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# Searching for $t \rightarrow ch$ with Multi-Leptons

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## Abstract

The results of a multi-lepton search conducted by the CMS collaboration with  $5 \text{ fb}^{-1}$  of data collected from 7 TeV  $pp$  collisions are used to place the first bound on the rare flavor-changing decay of the top quark to a Higgs boson and charm quark. Combining results from a number of exclusive three- and four-lepton search channels yields an estimated upper limit of  $\text{Br}(t \rightarrow ch) < 2.7\%$  for a Higgs boson mass of 125 GeV. The sensitivity of future dedicated searches for  $t \rightarrow ch$  could be improved by adding exclusive same sign di-lepton channels, as well as by sub-dividing channels based on  $b$ -quark tagging and partial kinematic top quark and Higgs boson tagging. This bound may be interpreted more widely within a range of new physics processes that yield final states with a  $W$ -boson in association with a Higgs boson. For such processes with kinematics that are similar to top-anti-top production and decay, the estimated limit on cross section times branching ratio corresponds to roughly  $\sigma \cdot \text{Br}(pp \rightarrow WhX) < 9 \text{ pb}$ .

# 1 Introduction

Once the existence of a Standard Model-like Higgs boson is established at the Large Hadron Collider (LHC) it will be possible to search for new physics produced in association with the Higgs. The myriad decay modes of the Higgs boson offer a wide range of possibilities for such searches. One attractive possibility is to focus on the leptonic final states of the Higgs boson in association with additional leptons coming from other particles accompanying the Higgs. Multi-lepton signatures originating from Standard Model production and decay of the Higgs boson itself provide considerable sensitivity [1], and in conjunction with additional leptons could provide powerful probes of non-Standard Model processes that include a Higgs.

One class of non-Standard Model processes of interest are those in which the Higgs boson appears only rarely in association with other particles. In this case, observation of a new physics process requires a large production cross section, making it fruitful to consider Standard Model processes with large production cross section. The production of top–anti-top quark pairs is particularly attractive in this respect, with a cross section of 100’s of pb at the LHC. This suggests looking for Higgs bosons in the decay products of the top quark, such as would arise through the rare neutral flavor-changing transition to a charm quark,  $t \rightarrow ch$ . In fact, no symmetry forbids this decay, but the Standard Model contribution to the branching ratio suffers both GIM and second-third generation mixing suppression and is extremely small, of order  $\text{Br}(t \rightarrow ch)_{\text{SM}} \simeq 10^{-13} - 10^{-15}$  [2, 3, 4]. Thus a positive observation of the process  $t \rightarrow ch$  well above the Standard Model rate would be a convincing indication of new physics beyond the Standard Model.

Pair production of top–anti-top followed by the rare decay  $t \rightarrow ch$  gives rise to multi-lepton final states with up to five leptons. The leading processes involve leptonic charged-current decay of one of the top quarks,  $t \rightarrow Wb$  with  $W \rightarrow \ell\nu$ , and flavor-changing decay of the other top quark,  $\bar{t} \rightarrow \bar{c}h$  with leptonic final state decay modes of the Higgs boson. These include  $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ , and  $h \rightarrow \tau\tau$  with leptonic decay of the tau-leptons,  $\tau \rightarrow \ell X$ , as well as  $h \rightarrow ZZ^* \rightarrow jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$ . Hadronic decay of one of the top quarks,  $t \rightarrow Wb$  with  $W \rightarrow jj$ , and flavor-changing decay of the other top quark,  $\bar{t} \rightarrow \bar{c}h$  with  $h \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$  also contributes. Such multi-lepton final states have relatively low Standard Model backgrounds, making them promising targets for a multi-lepton search.

To investigate the utility of searching for  $t \rightarrow ch$  in this way, we make use of the results of a multi-lepton search conducted by the CMS collaboration with  $5 \text{ fb}^{-1}$  of data collected from 7 TeV  $pp$  collisions [5] to estimate a limit on the branching ratio  $\text{Br}(t \rightarrow ch)$ . The power of this search lies in the combination of numerous exclusive channels. While any individual channel alone is not necessarily significant, the exclusive combination across multiple channels is found to provide an interesting sensitivity to  $\text{Br}(t \rightarrow ch)$  at the percent-

level. To our knowledge this is the first use of the Higgs boson as a probe for new physics in existing data.

