SCOTT ANTHONY

HONOURS PROJECT REPORT
HIGGS SEARCHES,COMBINATION

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Abstract

The Higgs Boson is predicted in the standard model. The Higgs boson has also been called the "God Particle" because if found it may yield many answers to problems that have troubled scientists for decades . Experiments such as the Tevatron particle accelerator in America have failed to find the elusive Higgs boson. Hence billions of pounds (~£3billion) has been spent looking for the Higgs as its importance is priceless.

The purpose of the project was to study the Higgs Boson in depth and using statistical analysis along with the software program ROOT be able to analysis several of the possible Higgs decay channels at certain mass points notably 120GeV and 130GeV. The Higgs to $\gamma\gamma$ channel and Higgs to ZZ* channel were the focus of the project.

<u>CONTENTS</u>

1.Introduction

The Higgs boson has attracted a lot of attention recently with the construction of the Large Hadron Collider (LHC) which is located in Switzerland It has the technology to accelerate particles to 99.9999991% of the speed of light. The project was split up into several parts. The physics aspect which involved learning in depth the physics surrounding the Higgs. The programming analysis which involved learning how the actual code operated and how it responded to changing certain properties of it. It was this code that was used to study the decay channels hence a good understanding of the code essential to project. Finally the last aspect of project was the study of the decay channels at specific mass points for the Higgs (120,130 and 140 GeV) and then to combine the channels.

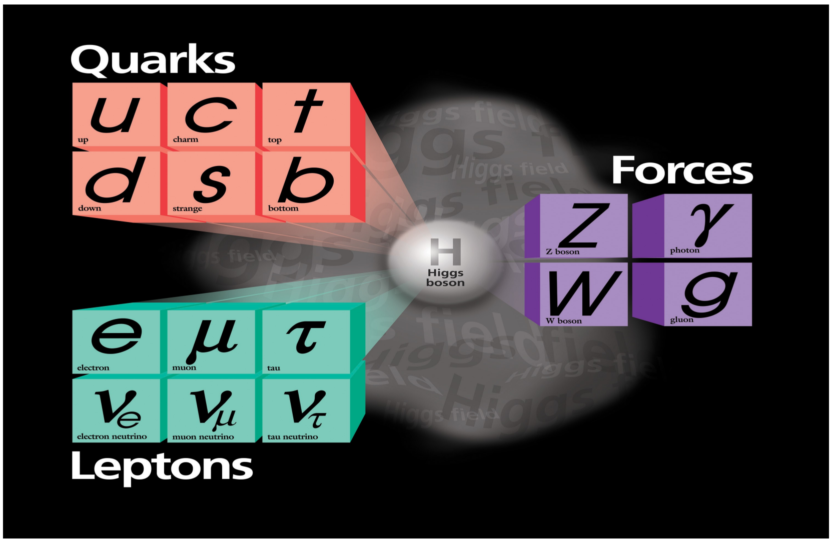


Figure 1-The Standard Model

The Standard Model; As shown in figure 1 this is the model which illustrates the current theory of fundamental particles and how they interact with each other. It combines three of the four fundamental forces with gravity the only force not included in the model. Standard Model includes fermions and bosons. Fermions are quarks and lepton which ultimately make up matter and bosons are the particles which mediate the forces. Photons for example mediate the electromagnetic force, W and Z bosons mediate the weak force and finally gluons mediate the strong force.

If the Higgs boson is found then it would ultimately explain why these particles have mass. Why is the W and Z bosons relatively heavy while the photons and gluons are massless. Could also lead to gravity being included in the standard model and finally having a grand unified theory (GUT)

2.Why has the Higgs Boson not been found?

First of all to produce the Higgs boson heavy particles are needed then theoretically the particles decay to produce the Higgs boson. The main problem that the particles mentioned are extremely heavy compared to typical particles like the protons, electrons and most of the quarks hence a lot of energy is needed to produce these particles.

In Collider experiments there is a higher probability of producing light particles than heavy particles and since the Higgs couples to heavy particles there is a much lower probability of these heavier particles being produced thus less chance of Higgs coupling to these particles.

Several experiments have already tried and failed to find the Higgs the main reason is the energies involved simply aren't high enough to produce the Higgs. Also another problem to overcome is that the mass of the Higgs is unknown albeit experiments at the Large Electron Positron Collider (LEP) showed that a mass of 114GeV[1] and below can be excluded at a 95% confidence level for the mass of the Higgs. However they concluded with a 95% probability that the Higgs lies somewhere in the region between 114-160GeV

The experiments to find the Higgs involve colliding millions of protons against each other and these collisions produce events which can lead to the Higgs. The difficulty in finding the Higgs is that out of these millions of collisions that happen instantaneously only a handful are interesting events hence differentiating these interesting events from the uninteresting events is another difficulty which poses a real challenge for the physicists.

