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Search for decays of the 125 GeV Higgs boson into a photon and a ϕ , ω or D^{*0} meson

MASTER THESIS

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Abstract

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Contents

Introduction	iii
1 Theory and Motivation	1
1.1 The Standard Model	1
1.2 The Higgs boson	6
1.3 Searching of a model beyond the SM	9
2 The CMS at the LHC	11
2.1 The Large Hadron Collider at CERN	11
2.2 The Compact Muon Solenoid experiment	12
2.3 The discovery of the Higgs boson at CMS	12
3 Analysis	13
3.1 Analysis overview	13
3.2 Samples and triggers	13
3.3 Object definitions	13
3.4 Corrections to data and simulations	13
3.5 Event selection	13
3.6 Signal and background modelling	14
3.7 Results	14
3.8 Multivariate analysis for final results	14
Conclusions	15
A Appendix	17
References	19

Introduction

This is the introduction.

Chapter 1

Theory and Motivation

This chapter aims to provide an overview of the Standard Model of Particle Physics (SM), with a particular focus on the pivotal role played by the Higgs boson. We will briefly introduce the SM and its fundamental particles, as well as the Lagrangian that governs their behavior. Additionally, we will delve into the details of the Higgs boson – its properties, its most frequent production and decay modes, and the Yukawa couplings to the three different fermion families. Finally, we will focus on the decay channels present in our analysis, and explore how a significant discrepancy between the measurements of these decay modes and the SM predictions might lead to new physics beyond the SM.

1.1 The Standard Model

One of the traits that distinguishes humans from other life forms is our sense of curiosity. Since ancient times, we have been trying to explain what happens around us, enabling us to predict and potentially harness the laws of nature. An extraordinary theory that has come very close to achieving this goal is the Standard Model of Particle Physics (SM), one of the most precise theories humanity has ever conceived, and the most successful theory of particle physics to date. The Standard Model is a theory capable of describing three of the four known fundamental forces in the Universe (electromagnetic, weak, and strong force, but not gravity). This is achieved by classifying a set of elementary particles and defining the interactions between them.

More in detail, the SM is a quantum field theory (QFT) defined by an internal local $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Each elementary particle has its own corresponding field in the theory and is categorized as a fermion or a boson, based on its spin (half-integer-spin particles are fermions, whereas integer-spin particles are bosons). There are twelve fermions organized in three families or generations of four members: a charged lepton (e.g. the electron), a neutral lepton (neutrino), an up-type quark and a down-type quark (in addition, each particle has its own corresponding antiparticle) (see Figure 1).

These three factors of the gauge symmetry group give rise to the three fundamental interactions between fermions, which are mediated by gauge bosons. To be precise, each generator of a local invariant gauge group induces a massless gauge boson. The same way that in quan-

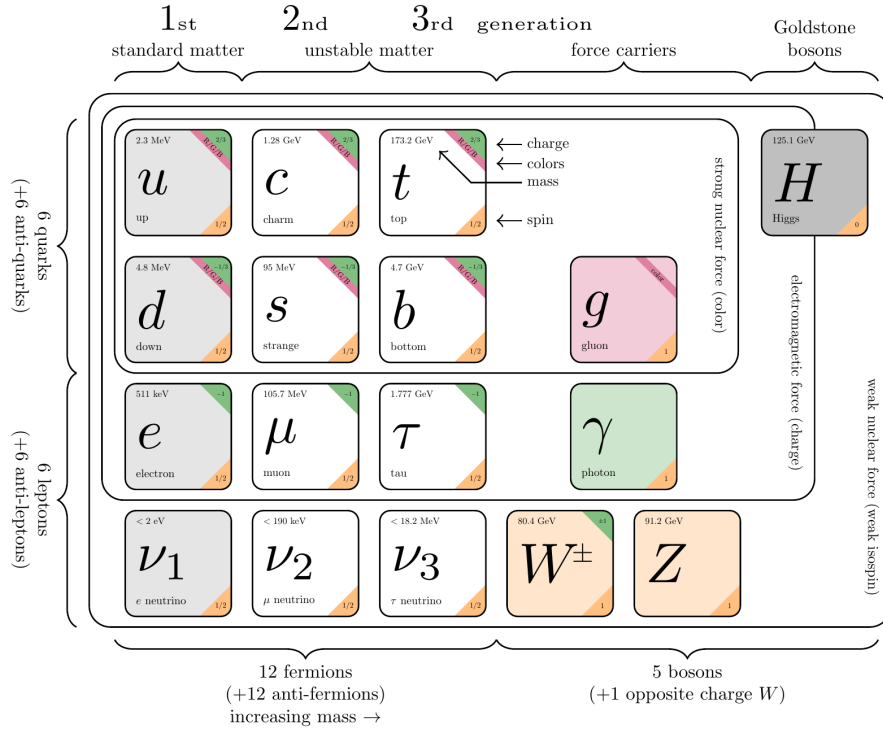


Figure 1: Elementary particles of the Standard Model.

tum electrodynamics (QED) the local gauge invariance of the theory under the $U(1)$ group leads to the existence of a massless, gauge field A_μ (the photon field), in the SM the process is analogous.

