Could ALICE Find the Elusive Higgs?

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Senior Project
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Figure 1: The Standard Model of Particle Physics (http://www.sciencedaily.com/images/2010/07/100726123934-large.jpg)
Abstract

The Higgs boson is the theoretical mechanism for creating the mass of particles. Although it has never been seen, the CERN Large Hadron Collider (LHC) is the most likely place for it to be created in the laboratory. The ALICE (A Large Ion Collider Experiment) detector is focused on the study of heavy ion collisions at the LHC and was not designed to find the Higgs boson; however, there is a chance it could be detected there. Although the luminosity (collision rate) for PbPb collisions is much lower than that for pp collisions, PbPb collisions have a higher probability to produce a Higgs boson because of the number of nucleons in the collision. ALICE has the capability of measuring the decay of a Higgs into two photons. In this paper we determine the probability of observing the Higgs at ALICE by estimating the rate of Standard Model Higgs production from established theories and combining it with the physical capabilities of ALICE. Code was developed to search for Higgs Boson candidates in the pp data collected during our two-month visit to CERN to work on ALICE in 2010.

Particle Physics: What’s It All About?

Every day people take for granted the fact that everything we encounter is made up of something smaller than what we can see on the surface. If asked, most people have probably heard something about atoms and molecules, and they might even know something about electrons, protons and neutrons. However, in order to probe the nature of the particles that are even smaller than these and the interactions between them, one must study particle physics.

The aim of particle physics is to probe and figure out the fundamental laws that control the make-up of matter at the subatomic level and ultimately the universe. This probing, as is the case for all areas of physics, comes in two different forms: theory and experimentation, both of which play a huge role in our search for the elusive Higgs Boson.

As a science, particle physics is relatively young and really took off in the 20th century. With help from physicists such as Paul Dirac, Hideki Yukawa and Richard Feynman, it has become the field we know today.

In nature, there are four fundamental forces that, as far as we can see, control the universe and all that happens in it. These forces are the strong nuclear force, the electromagnetic force, the weak nuclear force and the gravitational force. Of these forces, the strong nuclear force is the strongest and is an attractive force between nucleons (protons and neutrons). It is also responsible for the interactions between quarks and gluons, which make up protons, neutrons and other particles. However,
this force has a very short range ($\sim 1$ fm = $1 \times 10^{-15}$ m = roughly the diameter of a proton) and is negligible for distances greater than the size of a nucleus. The next strongest force is the electromagnetic force. This force is responsible for binding electrons to nuclei as well as molecular bonding. It is about 100 times weaker than the strong nuclear force and has a very long range that decreases as a function of the inverse square of the separation between interacting particles. The weak nuclear force is the next strongest of the four forces and is 100,000 times weaker than the strong nuclear force. Like the strong nuclear force, it also has a short range ($\sim 10^{-3}$ fm), but it is responsible for decay processes in nuclei. The gravitational force is the last of the fundamental forces and when compared to the strong nuclear force it has a relative strength of $10^{-39}$. Even though we see the effects of gravity in the way stars, planets and galaxies are held together (not to mention how we are bound to Earth), its relative strength makes it negligible when looking at the interactions of elementary particles.

When first looking into subatomic particles, the question that arises is: how do these particles interact? In the classical world where we can see things interacting with our own eyes, we have discovered how different objects interact and we can explain these interactions mathematically. This explanation of how things interact is known as classical mechanics; however, when scientists started trying to fit classical mechanics to the interactions observed on the atomic scale, the solutions did not match observations. This dilemma was solved when Albert Einstein proposed the idea of quantization in the early 1900s, and eventually the field of quantum mechanics was born.

The interactions of subatomic particle are now explained using Quantum Field Theory (QFT). QFT was first developed in the 1920s to deal with problems that arose while trying to create a quantum mechanical theory of the electromagnetic field. Today, QFT has become the language of particle physics, and from the combination of quantum mechanics and special relativity the modern theories of particle physics were born.

