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SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS

OF HIGGS BOSONS

WITH THE CMS EXPERIMENT

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SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS

OF HIGGS BOSONS

WITH THE CMS EXPERIMENT

A Dissertation

Submitted to the Graduate School

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in Partial Fulfillment of the Requirements

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SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS

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WITH THE CMS EXPERIMENT

Abstract

by

Nabarun Dev

DEDICATED TO

To my father, who taught me everything I needed to know.

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ACKNOWLEDGMENTS

I would like to acknowledge the light side of the force, Master Kenobi and Grand Master Yoda.

SYMBOLS

c	speed of light
h	Standard Model Higgs
H	Heavy Higgs
m	mass
e	elementary charge
E	energy
$\mathrm{p_T}$	Transverse Momentum
M_{col}	Collinear Mass
M_{T}	Transverse Mass

CHAPTER 1

INTRODUCTION

The Standard Model (SM) is the most well-tested and elegant description of nature available today. The discovery of the Higgs Boson in 2012 [1–3] added another feather in the hat of the SM. In the SM, elementary particles acquire mass from their interaction with the scalar Higgs field, the quantum of which is the Higgs Boson (h). This particle which had eluded particle physicists for years is a cornerstone of the SM, and in a way, was the last predicted missing piece associated with it. It was introduced, in 1964 by Brout, Englert, Higgs, Guralnik, Hagen and Kibble as a consequence of the electroweak symmetry breaking, in order to explain how elementary particles could have mass without violating the gauge invariance of the SM [4–7].

It was nearly 50 years before the h was discovered. During this period many important discoveries such as W/Z bosons (1983 at UA1/UA2 collaborations at CERN) and the top quark (1995 CDF/D0 at FermiLab) were made. The excellent performance of the Large Hadron Collider (LHC) at CERN (European Organization of Nuclear Research) in delivering proton-proton collisions, and the excellent work by the CMS (Compact Muon Solenoid) and ATLAS (A Large Toroidal Apparatus) collaborations made possible the discovery of the Higgs Boson in 2012. Although the CMS and the ATLAS are large general purpose detectors aimed at studying a wide range of physics, the discovery of the Higgs was one of their primary aims. They started collecting data in 2010, and the h discovery was made using the data collected from 2010 to 2012. In 2013, Peter Higgs and Franois Englert, two of the physicists associated with the development of the theory, were jointly awarded the Nobel Prize in Physics.

This discovery was a signficant step for particle physics, and while it put an end to the decades old search for the elusive h, it opened up a fertile sector for particle physicists to explore and understand. One of the very important tasks is to ascertain if the properties of the discovered h are indeed compatible with theoretical SM expectations. In fact, many studies since 2012 have found properties of the h such as the spin, couplings, and charge-parity (CP) assignment to be consistent with SM [8]. While more precise studies of the properties and couplings of the h is important, it also provides us with a portal to look for new physics Beyond the Standard Model (BSM). The SM, as mentioned above, is a remarkable theory that has stood the test of time. However, it is has its shortcomings and is not a complete theory. For example, the SM does not explain gravity and thus is inadequate as a candidate for an ideal "Theory of Everything". To address such shortcomings, many BSM theories have been proposed that modify the SM in such a way that they are consistent with existing observations, but at the same time try to address its imperfections. Many outcomes these theories predict are non-SM and the recently discovered h unlocks a pristine ground to look for these outcomes. In fact, the constraint on the branching fraction to non-SM decay modes of the h, derived from a combined study by CMS and ATLAS is B(non-SM) $< 34\%$ at 95% confidence level (CL) [8]. Thus, a significant contribution from exotic (non-SM) decays is allowed in the BSM Higgs sector.

One such interesting process that is forbidden in the SM but occurs in many new physics scenarios is interactions between charged leptons that violate the conservation of Lepton Flavor. In particular, Lepton Flavor Violating (LFV) decays of the h are allowed by these theories, and could be realized in decays of the h, which is neutral, into two charged leptons of different flavor. In this dissertation, we describe a search looking for LFV decay of the h into a muon (μ) and a tau lepton (τ). The tau lepton is short-lived and can further decay hadronically (τ_h) or into a electron. Since we can detect electrons better than tau leptons, the latter channel has a cleaner signature. In particular, the search described here looks for this electronic channel signature of a LFV decay of h boson, i.e. h $\rightarrow \mu\tau_e$. Indirect constraints on $h \rightarrow \mu\tau$ exist through interpretations of measurements of processes such as $\tau \rightarrow \mu\gamma$ [9]. These constraints set weak limits on such decays allowing significant branching fractions; $Br(H \rightarrow \mu\tau) < O(10\%)$ [10, 11]. A search was performed by CMS for $H \rightarrow \mu\tau$ with proton-proton collision data at center-of-mass energy of 8 TeV, collected during run I (2010-12) of the LHC. This improved the above limits by an order of magnitude to $Br(H \rightarrow \mu\tau) < O(1.51\%)$ at 95% confidence level [12]. However, an excess of events with a significance of 2.4 σ was also observed. This warrants us to do this search with a larger amount of data which would either lead us to confirm this excess, or squash it and set much stricter limits on this process. The dataset collected by the CMS detector in 2016 provides us with such an opportunity. It corresponds to proton-proton collision data at a much higher center-of-mass energy of 13 TeV and is almost two times in size of the run I dataset. Besides using this larger dataset, the analysis described in this thesis improves upon previous searches by introducing multivariate techniques.

