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FACOLTÀ DI SCIENZE MATEMATICHE, FISICHE E NATURALI

CORSO DI LAUREA MAGISTRALE IN FISICA

titolo

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ANNO ACCADEMICO 2013-2014

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Introduction

Il Modello Standard (MS) delle interazioni fondamentali è una delle teoria più dibattute degli ultimi anni ed ha ottenuto nell'ultimo secolo numerose conferme sperimentali, con altissimi livelli di precisione. L'ultimo pezzo mancante per la conferma della teoria è stato per un lungo periodo il bosone di Higgs, il quanto del campo scalare ritenuto responsabile della rottura spontanea della simmetria di *gauge* del MS. Grazie a questo meccanismo tutte le particelle elementari acquistano massa.
La massa del bosone di Higgs è un parametro libero della teoria e può variare in un ampio intervallo di valori. Numerosi esperimenti hanno cercato segni della sua esistenza, ma sono riusciti solo ad escludere alcuni intervalli di massa. Il *Large Hadron Collider* (LHC) è l'acceleratore di particelle costruito per investigare la rottura spontanea della simmetria e riuscire a dare una prova definitiva dell'esistenza del bosone di Higgs.

Chapter 1

The Standard Model and beyond

Particle Physics studies the building blocks of the matter, the so called fundamental particle, and how they are governed by the four fundamental forces[1].
The best theory, explaining our understanding of these particles and forces, is the *Standard Model* (SM): developed during the 1970s, it has successfully explained almost all experimental results and precisely predicted a wide variety of physical phenomena.
This chapter will describe in details the Standard Model and some theories developed in order to solve some unanswered questions.

1.1 The Standard Model

1.1.1 Fundamental Particles

All matter around us is made of elementary particles, the building blocks of matter. These particles are divided into two groups: *leptons*, with an entire value of electric charge, and *quarks*, with a fractional charge. Each group consists of six particles, which are related in pairs, or generations. The six quarks are paired in the three generations: the up quark and the down quark form the first generation, followed by the charm quark and strange quark, then the top quark and bottom (or beauty) quark. The six leptons are similarly arranged in three generations: the electron and the electron neutrino, the muon and the muon neutrino, and the tau and the tau neutrino. While electron, muon and tau are charged particles, the neutrinos are electrically neutral. In table 1.1 and 1.2, the features of leptons and quarks.

Beside these leptons and quarks, there are other particles responsible of carrying the fundamental forces, the so called *bosons*. The Electromagnetic Force, responsible of all eletrical and magnetic phenomena, is mediated by the phtons γ; the Weak Force, responsible of some decays, is mediate by $W^{\pm}$ and Z bosons; the Strong Force, responsible for example of the atomic structure, is mediated by the gluons (g). Last fundamental

[1]In the thesis, Natural Units will be used: $c = \hbar = 1$, where $\hbar = h/2\pi = 6.58211889(26) \cdot 10^{-23} MeVs$ and $c = 299792458\ ms^{-1}$.

Leptons		
Flavor	Charge	Mass[MeV]
neutrino e. (ν_e)	0	< 0.002
electron (e)	-1	0.511
neutrino mu (ν_μ)	0	< 0.19
muon (μ)	-1	105.66
neutrino tau (ν_τ)	0	< 18.2
tau (τ)	-1	1776.86±0.12

Table 1.1: Standard Model leptons features [1].

Quark		
Flavor	Carica	Massa[GeV]
up (u)	+2/3	$0.0022^{+0.0006}_{-0.0004}$
down (d)	-1/3	$0.0047^{+0.0005}_{-0.0004}$
charm (c)	+2/3	1.28 ± 3
strange (s)	-1/3	0.096 ± 0.084
top (t)	+2/3	173.1 ± 0.6
bottom (b)	-1/3	$4.18^{+0.04}_{-0.03}$

Table 1.2: Standard Model quarks features [1].

force, not yet included in the SM, is the Gravity that is the weakest. In table 1.3 the features of the bosons.

Bosons	Interaction	Charge	Mass[GeV]
photon (γ)	Electromagnetic	0	0
$W^{\pm}$	Weak	±1	80.385±0.015
Z^0	Weak	0	91.1876±0.0021
gluoni	Strong	0	0

Table 1.3: Standard Model bosons features [1].

