

A SEARCH FOR THE STANDARD MODEL HIGGS DECAYING TO TWO MUONS AT THE  
CMS EXPERIMENT

By  
ANDREW CARNES

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A SEARCH FOR THE STANDARD MODEL HIGGS DECAYING TO TWO MUONS AT THE  
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By

Andrew Carnes

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In 2012 two collaborations at the Large Hadron Collider announced the discovery of a new particle with properties similar to the Standard Model Higgs Boson. In order to determine whether the boson discovered with a mass of 125 GeV is actually the Standard Model Higgs, all of the different ways the particle can decay need to be investigated. If the probabilities for the different decays do not match the predictions of the Standard Model then this would imply new physics.

This dissertation presents the search for the Standard Model Higgs Boson decaying to  $\mu^+\mu^-$ . The search uses the  $35.9 \pm 0.9 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-proton collision data recorded by the CMS detector in 2016. The observed and expected upper limits on the rate at a 95 % confidence level are presented for Higgs masses in the range 120 to 130 GeV. The expected and observed upper limits at a mass of 125 GeV are  $x.xx$  and  $1.98^{+0.81}_{-0.57} \times \text{SM}$  respectively. These results provide the best results to date on the Higgs coupling to second generation fermions. No deviations from the Standard Model are observed.



## CHAPTER 1 INTRODUCTION

The Standard Model of particle physics is an extremely successful theory shown to correctly predict the behavior of the particles and forces which make up the most basic constituents of the universe. In fact, it correctly describes all of the forces known except for gravity. All of the elementary particles detailed in the Standard Model have been discovered except for one, the Higgs boson. As explained by special relativity, potential energy can be realized as mass and it is the potential from the interaction with the nonzero Higgs field that bestows mass onto the massive elementary particles in the Standard Model. On July 4, 2012 two collaborations at the Large Hadron Collider (LHC), the ATLAS and Compact Muon Solenoid (CMS), announced the discovery of a new boson at 125 GeV with properties similar to the Standard Model Higgs  $???$ . This discovery was fueled by the investigation into the Higgs decays to the vector bosons  $ZZ$  and  $\gamma\gamma$ . Soon after, evidence for the Higgs coupling to matter was found through the  $\tau^+\tau^-$  and  $b\bar{b}$  decays  $????$ . Whether the newly discovered boson is indeed the expected Standard Model Higgs remains to be determined. Insofar, all of the different decay modes will be investigated to search for deviations from the Standard Model predictions.

This leads to the study of the Higgs decay to  $\mu^+\mu^-$ . Although this decay is the smallest branching fraction expected to be detected  $??$ , the dimuon decay offers high efficiency and excellent momentum resolution, which should lead to a narrow peak over the falling background, mostly Drell Yan events. The tiny branching fraction enables greater sensitivity to small deviations from the predicted decay rate and in this respect offers an advantage over other channels where a miniscule deviation could be drowned out. Furthermore, the Higgs coupling to second generation fermions remains to be determined.

This dissertation presents the search for the Standard Model Higgs Boson decaying to  $\mu^+\mu^-$  using the proton-proton collision data recorded by the CMS experiment in 2016. In order to maximize the data available for the search, the first machine learning in the L1 Trigger

system at the LHC was developed and deployed for 2016 data collection. To further maximize the sensitivity of the search, an additional machine learning technique is invented to categorize events based upon the detector resolution and the event kinematics. The search looks for a Higgs boson with a mass between 120 and 130 GeV and presents the expected and observed upper limits in this range.

The dissertation first presents an overview of the Standard Model and the symmetry breaking mechanism within the theory responsible for the Higgs. After covering the theoretical basis for the Standard Model Higgs, the accelerating apparatus responsible for accelerating and colliding the protons, the LHC, is covered. Then the CMS detector responsible for measuring the paths, momentum, and energy of the particles emerging from every collision is reviewed. Next the machine learning implementation in the L1 trigger that enables the detector to save more of the relevant collisions data is detailed. After, the search for  $H \rightarrow \mu^+ \mu^-$  is presented and then finally the conclusions.

## CHAPTER 2 THE LARGE HADRON COLLIDER AND THE CMS EXPERIMENT

### 2.1 Large Hadron Collider

The Large Hadron Collider is a particle collider near Geneva, Switzerland run by the European Organization for Nuclear Research (CERN). The LHC is the largest and most powerful particle collider ever built, designed to collide protons with a center of mass energy of 14 TeV and a luminosity of  $10^{34} \text{cm}^{-2} \text{s}^{-1}$  ?. The luminosity is given by

$$L = \frac{n_b f N_p^2 \gamma}{4\pi \epsilon_n \beta^*} \quad (2-1)$$

where  $n_b$  is the number of bunches in each ring,  $f$  is the frequency for a bunch to circle the ring,  $N_p$  gives the number of protons in a bunch, and  $\gamma$  is the Lorentz factor.  $\epsilon_n$  is the normalized transverse emittance, a measure of the spread of the beam in momentum and position space.  $\beta^*$  measures the focus of the beam at the interaction point.  $\epsilon_n \beta^*$  represents the transverse area at the point of interaction. A large luminosity is characterized by a high frequency of bunch crossings with lots of protons in each bunch packed as densely as possible, and a large luminosity results in a high rate of collisions. With many collisions at high energy, the detectors can collect enough events from yet unexplored regimes of physics to discover new physics or to verify or discard the predictions different hypothesis, so these parameters are very important.

The collider itself is 26.7 km in circumference 45-170 m underground. 8.3 T supercooled superconducting magnets operating at 2 K steer the high energy proton beams. In order to save money the LHC not only reuses the tunnels of a previous collider, the Large Electron Positron Collider (LEP), but also reuses older accelerators which were state of the art at their time. These older accelerators ramp up the energy of the protons and inject them into the LHC. All of this together makes up the CERN accelerator complex.

First, the protons are created from a source of Hydrogen gas. The hydrogen atoms of the gas are placed into a large electric field that separates the atoms into unbound protons

## CERN's Accelerator Complex



Figure 2-1. The CERN Accelerator Complex ?

and electrons. The protons are then sent to a radio frequency quadrupole which focuses the protons and accelerates them. The radio frequency field is stronger for the protons in the back than in the front and consequently squeezes them into a tighter bunch. The protons then proceed to a linear accelerator, LINAC2, where they are accelerated to 50 MeV or 5% of the speed of light ( $c$ ). The protons then enter a series of synchrotrons. A synchrotron is a device that accelerates particles by guiding them around a fixed circular path with a magnetic field and boosting their speed with an electric field as they pass a certain point. Since a faster particle bends less in the same magnetic field, the magnetic field strength is synchronized with the speed of the accelerating particles to keep them in the fixed circular path.

After LINAC2 the protons enter the first of the synchrotrons, the Proton Synchrotron Booster (PSB) accelerating the protons to 1.4 GeV ( $0.81c$ ). From here the protons are injected into the Proton Synchrotron (PS) and accelerate to 25 GeV ( $0.999c$ ). The PS then injects

the protons into the Super Proton Synchrotron (SPS) further accelerating them to 450 GeV (0.999999c). Finally the protons are injected into the LHC where they accelerate up to 6.5 TeV (0.999999999c). Once accelerated to the appropriate collision energy, the proton beams are made to collide in the different detectors located around the ring. By colliding enough protons at large enough energies it is possible to probe corners of physics that have never been seen before. The two general purpose detectors at the LHC, ATLAS and CMS, are used to look for signs of new physics like the Higgs boson, dark matter, and extra dimensions by measuring the energy, the momentum, and the paths of the particles coming out of the collisions.

## 2.2 Compact Muon Solenoid Detector

The CMS detector, located in Cessy, France, is 21.6 m long, 15 m in diameter, and weighs more than the Eiffel Tower. Not only is the detector a massive and complex device it's also run by a huge collaboration involving approximately 3,800 people from 200 institutes spanning 43 different countries ?. The greatest achievement of the collaboration to date is the discovery of a Higgs like particle in 2012, a feat shared with ATLAS.



Figure 2-2. The CMS detector ?

CMS was built primarily to look for the Standard Model Higgs and signs of Beyond Standard Model (BSM) physics like Supersymmetry, extra dimensions, or new heavy weak bosons ?. Because BSM and Higgs decays to muons and electrons often have the highest

signal to background ratio, CMS is designed to identify and measure these particles with a high accuracy. In layman's terms a high signal to background ratio just means that these events have fewer look-alikes. Jets <sup>1</sup> and photons are measured to a high degree of accuracy as well. In order to measure the energy, momentum, and location of the different types of particles CMS deploys a variety of subdetectors working in concert. The defining feature of the detector is an extremely powerful solenoid which enables the accurate measurement of momentum for charged particles. The tracker and calorimeters fit snugly within the 6 m diameter solenoid. The muon detectors reside outside the magnet but within the return yoke.