The invariance of the SM under $SU(3)_C$ postulates the existence of the gluon. More precisely, the eight generators of $SU(3)_C$ introduce eight gluons that mediate the strong force between particles that possess color charge (quarks). This is known as the quantum chromodynamics (QCD) sector of the standard model.

Similarly, the invariance of the second and third factors $SU(2)_L \times U(1)_Y$ indicates the existence of the photon, the Z^0 and the W^\pm bosons. In this case, unlike in QED or QCD, we cannot directly associate the photon to the generator of the hypercharge group $U(1)_Y$ and the Z^0 , W^\pm bosons to the generators of the left weak isospin group $SU(2)_L$. Instead, the generators of $SU(2)_L \times U(1)_Y$ give rise to four intermediate vector bosons ($W_\mu^{1,2,3}$ for $SU(2)_L$ and B_μ for $U(1)_Y$), which are then mixed through the weak mixing angle or Weinberg angle θ_W to produce the physical γ (A_μ), Z^0 , W^\pm . The physical bosons are then defined as:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$

$$\begin{pmatrix} A_\mu \\ Z_\mu^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$$

By definition of the groups $SU(2)_L$ and $U(1)_Y$, the field $W_\mu^{1,2,3}$ couples only to left-handed (negative helicity) particles, whereas the hypercharge field B_μ couples to both left and right components with the same strength. Therefore, the intermediate boson mixing implies that

W^\pm only couple to left-handed particles, but Z^0 couples to both left and right-handed particles with different strengths, inducing parity violation (although not maximal).

All gauge bosons that arise from the generators of gauge invariant groups are to be massless, or else the principle of local gauge invariance is spoiled and the theory becomes unrenormalizable. But this is in contradiction with experiments, from where we know that the Z^0 , W^\pm bosons are in fact massive. This breaking of gauge invariance when giving a mass to a particle is not restricted only to gauge bosons, but also happens for fermions. In the SM, to be able to have massive fields, all particles obtain their masses using spontaneous symmetry breaking (SSB) via the Higgs mechanism.

Spontaneous symmetry breaking is a fundamental principle of QFT to explain how gauge bosons (and, in general, massive particles) can acquire non-vanishing mass. This process describes systems where the Lagrangian obeys symmetries, but the lowest-energy vacuum solutions do not exhibit the same symmetries. In the case of the Higgs mechanism, it relies on the existence of a $SU(2)$ doublet complex scalar field ϕ with hypercharge $Y = +1$, which can be written as

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

with $(\phi^+)^* = \phi^-$ and $(\phi^0)^* = \phi^0$, with Lagrangian density $\mathcal{L} = |D_\mu \phi|^2 - V(\phi)$ and potential $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$, where D_μ is the covariant derivative determined by $SU(2)_L \times U(1)_Y$. When expanding the field ϕ around a minimum of the potential V , one finds out that there are infinitely many values ϕ that minimize the potential. Suppose one expands ϕ around

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \text{so} \quad \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}.$$

Deciding to expand the field around a chosen minimum ϕ_0 spontaneously breaks the $SU(2)_L \times U(1)_Y$ symmetry, which in turn generates mass terms for the weak bosons in the Lagrangian. To convince oneself of the last implication it suffices to expand the $|D_\mu \phi|^2$ term around the chosen vacuum expectation value v , which will produce terms of the form $M_W^2 W_\mu^+ W^{-\mu}$ and $M_Z^2 Z_\mu^0 Z^{0\mu}$ in the Lagrangian density. This scalar field is called the Higgs field.

With that, the Standard Model of particle physics is governed by the following Lagrangian density:

$$\begin{aligned} \mathcal{L}_{\text{SM}} = & -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ & + |D_\mu \phi|^2 - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \\ & + i [\bar{L} \not{D} L + \bar{e} \not{D} e + \bar{Q} \not{D} Q + \bar{u} \not{D} u + \bar{d} \not{D} d] \\ & - [Y_e \bar{L} \phi e + Y_u \bar{Q} \phi^c u + Y_d \bar{Q} \phi d + \text{h.c.}] \end{aligned} \quad (1)$$

The used notation is the following: ϕ , Q , u , d , L , e are the SM Higgs, quarks and lepton fields. The left-handed doublets are denoted by capital letters as

$$Q_i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \text{ for quarks, and } L_\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix} \text{ for leptons,}$$

whereas for the right-handed singlets lowercase letters are used. We use the usual covariant derivative defined as

$$D_\mu = \partial_\mu + ig_s T^a G_\mu^a + ig \frac{\sigma^i}{2} W_\mu^i + ig' Y B_\mu$$

and where T^a and σ^i are the generators of SU(3) and SU(2), respectively.

The first line in Equation (1) describes the kinetic energies and interactions of the gauge boson fields. The field strength tensors associated to G_μ^a (gluons), W_μ^i and B_μ (W^\pm, Z^0, γ) are defined by

$$\begin{aligned} G_{\mu\nu}^a &= \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^c \\ W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon^{ijk} W_\mu^j W_\nu^k \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned}$$

where f^{abc} and ϵ^{ijk} are the group structure constants of SU(3) and SU(2), respectively (the strength tensor of the hypercharge field B_μ does not have this extra term since U(1) is abelian). This is why gluons and electroweak bosons are self-interacting.

