Top quark pair production cross-section in proton-proton collisions at $\sqrt{s}$ = 7 TeV

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Introduction

Physics is about understanding Nature: the characteristics of matter, its constituents and the interactions between them, the underlying processes that lead to the formation of larger objects and finally understanding how all these are manifested in our surrounding environment.

At present times, Modern Physics is based on the idea that matter is built from a few fundamental building blocks, the *elementary particles*. Remarkably, this idea is not new but dates as far back as the 6th century BC and the roots of the *natural philosophy*. The most striking example comes from Leucippus of Miletus (5th century BC.) who, together with Democritus of Abdera (c. 460 - 371 BC.), developed the idea of *atomism*, accepting that matter consists of many different indivisible and everlasting constituents, the *atoms* [1]. Undeniably, however, the main difference between the past and the present is the fact that the science of Physics reaches to conclusions based on the principles of the *Scientific Method*, instead of just following a philosophical reasoning. Consequently, any well-grounded theory must be accompanied by *experimental* observations before being accepted.

The Particle Physics era

The beginning of Particle Physics can be placed with the discovery of the electron in 1897 by Sir J.J. Thomson. From that point on many remarkable discoveries were made, starting with the improvements on the atomic model made by Thomson, Ernest Rutherford and Niels Bohr, and the parallel developments on the field of Quantum Mechanics and Relativity primarily by Max Planck, Albert Einstein, Louis de Broglie, Erwin Schrödinger, Werner Heisenberg and Paul Dirac. By the end of 1940s, physicists had discovered the proton, the neutron, the muon, the positron (anti-particle of electron), the neutrino (the electron and the muon partners) and they had derived a relativistic quantum field theory (QFT) in order to explain the electromagnetic field (Quantum Electrodynamics), mainly thanks to the work of Richard Feynman, Freeman Dyson, Julian Schwinger and Sin-Itiro Tomonaga. Clearly, until then Physics had made important steps forward, however, it still lacked a consistent theory that could explain all of these observations. This was about to change in the coming years.

Before the end of 1950s a number of experiments had already observed a plethora of new sub-atomic particles, collectively called *hadrons*, which indicated that protons and neutrons may not be fundamental particles. In the early 1960s, Murray Gell-Man and George Zweig independently theorized the existence of the quarks, as constituents of the hadrons, and subsequently the existence of the gluon, as the mediator particle of the force that keeps quarks together in the hadron, the *strong force* [2, 3, 4, 5]. The experimental results from the Stanford Linear Collider (SLAC) *deep-inelastic scattering* experiments verified that quarks and gluons are indeed the elementary constituents [6, 7]; the gluon existence was explicitly shown by a number of experiments, namely the TASSO [8], PLUTO [9], MARK-J [10] and JADE [11].

The quantum field theory that nowadays governs the strong interactions is *Quantum Chromodynamics* (QCD). Its final formulation came in 1975 by Hugh Politzer, David Gross and Frank Wilczek after discovering the *asymptotic freedom* property of QCD [12, 13, 14].

At the same period, an effort was made to formulate the *weak nuclear force* as a quantum field theory. Although a description of the force was provided by Enrico Fermi in 1930s, in order to explain beta radiation [15], it was only valid for relatively low energies. The issue was re-visited by Sheldon Glashow, Steven Weinberg and Abdus Salam, and by mid-1960s they had concluded to the *electroweak theory* under which the *electromagnetic* and the *weak interactions* are unified [16, 17, 18]. As an outcome of the theory was the prediction for the existence of a charged massive particle, the $W^{\pm}$, a neutral massive particle, the Z, and a neutral massless particle, the photon. The $W^{\pm}$ and Z particles are the weak force carriers while the photon is the electromagnetic force carrier. In order to accommodate the fact that the weak force carrier particles had mass, the electroweak theory incorporated the electroweak symmetry breaking mechanism proposed by Peter Higgs and others in the mid-1960s (Higgs mechanism) [19, 20, 21]. The outcome from including the Higgs mechanism not only explained the mass of those particles but also suggested the existence of yet another particle, the *Higgs boson*.

