Higgs FCNC $h \rightarrow t^*c$ decay at the Muon collider

G. Tetlalmatzi$^1$, J.G. Contreras$^2$, F. Larios$^2$, M.A. Pérez$^3$

$^1$Departamento de Ciencias Básicas, UPIBI-IPN, C.P. 07340, México D.F., México

$^2$Departamento de Física Aplicada, CINVESTAV-Mérida,
A.P. 73, 97310 Mérida, Yucatán, México

$^3$Departamento de Física, CINVESTAV,
A.P. 14-740, 07000, México D.F., México

We study the discovery potential of the flavor-changing neutral coupling (FCNC) $htc$ of the Higgs boson and the top quark through the rare tree-body decay $h \rightarrow Wbc$ at Muon colliders for a light Higgs boson with mass $114 \leq m_h \leq 145$ GeV. This decay mode may compete with the SM background induced by the $hWW$ coupling in some models with a tree-level $htc$ coupling and with models that predict this coupling at the one-loop level in the range $10^{-2} - 10^{-1}$. A future muon collider could test the scalar FCNC decay $t \rightarrow hc$ via Higgs decay $h \rightarrow t^*c \rightarrow bW+c$ down to values of the coupling $g_{tc} = 0.5$ (that are equivalent to BR($t \rightarrow hc) \sim 5 \times 10^{-3}$). The LHC could probe values of $g_{tc}$ one order of magnitude smaller, unless other processes beyond the SM appear that through intense multi jet activity may clutter the $t \rightarrow hc$ signal.

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I. INTRODUCTION

Top quark decays induced by flavor-changing neutral couplings (FCNC) constitute a direct and sensitive probe of new-physics effects at energy scales of a few hundred GeV $^1$ $^2$. While this type of process is highly suppressed in the Standard Model (SM) due to the GIM mechanism $^3$ $^4$, most of its extensions predict branching ratios for these decay modes that may be observable at the LHC $^5$. It has been suggested also that some Higgs-mediated FCNC top quark processes could be observed at the LHC $^6$ $^7$ and linear colliders $^8$. These processes are considered to be the most likely to shed light on the nature of the electroweak symmetry breaking mechanism if the FCNC top quark-Higgs boson couplings
are as big as expected in most models [2, 5]. Our general aim in this paper is to study the possibility of detecting the htc FCNC interaction at Muon colliders. There are studies focused on FCNC Higgs decays in this kind of colliders via its heavy lepton channels [9]. The CERN LHC is expected to discover a light Higgs boson with a mass $114 \leq m_h \leq 145$ GeV [10] and will determine some of its properties such as its fermionic and bosonic decay modes and couplings [11]. A $e^+e^-$ linear collider with a center of mass energy above 500 GeV will be able to significantly improve these preliminary measurements [12]. In particular, it has been suggested that the decay $t \rightarrow hc$ may be detected if the Higgs boson is somewhat lighter than the top quark in a linear collider with 500 fb$^{-1}$ integrated luminosity and $\sqrt{s} = 500$ GeV for models that predict branching ratios of order $10^{-4}$ for this FCNC decay mode [8]. In the present paper we address the question concerning the possibility that the FCNC htc coupling could be measured with a higher accuracy in a muon collider through the three-body decay mode $h \rightarrow t^*c \rightarrow Wbc$ for a light Higgs boson. In the SM, this decay mode is determined by the $W$ pair production channel $h \rightarrow WW^* \rightarrow Wbc$ but we expect that the htc coupling is high enough to compete with the SM contribution.

It has been estimated that a linear collider with 500 fb$^{-1}$ integrated luminosity and a center of mass energy of 500 GeV will begin to be sensitive to the htc coupling through the decay $t \rightarrow hc$ for extensions of the SM that predict branching ratios of this decay mode of order $10^{-5} - 5 \times 10^{-4}$. This correspond to a range of the htc coupling constant $\lambda_{tc}$ of order $0.06 - 0.4$ ($g_{tc}$ between 0.02 and 0.1) [8]. Models with a tree-level htc coupling have branching ratios of the order of $10^{-3} - 10^{-2}$, while models that induce this coupling at the one loop level predict branching ratios of order $10^{-5} - 10^{-4}$ for this FCNC channel [1, 2]. In particular, in the context of the MSSM the scalar $t \rightarrow hc$ decay would be greater than other channels like $t \rightarrow cg$, and SUSY-QCD effects could yield $BR(t \rightarrow hc) \sim 5 \times 10^{-4}$ [13]. Similar values are possible in the context of the two-Higgs-doublet model [14]. At the LHC, discovery limits for this decay mode were calculated in Ref. [6] and are of the order $5 \times 10^{-5}$, but the hadronic background may complicate the analysis. In the case of the muon collider, we expect that the production cross section on resonance for the chain $\mu^+\mu^- \rightarrow h \rightarrow t^*c \rightarrow Wbc$ may be high enough for some extensions of the SM in such a way that it can compete with the SM background induced by the $hWW^*$ coupling. We assume that a light Higgs boson will be observed at the LHC and examine in detail the discovery potential for its FCNC htc coupling at a Muon collider.
At the LHC, unfortunately it is quite difficult to observe the three-body decay $h \rightarrow Wbc$ due to the fact that the expected QCD background coming from 4 jet events is orders of magnitude larger than the signal coming from the $htc$ or $hWW$ vertices. In this case it will be necessary to look for the purely leptonic events in order to have a discovery channel for a light Higgs boson at the LHC [15].

