Rediscovering the Higgs Boson

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(Dated: December 18, 2020)

Shortly after the big bang, it is theorized that matter and energy within the expanding universe organized itself into some of the first fundamental particles. To explain why some of these indivisible particles exhibit mass and others do not, physicists developed the theory of the Higgs Field. This theory subsequently lead to the formulation of several new Bosons, previously unknown to the standard model - the last of which to be confirmed is the *Higgs* Boson. We examine a collection of ROOT files that contain information Higgs to Z-boson to four-lepton decay modes. A CMS virtual machine lets us interact with the ROOT datafiles, and repeat a subset of the computations used to confirm the 2012 discovery of the Higgs Boson particle. In this report, we are able to reproduce the result that shows evidence of the Higgs-Boson having a mass of 125 GeV/c^2 which concurs with the result from the 2012 experiment

Introduction- The *Standard Model of Particle Physics* is the accepted theory that governs humanity's understanding of sub-atomic world. It is composed of multiple kinds of indivisible quarks, leptons, and Bosons, each of which represent the universe at its most fundamental level [1]. Collectively, the particles in the standard model describe the strong nuclear force, weak nuclear force, electromagnetic force, as well as how all of the particles interact with each other. We provide a visualization of the components and organization of the standard model in Fig. (1). While is consistent within its own theory, has shown experimental validity, and holds incredible predictive prowess, the standard model is still an incomplete theory of particle physics [2, 3].

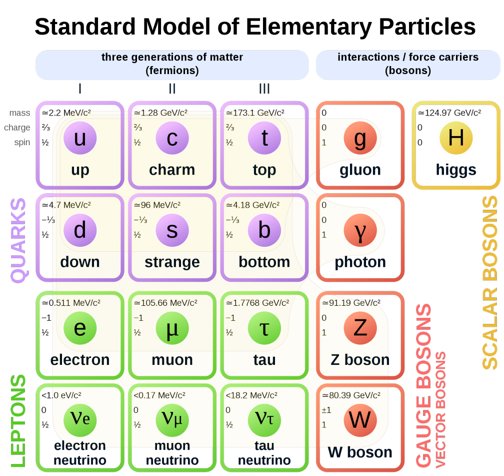

Figure 1. The typical organization for the Standard Model of particle physics

The Standard model leaves open may questions such as how some some particles have experimentally shown the properties of having mass, whereas other particles do not. Modern theories about this indicate that in the time immediately after the big bang, several of the fundamental particles were formed, but did not interact gravitationally - as if they had no mass [2]. In the mid-twentieth century, English Physicist Peter Higgs proposed that some time after the formation of the universe, a scalar field, dubbed *The Higgs Field* was created. Higgs proposed that it was the particles interaction with this field that gives that allows for the particles to exhibit mass [2, 4].

Applying this theory to the electroweak force model lead to the formulation of the W and Z Gauge Bosons, which have been subsequently experimentally confirmed [4]. We see these bosons appear in the standard model in the rightmost side of Fig. (1). However, the theory consequently gave rise to another previously unknown particle in the standard model: The *Higgs Boson.* Despite having a place in the Standard Model, the theory is unable to provide a prediction for the mass of the new Boson [3, 4]. Decades of consideration has provided an estimate of the mass to be as low at 114 GeV/c^2 to almost 1 TeV/c^2. [4]

This large range of masses makes the search for the Higgs Boson a very difficult process. We must systematically analyze data across this range and understand that the particle cross section may vary widely as well. To account for this the CERN detection apparatus was designed to process data over the large range of masses, and across five different decay modes. These decay modes model the Higgs Boson as decaying into one of five different pairs of elementary particles:

$$\begin{aligned} \text{Higgs Boson to Photons} \qquad & H \to \gamma\gamma \\ \text{Higgs Boson to Z Bosons} \qquad & H \to ZZ^* \\ \text{Higgs Boson to W Bosons} \qquad & H \to W^+W^- \\ \text{Higgs Boson to tau} \qquad & H \to \tau^+\tau^- \\ \text{Higgs Boson to Bottom Quarks} \qquad & H \to b\bar{b} \end{aligned} \tag{1}$$

