Scalar dark matter search at the LHC through flavor-changing neutral current top decay

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Phys. Rev. D **83**, 095017 — Published 23 May 2011
DOI: 10.1103/PhysRevD.83.095017

Scalar Dark Matter Search at the LHC through FCNC Top Decay

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(Dated: April 28, 2011)

We discuss an extended standard model electroweak sector which contains a stable scalar dark matter particle, the D boson. To search for the D boson at the LHC we exploit the flavor-changing neutral current (FCNC) top quark decay, $t \to cDD$, mediated by the lightest standard model-like Higgs h^0 in a two Higgs doublet model framework. The branching ratio for $t \to cDD$ in this case can be as high as 10^{-3}, after taking into account constraints arising from the D boson relic abundance. With an integrated luminosity of 10 (100) fb^{-1}, the 14 TeV LHC can explore values of this branching ratio that are one (two) order of magnitude smaller in $t\bar{t}$ production with $t\bar{t} \to c\bar{b}\ell^-(\bar{c}b\ell^+) + \not{E}_T$. For a D boson mass $\lesssim 60$ GeV, $m_{h^0} \lesssim 2M_Z$, 10 fb^{-1} luminosity and a branching ratio $BR(t \to cDD) \sim 10^{-4}$, the estimated number of signal events at the 14 TeV LHC is of order 80.

PACS numbers:

I. INTRODUCTION

A large number of direct and indirect experiments are currently underway [2–13] searching for the weakly interacting massive particle (WIMP) whose relic abundance presumably provides about 23% of the universe's energy density [1]. The successful launch of the Large Hadron Collider (LHC) at CERN provides an unparalleled opportunity to produce WIMPs in p-p collisions and infer their existence through large missing energy events. The interplay between experiments at the LHC and the direct and indirect searches will play a crucial role in identifying the WIMP dark matter particle.

It is almost universally agreed that the Standard Model (SM) offers no viable WIMP candidate, and therefore some extension of this highly successful theory is warranted. One particularly simple extension is to add a SM singlet real scalar field which yields a spin zero particle with mass on the order of the electroweak scale or less [14, 15]. An unbroken Z_2 parity, under which only the scalar field is odd, makes this spin zero particle (called D boson here) stable. For recent discussions see [16–24].

At the renormalizable level D only couples to the SM Higgs doublet. This coupling must be carefully adjusted to reproduce the required relic density of D, while making sure that constraints arising from the direct searches are not violated. However it is hard to achieve this within the SM+D framework [21, 22]. In order to obtain a consistent scenario with D boson dark matter, it is desirable to consider an extension of the SM, such as the two Higgs doublet model (2HDM) that we discuss here [21].

In this paper we propose a search for the D boson at the LHC by considering the impact D could have on rare top decays. With a total cross section $\sigma(t\bar{t}) \sim 800$ pb at LHC, a large number of $t\bar{t}$ pairs will be produced and top quark physics will be studied in great detail. In particular, flavor changing neutral current (FCNC) decays of the top quark such as $t \to ch^0(\gamma, Z, g)$, with branching fractions as low as 10^{-5} or so, can be explored [25]. In the presence of D, one could envisage FCNC processes such as $t \to ch^0 \to cDD$ which plays an important role in our discussion here. In the SM+D model, such processes arise at the loop level and are heavily suppressed. We therefore consider as a concrete example a 2HDM+D model in which the FCNC process $t \to cDD$ arises at tree level, mediated by the lightest SM-like Higgs boson h^0. A D boson with mass $\lesssim 100$ GeV in this model is a plausible dark matter candidate which is compatible with the direct searches [21, 22]. With the parameters of the model rather tightly constrained in order to achieve this, the 2HDM+D model, as we will show, gives rise to some rather unique signatures arising from $t \to cDD$ which may be detected at the LHC.

The paper is organized as follows. In Section II we describe the 2HDM+D model. The constraints from the relic abundance of D and the FCNC top decay into a pair of D's are discussed in Section III. The prospects of discovering the signal associated with this process at the LHC are outlined in Section IV. Our findings are summarized in Section V.