### 2.2.1 Silicon Tracker

The 3.8T magnetic field inside the solenoid enables the tracker to measure the transverse momentum of charged particles based upon the curvature of the track. Charged particles with lower transverse momentum ( $p_t$ ) bend more in a magnetic field than high  $p_t$  particles. As such, a measurement of the deviation of a curved track from a straight line, the sagitta, can be used to measure the curvature and determine the momentum ?.

$$p_t \cong \frac{L^2 q B}{8s} \quad (2-2)$$

Here L is the length of the straight line between the first and last position measurements, q is the charge of the particle, B is the magnetic field, and s is the sagitta.

The equation for the error in the momentum measurement shows that a higher magnetic field enables better  $p_t$  resolution, illuminating the design choice for a powerful magnet.

$$\frac{\delta p_t}{p_t} \propto \frac{p_t}{L^2 B} \quad (2-3)$$

---

<sup>1</sup> When a quark or gluon is created it can't exist alone, since it has color charge, and pulls other quarks from the vacuum creating a tight cone of composite colorless particles as well as their decays. This cone of particles is called a jet.



Figure 2-3. The sagitta measurement

The silicon tracker is made of tiny reverse biased bipolar diodes. When a charged particle travels through one of these diodes the ionization force of the particle releases electron hole pairs beyond the electrostatic equilibrium, inciting a current to flow. The tracker needs to be small enough such that the particles flowing through it don't deposit much energy. Energy deposition in the tracker would throw off energy measurements in the calorimeters. This means that the tracker needs to be smaller than a few radiation lengths <sup>2</sup>. The tracker at the thickest part is one radiation length. The tracker is placed nearest the collision point in order to identify primary and secondary vertices and to measure the momentum of particles before they are tainted by interactions with other detectors. <sup>3</sup> Being so near the collision point, the silicon tracker is bombarded by a constant flux of high intensity radiation. As such, the tracker is carefully designed to be robust to this radiation rich environment.

### 2.2.2 Calorimeters

The Electromagnetic Calorimeter (ECAL) is right outside the tracker and its main goal is to measure the energy of electrons and photons. It's designed to contain entire electromagnetic

---

<sup>2</sup> the length scale over which an electron deposits a substantial amount of energy into the material

<sup>3</sup> Vertex is shorthand for the location of the collision or decay that produced a set of particles.

showers for these particles and is consequently many radiation lengths thick. The ECAL is made of lead tungstenate scintillating crystals which release an amount of light proportional to the energy deposition. The light is collected and the total energy is calculated. The separation into individual crystals allows some spatial resolution as well. Particles with larger mass deposit less energy per unit distance into a solid. Many of the hadronic particles make it through the ECAL for this reason.



Figure 2-4. A slice of the CMS detector ?

The HCAL is placed outside the ECAL to collect the energy of the particles that survived the other subsystems, mostly strongly interacting hadronic particles from jets. The HCAL works in a similar manner to the ECAL except that layers of plastic scintillating material are interspersed with layers of a dense passive absorber like brass or steel. The density of the passive absorber increases the chance of interaction and shower production thus reducing the total length of the hadronic shower and enabling the measurement of the total energy for most of the cascades. Again the scintillation light is collected to determine the energy. If the ECAL and HCAL were placed outside the magnet the particles would interact with the solenoid material before entering the calorimeters, throwing off their measurements. The showers in the calorimeters are a consequence of the electromagnetic and strong forces, which means that particles without these interactions pass through the materials undetected, e.g. neutrinos or BSM weakly interacting particles. Since the momentum in an interaction is conserved any imbalance means that some particles escaped the detector. If there is an excess of missing



momentum beyond the amount expected due to neutrinos this may indicate the existence of dark matter or some other BSM particle. In order to measure the missing energy correctly it's important that the HCAL is built without any gaps and that it is dense enough to collect the energy of the strongly and electrically interacting particles.

While the momentum resolution in the tracker is proportional to the momentum, the energy resolution in the calorimeters decreases with increasing energy ?.

$$\frac{\delta E}{E} = \sqrt{\left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C} \quad (2-4)$$

The first term in the square root describes statistical fluctuations. The energy measured is proportional to the number of photons captured which has poissonian fluctuations and the error ( $\delta E$ ) for this term is  $\propto \sqrt{E}$ . The second term describes noise in the electronics whose error is energy independent, and the last term describes the errors in energy calibration which are proportional to energy.

### 2.2.3 Muon System

Neutrinos aren't the only Standard Model particles that make it through the tracker, ECAL, and HCAL. Muons have a relatively long lifetime  $\sim 10^{-6}s$  with  $c\tau \sim 100m$ . The large gamma factor in combination with their long lifetime enables them to travel hundreds of kilometers on average, well through the entire CMS detector before decaying. Muons are charged so their tracks show up in the tracker and some energy is deposited in the calorimeters but, muons are so much more massive than electrons that the energy deposition in the ECAL is minimal. Making it through the ECAL the muons enter the HCAL. The HCAL is designed to stop strongly interacting hadronic particles and collect their energy. But muons don't interact with the strong force and make it through the HCAL as well. This enables the muon system to be placed outside the magnet.

The muon system consists of a few different types of detectors which all involve the same basic principle. The charged muon ionizes some gas and the ionized particles are attracted to charged surfaces initiating a current in the surfaces. With a large enough voltage differential

between the charged surfaces the ionized particles may gain enough kinetic energy to further ionize other atoms in the gas initiating an avalanche effect and reducing the need for signal amplification later. The muon system uses this strategy in the different detectors. The types of detectors in the muon system are the Cathode Strip Chambers (CSC), the Drift Tubes (DT), and the Resistive Plate Chambers (RPC) ?.



Figure 2-5. A Look at the Muon System ?

### 2.2.3.1 Drift Tubes

The drift tubes are located in the barrel portion of CMS. Throughout the majority of the barrel the magnetic field is basically uniform. The drift tubes have aluminum plates on the top and bottom separated by aluminum I-beams shown in Figure 2-6. A wire acts as the anode and the I-beams are the cathodes. The tubes are designed to provide a constant drift velocity throughout each tube.



Figure 2-6. A Drift Tube ?

When a charged particle flies through the tube it ionizes the gas inside. The electrons drift at constant velocity to the anode. The distance from the anode is deduced from the drift time, utilizing the fact that the ionized electrons drift with a constant velocity. This calculation does however require a reference time. In each chamber the drift tubes are placed in layers and the average crossing time in the chamber is used as the reference time.

### 2.2.3.2 Cathode Strip Chambers

The CSCs are located in the endcaps of the detector which range in  $|\eta|$  from 0.8 to 2.4. One of the reasons the endcaps use CSCs instead of DTs is the nonuniform magnetic field which would adversely affect the drift times in the DT system. In this system there are oppositely charged strips and wires running roughly perpendicular to each other.

When a muon flies through the CSC it induces charge on the wires and the strips and ionizes gas in the chamber. The ionized particles in the gas float to the charged strips and wires initiating a current in the nearby wires and strips. The induced charge from the muon itself also contributes to the currents. The most intense currents should be those associated with the location of the muon. The position resolution in the phi direction is roughly  $100 \mu\text{m}$ .



Figure 2-7. A Cathode Strip Chamber ?

### 2.2.3.3 Resistive Plate Chambers

The RPCs are located both in the barrel and in the end caps. The RPCs have excellent timing resolution on the order of 1 ns. The RPCs use their excellent timing resolution to determine each particle's bunch crossing of origin. The accurate and rapid timing information helps with the online selection of muons, a huge priority for CMS considering that many interesting collisions produce muons. For this reason the RPCs focus on efficient online selection of muons instead of accurate offline reconstruction ?.

In this way the RPCs complement the DTs and CSCs. The RPCs consist of two high resistance parallel plates surrounding a volume of gas. The outsides of the plates are painted with graphite paint forming the electrodes. A large voltage differential is kept between the electrodes. When a charged particle crosses the plates it induces an electrical discharge in the plates which remains localized in time and space due to the large resistivity.

### 2.2.4 Trigger System

Collision events come at a rate of 10 MHz with each event taking up roughly a MB of information. If the detector had to store all of the information from each event this would amount to pushing terabytes of information into a storage system every second, which is remarkably infeasible. To deal with this issue CMS utilizes a trigger system, which selects only

interesting events cutting the rate down from 10 MHz to 1 KHz ?. Since bunch crossings happen every 25 ns the trigger needs to operate at an incredibly high rate.

