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Search for the FCNC decay of top-quark in c-quark and Z boson using the ATLAS detector

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Merci, merci, merci.

Abstract

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Contents

Introduction

CHAPTER 1

The theory framework

The construction of the Standard Model is the result of a long series of experiments and brilliant ideas in both theoretical and experimental fields. Towards the end of the 1960s, knowledge of what we consider to be the constituents elements of nature and the fundamental interactions among them, it was organized in the so-called Standard Model (MS), which aims to be a "theory of everything".
More recently, the only missing piece towards the completion of the SM, the Higgs boson, was discovered by the ATLAS and CMS collaborations.
The ambition is to find a theoretical representation of all phenomena experimentally accessible.
Since particle physics is characterized by phenomena that are both relativistic than quantum, the description of the Standard Model relies on the formalism of *Quantum Field Theories* (QFT), synthesis of quantum mechanical theory and relativistic. In these terms, the concept of field is associated both to material particles and to forces. Particles are mere manifestations of field: they are identified with the quanta of the material fields and force fields and the interaction among particles is determined by the exchange of virtual quanta of the field.
To search for extensions of the SM is possible postulate a scale of new physics high enough such that it will manifest itself through deviations of known observable, usually at high energies.
In this chapter, a concise description of the SM will be presented, from the gauge principle to the description of several theories for physics beyond the Standard Model which are crucial for the search of FCNC decay of top quark.

1.1 The gauge principle in quantum field theory

The mathematical framework of the SM is based on a quantum field theory description of the particles and their interactions. The interaction is a consequence of the invariance of physics under certain general symmetries: these invariances are called *gauge* because there is freedom in the choice of a certain number of parameters that can precisely "calibrate" the model. Each symmetry is therefore associated with a set of transformations that frame the "gauge group of the theory". The theory is introduced starting from the Lagrangian formalism developed in the classical mechanism, extending this formalism to classical field theory and finally to quantum field theory.

Lagrangian is defined as the difference between the kinetic energy and the potential energy of the system, as below:

$$\mathcal{L}(q, \dot{q}) = \frac{m}{2}(\dot{q})^2 - V(q) \tag{1.1}$$

and the *action* is defined as $S = \int dt \mathcal{L}(q, \dot{q})$.

Using a variational approch it can be shown that for any possible variation of the path of the particle, $\partial(q)$, the equation of motion of the system is the one that minimizes the *action*. The results are the so called *Euler-Lagrange* equations:

$$\frac{\mathcal{L}}{\partial q} - \frac{\partial}{\partial t}\frac{\mathcal{L}}{\partial \dot{q}} \tag{1.2}$$

The next step is the extension of the classical mechanics formalism to field theory. One possible way is to generalize the path of a particle which is a function of time $q(t)$, into a function of space-time coordinates $\phi(x)$ which is the vectorial (or tensorial) representation of the field with Lorentz invariance properties of the space-time.
The sub-set of dimension two vectorial representations used in particle physics is called spinors and they are divided into left-handed and right-handed, depending on their chirality: ψ_L and ψ_R. The usual representation for Lorentz and parity transformations is the *Dirac* spinor $\Psi = (\psi_L, \psi_R)$, which allows to describe properly the dynamics of relativistic particles.

At this point, the Lorentz-invariant Lagrangian is the following:

$$\mathcal{L}_D = \bar{\Psi}(i\gamma^\mu \partial\mu - m)\Psi \tag{1.3}$$

where γ are an extension of the Pauli matrices into a four dimension space-time and they are called Dirac matrices.

The QFT is also built on the *Noether*'s theorem that relates symmetries of the system to conserved observables.

Through this theorem, symmetries become a fundamental building block of the physical theory. A particular set of transformations, called gauge transformations, which by construction leave invariant the Lagrangian of the SM, constitute a building principle of the SM itself.