An interesting common feature of many of the models that allow LFV decays of the h is that they predict the existence of heavy neutral higgs bosons, H(CP-even) and A(CP-odd). These are also expected to have LFV decays into charged leptons of different flavor [13]. A direct search for these channels would thus provide a complementary probe of these models. In this dissertation, we also describe such a search for heavy neutral higgs boson (H) deacying in a lepton flavor violating manner into a muon and an electronically decaying tau, .i.e H $\rightarrow \mu\tau_e$. For this search, we probe H mass (m_H) in the range $200 < m_H < 900$ GeV, and use analysis techniques similar to the h $\to \mu\tau_e$ search. This search is the first ever direct search to look for this process. In this entire document, we denote neutral heavy Higgs boson simply by H and SM Higgs boson as h.

The dissertation is devoted to the description of the h $\to \mu\tau_e$ and H $\to \mu\tau_e$ searches using the CMS experiment at the LHC. In chapter **??**, we describe theoretical background and motivations for these searches. In the next chapter (**??**), we describe the experimental apparatus used for the search, i.e. the collider (LHC) and the detector (CMS). In the following chapter (**??**), the procedure for simulation of events and reconstruction of physics objects such as electrons, muons and jets are outlined. Chapter **??** describes the strategies followed to select events with the signal signature, and to increase the percentage of signal-like events in the sample thereby increasing the sensitivity of the searches. In chapter **??**, estimation of background processes for both searches is outlined. Chapter **??** provides a description of the statistical methods used for signal extraction and setting of exclusion limits, and also the uncertainties associated with the searches. Finally, chapter 2 lays out the results of both the searches performed.

CHAPTER 2

RESULTS

In this chapter the results of both the searches are presented. The results for the $h \to \mu\tau_e$ search are first presented. Results for the $H \to \mu\tau_e$ search follow.

2.0.1 $h \to \mu\tau_e$ results

The resulting distributions of the signal variable (after applying all selection requirements as outlined in **??**) are fit using a binned maximum likelihood fit. The entire procedure is described in detail in **??**. All systematic uncertainties are included as nuisance parameters, and the fit is performed simultaneously across all categories. The BDT response distributions of signal and background are shown superimposed for each category in Fig 2.1. The distribution of M_{col} for the M_{col}-fit analysis are also shown in Fig 2.2. We do not observe an excess of signal over expected background. Hence, upper exclusion limits on $\mathcal{B}(h \to \mu\tau_e)$ are set, following the procedure described in **??**. In table 2.0.1, the median expected limits, observed limits and the best fit branching fractions for $\mathcal{B}(h \to \mu\tau_e)$ are summarized. As noted earlier in this thesis, the tau lepton coming from the Higgs can also decay hadronically. This channel of the LFV Higgs decay, i.e. $h \to \mu\tau_{\text{h}}$ is studied in an analyses by different members of the same research team [14]. The limits on $\mathcal{B}(h \to \mu\tau_{\text{h}})$ from that search are combined with limits on $\mathcal{B}(h \to \mu\tau_e)$, as calculated above from the search described here. All limits are summarized graphically in Figure 2.3. The combined observed (median expected) upper limits on $\mathcal{B}(h \to \mu\tau)$ is 0.25 (0.25) % at 95% CL, for the BDT-fit analysis. The combined best fit branching fraction of $\mathcal{B}(h \to \mu\tau)$ is found to be 0.00 ± 0.12, also for the BDT-fit analysis. It is important to note that the $2.4\,\sigma$ excess observed by the earlier CMS search with 8 TeV data [12] has now been excluded by this search.

Table 2.1: Expected and observed upper limits at 95% CL, and best fit branching fractions in percent for each individual jet category, and combined,for the $\mathrm{h} \to \mu\tau_e$ analysis.

