

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

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Abstract of Dissertation Presented to the Graduate School
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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 (SM) 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. In particular, the SM predicts that the massive particles of the theory acquire their mass by interacting with a scalar particle called the Higgs boson. 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 was 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 as well as the best fit for the rate of production.

The dissertation first covers the LHC which is responsible for accelerating the colliding the protons. Then the dissertation presents the CMS detector responsible for measuring the paths, momentum, and energy of the emerging particles. Next, the dissertation explains the theory underlying the Standard Model and its predictions of the Higgs particle. After, the machine learning implementation in the L1 trigger that reduced the number of fakes in the data by a factor of three is detailed. And finally, the search for H to $\mu^+\mu^-$ is presented.

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 γ is the Lorentz factor. ϵ_n is the normalized transverse emittance, a measure of the spread of the beam in momentum and position space. β^* 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 ¹ 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.

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

¹ 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 ². 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. ³ 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

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

³ 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.

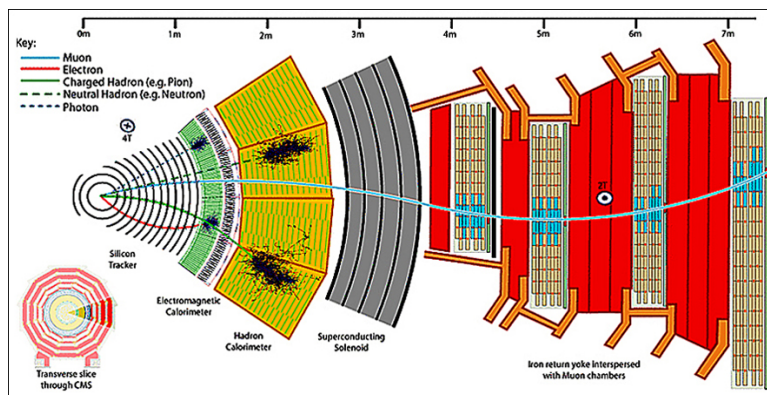


Figure 2-4. A slice of the CMS detector ?

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 (δE) 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 $c\tau \sim 100$ m. 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 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 gravity¹. The particles of the SM come in two types: fermions and bosons. Fermions are the spin $\frac{1}{2}$ particles that make up the different types of matter, and bosons are the integer spin particles responsible for the different forces. Electrons are the most familiar type of fermion, but there are more exotic kinds like the up and down quarks that make up protons and neutrons. Electrons, protons, and neutrons make up atoms, accounting for nearly all of the matter in our day to day experience, but there are actually many other matter particles. In fact, there are three generations of quarks and leptons¹ 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 force carrying particles that allow matter to interact and form more complex objects like atoms, molecules, and even people are the spin 1 bosons. These force carriers are the gluons, photons, and the W and Z particles. 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: particles with electric charge can interact through the electromagnetic force, those with color charge may interact via the strong force, and those with isospin or weak hypercharge 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. The strong

¹ Leptons are fermions like the electron that aren't quarks. The quarks interact with the strong force that binds nuclei together and the leptons do not.

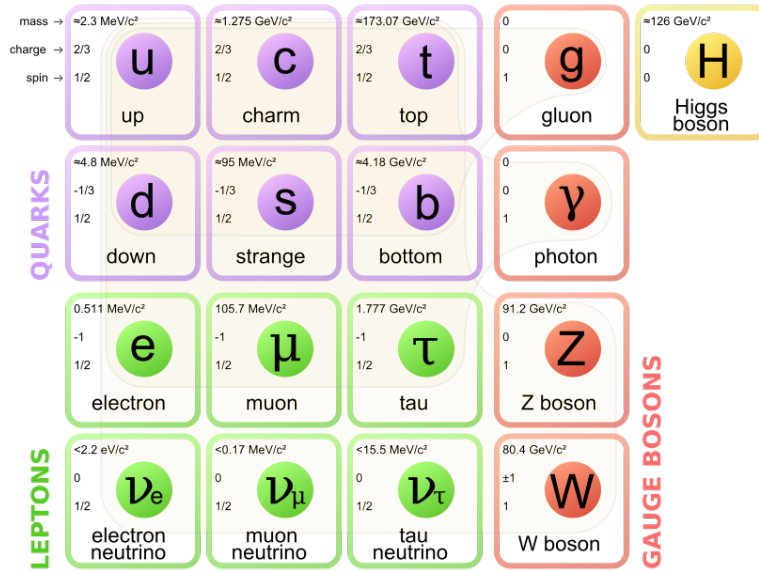


Figure 3-1. The Standard Model Particles

force binds quarks to form protons and neutrons, and even 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. But that isn't quite exact, in fact, the ratio of the strength of the forces is like so $1:10^{-3}:10^{-16}:10^{-41}$, strong : electromagnetic : weak : gravitational ² .

Of all the particles predicted by the SM, there is only one spin 0 particle, the Higgs boson, and it plays a special role in the theory. 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. The electron, muon, tau and the W and Z particles of the SM interact with the Higgs condensate and acquire mass. With such a large role in the SM, finding this particle or a BSM Higgs has been a huge priority for the CMS collaboration ?. In 2012 a Higgs particle

² Gravity is just included for perspective. The Standard Model does not describe this force and reconciling gravity with quantum mechanics is an open problem.

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.

In order to lay out the Standard Model in mathematical terms, a bunch of background information needs to be covered, and since the Standard Model is described by Quantum Field Theory (QFT), the mathematical formulation of QFT will be covered first. After developing the necessary mathematical formalism, the Standard Model and the Higgs mechanism will be derived and explained. Afterwards the experimental search for Higgs to dimuons will be described.

In this dissertation \hbar and the speed of light, c , are set to 1. Moreover, 0,1,2,3 and t,x,y,z are used interchangeably to label the components of a four vector. When relevant 0 represents time and 1,2,3 represent x,y,z respectively. Einstein summation notation is used indicating that repeated indices are summed over, so $x_i x_i y_j y_j$ is shorthand for $\sum_i \sum_j x_i x_i y_j y_j$. Repeated Greek indices assume sums over all four space and time components, while repeated Roman indices assume sums over only the spatial components.

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 different measurable probabilities. One of the most important is the probability for a set of particles to emerge from a collision of an initial set of particles. Another important one is the probability for a single particle to decay into another set 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 to collide and create a Higgs. As another example, the SM also predicts the branching fraction for a Z boson to decay into 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. Quantum Field Theory is written down in terms of a

Lagrangian, and the math for the various predictions follows from there, but first a brief aside about particles.

3.1.1 Particles, Symmetries, and Labels

Since QFT makes quantitative predictions in terms of particle collisions and particle decays it's interesting to contemplate what a particle really is. 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 as well 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. The suit and value are conserved quantities identifiable between frames. 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 allows the two to determine 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 some of these labels are the mass, charge, spin, color, isospin, and weak hypercharge with each label attached to a specific symmetry or group of symmetries. 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. The deep connection between conserved quantities, symmetries, and labels for particles will be seen later. For now the focus is to work out laws that people in different frames can confirm, and this is where the Lagrangian formalism comes into play.

3.1.2 The Lagrangian Formalism

The Lagrangian formalism is a mathematical device that allows physicists to describe the evolution of a physical system over time, and it's within this formalism that QFT can be

built. But before building the full mathematics of QFT, a simple example describing the free Newtonian particle is covered. The Newtonian example serves to illuminate the fact that the laws of physics are indistinguishable in different inertial frames. Moving to the full relativistic theory reveals that the symmetry goes deeper. Investigating the symmetries of the relativistic theory end up leading the way to QFT, a relativistic description of quantum mechanics.

Getting into the framework, the goal of physics is to describe how a physical system evolves over time, and this evolution 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 a path in some abstract space of possible states. As a concrete example, the differential equations describing the motion of a Newtonian particle determine the position and velocity of the particle at the next instant of time based upon the values in the previous instant of time. So how does one get the appropriate differential equation? At classical scales, nature tries to minimize the difference between the energy spent ³ and the energy available to spend and it minimizes the action S . At the more fundamental level of quantum mechanics, all possible paths contribute with different phases, but those close to the minimum add constructively, contributing the most. As the action gets larger, the paths away from the minimum count less and less and the quantum rule agrees with the classical rule. The classical case is analyzed first in order to begin investigating the symmetries that lead to QFT and an appropriate description of nature.

Equation 3-1 presents the action S , where 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 , $\delta S = 0$ if S is smooth: S must decrease, go through a slope of zero, and then increase (or vice versa). For a true extremum, δS must be 0 in all directions. So to get

³ Spent here just means used as kinetic energy.

the equations of motion vary the parameters of L and solve the system of equations for the values that yield zero change in the action.

$$\begin{aligned}\frac{\delta S}{\delta z_1} &= \int L(z_1 + dz_1, z_2, \dots) dt - \int L(z_1, z_2, \dots) dt = 0 \\ \frac{\delta S}{\delta z_2} &= \int L(z_1, z_2 + dz_2, \dots) dt - \int L(z_1, z_2, \dots) dt = 0 \\ &\dots\end{aligned}\tag{3-2}$$

Following this process provides 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.

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

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

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

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

With $x(t)$ fixed at the boundaries of the integral, ϵ must be zero at t_o and t_f , so integrating by parts yields the following equation

$$\delta S = 0 = \epsilon(t_f)\dot{x}(t_f) - \epsilon(t_o)\dot{x}(t_o) + \int m\ddot{x}\epsilon dt = 0\dot{x}(t_f) - 0\dot{x}(t_o) + \int m\ddot{x}\epsilon dt = \int m\ddot{x}\epsilon dt. \tag{3-6}$$

And this equation must be zero for any infinitesimal deviation ϵ ,

$$\delta S = 0 \rightarrow m\ddot{x} = 0, \tag{3-7}$$

implying that a free particle keeps the same velocity over time. Note that a Newtonian boost by constant velocity $v \rightarrow v' = v + u$ ⁴ leaves the equations of motion consistent. In the unprimed frame, the particle has velocity v with 0 acceleration. In the primed frame, the particle has velocity $v + u$ with 0 acceleration. Both observers see the particle act as if there are zero forces in play,

$$S = \frac{1}{2} \int m(v + u)^2 dt = \frac{1}{2} \int m(v')^2 dt \rightarrow \delta S = 0 \rightarrow m \frac{d}{dt}(v + u) = m \frac{d}{dt}(v') = 0. \quad (3-8)$$

If u is not constant but a function of time, $u(t)$, then the equations of motion do not describe the same time evolution,

$$m \frac{d}{dt}(v + u) = m\dot{v} + m\dot{u} = 0 \rightarrow \dot{v} = -\dot{u}. \quad (3-9)$$

In the case where $u(t)$ depends upon time, the difference between the primed and unprimed frames' equations of motion is then δF .

$$\delta F = m \frac{d}{dt}(v + u) - m \frac{dv}{dt} = m\dot{v} + m\dot{u} - m\dot{v} = m\dot{u} \quad (3-10)$$

In the unprimed frame, the particle identified by the mass moves with constant velocity, $\dot{v} = 0$. The observer in the primed frame looks at the particle with the same mass and sees it change velocity given by the equation $\dot{v} = -\dot{u}$. As an example, set v and u , and \dot{u} to zero for all times before $t=0$, and let u , and \dot{u} turn on after time 0. Both observers will agree that the particle is stationary up until time 0. After which, the observer in the primed frame will see the particle accelerate in strange ways. Meanwhile, the unprimed frame will continue to observe a stationary particle.

In general, every inertial frame finds $\delta F = 0$ and every accelerating frame finds an extra force δF unique to its acceleration. In this way, no observer in an inertial frame can perform an experiment and determine which inertial frame he or she is in. On the other hand, each

⁴ Renaming \dot{x} as v .

accelerating frame is identified by its δF . Put another way, in every inertial frame, a ball released at rest remains at rest. In an accelerating frame, the ball will accelerate according to the motion of the frame δF and this change in the laws of physics identifies the frame in a unique way. Conversely, the laws of physics remain the same boosting between inertial frames, and this invariance is a symmetry of physics. Of course this example is Newtonian and the correct way to boost is given by the Lorentz transformation from Special Relativity, but this gets the point across.

Delving further along the path of symmetry, the fundamental forces depend only on the distance from the charge and not the direction implying that rotations are also a symmetry. This can be seen by looking at the Lagrangian,

$$L = \frac{1}{2}m\dot{\vec{x}}^2 - U((\vec{x} - \vec{x}')^2). \quad (3-11)$$

Rotations leave dot products and consequently the magnitude of vectors unchanged so the Lagrangian is invariant under this transformation. Naturally if the Lagrangian is invariant the equations of motion will be as well,

$$m\frac{d\vec{v}}{dt} = \vec{\nabla}U. \quad (3-12)$$

In the equations of motion of 3-12, both sides are vectors and vectors transform the same way under rotations so the equations of motion are invariant. Note that in the case of rotations both the Lagrangian and the equations of motion are invariant, while for Newtonian boosts, only the equations of motion were invariant. This is due to the fact that Newtonian mechanics is the low velocity limit of relativistic mechanics. In the theory of Special Relativity, the action for a massive free particle is written like so,

$$S = \int \frac{m}{2}u^\mu u_\mu d\tau. \quad (3-13)$$

Just as rotations preserve the dot product, Lorentz transformations (boosts and rotations) preserve the four vector product. Building a Lagrangian out of four vector products then gaurantees that both the Lagrangian and the equations of motion will remain invariant under

Lorentz transformations. However, four vectors aren't the most fundamental objects with invariant products. By studying the properties of the Lorentz group, it's possible to find even more fundamental building blocks called spinors. Spinors, vectors, and scalars are necessary to describe the different types of observed particles and create a Lagrangian that can describe the real world.

3.1.3 QFT From Symmetry

As just explored, the laws of physics are invariant under boosts and rotations, and the Lagrangian provides a mathematical framework for physical predictions. These facts together imply that there's a good shot at building a proper QFT by creating the appropriate invariant Lagrangian. Four vector products remain invariant under Lorentz transformations so they are a natural ingredient, but, as aforementioned, there are other mathematical objects that could be used as well. In this vein, the symmetries under rotations and boosts are investigated in order to look for other building blocks. The goal is to find three different representations of the Lorentz group and use one representation for scalar spin 0 particles, another for the spin $\frac{1}{2}$ fermions, and another for the spin 1 bosons.

3.1.3.1 Rotations

Rotations in three dimensions are described by the $SO(3)$ group. Rotations preserve the lengths of vectors and the angles between them, which means that dot products between vectors remain invariant as well. In three dimensions, one can rotate about any of the three axes. The rotations about the x, y, and z axes may be characterized by the matrices below.

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_x & -\sin \theta_x \\ 0 & \sin \theta_x & \cos \theta_x \end{pmatrix} \quad (3-14)$$

$$R_y = \begin{pmatrix} \cos \theta_y & 0 & \sin \theta_y \\ 0 & 1 & 0 \\ -\sin \theta_y & 0 & \cos \theta_y \end{pmatrix} \quad (3-15)$$

$$R_z = \begin{pmatrix} \cos \theta_z & -\sin \theta_z & 0 \\ \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (3-16)$$

These rotations may be built up from repeated rotations by an infinitesimally small angle $d\theta$.

The matrices characterizing an infinitesimal rotation are produced by taking the limit as θ goes to zero.

$$dR_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -d\theta_x \\ 0 & d\theta_x & 1 \end{pmatrix} = 1 - id\theta_x \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} = 1 - id\theta_x J_x \quad (3-17)$$

$$dR_y = \begin{pmatrix} 1 & 0 & d\theta_y \\ 0 & 1 & 0 \\ -d\theta_y & 0 & 1 \end{pmatrix} = 1 - id\theta_y \begin{pmatrix} 0 & 0 & i \\ 0 & 0 & 0 \\ -i & 0 & 0 \end{pmatrix} = 1 - id\theta_y J_y \quad (3-18)$$

$$dR_z = \begin{pmatrix} 1 & -d\theta_z & 0 \\ d\theta_z & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = 1 - id\theta_z \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = 1 - id\theta_z J_z \quad (3-19)$$

Repeating an infinitesimal rotation many times builds the finite rotation, and in this way, the J matrices generate rotations along their respective axes. As such, they are aptly referred to as the generators of the group. Consider any of the J matrices,

$$R = (1 - i\frac{\theta}{N}J)^N = 1 + (-id\theta J) + \frac{1}{2!}(-id\theta J)^2 + \frac{1}{3!}(-id\theta J)^3 + \dots = e^{-i\theta J}. \quad (3-20)$$

Notice that even powers of J yield J^2 and that odd powers of J return J ,

$$= 1 - J^2 + J^2(1 + \frac{i^2}{2!}d\theta^2 + \frac{i^4}{4!}d\theta^4 + \dots) - iJ(d\theta + \frac{i^2}{3!}d\theta^3 + \frac{i^4}{5!}d\theta^5 + \dots) = (1 - J^2) + J^2 \cos \theta - iJ \sin \theta. \quad (3-21)$$

Plugging in J_z reveals that this process does in fact rebuild the rotation matrix R_z ,

$$\begin{aligned}
 R_z &= \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right) + \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \cos \theta_z + \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \sin \theta_z \\
 &= \begin{pmatrix} \cos \theta_z & -\sin \theta_z & 0 \\ \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix}.
 \end{aligned} \tag{3-22}$$

Similarly, the other generators rebuild their respective rotation matrices. The generators of the group are actually more fundamental than the rotation matrices. The multiplication table for the generators describes the algebra of the group, which describes the behavior of rotations at a local level. In fact the $SO(3)$ rotation matrices are just one of the groups with this local algebra, and a specific group obeying the local algebra is analogous to a specific solution of a differential equation: each solution has a different global behavior yet each obeys the same physics at the differential scale. Moreover, the multiplication table can be specified without declaring any particular representation for the generators.

$$\begin{aligned}
 J_x * J_y &= iJ_z + J_y * J_x \\
 J_y * J_z &= iJ_x + J_z * J_y \\
 J_z * J_x &= iJ_y + J_x * J_z
 \end{aligned} \tag{3-23}$$

The multiplication table can be specified in a more compact notation using the commutator⁵, $[a, b] = ab - ba$, which closes the group, and the antisymmetric tensor ϵ .

$$[J_k, J_l] = i\epsilon_{klm}J_m \tag{3-24}$$

⁵ The Lie Bracket defines the multiplication for a Lie Algebra and this reduces to the commutator for Lie groups of matrices like $SO(3)$. Using the commutator below returns another member of the group and thus the group is closed under commutation.

