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CMS Physics Analysis Summary

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Combined multilepton and diphoton limit on $t \to cH$

The CMS Collaboration

Abstract

Based on the CMS inclusive multilepton analysis and a CMS 2HDM search involving lepton and photon final states, we present a 95 % CL limit on the branching ratio of the flavor-changing decay $t \to cH$. The data sample corresponds to $19.5\,\mathrm{fb}^{-1}$ of integrated luminosity in pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment at the LHC in 2012. We find that $\mathcal{B}(t \to cH) < 0.56\,\%$, corresponding to a bound on the left- and right-handed top-charm flavor violating Higgs Yukawa couplings of $\sqrt{|\lambda^{H}_{tc}|^2 + |\lambda^{H}_{ct}|^2} < 0.14$. The observed bound is consistent with the expected bound of 0.65 %.

1 Introduction

We interpret the experimental results of two CMS searches – a search for Heavy Higgs models that uses multileptons as well as diphoton channels, and the CMS inclusive multilepton search [1, 2] – in the context of the rare flavor-changing decay of the top quark to a Higgs boson and a charm quark. The analyses are based on 19.5 fb^{-1} of integrated luminosity in pp collisions at $\sqrt{s} = 8$ TeV, collected by the CMS experiment at the LHC in 2012. Although not forbidden in the standard model (SM), the $\mathrm{t} \to \mathrm{cH}$ decay is highly suppressed in the SM due to the Glashow-Iliopoulos-Maiani mechanism and second-third generation mixing so that the SM branching ratio is quite small (10^{-13}–10^{-15}) [3]. With the relatively large production cross section of $\mathrm{t\bar{t}}$ at the LHC and the unique property of the top quark of having the largest coupling to the Higgs sector, there is strong motivation to search for flavor-changing neutral currents in top quark decay.

$\mathrm{t\bar{t}}$ production followed by one of the top quarks decaying to cH can give multilepton or diphoton final states, predominantly from the following Higgs decays ($\ell = \mathrm{e}, \mu, \tau$):

- $\mathrm{H} \to \mathrm{WW}^* \to \ell\nu\ell\nu$,
- $\mathrm{H} \to \tau\tau$,
- $\mathrm{H} \to \mathrm{ZZ}^* \to jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$,
- $\mathrm{H} \to \gamma\gamma$.

The final state with the highest sensitivity and lowest backgrounds in the search contains a b-tag from one top quark decay and a pair of photons from Higgs boson decay coming from a flavor-changing neutral current decay of the other top quark. The selection for the diphoton channels is described in HIG-13-025. For the other Higgs decay modes, we use multilepton channels that are implemented as in the SUS-13-002 analysis. This analysis recently produced a limit of $\mathcal{B}(\mathrm{t} \to \mathrm{cH}) = 1.28\,\%$ which complements the ATLAS result for the diphoton final state [4].

In the present reinterpretation, we take these multilepton channels and add the diphoton channels in order to exploit the strengths of both analyses. The description that follows is described in more detail in the references for the two analyses [1, 2].

2 Object Identification

From the about 20 proton-proton interactions per LHC bunch crossing, we select a reconstructed vertex that has highest Σp_{T}^2 of tracks associated with it. Additionally this vertex needs to be within 24 cm from the center of the detector in the z direction and within 2 cm in a direction transverse from the beam line. Several quality cuts that are used to identify leptons and photons required for the analysis, are given below.

We use electrons and muons with $p_{\mathrm{T}} \geq 10$ GeV and $|\eta| < 2.4$. They are reconstructed from measured quantities from the tracker, calorimeter, and muon system. The matching candidate tracks must satisfy quality requirements and spatially match with the energy deposits in the electromagnetic calorimeter and the tracks in the muon detectors, as appropriate. Details of reconstruction and identification can be found in [5] for electrons and in [6] for muons. Jets are reconstructed using particles with $|\eta| \leq 2.5$ via the particle-flow (PF) algorithm [7].

The hadronic tau decays yield either a single charged track (one-prong) or three charged tracks (three-prong) with or without additional electromagnetic energy from neutral pion decays as well as neutrinos. In this analysis, we use both one-prong and three-prong hadronic τ decays, reconstructed using the hadron plus strips (HPS) method [8]. We require the visible p_T of the τ to be greater than 20 GeV and $|\eta| \leq 2.3$.

