Chapter 2

Standard Model

The Standard Model is a Quantum Field Theory that modelates three of the four fundamental forces of Nature (electromagnetic,weak and strong). However, in this thesis we are only concerned in the no existence of flavour violation in the SM. In general we are focused in this chapter to know why the SM do not predict the branching ratio found at CMS.

The Standard Model has been completed with the discovery of the Higgs boson. The lagrangian of the Standard Model is given by

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + hc. + \Psi_i Y_{ij}\Psi_j\phi + hc. + |D_\mu\phi|^2 - V(\phi) \quad (2.1)$$

where $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ represents the electromagnetic interaction, $i\bar{\Psi}\not{D}\Psi + hc.$ represents the interaction of fermionic fields, $\Psi_i Y_{ij}\Psi_j\phi + hc.$ represents the interaction of the scalar(bosonic) field with the fermionic field,$|D_\mu\phi|^2$ represents implicitly the norm interactions and $V(\phi)$ is the Higgs Potential.

However the Standard Model needs to be extended for several reasons. Theoretically the Standard Model do not join the gravity in the Lagrangian of interactions. Furthermore, open questions as dark matter or dark energy can not be predicted by the theory. The new discovery of the neutrino masses is another issue within the Standard Model, since it predicts that neutrino are massless. Also, the Standard Model predicts that the amount of anti-matter is the same as the matter. However we know from our daily life that this prediction is not true. During the last years with the new experiments at CERN, physicists are trying to find new physics with errors of the Standard Model. One of those experiments is the one to be analyzed in this thesis. The decay of the $h^0 \to \tau\mu$ [10].

2.1 Interactions

As it was mentioned the interactions that the Standard Model predicts are the weak, strong and electromagnetic. We explain in general terms about the electromagnetic interaction and the weak interaction since they are both interactions concerned in this thesis.

2.1.1 Electromagnetic Interaction

In the Lagrangian of the Standard model exist the inner product of the electromagnetic tensor. The electromagnetic tensor is given by [2]

$$F^{\mu v} = \partial^{\mu} A^{v} - \partial^{v} A^{\mu} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix} \tag{2.2}$$

$$\tag{2.3}$$

$$\tag{2.4}$$

$$F_{\mu v} = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix} \tag{2.5}$$

where $A = (\phi, \vec{A})$ and *phi* are the scalar potential and a vector potential that satisfies the Maxwell equations

$$B = \bigtriangledown \times A \tag{2.6}$$

$$E = - \bigtriangledown \phi - \frac{\partial A}{\partial t} \tag{2.7}$$

The homogeneous Maxwell equations are written as

$$\partial^{\lambda} F^{\mu v} + \partial^{v} F^{\lambda \mu} + \partial^{\mu} F^{v \lambda} = 0 \tag{2.8}$$

Therefore all the electromagnetic theory of Maxwell is implicit in the tensors $F_{\mu v}$.

In this thesis is important to know about the electromagnetic interaction because in ultraperipheral collisions is the only interaction that takes places.

2.1.2 Weak Interaction

Every particle has a weak charge. The particles that are responsable of the weak interaction are W^+,W^- and Z. The so called charged weak interactions are due to the W's bosons. The neutral weak interactions are due to the Z boson.

2.1.3 Decay of Particles and Branching Ratio

Every particle decays into lighter particles, unless prevented from doing so by some conservation law. [4] The particles that do not experience desintegration are called stable particles and example of them is the photon. The reason the photon do not decay into other particles is because it is masless. The electron do not decay since it is the lightest charged particle and the conservation of charge prevents the decay. The proton do not decay since it is the lightest baryon, and baryon number conservation prevents it to decay. Other reason that particles do not decay into other specific particles or simply do not decay is the leptonic number conservation.2.2.2 However it is of our interst $h^0 \rightarrow \tau\mu$ since it do not conserve leptonic number and theoretically it must not exist at tree level.