Finding a 3x3 representation of the generators – that obey the algebra – and then repeatedly applying the infinitesimal transformations builds the SO(3) rotation group. The group acts on real 3x1 objects called vectors, and these 3x1 vectors are a suitable candidate for a Newtonian Lagrangian. Finding another representation obeying this algebra will provide a more fundamental ingredient for the Lagrangian and allow the construction of a proper QFT. Similar to the way real numbers are built from the squares of imaginary numbers, vectors are built from spinors.

Looking for the lowest order nontrivial nxn matrices satisfying the algebra gives the 2x2 Pauli matrices. The 1x1 matrices are the trivial solution: 1x1 matrices are simply scalar complex numbers, which commute and therefore fail to satisfy the algebra unless all of the J matrices are 0. The objects these 1x1 operators act on are 1x1 numbers called scalars which remain invariant under rotations and correspond to spin 0. The solution for the 2x2 case, the Pauli matrices are given by

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad (3-25)$$

However, plugging these into the commutator reveals a factor of two difference,

$$[\sigma_k, \sigma_l] = 2i\epsilon_{klm}\sigma_m. \quad (3-26)$$

Defining $J_k = \frac{1}{2}\sigma_k$ fixes this. These matrices act on an array of 2x1 complex numbers called spinors, and this new rotation group is called SU(2). By starting with vectors and analyzing the SO(3) rotation group along with its underlying algebra, new mathematical objects have been discovered. The 1x1 matrices satisfying the rotation algebra make up the spin 0 representation of SU(2), the complex 2x2 matrices acting on complex 2x1 objects satisfying the algebra make up the spin $\frac{1}{2}$ representation, and the complex 3x3 matrices acting on complex 3x1 objects satisfying the algebra make up the spin 1 representation. The pattern continues on. There are in fact many representations of SU(2). It's now possible to use these

representations to build rotationally invariant Lagrangians, using the 2x1 spinors of SU(2) to model fermions and the 3x1 representation to model bosons. While rotationally invariant Lagrangians are important for nonrelativistic theories, the real goal is to break down four vectors in the same way to find the most fundamental ingredients for relativistic Lagrangians.

3.1.3.2 The Lorentz Group

Four vector products are invariant with regards to rotations and boosts. This statement is defined by the mathematical equation below, where the Λ matrices represent the rotation/boost matrices of the Lorentz Group ⁶ and the η matrix is the Minkowski metric $\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$.

$$x'_\mu x'^\mu = x_\mu x^\mu \rightarrow \eta_{\sigma\rho} \Lambda^\sigma_\mu \Lambda^\rho_\nu x^\mu x^\nu = \eta_{\mu\nu} x^\mu x^\nu \rightarrow \eta_{\sigma\rho} \Lambda^\sigma_\mu \Lambda^\rho_\nu = \eta_{\mu\nu} \quad (3-27)$$

In this 3 + 1 dimensional space the rotations and their corresponding generators are now given by the following R and J matrices,

$$R_x = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \theta_x & -\sin \theta_x \\ 0 & 0 & \sin \theta_x & \cos \theta_x \end{pmatrix}, J_x = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix} \quad (3-28)$$

$$R_y = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_y & 0 & \sin \theta_y \\ 0 & 0 & 1 & 0 \\ 0 & -\sin \theta_y & 0 & \cos \theta_y \end{pmatrix}, J_y = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & i \\ 0 & 0 & 0 & 0 \\ 0 & -i & 0 & 0 \end{pmatrix} \quad (3-29)$$

⁶ The Lorentz group dealt with here is the proper orthochronous Lorentz Group SO(1,3).

$$R_z = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_z & -\sin \theta_z & 0 \\ 0 & \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, J_z = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad (3-30)$$

where the R matrices satisfy equation 3 – –27. The boosts are given by the B matrices,

$$B_x = \begin{pmatrix} \cosh \omega_x & \sinh \omega_x & 0 & 0 \\ \sinh \omega_x & \cosh \omega_x & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3-31)$$

$$B_y = \begin{pmatrix} \cosh \omega_y & 0 & \sinh \omega_y & 0 \\ 0 & 1 & 0 & 0 \\ \sinh \omega_y & 0 & \cosh \omega_y & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3-32)$$

$$B_z = \begin{pmatrix} \cosh \omega_z & 0 & 0 & \sinh \omega_z \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \sinh \omega_z & 0 & 0 & \cosh \omega_z \end{pmatrix}. \quad (3-33)$$

These also leave the four vector product invariant. Looking at the differential boosts yields the generators K.

$$dB_x = \begin{pmatrix} 1 & d\omega_x & 0 & 0 \\ d\omega_x & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = 1 + d\omega_x \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = 1 + d\omega_x K_x \quad (3-34)$$

$$dB_y = \begin{pmatrix} 1 & 0 & d\omega_y & 0 \\ 0 & 1 & 0 & 0 \\ d\omega_y & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = 1 + d\omega_y \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = 1 + d\omega_y K_y \quad (3-35)$$

$$dB_z = \begin{pmatrix} 1 & 0 & 0 & d\omega_z \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ d\omega_z & 0 & 0 & 1 \end{pmatrix} = 1 + d\omega_z \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} = 1 + d\omega_z K_z \quad (3-36)$$

As before with the algebra for rotations in three dimensions the Lorentz algebra is defined by its multiplication table, but now there are rotations and boosts. The multiplication table is given by the commutation relations below, which can be confirmed by brute force computation.

$$[J_i, J_j] = i\epsilon_{ijk} J_k \quad (3-37)$$

$$[J_i, K_j] = i\epsilon_{ijk} K_k \quad (3-38)$$

$$[K_i, K_j] = -i\epsilon_{ijk} J_k \quad (3-39)$$

Notice that the commutator between J matrices returns another J matrix, but that the commutator between K matrices returns a J matrix. This means that the J operators form their own subgroup, but the K operators don't. On the other hand, mixing the Js and Ks up by defining the Y^\pm operators allows the Lorentz algebra to be represented by two independent subgroups.

$$Y^\pm = \frac{1}{2}(J_i \pm iK_i) \quad (3-40)$$

$$[Y_i^\pm, Y_j^\pm] = i\epsilon_{ijk} Y_k^\pm \quad (3-41)$$

$$[Y_i^\pm, Y_j^\mp] = 0 \quad (3-42)$$

Both of the Y groups have the same commutation relations as SU(2). In this way, the Lorentz algebra can be viewed as if two orthogonal SU(2) rotation algebras have been glued together.

This is similar to the way in which orthogonal basis vectors are stuck together to create a larger dimensional space. Now, in order to figure out how to use this space to build the appropriate Lagrangians, the individual subspaces must be investigated. So looking at Y^+ alone is akin to looking along the Y^+ axis by setting Y^- to zero. Using (y_+, y_-) to label the representation, the simplest nontrivial case along the Y^+ axis is spin $\frac{1}{2} \times$ spin 0, given by $(\frac{1}{2}, 0)$.

Using $Y_i^- = \frac{1}{2}(J_i - iK_i) = 0$ implies that $J_i = iK_i$, and since Y_i^+ is the 2x2 representation obeying the SU(2) algebra, $Y_i^+ = \frac{\sigma_i}{2}$. Putting this together,

$$\begin{aligned} J_i &= iK_i \\ \rightarrow Y_i^+ &= \frac{1}{2}(J_i + iK_i) = \frac{\sigma_i}{2} = \frac{1}{2}(J_i + J_i) = J_i \\ \rightarrow J_i &= \frac{1}{2}\sigma_i \\ \rightarrow K_i &= \frac{-i\sigma_i}{2}. \end{aligned} \tag{3-43}$$

Finally, the finite Lorentz transformations for the $(\frac{1}{2}, 0)$ representation are given by

$$R^{(L)} = e^{i\theta_i J_i} = e^{i\theta_i \frac{\sigma_i}{2}} \tag{3-44}$$

for rotations, and

$$B^{(L)} = e^{i\phi_i K_i} = e^{i\phi_i \frac{\sigma_i}{2}} \tag{3-45}$$

for boosts. These act on 2x1 objects called left-chiral spinors, \mathcal{L} . A general Lorentz transformation on a left-chiral spinor can be written

$$\Lambda^{(L)} = e^{\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i} \tag{3-46}$$

. Replacing K_i with $-K_i$ takes Y_i^+ to Y_i^- , and gives the finite Lorentz transformations for the $(0, \frac{1}{2})$ representation

$$R^{(R)} = e^{i\theta_i J_i} = e^{\frac{i}{2}\theta_i \sigma_i} \tag{3-47}$$

for rotations, and

$$B^{(R)} = e^{i\phi_i K_i} = e^{-\phi_i \frac{\sigma_i}{2}} \quad (3-48)$$

for boosts. These act on 2x1 objects called right-chiral spinors, \mathcal{R} . The general Lorentz transformation on a right-chiral spinor can be written

$$\Lambda^{(R)} = e^{\frac{i}{2}\theta_i \sigma_i - \frac{1}{2}\phi_i \sigma_i} \quad (3-49)$$

Last but not least, rank 2 spinors are given by the $(\frac{1}{2}, \frac{1}{2})$ representation. This representation is a tensor combining two spinors via outer product, and as will be shown later, these objects are actually four vectors.

$$\alpha = \mathcal{L}\mathcal{R}^T \quad (3-50)$$

In order to transform α , both \mathcal{L} and \mathcal{R} must be transformed.

$$\alpha' = \Lambda^{(L)} \mathcal{L} \mathcal{R}^T \Lambda^{(R)T} = e^{\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i} \mathcal{L} \mathcal{R}^T e^{\frac{i}{2}\theta_i \sigma_i^T - \frac{1}{2}\phi_i \sigma_i^T} \quad (3-51)$$

However it would be nice if the transformation term on the right side was the Hermitian conjugate of the transformation on the left side. This would be the case if σ_i^T was $-\sigma_i^\dagger = -(\sigma_i^*)^T$, and this requires a transformation that turns σ into $-\sigma^*$. So \mathcal{R} is rearranged such that $\mathcal{R} \rightarrow \tilde{\mathcal{R}} = t\mathcal{R}$ where $t\sigma_i t^{-1} = -\sigma_i^*$. The matrix $t = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ satisfies the requirements. This change of basis for \mathcal{R} redefines α ,

$$\alpha = \mathcal{L}\tilde{\mathcal{R}}^T. \quad (3-52)$$

Defined in this manner, the $(\frac{1}{2}, \frac{1}{2})$ representation now transforms like so,

$$\alpha' = e^{\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i} \mathcal{L} \tilde{\mathcal{R}}^T e^{-\frac{i}{2}\theta_i \sigma_i^\dagger + \frac{1}{2}\phi_i \sigma_i^\dagger}. \quad (3-53)$$

Considering the fact that $\sigma_i^\dagger = \sigma_i$, the transformation reduces further,

$$\alpha' = e^{\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i} \alpha e^{-\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i}. \quad (3-54)$$

A transformation of the form $M' = HMH^\dagger$ where H is a Hermitian matrix, preserves the Hermitivity of the matrix M . Namely, M' will be Hermitian if M is Hermitian,

$$M'^\dagger = (MH^\dagger H)^\dagger = HM^\dagger H^\dagger = HMH^\dagger = M'. \quad (3-55)$$

On the other hand, M' will be anti-Hermitian if M is anti-Hermitian,

$$M'^\dagger = (MH^\dagger H)^\dagger = HM^\dagger H^\dagger = H(-M)H^\dagger = -MH^\dagger H = -M'. \quad (3-56)$$

The transformation of the $(\frac{1}{2}, \frac{1}{2})$ object α is of this type. With this in mind, note that any complex matrix can be broken up into a Hermitian piece and an anti-Hermitian piece, and that these pieces remain independent under the $(\frac{1}{2}, \frac{1}{2})$ Lorentz transformations constructed here.

Then note that a general complex 2x2 matrix has 8 free parameters, 4 from the Hermitian part and 4 from the anti-Hermitian part. Meanwhile, α has only 4, two from each spinor ⁷. This means that α may be represented by the Hermitian space alone. An appropriate basis for this space is the collection of Pauli matrices plus the identity,

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \text{ and } \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (3-57)$$

Thus any $(\frac{1}{2}, \frac{1}{2})$ object α may be written in terms of its four independent parameters like so,

$$\begin{aligned} \alpha &= \alpha_0 \sigma_0 + \alpha_1 \sigma_1 + \alpha_2 \sigma_2 + \alpha_3 \sigma_3 \\ \alpha &= \begin{pmatrix} \alpha_0 + \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & \alpha_0 - \alpha_3 \end{pmatrix}. \end{aligned} \quad (3-58)$$

⁷ A spinor has 2 complex components yielding 4 parameters. Two constraints reduce the number of free parameters to 2. One constraint requires a magnitude of 1, and the other requires that the overall phase doesn't matter.

Boosting α along the z direction hints that the four components transform like a four vector.

$$\alpha' = e^{\frac{1}{2}\phi_3\sigma_3} \begin{pmatrix} \alpha_0 + \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & \alpha_0 - \alpha_3 \end{pmatrix} e^{\frac{1}{2}\phi_3\sigma_3} \quad (3-59)$$

Exponentiating the σ_3 matrix and multiplying everything yields,

$$\begin{aligned} \begin{pmatrix} \alpha'_0 + \alpha'_3 & \alpha'_1 - i\alpha'_2 \\ \alpha'_1 + i\alpha'_2 & \alpha'_0 - \alpha'_3 \end{pmatrix} &= \begin{pmatrix} e^{\frac{1}{2}\phi_3} & 0 \\ 0 & e^{-\frac{1}{2}\phi_3} \end{pmatrix} \begin{pmatrix} \alpha_0 + \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & \alpha_0 - \alpha_3 \end{pmatrix} \begin{pmatrix} e^{\frac{1}{2}\phi_3} & 0 \\ 0 & e^{-\frac{1}{2}\phi_3} \end{pmatrix} \\ &= \begin{pmatrix} e^{\phi_3}(\alpha_0 + \alpha_3) & (\alpha_1 - i\alpha_2) \\ (\alpha_1 + i\alpha_2) & e^{-\phi_3}(\alpha_0 - \alpha_3) \end{pmatrix}. \end{aligned} \quad (3-60)$$

Then solving the systems of equations makes the transformation clearer,

$$\begin{aligned} \alpha'_1 &= \alpha_1 \\ \alpha'_2 &= \alpha_2 \\ \alpha'_0 &= (\cosh \phi_3)\alpha_0 + (\sinh \phi_3)\alpha_3 \\ \alpha'_3 &= (\sinh \phi_3)\alpha_0 + (\cosh \phi_3)\alpha_3. \end{aligned} \quad (3-61)$$

Finally the transformation can be written as a 4x4 matrix acting on the 4x1 four vector,

$$\alpha' = \begin{pmatrix} \cosh \phi_3 & 0 & 0 & \sinh \phi_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \sinh \phi_3 & 0 & 0 & \cosh \phi_3 \end{pmatrix} \begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} \quad (3-62)$$

The other transformations reproduce the usual 4x4 Lorentz transformations as well. In this way, four vectors are just rearranged versions of the $(\frac{1}{2}, \frac{1}{2})$ rank 2 spinors. In the way complex numbers are the square root of real numbers, spinors are the square root of four vectors.

In practice it's easier to work with 4 vectors as 4x1 column vectors, though one could use the $(\frac{1}{2}, \frac{1}{2})$ rank 2 spinor representation. With four vectors, spinors, and scalars in hand, the

invariant Lagrangians describing the different types of particles can now be built. Before doing this, however, there is a brief aside about group representations, particles, and labels.

3.1.3.3 The Poincare Group and Particle Labels

The Poincare group is the Lorentz Group plus translations. Physics experiments should be the same with a rotated apparatus, an apparatus moving at a different constant velocity, and also at another location. Adding translations to the group amounts to adding another the set of translation generators P_i . In the "Particles, Symmetries, and Labels" section the argument was made that particles are things that observers agree on between frames. Distinguishable particles have labels that remain invariant. A spin $\frac{1}{2}$ particle with mass m remains a spin $\frac{1}{2}$ particle with mass m for all observers. As it turns out these labels relate to different subspaces in the representation of the group.

Consider a group with certain generators. When the generators of the group are represented a certain way, say as some $N \times N$ matrices, there is a likelihood that there are some invariant subspaces. As an example, a representation of a group may act on a 5 dimensional space spanned by vectors e_1, e_2, e_3, e_4, e_5 . The group may always transform vectors in the e_1, e_2, e_3 subspace into one another, and those in e_4, e_5 into one another, but never mix up e_1, e_2, e_3 with e_4, e_5 . In this example the 5×5 operators could be decomposed into a 3×3 operator acting only on the e_1, e_2, e_3 subspace and a 2×2 operator acting only on the e_4, e_5 subspace. Each 5×5 member of the group could be written as a block diagonal matrix with a 3×3 block and a 2×2 block. The same goes for the generators. Since these subspaces retain their identity under the transformations of the group⁸, they may be considered different particles. The question is whether there are labels for the subspaces.