CMS tackled this issue by dividing the trigger into different tiers. The Level 1 Trigger is the first stage of the trigger system made from custom hardware which can operate at fantastic speed. The Level 1 Trigger reduces the rate from 10 MHz to 100 KHz and the events passing the L1 Trigger go onto the High Level Trigger (HLT) which further reduces the rate to 1 KHz. Due to the lower input rate the HLT can operate in software.

#### **2.2.4.1 L1 Trigger**

The L1 Trigger is made of up different subsystems that work together to decide whether to keep the data from a beam crossing for further processing. The University of Florida works with the Level 1 muon trigger system, the Endcap Muon Track Finder (EMTF) in particular. The muon system needs to determine the transverse momenta of muons and their location and choose the best candidates. Each of the different muon detectors have their own local triggers which send their best muon tracks to the Global Muon Trigger (GMT). The GMT chooses the best muon candidates from that set and passes these on to the Global Trigger (GT). The GT combines the information from the calorimeter triggering system. The GT uses this combined information to check whether the bunch crossing should be sent to the HLT or discarded. The L1 Trigger has many different trigger criteria defining separate triggers which are the trigger bits. If an event passes any of the triggers then it is forwarded for further processing.

The Track Finders (TF) play an important role in the L1 Trigger system. The EMTF combines the location and direction information from the different CSC stations into muon tracks and calculates the transverse momenta for the different tracks. The EMTF chooses the best candidates (highest momentum and highest quality) to send to the GMT. The Drift Tube Track Finder (DTTF) performs a similar process for muons in the DT system. The RPC system calculates the location and direction and forms tracks in the same stage. In the process the RPC trigger system assigns transverse momenta and quality, and like the others chooses the best tracks to send to the GMT.

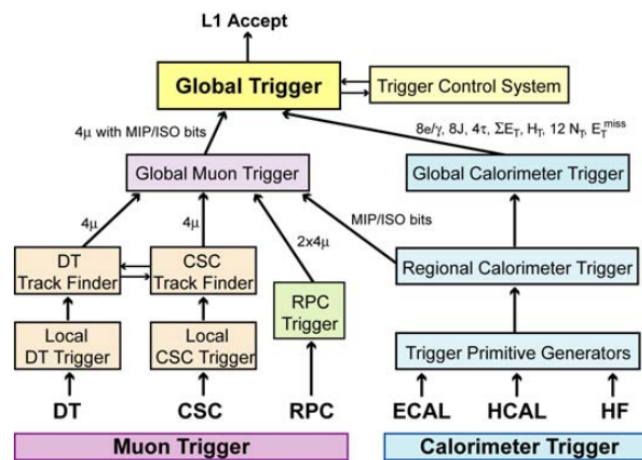


Figure 2-8. The L1 Trigger Architecture ?

## CHAPTER 3

### THE STANDARD MODEL

The Standard Model (SM) of particle physics is an incredibly successful theory that correctly describes the physics of all known particles and forces that make up the universe, excluding gravity<sup>1</sup>. The particles of the SM come in two types, fermions and bosons<sup>1</sup>. Fermions are the spin 1/2 particles and make up the different types of matter. Electrons are a familiar example, and the up and down quarks that make up protons and neutrons are some other examples of fermions. While electrons and the up and down quarks account for nearly all of the matter in our day to day experience there are actually many other fermions. In fact, there are three generations of quarks and leptons<sup>2</sup> with each generation heavier than the next. The up and down quarks are the first generation of quarks, charmed and strange are the next, and top and bottom are the third generation. For the leptons the electron and electron neutrino are the first generation, the muon and muon neutrino are the second, and the tau and the tau neutrino the third. Each fermion also has a corresponding antiparticle. As an example, the positron is the antiparticle for the electron.

The universe would be pretty boring if the particles couldn't attract or repel or form more complex objects like atoms, molecules, and even people. Luckily there are forces as well and these forces are described by the spin 1 bosons. The fermions attract and repel by exchanging bosons, which is why the bosons are often called force carriers. Gluons mediate the strong force, photons the electromagnetic force, and the W and Z bosons mediate the weak force. Every force has an associated charge. Just as those particles with electric charge can interact through the electromagnetic force, those with color charge may interact via the strong force, and those with isospin may interact through the weak force. The fundamental forces and particles interact to make the familiar composite objects that surround us in our daily lives.

---

<sup>1</sup> Bosons have integer spin.

<sup>2</sup> Leptons are fermions that aren't quarks.

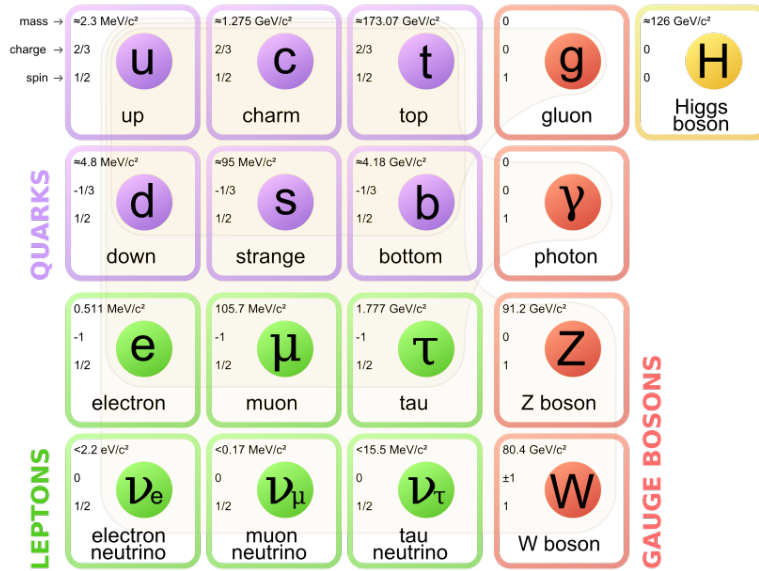


Figure 3-1. The Standard Model Particles

The strong force binds quarks to form protons and neutrons, the Van Der Waals version of the strong force binds the protons and neutrons together to form nuclei, and the electromagnetic force binds electrons and nuclei to form atoms. The size of the composite objects gives an idea of the relative strength of the forces. A proton is  $10^{-15}$  meters in size while an atom is  $10^{-10}$  meters and a solar system is  $10^{12}$  meters. The more tightly bound the stronger the force. In fact the ratio of the strength of the forces is like so  $1:10^{-3}:10^{-16}:10^{-41}$ , strong : electromagnetic : weak : gravitational<sup>3</sup>.

Of all the particles predicted by the SM, only the Higgs boson remains to be found. The Higgs boson is the only spin 0 particle of the SM. It is theorized that as the universe cooled from the Big Bang the Higgs field went through a phase transition and settled into a nonzero ground state forming a condensate. And it is the potential energy from the interactions with this ground state that give the massive fundamental particles their mass. With such a large role in the SM, finding this particle or a BSM Higgs has been a huge priority for the CMS

<sup>3</sup> Gravity is just included for perspective. The Standard Model does not describe this force and reconciling gravity with quantum mechanics is an open problem.



collaboration ?. In 2012 a Higgs particle with a mass of 125 GeV was found and to date remains consistent with the Standard Model. However, the properties need to be investigated further before declaring the discovered Higgs the Higgs of the Standard Model.

### **3.1 Quantum Field Theory**

The mathematical framework used to describe the physics of the SM as well as other Beyond Standard Model (BSM) field theories is called Quantum Field Theory (QFT). QFT enables the predictions of measurable quantities, namely the probabilities for different sets of particles to come out of a specific collision or for a single particle to decay into different sets of particles. These probabilities are encompassed in the cross sections and branching fractions. For example, the theory of the SM predicts the cross section for two protons colliding and making a Higgs. As another example, the SM also predicts the branching fraction for a Z boson decaying to two muons. These probabilities can be measured simply by colliding particles and counting the outcomes which in turn means that the theory can be tested. In fact, any QFT model can be tested in this manner. There are other commonly measured properties as well like the lifetime, spin, and mass of different particles.

#### **3.1.1 What is a Particle?**

Consider an observer in a frame  $x$  with particle  $p$  and an observer in another frame  $x'$ . If the observer in  $x'$  can't identify particle  $p$  then it doesn't make sense to call  $p$  a particle. More concretely, consider a world where in frame  $x$  an observer sees a neatly stacked deck of cards, but in  $x'$  the observer sees the cards scattered all over the place. Calling the deck of cards a particle doesn't really make sense. On the other hand, both parties can still agree on the individual cards which kept the same suit and value. These are conserved quantities. If the two observers get together later and compare notes they can see what happened to each card upon transforming from  $x$  to  $x'$  and work out a set of rules. The king of hearts may do one thing and the 10 of clubs another. They can then add the different forces into play repeat the process and compare again. Figuring this all out determines the laws of physics for the fundamental pieces called particles.

