Drew University

College of Liberal Arts

Probing Particle Physics:

The Search for New Physics in the WWγ Decay Mode with the ATLAS Detector at CERN

A Thesis in Physics

by

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Abstract

This paper first gives an overview of the field of high energy particle physics (HEP). An outline of the Standard Model of Elementary Particles (SM) is followed by a short introduction to particle accelerators and colliders. We then present some important information about the facility used in this work: the Large Hadron Collider and the ATLAS detector at CERN in Switzerland. We then describe anomalous quartic gauge couplings (AQGC's), which are used to investigate physics beyond the Standard Model in this paper. It then presents the statistical methods used to conduct experiments and make discoveries in HEP, as well as the probabilistic simulation technique used to compare theory to experiment.

Next, the original research is presented. First, we find the cross section for the $WW\gamma$ decay mode, a measure of how likely a given particle collision is to produce these three particles together. The cross section was found to be 0.2655 ± 0.00098 picobarns at leading order, and 0.34864 ± 0.0022 picobarns with the next-to-leading order correction. A calculation of the acceptance, the amount of signal that makes it into the final dataset, is conducted using an established Monte Carlo simulation program, MadGraph5, along with code written specifically for this project, run using another commonly used software, Rivet. Using the truth information produced by the software for simulated signal events, we calculate how much of the signal is accidentally thrown away by layers of selection cuts which are intended to cut out likely background events. We find that roughly 15% (0.1496 ± 0.0000058 (stat) ± 0.00179 (sys)) of the signal remains at the end of the selection cuts. This information will be used to make the results reproducible by an analysis that does not utilize the same selection cuts or detector.

Finally, an investigation of beyond-SM physics is performed using the Eboli Model with MadGraph5. The Eboli model contains 18 parameters that would change the strength of

AQGC's. We simulate the results of experiments in which these anomalous, beyond-SM couplings exist using only one parameter, labeled T1. We simulate the cross section for the process at several different strengths and use the expected sensitivity of our experimental data to set a 95% confidence limit on the possible strength of the model parameters. The limit is found to be 16.7 TeV^{-4}. The limit is contingent upon confirmation that that the experimental cross section for the WWγ decay mode analysis (still forthcoming) will agree with the SM. This investigation can be used to inform new theories of beyond-SM physics and acts as an outline of the process for setting a limit on each of the 14 parameters of the Eboli Model to which the WWγ analysis is sensitive. That study will be published with the official discovery of the WWγ decay mode by Professor Abbott's research group at the University of Oklahoma, within the ATLAS Collaboration, when that work is completed.

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1. Theory

The **Standard Model of Particle Physics (SM)** underlies much of our understanding of physical interactions on the scale of subatomic particles. It is often claimed to be the most precisely tested and confirmed theory in science, as its predictions have been verified through years of experiments to increasingly high precision. It bases its description of the physical world on the Standard Model Lagrangian, a mathematical function from which the equations of motion that describe all particles and interactions included in the model can be extracted [1].

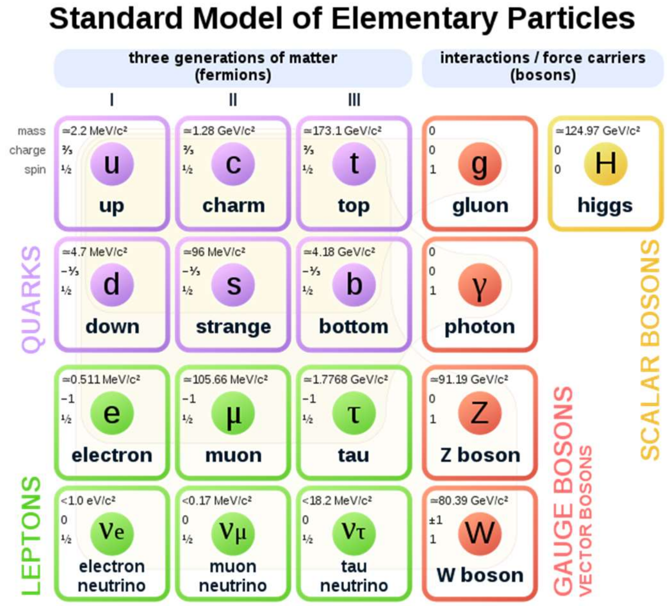


Figure 1: The particles of the standard model: Mass increases across and down the quark and lepton sections. From: https://en.wikipedia.org/wiki/File:Standard_Model_of_El

The SM states that all matter is composed of different combinations of the particles listed in Figure 1. These particles are **fundamental**, meaning that they cannot be subdivided into smaller pieces. There are six **flavors**, or types, of quark and six flavors of lepton. Leptons are also divided into three **families**, containing one lepton each and a corresponding neutrino, i.e. the electron family contains the electron and the electron neutrino. Leptons have a -1 or 0 electric charge and quarks have either a -1/3 or a 2/3 electric charge. Particles are only found naturally in integer charges, so quarks are never found alone but rather in groups of two, known as **mesons,** or three, **hadrons**, where the charges sum to an integer charge, such as $0, \pm 1, \pm 2$. When they are pulled apart, they immediately **hadronize**, meaning the energy needed to separate them becomes so great that it transforms into two new particles that combine with the lone quarks, creating hadrons or mesons before the original quarks are even fully separated. For example, the most famous hadron is the **proton**, consisting of two up quarks and a down quark, whose total charge sums to one. Each matter particle also has an antimatter analog, a corresponding particle with the opposite charge. Antimatter particles are denoted with a bar over the symbol, for example $\bar{e}$ would be the antielectron, or positron, with charge (+1). For example, the anti-electron, or the positron, has the same characteristics as the electron but a charge of positive one. If they collide, antiparticles and their corresponding matter particles annihilate, transforming all their mass into pure energy. The most common particles in the modern universe are the lightest ones. The lightest two quarks, up and down, are notable as the components of protons and neutrons in the atomic nucleus. The lightest leptons are neutrinos, but these rarely interact with other matter particles. The next lightest is the electron, which features prominently in the atom's electron cloud and as the conductor in modern electricity. According to the SM, three of the four fundamental forces, the electromagnetic, strong, and electroweak forces are mediated by the rapid exchange of force carrier bosons between the matter particles that are interacting [1]. Just like throwing a basketball back and forth between two people on ice would cause the people to exchange momentum and slide apart, the force carrier particles cause the repulsive and attractive forces that we see between particles [2]. The bosons exchanged between interacting particles are **virtual**, meaning that they exist only on very short timescales. The electromagnetic force is mediated by the

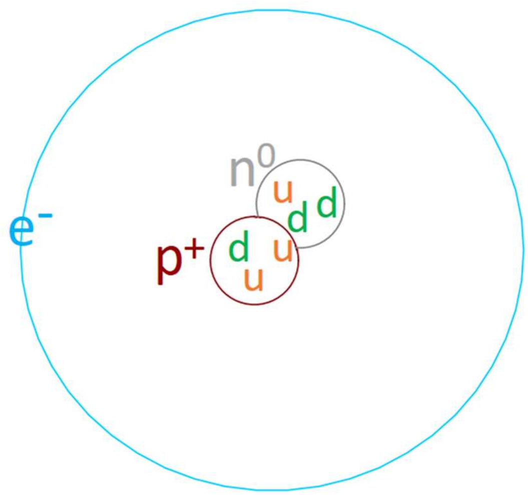


Figure 2: A simplistic sketch of the Hydrogen-2 atom with one proton containing two up quarks and a down quark, one neutron containing one up quark and two down quarks, and an electron in its orbital.

photon and the strong force by the gluon, both of which are massless particles. The weak force is mediated by the W and Z bosons, which are massive particles. The Higgs is not a force carrier, but rather a scalar boson, meaning it has spin 0. It is believed to be responsible for giving other particles mass [1].