Labels in physics need to be measurable, and by the current understanding of quantum mechanics these must be eigenvalues of Hermitian operators. The operators that label these

⁸ This assumes that the 3×3 and 2×2 pieces have no invariant subspaces besides themselves and 0.

subspaces are called the Casimir operators and must be built from the generators of the group. The operators should give the same values for e_1, e_2 , and e_3 since they transform into one another and represent the same particle, which implies that the Casimir labeling operator must be proportional to the identity in that subspace. The same goes for the operator in the e_4, e_5 subspace. The Casimir operator for SU(2) is the J^2 operator which labels the spin of the particle. The Poincare group has two Casimir operators corresponding to two labels the mass, m , and the spin, j . Looking at the irreducible representations⁹ of the Poincare group, the mass and spin arise naturally as labels for particles.

3.1.3.4 Building the Lagrangian for a Free Scalar Particle

Analyzing the symmetries of the SO(3) rotation group revealed the SU(2) group, the 2x2 complex Pauli matrices, and the complex 2x1 spinors. Analyzing the symmetries of the Lorentz group revealed the $(\frac{1}{2}, 0)$ left-chiral spinors, the $(0, \frac{1}{2})$ right chiral spinors, and the four vectors encoded in the $(\frac{1}{2}, \frac{1}{2})$ representation. Now, these pieces are put together to form relativistically invariant Lagrangians for free particles.

The $(0, 0)$ representation of the Lorentz group is a scalar, which means that it remains the same under Lorentz transformations. This representation is used for spin 0 particles. The equations of motion must relate the change in the scalar field Φ at one moment in space and time to the value of Φ at the next moment in space and time, so the Lagrangian must include both the field itself and the four vector derivative, ∂_μ . Note that both Newton's equations of motion, $F = m\ddot{x}$, and the Schrodinger equation for the free particle, $i\partial_t\psi = \frac{1}{2m}(-i\partial_x)(-i\partial_x)\psi$ ¹⁰ have at most second order derivatives. The same holds for Maxwell's equations of electromagnetism. Hence, as an assumption, the derivative term in the Lagrangian

⁹ This is the group theory term for the block diagonal pieces and the corresponding invariant subspaces. The irreducible representations, irreps, are those that can't be broken down in terms of smaller invariant subspaces and smaller block diagonal matrices. An arbitrary representation of the group is built from these irreps.

¹⁰ Here the one dimensional case is presented for simplicity

will be the lowest order possible. As a Lorentz invariant scalar, any power of Φ can be included. On the other hand, ∂_μ is a four vector, and must be paired with a ∂^μ to form the invariant four vector product. Cross terms between these invariant pieces like $\Phi\partial_\mu\partial^\mu\Phi$ or $\partial_\mu\Phi\partial^\mu\Phi$ are also invariant, but lead to feedback between the derivatives and the value of the function. This means that the derivatives $i\partial_t = E$ and $-i\partial_i = P_i$ will change over time, but E and \vec{P} should remain constant for a free particle. The cross terms are thrown out to prevent this. The Φ terms with an order different than Φ^2 cause the same problem, and these are thrown out too. All of these choices lead to the following action,

$$S = \int d^4x (c_0 + c_1\Phi^2 + c_2\partial_\mu\Phi\partial^\mu\Phi + c_3\partial_\mu\partial^\mu\Phi). \quad (3-63)$$

Note that the c_3 term is a total derivative and by the divergence theorem depends only on the values at the boundary, which are fixed. This implies that the contribution to the action from the c_3 term is the same regardless of how Φ changes in the volume. Because the Euler-Lagrange equations depend only on the variation in the volume, this term cannot contribute to δS and c_3 may be set to zero. The c_0 term is a more obvious constant and does not affect δS either, so it may be set to zero as well, leaving,

$$S = \int d^4x (c_1\Phi^2 + c_2\partial_\mu\Phi\partial^\mu\Phi). \quad (3-64)$$

Finding Φ such that $\delta S = 0$ amounts to applying the Euler-Lagrange equations $\partial_\mu \frac{\partial L}{\partial(\partial_\mu\Phi)} = \frac{\partial L}{\partial\Phi}$. These yield

$$\begin{aligned} 2c_2\partial_\mu\partial^\mu\Phi &= -2c_1\Phi \\ \rightarrow (-E^2 + \vec{P}^2)\Phi &= \frac{c_1}{c_2}\Phi = -m^2\Phi \\ \rightarrow \frac{c_1}{c_2} &= -m^2 \end{aligned} \quad (3-65)$$

In order to get the correct dispersion relation for a relativistic particle, c_1 is set to $\frac{-1}{2}m^2$ and c_2 is set to $\frac{1}{2}$. Notice that including any Φ^n with $n \neq 2$ in the Lagrangian would have contributed to the differential equation via $\frac{\partial L}{\partial\Phi}$ and that E , \vec{P} wouldn't be constant. Thus

the equation wouldn't work for a free particle. The resulting equation of motion for the scalar particle, $\partial_\mu \partial^\mu \Phi = m^2 \Phi$, is called the Klein-Gordon equation, and provides the correct description for spin 0 particles. This was all derived using symmetry, a reasonable assumption about the order of the derviations, and the fact that the Energy shouldn't change over time for a free particle. The final Lagrangian for the scalar particle is

$$S = \int d^4x \frac{1}{2} (\partial_\mu \Phi \partial^\mu \Phi - m^2 \Phi^2). \quad (3-66)$$

3.1.3.5 Building the Lagrangian for a Free Spin $\frac{1}{2}$ Particle

With the action for the free scalar particle in hand, the free spin $\frac{1}{2}$ particle is up next. The spin $\frac{1}{2}$ action must combine the \mathcal{L} and \mathcal{R} spinors of the $(\frac{1}{2}, 0)$ and $(0, \frac{1}{2})$ representations and the four vector, ∂_μ , in a Lorentz invariant way. Moving forward in this regard, the \mathcal{L} , \mathcal{R} , and ∂_μ transformations are now analyzed to find the lowest order invariant combinations. The transformation for the left-chiral spinor is

$$\Lambda^{(L)} = e^{\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i}, \quad (3-67)$$

and the transformation for the right-chiral spinor is,

$$\Lambda^{(R)} = e^{\frac{i}{2}\theta_i \sigma_i - \frac{1}{2}\phi_i \sigma_i}. \quad (3-68)$$

Taking the Hermitian conjugate of the left-chiral transformation gives,

$$(\Lambda^{(L)})^\dagger = e^{-\frac{i}{2}\theta_i \sigma_i^\dagger + \frac{1}{2}\phi_i \sigma_i^\dagger} = e^{-\frac{i}{2}\theta_i \sigma_i + \frac{1}{2}\phi_i \sigma_i}. \quad (3-69)$$

This reveals that $(\Lambda^{(L)})^\dagger$ is the inverse of $\Lambda^{(R)}$. Similarly, $(\Lambda^{(R)})^\dagger$ is the inverse of $\Lambda^{(L)}$. Thus, $\mathcal{L}^\dagger \mathcal{R}$ and $\mathcal{R}^\dagger \mathcal{L}$ are Lorentz invariants, which can be seen below,

$$(\mathcal{L}^\dagger \mathcal{R})' = \mathcal{L}^\dagger (\Lambda^{(L)})^\dagger \Lambda^{(R)} \mathcal{R} = \mathcal{L}^\dagger (\Lambda^{(R)})^{-1} \Lambda^{(R)} \mathcal{R} = \mathcal{L}^\dagger \mathcal{R} \quad (3-70)$$

$$(\mathcal{R}^\dagger \mathcal{L})' = \mathcal{R}^\dagger (\Lambda^{(R)})^\dagger \Lambda^{(L)} \mathcal{L} = \mathcal{R}^\dagger (\Lambda^{(L)})^{-1} \Lambda^{(L)} \mathcal{L} = \mathcal{R}^\dagger \mathcal{L}. \quad (3-71)$$

These are the lowest order invariant pieces involving the field alone. In order to couple the derivative to the field, the \mathcal{L} and \mathcal{R} spinors must attach to ∂_μ in an invariant way. Recall that a four vector may be expressed as an outer product of left and right spinors,

$$\alpha_{\tilde{L}\tilde{R}} = \mathcal{L}_\alpha \tilde{\mathcal{R}}_\alpha^T. \quad (3-72)$$

The following also works,

$$\alpha_{\tilde{R}\tilde{L}} = \mathcal{R}_\alpha \tilde{\mathcal{L}}_\alpha^T. \quad (3-73)$$

Recall that the \sim transformation sent σ_i to $-\sigma_i^*$. So the transformations for the \sim transposed spinors are,

$$(\Lambda^{(\tilde{L})})^T = e^{\frac{i}{2}\theta_i(-\sigma_i^*)^T + \frac{1}{2}\phi_i(-\sigma_i^*)^T} = e^{-\frac{i}{2}\theta_i\sigma_i^\dagger - \frac{1}{2}\phi_i\sigma_i^\dagger} = e^{-\frac{i}{2}\theta_i\sigma_i - \frac{1}{2}\phi_i\sigma_i} \quad (3-74)$$

and

$$(\Lambda^{(\tilde{R})})^T = e^{\frac{i}{2}\theta_i(-\sigma_i^*)^T - \frac{1}{2}\phi_i(-\sigma_i^*)^T} = e^{-\frac{i}{2}\theta_i\sigma_i^\dagger + \frac{1}{2}\phi_i\sigma_i^\dagger} = e^{-\frac{i}{2}\theta_i\sigma_i + \frac{1}{2}\phi_i\sigma_i}. \quad (3-75)$$

The equations above show that the $(\Lambda^{(\tilde{L})})^T$ transformation is the inverse of $\Lambda^{(L)}$, and that the $(\Lambda^{(\tilde{R})})^T$ transformation is the inverse of $\Lambda^{(R)}$. So the invariant pieces coupling the spinor to the four vector are,

$$\mathcal{R}^\dagger \alpha_{\tilde{L}\tilde{R}} \mathcal{R} = \mathcal{R}^\dagger \mathcal{L}_\alpha \tilde{\mathcal{R}}_\alpha^T \mathcal{R} \quad (3-76)$$

and

$$\mathcal{L}^\dagger \alpha_{\tilde{R}\tilde{L}} \mathcal{L} = \mathcal{L}^\dagger \mathcal{R}_\alpha \tilde{\mathcal{L}}_\alpha^T \mathcal{L}. \quad (3-77)$$

The two types of four vectors have slightly different transformations

$$\alpha'_{\tilde{L}\tilde{R}} = e^{\frac{i}{2}\theta_i\sigma_i + \frac{1}{2}\phi_i\sigma_i} \alpha_{\tilde{L}\tilde{R}} e^{-\frac{i}{2}\theta_i\sigma_i + \frac{1}{2}\phi_i\sigma_i} \quad (3-78)$$

$$\alpha'_{\tilde{R}\tilde{L}} = e^{\frac{i}{2}\theta_i\sigma_i - \frac{1}{2}\phi_i\sigma_i} \alpha_{\tilde{R}\tilde{L}} e^{-\frac{i}{2}\theta_i\sigma_i - \frac{1}{2}\phi_i\sigma_i}. \quad (3-79)$$

Both transform with positive θ under rotations, but the boosts are a different story. The $\tilde{L}\tilde{R}$ four vector transforms with positive ϕ while the $\tilde{R}\tilde{L}$ four vector transforms with negative

ϕ . Behaving the same way under rotations implies that the x,y,z components mix up the same way in both types of four vector. In this respect, rotating x,y,z or -x,-y,-z are both valid. Exemplifying this, an infinitesimal rotation around z by $d\theta_z$ gives

$$\begin{aligned}x' &= x - yd\theta_z \\y' &= y + xd\theta_z\end{aligned}\tag{3-80}$$

for positive x,y,z and

$$\begin{aligned}-x' &= -x - (-y)d\theta_z \\-y' &= -y' + (-x)d\theta_z\end{aligned}\tag{3-81}$$

for -x,-y,-z. These transformations are equivalent. Moving onto boosts, the opposite ϕ sign naively implies that the x,y,z terms mix up with t in the opposite way for the two types of rank 2 spinors. However, if both $L\tilde{R}$ and $R\tilde{L}$ represent a four vector, then the boost must yield the same transformation on the components. Therefore, to get from $L\tilde{R}$ to $R\tilde{L}$ take t,x,y,z to t,-x,-y,-z. Illuminating this, an infinitesimal boost along x by $d\phi_x$ gives

$$\begin{aligned}t' &= t + xd\phi_x \\x' &= x + td\phi_x\end{aligned}\tag{3-82}$$

for the $L\tilde{R}$ representation and

$$\begin{aligned}t' &= t + (-x)(-d\phi_x) \\-x' &= -x + t(-d\phi_x)\end{aligned}\tag{3-83}$$

for $R\tilde{L}$. The negative ϕ and the negative spatial components counteract to transform the four vector correctly. The $R\tilde{L}$ rank 2 spinor encodes a four vector in the same way as a $L\tilde{R}$ rank 2 spinor, except that the spatial components are coded into the rank 2 spinor with the opposite

sign. Writing the representations out in terms of the four vector components yields

$$\begin{aligned}
\alpha_{\tilde{L}\tilde{R}} &= \alpha_0\sigma_0 + \alpha_1\sigma_1 + \alpha_2\sigma_2 + \alpha_3\sigma_3 \\
\alpha_{\tilde{L}\tilde{R}} &= \alpha_\mu\sigma^\mu \\
\alpha_{\tilde{L}\tilde{R}} &= \begin{pmatrix} \alpha_0 + \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & \alpha_0 - \alpha_3 \end{pmatrix}
\end{aligned} \tag{3-84}$$

and

$$\begin{aligned}
\alpha_{\tilde{R}\tilde{L}} &= \alpha_0\sigma_0 - \alpha_1\sigma_1 - \alpha_2\sigma_2 - \alpha_3\sigma_3 \\
\alpha_{\tilde{R}\tilde{L}} &= \alpha_\mu\bar{\sigma}^\mu \\
\alpha_{\tilde{R}\tilde{L}} &= \begin{pmatrix} \alpha_0 - \alpha_3 & \alpha_1 + i\alpha_2 \\ \alpha_1 - i\alpha_2 & \alpha_0 + \alpha_3 \end{pmatrix}.
\end{aligned} \tag{3-85}$$

The action for the spin $\frac{1}{2}$ particle is built from the lowest order invariant combinations of the spinors themselves and the lowest order invariant term coupling ∂_μ to the spinors. These ingredients are $\mathcal{L}^\dagger\mathcal{R}$, $\mathcal{R}^\dagger\mathcal{L}$, $\mathcal{R}^\dagger\sigma^\mu\partial_\mu\mathcal{R}$, and $\mathcal{L}^\dagger\bar{\sigma}^\mu\partial_\mu\mathcal{L}$. In the scalar particle case m coupled the field to itself as potential energy ¹¹ with the same power as ∂_μ ¹². Following that example and throwing an i into the derivative terms¹³ to make them Hermitian gives the following Lagrangian,

$$S = \int d^4x \left(\mathcal{R}^\dagger\sigma^\mu i\partial_\mu\mathcal{R} + i\mathcal{L}^\dagger\bar{\sigma}^\mu i\partial_\mu\mathcal{L} - m\mathcal{L}^\dagger\mathcal{R} - m\mathcal{R}^\dagger\mathcal{L} \right). \tag{3-86}$$

¹¹ The mass term had a negative sign in the Lagrangian.

¹² E, P, and m must have the same power to get $E^2 = m^2 + \vec{P}^2$ right, and $E \sim \partial_0$, $P_i \sim \partial_i$ so m must have the same power as ∂_μ .

¹³ This gives the P_μ operator which equals $i\partial_\mu$.

The Euler-Lagrange equations reveal how the fields change over time,

$$\begin{aligned}
\sigma^\mu i\partial_\mu \mathcal{R} &= m\mathcal{L} \\
\bar{\sigma}^\mu i\partial_\mu \mathcal{L} &= m\mathcal{R}. \\
\sigma^\mu i\partial_\mu \mathcal{R}^\dagger &= -m\mathcal{L}^\dagger \\
\bar{\sigma}^\mu i\partial_\mu \mathcal{L}^\dagger &= -m\mathcal{R}^\dagger.
\end{aligned} \tag{3-87}$$

Notice that the mass term couples the left and right chiral spinors. At rest, $P=0$ and the equations reduce to $i\partial_0 \mathcal{R} = m\mathcal{L}$ and $i\partial_0 \mathcal{L} = m\mathcal{R}$ showing that $\partial_0^2 \mathcal{R} = -m^2 \mathcal{R}$ and $\partial_0^2 \mathcal{L} = -m^2 \mathcal{L}$. The mass is actually a frequency determining how quickly a particle oscillates between its right-chiral and left-chiral states. Another interesting point is that swapping the sign of m here swaps the roles of the fields and the conjugate fields.

Plugging $\mathcal{R} = \frac{1}{m} \bar{\sigma}^\nu i\partial_\nu \mathcal{L}$ into $\sigma^\mu i\partial_\mu \mathcal{R} = m\mathcal{L}$ shows that the constants chosen for the terms in the Lagrangian provide the correct dispersion relation,

$$\begin{aligned}
\sigma^\mu i\partial_\mu \frac{1}{m} \bar{\sigma}^\nu i\partial_\nu \mathcal{L} &= m\mathcal{L} \\
\rightarrow \sigma^\mu \bar{\sigma}^\nu P_\mu P_\nu &= m^2 \\
\rightarrow \eta_\nu^\mu P_\mu P_\nu &= m^2 \\
\rightarrow P^\mu P_\mu &= m^2 \\
\rightarrow E^2 - \vec{P}^2 &= m^2
\end{aligned} \tag{3-88}$$

The action for the spin $\frac{1}{2}$ particle can be rewritten into its more compact, canonical form,

$$S = \int d^4x \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi, \tag{3-89}$$

after defining

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}, \psi = \begin{pmatrix} \mathcal{L} \\ \mathcal{R} \end{pmatrix}, \text{ and } \bar{\psi} = \psi^\dagger \gamma_0. \tag{3-90}$$

The spin $\frac{1}{2}$ Lagrangian is called the Dirac Lagrangian and the resulting equations of motion are the Dirac equation.

