ETH Zürich
Department of Physics
Master of Science ETH in Physics

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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First acknowledgement.

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Abstract

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Contents

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 specific focus on the important role played by the Higgs boson. We will give a brief introduction to the SM and its fundamental particles, discuss the Lagrangian that governs their behaviour, and explore their interactions represented by Feynman diagrams. Moreover, we will examine the characteristics 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 concentrate on the decay channels subject of 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 exceptional theory that has come very close to achieving this goal is the Standard Model of Particle Physics (SM). It stands as one of the most precise theories ever conceived by humanity, and is the most successful theory of particle physics to date. The Standard Model serves as a theory capable of describing three of the four known fundamental forces in the Universe (electromagnetic, weak and strong forces, but not gravity). This is achieved by classifying a set of elementary particles and defining the interactions between them. Summaries of the SM can be found in [1, 2] among many others.

More in detail, the SM is a quantum field theory (QFT) defined by an internal local $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge symmetry. Each elementary particle has its 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 into 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

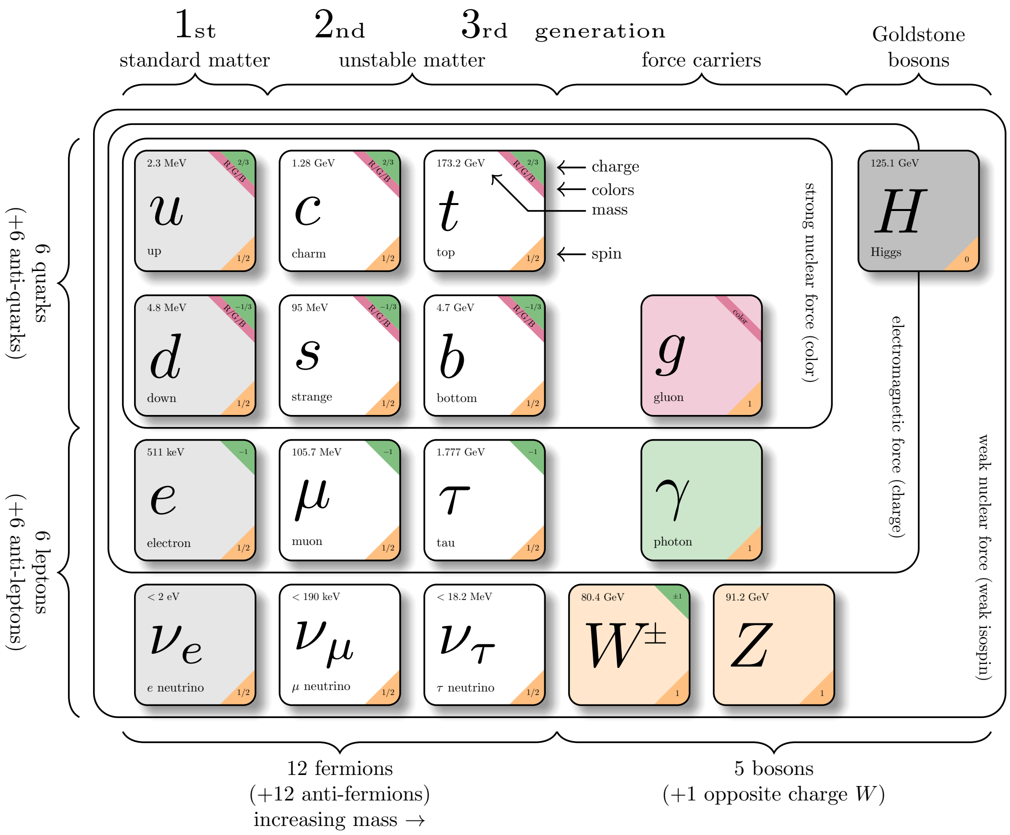


Figure 1: Elementary particles of the Standard Model. The electric charge, mass and spin of each particle are shown. Figure from [3].

of a local invariant gauge group induces a massless gauge boson. In the same way that in quantum 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 $\mathrm{SU}(3)_\mathrm{C}$ postulates the existence of the gluon. More precisely, the eight generators of $\mathrm{SU}(3)_\mathrm{C}$ introduce eight gluons that mediate the strong force between particles that possess color charge (quarks and gluons). This is known as the quantum chromodynamics (QCD) sector of the Standard Model.