Photons are reconstructed using the standard CMS procedure [9] and are selected for the analysis if $p_T \geq 20$ GeV and $|\eta| < 2.5$.

An isolation requirement strongly reduces the background from misidentified leptons or photons. We define the relative isolation I_{rel} as the ratio of the PF isolation energy in the cone defined by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the candidate object to the p_T of the object. For electrons and muons, we require $I_{rel} < 0.15$. For photons we apply a cut on the total isolation that varies slightly depending upon the p_T and η of the photon. PF isolation for leptons and photons is corrected with corrections arising due to pileup. For the isolation of the hadronic tau decays we require that the sum in a cone of $\Delta R < 0.5$ is less than 2 GeV after excluding the expected contribution from additional overlapping pp interactions in the same or preceding bunch crossing.

Leptons from decays considered in this search originate from the collision point "prompt" leptons). After the isolation selection, the most significant background sources are residual non-prompt leptons from heavy quark decays, where the lepton tends to be more isolated because of the high p_T with respect to the jet axis. This background is reduced by requiring that the leptons originate from within half a centimeter of the primary vertex in z and that the impact parameter d_{xy} between the track and the event vertex in the plane transverse to the beam axis be small: $d_{xy} \leq 0.02$ cm. The isolation and promptness criteria would retain the signal of prompt leptons, but restrict the background from misidentified leptons to the signal region.

We additionally classify events according to the amount of missing transverse energy, E_T^{miss}, which is defined as the magnitude of the vectorial sum of the momenta of all Particle Flow (PF) candidates. We also bin events depending on the presence or absence of b-tagged jets. An event is considered to contain b-jets if at least one jet passes the b-tagger which uses the medium working point of CMS Combined Secondary Vertex algorithm [10].

3 Search strategy

3.1 Multileptons

Multilepton candidate events are selected using dilepton triggers (DoubleElectron, DoubleMuon, MuEG). Candidate events therefore always contain two charged light leptons; furthermore, we require at least one additional charged lepton, irrespective of its flavor. Any candidate lepton must have $p_T > 10$ GeV and at least one of the electrons or muons must have $p_T > 20$ GeV. All τ_h must have visible $p_T > 20$ GeV. We categorize each of these multilepton candidate events into mutually exclusive search channels. Since the SM background level varies considerably depending on the event configuration and kinematics, the overall search sensitivity of the search is maximized by a detailed categorization that separates low- and high-background channels.

Events are classified by the presence of a τ_h since that increases SM background. The presence of a b-jet in the event is another search criterion because it helps segregate channels that suffer from SM $t\bar{t}$ background and also the signal from BSM models that favor the third generation.

The next criterion is whether an opposite-sign same-flavor (OSSF) dilepton pair can be made by using each identified lepton candidate only once. For example, both $\mu^+\mu^-\mu^-$ and $\mu^+\mu^-e^-$ events are OSSF1, $\mu^+\mu^+e^-$ is OSSF0. Channels with hadronic tau decays or an OSSF pair suffer from larger background contamination than OSSF0 channels.

We further classify events that have at least one OSSF pair as being "on-Z" if the reconstructed invariant mass $m_{\ell^+\ell^-}$ of any of the OSSF dilepton pairings in the event is in the Z-mass window 75 GeV $< m_{\ell\ell} <$ 105 GeV. Since there is considerably less SM background above the Z-mass window than below it, we separate the off-Z category into "above-Z" and "below-Z".

We also classify multilepton events by the hadronic activity which is measured by H_{T}, the scalar sum p_{T} of selected jets. We distinguish between H_{T} greater and less than 200 GeV since the SM backgrounds substantially belong to the latter category. Finally, based on similar logic for $E_{\mathrm{T}}^{\mathrm{miss}}$, the events are subdivided into five $E_{\mathrm{T}}^{\mathrm{miss}}$ bins, four 50 GeV-wide $E_{\mathrm{T}}^{\mathrm{miss}}$ bins from 0 to 200 GeV and the fifth for $E_{\mathrm{T}}^{\mathrm{miss}} \geq 200$ GeV.