3.1.3.6 Building the Lagrangian for a Free Spin 1 Particle

Last but not least is the Lagrangian for a spin 1 force carrying particle. The main ingredients are the A_μ and ∂_μ four vectors. The lowest order possible invariants are $\partial^\mu A^\nu \partial_\mu A_\nu$, $\partial^\mu A^\nu \partial_\nu A_\mu$, $A^\mu A_\mu$, and $\partial^\mu A_\mu$. However the last term is a total derivative and won't be included. The resulting action and equations of motion are

$$S = \int d^4x (c_0 i \partial^\mu A^\nu i \partial_\mu A_\nu + c_1 i \partial^\mu A^\nu i \partial_\nu A_\mu + c_2 A^\mu A_\mu). \quad (3-91)$$

$$c_2 A^\nu = -\partial_\mu (c_0 \partial^\mu A^\nu + c_1 \partial^\nu A^\mu). \quad (3-92)$$

This is the same form as the equation for the four vector potential in electromagnetism, which has $c_0 = \frac{1}{2}$ and $c_1 = -\frac{1}{2}$. The remaining term, c_2 looks like a mass term, so c_2 is set to $\frac{1}{2}m^2$ ¹⁴. The action and equations of motion with the appropriate constants become,

$$S = \int d^4x \left(\frac{-1}{2} \partial^\mu A^\nu \partial_\mu A_\nu + \frac{1}{2} \partial^\mu A^\nu \partial_\nu A_\mu + \frac{m^2}{2} A^\mu A_\mu \right) \quad (3-93)$$

$$-m^2 A^\nu = \partial_\mu (\partial^\mu A^\nu - \partial^\nu A^\mu). \quad (3-94)$$

Taking another derivative reveals that the equations reduce further and take on the correct dispersion relation, confirming the choice of constants,

$$\begin{aligned} -m^2 \partial_\nu A^\nu &= \partial_\nu \partial_\mu \partial^\mu A^\nu - \partial_\nu \partial_\mu \partial^\nu A^\mu = 0 \\ \rightarrow \partial_\nu A^\nu &= 0 \\ \rightarrow -m^2 A^\nu &= \partial_\mu \partial^\mu A^\nu \\ \rightarrow m^2 A^\nu &= i \partial_\mu i \partial^\mu A^\nu \\ \rightarrow m^2 &= E^2 - \vec{P}^2. \end{aligned} \quad (3-95)$$

¹⁴ The order of the mass should match the order of the derivatives.

The action for the spin 1 particle is called the Proca action. It's normally written in an equivalent form in terms of the tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$S = \int d^4x \left(\frac{-1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{m^2}{2} A^\mu A_\mu \right). \quad (3-96)$$

3.1.4 Lagrangians in Quantum Mechanics and QFT

The Lagrangians for the different types of free particles have been derived. Now it's important to know how to use them to predict results that can be verified by experiment. Quantum behavior is different than the classical behavior covered earlier. Classically, each particle takes a single well defined path, but in the quantum regime particles behave as if they take all possible paths from some initial point to some final point. Analogously, the fields from which particles arise behave as if they take all possible configurations between states. Each possibility contributes to the net probability as a unit complex number with a phase given by the action. These contributions are called probability amplitudes,

$$\mathcal{A}_j = e^{iS_j}. \quad (3-97)$$

Adding the amplitudes for every possibility gives the net amplitude, and squaring the net amplitude gives the probability,

$$P = \left| \sum_j \mathcal{A}_j \right|^2. \quad (3-98)$$

Consider a free non-relativistic quantum particle in one dimension with the Lagrangian $\mathcal{L} = \frac{1}{2}m\dot{x}^2$. The amplitude for the particle to start at x_0, t_0 and end at x_f, t_f can be calculated by discretizing time, $t \in t_0, t_1, \dots, t_f$. A path is then determined by specifying x at each point in time, $x(t) \in x(t_0), x(t_1), \dots, x(t_f)$. In this way, the action for a path x , $S(x)$, can be written

$$S(x) = \int dt L = \frac{m}{2} \int_{t_0}^{t_f} dt \dot{x}^2 = \frac{m}{2} \sum_i \frac{(x(t_i) - x(t_{i-1}))^2}{(t_i - t_{i-1})^2} (t_i - t_{i-1}) = \frac{m}{2} \sum_i \frac{(x(t_i) - x(t_{i-1}))^2}{\Delta t}. \quad (3-99)$$

The amplitude for the path is then given by,

$$\mathcal{A}(x) = e^{i\frac{m}{2} \sum_i \frac{(x(t_i) - x(t_{i-1}))^2}{(t_i - t_{i-1})^2}} = e^{i\frac{m}{2} \frac{(x(t_f) - x(t_{f-1}))^2}{\Delta t}} e^{i\frac{m}{2} \frac{(x(t_{f-1}) - x(t_{f-2}))^2}{\Delta t}} \dots e^{i\frac{m}{2} \frac{(x(t_1) - x(t_0))^2}{\Delta t}}. \quad (3-100)$$

Summing over all paths, $x(t)$, with fixed endpoints, $x(t_0) = x_0$ and $x(t_f) = x_f$, provides the net amplitude

$$\begin{aligned} \mathcal{A} &= \sum_x \mathcal{A}(x) = \sum_{x(t_{f-1})} \sum_{x(t_{f-2})} \dots \sum_{x(t_1)} e^{i\frac{m}{2} \frac{(x(t_f) - x(t_{f-1}))^2}{\Delta t}} e^{i\frac{m}{2} \frac{(x(t_{f-1}) - x(t_{f-2}))^2}{\Delta t}} \dots e^{i\frac{m}{2} \frac{(x(t_1) - x(t_0))^2}{\Delta t}} \\ &= \mathcal{C} \int dx_{t_{f-1}} dx_{t_{f-2}} \dots dx_{t_1} e^{i\frac{m}{2} \frac{(x(t_f) - x(t_{f-1}))^2}{\Delta t}} e^{i\frac{m}{2} \frac{(x(t_{f-1}) - x(t_{f-2}))^2}{\Delta t}} \dots e^{i\frac{m}{2} \frac{(x(t_1) - x(t_0))^2}{\Delta t}} \\ &= \int \mathcal{D}[x(t)] e^{i\frac{m}{2} \int_{t_0}^{t_f} dt \partial_t x \partial_t x}. \end{aligned} \quad (3-101)$$

Integrating by parts and using the average velocity $v = \frac{x_f - x_0}{t_f - t_0}$ for the boundary velocities provides the net amplitude for the particle to go from one place to another,

$$\begin{aligned} \mathcal{A} &= \int \mathcal{D}[x(t)] e^{i\frac{m}{2} x \partial_t x|_{t_0}^{t_f} + i\frac{m}{2} \int_{t_0}^{t_f} dt (-x \partial_t^2 x)} \\ &= e^{i\frac{m}{2} (x(t_f) - x(t_0))v} \int \mathcal{D}[x(t)] e^{i\frac{m}{2} \int_{t_0}^{t_f} dt (-x \partial_t^2 x)} \\ &= \mathcal{N} e^{\frac{-im(x_f - x_0)^2}{2(t_f - t_0)}} \\ &= \sqrt{\frac{m}{2i\pi(t_f - t_0)}} e^{\frac{-im(x_f - x_0)^2}{2(t_f - t_0)}}. \end{aligned} \quad (3-102)$$

The normalization \mathcal{N} is fixed by requiring that the probability for the particle to be somewhere at t_f is one. In other words, integrating over all x_f for constant x_0, t_0, t_f should give one. A more rigorous derivation of this propagator can be found in [Feynman and Hibbs](#) for example.

In general the amplitude to go from $\phi(t_0) = \phi_0$ to $\phi(t_f) = \phi_f$ is determined by the path integral,

$$\mathcal{A}(\phi_f, t_f; \phi_0, t_0) = \langle \phi_f, t_f | \phi_0, t_0 \rangle = \int \mathcal{D}[\cdot] e^{i \int_{t_0}^{t_f} dt L}. \quad (3-103)$$

Furthermore, the expectation value for an operation performed at time t_1 when the system starts in the state $\phi(t_0) = \phi_0$ and ends in $\phi(t_f) = \phi_f$ is

$$|\langle \phi_f, t_f | \mathcal{O}(t_1) | \phi_0, t_0 \rangle|^2 = \left| \int \mathcal{D}[\cdot] \mathcal{O}(t_1) e^{i \int_{t_0}^{t_f} dt L} \right|^2. \quad (3-104)$$

Of particular importance for QFT are scattering events. When two particles are measured at (t_1, \vec{x}_1) and (t_2, \vec{x}_2) some time in the past, what is the amplitude to measure two particles at (t_3, \vec{x}_3) and (t_4, \vec{x}_4) some time in the future? Considering that particles are in fact disturbances in the field, an equivalent question may be asked. How is the field amplitude correlated between spacetime points (t_4, \vec{x}_4) , (t_3, \vec{x}_3) , (t_2, \vec{x}_2) , and (t_1, \vec{x}_1) . So for two to two scattering the amplitude is given by

$$\langle 0 | \psi_i(t_4, \vec{x}_4) \psi_j(t_3, \vec{x}_3) \psi_k(t_2, \vec{x}_2) \psi_l(t_1, \vec{x}_1) | 0 \rangle = \frac{\int \mathcal{D}[\psi] \psi_i(t_4, \vec{x}_4) \psi_j(t_3, \vec{x}_3) \psi_k(t_2, \vec{x}_2) \psi_l(t_1, \vec{x}_1) e^{i \int_{-\infty}^{\infty} dt L}}{\int \mathcal{D}[\psi] e^{i \int_{-\infty}^{\infty} dt L}}, \quad (3-105)$$

where ψ is a field, 0 denotes the vacuum state, and i, j, k, l specify the types of particles observed. Calculating this path integral for the full Lagrangian determines the amplitude for the scattering event. Usually the correlation functions can only be calculated for the free fields where the Lagrangian density is quadratic in the fields. Interactions generally spoil this simplicity, but even if the Lagrangian is more complicated, the path integral for the full theory can usually be expanded in terms of the correlation functions from the free field. However, this only works in practice if the additional terms in the Lagrangian are small compared to the free part of the Lagrangian. This method of expansion is called perturbation theory.

3.1.5 Perturbation Theory and Feynman Rules

Unfortunately, the correlation functions determining the scattering and decay amplitudes for most of the interesting theories are not directly solvable. On the other hand, they can often be expanded in terms of the free solutions. When the magnitude of the additional complexity is small compared to the free part of the Lagrangian, only the first few terms of the series expansion are needed and the technique is called perturbation theory.

The best way to showcase perturbation theory is to run over the process for the scalar particle. The first step is to figure out the free solutions. The two point correlation function for the free case is given by

$$\langle 0 | \Phi(t_2, \vec{x}_2) \Phi(t_1, \vec{x}_1) | 0 \rangle = \frac{\int \mathcal{D}[\Phi] \Phi(t_2, \vec{x}_2) \Phi(t_1, \vec{x}_1) e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} (\partial_\mu \Phi \partial^\mu \Phi - m^2 \Phi^2)}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} (\partial_\mu \Phi \partial^\mu \Phi - m^2 \Phi^2)}}, \quad (3-106)$$

and it describes a particle going from (t_1, \vec{x}_1) to (t_2, \vec{x}_2) . Integrating by parts and throwing away the boundary term turns the path integrals into Gaussians

$$\langle 0 | \Phi(t_2, \vec{x}_2) \Phi(t_1, \vec{x}_1) | 0 \rangle = \frac{\int \mathcal{D}[\Phi] \Phi(t_2, \vec{x}_2) \Phi(t_1, \vec{x}_1) e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}}. \quad (3-107)$$

Focusing on the integral in the denominator and looking at the integral as a matrix multiplication simplifies things

$$\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi} = \int d\Phi_1 d\Phi_2 \dots d\Phi_N e^{i \frac{1}{2} \Phi_i K_{ij} \Phi_j}. \quad (3-108)$$

Transforming to the eigenbasis yields a multidimensional Gaussian integral

$$\begin{aligned} \int d\Phi_1 d\Phi_2 \dots d\Phi_N e^{i \frac{1}{2} \Phi_i K_{ij} \Phi_j} &= \int d\tilde{\Phi}_1 d\tilde{\Phi}_2 \dots d\tilde{\Phi}_N e^{i \frac{1}{2} \tilde{\Phi}_i \tilde{K}_{ij} \tilde{\Phi}_j} = \int d\tilde{\Phi}_1 d\tilde{\Phi}_2 \dots d\tilde{\Phi}_N e^{\frac{-1}{2i} \tilde{k}_i \tilde{\Phi}_i^2} \\ &= \prod_{i=1}^N \left(\frac{2i\pi}{\tilde{k}_i} \right)^{\frac{1}{2}} = \frac{(2i\pi)^{N/2}}{(\det K)^{\frac{1}{2}}} \equiv Z_0. \end{aligned} \quad (3-109)$$

The solution uses the fact that the determinant is the product of eigenvalues. The integral from the numerator can be dealt with by taking derivatives of the moment generating function

$$\int d\Phi_1 d\Phi_2 \dots d\Phi_N \Phi_k \Phi_l e^{i \frac{1}{2} \Phi_i K_{ij} \Phi_j} = \frac{1}{i} \frac{\delta}{\delta J_k} \frac{1}{i} \frac{\delta}{\delta J_l} \Big|_{J=0} \int d\Phi_1 d\Phi_2 \dots d\Phi_N e^{i \frac{1}{2} \Phi_i K_{ij} \Phi_j + i J_i \Phi_i}. \quad (3-110)$$

And the integral on the right can be solved using the substitution $\Phi' = \Phi + K^{-1}J$ to complete the square,

$$\begin{aligned} \int d\Phi_1 d\Phi_2 \dots d\Phi_N e^{i \frac{1}{2} \Phi_i K_{ij} \Phi_j + i J_i \Phi_i} &= \int d\Phi'_1 d\Phi'_2 \dots d\Phi'_N e^{i \frac{1}{2} \Phi'_i K_{ij} \Phi'_j - \frac{i}{2} J_i K_{ij}^{-1} J_j} \\ &= \frac{(2i\pi)^{N/2}}{(\det K)^{\frac{1}{2}}} e^{\frac{-i}{2} J_i K_{ij}^{-1} J_j} \\ &= Z_0 e^{\frac{-i}{2} \int d^4x d^4y J(y) K^{-1}(y, x) J(x)}, \end{aligned} \quad (3-111)$$

where the last line reverts back to continuous functions and operators. Applying the derivatives provides the numerator of the two point correlation function

$$\begin{aligned}
\int d\Phi_1 d\Phi_2 \dots d\Phi_N \Phi_k \Phi_l e^{i\frac{1}{2}\Phi_i K_{ij} \Phi_j} &= \frac{1}{i} \frac{\delta}{\delta J_k} \frac{1}{i} \frac{\delta}{\delta J_l} \Big|_{J=0} \int d\Phi_1 d\Phi_2 \dots d\Phi_N e^{i\frac{1}{2}\Phi_i K_{ij} \Phi_j + iJ_i \Phi_i} \\
&= \frac{1}{i} \frac{\delta}{\delta J_k} \frac{1}{i} \frac{\delta}{\delta J_l} \Big|_{J=0} Z_0 e^{\frac{-i}{2} J_i K_{ij}^{-1} J_j} \\
&= Z_0 i K_{ij}^{-1}.
\end{aligned} \tag{3-112}$$

Then plugging in the solutions for the numerator and denominator shows that the two point correlation function is given by the Feynman propagator, \mathcal{D}_F ,

$$\begin{aligned}
\langle 0 | \Phi(x_2) \Phi(x_1) | 0 \rangle &= \frac{\int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}} \\
&= \frac{Z_0 i K^{-1}(x_2, x_1)}{Z_0} \\
&= i K^{-1}(x_2, x_1) = i (-\partial_\mu \partial^\mu - m^2)^{-1} = \mathcal{D}_F(x_2, x_1).
\end{aligned} \tag{3-113}$$

In momentum space K is diagonal and $\mathcal{D}_F = \frac{i}{p^2 - m^2 + i\epsilon}$. Converting to the spacetime basis yields, $\mathcal{D}_F(x_2, x_1) = \int \frac{d^4 k}{\sqrt{2\pi^4}} \frac{i e^{-ik \cdot (x_2 - x_1)}}{p^2 - m^2 + i\epsilon}$, which represents a free particle propagating from one place to another.