1.1.2 Gauge Symmetries

The present belief is that all particles interactions may be dictated by the so called *local gauge symmetries* and this is connected with the idea that the conserved physical quantities (such as electric charge) are conserved in local regions of space and not just globally[2].

The fundamental quantity in classical mechanics is the action S, the time integral of the Lagrangian L:

$$S = \int L\,dt = \int \mathcal{L}(\phi, \partial\phi/\partial x_\mu)\,d^4x \tag{1.1}$$

where $\mathcal{L}$ is the Lagrangian Density[2], and ϕ is the filed, itself a function of the continuous parameters x_μ [3][4]. The *principle of least action* states that fixed the values of the coordinates at the initial time t_{in} and at the final time t_f, then classical trajectory which satisfies these conditions is an extremum of the action. This leads to the *Euler-Lagrange* equations (1.2) from which can be obtained the particle equations of motion.

$$\frac{\partial\mathcal{L}}{\partial\phi} - \frac{\partial}{\partial x_\mu}\frac{\partial\mathcal{L}}{\partial(\partial\phi/\partial x_\mu)} = 0 \tag{1.2}$$

QED

The interaction of electron with photon is described by the Quantum Electrodynamics. Let's start with a complex field ψ describing a free electron with mass m: its Lagrangian is

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi \tag{1.3}$$

and its equation of motion can be deduced by the Dirac Equation, obtained substituting 1.3 in 1.2.

The electromagnetic (em) field instead is described by a four-vector A_μ, the gauge potential. The field strength tensor is defined as:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{1.4}$$

and the equation of motion, in presence of an external current J^μ is:

$$\partial_\mu F^{\mu\nu} = QeJ^\nu \tag{1.5}$$

In case now the electron interacts with the em field, the new Lagrangian is:

$$\mathcal{L}_{EM} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{1.6}$$

where D_μ, known as covariant derivative, is defined as

$$D_\mu = \partial_\mu + ieQA_\mu \tag{1.7}$$

and the last term in 1.6 stands for Maxwell's equation.

It can be shown that 1.6 is invariant under the phase transformation:

$$\psi(x) \to e^{-iQ\theta}\psi(x) \tag{1.8}$$

with $\theta \in \Re$. This transformation belongs to the group U(1) and according to Noether's theorem, it implies the existence of a conserved current: the electric charge. In this case,

[2]however, following standard use in field theory, we will often refer to $\mathcal{L}$ simply Lagrangian.

known as *global "gauge" invariance*, once the value of θ is fixed, it is specified for all space and time.
More interesting is the case in which the parameter θ depends on space and time in a completely arbitrary way:

$$\psi(x) \to e^{-iQ\theta(x)}\psi(x) \tag{1.9}$$

and the Lagrangian 1.6 is not invariant. It can be shown that, in oder to restore the Lagrangian invariance, the potential A_μ must satisfy following condition:

$$A_\mu \to A_\mu + \frac{1}{e}\partial_\mu\theta \tag{1.10}$$

Under 1.9 and 1.10 the Lagrangian 1.6 is invariant.
One can observe the absent of mass term in the Lagrangian: this means that the boson associated to the potential A_μ, the photon, must be massless: the presence of a mass term would make the Lagrangian not invariant under gauge transformation.

QCD

The interaction between quarks and gluons is described by the Quantum Chromodynamics.
For quarks [5], it must be considered a new quantum number, the colour, such that each species of quark may have three different colours: $q_j,\ j = 1, 2, 3$ (red, green, blue). In order to avoid the existence of non-observed extra states with non-zero colour, one needs to further postulate that all asymptotic states are colourless, i.e. singlets under rotations in colour space. This assumption is known as the confinement hypothesis, because it implies the non-observability of free quarks: since quarks carry colour they are confined within colour-singlet bound states.
For free quark described by the field q_j, the Lagrangian is:

$$\mathcal{L} = \bar{q}_j(i\gamma^\mu\partial_\mu - m)q_j \tag{1.11}$$

In order to describe the interaction between quarks and gluons, it is needed to change the quark derivative by covariant objects. Since there are now eight independent gauge parameters, eight different gauge bosons $G^\mu_a(x)$, the so-called gluons, are needed:

$$D^\mu_{q_f} \equiv [\partial^\mu - ig_s\frac{\lambda^a}{2}G^\mu_a(x)] \tag{1.12}$$