Expected limits (%)					
	0-jet	1-jet	2-jets	VBF	Combined
BDT fit analysis	<0.83	<1.19	<1.98	<1.62	<0.59
M_{col} fit analysis	<1.01	<1.47	<3.23	<1.73	<0.75

Observed limits (%)					
	0-jet	1-jet	2-jets	VBF	Combined
BDT fit analysis	<1.30	<1.34	<2.27	<1.79	<0.86
M_{col} fit analysis	<1.08	<1.35	<3.33	<1.40	<0.71

Best fit branching fractions (%)					
	0-jet	1-jet	2-jets	VBF	Combined
BDT fit analysis	0.61 ± 0.36	0.22 ± 0.46	0.39 ± 0.83	0.10 ± 1.37	0.35 ± 0.26
M_{col} fit analysis	0.13 ± 0.43	-0.22 ± 0.75	0.22 ± 1.39	-1.73 ± 1.05	-0.04 ± 0.33
combined $\mu\tau$ (BDT fit)			0.00 ± 0.12		

The constraints on $\mathcal{B}(\mathrm{h} \to \mu\tau)$ can be transformed into constraints on Lepton Flavor Violating Yukawa Couplings $(Y_{\mu\tau}, Y_{\tau\mu})$. These couplings represent the strength of an interaction and are related to the decay width $\Gamma(\mathrm{h} \to \mu\tau)$ in the following way [11]:

$$\Gamma(\mathrm{h} \to \mu\tau) = \frac{m_h}{8\pi}(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2). \tag{2.1}$$

The decay width is also related to the branching fraction, $\mathcal{B}(\mathrm{h} \to \mu\tau)$ according

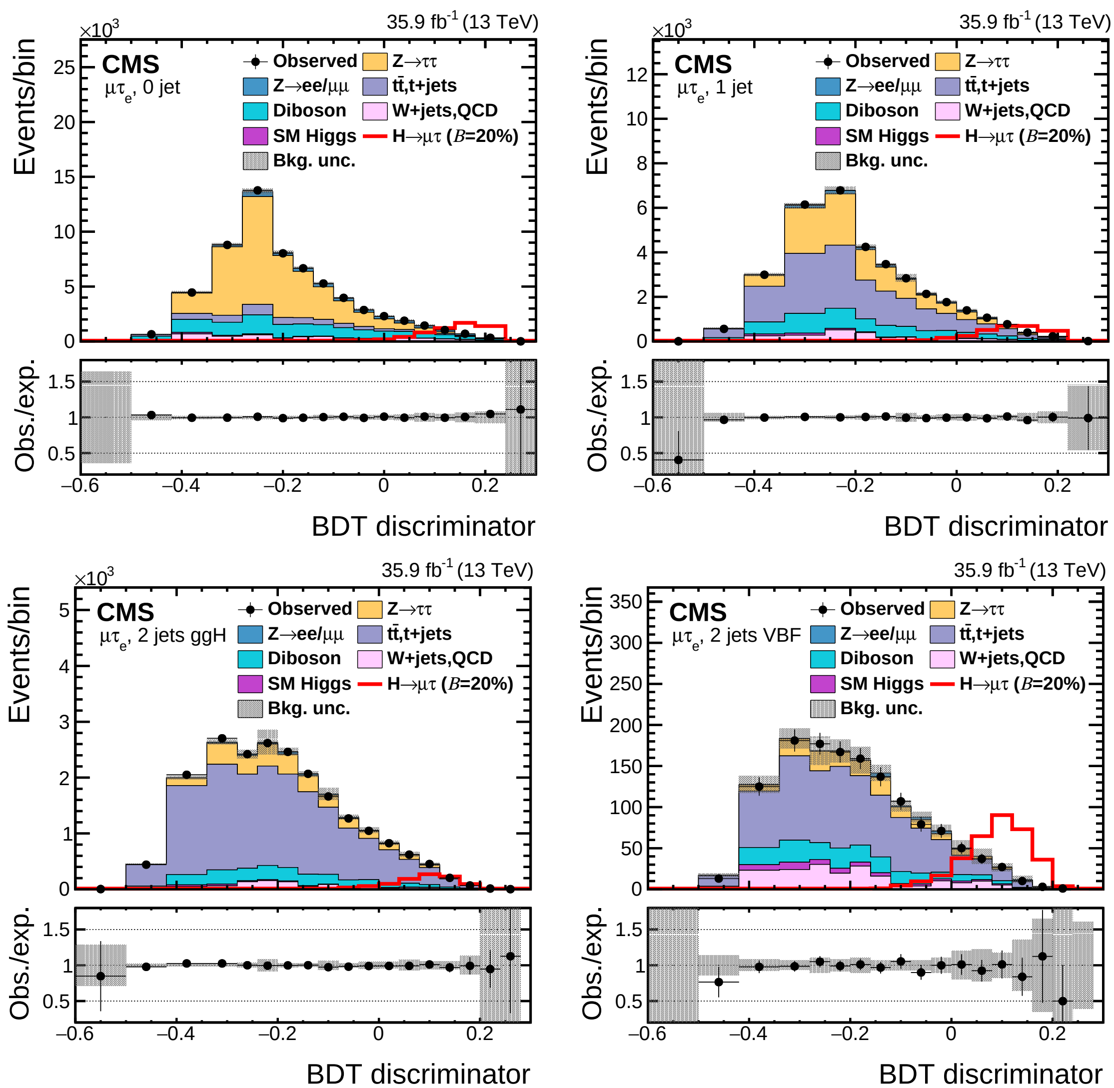

Figure 2.1: Distribution of BDT response in each category comparing signal and background estimations to observed collision data, for h $\rightarrow \mu\tau_e$ analysis. The bottom panel show the ratio of observed data and fitted background in each bin [14]