The second line in Equation (1) describes the Higgs field and generates the masses of the weak gauge bosons W^\pm, Z^0 and of the Higgs boson. In particular, the term $|D_\mu \phi|^2$ generates all interactions between the gauge bosons and the Higgs field.

The third line in Equation (1) is responsible for fermion kinetic energies as well as their interactions with all bosons (gluons and electroweak bosons). We have five terms: left-handed lepton doublets, right-handed lepton singlets (only charged leptons since right-handed neutrinos do not couple in the SM), left-handed quark doublets, right-handed up-type quark singlets and right-handed down-type quark singlets. The covariant derivative terms relative to each group apply only to these fermions that transform under that group. For instance, the first term would expand as

$$i\bar{L}\not{D}L = i\bar{L}\gamma^\mu D_\mu L = i \begin{pmatrix} \bar{\nu}_L^\alpha & \bar{e}_L^\alpha \end{pmatrix} \gamma^\mu \left(\partial_\mu + ig \frac{\sigma^i}{2} W_\mu^i + ig' Y B_\mu \right) \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix},$$

since the leptons do not carry color charge, but the fourth term would expand as

$$i\bar{u}\not{D}u = i\bar{u}\gamma^\mu D_\mu u = i\bar{u}_R^i \gamma^\mu \left(\partial_\mu + ig_s T^a G_\mu^a + ig' Y B_\mu \right) u_R^i,$$

because the right-handed quark is a singlet under SU(2)_L.

Finally, the couplings between the Higgs boson and the fermions, and in turn fermion masses, are generated by the fourth line in Equation (1). These terms are gauge invariant, but give rise to fermion masses. For example, for the leptons and taking the Higgs field expansion around ϕ_0 , the first term will expand as

$$Y_e \bar{L} \phi e = \frac{Y_e^{\alpha\beta}}{\sqrt{2}} \begin{pmatrix} \bar{\nu}_L^\alpha & \bar{e}_L^\alpha \end{pmatrix} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} e_R^\beta = \frac{Y_e^{\alpha\beta}}{\sqrt{2}} [v + h(x)] \bar{e}_L^\alpha e_R^\beta$$

which in addition to its hermitian conjugate will ultimately yield the term

$$\frac{Y_e^{\alpha\beta}}{\sqrt{2}} v [\bar{e}_L^\alpha e_R^\beta + \bar{e}_R^\alpha e_L^\beta] = \frac{Y_e^{\alpha\beta}}{\sqrt{2}} \bar{e}^\alpha e^\beta$$

after spontaneous symmetry breaking. One can easily identify the mass of the three charged leptons as

$$m_e = \frac{Y_e^{ee} v}{\sqrt{2}}, \quad m_\mu = \frac{Y_e^{\mu\mu} v}{\sqrt{2}} \quad \text{and} \quad m_\tau = \frac{Y_e^{\tau\tau} v}{\sqrt{2}}.$$

To generate mass terms for up-type like quarks the Yukawa term involves the charge conjugate of the Higgs doublet (as in the second term of the fourth line in Equation (1)).

The Standard Model Lagrangian (1) induces the interactions between all particles present in the theory. These interactions can be seen as Feynman diagram vertices, shown in Figure 2.

[TODO: Explain SM feynman diagrams]