Similarly, the invariance of the second and third factors $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ 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 with the generator of the hypercharge group $\mathrm{U}(1)_\mathrm{Y}$ and the Z^0, $W^\pm$ bosons with the generators of the left weak isospin group $\mathrm{SU}(2)_\mathrm{L}$. Instead, the generators of $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ give rise to four intermediate vector bosons ($W_\mu^{1,2,3}$ for $\mathrm{SU}(2)_\mathrm{L}$ and B_μ for $\mathrm{U}(1)_\mathrm{Y}$), 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:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$$
$$\begin{pmatrix} A_\mu \\ Z_\mu^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & \sin\theta_\mathrm{W} \\ -\sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$$

By the definition of the groups $\mathrm{SU}(2)_\mathrm{L}$ and $\mathrm{U}(1)_\mathrm{Y}$, 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 (non-maximal) parity violation.

All gauge bosons that arise from the generators of gauge-invariant groups are expected to be massless; otherwise, the principle of local gauge invariance is spoiled and the theory becomes unrenormalizable. However, this contradicts experimental observations, which confirm that the Z^0 and $W^\pm$ 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 allow for 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 used to explain how gauge bosons (and, in general, massive particles) can acquire non-vanishing mass while maintaining the theory gauge-invariant. 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 an $\mathrm{SU}(2)$ 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 $(\phi^0)^* = \phi^0$. This scalar field has a Lagrangian density given by $\mathcal{L} = \left|D_\mu\phi\right|^2 - V(\phi)$ and a potential $V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$, where D_μ is the covariant derivative determined by $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$. When expanding the field ϕ around a minimum of the potential V, one finds out that there are infinitely many values of 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 $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ 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 $\left|D_\mu\phi\right|^2$ 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:

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

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

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

and where T^a, σ^i (Pauli matrices) and Y (weak hypercharge) are the generators of SU(3), SU(2) and SU(1) respectively, and g_s, g and g' are the coupling constants. ϕ^c is the charge conjugate of ϕ defined by $\phi^c = i\frac{\sigma_2}{2}\phi^\dagger$.

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 the origin of gluons and electroweak bosons self-interactions.

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 eletroweak 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

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

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

$$i\bar{u}\not{D}u = i\bar{u}\gamma^\mu D_\mu u = i\bar{u}_R^i\gamma^\mu\left(\partial_\mu - ig_s T^a G_\mu^a - ig'\frac{Y}{2}B_\mu\right)u_R^i,$$

because the right-handed quark is a singlet under $\mathrm{SU(2)_L}$.

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

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

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

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

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 in Equation (1) governs the interactions between all particles within the theory. These interactions can be represented as vertices in Feynman diagrams. The vertices shown in Figure 2 are all possible interactions in the SM, and are constructed from the terms in the SM Lagrangian. Terms that, after SSB, involve only two fields do not result in vertices as they are interpreted as mass terms. Consequently, we only see vertices with at least three fields.

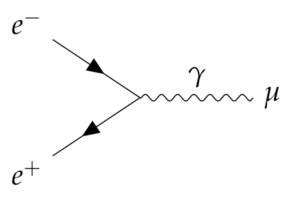
For instance, to derive the QED vertex for the electron, one must expand the terms $i\,(\bar{L}\not{D}L + \bar{e}\not{D}e)$ and keep the terms of the form $\bar{e} \cdot \ldots \cdot e$. This expansion ultimately yields two contributions. The first one corresponds to the coupling of the electron to the photon field:

$$-\frac{gg'}{\sqrt{g'^2 + g^2}} \bar{e}\gamma^\mu e A_\mu = -e\bar{e}\gamma^\mu e A_\mu \,. \tag{2}$$

