Study on Missing Transverse energy to improve reconstructed particle signal

Submitted by
TUSHAR
(V22124)

Post Graduate Project
Research work done with
Dr. Amal Sarkar

Submitted in partial fulfilment of the requirements for the award of

Masters in Science in Physics

Indian Institute of Technology Mandi
Kamand, Mandi- 175075
Himachal Pradesh,INDIA.

Declaration by the research Scholar

I hereby declare that the entire work embodied in the report is the result of investigations carried out by me in the **School of Physical Sciences**, Indian Institute of Technology Mandi, India, under the supervision of **Dr. Amal Sarkar** and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice due acknowledgements have been made wherever the work described is based on finding of other investigators.

Place:Mandi	Signature:
Date:	Name: TUSHAR

Contents

1 Abstract **3**

2 Introduction **3**

3 The CMS detector **5**
- 3.1 Trackers 5
- 3.2 Electromagnetic Calorimeter 6
- 3.3 Hadronic Calorimeter 6
- 3.4 Solenoidal Superconducting Magnet 7
- 3.5 Muon detectors/Chambers 7

4 The Missing Transverse energy (MET) **8**

5 Generating Data **8**
- 5.1 Higgs simultaneous decay to muon, anti-muon and neutrino 9
- 5.2 Higgs decaying to neutrino and an excited state 9

6 Event Generator Pythia 8.310 **10**

7 Boosted Higgs Events **12**

8 Signal Improvement **13**

9 Conclusion **16**

1 Abstract

Here in this report, the work done contains the study of Missing Transverse Energy (MET) to improve reconstructed particle measurement in compact muon solenoid (CMS) experiment which may be helpful in finding new physics or explaining the kinematics in simpler and effective ways. This report contains the study of missing transverse energy in the decay of higgs boson to a pair of anti-muon and muon and efforts have been put to find out a relation between the angle at which the particles came out and the missing energy that may be carried away by some other unknown/known particle. After finding this relation the signal strength of particles analysis can be increased and could eliminate some constraints currently being use due to which missing transverse energy comes into play. This study has the potential to find out the actual decay kinematics of heavy particles and may help to find new particles.

2 Introduction

In High energy physics, basically, the study about the origin of the universe is done 1. That is, how everything started. What initially was and how things developed to current scenario like planets, stars, black holes and all the rest of the things. There are a no of theories about the origin of the universe. Out of these the most prominent that is accepted by most of the scientists is the theory of the Big bang. This theory states that initially there was nothing except a singularity. From this singularity everything started.The universe started expanding and took the form of what is there today. Though still there are people who don't believe in this theory, But so far it is the most successful theory 2.

According to this theory the singularity bursted and it started to expand. Due to the expansion a lot of processes happened contributing to what is there now. After big bang there was a large amount of energy focused within small volume. Then the universe started to expand further. It can be said that this expansion of universe was like cooling. Then as universe keeps on expanding, particles got produced which were initially in the free state known as quark gluon plasma. Particles at this instant were not even interacting with each other. Then later on the particles starting interacting with each other. They started forming bound states,like hadrons,mesons. As time further progressed these bound states become even heavier by combining even further with other particles Then later on atoms were formed which even keeps on interacting with other atoms then formed molecules. Thus as the time keeps on, due to the interaction between matter new objects kept on forming. Galaxies formed, large masses of gases formed, stars formed, planets formed.

At European Organization for Nuclear Research (CERN) it is tried to recreate this process that is particles or heavy ions are collided at relativistic energy and are compressed to large energies in small volume. From this point the system starts expanding or cooling and then the ongoing processes are observed. After this statements about the different interactions are made or about what the matter or radiation in our universe have gone through. Statements about different phases the universe may have gone through can also be made and different processes of nature are explained and using these mechanism it is tried to make life easier. But the point from which the created system starts expanding and recreate the big bang process depends on the energy with which particles or heavy ions are collided. So it is tried to make accelerators which can accelerate particles to high energies, so high that early stages of universe evolution can be achieved and studied in the labs.

In Particle physics, particles available in nature are discovered and their properties are studied and how interactions takes place, which explains several phenomena of nature, are explained 3. AT CERN experiments are carried out since a long time now and a number of elementary particles have been identified. Along with this a number of properties have been studied of the particles. Also a number of phenomena have been explained using these particles. To correlate all the different kinds of particles available in the nature, a standard model has been proposed which categories particles into groups based on their properties.

Standard model basically explains the fundamental forces strong nuclear force, weak nuclear force and electromagnetic force (as gravitational force is very weak it is not considered in this model) found in the nature 4. This model contains elementary particles known to us up until now. It contains the elementary particles which are found in nature. Elementary particles are particles which is not made up of any other particle. With the help of these elementary particles standard model explains the working mechanism of the fundamental forces. In the standard model the particles are grouped as leptons, quarks and Interaction force carriers (Bosons). Quarks are the particles from which hadrons are made up of. They contains fractional electric charge 5. They also have color charge.There are six quarks having name up, down, charm, strange, top, bottom. Besides they have baryon number and half spin. Leptons are the particles which do not have color charge,have half spin,have integral electrical charge.

In leptons comes electron, muon, taun ,electron-neutrino, muon-neutrino, taun-neutrino. Now remains the force carriers/intermediaters. They are also known as exchange particles. These are the particles which are responsible for various interactions in the nature. The particles are grouped in different generations in this model. First generation contains up ,down quark and electron and it's neutrino, second generation has charm, strange quark and muon and it's neutrino.Third generation contains top, bottom quark and taun and it's neutrino. Besides there are force carriers photon, Z^0, W^-, W^+ bosons and gluons. The Z^0, W^-, W^+ bosons are also known as intermediators as they mediate weak nuclear force.

A new boson has been added in the standard model since 2012. It is the higgs boson. This particle is responsible for all particle's mass. Higgs has a mass around 125.09 GeV with an uncertainty of $\underline{+}0.21$ GeV 6. It is a scalar boson. It has both electric and color charge zero.Spin of higgs is also zero. Parity of this particle is +1.It has hyper-charge of +1 and iso-spin -1/2. Up until now only particles available in the standard model are known, but is that all! Obviously not, there may be other particles which are still unknown and which can explain several new phenomenon's of nature or known unexplained phenomenon's. Higgs boson is the particle (fundamental) of Higgs field 7. This field gives mass to other particles. Even higgs gain it's mass by interacting with other higgs. The mass gained by a particle depends on how much it resists the higgs field.

At CERN when ions (heavy/light) are collided at high energies then while measuring the processes like decay of a heavy particle to some other particle then measurements of momentum and energy of particle are taken, it is found that the energy is not conserved. That is some energy is missing 8. That missing energy can arise due to several reasons like energy carried by some neutral particle that went undetected through the detector, the precision with which detector can measure the energies of emerging particles, energy taken away by some unknown particle which may explain physics beyond standard model like explaining the dark energy or energy carried by particle which came out at large pseudorapidity and several other possibilities are also there.

