SEARCH FOR PRODUCTION OF A HIGGS BOSON AND A SINGLE TOP QUARK IN MULTILEPTON FINAL STATES IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV.

by

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2.1 Introduction

The physical description of the universe is a challenge that physicists have faced by making theories that refine existing principles and proposing new ones in an attempt to embrace emerging facts and phenomena.

At the end of 1940s Julian Schwinger [1] and Richard P. Feynman [2], based in the work of Sin-Itiro Tomonaga [3], developed an electromagnetic theory consistent with special relativity and quantum mechanics that describes how matter and light interact; the so-called "quantum eletrodynamics" (QED) had born.

QED has become the guide in the development of theories that describe the universe. It was the first example of a quantum field theory (QFT), which is the theoretical framework for building quantum mechanical models that describes particles and their interactions. QFT is composed of a set of mathematical tools that combines classical fields, special relativity and quantum mechanics, while keeping the quantum point particles and locality ideas.

This chapter gives an overview of the standard model of particle physics, starting with a description of the particles and interactions that compose it, followed by a description of the electroweak interaction, the Higgs boson and the associated production of Higgs boson and a single top quark (tH). The description contained in this chapter is based on references [4–6].

2.2 Standard model of particle physics

Particle physics at the fundamental level is modeled in terms of a collection of interacting particles and fields in a theory known as the "standard model of particle physics (SM)"[1].

The full picture of the SM is composed of three fields[2], whose excitations are interpreted as particles called mediators or force-carriers; a set of fields, whose excitations are interpreted as elementary particles, interacting through the exchange of those mediators and a field that gives the mass to elementary particles. Figure 2.1 shows an scheme of the SM particles organization. In addition to the particles in the scheme (but not listed in it), their corresponding anti-particles, with opposite quantum numbers, are also part of the picture; some particles are their own anti-particles, like photon or Higgs, or anti-particle is already listed like in the W^+ and W^- case.

The mathematical formulation of the SM is based on group theory and the use of Noether's theorem [8] which states that for a physical system modeled by a Lagrangian

[1] The formal and complete treatment of the SM is out of the scope of this document, however a plenty of textbooks describing it at several levels are available in the literature. The treatment in references [?] is quite comprehensive and detailed.

[2] Note that gravitational field is not included in the standard model formulation

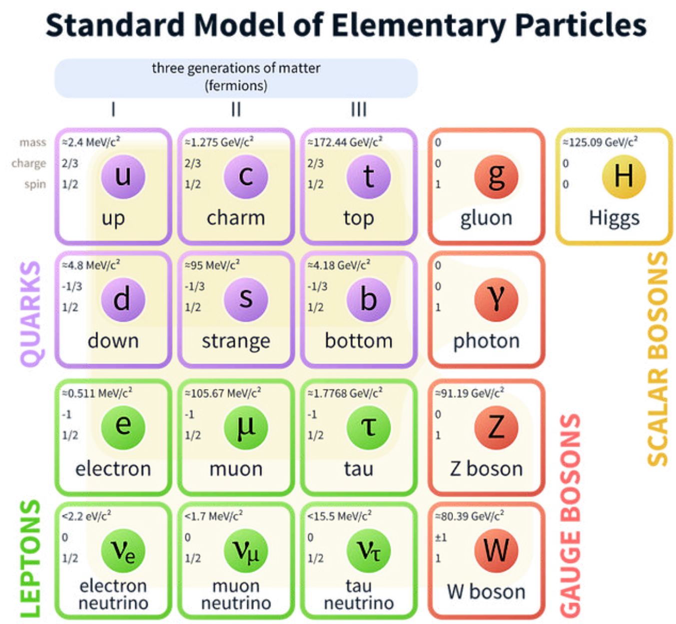

Figure 2.1: Schematic representation of the Standard model of particle physics. SM is a theoretical model intended to describe three of the four fundamental forces of the universe in terms of a set of particles and their interactions. [7].

that is invariant under a group of transformations a conservation law is expected. For instance, a system described by a time-independent Lagrangian is invariant (symmetric) under time changes (transformations) with the total energy conservation law as the expected conservation law. In QED, the charge operator (Q) is the generator of the U(1) symmetry which according to the Noether's theorem means that there is a conserved quantity; this conserved quantity is the electric charge and thus the law conservation of electric charge is established.

In the SM, the symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ describes three of the four fundamental interactions in nature(see section 2.2.2): strong interaction(SI), weak interaction(WI) and electromagnetic interactions (EI) in terms of symmetries associated to physical quantities:

- Strong: $SU(3)_C$ associated to color charge
- Weak: $SU(2)_L$ associated to weak isospin and chirality
- Electromagnetic: $U(1)_Y$ associated to weak hypercharge and electric charge

It will be shown that the electromagnetic and weak interactions are combined in the so-called electroweak interaction where chirality, hypercharge, weak isospin and electric charge are the central concepts.

2.2.1 Fermions

The basic constituents of the ordinary matter at the lowest level, which form the set of elementary particles in the SM formulation, are quarks and leptons. All of them have spin 1/2, therefore they are classified as fermions since they obey Fermi-Dirac statistics. There are six "flavors" of quarks and three of leptons organized in three generations, or families, as shown in table 2.1.

		Generation		
	Type	1st	2nd	3rd
Leptons	Charged	Electron (e)	Moun(μ)	Tau (τ)
	Neutral	Electron neutrino (ν_e)	Muon neutrino (ν_μ)	Tau neutrino (ν_τ)
Quarks	Up-type	Up (u)	Charm (c)	Top (t)
	Down-type	Down (d)	Strange (s)	Bottom (b)

Table 2.1: Fermions of the SM. There are six flavors of quarks and three of leptons, organized in three generations, or families, composed of two pairs of closely related particles. The close relationship is motivated by the fact that WI between leptons is limited to the members of the same generation; WI between quarks is not limited but greatly favoured, to same generation members.

There is a mass hierarchy between generations (see table 2.2), where the higher generation particles decays to the lower one, which can explain why the ordinary matter is made of particles in the first generation. In the SM, neutrinos are modeled as massless particles so they are not subject to this mass hierarchy; however, today it is known that neutrinos are massive so the hierarchy could be restated. The reason behind this mass hierachy is one of the most important open questions in particle physics, and it becomes more puzzling when noticing that the mass difference between first and second generation fermions is small compared to the mass difference with respect to the third generation.

Lepton	Mass (MeV/c^2)	Quark	Mass (MeV/c^2)
e	0.51	u	2.2
μ	105.65	c	1.28×10^3
τ	1776.86	t	173.1×10^3
ν_e	Unknown	d	4.7
ν_μ	Unknown	s	96
τ_μ	Unknown	b	4.18×10^3

Table 2.2: Fermion masses [9]. Generations differ by mass in a way that have been interpreted as a masss hierarchy. Approximate values with no uncertainties are used, for comparison purpose.

Usually, the second and third generation fermions are produced in high energy processes, like the ones recreated in particle accelerators.

2.2.1.1 Leptons

A lepton is an elementary particle that is not subject to the SI. As seen in table 2.1, there are two types of leptons, the charged ones (electron, muon and tau) and the neutral ones (the three neutrinos). The electric charge (Q) is the property that gives leptons the ability to participate in the EI. From the classical point of view, Q plays a central role determining, among others, the strength of the electric field through which the electromagnetic force is exerted. It is clear that neutrinos are not affected by EI because they don't carry electric charge.

Another feature of the leptons that is fundamental in the mathematical description of the SM is the chirality, which is closely related to spin and helicity. Helicity defines the handedness of a particle by relating its spin and momentum such that if they are parallel then the particle is right-handed; if spin and momentum are antiparallel the particle is said to be left-handed. The study of parity conservation (or violation) in β-decay has shown that only left-handed electrons/neutrinos or right-handed positrons/anti-neutrinos are created [10]; the inclusion of that feature in the theory was achieved by using projection operators for helicity, however, helicity is frame dependent for massive particles which makes it not Lorentz invariant and then another related attribute has to be used: *chirality*.

Chirality is a purely quantum attribute which makes it not so easy to describe in graphical terms but it defines how the wave function of a particle transforms under certain rotations. As with helicity, there are two chiral states, left-handed chiral (L) and right-handed chiral (R). In the highly relativistic limit where $E \approx p \gg m$ helicity and chirality converge, becoming exactly the same for massless particles.

In the following, when referring to left-handed (right-handed) it will mean left-handed chiral (right-handed chiral). The fundamental fact about chirality is that while EI and SI are not sensitive to chirality, in WI left-handed and right-handed fermions are treated asymmetrically, such that only left handed fermions and right-handed anti-fermions are allowed to couple to WI mediators, which is a violation of parity. The way to translate this statement in a formal mathematical formulation is based on the isospin symmetry group $SU(2)_L$.

Each generation of leptons is seen as a weak isospin doublet.[3] The left-handed charged lepton and its associated left-handed neutrino are arranged in doublets of weak isospin T=1/2 while their right-handed partners are singlets:

$$\begin{pmatrix}\nu_l\\ l\end{pmatrix}_L, l_R := \begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L, e_R, \mu_R, \tau_R, \nu_{eR}, \nu_{\mu R}, \nu_{\tau R} \tag{2.1}$$

The isospin third component refers to the eigenvalues of the weak isospin operator which for doublets is $T_3 = \pm 1/2$, while for singlets it is $T_3 = 0$. The physical meaning of this doublet-singlet arrangement falls in that the WI couples the two particles in the doublet by exchanging the interaction mediator while the singlet member is not involved in WI. The main properties of the leptons are summarized in table 2.3.

Altough all three flavor neutrinos have been observed, their masses remain unknown and only some estimations have been made [11]. The main reason is that the flavor eigenstates are not the same as the mass eigenstates which implies that when a neutrino is created its mass state is a linear combination of the three mass eigenstates and experiments can only probe the squared difference of the masses. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix encode the relationship between flavor and mass eigenstates.

2.2.1.2 Quarks

Quarks are the basic constituents of protons and neutrons. The way quarks join to form bound states, called “hadrons”, is through the SI. Quarks are affected by all the

[3] The weak isospin is an analogy of the isospin symmetry in strong interaction where neutron and proton are affected equally by strong force but differ in their charge.

Lepton	Q(e)	T_3	L_e	L_μ	L_τ	Lifetime (s)
Electron (e)	-1	-1/2	1	0	0	Stable
Electron neutrino(ν_e)	0	1/2	1	0	0	Unknown
Muon (μ)	-1	-1/2	0	1	0	2.19×10^{-6}
Muon neutrino (ν_μ)	0	1/2	0	1	0	Unknown
Tau (τ)	-1	-1/2	0	0	1	290.3×10^{-15}
Tau neutrino (τ_μ)	0	1/2	0	0	1	Unknown

Table 2.3: Leptons properties [9]. Q: electric charge, T_3: weak isospin. Only left-handed leptons and right-handed anti-leptons participate in the WI. Anti-particles with inverted T_3, Q and lepton number complete the leptons set but are not listed. Right-handed leptons and left-handed anti-leptons, neither listed, form weak isospin singlets with $T_3 = 0$ and do not take part in the weak interaction.

fundamental interactions which means that they carry all the four types of charges: color, electric charge, weak isospin and mass.

Flavor	Q(e)	I_3	T_3	B	C	S	T	B'	Y	Color
Up (u)	2/3	1/2	1/2	1/3	0	0	0	0	1/3	r,b,g
Charm (c)	2/3	0	1/2	1/3	1	0	0	0	4/3	r,b,g
Top(t)	2/3	0	1/2	1/3	0	0	1	0	4/3	r,b,g
Down(d)	-1/3	-1/2	-1/2	1/3	0	0	0	0	1/3	r,b,g
Strange(s)	-1/3	0	-1/2	1/3	0	-1	0	0	-2/3	r,b,g
Bottom(b)	-1/3	0	-1/2	1/3	0	0	0	-1	-2/3	r,b,g

Table 2.4: Quarks properties [9]. Q: electric charge, I_3: isospin, T_3: weak isospin, B: baryon number, C: charmness, S: strangeness, T: topness, B': bottomness, Y: hypercharge. Anti-quarks posses the same mass and spin as quarks but all charges (color, flavor numbers) have opposite sign.

