\not{E}_T > 25$ GeV, (d) $|\eta|(j, \ell)| < 2.4$, and (e) $|\Delta R(jj, \ell\ell, j\ell)| > 0.4$. In addition, we apply cuts on invariant mass of jets and cluster transverse mass of $\ell\ell$ and $c\ell\ell$ to effectively veto the background events: (a) $|M_{jj} - m_W| \leq 0.15 \times m_W$, (b) $|M_{bjj} - m_t| \leq 0.20 \times m_t$, (c) 50 GeV $\leq M_T(\ell\ell, \not{E}_T) \leq 150$ GeV, and (d) 100 GeV $\leq M_T(c\ell\ell, \not{E}_T) \leq 210$ GeV. These selection requirements remove more than 90% of the total background.

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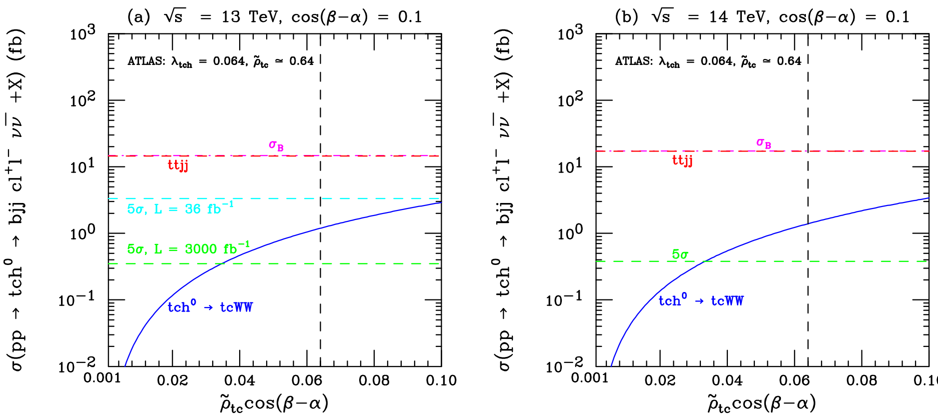

Figure 1: The cross section in fb of $pp \to t\bar{t} \to tch^0 \to bjjc\ell^+\ell^- + \not{E}_T + X$ at $\sqrt{s} = 13$ TeV and 14 TeV as a function of $\tilde{\rho}_{tc}$, as well as physics background, with all acceptance cuts, tagging and mistagging efficiencies and higher order QCD corrections.

4. Discovery Potential at the LHC

Applying all realistic cuts, we present our results for the Higgs signal at the LHC with $\sqrt{s} = 13$ TeV and $\sqrt{s} = 14$ TeV as well as cross sections for future hadron colliders with $\sqrt{s} = 27$ TeV and $\sqrt{s} = 100$ TeV for $0.01 \leq \cos(\beta - \alpha) \leq 0.2$.

To estimate the discovery potential at the LHC we include curves that correspond to the minimal cross section of signal (σ_S) required by our discovery criterion described in the following. We define the signal to be observable if the lower limit on the signal plus background is larger than the corresponding upper limit on the background with statistical fluctuations

$$\sigma_S \geq \frac{N}{L}\left[N + 2\sqrt{L\sigma_B}\right] . \tag{4.1}$$

Here L is the integrated luminosity, σ_S is the cross section of the FCNH signal, and σ_B is the background cross section. The parameter N specifies the level or probability of discovery. We take $N = 2.5$, which corresponds to a 5σ signal.

Figure 1 shows the Higgs signal cross section as a function of $\tilde{\rho}_{tc}$, along with cross section of total background and the most dominant background process ($ttjj$) for the Large Hadron Collider with $\sqrt{s}$ =13 and 14 TeV. We have also shown, minimum cross section required for 5σ significance at $L = 36.1 fb^{-1}$ and higher luminosities for HL LHC [21], i.e. $L = 300$ and 3000 fb^{-1}.

We present the 5σ discovery reach at the LHC for (a) $\sqrt{s} = 13$ TeV and (b) $\sqrt{s} = 14$ TeV in FIG. 2, in the parameter plane of $[\cos(\beta - \alpha), \tilde{\rho}_{tc}]$. We have chosen $L = 300$ and 3000 fb^{-1}. Figure 3 shows the discovery contours for $\sqrt{s}$ =27 and 100 TeV. High energy (HE) LHC with high luminosity (HL) is quite promising as it nearly covers the entire parameter space that we have used in our analysis.