Let us now consider the global $U(1)$[1] transformation of the form:

$$\Psi \to e^{i\theta}\Psi \tag{1.4}$$

It can be easily demonstrate that $\mathcal{L}_D$ is invariant under such a transformation and the related conserved observable is the current $\bar{\Psi}\mu\Psi$.
However, the Lagrangian is no longer invariant under the transformation: $\theta \to \theta(x)$ which means that the gauge invariance is required in each point of the space-time.
The inclusion of an additional field, the photon, which mediates the forces, make the Lagrangian explicitly invariant and it allows to choose a *gauge* of the theory, in fact the action of free electromagnetic field is invariant under $A_\mu \to A_\mu - \partial\theta$, with A_μ being the four-vector of the electrostatic and magnetic potential: $(V, \vec{A})$.

The above example is useful to understand how the SM is constructed. It is a gauge theory which, analogously to what described in this section, is invariant under:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \tag{1.5}$$

The $SU(3)_c$ describes the strong force (see next section) while $SU(2)_L \otimes U(1)_Y$ term describes the electro-weak sector (see section 1.1.2) . A more detailed discussions follows.

1.1.1 Quantum Chromodynamics

The strong interaction between quark and gluons is described by the *Quantum Chromodynamics* (QCD). It is a gauge theory based on non-abelian $SU(3)_c$[2] and associated to the three color charges (red, green and blue). A total number of 8 generators T^a of the group, also called Gell-Mann matrices, represent bosons mediating the force, called *gluons*. They are massless, in contrast with the weak mediators.

The QCD Lagrangian, can be expressed as:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a \tag{1.6}$$

[1] U(1) is the one-dimensional unitary group, i.e. any of its elements can be expressed as a 1×1 matrix whose inverse is equal to its transpose conjugate ($U^{-1} = \bar{U}^*$).

[2] S stands for "special", meaning that the group matrices have determinant 1. C stands for "colour", which is the conserved quantity associated with the symmetry

where the index a represent the 8 $SU(3)_C$ generators, $\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$ is the kinetic term of the gluons (G^a is the gluon field strength tensor) and the covariant derivative D_μ is defined as

$$D_\mu = \partial_\mu - ig_s T_a G^a_\mu \tag{1.7}$$

The coupling constant α_s ($\frac{g_s^2}{4\pi} \sim 1$), is dependent from the transferred momentum Q^2 that correspond to a dependence from the separation between quarks:

$$\alpha_s(Q^2) = \frac{33 - 2n_f}{12\pi} \ln\left(\frac{Q^2}{\Lambda^2_{QCD}}\right) \tag{1.8}$$

where n_f is the number of quark flavors and Λ^2_{QCD} is the QCD scale parameter, measured to be $\sim$ 200 MeV that sets the scale between different regimes of the theory.
In fact one can discern two cases:

$$\alpha_s(Q^2) \xrightarrow[Q^2 \gg \Lambda^2_{QCD}]{} 0$$

$$\alpha_s(Q^2) \xrightarrow[Q^2 \ll \Lambda^2_{QCD}]{} \infty$$

In the first case, the quark coupling is asymptotically cancelled, in the limit $Q^2 \to \infty$, quarks can be considered as free particles and this phenomena calls *Asymptotic Freedom*. On the contrary, when the separation become relevant, the coupling is so strong to confine quarks in hadronic structures and this different phenomena calls *Confinement*
The only states that occur are completely antisymmetric in the color variables (the color singlets), which is equivalent to saying that the possible compositions of quarks must be "white".
Interaction between particles, that carry charges of color, takes place through the exchange of gluons of the octet, therefore, not only between quarks and gluons but also between gluons and gluons. This is a very important difference between QED (*Quantum Electrodynamics*) and QCD. In QED, in fact, photons have no charge and cannot couple with each other.

1.1.2 The electro-weak sector

The first model of the weak interaction was proposed by Fermi in 1933, who proposed an effective field theory at low energies. According to this theory, charged current interactions are approximated by a point-like interaction with a couplig called G_F [1, 2]. At energies $\mathcal{O}$(100 GeV) the theory breaks and the real propagator of the interaction is the $W^\pm$ boson.
In 1957, a famous experiment conducted by Wu [3] proved that parity is maximally

violated by the charged weak interaction: it only couples to particles of left-handed chirality (and antiparticles of right-handed chirality). There also exists a neutral weak interaction, which couples both to left-handed and right-handed particles.
This discovery motivated the introduction of the vector-axial (V-A) structure of the Lagrangian of the weak force.
The model of the weak interaction was subsequently promoted to a gauge theory by requiring local invariance under symmetries of the $SU(2)$ group, and it was associated with a conserved quantity called the *weak isospin*.