II. S-CHANNEL HIGGS PRODUCTION AT THE MUON COLLIDER

A Muon collider designed with the purpose of studying the Higgs resonance with a very fined tuned center-of-mass (CM) energy equal to $m_h$ could become an effective Higgs factory where precise measurements of the Higgs mass and width could be achieved [16]. It is expected that such a machine could yield annual integrated luminosities of order $20fb^{-1}$. However, the luminosity depends on how broad the muon energy spectrum is allowed to be. Here we assume a very low (albeit supposedly feasible) energy spread of a few MeVs and an integrated luminosity of order $1fb^{-1}$.

Given the very narrow width of a light (below the $WW$ threshold) Higgs boson the production cross section is extremely sensitive to the energy of the colliding muons [16]. The Muon collider is expected to have a Gaussian shape of the energy spectrum of the colliding beams with an rms deviation

$$R = \frac{\sqrt{2}\sigma_E}{\sqrt{s}}.$$  \hfill (1)

Where $\sigma_E$ is the energy spread of the beams, and $\sqrt{s}$ is their CM energy. Notice that for $\sqrt{s} = 10^2$ GeV and $\sigma_E = 7$ MeV the rms deviation is $R = 10^{-4}$. Near the resonance region the production cross section of the s-channel process $\mu^-\mu^+ \rightarrow h \rightarrow X$ is

$$\sigma(\sqrt{s}) = \frac{4\pi\Gamma(h \rightarrow \mu^-\mu^+)\Gamma(h \rightarrow X)}{(s-m_h^2)^2 + m_h^2\Gamma_h^2}$$ \hfill (2)

where $\Gamma_h$ is the total width of the Higgs boson and $s = (p_{\mu^-} + p_{\mu^+})^2$ is the CM energy squared of the colliding muons. Neglecting Bremmstrahlung, we can write the effective cross section as the convolution of the cross section above with the Gaussian distribution of the CM energy centered at $\sqrt{s} = m_h$ [16]:

$$\bar{\sigma} = \frac{1}{\sqrt{2\pi}\sigma_E} \int \sigma(x)e^{x\sigma} \frac{1}{2\sigma_E^2} \left( x - m_h \right)^2 dx \hfill (3)$$
We can re-write the above formula as:

\[ \bar{\sigma} = \frac{4\pi}{\sqrt{\pi}} BF(h \to \mu\bar{\mu}) BF(h \to X) \frac{a^2}{Rm^2_h} \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{e^{-t^2/R^2}}{a^2 + t^2(t + 2)^2} dt \]  

(4)

where \( a \equiv \Gamma_h/m_h \) and the limits of integration \( t_{\text{max}}(t_{\text{min}}) \) have been taken as \( \pm 10^{-2} \). These limits cover all the significant contribution from the Gaussian distribution when we consider values of \( R = 10^{-4} \) and \( a \sim 10^{-4} \) for the rms deviation and the width-to-mass ratio of the light Higgs respectively.

In Fig. 1 we show the Muon collider resonant Higgs production: the two most important channels \( \mu^+\mu^- \to h \to b\bar{b} \) and \( \mu^+\mu^- \to h \to W^+W^- \) as well as the total, which is obtained by setting \( BF(h \to X) \equiv 1 \) in Eq. (4). As the Higgs mass approaches the Since the \( BF(W^- \to b\bar{c}) \) is of order \( 0.7\times|V_{cb}|^2 = 0.7\times0.04^2 \sim 10^{-3} \) we expect the \( \mu^+\mu^- \to h \to W^+b\bar{c} \) channel to be of order a few fb.