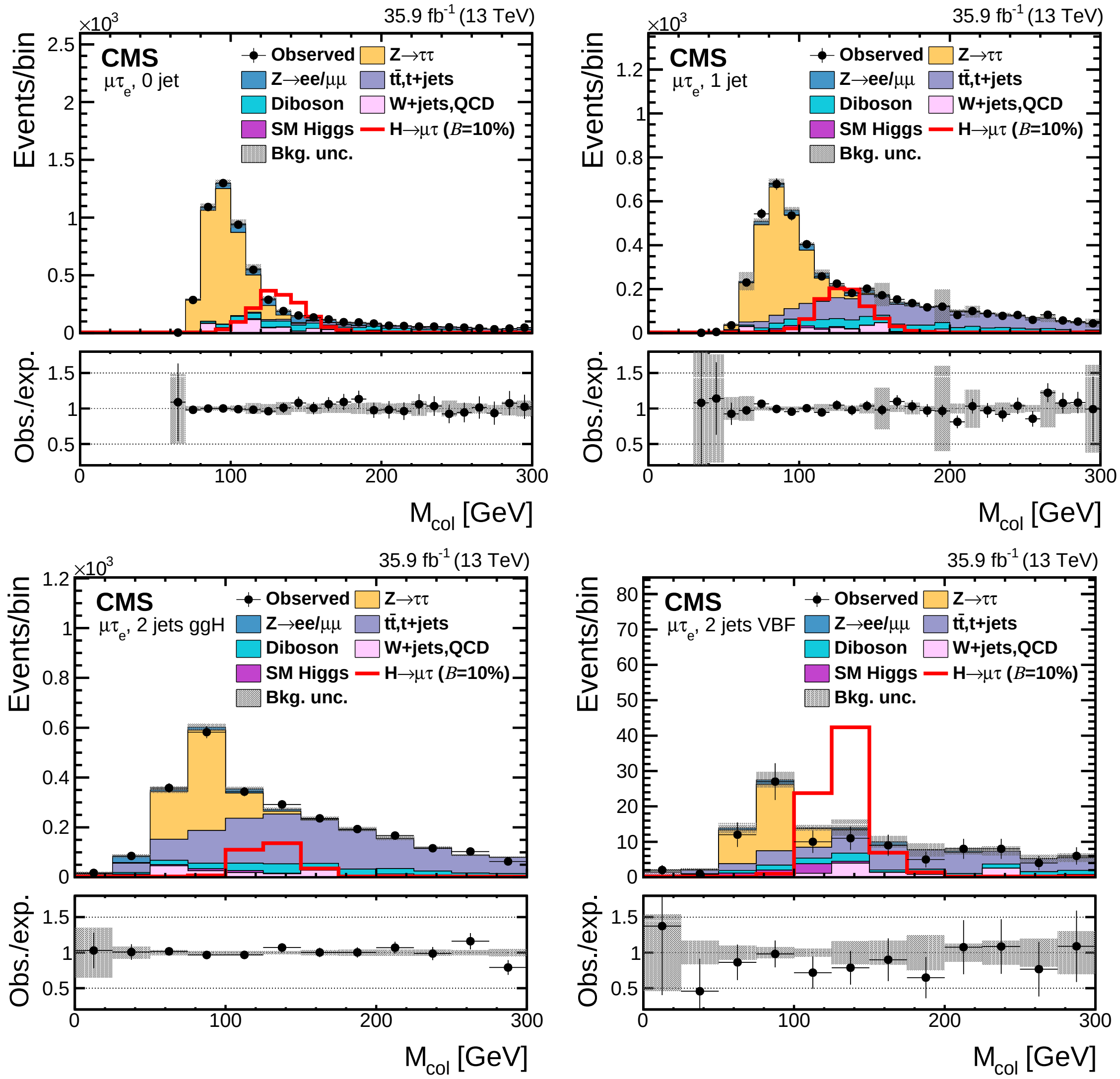

Figure 2.2: Distribution of M_{col} response in each category comparing signal and background estimations to observed collision data, for h $\rightarrow \mu\tau_e$ analysis. The bottom panel show the ratio of observed data and fitted background in each bin [14]