Table 2.4 summarizes the features of quarks, among which the most particular is their fractional electric charge. Note that fractional charge is not a problem, given that quarks are not found isolated, but serves to explain how composed particles are formed out of two or more valence quarks[4].

[4] Hadrons can contain an indefinite number of virtual quarks and gluons, known as the quark and gluon sea, but only the valence quarks determine hadrons' quantum numbers.

Color charge is the responsible for the SI between quarks and is the symmetry ($SU(3)_C$) that defines the formalism to describe SI. There are three colors: red (r), blue(b) and green(g) and their corresponding three anti-colors; thus each quark carries one color unit while anti-quarks carries one anti-color unit. As said above, quarks are not allowed to be isolated due to the color confinement effect, therefore their features have been studied indirectly by observing their bound states created when:

- one quark with a color charge is attracted by an anti-quark with the corresponding anti-color charge forming a colorless particle called a "meson."
- three quarks (anti-quarks) with different color (anti-color) charges are attracted among them forming a colorless particle called a "baryon(anti-baryon)."

In the first version of the quark model (1964), M. Gell-Mann [12] and G. Zweig [13, 14] developed a consistent way to classify hadrons according to their properties. Only three quarks (u, d, s) were involved in a scheme in which all baryons have baryon number B=1 and therefore quarks have B=1/3; non-baryons have B=0. The scheme organizes baryons in a two-dimensional space (I_3 - Y); Y (hypercharge) and I_3 (isospin) are quantum numbers related by the Gell-Mann-Nishijima formula [15, 16]:

$$Q = I_3 + \frac{Y}{2} \tag{2.2}$$

where $Y = B + S + C + T + B'$ are the quantum numbers listed in table 2.4. Baryon number is conserved in SI and EI which means that single quarks cannot be created but in pairs $q - \bar{q}$.

There are six quark flavors organized in three generations (see table 2.1) following a mass hierarchy which, again, implies that higher generations decay to first generation quarks.

	Quarks			T_3	Y_W	Leptons			T_3	Y_W
Doublets	$\binom{u}{d'}_L$	$\binom{c}{s'}_L$	$\binom{t}{b'}_L$	$\binom{1/2}{-1/2}$	1/3	$\binom{\nu_e}{e}_L$	$\binom{\nu_\mu}{\mu}_L$	$\binom{\nu_\tau}{\tau}_L$	$\binom{1/2}{-1/2}$	-1
Singlets	u_R	c_R	t_R	0	4/3	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$		
	d'_R	s'_R	b'_R	0	-2/3	e_R	μ_R	τ_R	0	-2

Table 2.5: Fermion weak isospin and weak hypercharge multiplets. Weak hypercharge is calculated through the Gell-Mann-Nishijima formula 2.2 but using the weak isospin and charge for quarks.

Isospin doublets of quarks are also defined (see table 2.5) and as for neutrinos, the mass eigenstates are not the same as the WI eigenstates which means that members of different quark generations are connected by the WI mediator; thus, up-type quarks are coupled not to down-type quarks directly but to a superposition of down-type quarks (q'_d) via WI according to:

$$
\begin{gathered}
q'_d = V_{CKM}\, q_d \\
\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
\end{gathered}
\tag{2.3}
$$

where V_{CKM} is known as Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [17,18]. The weak decays of quarks are represented in the diagram of figure 2.2; again the CKM matrix plays a central role since it contains the probabilities for the different quark decay channels, in particular, note that quark decays are greatly favored between generation members.

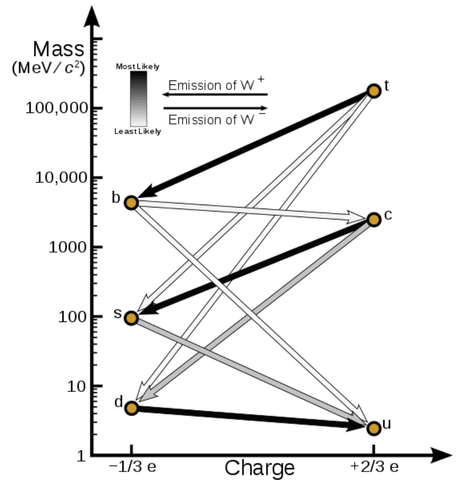

Figure 2.2: Transformations between quarks through the exchange of a WI. Higher generations quarks decay to first generation quarks by emitting a W boson. The arrow color indicates the likelihood of the transition according to the grey scale in the top left side which represent the CKM matrix parameters [19].

CKM matrix is a 3×3 unitary matrix parametrized by three mixing angles and the *CP-mixing phase*; the latter is the parameter responsible for the Charge-Parity symmetry violation (CP-violation) in the SM. The fact that the b quark decays almost all the times to a top quark is exploided in this thesis when making the selection of the signal events by requiring the presence of a jet tagged as a jet comming from a b quark in the final state. The effect of the *CP-mixing phase* on the cross section of associated production of Higss boson and a single top process is also explored in this thesis.

2.2.2 Fundamental interactions

Even though there are many manifestations of force in nature, like the ones represented in figure 2.3, we can classify all of them into one of four fundamental interactions:

- *Electromagnetic interaction (EI)* affects particles that are “electrically charged,”

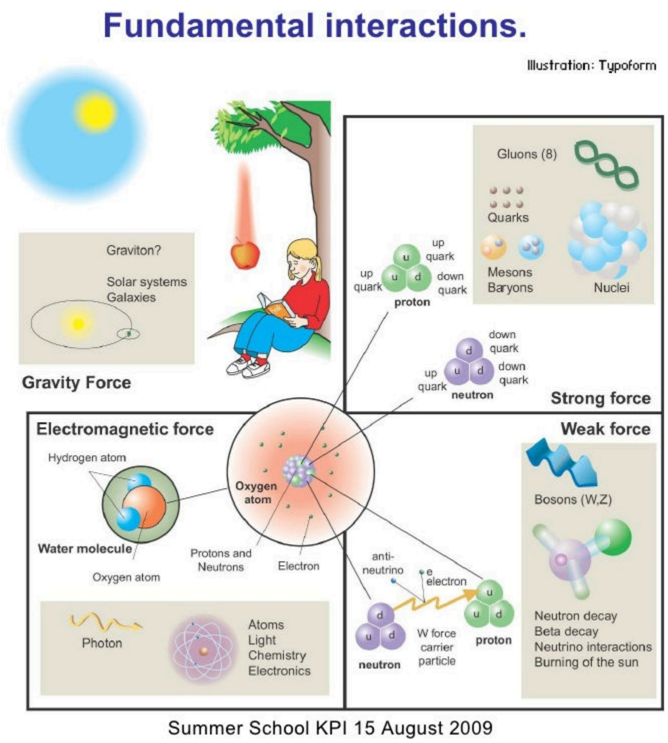

Figure 2.3: Fundamental interactions in nature. Despite the many manifestations of forces in nature, we can track all of them back to one of the fundamental interactions. The most common forces are gravity and electromagnetic given that all of us are subject and experience them in everyday life.

like electrons and protons. It is described by QED combining quantum mechanics, special relativity and electromagnetism in order to explain how particles with electric charge interact through the exchange of photons, therefore, one says that "Electomagnetic Force" is mediated by "photons". Figure 2.4a. shows a graphical representation, known as "feynman diagram", of electron-electron scattering.

- *Strong interaction (SI)* described by Quantum Chromodynamics (QCD). Hadrons like proton and neutron have internal structure given that they are composed of two or more valence quarks[5]. Quarks have fractional electric charge which means that they are subject to electromagnetic interaction and in the case of the

[5] particles made of four and five quarks are exotic states not so common.

proton they should break appart due to electrostatic repulsion; however, quarks are held together inside the hadrons against their electrostatic repulsion by the "Strong Force" through the exchange of "gluons." The analog to the electric charge is the "color charge". Electrons and photons are elementary particles as quarks but they don't carry color charge, therefore they are not subject to SI. The feynman diagram for gluon exchange between quarks is shown in figure 2.4b.

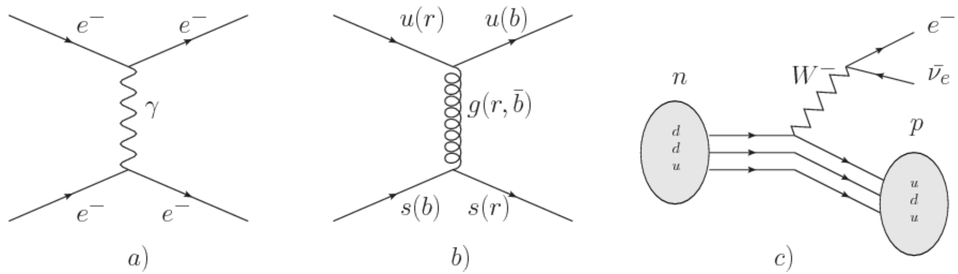

Figure 2.4: Feynman diagrams representing the interactions in SM; a) EI: e-e scattering; b) SI: gluon exchange between quarks ; c) WI: β-decay

- *Weak interaction (WI)* described by the weak theory (WT), is responsible, for instance, for the radioactive decay in atoms and proton-proton (pp) fusion within the sun. Quarks and leptons are the particles affected by the weak interaction; they possess a property called "flavor charge" (see 2.2.1) which can be changed by emitting or absorbing one weak force mediator. There are three mediators of the "weak force" known as "Z" boson in the case of electrically neutral changes and "$W^{\pm}$" bosons in the case of electrically charged changes. The "weak isospin" is the WI analog to electric charge in EI, and color charge in SI, and defines how quarks and leptons are affected by the weak force. Figure 2.4c. shows the feynman diagram of β-decay where a newtron (n) is transformed in a proton (p) by emmiting a W^- particle. Since this thesis is in the frame of the electroweak interaction, a more detailed description of it will be given in section 2.3

- *Gravitational interaction (GI)* described by General Theory of Relativity (GR). It is responsible for the structure of galaxies and black holes as well as the expansion of the universe. As a classical theory, in the sense that it can be formulated without even appeal to the concept of quantization, it implies that the spacetime is a continuum and predictions can be made without limitation to the precision of the measurement tools. The latter represent a direct contradiction of the quantum mechanics principles. Gravity is deterministic while quantum mechanics is probabilistic; despite that, efforts to develop a quantum theory of gravity have predicted the "graviton" as mediator of the Gravitational force[6].

Interaction	Acts on	Relative strength	Range (m)	Mediators
Electromagnetic (QED)	Electrically charged particles	10^{-2}	Infinite	Photon
Strong (QCD)	Quarks and gluons	1	10^{-15}	Gluon
Weak (WI)	Leptons and quarks	10^{-6}	10^{-18}	$W^{\pm}$, Z
Gravitational (GI)	Massive particles	10^{-39}	Infinite	Graviton

Table 2.6: Fundamental interactions features [20].

Table 2.6 sumarizes the main features of the fundamental interactions. The relative strength of the fundamental forces reveals the meaning of strong and weak; in a context where the relative strength of the SI is 1, the EI is about hundred times weaker and WI is about million times weaker thant the SI. A good description on how the relative strenght and range of the fundamental intreractions are calculated can be found in references [20, 21]. In the everyday life, only EI and GI are explicitly experienced due to the range of these interactions; i.e., at the human scale distances

[6] Actually a wide variety of theories have been developed in an attempt to describe gravity; some famous examples are string theory and supergravity.

only EI and GI have appreciable effects, in contrast to SI which at distances greater than 10^{-15}m become negligible.

QED was built successfully on the basis of the classical electrodynamics theory (CED) of Maxwell and Lorentz, following theoretical and experimental requirements imposed by

- lorentz invariance: independence on the reference frame.
- locallity: interacting fields are evaluated at the same space-time point to avoid action at a distance.
- renormalizability: physical predictions are finite and well defined
- particle spectrum, symmetries and conservation laws already known must emerge from the theory.
- gauge invariance.

The gauge invariance requirement reflects the fact that the fundamental fields cannot be directly measured but associated fields which are the observables. Electric (**"E"**) and magnetic (**"B"**) fields in CED are associated with the electric scalar potential "V" and the vector potential **"A"**. In particular, **E** can be obtained by measuring the change in the space of the scalar potential (ΔV); however, two scalar potentials differing by a constant "f" correspond to the same electric field. The same happens in the case of the vector potential **"A"**; thus, different configurations of the associated fields result in the same set of values of the observables. The freedom in choosing one particular configuration is known as "gauge freedom"; the tranformation law connecting two configurations is known as "gauge transformation" and the fact that the observables are not affected by a gauge transformation is called “gauge invariance”.