Each generation of left-handed fermions forms a doublet satisfying$I_3 = \pm\frac{1}{2}$, while right-handed fermions correspond to singlets of null isospin, as follows:

$$\chi_L = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \qquad l_R \tag{1.9}$$

where $l = (e, \mu, \tau)$, and a right-handed neutrino singlet is not introduced since there is still no observation of such a particle. A similar representation is given for quarks where both up (u, s, t) and down-types (d, c, b) have a right-handed component, singlet under $SU(2)_L$.

The transitions between quark doublet members corresponds to $SU(2)$ raising (τ^+) and lowering (τ^-) operators, giving the charge raising and lowering currents [4]:

$$\begin{aligned} J^+ \sim\ & g(\bar{u}\, d_c) = g(\bar{u}\, \bar{d}_c) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ d_c \end{pmatrix} = g(\bar{q}\, \tau^+ q) \\ J^- \sim\ & g(\bar{d}_c\, u) = g(\bar{u}\, \bar{d}_c) \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} u \\ d_c \end{pmatrix} = g(\bar{q}\, \tau^- q) \end{aligned} \tag{1.10}$$

where overall numerical factors have been omitted, d-quark is 'Cabibbo-rotated' ($\theta_c \sim 13°$) and g is the dimensionless weak coupling constant and quaks.

If there exist an appropriate symmetry, based on some underlying gauge theory, then a current involving τ_3 is also expected, since these operators are related via the commutation relation $[\tau^+, \tau^-,] = 2\tau^3$. Hence, with such a gauge theory symmetry, one would expect the existence of a neutral current (identified by the Z^0 boson) of the form :

$$\begin{aligned} J^0 \sim\ & 2g(\bar{q}\, \tau_3 q) = g(\bar{u}u - \bar{d}_c d_c) \\ =\ & g[\bar{u}u - \bar{d}_c d \cos^2\theta_c - \bar{s}_c s \sin^2\theta_c - (\bar{d}s + \bar{s}d)\cos\theta_c \sin\theta_c] \end{aligned} \tag{1.11}$$

The terms $\bar{d}s$ and $\bar{s}d$ correspond to strangeness-changing neutral currents (SCNC), which are heavy suppressed in nature.
For example, the decay branching ratio $K^+ \to \mu^+\nu_\mu$ is 63.5%, whereas that for $K^0_L \to \mu^+\mu^-$ is $\sim 10^{-8}$.

A mechanism to suppress this unwanted strangeness strangeness-changing neutral currents was suggested in 1970 by Glashow, Iliopoulos and Maiani (GIM) and it will be described in the next section.

1.1.2.1 GIM mechanism

Until the beginning of the 1970s, the only three light quarks u, d and s known at this time could explain the observed hadron spectrum and the observed weak decays of pions and kaons were mostly in good agreement with the predictions of the *Cabibbo mechanism*. Glashow, Iliopoulos and Maiani proposed the existence of a second orthogonal doublet, additional to $\binom{u}{d_c}$, containing a new quark c (charm) with charge $\frac{2}{3}$, as follows [5]:

$$q' = \begin{pmatrix} c \\ s_c \end{pmatrix} = \begin{pmatrix} c \\ -d\sin\theta_c + s\cos\theta_c \end{pmatrix} \tag{1.12}$$

Adding this term gives the total neutral current:

$$\begin{aligned} J^0 \sim\ & 2g(\bar{q}\,\tau_3 q + \bar{q}'\,\tau_3 q') = g(\bar{u}u + \bar{c}c - \bar{d}_c d_c - \bar{s}_c s_c) \\ =\ & g[\bar{u}u + \bar{c}c - \bar{d}d - \bar{s}s] \end{aligned} \tag{1.13}$$

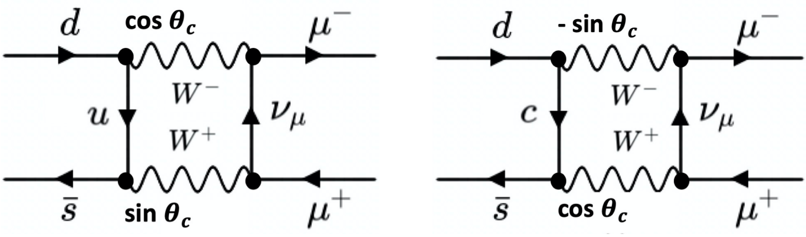
That is, the unwanted terms cancel, leaving a flavor diagonal result.

