SEARCH FOR RESONANT DOUBLE HIGGS PRODUCTION WITH bbZZ DECAYS IN THE $b\bar{b}\ell\ell\nu\bar{\nu}$ FINAL STATE IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

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University of Nebraska, 2019

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Since the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments, most of the quantum mechanical properties that describe the long-awaited Higgs boson have been measured. Due to the outstanding work of the LHC, over a hundred of fb^{-1} of data have been delivered to both experiments. Finally, it became sensible for analyses teams to start working with a very low cross section processes, which made it possible to observe rare decay modes of the Higgs boson, e.g., a recent success in observing ttH and VHbb processes. One of the main remaining untouched topics is a double Higgs boson production. However, additional hundred of fb^{-1} per year from the HL-LHC will not necessarily help us much with the SM double Higgs physics, the process may remain unseen even in the most optimistic scenarios. The solution is to work in parallel on new reconstruction and signal extraction methods as well as new analysis techniques to improve the sensitivity of measurements. This thesis is about both approaches: we have used the largest available dataset at the time the analysis has been performed and developed/used the most novel analysis methods. One of such methods is the new electron identification algorithm that we have developed at the CMS electron identification group, to which I have had a privilege to contribute during several years of my stay at CERN.

The majority of this thesis is devoted to techniques for the first search at the LHC for the double Higgs boson production mediated by a heavy narrow-width resonance

in the $b\bar{b}ZZ$ channel: $X \to HH \to b\bar{b}ZZ^* \to b\bar{b}\ell\ell\nu\bar{\nu}$. The measurement searches for a resonant production of a Higgs boson pair in the range of masses of the resonant parent particle from 250 to 1000 GeV using 35.9 fb^{-1} of data taken in 2016 at 13 TeV. Two spin scenarios of the resonance are considered: spin 0 and spin 2. In the absence of the evidence of the resonant double Higgs boson production from the previous searches, we proceed with setting the upper confidence limits.

"... a place for a smart quote"

Lenin, 1922.

ACKNOWLEDGMENTS

This will be a long list!

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Chapter 1

Introduction

This chapter describes the development of particle physics following the historical order of how particles were discovered and parts of the Standard Model (SM) were constructed.

1.1 "All things are made of atoms"

The SM is the theory of particles and their interactions that was built during many decades of intense experimental and theoretical work. Particles in this theory are elementary and have no size, meaning they cannot be divided further. This idea of the point-like particles is crucial since it reflects the goal of particle physics to find and describe the smallest and the most fundamental scale at which nature works. For the last several decades the SM is the most tested theory of elementary particles and forces and is presently generally accepted by the whole physics community. Formally, all SM elementary particles are split into two classes: fermions and bosons. Particles with a half-integer spin 1/2 (quarks and leptons) are called fermions since they obey Fermi-Dirac statistics [1]. The other class of particles is bosons. They are force carriers, have an integer spin, and are characterised by the Bose-Einstein statistics. A rigorous mathematical description of the SM will be given in the next chapter.

Our macroscopic world, from the smallest viruses to the biggest stars, is made of molecules and atoms. To show how deep and significant this simple idea is, let us quote Richard Feynman, a Physics Nobel Prize winner, who once summarised in a single phrase what he believed to be the most important fact about the world around us: "all things are made of atoms" [2]. Feynman himself was the father of quantum electrodynamics, and in this simple statement - delivered originally to Caltech students and now known to everyone through his series of physics books - he decided not to go into quantum mechanics principles and instead illustrated at the rather highly abstract level that everything is made of smaller particles. The quest to the smallest scale and the theory that would describe it were the key ideas that ultimately led to the development of the SM.

Today the physics community knows that molecules are made of atoms, which are not elementary particles either. Instead, atoms have heavy nuclei and light electrons "orbiting" around the nucleus on the electron shells. The nucleus is positively charged proportionally to the number of protons it contains. To provide the stability of the nuclei of the heavy atoms our world also needs neutrons, which have no electric charge. Going to an even smaller scale, it is now known that protons and neutrons are not elementary; rather, they are composed of point-like constituents that are called quarks (see Figure 1.1).

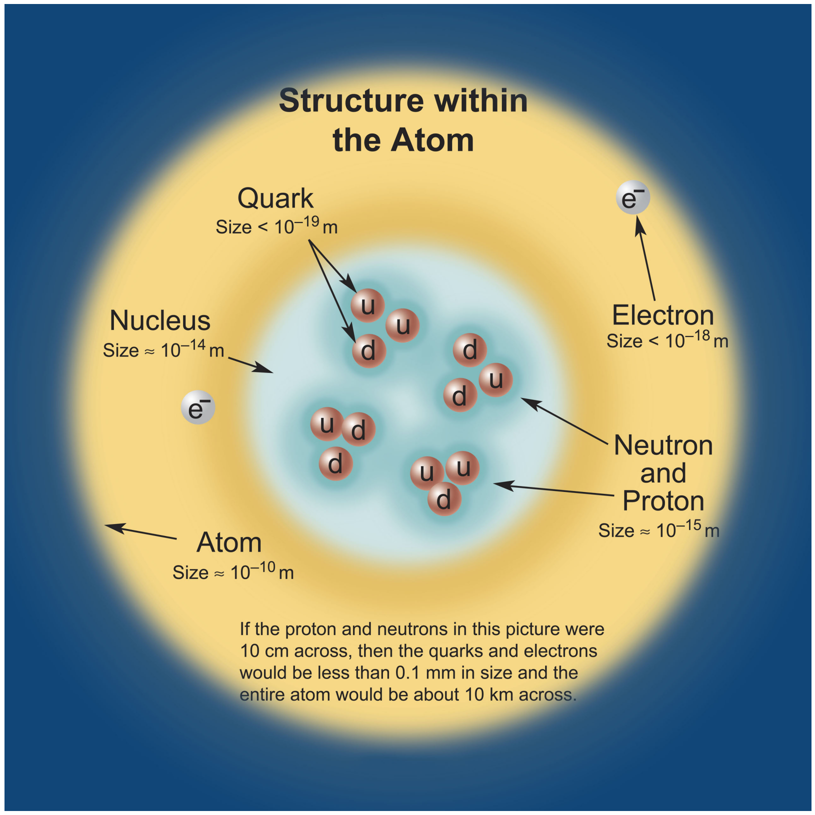

Figure 1.1: The structure of an atom. Approximate scale values are indicated.