This idea leads to Wigner's view: a particle is an object with conserved quantities that observers can agree on between frames. In our universe these labels are the mass, charge, spin, color, and isospin. And because different observers can agree on these quantities they can compare notes and work out the laws of physics for the different types of particles. All that remains is to work out laws that people in different frames can confirm.

### 3.1.2 The Lagrangian Formalism

This section covers the Lagrangian formalism that allows physicists to describe the evolution of a physical system over time. A simple example of the free Newtonian particle is given and different symmetries are observed. The most important of which is the fact that the laws of physics are indistinguishable in different inertial frames. Using this as a postulate along with the requirement that the speed of light remain constant in all frames of reference, QFT will then be built.

The goal of physics is to describe how a physical system evolves over time. The evolution over time is usually given by some differential equation describing the state the system will take in the next interval of time given the current time. Moving from state to state from one interval of time to the next, the system traces out some path in space and time or some other more abstract space of possible states. As it turns out nature tries to minimize the difference between the energy spent <sup>4</sup> and the energy available to spend and it minimizes the action  $S$ . In the equation below,  $L$  is the Lagrangian,  $T$  is the kinetic energy and  $U$  is the potential energy.

$$S = \int L dt = \int T - U dt \quad (3-1)$$

At an extremum of  $S$ ,  $\delta S = 0$  since  $S$  must go down and back up or vice versa. So to get the equations of motion just vary the parameters of  $L$  and solve for the values that yield zero change in the action.

---

<sup>4</sup> Spent here just means used as kinetic energy.

$$\delta S = \int L(z_1 + dz_1, z_2 + dz_2, \dots) dt - \int L(z_1, z_2, \dots) dt \quad (3-2)$$

This will yield the Euler-Lagrange equations, describing how the parameters  $z$  evolve over time. The  $z$ 's may be the position and velocity, or the quantum fields, or the temperature and volume or some other set of parameters that describe the system. The Lagrangian for a Newtonian free particle in one dimension is pretty simple and gets the point across.

$$S = \frac{1}{2} \int m \dot{x}^2 dt \quad (3-3)$$

If the action is at an extremum, perturbing the path  $x(t)$  by adding the infinitesimal  $\epsilon(t)$  leaves the action unchanged.

$$S' = \frac{1}{2} \int m(\dot{x} + \dot{\epsilon})^2 dt = \frac{1}{2} \int m(\dot{x}^2 + 2\dot{x}\dot{\epsilon} + \dot{\epsilon}^2) dt = \frac{1}{2} \int m(\dot{x}^2 + 2\dot{x}\dot{\epsilon}) dt \quad (3-4)$$

$$\delta S = S' - S = 0 = \frac{1}{2} \int m(\dot{x}^2 + 2\dot{x}\dot{\epsilon}) dt - \frac{1}{2} \int m\dot{x}^2 dt = \int m\dot{x}\dot{\epsilon} dt \quad (3-5)$$

Integrating by parts yields.

$$\delta S = 0 = \int m\ddot{x}\epsilon dt \quad (3-6)$$

And this equation must be zero for any small deviation  $dx$ .

### 3.1.3 QFT From Symmetry

### 3.1.4 Perturbation Theory

### 3.1.5 Feynman Rules

## 3.2 The Standard Model Higgs

### 3.2.1 SM Higgs Production and Decay Modes

The SM Higgs can be created in a variety of ways. Some of these cross sections are shown below for 14 TeV collisions. The production cross sections are functions of the mass of

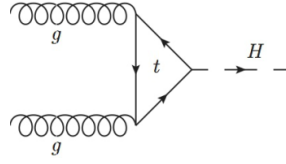


Figure 3-2. The Feynman diagram for two gluons fusing into a Higgs. There are three vertices and this is a third order diagram. Two vertices involve the strong force and one vertex involves the Higgs coupling. The matrix element for this diagram would have two factors of the strong force coupling and one factor for the Higgs coupling which involves the mass of the top quark.

the Higgs as well as the energy of the collisions. For a given collision energy the cross sections decrease as the Higgs mass increases: there are fewer kinematic possibilities for a heavier particle since more of the energy was used to create the particle. For a given mass, say 125 GeV, the cross section grows with collision energy. This contrasts with cross sections involving collisions of fundamental particles, e.g. electron antielectron collisions. This is an artifact of the fact that the LHC collides protons together.

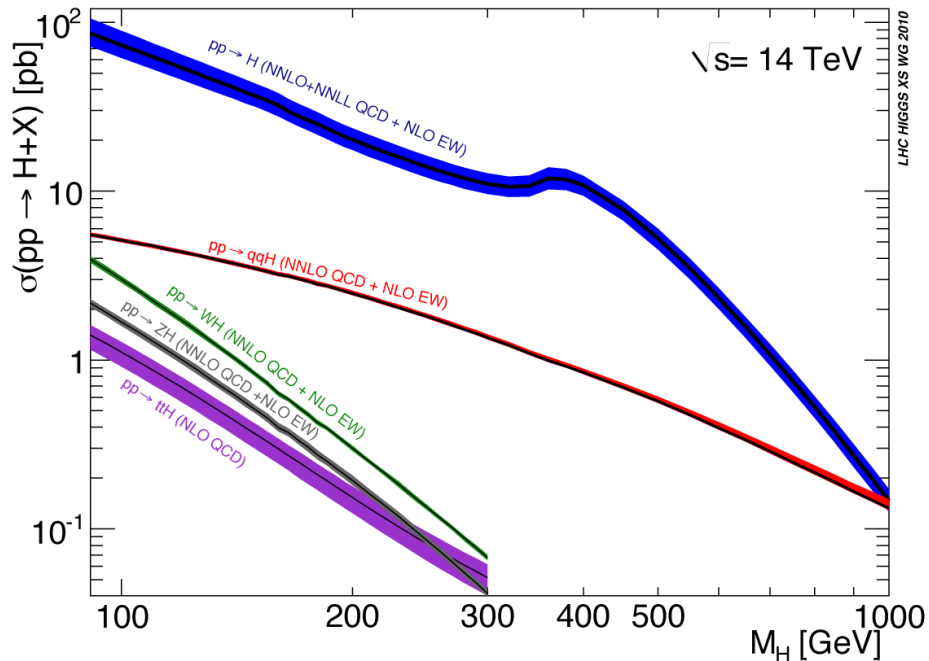


Figure 3-3. The highest production mode cross sections for the SM Higgs ?

Protons behave like a collection of an infinite number of quark-antiquarks, an infinite number of gluons, and the usual uud. The total momentum of the proton is divided up amongst them with lots of particles having little of the total momentum. The actual scattering events are between these more fundamental particles. The larger the total energy the smaller the fraction of energy needed to make a Higgs and since there are more particles with a lower fraction, this results in a growth of the cross section with collision energy.

The SM Higgs is unstable and decays with a width of  $\sim 5\text{MeV}$  at 125 GeV. The probability of each decay changes depending upon the mass of the Higgs. In general the Higgs couples more strongly to particles with higher mass making the decays to heavier particles more likely.

