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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

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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
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for the Degree of

Doctor of Philosophy
in
Physics

by
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SEARCH FOR LEPTON FLAVOR VIOLATING DECAYS OF
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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 processes. Observed (expected) upper limits on the branching fraction of h decaying into a muon and a tau lepton, $\mathcal{B}(h \rightarrow \mu\tau)$, 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 $\mu\tau$, $\sigma(gg \rightarrow H) \times \mathcal{B}(H \rightarrow \mu\tau)$ 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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SYMBOLS

| | |
|------------------|----------------------|
| c | speed of light |
| h | Standard Model Higgs |
| H | Heavy Higgs |
| m | mass |
| e | elementary charge |
| E | energy |
| 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 Francois Englert, two of the

physicists associated with the development of the theory, were jointly awarded the Nobel Prize in Physics.

This discovery was a significant 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 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 $B(\text{non-SM}) < 34\%$ 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 an 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 2.4σ 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) decaying 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 $h \rightarrow \mu\tau_e$ 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 2, 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 already 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 [1–3]. The SM is a gauge theory, in which three of the four known natural forces (strong, electromagnetic, weak and not gravity 2.1) are represented by the $SU(3)\times SU(2)\times U(1)$ 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.

2.1.1.1 Fermions of SM

Fermions are fundamental particles, i.e. they cannot be broken down into further constituents. 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 which 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 ($\sim 1.8 \text{ GeV}/c^2$) and μ ($\sim 105.7 \text{ MeV}/c^2$) have short lifetimes of $\sim 2.9 \times 10^{-13} \text{ s}$ and $\sim 2.2 \times 10^{-6} \text{ s}$ respectively. They eventually decay into an electron which is the lightest lepton ($\sim 0.5 \text{ MeV}/c^2$) 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 ($\sim < 10 \text{ mm}$) 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_τ). 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 ??). The three generations of leptons are pictorially shown below.

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

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 positive 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 of 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 ($\sim 173 \text{ GeV}/c^2$). 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 $\sim 938.3 \text{ MeV}/c^2$ and is stable (infinite lifetime). The neutron is made of one up quark and two down quarks. It has a mass of $\sim 939.5 \text{ MeV}/c^2$ and has a lifetime of $\sim 880 \text{ s}$. The three generations of quarks are pictorially shown below.

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Each particle described above has an anti-particle associated with it. Particles (matter) and their anti-particles (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.

2.1.1.2 Bosons of SM

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 (2.1). The eight gluons mediate the strong interactions between particles with color charge. Photons are the mediators of the next strongest fundamental force, 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 $\sim 80.4 \text{ GeV}/c^2$ and the Z boson has a mass of $\sim 91.2 \text{ GeV}/c^2$. 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.

TABLE 2.1
RELATIVE STRENGTHS AND RANGES OF ALL FOUR
FUNDAMENTAL FORCES, WITH THE STRONG FORCE AS THE
BASELINE.

| Interaction | Relative Strength | Range |
|-----------------|-------------------|--------------|
| Strong | 10^{39} | $10^{-15} m$ |
| Electromagnetic | 10^{36} | ∞ |
| Weak | 10^{25} | $10^{-18} m$ |
| Gravity | 1 | ∞ |

A pictorial summary of all particles in the SM, divided into different classes is shown in Figure 2.1.