Quarks were proposed by Gell-Mann and also by Zweig to explain periodicity in properties of observed subatomic particles [3]. Quarks are arranged in three families or three generations of doublets. A doublet is a mathematical construct that is used to explain a two-value system. For example, by design of Gell-Mann and Zweig, each quark doublet in their theory is a two quark system that has an "up" quark with the electric charge $+1/3$ and a "down" quark with the charge $-2/3$. For antiquarks, the signs of the charges are reversed. The physics world before Gell-Mann and Zweig got used to the fact that particles have integer charges due to an enormous number of observations. The fact that the quark charge values were fractional was so revolutionary to Gell-Mann that he decided not to publish his article in a highly prestigious journal but, expecting a rejection, decided to go with a second tier one [3]. However, with time out of all the theories that were trying to explain the difference in masses of observed hadrons it was the hypothesis of Gell-Mann and Zweig that turned out to be correct. Now, the quark theory is one of the key elements of the SM.

The SM includes six different types of quarks: up, down, charm, strange, top, and bottom. To distinguish one quark from another there is a "flavor" number assigned to them. For instance, a charm quark has $+1$ unit of "charmness", while a strange quark has -1 unit of "strangeness". All the other flavor fields are zero for quarks. This pattern is applied to all the other four quarks to fill the corresponding "quarkness" numbers. Another important characteristic of quarks was revealed at the e^+e^- colliders when physicists compared production rates of muons and hadrons. The theory was off by a factor of three. This was the motivation to introduce three quark colours: green, blue, and red.

Quarks were observed decades after electrons had been discovered. In particle physics, the electron belongs to a family of leptons. A lepton is an elementary particle with a spin 1/2 that participates in all but strong interactions, which will be discussed in more detail later in this chapter. The electron was discovered by Thompson [4] in 1897 when he was studying the properties of a cathode ray. Due to this discovery, that year may be considered the beginning of an era of a particle physics: dozens of particles were discovered in the next decades. In 1936, another lepton was observed, the muon [5], in an experiment of Anderson and Neddermeyer who studied cosmic radiation. In essence, a muon is almost a copy of an electron, but is 207 times heavier. No explanation for this mass difference exists in the SM. As a side note, according to Carl Bender, there is a story that Feynman was able to derive the mass of the muon starting with the mass of an electron, but the world has never seen that calculation published [6].

Leptons are also arranged in generations, analogously to quark families. Each generation is a doublet that consists of a charged lepton (electron, muon or tau) with the charge -1 and a neutral lepton (corresponding electron, muon, or a tau neutrino). Electron and muon neutrinos had been discovered in 1956 and 1962, respectively. The existence of the electron neutrino was deduced from the violation of the conservation of energy in a beta decay. The muon neutrino [7] was discovered by Schwartz, Lederman, and Steinberger during an experiment with a pion beam where leptons from the pion decays arrived to the aluminum spark chamber after passing a steel wall. Fifty-one events of interest had been observed after running the experiment for several months. Those events could not be initiated by electron neutrinos, since they will interact with the metal and produce electrons. The presence of narrow muon tracks in the chamber in each event, hence muons, was a clear indication that those neutrinos were of a different kind - they were muon neutrinos. Finally, a tau lepton and a tau neutrino were discovered in 1975 and 2000 correspondingly [8,9]. With that, all three families of the SM leptons were observed: a long-awaited tau neutrino, which decades ago was theoretically speculated to exist, was finally discovered experimentally. In a like manner to families of quarks, lepton masses grow with each generation, where a tau from the third generation is the heaviest lepton. To classify leptons of different families the lepton numbers were reserved: 1 unit of electron number to an electron and an electron neutrino, 1 unit of muon number to a muon and a muon neutrino, and 1 unit of tau number to a tau and a tau neutrino.

1.2 Fundamental forces

In nature there are four fundamental forces: gravitational, weak, electromagnetic, and strong forces. This thesis will classify all four forces [10] in terms of the relative strength, the range that they can cover, the spin of the mediator, and whether the force's nature is attractive, repulsive, or both. This should be taken critically, since this is quite an ambiguous categorisation. It has a deep pedagogical meaning, though, because it helps to illustrate in which regime each of the forces is dominant. According to the world known mathematical physicist Carl Bender, this is of great importance since it is one of the main approaches to solving physics problems: to know which effects are the dominant and which are sub-dominant. This helps to justify what effect can be neglected and what approximation can be used. Thus, it allows the possibility to do calculations for problems where closed-form solutions do not exists, which is almost all the complex phenomena around us [6].

The first force on our list of forces is the gravitational force. This force governs the Universe at the macroscopic level: planets, solar systems, etc. The first theory of gravity was formulated by Newton [11]. Einstein later developed a new theory of gravity (GR). The key difference is that the Newtonian gravity had several "absolutes" that GR does not have: absolute time and space, a preferred separation of spacetime into time and spatial parts, absolute simultaneity, etc. [12]. Butterworth gives a good historical perspective in [13]. It is worth noting that the gravitational force is not included in the SM. Attempts are ongoing to expand the SM, e.g., adding the graviton as a mediator, but no real success so far has been achieved to create a renormalizable theory that would combine both the SM and gravity [14]. Surprisingly, gravity is the weakest force - the only reason why the motion of planets and galaxies is governed by gravity is because those are gigantic objects. Gravity effects become the dominant ones at the macroscopic scale because of an enormous number of particles involved in the interaction. If the strength of the strongest force, which is the strong force, is set to 1, then the strength of the gravity will be about 10^{-41}. It is contemplated that the gravity mediator (the graviton), if it exists, would have a charge of zero, zero mass, spin 2, and should be a stable particle. The gravitational force is of the infinite range and its nature is purely attractive, while the other three forces can exhibit both an attractive and a repulsive behaviour. Einstein's general relativity theory, though not a quantum theory, is the only working theory of gravity as of now.

The next force, the weak force, is mediated by a charged W (charge +1/-1) boson or a neutral Z boson, thus giving name to charged and neutral weak interactions correspondingly. All SM fermions, quarks and leptons, experience the weak force. The relative strength of the weak force is 10^{-16} and the range of applicability is 10^{-3} fm. All three weak bosons (W^+, W^-, and Z) have spin 1 and are quite massive: $m_{W^\pm} = 80.385$ GeV and $m_Z = 91.189$ GeV. GeV is the unit of the "natural system of units", in which $\hbar = c = 1$. This system is very popular in the high-energy physics and is widely used in this thesis. Adoption of this system simplifies how many equations look and also makes a fine-structure constant $\alpha \approx 1/137$ dimensionless. Using the natural system of units [15], masses, momenta, and energies are measured in electronvolts (eV), with GeV (10^9 eV) and TeV (10^{12} eV) being the most popular units in a modern high-energy physics due to the energy regimes involved.