The corresponding field strengths are also introduced:

$$G^{\mu\nu}_a = \partial^\mu G^\nu_a - \partial^\nu G^\mu_a + g_s f^{abc} G^\mu_b G^\nu_c \tag{1.13}$$

where g_s is the constant coupling. Hence, in case of interaction the new Lagrangian is:

$$\mathcal{L}_{QCD} = \bar{q}_j(i\gamma^\mu D_\mu - m)q_j - \frac{1}{4}G^{\mu\nu}_a G^a_{\mu\nu} \tag{1.14}$$

It can be shown 1.14 in invariant under arbitrary global $SU(3)_C$ transformations in colour space 1.15:

$$q(x) \to q'(x) = Uq(x) \equiv e^{i\theta_a T^a} q(x), \quad a = 1, 2, ..., 8 \tag{1.15}$$

where T_a are the generators of the SU(3) (n = $N^2 - 1 = 3^2 - 1 = 8$) group linked with the λ_a Gell-Mann matrices.
More interesting is the case in which θ depends on local coordinates, $\theta_a = \theta_a$(x):

$$q(x) \to q'(x) = Uq(x) \equiv e^{i\theta_a(x)\frac{\lambda^a}{2}} q(x), \quad a = 1, 2, ..., 8 \tag{1.16}$$

The group is non-Abelian since not all the generators λ_a commute with each other.
To ensure the invariance of the Lagrangian 1.14, the gauge fields must transform as follow:

$$G^a_\mu \to G^a_\mu - \frac{1}{g_s}\partial_\mu \theta_a - f_{abc}\theta^b G^c_\mu \tag{1.17}$$

The field tensor $G^{\mu\nu}_a$ has a remarkable new property: imposing gauge symmetry (1.16 and 1.17) has required that the kinematic energy term in 1.14 in not purely kinetic but includes an induced self-interaction between the gauge bosons. Decomposing the Lagrangian into its different pieces, there are three terms analogues to QED describing the free propagation of quarks and gluons and the quark-gluon interaction. The remaining two terms show the presence of three and four gluon self-coupling in QCD and reflect the fact that gluons themselves carry color charge. They have no analogue in QED and arise on account of the non-Abelian character of the gauge group. As in QED, the absence of a mass term implies gluons must be massless.

The electroweak theory

Low-energy experiments have provided a large amount of information about the dynamics underlying flavour-changing processes. The detailed analysis of the energy and angular distributions in β decays, such as $\mu^- \to e^- \bar{\nu}_e \nu_\mu$, made clear that only the left-handed (right-handed) fermion (antifermion) chiralities participate in those weak transitions. Moreover, the strength of the interaction appears to be universal.
Using gauge invariance, it is possible to determine the right QED (1.1.2 and QCD 1.1.2 Lagrangians. To describe weak interactions, a more elaborated structure is needed, with several fermionic flavours and different properties for left- and right-handed fields. Moreover, the left-handed fermions should appear in doublets, and we would like to have gauge bosons in addition to the photon. The simplest group with doublet representations is SU(2) while to include also the electromagnetic interactions an additional U(1) group is needed. The obvious symmetry group to consider is then:

$$G \equiv SU(2)_L \otimes U(1)_Y \tag{1.18}$$

where L refers to left-handed fields and Y stands for the weak hypercharge.
Let's consider a single family of leptons:

$$\chi_L = \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \quad \psi_R = l_R^- \tag{1.19}$$

or for quarks

$$\chi_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \psi_R = u_R, \ or \ d_R \tag{1.20}$$

As in QED and QCD case, starts with free Lagrangian:

$$\mathcal{L} = i\bar{\chi}_L\gamma^\mu\partial_\mu\chi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R \tag{1.21}$$

The interaction is again introduced changing the derivative with the covariante:

$$D_\mu = \partial_\mu + igW_\mu^a T^a + ig' B_\mu Y \tag{1.22}$$

where W_μ^a a = 1, 2, 3 are the three gauge bosons associated with the group $SU(2)_L$, T^a its generators and g the constant couplings; B_μ, Y and g are instead respectively the gauge boson, the generator and the constant coupling for the group $U(1)_Y$. With W_μ^a and B_μ can be introduced also the tensor strength fields:

$$\begin{aligned} W_a^{\mu\nu} &= \partial^\mu W_a^\nu - \partial^\nu W_a^\mu + g\epsilon^{abc} W_b^\mu W_c^\nu \\ B^{\mu\nu} &= \partial^\mu B^\nu - \partial^\nu B^\mu \end{aligned} \tag{1.23}$$

