TOP-ANTITOP QUARK CROSS-SECTION MEASUREMENT IN PROTON-PROTON COLLISIONS AT $\sqrt{S}$ = 13 TEV WITH THE ATLAS EXPERIMENT AT THE CERN LARGE HADRON COLLIDER

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DEDICATION

I dedicate this dissertation to my parents and ladies of my life. First, I would like to dedicate this to my mother and father. I would not be the person I am today if it was not for them. Second, I dedicate this to my wife, Negina, for her love and support during this challenging time that I was away from her; without her love, I could not have completed this work. Third, I dedicate this to my daughter, Heda; I hope that once she is grown and read this dissertation, she will be proud of her Daddy. Last but not least, I dedicate this dissertation to my sister, Zohra, who loved us more than our mother.

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ABSTRACT

The top quark was first discovered at the Tevatron proton-antiproton collider in 1995 and was first observed in proton-proton collisions at the LHC by both the ATLAS and CMS experiments in 2010. The top quark is the most massive elementary particle in the framework of the Standard Model, which has a large coupling to the Higgs boson and unique role in the electroweak symmetry breaking. Moreover, the top quark is an important background for several analyses involving the Higgs boson and searches for new physics. Therefore, having an accurate understanding and value of inclusive production cross-section of $t\bar{t}$ is vital. The analysis developed by the candidate and presented in this dissertation has been subject of the first publication of the ATLAS experiment on top quark physics: the measurement of the top-antitop ($t\bar{t}$) total production cross-section. The analysis is updated here with the full dataset, corresponding to a data sample of 139 fb^{-1}, of 13 TeV proton-proton collisions collected from LHC Run 2 with ATLAS detector. This measurement uses two kinds of events: first, events with an opposite-charge electron-muon pair in the final states and jets are selected with no missing energy, requiring at least one of the jets to be tagged as coming from the hadronisation of a b-quark. Second, events with an opposite-charge same lepton pair ($ee/\mu\mu$) in the final states and jets are selected with missing energy, requiring at least one of the jets to be tagged as coming from the hadronisation of a b-quark. The cross-section is extracted, using a cut and count method for which an accurate background estimation is crucial, to be $\sigma_{t\bar{t}} = 816 \pm 1\ (stat) \pm 59\ (th.\ syst)\ \pm 29\ (exp.\ syst)$ pb and $\sigma_{t\bar{t}} = 799 \pm 2\ (stat) \pm 84\ (th.\ syst)\ \pm 33\ (exp.\ syst)$ pb in $e\mu$ channel and combined $ee/\mu\mu$ channel, respectively. The result of $e\mu$ channel is in excellent agreement with theoretical predictions and measurements done by ATLAS and CMS experiments, and $e\mu$ channel is considered as the cleanest and best channel for $t\bar{t}$ production cross-section measurement. Besides, a test of the Standard Model is performed by comparing Monte Carlo simulated samples with the experimental results. The Standard Model turned out to be extremely successful in describing the experimental results.