The first e in the latter expression refers to the electrical charge, therefore connecting both couplings g and g' with the electrical charge and the weak mixing angle, yielding $e = g' \cos\theta_{\mathrm{W}} = g \sin\theta_{\mathrm{W}}$. The second term that arises corresponds to the Z^0 boson:

$$\frac{1}{\sqrt{g'^2 + g^2}} \left(\frac{g'^2 - g^2}{2} \bar{e}_L \gamma^\mu e_L + g'^2 \bar{e}_R \gamma^\mu e_R \right) Z_\mu^0 \,.$$

We can see that the Z^0 couples to both left-handed and right-handed components of the electron but with different strengths. Hence, by removing the fields from Equation (2) and multiplying by i, the coupling of the electron to the photon associated with the QED vertex is



$$= -ie\gamma^\mu \,. \tag{3}$$

Each of the vertices in Figure 2 has an associated factor that can be computed from the SM Lagrangian density in a similar manner. Therefore, we can observe, for example, that the Higgs boson does not couple to the photon or the gluon field, and that there is no direct interaction between three fermions.

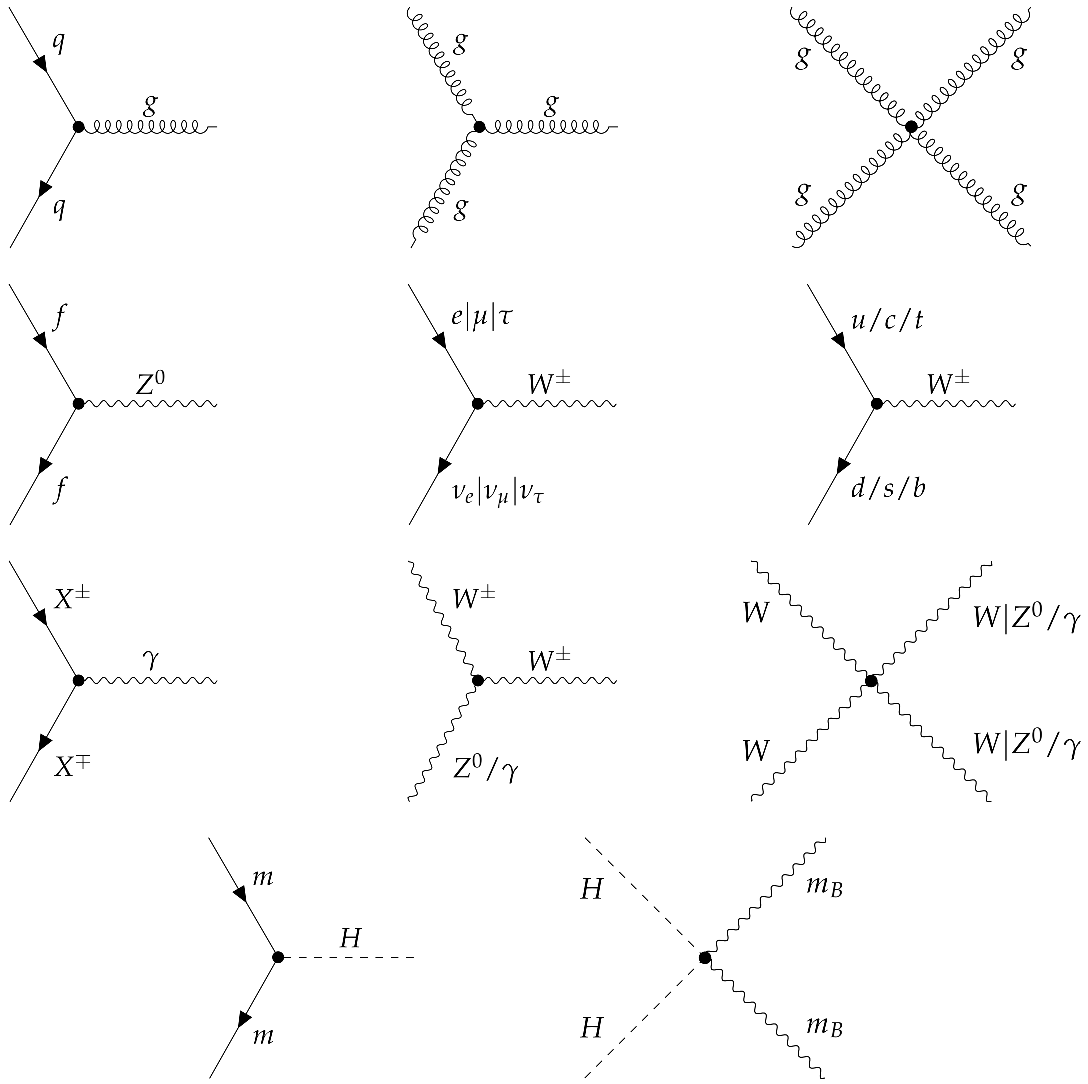


Figure 2: All possible interactions in the Standard Model, represented by Feynman diagrams. q is any quark, g is (any) gluon, $X^\pm$ is any charged particle, γ is a photon, f is any fermion, m is any massive particle (except neutrinos), m_B is any massive boson. In diagrams with multiple particle labels 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 electroweak boson case the valid diagrams are $WWWW$, $WWZZ$, $WW\gamma\gamma$ and $WWZ\gamma$.