The background is dominated by Z boson production with associated jets, in which the Z boson decays leptonically and a third lepton is a result of misidentification from a jet in the event. To estimate the rate of background contamination from such processes with two genuine leptons and a misidentified lepton, we use data with two reconstructed leptons and an additional isolated track scaled by a conversion factor between isolated tracks and selected lepton candidates from jets. This conversion factor is measured in control samples where no signal is expected to be present. Diboson (WZ, ZZ) background and background from $\mathrm{t\bar{t}}$ production is estimated using MC simulations. For further details on the background menthods, we refer to the analysis documentation [2].

3.2 Diphotons plus lepton

Candidate events in this category must have one lepton of any flavor and two photons that are compatible with a Higgs boson decay and pass all the identification and isolation requirements. The events are taken from a diphoton-triggered dataset. The leading photon must have $p_{\mathrm{T}} >$ 40 GeV and the next to leading photon should have $p_{\mathrm{T}} > 25$ GeV, while the lepton is required to have a minimum p_{T} of 10 GeV. The photon thresholds are chosen such that triggers for the particular dataset are maximally efficient. The events are then categorized into four $E_{\mathrm{T}}^{\mathrm{miss}}$ bins with lower edges at 0, 30, 50, and 100 GeV.

To determine the background, we consider the invariant mass distribution of the selected photons. The Higgs mass range, 120–130 GeV, is the signal region and excluded from the background estimate. We then use the sidebands around the Higgs mass window to fit for background shapes using a falling exponential function, and use the fit function to estimate the background contribution in the signal region. The fits are obtained from the channel with one or two hadronic taus, no light leptons, and two photons ($E_{\mathrm{T}}^{\mathrm{miss}}$ between 0–30 GeV), and applied in the diphoton plus lepton region. In this signal channel, the fit is normalized based on the ratio of the number events in the sideband region in that channel to the number of side band events from the original fit. Further details are found in [1].

4 Limit on $\mathcal{B}(\mathrm{t} \to \mathrm{cH})$

4.1 Signal Generation

For the generation of the signal, we simulated $\mathrm{t\bar{t}}$ production events with one top quark decaying to Wb and the other decaying to cH. We assume $m_{\mathrm{H}} = 126$ GeV with standard model branching ratios [11]. 500,000 signal events were generated with MADGRAPH using FastSim and the $\mathrm{t\bar{t}}$

Source of Uncertainty	Uncertainty
Luminosity	2.6 %
Initial state radiation	0–5 %
$E_{\mathrm{T}}^{\mathrm{miss}}$ Resolution correction for WZ:	∼4 %
Jet energy scale	0.5 %
B-Tag scale factor	0.1 % (WZ), 6 % ($\mathrm{t\bar{t}}$)
Muon ID/isolation at 10 (100) GeV	11 % (0.2 %)
Electron ID/isolation at 10 (100) GeV	14 % (0.6 %)
Tau ID/isolation at 10 (100) GeV	2 % (1.1 %)
$\mathrm{t\bar{t}}$ cross section	10 %
$\mathrm{t\bar{t}}$ fake contribution	50 %
WZ normalization	6 %
ZZ normalization	12 %
Fake electrons from internal conversion	50 %
Diphoton background	50 %
Monte Carlo signal statistical uncertainty	5–20 %

Table 1: Typical values of the uncertainties associated with this analysis. The $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution systematic is given for $\mathrm{WZ}(\ell\ell)$ background for different cuts on $E_{\mathrm{T}}^{\mathrm{miss}}$ and for different cuts on M_{T} given a cut of $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV.

NNLO production cross-section $\sigma(\mathrm{pp} \to \mathrm{t\bar{t}}) = 245.8\,\mathrm{pb}$ for 8 TeV [12, 13].[1] In particular, the Higgs boson was decayed exclusively to

- WW^* in 300,000 events,
- $\tau\tau$ in 100,000 events,
- ZZ^* in 50,000 events,
- $\gamma\gamma$ in 50,000 events.

For each of these Higgs decay modes, the signal samples were weighted according to the standard model Higgs branching ratios, and the efficiency of each signal region was then determined as the fraction of events being reconstructed in that signal region. Multiplying these efficiencies by cross-section, luminosity, the nominal value of $\mathcal{B}(\mathrm{t} \to \mathrm{cH}) = 1\,\%$, and an additional combinatorial factor of 2 to take account of the two top quarks finally gives the signal yields as shown in Tables 2 and 3.