The neutral flavor-changing decay of a top quark to the Higgs boson and charm quark,  $t \rightarrow ch$ , is of interest because it provides a direct probe of flavor violating couplings to the Higgs sector for the quark that is most strongly coupled to that sector. Previous probes of flavor violating couplings to the Higgs sector for the lighter quarks have been only indirect. It is also of general interest because up-type quark flavor violation is less well constrained than that for down-type quarks. Given that this process has not been investigated experimentally at any level previously, the percent-level bound on  $\text{Br}(t \rightarrow ch)$  obtained here begins to open up an interesting new window into flavor violating physics.

In §2 we present an effective operator analysis of the rare decay  $t \rightarrow ch$  and give the relation between the branching ratio and new physics scale of the leading operator that contributes to this process. In §3 we review multi-channel multi-lepton searches and compare the results of a CMS search with our simulation of top quark pair production and decay, including  $t \rightarrow ch$ , to obtain the first limits on  $\text{Br}(t \rightarrow ch)$  for a Standard Model-like Higgs boson. We also suggest improvements that could increase the intrinsic sensitivity of future dedicated multi-lepton searches for  $t \rightarrow ch$ . In §4 we discuss the wider applicability of this result couched in terms of a cross section times branching limit on new physics that yields final states with a  $W$ -boson in association with a Higgs boson.

It should be noted that, although throughout we refer to the flavor-violating decay of the top quark to a Higgs boson as  $t \rightarrow ch$ , since the identity of the charm quark is not integral to the analysis, the discussion and results apply more generally to the decay  $t \rightarrow Xh$  with inclusive  $X$  final states.

## 2 Effective Operator Description of $t \rightarrow ch$

New physics contributions to the flavor-violating top quark decay  $t \rightarrow ch$  may be encoded in an effective field theory description of the operators that can contribute to this process. For the field content of the minimal Standard Model, the leading coupling of the Higgs boson to up-type quarks is through the renormalizable dimension-four Yukawa coupling

$$\lambda_{ij} Q_i H \bar{u}_j + \text{h.c.} \tag{1}$$

where the quark fields are two component complex Weyl Fermions. The most relevant sub-leading interactions coupling the Higgs to up-type quarks come from dimension-six operators. Up to operator relations at this order, these may be written in terms of a single

non-renormalizable operator

$$\frac{\xi_{ij}}{M^2} H^\dagger H Q_i H \bar{u}_j + \text{h.c.} \quad (2)$$

At this order in an effective field theory expansion, both the Yukawa coupling (1) and dimension-six operator (2) contribute to the up-quark mass matrix and effective coupling to the physical Higgs boson

$$m_{ij} u_i \bar{u}_j + \lambda_{ij}^h h u_i \bar{u}_j + \text{h.c.} \quad (3)$$

where the up-quark mass matrix is given by

$$m_{ij} = \frac{v}{\sqrt{2}} \left[ \lambda_{ij} + \frac{v^2}{2M^2} \xi_{ij} \right] \equiv \frac{v}{\sqrt{2}} \lambda_{ij}^m \quad (4)$$

and where  $H^0 = \frac{1}{\sqrt{2}}(v + h)$  and  $\lambda_{ij}^m$  is the mass effective Yukawa coupling. The Higgs effective Yukawa coupling,  $\lambda_{ij}^h$ , of the physical Higgs boson to up-quarks is given at this order in the effective field theory description by the derivative of the mass matrix with respect to the Higgs expectation value

$$\lambda_{ij}^h = \frac{\partial m_{ij}}{\partial v} = \frac{1}{\sqrt{2}} \left[ \lambda_{ij}^m + \frac{v^2}{M^2} \xi_{ij} \right] \quad (5)$$

Since the mass effective Yukawa is by definition diagonal in the mass basis, flavor-violating interactions come only from the second term in parentheses in (5). The off-diagonal top-charm coupling to the Higgs boson in the effective field theory description up to dimension-six is then

$$\lambda_{tc}^h = \frac{\xi_{tc} v^2}{\sqrt{2} M^2} \quad (6)$$

Misalignment between the mass and Higgs effective Yukawa couplings,  $\lambda_{ij}^m$  and  $\lambda_{ij}^h$ , vanishes in the  $M \rightarrow \infty$  limit.