So if the missing transverse energy can be measured more accurately several possibilities of missing transverse energy can be eliminated like if the neutral particles are measured in much better way the possibility of particles like neutrino's taking away energy can be removed or the detectors can be improved so that they can measure physical observable more accurately like momentum. Then the possibility of uncertainty in measurement can be made very less.

By eliminating the possibilities of current physics and after doing so if there is still some missing energy it can be said that the energy is carried away by some other new particle which is unknown to us and could even find some undiscovered particles which can explain several things in nature. So methods which can bring improvements in the measurement of energy are constantly being developed so that other exotic particles can be discovered that still exist in theories or not even in them.

3 The CMS detector

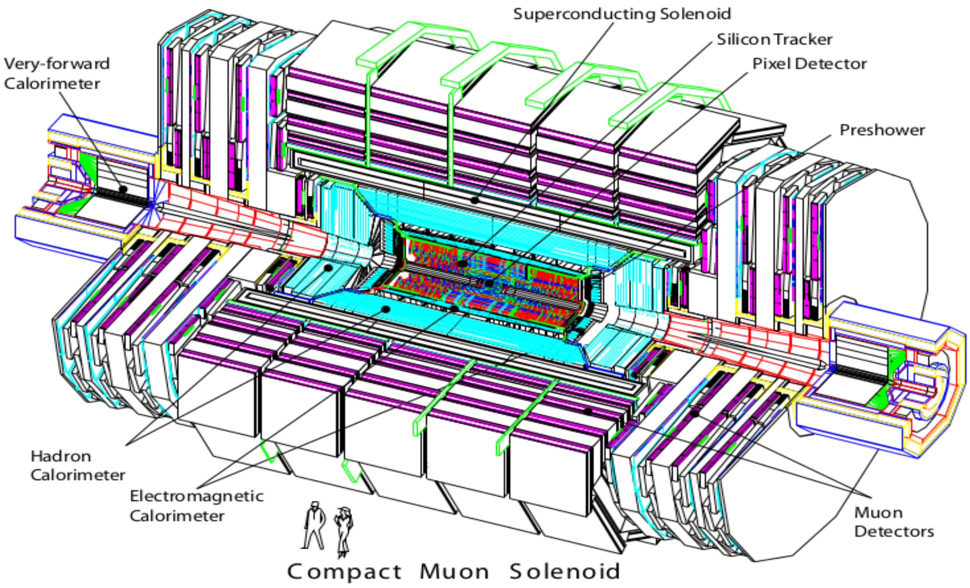

Figure 1: A picture Of CMS detector showing all it's inner parts.Name of all parts is marked with arrows. 22

At LHC (Large Hadron Collider) there are four detectors ATLAS, ALICE, CMS and LHCb. This works is biased towards CMS detector i.e. this work is in accord with CMS detector. CMS detector stands for compact muon solenoid. It is located in France. Studies about new physics is mainly carried out in this detector and ATLAS detector. The CMS detector has a large solenoidal superconducting magnet which produces a magnetic field of 3.8T. It is used to measure hadrons, leptons, photons, muons etc. It consists of various sub-detectors which works on different principles and detect particles. At CMS the coordinate system used is as, the direction of beam is taken as the z axis and the direction perpendicular to it pointing at the center of the LHC ring is taken as x axis. The direction perpendicular to both of these directions is taken as y axis.

3.1 Trackers

Now first of all their is silicon trackers which is at the very core of the detector. This detector measures the tracks left by particles as they pass through this detector and their momentum. This detector measures the tracks and momentum of particles and this is the very first subdetector the particles produced encounters. Trackers are made up of silicon because of durability, speed ,minimal noise factors. It is made up of pixels at the core,the inner barrel,the inner disks and the end caps. This tracker lets the particles pass through it and didn't try to stop them. It is effective only against charged particles as neutral particles pass through it unnoticed. It measures the curvature which is produced by the interaction of the particle with the atoms of the trackers. So tracks of particles having low momentum are measured with better accuracy than particles having high energy as they pass almost undeviated through the trackers.

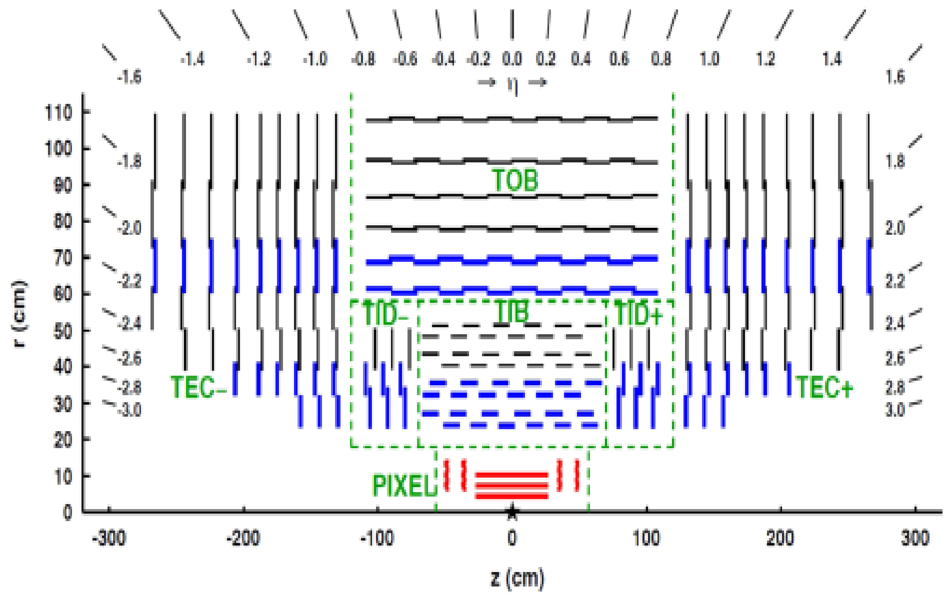

Figure 2: Layout of silicon tracker sub-detector in the CMS detector showing arrangement of the pixels, the inner barrel, the outer barrel, the inner disks and the end-caps. 23

3.2 Electromagnetic Calorimeter

This is the next subdetector which particles after passing through trackers encounters. This subdetector measures electrons, photons and other leptons. Unlike trackers, this subdetector try to stop the particles from passing through it and let them deposit all their energy over it. It is made up of thousands of lead tungstate calorimeters where particles deposits energy. It is of barrel type which surrounds the trackers. Particles mainly electrons, photons and other leptons are detected in the Ecal (Short hand for Electromagnetic calorimeters). They deposits their energy in the calorimeters. Now lead tungstate is a specific type of material which is also known as scintillators i.e. they produce photons based on the amount of energy deposits on their surface.