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II. SCALAR DARK MATTER IN TWO HIGGS DOUBLET MODEL

The renormalizable interaction of a real scalar dark matter particle D boson with two Higgs doublet fields H_1, H_2 can be written as [23]

$$-\mathcal{L}_D \ = \ \frac{\lambda_D}{4}D^4 + \frac{m_0^2}{2}D^2 + D^2(\lambda_1 H_1^\dagger H_1 + \lambda_2 H_2^\dagger H_2 + \lambda_3(H_1^\dagger H_2 + H_2^\dagger H_1)). \tag{1}$$

For simplicity, we assume that the λ_i's ($i = 1, 2, 3$) are all real. Note that an unbroken Z_2 symmetry under which $D \to -D$ has been imposed to keep the D boson stable. This requires that the vacuum expectation value of D is zero ($\langle D \rangle = 0$). Since D couples at the renormalizable level only to the Higgs doublets, it interacts weakly with the rest of SM fields and plays the role of stable WIMP dark matter. The two Higgs doublets, after electroweak symmetry breaking, have physical components $H_1^T = (-\sin\beta H^+, (v_1 + \cos\alpha H - \sin\alpha h^0 - i\sin\beta A)/\sqrt{2})$ and $H_2^T = (\cos\beta H^+, (v_2 + \sin\alpha H + \cos\alpha h^0 + i\cos\beta A)/\sqrt{2})$. Here $\tan\beta = v_2/v_1$ is the ratio of the vevs of the two Higgs doublets and α is the mixing angle of the CP-even neutral Higgs fiels [26]. With Z_2 unbroken, the D particles can only be produced or annihilated in pairs through Higgs exchange. Using the above information, we obtain the mass of D and the h^0DD interaction (note that h^0 is the SM-like Higgs in our discussion),

$$m_D^2 \ = \ m_0^2 + v^2(\lambda_1\cos^2\beta + \lambda_2\sin^2\beta + 2\lambda_3\cos\beta\sin\beta), \tag{2}$$

$$-\mathcal{L}_{h^0DD} \ = \ [-\lambda_1\cos\beta\sin\alpha + \lambda_2\sin\beta\cos\alpha + \lambda_3\cos(\beta+\alpha)]vh^0DD = \lambda_h v h^0 DD. \tag{3}$$

Here $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$, and both m_D and the effective coupling λ_h are free parameters in this model. The couplings of H and A to D are: $-\mathcal{L}_{HDD} = (\lambda_1\cos\beta\cos\alpha + \lambda_2\sin\beta\sin\alpha + \lambda_3\sin(\beta+\alpha))vHDD = \lambda_H vHDD$ and $-\mathcal{L}_{ADD} = 0$. For concreteness, in our numerical analysis we will neglect any contributions from H either by requiring a sufficiently small λ_H or an appropriately heavy mass m_H.

A two Higgs doublets extension of the SM is denoted as 2HDM I, 2HDM II and 2HDM III, where 2HDM I means that only one linear combination of H_1 and H_2 provides masses to both up and down type quarks. In 2HDM II H_1 provides masses both to down type quarks and charged leptons, and H_2 to the up quarks. Finally, in 2HDM III, both H_1 and H_2 provide masses to up and down type quarks, and charged leptons. In 2HDM I and II, the FCNC effects are generated at one loop level, and hence the FCNC top quark decay rate is too small to be detected at hadron colliders, even though it can be substantially larger than that predicted by the SM. In contrast, 2HDM III offers the possibility of a large detectable rate because of the presence of tree level FCNC. We therefore only focus on 2HDM III here, and we will refer to this model as 2HDM III+D.

The Yukawa couplings of H_1, H_2 to the fermions in this model are given by [27]

$$\begin{aligned} -\mathcal{L}_{III} \ &= \ \overline{Q_L}\lambda_1^u\widetilde{H}_1 U_R + \overline{Q_L}\lambda_2^u\widetilde{H}_2 U_R + \overline{Q_L}\lambda_1^d H_1 D_R + \overline{Q_L}\lambda_2^d H_2 D_R \\ &+ \ \overline{L_L}\lambda_1^l H_1 E_R + \overline{L_L}\lambda_2^l H_2 E_R + h.c., \end{aligned} \tag{4}$$

where $\widetilde{H}_i = i\sigma_2 H_i^*$. The coupling of the SM-like Higgs h^0 to fermions reads

$$\begin{aligned} -\mathcal{L}_{III} \ &= \ \overline{U}_L M^u U_R \frac{\cos\alpha}{v\sin\beta}h^0 - \overline{U}_L \tilde{M}^u U_R \frac{\cos(\alpha-\beta)}{v\sin\beta}h^0 - \overline{D}_L M^d D_R \frac{\sin\alpha}{v\cos\beta}h^0 \\ &+ \ \overline{D}_L \tilde{M}^d D_R \frac{\cos(\alpha-\beta)}{v\cos\beta}h^0 - \overline{E}_L M^l E_R \frac{\sin\alpha}{v\cos\beta}h^0 + \overline{E}_L \tilde{M}^l E_R \frac{\cos(\alpha-\beta)}{v\cos\beta}h^0 + h.c. \ , \end{aligned} \tag{5}$$

where $M^{u,d,l} = (\lambda_1^{u,d,l}v_1 + \lambda_2^{u,d,l}v_2)/\sqrt{2}$ denote the diagonal masses of the up and down type quarks and charged leptons. The off-diagonal entries $\tilde{M}^u = \lambda_1^u v/\sqrt{2}$ and $\tilde{M}^{d,l} = \lambda_2^{d,l}v/\sqrt{2}$ are not fixed.