**The Standard Model**

Every physicist dreams of one day having a “theory of everything;” however, there is much work to be done to combine current theories. Figure 2 gives a very rough idea about how all the theories may fit together, but in reality, we have only truly unified electromagnetism and weak theory under electroweak theory, and we are still in the process of unifying Electroweak Theory and Quantum Chromodynamics (QCD).
Figure 2: Summation of Elementary Particles (http://en.wikipedia.org/wiki/File:Particle_overview.svg)

During the 20th century, scientists discovered more and more elementary particles and it was necessary to figure out how all these particles fit together. The Standard Model (SM) was created to describe the elementary particles and their fundamental interactions. In the SM, there are three types of elementary particles: leptons, quarks and mediators.

There are six different leptons, which are classified by their charge, electron number ($L_e$), muon number ($L_\mu$), and tau number ($L_\tau$). Each of the lepton numbers tell us the generation (or family) a lepton falls into.

<table>
<thead>
<tr>
<th>$l$</th>
<th>$m$ (MeV/c²)</th>
<th>$Q$</th>
<th>$L_e$</th>
<th>$L$</th>
<th>$L_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$</td>
<td>0.511</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>~0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>105.7</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>~0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>1784</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>~0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1: Lepton Classification

Table 1 is a summary of how the classification system works. In the table, $l$ is the lepton type, $m$ is the mass in MeV/c² (an electron’s mass is $0.511\text{MeV/c}^2 = 9.11\times10^{-31} \text{ kg}$). Along with these six particles, there is a corresponding antiparticle for each. In order to make a table like table 1 for the
antiparticles, all that we have to do is reverse all the signs and put either a + subscript, such as e+, for the particles with charge, and a bar, such as \( \bar{\nu} \), for particles without charge. With all these antiparticles, there are a total of 12 lepton type particles.

Quarks are similar to leptons in that there are three different generations, but instead of being characterized by electric charge and lepton number they are identified by their charge and “flavor.” There are six different flavors of quarks: they are up (U), down (D), strange (S), charmed (C), Top (T), and bottom (B). Just like the leptons, there is also an anti-quark corresponding to each quark, and they are also denoted with the over-bar (i.e. \( \bar{u} \) for the anti-up quark).

<table>
<thead>
<tr>
<th>q</th>
<th>m (MeV/c²)</th>
<th>Q</th>
<th>D</th>
<th>U</th>
<th>S</th>
<th>C</th>
<th>B</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>5</td>
<td>-( \frac{1}{3} )</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>u</td>
<td>2.2</td>
<td>( \frac{2}{3} )</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>s</td>
<td>95</td>
<td>-( \frac{1}{3} )</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>1250</td>
<td>( \frac{2}{3} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>4200</td>
<td>-( \frac{1}{3} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>t</td>
<td>174200</td>
<td>( \frac{2}{3} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Table 2: Quark Classification**

From these particles, the first generation leptons and quarks (\( e, u, \) and \( d \)) make up the matter that we see around us. Along with the particles that make up the universe, the SM also includes the mediators for the interactions between particles. As mentioned earlier, there are four fundamental forces and each has its own interaction mediator. The photon is the mediator for the electromagnetic force, the two \( W \)’s and \( Z \) bosons for the weak force, the gluon for the strong force, and presumably the graviton for the gravitational force (although this is not included in the SM because it has not been observed and it is not unified with the SM). These are organized in table 3.

<table>
<thead>
<tr>
<th>Mediator</th>
<th>Charge</th>
<th>m (MeV/c²)</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon</td>
<td>0</td>
<td>0</td>
<td>strong</td>
</tr>
<tr>
<td>photon (( \gamma ))</td>
<td>0</td>
<td>0</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>( W^\pm )</td>
<td>( \pm 1 )</td>
<td>81800</td>
<td>(charged) weak</td>
</tr>
<tr>
<td>( Z^0 )</td>
<td>0</td>
<td>92600</td>
<td>(neutral) weak</td>
</tr>
</tbody>
</table>