The partial decay width of the top quark to a Higgs boson and massless charm quark from the effective Higgs interaction (3) with the coupling (6) is given by

$$\Gamma(t \rightarrow ch) = \frac{|\xi_{tc}|^2 m_t}{64\pi G_F^2 M^4} \left( 1 - \frac{m_h^2}{m_t^2} \right)^2 \quad (7)$$

where  $G_F^{-1} = \sqrt{2}v^2$ . For comparison, the partial decay width of the top quark to the  $W$ -boson and massless  $b$ -quark through the minimal charged current interaction is

$$\Gamma(t \rightarrow Wb) = \frac{G_F m_t^3 |V_{tb}|^2}{8\pi\sqrt{2}} \left( 1 - \frac{m_W^2}{m_t^2} \right)^2 \left( 1 + \frac{2m_W^2}{m_t^2} \right) \quad (8)$$

Assuming  $\text{Br}(t \rightarrow Wb)$  is close to unity, the leading order branching ratio for  $t \rightarrow ch$  is then given by

$$\text{Br}(t \rightarrow ch) \simeq \frac{|\xi_{tc}|^2}{4\sqrt{2}G_F^3 m_t^2 M^4 |V_{tb}|^2} \frac{(1 - m_h^2/m_t^2)^2}{(1 - m_W^2/m_t^2)^2 (1 + 2m_W^2/m_t^2)} \quad (9)$$

For Higgs boson and top quark masses of  $m_h = 125$  GeV and  $m_t = 173.5$  GeV respectively, the numerical value of the branching ratio in terms of the dimension-six operator scale and flavor-violating Higgs effective Yukawa coupling are

$$\text{Br}(t \rightarrow ch) \simeq \left( \frac{180 \text{ GeV}}{M/\sqrt{\xi_{tc}}} \right)^4 \simeq 0.57 |\lambda_{tc}^h|^2 \quad (10)$$

### 3 A multi-lepton search for $t \rightarrow ch$

Multilepton searches at hadron colliders provide great sensitivity to new physics processes. In this work we follow and use the results of the multi-lepton search strategies adopted by the CMS collaboration [5, 6]. The sensitivity to new physics arises from dividing three- or more-lepton final states into a large number of exclusive search channels based on lepton flavor and charge combinations, hadronic activity, missing transverse energy, and the kinematic properties of the leptons in an event. We first review the details of this search strategy before applying it to obtain a bound on  $\text{Br}(t \rightarrow ch)$ .

#### 3.1 Multi-lepton signal channels

Standard Model backgrounds to multi-lepton searches for new physics are small and may be further reduced by imposing cuts on hadronic activity or missing energy. In this case hadronic activity is characterized by the variable  $H_T$ , the scalar sum of the transverse jet energies for all jets passing the preselection cuts. The missing transverse energy, MET, is given by the magnitude of the vector sum of the momenta of all reconstructed objects. Both  $H_T$  and MET are sensitive discriminating observables for new physics in a given lepton flavor and charge channel.

The CMS multilepton search [5] exploits the background discrimination of  $H_T$  and MET in the following way: Events with  $H_T > 200$  (MET  $> 50$ ) GeV are assigned HIGH  $H_T$  (MET), while those with  $H_T < 200$  (MET  $< 50$ ) GeV are assigned LOW  $H_T$  (MET). The HIGH  $H_T$  and HIGH MET requirements (individually or in combination) lead to a significant reduction in Standard Model backgrounds.<sup>1</sup>

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<sup>1</sup>It is also possible to reduce backgrounds using an  $S_T$  variable defined to be the scalar sum of MET,  $H_T$ , and leptonic  $p_T$  [5], but for simplicity we will not make use of  $S_T$  here.