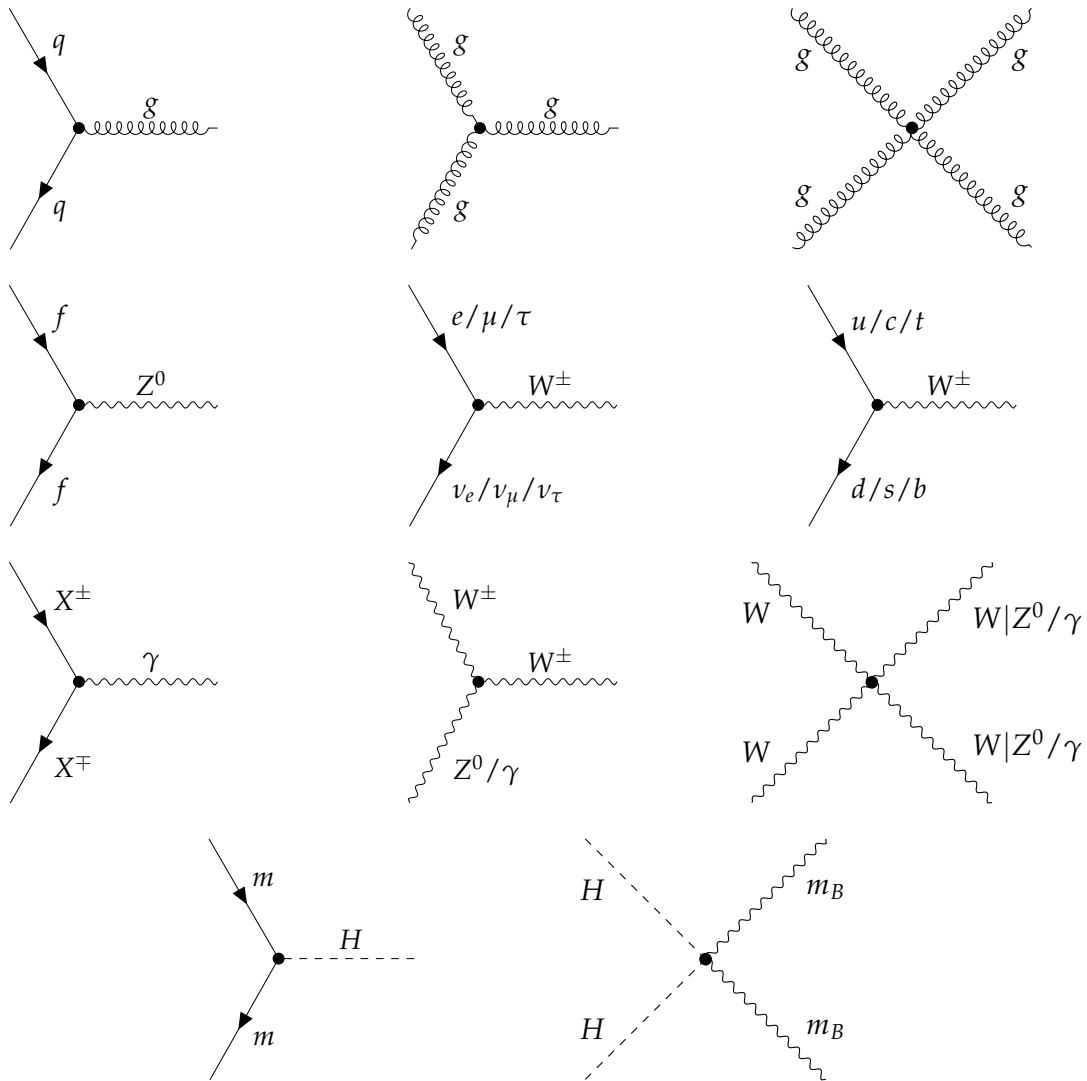


Figure 2: All possible interactions in the Standard Model, represented by Feynman diagrams. q is any quark, g is (any) gluon, X^\pm is any charged particle, γ is a photon, f is any fermion, m is any massive particle (with the possible exception of the neutrinos), m_B is any boson with mass. In diagrams with multiple particle labels separated by / one particle label is chosen. In diagrams with particle labels separated by | the labels must be chosen in the same order. For example, in the four boson electroweak case the valid diagrams are $WWWW$, $WWZZ$, $WW\gamma\gamma$ and $WWZ\gamma$. The conjugate of each listed vertex (reversing the direction of arrows) is also allowed.

The Standard Model has proven to predict numerous measurements with exceptional precision, yet the theory does not explain why the masses of all particles are given by the values

we measure. In fact, aside from the mass of the photon, which is protected by the unbroken $U(1)$ gauge symmetry of QED, the SM does not predict any other mass value. All fermion masses (or equivalently the Yukawa couplings) are free parameters of the theory.

While this theory has been remarkably successful, it cannot serve as the final theory of nature, as numerous unresolved puzzles persist. Many cosmological observations remain unaccounted for by the SM, i.e., the baryon-antibaryon asymmetry, the behaviour of gravity as described by General Relativity, the accelerated expansion of the Universe — potentially described by dark energy — and the absence of a suitable candidate for dark matter. Furthermore, the SM fails to explain the non-vanishing mass of the neutrinos as a consequence of neutrino flavour oscillation. In pursuit of a superior theory capable of encompassing the SM as well as these (and many other) discrepancies, the physics community is thoroughly trying to “break” the Standard Model to unveil hints towards an ultimate theory.

1.2 The Higgs boson

In 1964, Peter Higgs, along with five other theoretical physicists, proposed the Higgs mechanism to explain how certain particles (fermions and weak bosons) might acquire mass in local gauge theories [1, 2, 3]. If these ideas were correct, a spin-0 particle (namely the Higgs boson) should exist and possess some well-defined properties. Nearly 50 years later, on the 4th of July of 2012, a scalar particle consistent with the Higgs boson was discovered at the LHC by the CMS and ATLAS collaborations [4, 5].

The Higgs boson is a weak isospin $SU(2)_L$ doublet, massive scalar boson, this is, a particle with spin 0. Table 1 summarizes the SM predicted properties [6, 7] as well as the measured properties of the Higgs boson from the Particle Data Group (PDG) [8].

Property	SM prediction	Mesasured value
Mass	$m \lesssim 700 \text{ GeV}$	$m = 125.25 \pm 0.17 \text{ GeV}$
Spin	$J = 0$	$J = 0$
Electric charge	$q = 0$	$q = 0$
Full width	$\Gamma = 4.12 \pm 0.06 \text{ MeV}$	$\Gamma = 3.2^{+2.8}_{-2.2} \text{ MeV}$
Lifetime	$\tau = (1.60 \pm 0.02) \times 10^{-22} \text{ s}$	$\tau = 2.1^{+4.5}_{-1.0} \times 10^{-22} \text{ s}$

Table 1: Properties of the Higgs boson. The SM prediction for the full width and the lifetime depend on the Higgs mass, which is assumed to be $m = 125.25 \text{ GeV}$.