**Table 3: Mediator Classification**
Today, experimentation has, for the most part, successfully verified the SM, but there is still one key piece to completing this model and answering the question of the origin of mass. [1]

The Higgs Boson

The answer the SM proposes to the question of the origin of mass is the Higgs Mechanism, which was first purposed in 1964 by six different physicists. From these six physicists—François Englert, Robert Brout, Peter Higgs, Gerald Guralnik, C. R. Hagen, and Tom Kibble—three different papers were written describing the Higgs Mechanism, which is an explanation of how a non-zero vacuum expectation value spontaneously breaks electroweak gauge symmetry [2] [3] [4].

In non-scientific terms, the Higgs Mechanism is analogous to a pool of some sticky substance. As a particle, that would otherwise be mass-less, moves through this pool, the substance “sticks” to it and it acquires mass. Just as in electromagnetism, weak theory and strong theory, there has to be a mediating particle. This particle is the Higgs Boson.

Another common analogy used by the scientists at CERN to help describe what exactly the Higgs Mechanism and Boson are and do, is to think of a room full of scientists. As long as nothing interferes with this room, the scientist will remain spread out evenly throughout the room talking amongst themselves. Sometime later, a well-known physicist, such as Albert Einstein, enters the room. As he makes his way across the room, the other scientists inherently congregate around him making it harder and harder to get across the room. In other words, he experiences a change in momentum, which is a sign of a change in mass. In this scenario, a particle entering the Higgs-field is analogous to the well-known physicist entering the room, and as the particle moves through the Higgs-field, it acquires mass. [6]

Expanding on the analogy, a person sticks his head through the door of the room and starts a rumor that a well-known physicist is going to be coming. Immediately, the scientists begin to gather in bunches to discuss this rumor and the same effect is felt. This bunching due to a rumor is analogous to the Higgs Boson. From this simple illustration, we see that the Higgs Boson and the Higgs Mechanism should coexist; however, the only way to experimentally support this theory is to detect a Higgs Boson, and this has yet to be done. [5]

Another, more scientific way to think about the Higgs Mechanism is to compare the Higgs field to an electric field. Placing a charged particle in an electric field will result in that particle experiencing a force exerted. Now looking
at a Higgs field, placing a mass-less particle (rather than a charged particle) into this field, the particle will gain mass just as the charged particle experienced a force in the electric field.

In the SM, there is only one theorized Higgs Boson; however, there are also many non-SM theories of the Higgs. Some of these theories even predict more than one Higgs Boson, but for the sake of our project, we have chosen to focus on the SM Higgs. [5]

The Search for the Higgs Boson

In order to justify this theory for the origin of mass in the universe, there has to be experimental evidence to support it. So, scientists all over the world have been searching for some sign of the Higgs Boson.

The only place a Higgs Boson is going to be created and detected is going to be at a particle accelerator, where streams of particles are collided at very high energies. In particle physics, the unit of energy used is the electron volt (eV). The eV is equal to the amount of energy gained by an $e^-$ moving through a potential difference of 1 volt. The highest energy collisions are in TeV ($10^{12}$ eV). To gain some perspective on what will happen during the collisions, we consider classical collision theory.

From classical theory we are introduced to the concept of the collision cross-section. The cross-section in classical theory is the cross-sectional area of the target and is directly proportional to the probability of scattering occurring. In quantum collision theory, the cross-section is not an area, but it still represents the probability for an interaction to occur. The higher the cross-section is for a particular interaction, the higher the probability of interaction occurring in a collision.

Figure 3: Classical cross-section (http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/crosec.html)
Figure 4: Cross-Sections for SM Higgs production of various masses at the LHC [15]

From Higgs theory, there will be many different mechanisms contributing to the production of the Higgs Boson. Figure 3 shows the cross-section for these various mechanisms that would produce the Higgs Boson in the Standard Model of Particle Physics as a function of its possible mass. The units for cross-section are barns \((b=10^{-24}\, \text{cm}^2)\), which is a big number in particle physics. For SM Higgs production, the cross-sections for the various production methods is on the order of femto-barns \((\text{fb}=10^{-15}\, \text{b})\). In order to find the total cross-section, one sums the contributions for a particular mass. The vertical black line in figure 3 shows the mass we picked \((120\, \text{GeV/c}^2)\) to find the total cross-section. This gives the total probability of creating a Higgs Boson at 120 GeV/c^2. However, the cross section is not the only contributor to the probability of finding one.

