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Search for Top Quark Flavour Changing Neutral Couplings with the CMS Experiment at the LHC

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A dissertation submitted to Ain Shams University and Vrije Universiteit Brussel in accordance with the requirements of the double-degree of PhD
PhD in Physics, Ain Shams University,
PhD in Sciences, Vrije Universiteit Brussel

June 2018

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Date of Private Defence: 25 May 2018.
Date of Public Defence: 27 June 2018.

Cover information: The photo in the front cover is for the first half of the inner tracker barrel of CMS experiment, it is taken from [1]. The symbols in the back cover means "top-FCNC" in old Ancient Egyptians language.
The cover is kindly designed by my friend Dr. Haiam Adel.

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"Knowledge is the conformity of the object and the intellect"

Ibn Rushd (Averroes)

Introduction

Since the beginning of life, curiosity guides humans to discover the universe and develop knowledge regarding it's existence. Historically the ancient Egyptians and the ancient Greeks are the first people who wrote and documented their beliefs about the creation of the universe. Both gave religious or mythological explanations for natural phenomena, proclaimed that every event had a natural cause.

The universe according to ancient Egyptians beliefs is created by a self-created deity god called "Atum". Atum represents the god of preexistence and post-existence where the energy and matter are contained. Atum created himself from the dark primordial waters "Nu". In this abyss everything was formless and inert so he creates the first piece of land "ben-ben" to stand on it, then it creates two other gods "Shu" and "Tefnut" that represent the gods of air and moisture respectively. Then by marriage of these two gods the family increased to be nine gods. Atum then arises to the sky in order to light his creation on the land. On the other hand the ancient Greeks believed that everything is made from four basic elements. These elements are "air, water, earth and fire". The basic idea of both Egyptian and Greek beliefs indicates that both agree that there are one or more basic building blocks of the universe. Now this idea evolved via thousands of scientists from different countries.

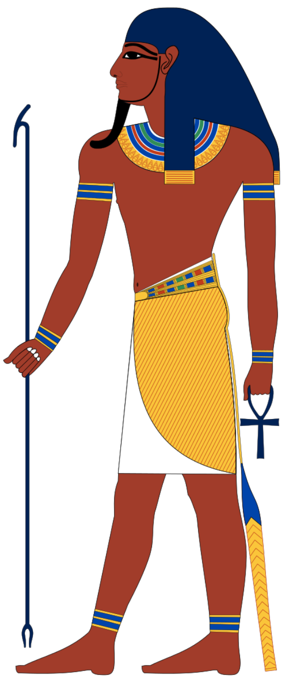

Figure 1: Atum: The god of creation in the ancient Egyptians beliefs.

During the twentieth century, several experimentally confirmed theories gave a description of matter and its composition. These theories are combined into the most successful physics theory called the Standard Model (SM) of particle physics, which explains almost all experimental results and precisely predicted many phenomena. Unfortunately the SM is not the theory of everything, some phenomena are not embraced in the SM like gravity, the composition of dark matter and the neutrino masses. These shortcomings of the SM motivate scientists to search for new physics Beyond the Standard Model (BSM). The main purpose of these BSM theories is to establish a more general understanding of particle physics especially in the conditions where the SM fails, such as at very high energies.

The top quark is an excellent candidate for searching for such new physics phenomena. Since it is the heaviest particle in SM, physicists believe that it has an enhanced sensitivity to various new particles and interactions suggested by BSM theories. One of interesting phenomenon is the presence of flavour-changing neutral current (FCNC) interactions involving the top- quark in which the flavour of the top quark is changed by means of neutral bosons. The FCNC interactions are highly suppressed in the SM by the so-called Glashow–Iliopoulos–Maiani (GIM) mechanism [2].

FCNC interactions were confirmed for the first time in 2005 by the Collider Detector at Fermilab (CDF) experiment in the $B_s^0 \to \phi\phi$ decay process[3]. The results of this search matched the SM predictions. After the construction of the Large Hadron Collider (LHC) the FCNC interactions involving b-quarks are observed in CMS and LHCb experiments in $B_s^0 \to \mu^+\mu^-$ [4]. This observation also agrees with the SM prediction and has put stringent limits on BSM theories.

Although the FCNC interactions of the top quark are suppressed in the SM by the GIM mechanism, many BSM theories predict the existence of these processes with higher branching ratios, where some are within the reach of the current experiments. The observation of a SM-like Higgs boson by the ATLAS and CMS experiments in 2012 [5] initiated the study of FCNC interactions involving a top quark and a Higgs bosons. Up to date the results of these studies are still far from being sensitive to Standard Model predictions. This leaves a large phase space to confirm or exclude the presence of such new physics phenomena.