Charged weak interactions are interesting due to the fact that a primitive interaction vertex can be thought of as a point where a charged lepton is converted to a neutral lepton or vice versa. A good example is a muon decay, which is a conversion of the muon to a muon neutrino with the help of the W boson, which further decays to an electron and a corresponding electron antineutrino. It is worth noting that charged weak interactions do not conserve the flavor of quarks; e.g., members of doublets of the third and the second families can be converted into members of the lower family of quarks. This fact is reflected in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [16]. This matrix describes the strength of the flavor-changing weak interactions. Since diagonal elements of this matrix are less than one and off-diagonal elements are non-zero, the CKM matrix represents a mismatch of quantum states of quarks when they propagate freely and when they take part in the weak interactions. In other words, the CKM matrix with non-zero off-diagonal elements means cross-generation interactions are allowed and this is the information that the CKM matrix quantifies.

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}. \tag{1.1}$$

The third force, the electromagnetic (EM) force, is one of the main forces that we experience in our everyday life. The reason one can sit in the chair and does not fall further down due to gravity, is that electrons of the body repel electrons of the chair. The relative strength of the EM force is 10^{-3} and the range of applicability is infinite. A photon, as the EM force's mediator, has zero mass and spin 1. The theory that describes photon interaction with leptons and quarks is called quantum electrodynamics (QED) and was developed in 1940s and 1950s by Tomonaga, Schwinger, Feynman, and Dyson [17]. Electric charge is conserved in EM interactions and no single photon-to-fermion vertex is possible; there are always two fermions that must be involved.

In the SM several multi-boson vertices are allowed. W and Z bosons that participate in weak interactions can couple to each other, so $WWZ, WWWW$, and $WWZZ$ vertices are possible in the SM. In addition, W bosons can couple to photons, so γWW, γWWZ, and $WW\gamma\gamma$ vertices are allowed too. Even though Z boson is massive and photon is a massless boson, Z boson has a neutral charge. This makes it possible that any interaction where the photon is a force carrier, can also be mediated by the Z boson.

The strong force, the fourth force of nature, is the strongest known force. Gluons are the carriers of this force and each gluon carries one unit of color and one unit of anticolor. There are nine types of gluons but, technically, the ninth gluon is a color invariant and would give rise to an infinite range of the strong force, which contradicts experiments. That is why modern physics assumes that in our world only eight gluons exist [3, 16]. Gluons carry color charge and, thus, can couple to each other. For several high order processes in quantum chromodynamics (QCD), 3- and 4-gluon vertices have to be introduced to restore gauge invariance and no higher order vertices are required [18].

To summarise the knowledge about the SM forces, one often refers to the Feynman diagram representation [19]. Fig. 1.2 shows all allowed SM particle interactions and corresponding simple vertices.

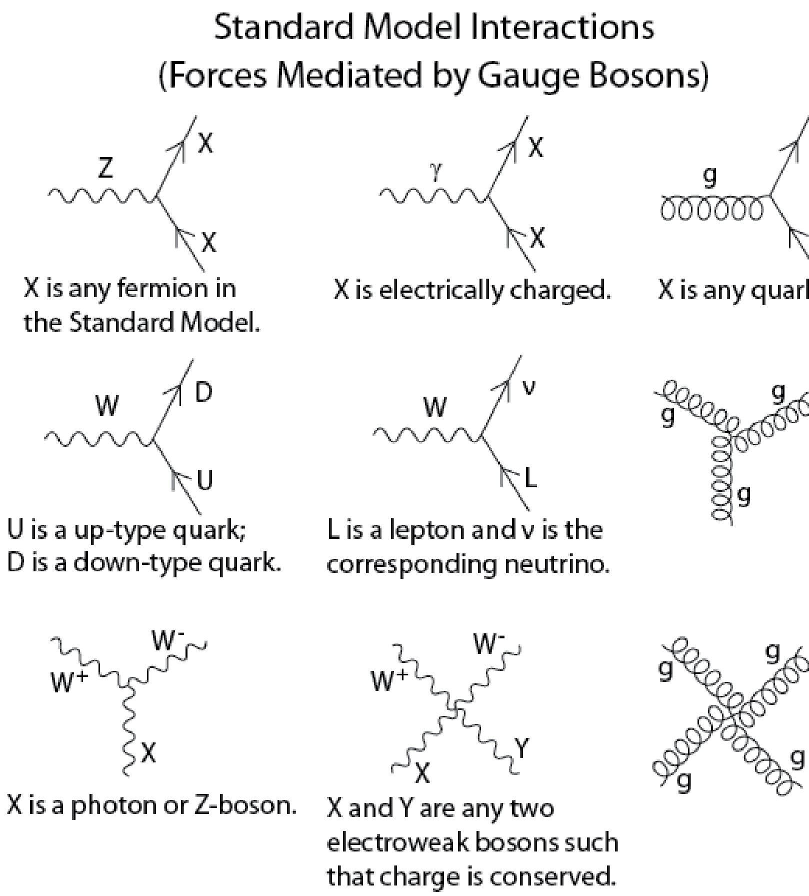

Figure 1.2: All SM interaction and simple vertices.

1.3 The Brout-Englert-Higgs mechanism

The description of the SM picture will not be complete without mentioning the main particle - the Higgs boson - that was predicted almost 60 years ago, but was not observed yet missing until 2012 (see Fig. 1.3 [20]). After the electroweak (EW) unification by Glashow, Salam, and Weinberg [21], it was still not clear what the origin of the mass of fundamental particles is. In 1964, Robert Brout and François Englert [22], Peter Higgs [23], Gerald Guralnik, C. Richard Hagen, and Tom Kibble [24] (BEHGHK authors), proposed the method by which the particles can acquire mass. This technique consists of three stages and we will discuss them one-by-one:

1. The Brout-Englert-Higgs (BEH) mechanism

2. The BEH field

3. The Higgs boson.

The first stage, the BEH mechanism, is simply a spontaneous symmetry breaking (SSB) mechanism, which is a mathematical trick consisting of rewriting the original scalar fields in the EW Lagrangian, rearranging equations, and requiring that the fields are real. What does this lead to? The BEH authors started with a scalar complex field and a massless vector field and after SSB obtained a single real scalar field (Higgs boson) and a massive vector field. In terms of our physical world this it what gives mass to W and Z bosons.