Further background reduction may be accomplished with a  $Z$ -boson veto, in which the invariant mass of opposite-sign same-flavor (OSSF) lepton pairs is required to lie outside a 75 – 105 GeV window around the  $Z$  mass; we simply denote events passing the  $Z$  veto as No  $Z$ . In the case of  $3\ell$  events, it is also useful to differentiate between events with no OSSF pairs, which we denote DY0 to indicate no possible Drell-Yan pairs, and one OSSF pair which we denote DY1. Although the CMS multi-lepton analysis [5, 6] also includes channels with one or more objects consistent with hadronically decaying  $\tau$ -leptons, in this analysis we will focus our attention on  $\ell = e, \mu$  only. We do implicitly include leptonically decaying  $\tau$ -leptons in our analysis, which for all practical purposes in the detector are simply  $e$ - or  $\mu$ -leptons.

The  $3\ell$  or  $4\ell$  channels may be divided into 20 possible combinations of  $H_T$  HIGH/LOW; MET HIGH/LOW;  $Z$ /No  $Z$ ; and DY0/DY1. The 20 channels are presented in Table 1. For each of the  $3\ell$  and  $4\ell$  categories, channels are listed from top to bottom in approximately descending order of backgrounds, or equivalently ascending order of sensitivity, with the last such channel at the bottom dominated by Standard Model backgrounds. However, all channels contribute to the limit.

## 3.2 Simulation details

We closely follow the CMS multilepton analysis [5], applying the same cuts to our signal sample and making use of the CMS background estimates and observations with  $5 \text{ fb}^{-1}$  of 7 TeV  $pp$  collision data. For our signal, we simulate  $t\bar{t}$  production events with one side decaying through conventional charged current interaction via  $t \rightarrow Wb$  and the other side decaying via  $t \rightarrow ch$ . For definiteness we take  $m_h = 125 \text{ GeV}$  with Standard Model branching ratios. For simulating signal processes, we have used MadGraph v4 [7, 8] and rescaled the  $t\bar{t}$  production cross section to the NLO value  $\sigma(pp \rightarrow t\bar{t}) = 165 \text{ pb}$  at 7 TeV [9]. The Higgs boson was decayed inclusively using BRIDGE [10]. The branching ratios and total width for Higgs decay in BRIDGE were taken from the LHC Higgs Cross Section Group [11]. Subsequent showering and hadronization effects were simulated using Pythia [12]. Detector effects were simulated using PGS [13] with the isolation algorithm for muons modified to more accurately reflect the procedure used by the CMS collaboration. In particular, we introduce a `trkiso` variable for each muon [14]. The variable `trkiso` is defined to be the sum  $p_T$  of all tracks, ECAL, and HCAL deposits within an annulus of inner radius 0.03 and outer radius 0.3 in  $\Delta R$  surrounding a given muon. Isolation requires that for each muon, `trkiso`/ $p_{T_\mu}$  is less than 0.15. The efficiencies of PGS detector effects were normalized by simulating the TeV3 mSUGRA benchmark studied in [6] and comparing the signal in  $3\ell$  and  $4\ell$  channels. To match efficiencies with the CMS study

			Observed	Expected	Signal
4 Leptons					
MET HIGH	HT HIGH	No Z	0	$0.018 \pm 0.005$	0.02
MET HIGH	HT HIGH	Z	0	$0.22 \pm 0.05$	0.0
MET HIGH	HT LOW	No Z	1	$0.2 \pm 0.07$	0.11
MET HIGH	HT LOW	Z	1	$0.79 \pm 0.21$	0.04
MET LOW	HT HIGH	No Z	0	$0.006 \pm 0.001$	0.0
MET LOW	HT HIGH	Z	1	$0.83 \pm 0.33$	0.04
MET LOW	HT LOW	No Z	1	$2.6 \pm 1.1$	0.08
MET LOW	HT LOW	Z	33	$37 \pm 15$	0.15
3 Leptons					
MET HIGH	HT HIGH	DY0	2	$1.5 \pm 0.5$	0.48
MET HIGH	HT LOW	DY0	7	$6.6 \pm 2.3$	2.1
MET LOW	HT HIGH	DY0	1	$1.2 \pm 0.7$	0.26
MET LOW	HT LOW	DY0	14	$11.7 \pm 3.6$	1.68
MET HIGH	HT HIGH	DY1 No Z	8	$5 \pm 1.3$	1.54
MET HIGH	HT HIGH	DY1 Z	20	$18.9 \pm 6.4$	0.41
MET HIGH	HT LOW	DY1 No Z	30	$27 \pm 7.6$	5.8
MET HIGH	HT LOW	DY1 Z	141	$134 \pm 50$	2.0
MET LOW	HT HIGH	DY1 No Z	11	$4.5 \pm 1.5$	0.80
MET LOW	HT HIGH	DY1 Z	15	$19.2 \pm 4.8$	0.72
MET LOW	HT LOW	DY1 No Z	123	$144 \pm 36$	3.1
MET LOW	HT LOW	DY1 Z	657	$764 \pm 183$	2.4