As stated previously, the SM does not predict the mass of any particle (except for the photon), including the mass of the Higgs boson. Nevertheless, some theoretical arguments, such as radiative corrections and unitarity considerations, enabled theorists to establish upper bounds on the Higgs mass [6].

To understand the production and decay modes of the Higgs boson, it’s important to recall that the Higgs boson couples to all the other particles of the SM (it couples to the gauge bosons via the $|D_\mu \phi|^2$ term in Higgs part of Equation (1) and to fermions via the Yukawa couplings in the last line of Equation (1)), as well as to itself. By expanding the terms in the Lagrangian,

it can be seen that the coupling between the Higgs boson and any massive particle is directly proportional to the particle's rest mass.

Collecting the relevant Feynman vertices one can get the dominant production modes for the Higgs boson, as seen in Figure 3. Since the heavier the particle, the stronger its Higgs coupling constant is, we see that in most cases particles present in the vertex where the Higgs boson is produced are very heavy (top and bottom quarks and massive gauge bosons).

[TODO: Talk about Higgs production at LHC]

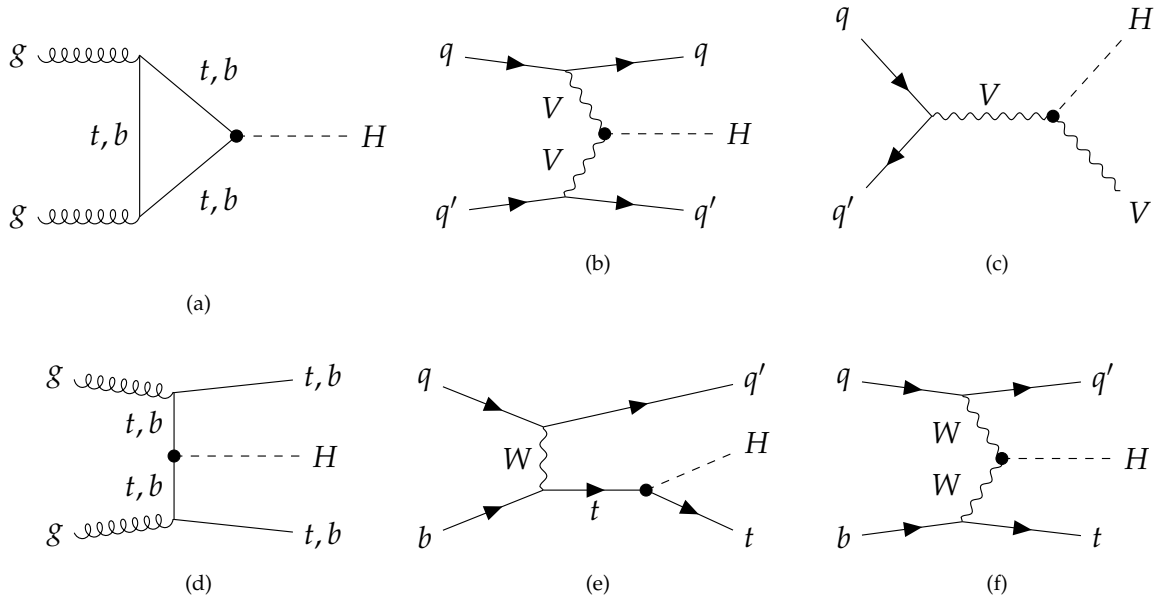


Figure 3: Higgs boson production in (a) gluon-gluon fusion (ggH), (b) vector boson fusion (VBF), (c) associated production with a W or Z (V) boson (VH), (d) associated production with a top or bottom quark pair (ttH or bbH), (e, f) associated production with a single top quark (tH).

[TODO: Higgs production rates SM/measured]

To compare the different production cross sections with the SM it is useful to define the *signal strength* μ as the measured production cross section times branching fraction divided by the expected SM value. According to the SM, the total Higgs boson cross section at a center of mass energy of $\sqrt{s} = 13$ TeV is $\sigma = 55400 \pm 2600$ fb [7], with around 87% coming from gluon fusion. The predicted and measured cross section of the Higgs boson at $\sqrt{s} = 13$ TeV from different production modes are shown in Table 2.

[COMMENT: I am not sure if I can compute the measured σ like $\sigma_{measured} = \sigma_{SM}\mu$, because there is also the cross section. I have computed, both for the production cross sections and decay branching ratios, the measurements like $v_{measured} = v_{SM}\mu$, where v is either the production cross section or the decay branching ratio. Is this correct?]