When the gauge tranformation:

$$
\begin{aligned}
\mathbf{A} \rightarrow & \mathbf{A} - \Delta f \\
V \rightarrow & V - \frac{\partial f}{\partial t}
\end{aligned}
\tag{2.4}
$$

is applied to Maxwell equations, they are still satisfied and the fields remain invariant. Thus, CED is invariant under gauge transformations and is called a “gauge theory”. The set of all gauge transformations form the “symmetry group” of the theory, which according to the group theory, has a set of “group generators”. The number of group generators determine the number of “gauge fields” of the theory.

As mentioned in the first lines of section 2.2, QED has one symmetry group (U(1)) with one group generator (the Q operator) and one gauge field (the electromagnetic field A^{μ}). In CED there is not a clear definition, beyond the historical convention, of which fields are the fundamental and which are the associated, but in QED it is clear that the fundamental field is A^{μ}. When a gauge theory is quantized, the gauge field is quantized and its quanta is called “gauge boson”. The word boson characterizes particles with integer spin which obvey Bose-einstein statistics.

As will be detailed in section 2.3, interactions between partcles in a system can be obtained by considering first the Lagrangian density of free particles in the system, which of course is incomplete because the interaction terms have been left out, and demanding global phase transformation invariance. Global phase transformation invariance means that a gauge transformation is performed identically to every point in the space[7] and the Lagrangian remains invariant. Then, the global transformation is promoted to a local phase transformation (this time the gauge transformation depends on the position in space) and again invariance is required.

Due to the space dependence of the local tranformation, the Lagrangian density is not invariant anymore. In order to restate the gauge invariance, the gauge covariant derivative is introduced in the Lagrangian and with it the gauge field responsible for the interaction between particles in the system. The new Lagrangian density is gauge invariant, includes the interaction terms needed to account for the interactions and provides a way to explain the interaction between particles through the exchange of the gauge boson.

This recipe was used to build QED and the theories that aim to explain the fundamental interactions.

2.2.3 Gauge bosons

The importance of the gauge bosons comes from the fact that they are the force mediators or force carriers. The features of the gauge bosons reflect those of the fields they represent and they are extracted from the Lagrangian density used to describe the interactions. In section 2.3, it will be shown how the gauge bosons of the EI and WI emerge from the electroweak Lagrangian. The SI gauge bosons features are also extracted from the SI Lagrangian but it is not detailed in this document. The main features of the SM gauge bosons will be briefly presented below and summarized in table 2.7.

[7] Here space corresponds to the 4-dimensional space i.e. space-time.

- **Photon**. EI occurs when the photon couples to (is exchanged between) particles carrying electric charge; however, the photon itself does not carry electric charge, therefore, there is no coupling between photons. Given that the photon is massless the EI is of infinite range, i.e., electrically charged particles interact even if they are located far away one from each other; this also implies that photons always move with the speed of light.

- **Gluon**. SI is mediated by gluons which, same as photons, are massless. They carry one unit of color charge and one unit of anticolor charge which means that gluons couple to other gluons. As a result, the range of the SI is not infinite but very short due to the attraction between gluons, giving rise to the "color confinement" which explains why color charged particles cannot be isolated but live within composited particles, like quarks inside protons.

- **W, Z**. The WI mediators, $W^{\pm}$ and Z, are massive which explains their short-range. Given that the WI is the only interaction that can change the flavor of the interacting particles, the W boson is the responsible for the nuclear transmutation where a neutron is converted in a proton or vice versa with the involvement of an electron and a neutrino (see figure 2.4c). The Z boson is the responsible of the neutral weak processes like neutrino elastic scattering where no electric charge but momentum transference is involved. WI gauge bosons carry isospin charge which makes posible the interaction between them.

Interaction	Mediator	Electric charge (e)	Color charge	Weak Isospin	mass (GeV/c^2)
Electromagnetic	Photon (γ)	0	No	0	0
Strong	Gluon (g)	0	Yes -octet	No	0
Weak	$W^{\pm}$	±1	No	±1	80.385 $\pm$ 0.015
	Z	0	No	0	91.188 $\pm$ 0.002

Table 2.7: SM gauge bosons main features [9].

2.3 Electroweak unification and the Higgs mechanism

Physicists dream of building a theory that contains all the interactions in one single interaction, i.e., showing that at some scale in energy all the four fundamental interactions are unified and only one interaction emerges in a "Theory of everything". The first sign of the feasibility of such unification comes from success in the construction of the CED. Einstein spent years trying to reach that dream, which by 1920 only involved electromagnetism and gravity, with no success; however, a new partial unification was achieved in the 1960's, when S.Glashow [22], A.Salam [23] and S.Weinberg [24] independently proposed that electromagnetic and weak interactions are two manifestations of a more general interaction called "electroweak interaction (EWT)". Both, QCD and EWT, were developed in parallel and following the useful prescription provided by QED and the gauge invariance principles.

The theory of weak interactions was capable of explaining the β-decay and in general the processes mediated by $W^{\pm}$ bosons. However, there were some processes like the "$\nu_\mu - e$ scattering" which would require the exchange of two W bosons (see figure 2.5 top diagrams) giving rise to divergent loop integrals and then non finite predictions. By including neutral currents involving fermions via the exchange of neutral bosons Z, those divergences are compensated and the predictions become realistic.

Neutral weak interaction vertices conserve flavor in the same way as the electromagnetic vertices do, but additionally, the Z boson can couple to neutrinos which implies that processes involving charged fermions can proceed through EI or WI but processes involving neutrinos can proceed only through WI.

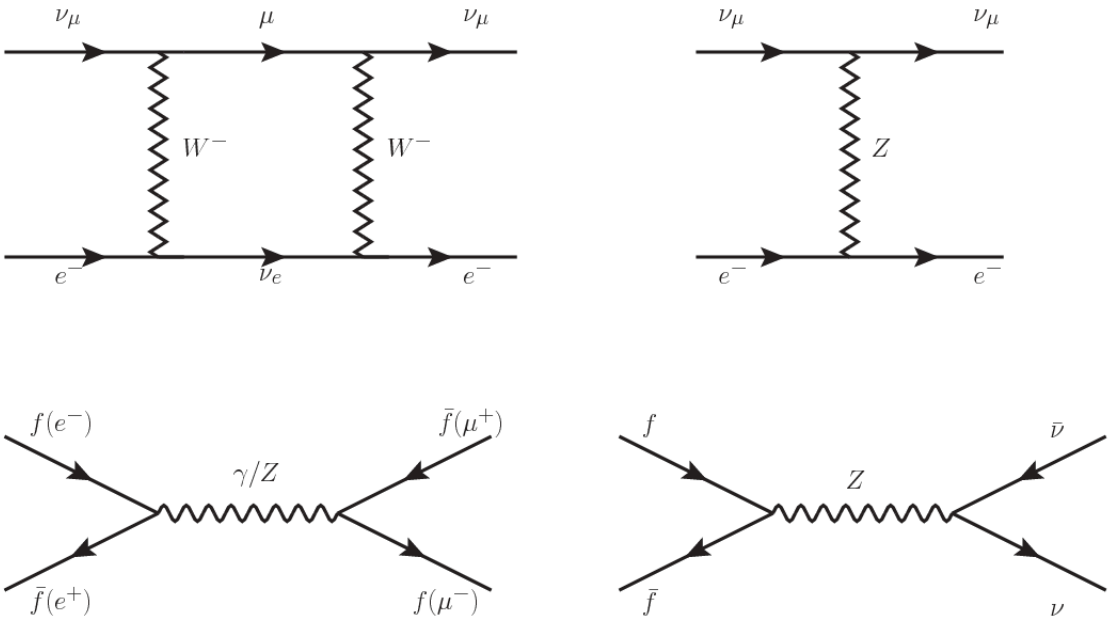

Figure 2.5: Top: $\nu_\mu - e^-$ scattering going through charged currents (left) and neutral currents (right). Bottom: neutral current processes for charged fermions (left) and involving neutrinos (right). While neutral current processes involving only charged fermions can proceed through EI or WI, those involving neutrinos can only proceed via WI.

The prescription to build a gauge theory of the WI consists of proposing a free field Lagrangian density that includes the particles involved; next, by requesting invariance under global phase transformations first and generalizing to local phase transformations invariance later, the conserved currents are identified and interactions are generated by introducing gauge fields. Given that the goal is to include the EI and WI in a single theory, the group symmetry considered should be a combination of $SU(2)_L$ and $U(1)_{em}$, however the latter cannot be used directly because the EI treats left and right-handed particles indistinctly in contrast to the former. Fortunately, the weak hypercharge, which is a combination of the weak isospin and the electric charge (eqn 2.2) is suitable to be used since it is conserved by the EI and WI. Thus, the symmetry group to be considered is

$$G \equiv SU(2)_L \otimes U(1)_Y \tag{2.5}$$

The following treatment applies to any of the fermion generations, but for simplicity the first generation of leptons will be considered [5, 6, 25, 26].

Given the first generation of leptons

$$\psi_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \qquad \psi_2 = \nu_{eR}, \qquad \psi_3 = e^-_R \tag{2.6}$$

the charged fermionic currents are given by

$$J_\mu \equiv J^+_\mu = \bar{\nu}_{eL}\gamma_\mu e_L, \qquad J^\dagger_\mu \equiv J^-_\mu = \bar{e}_L \gamma_\mu \nu_{eL} \tag{2.7}$$

and the free Lagrangian is given by

$$\mathcal{L}_0 = \sum_{j=1}^{3} i\overline{\psi}_j(x)\gamma^\mu \partial_\mu \psi_j(x). \tag{2.8}$$

Mass terms are included directly in the QED and QCD free Lagrangians since they preserve the invariance under the symmetry transformations involved which treat left-handed and right-handed similarly, however mass terms of the form

$$m_W^2 W^\dagger_\mu(x) W^\mu(x) + \frac{1}{2} m_Z^2 Z_\mu(x) Z^\mu(x) - m_e \bar{\psi}_e(x)\psi_e(x) \tag{2.9}$$

which represent the mass of $W^\pm$, Z and electrons, are not invariant under G transformations, therefore the gauge fields described by the EWI are in principle massless.

Experiments have shown that the gauge fields are not massless; however, they have to acquire mass through a mechanism compatible with the gauge invariance; that mechanism is known as the “Higgs mechanism” and will be considered later in this section. The global transformations in the combined symmetry group G can be written as

$$\begin{aligned}\psi_1(x) &\xrightarrow{G} \psi_1'(x) \equiv U_Y U_L \psi_1(x),\\ \psi_2(x) &\xrightarrow{G} \psi_2'(x) \equiv U_Y \psi_2(x),\\ \psi_3(x) &\xrightarrow{G} \psi_3'(x) \equiv U_Y \psi_3(x)\end{aligned} \tag{2.10}$$

where U_L represent the $SU(2)_L$ transformation acting only on the weak isospin doublet and U_Y represent the $U(1)_Y$ transformation acting on all the weak isospin multiplets. Explicitly

$$U_L \equiv \exp\left(i\frac{\sigma_i}{2}\alpha^i\right), \qquad U_Y \equiv \exp(iy_i\beta) \qquad (i=1,2,3) \tag{2.11}$$

with σ_i the Pauli matrices and y_i the weak hypercharges. In order to promote the transformations from global to local while keeping the invariance, it is required that $\alpha^i = \alpha^i(x)$, $\beta = \beta(x)$ and the replacement of the ordinary derivatives by the covariant derivatives

$$\begin{aligned}D_\mu\psi_1(x) &\equiv \left[\partial_\mu + ig\sigma_i W_\mu^i(x)/2 + ig' y_1 B_\mu(x)\right]\psi_1(x)\\ D_\mu\psi_2(x) &\equiv \left[\partial_\mu + ig' y_2 B_\mu(x)\right]\psi_2(x)\\ D_\mu\psi_3(x) &\equiv \left[\partial_\mu + ig' y_3 B_\mu(x)\right]\psi_3(x)\end{aligned} \tag{2.12}$$

introducing in this way four gauge fields, $W^i_\mu(x)$ and $B_\mu(x)$, in the process. The covariant derivatives (eqn 2.12) are required to transform in the same way as fermion fields $\psi_i(x)$ themselves, therefore, the gauge fields transform as:

$$\begin{aligned} B_\mu(x) \xrightarrow{G} B'_\mu(x) \equiv& B_\mu(x) - \frac{1}{g'}\partial_\mu\beta(x) \\ W^i_\mu(x) \xrightarrow{G} W^{i\prime}_\mu(x) \equiv& W^i_\mu(x) - \frac{i}{g}\partial_\mu\alpha_i(x) - \varepsilon_{ijk}\alpha_i(x)W^i_\mu(x). \end{aligned} \tag{2.13}$$

The G invariant version of the Lagrangian density 2.8 can be written as

$$\mathcal{L}_0 = \sum_{j=1}^{3} i\overline{\psi}_j(x)\gamma^\mu D_\mu\psi_j(x) \tag{2.14}$$

where free massless fermion and gauge fields and fermion-gauge boson interactions are included. The EWI Lagrangian density must additionally include kinetic terms for the gauge fields ($\mathcal{L}_G$) which are built from the field strengths, according to

$$B_{\mu\nu}(x) \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \tag{2.15}$$

$$W^i_{\mu\nu}(x) \equiv \partial_\mu W^i_\nu(x) - \partial_\nu W^i_\mu(x) - g\varepsilon^{ijk}W^j_\mu W^k_\nu \tag{2.16}$$

the last term in eqn. 2.16 is added in order to hold the gauge invariance; therefore,

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}(x)B^{\mu\nu}(x) - \frac{1}{4}W^i_{\mu\nu}(x)W_i^{\mu\nu}(x) \tag{2.17}$$

which contains not only the free gauge fields contributions, but also the gauge fields self-interactions and interactions among them.