The Feynman propagators are the building blocks for the higher order correlation functions. Take the four point function as an example,

$$\begin{aligned}
\langle 0 | \Phi(x_4) \Phi(x_3) \Phi(x_2) \Phi(x_1) | 0 \rangle &= \frac{\int \mathcal{D}[\Phi] \Phi(x_4) \Phi(x_3) \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}} \\
&= \frac{\frac{1}{i} \frac{\delta}{\delta J(x_4)} \frac{1}{i} \frac{\delta}{\delta J(x_3)} \frac{1}{i} \frac{\delta}{\delta J(x_2)} \frac{1}{i} \frac{\delta}{\delta J(x_1)} \Big|_{J=0} \int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi + iJ\Phi}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi (-\partial_\mu \partial^\mu - m^2) \Phi}} \\
&= \frac{\delta}{\delta J(x_4)} \frac{\delta}{\delta J(x_3)} \frac{\delta}{\delta J(x_2)} \frac{\delta}{\delta J(x_1)} \Big|_{J=0} e^{-\frac{1}{2} \int d^4 x d^4 y J(y) \mathcal{D}_F(y, x) J(x)} \\
&= \frac{\delta}{\delta J(x_4)} \frac{\delta}{\delta J(x_3)} \frac{\delta}{\delta J(x_2)} \frac{\delta}{\delta J(x_1)} \Big|_{J=0} \sum_{n=0}^{\infty} \frac{1}{n!} \left(-\frac{1}{2} \int d^4 x d^4 y J(y) \mathcal{D}_F(y, x) J(x) \right)^n.
\end{aligned} \tag{3-114}$$

When $J=0$ only the term with four Js and four derivatives survives. The four derivatives hit the Js and leave terms like $\mathcal{D}_F(d, c) \mathcal{D}_F(b, a)$. In this case, there are $4! = 24$ ways to rearrange

a,b,c, and d. However, the order of the spacetime points within the propagator doesn't matter nor does the order of the propagators, so this reduces the total to $\frac{4!}{2!2^2} = 3$ ways. The $\frac{1}{n!}$ and the $\frac{1}{2^n}$ from the expansion naturally take care of the degeneracy,

$$\begin{aligned}
& \langle 0 | \Phi(x_4) \Phi(x_3) \Phi(x_2) \Phi(x_1) | 0 \rangle \\
&= \frac{\delta}{\delta J(x_4)} \frac{\delta}{\delta J(x_3)} \frac{\delta}{\delta J(x_2)} \frac{\delta}{\delta J(x_1)} \Big|_{J=0} \frac{1}{8} \int d^4 y_j d^4 x_j d^4 y_i d^4 x_i J(y_j) J(x_j) J(y_i) J(x_i) \mathcal{D}_F(y_j, x_j) \mathcal{D}_F(y_i, x_i) \\
&= \mathcal{D}_F(x_4, x_3) \mathcal{D}_F(x_2, x_1) + \mathcal{D}_F(x_4, x_2) \mathcal{D}_F(x_3, x_1) + \mathcal{D}_F(x_3, x_2) \mathcal{D}_F(x_4, x_1).
\end{aligned} \tag{3-115}$$

Any higher order correlation functions are built from the propagators in the same way: add up all possible combinations of the propagators for the appropriate order and account for the degeneracies.

This solves the free theory, which is nice, but it isn't that useful. Particles interact and the interacting solutions are the ones needed to describe scattering and decays. Fortunately, the interacting theories can be expanded in terms of the free correlations. For example, the two point correlation function for an interacting theory is given by,

$$\begin{aligned}
\langle 0 | \Phi(x_2) \Phi(x_1) | 0 \rangle &= \frac{\int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi + \mathcal{L}_{\text{int}}}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi + \mathcal{L}_{\text{int}}}} \\
&= \frac{\int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} e^{i \int_{-\infty}^{\infty} d^4 x \mathcal{L}_{\text{int}}}}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} e^{i \int_{-\infty}^{\infty} d^4 x \mathcal{L}_{\text{int}}}} \\
&= \frac{\int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} \sum_{n=0}^{\infty} \frac{1}{n!} \left(i \int_{-\infty}^{\infty} d^4 x \mathcal{L}_{\text{int}} \right)^n}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} \sum_{n=0}^{\infty} \frac{1}{n!} \left(i \int_{-\infty}^{\infty} d^4 x \mathcal{L}_{\text{int}} \right)^n},
\end{aligned} \tag{3-116}$$

where \mathcal{L}_{int} may be written as a powerseries in Φ . Expanding this way, the numerator becomes a series of integrals of the form

$$\int d^4 x_{i_1} d^4 x_{i_2} \dots d^4 x_{i_k} \int \mathcal{D}[\Phi] \Phi(x_{i_1}) \dots \Phi(x_{i_k}) \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4 x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi}, \tag{3-117}$$

which are just correlation functions of the free field. Likewise, the denominator is also an expansion of the free correlations. In this way, any solution of the full theory may be written in terms of the free field solutions. Furthermore, when the interaction is small compared to the free part of the Lagrangian, the series expansions converge, and only a few terms are needed.

The simplest interacting theory is $\mathcal{L}_{\text{int}} = -\frac{\lambda}{4!}\Phi^4(x)$, and the two point correlation function describing the propagation of a particle is given by

$$\langle 0 | \Phi(x_2) \Phi(x_1) | 0 \rangle = \frac{\int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\int_{-\infty}^{\infty} d^4z \frac{-i\lambda}{4!} \Phi(z)^4 \right)^n}{\int \mathcal{D}[\Phi] e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\int_{-\infty}^{\infty} d^4z \frac{-i\lambda}{4!} \Phi(z)^4 \right)^n}. \quad (3-118)$$

Consider the numerator up to first order in λ

$$\begin{aligned} N(\lambda^1) &= \int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi} \left(1 + \int_{-\infty}^{\infty} d^4z \frac{-i\lambda}{4!} \Phi(z)^4 \right) \\ &= Z_0 \mathcal{D}_F(x_2, x_1) + \int_{-\infty}^{\infty} d^4z \frac{-i\lambda}{4!} \int \mathcal{D}[\Phi] \Phi(x_2) \Phi(x_1) \Phi(z)^4 e^{i \int_{-\infty}^{\infty} d^4x \frac{1}{2} \Phi(-\partial_\mu \partial^\mu - m^2) \Phi}. \end{aligned} \quad (3-119)$$

The first term is just the Feynman propagator, but the order λ term contains a correlation function with six Φ s. Solving the six point integral requires adding up all combinations of terms of the form $\mathcal{D}_F(a, b) \mathcal{D}_F(c, d) \mathcal{D}_F(e, f)$ while accounting for the appropriate degeneracies. There are $\frac{6!}{3!2^3} = 15$ possible propagator triples: 12 ways to put x and y in separate propagators and 3 ways to put them in the same one. With this information the perturbation series for the numerator is finally in hand,

$$\begin{aligned} N(\lambda^1) &= Z_0 \underbrace{\mathcal{D}_F(x_2, x_1)}_A + Z_0 \frac{12}{4!} (-i\lambda) \underbrace{\int_{-\infty}^{\infty} d^4z \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_1, z) \mathcal{D}_F(z, z)}_B \\ &\quad + Z_0 \frac{3}{4!} (-i\lambda) \underbrace{\mathcal{D}_F(x_2, x_1) \int_{-\infty}^{\infty} d^4z \mathcal{D}_F(z, z) \mathcal{D}_F(z, z)}_C. \end{aligned} \quad (3-120)$$

The perturbation series for any n -point correlation function can be represented in terms of Feynman diagrams, which assign symbols to the different pieces of math. In this simple

scalar interacting theory, a line represents a factor of $\mathcal{D}_F(a, b)$ ($\mathcal{D}_F(z, z)$ if it's a loop) and an internal vertex representing an interaction, provides a factor of $-i\lambda \int d^4z$. The Feynman diagrams for $N(\lambda^1)$ are shown in Figure 3-2. In those diagrams, A and B are fully connected while C is disconnected. The separation reveals the fact that the pieces may be calculated independently and then multiplied. The fully connected pieces are the fundamental expressions from which any correlation function may be derived. There are two types of connected diagrams, those with external points and those with no external points. Those with zero external points represent vacuum fluctuations. The denominator is a normalization that serves

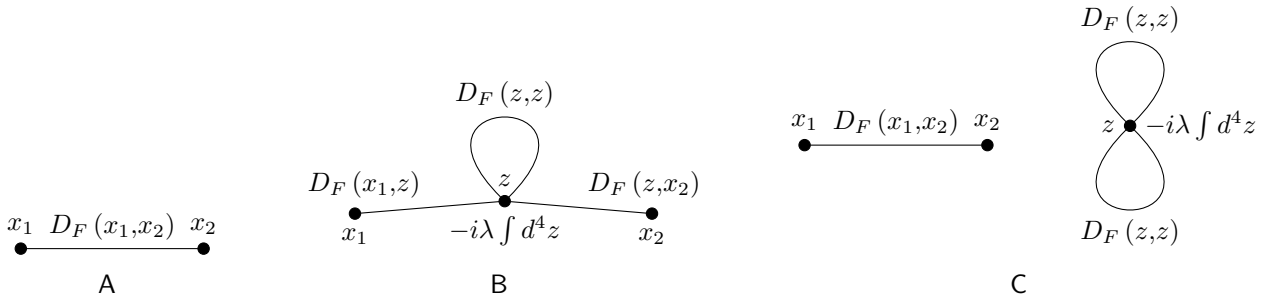


Figure 3-2. Feynman diagrams for $N(\lambda^1) = Z_0 A + Z_0 \frac{12}{4!} B + Z_0 \frac{3}{4!} C$.

to eliminate Z_0 and the disconnected diagrams with vacuum fluctuations like C. It removes the contributions where the vacuum fluctuates independently from the process of interest. Finally, the propagator for the fully interacting theory up to first order in λ is

$$\langle 0 | \Phi(x_2) \Phi(x_1) | 0 \rangle_{\lambda^1} = A + \frac{12}{4!} B = \mathcal{D}_F(x_2, x_1) + \frac{12}{4!} (-i\lambda) \int_{-\infty}^{\infty} d^4z \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_1, z) \mathcal{D}_F(z, z). \quad (3-121)$$

The factors out front are called symmetry factors and provide a weight for each diagram. In this theory the symmetry factor for a diagram is the number of nondegenerate ways to place pairs of points into the propagators with a factor of $\frac{1}{4!}$ for every interaction vertex.

The Feynman rules for a theory can be used to build the perturbation series for any process, and this is why they are so ubiquitous. Any n-point correlation function is the

weighted¹⁵ sum of all possible diagrams with n external points – excluding those with disconnected vacuum fluctuations. For $2 \rightarrow 2$ scattering, the correlation function to first order requires the six diagrams shown in Figure 3-3. The first three diagrams are of the form

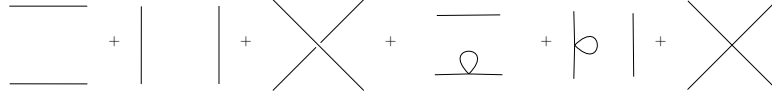


Figure 3-3. The Feynman diagrams for $\langle 0 | \Phi(x_4) \Phi(x_3) \Phi(x_2) \Phi(x_1) | 0 \rangle_{\lambda^1}$ representing the matrix element for $2 \rightarrow 2$ scattering up to first order.

A^*A , and these represent the three ways to put four points into $\mathcal{D}_F \mathcal{D}_F$. The next two terms are of the form A^*B , and the last one is a new diagram where the particles actually scatter instead of propagating separately. And the last term is built from the following factors: the interaction vertex provides a factor of $-i\lambda \int d^4z$ and the four propagators provide a factor of $\mathcal{D}_F(x_1, z) \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_3, z) \mathcal{D}_F(x_4, z)$. The symmetry factor is $1 = \frac{4!}{4!}$ with the $\frac{1}{4!}$ from the internal vertex and the $4!$ for the ways to place the z s among x_1, x_2, x_3, x_4 . All of this results in a mathematical expression for the last diagram,

$$D = -i\lambda \int d^4z \mathcal{D}_F(x_1, z) \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_3, z) \mathcal{D}_F(x_4, z). \quad (3-122)$$

Summing the six diagrams yields the full four point correlation function to first order,

$$\begin{aligned} \langle 0 | \Phi(x_4) \Phi(x_3) \Phi(x_2) \Phi(x_1) | 0 \rangle_{\lambda^1} &= \mathcal{D}_F(x_1, x_3) \mathcal{D}_F(x_2, x_4) + \mathcal{D}_F(x_1, x_2) \mathcal{D}_F(x_3, x_4) + \mathcal{D}_F(x_1, x_4) \mathcal{D}_F(x_2, x_3) \\ &+ \mathcal{D}_F(x_1, x_3) \frac{12}{4!} (-i\lambda) \int_{-\infty}^{\infty} d^4z \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_4, z) \mathcal{D}_F(z, z) \\ &+ \mathcal{D}_F(x_2, x_4) \frac{12}{4!} (-i\lambda) \int_{-\infty}^{\infty} d^4z \mathcal{D}_F(x_1, z) \mathcal{D}_F(x_3, z) \mathcal{D}_F(z, z) \\ &+ -i\lambda \int d^4z \mathcal{D}_F(x_1, z) \mathcal{D}_F(x_2, z) \mathcal{D}_F(x_3, z) \mathcal{D}_F(x_4, z). \end{aligned} \quad (3-123)$$

¹⁵ The weights are the symmetry factors.

The Feynman rules for the actual interactions of the Standard Model are derived from the interacting Lagrangians in a similar way.

3.1.6 Interactions

The spin 1 and spin $\frac{1}{2}$ Lagrangians were obtained after a lengthy adventure through the Lorentz group symmetries. Now the goal is to couple them to produce theories where fermions and bosons interact as observed in nature. The simplest Lorentz invariant term that couples a vector to the Dirac spinors is $\bar{\psi}\gamma^\mu A_\mu\psi$, providing an interacting theory that looks like

$$\begin{aligned} S &= \int d^4x \frac{-1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{m_A^2}{2} A^\mu A_\mu + \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi + q \bar{\psi} \gamma^\mu A_\mu \psi \\ &= \int d^4x \frac{-1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{m_A^2}{2} A^\mu A_\mu + \bar{\psi} [i\gamma^\mu (\partial_\mu - iqA_\mu) - m] \psi \end{aligned} \quad (3-124)$$

To describe electromagnetism, the photon field should be massless and the interacting theory should be gauge invariant. Setting m_A to zero and checking whether $A_\mu \rightarrow A_\mu(x) + \partial_\mu \alpha(x)$ is a symmetry, provides

$$S = \int d^4x \frac{-1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} [i\gamma^\mu (\partial_\mu - iqA_\mu - iq\partial_\mu \alpha) - m] \psi, \quad (3-125)$$

which isn't gauge invariant. In effect, the gauge transformation on A_μ has shifted the derivative, $\partial_\mu \rightarrow \partial_\mu - iq\partial_\mu \alpha$. In order to retain gauge invariance, a simultaneous transformation that sends $\partial_\mu \rightarrow \partial_\mu + iq\partial_\mu \alpha$ is needed to cancel out the extra term. The correct transformation is $\bar{\psi}\partial_\mu\psi \rightarrow \bar{\psi}e^{-iq\alpha}\partial_\mu e^{iq\alpha}\psi$. So, if

$$A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \alpha(x) \quad (3-126)$$

and

$$\psi(x) \rightarrow e^{iq\alpha(x)}\psi(x) \quad (3-127)$$

the Lagrangian is gauge invariant. The second equation reveals that the field is invariant under local transformations of the phase.

Requiring gauge invariance requires the fermion field to maintain U(1) invariance. By running the logic in reverse and demanding more complicated unitary invariances on

the fermion field(s), Lagrangians may be produced that describe new forces. In the case of electromagnetism above, demanding that the fermion field is invariant under a local U(1) transformation, sends $\bar{\psi}\partial_\mu\psi \rightarrow \bar{\psi}e^{-iq\alpha}\partial_\mu e^{iq\alpha}\psi$ effectively shifting the derivative, $\partial_\mu \rightarrow \partial_\mu + iq\partial_\mu\alpha$. Now A_μ needs to cancel the shift requiring

$$\partial_\mu + iq\partial_\mu\alpha + c(A_\mu + a_\mu) = \partial_\mu + cA_\mu. \quad (3-128)$$

Therefore $c=-iq$ and $a_\mu = \partial_\mu\alpha$. Furthermore, $F^{\mu\nu}F_{\mu\nu}$ must remain invariant under $A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu\alpha(x)$. These conditions plus Lorentz invariance force the Lagrangian to be of the form,

$$S = \int d^4x \frac{-1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu) (\partial^\mu A^\nu - \partial^\nu A^\mu) + \bar{\psi} [i\gamma^\mu (\partial_\mu - iqA_\mu) - m] \psi, \quad (3-129)$$

effectively deriving the Lagrangian for Quantum Electrodynamics (QED).

The QED U(1) symmetry has a single generator and, as a consequence, bypasses any commutation issues. The SU(2) transformation $\psi \rightarrow U\psi$ with $U = e^{\frac{i}{2}q\alpha_i(x)\sigma_i}$ is a bit more complicated. If

$$\bar{\psi}U^\dagger i\gamma^\mu (\partial_\mu + cA'_\mu) U\psi = \bar{\psi}i\gamma^\mu (\partial_\mu + cA_\mu) \psi \quad (3-130)$$

is true when $A_\mu \rightarrow A'_\mu$ then the derivative term will be gauge invariant under SU(2). This is true when $(\partial_\mu + cA'_\mu) U\psi = U(\partial_\mu + cA_\mu) \psi$. The transformation $A_\mu \rightarrow UA_\mu U^\dagger + \Delta A_\mu$ helps simplify the conditions for gauge invariance,

$$\begin{aligned} (\partial_\mu + cA'_\mu) U\psi &= \partial_\mu(U\psi) + cA'_\mu U\psi \\ &= (\partial_\mu U)\psi + U(\partial_\mu\psi) + cA'_\mu U\psi \\ &= (\partial_\mu U)\psi + U(\partial_\mu\psi) + cUA_\mu U^\dagger U\psi + c\Delta A_\mu \\ &= U(\partial_\mu + cA_\mu)\psi + (\partial_\mu U)\psi + c\Delta A_\mu \\ &\rightarrow c\Delta A_\mu = -(\partial_\mu U)\psi = -(\partial_\mu U)U^\dagger U\psi = U\partial_\mu U^\dagger\psi \end{aligned} \quad (3-131)$$

The last line uses the fact that for a unitary matrix U , $UU^\dagger = 1$ and $\partial_\mu(UU^\dagger) = 0$. To preserve gauge invariance under a unitary transformation $\psi \rightarrow U\psi$, cA_μ must transform as

$$cA_\mu(x) \rightarrow cUA_\mu(x)U^\dagger + U\partial_\mu U^\dagger. \quad (3-132)$$

For invariance under $SU(2)$ the derivative can be calculated

$$\begin{aligned} cA_\mu(x) &\rightarrow cUA_\mu(x)U^\dagger + c\Delta A_\mu \\ &= cUA_\mu(x)U^\dagger - iq\frac{\sigma_i}{2}\partial_\mu\alpha_i(x). \end{aligned} \quad (3-133)$$

Choosing $c=-iq$ and $\Delta A_\mu = \frac{\sigma_i}{2}\partial_\mu\alpha_i(x)$ determines the coupling constant and the transformation for the $SU(2)$ invariant Lagrangian.