In our discussion, we follow Ref. [28] and parameterize the off-diagonal entries to have the geometric mean form $\tilde{M}_{ij}^{u,d,l} = \rho_{ij}^{u,d,l}\sqrt{m_i m_j}$ with $\rho_{ij} \simeq 1$ for concreteness, and ρ_{ii} should vanish. With this parametrization for $\tilde{M}^i$, the Yukawa couplings are identical to those in MSSM, if the off-diagonal elements are set equal to zero. To simplify our analyses, we further ignore the off-diagonal elements except those involving the top quark. This parametrization, together with the assumption of a sufficiently heavy non SM-like Higgs H allows one to satisfy a variety of experimental constraints, for instance from quark flavor changing processes and rare B decays [29]. Note that the couplings of h^0 to W, Z in 2HDM III is given by

$$\mathcal{L}_{h^0WW} = \frac{2M_W^2}{v}\sin(\beta-\alpha)h^0W^2 \ , \ \ \mathcal{L}_{h^0ZZ} = \frac{M_Z^2}{v}\sin(\beta-\alpha)h^0Z^2 \ , \tag{6}$$

which will alter the Higgs decay width from its SM value.

III. DARK MATTER CONSTRAINTS AND TOP QUARK FCNC DECAY IN 2HDM+D MODEL

The annihilation of a pair of D's into SM particles proceeds through s-channel h^0 exchange. Let us first consider $DD \to h^0 \to f\bar{f}'$. We parameterize the Higgs-fermion and Higgs-D interactions as

$$-\mathcal{L}_Y = a^f_{ij} \bar{f}^i_L f^j_R h^0 + h.c. + b h^0 D^2 \ , \quad f = u, d, l \tag{7}$$

where $R(L) = (1 \pm \gamma_5)/2$. In the 2HDM III+D we have

$$\begin{aligned} a^u_{ij} &= M^u_{ij} \frac{\cos\alpha}{v \sin\beta} - \tilde{M}^u_{ij} \frac{\cos(\alpha-\beta)}{v\sin\beta}, & (8)\\ a^d_{ij} &= -M^d_{ij} \frac{\sin\alpha}{v\cos\beta} + \tilde{M}^d_{ij} \frac{\cos(\alpha-\beta)}{v\cos\beta}, & (9)\\ a^l_{ij} &= -M^l_{ij} \frac{\sin\alpha}{v\cos\beta} + \tilde{M}^l_{ij} \frac{\cos(\alpha-\beta)}{v\cos\beta}, & (10)\\ b &= \lambda_h v. & (11) \end{aligned}$$

The partial decay width of h^0 into fermions is given by

$$\Gamma(h^0 \to f\bar{f}') = \frac{1}{8\pi}[\sum_f N^c_f |a_{ff}|^2 (m^2_{h^0} - 4m^2_f)^{3/2} \frac{1}{m^2_{h^0}} + \frac{1}{m^3_{h^0}} \sum_{f\neq f'} N^c_f |a_{ff'}|^2 (m^2_{h^0} - m^2_f - m^2_{f'} - 2m_f m_{f'}) \sqrt{(m^2_{h^0} - m^2_f - m^2_{f'})^2 - 2m^2_f m^2_{f'}}], \tag{12}$$

where N^c_f is the number of colors of the f-fermion (3 for a quark and 1 for a lepton). The sum is over fermions with $m_f < m_D$. In the non-relativistic limit the total averaged annihilation rate of a DD pair is then given by

$$\langle \sigma_{ann} v_{rel} \rangle = \sigma_{ann} v_{rel} = \frac{8b^2}{(4m^2_D - m^2_{h^0})^2 + m^2_h \Gamma^2_h} \frac{\Gamma(\tilde{h}^0 \to X')}{2m_D}, \tag{13}$$