The three weak isospin conserved currents resulting from the $SU(2)_L$ symmetry are given by

$$J^i_\mu(x) = \frac{1}{2}\bar{\psi}_1(x)\gamma_\mu\sigma^i\psi_1(x) \tag{2.18}$$

while the weak hypercharge conserved current resulting from the $U(1)_Y$ symmetry is given by

$$J^Y_\mu = \sum_{j=1}^{3}\overline{\psi}_j(x)\gamma_\mu y_j\psi_j(x) \tag{2.19}$$

In order to evaluate the electroweak interactions modeled by an isotriplet field W^i_μ which couples to isospin currents J^i_μ with strength g and additionally the singlet field B_μ which couples to the weak hypercharge current J^Y_μ with strength $g'/2$. The interaction Lagrangian density to be considered is

$$\mathcal{L}_I = -gJ^{i\mu}(x)W^i_\mu(x) - \frac{g'}{2}J^{Y\mu}(x)B_\mu(x) \tag{2.20}$$

Note that the weak isospin currents are not the same as the charged fermionic currents that were used to describe the WI (eqn 2.7), since the weak isospin eigenstates are not the same as the mass eigenstates, but they are closely related

$$J_\mu = \frac{1}{2}(J^1_\mu + iJ^2_\mu), \qquad J^\dagger_\mu = \frac{1}{2}(J^1_\mu - iJ^2_\mu). \tag{2.21}$$

The same happens with the gauge fields W^i_μ which are related to the mass eigenstates $W^\pm$ by

$$W^+_\mu = \frac{1}{\sqrt{2}}(W^1_\mu - iW^2_\mu), \qquad W^-_\mu = \frac{1}{\sqrt{2}}(W^1_\mu + iW^2_\mu). \tag{2.22}$$

The fact that there are three weak isospin conserved currents is an indication that in addition to the charged fermionic currents, which couple charged to neutral leptons, there should be a neutral fermionic current that does not involve electric charge exchange; therefore, it couples neutral fermions or fermions of the same electric charge. The third weak isospin current contains a term that is similar to the electromagnetic current (j_μ^{em}), indicating that there is a relation between them and resembling the Gell-Mann-Nishijima formula 2.2 adapted to electroweak interactions

$$Q = T_3 + \frac{Y_W}{2}. \tag{2.23}$$

Just as Q generates the $U(1)_{em}$ symmetry, the weak hypercharge generates the $U(1)_Y$ symmetry as said before. It is possible to write the relationship in terms of the currents as

$$j_\mu^{em} = J_\mu^3 + \frac{1}{2} J_\mu^Y. \tag{2.24}$$

The neutral gauge fields W_μ^3 and B_μ cannot be directly identified with the Z and the photon fields since the photon interacts similarly with left and right-handed fermions; however, they are related through a linear combination given by

$$\begin{aligned} A_\mu =& B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \\ Z_\mu =& -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \end{aligned} \tag{2.25}$$

where θ_W is known as the “Weinberg angle.” The interaction Lagrangian is now given by

$$\mathcal{L}_I = -\frac{g}{\sqrt{2}}(J^\mu W_\mu^+ + J^{\mu\dagger} W_\mu^-) - \left(g\sin\theta_W J_\mu^3 + g'\cos\theta_W \frac{J_\mu^Y}{2}\right) A^\mu - \left(g\cos\theta_W J_\mu^3 - g'\sin\theta_W \frac{J_\mu^Y}{2}\right) Z^\mu \tag{2.26}$$

the first term is the weak charged current interaction, while the second term is the electromagnetic interaction under the condition

$$g\sin\theta_W = g'\cos\theta_W = e, \quad \frac{g'}{g} = tan\theta_W \tag{2.27}$$

contained in the eqn.2.24; the third term is the neutral weak current.

Note that the neutral fields transformation given by the eqn. 2.25 can be written in terms of the coupling constants g and g' as:

$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2+g'^2}}, \qquad Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2+g'^2}} \tag{2.28}$$

So far, the Lagrangian density describing the non-massive EWI is:

$$\mathcal{L}_{nmEWI} = \mathcal{L}_0 + \mathcal{L}_G \tag{2.29}$$

where fermion and gauge fields have been considered massless because their regular mass terms are manifestly non invariant under G transformations; therefore, masses have to be generated in a gauge invariant way. The mechanism by which this goal is achieved is known as the “Higss mechanism” and is closely connected to the concept of “spontaneous symmetry breaking.”

2.3.1 Spontaneous symmetry breaking (SSB)

Figure 2.6 left shows a steel nail (top) which is subject to an external force; the form of the potential energy is also shown (bottom).

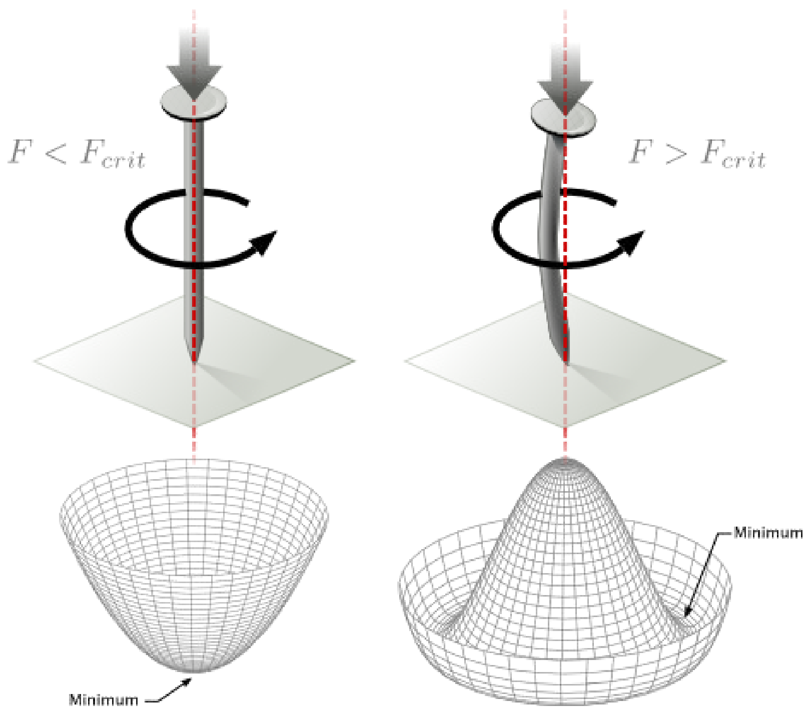

Figure 2.6: Spontaneous symmetry breaking mechanism. The steel nail, subject to an external force (top left), has rotational symmetry with respect to its axis. When the external force overcomes a critical value the nail buckles (top right) choosing a minimal energy state (ground state) and thus *"breaking spontoaneously the rotational symmetry"*. The potential energy (bottom) changes but holds the rotational symmetry; however, an infinite number of asymmetric ground states are generated and circularly distributed in the bottom of the potential [27].

Before reaching the critical force value, the system has rotational symmetry with respect to the nail axis; however, after the critical force value is reached the nail buckles (top right). The form of the potential energy (bottom right) changes, preserving its rotational symmetry although its minima does not exhibit that rotational symmetry any longer. Right before the nail buckles there is no indication of the direction the

nail will bend because any of the directions are equivalent, but once the nail bends, choosing a direction, an arbitrary minimal energy state (ground state) is selected and it does not share the system's rotational symmetry. This mechanism for reaching an asymmetric ground state is known as *"spontaneous symmetry breaking"*.
The lesson from this analysis is that the way to introduce the SSB mechanism into a system is by adding the appropriate potential to it.

Figure 2.7 shows a plot of the potential $V(\phi)$ in the case of a scalar field ϕ

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \tag{2.30}$$

If $\mu^2 > 0$ the potential has only one minimum at $\phi = 0$ and describes a scalar field with mass μ. If $\mu^2 < 0$ the potential has a local maximum at $\phi = 0$ and two minima at $\phi = \pm\sqrt{-\mu^2/\lambda}$ which enables the SSB mechanism to work.

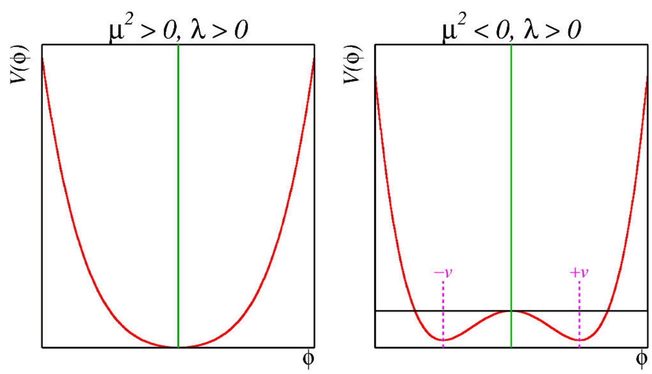

Figure 2.7: Shape of the potential $V(\phi)$ for $\lambda > 0$ and: $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The case $\mu^2 < 0$ corresponds to the potential suitable for introducing the SSB mechanism by choosing one of the two ground states which are connected via refletion symmetry. [27].

In the case of a complex scalar field $\phi(x)$

$$\phi(x) = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \tag{2.31}$$

the Lagrangian (invariant under global $U(1)$ transformations) is given by

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi), \qquad V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \tag{2.32}$$

where an appropiate potential has been added in order to introduce the SSB.

As seen in figure 2.8, the potential has now an infinite number of minima circularly distributed along the ξ-direction which makes possible the occurence of the SSB by choosing an arbitrary ground state; for instance, $\xi = 0$, i.e. $\phi_1 = v, \phi_2 = 0$

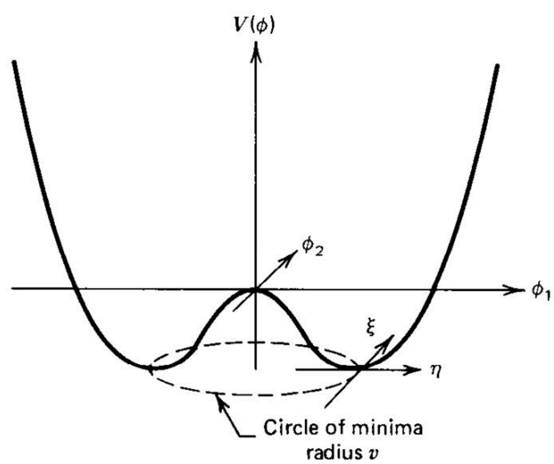

Figure 2.8: Potential for complex scalar field. There is a circle of minima of radius v along the ξ-direction [6].

$$\phi_0 = \frac{v}{\sqrt{2}} \exp(i\xi) \quad \xrightarrow{SSB} \quad \phi_0 = \frac{v}{\sqrt{2}} \tag{2.33}$$

As usual, excitations over the ground state are studied by making an expansion about it; thus, the excitation can be parametrized as:

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \eta(x) + i\xi(x)) \tag{2.34}$$

which when substituted into eqn. 2.32 produces a Lagrangian in terms of the new fields η and ξ

$$\mathcal{L}' = \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \mu^2\eta^2 - V(\phi_0) - \lambda v \eta(\eta^2 + \xi^2) - \frac{\lambda}{4}(\eta^2 + \xi^2)^2 \tag{2.35}$$

where the last two terms represent the interactions and self-interaction between the two fields η and ξ. The particular feature of the SSB mechanism is revealed when looking to the first three terms of $\mathcal{L}'$. Before the SSB, only the massless ϕ field is present in the system; after the SSB there are two fields of which the η-field has acquired mass $m_\eta = \sqrt{-2\mu^2}$ while the $\xi - field$ is still massless (see figure 2.9).