4.2 Statistical procedure

Table 1 lists the salient systematic effects and the resultant uncertainties affecting this search. All channels share systematic uncertainties for luminosity, renormalization scales, and trigger efficiency. The precision in estimating lepton selection efficiencies increases with lepton p_{T}.

We do a counting experiment with several channels to compute the limit. The statistical model for the number of events in each channel is a Poisson distribution with expected value, observed value, and log-normal distributions for nuisance parameters. The significant nuisance parameters are the luminosity uncertainty, trigger efficiency, lepton identification efficiencies and background uncertainties. The expected value in the model is the sum of the signal and the expected backgrounds.

[1] To obtain more conservative results, the cross-section was reduced by $1\sigma = 10.5$ pb. This applies to all results derived in this section.

OSSF pair	$N_{\tau_{had}}$	E_T^{miss} [GeV]	H_T [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
below Z	0	50–100	0–200	≥ 1	48	48 ± 23	9.5 ± 2.3	10.3 ± 2.5
n/a	0	50–100	0–200	≥ 1	29	26 ± 13	5.9 ± 1.3	6.4 ± 1.4
below Z	0	0–50	0–200	≥ 1	34	42 ± 11	5.9 ± 1.2	6.4 ± 1.3
n/a	0	0–50	0–200	≥ 1	29	23 ± 10	4.3 ± 1.1	4.7 ± 1.2
below Z	0	50–100	> 200	≥ 1	10	9.9 ± 3.7	3.0 ± 1.1	3.3 ± 1.2
below Z	0	0–50	> 200	≥ 1	5	10 ± 2.5	2.8 ± 0.8	3.1 ± 0.9
below Z	0	50–100	0–200	0	142	125 ± 27	9.7 ± 2.1	10.6 ± 2.3
n/a	1	0–50	0–200	≥ 1	237	240 ± 113	13.1 ± 2.6	14.3 ± 2.8
n/a	0	50–100	0–200	0	35	38 ± 15	4.3 ± 1.1	4.7 ± 1.2
above Z	0	0–50	0–200	≥ 1	17	18 ± 6.7	2.8 ± 0.8	3.1 ± 0.9

Table 2: The ten most sensitive signal regions for $\mathrm{t} \to \mathrm{cH}$ where $\mathrm{H} \to \mathrm{WW}$, $\tau\tau$, or ZZ, along with the number of observed, background, and expected signal events (assuming $\mathcal{B}(\mathrm{t} \to \mathrm{cH}) = 1\,\%$), ordered by sensitivity. All signal regions shown have exactly three selected leptons. The results are binned in E_T^{miss}, H_T, the presence of a b-tag or hadronic tau, and – if applicable – the OSSF pair invariant mass with respect to the Z window. The signal efficiency of a channel is the fraction of signal events reconstructed in that channel. The uncertainties stated contain both systematic and statistical uncertainties.

$N_{\tau_{had}}$	E_T^{miss} [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
0	50–100	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39	3.1 ± 0.4
0	30–50	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30	2.4 ± 0.3
0	0–30	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24	1.9 ± 0.3
0	50–100	0	7	9.5 ± 4.4	2.22 ± 0.31	2.4 ± 0.3
0	> 100	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14	1.0 ± 0.2
0	> 100	0	1	2.2 ± 1.0	0.94 ± 0.17	1.0 ± 0.2
0	30–50	0	29	21 ± 10	1.51 ± 0.22	1.6 ± 0.2
1	30–50	≥ 1	2	2.1 ± 1.2	0.43 ± 0.09	0.5 ± 0.1
1	0–30	≥ 1	6	6.4 ± 3.3	0.48 ± 0.12	0.5 ± 0.1
1	50–100	≥ 1	1	1.5 ± 0.8	0.30 ± 0.08	0.3 ± 0.1

Table 3: The ten most sensitive signal regions for $\mathrm{t} \to \mathrm{cH}$ where $\mathrm{H} \to \gamma\gamma$ along with the number of observed, background, and expected signal events (assuming $\mathcal{B}(\mathrm{t} \to \mathrm{cH}) = 1\,\%$), ordered by sensitivity. All signal regions shown have exactly one selected light lepton or either one or two hadronic taus as well as two photons in the Higgs mass window. Furthermore, the results are binned in E_T^{miss} and the presence of a b-tag. The signal efficiency of a channel is the fraction of signal events reconstructed in that channel. The uncertainties stated contain both systematic and statistical uncertainties.