The second stage is the BEH field. It exists everywhere and has been present almost since the Big Bang [25]. It is a property of our world. All the fundamental particles that interact with the BEH field acquire mass. Those, which do not interact directly (at the tree level) have no mass and all their energy is in the form of the momentum. Such particles can travel with the speed of light. The more the particle interacts with the BEH field, the higher is the coupling to the Higgs boson or simply the higher is the mass of the particle. The coupling of the Higgs boson to fermions is proportional to the mass of the fermions, and for W and Z bosons it is proportional to the squared mass of bosons, making the top quark and the Z boson the most massive fermion and boson respectively (see Fig. 1.4 [26]).

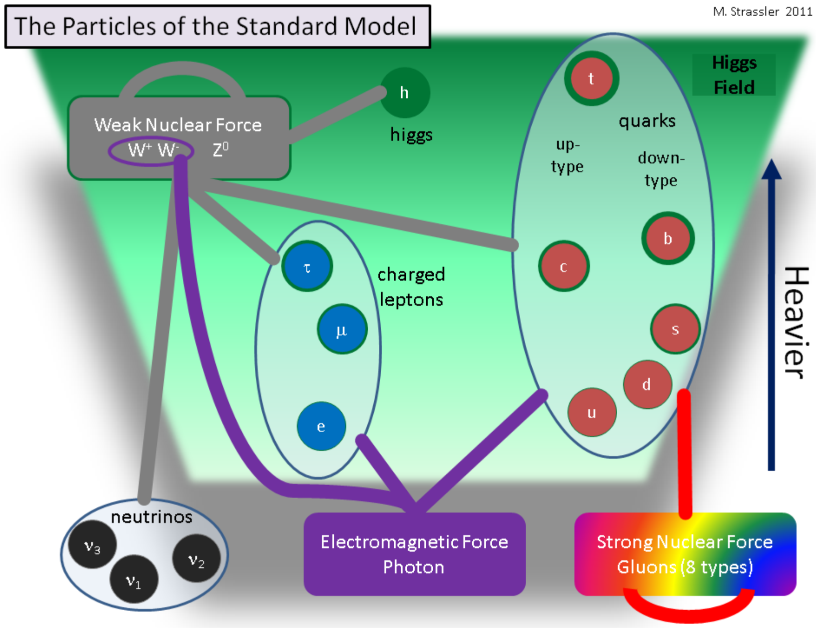

Figure 1.3: SM particles and force carriers. Self-interactions are also shown. The strength of the coupling to the Higgs boson increases from the bottom to the top, which is illustrated by the shades of the green color (the Higgs field).

The third and, arguably the most important stage, the Higgs boson. The Higgs boson is the excitation of the BEH field. Thus, the Higgs bosons can be produced at colliders by pumping more and more energy in a small space-time region exciting the BEH field to "produce" the Higgs bosons. In reality this happens through making the LHC beams more energetic and thus, during the collision, producing more energetic gluons (and also more energetic quarks). The main Higgs boson production mechanism is called a gluon fusion, when through the top quark loop a single Higgs boson is produced. This accounts for about 90% of the overall LHC Higgs production at the 13 TeV energy. The second mechanism is a vector boson fusion. The third mechanism is the associated production with a weak boson. The smallest contributor to the Higgs boson production is the ttH process, which stands for the associated production of the Higgs boson with the top anti-top quark pair. All mentioned Higgs boson production mechanisms are presented in the form of Feynman diagrams in Fig. 1.5.

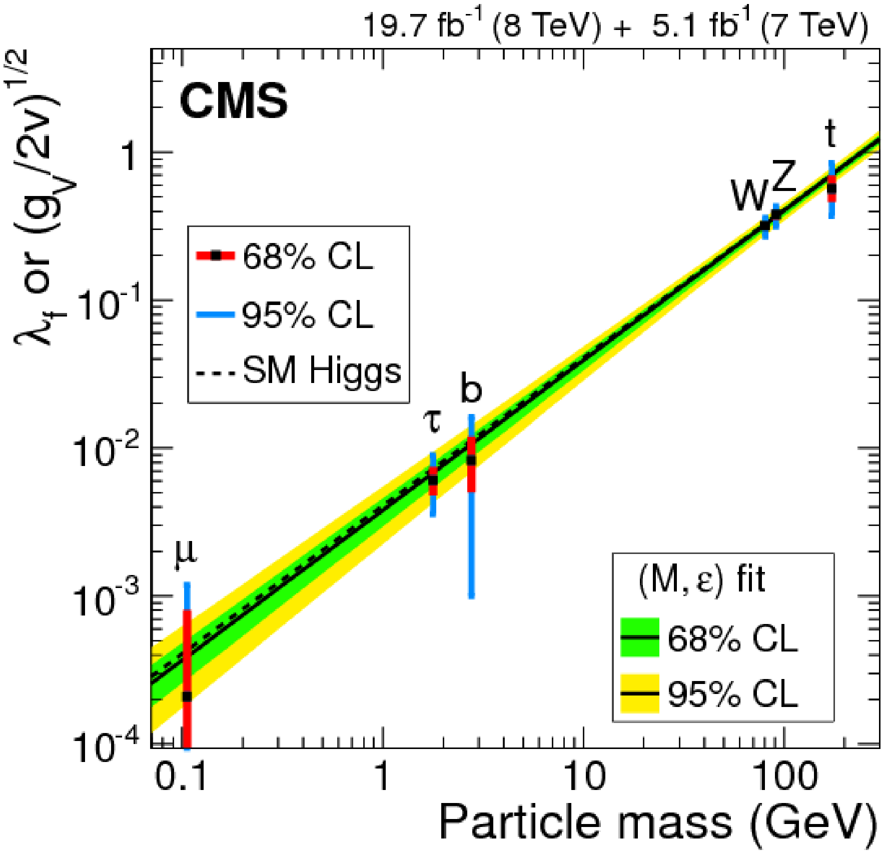

Figure 1.4: Coupling of particles to SM Higgs boson versus the mass of the particle, log-log scale is used.