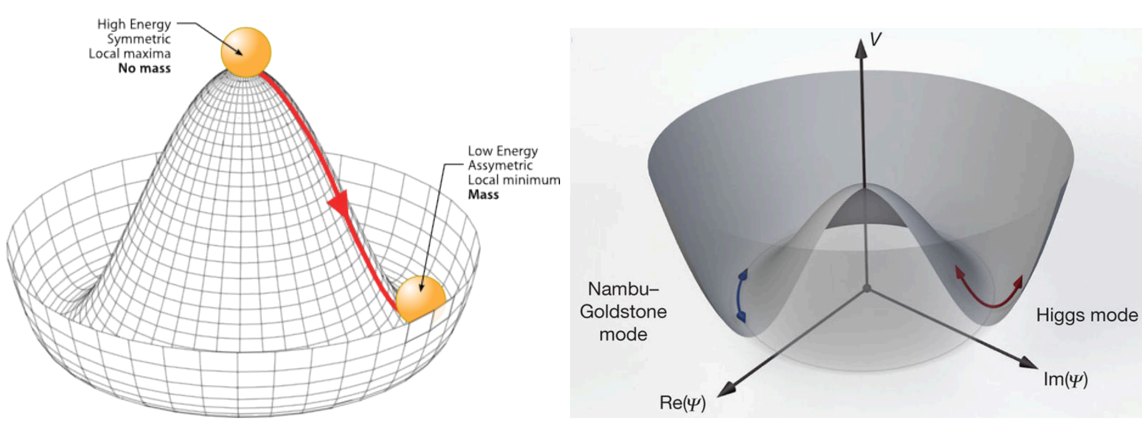

Figure 2.9: SSB mechanism for a complex scalar field [27, 28].

Thus, *the SSB mechanism serves as a method to generate mass but as a side effect a massless field is introduced in the system.* This fact is known as the Goldstone theorem and states that a massless scalar field appears in the system for each continuous symmetry spontaneously broken. Another version of the Goldstone theorem states that *"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 (Nambu-Goldstone bosons) as broken generators."* [26] The Nambu-Goldstone boson can be understood considering that the potential in the ξ-direction is flat so excitations in that direction are not energy consuming and thus represent a massless state.

2.3.2 Higgs mechanism

When the SSB mechanism is introduced in the formulation of the EWI in an attempt to generate the mass of the so far massless gauge bosons and fermions, an interesting effect is revealed. In order to keep the G symmetry group invariance and generate the mass of the EW gauge bosons, a G invariant Lagrangian density ($\mathcal{L}_S$) has to be added to the non massive EWI Lagrangian (eqn. 2.29)

$$\mathcal{L}_S = (D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2, \qquad \lambda > 0, \mu^2 < 0 \tag{2.36}$$

$$D_\mu\phi = \left(i\partial_\mu - g\frac{\sigma_i}{2}W_\mu^i - g'\frac{Y}{2}B_\mu\right)\phi \tag{2.37}$$

ϕ has to be an isospin doublet of complex scalar fields so it preserves the G invariance; thus ϕ can be defined as:

$$\phi = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix} \equiv \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}. \tag{2.38}$$

The minima of the potential are defined by

$$\phi^\dagger\phi = \frac{1}{2}(\phi_1^2+\phi_2^2+\phi_3^2+\phi_1^4) = -\frac{\mu^2}{2\lambda}. \tag{2.39}$$

The choice of the ground state is critical. By choosing a ground state, invariant under $U(1)_{em}$ gauge symmetry, the photon will remain massless and the $W^\pm$ and Z bosons masses will be generated which is exactly what is needed. In that sense, the best choice corresponds to a weak isospin doublet with $T_3 = -1/2$, $Y_W = 1$ and $Q = 0$ which defines a ground state with $\phi_1 = \phi_2 = \phi_4$ and $\phi_3 = v$:

$$\phi_0 \equiv \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \qquad v^2 \equiv -\frac{\mu^2}{\lambda}. \tag{2.40}$$

where the vacuum expectation value v is fixed by the Fermi coupling G_F according to $v = (\sqrt{2}G_F)^{1/2} \approx 246$ GeV.

The G symmetry has been broken and three Nambu-Goldstone bosons will appear. The next step is to expand ϕ about the chosen ground state as:

$$\phi(x) = \frac{1}{\sqrt{2}}\exp\left(\frac{i}{v}\sigma_i\theta^i(x)\right)\begin{pmatrix}0\\ v+H(x)\end{pmatrix} \approx \frac{1}{\sqrt{2}}\begin{pmatrix}\theta_1(x)+i\theta_2(x)\\ v+H(x)-i\theta_3(x)\end{pmatrix} \tag{2.41}$$

to describe fluctuations from the ground state ϕ_0. The fields $\theta_i(x)$ represent the Nambu-Goldstone bosons while $H(x)$ is known as “higgs field.” The fundamental feature of the parametrization used is that the dependence on the $\theta_i(x)$ fields is factored out in a global phase that can be eliminated by taking the physical “unitary gauge” $\theta_i(x) = 0$. Therefore the expansion about the ground state is given by:

$$\phi(x)\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H(x)\end{pmatrix} \tag{2.42}$$

which when substituted into $\mathcal{L}_S$ (eqn. 2.36) results in a Lagrangian containing the now massive three gauge bosons $W^{\pm}, Z$, one massless gauge boson (photon) and the new Higgs field (H). The three degrees of freedom corresponding to the Nambu-Goldstone bosons are now integrated into the massive gauge bosons as their longitudinal polarizations which were not available when they were massless particles. The effect by which vector boson fields acquire mass after an spontaneous symmetry breaking, but without an explicit gauge invariance breaking is known as the *"Higgs mechanism"*.

The mechanism was proposed by three independent groups: F.Englert and R.Brout in August 1964 [29], P.Higgs in October 1964 [30] and G.Guralnik, C.Hagen and T.Kibble in November 1964 [31]; however, its importance was not realized until S.Glashow [22], A.Salam [23] and S.Weinberg [24], independently, proposed that electromagnetic and weak interactions are two manifestations of a more general interaction called "electroweak interaction" in 1967.

2.3.3 Masses of the gauge bosons

The mass of the gauge bosons is extracted by evaluating the kinetic part of Lagrangian $\mathcal{L}_S$ in the ground state (known also as the vacuum expectation value), i.e.,

$$\left|\left(\partial_\mu - ig\frac{\sigma_i}{2}W^i_\mu - i\frac{g'}{2}B_\mu\right)\phi_0\right|^2 = \left(\frac{1}{2}vg\right)^2 W^+_\mu W^{-\mu} + \frac{1}{8}v^2(W^3_\mu, B_\mu)\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} \tag{2.43}$$

comparing with the typical mass term for a charged boson $M_W^2 W^+ W^-$

$$M_W = \frac{1}{2}vg. \tag{2.44}$$

The second term in the right side of the eqn.2.43 comprises the masses of the neutral bosons, but it needs to be written in terms of the gauge fields Z_μ and A_μ in order to be compared to the typical mass terms for neutral bosons, therefore using eqn. 2.28

$$\begin{aligned}\frac{1}{8}v^2[g^2(W_\mu^3)^2-2gg'W_\mu^3B^\mu+g'^2B_\mu^2] =& \frac{1}{8}v^2[gW_\mu^3-g'B_\mu]^2+0[g'W_\mu^3+gB_\mu]^2 \\ =& \frac{1}{8}v^2[\sqrt{g^2+g'^2}Z_\mu]^2+0[\sqrt{g^2+g'^2}A_\mu]^2\end{aligned} \tag{2.45}$$

and then

$$M_Z=\frac{1}{2}v\sqrt{g^2+g'^2}, \qquad M_A=0 \tag{2.46}$$

2.3.4 Masses of the fermions

The lepton mass terms can be generated by introducing a gauge invariant Lagrangian term describing the Yukawa coupling between the lepton field and the Higgs field

$$\mathcal{L}_{Yl}=-G_l\left[(\bar{\nu}_l,\bar{l})_L\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}l_R+\bar{l}_R(\phi^-,\bar{\phi}^0)\begin{pmatrix}\nu_l\\ l\end{pmatrix}_L\right], \qquad l=e,\mu,\tau. \tag{2.47}$$

After the SSB and replacing the usual field expansion about the ground state (eqn.2.40) into $\mathcal{L}_{Yl}$, the mass term arises

$$\mathcal{L}_{Yl}=-m_l(\bar{l}_Ll_R+\bar{l}_Rl_L)-\frac{m_l}{v}(\bar{l}_Ll_R+\bar{l}_Rl_L)H=-m_l\bar{l}l\left(1+\frac{H}{v}\right) \tag{2.48}$$

$$m_l=\frac{G_l}{\sqrt{2}}v \tag{2.49}$$

where the additional term represents the lepton-Higgs interaction. The quark masses are generated in a similar way as lepton masses but for the upper member of the quark doublet a different Higgs doublet is needed:

$$\phi_c = -i\sigma_2\phi* = \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix}. \tag{2.50}$$

Additionally, given that the quark isospin doublets are not constructed in terms of the mass eigenstates but in terms of the flavor eigenstates, as shown in table2.5, the coupling parameters will be related to the CKM matrix elements; thus the quark Lagrangian is given by:

$$\mathcal{L}_{Yq} = -G_d^{i,j}(\bar{u_i}, \bar{d'_i})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{jR} - G_u^{i,j}(\bar{u_i}, \bar{d'_i})_L \begin{pmatrix} -\bar{\phi}^0 \\ \phi^- \end{pmatrix} u_{jR} + h.c. \tag{2.51}$$

with i,j=1,2,3. After SSB and expansion about the ground state, tha diagonal form of $\mathcal{L}_{Yq}$ is:

$$\mathcal{L}_{Yq} = -m_d^i \bar{d}_i d_i \left(1 + \frac{H}{v}\right) - m_u^i \bar{u_i} u_i \left(1 + \frac{H}{v}\right) \tag{2.52}$$

Fermion masses depend on arbitrary couplings G_l and $G_{u,d}$ and are not predicted by the theory.

2.3.5 The Higgs field

After the characterization of the fermions and gauge bosons as well as their interactions, it is necessary to characterize the Higgs field itself. The Lagrangian $\mathcal{L}_S$ in eqn. 2.36 written in terms of the gauge bosons is given by

$$\mathcal{L}_S = \frac{1}{4}\lambda v^4 + \mathcal{L}_H + \mathcal{L}_{HV} \tag{2.53}$$

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}m_H^2 H^2 - \frac{1}{2v}m_H^2 H^3 - \frac{1}{8v^2}m_H^2 H^4 \tag{2.54}$$

$$\mathcal{L}_{HV} = m_H^2 W_\mu^+ W^{\mu-}\left(1 + \frac{2}{v}H + \frac{2}{v^2}H^2\right) + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \left(1 + \frac{2}{v}H + \frac{2}{v^2}H^2\right) \tag{2.55}$$

The mass of the Higgs boson is deduced as usual from the mass term in the Lagrangian resulting in:

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v \tag{2.56}$$

however, it is not predicted by the theory either. The experimental efforts to find the Higgs boson, carried out by the "Compact Muon Solenoid (CMS)" experiment and the "A Toroidal LHC AppartuS (ATLAS)" experiments at the "Large Hadron Collider(LHC)", gave great results by July of 2012 when the discovery of a new particle compatible with the Higgs boson predicted by the electroweak theory [32, 33] was announced. Although at the announcement time there were some reservations about calling the new particle the "Higgs boson", today this name is widely accepted. The Higgs mass measurement, reported by both experiments [34], is in table 2.8.