A_μ is a matrix which may be expanded in terms of the $SU(2)$ generators, $A_\mu = A_\mu^1\frac{\sigma_1}{2} + A_\mu^2\frac{\sigma_2}{2} + A_\mu^3\frac{\sigma_3}{2}$. Note that $U(1)$ only requires a single particle while $SU(2)$ requires three. For a general unitary transformation, there will be a force carrying particle for each generator, and an expansion $A_\mu = T^c A_\mu^c$. By representing A_μ in terms of the generators, the transformation for each component, A_μ^c , may be calculated for a general unitary transformation,

$$A_\mu^c \rightarrow A_\mu^c - f^{abc}\alpha^a A_\mu^b + \partial_\mu\alpha^c, \quad (3-134)$$

where $[T^a, T^b] = if^{abc}T^c$ defines the Lie algebra of the group. For $SU(2)$ in particular, $A_\mu = \frac{\sigma_c}{2}A_\mu^c$ and $f^{abc} = \epsilon^{abc}$. This defines the D_μ part of the $SU(2)$ Lagrangian, but $F_{\mu\nu}$ still needs to be defined so that it remains invariant under equation 3-134. Defining

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - iq[A_\mu, A_\nu] \quad (3-135)$$

makes $F_{\mu\nu}$ covariant, $F_{\mu\nu} \rightarrow UF_{\mu\nu}U^\dagger$, and to make it invariant, the trace is taken. So finally, the full gauge invariant Lagrangian with massless fermions is given by

$$S = \int d^4x \mathcal{N} \text{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\psi}i\gamma^\mu D_\mu\psi, \quad (3-136)$$

where $D_\mu = \partial_\mu - iqA_\mu$ is the covariant derivative. The Lagrangian holds for any unitary gauge transformation, U(1) provides electromagnetism, adding on SU(2) provides the electroweak interactions, and adding SU(3) provides the strong force. All three together, describe the Standard Model. For SU(N) invariant theories the Lagrangian is given by,

$$S = \int d^4x \frac{-1}{2} \text{tr}(F_{\mu\nu} F^{\mu\nu}) + \bar{\psi} i \gamma^\mu D_\mu \psi = \int d^4x \frac{-1}{4} F_{\mu\nu}^a F_a^{\mu\nu} + \bar{\psi} [i \gamma^\mu (\partial_\mu - iq T^i A_\mu^i)] \psi. \quad (3-137)$$

where

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + q f^{abc} A_\mu^b A_\nu^c. \quad (3-138)$$

\mathcal{N} is set to $-\frac{1}{2}$ in order to get the appropriate $-\frac{1}{4}$ in front of the $F_{\mu\nu}^a$ tensors¹⁶.

The SU(2) invariant Lagrangian of equation 3-137 provides the weak interaction.

Unfortunately, the theory has massless fermions and massless weak force particles, while in real life these particles have mass. Adding mass terms directly ruins the SU(2) invariance, so another mechanism is needed, and this is where the Higgs comes into play.

3.1.7 The Higgs Mechanism

The W and Z bosons observed in nature are massive, but directly adding a mass term for a force carrying particle ruins the gauge symmetry,

$$\frac{1}{2} m_A^2 A_\mu A^\mu \rightarrow \frac{1}{2} m_A^2 (U A_\mu U^\dagger + \Delta A_\mu)(U A^\mu U^\dagger + \Delta A^\mu). \quad (3-139)$$

Meanwhile for the matter particles, the gauge transformation acts on a column of fermions which leaves the $\bar{\psi} m \psi$ term invariant,

$$\begin{pmatrix} \bar{\psi}_1 \\ \dots \\ \bar{\psi}_n \end{pmatrix} m \begin{pmatrix} \psi_1 & \dots & \psi_n \end{pmatrix} \rightarrow \begin{pmatrix} \bar{\psi}_1 \\ \dots \\ \bar{\psi}_n \end{pmatrix} U^\dagger m U \begin{pmatrix} \psi_1 & \dots & \psi_n \end{pmatrix}, \quad (3-140)$$

¹⁶ The calculation uses the fact that the SU(N) the generator matrices form an orthogonal basis, $\text{tr}(T^a T^b) = \frac{1}{2} \delta^{ab}$.

but this term restricts the fermions to the same mass. In order to describe the massive fermions and massive W and Z particles as seen in nature the Higgs mechanism is needed. Relativistically, mass is energy, so the idea is to produce $m_A^2 A_\mu A^\mu$ and $\bar{\psi} m \psi$ terms via some interaction energy involving a new field. Because mass is a scalar, the interactions require a scalar field, and because the mass is derived from a nonzero interaction energy, the groundstate of the scalar field should be nonzero. For all of these reasons, the Higgs mechanism adds a scalar field with a ϕ^4 potential term to the Lagrangian,

$$\mathcal{L}_\phi^{\text{toy}} = (\partial^\mu \phi - iq A^\mu \phi)^\dagger (\partial_\mu \phi - iq A_\mu \phi) + \frac{m_h^2}{2} \phi^\dagger \phi - \frac{\lambda}{4} (\phi^\dagger \phi)^2. \quad (3-141)$$

As ϕ goes into the groundstate, $\phi \rightarrow \phi_0$, the force carrying field(s) acquire mass through the $A^2 \phi_0^2$ terms. Similarly, interaction terms coupling the left and right spinors provide the fermions with mass as $\phi \rightarrow \phi_0$

$$\mathcal{L}_I^{\text{toy}} = -\beta(L^\dagger \phi R + R^\dagger \phi L). \quad (3-142)$$

The toy examples of equations 3-141 and 3-142 cover the basic ideas behind the Higgs mechanism, but correctly describing the electroweak interaction requires a more complex and intricate theory, the U(1)xSU(2) Weinberg-Salam Lagrangian. The Weinberg-Salam Lagrangian includes a U(1) gauge field and an SU(2) gauge field. In the theory, the U(1) field and the third component of the SU(2) field mix up, with one orthogonal piece providing the massive Z boson and the other the massless photon. The remaining first and second components of the SU(2) field mix up to provide the massive W^+ and W^- bosons.

The Weinberg-Salam Lagrangian for the electron (e) and electron neutrino (ν_e) of equation 3-143 is written in terms of left and right handed Dirac spinors. Left and right handed Dirac spinors are defined in terms of the left and right handed spinors as follows, $\psi_L = \begin{pmatrix} L \\ 0 \end{pmatrix}$ and $\psi_R = \begin{pmatrix} 0 \\ R \end{pmatrix}$. In nature, the weak force treats left and right handed particles differently. The W^+ and W^- particles interact only with left handed particles and interact with those of the same generation symmetrically. In this regard, the Lagrangian is written to

respect the interchange of the left handed particles with the SU(2) transformation acting on $L = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$. The remaining right handed particles are denoted by $R = e_R$. In addition, only left handed neutrinos have been observed in nature, so ν_e is left handed. The electroweak Lagrangian is then,

$$\begin{aligned} \mathcal{L} = & (\partial^\mu \phi - iq_w \frac{\sigma_i}{2} W_i^\mu \phi - iq_b B^\mu \phi)^\dagger (\partial_\mu \phi - iq_w \frac{\sigma_i}{2} W_i^\mu \phi - iq_b B^\mu \phi) \\ & + \bar{L} i \gamma^\mu (\partial_\mu - iq_w \frac{\sigma_i}{2} W_i^\mu - iq_b B_\mu) L + \bar{R} i \gamma^\mu (\partial_\mu - iq_b B_\mu) R \\ & - \beta (\bar{\nu}_e \phi_+ e_R + \bar{e}_R \phi_+^* \nu_e + \bar{e}_L \phi_- e_R + \bar{e}_R \phi_-^* e_L) - \frac{1}{4} G_i^{\mu\nu} G_{\mu\nu}^i - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \\ & + \frac{m_h^2}{2} \phi^\dagger \phi - \frac{\lambda}{4} (\phi^\dagger \phi)^2. \end{aligned} \quad (3-143)$$

The SU(2) field, W_μ , is a complex 2x2 matrix expanded in terms of the Pauli matrices which operates on 2x1 complex column vectors. Therefore ϕ is written

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_- \end{pmatrix}. \quad (3-144)$$

To isolate the mass terms, the scalar field is expanded about its minimum, $|\phi| = \phi_0 = \sqrt{\frac{m_h^2}{\lambda}}$.

The minimum is degenerate, only requiring that $|\phi_+|^2 + |\phi_-|^2 = \phi_0^2$. The particular solution

$$\phi = \begin{pmatrix} 0 \\ \phi_0 + \frac{1}{\sqrt{2}} h(x) \end{pmatrix} \text{ fixes the fermion mass terms such that the electron acquires mass in}$$

the correct way and that the strange mass-like coupling between the electron and neutrino disappears,

$$\beta (\bar{L} \phi R + \bar{R} \phi^\dagger L) = \beta (\bar{\nu}_e \phi_+ e_R + \bar{e}_R \phi_+^* \nu_e + \bar{e}_L \phi_- e_R + \bar{e}_R \phi_-^* e_L) \rightarrow \beta (\bar{e}_L \phi_0 e_R + \bar{e}_R \phi_0 e_L). \quad (3-145)$$

Fixing $\phi^+ = 0$ and $\text{Im} \phi^- = 0$ comes at a cost, breaking the SU(2) symmetry of the

Lagrangian. The coupling is no longer in the invariant form $\bar{L} \phi R + \bar{R} \phi^\dagger L \rightarrow \bar{L} U^\dagger U \phi R + \bar{R} \phi^\dagger U^\dagger U L$.

As in the toy example, the $(D^\mu \phi)^\dagger (D_\mu \phi)$ term bestows mass onto the force carriers,

$$\begin{aligned}
D_\mu \phi &= (\partial_\mu - iq_{w\phi} \frac{\sigma_i}{2} W_\mu^i - iq_{b\phi} B_\mu) \phi \\
&= \left[\begin{pmatrix} \partial_\mu - iq_{b\phi} B_\mu & 0 \\ 0 & \partial_\mu - iq_{b\phi} B_\mu \end{pmatrix} - \frac{i}{2} q_{w\phi} \begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3 \end{pmatrix} \right] \begin{pmatrix} 0 \\ \phi_0 + \frac{1}{\sqrt{2}} h \end{pmatrix} \\
&= -\frac{i}{2} \begin{pmatrix} q_{w\phi} \phi_0 (W_\mu^1 - iW_\mu^2) + \frac{1}{\sqrt{2}} q_{w\phi} h (W_\mu^1 - iW_\mu^2) \\ i\sqrt{2} \partial_\mu h + \phi_0 (2q_{b\phi} B_\mu - q_{w\phi} W_\mu^3) + \frac{1}{\sqrt{2}} h (2q_{b\phi} B_\mu - q_{w\phi} W_\mu^3) \end{pmatrix}.
\end{aligned} \tag{3-146}$$

The ϕ_0^2 terms determine the masses,

$$(D^\mu \phi)^\dagger (D_\mu \phi) = q_{w\phi}^2 \frac{\phi_0^2}{4} (W_\mu^1)^2 + q_{w\phi}^2 \frac{\phi_0^2}{4} (W_\mu^2)^2 + \frac{\phi_0^2}{4} (q_{w\phi} W_\mu^3 - 2q_{b\phi} B_\mu)^2 + \text{other terms.} \tag{3-147}$$

The orthogonal term $q_{w\phi} W_\mu^3 + 2q_{b\phi} B_\mu$ is missing from the covariant derivative and remains massless, providing the photon field. This leaves

$$m_w = \frac{q_{w\phi} \phi_0}{\sqrt{2}}, \quad m_z = \frac{m_w}{q_{w\phi}}, \quad \text{and} \quad m_\gamma = 0. \tag{3-148}$$

The photon, A_μ , is a linear combination of W_μ^3 and B_μ . The U(1) symmetry corresponding to electromagnetism is then

$$\begin{aligned}
U_A &= e^{i(Q_{wi} T^3 + Q_{bi}) \alpha(x)} \\
W_\mu^3 &\rightarrow W_\mu^3 + \frac{1}{g_w} \partial_\mu \alpha \\
B_\mu &\rightarrow B_\mu + \frac{1}{g_b} \partial_\mu \alpha
\end{aligned} \tag{3-149}$$

where T^3 is the third SU(2) generator for the given representation, and the Qs are the normalized charges defined by,

$$q_{wi} = Q_{wi} g_w \quad \text{and} \quad q_{bi} = Q_{bi} g_b. \tag{3-150}$$

The U(1) gauge symmetry leads to conservation of electromagnetic charge, $Q = Q_w I_3 + Q_b$, implying that the electromagnetic charge for a given particle is $Q_i = Q_{wi} I_{3i} + Q_{bi}$. I_3 represents

the eigenvalue of the T^3 generator denoting the particle eigenstate. For example, the operator $T^3 = \frac{\sigma^3}{2}$ acting on L has two eigenstates, ν_e and e_L , corresponding to eigenvalues $\frac{1}{2}$ and $-\frac{1}{2}$ respectively. Similarly, the eigenstates $\phi^+ = 0$ and $\phi^- = \phi_0 + h$ correspond to eigenvalues $\frac{1}{2}$ and $-\frac{1}{2}$.

In order to agree with experiment, the left handed particles and the scalar field are assigned $Q_{wi} = 1$, and the right handed particles are assigned $Q_{wi} = 0$. The electromagnetic charge Q_i and the isospin Q_{wi} values fix the remaining electroweak Q_{bi} values,

$$\begin{aligned} Q_{eL} &= Q_{weL} I_3 + Q_{beL} = \frac{-1}{2} + Q_{beL} \\ Q_{eR} &= Q_{weR} I_3 + Q_{beR} = 0 + Q_{beR} \\ Q_{\nu_e} &= Q_{w\nu_e} I_3 + Q_{b\nu_e} = \frac{1}{2} + Q_{b\nu_e} \\ Q_\phi &= Q_{w\phi} I_3 + Q_{b\phi} = \frac{-1}{2} + Q_{b\phi}, \end{aligned} \tag{3-151}$$

providing,

$$Q_{beL} = \frac{-1}{2}, Q_{beR} = -1, Q_{b\nu_e} = \frac{-1}{2}, \text{ and } Q_{b\phi} = \frac{+1}{2}. \tag{3-152}$$

The electroweak Lagrangian reduces to,

$$\begin{aligned} \mathcal{L} &= (\partial^\mu \phi - ig_w \frac{\sigma_i}{2} W_i^\mu \phi - \frac{i}{2} g_b B^\mu \phi)^\dagger (\partial_\mu \phi - ig_w \frac{\sigma_i}{2} W_i^\mu \phi - \frac{i}{2} g_b B^\mu \phi) \\ &+ \bar{L} i \gamma^\mu (\partial_\mu - ig_w \frac{\sigma_i}{2} W_i^\mu + \frac{i}{2} g_b B_\mu) L + \bar{R} i \gamma^\mu (\partial_\mu + ig_b B_\mu) R \\ &- \beta (\bar{L} \phi R + \bar{R} \phi^\dagger L) - \frac{1}{4} G_i^{\mu\nu} G_{\mu\nu}^i - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{m_h^2}{2} \phi^\dagger \phi - \frac{\lambda}{4} (\phi^\dagger \phi)^2 \end{aligned} \tag{3-153}$$

with $\phi = \begin{pmatrix} 0 \\ \phi_0 + \frac{1}{\sqrt{2}} h(x) \end{pmatrix}$ and $L = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$. In equation 3-153, the W^+ particle is $W_\mu^1 + iW_\mu^2$, and the W^- particle is $W_\mu^1 - iW_\mu^2$. As for the neutral bosons, the photon is $g_w W_\mu^3 + g_b B_\mu$, the Z boson is $g_w W_\mu^3 - g_b B_\mu$, and the Higgs boson is $h(x)$. Adding the next two generations of leptons, the three generations of quarks, and the SU(3) interactions to the electroweak Lagrangian defines the entire Standard Model.

3.2 The Standard Model Higgs and the LHC

The SM Higgs interacts with the massive particles of the SM and even with the massless gluons and photons through second order processes. As such, it can be produced by colliding certain combinations of these particles, and it can decay into them as well. At a particle collider like the LHC, the number of particles expected per second, for a certain process, is given by the cross section times the luminosity, $R = \sigma_i * L$. The cross section is proportional to the probability for a production process and consequently, describes how likely a collision attempt is to produce some particle(s) of interest. The luminosity roughly describes the density and the frequency of the incoming particles. Some of the Higgs cross sections for 14 TeV proton-proton collisions are shown in Figure 3-4.

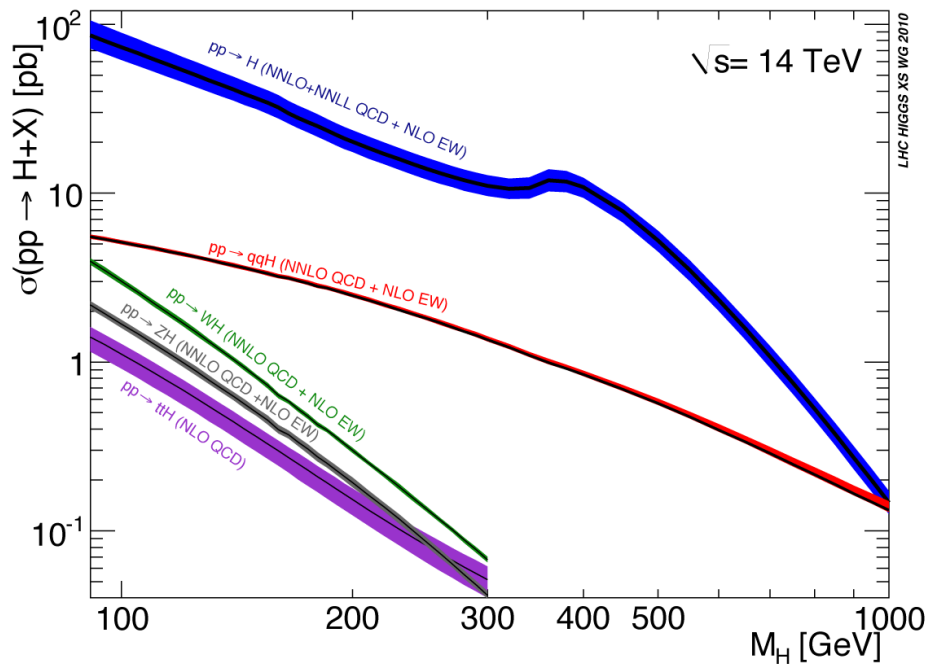


Figure 3-4. The highest production mode cross sections for the SM Higgs at 14 TeV ?