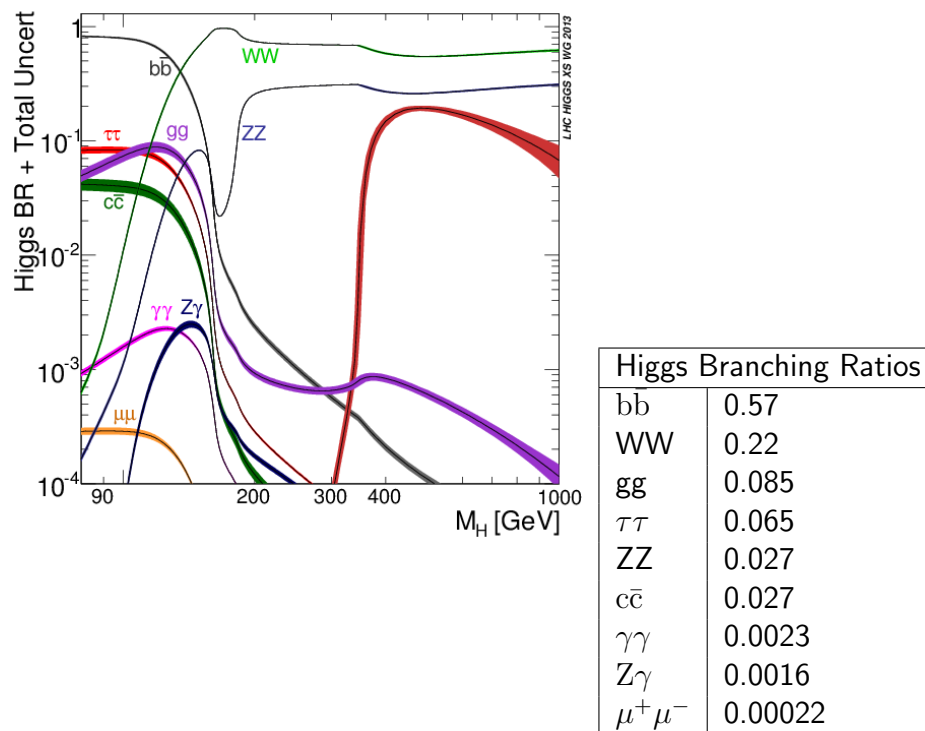


Figure 3-4. The graphic on the top left presents the SM Higgs branching fractions as functions of mass while the table on the bottom right displays the branching fractions for a 125 GeV SM Higgs ?.

The muon has the lowest mass – excluding the photon and gluon – of the particles in Figure 3-4 and consequently  $H \rightarrow \mu^+ \mu^-$  has the lowest branching fraction in the set.<sup>5</sup> The gluons and photons are massless and do not couple to the Higgs at leading order. These massless vector bosons interact with the Higgs through a loop of top quarks. The extremely heavy mass of the top quark, about 173 GeV, balances the fact that the loop production is a higher order mechanism.

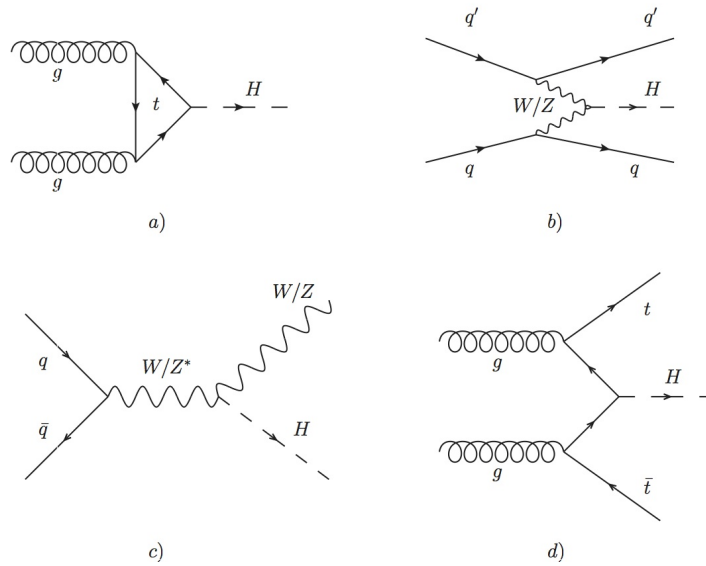


Figure 3-5. The SM production modes with the highest cross sections. a) Gluon Gluon Fusion (GF) b) Vector Boson Fusion (VBF) c) Associated Production with a Vector Boson (VH) d)  $t\bar{t}H$

The Higgs to massless vector boson coupling via the top loop is seen in the GF Feynman diagram in Figure 3-5. At  $M_h = 125$  GeV,  $\sqrt{s} = 13$  TeV, the GF channel comprises 87% of the total Higgs production cross section, VBF 7%, VH 4%, and  $t\bar{t}H$  1%<sup>?</sup>. Besides  $t\bar{t}H$ , the process  $q + \bar{q} \rightarrow H$  isn't considered due to its low cross section. The low masses of the other quarks suppress the process.

<sup>5</sup> The Higgs also couples to the electron and the first generation quarks but the masses are so light that CMS does not expect to see the SM Higgs in those modes.

Quark gluon (qg) scattering is a major background for the Higgs to two jets decays since the process closely resembles GF in this mode.

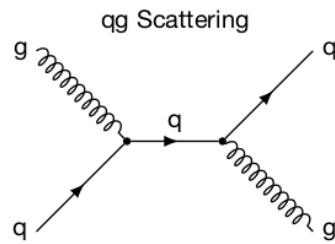


Figure 3-6. Quark gluon scattering creates many two jet events. This background looks very similar to GF when the Higgs decays to two jets. The colliding protons are made of quarks and gluons so this process is extremely common.

## CHAPTER 4 RESULTS

### 4.1 Fusce Eget Tempus Lectus,

**Algorithm 4.1.** *Euclids algorithm*

1: <b>procedure</b> EUCLID( $a, b$ )	▷ <i>The g.c.d. of <math>a</math> and <math>b</math></i>
2: $r \leftarrow a \bmod b$	
3: <b>while</b> $r \neq 0$ <b>do</b>	▷ <i>We have the answer if <math>r</math> is 0</i>
4: $a \leftarrow b$	
5: $b \leftarrow r$	
6: $r \leftarrow a \bmod b$	
7: <b>end while</b>	
8: <b>return</b> $b$	▷ <i>The gcd is <math>b</math></i>
9: <b>end procedure</b>	

**Proposition 4.1.** *The Upsilon Function*

(1) *If  $\beta > 0$  and  $\alpha \neq 0$ , then for all  $n \geq -1$ ,*

$$I_n(c; \alpha; \beta; \delta) = -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c - \delta) \\ + \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(-\beta c + \delta + \frac{\alpha}{\beta}\right)$$

(2) *If  $\beta < 0$  and  $\alpha < 0$ , then for all  $x \geq -1$*

$$I_n(c; \alpha; \beta; \delta) = -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c - \delta) \\ - \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(\beta c - \delta - \frac{\alpha}{\beta}\right)$$

*Proof.* Case 1.

$\beta > 0$  and  $\alpha \neq 0$ . Since, for any constant  $\alpha$  and  $n \geq 0$ ,  $e^{\alpha x} \text{Hh}_n(\beta x - \delta) \rightarrow 0$  as  $x \rightarrow \infty$

thanks to (B4), integration by parts leads to

$$I_n = -\frac{1}{\alpha} \text{Hh}(\beta c - \delta) e^{\alpha c} + \frac{\beta}{\alpha} \int_c^\infty e^{\alpha x} \text{Hh}_{n-1}(\beta x - \delta) dx$$



In other words, we have a recursion, for  $n \geq 0$ ,  $I_n = -(e^{\alpha c} \alpha) \text{Hh}_n(\beta c - \delta) + (\frac{\beta}{\alpha}) I_{n-1}$  with

$$\begin{aligned} I_{-1} &= \sqrt{2\pi} \int_c^\infty e^{\alpha x} \varphi(-\beta x + \delta) dx \\ &= \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha \delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi(-\beta c + \delta + \frac{\alpha}{\beta}) \end{aligned}$$

Solving it yields, for  $n \geq -1$ ,

$$\begin{aligned} I_n &= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^i \text{Hh}_{n-i}(\beta c + \delta) + \left(\frac{\beta}{\alpha}\right)^{n+1} I_{-1} \\ &= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c + \delta) \\ &\quad + \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha \delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi(-\beta c + \delta + \frac{\alpha}{\beta}) \end{aligned}$$

where the sum over an empty set is defined to be zero.  $\square$

*Proof. Case2.*  $\beta < 0$  and  $\alpha < 0$ . In this case, we must also have, for  $n \geq 0$  and any constant  $\alpha < 0$ ,  $e^{\alpha x} \text{Hh}_n(\beta x - \delta) \rightarrow 0$  as

$x \rightarrow \infty$ , thanks to (B5). Using integration by parts, we again have the same recursion, for  $n \geq 0$ ,  $I_n = -(e^{\alpha c} / \alpha) \text{Hh}_n(\beta c - \delta) + (\beta / \alpha) I_{n-1}$ , but with a different initial condition

$$\begin{aligned} I_{-1} &= \sqrt{2\pi} \int_c^\infty e^{\alpha x} \varphi(-\beta x + \delta) dx \\ &= -\frac{\sqrt{2\pi}}{\beta} \exp\left\{\frac{\alpha \delta}{\beta} + \frac{\alpha^2}{2\beta^2}\right\} \phi(\beta c - \delta - \frac{\alpha}{\beta}) \end{aligned}$$