If the Higgs Boson exists, it is not a stable particle and the only way to detect it will be via its decay products. These decays are different combinations of quarks, leptons, and other bosons, and each of the decays has a different probability. Together, these probabilities form the branching ratios for the different decay mechanisms theorized for the Higgs Boson, and like the cross-section, the higher the branching ratio, the higher the probability of the Higgs decaying to that mode.
Figure 5: The branching ratio for different decay mechanisms of the SM Higgs Boson. [16]

Figure 5 is a plot of the different branching ratios of the Higgs Boson as a function of mass. If the branching ratio is 1, the mechanism that corresponds to this will happen one hundred percent of the time, and any branching ratio below one corresponds to the percentage of that mechanism happening. For our search we focused on the $\gamma\gamma$-decay mechanism (shown by the smallest red dashed line) for reasons that will be discussed later.

In Higgs theory, the mass of the Higgs Boson cannot be determined because of an unknown parameter called $\lambda$, which is the Higgs self-coupling parameter [5]. When Higgs theory is coupled with the SM, a Higgs Boson with a mass between 130 GeV/c$^2$ and 180 GeV/c$^2$ would allow for an effective SM description for energy levels all the way up to the Planck level ($10^{16}$ TeV) [1]. With this in mind experiments at colliders such as LEP (The Large Electron-Positron Collider at CERN from 1989 to 2000 [17]) and the Tevatron at Fermilab (1983 to 2011) have been searching for a Higgs Boson with a mass within the range of 100 GeV/c$^2$ to 200 GeV/c$^2$, but have yet to find it. However, from these experiments, physicists have been able to rule out the possibility of certain masses, which has helped narrow down the current search at the LHC.
Figure 6: Allowed masses for the search for the Higgs Boson as of July 19, 2010 [10]

Figure 6 shows the possible masses for the Higgs boson in units of GeV/c^2, which is the particle physics unit of mass. The shaded areas are masses where the Higgs boson will not be found. These have been excluded by searches at LEP (Large Electron-Positron Collider), the Tevatron, and other indirect measurements. For our search, we chose to consider a mass of 120 GeV/c^2 because it falls within the first range of possible masses and was our best option because the branching ratio of γγ-decay is at its peak there.

The newest tool in the search for the Higgs Boson is the Large Hadron Collider (LHC), which is located on the French-Swiss Border near Geneva, Switzerland, the location of CERN, Conseil Européen pour la Recherche Nucléaire (French for the European Organization for Nuclear Research). In particle physics, the higher the energy of the collision, the more particles are created. Prior to the LHC, the most energetic collisions obtained were at Fermi Lab’s Tevatron Collider, and the highest energies they reached were 1.96 TeV. Now, with the LHC finally fully operational, physics has seen the dawn of a new era in collision physics with the LHC reaching energies of 7 TeV on its way to collision energies of 14 TeV.
The Search at the LHC

At the LHC, there are six experiments that are run by international collaborations. They are: ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment), LHCb (Large Hadron Collider beauty), TOTEM (TOTal Elastic and diffractive cross section Measurement), and LHCf (Large Hadron Collider forward). ATLAS and CMS are the main two detectors that are looking for the Higgs Boson as well as extra dimensions and particles that would help explain dark matter. This being the case, both have been optimized for Higgs detection. ALICE, although optimized to study heavy ion collisions, may also have the capability to detect the elusive Higgs.