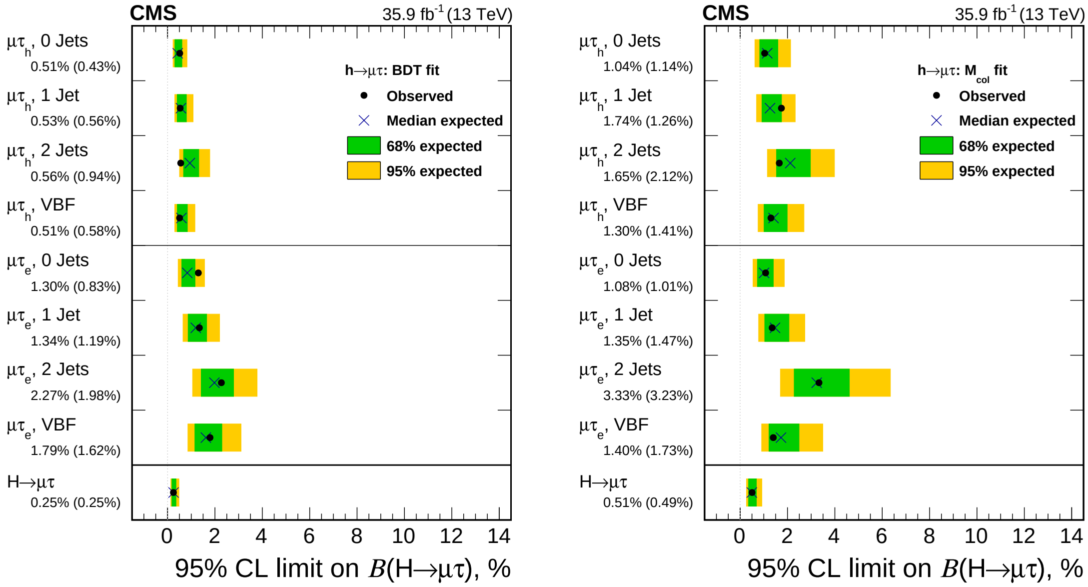

Figure 2.3: Observed and median expected upper exclusion limits for $\mathrm{h} \to \mu\tau_e$, $\mathrm{h} \to \mu\tau_\mathrm{h}$ and combined $\mathrm{h} \to \mu\tau$ channels, for the BDT fit (left) and M_col fit analysis (right). The $\pm 1\sigma$ and $\pm 2\sigma$ bands for expected limits are also shown in light green and yellow respectively [14].

to the following equation:

$$\mathcal{B}(\mathrm{h} \to \mu\tau) = \frac{\Gamma(\mathrm{h} \to \mu\tau)}{\Gamma(\mathrm{h} \to \mu\tau) + \Gamma_{SM}}. \tag{2.2}$$

,where the SM Higgs decay width is assumed to be $\Gamma_{SM} = 4.1$ MeV [15] for $m_\mathrm{H} = 125\,\mathrm{GeV}$. Using equations 2.1 and 2.2, we derive the constraints on Yukawa couplings at 95% CL. The limits for the Yukawa couplings are summarized in Table 2.2. Fig. 2.4 pictorially summarizes all existing limits on Yukawa couplings from different direct and indirect searches. It also shows the theoretical "naturalness" limit considering/expecting LFV couplings to be smaller than those of couplings for SM decays of the Higgs [11], which can be considered a benchmark for sensitivity of this search. The limits derived from this search are most stringent till date, and surpass the above benchmark.

Table 2.2: 95% CL observed upper limit on the Yukawa couplings, for the BDT fit and the M_{col} fit analysis.

	BDT fit	M_{col} fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$	$< 2.05 \times 10^{-3}$

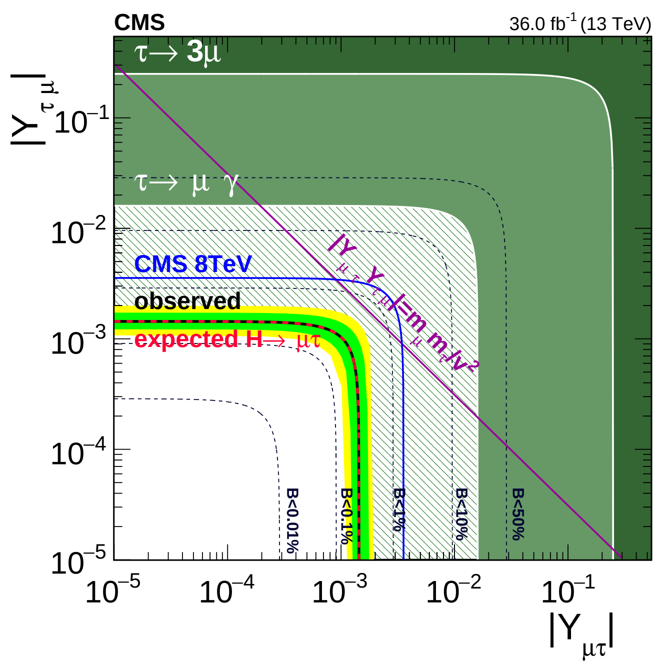

Figure 2.4: Observed (black solid)and median expected (red dashed) upper limits on $h \to \mu\tau$ Yukawa couplings from this analysis. The light green and yellow bands show the $\pm 1\sigma$ and $\pm 2\sigma$ spreads of the expected limit. Blue solid line shows the result from the previous CMS search with 8 TeV data [12]. The naturalness limit is shown as a purple straight line. [14]