Therefore, the properly Lagrangian is given by:

$$\mathcal{L} = i\bar{\chi}_L\gamma^\mu D_\mu\chi_L + i\bar{\psi}_R\gamma^\mu D_\mu\psi_R - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} \tag{1.24}$$

In 1.24 $W_{\mu\nu} = W_{\mu\nu}^a \sigma^a/2$ with σ^a 2x2 Pauli's matries.
As in QED and QCD case, also electroweak interaction is invariant under global transformation:

$$\begin{aligned} \chi_L &\to \chi_L' = e^{i\alpha_a T^a + i\beta Y}\chi_L \\ \psi_R &\to \psi_R' = e^{i\beta Y}\psi_R \end{aligned} \tag{1.25}$$

Moving to local transformation, in order to guarantee Lagrangian 1.24 to be invariant, the gauge bosons must have following transformation rules:

$$\begin{aligned} W_\mu^a &\to U_L(x) W_\mu^a \frac{\sigma_a}{2} U_L(x)^\dagger - \frac{i}{g}\partial_\mu U_L(x) U_L(x)^\dagger, \\ B_\mu &\to B_\mu + \frac{1}{g'}\partial_\mu\beta \end{aligned} \tag{1.26}$$

where $U(x)_L = e^{i\sigma_a/2\ \alpha(x)^a}$. The transformation of B_μ is identical to the one obtained in QED for the photon, while the $SU(2)_L$ W_μ^a fields transform in analogous way to the

gluon fields of QCD.
The gauge symmetry forbids to write a mass term for the gauge bosons in 1.24. Fermionic masses are also not possible, because they would communicate the left- and right-handed fields, which have different transformation properties, and therefore would produce an explicit breaking of the gauge symmetry. Thus, the $SU(2)_L \otimes U(1)_Y$ Lagrangian in 1.24 only contains massless fields.
The term containing the $SU(2)_L$ matrix:

$$\frac{\sigma^a}{2} W^a_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} W^3_\mu & W^+_\mu \\ W^-_\mu & -\sqrt{2} W^3_\mu \end{pmatrix} \tag{1.27}$$

gives rise to charged-current interactions with the bosons field $W^\pm_\mu \equiv (W^1_\mu \mp i W^2_\mu)/\sqrt{2}$.
La Lagrangian 1.24 contains also interactions with the neutral gauge field W^3_μ and B_μ; one can define

$$Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'2}}, \quad A_\mu = \frac{g W^3_\mu + g' B_\mu}{\sqrt{g^2 + g'2}} \tag{1.28}$$

and thinking them as a rotation, introducing the Weinberg angle θ_W so that $\cos\theta_W = g/\sqrt{g^2 + g'2}$ (and $\sin\theta_W = g'/\sqrt{g^2 + g'2}$):

$$Z_\mu = \cos\theta_W W^3_\mu - \sin\theta_W B_\mu, \quad A_\mu = \sin\theta_W W^3_\mu + \cos\theta_W B_\mu \tag{1.29}$$

or reversing:

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} \tag{1.30}$$

With these definitions, it can be observed the A_μ in1.24 couple in the same way with l_L and l_R as the photon: to get QED from these one needs to impose

$$g \sin\theta_W = g' \cos\theta_W = e \tag{1.31}$$

At the same time, Z_μ, can be identify with the Z boson, mediator of the Weak Interaction.
Once again, no mass term is present in 1.24 and this means that $W^\pm$ and Z must be massless: this is in contrast with experimental evidence [6][7].
The way to generate the mass of the particle is through the so called *Spontaneous Symmetry Breaking* (SSB): this mechanism appear in those cases where one has a symmetric Lagrangian, but a non-symmetric vacuum.