The GIM mechanism gives also an estimation of the charmed quark, before the J/Ψ discovery occurred in 1974.
In the three-quarks picture, and according to the Cabibbo mechanism alone, s $\rightarrow$ d transitions via *Flavor Changing Neutral Current* FCNC processes would be possible at all orders of the perturbation expansion.
For example, the process $K_L^0 \rightarrow \mu^+\mu^-$ FCNC decay could take place, in terms of known quark (u and d-quarks), via the "box-diagram" of Figure1.1(a).
The calculated rate is larger then what was observed experimentally. However, including the diagram of Figure1.1(b), the total amplitude is:

$$\mathcal{M} = \mathcal{M}_{(a)} + \mathcal{M}_{(b)} \sim f(m_u)g^4\cos\theta_c\sin\theta_c - f(m_c)g^4\cos\theta_c\sin\theta_c \tag{1.14}$$

Thus, the c-quark induces a cancellation, giving a BR compatible with the experiments, but not a total cancellation because $m_c \neq m_u$. Hence, the predictions on the mass of the c-quark that in the end it is $\sim$ 3 GeV.

In addition to this major prediction, the GIM mechanism led to the prediction that FCNC processes are forbidden at tree-level Leading Order. The branching ratios of several FCNC decays of the top quark in the SM are given in Table 1.1 The FCNC production is also sensitive to numerous new physics models, as is mentioned in more details in section 1.3.
The GIM hypothesis represent a generalization of Cabibbo's idea. The introduction of the forth quark (c) restored the symmetry in the (then known) numbers of quark and



(a) (b)

Figure 1.1 – Feynman diagrams of $K_L^0 \to \mu^+\mu^-$ via (a) u-quark exchange and (b) c-quark exchange

	$t \to uZ$	$t \to cZ$	$t \to u\gamma$	$t \to c\gamma$	$t \to ug$	$t \to cg$	$t \to uH$	$t \to cH$
BR	8×10^{-17}	1×10^{-14}	3.7×10^{-16}	4.6×10^{-14}	3.7×10^{-14}	4.6×10^{-12}	2×10^{-17}	3×10^{-15}

Table 1.1 – Branching ratios for top quark FCNC interactions in the SM [6].

leptons.
These ideas were extended by Kobayashi and Maskawa (1973), who introduced a framework of six quarks and it will be described in the next section.

1.1.2.2 CKM matrix

In 1973 Kobayashi and Maskawa extended the Cabibbo's mechanism allowing to describe the transitions within and in-between 3 generations of quarks using the so-called *CKM* 3×3 matrix [7, 8], which relates the weak eigenstate of down-type to their mass eigenstate:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} |V_u d| & |V_u s| & |V_u b| \\ |V_c d| & |V_c s| & |V_c b| \\ |V_t d| & |V_t s| & |V_t b| \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1.15}$$

By convention, the up-type quarks are taken to be pure states. Therefore, partners of the up-type quarks within the weak isospin doublets are the weak eigenstates d', s' and b' which are the pure states.
The CKM matrix is fully defined by 4 independent parameters, which must be determined experimentally. These parameters are: 3 mixing angles and 1 CP-mixing phase, which violates the CP[3]symmetry in the SM [9]. The diagonal elements of the CKM matrix are close to 1, reflecting the fact that transitions are favoured between quarks of the same generation.
The CKM matrix is unitary, i.e. the sum of the transition probabilities for any quark flavor is equal to 1. If this assumption was to be disproved, it could imply the existence

of a fourth quark generation **CITARE FORSE PARAGRAFO BDM**.

METTERE Electroweak symmetry breaking ???