Table 1: Observed number of events, expected number of background events, and expected number of  $t \rightarrow ch$  signal events with  $\text{Br}(t \rightarrow ch) = 1\%$  in various CMS multi-lepton channels after acceptance and efficiency for  $5 \text{ fb}^{-1}$  of 7 TeV proton-proton collisions. HIGH and LOW for MET and HT indicate  $\cancel{E}_T \gtrsim 50 \text{ GeV}$  and  $H_T \gtrsim 200 \text{ GeV}$  respectively. DY0  $\equiv \ell^\pm \ell^\mp \ell^\mp$ , DY1  $\equiv \ell^\pm \ell^+ \ell^-$ ,  $\ell'^\pm \ell^+ \ell^-$ , for  $\ell = e, \mu$ . No Z and Z indicate  $|m_{\ell\ell} - m_Z| \gtrsim 15 \text{ GeV}$  for any opposite sign same flavor pair.

we applied an efficiency correction of 0.87 per lepton to our signal events [1]. We applied preselection and analysis cuts in accordance with those used in the CMS analysis [5]. A total of 500,000 events were simulated to give good statistical coverage of all the relevant multi-lepton channels.

### 3.3 Results

The multi-lepton final states coming from  $t \rightarrow ch$  in  $t\bar{t}$  pair production arise mainly from charged current decay of one top quark,  $t \rightarrow Wb$  with  $W \rightarrow \ell\nu$ , and flavor-violating decay of the other top quark,  $\bar{t} \rightarrow \bar{c}h$ , with  $h$  decaying to final states with two or more leptons. The most relevant Higgs final states are those with two leptons that arise from  $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$  and  $h \rightarrow \tau\tau$  with leptonic decays of the tau-leptons,  $\tau \rightarrow \ell X$ , as well as  $h \rightarrow ZZ^* \rightarrow jj\ell\ell, \nu\nu\ell\ell$ . All of these decay modes give three-lepton final states. Although the total branching ratio of the Higgs to two leptons is comparable for  $h \rightarrow WW^*$  and  $h \rightarrow ZZ^*$ , leptons coming from  $Z$  and/or  $Z^*$  decays are less significant because they fall into higher-background DY1 channels with either  $Z$  or No  $Z$ . In contrast, pairs of leptons coming from  $WW^*$  decay are uncorrelated in flavor and fall into lower-background DY0 channels, in addition to the higher-background DY1 channels. There are additionally four- and five-lepton final states from charged current decay of one top quark,  $t \rightarrow Wb$  with  $W \rightarrow jj$  or  $\ell\nu$  respectively, and flavor-violating decay of the other top quark,  $\bar{t} \rightarrow \bar{c}h$ , with  $h \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ . The small total branching ratio for these final states makes them less significant than the three-lepton final states in obtaining a bound from the  $5 \text{ fb}^{-1}$  of integrated luminosity in the CMS search [5]. However, in the future with more integrated luminosity, these channels should contribute more significantly to the sensitivity for  $t \rightarrow ch$ .