ABSTRAK

Zarah top telah dijumpai untuk pertama kali di pelanggar Tevatron proton-antiproton pada 1995 dan telah berjaya dihasilkan semula melalui pelanggaran proton-proton di Pelanggar Hadron Besar (LHC) menggunakan pengesan ATLAS and CMS pada tahun 2010. Zarah top merupakan zarah yang terberat dalam kalangan model asas (Standard Model) yang juga mempunyai tugas unik dalam menjelaskan penemuan, zarah Higgs dan fenomena pemecahan simetri elektroweak. Tambahan pula, zarah top merupakan latarbelakang utama untuk analisa melibatkan zarah Higgs dan menyumbang kepada fizik baru yang melampaui model asas. Hubungkait ini menunjukkan kepentingan memahami dan menyelidik nilai keratan rentas penghasilan pasangan $t\bar{t}$. Kajian ini merupakan penerbitan pertama dari eksperimen ATLAS untuk pengukuran nilai keratan rentas penghasilan pasangan $t\bar{t}$. Analisa ini merangkumi pengukuran dari tahun 2015 hingga 2018 untuk sampel data 2 yang mempunyai kadar luminous 139 fb^{-1} dari pelanggaran 13 TeV proton-proton dalam eksperimen ATLAS. Analisa nilai keratan rentas penghasilan $t\bar{t}$ di tentukan menggunakan kaedah pilih dan kira peristiwa pengukuran dua pasangan iaitu pasangan electron-muon dan b-jet serta pasangan elektron-elektron atau muon-muon beserta b-jet. Anggaran bacaan latarbelakang yang jitu amat penting bagi kedua-dua peristiwa, iaitu $\sigma_{t\bar{t}} = 816 \pm 1\ (stat) \pm 59\ (th.\ syst)\ \pm 29\ (exp.\ syst)$ pb dan $\sigma_{t\bar{t}} = 799 \pm 2\ (stat) \pm 84\ (th.\ syst)\ \pm 33\ (exp.\ syst)$ pb dalam $e\mu$ dan gabungan pasangan $ee/\mu\mu$, secara berasingan. Bacaan dari pasangan $e\mu$ adalah selari dengan anggaran teori dan pengukuran dari eksperimen CMS, dan pasangan $e\mu$ merupakan cara terbaik untuk pengiraan nilai keratan rentas $t\bar{t}$ disebabkan keadaan semulajadi pasangan $e\mu$. Simulasi Monte Carlo terhadap model asas juga menunjukkan hasil yang sama bagi menjelaskan data dari eksperimen ATLAS.

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LIST OF ABBREVIATIONS

LHC - Large Hadron Collider
ATLAS - A Toroidal LHC Apparatus
CMS - Compact Muon Solenoid
LEP - Large Electron Positron Collider
CDF - Collider Detector at Fermilab
stat. - Statistical uncertainty
th. syst. - Theoretical Systematic Uncertainty
exp. syst. - Experimental Systematic Uncertainty
CP - charge conjugation parity
LS1 - Long Shutdown 1
CKM - Cabibbo Kobayashi Maskawa
SM - Standard Model
BSM - Beyond the Standard Model
QED - Quantum Electrodynamics
QCD - Quantum Chromodynamics
QFT - Quantum Field Theory
PDF - Parton Distribution Function
LO - Leading Order
NLO - Next-to-Leading Order
NNLO - Next-to-Next-to-Leading Order
NNLL - Next-to-Leading Log
MC - Monte Carlo
MDT - Monitored Drift Tube
ECAL - Electromagnetic Calorimeter
SCT - Semiconductor Tracker
RPC - Resistive Plate Chamber

TGC	-	Thin Gap Chamber
TRT	-	Transition Radiation Tracker
HCAL	-	Hadron Calorimeter
FCAL	-	Forward Calorimeter
HLT	-	High-Level-Trigger
IBL	-	Insertable B-Layer
ID	-	Inner Detector
ISR	-	Initial-State Radiation
FSR	-	Final-State Radiation
JER	-	Jet Energy Resolution
JES	-	Jet Energy Scale
JVT	-	Jet Vertex Trigger
L1	-	Level-1
L1 Calo	-	L1 Calorimeter Trigger System
L1 Muon	-	L1 Muon Trigger System
L1 Topo	-	L1 Topological Trigger Modules
MS	-	Muon Spectrometer
MIPs	-	Minimum Ionizing Particles
CTP	-	Central Trigger Processors
CTP	-	Cathode Strip Chambers
BDT	-	Boosted Decision Tree
EWSB	-	Electroweak Symmetry Breaking
Rols	-	Regions-of-Interest