What is an event?

An event (As shown in figure 2 below) is what gives physicists knowledge about particles. By observing these events which is a collision between two protons which as a result produces a bunch of particles and its this final state which is the event. Physicists can learn a great deal about particles and their properties. The faster the particles velocity the greater the energy needed ideally particles will be travelling as close to the speed of light. At the Large Hadron Collider (LHC) particles will be travelling at 99.9999991% of the speed of light.

Figure 2-A simulated Higgs event.

2.1 Higgs Production Modes

The Higgs has several production modes. In total there are 4 which are;

A. Gluon (from proton 1) + Gluon (from proton 2) ------> Higgs

B. Quark (proton 1) + Quark (proton 2) ---->jet+jet+ Higgs

C. Gluon (proton 1) + Gluon (proton 2) ----> top+top+ Higgs

D. Quark (proton 1) + quark (proton 2) ---->W Boson + Higgs

Feynman Diagrams illustrating the four production modes.

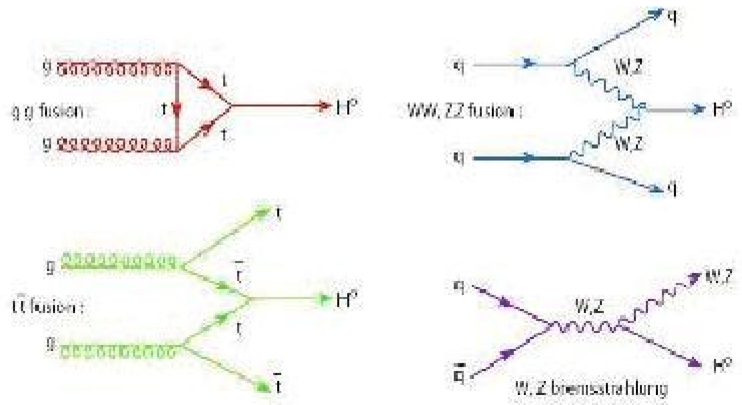


Figure3-Production Modes (A,B,C,D)

It is in these modes that the Higgs is produced, and subsequently decays into other particles and it is these decays which can be studied as these particles are theoretically the remnants of the Higgs particle which has decayed. Hence this leads to the decay channels.

2.2 Decay Channels

Figure 4 shows all the possible decay modes of the Higgs boson. It can be seen that in the 50-130 GeV the bb decay channel is dominant although is has already been proved at the LEP experiment that a mass of 114GeV for the Higgs boson is not possible as it would have been found by now.

Now If the Higgs rest mass lies in the region 130-160GeV then the dominant decay mechanism is to two W bosons. Although these processes are the dominant ones that doesn’t necessarily rule out the other decay channels as all the other processes are possible in producing the Higgs but its just the fact that the quark anti-quark pair bb and two bosons are by far the most like to occur.