Standard Model of Elementary Particles

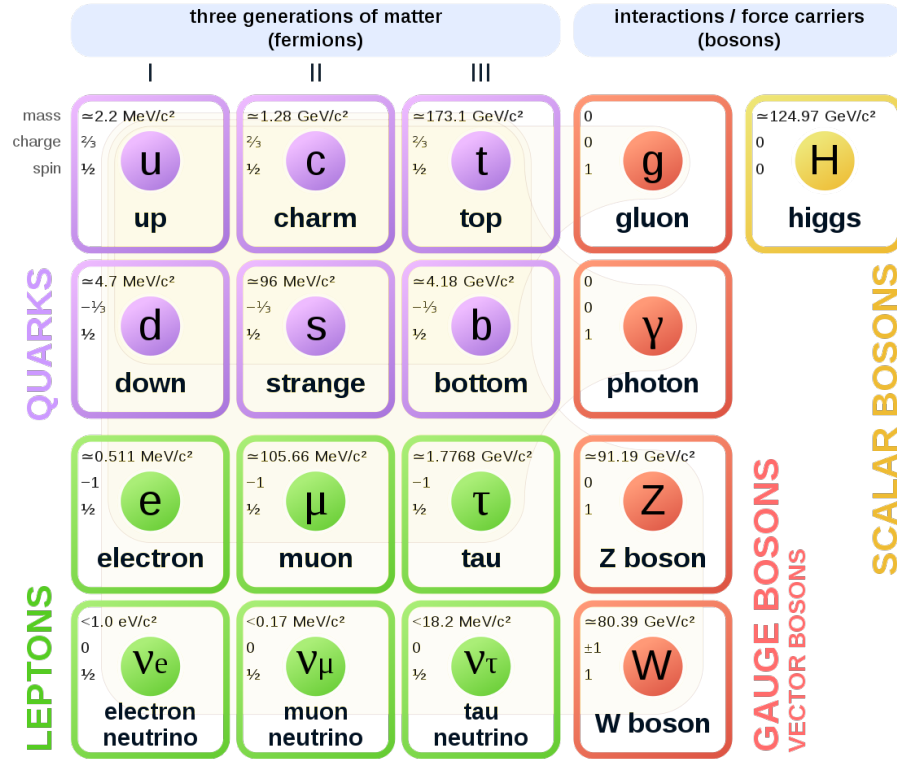


Figure 2.1. A pictorial summary of particles in the SM. The Higgs boson is shown in yellow. Gauge bosons are shown in red. Leptons and quarks are shown in green and violet respectively [14]. .

2.1.2 Theory of interactions

The SM follows the Lagrangian formalism to describe interaction between the particles. Given the SM is a gauge theory, symmetries of the Lagrangian are central to its understanding. In a gauge theory, the Lagrangian is invariant under certain (groups of) transformations and each such symmetry is associated with a conservation law (Noether's theorem). The underlying symmetry group that the SM Lagrangian is invariant under is $SU(3) \times SU(2) \times U(1)$, where the group $SU(3)$ corresponds to the strong interaction while the group $SU(2) \times U(1)$ corresponds to the electromagnetic and weak (electroweak) interaction. Each of the group generator is associated with an underlying vector field, the quanta of which are the gauge bosons (gluons, photons, W and Z) described above. We describe the SM interactions briefly below in order of strength.

2.1.2.1 Strong and Electroweak interactions

The theory that describes the strong interaction is called Quantum Chromodynamics (QCD). It is a non-abelian gauge field theory based on $SU(3)$ symmetry. Color charge is the quantity conserved under this symmetry. There are three colors: green (g), red (r) and blue (b). Each color has a corresponding anticolor (negative color). As noted earlier, all quarks and gluons have non-zero color charge. Quarks carry a single color, while each of the eight gluons have a color and anticolor charge. The theory being non-abelian, the generator matrices (Gell-Mann matrices) do not commute. The consequence of this is that gluons (unlike photons) can interact with each other.

The theory that was originally formulated to describe the electromagnetic interaction is called Quantum Electrodynamics (QED). It is a gauge field theory based on $U(1)$ symmetry. Electric charge is quantity conserved under this symmetry and all particles that interact via electromagnetic interaction need to carry electric charge.

Unlike the gluons, the photon (because it is electrically neutral) cannot interact with itself. The weak interaction was initially formulated based on the SU(2) symmetry group, with conserved quantity being the weak isospin. The associated gauge bosons are massive and can be electrically neutral (Z) or charged (W). Quarks of (same) different generations can interact with each other via (Z) W bosons. In the 1960s Glashow, Salam and Weinberg combined the theories describing electromagnetic and weak interactions, after realising that they were different aspects of the same overarching interaction. This is regarded as electroweak unification, and the electroweak interaction is described by a gauge field theory based on combined SU(2)xU(1) symmetry group. The conserved quantities, weak isospin (T) and electric charge (Q) are related via:

$$Q = T_3 + \frac{Y_W}{2}$$

, where T_3 is the third component of T and Y_W is a quantum number called the weak hypercharge.

The gauge bosons, in this theory, are divided into a triplet with two electrically charged and one neutral component (corresponding to Ws and Z), and a singlet with no electric charge (corresponding to the photon). However, in order to maintain gauge invariance of the theory, no mass terms are allowed in the Lagrangian. This would require ALL the gauge bosons (and fermions) to be massless. This is known not to be the case. This broken symmetry (photons being massless and W/Z bosons being massive) is explained by the Higgs mechanism, described in the next section.