ALICE and Our Search for the Higgs

The focus of ALICE is the collisions of heavy ions, in this case lead nuclei. By colliding these nuclei, the hope is to recreate conditions that would have been present at the beginning of the universe according to the “Big Bang Theory” [21][22]. ALICE’s main focus is on a phase of matter that would have been present $10^{-12}$ to $10^{-6}$ seconds after the Big Bang. This phase of matter is known as the Quark-Gluon plasma (QGP), and in this phase quarks and gluons are deconfined (non-structural, a hot dense particle soup). The only way to study this phenomenon is through the collisions of heavy ions, which provide this hot-dense environment. Although ALICE is designed for the study of heavy ion collisions, it could still detect a Higgs Boson. ALICE can be divided into three parts: a tracking system, detectors for unique particles, and detectors to help characterize events. In figure 7, there are 17 parts that make up ALICE. Nine of these are:

1. The inner tracking system (ITS), which surrounds the collision point and has very good position resolution to measure the interaction vertex and the decays of heavy particles.
2. The forward multiplicity detectors (FMD), that focuses on charged particles emitted at small angles relative to the beam.
3. The time projection chamber (TPC), the main tracking section of ALICE that uses ionized gas to track charged particles.
4. The transition radiation detector (TRD), is used to distinguish electrons and positrons from pions using their transition radiation.
5. The time of flight (TOF), that measures the time it takes a particle to travel from the interaction to the detector (and therefore measures velocity).
6. High momentum particle identification (HMPID), that determines the identities of particles with high momenta through Cerenkov radiation.
7. The electro-magnetic calorimeter (EMCal), that is used to detect photons, electrons and neutral pions as well as the neutral energy in jets
8. The photon spectrometer (PHOS), used to measure high energy photons and neutral pions (through their decay to two photons)
9. The muon spectrometer (MUON), that is designed to detect pairs of muons.

Figure 7: This is a schematic of the ALICE detector and its many components. ALICE is one of six experiments at the CERN Large Hadron Collider and is focused on heavy ion collisions that could result in a quark-gluon plasma where quarks and gluons are deconfined [18].

Comparing the branching ratios of the Higgs to the physical capabilities of ALICE, the most feasible place to look is the $\gamma\gamma$-decay channel using the array of PHOS and EMCal, the two electromagnetic calorimeters at ALICE that have the capability of detecting photons as well as measuring their energies.

In a head on collision of two beams, one assumption for Higgs production is that a Higgs Boson would be created with small momentum relative to its mass. If this were the case, the Higgs Boson would have to decay into two photons that emerge in opposite directions in order for momentum to be conserved. Given this, one needs to find where PHOS and EMCal are 180° apart from one another (shown in figures 8-10) [7][8][9][10].
Figure 8: This shows a radial cross-section of ALICE giving the azimuthal coverage of the TPC, PHOS, and EMCal. The green overlap is where PHOS and EMCal are $\pi$ radians apart and the dashed lines show the azimuthal range of the $\gamma\gamma$-decay.

Figure 9: This shows the coverage of the TPC, PHOS, and EMCal as defined by the pseudorapidity ($\eta$), which is a relativistic variable related to the angle $\theta$. 
particle makes with the beam axis. Again the dashed lines show the range of the γγ-decay.

Figure 10: This figure shows both the azimuthal and pseudorapidity coverage of the TPC, PHOS, and EMCal with the overlap depicting the region where PHOS and EMCal are π radians apart.

There are several possible scenarios for photon detection. Given the ALICE detector configuration (figure 7), when two photons are produced there are several different ways they could be detected in ALICE. The first way would be for both photons to convert into an electron and a positron by interacting with material in the detector. If this were the case, the electron-positron pair would be split due to the magnetic field in the detector, leaving tracks. These tracks could be used to reconstruct the photon that created them. The electron-positron pair could also be detected as energy deposits in the calorimeters PHOS and EMCal. In the second scenario, one of the photons would make it all the way through to one of the calorimeters, while the other splits into an electron-positron pair and leaves two tracks. The final possibility would be that both photons reach the calorimeters and leave their energy deposits.
Figure 11: This is a pictorial representation of the three possible scenarios for the $\gamma\gamma$-decay of the Higgs Boson.