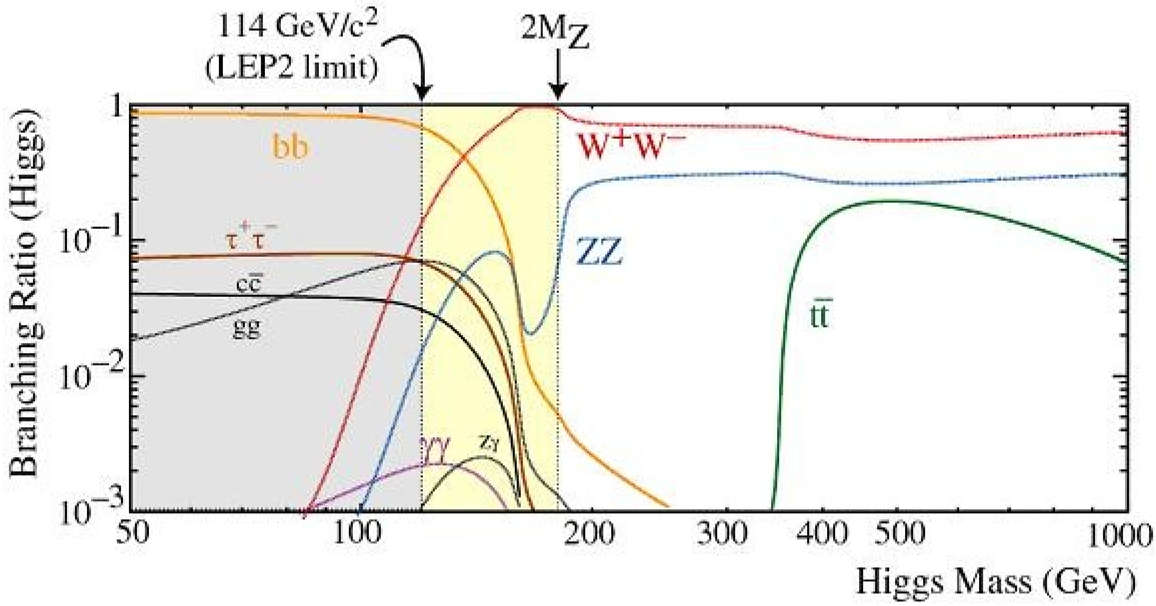


Figure 4-Decay channels and corresponding Branching Ratios

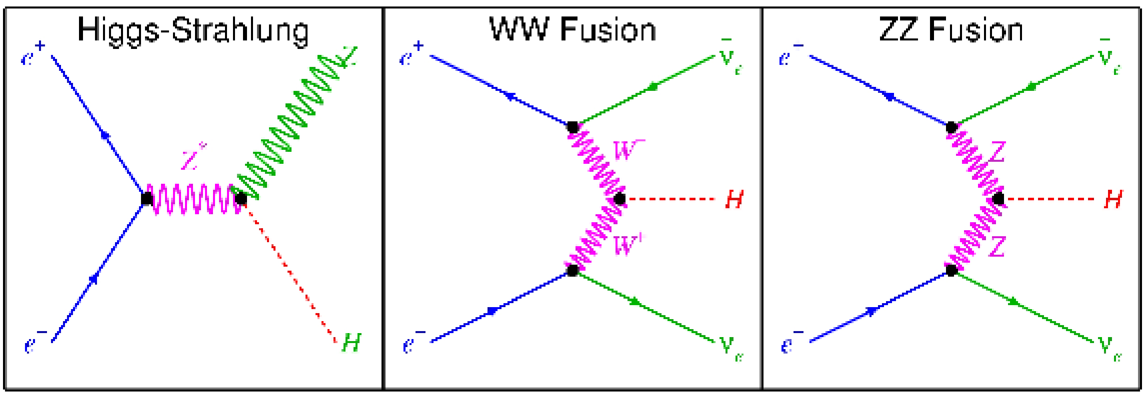


Figure 5-Feynman diagrams indicating Higgs[2]

Branching ratios; This is an important ratio and is the ratio of particles that decay into a certain decay mode with respect to the total number of particles present. An example of this would be for instance referring to figure 4. For a Higgs mass of 200GeV which is extremely unlikely but for this example will do. At 200GeV around 80% of decays will be W^+W^- and 20% ZZ and a few 10^{-3} bb decays hence these three decay will together all make up the total decays in the system.

Cross Sections; Cross sections is the probability of an interaction between particles which results in a particle or nuclear reaction. Cross sections are measured in barns $10^{-28}m^2$. A barn is relatively a massive quantity with respect to particle physics hence in project femtobarns are the units used and one femtobarn is equal to $10^{-42}m^2$. The luminosity is a direct measure of collisions that have occurred. Hence the greater the luminosity the more collisions that occur and the greater chance of seeing rarer events. The formula N=σL is the cross section formula and relates cross section and the integrated luminosity.

3.Method used to analyze data

Statistical analysis was the main tool for project and it was vital that a good understanding of the statistical methods involved in analysis the data was achieved.

Throughout project two plots were constructed from the code run in ROOT. There was the Expected Mass Distribution (EMD) showed the signal onto of the background and also the resultant Probability Density Functions (PDFS). The PDFs contained two Gaussian like plots and these plots were called H0 and H1. Where the H0 hypothesis displayed only background events whereas the H1 hypothesis displayed signal and background events together. The invariant mass (The EMDs) is the variable used to discriminate between signal and background.

H0- This is the background PDF and shows all LLR values for all possible n values if there is no Higgs. This is also know as the 'Null Hypothesis'.

H1-This PDF simulates all possible experiments that have the Higgs signal. Hence this includes signal and background. This is also known as the 'Alternate Hypothesis'.

The statistical method is described in depth in my project partners report[3] hence not going into too much depth just a brief overview of the method used;

3.1 Log Likelihood Ratio (LLR)

This statistical tool was the main process used in project. It computes a signal on top of a background and produces two Probability Density Functions(PDFs). The PDF's are called H0 and H1 and H1 contains the signal and background whereas H0 only contains background diagram figure 6 illustrates this. Also -2lnQ is the Log Likelihood Function (LLR).

