Kinematics study of Higgs production in $H \rightarrow W^+W^- \rightarrow 2l + 2\nu$ channel

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
Date:

Signature:
Name: TUSHAR

Contents

Abstract

In this report, the study of the channel of Higgs [1] decaying into a pair of W bosons [2] has been studied in pythia monte carlo mode [3] . The pair of W boson further decays to a lepton [4] and a neutrino. The leptons that were used for analysis purposes in this work, like reconstruction, were muons. This channel is analysed for pp collisions and pb-pb collisions. The changes that arises due to the change of pp collisions to pb-pb collisions were also observed. These changes are referred to as nuclear effects. The nuclear effects arises because of the presence of other nucleons . Detail study of collision geometry has been performed. All the analysis is done using pythia 8.312 monte Carlo event generator [5].

Chapter 1

Introduction

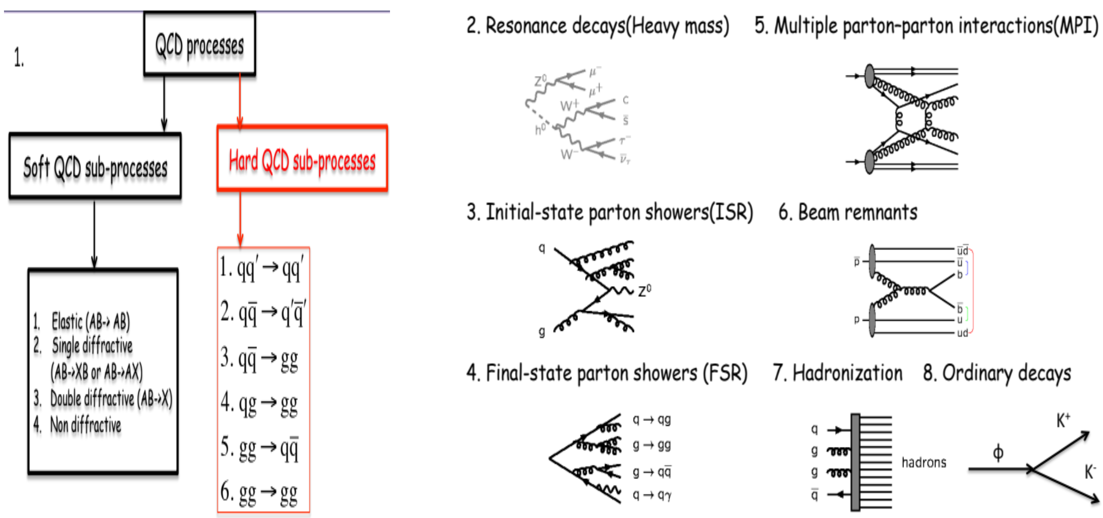
High energy physics is the branch of physics which deals with the study of origin of universe, interaction between subatomic particles and how it evolved to what is there today. In particle physics the basic building blocks of matter and the physical laws that govern the interactions among them are studied[6]. There are four fundamental forces in the nature. These are strong nuclear force, weak nuclear force, electromagnetic force and gravitational force. The model that is most successful in explaining the working of these forces at present is Standard Model [7]. It contains all the particles that has been discovered by now.
This model includes 6 quarks, 6 leptons, 5 force mediators, their anti-particles and Higgs boson. All the matter is made up of leptons and quarks. And the interactions between them is mediated by the force mediators. The force mediators are photons (responsible for electromagnetic interaction) gluons (responsible for strong interactions), W^{+}_{-} & Z^{o} bosons (responsible for weak nuclear force). The mediators for gravitational force has not been discovered yet.
But the proposed particle responsible for gravitational force is graviton [8]. Since the graviton is not discovered till present, the standard model is incomplete. This is one the reason why people around the world are working beyond standard model (BSM) [9]. Also there is Higgs boson which responsible for giving mass to all particles. The mass gaining mechanism can be understood as there is Higgs field present everywhere in the universe. Particles interact with this field. Those particles which interact weakly with the field are lighter and the particle which interact strongly with the field are heavier. Still with the help of the Standard model all the matter in the universe and the interactions between them can't be explained.
In this report analysis is done on the channel in which higgs decays into a pair of bosons which further decays into 2 leptons and 2 neutrinos. Analysis on W boson is useful in many aspects. Initially when the universe was cooling and electromagnetic and weak force were unified (also known as electroweak force), then photons and W,Z bosons were all mass-less. Later Higgs particles were formed and the Higgs field permeated the space. Due to this the electroweak force get separated and the W, Z bosons gained mass. This phenomena is also known as the spontaneous electroweak breaking.
By studying this the current working channel and finding the coupling coefficient between Higgs and W bosons, the spontaneous electroweak symmetry breaking can be explained. Also since W bosons are mediators of weak force they do not interact with the strongly coupled medium. Here the strongly coupled medium is referred to as the quark gloun plasma (QGP) [10]. Since W bosons don't interact with the QGP it can be used as a probe to study the nuclear effects. The nuclear effects here means the effects that are induced due to presence of other nucleons in the system.
In pp collisions the nucleus of Hydrogen ion contains only a single proton but in the pb-pb collisions the nucleus contains neutrons and protons. It is this collection of neutron and protons that collides. Due to this the after effects of collision are different from the aftereffects of pp collisions. In pb-pb collisions QGP is formed. But the W bosons don't interact with this strongly coupled medium. So the nuclear modification induced effect etc. can be measured. Also, since the production of W boson does not depends on the production medium as well as

it does not interact with it, the centrality dependence in heavy ion collision can be verified. So the kinematics of the W bosons may provide a method to observe the nuclear effects and to find the parton distribution function in case of heavy ion collision.