Figure 12: These plots show the conversion points were photons could possibly convert to an electron and positron [19].

Figure 12 shows where photons are likely to split into an electron-positron pair. From this, the fraction of photons that will actually make it all the way to EMCal does significantly drop. Of the three possibilities in figure 11, the simplest case is Case III, which is also the least probable. Given the selected decay mechanism we determined the energies and trajectories that would be produced
from a theoretical Higgs at 120 GeV/c². In order to figure this out one must use relativistic mechanics.

\[ E^2 = (mc^2)^2 + (pc)^2 \quad (1) \]

In equation 1, \( mc^2 \) is the rest mass energy of the Higgs Boson, 120 GeV/c². Since the Higgs is going to be produced by two beams that have approximately the same energy and are traveling in opposite directions, the Higgs Boson that is produced should have little or no longitudinal momentum, and we considered the total momentum (\( p \) in the \( pc \) term of equation 1) to be small compared to the mass. From this equation, the energy and trajectory of the resulting photons can be determined.

![Diagram showing resulting photon angles for the decay of a 120 GeV/c² Higgs with momenta between 0 and 20 GeV/c](image)

**Figure 13: Resulting photon angles for the decay of a 120 GeV/c² Higgs with momenta between 0 and 20 GeV/c**

For this search, the energies and trajectories of two photons produced from a Higgs with momenta of 1 GeV/c, 10 GeV/c, and 20 GeV/c were calculated using equation 1. Based on conservation of energy, the two angles, \( \theta_1 \) and \( \theta_2 \), would be equal and each would have half of the total energy of the produced Higgs.

From equation 1:
\[
(mc^2)_H^2 = (E_{\gamma_1} + E_{\gamma_2})^2 - (\vec{p}_c_{\gamma_1} + \vec{p}_c_{\gamma_2})^2 \tag{2}
\]

\[
|E_{\gamma_1}| = |E_{\gamma_2}| = \frac{|E_H|}{2} \tag{3}
\]

\[
\frac{pc_\gamma}{2} = |E_\gamma| \cos \theta \tag{4}
\]

\[
\theta = \cos^{-1}\left(\frac{pc_\gamma}{2|E_\gamma|}\right) \tag{5}
\]

From equations 2 through 5, we determined the energies and angles that would be produced from a decaying Higgs Boson with momenta of 1 GeV/c, 10 GeV/c, and 20 GeV/c, seen in Table 4. These energies and angles set the parameters for our search at ALICE.

<table>
<thead>
<tr>
<th>pc (GeV)</th>
<th>E_H (Gev/c^2)</th>
<th>E_\gamma (Gev/c^2)</th>
<th>\theta (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.0</td>
<td>60.0</td>
<td>89.5</td>
</tr>
<tr>
<td>10</td>
<td>120.4</td>
<td>60.2</td>
<td>85.2</td>
</tr>
<tr>
<td>20</td>
<td>121.7</td>
<td>60.8</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Table 4: Theorized energies and angles of dispersion for the produced photons from the decay of a 120 GeV/c^2 Higgs Boson.

Using this information, photons with energies $\geq 50$ GeV that are 180±10° apart from each other should be considered.

The Number of Higgs Produced in a Year at ALICE

In order to calculate the number of Higgs expected to be produced in ALICE in one year, we need both the cross-section, the probability per collision to produce one, and the number of collisions expected at ALICE. This requires knowledge of the beam luminosity.