In Fig. 2 we show the resonant Higgs production cross section of a light Higgs decaying to the \( W^+b\bar{c} \) state. An additional reduction factor of order 0.6 could be used to account for Bremmstrahlung[16]. Fig. 2 shows a very small cross section of order 1 fb that would hardly yield one event with the integrated luminosity we consider. Comparing with the more general \( h \to Wjj \) decay channel the \( Wbc \) contains a CKM \( V_{cb} \) factor of order \( 10^{-3} \) that explains why this SM decay of the light Higgs is so suppressed.

In other words, the \( Wjj \) mode is \( 10^3 \) times higher and can yield a significant number of events. In fact, the \( h \to WW^* \) mode turns out to be as good probe as \( h \to bb \) even for a light Higgs (the latter is a dominant decay channel but it has a substantial background)[16].

The effective \( htc \) coupling we use is defined as:

\[ \mathcal{L} = \frac{g}{2\sqrt{2}} g_{tc} h \tilde{t}c + h.c. \]  

(5)

The effective coupling \( g_{tc} \) is very small in the SM \( g_{tc}^{SM} \sim 10^{-6} \) but could be several orders of magnitude higher in other models like the THDM where an ansatz \( g_{tc}^{SM} \sim \sqrt{m_t m_c}/M_W \sim 0.2 \) is considered assuming the FC couplings scale with the quark masses[17]. It has recently been estimated that the LHC could measure \( g_{tc} \) down to the order of 0.04[6].

In Fig. 3 we show the production cross section for the FC process \( \mu^+\mu^- \to h \to t\bar{c} \to W^+b\bar{c} \) for a range of the Higgs mass. There, the coupling \( g_{tc} \) is taken as \( g_{tc} = 1 \). For this size the contribution from the SM \( \mu^+\mu^- \to h \to WW^*c \to W^+b\bar{c} \) is about two orders of magnitude smaller. Fig. 3 does not include the SM process; if we take \( g_{tc} \) of order 0.1 the two
FIG. 1: The total $\mu^+\mu^- \rightarrow h$, $\mu^+\mu^- \rightarrow b\bar{b}$ and $\mu^+\mu^- \rightarrow h \rightarrow W^+W^-$ cross section for a Muon collider operating at $\sqrt{s} = m_h$ with an energy spread $R = 10^{-4}$ ($\Delta E \sim 7$MeV).

contributions become similar and we would have to include interference effects. However, as cross sections of order a few fb are deemed to provide too little statistics we can realize the coupling $g_{tc}$ has to be a least of order 0.5 to yield enough production. In this respect, the LHC has a much better sensitivity to this coupling than the Muon collider.

FIG. 2: The effective $\sigma(h \rightarrow W^+bc)$ cross section for a Muon collider operating at $\sqrt{s} = m_h$ with a energy spread $R = 10^{-4}$ ($\Delta E \sim 7$MeV).
III. A MUON COLLIDER VS THE LHC

As mentioned before, for a Higgs mass smaller than the Top mass, the decay $t \to h c \to b \bar{b} c$ could be used to measure the coupling $g_{tc}$. With the high statistics of top pair events at the LHC a very good sensitivity could be reached for this coupling; Ref. [6] obtained a potential limit $g_{tc} \leq 0.04$ for a total integrated luminosity of $100 \text{ fb}^{-1}$.

However, this limit could be greatly weakened if other (beyond the SM) processes came into play that would produce the same experimental signature as the one studied by Ref. [6]. Such signature is based on a final state $l \nu bb j$ where a $b \bar{b}$ pair comes from the decay of the Higgs, and the other $b$ jet (as well as the lepton and neutrino) comes from the decay of the $\bar{t}$ quark.

Let us assume that supersymmetric partners are discovered at the LHC. It is well known that multi-jet events with high missing transverse energy are among the typical signals of these new resonances. Such is the case for some mSUGRA scenarios like the test points LM1 or LM3 used by the CMS Collaboration to evaluate their physics performance (see Chapter 13 in [18]). Some of these processes have a total cross section around 50 pb that is one order of magnitude smaller than the total cross section for $t \bar{t}$ production. The analysis of Ref. [6] requires high $P_T$ for the jets, leptons and missing $P_T$, and by doing this they cut out a lot.

FIG. 3: The effective $\sigma(h \to tc \to W^+b\bar{c})$ cross section for a Muon collider operating at $\sqrt{s} = m_h$ with an energy spread $R = 10^{-4}$ ($\Delta E \sim 7\text{MeV}$).
of the $t\bar{t}$ cross section (as well as other processes with lower transverse momenta). On the other hand, such high $P_T$ cuts are not expected to affect as much mSUGRA processes which have very high transverse momenta. A detailed quantitative study of this question is beyond the scope of this paper. However, our claim is that the presence of this kind of background would not invalidate their analysis, but it would potentially weaken their limits.