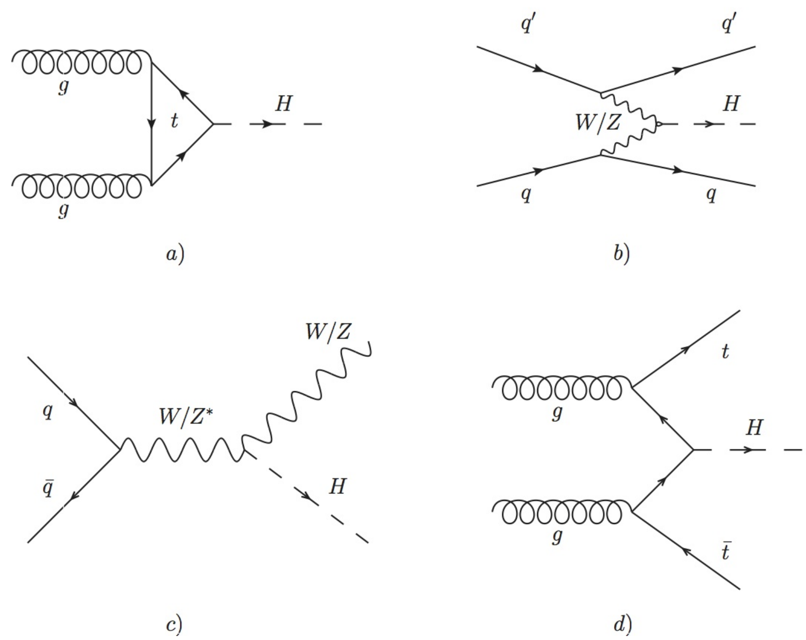

Figure 1.5: SM Higgs boson production modes: a) a gluon fashion, b) a vector boson scattering, c) an associated production with a vector boson, d) an associated production with the top anti-top pair.

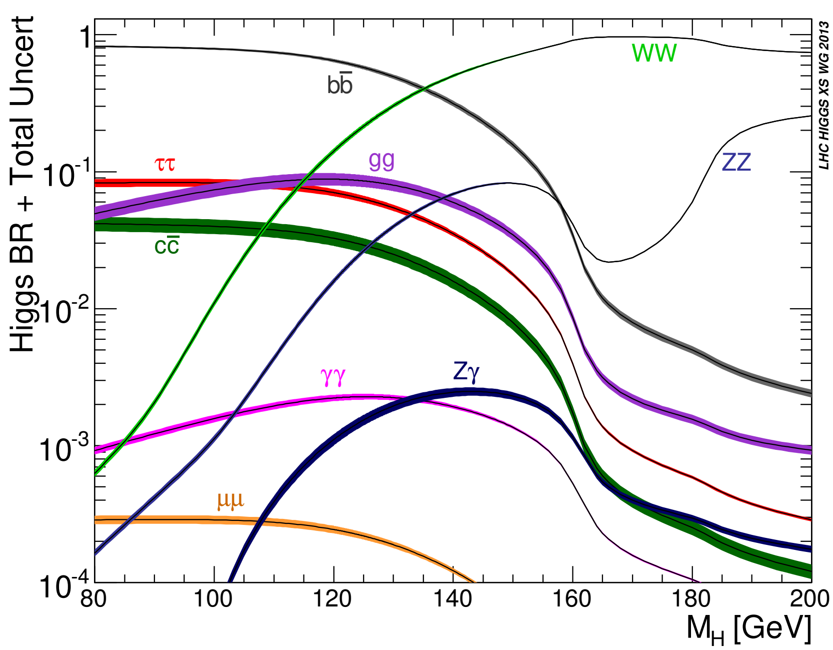

Figure 1.6: Higgs boson decay channels. At 125 GeV the dominant decay mode is $H \to b\bar{b}$.

When describing Higgs boson physics one cannot avoid mentioning the decay channels of the Higgs boson. In physics, the term "branching fraction" is used to quantify the probabilities with which a parent particle decays to daughter particles (see Fig. 1.6). The work of this thesis focuses on two specific Higgs boson decays, $H \to b\bar{b}$ and $H \to ZZ$. The first one has the highest branching fraction, while the second one gives a clean signature when subsequent $Z \to \ell\ell$ decays are selected.

Before we conclude with the BEHGHK method, a little bit of history, an irony of life, actually. The BEH particle is called the Higgs boson, but Peter Higgs was not the first to publish the article on the BEH mechanism, in fact, he was the last of the BEHGHK authors! His very first article was rejected since it contained no specific predictions or conclusions drawn from his calculations. This is why he was out-published by others. But this rejection made him write another article where he explicitly predicted the existence of the new boson. And this is what has made all the difference, he was the first to predict a new boson, and this boson now is called the Higgs boson.

Even though the facts above tell us about how great the SM is, the SM is still far from being perfect. Masses of elementary particles are the parameters in this theory; they do not come from SM predictions. It is hypothesized that the SM could be a part of the larger ultimate theory, the so-called "The Theory of Everything" (TOE), which is to be written (had been a dream of another genius, Einstein [27]). There is hope that the TOE will be able to explain many phenomena, such as the quark mass hierarchy, flavor mixing, etc. Also, in the SM all neutrinos are massless, however, it has been shown that they have a non-zero mass [28]. This fact is one of the main motivations for physicists to look for extensions of the SM.

Chapter 2

Theory

In the previous chapter, we introduced the SM and discussed particles and their interactions that are described by this theory. In this chapter we will start with the general mathematical formalism of the SM. Then, in the second part we will focus on the double Higgs boson physics in the Beyond the Standard Model (BSM) theory.

2.1 Lagrangian formalism of the Standard Model

The SM uses the Lagrangian mechanics as the mathematical approach to describe quantitatively the interactions of elementary particles and fields. The SM Lagrangian can be split into four main contributions [29]:

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_{ferm} + \mathcal{L}_{H} + \mathcal{L}_{Yuk} \tag{2.1}$$

where

- $\mathcal{L}_{YM}$ represents gause bosons and their self-interactions,
- $\mathcal{L}_{ferm}$ describes fermions and their interactions with the gauge bosons,

- $\mathcal{L}_H$ characterises Higgs boson, its self-interaction, and interaction with the gauge bosons to give them mass,

- $\mathcal{L}_{Yuk}$ gives details of fermions and their interactions with the Higgs boson, which, through the Yukawa mechanism, give mass to fermions.