The Higgs cross sections are functions of the mass of the Higgs as well as the energy of the collisions. For a given collision energy, as in Figure 3-4, the cross sections decrease as the Higgs mass increases. When a larger portion of the collision energy was used to create the mass of the particle, there is less energy to distribute among the kinematic degrees of freedom

and therefore fewer possibilities for distribution. On the other hand, for a specific Higgs mass, the cross section grows with collision energy at the LHC. This contrasts with cross sections involving collisions of fundamental particles, e.g. electron antielectron collisions, due to the fact that the LHC collides protons together.

Protons behave like a quantum superposition of an infinite number of quark-antiquarks, an infinite number of gluons, and the usual uud. As a consequence, the total momentum of a proton in a collision is divided up amongst these constituents called partons. This experimentally verified phenomena is modelled by the parton distribution function, which describes the number of partons with a given fraction of the total momentum. In general, there are many partons with very little of the momentum and this behavior implies that the cross section should increase with increasing proton momentum. With a larger proton momentum, the minimum creation energy for the process is a smaller fraction than before, and with more partons at this smaller fraction, it's as if a larger number with the necessary energy are now colliding. This effective increase in the density of energetic partons results in a growth of the cross section with collision energy.

If a SM Higgs is produced, it's predicted to decay in about 10^{-22} seconds¹⁷, which means that the particle itself can't be directly detected at the LHC, only the decay products can. The SM decay probabilities for the different products are listed in Figure 3-5. These probabilities are determined by the coupling, which for the Higgs is the mass of the particle. With a stronger coupling to more massive particles, the decays to the more massive particles are more probable.

¹⁷ Assuming a 125 GeV SM Higgs boson

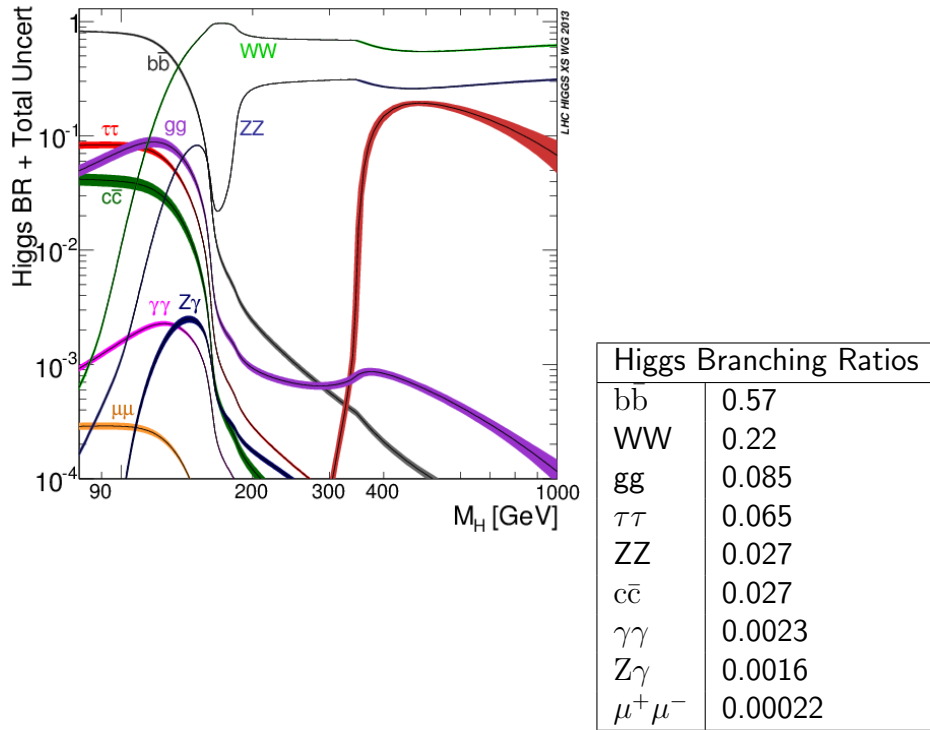


Figure 3-5. The graphic on the top left presents the SM Higgs branching fractions as functions of mass while the table on the bottom right displays the branching fractions for a 125 GeV SM Higgs ?.

The muon has the lowest mass¹⁸ of the particles in Figure 3-5 and consequently $H \rightarrow \mu^+\mu^-$ has the lowest branching fraction in the set.¹⁹ The gluons and photons are massless and do not couple to the Higgs at leading order, but through second order processes. Gluons interact with the Higgs through a loop of top quarks, as seen in Figure 3-6a. The extremely heavy mass of the top quark, about 173 GeV, balances the fact that the loop production is a higher order mechanism. The photons interact with the Higgs through a either a loop of W bosons or a loop of top quarks. Figure 3-6 shows the highest probability production mechanisms at the LHC. At $M_h = 125$ GeV, $\sqrt{s} = 13$ TeV, the GGF channel

¹⁸ excluding the photon and gluon

¹⁹ 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.

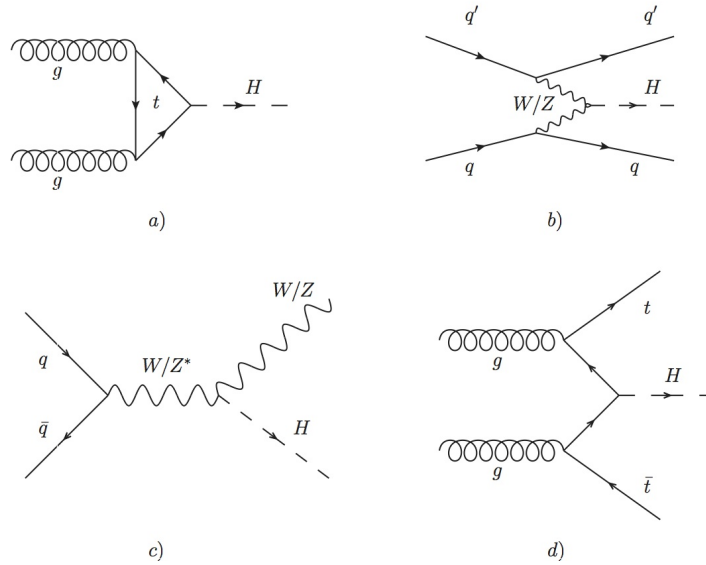


Figure 3-6. The SM production modes with the highest cross sections. a) Gluon Gluon Fusion (GGF) b) Vector Boson Fusion (VBF) c) Associated Production with a Vector Boson (VH) d) $t\bar{t}H$

comprises 87% of the total Higgs production cross section, VBF 7%, VH 4%, and $t\bar{t}H$ 1% ?.

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 these other quarks suppress the process.

Colliding protons full of quarks and gluons results in many quark-gluon (qg) scattering events like the one in Figure 3.2. Quarks and gluons are detected at CMS as collimated jets of energy deposition and not single particles with well defined tracks. Because of this, the different quarks and gluons are difficult to differentiate from one another, and it's difficult to differentiate the quark/gluon Higgs decays from this large background. The Higgs decay

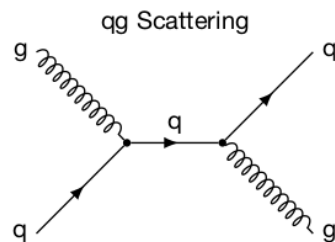


Figure 3-7. The quark-gluon background looks very similar to the GGF production channel when the Higgs decays to two jets. Protons are made of quarks and gluons so this process is extremely common in proton colliders like the LHC.

to b-quarks is an exception as the b-quark upon production forms a reasonably long lived hadron, which travels from the initial collision point and then decays. In this way, jets that come from displaced vertices are probably b-jets and these events can be collected for study without collecting the majority of the enormous qg background. In this regard, $H \rightarrow b\bar{b}$ is an important and viable process that allows scientists at the LHC to study the Higgs coupling to fermions and to third generation quarks in particular. The other viable decays to study are those with isolated lepton or photon final states that distinguish them from the overwhelming jet background.

CHAPTER 4

THE SEARCH FOR $H \rightarrow \mu^+ \mu^-$

If the Higgs decays to $\mu^+ \mu^-$, the signal should be highly concentrated in the di-muon mass spectrum. When a particle decays into a set of products, the mass remains invariant,

$$m_{\text{mother}} = m_{\text{sys}} = \sqrt{E_{\text{sys}}^2 - \vec{p}_{\text{sys}}^2}. \quad (4-1)$$

As a consequence, the mass of the decay products is concentrated at the mass of the mother particle. However, the mass nature assigns to temporary particles is stochastic, and the mass spectrum centered at m_{mother} appears spread out in a Gaussian-like shape. Incorrect momentum measurements can make the spread worse. If the SM Higgs exists and decays to $\mu^+ \mu^-$, there will be a peaked structure in the $m_{\mu^+ \mu^-}$ spectrum. The search for $H \rightarrow \mu^+ \mu^-$ attempts to discover particle by searching for the peak in signal rich regions. The analysis strategy is covered in the next section, but first some of the necessary statistical methods are covered.

4.1 Discovery, Limits, and Measurement, and Sensitivity

This section briefly covers some of the statistical methods needed and provides context for the goals of the $H \rightarrow \mu^+ \mu^-$ search. The test of a coin for bias is used as a simple example to explain the concepts of discovery, limits, measurement and sensitivity. After covering these important topics, the analysis strategy for $H \rightarrow \mu^+ \mu^-$ is covered. The section starts with discovery.

Many scientific endeavors attempt to disprove some null hypothesis in order to claim the observation of a new effect. For example, to test whether a coin is biased, the experimentalist assumes that the coin is unbiased and then performs an experiment, tossing the coin many times. If all of the tosses are heads, then it's very unlikely that the coin is unbiased, and it's therefore reasonable to rule out the null and to declare the discovery of a biased coin.

In order to quantify how rarely an unbiased coin would yield an experiment with N_{heads} , a model for the probability density function (PDF) is needed. The binomial distribution with

$x = N_{\text{heads}}$, $\rho = p_{\text{heads}} = 0.5$, and $N = N_{\text{tosses}}$, is the appropriate PDF,

$$p(x, N; \rho) = \frac{N!}{x!(N-x)!} \rho^x (1-\rho)^{N-x}. \quad (4-2)$$

With the PDF, the probability for the null to produce different experiments can be compared in terms of p-values. The p-value assuming the null, $P(x \succ Y | \text{null})$, is the probability to observe something at least as extreme, \succ , as the outcome Y given the null. Declaring the cutoff p-value for the coin flipping experiment sets the minimum threshold of heads, h , needed for discovery. If observing N_{heads} is rarer than the cutoff, h , i.e. $P(N_{\text{heads}} \geq h | \text{null}) < p_{\text{cutoff}}$, then the null hypothesis is ruled out. Traditionally, different fields require different p-values, and in high energy physics 3σ leads to an "observation" and 5σ leads to a "discovery". These correspond to p-values of 0.3% and 0.00006% respectively.

As an example, when tossing an unbiased coin 100 times, observing 64 heads or greater should occur just more than 0.3% of the time, so observing 64 heads would be just too likely to invalidate the null. On the other hand, an experiment with an observation of 65 heads or greater should occur less than 0.3% of the time and anything greater than this is even more rare. Therefore, any experiment with $N_{\text{heads}} \geq 65$ would invalidate the null at 3σ and lead to an "observation".

Besides discovery, setting a limit is also important. Upon tossing a coin 100 times and finding $N_{\text{heads}} = 40$, the experimentalist may ask which values of p_{heads} are too high to yield an experiment with a value so low. In this case, all p_{heads} that predict experiments with 40 heads or fewer at too rare a probability may be ruled out at the $x\%$ level. For 3σ , $p_{\text{heads}} \geq 0.542$ may be ruled out as $p_{\text{heads}} \geq 0.542$ yields 40 heads or fewer less than 0.3% of the time, while smaller values for p_{heads} do not.

Finally, measuring values is also important. In the case of the coin, the experimenter flips the coin 100 times and attempts to measure how biased the coin is. The value stated as the measured value is usually the best fit, and the best fit value is the one that maximizes the (log-)likelihood of seeing the data observed. In practice, minimizing the negative log-likelihood

is more convenient,

$$-\frac{\partial}{\partial p_{\text{heads}}} \ln[p(x, N; \rho)] = 0 \rightarrow \hat{\rho} = \frac{x}{N}. \quad (4-3)$$

When performing many independent experiments the PDFs for each experiment multiply and the negative log likelihood is,

$$-\ln[p] = -\ln \left[\prod_i p_i \right] = -\sum_i \ln[p_i]. \quad (4-4)$$

Over many coin flipping experiments, the best fit value for \hat{p} is the mean of the individual best fit values,

$$-\frac{\partial}{\partial p_{\text{heads}}} \ln[p] = 0 \rightarrow \hat{\rho} = \frac{1}{n} \sum_i \frac{x_i}{N_i} \quad (4-5)$$

The Poisson and Gaussian distributions are limits of the binomial with $\lambda = N\rho$ and $\mu = N\rho$, so the best fit parameters for λ and μ are also means of the individual experiments. This is why averaging the measurements of many experiments provides a better estimate of the true value.

In order to quantify the uncertainty of the measured value, limiting values of μ are computed. The idea is to find $\mu = \mu_{10}$ such that observing anything higher than $\hat{\mu}$ occurs less than $x\%$ of the time, and to find a value μ_{hi} such that observing anything lower than $\hat{\mu}$ occurs less than $x\%$ of the time. This defines a confidence interval of $100\% - 2x\%$. Generally, a confidence interval of $1\sigma = 68\%$ is taken leaving $x = 16\%$.

When the PDF is Gaussian these limits are simply $\hat{\mu} \pm \sigma$. In the limit of large statistics, the likelihood becomes Gaussian, so the interval can be estimated without searching through the set of μ s,

$$\text{NLL} = -\ln[p] = -\ln \left[A e^{\frac{(x-\mu)^2}{2\sigma^2}} \right] = -\ln[A] + \frac{(x-\mu)^2}{2\sigma^2}. \quad (4-6)$$

Expanding about the minimum, $\hat{\mu}$, shows that the width of the PDF near the minimum, defined by σ , can be estimated by the second derivative,

$$\text{NLL}(\hat{\mu}) + 0(x - \hat{\mu}) + \frac{1}{2}\text{NLL}''(\hat{\mu})(x - \hat{\mu})^2 = -\ln[A] + \frac{(x - \hat{\mu})^2}{2\sigma^2} \rightarrow \sigma^2 = \frac{1}{\text{NLL}''(\hat{\mu})}. \quad (4-7)$$

Note that σ may be determined by moving x away from the minimum until $\Delta\text{NLL} = 1$.

The $\Delta\text{NLL} = 1$ method is sometimes used as an estimate of the uncertainty even when the likelihood is not Gaussian. In some cases the PDF may be multidimensional, and in those cases, σ^2 is the covariance matrix with $\partial_{\theta_1}\partial_{\theta_2}\text{NLL}(\hat{\theta}) = (\sigma^2)^{-1}$. The covariance matrix can be used to estimate the individual contributions to the uncertainty on some parameter of interest. A lower dimensional PDF may always be formed by integrating over the other variables.

An analysis is often designed to maximize the chance of discovery, which is accomplished by minimizing the expected p-value. The lower the expected p-value given the null, the higher the sensitivity. Consider an experiment flipping a coin N times,

$$p(x, N; \rho) = \frac{N!}{x!(N-x)!} \rho^x (1-\rho)^{N-x}. \quad (4-8)$$

The experimenter may ask what p-value, given the null, is expected if the coin has a true value $\rho = \rho_i$. For a coin with ρ_i , the observed N_{heads} is most frequently $N\rho_i$. Therefore, given the null $\rho = \rho_{\text{null}} = 0.5$, one expects

$$p(x = N\rho_i, N; \rho = \rho_{\text{null}}) = \frac{N!}{(N\rho_i)!(N - N\rho_i)!} \rho_{\text{null}}^{N\rho_i} (1 - \rho_{\text{null}})^{N - N\rho_i}. \quad (4-9)$$

In the limit of large statistics, the binomial distribution may be approximated by a Gaussian with $\mu = N\rho$, and $\sigma = \sqrt{N\rho(1-\rho)}$. The p-values for a Gaussian are determined by the number of standard deviations away from the mean, Z . The larger Z is the smaller the p-value and the more sensitive experiment. The sensitivity is given by $Z = \frac{(x-\mu)}{\sigma}$, and for a coin with ρ_i , the expected sensitivity is

$$Z = \frac{(x - \mu)}{\sigma} = \frac{\sqrt{N}(\rho_i - \rho_{\text{null}})}{\sqrt{\rho_{\text{null}}(1 - \rho_{\text{null}})}}. \quad (4-10)$$

Note that the sensitivity scales as the \sqrt{N} . In the limit of large statistics the Poisson distribution may also be approximated as a Gaussian with $\mu = \lambda$ and $\sigma = \sqrt{\lambda}$. In particle physics, one often tries to rule out the background only hypothesis by observing enough signal. If the Standard Model or some other theory predicts $\mu = S + B$ and the null predicts $\mu = B$.