The signal contributions to each of the exclusive multi-lepton channels are shown in Table 1. Events are entered in the table exclusive-hierarchically from the top to the bottom. In this way each event appears only once in the table, and in the lowest possible background channel consistent with its characteristics. The strongest limit-setting channels for  $t \rightarrow ch$  are those with three leptons. The best limits come from [MET HIGH, HT LOW, DY1 No Z], which alone constrains  $\text{Br}(t \rightarrow ch) < 3.7\%$ , and [MET HIGH, HT LOW, DY0], which constrains  $\text{Br}(t \rightarrow ch) < 4.2\%$ . In each case the lack of a reconstructed  $Z$  or OSSF lepton pair reflects the contributions from  $h \rightarrow WW^*$  and  $h \rightarrow \tau\tau$ , while the MET comes predominantly from neutrinos emitted in the  $W$  and  $\tau$ -lepton decays. Significant limits also come from the channel [MET HIGH, HT HIGH, DY1 No Z], which constrains  $\text{Br}(t \rightarrow ch) < 6.5\%$ ; and [MET LOW, HT LOW, DY0], which constrains  $\text{Br}(t \rightarrow ch) < 7.9\%$ ; these likewise reflect dominant contributions from the Higgs decays  $h \rightarrow WW^*$  and  $h \rightarrow \tau\tau$ . All other channels give constraints on the branching ratio that are weaker than 10% in an

individual channel.

Although limits may be placed on the signal from any individual channel in the multi-lepton search, the greatest sensitivity comes from combining all exclusive channels. Combining all multilepton channels, we find that the  $5 \text{ fb}^{-1}$  multi-lepton CMS results [5] yield an observed limit of  $\text{Br}(t \rightarrow ch) < 2.7\%$ , with an expected limit  $\text{Br}(t \rightarrow ch) < 1.7\%$ . This corresponds to a bound on the scale of the dimension-six effective operator (2) introduced in §2 of  $M^2/|\xi_{tc}| > (440 \text{ GeV})^2$  or equivalently on the flavor-violating Higgs Yukawa coupling (6) of  $\lambda_{tc}^h < 0.22$ . This limit represents a combined Bayesian 95% CL limit computed using the observed event counts, background estimates, and systematic errors listed in Table 1.

An upper limit on the branching ratio  $\text{Br}(t \rightarrow ch)$  can also be expressed in terms of a limit on the cross section times branching ratio  $\sigma \cdot \text{Br}(pp \rightarrow t\bar{t} \rightarrow Wbhc)$ . This is related to the cross section and branching ratio individually by  $\sigma \cdot \text{Br}(pp \rightarrow t\bar{t} \rightarrow Wbhc) \simeq \sigma(pp \rightarrow t\bar{t}) \cdot 2 \text{Br}(t \rightarrow hc)$  where the factor of two accounts for combinatorics of the top quark decay. With this, our estimate for the observed upper limit of  $\text{Br}(t \rightarrow ch) < 2.7\%$  corresponds to  $\sigma \cdot \text{Br}(pp \rightarrow t\bar{t} \rightarrow Wbhc) < 8.9 \text{ pb}$  for 7 TeV  $pp$  collisions. While this limit is specific to the acceptance and efficiency associated to top–anti-top production and decay, it does give a rough indication of the cross section times branching limit that would be obtained from the results of the CMS multi-lepton search [5] for other new physics processes  $pp \rightarrow WhX$  with similar kinematics.

The sensitivity of future dedicated multi-lepton searches for flavor-changing top quark decay  $t \rightarrow ch$  could be improved in a number of ways. The most straightforward improvement would be to include the CMS exclusive multi-lepton channels that contain  $\tau$ -leptons. For simplicity these were neglected in this study. These channels have higher backgrounds, but would contribute a bit to the overall sensitivity. Another improvement would be to sub-divide the exclusive multi-lepton channels according to whether there are tagged  $b$ -quarks in an event. The  $t \rightarrow ch$  signal has both a  $b$ - and  $c$ -quark in the final state, and so would fall primarily in the  $b$ -tagged channels. Although there is background from  $t\bar{t}$  production with fully-leptonic decay and a fake lepton in these channels, other Standard Model backgrounds from, e.g.  $WZ$  production with fully leptonic decay, would be reduced in these channels. Yet another possibility would be to incorporate exclusive same-sign dilepton channels, again with  $b$ -quark tagging sub-division [15]. Although the backgrounds in these channels are by definition larger than those of three- or more-lepton channels, this would bring in other relevant final states of the  $t\bar{t}$  signal such as charged current decay of one top quark,  $t \rightarrow Wb$  with  $W \rightarrow \ell\nu$ , and flavor-violating decay of the other top quark,  $\bar{t} \rightarrow \bar{c}h$  with  $h \rightarrow WW^* \rightarrow \ell\nu jj$ . Since the Higgs boson is neutral, the charges of the two leptons from these decays are uncorrelated and same-sign half the time. Finally, further