In the SM, heavier massed particles spontaneously decay into lighter massed particles, where the specific particles along the decay chain is called the **decay mode**. This term is also used to refer to the group of particles whose decay is being studied, in this case WWγ. So, this analysis concerns the production of positively and negatively charged W bosons and a photon and the spontaneous, nearly instantaneous decay of the W bosons into electrons, muons and neutrinos, known as a **fully leptonic decay**. All decays must adhere to conservation of energy and momentum, meaning the sum of the energy and momentum of the incoming particles must equal the total energy and momentum of the outgoing particles, so only certain combinations of particles can be produced out of each original particle. Charge must be conserved, so if charged particles are produced, the total charge must sum to the charge of the original particle. Physicists also define the quantity "**lepton number**" that must be conserved, so that the number of leptons in each family is conserved, or the total ingoing lepton number must equal that of the product.

Table 1: Lepton number by family

	Electron Family	**Muon Family**	**Tau Family**
Leptons	Electron, electron neutrino	Muon, muon neutrino	Tau, tau neutrino
Matter	+1 Electron Number	+1 Muon Number	+1 Tau Number
Antimatter	-1 Electron Number	-1 Muon Number	-1 Tau Number

Since the W particle is not a lepton, its lepton number is zero. Therefore, the lepton number of all the particles produced must sum to zero. In order to conserve charge, the charge must sum to the charge of the W boson. Conserving charge and lepton number, a W^+ can decay to $\bar{e}\nu_e$ or $\bar{\mu}\nu_\mu$ and a W^- can decay to $e\bar{\nu}_e$ or $\mu\bar{\nu}_\mu$. There is also a possible decay path including τ or $\bar{\tau}$, but we neglect these because they are more difficult to find since they cannot be detected directly like electrons and muons can, but rather must be reconstructed indirectly. Consequently, the possible fully-leptonic $W^+W^-\gamma$ decays are: $e\bar{\nu}_e\bar{\mu}\nu_\mu\gamma$, $\mu\bar{\nu}_\mu\bar{e}\nu_e\gamma$, $e\bar{\nu}_e\bar{e}\nu_e\gamma$, and $\mu\bar{\nu}_\mu\bar{\mu}\nu_\mu\gamma$.

Despite the rigorous corroboration of the SM during the nearly 50 years of its existence, it has some gaping holes. The most obvious: it does not include the fourth fundamental force, gravity in any way. String Theory, the leading candidate for a theory of quantum gravity, postulates an additional force-carrier to mediate gravity, a boson with spin 2 which has been dubbed the graviton, but no such particle has been observed and String Theory has not yet been confirmed empirically. Another issue is that the SM predicts the neutrino to be massless, but a nonzero mass has been confirmed experimentally. It also fails to explain dark matter, dark

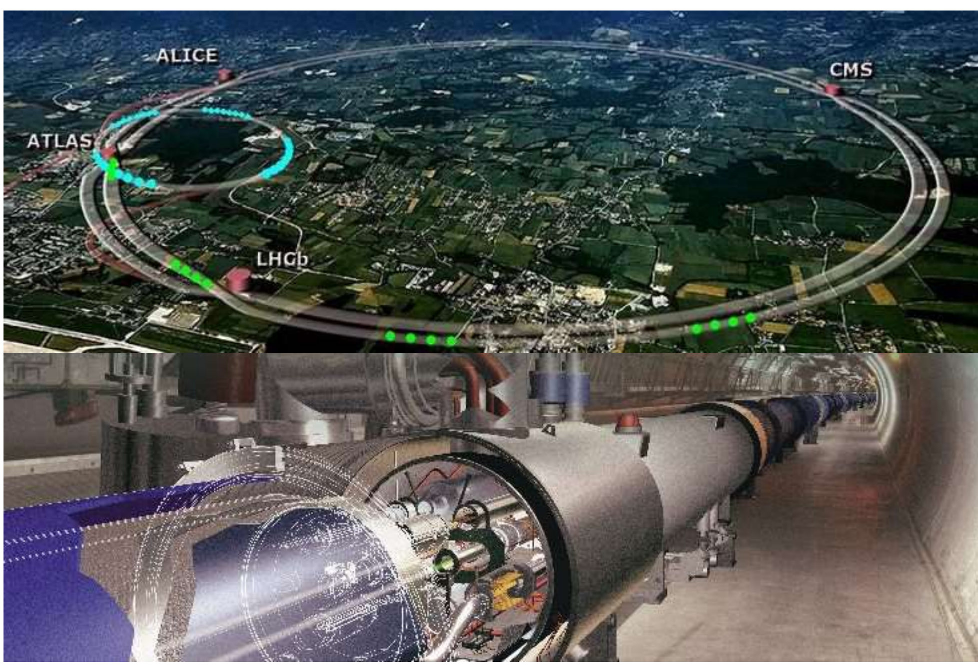


Figure 3:

On top, the path of the 27 km LHC ring underneath the French and Swiss countryside, with the locations of the various detectors marked [17].

Beneath, a simulated image of the beam pipe in the LHC tunnel opened to show the sensitive equipment inside [18].

energy, and the expansion of the universe. While it contains a corresponding antiparticle for each matter particle, it cannot explain the matter-antimatter asymmetry of the universe, the fact that there appears to be so much more matter than antimatter. Experimental and theoretical physicists alike relentlessly poke and prod at the Standard Model, trying to find where it could connect into a broader theory.

To contribute to this effort to search for new physics beyond the SM, this paper sets limits on how far any new physics could deviate from the SM and still produce results within the uncertainty on the result of the proton-proton to WWγ analysis [See Section 2]. This allows us to constrain future theories, helping theorists and experimentalists to create a more complete model of physics.

1.1. Collider Physics: $E = mc^2$ Machines

In order to see an object, one must probe it with a wavelength equal to or smaller than the size of the object. It is believed to be impossible to isolate and view a fundamental particle because they are point particles, meaning they are infinitely small and have no "size". However, their passage can be measured by the effect they have on the particles around them. For example, charged particles passing rapidly through a gas can ionize atoms, freeing electrons. These electrons migrate to wires placed at intervals along the particle's trajectory, inducing a measureable current, evidence of the passage and properties of the particle.

This approach works for light charged particles which are stable over long enough periods of time to be detected and tracked, but the subject of study is usually the rare heavy particles that cannot be found hanging around in the modern universe due to its comparatively low energy density. In order to produce these rare heavy fundamental particles in enough abundance to measure their properties, particle accelerators exploit Einstein's famous equation,

$$E = mc^2$$

where E is energy, m is mass, and c is the speed of light. This equation shows that energy and mass are different forms of the same substance, which can transition between the two. If enough energy is supplied, massive particles will be produced. Circular particle accelerators use superconducting magnets to bend the path of the small charged particles, such as protons, keeping them traveling around the beam pipe ring. Meanwhile, radiofrequency cavities are located along the beam pipe, where strong electromagnetic fields provide an impulse to accelerate the particles to nearly the speed of light. Then, two of these beams traveling in opposite directions crash those particles together in the center of large detectors also located along the beam pipe. The collisions combine the rest energy and kinetic energy of the two colliding particles into a momentary pocket of high energy density. That pool of energy is then converted to mass and momentum, creating the massive particles that we wish to study. The more massive the desired particle, the higher the energy needed to produce it in large numbers.

Because the pocket of high energy density disappears on conversion into a particle, the heavy particle is left in an area of normal energy density, where it does not naturally persist. It decays almost immediately into lighter particles, long before it can reach the detector. The lighter particles, like electrons, hadronized quarks, photons, and neutrinos travel from the decay location, known as the decay vertex. According to conservation of energy, the rest and kinetic energy of these particles must equal the energy of the heavy particle that decayed. By projecting the trajectory of the particles from each collision and decay back to the vertex where they originated, software can determine which particles came from each vertex. The energy of those particles is then summed to find the energy of the original massive particle. However, neutrinos are often a product of these decays and barely interact with other matter particles, so they are not detected by the collider detectors.

These collisions adhere to conservation of momentum, which states that the sum of the momentum of the colliding particles must equal the sum of the momentum of the products. In a collision of protons as in this experiment, protons are accelerated to a known momentum (in our case 13 TeV), but this momentum is distributed unevenly among the fundamental particles inside the proton. Since these are what actually collide, for example two up quarks, we do not know the total incoming momentum in the collision. However, we do know that virtually all of the momentum is in the direction along the beam pipe, meaning that the momentum **transverse**, or perpendicular, to the beam pipe does have a known sum: zero. Therefore, the **transverse momentum** can be used to indirectly detect long-lived particles that cannot be detected directly, usually neutrinos, by how much transverse momentum is missing.