where $\Gamma(\tilde{h}^0 \to X') = \sum_i \Gamma(\tilde{h}^0 \to X_i)$, with $\tilde{h}^0$ being a "virtual" Higgs having the same couplings as the Higgs h^0 to other states, but with a mass of $2m_D$. The X_i indicates any possible decay mode of $\tilde{h}^0$. Note that the sum should also include other decay channels, for instance $h^0 \to \gamma\gamma, gg$ and $h^0 \to W^+W^-, ZZ$, if allowed by the relevant kinematics. For a given model, $\Gamma(\tilde{h}^0 \to X')$ is obtained by calculating the h^0 width and setting the mass equal to $2m_D$. In Eq. (13), v_{rel} is the average relative velocity of the two D particles. For cold dark matter the velocity is small, and therefore to a good approximation, the average relative speed of the two D's is $v_{rel} = 2p_{D_{cm}}/m_D$, and $s = (p_f + p_{\bar{f}})^2$ is equal to $4m^2_D$.

The present relic density of D is given by $\rho_D = m_D s_0 Y_\infty$, where $s_0 = 2889.2$ cm^{-3} is the present entropy density. Y_∞ is the asymptotic value of the ratio n_D/s_0, with $Y^{-1}_\infty = 0.264\sqrt{g_*} M_{Pl} m_D \langle \sigma_{ann} v_{rel} \rangle x^{-1}_f$ through the time (temperature) evolution which is obtained by solving the Boltzmann equation, where $x_f = m_D/T_f$ and T_f is the freeze-out temperature of the relic particle. The relic density can be expressed in terms of the critical density

$$\Omega_D h^2 \simeq \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{M_{Pl}} \frac{x_f}{\sqrt{g_*}} \frac{1}{\langle \sigma_{ann} v_{rel} \rangle}, \tag{14}$$

where g_* is the number of relativistic degrees of freedom with mass less than T_f. The freeze-out temperature x_f can be estimated through the iterative solution of the Boltzman equation [30]

$$x_f = \ln\left[c(c+2)\sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{M_{Pl} m_D \langle \sigma_{ann} v_{rel} \rangle}{\sqrt{g_* x_f}}\right] \simeq \ln \frac{0.038 M_{Pl} m_D \langle \sigma_{ann} v_{rel} \rangle}{\sqrt{g_* x_f}}, \tag{15}$$

where the constant c, of order unity, is determined by matching the late-time and early-time solutions, and $g(=1)$ counts the internal degrees of freedom of the dark matter particle (D).

It is important to note that in the SM+D model, a D boson mass range 10 GeV $\lesssim m_D \lesssim (50, 70)$ GeV, with a SM Higgs mass of $(120, 200)$ GeV, is ruled out by the upper limits on the WIMP-nucleon spin-independent elastic cross-section from the XENON10 and CDMSII experiments [21, 22]. However, it has been shown that the direct

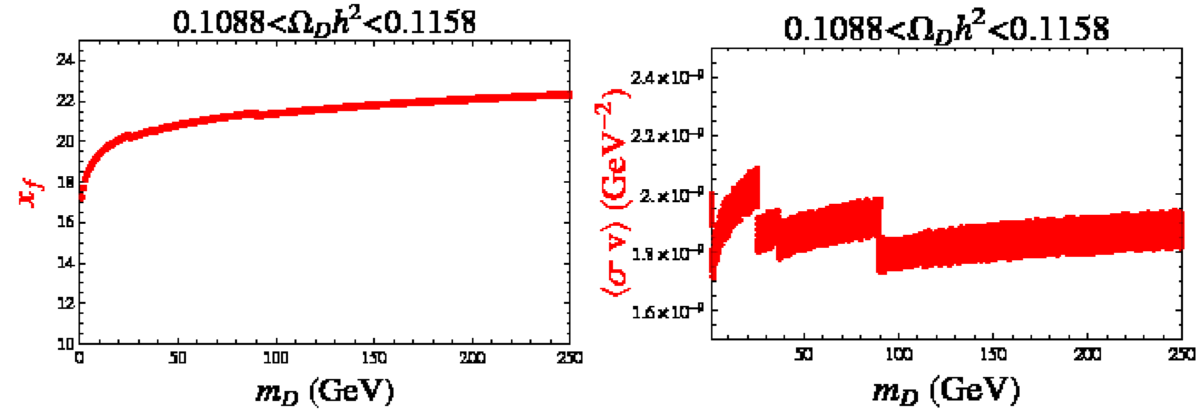

FIG. 1: x_f (left) and $\langle \sigma_{ann} v_{rel} \rangle$ (right) vs. D mass m_D with $0.108 \leq \Omega_D h^2 \leq 0.1158$ [1].