In this thesis a research for FCNC interactions involving a top quark and a Higgs boson is presented with a signature of two leptons in the final state with equal electric charges. The analysis is done using data of pp-collisions collected in 2016 by the CMS experiment at a center-of-mass energy of 13 TeV and an integrated luminosity of $36 fb^{-1}$. We probe the FCNC interactions in top-quark pair decays as well as in the single top quark production through Hqt-couplings, where the quark q is either an up-quark or a charm-quark. The thesis has seven building blocks called chapters which explain the process of the doctoral study. This process needs some theoretical bases which will be introduced in the first chapters. In order to perform this study an experimental setup has to work with certain conditions that will be described in the second chapter. The skeleton of the proton-proton collisions will be demonstrated in chapter three. The reconstruction of the final state particles which are emerged from these collisions will be explained in chapter four. The analysis of the collected information will be illustrated in chapters five and six. Finally the author presents conclusions and prospects in chapter seven.

"It is inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact"

Isaac Newton

Chapter 1

Theoretical Basis and Concepts

One of the recurrent dreams in elementary particles physics is that of a possible fundamental synthesis between electromagnetism and weak interactions.
This qoute had been said by A. Salam in Weak and Electromagnetic Interactions Elementary Particle Theory (1968) [6].

1.1 The fundamental particles and forces

Almost all commonly encountered physical phenomena can be described in terms of the electron, electron neutrino, proton and neutron, interacting by the electromagnetic, strong and weak forces.

The negative electrons are bound to the positive nucleus via the electrostatic attraction, which is the low-energy manifestation of the fundamental theory of electromagnetism, namely Quantum Electrodynamics (QED). Inside the atomic nucleus, the protons and neutrons are bound together by the strong nuclear force, that is a manifestation of the fundamental theory of strong interactions, called Quantum Chromodynamics (QCD). The fundamental interactions of particle physics are completed by the weak force, which is responsible for the nuclear β-decays of radioactive isotopes in which the electron and another particle called the electron neutrino ν_e are produced. This picture is completed by gravity, which although extremely weak, is always attractive and is therefore responsible for large-scale structures in the Universe. This represents a simple physical model with just four "fundamental" particles and four fundamental forces. However, at higher energy scales, further structures are observed. For example, the protons and neutrons are found to be bound states of smaller fundamental particles called quarks [7].

The Standard Model (SM) of particle physics describes all the known elementary particles and their interactions. It provides a successful description of all current experimental data and represents one of the triumphs of modern physics.

Within this model all particles are built from a number of fundamental, spin $\frac{1}{2}$, particles called fermions (quarks and leptons) and the interactions among those particles take place through bosons, which are described in terms of particles of spin 1 and work as mediators of forces between the fermion constituents. For each fermion there is an anti-fermion, which has the same mass but it is oppositely charged. Furthermore, quarks carry colour charge while leptons do not. From the upper limits on the possible neutrino masses, neutrinos ν have been recently observed to have non-zero mass unlike previously assumed. They have masses at least nine orders of magnitude lighter than the other fermions. Furthermore, because they are neutral, the question whether each neutrino is its own antiparticle (Majorana particles) or not (Dirac particles) remains unanswered. In general the different types of quarks and leptons are also characterized as flavours.

According to the SM fermions are categorized into three generations, each identical to the other except for their mass and flavour quantum numbers. The first generation combines the up and down quarks, together with the electron and the electron-neutrino, while the second generation consists of the charm and strange quarks, muon and muon-neutrino and finally, the top and bottom "or beauty" quarks together with the tau lepton and tau-neutrino make up the third generation as can be seen in Figure 1.1. Ordinary matter on earth is essentially composed of particles from the first generation: up and down quarks in the nucleus, and electrons in the electron shells.