LIST OF SYMBOLS

$p\bar{p}$ - Proton-Antiproton
pp - Proton-Proton
$t\bar{t}$ - Top-Antitop Quark
σ - Cross-Section
$\sigma_{t\bar{t}}$ - $t\bar{t}$ Production Cross-Section
$\sqrt{s}$ - Centre-of-Mass Energy
η - Pseudorapidity
θ - Polar Angle
y_t - Yukawa Coupling
m_t - The Mass of Top Quark
p_T - Transverse Momentum
τ_{QCD} - Hadronisation Time in QCD
I_W - Isospin
Y - Hypercharge
Ψ - Fermion Fields
γ_5 - Matrix
u - Up Quark
d - Down Quark
c - Charm Quark
s - Strange Quark
t - Top Quark
b - Bottom Quark
u_R - Right-Handed Up Quark
d_R - Right-Handed Down Quark
c_R - Right-Handed Charm Quark
s_R - Right-Handed Strange Quark

t_R - Right-Handed Top Quark

b_R - Right-Handed Bottom Quark

q - Quark

$\bar{q}$ - Antiquark

ℓ - Lepton

$\bar{\nu}_\ell$ - Lepton-Flavour Antineutrino

ν_ℓ - Lepton-Flavour Neutrino

ν - Neutrino

ν_e - Electron Neutrino

ν_μ - Muon Neutrino

ν_τ - Tau Neutrino

V_{CKM} - Cabibbo Kobayashi Maskawa Matrix

υ - Vacuum Expectation Value of Higgs Field

$V(\phi)$ - Higgs Potential

μ - Free Parameter of Higgs Potential

λ - Free Parameter of Higgs Potential

ϕ^+ - Complex Scalar Field

ϕ^0 - Complex Scalar Field

$\mathcal{L}$ - Lagrangian

∂_μ - Covariant Four-Derivative

∂^μ - Contravariant Four-Derivative

$\vec{W}_\mu$ - Gauge Field

$\vec{B}_\mu$ - Gauge Field

$\vec{\sigma}$ - Pauli Matrices

Q - Electric Charge

g' - Coupling Constant of the $U(1)_Y$ Gauge Symmetry

g_W - Coupling Constant of the $SU(2)_L$ Gauge Symmetry

θ_W - Weak Mixing Angle

m_Z - Mass of Z Boson

m_W - Mass of $W^{\pm}$ Boson

m_H - Mass of Scalar Particle H

m_b - Mass of Bottom Quark

$F_i(x_i)$ - Probability of Carrying x_i Fraction Momentum by Parton

$\hat{\sigma}_{ij}$ - Perturbative Cross-Section for the Collisions of Partons i

q - Four-Momentum of the W Boson

Q^2 - Virtuality of the W Boson

$\sigma_{t-channel}$ - Single Top Quark Production Cross-Section in t Channel

$\sigma_{tW-channel}$ - Single Top Quark Production Cross-Section in tW Channel

$\sigma_{s-channel}$ - Single Top Quark Production Cross-Section in s Channel

Γ_t - The Decay Width of Top Quark

G_F - Fermi Constant

α_s - The Strong Interaction Coupling

τ_t - Lifetime of Top Quark

$\mathcal{B}$ - Branching Fraction

$\frac{dN}{dt}$ - Event Rate

L - Instantaneous Luminosity

f - Frequency

σ_x - Width of the Gaussian Beams in the x Direction

σ_y - Width of the Gaussian Beams in the y Direction

N_b - The Number of Proton Bunches in the Beam

N_1 - The Number of Protons in Each Bunch of the Beams

N_2 - The Number of Protons in Each Bunch of the Beams

$\mathcal{L}_{int}$ - Integrated Luminosity

σ_{pp} - The Probability of Proton-Proton Collisions

Xe - Xenon

CO_2 - Carbon Dioxide

O_2 - Molecular Oxygen

λ_I - The Interaction Length

X_0 - The Radiation Length

d_0 - Transverse Impact Parameter

z_0 - Longitudinal Impact Parameter, z-Component

ϵ - Efficiency

τ_μ - The Lifetime of Muon

d_{ij} - The Separation of Two Objects

$\triangle R_y$ - The Angular Distance Between Two Objects

R - The Distance Parameter

$E_{x,y}^{miss}$ - Components of Missing Transverse Momentum

E_T^{miss} - Missing Transverse Energy

m_{ll} - Reconstructed Mass of Two Leptons

$\sigma_{t\bar{t}}^{th}$ - Theoretical Cross-Section of $t\bar{t}$

$N_{t\bar{t}}^0$ - Initial Number of Events in the $t\bar{t}$ MC Sample

$N_{t\bar{t}}^{MC}$ - Number of Events in $t\bar{t}$ MC Sample After Selections

N_{bkg} - Estimated Total Background

N_{data} - Observed Experimental Data Events

$\epsilon_{t\bar{t}}$ - $t\bar{t}$ Signal Efficiency