The mathematical tool to calculate the rate of decay is the branching ratio. The branching ratio is the pariticular rate of certain particle to decay in certain mode normalized by the total width or the total possibilities of decay. In mathematical expressions the branching ratio is

$$\text{Branching Ratio of the ith mode} = \frac{\Gamma_i}{\Gamma_{total}} \tag{2.9}$$

where

$$\Gamma_{total} = \frac{\hbar}{\tau} \tag{2.10}$$

where τ is the lifetime of the particle. The branching ratio is one of the fundamental quantities calculated by phenomenologists. It give us the information of expecting certain decay of different particles and theoretically it confirms that the Lagrangians of interaction are correct. In our particular case, the simply reason of finding the decay $h^0 \rightarrow \tau\mu$ tell us that something wrong happens with the Standard Model, since it should not exist or there must exist loop corrections in order that this anomaly disappears. However CMS experiment at CERN confirmed a statistical desviation of 3 σ of the calculations and the branching found in the experiment. This is the reason of this calculation so important. The Standard Model could be predicting something completely wrong.

2.2 Spectrum of Particles

Formally we take as indivisible particles as those ones that experimentally have shown that there is no way to divide them in smaller ones. Therefore the matter that composes all the Universe is made of indivisible particles, which we call as *elementary particles*. When the atom was discovered, it was thought that the matter wasn't able to be divided by smaller structures, however it was discovered by Ernest Rutherford that there should exist a nuclei of atoms. It was discovered as well the electron of the atoms, showing that atoms could be divided by smaller structures. So we take as elementary particles as those ones which cannot be divided by smaller ones, unless it is demonstrated the opposite experimentally. An example of an elementary particle is the electron or the higgs boson.

All the elementary particles can be divided by two general groups. The *bosons* and the *fermions*. We will explain briefly the characteristics and subgroups of both.

2.2.1 Bosons

All particles have an intrinsic property called spin. The bosons spin is an integer of $\hbar$ including 0. An example is the Higgs boson, which has spin 0. The bosons W and Z^0 have spin $1\hbar$. [1]. In addition, an important property of Bosons is that

[1] $\hbar$ is the Planck's constant

they are not ruled by Pauli's Exclusion Principle, which states that there can not exist two particles in the same state(in this case, Pauli mentioned electrons, which resulted to be fermions, so we take instead of electrons, particles). And as implication, the bosons follow the rules of Bose-Einstein statistics given by equation 2.11. At the same time, gases composed of bosons, with extremely low temperatures (close to absolute zero), macroscopally have an state called as Bose-Einstein Condensate.

$$\eta(\epsilon, T, \mu) = \frac{g_i}{e^{\frac{\epsilon-\mu}{k_B T}} - 1} \tag{2.11}$$

where k_B is Boltzmann constant and η is the number of particles with a certain energy ϵ, temperature T and chemical potential μ.

In addition, the bosons have an special and important role in particle physics. They are the responsable of the the interactions between particles or forces. The Higgs boson, is the responsable of the mass of particles. The photon is the responsable of the electromagnetic interaction, the bosons W, Z^0 are responsable of the weak force. They are called as well as force carrier particles.

2.2.2 Fermions

The spin of fermions, are a fraction of $\hbar$. As an example, the electron is a fermion which spin is $\frac{1}{2}\hbar$. An *up* quark is a fermion of $\frac{1}{2}\hbar$ also. The fermions are ruled by Pauli's Exclusion Principle wich states that there can not be two fermions in the same state. As consequence, they follow another statistical rules. The statistics that they follow is the Fermi-Dirac distribution.

$$\eta^*(\epsilon, T, \mu) = \frac{g_i}{e^{\frac{\epsilon-\mu}{k_B T}} + 1} \tag{2.12}$$

where η is the number of particles with energy ϵ_i, g_i is the number of degenerative states.

Since not all fermions have the same features, the fermions are divided by two big groups, *quarks* and *leptons*.