2.0.2 $\mathrm{H} \to \mu\tau_e$ results

The resulting M_{col} distributions for signal and background estimation (after applying all selection requirements as outlined in **??**), after a binned maximum likelihood fit, are shown superimposed along with the observed data Fig 2.5. All systematic uncertainties are included as nuisance parameters, and the fit is performed simultaneously across all categories. We do not observe an excess over expected background in the entire range. Unlike the $\mathrm{h} \to \mu\tau_e$ analysis described above where the production cross-section of the SM Higgs boson is known, here we are looking for LFV decay of a hypothetical heavy Higgs bosons of different masses. Hence, we set upper exclusion limits on production cross-section times branching fraction, $\sigma(\mathrm{gg} \to \mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\tau_e)$. The procedure is the same as used above and described in **??**. The observed and median expected upper limits at 95% CL on $\sigma(\mathrm{gg} \to \mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\tau_e)$ are summarized in table 2.3 for different categories and Higgs masses. The limits are also summarized graphically in Figure 2.6. The observed (median expected) limits range from 159.4 (95.6) pb to 2.9 (4.9) pb for heavy Higgs masses in the range between 200 and 900 GeV. This search was combined with LFV heavy Higgs decay search with the tau lepton decaying hadronically, i.e. $\mathrm{H} \to \mu\tau_{\mathrm{h}}$ to produce constraints $\mathrm{H} \to \mu\tau$. The combined observed (median expected) upper limits on $\sigma(\mathrm{gg} \to \mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\tau)$ range from 51.9 (57.4) pb to 1.6 (2.1) pb. These limits are shown graphically in Figure 2.7. This is the first direct search till date to set limits on this decay.

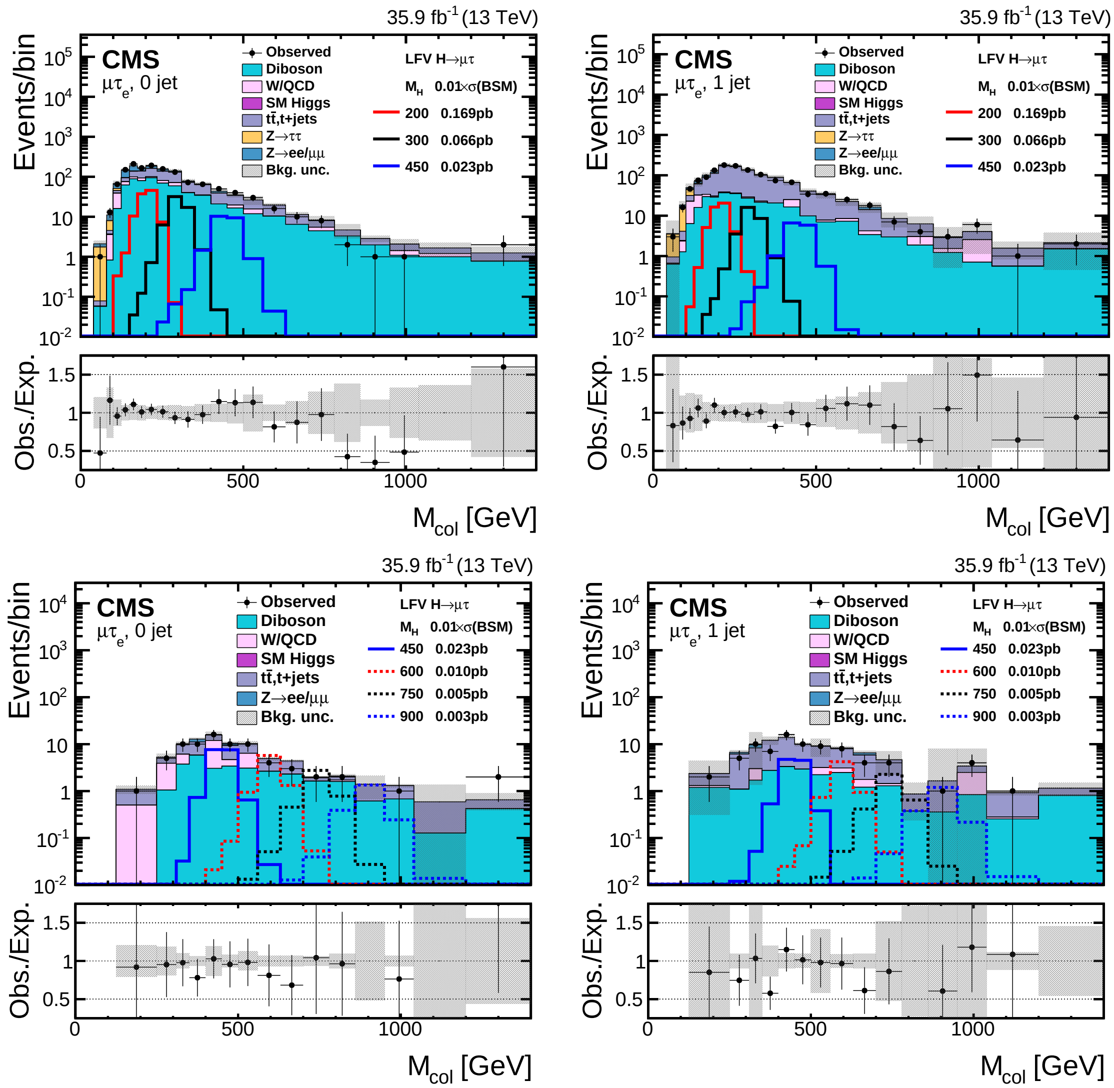

Figure 2.5: Distribution of M_{col} in 0-jet (left) and 1-jet (right) for lowmass (top) and highmass (range), comparing signal and background estimations to observed collision data, for H $\rightarrow \mu\tau_e$ analysis. The bottom panel show the ratio of observed data and fitted background in each bin [**?**]