signal specific sub-divisions of channels could be utilized based on partial kinematic tagging information of the top quark and/or Higgs boson to isolate regions of phase space that are populated only by the signal.

We emphasize that in respect to possible improvements focused at the  $t \rightarrow ch$  signal, the current work represents a proof of principle illustrating the power of the CMS exclusive channel multi-lepton search strategy [5, 6] that may be extended for certain new physics signals by a targeted refinement of the search channels.

## 4 Conclusions

The discovery of a Standard Model-like Higgs opens the door to a plethora of new searches that employ Higgs decay products to probe new physics processes that involve Higgs boson associated production or decay. In this paper we have studied one of the simplest such processes, the rare flavor-violating top quark decay to a Higgs boson and charm quark,  $t \rightarrow ch$ . Using the results of the CMS multi-lepton search with  $5 \text{ fb}^{-1}$  of 7 TeV  $pp$  collision data [5], we obtain the estimated upper bounds of  $\text{Br}(t \rightarrow ch) < 2.7\%$  and  $\sigma \cdot \text{Br}(pp \rightarrow t\bar{t} \rightarrow Wbhc) < 8.9 \text{ pb}$  for a 125 GeV Standard Model Higgs boson with Standard Model branching ratios. Future multi-lepton searches at the LHC optimized for this signal, including  $\tau$ -lepton channels, exclusive same-sign di-lepton channels, sub-division of channels based on  $b$ -quark tagging, and with increasing integrated luminosity, should be able improve the sensitivity to  $t \rightarrow ch$  considerably.

The results presented here should be more widely applicable to a range of new physics processes that yield final states with a  $W$ -boson in association with a Higgs boson. For processes with kinematics that are similar to top–anti-top production and decay, our estimated bound from the CMS multi-lepton search [5] corresponds very roughly to  $\sigma \cdot \text{Br}(pp \rightarrow WhX) \lesssim 9 \text{ pb}$ . Just one example of many such new physics processes that are of interest is production of supersymmetric wino- or Higgsino like chargino and neutralino, either directly or from cascade decays, with decay of the chargino to a  $W$ -boson and lighter neutralino or the Goldstino, and decay of the neutralino to a Higgs boson and a lighter neutralino or the Goldstino,  $pp \rightarrow X \rightarrow \chi^\pm \chi_i^0 Y \rightarrow Wh\chi_j^0 \chi_j^0 Y$ . In many scenarios the branching ratios  $\text{Br}(\chi^\pm \rightarrow W\chi_j^0)$  and  $\text{Br}(\chi_i^0 \rightarrow h\chi_j^0)$  can approach unity [16]. While the upper limit on the cross section times branching ratio obtained above does not quite bound direct electroweak chargino–neutralino production with these decays, it would provide bounds on certain scenarios with strong superpartner production where the chargino and neutralino are emitted in cascade decays. The future improvements to exclusive channel multi-lepton searches mentioned above would improve the sensitivity also to these supersymmetric pro-

cesses with associated Higgs bosons. In particular, direct chargino-neutralino production would yield final states without  $b$ -quarks, and so would appear as signal in the  $b$ -quark anti-tagged subdivision of exclusive same sign di-lepton and multi-lepton channels.

The Higgs boson will provide a new calibration for experimental physics at high energy colliders. Higgs boson leptonic decay modes are but one of many possible applications of Higgs decays to the search for new physics.

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