1.2 Top quark physics

The heaviest known elementary particle described by the Standard Model is the top quark.
In 1995, the top quark discovery in FERMILAB [10, 11] was a great success for the SM predictions e.g. the corroboration of existence of a weak isospin partner of the top quark. Due to its large mass, the predicted lifetime $\tau_t \approx 5 \times 10^{-25}$ s (in agreement with theoretical expectations [12]) entail that it decays before hadronising.
In the next sections, the production mechanism is reported, as well as a dissertation about the decay channels.

1.2.1 Production

The top quark can either be produced as pairs, via strong interaction, or as a single top quark via electroweak interaction that doe not preserve the flavor.
The main parton sub-processes that lead to top-pair production are the quark-antiquark annihilation ($q\bar{q} \to t\bar{t}$, Figure1.2(a)) and the gluon-gluon fusion ($gg \to t\bar{t}$, Figures 1.2(b) and 1.2(c)).
Since in protons there are not valence antiquark, the quark-antiquark annihilation is

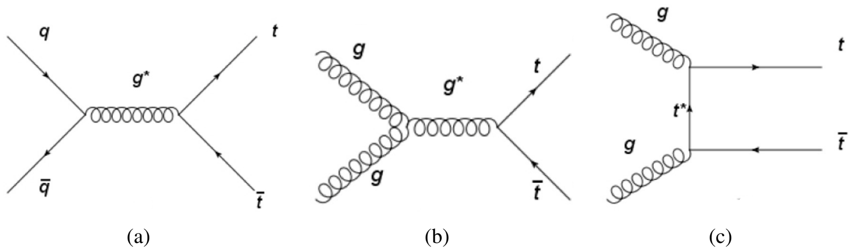


Figure 1.2 – Feynman diagrams of $t\bar{t}$ production via (a) quark-antiquark annihilation ($q\bar{q} \to t\bar{t}$) and (b,c) gluon-gluon fusion ($gg \to t\bar{t}$)

suppressed by the parton distribution functions (PDF) of the antiquark in the proton. Therefore, at LHC the dominant process turns out to be the gluon-gluon fusion, while

[3]Charge transformation followed by a parity transformation.

in a proton-antiproton collider, such as Tevatron, the dominant process is the quark-antiquark annihilation, in fact:

- Tevatron: $q\bar{q} \rightarrow t\bar{t} \approx 86\%$, $gg \rightarrow t\bar{t} \approx 15\%$
- LHC: $q\bar{q} \rightarrow t\bar{t} \approx 20\%$, $gg \rightarrow t\bar{t} \approx 80\%$

Top-pairs can be produced also for weak interaction when two quarks exchange Z^0 or a γ; however the cross-section of these type of processes is negligible when compared to the production cross-section through strong interaction.
Although at LHC the top quarks are mainly produced in the process described above, a not negligible number of tops are produced singly by weak interaction but with a production cross section equal to approximately 1/3 of the top-pair production cross-section, which is, at $\sqrt{13}$ TeV and taking into account a top quark mass of 172.5 $\mathrm{GeV/c^2}$, $\sigma_{t\bar{t}} = 831.8^{+19.8+35.1}_{-29.2-35.1}$ pb [13].

1.2.2 Decay channels

Since the top quark mass is greater than the W boson mass, it decay through weak interaction, mainly in $t \rightarrow W^+b$; according to SM is 100% of the possible cases.
The other channels ($t \rightarrow W^+s$, $t \rightarrow W^+d$) are strongly suppressed by the CKM matrix elements (see section1.1.2.2). Exploiting the matrix unitarity and the B meson oscillations it is possible to extract the following BRs[14]:

$$\begin{aligned}
&\mathrm{BR(t \rightarrow W^+b)} \sim 0.998 \\
&\mathrm{BR(t \rightarrow W^+s)} \sim 1.9 \cdot 10^{-3} \\
&\mathrm{BR(t \rightarrow W^+d)} \sim 10^{-4}
\end{aligned}$$

Therefore, the top decay total width is given by, in good approximation, the decay ($t \rightarrow W^+b$), thus equals to $\Gamma_t = 1.44$ GeV. The W boson may decay in only two ways: "leptonically" ($W \rightarrow l\nu$) or "hadronically" ($W \rightarrow q\bar{q}'$). This leads to three different categories of $t\bar{t}$ decays: dileptonic, semi-leptonic or hadronic. The Figure 1.3 summarise the BRs associated to each channel.
At the hadron colliders, the dominant hadronic mode is the hardest to detect due to the large QCD background.

