SEARCH FOR $t\bar{t}Z' \rightarrow t\bar{t}t\bar{t}$ PRODUCTION IN THE MULTILEPTON FINAL STATE IN pp COLLISIONS AT $\sqrt{s} = 13$ AND 13.6 TEV WITH THE ATLAS DETECTOR

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A DISSERTATION

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ABSTRACT

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I dedicate this work to the Opossum and his noble pursuit of snacks.

ACKNOWLEDGMENTS

Una Salus Victis Nullam Sperare Salutem.

PREFACE

This is my preface. remarks remarks remarks

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Chapter 2. Theoretical Overview

2.1 The Standard Model

- SM describes fundamental forces & elementary particles

- more descriptions (a bit of history + recent developments - higgs & neutrino masses) - limitations: gravity & general relativity, arbitrary free parameters

2.1.1 Elementary particles

- Bosons (Bose-Einstein statistics, integer spin) & fermions (Fermi-Dirac statistics, half-integer spin)

- Fermions - building blocks: quarks & leptons [protons/neutrons constituents?]

- Bosons - force carriers & interaction mediators (elementary bosons == gauge bosons

(chart of elementary particles here)

Fermions

- elementary particles

- half-integer spin

Quarks

- building blocks for hadrons & bosons

- up down —— charm strange —— bottom top [by order of discovery and mass]

- charge doublets: +2/3 and -1/3 charge

- color charge & color confinement in hadrons

- interacts with all 4 fundamental forces

Leptons

- electron —— muon —— tau + neutrino [by order of mass]

- charge -1, neutrinos charge neutral

- interacts with all forces except strong, neutrinos only weak and gravitational

Bosons

- force mediators

- integer spin

Scalar

- spin 0

- Higgs massive, charge neutral, provides rest mass for all elementary particles,

Vector

- spin 1

- W/Z (weak), photon (QED/electrodynamic), gluons (QCD/strong)

- photon/gluon massless, charge neutral, gluon carries color charge out of 8 combinations of quark colors (color octet)

- W/Z massive, charged/neutral

2.1.2 Mathematical formalism

- QFT: treats particles as excitations of corresponding quantum fields: fermion field ψ, electroweak boson fields $W_{1/2/3}$ & B, gluon field G_α, Higgs field ϕ

- Lagrangian: gauge QFT containing local gauge symmetries of $SU(3)_C \times SU(2)_L \times U(1)_Y$ and global Poincar symmetry: translational symmetry, rotational symmetry & special relativity frame invariance

- Noether's theorem: local symmetries -¿ strong/weak/EM, Poincar ¿ momentum, angular momentum & energy conservation

- unexpanded Lagrangian with description of each part: kinetic terms, coupling terms, mass/Higgs terms)

Quantum chromodynamics

- strong interaction, $SU(3)_C$ gauge group under Yang-Mills theory

- C = color charge conservation

- QCD Lagrangian, expansion & brief explanation

Electroweak

- unified weak & electromagnetic interactions, $SU(2)_L \times U(1)_Y$ gauge group

- L = left-handed chirality ¿ weak isospin (I) conservation

- Y = weak hyper charge conservation

- Q = charge conservation = $I_3 + 1/2Y$

- QED Lagrangian, expansion & brief explanation

Higgs

2.1.3 Beyond the Standard Model

2.2 Four-top quark production

- Top: heaviest particle, strong coupling to many BSM particles in BSM models.

- 4top: xsec relevant to and enhanced by many BSM models

- Predicted by SM and observed [observation paper]

- Predicted xsec and observed xsec

- (insert Feynman diagrams)

- Decay products & final state topologies

Top-philic vector resonance

- Top-philic boson: simplified model, couples strongly to top and weakly to others

- color singlet vector boson (Z')

- (Lagrangian here)

- two body decay Z' into $t\bar{t}$ with $m_{Z'}$ in TeV range $\rightarrow$ top mass

- decay channels: $t\bar{t}Z'$ s & t channels, tWZ', tjZ'

- (Feynman diagrams here)

Effective field theory

2.3 Collider physics

[pp collision, pdf, cross section, luminosity]

Luminosity

Proton-proton collisions

jets, parton shower, hadronization

Parton distribution function

Cross section

Chapter 3. LHC & ATLAS Experiment

3.1 The Large Hadron Collider

theoretical predictions are tested with experimental data obtained from particle accelerators world's largest accelerator built by CERN situated on the border of Switzerland and France has been operating since xxxx

lifetime divided into 3 runs, currently on Run 3 with planned upgrades on the horizon

responsible for a number of discoveries aka Higgs, etc.

