SEARCH FOR TTBAR RESONANCES IN THE ALL-HADRONIC CHANNEL WITH RUN 2 LEGACY DATASET

by

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Dedication

To my parents.

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Abstract

We present a search for new massive particles decaying to a $t\bar{t}$ pair with 2016, 2017 and 2018 ultra-legacy Run2 datasets at $\sqrt{s}\ = 13$ TeV. We consider a topology of fully hadronic top quark decay where each top quark's decay products are reconstructed within a single jet. We utilize deep neural network top tagging to improve our sensitivity to these objects. In addition to adding the full Run 2 dataset, additional dark matter interpretations are added that have not been investigated before by CMS.

Chapter 1

Introduction

1.1 Motivation

The standard model has satisfied experimental results in particle physics for 100 years. Many searches in particle physics seek to better understand this standard model, and to analyze theories that expand on it.

WIth the discovery of the electron in 1897, the field of elementary particle physics began to grow. The electron was the first of what we consider now to be fundamental particles - particles that have no known substructure or excited states. In the early 1900s, Rutherford, Marsden, and Geiger discovered that atoms have nuclei in the center of the atom. For this experiment, Geiger also developed the Geiger counter, as originally he had to count the alpha particles scattering onto the gold foil by measuring flashes of light by eye.

Radioactivity was discovered before the particles responsible for radiation were discovered. In 1896, Becquerel discovered radiation of “beta rays”, now known to be electrons. The gamma ray, or photon, was theorized by Planck to explain black body radiation, and alpha rays, used in the gold foil experiment to bombard nuclei, are bound states of two protons and two neutrons.

Elementary particle physics also gained the name “high energy experimental” physics, as scattering experiments became more common in the 1950s. These scattering experiments led to the discovery of hundreds of particles with short life spans. These new particles lacked a theory to explain them, or to predict future similar particles. Murray Gell-Mann developed a “quark model” theory to explain the new particles as “hadrons”, or bound states of the at the time three known quarks - the up, down, and strange quarks. Quarks were so named from a line in a James Joyce novel that contained the phrase “three quarks”. Three additional quarks have since been discovered.

In particle physics, spin is measured in units of $\hbar$. Electrons are spin ½ particles, and belong to a group called “fermions”, all with spin ½ particles. There are three generations of fundamental particles, with the first generation consisting of the up quark, down quark, electron, and electron neutrino. The first particle of generation greater than the first was the muon. Initially, it was mistaken for the pion, as the pion has a mass of 135 MeV and the muon a mass of 105.7 MeV. Further experiments showed that the new, higher generation particle did not interact hadronically, and so it must have been the second generation of the electron.

The fundamental forces in the Standard Model are the electromagnetic, weak, and strong forces. Gravity, which is weaker than the weak force by several orders of magnitude, does not have a place in our current Standard Model. Many searches in the current field of particle physics seek to unify our understanding of gravity with the Standard Model.

The electromagnetic and weak forces are united under the electroweak theory, which is a generalization of Quantum Electrodynamics (QED).

The force particles are guage bosons - spin 1 bosons that act as force carriers for the three fundamental forces. The massless photon carries the electromagnetic force. Gluons, of which there are 8 massless and neutral versions, carry the strong force. The weak force is carried by three particles - W^+, W^-, and Z^0.

Chapter 2

Theory

One of the most compelling questions in participle physics today is the hierarchy problem. The Randall Sundrum Kaluza Klein model proposes a solution in which the Planck scale is located on one membrane and the TeV scale a distance L away in a fourth spatial dimension.

2.1 Standard Model Particle Interactions

Particles interact by exchanging force particles, all of which are spin-1 bosons in the Standard Model. The force particles are excitations of their corresponding fields. For the electromagnetic field, the force particle is the photon. The cross section of an interaction between particles is proportional to the scattering amplitude. In the simplest case of an electromagnetic interaction, an electron and muon collide with each other and exchange a photon. The coupling strength of the electromagnetic interaction is e, and the scattering amplitude is $sin^{-4}(\frac{\theta}{/}2)$. This relationship to the scattering angle occurs because the mediation force particle is massless. In the weak force interactions, the mediating particle is not massless, since the mass of the Z boson is 91 GeV and the mass of the W boson is 80 GeV. Therefore, weak interactions are suppressed when $q^2 << M^2{}_W$.

Chapter 3

The CMS Detector

3.1 Introduction

The Large Hadron Collider (LHC) beam energy, originally at 7 TeV, now for Run 3 at 13.6 TeV, allows us to study physics at the highest energy scale in history. The collaboration also performs studies of heavy ions at 30x the energy of previous heavy ion experiments. With a luminosity for pp collisions 100x greater than previous experiments, and pp cross section of about 100 mb, measurements can be done to greater precision than ever before, and searches can probe the highest ever possible masses at the TeV scale.