Then these photons falls on photo-diode multipliers which on receiving scintillation light produce multiple photons thus amplifying the signal which is then converted to electrical signal by transducers and then stored in the read-out chambers. These signal are further processed and then energy of incident particles is calculated based on these electrical signals. This part of the detector measures both charged and neutral particles as it detects particles based on their energy deposition. But unlike silicon trackers, this subdetector measures particles having higher momentum with more accuracy than the particles having low momentum.

3.3 Hadronic Calorimeter

The hadronic Calorimeters (Hcal) are the next sub-detector of the CMS detector. It has two main parts barrel and end-caps. Barrel Hcal measures particles coming out with very low pseudo-rapidity and Endcaps Hcals measures particles coming out with high pseudo-rapidity. It's working principle is almost the same as that of Ecal. It's main purpose is to detect the hadrons. As hadrons are heavier than leptons they carry more energy as compared to leptons and thus pass through the Ecal and strikes the Hcals where they are completely blocked that is they can't go further and they deposit all of the their leftover energy there. The hadrons after striking the Hcal produce secondary showers of particles like pions, muons which after falling on scintillators present in Hcals emit photons. The no of photons emitted directly depends on the energy of particles falling on the scintillators. Then these photons falls on photo-multipliers which produce multiple photons and amplify the signal. An electrical signal is generated by transducers from these photons and stored in readout chambers for further analysis.

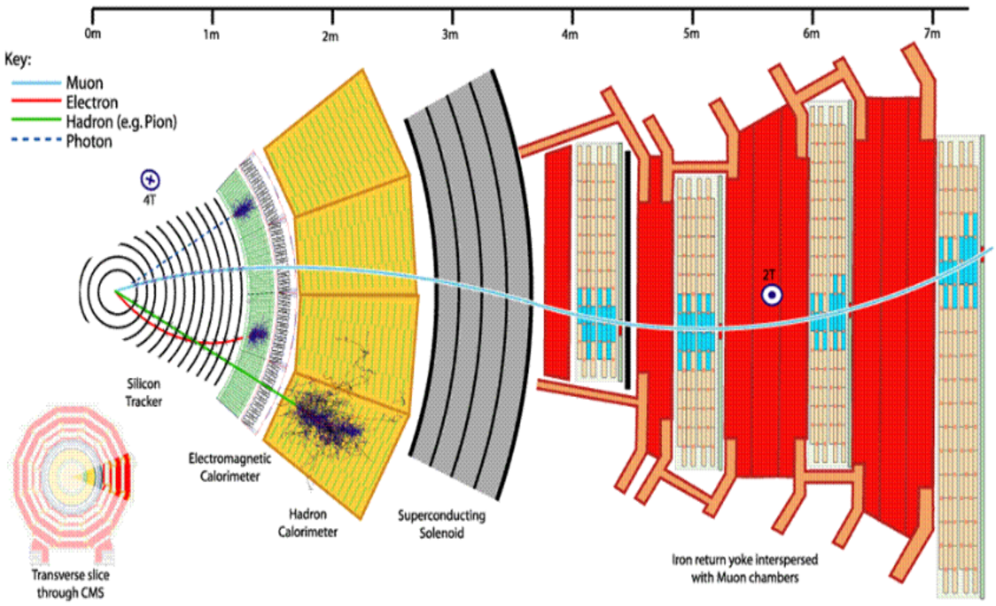

Figure 3: Slice of CMS detector showing how particles travels through different parts of the detector. 24

3.4 Solenoidal Superconducting Magnet

After the Hadronic calorimeters there comes the characteristic component of the CMS detector due to which CMS got it's name. The super-conducting solenoidal magnet which produces magnetic field of almost 3.8T. The purpose of the solenoidal magnet is to bent the trajectory of the particles. Effects of this magnetic field is also there in Ecals and Hcals and curvature is induced because of this field in the path of particles. The charged particles deviates one side and the uncharged particles deviates the other side. Due to this we can tell whether the particle is positively charged or negatively charged. Also based on how much is the curvature in the path of particle, the amount of charge the particle holds can also be found out. Like due to magnetic field the particles bends and strikes at different points of the detector. So the curvature depends on the charge, mass other properties of the particle. Now from the data of the previous run or from the results calculated by theoretical calculations it can be told that if a particles has striked at a point then how much charge it was having.

3.5 Muon detectors/Chambers

The final subdetector where only the most energetic particles reaches is the muon detector. It is basically gas ionisation detector and works on the same principle of detection after ionisation. There is gases filled in this detector which is mostly xenon or argon or some mixture of other gases. When a particle enters this detector it collides with the gaseous atoms present there and ionises them.

This electron then under the presence of electric field starts moving towards the anode and on the way ionises further atoms. Due to this avalanche is produced and all the electrons gets accumulated at the anode. The no of electrons accumulated at the anode is proportional to the energy of the particle with which it ionised the first atom. Thus the energy, momentum ,track followed by the particle can be measured as it will keep on ionising more atoms on it's way until it itself falls on the cathode or anode depending on the charge of the particle after bending under the presence of magnetic field produced by the superconducting solenoid.

There are steel yokes present in the muon chamber. They are used to bend the magnetic field in the detector itself that is they make sure that the magnetic field produced by the superconducting solenoid remains only inside the CMS detector and does not go outside it. So in a way they keeps the field up to muon chambers only. Additionally they are helpful in blocking the energetic particles so that the particles looses energy and remains only in the detector, do avalanche and get detected by the detector.

4 The Missing Transverse energy (MET)

As mentioned missing energy is the energy lost in a process which could not be measured and the reason, where it lost, is unknown. People working at CERN measure transverse (Direction perpendicular to the beams direction) components of physics observable at the detectors like transverse momentum or transverse energy. It is because of the geometry of the detector that the transverse quantities can be measured better than at any other direction's. As in general the detector is like a big barrel. Nearly, In the center of it the collisions happened then particles come out, based on the energy of the colliding beams, mostly in the transverse direction i.e. vertically, like in this case where beams are collided with energy 13TeV. Missing Transverse energy is the transverse component of the missing energy. The terms missing transverse momentum and missing transverse energy will be used interchangeably from now on as they have basically the same meaning. More formally it is the energy imbalance in the transverse plane of colliding beams and is abbreviated as the MET. MET is used instead of MTE because of the convention scientists, at CERN, are using. The notation "MET" is in use since long time so it's not a wise act to change this notation. So MET is basically short notation for missing transverse energy. Majorly, missing transverse energy is due to particles like neutrinos or potentially weak interacting non-standard model particles or particles which after interaction/no interaction emerged out at large pseudorapidity almost parallel to the beam.

Missing energy can be found in a number of processes like decay of higgs. If the decay of higgs like in a pair of muons (Here pair of muon means muon and anti-muon) is observed then sometimes the pair of muons came out opposite to each other implying that higgs decay only into muons pairs and to conserve momentum they came out opposite to each other. But in some cases the muons pairs came out at some angle which means that a third particle must came out along with the muons pairs which can take into account for momentum conservation. Up until now scientists only consider those events in which pair of muons emerged opposite to each other so that the effect of missing transverse energy can be mitigated and the properties of higgs can be studied with much more accuracy. However, the signal strength of such events is very less so the confidence level with which the properties are determined also decreases. If the effect of missing energy can be understood then the discarded events can also be included in the analysis and the signal strength of corresponding parent particle will increase.

