This Dissertation

entitled

SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS OF

STANDARD MODEL HIGGS AND NEUTRAL HEAVY HIGGS BOSONS

TO A MUON AND AN ELECTRONICALLY DECAYING TAU LEPTON

typeset with NDdiss2$_\varepsilon$ v3.2017.2 (2017/05/09) on September 30, 2019 for

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SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS OF STANDARD MODEL HIGGS AND NEUTRAL HEAVY HIGGS BOSONS TO A MUON AND AN ELECTRONICALLY DECAYING TAU LEPTON

A Dissertation

Submitted to the Graduate School

of the University of Notre Dame

in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Physics

by

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September 2019

SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS OF STANDARD MODEL HIGGS AND NEUTRAL HEAVY HIGGS BOSONS TO A MUON AND AN ELECTRONICALLY DECAYING TAU LEPTON

Abstract

by

Nabarun Dev

This dissertation presents searches for Lepton Flavor Violating decay of the Standard Model Higgs Boson (h) as well as neutral Heavy Higgs Bosons (H) into a muon and an electronically decaying tau lepton. Data collected by the CMS detector in 2016, in proton-proton collisions at the LHC, at a center-of-mass energy of 13 TeV were used to perform both searches. No evidence of signal was found in either search, and stringent upper exclusion limits were set on both proesses. Observed (expected) upper limits on the branching fraction of h decaying into a muon and a tau lepton, $\mathcal{B}(\mathrm{h} \to \mu\tau)$, was set at 0.25 (0.25) % at 95% CL. These are the most stringent limits set on this process til date. Observed (expected) upper limits on product of H cross-section and branching ratio to $\mu\tau$, $\sigma(\mathrm{gg} \to \mathrm{H}) \times \mathcal{B}(\mathrm{H} \to \mu\tau)$ range from 51.9 (57.4) pb to 1.6 (2.1) pb, at 95% CL, for H masses in the range between 200 and 900 GeV. This search is the first direct search to set limits on this decay.

DEDICATED TO

To my parents,

Prashanta and Sumitra,

who taught me everything I needed to know.

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ACKNOWLEDGMENTS

I would like to begin by thanking my PhD advisor and mentor, Prof. Colin Jessop. Colin guided, encouraged and supported me througout all my endeavours during my PhD, both during the time spent at Notre Dame and doing research abroad at CERN in Geneva. A lot of what I have learnt and grown to be, in terms of scientific method, collaborating with fellow researchers and communicating what I have learnt to an audience were due to Colin's guidance.

I would also like to thank my committee members Profs. Mike Hildreth, Randal Ruchti and Dinshaw Balsara for taking the time to review my research over the last few years, and providing feedback and encouragement. I would also like to thank Notre Dame and CMS faculty members, Profs. Kevin Lanon, Chris Neu, Nancy Marinelli and others who advised me with my research from time to time. I am also thankful to Dr. Alexandre Zabi and Dr. David Petyt for their guidance and encouragement.

Special thanks are in order for Dr. Silvia Taroni and Dr. Maria Cepeda Hermida who worked hard to teach me the ropes of the trade. This includes everything an experimental particle physics student needs to learn from ground up, from programming to processing huge amounts of data to preparing talks and posters to drafting physics papers.

I would also like to thank the Notre Dame Physics Department for nurturing and supporting my growth as a scientist. I would especially like to thank Susan, Shari and Shelley in the physics office for helping me smoothly through many tasks over the years. I would like to thank my friends and colleagues Fanbo Meng, Prasanna Siddireddy, Michael Planer, Charlie Mueller, Robin Luo, Matthias Wolf, Anna Woodard, Carlos Alvarado, Fatemeh Elahi, Nathan Kellams for helping me learn and making research fun. I would like to thank my classmates James Kelly, Anthony Ruth, Allison Reinsvold, Elizabeth Louden, Rodolfo Capedevilla, Laura Collins, Ek Adhikari, Matthew Hall, Alison Deatsch and fellow chemistry PhD student Patrick Louden for being my family at Notre Dame.