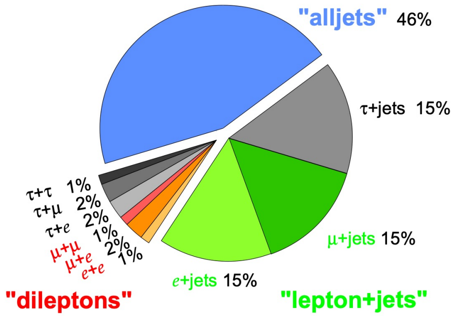


Figure 1.3 – Branching rations associated to each $t\bar{t}$ decay channel[15].

1.3 Theories for physics beyond the Standard Model

The previous sections describe the core components of what we call *Standard Model* and report few major successes of many. Its predictive power makes this model the most tested in physics and it reaches the culmination of success on 4 July 2012, when the ATLAS and CMS experiments at CERN announced the observation a new particle in the mass region around 125 GeV, the Higgs boson [16].
But in spite of its important achievements, the SM falls short of explaining several important observations that in this section are briefly reported.

SM considers neutrinos as massless particles but this is in contradiction with the results of many experiments, which observed, in several different contexts, the *neutrino oscillations*.
It is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton family number (e, μ, or τ) can later be measured to have a different lepton family number and this mechanism, implies that the neutrino has a non-zero mass since it arises from mixing between the flavor and mass eigenstates of neutrinos.

SM can not describe *dark matter* and *dark energy*. The first evidence of dark matter came with the observation of the rotational speed of galaxies, which suggests the existence of a huge amount of undetected mass [17].
None of the SM particles could explain this phenomenon and, since a dark matter has never been directly observed implies that it interact only weakly with the ordinary matter and radiation or does not interact at all.
Likewise, dark energy is an unknown form of energy that affects the universe on the largest scales. The first observational evidence for its existence came from supernovae measurements, which showed that the universe does not expand at a constant rate; rather, the expansion of the universe is accelerating.
The data collected by Planck spacecraft, indicate that dark energy contributes 68% of

the total energy in the present-day observable universe. The mass–energy of dark matter and ordinary (baryonic) matter contributes 27% and 5%, respectively, and other components such as neutrinos and photons contribute a very small amount [18].

After the Big Bang one could expect that the universe produced the same amount of particles-antiparticles and that the constant annihilation of pairs would have constituted a universe of radiation. What we observe actually is large cosmological matter (but not antimatter) structures. The mechanism suggested by the SM through the CP-symmetry violation of neutral oscillating hadrons is not sufficient to explain alone this phenomenon.

There are also some other strong indications that the SM could be not yet complete. Indeed, it is based on 19 parameters (excluding neutrino masses) that must be determined experimentally and no known theoretical origin. Moreover, gravity could not be included as a gauge theory because, describing graviton (the associated gauge boson) interactions, the classical theory of Feynman diagrams, and semiclassical corrections with at least two loops lead to *ultraviolet divergences*. These infinite results cannot be removed because quantized general relativity is not perturbatively renormalizable, unlike QED and models such as the Yang–Mills theory. Therefore, when the probability of a particle to emit or absorb gravitons is calculate, the theory loses predictive veracity. Those problems and the complementary approximation framework are grounds to show that a theory more unified than quantized general relativity is required to describe the behavior near the Planck scale. The problem of *naturalness* is also much debated in literature. The Higgs boson is very sensitive to loop corrections (involving top quark and himself mainly) and if one considers the a theory close to the Planck scale, thus these corrections may explain why the Higgs boson mass is so relatively small compared e.g. with the top quark mass. Another problem is, in fact, the mass scale of fermions that it ranges across many orders of magnitude without any clear explanation.
Many are models of "new physics" that attempt to describe and explain the phenomena mentioned above but so far there is no evidence of new physics beyond SM. In this section we will briefly describe some of these interesting theories for the topics of this thesis