5 Generating Data

It can be measured how much energy is missing by the measuring the angle with which the muons pairs came out. After finding out the correlation between the missing energy and the angle with which the particles emerged, the amount of energy carried away by the other particle can be known. Now this higgs decay process, which is of interest, into three particles will be co-planar. This can be said from the knowledge of the classical mechanics. Now the higgs can decay into a pair of muons via two modes. First one is that higgs decayed into all the three particles simultaneously and second one in which higgs first decayed into an excited state and the particle which is carrying for missing energy and then the excited state decayed into muons pair. For both the processes to obtain a relation between the missing energy and the angle with which the muons pairs came out events are generated using pythia 8.310 and using root from the classical idea of decay of a particle into three particles.

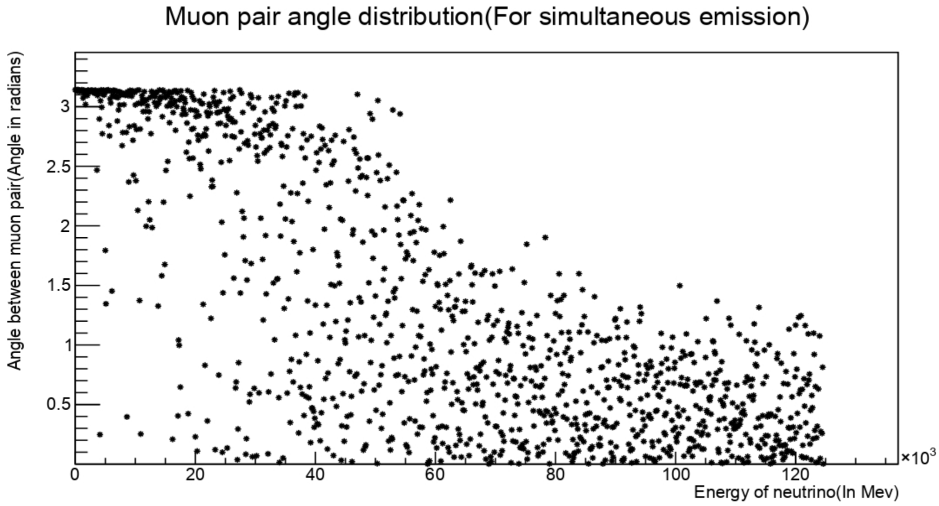

Figure 4: Angular correlation between muon pair and energy taken away by neutrino when the higgs decayed simultaneously into neutrino and muon anti-muon pairs

5.1 Higgs simultaneous decay to muon, anti-muon and neutrino

For the first case in which higgs decayed into three particles neutrino (Here neutrino acts as the proxy of the particle who carried away the missing transverse energy) and muon pair simultaneously, the muon pair come out at same energy or with different energy. Most probably they will emerge at different energy. So the angle with which muon pair came out was calculated in different cases when neutrino was taking different amount of energy. The energy is provided to neutrino in steps of 100 MeV starting from 0 MeV to 124808 Mev (124808 MeV is the maximum energy for at least the production of muon pair at rest).Then the angle between muon pair is calculated. After giving energy to neutrino the left energy of higgs is distributed to muon and antimuon via random function. For simplicity it is supposed that the process is happening in x-y plane only. So the z-component of all particles is set to 0. Then the x component of the neutrino momentum using random function is generated and the y component is calculated from relativistic energy mass relation ($E^2 = M^2 + p^2$).

After it the x component of momentum for muon is selected randomly using random function and x component for anti-muon using conservation of momentum. Then for y component of momentum for muon the mass energy relationship ($E^2 = M^2 + p^2$) is used. For y momentum of antimuon conservation of momentum is used. After it angle between muon pair can be calculated using dot product formula ($cos(\theta) = A.B/|A||B|$). Then the data can be stored and ploted. The graph obtained from root is figure 4.

5.2 Higgs decaying to neutrino and an excited state

Now for the second case higgs will first decay into a neutrino and an excited state which will later decay into muon pair. For this again take energy of neutrino in steps of 100 MeV. Then give the leftover energy to the excited state particle. Again, since the process is co-planar, the z component of momentum is set to zero. Here it is supposed that the process happened in x-y plane for simplicity.

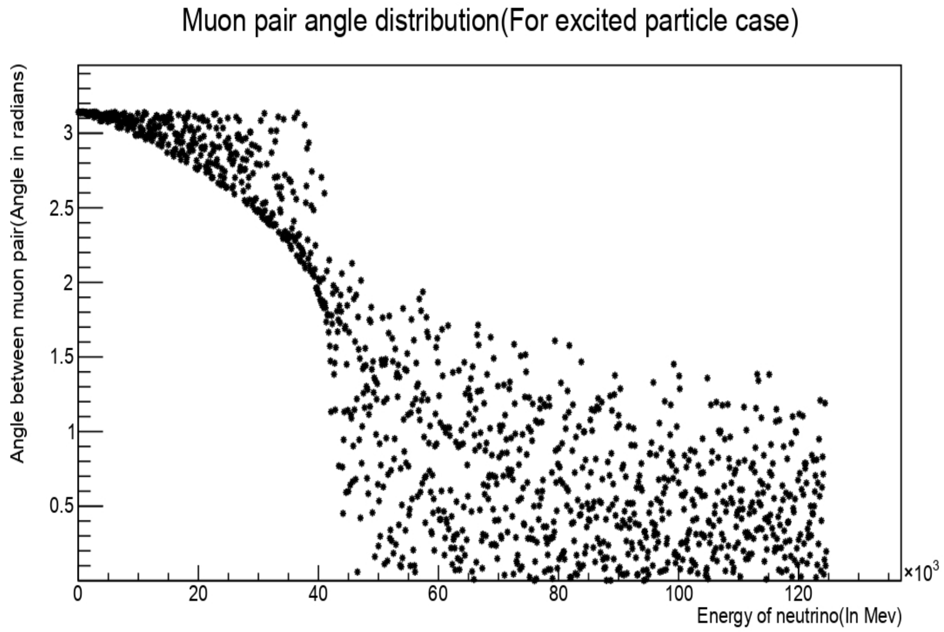

Figure 5: Angular correlation between muon pairs and energy taken by neutrino when higgs decayed into neutrino and an excited state particle and then the excited state decayed into muon pairs

Assign the x component of momentum to neutrino randomly and y momentum using mass relationship. Then using conservation of momentum the momentum for excited state particle is calculated. Now muon and antimuon have almost the same mass. So they will come out with same energy. So distribute the energy of excited state particle equally to muon and anti-muon. Again select x momentum for muon using random function, y component using mass energy relationship. For the anti-muon again momentum conservation have been used. Calculating the angle between muon pair using dot product formula ($cos(\theta) = A.B/|A||B|$). The figure 5 shows the output obtained obtained by root.