Once the Higgs boson is produced it decays almost instantly into lighter particles. According to the SM Yukawa couplings of the Higgs field to the fermions, at the first loop order, the Higgs boson predominantly decays to the most massive particles that are kinematically accessible. Despite that, there are certain decay modes where the Higgs boson decays into massless particles (to a pair of gluons or photons), for the first loop contributions are not negligible. The most relevant Feynman diagrams of the Higgs boson decay are shown in Figure

Production mode	SM σ [fb]	Measured σ [fb]	Measured μ
ggH	48400 ± 2400	47000 ± 4500	0.97 ± 0.08
VBF	3770 ± 80	3020 ± 870	0.80 ± 0.12
WH	1365 ± 28	2030 ± 360	1.49 ± 0.26
Z^0H	879 ± 36	1130 ± 220	1.29 ± 0.24
ttH +tH	582 ± 61	660 ± 130	1.13 ± 0.18
bbH	480 ± 120	Not measured	Not measured

Table 2: Cross section of the Higgs boson's most frequent production modes at $\sqrt{s} = 13$ TeV. SM values from [7], measured values from [9].

4. Table 3 shows the most frequent decay channels for the Higgs boson, comparing the SM predicted value to the measured value for the different channels.

[TODO: Higgs decays. Why no measurement $H \rightarrow gg$.]

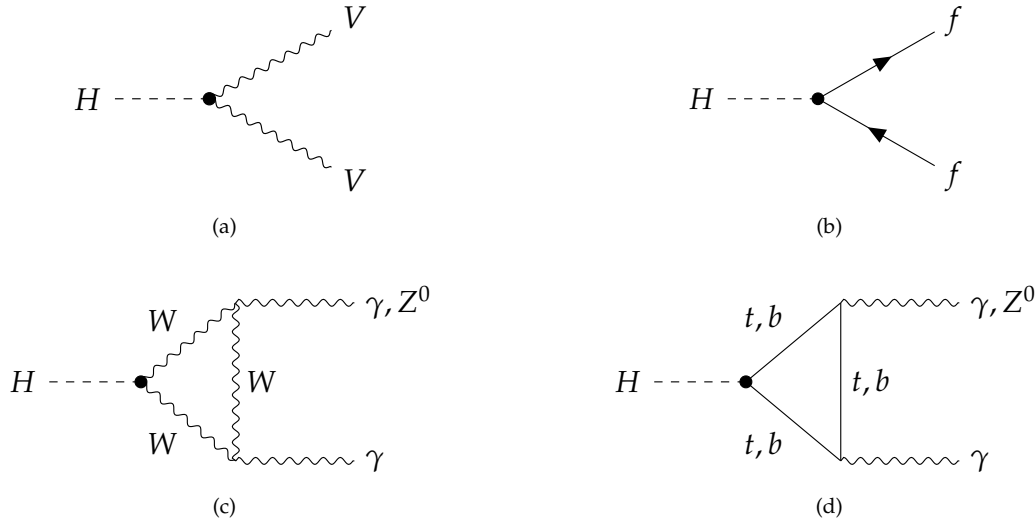


Figure 4: Higgs boson decays into (a) heavy vector boson pairs (V is Z^0/W^\pm), (b) fermion-antifermion pairs, and (c, d) photon pairs or $Z^0\gamma$. Note that $H \rightarrow gg$ is forbidden at tree level, but its non-negligible branching fraction comes from a heavy quark loop like in (b).

Decay channel	SM \mathcal{B} (%)	Measured \mathcal{B} (%)	Measured μ
$H \rightarrow b\bar{b}$	57.8 ± 0.7	60 ± 12	1.04 ± 0.20 [10]
$H \rightarrow WW^*$	21.8 ± 0.3	20.7 ± 2.1	0.95 ± 0.09 [11]
$H \rightarrow gg$	8.2 ± 0.4	Not measured (QCD bkg)	
$H \rightarrow \tau^+\tau^-$	6.23 ± 0.10	6.1 ± 1.1	0.98 ± 0.18 [12]
$H \rightarrow c\bar{c}$	2.87 ± 0.16	< 40	< 14 [13]
$H \rightarrow ZZ^*$	2.68 ± 0.04	2.6 ± 0.3	0.97 ± 0.12 [9]
$H \rightarrow \gamma\gamma$	0.227 ± 0.005	0.254 ± 0.021	1.12 ± 0.09 [14]
$H \rightarrow Z\gamma$	0.155 ± 0.009	0.37 ± 0.14	2.4 ± 0.9 [15]
$H \rightarrow \mu^+\mu^-$	0.0216 ± 0.0004	0.026 ± 0.009	1.19 ± 0.43 [16]

Table 3: Most frequent decay modes of the Higgs boson.

1.3 Searching of a model beyond the SM

If the Standard Model is right, the coupling between the Higgs boson and every massive fermion is proportional to the fermion's mass. That is why we can create the plot in Figure 5, which according to the SM should follow a straight line. So far the measured values for the massive weak bosons, the third generation of fermions (top and bottom quarks and the tau lepton) and the second generation lepton (the muon) are in perfect agreement with the Standard Model predictions, as seen in Figure 5. [TODO: cite the source of this plot].