3.1.1 Overview

[Basic info: location, size, main working mechanism, main detectors, main physics done]

- 27km circumference, reusing LEP tunnels 175m below ground level

- 7-13-13.6 TeV center of mass energies for pp collisions

- other than pp, also collides pPb, PbPb at 4 points with 4 main detectors: ATLAS, CMS (general purpose detectors), ALICE (heavy ion physics, ion collisions), LHCb (*b*-physics)

3.1.2 Operations

- focuses mainly on pp collisions for this thesis - beams split into bunches of 1.1×10^{11} protons with instantaneous luminosity of up to 2×10^{34} cm^{-2}s^{-1}

- beam energies ramp up in other accelerators before injection, full ramp up to 6.5 GeV about 20 minutes

(insert full diagram of accelerator chain)

Linac 4: hydrogen atoms, accelerated up to 160 MeV

PSB: H atoms stripped of electrons before injection, accelerated to 2 GeV

PS: 26 GeV, SPS: 450 GeV

LHC: injection in opposite directions, 6.5 TeV per beam

Run 1: 2010-2012, Run 2: 2015-2018, Run 3: 2022-2025, HL-LHC: 2029-?

COM energies: 7 & 8 TeV, 13 TeV, 13.6 TeV, 13.6 & 14 TeV

inbetween periods: long shutdowns (LS1, LS2, LS3)

(add HL-LHC timeline graph)

3.1.3 Physics

top factory

Higgs studies (insert SM processes cross sections chart)

3.2 The ATLAS detector

[goals, coordinate system]

right-handed cylindrical system, z-axis follows beamline, azimuthal and polar (0 in the beam direction) angles measured with respect to beam axis.

pseudorapidity $\eta = -\ln \tan(\theta/2)$, approaches $\pm \inf$ along and 0 orthogonal to the beamline

distance $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

transverse momentum p_{T} component of momentum orthogonal to the beam axis

3.2.1 Inner detector

3.2.2 Calorimeter systems

3.2.3 Muon spectrometer

3.2.4 Forward detectors

3.2.5 Magnetic systems

3.2.6 Trigger & data acquisition

Chapter 4. Data & Simulated Samples

4.1 Data samples

[trigger selection] [other cuts made] [luminosity]

4.2 Monte Carlo samples

4.2.1 Simulation

[geant4, madgraph, pdf set, etc.]

4.2.2 Signal samples

4.2.3 Background samples

Chapter 5. Particle Reconstruction & Identification

5.1 Object reconstruction

5.1.1 Vertex & track reconstruction

5.1.2 Jets

5.1.3 Electrons

[isolation criteria along with muon]

5.1.4 Muons

5.1.5 Missing transverse momentum

5.1.6 Topological clustering

5.1.7 Pile-up & overlap removal

5.2 Particle identification

b-tagging

[details about optimization work & b-tagging calibration work]

Chapter 6. Event Selection

[event selection criteria]

6.1 Object definition

[lepton pt cut study here]

6.2 Background estimation

6.2.1 Fake & non-prompt leptons

6.2.2 Irreducible background

6.3 Analysis regions

6.3.1 Control regions

$t\bar{t}W$ **CRs**

6.3.2 Signal regions

[include blinding strategy]

6.3.3 Validation region

6.4 Signal extraction

SM MVA

BSM MVA

Chapter 7. Systematic Uncertainties

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Chapter 8. Results

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A.1 Statistical inference

A.2 Hypothesis testing

A.3 χ^2 template fitting