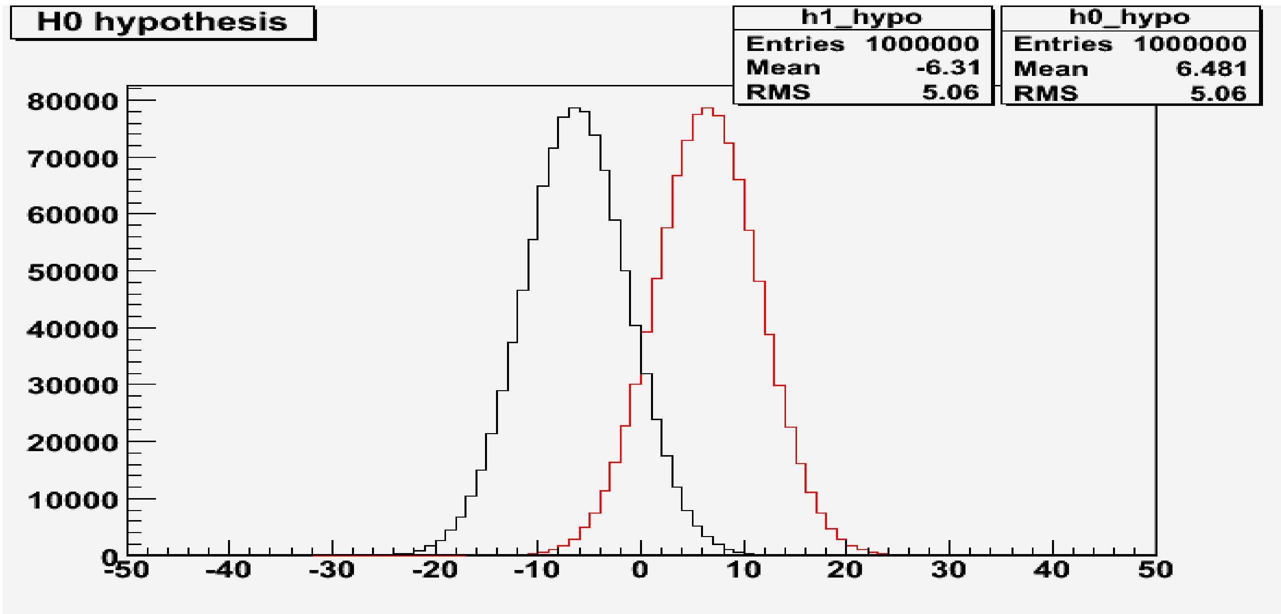


figure 6-A typical PDF

-2InQ

Then from the Pdfs the sensitivity could be calculated using the formula

$$\lambda = \frac{Mean\,H0 - (Mean\,H1)}{Width\,H0}$$

This formula gave specific λ values for each different PDF and was the essential formula used throughout project.

3.2. CL_s Exclusion Method

This method is used to find values for exclusions at certain mass points. The number of pseudo experiments is essential as this decides whether exclusion can be calculated although this depends on the PDFs having a Gaussian shape if the PDFs are not Gaussian then discovery becomes much more difficult. In order to exclude the Higgs (given that it doesn't exist) need a Cl_s value of less than 0.05.

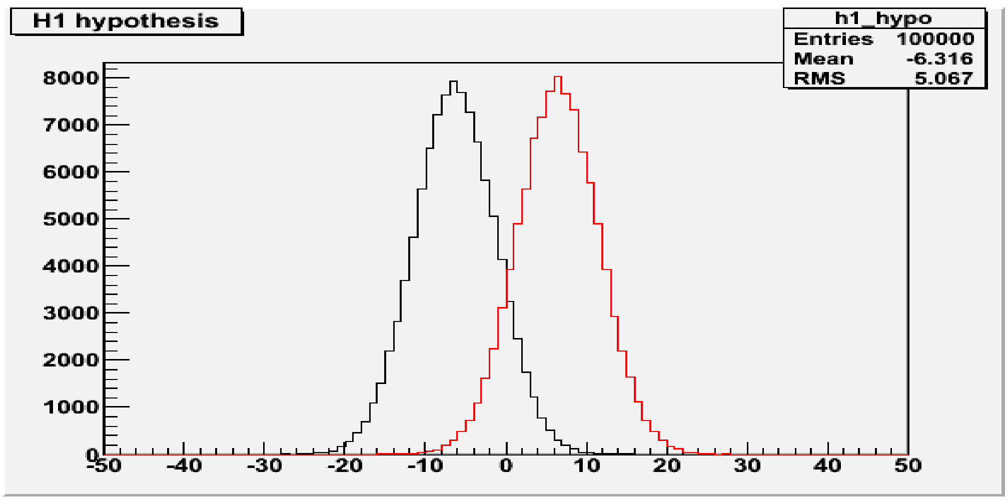
For discovery 10^8 pseudo experiments have to be run to achieve the 5sigma discovery and problem was computational power and time. Thus maximum amount of pseudo experiments run in project was 10^7