I would like to thank my parents, family and friends for being there for me over the years, believing in me and standing by me during hard times. I would specially like to thank my father for having encouraged me to do what I wanted during my formative years, and not to be influenced by the crowd, even if the chance for success was small.

It wouldn't make sense for me to thank my wife, Namrata, because I consider everything I do as much hers as mine.

Lastly, I would like to thank all the Yodas, Kenobis, scientists, technicians and engineers, not only associated with CMS and LHC, but every other experimentalist, theorist and Ewok whose collective work over millenia make little things like this thesis possible.

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 [? ? ?] 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 [? ? ? ?].

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 [**?**]. 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) [**?**]. 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 $\to \mu\tau_e$. Indirect constraints on $h \to \mu\tau$ exist through interpretations of measurements of processes such as $\tau \to \mu\gamma$ [**?**]. These constraints set weak limits on such decays allowing significant branching fractions; $Br(H \to \mu\tau) < O(10\%)$ [**? ?**]. A search was performed by CMS for $H \to \mu\tau$ 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 $Br(H \to \mu\tau) < O(1.51\%)$ at 95% confidence level [**?**]. 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 [**?**]. 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 $\to \mu\tau_e$. 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 $\rightarrow$ $\mu\tau_e$ and H $\rightarrow$ $\mu\tau_e$ 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 **??** lays out the results of both the searches performed.

CHAPTER 2

THEORETICAL BASES

In this chapter we describe the theoretical motivations that drive the searches described in this thesis. We start with a description the standard model (SM), its particle content and interactions and the Higgs mechanism. We then talk about the inadequacies of the SM, and the existence of physics beyond the standard model (BSM). We then outline a few BSM models and how they point towards the possibility of the decays that we search for in this thesis.

2.1 The Standard Model

The SM is the result of human endeavors over centuries to understand what we and the world around us are made of, and capture those ideas in beautiful mathematical form. Our understanding of the world around us has refined progressively from the ancient times, when best tools of observation we had were nothing but our own eyes to the current day when we are able we collide particles that make up matter at unprecedented speeds, and have sophisticated tools like the CMS detector to aid us. From the ancient greeks who pondered over philosophical questions about what the basic elements of nature were, to the discovery of electron in 1898 by J.J.Thompson, to Rutherford's famous gold foil experiment, to the discovery of the neutron by James Chadwick in 1932 have been stepping stones towards our understanding of nature and the formulation of SM. During the course of its formulation and after, the SM has accurately explained phenomena alreafy known and predicted the existence of particles that were discovered later. The last of these particles is the Higgs Boson, discovered in 2012 at CERN by the CMS and the ATLAS experiments [**?** **?** **?**]. The SM is a gauge theory, in which three of the four known natural forces (strong, electromagnetic, weak and not gravity **??**) are represented by the SU(3)xSU(2)xU(1) symmetry group. This symmetry group describes under which transformations the SM is invariant. By Noether's theorem each of the above symmetries associated with the SM Lagrangian is associated with a conserved quantity: color charge, weak isospin and electric charge. The following describes the elementary particles of the SM, the interactions among these and finally, the spontaneous symmetry breaking mechanism.

2.1.1 Elementary particles

There are two kinds of elementary particles in the SM. They are characterized by the intrinsic angular momentum that they carry, i.e. by their spin. Fermions, which has half-integer spins, form the building blocks of matter. Bosons, which have integer spins, are the force-carriers or mediators of interactions.

Fermions are fundamental particles, i.e. they cannot be broken down into further consituents. The space-time evolution of the fermions is described by the Dirac equation and their behavior follows Fermi-Dirac statistics. All fermions are subject to the Pauli exclusion principle. The fermions can be further categorized into two classes depending on their interaction with the strong force. Fermions wich do not interact with the strong force are called leptons, and do not carry any color charge. Quarks carry color charge and interact via the strong force. Both leptons and quarks are further classified into three generations. Each lepton generation consists of a lepton and a neutrino while each quark generation consists of a up type and a down type quark. These are outlined in detail below.