Nowadays, the *Standard Model* is the model that describes the strong, the weak and the electromagnetic interactions. It combines the QCD and electroweak theory into a single consistent theory and provides a description on how the elementary particles interact with each other and form the matter. The success of this theory has been outstanding until today, making it a corner-stone for Particle Physics.

In 1973, Makoto Kobayashi and Toshihide Maskawa hypothesized the existence of the bottom and the top quarks as a means to explain CP violation within the Standard Model [22]. Eventually, the bottom quark was discovered in 1977 at the E288 experiment [23], and the top quark was discovered in 1995 at the Tevatron experiments CDF and DØ [24, 25]. Another success of the Standard Model, and the highlight up until recently, was the discovery of the W and Z bosons in 1983 by the UA1 and UA2 experiments with their mass close to the expected values [26, 27]. The most exciting result, however, comes from the two general purpose experiments of the Large Hadron Collider (LHC), ATLAS and CMS, which in July 4 2012 announced the discovery of a new boson which appears to be consistent with the theorized properties of the Higgs boson [28, 29]. If further investigation verifies that is indeed the Higgs boson, this will be a great success for the Standard Model.

The top quark

The top quark is one of the latest discoveries in Particle Physics and the heaviest elementary particle known to date. Due to its large mass, it is the only quark that decays before it hadronizes, therefore allowing to be probed directly by its products. In addition, its mass is at about the same scale of the electroweak symmetry breaking mechanism, indicating that it couples strongly to the proposed Higgs boson.

In proton-proton collisions, the most common production channel for top quarks is through the top quark-pair production ($t\bar{t}$). This thesis is focused in particular on measuring the cross-section of this signature. Since its discovery in 1995, the cross-section of the $t\bar{t}$ production channel has been measured by both the CDF and DØ experiments at the Tevatron collider. However, the Tevatron ran with proton-antiproton collision at $\sqrt{s} = 1.96$ TeV. Therefore the cross-section measurement presented here is a test of QCD, and the Standard Model consistency in general, as it probes a region of the phase space which was previously unexplored.

Additionally, given the facts stated above, precise measurements of the properties of the top quark are very important for gaining a better understanding on the mechanism that gives mass to the particles (the electroweak symmetry breaking). Many of such analyses require a pure sample with enough statistics, therefore a good understanding of the complex topology of the $t\bar{t}$ signature is essential in this case. Last, but not least, many physics processes beyond the Standard Model (e.g. Supersymmetry) take into account that the $t\bar{t}$ might be a potential background which needs to be understood. The cross-section measurement effectively paves the way for those analyses.

This thesis

The analysis we present in this thesis uses the first data recorded by the ATLAS detector at the LHC, collected from March 2010 until November 2011. The total amount corresponds to an integrated luminosity 35.3 pb^{-1}.

In chapter 1 we provide an overview of the theory on which this thesis is based on. We highlight the key aspects of the Standard Model, we discuss the physics related with the top quark and in particular the motivation behind the $t\bar{t}$ cross-section measurement, and we describe the simulation process and the relevant samples that are used for the analysis. In chapter 2 the experimental setup is presented. This includes a brief description of the CERN accelerator complex and a detailed presentation of the different sub-systems of the ATLAS detector. Chapter 3 introduces the muon online reconstruction, which is relevant for selecting events with a muon in the final state, such as in the $t\bar{t}$ single-muon topology. We present the performance of the trigger system using the very first data collected and we discuss the methodology for obtaining the trigger efficiency for the $t\bar{t}$ topology without using simulated events. In chapter 4 we describe the offline reconstruction of the objects that appear in the final state of the $t\bar{t}$ single-lepton topology. We discuss the selection requirements applied for collecting the $t\bar{t}$ sample and we give an introduction to the most important aspects of the cross-section analysis. Chapter 5 deals specifically with the characterization of the background with respect to the observable that is used in the cross-section measurement. We discuss and apply a methodology for deriving the shape of the background directly from data. Lastly, in chapter 6 the cross-section analysis is described in detail. We present the measurement as obtained from each of the two single-lepton channels of interest, $t\bar{t}(\mu)$ and $t\bar{t}(e)$, as well as the result after combining them. The related systematic uncertainties are also discussed.