4.Higgs ->γγ channel

This is the channel that I have been studying. It is the most promising discovery channel for finding the Higgs in the mass region between 114-150GeV[4]. The Higgs boson is produced by the gluon fusion process by a heavy top quark loop and by Vector Boson Fusion (VBF).[5]

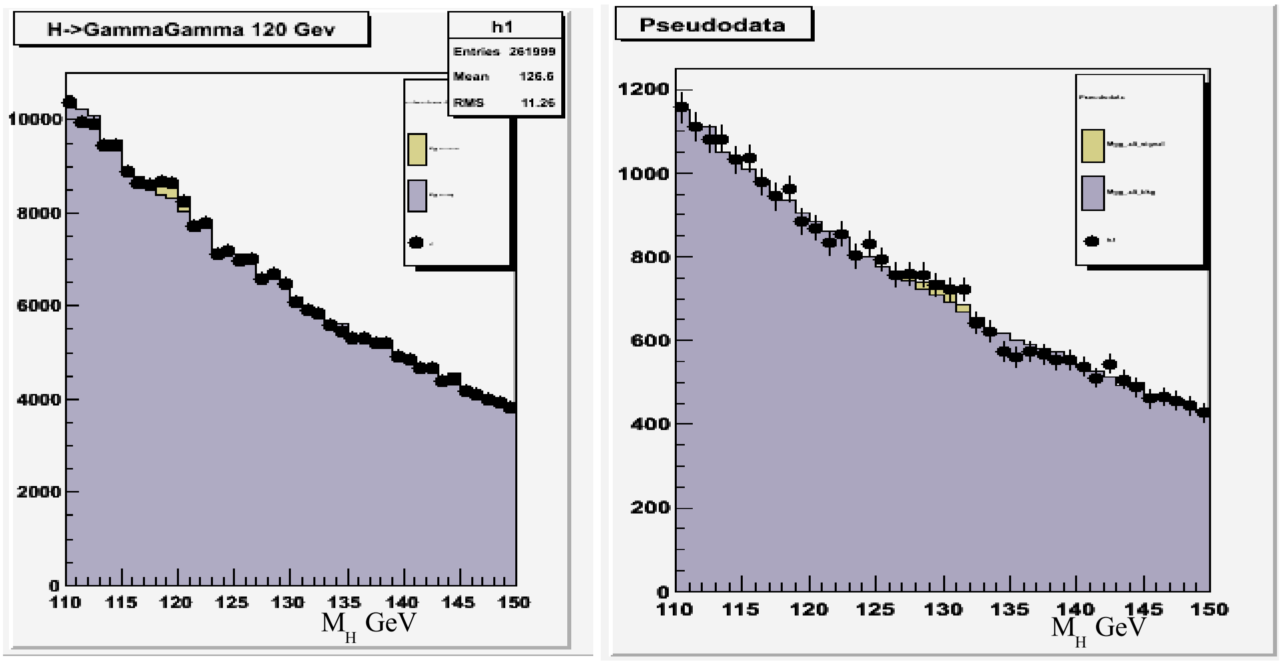
The Higgs has to be observed above a large background of irreducible photon-photon background. Thus the Higgs particle will have to be discovered as a slight bump on top of a well understood background. The convenient property of the Higgs->γγ is that once the PDFs are produced they produce nice Gaussian distributions hence results from these distributions are accurate.

The following figures show results for the Higgs -->γγ channel at Luminosity's of $10fb^{-1}$ and $30fb^{-1}$. Each Luminosity has an EMD and a resultant PDF.