In a sloppy terminology, physicists use the term **missing transverse energy (MET)** interchangeably with missing transverse momentum because since the rest mass of colliding particles is negligible compared to their kinetic energy, the scalar quantity energy approximately equals the magnitude of the momentum vector. It can be thought of as this amount of energy

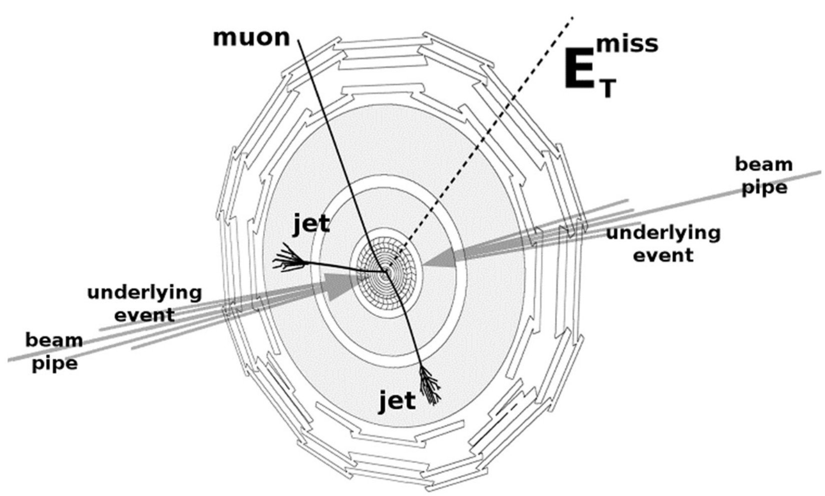


Figure 4: Visualizing missing transverse energy, (E_T^{miss}) for a collision detected via two jets and a muon. When their transverse energy is summed, the missing transverse energy is found to be along the dotted line, implying the existence of a neutrino there. [10]

cataloged at a location such as along the dotted line in Figure 4. Technically since energy is a scalar, a quantity without a direction, it cannot be "transverse" to anything, but nevertheless MET has become standard.

Since the incoming transverse momentum sums to zero, the transverse momentum of all the product particles traveling from the collision point, or **vertex**, must also sum to zero. Amounts of missing transverse momentum too large to be caused by the resolution limit of the detector usually reveal neutrinos. With all the decayed particles accounted for, their transverse momentum can be summed to find the transverse momentum of the heavy particle. It is possible for a particle collision to produce several heavy particles at the primary vertex, the location where the protons collided, as in the case of the WWγ decay mode. Then each W boson decays, and the sum of the energy of all products together equal the known energy of two W bosons and a photon. Since particles can decay to any other particle of equal or lesser mass as long as momentum, energy, and charge are conserved, there are many possible combinations of light leptons that reach the detector from a given decay mode. Each of these combinations is called a final state. Final states for WWγ include $e\nu\mu\nu\gamma$, $e\nu jj\gamma$, $\mu\nu jj\gamma$, and $jjjj\gamma$ where j is a jet of particles produced by a quark interacting with the detector.

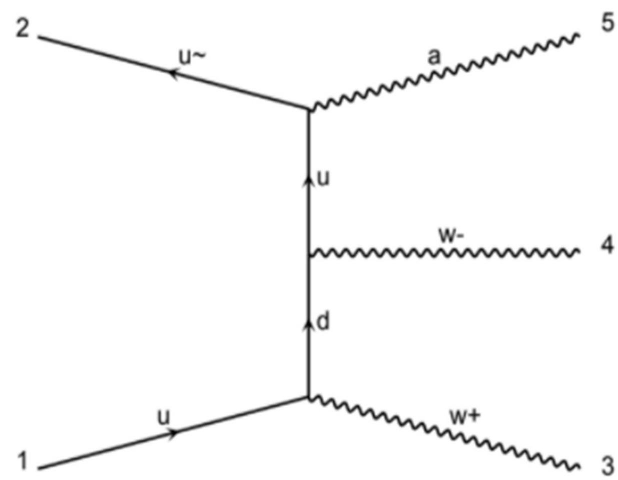


Figure 5: A Feynman diagram representing a WWγ generation event. An up quark and up antiquark collide and combine to form a W+ and W- boson and a photon (a). The primary vertex is the central vertical line. The left to right direction represents the arrow of time.

Particle physicists use Feynman diagrams to visualize and calculate particle production and decays. By convention, one reads from left to right but the diagrams can be rotated in many directions. Matter particles are represented by a straight line with an arrow toward the vertex, antimatter particles with an arrow pointing away. Force carrier particles are represented by a squiggly line.

1.1.1. The Large Hadron Collider

Table 2: Specifications of the LHC *[3]*	
Beam pipe Circumference	26,659 m
Operating temperature	1.9 K (-271.3ºC)
No. of magnets	9593
Nominal energy, proton collisions	13 TeV
No. of bunches per proton beam	2808
No. of protons per bunch	$1.2*10^{-11}$
No. of collisions per second	1 billion
Data recorded and stored per year	30 petabytes

The particle accelerator used for this analysis is the Large Hadron Collider (LHC), a circular accelerator located at CERN. It accelerates bunches of protons traveling in opposite directions in the beam pipe to 0.999999991c, where c is the speed of light. These bunches cross paths, causing many collisions at strategically chosen points along the beam pipe. Five separate detectors are located along the beam pipe at 5 different collision points. The ATLAS detector used in this experiment is a general purpose detector. It consists of several detectors shaped like cylindrical layers around the beam pipe, with the

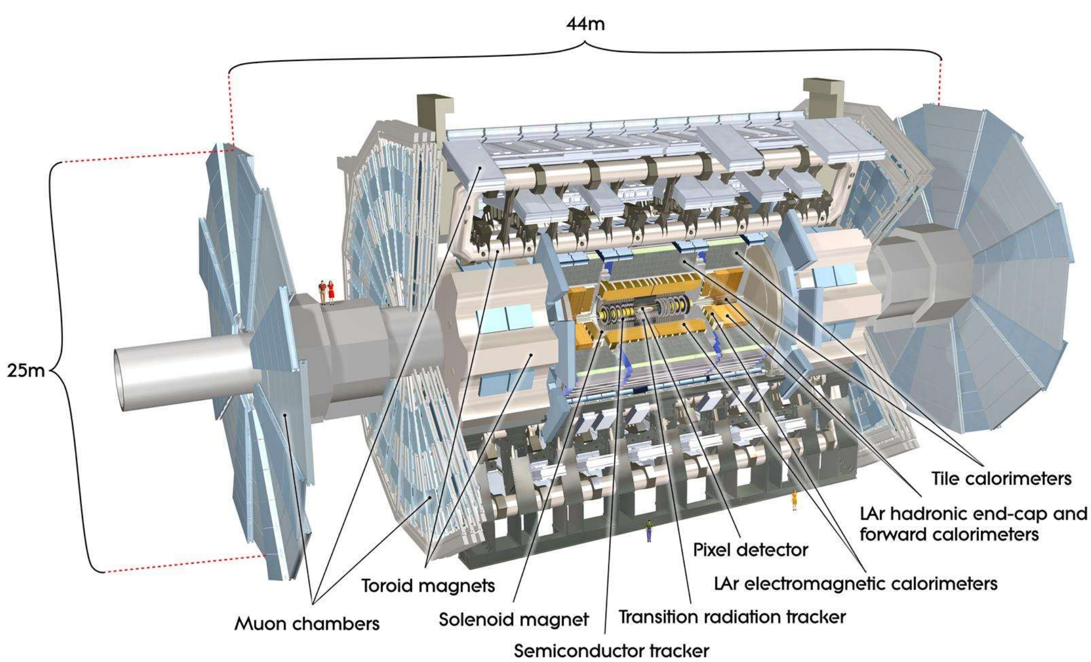


Figure 6: The ATLAS Detector. Two people stand on the spar for scale. Detectors form cylindrical layers around the beam pipe. [13]

collision point at the very center. The Central Solenoid Magnet (CSM) surrounds the inner Transition Radiation Tracker (TRT) detector, creating a uniform magnetic field, causing the trajectory of charged particles to curve. Inside the TRT, an ionizable gas surrounds thin gold wires. As particles fly away from the collisions, they ionize the gas within the tubes. The freed electrons hit the thin gold wires and are detected as current. The momentum of the lepton is calculated using the radius of curvature of the lepton track. Using Newton's second Law:

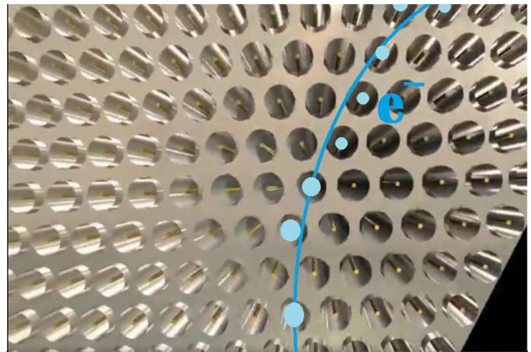


Figure 7: Straw tubes within the TRT hold ionizable gas and track the path of a particle as it passes from tube to tube. My annotations in blue. Image from [15]

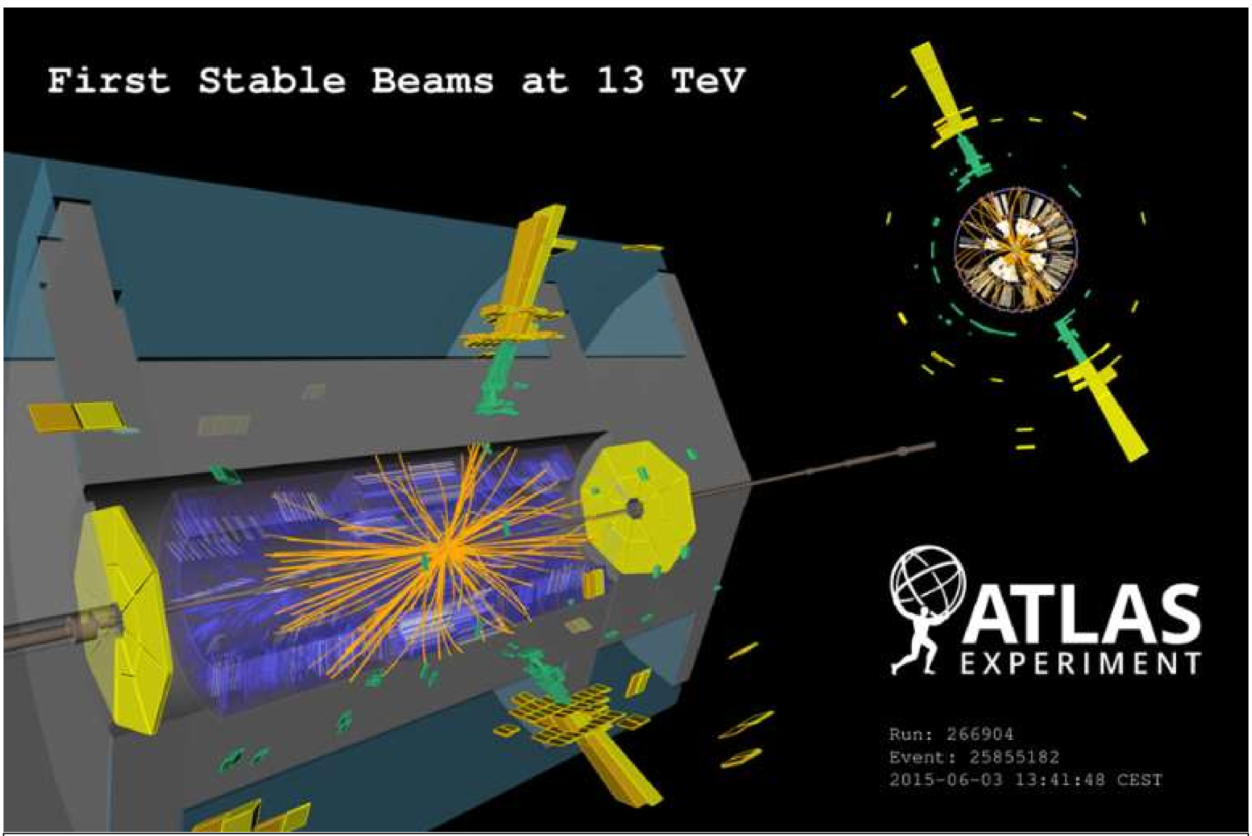


Figure 8: Rendering of a particle collision [14]: Particles traveling toward each other through the beam pipe collide at the center of the ATLAS detector. Different parts of the detector track and measure the particles as they travel from the collision point, making the orange tracks, then the green and yellow blocks. Right: a rendering looking down the beam pipe at the particles flying out from the collision point.

$$\boldsymbol{F} = m\boldsymbol{a}.$$

Since the force is that of a point particle in a magnetic field and the acceleration is centripetal:

$$q\boldsymbol{v} \times \boldsymbol{B} = \frac{mv^2}{r}$$

As the particle is traveling transverse to the magnetic field, the cross product simplifies to simple multiplication:

$$qvB = \frac{mv^2}{r}$$

Rearranging and recognizing that momentum is equal to mass times velocity, the momentum of the particle is:

$$p = qBr$$

The momentum and radius of curvature of the particle is found based on the succession of wires in which it induces current. Since particles in a magnetic field curve according to their charge, the direction of curvature reveals the charge of the lepton, though not the flavor. Photons and neutrons do not leave a trail in this part of the detector because they are not charged.

After the particles leave the tracking part of the detector, they move into the calorimeters, which measure the energy of the particle. The electromagnetic calorimeter measures the energy of electrons and photons. Particles travel through layers of lead and steel that slow it down, interspersed with liquid argon. Each time a particle hits the liquid argon in the calorimeter, it ionizes the atoms, producing more low-energy electrons. This results in a **particle shower** which is read out by the copper electrodes inside the calorimeter. The energy possessed by all the particles in the shower is used to find the energy of the original electron or photon. To distinguish between photons and electrons, they check whether it also left a track in the tracker.