$\delta\sigma_{t\bar{t}}(stat)$ - Statistical Uncertainty of the $t\bar{t}$ Production Cross-Section

μ_f - Factorizarion Scale

χ^2 - Chi-Square

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In 1973, Kobayashi and Maskawa predicted the existence of top quark [1] during their explanation of the observed CP violation. In 1995 $D\emptyset$ and CDF experiments at the Tevatron collider at Fermilab confirmed this prediction [2, 3]. This discovery gave birth to a new field of physics, so-called top quark physics. Properties of the top quark, such as its inclusive production cross-section, its mass, have been obtained at Tevatron during its Run 1 and Run 2 [4]. Moreover, starting from the Tevatron Run 2, the quest for physics beyond the Standard Model (BSM) in the top quark sector began [4]. However, due to the limited amount of top quark data collected, the accuracy of these inspections was limited.

On the other hand, the Large Hadron Collider (LHC) is considered a top quark factory. The LHC began taking data in 2010, at centre-of-mass energy $\sqrt{s} = 7$ TeV, and after three years the ATLAS and CMS detectors, the two multipurpose particle detectors at the LHC, accumulated almost one million events of top quark [4]. The ATLAS and CMS collaborations published the first measurement of the $t\bar{t}$ production cross-section in 2010 [5, 6] using the collected proton-proton collision data. The total dataset collected during Run 1 of LHC was used for various precision measurements of the top quark where the LHC operated at a centre-of-mass collision energy of 7 TeV corresponding to an integrated luminosity of 35 pb^{-1} in 2010 and 5 fb^{-1} in 2011, and 8 TeV corresponding to an integrated luminosity of 20 fb^{-1}. After two years of shutdown for the upgrades and maintenance of the accelerator system and of the detectors, the LHC resumed its operation in 2015 (Run 2) at centre-of-mass energy $\sqrt{s} = 13$ TeV. The measurement of the $t\bar{t}$ production cross-section was the first publication of LHC Run 2 related to top quark physics in 2016 [4].

There are many reasons behind the importance of top quark physics, owing to its very short lifetime and its mass being comparable to the scale of electroweak symmetry breaking, motivating its unique role in searches for many types of new physics. Studies of top quark allow us to probe the strong interaction at 13 TeV, allowing important tests of the Standard Model at this centre-of-mass energy. Tests of the strong interaction either in perturbative or non-perturbative regimes can be performed, and a precise determination of its properties, such as its mass, its couplings and decay branching ratios, is crucial to for the full understanding of the fundamental interactions at the electroweak symmetry-breaking scale and beyond.

The mass of the top quark is $m_t = 173.34 \pm 0.27 \pm 0.71$ GeV [7] making it the heaviest known fundamental particle. It is almost 185 times heavier than the proton. With such a great mass, the top quark is the fermion interacting most strongly with the Higgs boson, with a Yukawa coupling close to unity $y_t = \frac{m_t}{v}$. Thus, it has been conjectured that the top quark has a unique role in the electroweak symmetry breaking. Because the mass of the top quark is of the order of the electroweak scale, it is particularly interesting for searches BSM. Searches for BSM can be done by measuring properties of the top quark or by searching for tops that are decay products from a heavier particle/state.