6 Event Generator Pythia 8.310

Pythia is an event generator which is used by people working in particle physics or heavy ion physics to generate events close to the real life[**13**]. Close to real life here means events which are almost the same as those we get from the our detectors in real life. When particles like proton proton or other particles are collided at almost the speed of light then this is specifically known as the particle physics and when atoms like lead (Pb), gold (Au) or other atoms are collided at nearly speed of light then this analysis is called heavy ion physics. Pythia can be used to generate events for both the analysis that is particle physics as well as heavy ion physics. It is a computational software which is made by analysis a number of real life events and processes so that it can also mimic them. Depending on the needs it can take into account certain interactions or even neglect them. For e.g. Hard QCD interactions can be included by (Events which are accompanied by large momentum exchange) as per the needs. Similarly, Hadronisation(Forming of bound stated by quarks to other particles like protons/neutrons) can be turned on or off, of the particles if required in the processes or include or exclude a number of processes as per the needs. It uses Monte Carlo method to generate events. Therefore pythia is the suitable software for the work here.

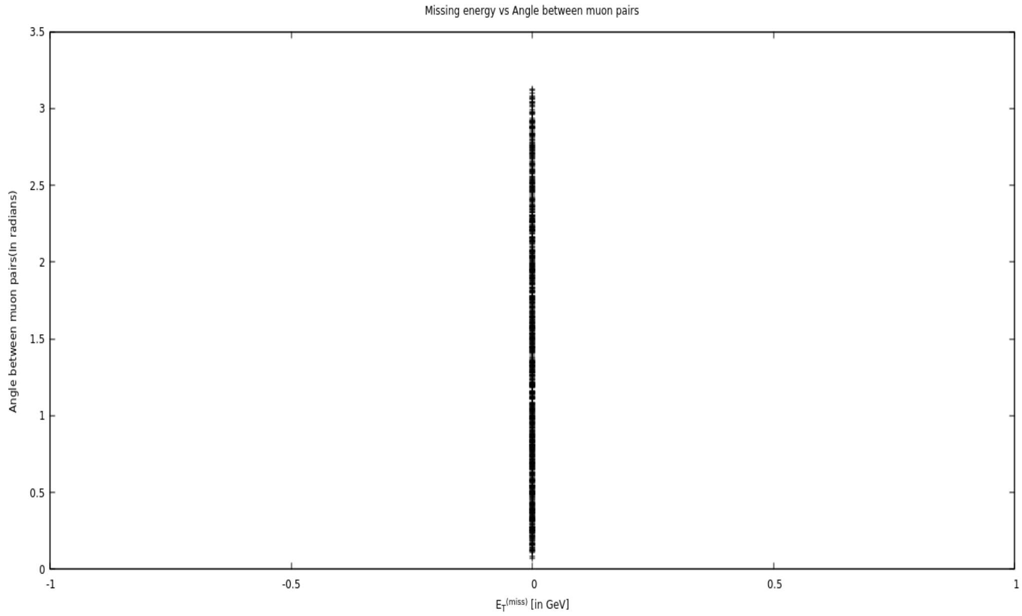

Figure 6: Missing Energy obtained from higgs decay to muon pair event obtained from pythia 8.310 is shown.As can be seen missing energy is zero i.e. pythia generated events with energy conservation.The x axis contains missing energy in decay process and y axis has angle between muon and antimuon pair in radians

For the purpose of this work pythia 8.310 has been used. In pythia 8.310 bugs of previous has been removed and new processes discovered recently have been added. Pythia 8.310 uses Lund Monte Carlo method for event generation and far more effective in generating events close to real life as compared to it's version. By using this event generator, the event of interest which is higgs decaying into muon pairs and a neutrino which acts as a proxy for missing energy are generated. But pythia has only real life processes in it. We can not forcefully make any particle to decay into arbitrary no of particles. So here the process of higgs boson decaying to muon pair have been taken into use and events are generated for this channel so that the data can be matched to the data of nearly real situation and checked if the work done till now is correct or not. After matching the data it can be said if the isolated classical analysis is feasible or some changes needs to be done in the work.

For the generation of events p p collision were taken. They were made to collide at 13 TeV center of mass energy. Also the production of higgs boson via all modes were open. But for the decay of higgs only the channel of higgs decaying to muon pair was ON. Rest of the channels were off.Also to make sure that muon pair coming from decay of higgs were selected the decay of other particles to muon or anti-muons were disabled. For e.g. if higgs boson got produced in via association pair by vector boson fusion to let's say higgs and Z_0 boson and then higgs and Z_0 both got decayed into muon pair then there is a possibility of selecting muon from higgs and anti-muon from Z_0 or muon from Z_0 and anti-muon from higgs boson. Therefore to avoid such errors Z_0 were forced to decay into electron pair. After it collisions were initiated and data were stored in a file for plotting and analysis. After doing analysis of the data it can be seen from figure 6 that pythia was generating events in which almost no energy was missing. That is it was conserving all energy and initial and final state momentum. Here it can seen from figure 6 that the pythia generator is not generating events with missing energy. All the higgs decaying to muon pair were in accord with the energy conservation. So any statements can't be made from the work done in root. But after observing the events an interesting thing going

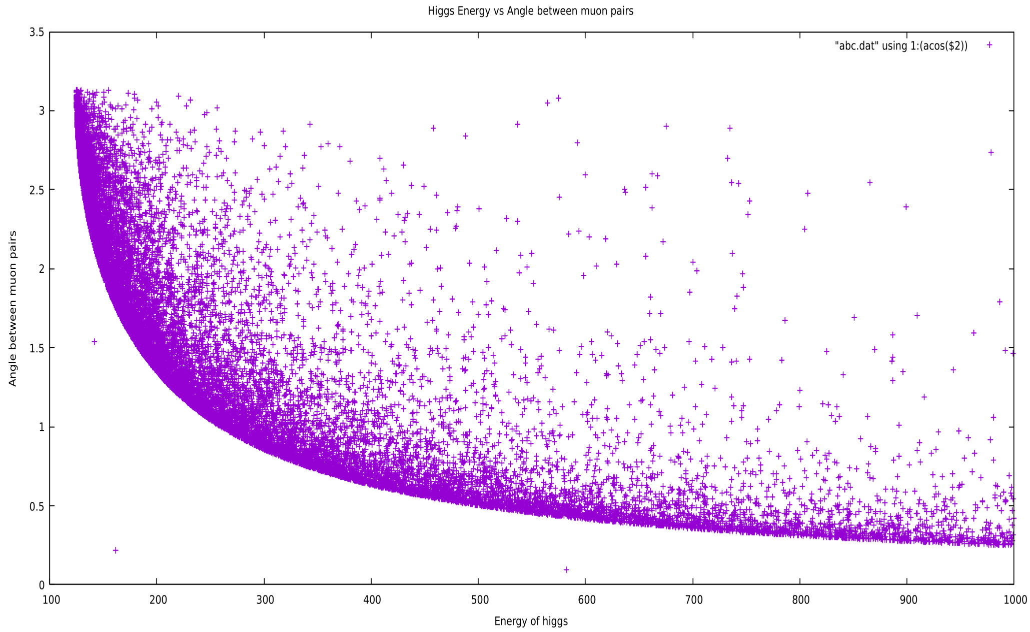

Figure 7: Correlation between muon pair and higgs energy.Data is generated using pythia 8.310.The x axis contains Energy of boosted higgs in GeV and y axis contains angle between muon and anti-muon pair in radians