Property	Value
Electric charge	0
Colour charge	0
Spin	0
Weak isospin	-1/2
Weak hypercharge	1
Parity	1
Mass (GeV/c^2)	125.09$\pm$0.21 (stat.)$\pm$0.11 (syst.)

Table 2.8: Higgs boson properties. Higgs mass is not predicted by the theory and the value here corresponds to the experimental measurement.

2.3.6 Production of Higgs bosons at LHC

At LHC, Higgs boson is produced as a result of the collision of two counter-rotating protons beams. A detailled description of the LHC machine will be presented in chapter **??**. "The total cross section" is a parameter that quantifies the number of pp collisions that happen when a number of protons are fired at each other. Different results can be obtained after a pp collision and for each one the "cross section" is defined as the number of pp collisions that conclude in that particular result with respect to the number of protons fired at each other.

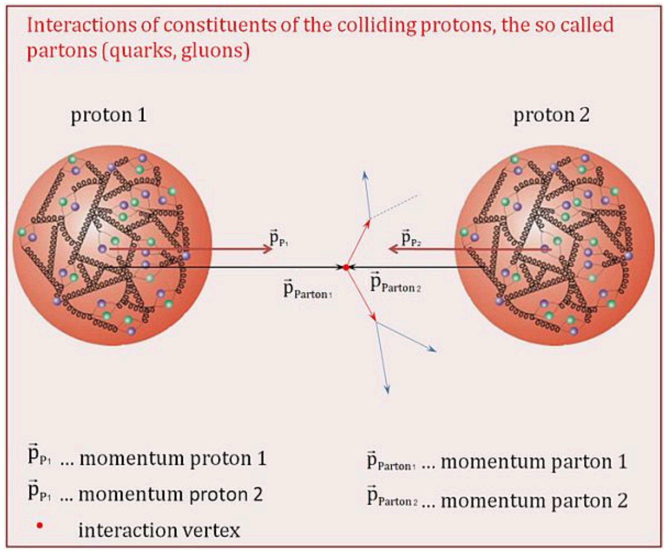

Figure 2.10: Proton-proton collision. Protons are composed of 3 valence quarks, a sea of quarks and gluons; therefore in a proton-proton collision, quarks and gluons are those who collide. [35].

Protons are composed of quarks and these quarks are bound by gluons; however, what is commonly called the quark content of the proton makes reference to the valence quarks. A sea of quarks and gluons is also present inside the proton as represented in figure 2.10. In a proton-proton (pp) collision, the constituents (quarks and gluons) are those who collide. The pp cross section depends on the momentum of the colliding particles, reason for which it is needed to know how the momentum is distributed inside the proton. Quarks and gluons are known as partons and the functions that describe how the proton momentum is distributed among partons inside it are called "parton distribution functions (PDFs)"; PDFs are determined from experimental data obtanied in experiments where the internal structure of hadrons is tested.

In addition, in physics, a common approach to study complex systems consists in starting with a simpler version of them, for which a well known description is available, and add an additional “perturbation” which represents a small deviation from the known behavior. If the perturbation is small enough, the physical quanties associated with the perturbed system are expressed as a series of corrections to those of the simpler system; therefore, the more terms are considered in the series (the higher order in the perturbation series), the more precise is the the description of the complex system.

This thesis explores the Higgs production at LHC; therefore the overview presented here will be oriented specifically to the production mechanisms after pp collisions at LHC.

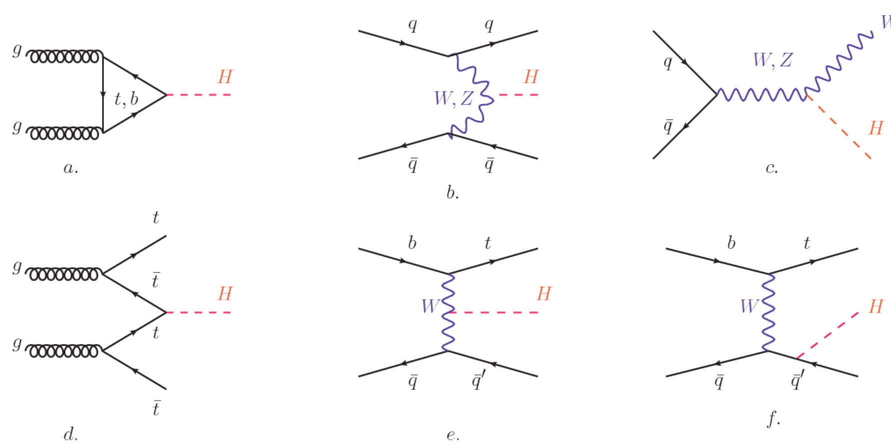

Figure 2.11: Main Higgs boson production mechanism Feynman diagrams. a. gluon-gluon fusion, b. vector boson fusion (VBF), c. Higgs-strahlung, d. Associated production with a top or bottom quark pair, e-f. associated production with a single top quark.

Figure 2.11 shows the Feynman diagrams for the leading order (first order) Higgs production processes at LHC, while the cross section for Higgs production as a function of the center of mass-energy ($\sqrt{s}$) for pp collisions is showed in figure 2.12 left. The tags NLO (next to leading order), NNLO (next to next to leading order) and N3LO (next to next to next to leading order) make reference to the order at which the pertubation series have been considered.

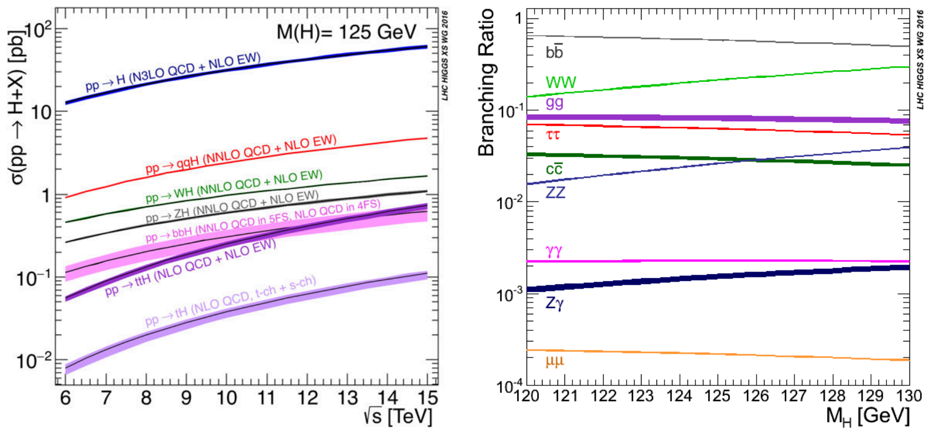

Figure 2.12: Higgs boson production cross sections (left) and decay branching ratios (right) for the main mechanisms. The VBF is indicated as qqH [36].

As shown in eqns 2.47, 2.51 and 2.55, the strength of the Higgs-fermion interaction is proportional to the fermion mass while the strength of the Higgs-gauge boson interaction is proportional to the square of the gauge boson mass, which implies that the Higgs production and decay mechanisms are dominated by couplings $H-(W,Z,t,b,\tau)$.

The main production mechanism is the gluon fusion (figure 2.11a and $pp \to H$ in figure 2.12) given that gluons carry the highest fraction of momentum of the protons in pp colliders. Since the Higgs boson does not couple to gluons, the mechanism proceeds through the exchange of a virtual top-quark loop given that for it the coupling is the biggest. Note that in this process, the Higgs boson is produced alone, which makes this mechanism experimentally clean when combined with the two-photon or the four-lepton decay channels (see section 2.3.7).

Vector boson fusion (figure 2.11b and $pp \to qqH$ in figure 2.12) has the second largest production cross section. The scattering of two fermions is mediated by a weak gauge boson which later emits a Higgs boson. In the final state, the two fermions tend to be located in a particular region of the detector which is used as a signature when analyzing the datasets provided by the experiments. More details about how to identify events of interest in an analysis will be given in chapter **??**.

The next production mechanism is Higgs-strahlung (figure 2.11c and $pp \to WH, pp \to ZH$ in figure 2.12) where two fermions annihilate to form a weak gauge boson. If the initial fermions have enough energy, the emergent boson eventually will emit a Higgs boson.

The associated production with a top or bottom quark pair and the associated production with a single top quark (figure 2.11d-f and $pp \to bbH, pp \to t\bar{t}H, pp \to tH$ in figure 2.12) have a smaller cross section than the main three mechanisms above, but they provide a good opportunity to test the Higgs-top coupling. The analysis reported in this thesis is developed using these production mechanisms. A detailed description of the tH mechanism will be given in section 2.4.

2.3.7 Higgs boson decay channels

When a particle can decay throught several modes, also known as channels, the probability of decaying throught a given channel is quantified by the "branching ratio (BR)" of the decay channel; thus, the BR is defined as the ratio of number of decays going throught that given channel to the total number of decays. In regard to the Higgs boson decay, the BR can be predicted with accuracy once the Higgs mass is known [37, 38]. In figure 2.12 right, a plot of the BR as a function of the Higgs mass is presented. The largest predicted BR corresponds to the $b\bar{b}$ pair decay channel (see table 2.9).

Decay channel	Branching ratio	Rel. uncertainty
$H \to b\bar{b}$	$5.84 \times 10^{-}1$	$+3.2\% - 3.3\%$
$H \to W^{+}W^{-}$	$2.14 \times 10^{-}1$	$+4.3\% - 4.2\%$
$H \to \tau^{+}\tau^{-}$	$6.27 \times 10^{-}2$	$+5.7\% - 5.7\%$
$H \to ZZ$	$2.62 \times 10^{-}2$	$+4.3\% - 4.1\%$
$H \to \gamma\gamma$	$2.27 \times 10^{-}3$	$+5.0\% - 4.9\%$
$H \to Z\gamma$	$1.53 \times 10^{-}3$	$+9.0\% - 8.9\%$
$H \to \mu^{+}\mu^{-}$	$2.18 \times 10^{-}4$	$+6.0\% - 5.9\%$

Table 2.9: Predicted branching ratios and the relative uncertainty for a SM Higgs boson with $m_H = 125GeV/c^2$. [9]

2.4 Associated production of a Higgs boson and a single Top quark.

Associated production of Higgs boson has been extensively studied [39–43]. While measurements of the main Higgs production mechanisms rates are sensitive to the strength of the Higgs coupling to W boson or top quark, they are not sensitive to the relative sign between the two couplings. In this thesis, the Higgs boson production mechanism explored is the associated production with a single top quark (th) which offers sensitiveness to the relative sign of the Higgs couplings to W boson and to top quark. The description given here is based on the reference [41]

A process where two incoming particles interact and produce a final state with two particles can proceed in three ways also called channels (see, for instance, figure 2.13 ommiting the red line). The t-channel represents processes where an intermediate particle is emited by one of the incoming particles and absorbed by the other. The s-channel represents processes where the two incoming particles merge into an intermediate particle which eventually will split into the particles in the final state. The third channel, u-channel, is similar to the t-channel but the two outgoing particles