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, such as 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 [4, 5, 6]. 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 2012, a scalar particle consistent with the Higgs boson was discovered at the LHC by the CMS and ATLAS collaborations [7, 8].

The Higgs boson is a weak isospin $SU(2)_L$ doublet, massive scalar neutral boson. Table 1 summarizes the SM predicted properties [9, 10] as well as the measured properties of the Higgs boson from the Particle Data Group (PDG) [11].

Property	SM prediction	Mesasured value
Mass	$m \lesssim 700$ GeV	$m = 125.25 \pm 0.17$ GeV
Spin	$J = 0$	$J = 0$
Electric charge	$q = 0$	$q = 0$
Full width	$\Gamma = 4.12 \pm 0.06$ MeV	$\Gamma = 3.2^{+2.8}_{-2.2}$ MeV
Lifetime	$\tau = (1.60 \pm 0.02) \times 10^{-22}$ s	$\tau = 2.1^{+4.5}_{-1.0} \times 10^{-22}$ 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 $m = 125.25$ 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 [9].

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 massive particles of the SM (it couples to the gauge bosons via the $|D_\mu \phi|^2$ term in the Higgs part of the SM Lagrangian and to fermions via the Yukawa couplings), 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 determine the dominant production modes for the Higgs boson, as shown in Figure 3. Since the heavier the particle, the stronger its Higgs coupling constant is, we observe that in most cases, the particles involved in the vertex where the Higgs boson is produced are very heavy (top and bottom quarks and massive gauge bosons).