detection constraints can be evaded if the Higgs-nucleon coupling happens to be sufficiently small due to cancelations among the various contributions arising from the underlying Yukawa couplings. This can be realized in the 2HDM+D model by setting $\tan\alpha \tan\beta \simeq 0.405$, without violating the relic density constraint [21]. It is shown in Ref. [21] that by setting $\tan\alpha \tan\beta = 0.45$ in the 2HDM+D model, and for all reasonable values of the D boson mass, the D boson-nucleon elastic cross section is smaller than $\mathcal{O}(10^{-44})$ cm^2, which is the upper limit from XENON10 [2] and CDMS II [3, 4]. For $m_D \gtrsim 40$ GeV and with $m_{h^0} \gtrsim 120$ GeV, the relevant cross section is smaller than $\mathcal{O}(10^{-45})$ cm^2, which is the projected sensitivity of XENON100 [31] and SuperCDMS [32]. If $\tan\alpha \tan\beta$ is greater than about 0.52, the model with low m_D and m_{h^0} would be ruled out by XENON100 [33]. Thus, we employ $\tan\alpha \tan\beta = 0.45$ in the following analyses.

For given values of m_D and $\Omega_D h^2$, x_f and g_* and therefore also $\langle \sigma_{ann} v_{rel} \rangle$, can be determined. One can then estimate the interaction strength b in Eq. (7). In Fig. 1 we plot x_f (left panel) and $\langle \sigma_{ann} v_{rel} \rangle$ (right panel) versus m_D, with $0.108 \leq \Omega_D h^2 \leq 0.1158$ from cosmological observations [1]. In Fig. 2, we show the allowed range for the parameter $\lambda_h = b/v$ as a function of m_D for several values of Higgs mass m_{h^0}, and with $\tan\beta = 3$ and 30. The D boson mass, we note, can be as low as 1 GeV or so. Since we are interested in producing D particles and studying their properties through the FCNC top quark decay at the LHC, we limit ourselves to a D mass below 100 GeV. Note that as the D mass decreases, λ_h becomes larger. For small enough m_D, λ_h can approach unity, which may spoil the applicability of perturbative calculation. Thus, we will only consider $\lambda_h \lesssim 1$.

We next explore D-physics through the FCNC decay of top quark, where a major difference between 2HDM III+D and SM+D can show up. The decay amplitude for $f_i \to f_j DD$ is given by

$$M(f_i \to f_j DD) = \frac{2b}{s - m_h^2 + i\Gamma_h m_{h^0}} \bar{f}_j (a^f_{ji} R + a^{f*}_{ij} L) f_i. \tag{16}$$

In the SM the branching ratio $BR(t \to cDD)$ was estimated to be $\lesssim 10^{-13}$ in Ref. [23]. Using Eq. (7), the corresponding results for the 2HDM III+D model are shown in Fig. 3. We find that the branching ratio $BR(t \to cDD)$ for this case can be as large as $\sim 10^{-3}$, if $\tan\beta$ is sufficiently small $\tan\beta = 3$ and the h^0 mass is below the $h^0 \to VV$ threshold (V stands for vector bosons W and Z). With $\tan\beta = 30$, the upper limit for $BR(t \to cDD)$ is $\sim 10^{-5}$ because top quark FCNC coupling decreases for larger $\tan\beta$ values. If the h^0 mass is larger than the VV threshold, we find $BR(t \to cDD) \lesssim 10^{-5}$ for small $\tan\beta$, and $BR(t \to cDD) \lesssim 10^{-7}$ for large $\tan\beta$.

IV. OBSERVABILITY OF FCNC TOP DECAY $t \to cDD$ AT THE LHC

In the following we discuss the search for D particles through FCNC top decay at the LHC. We are interested in the $t\bar{t}$ pair production $pp \to t\bar{t}X$, with one of the top quarks decaying into a pair of D bosons through the FCNC process $t \to cDD$ (or $\bar{t} \to \bar{c}DD$). To circumvent potentially large QCD backgrounds, we require that the W boson from the second top quark decays leptonically. Consequently the process we are interested in is

$$t\bar{t} \to c\ \bar{b}\ \ell^- (\bar{c}\ b\ \ell^+) + \not{E}_T,\ \ \ell = e, \mu. \tag{17}$$