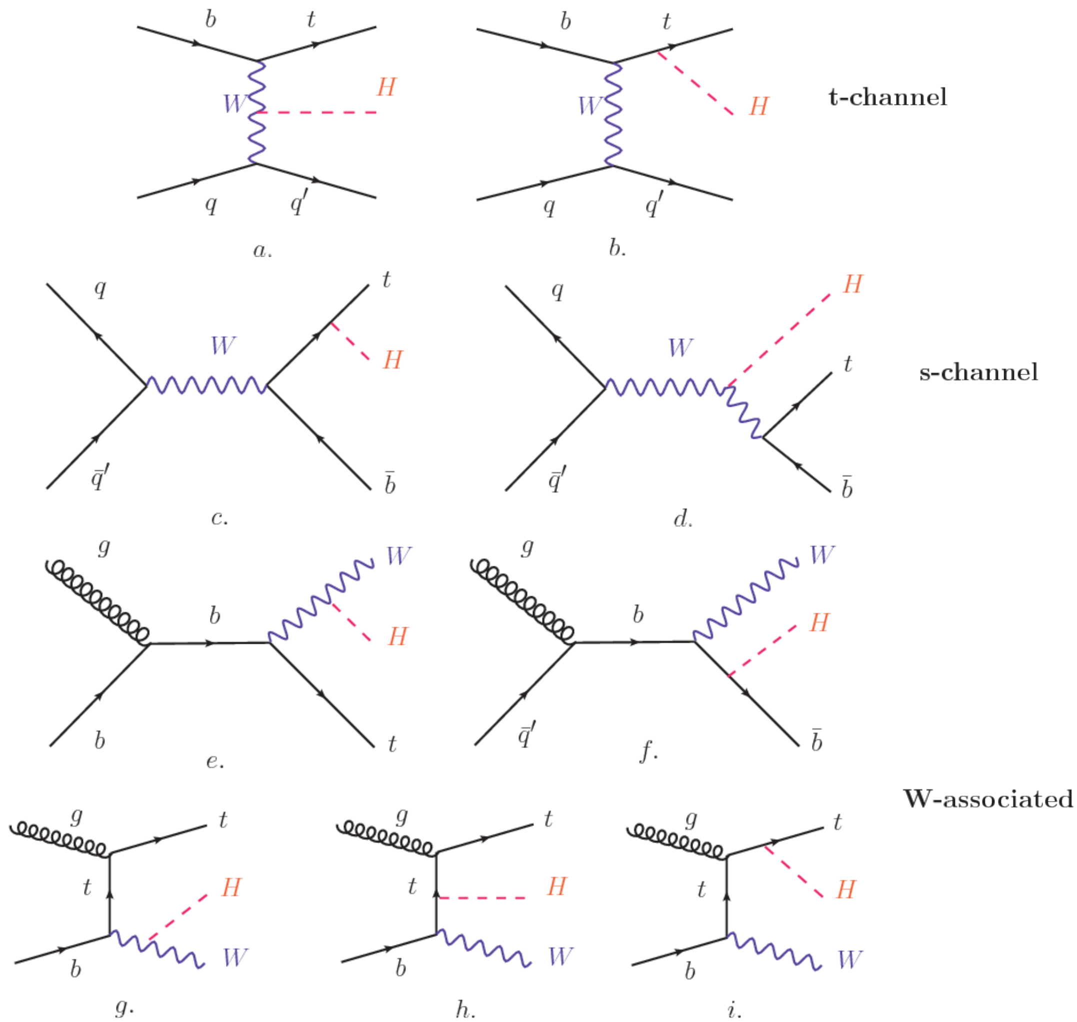

Figure 2.13: Associated Higgs boson production mechanism Feynman diagrams. a.,b. t-channel (tHq), c.,d. s-channel (tHb), e-i. W-associated.

interchange their roles.

The *th* production, where Higgs boson can be radiated either from the top quark or from the W boson, is represented by the leading order Feynman diagrams in figure 2.13. The cross section for the *th* process is calculated, as usual, summing over the contributions from the different feynman diagrams; therefore it depends on the interference between the contributions. In the SM, the interference for t-channel (tHq process) and W-associated (tHW process) production is destructive [39] resulting in the small cross sections presented in table 2.10.

tH production channel	Cross section (fb)
t-channel ($pp \to tHq$)	$70.79^{+2.99}_{-4.80}$
W-associated ($pp \to tHW$)	$15.61^{+0.83}_{-1.04}$
s-channel($pp \to tHb$)	$2.87^{+0.09}_{-0.08}$

Table 2.10: Predicted SM cross sections for tH production at $\sqrt{s} = 13$ TeV [44, 45].

While the s-channel contribution can be neglected, it will be shown that a deviation from the SM destructive interference would result in an enhancement of the th cross section compared to that in SM, which could be used to get information about the sign of the Higgs-top coupling [41, 42]. In order to describe th production processes, Feynman diagram 2.13b will be considered; there, the W boson is radiated by a quark in the proton and eventually it will interact with the b quark. In the high energy regime, the effective W approximation [46] allows to describe the process as the emmision of an approximately on-shell W and its hard scattering with the b quark; i.e. $Wb \to th$. The scattering amplitude for the process is given by

$$\mathcal{A} = \frac{g}{\sqrt{2}} \left[(\kappa_t - \kappa_V) \frac{m_t \sqrt{s}}{m_W v} A\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) + \left(\kappa_V \frac{2m_W}{v} \frac{s}{t} + (2\kappa_t - \kappa_V) \frac{m_t^2}{m_W v} \right) B\left(\frac{t}{s}, \varphi; \xi_t, \xi_b\right) \right], \tag{2.57}$$

where $\kappa_V \equiv g_{HVV}/g_{HVV}^{SM}$ and $\kappa_t \equiv g_{Ht}/g_{Ht}^{SM} = y_t/y_t^{SM}$ are scaling factors that quantify possible deviations of the couplings, Higgs-Vector boson (H-W) and Higgs-top (H-t) respectively, from the SM couplings; $s = (p_W + p_b)^2$, $t = (p_W - p_H)^2$, φ is the Higgs azimuthal angle around the z axis taken parallel to the direction of motion of the incoming W; A and B are funtions describing the weak interaction in terms of the chiral states of the quarks b and t. Terms that vanish in the high energy limit have been neglected as well as the Higgs and b quark masses[8].

The scattering amplitude grows with energy like $\sqrt{s}$ for $\kappa_V \neq \kappa_t$, in contrast to the SM ($\kappa_t = \kappa_V = 1$), where the first term in 2.57 cancels out and the amplitude is constant for large s; therefore, a deviation from the SM predictions represents an enhancement in the tHq cross section. In particular, for a SM H-W coupling and a H-t coupling of inverted sigh with respect to the SM ($\kappa_V = -\kappa_t = 1$) the tHq cross section is enhanced by a factor greater 10 as seen in the figure 2.14 taken from reference [41]; reference [47] has reported similar enhancement results.

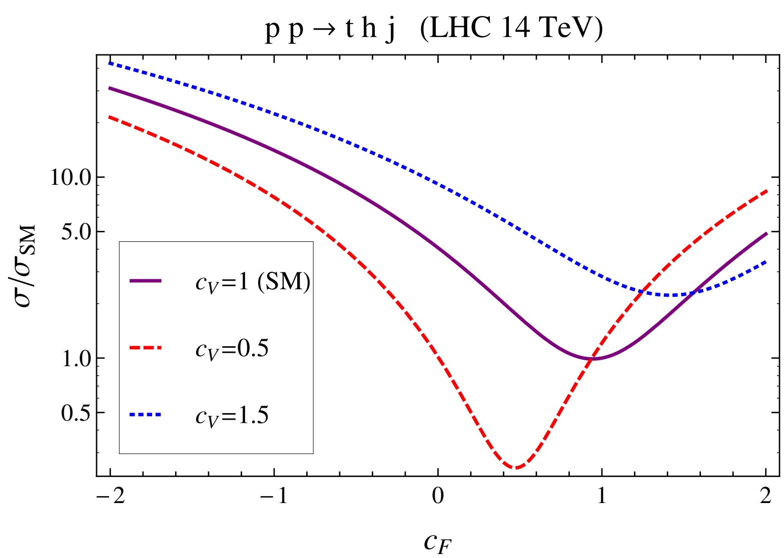

Figure 2.14: Cross section for tHq process as a function of κ_t, normalized to the SM, for three values of κ_V. In the plot c_f refers to the Higgs-fermion coupling which is dominated by the H-t coupling and represented here by κ_t. Solid, dashed and dotted lines correspond to $c_V \to \kappa_V = 1, 0.5, 1.5$ respectively. Note that for the SM ($\kappa_V = \kappa_t = 1$), the destructive effect of the interference is maximal.

A similar analysis is valid for the W-associated channel but, in that case, the interference is more complicated since there are more than two contributions and an ad-

[8] A detailed explanation of the structure and approximations used to derive $\mathcal{A}$ can be found in reference [41]

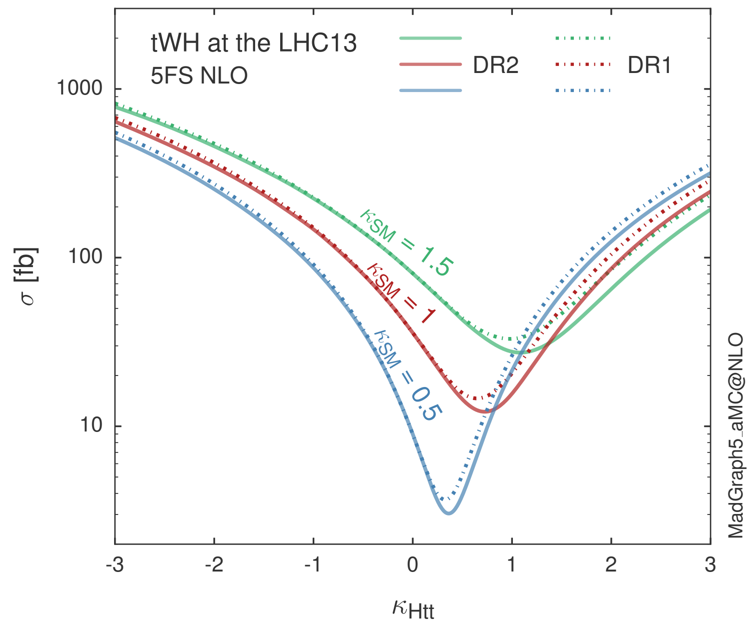

Figure 2.15: Cross section for tHW process as a function of κ_{Htt}, for three values of κ_{SM} at $\sqrt{s} = 13$ TeV. $\kappa_{Htt}^2 = \sigma_{Htt}/\sigma_{Htt}^{SM}$ is a simple rescaling of the SM Higgs interactions.

ditional interference with the production of Higgs boson and a top pair process($t\bar{t}H$). The calculations are made using the so-called Diagram Removal (DR) technique where interfering diagrams are removed (or added) from the calculations in order to evaluate the impact of the removed contributions. DR1 was defined to neglect $t\bar{t}H$ interference while DR2 was defined to take $t\bar{t}H$ interference into account [48]. As shown in figure 2.15, the tHW cross section is enhanced from about 15 fb (SM: $\kappa_{Htt} = 1$) to about 150 fb ($\kappa_{Htt} = -1$). Differences between curves for DR1 and DR2 help to gauge the impact of the interference with $t\bar{t}H$.

Results of the calculations of the tHq and tHW cross sections at $\sqrt{s} = 13$ TeV can be found in reference [49] and a summary of the results is presented in table 2.11.

	$\sqrt{s}$ TeV	$\kappa_t = 1$	$\kappa_t = -1$
$\sigma^{LO}(tHq)$(fb) [41]	8	≈ 17.4	≈ 252.7
	14	≈ 80.4	≈ 1042
$\sigma^{NLO}(tHq)$(fb) [41]	8	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.0}$
	14	$88.2^{+1.7}_{-0.0}$	$982.8^{+28}_{-0.0}$
$\sigma^{LO}(tHq)$(fb) [47]	14	≈ 71.8	≈ 893
$\sigma^{LO}(tHW)$(fb) [47]	14	≈ 16.0	≈ 139
$\sigma^{NLO}(tHq)$(fb) [49]	8	$18.69^{+8.62\%}_{-17.13\%}$	-
	13	$74.25^{+7.48\%}_{-15.35\%}$	$848^{+7.37\%}_{-13.70\%}$
	14	$90.10^{+7.34\%}_{-15.13\%}$	$1011^{+7.24\%}_{-13.39\%}$
$\sigma^{LO}(tHW)$(fb) [48]	13	$15.77^{+15.91\%}_{-15.76\%}$	-
$\sigma^{NLO}DR1(tHW)$(fb) [48]	13	$21.72^{+6.52\%}_{-5.24\%}$	≈ 150
$\sigma^{NLO}DR2(tHW)$(fb) [48]	13	$16.28^{+7.34\%}_{-15.13\%}$	≈ 150

Table 2.11: Predicted enhancement of the tHq and tHWcross sections at LHC for $\kappa_V = 1$ and $\kappa_t = \pm 1$ at LO and NLO; the cross section enhancement of more that a factor of 10 is due to the flippling in the sign of the H-t coupling with respect to the SM one.