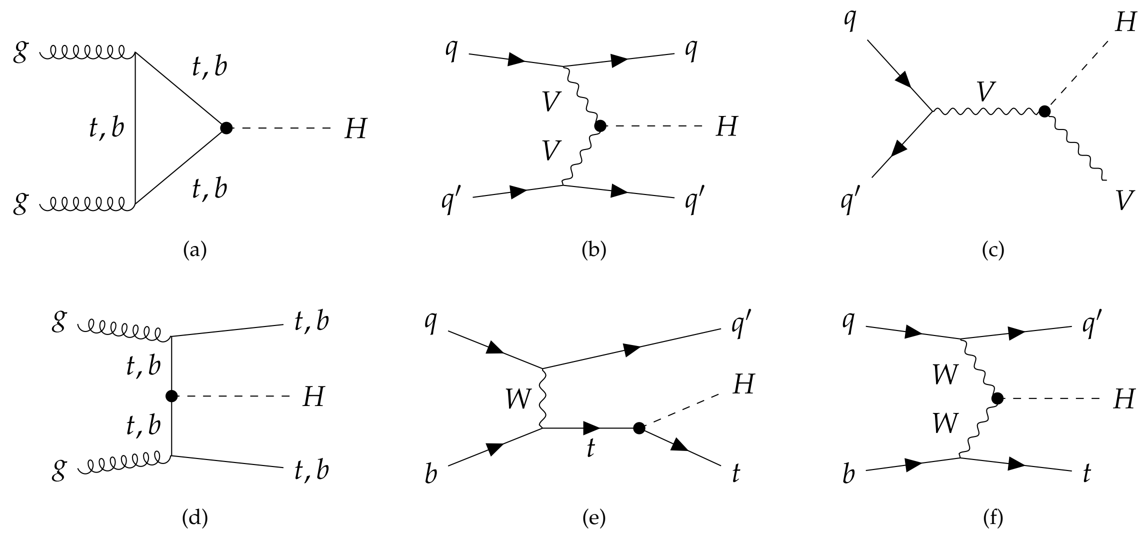


Figure 3: Higgs boson production in (a) gluon-gluon fusion (ggH), (b) vector boson fusion (VBF), (c) associated production with a W or Z (V) boson (VH), also known as Higgsstrahlung, (d) associated production with a top or bottom quark pair (ttH or bbH), or tt fusion, and (e, f) associated production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

Despite being a second-order process (it requires a heavy quark loop), the strong coupling to heavy quarks makes gluon fusion the process that contributes the most to the production of the Higgs boson at the LHC, a proton-proton collider. The LHC is a gluon-gluon collider when it comes to Higgs production, as gluons dominate the production of Higgs bosons with a mass of around 125 GeV. The second most important process at the LHC is vector boson fusion, where two fermions collide and exchange a virtual vector boson, which radiates a Higgs boson. The third contribution to Higgs boson production, and the first one at LEP, is associated production with a vector boson or Higgsstrahlung. In this production mode, a fermion and antifermion collide and can form a virtual $W^{\pm}$ or Z^0 boson which, if it carries enough energy, can emit a Higgs boson.

[**TODO:** Add higgs production signatures]

To compare the different production cross sections with the SM predictions, we introduce some important quantities to describe interactions at particle colliders. The *center-of-mass energy* $\sqrt{s}$ describes the combined energy of the collided particle beams and is defined as the square root of the Mandelstam variable

$$\sqrt{s} = \sqrt{(p_1 + p_2)^2}\,,$$

where p_1 and p_2 are the four-momenta of the two particles. When colliding elementary particles (e.g., e^+e^-), the center-of-mass energy is precisely the available energy to produce particles in the collision. When colliding composite particles (e.g., protons), however, the available energy to produce particles is slightly less due to the parton distribution functions within the proton, and there is an energy spread. The *cross section* σ of a process describes the likelihood of a specific final state, as a measure of the effective area or target size for a particular interaction. It is measured in units of area, usually barns, defined as barn $= 10^{-28}$ cm^2. The number of events per unit time can be expressed in terms of the *instantaneous luminosity* $\mathscr{L}$ and the cross section of the studied event σ as

$$\frac{\mathrm{d}N_{\text{events}}}{\mathrm{d}t} = \mathscr{L}\sigma \,,$$

and the *integrated luminosity* is defined as

$$L = \int \mathscr{L}\mathrm{d}t \,.$$

Finally, the *signal strength* μ expresses a measured cross section divided by the expected SM value.

Having established these fundamental concepts, we can now compare the theoretical and measured cross sections for the production of the Higgs boson. Our analysis uses 2018 data from the LHC, with a center-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of $L = 39.50$ fb^{-1}. According to the SM, the total Higgs boson cross section at a center-of-mass energy of $\sqrt{s} = 13$ TeV is $\sigma = 55500 \pm 2800$ fb [10], with around 87% coming from gluon fusion, 7% from vector boson fusion and 4% from Higgsstrahlung. The predicted and measured cross section of the Higgs boson at $\sqrt{s} = 13$ TeV from different production modes are shown in Table 2.

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	580 ± 60	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 [10], measured values from [12]. At the moment of this writing, the bbH production channel has not bean measured yet.

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. However, there are certain decay modes where the Higgs boson decays into massless particles (to a pair of gluons or photons), as the first-loop contributions are not negligible. The most relevant Feynman diagrams of the Higgs boson decay are shown in Figure 4, whereas Table 3 presents the most frequent decay channels for the Higgs boson, comparing the SM predicted value to the measured value for the different channels.