The first term in the SM Lagrangian in full can be written as:

$$\mathcal{L}_{YM} = -\frac{1}{4}W^i_{\mu\nu}(x)W_i^{\mu\nu}(x) - \frac{1}{4}B_{\mu\nu}(x)B^{\mu\nu}(x) - \frac{1}{4}G^a_{\mu\nu}(x)G_a^{\mu\nu}(x) \tag{2.2}$$

where

$$B_{\mu\nu}(x) \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \tag{2.3}$$

$$W^i_{\mu\nu}(x) \equiv \partial_\mu W^i_\nu(x) - \partial_\nu W^i_\mu(x) - g\varepsilon^{ijk}W^j_\mu W^k_\nu \tag{2.4}$$

$$G^a_{\mu\nu}(x) \equiv \partial_\mu G^a_\nu(x) - \partial_\nu G^a_\mu(x) - g_s f^{abc}G^b_\mu G^c_\nu \tag{2.5}$$

with μ and ν indices running from 0 to 3, SU(2) indexes $i, j, k = 1, 2, 3$, SU(3) indices given by $a, b, c = 1, ..., 8$, and ∂_μ and ∂_ν represent four-vector covariant derivatives. According to the Noether's theorem, each symmetry is intrinsically connected to the conservation law [30]. The fields in the $\mathcal{L}_{YM}$ are connected to their corresponding underlying symmetries in the following way:

- $B_{\mu\nu}$ corresponds to $U(1)_Y$ symmetry of the weak hypercharge Y_k with U(1) being a unitary one-by-one matrix (a scalar),

- $W^i_{\mu\nu}$ corresponds to $SU(2)_I$ symmetry of the weak isospin I^i_w. Another common representation is $SU(2)_L$, since only left-handed SM fermions are transformed under this symmetry. $SU(2)_L$ is a unitary two-by-two matrix with the determinant equal to one.

- $G^a_{\mu\nu}$ corresponds to $SU(3)_c$ symmetry of the QCD color charge with $SU(3)_c$ being a unitary three-by-three matrix with the determinant equal to one.

The "B" field is a kinematic term, "W" and "G" terms describe interactions among the gauge bosons, g and ε are $SU(2)_L$ coupling and structure constants, g_s and f are coupling and structure constants for $SU(3)_c$.

The second term in the SM Lagrangian is:

$$\mathcal{L}_{ferm} = i\bar{\Psi}_L \not{D} \Psi_L + i\bar{\psi}_{l_R} \not{D} \psi_{l_R} + i\bar{\Psi}_Q \not{D} \Psi_Q + i\bar{\psi}_{u_R} \not{D} \psi_{u_R} + i\bar{\psi}_{d_R} \not{D} \psi_{d_R} \tag{2.6}$$

Notice, that the mass terms are still absent. In the Eq. 2.6, Ψ represents a doublet of a charged lepton and a corresponding neutral lepton within the same lepton family of $SU(2)_L$, the subindex Q is reserved for a family of quarks, and ψ_R describes a right-handed leptonic singlet. Gauge boson interactions are present due to the derivative term:

$$D_\mu = \partial_\mu + igI^i_w W^i_\mu + ig' Y_w B_\mu + ig_s T^a_c G^a_\mu \tag{2.7}$$

Physical fields in this notation are represented by a linear combination of W and B fields:

$$\begin{aligned} A_\mu =& B_\mu \cos\theta_W + W^3_\mu \sin\theta_W \\ Z_\mu =& -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W \end{aligned} \tag{2.8}$$

where θ_W is known as the *Weinberg angle* [31].

With the first two terms of the SM Lagrangian - $\mathcal{L}_{YM}$ and $\mathcal{L}_{ferm}$ - one obtains a valid theory of fermions and bosons, however, these particles are massless in this theory [32], which evidently contradicts the reality. To solve this issue and to ensure that weak bosons are massive, one has to introduce a Higgs field. Higgs mechanism enters the SM Lagrangian through the corresponding Higgs Lagrangian term given by

$$\mathcal{L}_H = (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi), \qquad V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 \tag{2.9}$$

where

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 = (v + H + i\chi)/\sqrt{2} \end{pmatrix} \quad \text{with} \quad v = 2\sqrt{\frac{\mu^2}{\lambda}} \tag{2.10}$$

here μ and λ are parameters of the Higgs potential. The Higgs field vacuum expectation value (*vev*) v, after the SSB, can be expressed in terms of μ and λ. The Higgs potential before and after the SSB is shown in Fig. 2.1. The importance of the $\mathcal{L}_H$ in the SM Lagrangian is crucial: after rearranging terms, the bosons finally have masses given by:

$$M_W = \frac{gv}{2}, \quad M_Z = \frac{M_W}{\cos\theta_W}, \quad M_H = \sqrt{2\mu^2} \tag{2.11}$$

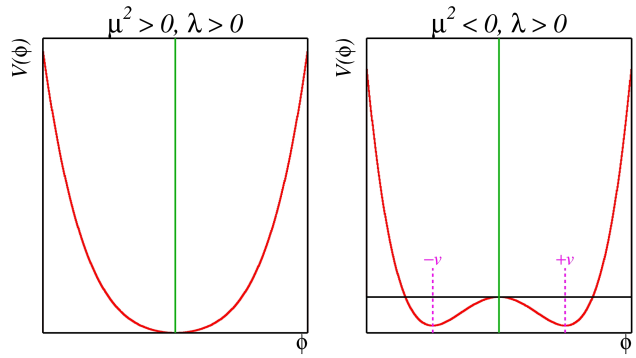

Figure 2.1: Shape of the Higgs potential before and after the SSB that is determined at the leading orders by μ and λ parameters [33].

The final contribution to the SM Lagrangian is the Yukawa term, with Yukawa Lagrangian given by:

$$\mathcal{L}_{Yuk} = -i\bar{\Psi}_L G_l \psi_{l_R} \Phi - i\bar{\Psi}_Q G_u \psi_{u_R} \tilde{\Phi} - i\bar{\Psi}_Q G_d \psi_{d_R} \Phi + h.c. \tag{2.12}$$

where $\tilde{\Phi} = i\sigma^2\Phi^*$. The masses of fermions enter the equations through the 3×3 matrices G, which are free parameters in the SM and have to be determined from the experiment. The mass of each fermion is proportional to the Yukawa coupling of the corresponding fermion to the Higgs boson, as shown in Fig. 1.4.

The Higgs boson mass is proportional to the μ parameter. In 2012, using precise single Higgs boson mass measurements from both ATLAS and CMS experiments, the value of μ was determined. Additionally, many analyses at CERN have been targeting the measurement of the λ parameter, because it is related to the shape of Higgs potential. The simplest potential characterised by μ and λ parameters, sufficient to obtain the SSB phenomenon and give mass to fermions and bosons of the SM, is the "Mexican hat" Higgs potential. However, the shape of the Higgs potential may be different, thus, direct precise determination of the μ and λ parameters is a sensitive tool to test the limitations of the SM and may open doors to the BSM effects. The simplest interaction suitable for probing the Higgs potential directly is the one where two Higgs bosons (HH) are present. All this makes HH physics, the topic of this thesis, one of the main goals for the future High Luminosity LHC (HL-LHC) that will start operations in 2026.