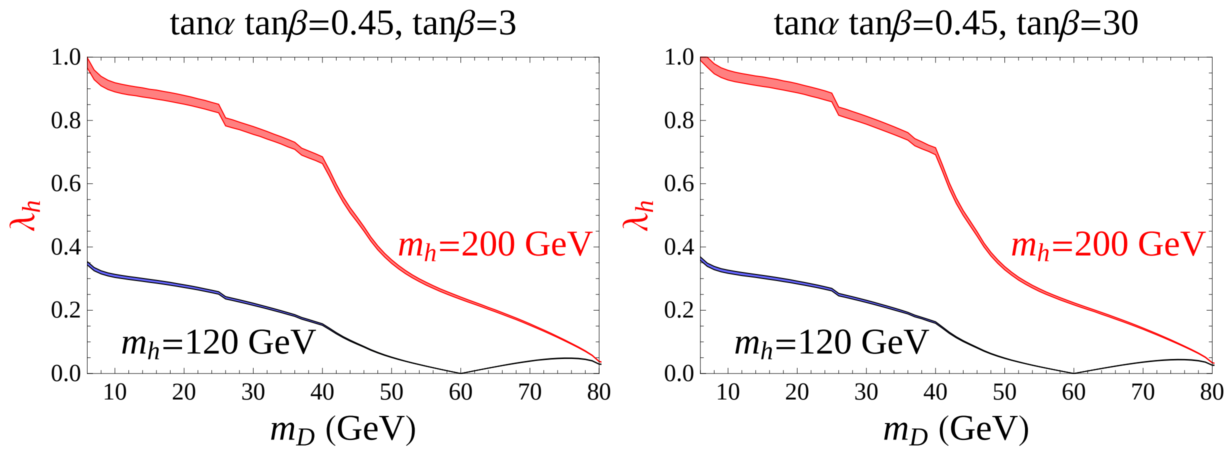

FIG. 2: λ_h in 2HDM III+D model vs. m_D with $\tan\alpha\tan\beta = 0.45$, $\tan\beta = 3$ (left) and $\tan\beta = 30$ (right), where the shaded areas are for m_{h^0} =120 and 200 GeV, respectively. In 2HDM III+D, we have assumed the physical Higgs h^0 to be much lighter than the other neutral scalar bosons.

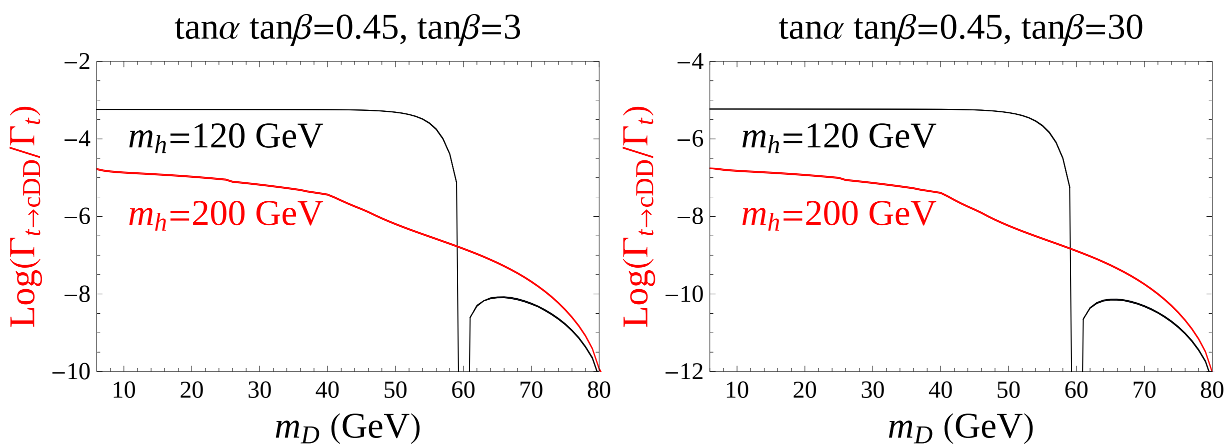

FIG. 3: The branching ratios of $t \to cDD$ in 2HDM III+D as a function of m_D with $\tan\alpha\tan\beta = 0.45$, $\tan\beta = 3$ (left) and $\tan\beta = 30$ (right). Γ_t denotes the total decay width of top quark, dominated by $t \to bW$.

The overall branching fraction is given by

$$BR(t\bar{t} \to \ell^-\ \bar{b}\ c\ (\ell^+\ b\ \bar{c}) + \not{E}_T) = 2 \times \frac{2}{9} \times BR_{t\to cDD} \times (1 - BR_{t\to cDD}), \tag{18}$$

where the factor $\frac{2}{9}$ is the leptonic decay branching ratio of the W boson.