[**TODO:** Talk more about the decays: Why no measurement H->gg (QCD bkg)? What does the * in WW* ZZ* mean?]

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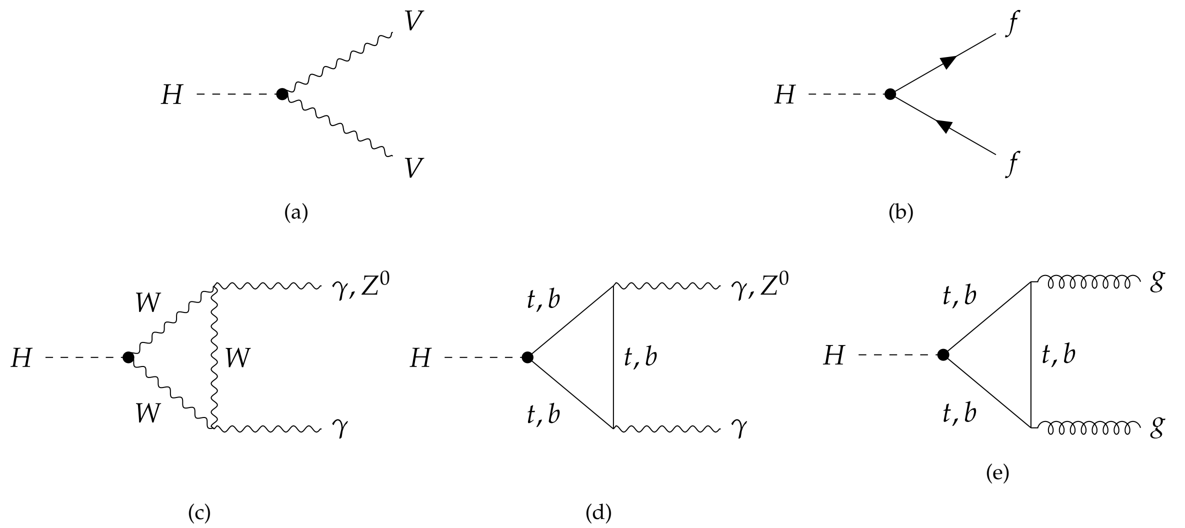

Figure 4: Higgs boson decays into (a) heavy vector boson pairs (V is $Z^0/W^{\pm}$), (b) fermion-antifermion pairs, (c, d) photon pairs or $Z^0\gamma$, and (e) gluon pairs.

Decay channel	SM $\mathcal{B}$ (%)	Measured $\mathcal{B}$ (%)	Measured μ
$\mathrm{H} \to b\bar{b}$	57.8 ± 0.7	60 ± 12	1.04 ± 0.20 [13]
$\mathrm{H} \to WW^*$	21.8 ± 0.3	20.7 ± 2.1	0.95 ± 0.09 [14]
$\mathrm{H} \to gg$	8.2 ± 0.4	-	-
$\mathrm{H} \to \tau^+\tau^-$	6.23 ± 0.10	6.1 ± 1.1	0.98 ± 0.18 [15]
$\mathrm{H} \to c\bar{c}$	2.87 ± 0.16	< 40	< 14 [16]
$\mathrm{H} \to ZZ^*$	2.68 ± 0.04	2.6 ± 0.3	0.97 ± 0.12 [12]
$\mathrm{H} \to \gamma\gamma$	0.227 ± 0.005	0.254 ± 0.021	1.12 ± 0.09 [17]
$\mathrm{H} \to Z\gamma$	0.155 ± 0.009	0.37 ± 0.14	2.4 ± 0.9 [18]
$\mathrm{H} \to \mu^+\mu^-$	0.0216 ± 0.0004	0.026 ± 0.009	1.19 ± 0.43 [19]

Table 3: Most frequent decay modes of the Higgs boson. SM values from [10].

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1.3 Searching of a model beyond the SM

[**TODO:** Improve the section]

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.