Top quark has a very short lifetime. Because the hadronisation time is longer compared to the lifetime of the top quark, it decays, semi-weakly to a W boson and a b-quark about 100% of the time, before forming hadrons. All quarks, when created in collisions, hadronise into jets of particles, except the top quark. Thus, the top quark gives a distinctive possibility to investigate the properties of a bare quark that exists for a short time and decays into its final states.

Besides its unique role in the electroweak symmetry breaking mechanism, the study of a bare quark, tests of the SM and its potential link to physics beyond the SM, the top quark appears as an important background in searches of new particles, such as particles predicted by supersymmetry (SUSY) theory. Therefore, this dissertation aims to obtain the production cross-section of top-antitop quark ($t\bar{t}$) pairs at 13 TeV with LHC Run 2 full dataset accumulated by the ATLAS detector, and examine how the statistical uncertainty changes with the increased amount of integrated luminosity this study will use.

1.2 Problem Statement

ATLAS is one of the two large multipurpose detectors at LHC, designed for a variety of physics. One of the key areas of the ATLAS physics programme concerns studies of the top quark, where one of the main goals is the precision measurement of the $t\bar{t}$ production cross-section. The ATLAS and CMS experiments have been performing this measurement since 2010, using events in different final state topologies. The most precise measurements by the ATLAS collaboration are performed, at three different centre-of-mass energies, 7, 8 and 13 TeV, in the $e\mu$ channel, reaching or even exceeding the precision of the theoretical predictions [8, 9]. However, the precision could be still improved, since the full data accumulated by the ATLAS in Run 2 between 2015 and 2018 is not used for this analysis yet. Using the LHC Run 2 full dataset collected by the ATLAS detector and with the better understanding of the detector, the contribution of the systematic uncertainty sources in the $t\bar{t}$ production cross-section measurement will decrease. Over the years, a vast amount of data has been accumulated by the ATLAS detector, and Monte Carlo (MC) simulation has been used to generate $t\bar{t}$ signal samples and its corresponding backgrounds, needed for the extraction of the experimental result. It is expected to have an improved production cross-section measurement by using the whole experimental data accumulated by the ATLAS detector in Run 2 as well as the most recent simulated MC results for this analysis, and events in the $e\mu$ channel rather than ee and $\mu\mu$ channels, where larger backgrounds contaminate the selection.

It is also important to validate the simulation samples by comparing them with experimental data. In the past ATLAS $t\bar{t}$ cross-section measurements have been consistent with the Standard Model predictions. However, statistical and systematic uncertainties were large. Thanks to the more integrated luminosity and high centre-of-mass energy in the Run 2, more accurate validation of the model can be performed.

1.3 Objectives

i. To determine the production cross-section of $t\bar{t}$ and effects of the statistical uncertainty and systematic uncertainty sources in $e\mu$ channel at 13 TeV using LHC Run 2 full dataset collected by ATLAS detector.

ii. To determine the production cross-section of $t\bar{t}$ and effects of the statistical uncertainty and systematic uncertainty sources in ee and $\mu\mu$ channels at 13 TeV using LHC Run 2 full dataset collected by ATLAS detector.

iii. To verify the advantage of $e\mu$ channel over the ee and $\mu\mu$ channels for measurement of the production cross-section of $t\bar{t}$ in dilepton channel and to compare the experimental results with theoretical predictions and Monte Carlo simulation.

1.4 Scope of the Study

This research uses the full experimental data produced at centre-of-mass energy $\sqrt{s} = 13$ TeV in Run 2 of LHC, accumulated by the ATLAS detector [10]. This data is recorded in the condition where all the subsystems were operational. These raw data are then passed to the reconstruction algorithms and made accessible from laboratories all over the world, thanks to the CERN grid system. After further processing and skimming are performed by the ATLAS collaboration, the data is saved in the analysis format to be used for further analyses and measurements. For this analysis, the data comprises those events which have passed either a single-electron or single muon trigger, with the lepton transverse momentum $p_T > 25$ GeV. In this dissertation, data Ntuples are produced at the INFN computing farm in Trieste, Italy, using the data shared in the CERN grid system.