Solving it yields (B8), for  $n \geq -1$ .  $\square$

*Finally, we sum the double exponential and the normal random variables*

*Proposition B.3.*

Suppose  $\{\xi_1, \xi_2, \dots\}$  is a sequence of i.i.d. exponential random variables with rate  $\eta > 0$ , and  $Z$  is a normal variable with distribution  $N(0, \sigma^2)$ . Then for every  $n \geq 1$ , we have: (1) The density functions are given by:

$$f_{Z+\sum_{i=1}^n \xi_i}(t) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} \text{Hh}_{n-1}\left(-\frac{t}{\sigma} + \sigma\eta\right)$$

$$f_{Z-\sum_{i=1}^n \xi_i}(t) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} \text{Hh}_{n-1}\left(\frac{t}{\sigma} + \sigma\eta\right)$$

(2) The tail probabilities are given by

$$P(Z + \sum_{i=1}^n \xi_i \geq x) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} I_{n-1}\left(x; -\eta, -\frac{1}{\sigma}, -\sigma\eta\right)$$

$$P(Z - \sum_{i=1}^n \xi_i \geq x) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} I_{n-1}\left(x; \eta, \frac{1}{\sigma}, -\sigma\eta\right)$$

*Proof. Case 1. The densities of  $Z + \sum_{i=1}^n \xi_i$ , and  $Z - \sum_{i=1}^n \xi_i$ . We have*

$$\begin{aligned} f_{Z+\sum_{i=1}^n \xi_i}(t) &= \int_{-\infty}^{\infty} f_{\sum_{i=1}^n \xi_i}(t-x) f_Z(x) dx \\ &= e^{-t\eta} (\eta^n) \int_{-\infty}^{\infty} t \frac{e^{x\eta} (t-x)^{n-1}}{(n-1)!} \frac{1}{\sigma\sqrt{2\pi}} e^{-x^2/(2\sigma^2)} dx \\ &= e^{-t\eta} (\eta^n) e^{(\sigma\eta)^2/(2)} \int_{-\infty}^{\infty} t \frac{(t-x)^{n-1}}{(n-1)!} \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\sigma^2\eta)^2/(2\sigma^2)} dx \end{aligned}$$

*Letting  $y = (x - \sigma^2\eta)/\sigma$  yields*

$$\begin{aligned} f_{Z+\sum_{i=1}^n \xi_i}(t) &= e^{-t\eta} (\eta^n) e^{(\sigma\eta)^2/(2)} \sigma^{n-1} \\ &\times \int_{-\infty}^{t/\sigma - \sigma\eta} \frac{(t/\sigma - y - \sigma\eta)^{n-1}}{(n-1)!} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy \end{aligned}$$

$$= \frac{e^{(\sigma\eta)^2/2}}{\sqrt{2\pi}} (\sigma^{n-1} \eta^n) e^{-t\eta} \text{Hh}_{n-1}(-t/\sigma + \sigma\eta)$$

because  $(1/(n-1)! \int_{-\infty}^{\infty} a(a-y)^{n-1} e^{-y^2/2} dy = \text{Hh}_{n-1}(a)$ . The derivation of  $f_{Z+\sum_{i=1}^n \xi_i}(t)$  is similar.

Case 2.  $P(Z + \sum_{i=1}^n \xi_i \geq x)$  and  $P(Z - \sum_{i=1}^n \xi_i \geq x)$ . From (B9), it is clear that

$$\begin{aligned} P(Z + \sum_{i=1}^n \xi_i \geq x) &= \frac{(\sigma\eta)^n e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} \int_x^{\infty} e^{(-i\eta)} \text{Hh}_{n-1}(-\frac{t}{\sigma} + \sigma\eta) dt \\ &= \frac{(\sigma\eta)^n e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} I_{n-1}(x; -\eta, -\frac{1}{\sigma}, -\sigma\eta) \end{aligned}$$

by (B6). We can compute  $P(Z - \sum_{i=1}^n \xi_i \geq x)$  similarly.

**Theorem 4.1.** Theorem With  $\pi_n := P(N(t) = n) = e^{-\lambda T} (\lambda T)^n / n!$  and  $I_n$  in Proposition ?? , we have

$$\begin{aligned} P(Z(T) \geq a) &= \frac{e^{(\sigma\eta_1)^2 T/2}}{\sigma\sqrt{2\pi T}} \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n P_{n,k}(\sigma\sqrt{T}\eta_1)^k \times I_{k-1}(a - \mu T; -\eta_1, -\frac{1}{\sigma\sqrt{T}}, -\sigma\eta_1\sqrt{T}) \\ &\quad + \frac{e^{(\sigma\eta_2)^2 T/2}}{\sigma\sqrt{2\pi T}} \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n Q_{n,k}(\sigma\sqrt{T}\eta_2)^k \\ &\quad \times I_{k-1}(a - \mu T; \eta_2, \frac{1}{\sigma\sqrt{T}}, -\sigma\eta_2\sqrt{T}) \\ &\quad + \pi_0 \phi(-\frac{a - \mu T}{\sigma\sqrt{T}}) \end{aligned}$$

Proof by the decomposition (B2)

$$P(Z(T) \geq a) = \sum_{n=0}^{\infty} \pi_n P(\mu T + \sigma\sqrt{T}Z + \sum_{j=1}^n Y_j \geq a)$$

$$\begin{aligned}
&= \pi_0 P(\mu T + \sigma \sqrt{T} Z \geq a) \\
&+ \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n P_{n,k} P(\mu T + \sigma \sqrt{T} Z + \sum_{j=1}^n \xi_j^+ \geq a) \\
&+ \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n Q_{n,k} P(\mu T + \sigma \sqrt{T} Z - \sum_{j=1}^n \xi_j^- \geq a)
\end{aligned}$$

*The result now follows via (B11) and (B12) for  $\eta_1 > 1$  and  $\eta_2 > 0$ .*

## CHAPTER 5 SUMMARY AND CONCLUSIONS

### 5.1 Non Porttitor Tellus

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## APPENDIX A

### THIS IS THE FIRST APPENDIX

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APPENDIX B  
AN EXAMPLE OF A HALF TITLE PAGE

L<sup>A</sup>T<sub>E</sub>X 2<sub>ε</sub>

Figure B-1. L<sup>A</sup>T<sub>E</sub>X 2<sub>ε</sub>. logo



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## APPENDIX C DERIVATION OF THE $\Upsilon$ FUNCTION

**Proposition C.1.** *The Upsilon Function*

(1) If  $\beta > 0$  and  $\alpha \neq 0$ , then for all  $n \geq -1$ ,

$$\begin{aligned} I_n(c; \alpha; \beta; \delta) &= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c - \delta) \\ &\quad + \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(-\beta c + \delta + \frac{\alpha}{\beta}\right) \end{aligned}$$

(2) If  $\beta < 0$  and  $\alpha < 0$ , then for all  $x \geq -1$

$$\begin{aligned} I_n(c; \alpha; \beta; \delta) &= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c - \delta) \\ &\quad - \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(\beta c - \delta - \frac{\alpha}{\beta}\right) \end{aligned}$$

*Proof.* Case 1.

$\beta > 0$  and  $\alpha \neq 0$ . Since, for any constant  $\alpha$  and  $n \geq 0$ ,  $e^{\alpha x} \text{Hh}_n(\beta x - \delta) \rightarrow 0$  as  $x \rightarrow \infty$  thanks to (B4), integration by parts leads to

$$I_n = -\frac{1}{\alpha} \text{Hh}(\beta c - \delta) e^{\alpha c} + \frac{\beta}{\alpha} \int_c^\infty e^{\alpha x} \text{Hh}_{n-1}(\beta x - \delta) dx$$

In other words, we have a recursion, for  $n \geq 0$ ,  $I_n = -(e^{\alpha c} \alpha) \text{Hh}_n(\beta c - \delta) + \left(\frac{\beta}{\alpha}\right) I_{n-1}$  with

$$\begin{aligned} I_{-1} &= \sqrt{2\pi} \int_c^\infty e^{\alpha x} \phi(-\beta x + \delta) dx \\ &= \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(-\beta c + \delta + \frac{\alpha}{\beta}\right) \end{aligned}$$