Leptons and Flavour Violation

The leptons have the important characteristic that they do not strongly interact. The first lepton found was the electron. They are divided in two groups, the charged leptons and the neutral leptons which are called neutrinos. The leptons can be of six different types or flavours. The types are *electron(e),muon (μ),tau (τ), electron neutrino (v_e) and muon neutrino (v_μ),tau neutrino v_τ).* Furhtermore the leptons are divided in three generations or families. Each lepton have a so called *Leptonic number.* As it is expected, bosons have leptonic number 0. The leptons are shown in Table. 2.1. [2] In any interaction or decay the leptonic number must be conserved. The leptonic number can be muonic, taunic or electronic. In total the sum must be conserved. Example

$$\mu^- \to e^- + \bar{v}_e + \nu_\mu \tag{2.13}$$

[2]Table extracted from [4]

From table 2.1 we have that:

$$\begin{aligned} L &= 0 = 1 - 1 + 0 \text{ Leptonic number conserved} \\ L_\mu &= 1 = 0 + 0 + 1 \text{ Muon Leptonic number conserved} \\ L_e &= 0 = 1 - 1 + 0 \text{ Tau Leptonic number conserved} \end{aligned} \quad (2.14)$$

However in

$$h^0 \to \tau\bar{\mu} \quad (2.15)$$

$$\begin{aligned} L &= 0 = 1 - 1 \text{ Leptonic number conserved} \\ L_\mu &= 0 \neq 0 - 1 \text{ Muon Leptonic number no conserved} \\ L_\tau &= 0 \neq 1 + 0 \text{ Tau Leptonic number no conserved} \end{aligned} \quad (2.16)$$

As it is noticed in eq.2.16, the leptonic number is violated and therefore the Standard Model do not predict this decay. Quatum Loop corrections are needed within the Standard Model in order to solve this problem.

Lepton	Generation	Q	L_e	L_μ	L_τ
e	1	-1	1	0	0
ν_e	1	0	1	0	0
μ	2	-1	0	1	0
ν_μ	2	0	0	1	0
τ	3	-1	0	0	1
ν_τ	3	0	0	0	1

Table 2.1: Leptons generations or families. and their quantum numbers. For each antiparticle the numbers are of the same magnitude but opposite sign.

Quarks

It is the mixture of the quarks that constitute the nucleons of the atoms, *ie.* the protons and the neutrons. In general, they form *baryons* and *mesons*. Mesons are particles that are constituted by a quark and a anti-quark. Baryons are particles that are constituted by three quarks. As an example, two *up* quarks and one *down* quark constitute the proton, which is a *baryon*, since it is formed by three quarks. As another example, two *down* and one *up* quark constitute a neutron. A π^+ meson is constituted by an *up* quark and a *down* quark.

This kind of fermions have an important charecteristic, which made hesitate physicists. If we notice, a proton should not follow the rules of Pauli's Exclusion Principle, since it is made of two *up* quarks and one *down* quark, and therefore we have two fermions in the same state. The same happens when we combine three quarks in order to obtain the neutron (two *down* particles and one *up*). However, as we mentioned before, all fermions follow the Pauli's Exclusion Principle.

It is introduced a new variable to quarks, that we call as *color*, which solves the problem of the Statistics of Fermi-Dirac. If we a have a quark that can have three possible colors *red* ,*green* and *blue*, we have that proton is made of $u_R u_G d_B$, and therefore there are not two fermions in the same state. Thus, quarks are differentiated of leptons by a quantum number that they posses called *color*. At the same time, it is stated that all particles that we observe experimentally are *colorless* , *ie*, the combination of their color quantum numbers must give as result, the white color. By this way, the known particles as the proton, can only be observed by one configuration.

2.2.3 The J/Ψ Meson

All the features mentioned of the Quarks were developed betweem 1964 and 1974. During that time, physicists were not quite sure about what was the nature of the particles of the quarks. The isolated quarks never were detected experimentally (not even today). However using neutrino beams in CERN, it was discovered that almost all the particles just passed trough without being rejected and some of them bounced back. [3] It was an anology of the Rutherford experiment, where he found that the positive charge and most of the mass was concentrated in the nucleous of the atom. However, in this case instead of one lump, there were three of them giving argument to the existence of the quark. Altough, it was not enough evidence for the existence of the quarks.