-2InQ

Figure 7-The Probability Density Function (PDF) for Higgs->γγ at mass of 130Gev at a luminosity *of* $10fb^{-1}$



Figures 8 and 9- The expected mass distribution a mass point of 120GeV and the EMD for Higgs->γγ at mass of 130Gev and luminosity of 30fb$^{-1,}$here the purple area constituents the background signal and the yellow area displays the signal on top of the background

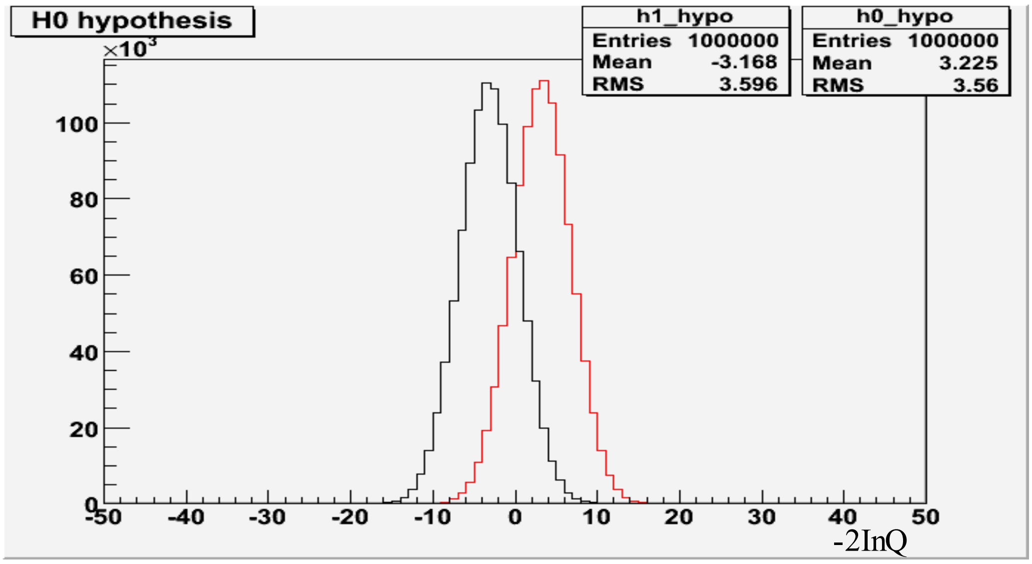


Figure 10-Probability Density Function (PDF) for Higgs->γγ at mass of 130Gev at a luminosity of 30fb^{-1} and a sensitivity value of λ=4.3

The resultant PDFS gave λ values of 1.79 and 2.52 for 10fb^{-1} and 30fb^{-1} respectively. the trend was that the sensitivities for Higgs->γγ decreased as Higgs mass increased .Once data had been analyzed for a mass point of 130 GeV the process was repeated again for a mass point of 120GeV.Below is the Expected Mass Distribution at 120GeV.

4.1 Discovery and Exclusion plots for H->γγ

Once data had been collected and analyzed several other plots could now be constructed. First plot was the discovery plot for H->γγ then the exclusion plot for H->γγ.

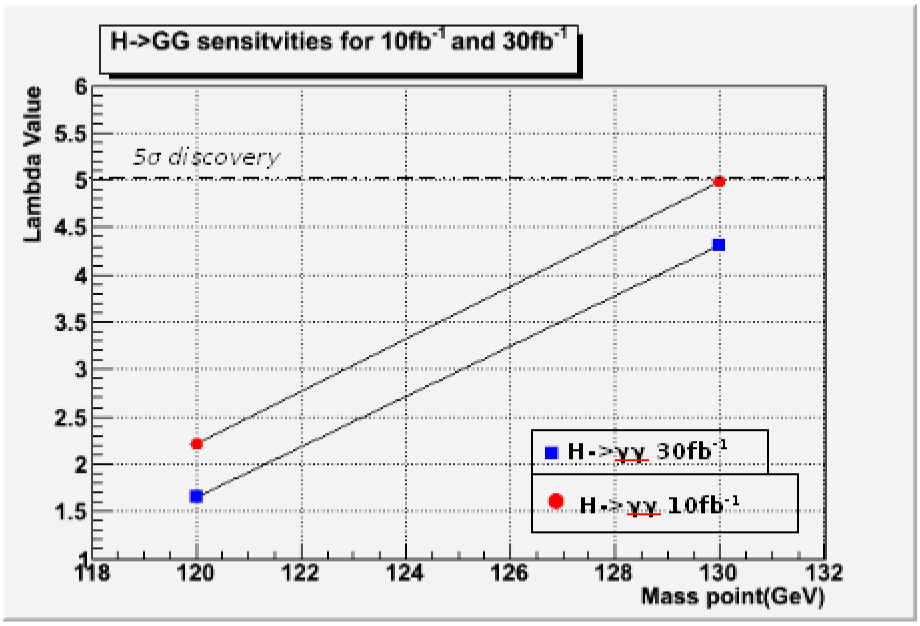


Figure11-Discovery plot H->γγ

There was a limitation on the 30fb^{-1} as this was 10fb^{-1} at 120GeV due to a limitation in the code. For the discovery plot the 5σ line is drawn on the diagram and this indicates discovery of the Higgs whereas 3σ indicates evidence of the Higgs. As results show discovery is not possible in the one channel here hence channels have to be combined to increase sensitivities. In the Exclusion plot The 95% Confidence Limit is drawn on. From figure 12 it is possible to exclude using one channel only.