Solving it yields, for  $n \geq -1$ ,

$$\begin{aligned}
I_n &= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^i \text{Hh}_{n-i}(\beta c + \delta) + \left(\frac{\beta}{\alpha}\right)^{n+1} I_{-1} \\
&= -\frac{e^{\alpha c}}{\alpha} \sum_{i=0}^n \left(\frac{\beta}{\alpha}\right)^{n-i} \text{Hh}_i(\beta c + \delta) \\
&\quad + \left(\frac{\beta}{\alpha}\right)^{n+1} \frac{\sqrt{2\pi}}{\beta} e^{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}} \phi\left(-\beta c + \delta + \frac{\alpha}{\beta}\right)
\end{aligned}$$

where the sum over an empty set is defined to be zero.  $\square$

*Case2.*  $\beta < 0$  and  $\alpha < 0$ . In this case, we must also have, for  $n \geq 0$  and any constant  $\alpha < 0$ ,  $e^{\alpha x} \text{Hh}_n(\beta x - \delta) \rightarrow 0$  as

$x \rightarrow \infty$ , thanks to (B5). Using integration by parts, we again have the same recursion, for  $n \geq 0$ ,  $I_n = -(e^{\alpha c}/\alpha) \text{Hh}_n(\beta c - \delta) + (\beta/\alpha) I_{n-1}$ , but with a different initial condition

$$\begin{aligned}
I_{-1} &= \sqrt{2\pi} \int_c^\infty e^{\alpha x} \varphi(-\beta x + \delta) dx \\
&= -\frac{\sqrt{2\pi}}{\beta} \exp\left\{\frac{\alpha\delta}{\beta} + \frac{\alpha^2}{2\beta^2}\right\} \phi\left(\beta c - \delta - \frac{\alpha}{\beta}\right)
\end{aligned}$$

Solving it yields (B8), for  $n \geq -1$ .

Finally, we sum the double exponential and the normal random variables

*Proposition B.3.*

Suppose  $\{\xi_1, \xi_2, \dots\}$  is a sequence of i.i.d. exponential random variables with rate  $\eta > 0$ , and  $Z$  is a normal variable with distribution  $N(0, \sigma^2)$ . Then for every  $n \geq 1$ , we have: (1) The density functions are given by:

$$f_{Z+\sum_{i=1}^n \xi_i}(t) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} \text{Hh}_{n-1}\left(-\frac{t}{\sigma} + \sigma\eta\right)$$

$$f_{Z-\sum_{i=1}^n \xi_i}(t) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} \text{Hh}_{n-1}\left(\frac{t}{\sigma} + \sigma\eta\right)$$

(2) The tail probabilities are given by

$$P(Z + \sum_{i=1}^n \xi_i \geq x) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} I_{n-1}(x; -\eta, -\frac{1}{\sigma}, -\sigma\eta)$$

$$P(Z - \sum_{i=1}^n \xi_i \geq x) = (\sigma\eta)^n \frac{e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} e^{-t\eta} I_{n-1}(x; \eta, \frac{1}{\sigma}, -\sigma\eta)$$

*Proof. Case 1. The densities of  $Z + \sum_{i=1}^n \xi_i$ , and  $Z - \sum_{i=1}^n \xi_i$ . We have*

$$\begin{aligned} f_{Z+\sum_{i=1}^n \xi_i}(t) &= \int_{-\infty}^{\infty} f_{\sum_{i=1}^n \xi_i}(t-x) f_Z(x) dx \\ &= e^{-t\eta} (\eta^n) \int_{-\infty}^{\infty} t \frac{e^{x\eta} (t-x)^{n-1}}{(n-1)!} \frac{1}{\sigma\sqrt{2\pi}} e^{-x^2/(2\sigma^2)} dx \\ &= e^{-t\eta} (\eta^n) e^{(\sigma\eta)^2/(2)} \int_{-\infty}^{\infty} t \frac{(t-x)^{n-1}}{(n-1)!} \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\sigma^2\eta)^2/(2\sigma^2)} dx \end{aligned}$$

*Letting  $y = (x - \sigma^2\eta)/\sigma$  yields*

$$\begin{aligned} f_{Z+\sum_{i=1}^n \xi_i}(t) &= e^{-t\eta} (\eta^n) e^{(\sigma\eta)^2/(2)} \sigma^{n-1} \\ &\times \int_{-\infty}^{t/\sigma - \sigma\eta} \frac{(t/\sigma - y - \sigma\eta)^{n-1}}{(n-1)!} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy \\ &= \frac{e^{(\sigma\eta)^2/2}}{\sqrt{2\pi}} (\sigma^{n-1} \eta^n) e^{-t\eta} Hh_{n-1}(-t/\sigma + \sigma\eta) \end{aligned}$$

*because  $(1/(n-1)!) \int_{-\infty}^a (a-y)^{n-1} e^{-y^2/2} dy = Hh_{n-1}(a)$ . The derivation of  $f_{Z+\sum_{i=1}^n \xi_i}(t)$  is similar.*

*Case 2.  $P(Z + \sum_{i=1}^n \xi_i \geq x)$  and  $P(Z - \sum_{i=1}^n \xi_i \geq x)$ . From (B9), it is clear that*

$$P(Z + \sum_{i=1}^n \xi_i \geq x) = \frac{(\sigma\eta)^n e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} \int_x^{\infty} e^{(-i\eta)} Hh_{n-1}\left(-\frac{t}{\sigma} + \sigma\eta\right) dt$$

$$= \frac{(\sigma\eta)^n e^{(\sigma\eta)^2/2}}{\sigma\sqrt{2\pi}} I_{n-1}(x; -\eta, -\frac{1}{\sigma}, -\sigma\eta) dt$$

by (B6). We can compute  $P(Z - \sum_{i=1}^n \xi_i \geq x)$  similarly.

**Theorem C.1.** *Theorem With  $\pi_n := P(N(t) = n) = e^{-\lambda T}(\lambda T)^n/n!$  and  $I_n$  in Proposition ?? , we have*

$$\begin{aligned} P(Z(T) \geq a) &= \frac{e^{(\sigma\eta_1)^2 T/2}}{\sigma\sqrt{2\pi T}} \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n P_{n,k}(\sigma\sqrt{T}\eta_1)^k \times I_{k-1}(a - \mu T; -\eta_1, -\frac{1}{\sigma\sqrt{T}}, -\sigma\eta_1\sqrt{T}) \\ &\quad + \frac{e^{(\sigma\eta_2)^2 T/2}}{\sigma\sqrt{2\pi T}} \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n Q_{n,k}(\sigma\sqrt{T}\eta_2)^k \\ &\quad \times I_{k-1}(a - \mu T; \eta_2, \frac{1}{\sigma\sqrt{T}}, -\sigma\eta_2\sqrt{T}) \\ &\quad + \pi_0 \phi\left(-\frac{a - \mu T}{\sigma\sqrt{T}}\right) \end{aligned}$$

*Proof by the decomposition (B2)*

$$\begin{aligned} P(Z(T) \geq a) &= \sum_{n=0}^{\infty} \pi_n P(\mu T + \sigma\sqrt{T}Z + \sum_{j=1}^n Y_j \geq a) \\ &= \pi_0 P(\mu T + \sigma\sqrt{T}Z \geq a) \\ &\quad + \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n P_{n,k} P(\mu T + \sigma\sqrt{T}Z + \sum_{j=1}^n \xi_j^+ \geq a) \\ &\quad + \sum_{n=1}^{\infty} \pi_n \sum_{k=1}^n Q_{n,k} P(\mu T + \sigma\sqrt{T}Z - \sum_{j=1}^n \xi_j^- \geq a) \end{aligned}$$

*The result now follows via (B11) and (B12) for  $\eta_1 > 1$  and  $\eta_2 > 0$ .*

## APPENDIX D DERIVATION OF THE $\Upsilon$ FUNCTION

We first decompose the sum of the double exponential random variables.

The memoryless property of exponential random variables yields  $(\xi^+ - \xi^- | \xi^+ > \xi^-) =^d \xi^+$  and  $(\xi^+ - \xi^- | \xi^+ < \xi^-) =^d -\xi^-$ , thus leading to the conclusion that

$$\xi^+ - \xi^- = \begin{cases} \xi^+ & \text{with probability } \eta_2/(\eta_1 + \eta_2) \\ -\xi^- & \text{with probability } \eta_1/(\eta_1 + \eta_2) \end{cases}.$$

because the probabilities of the events  $\xi^+ > \xi^-$  and  $\xi^+ < \xi^-$  are  $\eta_2/(\eta_1 + \eta_2)$  and  $\eta_1/(\eta_1 + \eta_2)$ , respectively. The following proposition extends (B.1.)

