LITERATURE REVIEW

Search for Higgs Resonances beyond the standard model decaying leptonically at the ATLAS detector at CERN

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Abstract

The top quark is the heaviest particle in the Standard Model, with a strong coupling to the Higgs boson. It is often seen as a window to new physics, therefore understanding its production is a key ingredient for testing the Standard Model or physics Beyond the Standard Model. In this document, the production cross section of top-antitop pairs in its semileptonic decay channel is measured as a function of the jet multiplicity in the ATLAS experiment, using proton-proton collisions at the center-of-mass energy of $\sqrt{s} = 7$ TeV. The top-antitop production with extra jets is the main background for many analyses, including the top-antitop-Higgs production studies. The analysis performed is extended in a search for Beyond the Standard Model physics which predicts a resonance decaying in a top-antitop pair, using ATLAS data at center-of-mass energy of $\sqrt{s} = 7$ TeV. The latter analysis is repeated for ATLAS data collected with $\sqrt{s} = 8$ TeV. Performance studies of b-tagging algorithms in the ATLAS Trigger System are also presented.

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Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own research work in the Experimental Particle Physics group of the School of Physics and Astronomy in the University of Glasgow. It has not been submitted for any other degree at the University of Glasgow or any other institution.

Danilo Enoque Ferreira de Lima

Author's Contribution

The research detailed in this document is the result of a collaborative effort in the ATLAS experiment. In parallel, a clear description of the work requires an account of all sectors involved in the analyses, even the ones in which the author did not contribute directly. The list below is presented to clarify the author's contribution in each chapter.

- Chapter **??**: The author contributed the data to simulation comparison plots, which were used in the ATLAS Collaboration, to perform a recalibration of the b-jet trigger taggers.

- Chapter **??**: The author performed the data to simulation comparison at reconstruction level, including a calculation of all systematic uncertainty effects, all the Monte Carlo simulation backgrounds and the implementation of the correction factors (but not including the data-driven background parametrisation estimates for the W + jets and QCD multi-jets backgrounds); the full unfolding procedure described, calculating all the correction factors from simulation; the propagation of systematic uncertainties through the unfolding procedure; the final unfolded data to particle-level simulaton comparison.

- Chapter **??**: The author contributed the data to simulation comparison estimates, including all systematic effect estimates and all Monte Carlo simulation background estimates (but not the W + jets and QCD multi-jets backgrounds' parametrisation estimate).

- Chapter **??**: The author contributed the data to simulation comparison estimates, including all systematic effects estimates and all Monte Carlo simulation background estimates (but not the W + jets data-driven parametrisation estimate). The author also contributed in the QCD multi-jets background parametrisation and estimation in this analysis.

Chapter 1

Introduction

Particle physics is a recent topic in the history of science, although the idea of dividing matter in elementary building blocks is as old as Democritus' (460 BC - 370 BC) atomic hypothesis [?] [1]. The ancient view of matter and how it interacts has been the theme of many discussions in the history of mankind, evolving from the classical Greek philosophers to the modern view of atomic structure. The idea of indivisible fundamental elements of matter has been extended in the 20^{th} century, to include the experimental evidence on the structure of the atom, which led to the development of Quantum Mechanics [?] and, later, Quantum Field Theory [?], which are widely accepted. The proton and neutron in the atom were then subdivided, in this view of matter, into elementary constituents rich in the way they behave and in implications for the future of physics.

Questions could be asked on whether the fundamental elements of matter do exist or whether they are a mathematical tool to describe the observed phenomena, which would lead us to question what it means to observe something. This point will not be discussed in this document, since our goal will be simply to compare the experimental results with the theoretical predictions. Observed phenomena is understood, in this text, as any direct or indirect result of a physical experiment that can be perceived through any rational being's senses, which allows this being to reach a conclusion that the experiment is the most probable cause of the observed phenomena. In the context of Quantum Mechanics, the predictions are made in terms of probabilities, therefore, the experiments are to be repeated many times to have a good comparison of the expected and observed behaviour.

[1] There is dispute on whether the idea of the atom started in Greek or Indian philosophy. The Indian philosophers Jain, Ajivika and Carvaka in the 5^{th} century BC might have started an epistemological discussion on this subject independently [?].

A second issue could be raised on the value of the expression "widely accepted" for a scientific model. If an assessment of a scientific model is to be objective and within the framework of empiricism, whether it is accepted by a community or not should not affect the critique of any model under study. In this document, this issue is not raised either, and we limit ourselves to the study of the models based on a rational and objective analysis over experimental evidence.