Leptons comprise of the familiar electron (e), its heavier cousins muon (μ) and tau lepton (τ) which carry the same negative electric charge as the electron ($1.6 \times 10^{-19} C$).

The heavier leptons τ ($\sim 1.8\,\mathrm{GeV}/c^2$) and μ ($\sim 105.7\,\mathrm{MeV}/c^2$) have short lifetimes of $\sim 2.9 \times 10^{-13}\,\mathrm{s}$ and $\sim 2.2 \times 10^{-6}\,\mathrm{s}$ respectively. The eventually decay into an electron which is the lightest lepton ($\sim 0.5\,\mathrm{MeV}/c^2$) and has infinite lifetime, or lighter hadrons. In the CMS detector, the μ survives long enough to reach the muon systems is thus detected as its own distinct signature. The τ on the other hand, owing to its extremely short lifetime, can travel only a very short distance ($\sim< 10\,mm$) before decaying. Thus, only decay products of tau leptons are able to be directly detected by CMS. Each charged lepton is associated with an electrically neutral neutrino. They are called electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_μ). Because neutrinos carry no electric charge, they do not interact via electromagnetic interaction. This means the only way they interact is via the weak interaction. This makes neutrinos are very difficult to detect. In particular, they pass through the CMS detector effectively without interacting at all, and their presence and the energy they carry can only be estimated using imbalance in transverse momentum of observed particles (see section **??**).

Quarks come in two generations: up-type and down-type. The up-type quarks are the up quark (u), charm quark (c) and top quark (t). Their down-type counterparts are down quark (d), strange quark (s) and bottom quark (b). Each up-type quark carries a negative electric charge of 2/3 times the charge of the electron. Each down-type quark carries a negative charge of 1/3 times the charge od the electron. Just like the leptons, each progressive generation is heavier with the third generation consisting of the top and bottom quarks being the heaviest. In fact, the top quark was the last of the SM fermions to be discovered in 1995, and is the heaviest particle in the SM ($\sim 173\,\mathrm{GeV}/c^2$). As mentioned above, all quarks carry color charge. Color charge is to strong force as electric charge is to electromagnetic force. This allows quarks to interact via the strong force. Due to a phenomenon called color confinement, quarks aggregate together into colorless (having zero color charge) particles called hadrons.

Hadrons are either formed of 3 (anti-) quarks (baryons) or 2 (anti-) quarks (mesons). The proton and neutron are baryons. It is made of two up quarks, and one down quark. It has a mass of $\sim 938.3\,\mathrm{MeV}/c^2$ and is stable (infinite lifetime). The neutron is made of one up quar and two down quarks. It has a mass of $\sim 939.5\,\mathrm{MeV}/c^2$ and has a lifetime of $\sim 880\,\mathrm{s}$.

Each particle described above has an anti-particle associated with it. Particles (matter) and their anti-paritcles (anti-matter) are almost identical except they have opposite physical charges (electric charge, color charge). For example, The anti-particle of an electron is the positron which is nearly identical to the electron except for the fact that it has positive electric charge.

The bosons in SM are carriers or mediators of force. Their behavior follow bose-einstein statistics and they are not constrained by the Pauli exclusion principle. The strong interaction, as its name suggests, is the strongest of the fundamental forces. The eight gluons mediate the strong interactions between particles with color charge. Photons are the mediators of the next strongest fundamental forece, the electromagnetic force. Gluons and photons are massless, electrically neutral and have spin 1. Additionally, gluons carry color charge. This is in contrast to photons which are electrically neutral. The W^+,W^- and Z gauge bosons mediate the weak interactions between particles of different flavors. Both bosons have spin 1. However, unlike the photons and the gluons, they are heavy. The W boson has a mass of $\sim 80.4\,\mathrm{GeV}/c^2$ and the Z boson has a mass of $\sim 91.2\,\mathrm{GeV}/c^2$. Finally, the Higgs boson which is a massive, scalar (spin 0) and electrically neutral boson is responsible for giving masses to W, Z bosons and fermions.

2.1.2 Theory of interactions

2.2 Physics beyond the standard model

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