1.1.3 Spontaneous Symmetry Breaking and the Higgs Boson

Let's consider a complex scalar field $\phi(x) = (\phi_1 + \phi_2)/\sqrt{2}$, with Lagrangian:

$$\mathcal{L} \equiv T - V = (\partial_\mu \phi)^* (\partial^\mu \phi) - \mu^2 (\phi^* \phi) - \lambda (\phi^* \phi)^2 \tag{1.32}$$

1.32 is invariant under global phase transformation of the scalar field (it possesses a U(1) global gauge symmetry).
Considering the case when $\lambda > 0$, for the quadratic piece there are two possibilities:

- $\mu^2 > 0$: the potential has only the trivial minimum $\phi = 0$

- $\mu^2 < 0$: the minimum is every point belong to the circle (in the ϕ_1, ϕ_2) of radius ν such that:

$$(\phi_1)^2 + (\phi_2)^2 = \nu^2 \quad with\ \nu^2 = -\frac{\mu^2}{\lambda} \tag{1.33}$$

as shown in Figure 1.1

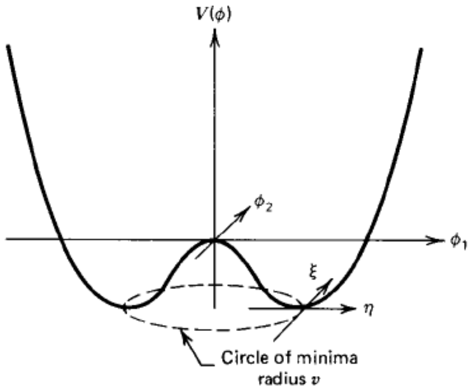

Figure 1.1: The potential $V(\phi)$ for a complex scalar field with $\lambda > 0$ and $\mu^2 < 0$.

Owing to the U(1) phase-invariance of the Lagrangian 1.32, there is an infinite number of degenerate states of minimum energy. By choosing a particular solution, $\phi_1 = \nu$ and $\phi_2 = 0$, as the ground state, the symmetry gets spontaneously broken. Parametrising the excitations over the ground state as:

$$\phi(x) \equiv \frac{1}{\sqrt{2}}[\nu + \eta(x) + i\xi(x)] \tag{1.34}$$

and substituting into 1.32, one obtains:

$$\mathcal{L}' = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2 \eta^2 + const. + O(\eta^3) + O(\xi^3) \tag{1.35}$$

The third term has the form of a mass term for η-field: the η-mass is $m_\eta = \sqrt{-2\mu^2}$. The first term in 1.35 represents the kinetic energy of the ξ-field but there is no corresponding mass term for the ξ. The fact there are massless excitations associated with the SSB mechanism is completely general result, known as the *Goldstone theorem*: if a Lagrangian is invariant under a continuous symmetry group G, but the vacuum is only invariant under a subgroup $H \subset G$, then there must exist as many massless spin-0 particles (Goldstone bosons) as broken generators (i.e., generators of G which do not belong to H).

The Higgs Mechanism

Let's move to consider the case for spontaneous breaking of U(1) local gauge symmetry. Taking into account the covariant derivative 1.7 where the gauge filed transforms as in 1.10, the new Lagrangian can be written as

$$\mathcal{L} = D^{\mu}\phi^{*}D_{\mu}\phi - \mu^{2}\phi^{*}\phi - \lambda(\phi^{*}\phi)^{2} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{1.36}$$

If $\mu^2 > 0$, 1.36 is just the QED Lagrangian for a charged scalar particle of mass μ. For the case $\mu^2 < 0$, it is interesting to note that to lowest oder in ξ, 1.34 can be expressed as

$$\phi(x) \equiv \frac{1}{\sqrt{2}}[\nu + \eta(x)]e^{i\xi(x)/\nu} \tag{1.37}$$

and this suggests to use different set of real field: h, θ, A_μ where now

$$\begin{aligned} \phi(x) &\to \frac{1}{\sqrt{2}}[\nu + h(x)]e^{i\theta(x)/\nu}, \\ A_\mu &\to A_\mu + \frac{1}{e\nu}\partial_\mu\theta \end{aligned} \tag{1.38}$$

This is a particular choice of gauge, with $\theta(x)$ chosen so that h is real. Substituting 1.38 in 1.36, one obtains:

$$\begin{aligned} \mathcal{L}' =& \frac{1}{2}(\partial_\mu h)^2 - \lambda\nu^2 h^2 + \frac{1}{2}e^2\nu^2 A_\mu^2 - \lambda\nu h^3 - \frac{1}{4}\lambda h^4 \\ &+ \frac{1}{2}e^2 A_\mu^2 h^2 + \nu e^2 A_\mu^2 h - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \end{aligned} \tag{1.39}$$