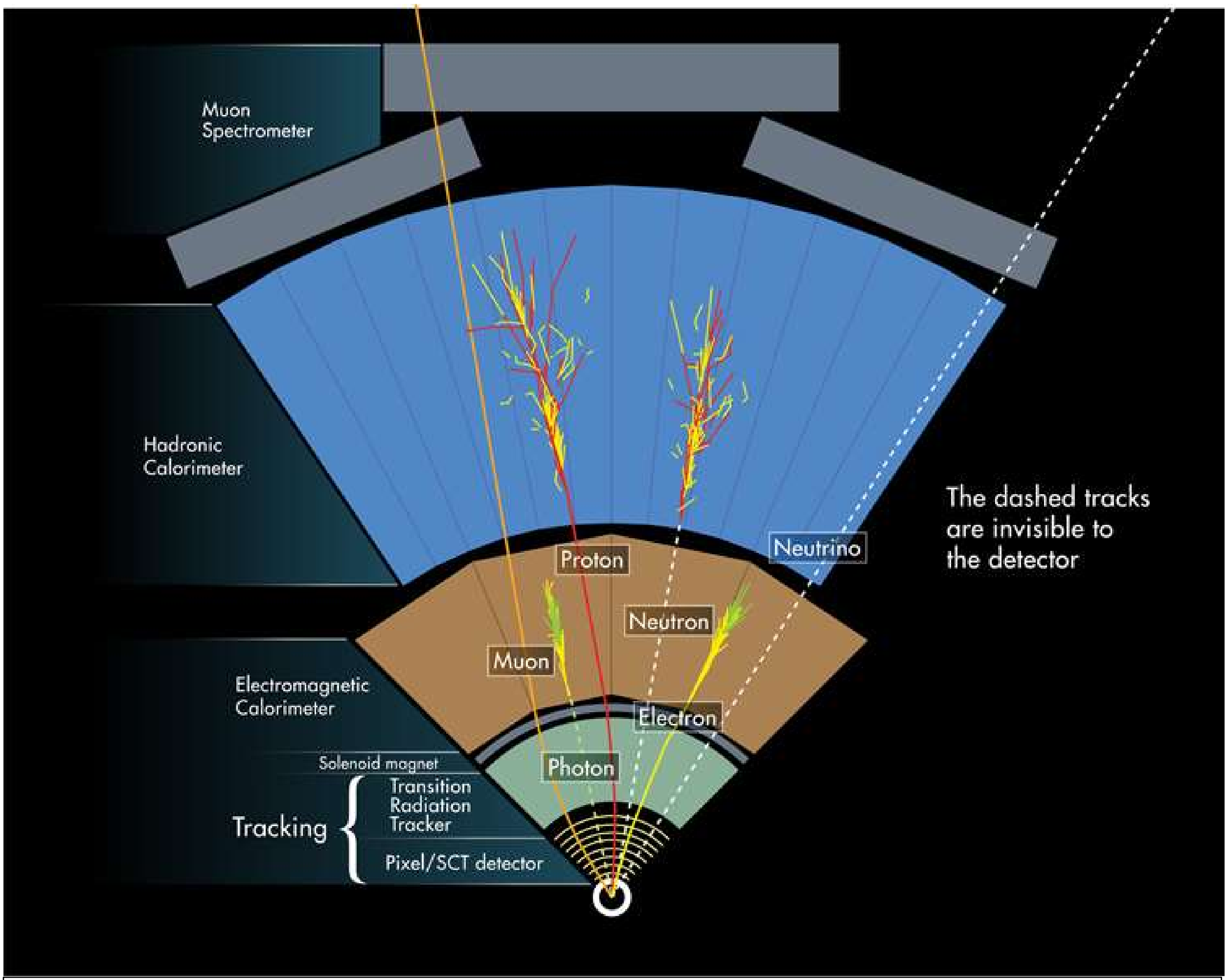


Figure 9: Characteristic detection locations and shower shapes for different particles in a slice of the cylindrical detector. Dashed lines show the path of particles that cannot be detected in that detector area. [12]

The hadronic calorimeter measures the energy of quark-based particles such as protons and neutrons. This part of the detector is made of a scintillating material, which uses the energy imparted by a particle traveling through it to radiate light. The photons are caught by interspersed optical fibers and carried to photomultipliers, where they can be read out as current.

The calorimeters are thick enough to stop hadrons, electrons, and photons entirely, forcing them to deposit all their energy and measuring it. By the time we get to the outer muon detectors, muons are the only charged particles left. The toroidal magnets provide a large magnetic field to curve the path of the muons and the muon detectors use the straw tube method to measure their momentum *[4]*.

The only SM particle not detected by ATLAS is the neutrino, which is found indirectly by the aforementioned calculation of missing transverse energy.

1.2. Statistical Analysis and Discovery Methods

Since most of the time it is impossible to be positive which particle decayed into each detected lepton or photon in a specific event, discoveries in particle physics are made through statistical methods. Since particle production is a probabilistic process, the probability that any given particle will be generated by a given collision is given by its cross section, which can be calculated theoretically. The cross section represents the area through which the particles must pass in order for a given type of interaction to occur. If the cross section is small, the particles must pass very close to each other for the interaction happen, making it less probable. A large cross section means the interaction can happen at larger distances and thus will occur more frequently. Thus, it is used as a measure of the probability of the interaction between two particles. In collider physics, it is calculated:

$$\text{cross section} = \frac{\text{number of signal events}}{\text{integrated luminosity} * \text{efficiency} * \text{acceptance}}$$

where the integrated luminosity is the total amount of events detected, the efficiency is the proportion of signal events that the detector successfully detects, and the acceptance is the term that this paper is concerned with, the proportion of signal events detected that make it into our final data set.

Since the decays are random processes, they are usually approximated using a normal distribution. The probability of each possible decay is known in the form of well-established theoretical **branching ratios**, fractions derived from the Standard Model theory that describe the portion of all decays that decay by a certain mode. According to the statistics of large numbers, as the number of data points, in this case signal events, becomes very large, the experimental mean converges on the theoretical branching ratio. New particles or decay modes are discovered when an excess of signal events relative to expectations from known processes are recorded in a certain energy range, indicating a particle or group of particles produced in that range. To determine whether an excess is due to the new particle or mode rather than a statistical fluke, researchers conduct a hypothesis test with null hypothesis (H_0) and alternate hypothesis (H_a):

$$H_0\text{: the proposed particle/decay is not the cause of the signal in the data}$$

$$H_a\text{: the proposed particle/decay is the cause of the signal in the data}$$

They find the p-value, the probability that if the null hypothesis were true, the signal would be still be observed. In this case, this is the probability that the observed signal would be present even if the particle did not really exist. This p-value correlates to significance, or sigma (σ), the number of standard deviations from the mean that the experimental result falls, as visualized in Figure 10. For large statistics, or data containing many events, sigma is approximated:

$$\sigma = \frac{s}{\sqrt{b}}$$

where *s* is the number of signal events in the dataset and *b* is the number of background events. Systematic uncertainty on the amount of background lowers the σ. They then compare to the p-value to the industry standard threshold for discovery, which is 5σ, or 5 standard deviations from the mean, to make one of the following conclusions:

$$\text{Conclusion of hypothesis test: } \begin{cases} \text{fail to reject } H_0, & \text{significance} > 5\sigma \\ \text{reject } H_0 \text{ and support } H_a, & \text{significance} \leq 5\sigma \end{cases}$$

At 5σ, the p-value is 1 in 3.5 million, meaning there is a 1 in 3.5 million chance that we would have gotten a result as or more extreme as we did if the null hypothesis were true. This is so unlikely that scientists feel comfortable rejecting the null hypothesis and supporting the alternate hypothesis, which is that the particle/decay mode in question exists and is responsible for the signal.

A result is considered "evidence" for the process at 3σ, and the 2017 paper which this analysis follows has already achieved the 3σ mark [5]. Our research group aims to publish a 5σ or higher discovery of the WWγ decay mode, and this investigation goes toward that goal. The higher σ is above 5σ, the more accurate the cross section measurement will be.

The most efficient way to increase σ is to remove background without removing signal. In particle colliders, **background** is produced by the decay of other heavy particles that decay to the same final state or **fakes** that mimic the signal. Different heavy particles can decay to similar combinations of light matter particles.

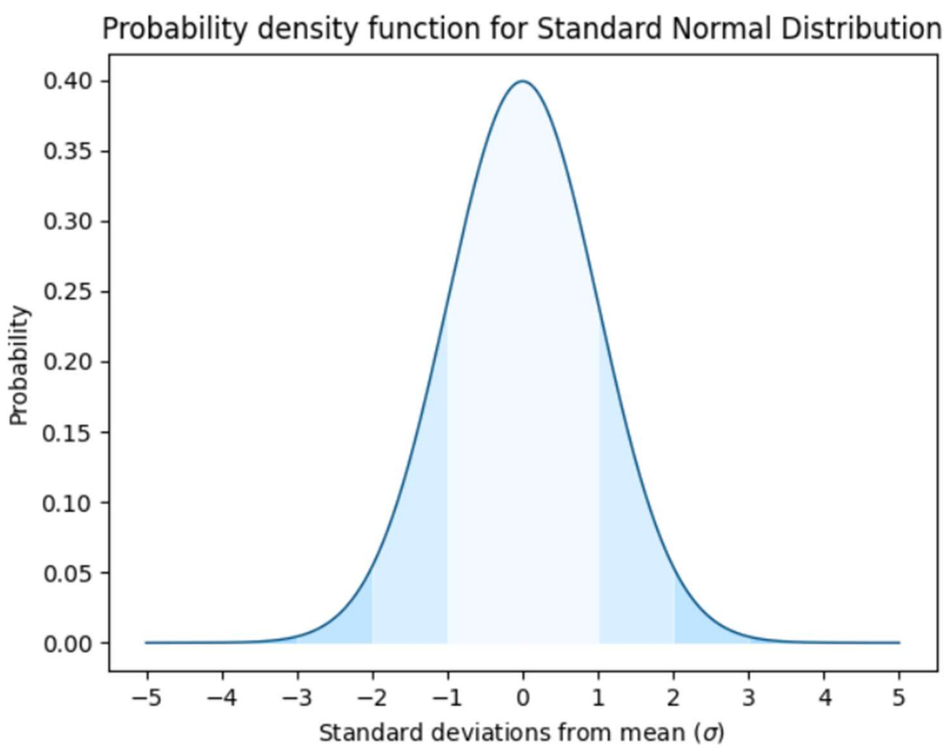
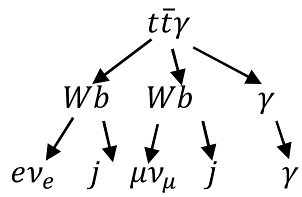


Figure 10: The area under the probability density function from one standard deviation to another gives the probability that a result within that range is produced given the null hypothesis. The probability of getting a result more than 5σ from the mean corresponds to an area so small that it is not even visible on the graph.