5. Conclusions

It is a generic possibility of theories beyond Standard Model to have contributions to tree-level FCNH interactions, especially for the third generation quarks. These contributions arise naturally

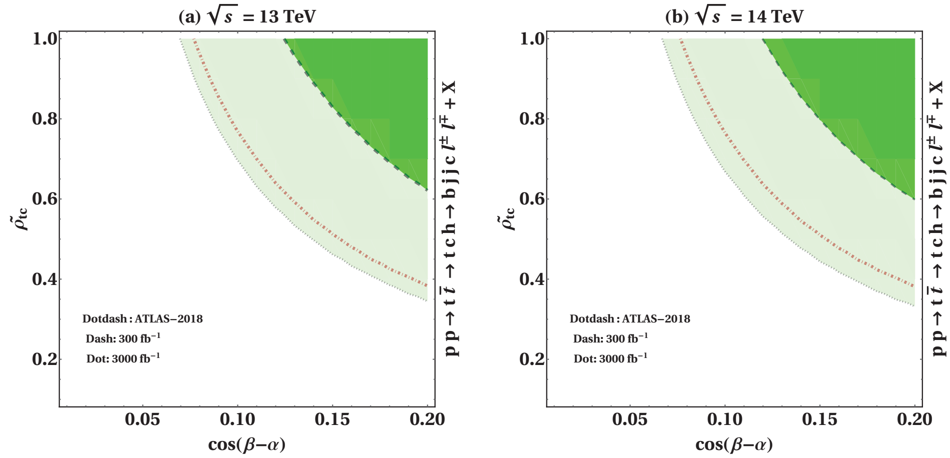

Figure 2: The 5σ discovery contours at the LHC in the plane of $[\cos(\beta-\alpha), \tilde{\rho}_{tc}]$ for (a) $\sqrt{s} = 13$ TeV and (b) $\sqrt{s} = 14$ TeV with $L = 300 fb^{-1}$ (dash) and $L = 3000 fb^{-1}$ (dot).

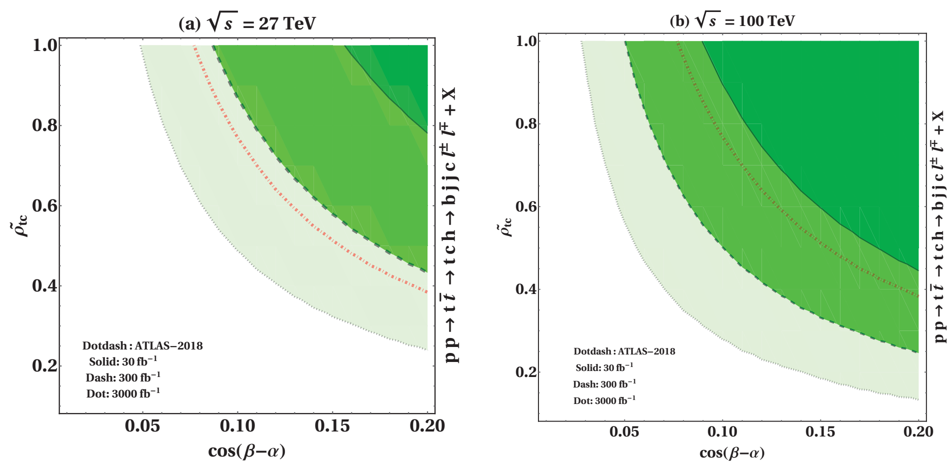

Figure 3: The 5σ discovery contours at future pp colliders in the plane of $[\cos(\beta-\alpha), \tilde{\rho}_{tc}]$ for (a) $\sqrt{s} = 27$ TeV, and (b) $\sqrt{s} = 100$ TeV, with $L = 30 fb^{-1}$ (solid), $L = 300 fb^{-1}$ (dash) and $L = 3000 fb^{-1}$ (dot).

in models with additional Higgs doublets, such as the special two Higgs doublet model for the top quark (T2HDM), or a general 2HDM. In the alignment limit, the light Higgs boson (h^0) resembles the standard Higgs boson, and it has a mass below the top mass. This could engender the rare decay $t \to ch^0$. The flavor changing heavy Higgs decays ($H^0 \to t\bar{c} + \bar{t}c$ [22] as well as $H^0 \to \tau\bar{\mu} + \bar{\tau}\mu$ [32]) and FCNH top decay ($t \to ch^0$) are complementary to search for new physics at the LHC. The coupling g_{tch} is proportional to $\cos(\beta-\alpha)$ while $g_{H\tau\mu}$ and $g_{Htc} \propto \sin(\beta-\alpha)$.

Based on our analysis, we find that LHC at $\sqrt{s} = 14$ TeV, with $L = 3000$ fb^{-1}, can probe to as low as $\mathscr{B}(t \to ch^0) \simeq 1.17 \times 10^{-3}$, $\lambda_{tch} = \tilde{\rho}_{tc} \cos(\beta-\alpha) \simeq 0.069$. It gets better with $\sqrt{s} = 27$ TeV and $\sqrt{s} = 100$ TeV, which can reach up to $\mathscr{B}(t \to ch^0) \simeq 6.1 \times 10^{-4}$, $\lambda_{tch} \simeq 0.048$ and $\mathscr{B}(t \to ch^0) \simeq 2 \times 10^{-4}$, $\lambda_{tch} \simeq 0.028$ respectively.

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