Then the expected sensitivity for discovery is,

$$Z = \frac{(x - \mu)}{\sigma} \sigma = \frac{(S + B - B)}{\sqrt{B}} = \frac{S}{\sqrt{B}} = \frac{\sqrt{N} \rho_s}{\sqrt{\rho_b}}. \quad (4-11)$$

This also scales with the \sqrt{N} . So one way to ensure a sensitive experiment is to collect a lot of data, but that's not the only way. With many bins the PDFs for each bin multiply and the NLL in the high statistics limit is,

$$-\ln\left[\frac{P}{C}\right] = -\ln\left[\prod_i p_i\right] = -\sum_i \ln[p_i] = -C + \sum \frac{((x_i - \mu_i)^2)}{2\sigma_i^2}, \quad (4-12)$$

where C is the sum of the normalizations for the Gaussians. After normalizing by C and the factor of 2, the NLL is a sum of χ^2 variables and therefore itself a χ^2 variable,

$$\chi_{\text{nll}}^2 = -2\ln\left[\frac{P}{C}\right] = \sum \frac{((x_i - \mu_i)^2)}{\sigma_i^2}. \quad (4-13)$$

This shows that the expected sensitivity with many bins may be estimated by

$$Z^2 = \frac{(x_{\text{nll}} - \mu_{\text{nll}})^2}{\sigma_{\text{nll}}^2} = \sum_i \frac{S^2}{B}. \quad (4-14)$$

The test statistic t formed from the NLL is a random variable, with its own distribution,

$$t = -2\ln\left[\frac{p(x_i, \theta)}{p(x_i, \hat{\theta})}\right] = \sum \frac{((x_i - \mu_i)^2)}{\sigma_i^2}. \quad (4-15)$$

It is standardized by the PDF with the parameters set to the best fit values, $C = p(x_i, \hat{\theta})$.

With the PDF for the background only hypothesis, the distribution for t may be approximated by Monte Carlo methods, or by assuming that with enough data t reduces to a χ^2 distribution.

In either case, the expected p-value for the Standard Model against the background only null may be calculated using the PDFs for the S+B and the background only hypotheses.

Similarly, the expected upper limit on S may be calculated using t with S+B as the null and the background as the expected hypothesis. The expected upper limit on S is calculated by finding the value of S high enough that observing the expected background has a p-value of

5%. A higher expected sensitivity and lower upper limit are important goals in the design of a physics analysis.

Upon collecting data, the test statistic t may be used with the data observed and the background only as the null to check for discovery. The observed upper limit on S is computed by finding a high enough value of S such that observing the data has a p-value of 5%. These can be compared to the expected p-value for the SM against the null and to the expected upper limit on S when assuming the background-only as truth.

4.2 The Analysis Strategy

The goal of the $H \rightarrow \mu^+\mu^-$ search is to discover the decay, and barring that to set an upper limit on the rate of production. The best fit for the rate of production is also reported. In order to do all of this, the analysis needs the data, a PDF for the SM signal, and a PDF for the background. The analysis fits Monte Carlo samples along $m_{\mu^+\mu^-}$ for the signal, and fits data along $m_{\mu^+\mu^-}$ for the background. The data at the collected luminosity has far better statistics than the Monte Carlo available for the background, and the larger statistics provide lower uncertainty in the bins of the PDF. There is too much data to process to use all of it in the statistical analysis, and that would be wasteful anyways, so basic selections are made to look only at data likely to contain $H \rightarrow \mu^+\mu^-$ signal and unlikely to miss it. With a reasonable amount of data to look at, the Monte Carlo is validated against the data to make sure it agrees with observation. Some corrections like efficiency scale factors, trigger scale factors, and momentum corrections are applied to the Monte Carlo to ensure better agreement with the data. The background Monte Carlo is used to help with the data Monte Carlo validation, and to optimize the sensitivity, but not for the limit setting, discovery p-values, or measurement.

The analysis attempts to maximize the odds of discovering $H \rightarrow \mu^+\mu^-$ by maximizing the sensitivity. Because the sensitivity increases with the amount of data, improvements to the Level-1 Muon Trigger are made to increase the $\mu^+\mu^-$ data saved for the analysis. Moreover, the sensitivity improves with increased signal and worsens with increased background – recall that in the limit of large statistics, $Z = \frac{S}{\sqrt{B}}$. As such, the ideal situation is one where the signal

is concentrated into a single bin with little or no background. This isn't possible in practice, but regions of feature space may be found where the signal is more concentrated or where there is little background or both.

The analysis corrects the muon momentum to narrow the $m_{\mu^+\mu^-}$ peak, improving its resolution, and concentrating the signal. Further work is done, to find regions of feature space where the signal peak is narrow. To further improve the sensitivity, Boosted Decision Trees (BDTs) are trained to separate signal and background. The training produces a discriminating feature with a higher concentration of signal and lower concentration of background at large values. With the PDF in a single dimension, low sensitivity regions merge with high sensitivity regions of feature space polluting the chance for discovery, so the sensitive regions must be extracted. A novel algorithm then optimally and automatically categorizes the events by resolution and BDT score to maximize the expected sensitivity of the analysis. The PDFs are fit in each orthogonal category and multiplied in the log likelihood.

4.3 Improving the Level-1 Muon Trigger

The LHC collides bunches of protons every 25 ns at a center of mass energy of 13 TeV. The CMS experiment detects the resulting particles and measures their kinematics using a variety of subdetectors working in concert. With 40 million proton bunch crossings per second amounting to roughly 40 TB of data each second, saving the information from every event is not feasible. As such, the CMS trigger system chooses the interesting events to save to disk, operating in two stages ?. The Level-1 (L1) trigger runs in hardware online reducing the throughput of data from 40 MHz to 100 KHz. From there, the High Level Trigger (HLT) operates in software online reducing the rate from 100 KHz to 1 KHz. In the end, about 1 GB/s is saved to disk.

With 40 MHz of input, the L1 Trigger has only 4 μ s to decide whether to keep the information for an event. The Endcap Muon Track Finder (EMTF) – part of the L1 Trigger dedicated to muons – has only about 500 ns to determine the location, tracks, and momentum of the muons passing through the Cathode Strip Chambers (CSC) and Resistive Plate

Chambers (RPC) in the endcaps of CMS ?. High momentum muons are an important object for many physics analyses at CMS and the most important object for $H \rightarrow \mu^+ \mu^-$. As such, an accurate momentum assignment distinguishing low momentum muons (background) from high momentum muons (signal) is key to the L1 Trigger. In order to meet the timing requirements, the EMTF's logic is implemented in Field Programmable Gate Arrays (FPGAs), a type of reprogrammable hardware that allows vast parallelization and speeds much greater than even the best CPUs.

To improve the transverse momentum (p_t) assignment for muons in the endcaps at Level-1, the EMTF team trained Boosted Decision Trees (BDTs) offline using TMVA ?, and stored the prediction scheme into a 1.2 GB Look-Up Table (LUT). The FPGAs then use the LUT online to assign the p_t in a single operation. Using the LUT to turn the BDT p_t assignment into a simple look-up enables the EMTF to utilize the power of a robust machine learning algorithm for its momentum predictions while still operating at the required time scale. Putting a parallelized version of the BDTs directly into the FPGAs, while hypothetically possible, would require more than the available number of logic gates. Such an implementation would still be slower than the LUT method, and changing the p_t assignment would require reprogramming the FPGA logic each time. The LUT method provides a simple way to run any machine learning evaluation at high speed by turning the evaluation into a single operation.

4.3.1 Metrics of Success

Two metrics are used to measure the success of the EMTF: the rate and the efficiency. The rate at X GeV is defined as the number of muons with a predicted p_t greater than X GeV. In other words, the rate consists of both true and false positives above the p_t threshold. The efficiency at X GeV is defined as the number of muons with both predicted p_t and true p_t greater than X GeV divided by the number of muons with true p_t above X GeV. Put another way, the efficiency measures the percentage of muons with true p_t above X GeV correctly predicted above X GeV. A good trigger will minimize the data saved without losing

the interesting high p_t events where unexplored physics lies, i.e. it will minimize rate while maximizing the efficiency.

4.3.2 The EMTF Regression Project

A muon traveling through the endcap detectors has a chance to leave hits in four sequential stations labeled 1, 2, 3, and 4. The specific combination of hits like 1,3,4 is called the mode. Each station records the ϕ and θ location of a hit, among other information. The CSCs have better spatial resolution, so the ϕ and θ information is taken from the CSCs by default, but the RPC measurements for the station are used if the CSCs missed the hit in the same station. The charged muons travel through a magnetic field following curved paths due to the Lorentz force. The force causes the high p_t muons in a magnetic field to bend less and the low p_t muons to bend more. The difference in ϕ and θ between stations i and j , $\Delta\phi_{ij}$ and $\Delta\theta_{ij}$, quantify the curvature of the track. With most of the curvature accounted for by the $\Delta\phi$ variables, the $\Delta\phi$ s provide the majority of the p_t discrimination.

A major difficulty in minimizing the rate is the steeply falling p_t distribution. A typical interesting event has p_t greater than 25 GeV, and there are about one thousand 5 GeV muons for every 25 GeV muon. With so many more low p_t events, predicting the low momentum muons poorly will drastically increase the rate. Moreover, in addition to the large number of low p_t muons, there are other notable difficulties: the muons travel through a non-uniform magnetic field, some scatter between detector stations, and those with high p_t often shower charged particles upon interacting with the detector material. Moreover, low p_t muons may spiral completely before getting to the next station. The scattering, showering, and spiraling add noise to the underlying true behavior, while the number of low p_t muons requires that the regression focus on the low momentum regime to prevent an explosion in the rate.

In order to assign p_t in a robust way and deal with the aforementioned difficulties, a BDT is trained for each possible mode using the discretized values for the features of Table 4-1. The loss function and weights are chosen to focus on the low p_t events and minimize the rate while maintaining acceptable efficiency. Features are chosen for each mode to give the BDT the

information needed to predict the p_t while dealing with the non-uniform magnetic field and the problematic scattering and showering effects.

The $\Delta\phi$ variables available for each mode are used as features to determine the curvature and get most of the p_t discrimination. However, the power of these variables depends largely on the track position in θ . The magnetic field varies as a function of θ affecting the magnitude of the curvature for a given p_t , thus correlating $\Delta\phi$, p_t , and θ . The link between these three makes θ the next most important training feature.

Variables modeling the mean and RMS of the available $\Delta\phi$ s for the mode are also used as features in order to identify scattering and showering effects. If a muon were to scatter or shower between stations the recorded hit in a station may not be the true hit of the muon. Any $\Delta\phi$ involving this station will be an outlier. To determine the severity of the deviation and the likelihood of scattering/showering, the idea is to identify the outlier station and to compare the mean and RMS $\Delta\phi$ with and without the outlier station. The greater the difference the greater the severity. The nominal mean and RMS $\Delta\phi$ features are calculated using all available $\Delta\phi$ s for the mode. The exclusive mean and RMS are calculated using all available $\Delta\phi_{ij}$ for the mode with i or $j \neq S_{out}$, where S_{out} is the outlier station. S_{out} is the excluded station such that leaving it out of the sum minimizes the mean and RMS. The outlier station, S_{out} , is also used as a feature. Including the nominal mean and RMS of $\Delta\phi$, the exclusive RMS and mean of $\Delta\phi$, and S_{out} as features helps the BDT differentiate scattering, showering, and normal events.

The features described above are the most important features, but not the whole collection. The front-rear (FR) bit designates whether the muon hit a front or rear CSC chamber in the station, and it is also included. The $\Delta\theta$ s provide additional curvature information, and these are included as well. The B feature for each station is included as well, and it flags whether the ϕ , θ information for the station came from the CSCs or the RPCs. If there are bits available for the B_i feature it also includes information about the single station $\Delta\phi$ bend angle within a CSC chamber. Lastly, the $+/-$ feature stores the signs of the later $\Delta\phi$ s relative to the first $\Delta\phi_{ij}$ for the mode.

4.3.3 Putting the BDTs into a Look-up Table

After training BDTs for each mode, the mode and the fundamental features from which the others can be derived are discretized and fit into a 30 bit word. The discretization scheme is different for each mode, detailed in Table 4-1. With the feature space compressed into 30 bits, there are 2^{30} possibilities that need to be assigned a p_t . A LUT is created by looping over all 2^{30} possible bit words, decoding each word into the fundamental features, deriving the secondary features, and sending the values to the BDT to assign the p_t prediction. Using 9 bits for the p_t , this amounts to a 1.2 GB LUT where each bit word value is an address and the p_t is the value in memory. Discretizing the feature space and creating a LUT turns the p_t assignment into a single operation. The LUT is then used by the FPGA logic online to assign p_t to muon tracks in the EMTF. The LUT method is a simple way to run any machine learning method quickly, but compressing the features into 30 or so bits may not always be feasible for the application.

Table 4-1. The feature discretization scheme for each mode.

Four Station Modes

Mode	Feature	$\Delta\phi_{12}$	$\Delta\phi_{23}$	$\Delta\phi_{34}$	$+/-$	$\Delta\theta_{14}$	B_1	B_2	B_3	B_4	FR_1	θ	Mode
1-2-3-4	Bits	7	5	4	2	2	2	1	1	1	1	3	1

Three Station Modes

Mode	Feature	$\Delta\phi_{12}$	$\Delta\phi_{23}$	$+/-$	$\Delta\theta_{13}$	B_1	B_2	B_3	FR_1	FR_2	θ	Mode
1-2-3	Bits	7	5	1	3	2	1	1	1	1	5	3
Mode	Feature	$\Delta\phi_{12}$	$\Delta\phi_{24}$	$+/-$	$\Delta\theta_{14}$	B_1	B_2	B_4	FR_1	FR_2	θ	Mode
1-2-4	Bits	7	5	1	3	2	1	1	1	1	5	3
Mode	Feature	$\Delta\phi_{13}$	$\Delta\phi_{34}$	$+/-$	$\Delta\theta_{14}$	B_1	B_3	B_4	FR_1	FR_3	θ	Mode
1-3-4	Bits	7	5	1	3	2	1	1	1	1	5	3
Mode	Feature	$\Delta\phi_{23}$	$\Delta\phi_{34}$	$+/-$	$\Delta\theta_{24}$	B_2	B_3	B_4	FR_2	—	θ	Mode
2-3-4	Bits	7	5	1	3	2	1	1	1	—	5	4

Two Station Modes

Mode	Feature	$\Delta\phi_{XY}$	$\Delta\theta_{XY}$	B_X	B_Y	FR_X	FR_Y	θ	Mode
X-Y	Bits	7	3	3	3	1	1	5	7

X-Y runs through the possible two station combinations: 1-2, 1-3, 1-4, 2-3, 2-4, 3-4.

4.3.4 Results and Conclusions

The LUT scheme utilizing the BDT predictions has been implemented in the EMTF for 2016 and 2017 data taking. As seen in Figure 4-1, the upgraded system – compared to the legacy system – reduces the rate at 25 GeV by a factor of three with no loss in efficiency. The legacy system was used in the endcaps until 2015. The improvements in the EMTF, in essence, save 3x the amount of data in the endcaps for $H \rightarrow \mu^+\mu^-$, which is a huge gain for the analysis.

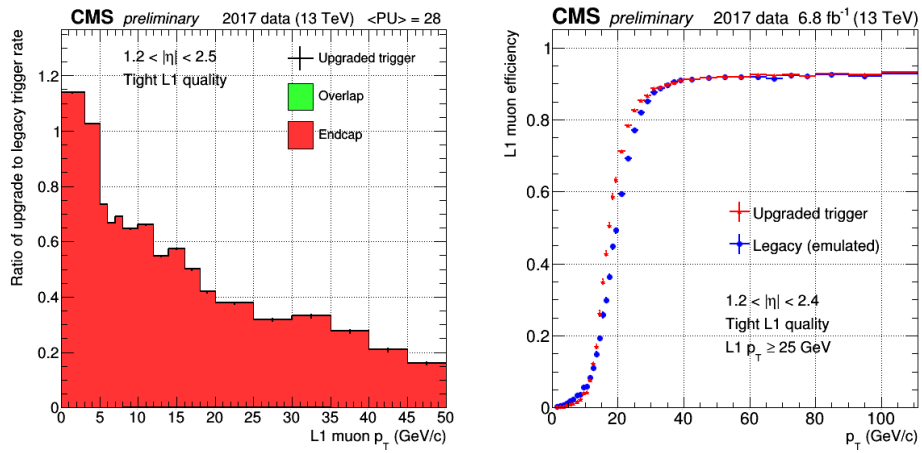


Figure 4-1. On the left, the upgraded EMTF rate divided by the legacy rate is shown for a variety of p_T thresholds. On the right, the upgraded and legacy efficiencies are presented for a 25 GeV threshold. The upgraded EMTF has a 3x lower rate than the legacy system at 25 GeV with virtually no difference in plateau efficiency for the same threshold. Plots are taken from ?.

4.4 Data and Monte Carlo Samples

4.5 Event Selection

4.6 Muon Momentum Calibration

4.7 Maximizing the Sensitivity

4.8 Modeling the Signal

4.9 Modeling the Background

4.10 Systematic Uncertainties

4.10.1 Signal

4.10.2 Background

4.11 Results

APPENDIX A

THIS IS THE FIRST APPENDIX

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APPENDIX B
AN EXAMPLE OF A HALF TITLE PAGE

L^AT_EX 2_ε

Figure B-1. L^AT_EX 2_ε. logo

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APPENDIX C DERIVATION OF THE Υ 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 α 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 Υ 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 ξ_i^+ and ξ_i^- are i.i.d. exponential random variables with rates η_1 and η_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.

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

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

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

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

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

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

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

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 $x \rightarrow \infty$,

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

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

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

for arbitrary constants α, c and β .

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BIOGRAPHICAL SKETCH

This section is where your biographical sketch is typed in the [bio.tex](#) file. It should be in third person, past tense. Do not put personal details such as your birthday in the file. Again, to make a full paragraph you must write at least three sentences.