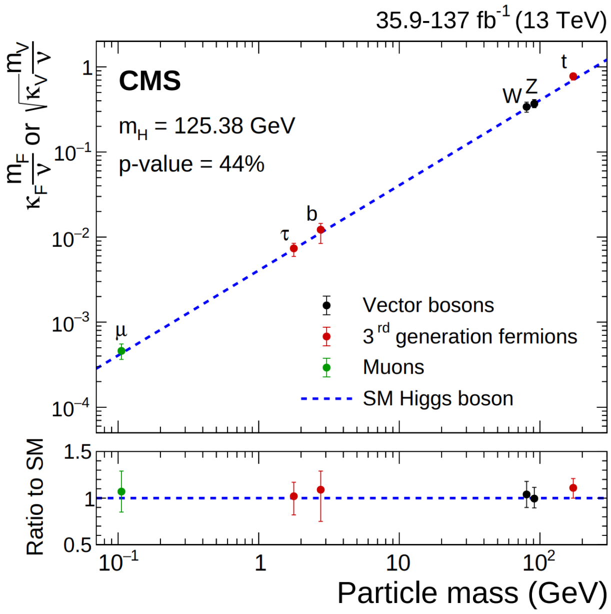


Figure 5: Yukawa couplings [19].

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 $H \longrightarrow M\gamma$, 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 rations and measured upper limits, when these are available.]

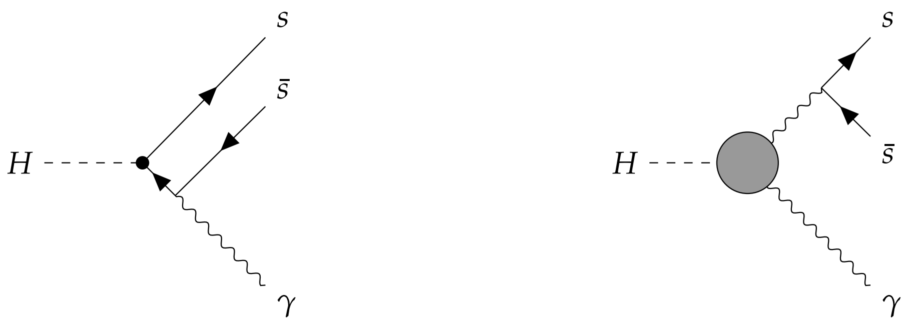
As seen before, the most significant Higgs production channel is gluon fusion, responsible for 87% of all Higgs production. Therefore, within the limited timeframe of this project, our

Higgs boson rare decay	Coupling
$\mathrm{H} \longrightarrow \phi\gamma$	strange quark
$\quad \hookrightarrow K^+K^-$ (49.1±0.5%)	
$\mathrm{H} \longrightarrow \rho^0\gamma$	up/down quark
$\quad \hookrightarrow \pi^+\pi^-$ (∼100%)	
$\mathrm{H} \longrightarrow K^{*0}\gamma$	flavor violating down/strange quark
$\quad \hookrightarrow K^{\pm}\pi^{\mp}$ (∼100%)	
$\mathrm{H} \longrightarrow \phi\gamma$	strange quark
$\quad \hookrightarrow \pi^+\pi^-\pi^0$ (15.4±0.4%)	
$\mathrm{H} \longrightarrow \omega\gamma$	up/down quark
$\quad \hookrightarrow \pi^+\pi^-\pi^0$ (89.2±0.7%)	
$\mathrm{H} \longrightarrow D^{*0}\gamma$	flavor violating up/charm quark
$\quad \hookrightarrow D^0 + \pi^0/\gamma$ (∼100%)	
$\qquad \hookrightarrow K^-\pi^+$ (3.95±0.03%)	
$\qquad \hookrightarrow K^-\pi^+\pi^0$ (14.4±0.5%)	

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

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]



(a) (b)

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.]

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 [7].

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$p\bar{p}$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 [20].
- The discovery of the W and Z bosons in the UA1 and UA2 experiments in 1983 [21, 22].
- The determination of the number of light neutrino families at LEP in 1989 [23].
- The discovery of direct CP violation in the NA48 experiment in 1999 [24].

- The discovery of the Higgs boson at LHC by the CMS and ATLAS collaborations in 2012 [7, 8].

[**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 mvaid 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

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