on was observed. As it is known that higgs and other vector boson like Z boson or W^-, W^+ are supposed to produce in electromagnetic interaction. Higgs were not produced in direct collision. And as the proton beams are coming opposite to each other with same energy so vector bosons produced should not have any momentum that is they should be produced almost at rest. But in the events generated by pythia higgs were not at rest. They were even produced at energy of 3 TeV. Due to this there were boosted higgs. So even if it decay into muon and antimuon they would not come out opposite to each other as is expected for muon pair decaying from higgs at rest. So analysis of the angle at which muon pair were coming out in these events were done that is here the correlation between energy carried by higgs and angle at which muon and antimuon emerged were tried to find out. For different algorithm was devised. The energy of proton beams were kept same i.e. 13 TeV. Same channels were allowed like higgs decaying only to muon and antimuon. But some events were generated in which higgs was having high energy even nearly 3 TeV. These events with higgs carrying energy greater than 1 TeV were distorting the graphs. So of all the events these events were removed in which higgs was having energy greater than 1 TeV. Rest of algorithm is same, for this analysis, to that of the previous one in which the correlation between missing energy and angle between muon pair were tried to be find out. The analysis is done for 10K events and have obtained the figure 7 between energy carried by the higgs and the angle between muon pair.

7 Boosted Higgs Events

Now the analysis of boosted higgs based on the current understanding were done using language root to draw out conclusion and to propose a model for the ongoing process and understanding the missing energy better. This time higgs is decaying to muon pair but is having energy more than Higgs boson rest mass and the energy carried by higgs varies from 125.02 GeV (It's rest mass) to 1 TeV (Restriction put in pythia). This analysis started with higgs at rest and continued upto higgs having energy 1 TeV. Then the higgs has been given momentum in x and y direction based on the energy it is having and the components of momentum were calculated from relativistic mass energy relationship. Similarly, for muon and antimuon some quantities were selected randomly and other based on conservation of momentum and conservation of energy. Then angle between muon and antimuon was calculated from it's four vector and plotted against the energy of higgs. As it can be observed from the data that the mechanism

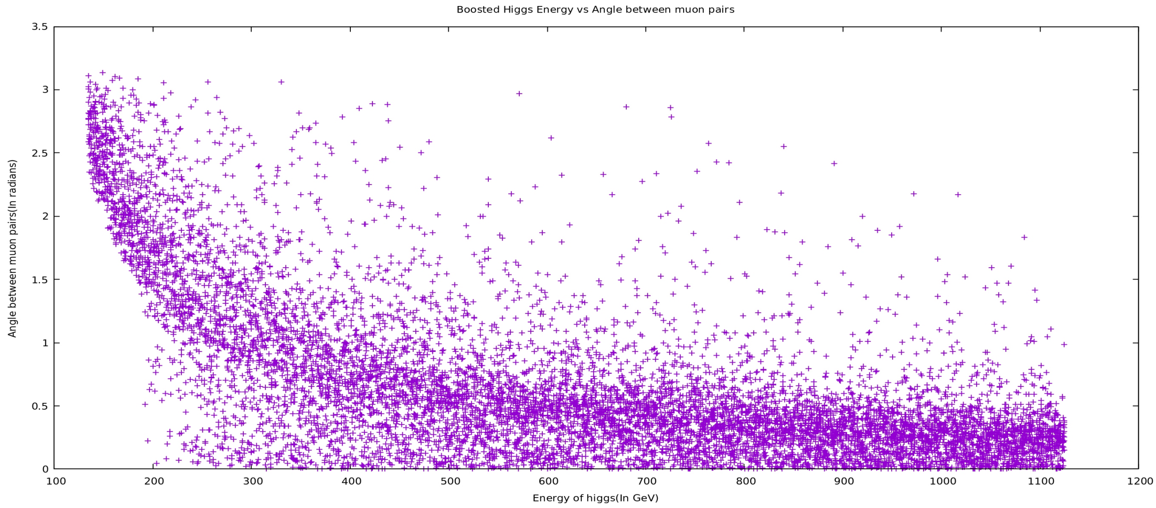

Figure 8: Correlation between higgs energy and angle between muon pair.Data generated using the model prepared in root based on the understanding of decay mechanism and conservation laws.The x axis contains Energy of boosted higgs in GeV and y axis contains angle between muon and anti-muon pair in radians

that is devised in root is generating events similar to events to that of pythia as both the figure 8 and 7 is showing the same trend of data. So it can be said that the analysis is going in the right direction.

8 Signal Improvement

The analysis were done using channel in which higgs decayed into a pair of muons. But in a single collision event there are possibilities that the muon are produced somewhere else in the event or the anti-muon is produced from other interaction like W^- which is produced in vector boson fusion associated production of higgs got decayed into muon and muon neutrino or W^+ decayed into anti-muon and anti muon neutrino. So there are chances that instead of the muon and antimuon pair coming out of the higgs, some muon or some other antimuon have been selected and formed the wrong pair. Even though this problem was known at the time of generating events from pythia and suitable algorithm was devised for it but it should be checked how good that algorithm is working as there is always space for uncertainties and errors. So for this all pair of muon and antimuon have been selected from a single event.

Then their four vector is obtained from data provided by pythia 8.310. Then the four vector of muon and antimuon are added and using relativistic mass energy relationship and mass is calculated from the combined four vector of the muon and anti-muon. If the right pair have been selected then the mass should come out to be 125.02 and if wrong muon and antimuon is selected then the mass should be different and will depend on the wrongly selected muon and antimuon. For eg if a muon is selected from Z boson decay and antimuon from the higgs decay then the mass using this approach should lie in the range 91.87 (rest mass of Z boson) and 125.02 (rest mass of higgs boson). Also this analysis is done in two manners. First one when no restriction in put on any of the particle like higgs is allowed to decay through any channel based on the branching ratio. Same for all other bosons and all other particles. Second one is done in which all the particle, if possible, is allowed to decay into muon or antimuon . Like higgs only decaying to muon and antimuon.