The Goldstone boson does not appear in the theory. That is because it corresponding only to the freedom to make a gauge transformation. The Lagrangian 1.39 describes just two interacting massive particles, a vector gauge bosoon A_μ and a massive scalar h, which is called a *Higgs particle*. This is called the "*Higgs mechanism*".
Consider now the case of $SU(2)_L \otimes U(1)_Y$ symmetry [8] with the Lagrangian

$$\mathcal{L} = (D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \tag{1.40}$$

D_μ is the covariant derivative 1.22 and ϕ is an SU(2) doublet of complex scalar fields:

$$\phi(x) \equiv \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} \tag{1.41}$$

1.40 is invariant under local $SU(2)_L \otimes U(1)_Y$ transformations.
In $\mu^2 < 0$ and $\lambda^2 > 0$ conditions, to generate gauge boson masses, a vacuum expectation value of $\phi(x)$ must be chosen:

$$\phi_0 \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu \end{pmatrix} \tag{1.42}$$

In this way, the symmetry is broken and this generates a mass for the corresponding gauge boson. This particular choice of ϕ_0 breaks both $SU(2)$ and $U(1)_Y$ gauge symmetries but since it is neutral, the $U(1)_{em}$ remains unbroken and this means the photon remains massless.
Now, substituting the vacuum expectation value ϕ_0 for $\phi(x)$ in the Lagrangian 1.40, the expression for W and Z bosons mass are:

$$M_W^2 = \frac{\nu^2 g^2}{4}, \quad M_Z^2 = \frac{\nu^2 g^2}{4\cos^2\theta_W} = \frac{M_W^2}{\cos^2\theta_W} \tag{1.43}$$

From experimental observation [1]:

$$M_Z = XXX \pm 0XXX\ GeV, \quad M_W = XXX \pm XX\ GeV \tag{1.44}$$

From these experimental numbers, one obtains the electroweak mixing angle:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = XXXX \tag{1.45}$$

The scalar vacuum expectation value is:

$$\nu = (\sqrt{2}G_F)^{-1/2} = 246\ GeV \tag{1.46}$$

where $G_F =$ XXXXX is the Fermi coupling whose value can be measured with the muon lifetime [9].
From 1.40, the potential $V(\phi)$ can be seen as:

$$V(\phi) = -\frac{1}{4}\lambda\nu^2 + V_H + V_{HG^2} \tag{1.47}$$

The first term stands for mass of the new Higgs boson: $m_H = \sqrt{2\lambda\nu^2}$; the second represents Higgs boson self-interaction and the last the coupling with the weak bosons (W and Z).
It is interesting to note the same Higgs doublet which generates weak bosons masses can give masses also to leptons and quarks. In particular, let's consider the following Lagrangian:

$$\mathcal{L} = -G_e[(\bar{\nu}_e,\ \bar{e})_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} e_R + \bar{e}_R(\phi^-,\ \bar{\phi}^0)\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L] \tag{1.48}$$

Substituting the expression of ϕ:

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \nu + h(x)\end{pmatrix} \tag{1.49}$$

into 1.48, the Lagrangian becomes:

$$\mathcal{L} = -\frac{G_e}{\sqrt{2}}\nu(\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}}h(\bar{e}_L e_R + \bar{e}_R e_L) \tag{1.50}$$

Choosing G_e so that $m_e = G_e\nu/\sqrt{2}$, since the G_e is arbitrary, the actual mass of the electron is not predicted.
The quark masses are generated in the same way with the difference that to generate a mass for the upper member of a quark doublet, a new Higgs doublet from ϕ must be used:

$$\phi_c = i\tau\phi^* = \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} \xrightarrow[breaking]{} \frac{1}{\sqrt{2}}\begin{pmatrix} \nu + h(x) \\ 0 \end{pmatrix} \tag{1.51}$$

The new Lagrangian can be written as:

$$\mathcal{L} = -G_d(\bar{u},\ \bar{d})_L\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_R - G_u(\bar{u},\ \bar{d})_L\begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} u_R \ + \ hermitian\ coniugate \tag{1.52}$$