2.1.2.2 The Higgs mechanism

In order to explain how massive gauge bosons come about, the idea of electroweak spontaneous symmetry breaking (EWSB) is introduced. The phenomenon by which

EWSB is utilized to give mass to particles is called the Higgs mechanism. Under this mechanism, a new scalar field (ϕ) called the Higgs field and an associated potential $V(\phi)$ is introduced. This is represented as doublet and has four degrees of freedom. Three of these four degrees of freedom correspond to the polarizations of the massive W and Z bosons. In order for the Higgs field to interact with W and Z but not the photon, symmetry has to be broken. The minimum of the potential, i.e. the vacuum state or ground state must be non-zero for this to happen. The parameters of $V(\phi)$ is so chosen that it has a Mexican-hat (sombbrero) shape, which has infinite degenerate non-zero minima. This non-zero minimum is called the vacuum expectation value (vev), which is measured to be 246 GeV. The direction of symmetry breaking is such that it gives mass to the Z boson but leaves the photon massless. This breaking of symmetry is called spontaneous because there is no particular reason for this direction have been picked. Nature just happened to spontaneously pick this direction. The Higgs field gives rise to a new massive scalar particle. This particle is the Higgs boson, and corresponds to the fourth remaining degree of freedom of the scalar doublet mentioned above. The fermions acquire mass via Yukawa interaction of the Higgs boson. The strength of the Yukawa coupling of the Higgs boson with fermions is proportional to the fermion masses. To summarize, the Higgs mechanism allows the introduction of a mass term for the gauge bosons without breaking the underlying gauge symmetry of the SM Lagrangian. Addition of this field, gives rise to another massive particle, the interactions with which give masses to gauge bosons and fermions. This massive particle is a scalar boson called the Higgs boson, which was discovered in 2012 at CERN by CMS and ATLAS, 50 years after it was first predicted to exist. Before the LHC, experiments at LEP and Tevatron looked for existence of the Higgs boson. It was the last missing piece of the SM, and its discovery can be thought to conclude an era in particle physics and lead us into a newer equally exciting era.

2.1.3 Higgs Boson production and decays at the LHC

There are several different ways the Higgs boson can be produced at the LHC. The LHC collides protons at high energy, and the production modes of the Higgs boson, in order of cross-section, at the LHC are :

- **Gluon-Gluon Fusion (ggH):** Since gluons are massless, they do not directly couple to the h . This production mode proceeds via quark loop. The ggH production cross-section at 13 TeV is $\sim 48.37 \text{ pb}$ at N3LO [15].
- **Vector Boson Fusion (VBF):** This production mode has the second largest cross section at the LHC. This mode is characterized by two high-momentum quarks in the final state which hadronize to form jets. The VBF production cross-section at 13 TeV center-of-mass energy is $\sim 3.77 \text{ pb}$ at NNLO.
- **Associated Production:** The third largest h production mode at the LHC involves the production of a virtual W^*/Z^* boson that splits into a real boson W/Z boson and a h . The WH production cross-section is $\sim 1.36 \text{ pb}$ and the ZH production cross-section is $\sim 0.87 \text{ pb}$, at NNLO level for a center-of-mass energy of 13 TeV at the LHC.
- **ttH Production:** In this production mode, the h is produced in along with a pair of top quarks. The production cross-section at 13 TeV center-of-mass energy is $\sim 0.50 \text{ pb}$ at NLO.

The Feynman diagrams for h production modes described above are shown in Figure 2.2. The cross-section of each process as a function of center-of-mass energy is shown in Figure 2.3.