For our numerical analyses, we adopt the CTEQ6L1 parton distribution function [34] and evaluate the SM backgrounds by using the automatic package Madgraph [35]. We work at the parton-level, but simulate the detector effects by the kinematical acceptance and employ Gaussian smearing for the electromagnetic and hadronic energies. We employ the following basic acceptance cuts for the event selection [36, 37]

$$p_T(\ell) \geq 15 \text{ GeV}, \ |\eta(\ell)| < 2.5, \tag{19}$$
$$p_T(j) \geq 25 \text{ GeV}, \ |\eta(j)| < 3.0, \tag{20}$$
$$\Delta R_{jj},\ \Delta R_{j\ell} \geq 0.4, \tag{21}$$
$$\not{E}_T \geq 30 \text{ GeV}. \tag{22}$$

To simulate the detector effects on the energy-momentum measurements, we smear the electromagnetic and jet energies

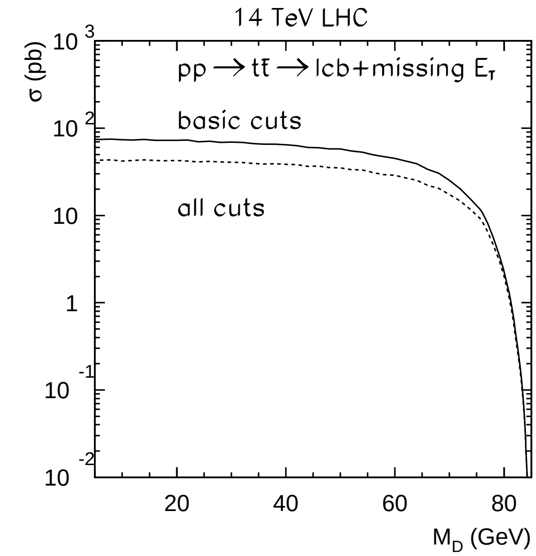

FIG. 4: Production cross section of $pp \to t\bar{t}X$ with $t\bar{t} \to \ell\ c\ b + \not{E}_T$ vs. D mass after basic cuts and M_T cut at 14 TeV LHC. Branching fractions for top quark FCNC decay $2 \times BR_{t\to cDD}(1 - BR_{t\to cDD})$ are not included while W leptonic decay rate is included.

σ(pb)	signals	$jt(\bar{t})$	$b\bar{t}(\bar{b}t)$	$jjW^{\pm}$	$jcW^{\pm} + c\bar{c}W^{\pm}$	$jbW^{\pm} + b\bar{b}W^{\pm}$	$t\bar{t}$
basic cuts	72	7.5	0.32	2.8	2.4	12.7	0.1
all cuts	44	0.03	1.6×10^{-3}	8.6×10^{-3}	0.01	0.05	0.05

TABLE I: $t\bar{t}$ production cross section with $t\bar{t} \to c\bar{b}\ell^-(\bar{c}b\ell^+) + \not{E}_T$ after basic cuts and M_T cut, assuming $m_D = 20$ GeV. Branching fractions for top quark FCNC decay $2 \times BR_{t\to cDD}(1 - BR_{t\to cDD})$ are not included, while the W leptonic decay rate is included. For comparison, the background processes are also included with the sequential cut as indicated.

by a Gaussian distribution whose width is parameterized as [36, 37]

$$\frac{\Delta E_\ell}{E_\ell} = \frac{a_{cal}}{\sqrt{E_\ell/\mathrm{GeV}}} \oplus b_{cal}, \quad a_{cal} = 10\%,\ b_{cal} = 0.7\%, \tag{23}$$

$$\frac{\Delta E_j}{E_j} = \frac{a_{had}}{\sqrt{E_j/\mathrm{GeV}}} \oplus b_{had}, \quad a_{had} = 50\%,\ b_{had} = 3\%. \tag{24}$$

In principle, the leading SM background to our signal is from the decay of W to lepton plus two jets. For instance, the leading irreducible backgrounds to our signal are $jt(\bar{t})$ and $jbW^{\pm}, b\bar{b}W^{\pm}$. Also, $t\bar{t}$ production with both W's decaying leptonically can be a reducible background if one of the charged leptons is not detected. This background should be included in our analyses when the transverse momentum and pseudo-rapidity of the lepton are in the range $p_T(\ell) < 10$ GeV and $|\eta(\ell)| > 2.5$. The SM backgrounds always come with W leptonic decays with missing neutrinos. To suppress backgrounds, we veto the events with small transverse mass of the lepton and missing energy $M_T = \sqrt{(E_{T\ell} + \not{E}_T)^2 - (\vec{p}_{T\ell} + \not{\vec{p}}_T)^2} < 90$ GeV [38]. Furthermore, we take the b-quark tagging efficiency as 50% and a probability of 0.4%(10%) for a light (c-quark) jet to be mis-identified as a b jet [36, 37]. In Fig. 4 we show the total $t\bar{t}$ production cross section, with $t\bar{t} \to c\bar{b}\ell^-(\bar{c}b\ell^+) + \not{E}_T$, versus the D mass after basic cuts and M_T cut. Assuming $m_D = 20$ GeV, we list in Table I the cross section values of our signal and SM backgrounds with basic cuts and M_T cut separately at the 14 TeV LHC. One can see that the backgrounds are substantially suppressed.