As a result, some events due to other decay modes may be misidentified as WWγ. For instance, $t\bar{t}\gamma$, a top quark, a top antiquark and a photon, can decay to the same final state. The decay generally happens as follows:



Most of these events can be removed by adding a selection cut which vetoes b-jets, the *j*s in the equation above. However, the software cannot catch all of these events, so background remains. Another source of error are **fakes**, misidentified particles. In this case, fakes are most often an electron misidentified by the detector as a photon or vice versa, so that the event appears to have the desired final state. To remove background, researchers apply **selection cuts** which remove data that is unlikely to be the result of the decay mode they are looking for.

Selection cuts typically require that the particles have more than a certain amount of momentum and that they go through the central part of the detector where the detector resolution is best. Although this removes a significant chunk of background, some signal is lost in the process. To find out what portion of signal is lost, **Monte Carlo simulation**, a probabilistic simulation technique, is used to generate an abundance of simulated WWγ decays. They are then filtered using the selection cuts for the analysis. Since the total number of WWγ events is specified by the user and the number of events that comes out is known, the ratio of signal events that make it through to the final data set is known. This number is called the acceptance, and helps to produce the cross section, the number representing the probability that the decay mode will occur.

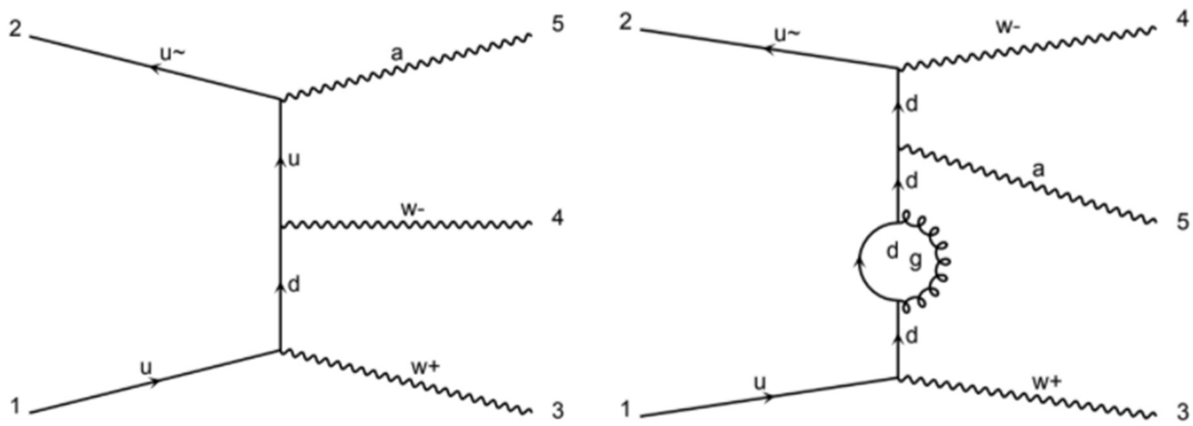


Figure 11: Feynman Diagrams for leading order, LO, (left) and next-to-leading order NLO (right). Note the presence of a loop in NLO, whereas only direct transitions are allowed at LO [16].

The simulated events can be generated to various degrees of precision, Leading Order (LO), which comprises the vast majority of the events produced and Next-to-Leading Order (NLO), which is usually evaluated second to provide a correction to the LO cross section. LO means that only processes involving direct transitions at vertices are allowed. NLO adds processes including **loops**, or short-lived intermediate virtual states, to the mix [1]. Since NLO includes ways to produce the heavy particles, the calculation is more time-consuming, but the cross section is typically higher.

1.3. Beyond the Standard Model

To find where the SM might connect to a broader theory of physics, researchers conduct precise experiments and compare their data with simulations based on the SM and simulations based on theories of physics beyond the SM. They alter parameters of the SM or insert new parameters related to possible beyond-SM effects. Then they conduct simulations at several strengths of the parameter and find the strength at which the results diverge at a measureable level from the SM. This level will be based on the experiment's precision, which results in the sensitivity of the results to demonstrate the effect of the new physics. If no divergence is observed in the dataset, they can logically state that any new physics related to that parameter must have strength less than the identified parameter strength. These limits help to inform new theories of physics, and discount those who do not produce results in accordance with experimental results.

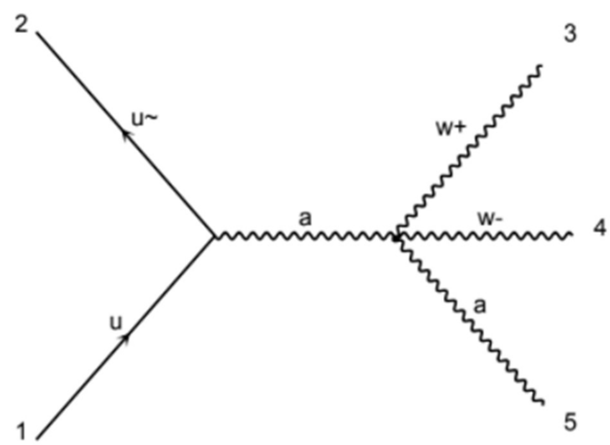


Figure 12: A Feynman diagram for a quartic gauge coupling at the vertex between the W bosons and the two photons, represented by a's [16].

We conduct this test using **anomalous quartic gauge couplings (AQGC's)**. The **coupling** is the strength of the interaction between particles, in this case, the WWγγ bosons shown in Figure 12, also known as **gauge bosons** or **gauges**. Anomalous refers to the fact that these couplings are different from those predicted in the SM. It is a quartic coupling because four gauge bosons are interacting: the virtual photon produced due to the high energy density in the collision, then the three bosons that come from that photon.

We use the Eboli model to inspect these AQGC's [6]. This model contains 18 parameters that change the couplings, resulting in different cross sections from the SM. The parameters are mathematically derived operators from theories beyond the SM, and their physical meaning is not yet well understood. However, they are divided into three groups, scalar, tensor, and a

S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Allowed by SM

Figure 13: Parameters of Eboli Model and decay modes that are sensitive to each parameter. [19]

combination of the two called mixed. The WWγ decay mode is sensitive to 14 of these parameters. These couplings are all allowed by the SM, which means that they are already present in SM physics. However, we look for anomalous couplings, meaning those that are stronger or weaker than predicted by the SM.

1.4. A Note on Units

Units used in high energy physics are not the standard SI units like meters and Joules. Cross sections are measured in picobarns (pb). One barn is equal to 10^{-2} m^2, which is roughly equal to the size of an atomic nucleus containing 100 protons and neutrons [1]. As a measure of energy, particle physicists usually use the electron volt (eV), which is equal to approximately $1.602 * 10^{-19}$ Joules with a prefix like giga (G) which means $* 10^9$ or tera (T) which means $* 10^{12}$. Though the 13 TeV with which particles collide seems very small compared to the 1200 Joules which a toaster oven consumes every second, keep in mind that the particles themselves are nearly massless, so the ratio of interacting mass to energy is actually very large. Not only that, but with one billion collisions per second, there is a lot of energy radiating from the collision points.

More disconcerting is that momentum is also measured in eV. Momentum of particles at relativistic speeds like those in the collider are usually measured in eV/c^2, where c is the speed of light, roughly $3 * 10^8$ meters per second. However, for ease of calculation and numerical comparison, particle physics have set the speed of light to a dimensionless 1. As long as it is used consistently and taken into account if the measurements are ever translated to other units, this approach is valid and takes considerably less effort to use.