While we generally aim at using as many channels as possible, using all channels to set limits is not feasible for practical reasons. Thus, we select all but the most insensitive channels and include them in the fit to set 95% confidence level (C.L.) upper limits on $\mathcal{B}(\mathrm{t} \to \mathrm{cH})$ using the modified frequentist construction CL_s (usually referred to as LHC-type test statistic).

4.3 Result

The signal predominantly populates channels that have three leptons (no hadronic tau), no OSSF pair or an OSSF pair off Z, and a b-tag, as well as diphoton channels with a b-tag. The most sensitive multilepton channels are given in Table 2. The diphoton channels are listed in Table 3. No significant excess is observed.

Higgs Decay Mode		observed	expected	1σ range
$\mathrm{H} \to \mathrm{WW}^*$	($\mathcal{B}$ = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$\mathrm{H} \to \tau\tau$	($\mathcal{B}$ = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$\mathrm{H} \to \mathrm{ZZ}^*$	($\mathcal{B}$ = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28 %	1.17 %	(0.85–1.73) %
$\mathrm{H} \to \gamma\gamma$	($\mathcal{B}$ = 0.23 %)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons		0.56 %	0.65 %	(0.46–0.94) %

Table 4: Comparison of the observed and median expected 95% C.L. limits on $\mathcal{B}(\mathrm{t} \to \mathrm{cH})$ from individual Higgs decay modes along with the 1σ uncertainty ranges.

The limit calculations yield an observed limit of $\mathcal{B}^{\mathrm{obs}}_{95\,\%}(\mathrm{t} \to \mathrm{cH}) = 0.56\,\%$ and an expected limit of $\mathcal{B}^{\mathrm{exp}}_{95\,\%}(\mathrm{t} \to \mathrm{cH}) = (0.65^{+0.29}_{-0.19})\,\%$. The $\mathrm{t} \to \mathrm{cH}$ branching ratio is related to the left- and right-handed top flavor changing Yukawa couplings by $\mathcal{B}(\mathrm{t} \to \mathrm{cH}) \simeq 0.29\left(|\lambda^{\mathrm{H}}_{\mathrm{tc}}|^2 + |\lambda^{\mathrm{H}}_{\mathrm{ct}}|^2\right)$ [3], so that the observed limit corresponds to a limit on the couplings of $\sqrt{|\lambda^{\mathrm{H}}_{\mathrm{tc}}|^2 + |\lambda^{\mathrm{H}}_{\mathrm{ct}}|^2} < 0.14$.

To facilitate interpretation in a broader context [14], we also provide limits on $\mathcal{B}(\mathrm{t} \to \mathrm{cH})$ from individual Higgs decay modes. For this purpose, we assume the SM branching ratio for the 126 GeV Higgs decay mode under consideration, and ignore other decay modes. Table 4 shows the results, illustrating the analysis sensitivity for the $\mathrm{t} \to \mathrm{cH}$ decay in each of the Higgs decay modes. We note that, upon varying the Higgs boson mass, the limit changes by $-7\,\%/\mathrm{GeV}$ in the WW mode, by $-9\,\%/\mathrm{GeV}$ for ZZ, and by $+3\,\%/\mathrm{GeV}$ for $\tau\tau$ due to shifts in the Higgs branching ratios, while the limit from the diphoton mode remains constant within a few GeV.

5 Conclusion

We reinterpreted a diphoton and a multilepton search, focusing on regions that are sensitive to $\mathrm{t} \to \mathrm{cH}$. Given the good agreement between data and background, we place an upper limit of 0.56 % on $\mathcal{B}(\mathrm{t} \to \mathrm{cH})$, where the expected limit is 0.65 %. This is a significant improvement of the earlier limit of 1.28 % produced by the multilepton search alone.

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