IN THE INTRO??While the mass parameter has been measured fairly accurately, λ parameter requires even HL-LHC to run for many years to get enough statistics since HH processes are rare and are of almost three orders of magnitude lower rate than the single Higgs boson production. Technically, the amount of the HL-LHC data is not enough to reach the sensitivity of the SM for HH processes. However, several BSM models predict resonant HH production to which even the current LHC data could be sensitive. In these theories, HH is produced through the decay of a heavy narrow width resonance, which is not a part of the SM; thus, if such processes are found, this will open a new chapter in the HEP physics. In this thesis we focus on the resonant production of the HH system, which further decays to leptons and quarks. With the available CMS data, resonant HH analyses are starting to approach the needed sensitivity to rule out some BSM theories and test further the most promising ones.

2.2 Double Higgs in Beyond the Standard Model

Several BSM theories [34–36] predict a resonant production of double Higgs boson events through a heavy resonance of a narrow width ($\sim O(1-10)$ GeV) [37]. In this dissertation data is compared to predictions from the Warped Extra Dimensions theory (WED) [38]. WED theory addresses the hierarchy problem by adding additional fifth dimension to the 4-dimensional (4D) space-time. In the framework introduced by Randall and Sundrum (RS) [39], 4D space is an EFT approximation of the higher dimensional space. The extra dimension exists between the gravity (Planck) and weak (TeV) flat 4D branes 2.2 and is called the "bulk". The bulk is described by the exponentially decaying metric.

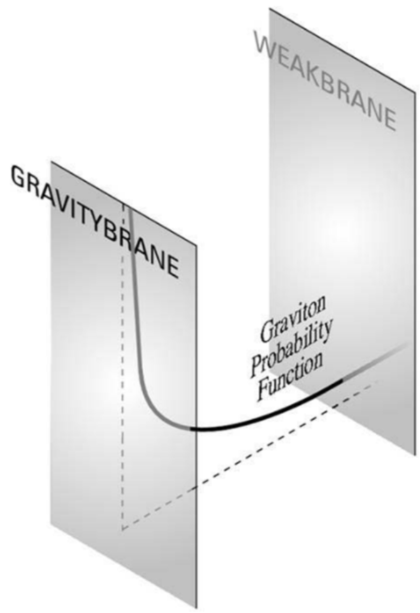

Figure 2.2: 5D space in the RS model [40].

The free parameters of the RS model are the brane separation factor k and the size of the compactified dimension r_c. The curvature factor is given by $k \approx \sqrt{\frac{\Lambda}{M_5^2}}$, where Λ is the ultraviolet cutoff of the theory and M_5 is the 5D Planck mass. The radius of the extra dimension r_c is proportional to the parameter $1/k$ and the logarithm of $1/vev$. The hierarchy between the Planck scale and the electroweak scale is reproduced for $k \cdot r_c \approx 11$. In this case the RS model matches the observations of the Higgs boson being closer to the TeV brane and fermions having light mass (located near the Planck brane).

Since LHC had provided us with no evidence of the SM particles interacting with the RS particles, the RS model considered in this thesis hypothesises that SM particles are confined to branes. Another reason could be due to the fact that Kaluza-Klein (KK) [41] partners of the SM particles are too massive to be produced at the LHC, but this scenario is not addressed in this dissertation. In the RS model under study, two new particles appear: a graviton and a radion. When the bulk is compactified, the WED theory predicts the existence of the KK excitations of the gravitational field, with the zero-th KK mode being a graviton, the mediator of the gravitational force. The graviton (spin 2) is the first WED particle predicted by the RS model. The graviton can propagate freely in the full higher-dimensional space of the 5D bulk. The other RS particle is a radion (spin 0). Its existence is required to stabilise the size of the extra dimension.

The theoretical arguments put forward by the authors [42] suggest the RS parameters k and $\bar{M}_{Pl}$ to be constrained by the following range of values: $0.01 \leq k/\bar{M}_{Pl} \leq 1$, where the parameter k is of the order of the Planck scale and $\bar{M}_{Pl} = \sqrt{\frac{M_5^3}{k} \cdot (1 - e^{-2\pi k r_c})}$ is a reduced 4D M_{Pl}. Considered in this measurement graviton and radion are RS particles with a KK state mass of the order of TeV.

With a part of the KK 5D wave function, often called a profile, expressed as $f_X^{(n)}(\phi)$, where n refers to the nth KK mode, the graviton can be decomposed as $\sum_{n=0}^{\infty} h_{\mu\nu}^{(n)}(x_\mu) \cdot f_X^{(n)}(\phi)$. Its zero-th mode corresponds to the massless graviton and the first mode corresponds to the lightest KK graviton (later graviton) which has the effective mass of the O(TeV). The profiles for all the matter fields are described by a combination of Bessel and exponential functions. The Lagrangian describing the interaction of the graviton with the SM fields is given then by

$$\mathcal{L}_{graviton} = -\frac{x_1 \tilde{k}}{m_G} h^{\mu\nu(1)} \times d_i T_{\mu\nu}^{(i)}, \tag{2.13}$$

where $x_1 = 3.83$ is the first zero of the Bessel function for a given profile, $\tilde{k} = k/\bar{M}_{Pl}$,

$h^{\mu\nu}$ is a symmetric tensor, m_G is the effective mass of the graviton of the order of TeV, d_i is an integral of the profiles of the SM fields and KK graviton, and $T^{(i)}_{\mu\nu}$ is a 4D canonical energy-momentum tensor [43] for any SM field i. A free parameter $\tilde{k}$ varies from 0.01 to 1 when m_G is varied from 100 to 1500 GeV.

For radion, the Lagrandian is given by:

$$\mathcal{L}_{radion} = -\frac{r}{\Lambda_R} \times a_i T^{\mu(i)}_{\mu}, \tag{2.14}$$

where r is a 5D radion field, Λ_R is the scale parameter proportional to $k \cdot \sqrt{(\frac{M_5}{k})^3}$, and a_i is the coupling of the radion to the SM field i. In the studied RS model the profiles of the graviton and radion arise naturally as being localised at the TeV brane for the coupling of a radion and a graviton to the massive SM fields to be of the order of 1 [44].