The electroweak theory stablished by Abdus Salam, was verified by the discovery of the Z and W boson. The electroweak theory and the quark model led to calculations about known decay modes that contradicted observation, unless by a so called GIM(Glashow-Iliopoulos-Maiani) Mechanism was true. The GIM mechanism predicted the appearence of a charm/anticharm meson. In summer 1974 is found the charm/anticharm meson in Brookhaven by Samuel C.C. Ting. He called this meson J. In November of the same year the same particle was discovered by Burton Richter at SLAC. He called the particle Ψ. The particle was named J/Ψ, and the remarkable discovery was that it was the key for the quark theory. Its mass is of 3,01 [GeV], spin 1 and charge 0 Coulombs.

In this thesis, we studied the photoproduction of the J/Ψ with the ALICE-Experiment. We explain the photoproduction in chapter 7.

2.3 The Higgs Mechanism

The importance of the Higgs Mechanism radicates in the property of giving mass to the gauge bosons. Without the Higgs Mechanism the bosons Z and W would be massless and experimentally we know that this fact is not true. In general terms, the Higgs Mechanism is a spontaneous breaking mechanism of U(1) symmetry by introducing a new field and making a variation nearly or in the neighborhood of the minimum of the Higgs potential. If a symmetry is spontaneously broken, every point of all the space should be invariant under certain transformation by the exception of certain minimum value which is called as the *vacuum expectation value* v.e.v v. The physical particles (with masses) are generated by an expansion of the fields around the minimum. We introduce this fields into the Lagrangian to have it in explicit form of fields. The symmetry will be spontaneosluy broken, since around the minimum the symmetry does not hold any more, and around this value the fields become massive.

The Higss Lagrangian extracted from Eq. 2.1 is given by

$$\mathcal{L}_{SSB} = |D_\mu \phi|^2 - V(\phi) \tag{2.17}$$

where the Higgs potential is given by

$$V(\phi) = -\frac{\mu}{2}|\phi|^2 + \frac{\lambda}{4}|\phi|^4 \tag{2.18}$$

where μ is a mass term and λ is a quartic[3] coupling term. Now we are interested in findind the point ϕ_0 which will be the value where the potential $V(\phi_0)$ is a minimum. Therefore, we find the minimum simply by applying the derivative of V and making equal to zero.

$$\begin{aligned} \frac{\partial V}{\partial \phi}|_{\phi_0} &= -\mu\phi_0 + \lambda\phi_0^3 \\ &= \phi(-\mu + \lambda\phi^2) = 0 \end{aligned} \tag{2.19}$$

Isolating ϕ_0 we find two cases. When

$$\begin{aligned} \phi_0 &= 0 \\ \phi_0 &= \pm\frac{\mu}{\lambda} \end{aligned} \tag{2.20}$$

We derive to find which of these three inflections points are minimum values of the potential

$$\frac{\partial^2 V}{\partial \phi^2} = -\mu + 3\lambda\phi^2 \tag{2.21}$$

For $\phi_0 = 0$

$$\frac{\partial^2 V}{\partial \phi^2}|_{\phi_0=0} = -\mu \tag{2.22}$$

Therefore $\phi_0 = 0$ is not a minimum, it is a local maximum and consequently $\pm\frac{\mu}{\lambda}$ are the expectation vacuum value.