2. Introduction

The WWγ research group is attempting to officially discover the $W^+W^-\gamma$ decay mode, and publish the cross section for a given proton-proton collision to produce those three particles: a positively- and negatively-charged W boson and a photon. The W bosons decay to lighter matter particles in about 10^{-25} seconds, which means that the detector receives the lighter resultant particles that appear to originate at the same vertex, known as "prompt" leptons. Hence, leptons not originating at this vertex can be removed as background. This analysis detects fully leptonic decay with opposite-sign leptons, meaning that both W bosons decay to leptons, so that 'signal events' is defined as events with final state $e^{\pm}\nu\ \mu^{\mp}\nu\ \gamma$. Although this state does not produce most signal, it is less likely to be produced by other decay modes, lowering the amount of background to be dealt with. Moreover, though the W boson decays to quark jets 2/3 of the time, much more often than the lepton decay, the ATLAS detector has poor resolution for jets compared to leptons, so the quality of the measurement is higher using the leptonic decay mode.

In this paper, I first calculate the cross section for our detector. The events are generated using a Monte Carlo simulation program, MadGraph [7], at LO and NLO. I then use an event processing program, Rivet [8], to pass the WWγ events through the selection cuts for this analysis. I calculate the portion of WWγ events that made it through all selection cuts into the final dataset, known as the **acceptance**. The acceptance makes the cross section independent of our selection cuts and therefore repeatable by another research group.

I then use a similar process to place preliminary limits on new physics beyond the SM. These limits will be further investigated with less approximation before the WWγ paper is published. Instead of running MadGraph with the Standard Model, I use the Eboli Dimension-8

Model [6]. I calculate the cross section and acceptance for a parameter over many strengths. We define the normalized cross section, μ, as the following ratio:

$$\mu = \frac{\text{measured cross section}}{\text{predicted SM cross section}}.$$

It is likely that for real data μ will be close to 1, because that would mean purely SM effects. However, the uncertainty can be of interest, because it presents a range in which beyond-SM physics could play a role. We expect to measure $\mu \approx 1 \pm 0.2$, where 0.2 is one standard deviation. The 95% confidence level (CL) is at approximately 2σ, so doubling the standard deviation of μ, our 95% CL is at 0.4, or a cross section increase of 40% from the prediction of the SM. Therefore, I find the strength at which the cross section is approximately 40% greater than the SM predicts ($\mu = 1.4$). This is the level to which our experimental results will be sensitive. I outline the process for the event generation and processing, the acceptance calculation over various strengths, and the setting of limits for one of the 16 Dim-8 parameters. Details of the analysis will be discussed in part 4.

3. Acceptance Calculation

The acceptance represents the fraction of actual WWy events that make it through the selection cuts into the final data set. This calculation requires knowledge of which events were truly WWy events, known as **truth information**. Truth information is not available on experimental data since the events are identified as WWγ using the selection cuts that we are presently trying to evaluate. However, truth information is available for simulated events, and is partially defined by the user's input to a Monte Carlo system. Using MadGraph5 version 2.7.2, we generate sets of 15000 WWγ events using the default generation model, "sm" for Standard Model, and specify LO or NLO. These simulated events represent 15000 collisions that produced a W^+ and W^- boson and a photon (γ). In addition to recording information about each of the events, the program also outputs a cross section for the process as a whole. The cross section at LO was and 0.2655 ± 0.00098 pb, while at NLO it was and 0.34864 ± 0.0022 pb.

We also stipulate that these events result in the final state: $e^{\pm}\nu\ \mu^{\mp}\nu\ \gamma$, because this is the only final state that our analysis utilizes. The simulation calculates when each W decays and defines the characteristics of the particles we detect, which are used in turn to make the selection cuts. The probability of producing different particles at each step in the decay chain is set using well known branching ratios. Each consecutive particle in the chain is then found using a random seed, a pseudorandom number generation method. It is similar to rolling a die where each possible outcome of the roll is assigned to which possible path the decay chain follows. In this case, the random seed would define the outcome of the dice roll, and each possible random number outcome is assigned to the production of a particular particle. The events that emerge are weighted, where more probable decays have a higher weight. This avoids repeat calculations so that informative results can be produced using less computing power.

The output file from this process contains all the truth information about the event generation and decay. This file is then passed through the selection cuts using the software Rivet. The program is structured execute the commands that I coded iteratively on each event in the input file. I created code to read in the necessary truth information, identify the particles of interest, and apply the selection cuts. We will pass through a brief description of each step.

3.1. Reading in particles

In Monte Carlo event generators, particles are generally assigned an identification number like “11” rather than a word, like “electron”. There are many event generators and processors used by the particle physics community, but a central coordinating board, the Particle

Data Group, has created some central definitions so that different programs can be interfaced and compared more easily. Central to that goal is the Monte Carlo Particle Numbering Scheme, which establishes an identification number for each type of proven or proposed particle, called the particle ID, or PID, so that all programs identify particles the same way [9]. Table 3 shows the PID of some relevant particles.

The first step in reading in the events is calling the particle ID for each of the particles and assigning the particles in the final state to an array. We then read in their characteristics such as transverse momentum (p_T) and location within the detector (η). We make an initial cut and remove photons of momentum less than 1 GeV, and η greater than five, as these events are unlikely to be reliably detected. We then filter out events that no longer have the right amount of leptons for the desired final state: exactly two opposite sign, opposite flavor leptons.

The remaining events represent the suitable WWγ events that would ideally all make it into the data set, if no selection cuts were applied. At this point, we start a counter which sums the weight of every event in this data set. We count the sum of weights rather than the number of

Table 3: Particle Identification (PID) Numbers for Standard Model Particles

Quarks		**Leptons**		**Bosons**	
Down (d)	1	Electron (e^-)	11	Gluon (g)	21
Up (u)	2	Electron neutrino (ν_e)	12	Photon (γ)	22
Strange (s)	3	Muon (μ^-)	13	Z boson (Z^0)	23
Charm (c)	4	Muon neutrino (ν_μ)	14	W boson (W^+)	24
Bottom (b)	5	Tau (τ)	15	W boson (W^-)	-24
Top (t)	6	Tau neutrino (ν_τ)	16	Higgs (H_1^0)	25

Note: Antimatter particles have the opposite sign PID to their matter counterparts.

events because the weights take into account the aforementioned shortcuts for computing efficiency to avoid generating repeat events.

3.2. Selection Cuts

We then apply the selection cuts that will be used in this analysis, summarized in Table 4. An event failing any one of the cuts is rejected. If an event passes all the cuts, then it would be present in our final data set, were we using real data. We add its weight to a second counter, which keeps track of all the events that passed the cuts.

Table 4: Selection cuts and results of cuts

Selection Cut	**Sum of Weights After Cut**	**Events remaining**
Initial Sum-of-Weights	4174.35	100%
Photon $\boldsymbol{p_T}$ > 15 GeV	2051.78	49.15%
No Additional Photon with $\boldsymbol{p_T}$ >15 GeV	2051.78	49.15%
Missing transverse energy, MET > 20 GeV	1814.1	43.46%
Require Zero Bjets	1792.91	42.95%
Leading Lep $\boldsymbol{p_T}$ > 27 GeV	1647.37	39.46%
Next-to-leading lepton $\boldsymbol{p_T}$ > 20 GeV	1254.76	30.05%
Lepton $\|\eta\| < 2.47$, Photon $\|\eta\| < 2.37$	751.736	18.01%
Veto Crack region $1.37 <\|\eta\|<1.52$	624.37	14.96%
Note: Leading lepton refers to the lepton with highest transverse momentum. The crack region is a location of poor resolution in the detector. B jets are groups of particles produced by the decay of the bottom quark which can be mistakenly identified as products of WWγ. Meanwhile, η is a measure of location in the detector, defined in Figure 14.		