Each one of these decay modes represents a possible outcome of a Higgs particle, giving us five different types of events to look for and examine for evidence of it's existence. We are particularly interested in the decay to the Z-Boson pair, which can further decay into a quadruplet of leptons. This is called *"The Golden Channel"* because it has the clearest signature of all decay modes [5]. We denote this decay mode as:

$$H \to ZZ^* \to 4l \tag{2}$$

Due to the increase luminosity of the second Higgs detection run, the ATLAS detector facility at the Large Hadron Collider (LHC) was able to detect numerous candidate event over the course of three years. A subset of this information has been made publicly available through CERN, which we will use to replicate the analysis that lead to the confirmation of the the Higgs Boson. In this work, we replicate some of the steps that the team at CERN has used to predict the mass of the Boson, and subsequently confirm it's existence.

Methods- We explore a simplified re-implementation of parts of the Compact Muon Solenoid (CMS) Higgs to four lepton analysis as explored in CERN's publication which documents the details of the discovery of the Higgs Boson. Given the high volume of collected data, we use the *ROOT* software tool which is an open-source data analysis framework that allows for the processing of large quantities of experimental data [6]. The analysis code we run to mimic the Higgs discovery does not use the original analysis code, and instead opts for a more simple and condensed version which skips some of the more advanced computations. The analysis code provided reuses many of the tools, principles, and parameters from the original CMS experiment, but does not explicitly provide the original cuts or data itself. The code, and procedure allows for the development of a qualitative representative of how the Higgs was discovered. We develop a subset of that procedure in this report.

We begin the analysis process by installing and configuring the *Oracle Virtual Machine* application. To accompany this, we download *BuildFile.xml* which Oracle uses to construct our virtual machine (VM) locally. This VM will allow us to interact with and process the CMS data and handle the ROOT file format. We begin the analysis process my formatting parts of the VM directory tree, which we will use to store the raw *.root* files, and demo analysis python files. Following the steps are listed on the CERN Opendata page, we collect 18 for the *.root* files and store them to our local VM. We can use the ROOT program to examine other properties of these files if desired.

Finally, we download a *C++* script that will produce a histogram visualization of the data collected in the CMS Experiment. Running the script produces the graphic as seen in Fig. (2) which is nearly identical to the Fig. (4) found in the original Higgs Boson Discovery paper [4]. This figure represents data as collected and analyzed from the ZZ^* to $4l$ decay that we are interested in. From this figure, we find a few key details about the CMS experimental data. This histogram shows

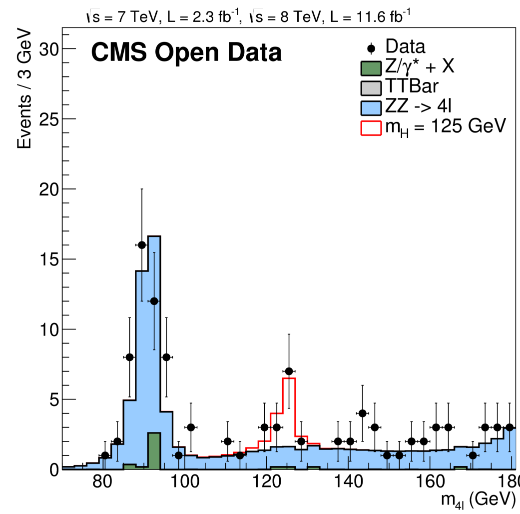

Figure 2. Distribution of the invariant mass for the $ZZ^* \to 4l$ decay analysis

the occurrence of events (y-axis) as a function of mass-energy measurements (x-axis) with the small black dots and error bars. This gives an an effective distribution of mass for this particular decay mode. The light-blue filled in histogram represents the expected background events, being the $ZZ^* \to 4l$ decay. The red outlined histogram shows expected mass-energy where the peak of the fit around 125 GeV/c^2 indicates that the Higgs Boson is most likely that mass-energy value. This is consistent with CERN's results [4].

