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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The exciting work in HEP includes not only the analysis of the data taken by the experiment but also the development of detection systems. In this thesis, the results of the search for the production of a Higgs-boson in association with a single top-quark (tH) are presented; the focus is on leptonic signatures provided by the $H \to WW$, $H \to \tau\tau$, and $H \to ZZ$ decay modes. This process is of particular interest due to its sensitivity to the relative sign of the top-Higgs coupling and the vector bosons-Higgs coupling.

The analysis exploits signatures with two same-sign leptons or three leptons in the final state and uses the 2016 data sample collected with the CMS detector at the LHC at a center of mass energy of 13 TeV. Multivariate techniques are used to discriminate the signal from the dominant backgrounds. The analysis yields a 95% confidence level (C.L.) upper limit on the combined $tH + t\bar{t}H$ production cross section times branching ratio of 0.64 pb, with an expected limit of 0.32 pb, for a scenario with κ_t = -1.0 and κ_{V} = 1.0. Values of κ_t outside the range of -1.25 to +1.60 are exclude at 95% C.L., assuming κ_{V} = 1.0. Sensitivity to CP mixing in the Higgs sector was investigated by considering scenarios for different values of the mixing angle α_{CP}. Upper limit on the combined $tH + t\bar{t}H$ production cross section times branching ratio of 0.6 pb is set for a scenario with $\alpha_{CP} = 180^o$ which corresponds to the scenario with κ_t = -1.0 and κ_{V} = 1.0.

On the detection systems side, contributions to the construction of the CMS forward pixel detector (FPix) are presented; it is responsible for tracking with extreme accuracy the paths of particles emerging from the proton-proton collisions at CMS. FPix is a modular detector composed of 672 modules built using a semiautomatic pick-and-place robotic system which integrates optical tools, pattern recognition algorithms, and glue dispensing subsystems, to locate the constituent module parts on the work field and glue them together with a precision of 10 μm. Fully assembled modules were tested and characterized.

DEDICATION

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Chapter *1*

Introduction

Along the last hundred years, the exploration of nature at the atomic and subatomic scales has revealed the existence of the quantum world; several theories attempting to describe it have been created and many experiments to test it have been designed. Thus, challenges are three-fold; on the theoretical side, the standard model of particle physics (SM) gathers the best understanding of nature that is consistent with the experimental data and although it is extremely successful, it is known that SM is not the final version of a theory of everything; on the data analysis side, statistical methods have been developed in order to obtain the most from that experimental data; on the experimental side, detection systems are under continuous research and development. In this thesis, all three aspects are explored.

The context of SM is presented in Chapter 2, starting with a description of the basic components of the matter, quarks and leptons, and how they interact to produce a universe as it is. The language used in this description is the quantum field theory based on the principles of the gauge invariance, which states that the function describing the energy of a system is invariant under certain transformations; from the physics point of view, that gauge invariance means that a physical system can be described by more than one mathematical model. Although the choice of the gauge could make, for instance, the mathematical treatment of the model more or less challenging, it does not have any effect on the observables of the physical system, i.e., a physical system is independent of the model used to describe it.

Interactions the SM are represented in terms of the exchange of particles, known as Gauge bosons; among the gauge bosons, the Higgs boson is responsible for providing the mass to the elementary particles, hence, a fundamental part of characterization of the Higgs boson consist of finding the way it interacts with the rest of elementary particles, i.e., how the Higgs boson couples with other particles. In this thesis the coupling of the Higgs boson with the top quark is investigated; in particular, the search for the production of a Higgs-boson in association with a single top-quark (tH) is considered; the focus is on the $H \to WW$, $H \to \tau\tau$, and $H \to ZZ$ decay modes that provide leptonic signatures in the final state. This process is of special interest due to its sensitivity to the relative sign of the top-Higgs coupling and the vector bosons-Higgs coupling; in addition, tH process is sensitive to Charge-Parity (CP) symmetry violation effects related with the Higgs boson. Thus, a description of the incorporation of the Higgs boson in the SM and the specifics of the tH process are also presented in Chapter 2.

Despite the fact that the SM is a very successful theory, capable of explaining and make predictions about a vast amount of natural phenomena, by early 2012 a fundamental piece of it was missing; the Higgs boson had not been found and the verification of the theory was not complete. Its existence was postulated in the 1960s and several efforts to find it were made like the experiments at the Fermi National accelerator Laboratory (Fermilab). The Higgs boson discovery was announced in July 2012 by the CMS and ATLAS experiments at CERN[1] from proton-proton collision

[1] CMS stand for Compact Muon Solenoid, ATLAS stand for A Toroidal LHC ApparatuS, CERN stand for Conseil Européen pour la Recherche Nucléaire

experiments. The data set used in this thesis were collected by the CMS experiment and the description of the experimental setup and the different subdetection systems is presented in Chapter 3.

Thanks to the increasing development in computing, tools like Monte Carlo (MC) generators, simulation and reconstruction algorithms and software, allow for evaluating the theory predictions and comparing them with real data. MC generators are used to create a set of data samples that reflects the theoretical principles and details of the process under investigation, thus, predictions are obtained from the numerical solution of the mathematical models; however, a direct comparison with the data obtained from the experiments is not possible because of a variety of factors, for instance, the presence of the detection systems. The effect of the detection systems can be simulated and attached to the MC data samples such that the resulting samples account for these effects.

Experimental data are also processed; given that the whole detector is composed of several subdetectors, the information coming from these subdetection systems is combined to reconstruct the features of the particles produced after the proton-proton collision. The process of matching the information from different subdetection systems is known as event reconstruction. The result of the event reconstruction is a set of objects that are identified with the particles expected in the final state and that are predicted by the theory; in the tH process case, those final state particles are leptons and jets. Chapter 4 presents the details about the computational tools used in this thesis.

The statistical tools used to treat the data samples are described in Chapter 5; these tools include the Boosted Decision Trees (BDT) method employed to discriminate signal and background events based on their features, and the statistical inference methods used to account for the uncertainties introduced in the analysis and to extract the asymptotic limits on the $tH + t\bar{t}H$ production cross section.

In Chapter 6, the search for the production of a Higgs-boson in association with a single top-quark (tH) is presented. First, the features of the signal and background processes are described; then, the MC and data samples considered, and the strategies oriented to identify the physics objects are defined. The event selection proceeds in two steps; first, an event pre-selection based on the signal features is performed; later, the signal is extracted based on BDT discriminators, and upper limits on the $tH + t\bar{t}H$ production cross section are set. Finally, the sensitivity to CP-mixing in tH process is investigated and upper limits on the $tH + t\bar{t}H$ production cross section are set.

In Chapter 7, the upgrade of the CMS forward pixel detection systems (FPix) is presented. The HEP group at University of Nebraska (UNL), played a leading role in the so called Phase 1 FPix upgrade, serving as a FPix modules assembly site; the assembly process was designed as a production line composed of several stages among which the gluing and encapsulation stages are described in detail. These stages were implemented using a semi automated pick-and-place robotic system integrating vision, vacuum, and dispensing subsystems. The employment of the semi automated setup, capable to provide a precision in motion of about 10 μm, endow of uniformity and speed up the module production. The commissioning of the assembly site started from scratch in late 2012 and by mid 2015 the production yields reached the same level as other experienced assembly sites.

Chapter 8 presents the conclusions from both analysis and hardware development sides.

CHAPTER 2

Theoretical approach

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 on 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 electrodynamics* (QED) was born.

QED has become the blueprint for developing 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 their interactions, followed by a description of the electroweak interaction, the Higgs boson and the associated production of Higgs