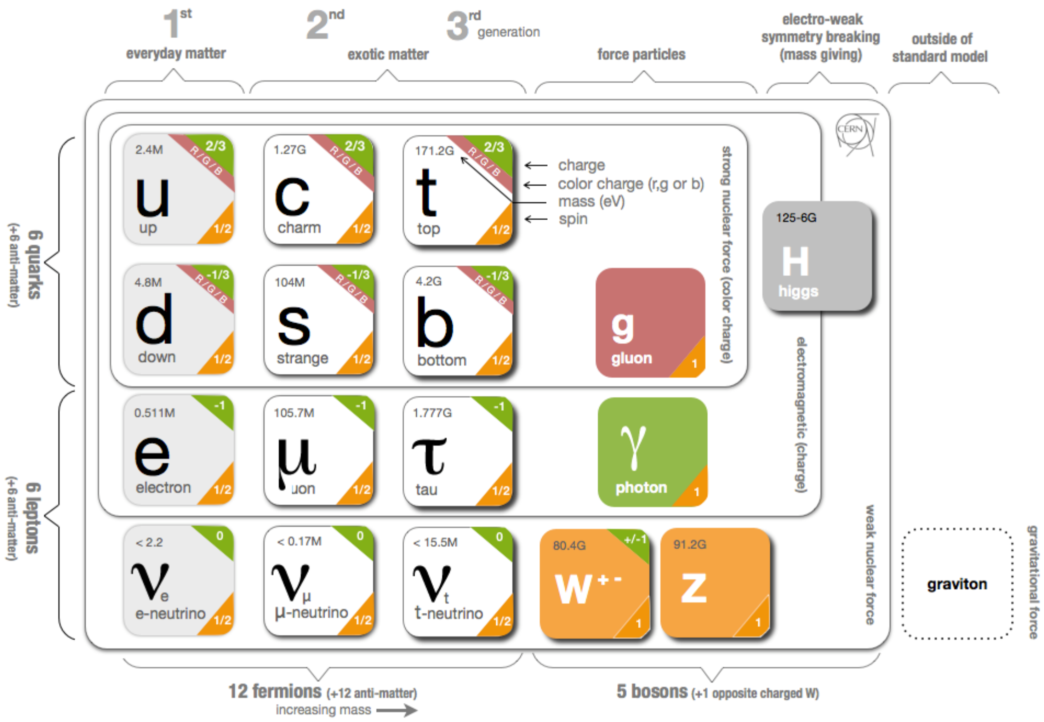

Figure 1.1: The particle content of the SM. All twelve fundamental particles carry the charge of the weak interaction, known as weak isospin, so they undergo weak interactions. With the exception of the neutrinos, the other nine particles are electrically charged and participate in the electromagnetic interaction of QED. Only the quarks undergo the strong force interactions because they carry colour charge (the QCD equivalent of electric charge). The figure taken from CERN website [8]

Each of the three forces of relevance to particle physics is described by a Quantum Field Theory (QFT) corresponding to the exchange of a spin-1 force-carrying particle, known as a gauge boson. The strong interaction is responsible for binding the quarks. This interquark force is mediated by gauge bosons called "gluons" which are massless, electrically neutral but carry colour charge. The massless photons γ, mediate the electromagnetic interaction between charged particles. The quanta of the weak interaction fields are the charged $W^{\pm}$-boson and the neutral Z^0-boson. These last two carry mass and make the weak interaction short-ranged. On the contrary, the electromagnetic interaction has an infinite range because of the massless mediator. Gluon fields despite being massless are confined, so the strong force is not observed as a long range force. The SM is completed by the discovery of the Brout-Englert-Higgs boson (commonly called Higgs boson) which has been confirmed by the CMS and the ATLAS experiments in July 2012 [5]. The Higgs particle is the only known spin-0 boson, also called a scalar particle, and is responsible for giving the mass of all aforementioned particles.

Due to the QCD confinement of quarks, quarks can not exist as free particles so they are bound through gluons into *hadrons* which are divided into two categories. *Baryons*, such as protons and neutrons, are composed of three quarks while *mesons*, such as π^0 and K^0 are composed of a quark and an anti-quark. Almost all baryons (except the proton) and mesons are unstable (short-lived) particles that decay via $W^{\pm}$ or Z^0 bosons, the latter particles usually decay into a charged lepton and neutrino or into quarks. Z^0 can also decay into 2 charged leptons.

1.2 The Standard Model (SM)

The SM is a gauge field theory where the particles are represented by fields. Their interactions and kinematics are described by mathematical constructions called Lagrange densities or shortly Lagrangians. The SM Lagrangian is invariant under Lorentz transformation that implies the conservation of energy and momentum.

The SM theory is based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ group. $SU(3)_c$ describes the strong interactions and the index C refers to the color charge which is conserved under $SU(3)$ symmetry. The conservation of color charge implies the existence of eight gauge bosons that are gluons. Gluons interact with each other in a similar way as quarks do. Similarly to quarks they can not be found freely. Under $SU(3)_c$ quarks are color triplets while leptons are color singlets; therefore quarks carry a color index ranging between one and three, whereas leptons do not take part in strong interactions.

$SU(2)_L \times U(1)_Y$ describes the non-abelian gauge group of the electroweak interaction. L refers to the left chiral nature of the $SU(2)$ coupling and Y refers to the weak hypercharge which is carried by the gauge field B_μ and is related to the electric charge Q and the weak isospin T_3 by

$$Y = 2(Q - T_3). \tag{1.1}$$

The three gauge fields W^1_μ, W^2_μ and W^3_μ are associated to $SU(2)_L$ with three generators that can be written as half the Pauli matrices:

$$T_1 = \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, T_2 = \frac{1}{2}\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, T_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{1.2}$$