In order to optimise the analysis, to compare with the experimental data, and to study the efficiency and uncertainties of signal and background, simulated events are required. Therefore, MC simulation is used to generate and process such samples [9] by the ATLAS collaboration.

This research used the full dataset collected by the ATLAS detector and MC simulation to perform the analysis. The research presented in this dissertation entailed defining and optimising cuts to be applied on both the experimental data and MC simulated samples to suppress the background events and increase the significance of the $t\bar{t}$ signal in the sample. The production cross-section of $t\bar{t}$ and the estimation of the statistical uncertainty and systematic uncertainty are calculated using the event yields. The fake lepton background estimation is also done in this research using both experimental data and MC simulated samples. One of the most critical aspects of this analysis is the choice of a channel and selection criteria, in order to reduce as much as possible, the contribution from the background. Dilepton channel comprises three sub-channels such as ee, $\mu\mu$ and $e\mu$ channels. Events in the $e\mu$ channel are chosen, in this research, to obtain the production cross-section of $t\bar{t}$ due to its characteristic of having a considerable amount of signal and less contribution of backgrounds after analysis cuts are applied.

The ROOT framework based on the C++ programming language is used to perform the analysis on experimental data events, $t\bar{t}$ simulated events and background events, and to plot the histograms of the observables. The same analysis cut chains are applied in both simulated and experimental events since experimental data is polluted with the backgrounds and measuring any physical observable without purification will lead to the wrong result. Therefore, cuts are applied to enhance the significance of the signal over the backgrounds and purify the data as much as possible to obtain the $t\bar{t}$ production cross-section with high accuracy.

1.5 Significance of the Study

The purpose of this research is to obtain the $t\bar{t}$ production cross-section at $\sqrt{s} = 13$ TeV using the events in $e\mu$ channel. This measurement is of great significance for the validation of the SM, calculation of top quark mass, and possible discovery of new physics. Moreover, $t\bar{t}$ is an important background in several analyses such as those involving the Higgs boson and searches for new heavy particles. Therefore, having an accurate understanding and value of inclusive production cross-section of $t\bar{t}$ is vital. Besides, the advantages of the $e\mu$ channel over the ee and $\mu\mu$ channels, for this measurement, are discussed in this dissertation. Despite many measurements over the last two decades, the precision can be further improved, and the most recent data should be used.

1.6 Dissertation Outline

This dissertation reports the extraction of $t\bar{t}$ production cross-section in $e\mu$ channel using the LHC Run 2 full dataset collected by ATLAS detector. A cut and count method is applied to obtain the $t\bar{t}$ production cross-section.

Chapter 1 provides a brief introduction to the background of the top quark. Also, problem statement, objectives, the scope of the study and significance of the study are covered in this chapter.

Chapter 2 describes the Standard Model theory. A detailed literature review of top-antitop quark and its production cross-section measurement is reported in this chapter. Moreover, a comprehensive description of LHC, ATLAS detector, collision data and MC simulation is provided.

Chapter 3 describes the methodology of object reconstruction in ATLAS, extraction of cross-section, determination of effects of statistical uncertainty and some systematic uncertainty sources in the final result. The reconstruction and object selection criterion are described. In addition, analysis setup, which includes the event selection and fake lepton estimation are also described in this chapter.

Chapter 4 reports the results of the $t\bar{t}$ production cross-section measurements in pretag and b-tag samples of $e\mu$ channel, and combined $ee/\mu\mu$ channel. The result of a pretag and b-tag sample of each channel is discussed, and a comparison between the $e\mu$ channel and ee and $\mu\mu$ channels is made.

Chapter 5 concludes the entire research, which was to fulfil all the purposed objectives. During this research, we recognised some of the points that could improve the results of this measurement in future works. Those points are mentioned as future directions in this chapter.

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