**Proposition B.1.** For every  $n \geq 1$ , we have the following decomposition

$$\sum_{i=1}^n Y_i =^d \begin{cases} \sum_{i=1}^k \xi_i^+ & \text{with probability } P_{n,k}, k = 1, 2, \dots, n \\ -\sum_{i=1}^k \xi_i^- & \text{with probability } Q_{n,k}, k = 1, 2, \dots, n \end{cases}.$$

where  $P_{n,k}$  and  $Q_{n,k}$  are given by

$$P_{n,k} = \sum_{i=k}^{n-1} \binom{n-k-1}{i-k} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{i-k} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{n-i} p^i q^{n-i}$$

$$1 \leq k \leq n-1$$

$$Q_{n,k} = \sum_{i=k}^{n-1} \binom{n-k-1}{i-k} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{n-i} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{i-k} p^{n-i} q^i$$

$$1 \leq k \leq n-1, P_{n,n} = p^n, Q_{n,n} = q^n$$

and  $\binom{0}{0}$  is defined to be one. Hence  $\xi_i^+$  and  $\xi_i^-$  are i.i.d. exponential random variables with rates  $\eta_1$  and  $\eta_2$ , respectively.

As a key step in deriving closed-form solutions for call and put options, this proposition indicates that the sum of the i.i.d. double exponential random variable can be written, in

distribution, as a randomly mixed gamma random variable. To prove Proposition B.1, the following lemma is needed.

Lemma B.1.

$$\sum_{i=1}^n \xi_i^+ - \sum_{i=1}^n \xi_i^-$$

$$=^d \left\{ \begin{array}{ll} \sum_{i=1}^k \xi_i & \text{with probability } \binom{n-k+m-1}{m-1} \left(\frac{\eta_1}{\eta_1+\eta_2}\right)^{n-k} \left(\frac{\eta_2}{\eta_1+\eta_2}\right)^m, k = 1, \dots, n \\ -\sum_{i=1}^l \xi_i & \text{with probability } \binom{n-l+m-1}{n-1} \left(\frac{\eta_1}{\eta_1+\eta_2}\right)^n \left(\frac{\eta_2}{\eta_1+\eta_2}\right)^{m-l}, l = 1, \dots, m \end{array} \right\}.$$

We prove it by introducing the random variables  $A(n, m) = \sum_{i=1}^n \xi_i - \sum_{j=1}^m \tilde{\xi}_j$ . Then

$$A(n, m) =^d \left\{ \begin{array}{ll} A(n-1, m-1) + \xi^+ & \text{with probability } \eta_2/(\eta_1 + \eta_2) \\ A(n-1, m-1) - \xi^- & \text{with probability } \eta_1/(\eta_1 + \eta_2) \end{array} \right\}.$$

$$=^d \left\{ \begin{array}{ll} A(n, m-1) & \text{with probability } \eta_2/(\eta_1 + \eta_2) \\ A(n-1, m) & \text{with probability } \eta_1/(\eta_1 + \eta_2) \end{array} \right\}.$$

via B.1.. Now suppose horizontal axis that are representing the number of  $\{\zeta_i^+\}$  and vertical axis representing the number of  $\{\zeta_i^-\}$ . Suppose we have a random walk on the integer lattice points. Starting from any point  $(n, m)$ ,  $n, m \geq 1$ , the random walk goes either one step to the left with probability  $\eta_1/(\eta_1 + \eta_2)$  or one step down with probability  $\eta_2/(\eta_1 + \eta_2)$ , and the random walks stops once it reaches the horizontal or vertical axis. For any path from  $(n, m)$  to  $(k, 0)$ ,  $1 \geq k \geq n$ , it must reach  $(k, 1)$  first before it makes a final move to  $(k, 0)$ . Furthermore, all the paths going from  $(n, m)$  to  $(k, 1)$  must have exactly  $n-k$  lefts and  $m-1$  downs, whence the total number of such paths is  $\binom{n-k+m-1}{m-1}$ . Similarly the total number of paths from  $(n, m)$  to  $(0, l)$ ,  $1 \geq l \geq m$ , is  $\binom{n-l+m-1}{n-1}$ . Thus



$$A(n, m) = {}^d \left\{ \begin{array}{ll} \sum_{i=1}^k \xi_i & \text{with probability } \binom{n-k+m-1}{m-1} \left(\frac{\eta_1}{\eta_1+\eta_2}\right)^{n-k} \left(\frac{\eta_2}{\eta_1+\eta_2}\right)^m, k = 1, \dots, n \\ -\sum_{i=1}^l \xi_i & \text{with probability } \binom{n-l+m-1}{n-1} \left(\frac{\eta_1}{\eta_1+\eta_2}\right)^n \left(\frac{\eta_2}{\eta_1+\eta_2}\right)^{m-1}, l = 1, \dots, m \end{array} \right\}.$$

and the lemma is proven.

Now, let's prove the proposition B.1. By the same analogy used in Lemma B.1 to compute probability  $P_{n,m}, 1 \leq k \leq n$ , the probability weight assigned to  $\sum_{i=1}^k \xi_i^+$  when we decompose  $\sum_{i=1}^k Y_i$ , it is equivalent to consider the probability of the random walk ever reach  $(k,0)$  starting from the point  $(i,n-i)$  being  $\binom{n}{i} p^i q^{n-i}$ . Note that the point  $(k,0)$  can only be reached from point  $(i,n-i)$  such that  $k \geq i \geq n-1$ , because the random walk can only go left or down, and stops once it reaches the horizontal axis. Therefore, for  $1 \leq k \leq n-1$ , (B3) leads to

$$\begin{aligned} P_{n,k} &= \sum_{i=k}^{n-1} n-1 P(\text{going from } (i, n-i) \text{ to } (k, 0)) \cdot P(\text{starting from } (i, n-i)) \\ &= \sum_{i=k}^{n-1} \binom{i + (n-i) - k - 1}{(n-i) - 1} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{i-k} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{n-i} p^i q^{n-i} \\ &= \sum_{i=k}^{n-1} \binom{n-k-1}{n-i-1} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{i-k} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{n-i} p^i q^{n-i} \\ &= \sum_{i=k}^{n-1} \binom{n-k-1}{i-k} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{i-k} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{n-i} p^i q^{n-i} \end{aligned}$$

Of course  $P_{n,n} = p^n$ . Similarly, we can compute  $Q_{n,k}$ :

$$\begin{aligned} Q_{n,k} &= \sum_{i=k}^{n-1} n-1 P(\text{going from } (n-i, i) \text{ to } (0, k)) \cdot P(\text{starting from } (n-i, i)) \\ &= \sum_{i=k}^{n-1} \binom{i + (n-i) - k - 1}{(n-i) - 1} \binom{n}{n-i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{n-i} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{i-k} p^{n-i} q^i \end{aligned}$$

$$= \sum_{i=k}^{n-1} \binom{n-k-1}{i-k} \binom{n}{i} \left(\frac{\eta_1}{\eta_1 + \eta_2}\right)^{n-i} \left(\frac{\eta_2}{\eta_1 + \eta_2}\right)^{i-k} p^{n-i} q^i$$

with  $Q_{n,n} = q^n$ . Incidentally, we have also got  $\sum k = 1n(P_{n,k} + Q_{n,k}) = 1$

B.2. Let's develop now the results on Hh functions. First of all, note that  $Hh_n(x) \rightarrow 0$ , as  $x \rightarrow \infty$ , for  $n \geq -1$ ; and  $Hh_n(x) \rightarrow \infty$ , as  $x \rightarrow -\infty$ , for  $n \geq -1$ ; and  $Hh_0(x) = \sqrt{2\pi}\phi(-x) \rightarrow \sqrt{2\pi}$ , as  $x \rightarrow -\infty$ . Also, for every  $n \geq -1$ , as  $x \rightarrow \infty$ ,

$$\lim Hh_n(x) / \left\{ \frac{1}{x^{n+1}} e^{-\frac{x^2}{2}} \right\} = 1$$

and as  $x \rightarrow \infty$

$$Hh_n(x) = O(|x|^n)$$

Here (B4) is clearly true for  $n = -1$ , while for  $n \geq 0$  note that as  $x \rightarrow \infty$ ,

$$\begin{aligned} Hh_n(x) &= \frac{1}{n!} \int_x^\infty \infty (t-x)^n e^{-\frac{t^2}{2}} dt \\ &\leq \frac{2^n}{n!} \int_{-\infty}^\infty |t|^n e^{-t^2} 2dt + \frac{2^n}{n!} \int_{-\infty}^\infty -\infty |x|^n e^{-t^2} 2dt = O(|x|^n) \end{aligned}$$

For option pricing it is important to evaluate the integral  $I_n(c; \alpha; \beta; \delta)$ ,

$$I_n(c; \alpha; \beta; \delta) = \int_c^\infty \infty e^{\alpha x} Hh_n(\beta x - \delta) dx, n \geq 0$$

for arbitrary constants  $\alpha, c$  and  $\beta$ .

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