Luminosity is directly related to the intensity of the beam and from it we can determine the number of collisions in a given time frame. The design of the LHC allows for a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ for $pp$-collisions (proton-proton) and $10^{27}$ cm$^{-2}$s$^{-1}$ for $PbPb$-collisions (lead-lead) [7]. Multiplying these luminosities by the amount of time each type of collisions are run for a year, yields the approximate integrated luminosity for both $pp$-collisions and $PbPb$-collisions, and with this
integrated luminosity, we can determine the approximate number of Higgs Bosons that will be produced by multiplying it with the experimental cross-section determined from Figure 2.

\[ N_H = \sigma L dt \quad (6) \]

Once this is known, we also need to know how many of these Higgs Bosons would decay into two photons. Assuming a mass of 120 GeV/c², Figure 3 provides the branching ratio. Multiplying the total number of Higgs by the branching ratio (~0.2%) gives an approximate number of Higgs Bosons that would decay into two photons. These theoretical numbers are found in Table 5.

|                     | \( L \) (cm\(^2\)s\(^{-1}\)) | \( dt \) (s) | \( \sigma \) (cm\(^2\)) | \( N_H \)   | \( N_{H\rightarrow\gamma\gamma} \) |
|---------------------|-------------------------------|--------------|----------------|----------|----------------|---|
| \( pp \)-collisions | \( 10^{34} \)                  | \( 10^{7} \) | \( 5.1\times10^{-35} \) | \( 5.1\times10^{6} \) | \( 1.2\times10^{4} \) |
| \( PbPb \)-collisions | \( 10^{27} \)                  | \( 10^{6} \) | \( 1.1\times10^{-30} \) | \( 1.2\times10^{3} \) | \( 2.4 \) |

Table 5: Approximate Number of Higgs Bosons produced via \( pp \) and \( PbPb \) collisions, and the approximate number that will decay into two photons.

Although theoretically there could be \( 1.2\times10^{4} \gamma\gamma \)-decaying Higgs Bosons produced at ALICE in \( pp \)-collisions, the number of detectible Higgs Bosons decreases due to the coverage of the calorimeters at ALICE, which is shown in Figures 8 through 10. Using the dimensions from figure 8, the percentage of ALICE that PHOS and EMCal cover is approximately 27%. From this, the number of Higgs that would be probable to find at ALICE decreases to 3240 Higgs Bosons via \( pp \)-collisions and 0.65 Higgs Bosons via \( PbPb \)-collisions. Despite this low probability, we attempted to build an analysis algorithm that could search for candidates.

**Analysis Code**

Our main goal for our code was to search through the copious amounts of data for photons in both PHOS and EMCal that had energies \( \geq 40 \) GeV. Since analysis on the data is already being done, we used a framework based on ALICE code and Root code called AliRoot [20]. The current search for photons at ALICE focuses on photons with transverse momenta (\( p_T \)) less than 30 GeV for the study of the QGP. Since we are interested in photons with \( p_T > 30 \) GeV, we modified the code to search for possible candidates.

PHOS and EMCal are both classified as electromagnetic calorimeters, which
are made by alternating layers of dense materials with layers of scintillators. The main purpose of electromagnetic calorimeters is to measure the energies of both charged and neutral particles, such as electrons (charged) and photons (neutral). When particles hit electromagnetic calorimeters, cones of lower energy photons, electrons, and positrons are created. Cones that are consistent with incident photons are narrow compared to cones from charged particles and there is no accompanying track in the tracking detector indicating the trajectory of the photon.

There are two processes that contribute to the production of these cones, they are: pair production and Bremsstrahlung radiation. Pair production, as its name implies, is the production of an electron-positron pair. This pair is produced when energetic photons interact with a nucleus within the detector material [18]. Bremsstrahlung radiation occurs when charged particles are accelerated (or decelerated by hitting the material in our case) [29]. The acceleration causes electromagnetic radiation in the form of a photon, which if it possesses enough energy could undergo pair production, thus restarting the cycle. When there is not enough energy for either pair production or Bremsstrahlung radiation, the shower energy is converted to light, which is collected in the scintillator layers and stored as data for the incident particle. This data is then analyzed with help from computer code in the form of algorithms.

In AliRoot, the code used to identify photons is called AliAnaPhoton, and it was written as part of the ALICE Off-line Project. The main objective of this code is to identify energy deposits in the calorimeters that correspond to photons as the incident particle and return different parameters that belong to the photons. In our code, we focused on generating histograms to tell us the distribution of the various $p_T$ and the location of the photons in azimuthal angle ($\phi$) and pseudorapidity ($\eta$) (see figures 8-10 for ALICE coverage).