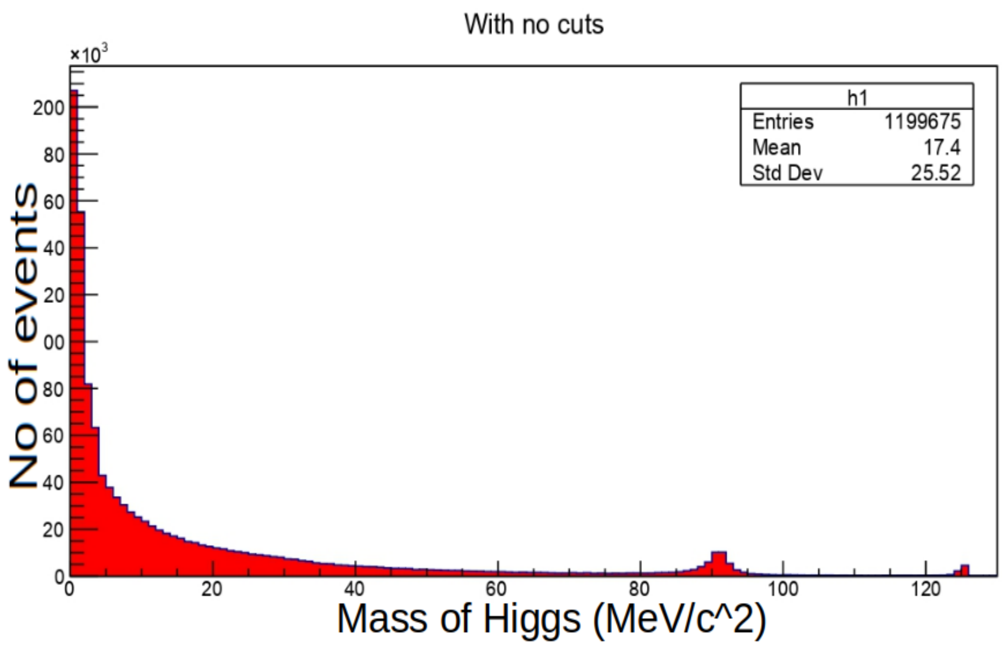

Figure 9: On x axis is mass in GeV/c^2 and y axis shows no of events. This histogram shows Muon anti-muon combined four vector mass on x axis with no of events on y axis. This analysis is done using pythia 8.310 for 10 million events.

Z boson also decaying to muon and antimuon, W^- decaying to muon and muon neutrino and same for rest of the particles. This second analysis is done to increase the abundance of muons and anti-muons as if no restriction is put then the branching fraction of other channels are more muon antimuon production is dominated. For eg higgs prefers to decay into photons pairs and gluons more than the muon pair as those channel have high branching fraction. By putting the above said restriction the abundance of muon and anti-muons can be increased significantly and the analysis of interest can be done more precisely. This analysis is done using pythia 8.310 with root as a plugin. It means this time pythia interface is used with root libraries

S.no	Energy (GeV)	Angle (Radian)
1	199.91	1.33
2	300.35	0.84
3	400.26	0.62
4	500.17	0.49
5	600.08	0.40
6	700.52	0.35
7	800.44	0.31
8	900.35	0.26
9	1000.00	0.23

Table 1: Cuts obtained from the analysis of boosted higgs decay. Here angle is between muon and antimuon and is in radians.

for generating histograms. As it can be seen from figure 9 that muon antimuon coming from higgs is very less as compared of other sources. This signifies a large number of error in the

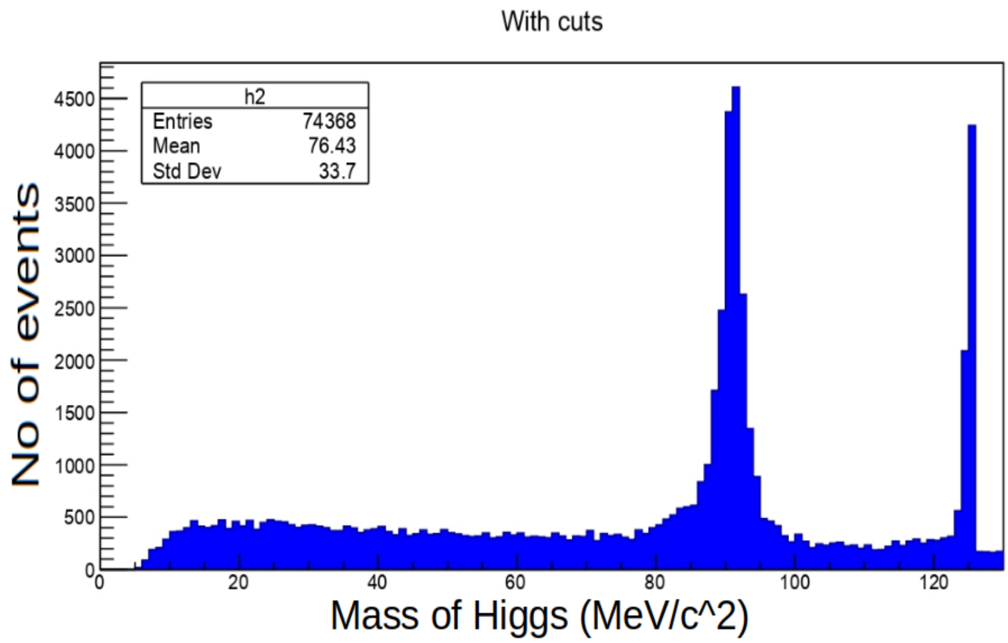

Figure 10: On x axis is mass in GeV/c^2 and y axis shows no of events. This histogram shows no of events containing invariant mass obtained from the different muon and anti-muon pair obtained from all the processes. Cuts are applied here.

formation of right muon and antimuon pair which came from the higgs. In this histogram all muon and anti-muon pair were taken into account. It can be seen that the no of muon pair coming from higgs decay is very less. This is expected since the branching fraction of higgs boson decaying to muon pair is $2.18x10^{-4}$ and a lot muons and anti-muons got produced it other processes. Now the work done for boosted higgs decay will be put into use. From the figure 7 it can be observed that if higgs is having some energy then at what angle will the muon and antimuon will came out. So from the graph selection will be made which will be used for strengthening the higgs signal. Here selection refers to certain conditions that are applied to include some events or reject some events for a particular analysis. The cuts that will be used are as given in the table 1 are obtained from the analysis of boosted higgs decay into muon pair. When these cuts are applied then the muon and anti-muons which came out from the higgs decay will be identified with more accuracy and this will increase the signal strength of the channel of higgs decaying into muon and anti-muon. It can be seen from the figure 10 that after the use of the cuts there is two sharp peak. One around 90 GeV and another around 125 GeV. One clearly corresponds to higgs and the other one seems to belong to Z^0 boson. From the peaks it seems that the muon pair produced in the Z^0 boson decay also follows the same energy and angular correlation as that of the muon pair obtained from the higgs decay. We need to sharpen our cuts to remove this peak or to further amplify our signal. This can be done by making cuts in less energy step interval like in the step of 50 GeV or even further.For this histograms cuts were made in the 100 GeV range. But further sharpening of cuts will not be done in this work as the idea is shown and the accuracy with which one want to define the cuts is arbitrary. So to compare the effect of including the analysis of boosted higgs decay is shown in the figure 11 It can be seen that there is an increase in the signal of higgs production after the cuts were applied on it.