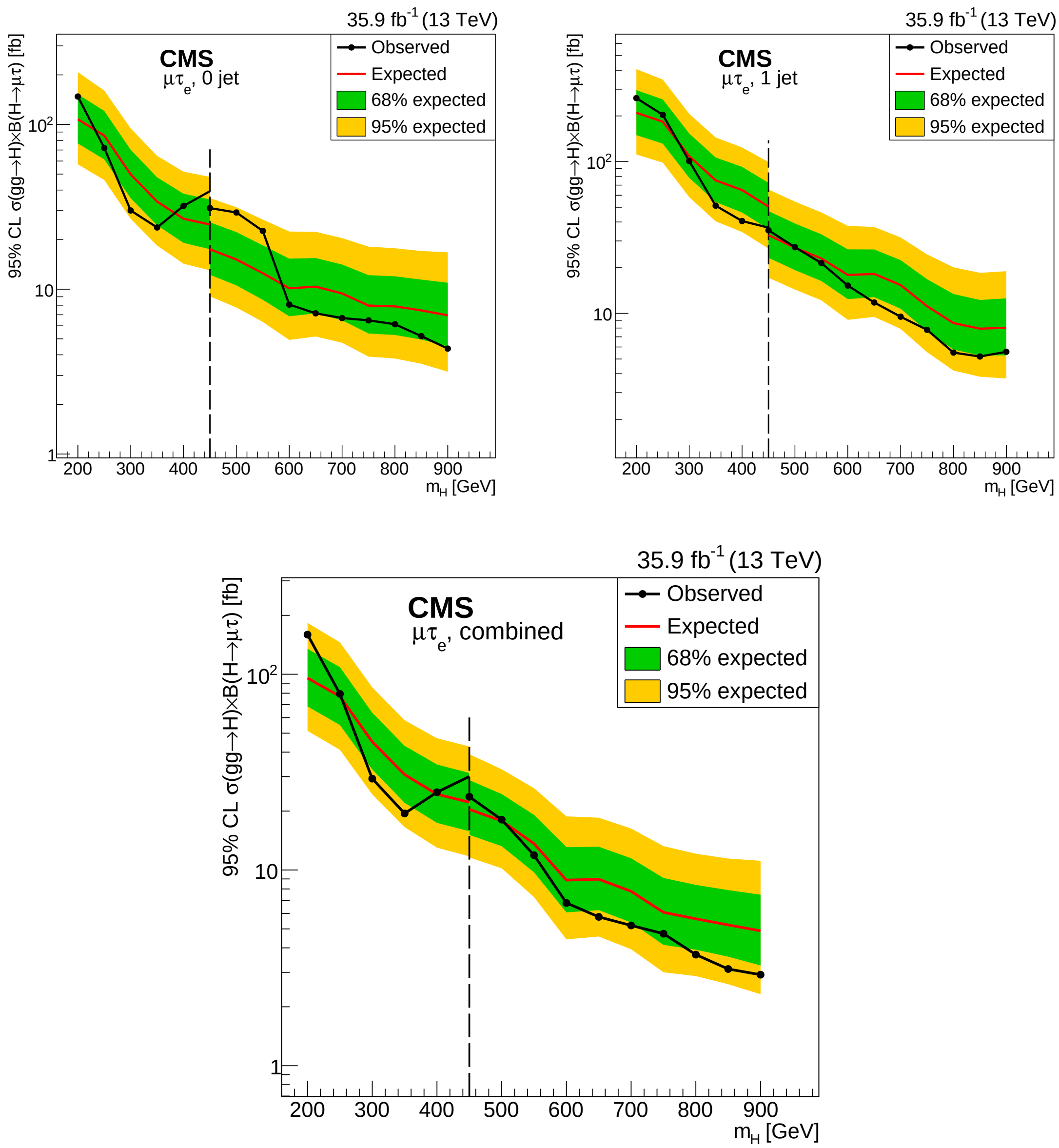

Figure 2.6: Observed and Median expected 95% upper exclusion limits for 0-jet (upper left), 1-jet (upper right) and combined (bottom),for the H $\rightarrow \mu\tau_e$ analysis. [?]