If we make an expansion about the minimum we obtain

$$\begin{aligned} \phi(x) &= \phi(x^{'}) + \frac{1}{2}\phi^{'}(x)(x - x^{'}) + ... \\ &= v + h(x) \end{aligned} \tag{2.23}$$

[3] λ is dimensionless

where $v = \phi(x^{'})$ and for simplicity we called $h(x)$ to all the other terms of the expansion. We introduce the expansion around the minimum in the Lagrangian of the Higgs Sector.

$$\begin{aligned}
\mathcal{L}_{SSB} &= \frac{1}{2}(\partial_\mu \phi)^2 + \frac{\mu^2}{2}\phi^2 - \frac{\lambda}{4}\phi^4 \\
&= \frac{1}{2}[\partial_\mu(v + h(x))]^2 + \frac{\mu^2}{2}(v + h(x))^2 - \frac{\lambda}{4}(v + h(x))^4 \\
&= \frac{1}{2}(\partial_\mu h(x))^2 + \frac{\mu^2 h(x)^2}{2} + \mu^2 h(x) v + \frac{1}{2}\mu^2 v^2 \\
&- \frac{\lambda}{4}(v^4 + 4v^3 h(x) + 6v^2 h(x)^2 + 4v h(x)^3 + h(x)^4) \\
&= \frac{1}{2}(\partial_\mu h(x))^2 + \frac{1}{2}v^4\lambda + v^3\lambda h(x) + \frac{1}{2}v^2\lambda h(x)^2 - \frac{1}{4}\lambda v^4 \\
&- \lambda v^3 h(x) - \frac{3}{2}\lambda v^2 h^2(x) - \lambda v h^3 - \frac{\lambda}{4}h(x)^4 \\
&= \frac{1}{2}(\partial_\mu h(x))^2 - \lambda v^2 h(x)^2 - \lambda v h(x)^3 - \frac{\lambda}{4}h(x)^4 + \frac{\lambda}{4}v^4 \qquad (2.24)
\end{aligned}$$

As it can be noticed, the field $h(x)$ has become massive since we have the same terms $\frac{1}{2}(\partial_\mu \phi)^2 + \frac{\mu^2}{2}\phi^2 - \frac{\lambda}{4}\phi^4$ sumed with the coupling of the mass with the variables λv^2. Also, the symmetry is broken since the Lagrangian is not conserved with a transformation of $h \to -h$. Therefore we have found a way to obtain massive Higgs field and break the symmetry. In figure 2.1 is shown the higgs potential.

The generalized Higgs Potential depends on real and imaginary fields. And the symmetry is not just under parity change $h(x) \to h(-x)$. It is any transformation $h \to he^{i\alpha}$. However, for the thesis purpouses we are interested in the higgs massive field.[4] In the Higgs sector it is estimated a boson with mass 125 [GeV] with spin 0 which is called the higgs boson. It is important in our analysis since it is the particle that decays into a muon and tau particle.

[4]We do not show the complete Higgs Potential since we do not use in any of the thesis calculations the bosons W and Z.

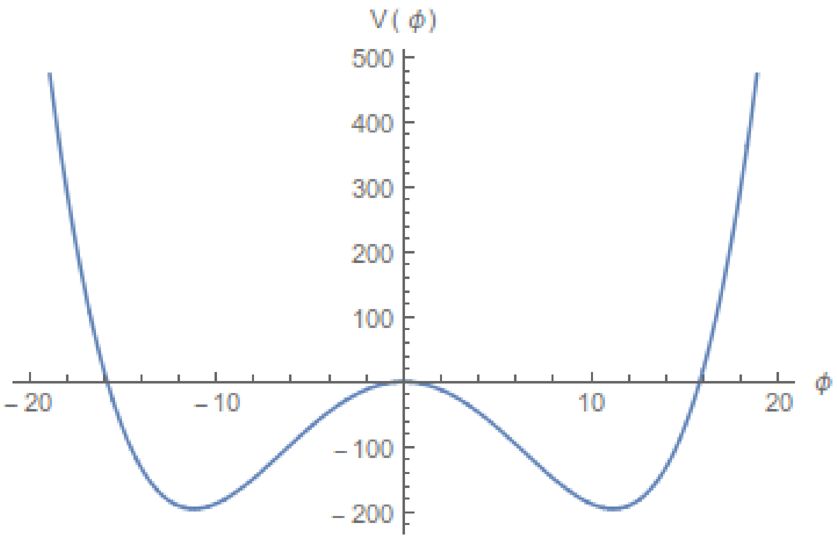

Figure 2.1: The Higgs Potential