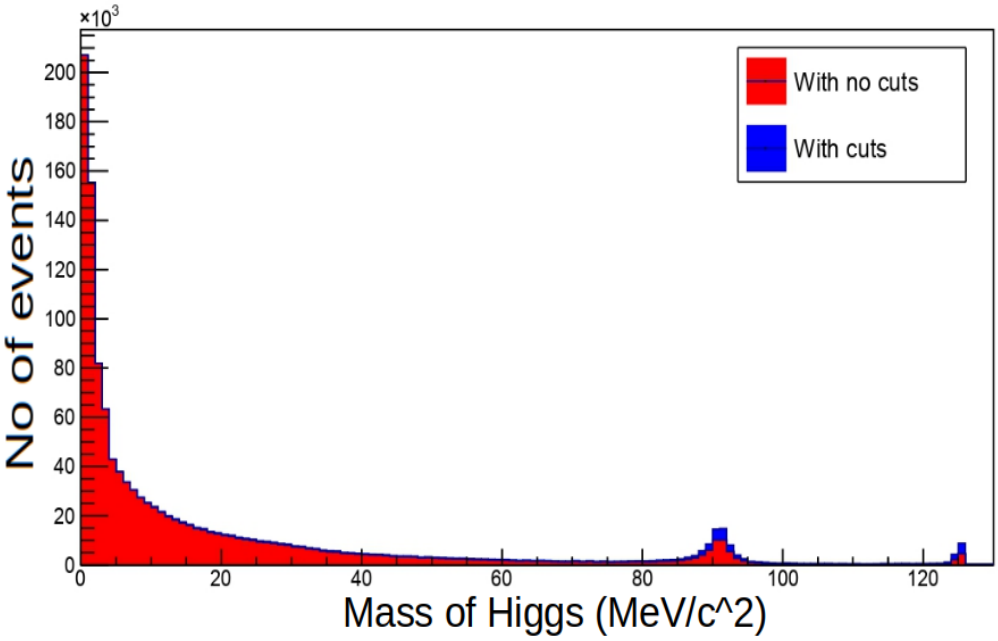

Figure 11: On x axis is mass in units of GeV/c^2 and y axis shows no of events.This histogram shows benefits of including the cuts in the analysis.Signal strengthened around 125GeV i.e. signal strength increase for higgs

9 Conclusion

The analysis of Higgs boson decaying into muon, anti-muon and a particle like neutrino have been done where the energy assigned to neutrino is treated as the missing energy. Also same analysis is done for boosted higgs decaying into muon and antimuon where higgs was having energy ranging between 125.02 GeV to 1,000 GeV. From this study a certain conditions (selections) on the energy and angle, at which muon and antimuon will come out after higgs decay, have been found. These selections were used to find the correct pair of muon and anti-muon that came only from higgs decay of all the muons and anti-muons received after collision process. After successfully finding the correct pair the number of higgs produced, after the process of collision, has been found. It is found that the mass of higgs is concentrated around 125 GeV implying that they (the selected muon pair) indeed decayed from higgs and thus the signal strength of the Higgs boson has increased. Therefore, it can be said if the same analysis is done for the events in which missing energy is involved then certain cuts can also be found for those events. Then for studying the higgs properties we can add these events also into the analysis as of now these events are excluded from the study of Higgs because of unknown nature of missing energy. Including this process the signal strength can be increased for all Higgs channels even further. **??**

References

1. High-energy nuclear physics, Available at `https://en.wikipedia.org/wiki/High-energy_nuclear_physics`

2. In Defense of Big Bang, Available at `https://neildegrassetyson.com/essays/1996-12-in-defense-of-the-big-bang/#:~:text=The%20answer%20is%20simple%3A%20regardless,and%20evolution%20of%20the%20universe.`

3. Particle physics, Available at https://en.wikipedia.org/wiki/Particle_physics
4. Standard Model, Available at https://en.wikipedia.org/wiki/Standard_Model
5. Quarks, Available at https://en.wikipedia.org/wiki/Quark
6. Higgs boson, Available at https://en.wikipedia.org/wiki/Higgs_boson#Sources
7. DOE Explains...the Higgs boson, Available at https://arxiv.org/abs/2009.04363
8. Missing energy, Available at https://en.wikipedia.org/wiki/Missing_energy
9. A search for Zγ decay mode of the higgs boson in pp collisions at $\sqrt{13}$ TeV with the ATLAS detector, https://arxiv.org/abs/2005.05382
10. "A search for the Z decay mode of the Higgs boson in pp collisions at 13 TeV with the ATLAS detector", G. Aad, et. al, [ATLAS Collaboration], https://arxiv.org/abs/2005.05382
11. Measurement of Higgs boson decay to a pair of muons in proton-proton collisions at 13 TeV, The CMS Collaboration, https://cds.cern.ch/record/2725423?ln=en#:~:text=The%20measurement%20is%20performed%20using,experiment%20at%20the%20CERN%20LHC.
12. Physics at a High-Luminosity LHC with ATLAS (Update), The ATLAS Collaboration, https://cds.cern.ch/record/1484890?ln=en
13. Observation of Higgs Boson Decay to Bottom Quarks, A. M. Sirunyan, et. al, [CMS Collaboration], https://arxiv.org/abs/1808.08242
14. Search for 2HDM neutral Higgs bosons through $l^+l^-b\bar{b}$ final states at CMS in run 2 LHC data, Jaffel Khawla, https://cds.cern.ch/record/2871603
15. Pythia 8.3, documentation available at https://pythia.org/
16. Evidence for Higgs boson decay to a pair of muons, CMS collaboration, https://arxiv.org/abs/2009.04363
17. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, The ATLAS collaboration, https://arxiv.org/abs/1207.7214
18. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, The CMS collaboration, https://arxiv.org/abs/1207.7235
19. Broken Symmetries and the Masses of Gauge Bosons, Peter W. Higgs, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.13.508
20. The discovery and measurements of a Higgs boson, F. Gianotti and T. S. Virdee, https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0384
21. The Higgs Boson Search and Discovery, Gregorio Bernardi and Jacobo Konigsberg, https://cdsweb.cern.ch/record/2217161/files/9789814733519_0015.pdf
22. Image of CMS detector in figure 1 is taken from https://www.mdpi.com/2410-390X/6/4/73

23. Image of silicon trackers in figure 2 is taken from https://cds.cern.ch/record/2871603

24. Image of slice of CMS detector in figure 3 is taken from https://twiki.cern.ch/twiki/bin/view/CMSPublic/WorkBookCMSExperiment