Table 2.3: The observed (median expected) 95% CL upper limits on $\sigma(\mathrm{gg} \rightarrow \mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \mu\tau_e)$.

m_{H} (GeV)	0 jet	1 jet	comb
200	147.8 (107.5)	262.1 (209.8)	159.4 (95.6)
300	30.1 (49.8)	100.8 (108.6)	29.3 (45.2)
450	31.1 (17.5)	35.3 (32.8))	23.7 (20.4)
600	8.1 (10.4)	15.2 (17.9)	6.8 (8.9)
750	6.5 (8.0)	7.8 (18.2)	4.7 (6.1)
900	4.4 (6.9)	5.6 (15.4)	2.9 (4.9)

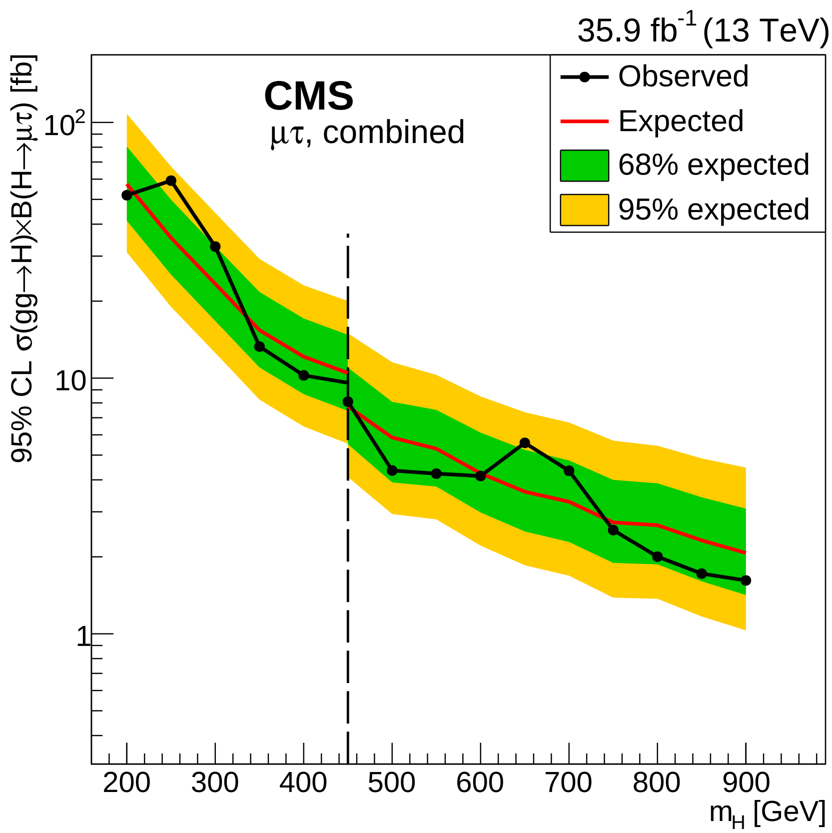

Figure 2.7: Observed and Median expected 95% upper exclusion limits for combined $\mathrm{H} \rightarrow \mu\tau$ analysis [**?**].

CHAPTER 3

CONCLUSION

This dissertation describes two searches for Beyond the Standard Model (BSM) decays. Both searches were performed with data collected by the CMS detector in 2016, in proton-proton collisions at the LHC, at a center-of-mass energy of 13 TeV.

The search for SM Higgs (h) decaying into a muon and an electronically decaying tau ($\mathrm{h} \to \mu\tau_e$) is now a pubslished result in a peer-reviewed journal [14]. This search, (in combination with $\mathrm{h} \to \mu\tau_{\mathrm{h}}$) has set most stringent upper bounds till date on the branching fraction of h decaying to $\mu\tau$. The observed (median expected) upper limits on $\mathcal{B}(\mathrm{h} \to \mu\tau)$ is 0.25 (0.25) % at 95% CL. Upper limit on off-diagonal $\mu\tau$ Yukawa couplings, derived from the above constraint, is also set to be $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$ at 95% CL. These limits constitute a significant improvement over all previous results.

The search for flavour violating decays of a neutral heavy Higgs boson (H) into a muon and an electronically decaying tau ($\mathrm{h} \to \mu\tau_e$) is complete, and on its way to being a part of a peer-reviewed publication. This search, (in combination with $\mathrm{H} \to \mu\tau_{\mathrm{h}}$) has set upper limits on product of H cross-section and branching ratio to $\mu\tau$. These observed (median expected) limits on $\sigma(\mathrm{gg} \to \mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\tau)$ range from 51.9 (57.4) pb to 1.6 (2.1) pb for H masses in the range between 200 and 900 GeV. This search is the first direct search to set limits on this decay.

As the LHC excellent performance in delivering proton-proton collisions continues, and CMS collects more an more data, there is room for above results to above. The very next step would be to perform these searches with the entire dataset collected in the run II (2015-2018) period. This would amount to more than 3 times the data used in the above searches, and with more innovative techniques to select signal events and reduce backgrounds, the sensitivity of the searches can be increased.

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