[TODO: Clean and redo plot of the couplings to the different families]

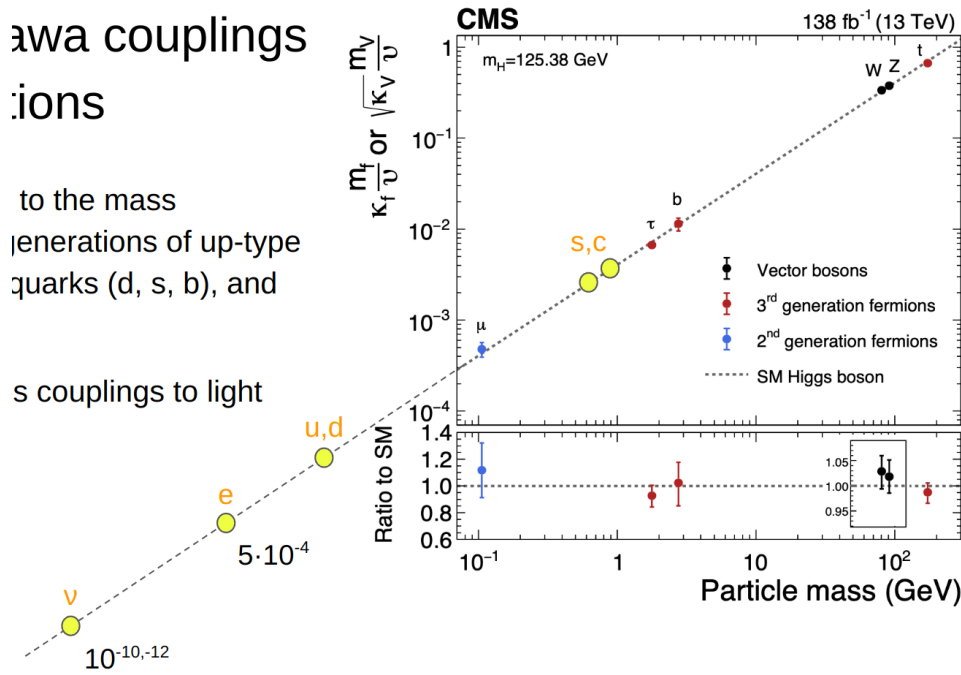


Figure 5: Yukawa couplings.

It is interesting to explore the SM with regard to lighter fermions, specifically the second-generation strange and charm quarks, as well as all first-generation fermions, including the up and down quarks and the electron. Additionally, the non-vanishing mass of the neutrinos hints at a Yukawa-type coupling for them as well.

In this analysis, our primary focus lies on decays of the form $H \rightarrow M\gamma$, where M represents a light vector meson. It is important to note that, given that the Higgs boson has spin 0 and the photon has spin 1, the meson M must be a *vector* meson to conserve total angular momentum.

Table 4 presents exotic decays of this form. The first three rows involve similar processes in which the vector meson decays into a pair of lighter, charged scalar mesons. These are currently under analysis as of the writing of this document. Our specific focus within this analysis, however, lies in the lower half of the table, where the vector meson decay involves a pair of charged scalar mesons as well as neutral particles, specifically either pions or photons.

[TODO: Include comparison between SM branching ratios and measured upper limits, when these are available.]

Higgs boson rare decay	Coupling
$H \rightarrow \phi\gamma$ $\quad \quad \quad \searrow K^+ K^- \quad (49.1 \pm 0.5\%)$	strange quark
$H \rightarrow \rho^0\gamma$ $\quad \quad \quad \searrow \pi^+ \pi^- \quad (\sim 100\%)$	up/down quark
$H \rightarrow K^{*0}\gamma$ $\quad \quad \quad \searrow K^\pm \pi^\mp \quad (\sim 100\%)$	flavor violating down/strange quark
<hr/>	
$H \rightarrow \phi\gamma$ $\quad \quad \quad \searrow \pi^+ \pi^- \pi^0 \quad (15.4 \pm 0.4\%)$	strange quark
$H \rightarrow \omega\gamma$ $\quad \quad \quad \searrow \pi^+ \pi^- \pi^0 \quad (89.2 \pm 0.7\%)$	up/down quark
$H \rightarrow D^{*0}\gamma$ $\quad \quad \quad \searrow D^0 + \pi^0 / \gamma \quad (\sim 100\%)$ $\quad \quad \quad \quad \quad \searrow K^- \pi^+ \quad (3.95 \pm 0.03\%)$ $\quad \quad \quad \quad \quad \searrow K^- \pi^+ \pi^0 \quad (14.4 \pm 0.5\%)$	flavor violating up/charm quark

Table 4: Higgs rare decays of the form $H \rightarrow M\gamma$, where M is a vector containing light quarks.

As seen before, the most significant Higgs production channel is gluon fusion, responsible for 87% of all Higgs production. Therefore, within the limited timeframe of this project, our primary focus will be on this production mode. Although other modes, such as vector boson fusion or associated production with a W/Z boson, share reasonable similarities with ggH in terms of implementation, we will concentrate on the latter.