After we confirm that the plot is looking as expected, and the *.root* files are behaving properly, we can proceed by collecting and running the Python demo analyzer files. The first script will produce another ROOT file that contains as possible candidate event for the Higgs detection. The second script also produces a ROOT file, but contains the Higgs signal distribution with reduced statistics We return to the terminal to run a related ROOT command, this time running a new $C++$ file which produces a new histogram, shown in Fig. (3). This new figure introduces a This figure resembles Fig. (2) in that is shows the same data set. However, it adds a "user data" indicator that shows over this set of data, the model computes the Higgs to have a mass-energy o 125 GeV/c^2.

With this portion of the experiment completed, we collect a new set of python scripts to allow us to proceed. Instead of processing a single file, we will process *index files* which contain chains of file information. We download a list of index files to our local VM and a *JSON* validation file. Due to the complexity of the ROOT program, and the time required to develop a thorough understanding how how to manipulate the data, out analysis

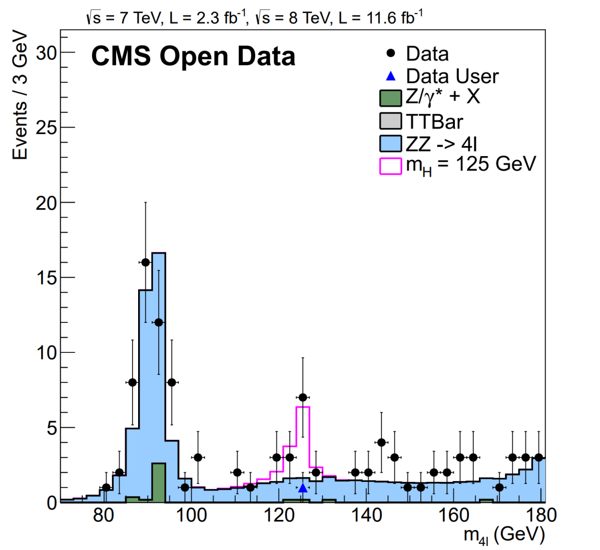

Figure 3. Distribution of the invariant mass for the $ZZ^* \to 4l$ decay analysis, notice the introduction if the *user data* mark at around 125 GeV

of the experiment terminates here. Later steps rely on a proficiency in $C++$ and $ROOT$ that we were unable to develop in time for this lab.

While this lab boasts an exceptional set of instructions, we were unable to complete the full methodology section. Future work in this lab would entail a more thorough exploration of the nature of making "cuts" in the data with the $ROOT$ analysis tool. With this foundation, we could explore the full data set in a way that would allow us to develop a more through set of results by subjecting the data to these different cuts, and allowing for different fits. Each fit would present a slightly different mean and variance value indicating slightly different predictions for the mass and it's uncertainty.

Discussions- The confirmation of the discovery of the Higgs Boson particle represents an enourmous milestone in the development of the Standard Model and particle physics as a whole. The existence of the this Boson particle is further support of the predictive power of the theories built into the standard-model and allows us to gain a new view on the properties of mass at the subatomic level. Additionally, the support of the Higgs field and it's interaction with other particles.

In this work, we wanted to determine the uncertainty of the Higgs-Boson's mass. The procedure would be to make cuts in the raw data set to produce subsection of mass ranges. With each, we could fit the dat the composes the red-histograms in Fig. (2) and determine the uncertainty up to 95% confidence level and compare the results and its uncertainty to the reported value. However, we underestimate the time required to accurately complete this portion of the lab. As a result, we are unable to formally determine any experimental uncertainty in this experiment at this time.

Conclusions- The 2012 CERN search for the Higgs Boson particle using proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV. The search was conducted over five different decay modes, but results here are focused around the Higgs to four-lepton decay as Eq. (2). Above the expected background, a mass near 125 GeV was detected indicating the production of a new particle with that mass. Our results are a simplified reconstruction of a portion of the data processing phase of the CERN experiemnt. We are unable to determine an formal experimental uncertainty at this time.

Acknowledgement- This project would not be possible without the contributions from the following individuals and organizations: Prof. Elena Long for guidance in this lab. This project has made use of data, software and/or web tools obtained from CMS OpenData Analysis and CERN.

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