1.3.1 Quark singlets

The need to suppress the FCNC mechanism lead to two dogmas [19, 20]:

- they are not mediated by Z^0 boson at tree-level
- no FCNC mechanism in the scalar sector at tree-level

It is possible to overcome these dogmas using extensions of the SM, like the Quark Singlets (QS) [21] that introduces a vector-like quark ($\mathrm{Q} = \frac{1}{3}$ or $\mathrm{Q} = \frac{2}{3}$), thus a small violation of the 3×3 V_{CKM} unitarity (see Section 1.1.2.2), mediated by Z^0 boson and natural FCNC suppression at tree-level.

Given x_L and x_R, $SU(2)_L$ singlets

$$\begin{pmatrix} d' \\ s' \\ b' \\ x' \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| & |V_{ux}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| & |V_{cx}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| & |V_{tx}| \end{pmatrix} \begin{pmatrix} d \\ s \\ b \\ x \end{pmatrix} \tag{1.16}$$

The non orthogonality of the columns leads to terms of the type:

$$J_\mu = \frac{g}{cos\theta_W} Z_{bd} \bar{b}_L \gamma_\mu d_L Z^\mu \tag{1.17}$$

where

$$Z_{bd} = V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \tag{1.18}$$

and Z_{bd} is suppressed by $\frac{m_q}{m_x}$.

In this way is possible to have deviations from 3×3 unitarity.
The PMNS matrix in the leptonic sector, in the context of see-saw mechanism is not 3×3 unitarity [22].
Vector-like quarks provide the simplest model with spontaneous *CP violation* and a framework to have a common origin of all CP violation because it is a potential solution of the *strong CP problem* without involving other particles, e.g. axions.

1.3.2 Two Higgs Doublet Model

The LHC discovery of a Standard-Model-like Higgs H(125) particle in 2012[16] could be a portal to an extended Higgs sector predicted by several models, one of this is the Two-Higgs-Doublet Model (2HDM) [23]. The most natural extension of the Standard Model scalar sector is the addition of an extra $SU(2)_L$ doublet.

The 2HDM is an *Effective Field Theory* (EFT[4]) consisting of two complex Higgs doublets, which provide masses to both the up-type and the down-type fermions:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \tag{1.19}$$

with the minimum of the potential corresponding to

$$\Phi_{1,0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \qquad \Phi_{2,0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix}. \tag{1.20}$$

[4]An EFT corresponds to a low-energy approximation to a more fundamental underlying theory, characterized by an energy scale Λ (e.g. the mass of new particles)

After electroweak symmetry breaking (EWSB), there are five physical scalar fields, consisting of neutral bosons h, H, A of which the first two bosons are CP-even, opposed to the A-boson which is CP-odd and of two charged Higgs states $H^{\pm}$.
The model is parametrised by the five Higgs masses (m_H, m_h, $m_{H^{\pm}}$, m_A), the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = \nu_2/\nu_1$ and the mixing angle α between the CP-even Higgs states.
There exist four types of 2HDM which simultaneously forbid the presence of FCNC and preserve CP symmetry:

- in Type I all fermions couple to the second doublet Φ_2. It follows that BR are independent of $\tan\beta$;
- in Type II or MSSM-like scenario, lepton and down-type quarks couple to the first doublet Φ_1, whilst up-type quarks couple to Φ_2 ;
- in Type III or lepton specific scenario, quarks couple to Φ_2 while leptons couple to the other doublet;
- in Type IV or flipped model, the coupling of the leptons is reversed with respect to the Type-II model.

1.3.3 Minimal Supersymmetric Standard Model

CHAPTER 2

The LHC accelerator and the ATLAS experiment

2.1 The LHC accelerator

2.2 The ATLAS detector

2.2.1 Magnet system

2.2.2 The inner Detector

2.2.3 The calorimetric system

2.2.4 Muon spectrometer

2.2.5 ATLAS trigger and data acquisition

CHAPTER 3

The Trigger system upgrade for High-Luminosity LHC

3.1 Resistive Plate Chambers

3.2 Hit digitization in the BI region

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APPENDIX A

Mass Resolution

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