2.2 Physics beyond the standard model

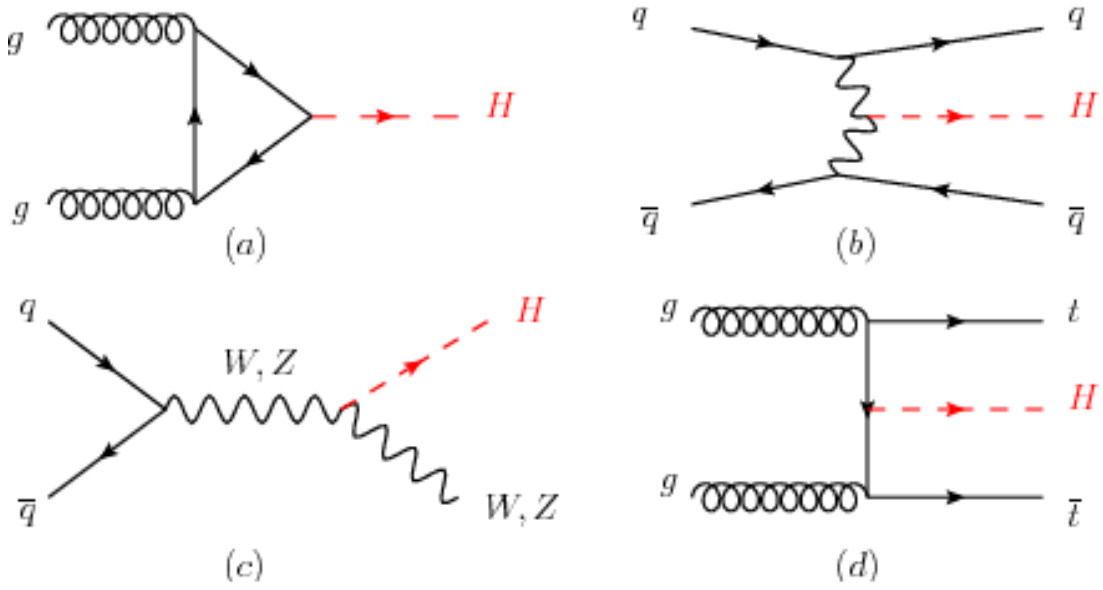


Figure 2.2. Feynman diagrams for Higgs production modes at LHC: (a) gluon-gluon fusion, (b) vector boson fusion, (c) associated production and (d) ttH [16].

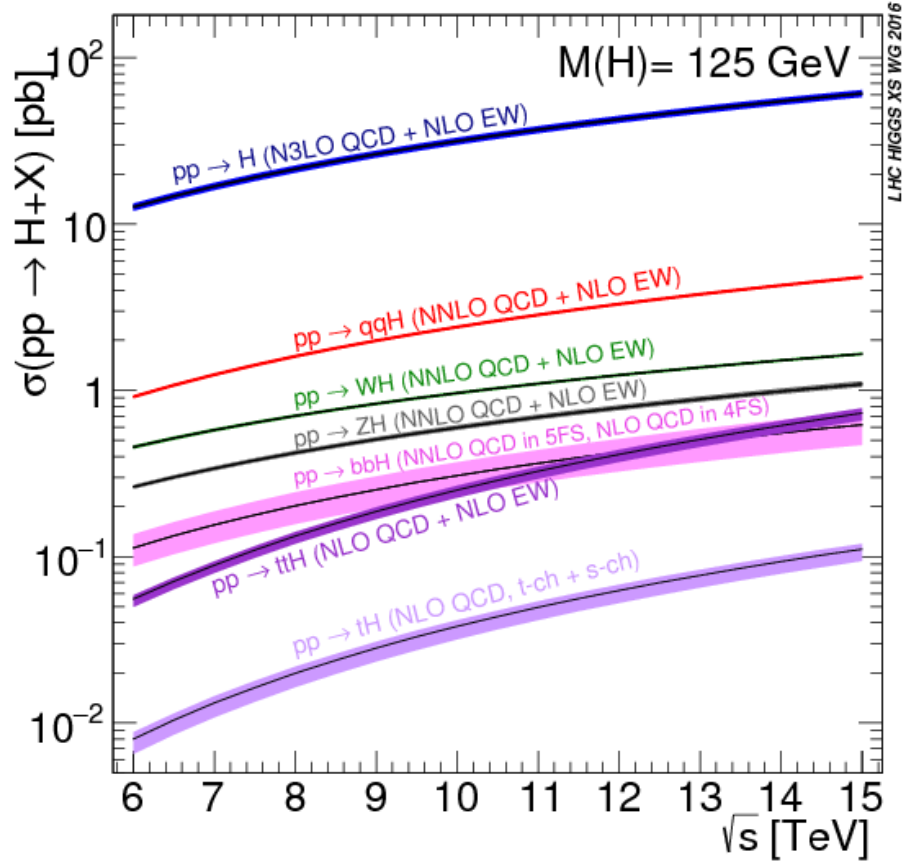


Figure 2.3. The SM Higgs boson production cross-section as a function of the center-of-mass energy in proton-proton collisions at the LHC [16].

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