After including the appropriate branching fractions for the individual FCNC top quark decay, the expected number of events that we are interested in is given by

$$N = L \times \sigma(pp \to t\bar{t}X) \times 2 \times \frac{2}{9} \times BR_{t\to cDD} \times (1 - BR_{t\to cDD}), \tag{25}$$

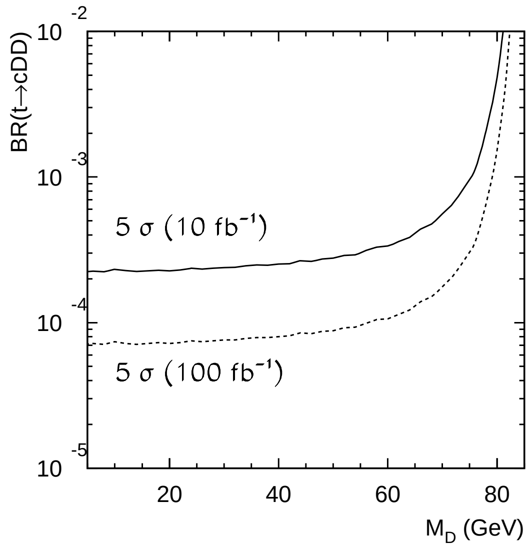

FIG. 5: The 5σ discovery limit for $BR(t \to cDD)$ through $pp \to t\bar{t}X$ with $t\bar{t} \to \ell\ c\ b + \not{E}_T$ in the BR-m_D plane at 14 TeV LHC with integrated luminosity of 10 fb^{-1} (solid) and 100 fb^{-1} (dashed), including all the judicious cuts described in the early section.

where L is the integrated luminosity. In Fig. 5 we show the 5σ signal significance obtained in terms of Gaussian statistics, given by the ratio $S/\sqrt{B}$ of signal to background events with luminosities of 10 fb^{-1} and 100 fb^{-1}. Assuming 10 fb^{-1} luminosity and $BR(t \to cDD) \gtrsim 10^{-4}$ at 14 TeV LHC, we can expect to observe more than 80 events for $m_D \lesssim 60$ GeV after including all selection cuts and detector effects. With an integrated luminosity of 10 (100) fb^{-1} and the same D mass range, one can explore branching ratios of $t \to cDD$ as low as 2×10^{-4} (7×10^{-5}) at 14 TeV LHC. The $BR(t \to cDD) > 2 \times 10^{-4} (7 \times 10^{-5})$ corresponds λ_h value around $0.1 \sim 0.3$ for $\tan\beta = 3$ and $m_{h^0} = 120$ GeV. We also estimate the signal event number to be 15 with $BR(t \to cDD) = 10^{-3}$ and 1 fb^{-1} luminosity at the 7 TeV LHC. However, one cannot get 5σ significance with less than 100 fb^{-1} luminosity at 7 TeV LHC.

V. CONCLUSION

A stable SM singlet real scalar field, called the D boson, provides a plausible cold dark matter candidate that is compatible with the relic abundance measurements. We implement this scenario in a two Higgs doublet model (type III) extension which contains tree level flavor changing decay $t \to cDD$ mediated by the lightest SM-like Higgs boson h^0. The existence of D can be explored at the LHC through this FCNC top quark decay, with a branching ratio which can approach 10^{-3} for $m_{h^0} \lesssim 2M_{W,Z}$. In $t\bar{t}$ production with $t\bar{t} \to c\ \bar{b}\ \ell^-(\bar{c}\ b\ \ell^+) + \not{E}_T$, with $m_D \lesssim 60$ GeV and an integrated luminosity of 10 (100) fb^{-1} at the 14 TeV LHC, one can reach 5σ significance with a branching ratio $BR(t \to cDD) > 2 \times 10^{-4}$ (7×10^{-5}).

Acknowledgment

We thank Tao Han for providing his Fortran codes HANLIB for our calculations. This work is supported by the DOE under grant No. DE-FG02-91ER40626.

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