Once the original AliAnaPhoton was altered to search for photons that possibly resulted from the decay of a Higgs Boson, a macro was written to run our analysis on the grid.

**AliEn and the Grid**

There are two different ways to go about analyzing data. One way is to download all of the data onto a local machine; however, since the amount of data collected each shift is on the order of terabytes (TB=1000 GB), no one computer could handle analyzing all the data by itself. The other way is to use AliEn, which stands for ALICE Environment, an open source grid framework that uses computers spread across the world (with the highest concentration in Europe) to split up analysis jobs to increase efficiency.

In order to get access to the grid, certain permissions need to be attained.
First one needs to gain permission to join the CERN network. Once added to the ALICE database, special certificates are needed to access the grid from a personal computer. Finally, after all this is complete one can begin accessing the data and start the analysis process.

![Map of the AliEn Grid across the globe](http://alimonitor.cern.ch/map.jsp)

**Figure 14:** The AliEn Grid across the globe (http://alimonitor.cern.ch/map.jsp)

![Map of the AliEn Grid zoomed in view of Europe](http://alimonitor.cern.ch/map.jsp)

**Figure 15:** A zoomed in view of the Grid across Europe (http://alimonitor.cern.ch/map.jsp)

Figures 14 and 15 show AliEn stretching across the globe making the ALICE experiment a truly worldwide project.

After we had attained all of the permissions and certificates we needed, we began trying to run our analysis on the data that was collected during our stay at ALICE from July to August. All of the data that is collected at ALICE is separated and stored by run number. In order to check if our analysis algorithm worked, it
was run over one of the specific run numbers. Our code did return the correct information, but as expected, it did not return any Higgs candidates.

When Jobs are submitted, the user can monitor his or her jobs using MonALISA, which stands for MONitoring Agents using a Large Integrated Services Architecture. Figure 16 shows one of the times when we had a job running (williamt); however, manually submitting jobs one at a time for hundreds of runs would be less than ideal, not to mention time consuming.

![Running jobs per user](image)

**Figure 16: Running Jobs per user on the Grid [11].**

In order to increase our chances of seeing a Higgs Boson, more runs had to be analyzed. Taking all of the run numbers that corresponded to runs that were collected during our stay, we wrote a script that would submit a job with our analysis code for each of the specified run numbers. We were unable to complete the analysis of all these runs in time for the writing of this report, but the foundation for a future senior project has been laid.

**Conclusions and Future Outlook**

The Higgs Boson is the most important unfound SM particle. With the LHC up and running, the probability of finding the Higgs is greater than ever. Although ALICE is primarily focused on studying heavy ion collisions and the QGP, there is a chance the Higgs could be found there.
From the theory, approximately $1.2 \times 10^4$ Higgs Bosons with a mass of 120 GeV/$c^2$ could be produced and decay into two photons with the expected luminosities, in a given year. Although heavy ion collisions will increase the number of nucleons in each collision, this will not have a significant effect on the number of detectable Higgs, due to the much lower luminosity.

With a focus on photons that would reach the calorimeters (the least probable case), the coverage of ALICE was significantly reduced. Using AliRoot, code was developed to search for possible candidates in PHOS and EMCal. The code works for individual runs; however, the hope is to get it to a place where it uses the grid to analyze multiple runs, which will increase the chances of seeing the Higgs.

There is definitely a lot more work to be done in order to complete this project, and a number of things could be done to improve it. The first task would be to complete the macro in order to analyze multiple runs on the grid. After this, the project could be expanded to include the other photon detection possibilities, and algorithms could be developed to search for these possibilities. Whatever happens, the search for the elusive Higgs will continue. Hopefully, the question will be when and not if, it will be found.
References:


11. http://alimonitor.cern.ch


21. Not the popular CBS television sitcom