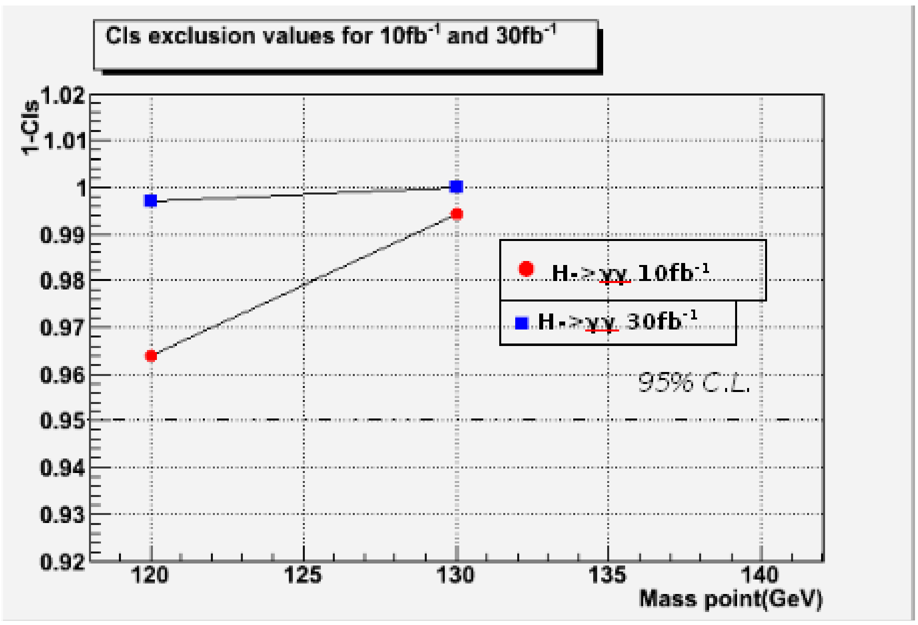


Figure12-Exclusion plot H->γγ

From figure 12 it can be seen that excluding at $10fb^{-1}$ and $30fb^{-1}$ is not really viable as its an extremely large amount of data to exclude from.

5.Combination of H->ZZ* and H-> γγ

After analysis of Higgs->γγ had been completed could then go on and combine multiple decay channels. My project partner was working on the Higgs-> to ZZ hence combining these channels was essential to increase sensitivities as plots below show. Below are the combination plots and separate channels for $10fb^{-1}$ and $30fb^{-1}$