A current model of matter that is able to predict a large amount of phenomena with excellent accuracy is called the Standard Model [?]. It includes a myriad of fundamental elements with a complex interaction between them. The "top" quark is one of the particles in the Standard Model and it interacts through all kinds of forces in the model: the strong interaction, the weak interaction and the electromagnetic interaction. It was discovered at Fermilab, only in 1995 [?, ?], with interesting properties, including a large rest mass [?], compared to the other particles in the Standard Model. It belongs to the classification of a "quark" in the Standard Model, of which there are six flavours.

An interesting effect of the fact that quarks interact through the strong force is that, in most cases, quarks cause showers of particles to be produced through a mechanism dominated by the strong interaction. Due to the top quark's short lifetime, it decays very fast through weak interactions, instead of generating a shower of particles through the strong force, as do other quarks. A study of the strong force radiation emitted in the production and decay of the top quark allows one to clarify a bit more the connection between the top quark and the strong force. Another observed characteristic of the top quark is that it decays very often into the second heaviest quark, the b-quark [?], which needs to be well detected if one wants to study the top quark.

The Higgs boson [?,?], observed in 2012, plays a central role in the Standard Model [?], particularly in the mechanism of electroweak symmetry breaking (see Chapter ?? for more details). Furthermore, it also couples strongly to the top quark, which proposes that the study of this connection can be a useful way of probing the characteristics of both of these particles. Exploring the properties of both particles is also a helpful guide towards testing other models besides the Standard Model, which predict alternative mechanisms for electroweak symmetry breaking.

Although widely accepted, the Standard Model is not the only theory of matter in particle physics and a large amount of competing theories see the special properties of the top quark as an excellent scenario to extend the Standard Model's predictions with fresh ideas of what could happen in unprobed environments. These competing models, frequently referred as being "Beyond the Standard Model", often expect that unobserved particles have a connection with the top quark.

This thesis focuses on studies on the top quark, taking advantage of its interesting position in the Standard Model to explore its relation to the strong interaction and novel mechanisms by which it could be produced, in the context of models Beyond the Standard Model. The former is done by measuring the production cross section of top-antitop pairs from proton-proton collisions as a function of the number of jets produced by strong force radiation. The latter is achieved in two separate analyses, comparing the invariant mass of the top-antitop system, produced in proton-proton collisions, with the one predicted by the Standard Model or by proposals Beyond the Standard Model.

This document is divided into three main parts. The first part of this thesis is composed only of Chapter **??**, which discusses the current understanding of the Standard Model in a brief overview, focusing on its relation with the relevant aspects of the top quark used in the studies in this thesis. The second part focuses on the experimental setup used to perform the analyses. The measurements and searches are done using the results of proton-proton collisions in the ATLAS [**?**] detector, at the Large Hadron Collider (LHC) [**?**], which also deserves an introduction in Chapter **??**. Chapter **??** shows a few performance studies in the selection of b-quark-enriched events in ATLAS.

The third part details the three physics analyses performed. Chapter **??** explains the measurement of the top-antitop production cross section as a function of the jet multiplicity in the final state, using data of proton-proton collisions in ATLAS at a center-of-mass energy of 7 TeV. The observed data is corrected for the detector effects in an "unfolding" procedure and a comparison of different simulations of the Standard Model prediction is shown. Chapter **??** discusses the selection of top-antitop pairs produced in proton-proton collisions at center-of-mass energy of 7 TeV, with a focus in probing for Beyond the Standard Model physics. A comparison is done between the Standard Model predicted and the observed spectra for the top-antitop invariant mass. Comparisons are also done between data and alternate models for top-antitop pair production. Chapter **??** extends the previous chapter, by performing a very similar analysis using data from proton-proton collisions at a center-of-mass energy of 8 TeV. Chapter **??** summarises the targets proposed and the results obtained. The appendix contains a few data to simulation comparison distributions related to the analysis discussed in Chapter **??**.

As a final comment, the units used in this document are such that $\hbar = c = 1$, so that, in this system, the units of length and time are the same and they are the inverse of the units of energy and mass:

$$[\text{length}] = [\text{time}] = [\text{energy}]^{-1} = [\text{mass}]^{-1} = [\text{momentum}]^{-1}. \tag{1.1}$$

In this system, a particle's mass is numerically equal to its energy in its rest frame mc^2 and its inverse Compton wavelength $mc/\hbar$. The Einstein summation convention of summing repeated indices in vectors and tensors is adopted.