The LHC contains multiple experiments. At opposite points of the collider, 27 km apart, sit the A ToroidaL ApparatuS (ATLAS) and Compact Muon Solenoid (CMS) experiments. The experiments perform similar searches and measurements without sharing preliminary results. This ensures a mitigation of biases from persons performing the analyses.

The CMS experiment has 5 layers. From innermost to outermost layer sits the tracker, the electromagnetic calorimeter, the hadronic calorimeter, the solenoid, and the muon chambers. The solenoid has a 4T magnetic field. It is 13 meters long with a 6 meter inner diameter. To keep the solenoid compact, the coil is wound 4 times over to generate the 4T magnetic field. The 4T field requires a large return yoke, and so 6 endcaps and 5 barrel wheels, weighing up to 1920 tons, make up the yoke. In order to slide the solenoid in and out of the detector, the solenoid is placed on a system of air pads and grease pads that can slide the solenoid a total of 11 meters into or out of the detector. The process of sliding the solenoid 11 meters takes 1 hour to complete.

The superconducting solenoid needs to be cooled to temperatures between 4.5K and 80K. To do this, liquid helium is used and the solenoid is insulated with a 40 m^3 vacuum chamber. The solenoid is built to withstand a misalignment up to 10 mm between the coils and the return yoke.

The CMS solenoid is 13m long with a 6m bore diameter. The tracker, ECAL, and HCAL are situated within the bore. Due to the number of turns needed to generate a 4T magnetic field, and due to the compact nature of CMS, the solenoid is wound in 4 layers.

3.2 The Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) surrounds the tracker. Its purpose is to absorb the energy from electrons and photons, and was built with the motivation of detecting the decay of two photons for Higgs boson searches. The ECAL is composed of thousands of lead tungstate ($PbWO_4$) crystals, which are mounted on a barrel layer and two endcaps. Before the endcaps, a preshower made of two planes of lead reduces false signals.

Lead tungstate crystals are useful in a compact detector because they are radiation-hard and have a small radiation length and small Moliere radius. Additionally, the scintillation decay time of lead tungstate is approximately 25ns, which is the same as the bunch crossing separation in the LHC. The barrel receives the particle data through avalanche photodiodes, which apply a reverse bias voltage to get a current gain effect of about 50. The endcaps use vacuum phototriodes, which are photomultipliers with a single gain state. The vacuum phototriodes usee in the ECAL were developed specifically for CMS, and are useful in the endcaps because they are more radiation resistant than diodes.

The barrel of the ECAL covers $|\eta| < 1.479$, and the endcaps cover $1.479 < |\eta| < 3.0$. Water cools the submodules containing the crystals at a temperature of 18°C.

The energy resolution in the ECAL is described by Equation 3.1.

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}} + \left(\frac{N}{E}\right)^2\right)^2 + C^2 \tag{3.1}$$

S is the stochastic term, and is comprised of photostatistics (about 2.1%), fluctuations in energy deposited in the preshower (about $5\%/\sqrt{E}$), and fluctuations in the lateral shower containment (about 1.5%). N is the noise term, and is comprised of electronics, digitization, and pileup noise. C is the constant term, and is made up of leakage from the back of the crystals, intercalibration errors, and non-uniformity in light collection, the last being less than a 0.3% contribution.

3.3 The Hadron Calorimeter

The Hadron Calorimeter (HCAL) is designed to absorb the energy from the hadronic particles. It is split in four sections: the barrel (HB), the endcap (HE), the outer calorimeter (HO), and the forward calorimeter (HF). The barrel (HB), covers $|\eta| < 1.3$, and the endcaps (HE), cover $1.3 < |\eta| < 3.0$. The HB is a sampling calorimeter of absorber (bronze) and scintillator (plastic). The brass absorber is divided into 36 wedges in ϕ. The plastic scintillator is divided into 16 sectors in η.

The HCAL has a limited distance between the ECAL and the solenoid to absorb the hadronic particles. For particles that are unable to be stopped in that distance, an outer calorimeter is placed outside the solenoid in the central eta region.

The HF has to withstand very high flux of particles. To handle this, quartz fibers are used as the calorimeter medium.

3.4 The Tracker

At the innermost layer of the detector, held within the 6 meter bore of the solenoid, sits the silicon tracking system. WIth 1000 particles from 20 overlapping collisions bombarding the detector every 25 ns, the tracker needs a high power density system to accurately and precisely measure the tracks of individual charged particles. The high energy particles subject the electronics to high radiation levels. To withstand this over a length of time of now over a decade, silicon was used. The tracker is composed of an inner 3 layers pixel detector, with 10 barrel layers of silicon strip tracking. The tracker was built over the course of over a decade, with the input of hundreds of particle physicists from 51 institutes, including the University at Buffalo.

The information from the tracker is vital to the high level trigger (HLT) decisions, which reduce the rate of incoming collisions data by a factor of 400.

Chapter 4

Particle Flow

4.1 Introduction

Chapter 5

Search for ttbar resonances in the all-hadronic channel with Run 2 legacy dataset

Bibliography