In 1.52, the (u, d) quark doublet are considered even if the weak interactions operate on $(u,\ d')_L$ where the primed states are linear combinations of the flavour eigenstates[3]. Using these new doublets, 1.52 is therefore of the form:

$$\mathcal{L} = -G_d^{ij}(\bar{u},\ \bar{d}')_L\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{jR} - G_u^{ij}(\bar{u},\ \bar{d}')_L\begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} u_{jR} \ + \ hermitian\ coniugate \tag{1.53}$$

with i, j = 1, ..., N, where N is the number of quark doublet. Substituting ϕ_c expression, the masses depend on the arbitrary couplings $G_{u,d}$ but, as for electron, it cannot be predicted.
The choose of a particular single Higgs doublet is sufficient on one hand to generate the masses of both of the gauge bosons and the fermions but on the other hand, the masses of the fermoins are just parameteres of the theory and are not predicted.
To summarise, the complete Lagrangian of the SM is:

$$\begin{aligned}\mathcal{L}_{SM} = &\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{L}\gamma^\mu(i\partial_\mu - g\frac{1}{2}\tau\cdot W_\mu - g'\frac{Y}{2}B_\mu)L \\ &+ \bar{R}\gamma^\mu(i\partial_\mu - g'\frac{Y}{2}B_\mu)R + |i\partial_\mu - g\frac{1}{2}\tau\cdot W_\mu - g'\frac{Y}{2}B_\mu|^2 - V\phi \\ &- (G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + \ hermitian\ conjugate)\end{aligned} \tag{1.54}$$

The first two terms represent the $W^\pm$, Z, γ kinetic energies and the self-interactions; the third and the fourth term the lepton and quark kinetic energies and their interaction with weak W, Z and γ; the last terms stand for masses and coupling of the Higgs, bosons, leptons and quark.

1.2 The Higgs boson

The SM Higgs boson is a CP-even scalar of spin 0 [1]. Its mass is given by $m_h = \sqrt{2\lambda\nu^2}$, where λ is the Higgs self-coupling parameter in the potential $V(\phi)$. The experimentally

[3] Linear combination of the flavour eigenstates considering Cabibbo-Kobayashi-Maswaka (CKM) matrix: $d'_i = \sum_{n=1}^{N} V_{in}d_n$ where N = 3 is the number of quarks, V_{in} is CKM matrix and d_n are the d type quarks d, s, b.

Higgs mass, $m_h \simeq 125\ GeV$ [10][11], implies $\lambda \simeq 0.1$ and $|m| \simeq 88.8\ GeV$.
The Higgs boson couplings to the fundamental particles are set by their masses: very weak for light particles, such as up and down quarks, and electrons, but for heavy particles such as the W and Z bosons and the top quark. In particular, the SM Higgs coupling fo fundamental fermions are linearly proportional to the fermion masses. whereas the couplings to bosons are proportional to the squares of the boson masses. As consequence, the dominant mechanism for Higgs boson production and decay involve the coupling of H to W, Z and/or the third generation quarks and leptons. The Higgs boson coupling to gluons is induced at leading order by a one-loop process in which H couples to a virtual $t\bar{t}$ pair. Likewise, the Higgs boson couplings to photons is also generated via loops, although in this case the one-loop graph with a virtual W^+W^- pair provides the dominant contribution and the one involving a virtual $t\bar{t}$ pair is subdominant.

Chapter 2

Il Modello Standard e la Fisica del Bosone di Higgs

La fisica delle particelle elementari è una branca della fisica che si occupa dello studio dei costituenti elemetari della materia e delle loro interazioni fondamentali. I vari risultati ottenuti negli ultimi 50 anni di esperimenti portano al successo un unico modello teorico: il Modello Standard (MS) dell'interazioni elettrodeboli e forti delle particelle fondamentali.

Chapter 3

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Chapter 4

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Conclusion

In questo lavoro di tesi ho analizzato il processo di produzione associata, nell'ambito dell'esperimento CMS a LHC, per m_H =125 GeV. Lo stato finale analizzato è il seguente:

$$(W \rightarrow \mu + \nu_\mu)(H \rightarrow \tau^+\tau^- \rightarrow \tau_{jet} + \tau_{jet} + 2\nu_\tau),$$

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