2.5 The CP-mixing in tH processes

In addition to the sensitivity to sign of the H-t coupling, tHq and tHWprocesses have been proposed as a tool to investigate the possibility of a H-t coupling that does not conserve CP [43, 48, 50]. Current experimental results are consistent with SM H-V and H-t couplings; however, negative H-t coupling is not excluded completely [52].

In this thesis, the sensitivity of th processes to CP-mixing is also studied in the effective field theory framework and based in references [43, 48]; a generic particle (X_0) of spin-0 and a general CP violating interaction with the top quark, can couple to scalar and pseudoscalar fermionic densities. The H-W interaction is assumed to be SM-like. The Lagrangian modeling the H-t interaction is given by

$$\mathcal{L}_0^t = -\bar{\psi}_t \left(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5\right) \psi_t X_0, \tag{2.58}$$

where α is the CP-mixing phase, $c_\alpha \equiv \cos\alpha$ and $s_\alpha \equiv \sin\alpha$, κ_{Htt} and κ_{Att} are real dimensionless rescaling parameters[9], $g_{Htt} = g_{Att} = m_t/v = y_t/\sqrt{2}$ and $v \sim 246$ GeV is the Higgs vacuum expectation value. In this parametrization, it is easy to recover three special cases

- CP-even coupling $\rightarrow \alpha = 0^o$
- CP-odd coupling $\rightarrow \alpha = 90^o$
- SM coupling $\rightarrow \alpha = 0^o$ and $\kappa_{Htt} = 1$

The loop induced X_0 coupling to gluons can also be described in terms of the parametrization above, according to

$$\mathcal{L}_0^g = -\frac{1}{4}\left(c_\alpha \kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\right) X_0. \tag{2.59}$$

where $g_{Hgg} = -\alpha_s/3\pi v$ and $g_{Agg} = \alpha_s/2\pi v$. Under the assumption that the top quark dominates the gluon-fusion process at LHC energies, $\kappa_{Hgg} \rightarrow \kappa_{Htt}$ and $\kappa_{Agg} \rightarrow \kappa_{Att}$, so that the ratio between the gloun-gluon fusion cross section for X_0 and for the SM Higgs prediction can be written as

$$\frac{\sigma^{gg\rightarrow X_0}_{NLO}}{\sigma^{gg\rightarrow H}_{NLO,SM}} = c^2_\alpha \kappa^2_{Htt} + s^2_\alpha \left(\kappa_{Att} \frac{g_{Agg}}{g_{Hgg}}\right)^2. \tag{2.60}$$

If the rescaling parameters are set to

$$\kappa_{Htt} = 1, \qquad \kappa_{Att} = \left|\frac{g_{Hgg}}{g_{Agg}}\right| = \frac{2}{3}. \tag{2.61}$$

the gluon-fusion SM cross section is reproduced for every value of the CP-mixing angle α; therefore, by imposing that condition to the Lagrangian density 2.58, the

[9] analog to κ_t and κ_V

CP-mixing angle is not constrained by current data. Figure 2.16 shows the NLO cross sections for t-channel tX_0(blue) and $t\bar{t}X_0$ (red) associated production processses as a function of the CP-mixing angle α. X_0 is a generic spin-0 particle with top quark CP-violating coupling. Rescaling factors κ_{Htt} and κ_{Att} have been set to reproduce the SM gluon-fusion cross sections.

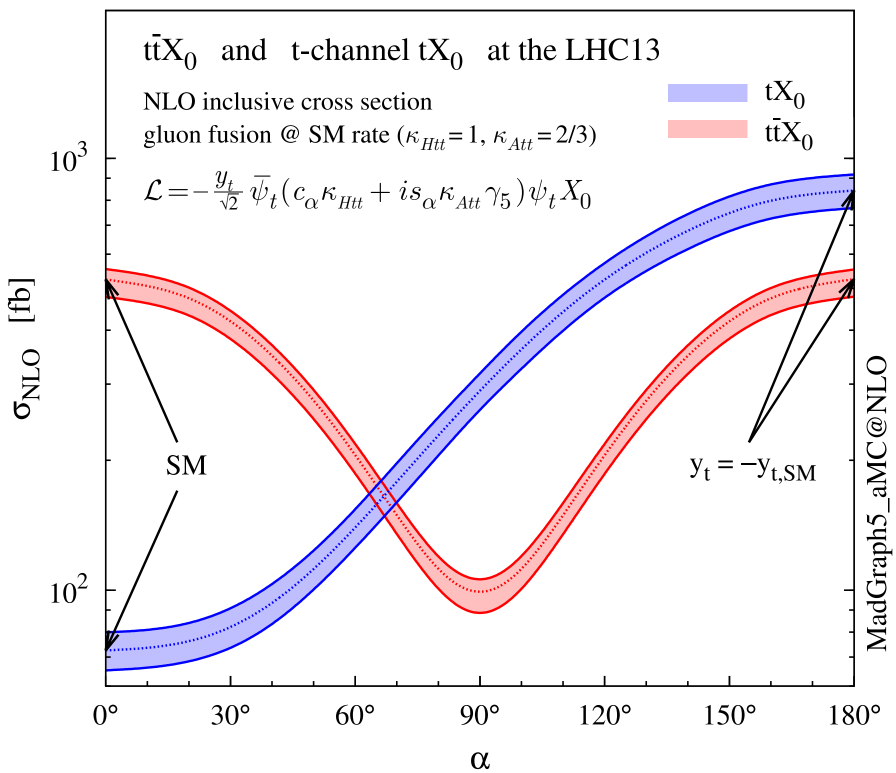

Figure 2.16: NLO cross sections for t-channel tX_0(blue) and $t\bar{t}X_0$ (red) associated production processses as a function of the CP-mixing angle α. X_0 is a generic spin-0 particle with top quark CP-violating coupling [43].

It is interesting to notice that the tX_0 croos section is enhanced, by a factor of about 10, when a continuous rotation in the scalar-pseudoscalar plane is applied; this enhancement is similar to the enhancement produced when the H-t coupling is flipped in sign with respect to the SM ($y_t = -y_{t,SM}$ in the plot), as showed in section 2.4. In contrast, the degeneracy in the $t\bar{t}X_0$ cross section is still present given that it depends quadratically on the H-t coupling, but more instersting is to notice that $t\bar{t}X_0$ cross section is exceeded by tX_0 cross section after $\alpha \sim 60^o$.

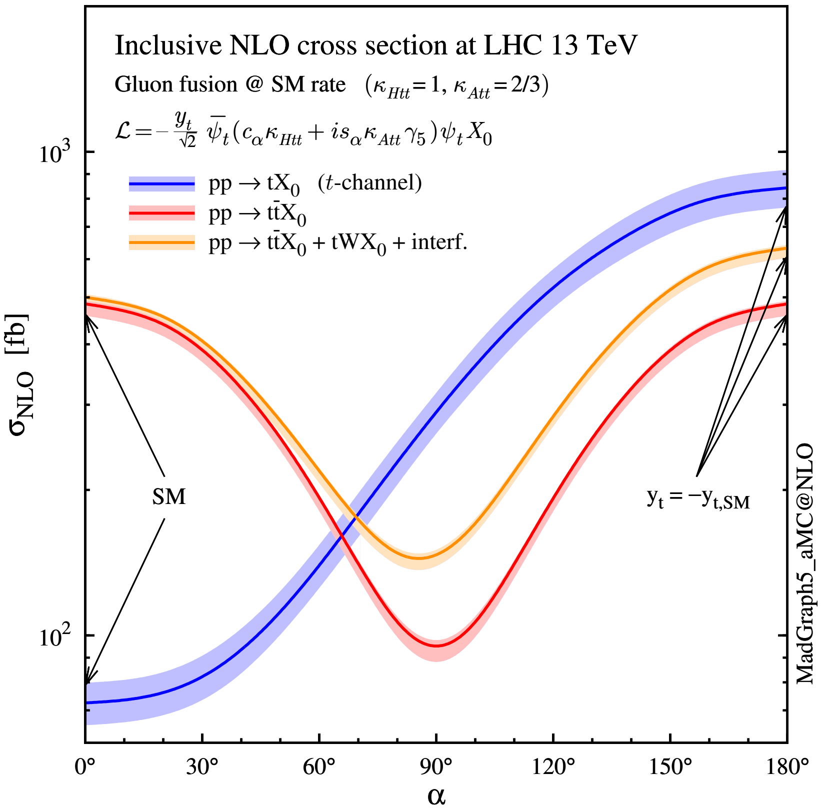

Figure 2.17: NLO cross sections for t-channel tX_0(blue), $t\bar{t}X_0$ (red) associated production processses and combined $tWX_0 + t\bar{t}X_0$ (including interference) production as a function of the CP-mixing angle α [43].

A similar parametrization can be used to investigate the tHW process sensitivity to CP-violating H-t coupling. As said in 2.4, the interference in the W-associated channel is more complicated because there are more than two contributions and also there is interference with the $t\bar{t}H$ production process.

Figure 2.17 shows the NLO cross sections for t-channel tX_0(blue), $t\bar{t}X_0$ (red) associated production and for the combined $tWX_0 + t\bar{t}X_0+$ interference (orange) as a function of the CP-mixing angle. It is clear that the effect of the interference in the combined case is the lifting of the degeneracy present in the $t\bar{t}X_0$ production. The constructive interference enhances the cross section from about 500 fb at SM ($\alpha = 0$) to about 600 fb ($\alpha = 180^o \to y_t = -y_{t,SM}$).

An analysis combining tHq and tHWprocesses will be made in this thesis taking advantage of the sensitivity improvement.

2.6 Experimantal status of the anomalous Higg-fermion coupling.

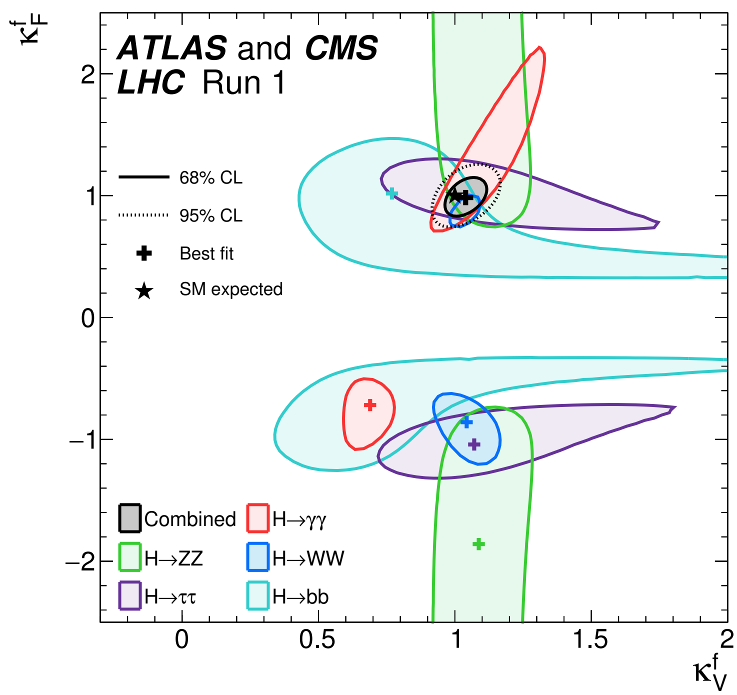

Figure 2.18: Combination of the ATLAS and CMS fits for coupling modifiers κ_t-κ_V; also shown the individual decay channels combination and their global combination. No assumptions have been made on the sign of the coupling modifiers [52].

ATLAS and CMS have performed analysis of the anomalous H-f coupling by making likelihood scans for the two coupling modifiers, κ_t and κ_V, under the assumption that

$\kappa_Z = \kappa_W = \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b = \kappa_f$. Figure2.18 shows the result of the combination of ATLAS and CMS fits; also the individual decay channels combination and the global combination results are shown.

While all the channels are compatible for positive values of the modifiers, for negative values of κ_t there is no compatibility. The best fit for individual channels is compatible with negative values of κ_t except for the $H \to bb$ channel which is expected to be the most sensitive channel; therefore, the best fit for the global fit yields $\kappa_t \geq 0$. Thus, the anomaluos H-t coupling cannot be excluded completely.

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