In the SM, the HH production is dominated by two processes, which Feynman diagrams are shown on Fig.2.3: the "box" and the "triangular" diagrams. They interfere destructively and the total cross section is thus lowered (Fig. 2.5 on the right). The box diagram dominates the double Higgs boson production and peaks near 400 GeV [45]. In this measurement, though, the gravitons and radions in the search are expected to be produced by the BSM "contact interaction" Feynman diagram allowed by the WED scenario. These process is shown on Fig. 2.4. A graviton and a radion subsequent decays to HH system are thoroughly studied and the experimental results are compared to the theoretical predictions calculated for the WED model with the parameters $\tilde{k} = 0.1$ and $\Lambda_R = 3$ TeV.

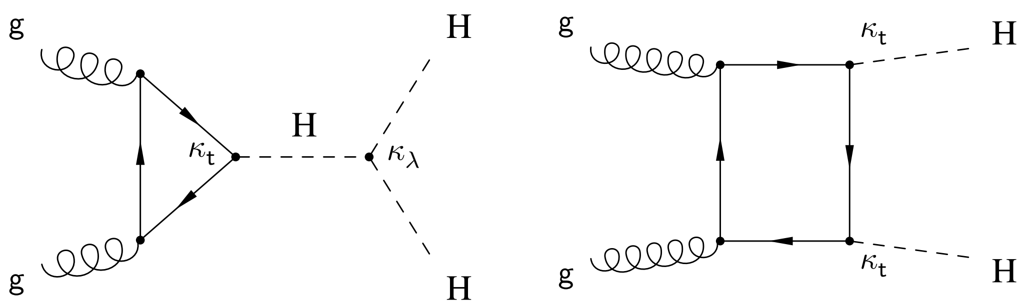

Figure 2.3: SM double Higgs boson production. Left: triangular diagram with the virtual top quark loop. Right: the box diagram which dominates the overall HH production rate.

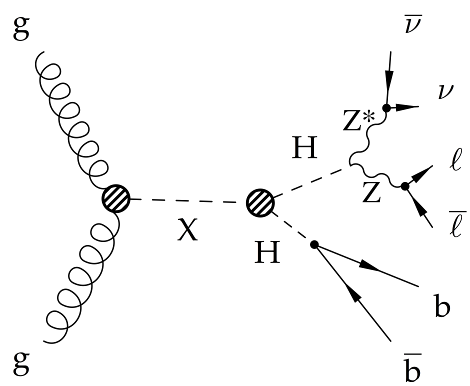

Figure 2.4: BSM Resonant double Higgs decay in the 2 b, 2 lepton, and 2 neutrino final state.

The kinematic distribution of the double Higgs mass remains to a high degree unchanged between 13-14 and 100 TeV (see Fig. 2.5 on the left), therefore, we can compare 100 TeV results produced by theorist to those analysed in this thesis that use the data delivered by the current 13 TeV LHC machine. Fig. 2.5 refers to the box and the triangular diagrams as "box" and "tri", and to the non-linear interaction as "nl" [46].

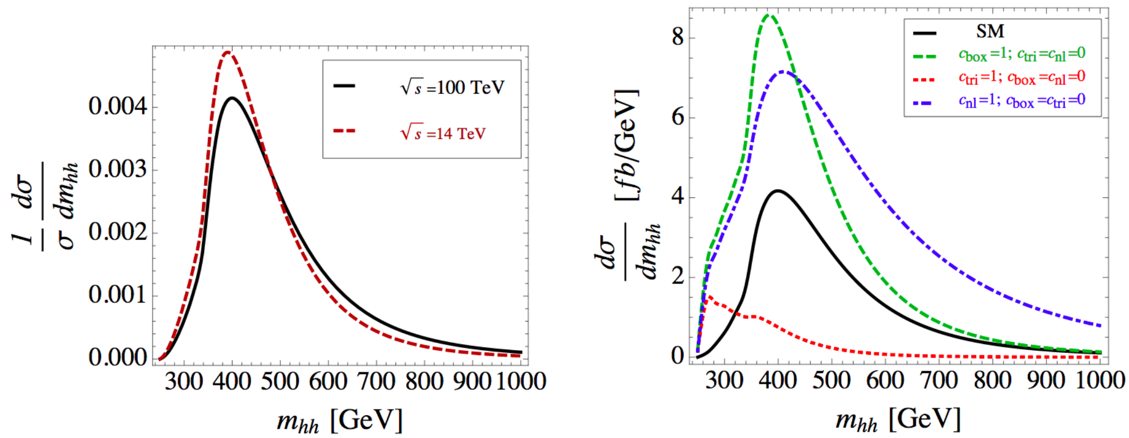

Figure 2.5: Left: comparison of the double Higgs boson mass distribution at the LO at $\sqrt{14}$ and $\sqrt{100}$ TeV center-of-mass energy. Right: the total SM HH cross section and the individual contributions [46].

This thesis separately addresses resonant graviton and radion decays into two SM Higgs bosons with the subsequent decays of one Higgs boson to a pair of b quarks, and the other Higgs boson to W or Z boson pairs. W bosons are allowed to decay only leptonically. For Z boson decays, the signature is characterised by the on-shell Z boson decaying into a pair of charged leptons and the off-shell Z boson decaying to neutrinos (see Fig. 2.4). The final state that this thesis focuses on, consists of two b quarks, two charged leptons, and two neutrinos. This signature has a branching fraction of approximately 2.8%.

To finish this chapter, it is instructive to show all the decay channels of the double Higgs system to the SM particles, which is summarised in the Fig. 2.6. Both the horizontal and the vertical axes show decays of a single Higgs boson to two SM particles. In this representation, each square on the plot specifies a branching fraction of one of the double Higgs boson decays, with the probability of the decay given by the colour field on the right.

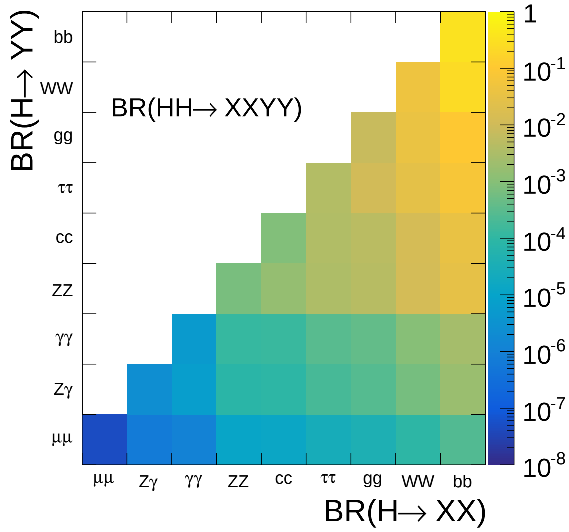

Figure 2.6: Double Higgs decay channels. The SM branching fractions are represented by the colour palette.

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