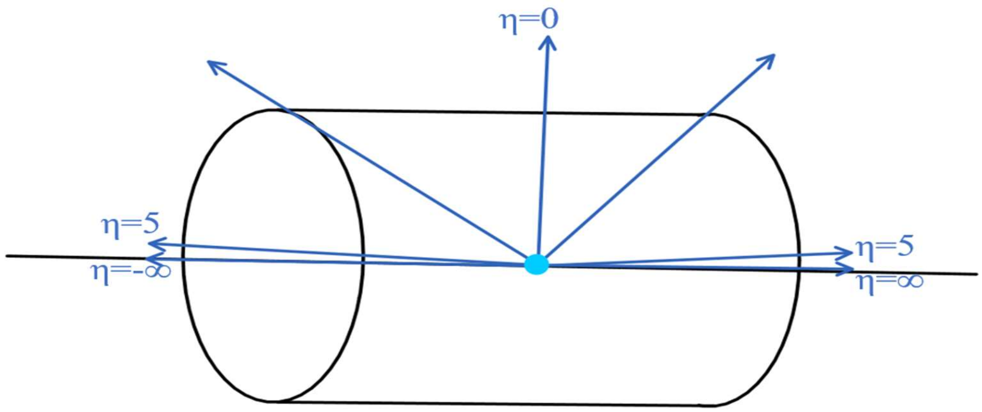


Figure 14: The sketch in black represents the cylindrical detector with the beam pipe traveling through the center. A measure of location within the detector is η, the angular displacement of the particle from the plane transverse, or perpendicular, to the beam pipe.

After the program iterates through all of the simulated events, we calculate the acceptance by dividing the initial sum-of-weights counter by the second sum-of-weights counter to find the ratio of appropriate events present in the final data set. The acceptance of this study was found to be 0.1496 ± 0.0000058 (stat) ± 0.00179 (sys) at LO.

4. Anomalous Quartic Gauge Coupling Study

With the expected acceptance due to the Standard Model, we can proceed to calculating the effect of physics beyond the SM. Rather than using the default SM model in MadGraph, we use the Eboli Dimension-8 model (version: April8.tgz). These calculations can only be done at leading order in the current model. To inspect the overall effect that AQGC will have on the WWγ decay process, we change the strength to which the parameter is set, and measure the impact on cross section and acceptance. None of these parameters are present in the SM, so for comparison with the SM we set the strengths to $1 * 10^{-20}\ \mathrm{TeV}^{-4}$, at which point they have no effect within the significant figures of our analysis. We plot the product of cross section and acceptance as a function of parameter strength, which we fit to a quadratic. For the purposes of this paper we develop the method and code for this process, and carry it out on only one parameter, LT1, chosen arbitrarily.

The methodology of this part of the experiment is strongly based on that of Section 3. We generate the events identically, besides using the Eboli model set to the desired parameter strength. MadGraph outputs the cross section at leading order. This model cannot calculate at NLO, however, it is an accepted assumption that the AQGC cross section will increase by the same proportion as the SM cross section does. Figure 15 shows the quadratic fit that we found

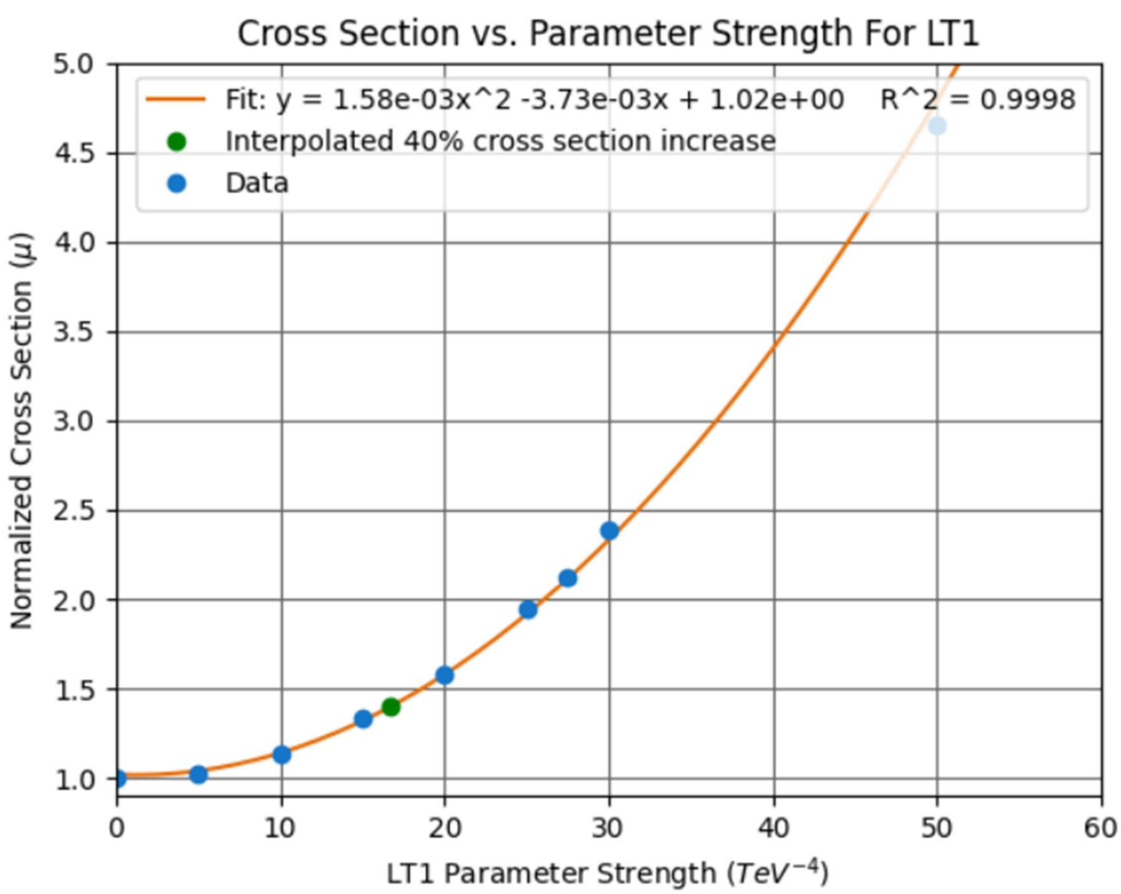


Figure 15: Change in cross section due to variation in parameter strength. Simulated cross sections at different parameter strengths (blue), were fit to a quadratic (orange) using the function polyfit in python's numpy package. The limit on the LT1 parameter strength was found by interpolating the strength at a 40% increase from the SM (green).

for our simulated data. By interpolating from the fit, we found that the addition of LT1 will become detectable in the results of the cross section to a 95% confidence limit at a parameter strength of 16.7 TeV^{-4}. Since no deviation is expected, we can place a limit on the LT1 parameter at this strength, pending confirmation from experimental results. This limit means that any beyond-SM theories must produce an LT1 parameter with a strength less than or equal to 16.7 TeV^{-4}.

5. Discussion and Conclusion

This research showed that the acceptance for the WWγ analysis is 0.15 $\pm$ 0.0000058 (stat) $\pm$ 0.0018 (sys). This means that approximately 15% of the WWγ events will make it through the selection cuts into the final data set. It forms an important part of the calculation of cross section that will ultimately be published to officially discover the WWγ decay mode.

The results of the AQGC study placed the limit of the LT1 parameter at 17 TeV^{-4}. A previous study placed it at $[-0.2, 0.2] * 10^3\ \text{TeV}^{-4}$ [5]. This means that our analysis showed an order of magnitude improvement over the previous result. This improvement is due to the increased sensitivity of this analysis, which was made possible by the increased energy and luminosity of the collider, leading to more signal events. Now that this process has been developed, the rest of the parameters can be similarly analyzed by running the code from this study. The results of the AQGC study can be used to inform future theories of physics beyond the Standard Model.

In addition to officially discovering the WWγ decay mode, the WWγ analysis will improve our ability to find new particles. The particles we are currently searching for, including gravitons, axions, dark matter candidates, and particles of the theory of Super Symmetry, are more elusive even than the ones that were recently discovered, like the Higgs boson. Since they are observed so much less often, their signal is even more difficult to find than what we have now. One way this can be mediated is to use a modified version of background subtraction. If we know the frequencies with which $WW\gamma$ is produced and decays through different modes, then we can actually subtract its contribution from the data, allowing us to see the signal due to new particles much better. This allows us to discover or disprove proposed elusive particles and further inform theories of physics.

This research aligns with the broadest goal of physics, which is to describe how the universe works from a mechanical perspective. To do that, we must understand all the components and how they interact with one another. While this project addresses one specific component of the full system, it takes us one step closer to a theory presenting a full picture of the universe.

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