IV. CONCLUSIONS

The Higgs FCNC $h \rightarrow t^* \bar{c} \rightarrow W^+ b \bar{c}$ may compete with the SM background induced by the $hWW$ coupling in some models with a tree-level $htc$ coupling and with models that predict this coupling at the one-loop level in the range $10^{-2} - 10^{-1}$. For a light Higgs boson of mass around 120 GeV a future muon collider could test the scalar FCNC decay $t \rightarrow hc$ via Higgs decay $h \rightarrow t^* c \rightarrow bW^+ c$ down to values of the coupling $g_{tc} = 0.5$ (that are equivalent to BR($t \rightarrow hc) \sim 5 \times 10^{-3}$). The LHC could probe values of $g_{tc}$ one order of magnitude smaller, unless other processes beyond the SM appear that through intense multi jet activity may clutter the $t \rightarrow hc$ signal.

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[1] W. Bernreuther, J. Phys. G35, 083001 (2008); D. Chakraborty, J. Konigsberg, D. Rainwater, Ann. Rev. Nucl. Part. Sci. 53, 301 (2003); F. Larios, R. Martinez, M.A. Perez, Int. J. Mod. Phys. A 21, 17 (2006).

[2] S. Bejar, J. Guasch and J. Sola, FCNC top quark decays beyond the standard model, in Proc. of the 5th International Symposium on Radiative Corrections (RADCOR 2000) ed. Howard E. Haber, arXiv:hep-ph/0101294; J. Guasch, W. Hollik, J. I. Illana, C. Schappacher and J. Sola,
[3] J.L. Diaz-Cruz, R. Martinez, M.A. Perez, and A. Rosado, Phys. Rev. D41, 891 (1990);
[4] G. Eilam, J.L. Hewett and A. Soni, Phys. Rev. D44, 1473 (1991); Phys. Rev. D59, 039901 (1999).
[5] A. Cordero-Cid, M.A. Perez, G. Tavares-Velasco, and J.J. Toscano, Phys. Rev. D70, 074003 (2004); F. Larios, R. Martinez, M.A. Perez, Phys. Rev. D72, 057504 (2005).
[6] J.A. Aguilar-Saavedra and G.C. Branco, Phys. Lett. B495, 347 (2000); T. Han, Int. J. Mod. Phys A23, 4107 (2008).
[7] K. Tsumura and L. Velasco-Sevilla, arXiv:0911.2149 [hep-ph].
[8] T. Han, J. Jiang, M. Sher Phys. Lett. B516, 337 (2001).
[9] J.L. Diaz-Cruz, R. Noriega-Papaqui and A. Rosado, Phys. Rev. D71, 015014 (2005); S. Kanemura, T. Ota and K. Tsumura, Phys. Rev. D73, 016006 (2006); U. Cotti, M. Pineda and G. Tavares-Velasco, hep-ph/0501162.
[10] H. Flaecher et al., Eur. Phys. J. C60, 543 (2009); The TLVNP working group, arXiv:0903.4001; M. Goebel, arXiv:0905.2488; arXiv:0811.4682.
[11] A. Belyaev, F. Maltoni and L. Reina, arXiv:hep-ph/0110274.
[12] J. A. Aguilar-Saavedra et al., arXiv:hep-ph/0106315; T. Abe et al., arXiv:hep-ex/0106056; A. Djouadi et al., arXiv:0709.1893.
[13] J. Guasch and J. Sola, Nucl. Phys. B 562, 3 (1999); S. Bejar, J. Guasch and J. Sola, JHEP 0510, 113 (2005); S. Bejar, J. Guasch and J. Sola, Nucl. Phys. Proc. Suppl. 157, 147 (2006); S. Bejar, J. Guasch, D. Lopez-Val and J. Sola, Phys. Lett. B 668, 364 (2008).
[14] S. Bejar, J. Guasch and J. Sola, Nucl. Phys. B 600, 21 (2001); S. Bejar, J. Guasch and J. Sola, Nucl. Phys. B 675, 270 (2003).
[15] R. Gonzalez Suarez [CMS Collaboration], arXiv:0810.1468 [hep-ph].
[16] V. D. Barger, M. S. Berger, J. F. Gunion and T. Han, Phys. Rept. 286, 1 (1997) arXiv:hep-ph/9602415.
[17] T.P. Cheng and M. Sher, Phys. Rev. D35, 3484 (1987).
[18] The CMS Collaboration: G.L Bayatian et al., J. Phys. G: Nucl. Part. Phys. 34 (2007) 995-1579. See also, S. Caron [ATLAS Collaboration and CMS Collaboration], [arXiv:hep-ex0810.3574].