[TODO: Explain direct/indirect veritces in the decay of the higgs]

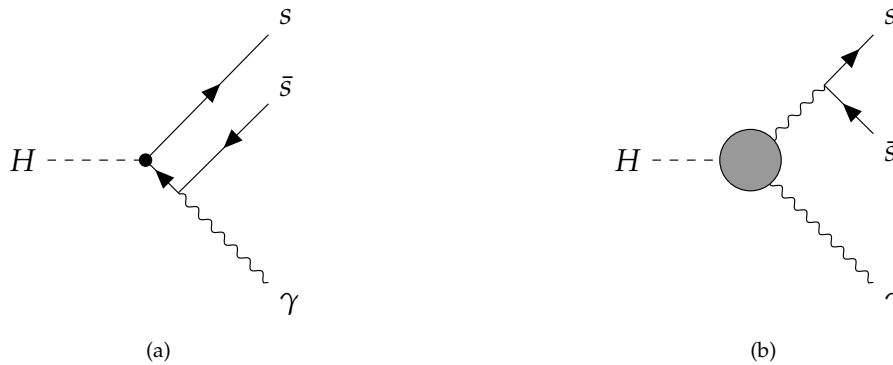


Figure 6: Direct and indirect contributions involved in the decays under analysis.

[TODO: unmeasured sectors of the higgs]

[TODO: Explain how deviations from SM predictions in these sectors could point to new physics and justify the need for precise measurements.]

[COMMENT: I don't know if I should add something else to this chapter? I have still some points to develop further, this is the first draft and like so is very provisional.]

Chapter 2

The CMS at the LHC

This chapter will provide an overview about the European Organization for Nuclear Research, known by its acronym CERN (Conseil Européen pour la Recherche Nucléaire), the Large Hadron Collider (LHC) and the Compact Muon Solenoid (CMS) experiment. It will also go through the discovery of the Higgs boson at the LHC in 2012 by the CMS collaboration [4].

2.1 The Large Hadron Collider at CERN

The European Organization for Nuclear Research (CERN) is an intergovernmental organization composed of 23 member states that operates the world's largest particle physics laboratory. Established in 1954, CERN is situated on the Franco-Swiss border near Geneva, Switzerland, and is one of the largest and most influential research organizations in particle physics. The missions of CERN include world-class research in fundamental physics, sustainable and environmentally responsible accelerator facilities, global collaboration in science and technology advancement and the education and engagement of future scientists, engineers and the broader public.

CERN has been home to many accelerators, including the original linear accelerator LINAC 1 (in operation from 1959 until 1992), the LINAC 2 (1978 - 2018), the Super Proton-Antiproton Synchrotron ($S\bar{p}\bar{p}S$) (1981-1991), the Large Electron-Positron Collider (LEP) (1989-2000), and the current Large Hadron Collider (LHC), which was constructed between 1998 and 2008 and achieved its first collisions in 2010.

During its nearly 70-year history since its creation, many important achievements in particle physics have been made through experiments at CERN, including:

- The discovery of neutral currents by studying neutrinos produced by the PS/SPS neutrino beam interacting in the Gargamelle bubble chamber in 1973 [17].
- The discovery of the W and Z bosons in the UA1 and UA2 experiments in 1983 [18, 19].
- The determination of the number of light neutrino families at LEP in 1989 [20].
- The discovery of direct CP violation in the NA48 experiment in 1999 [21].

- The discovery of the Higgs boson at LHC by the CMS and ATLAS collaborations in 2012 [4, 5].

[**TODO:** What is the LHC? Explain the current accelerator and current experiments/collabs]

2.2 The Compact Muon Solenoid experiment

[**TODO:** talk about CMS: what is it, explain the detector, mention discoveries and relevant papers, talk about computer facilities and clusters]

2.3 The discovery of the Higgs boson at CMS

[**TODO:** Discovery of the higgs]

Chapter 3

Analysis

This chapter is the central cornerstone of this dissertation. In it, we will discuss the analysis conducted, starting with a general overview, followed by an explanation of the samples, triggers, and object definitions. We will then discuss the corrections made to the data and simulations to enhance the analysis results. We will also cover the various criteria utilized in event selection and how the signal and background have been modeled. Ultimately, we will present the expected limits for each channel. The chapter concludes by addressing the subsequent steps required prior to data unblinding and the attainment of the final experimental measurement.

3.1 Analysis overview

3.2 Samples and triggers

[TODO: Explain data, background and signal MC simulation, triggers]

3.3 Object definitions

[TODO: Primary vertex, leptons?, jets, missing energy, photons, mesons]

3.4 Corrections to data and simulations

[TODO: Pileup reweighting, L1 prefiring corrections, photon scale and resolution, photon mva id efficiency, Lepton ID reconstruction efficiency and energy scale (?), meson reconstruction (+regression of the pt), triggers scale factors]

3.5 Event selection

[TODO: Gluon fusion selection for each channel]

3.6 Signal and background modelling

[**TODO:** signal, background model from MC and data, bias studies]

3.7 Results

3.8 Multivariate analysis for final results

[**TODO:** talk about MVA and what are next steps before unblinding data]

Conclusions

These are the conclusions of the project.

Appendix A

Appendix

First appendix

References

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