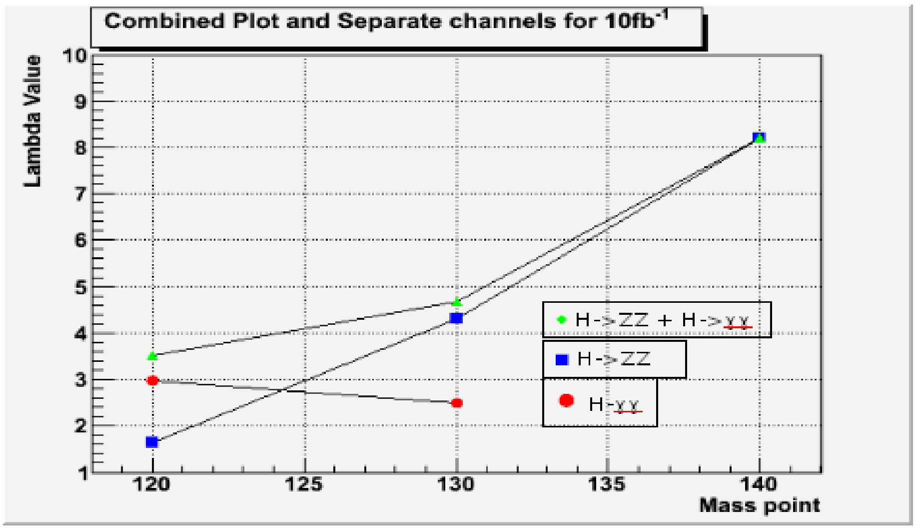


Figure 13-Combination plot with separate channels for $10fb^{-1}$

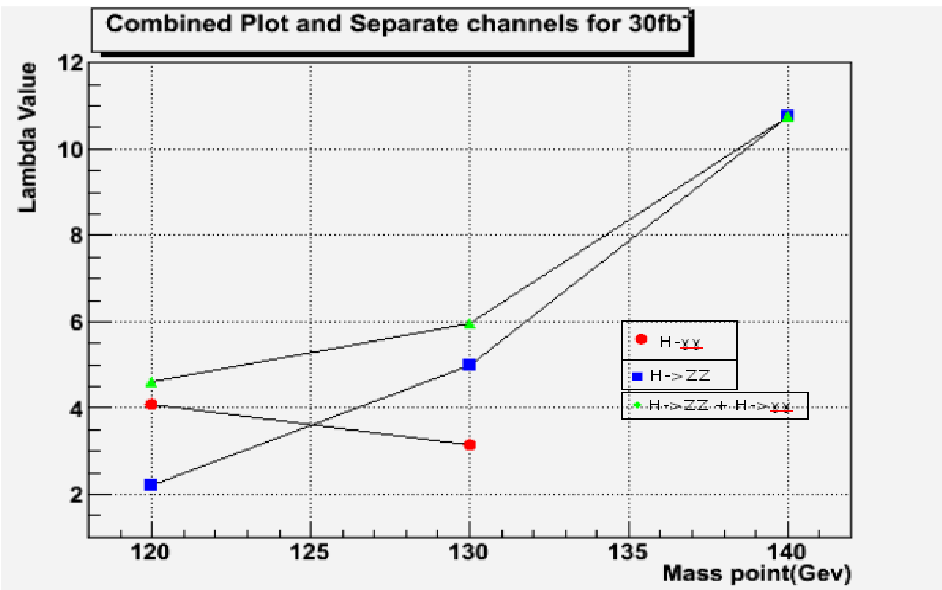


Figure 14-Combination plot with separate channels for 30fb-1

Whilst using the ATLAS Monte Carlo a problem became evident. When the distributions were scaled up past the original luminosity the sensitives didn't change when the Poisson statistic fluctuation was on. It was only when it was turned of that the sensitivities behaved as expected. These values are shown below in figure 14.With the infinite Monte Carlo statistics not taken into account the lambda values vary with $\sqrt{scale factor}$ because the Monte Carlo data is not taking into account thus results behave as expected, whereas when there is finite Monte Carlo statistics the lambda values remain the same for Luminosity beyond 30fb^{-1}

Luminosity	Infinite Monte Carlo statistics (λ)	Finite Monte Carlo statistics (λ)
10fb^{-1}	5.70	4.67
30fb^{-1}	10.55	5.96
70fb^{-1}	16.1	5.86
100fb^{-1}	19.3	5.99

Figure 15 - λ values for Channel Combination 130 GeV

The results shows with infinite Monte Carlo statistics λ increases as it should whereas with finite Monte Carlo statistics λ doesn't change it remains almost constant like.

6.Conclusions

From the statistical methods described in my project partners report results could be analyzed and results for H->γγ and H->ZZ could then be combined to increase the sensitivities. Thus a combination was achieved. Also sensitivity for H->γγ decreased as Higgs mass increased increased whereas H->ZZ was the opposite as its sensitivity increased as the Higgs mass increased..

From figure 14, H->ZZ at 130GeV gives a 5σ discovery while H->γγ at 130GeV gives a 3σ discovery hence one channel on its own does not give enough sensitivity. Thus once combined these two channels give a combined sensitivity of 6σ and this is why its essential to combine channels.

Root was a good option to run code although limited by the amount of pseudos that could be run hence more computational power and time would be ideal because as a result this would increase sensitivities as 10^8 pseudo experiments could then be run.

7.Acknowledgments

I would like to thank Professor Tony Doyle, Dr. Samir Ferrag and Miss C.Wright for there ongoing support and knowledge. Also like to thank my project partner Gavin. Without these people project would not have been possible.

As part of my fourth year studies, an honours project has to be completed. I chose the Higgs Boson as it is in my field of interest and is currently an active field of research . I was working with my project partner, Gavin as the project branched of two separate channels although we worked together on some aspects of the project. The project was split up into different sections hence I worked on some aspects of the project in depth and Gavin worked on some aspects in depth. I will be referring to Gavin's report as it contains a greater depth of detail on the statistical methods used to analyze the decay channels.

8.References

[1.] Gavin Davies “Higgs searches at the Tevatron”, 2007

[2.] Image courtesy of pi.physik.uni-bonn.de/~brock/feynman/vtp_ws0506/

[3.] Gavin Anthony, Higgs searches: statistical methods, 2009

[4.]J.-F. MarchandSearch for the standard model H->γγ decay with the Atlas detector at LHC 2008

[5.]J.-F. MarchandSearch for the standard model H->γγ decay with the Atlas detector at LHC 2008