Chapter 2

Event generator pythia

The event generator used for this case is pythia 8.310 [3]. Pythia is a monte carlo event generator. It's basically a program which is used to generate the events for analysis purposes. It is mostly based on the real data obtained from the detectors. It can simulate the collision between particles such as e^-, e^+, proton and many other heavy ions like Pb, Au etc. in the energy range 10 GeV to 100 GeV. The physics processes it includes are QCD processes, Resonance decays, Initial state processes, Beam remnants, Harmonization and other ordinary decays as shown in figure 2.1 . For the generation of event in heavy ion collision it used an inbuilt module called "Angantyr" . This module combines several nucleon nucleon collisions in one heavy ion collision.



(a) QCD processes in pythia

(b) Other processes in pythia

Figure 2.1: Physics processes used in pythia

The events are generated using a systematic approach. Initially, 2 beams of particles are coming opposite to each other.Though, one beam can be made stationary and the other approaching it, but it is usually not done. And the both beam could also be of different energy. Now one parton from each beam starts off a sequence of branchings, such as $q \to q + g$. These build up an initial state shower. One incoming parton from each of the two showers enter the hard process, after which a number of particles are produced in outgoing directions. This process determines the main characteristics of the events based on number of outgoing particles. At this point the hard process may produce short lived resonance particles like $Z, W+^-$ which will further decay. For every process to happen or for the creation or annihilation of every particles certain probabilities are made based on the available energy, reaction cross-section and other event characteristic. The outgoing particle may interact to produce additional shower of particles. For this possibility also certain probability is made based on energy of particle and

other parameters. Also the mechanism of QCD also ensures that emerging quarks and gluons are not observable and merge to form color neutral particle.
This all happens only for a single event. This process is repeated the number of times as number of events are to be produced. The data production was done in two sets. Constraints have been applied on one event set such as the Higgs boson is allowed to decay into a pair of W bosons and further the W bosons should only decay to a pair of μ lepton and μ neutrino. No such force decay constraints were applied on the second the set of events. The first set of events were used to find out the signal distribution to extract signal from the other set of events containing signal events as well as background events.

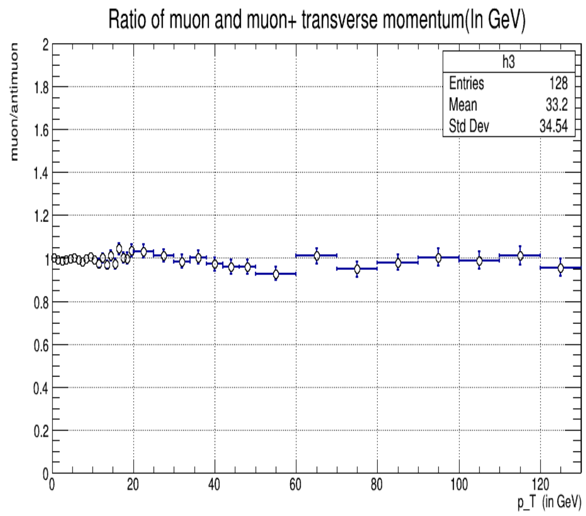
Chapter 3

Event production and verification

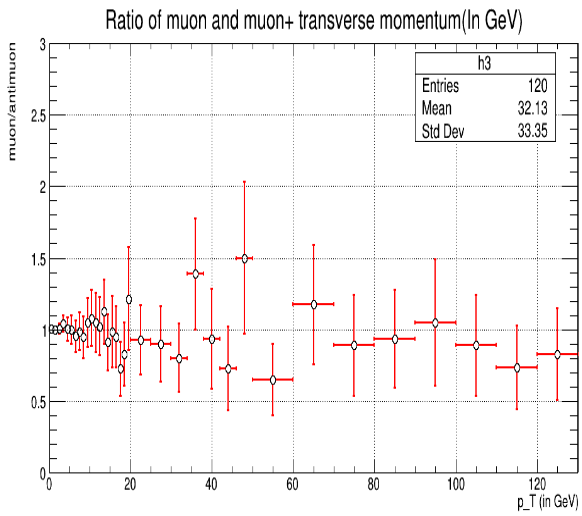
The events as mentioned were produced using pythia event generator. The events needs to verified first if there really is production of W bosons or not. Normally if there were no production of W bosons and their subsequent decay to muon and neutrino than the ratio of muon and antimuoun p_T should be equal to 1 in around 40 GeV . This is because muouns produced from the decay of W bosons should have p_T around $M_W/2$. But if there is W boson production in the events than the ratio will shift from 1.

Formation of W bosons will take place when flavour change takes place i.e. u quark changes to d quark or d quark changes to u quark. When u quark changes to d quark then W^- boson is produced and when d quark changes to u quark then W^+ boson is formed. Protons have two u quark and one d quark [11] . Lead (Pb) contains 82 protons and 126 neutrons [12]. Neutrons contains 2 d quarks and 1 u quark. As the number of neutrons are more than the protons in lead, the possibility of change of d quark to u quark is more as compared to the case of proton proton collision. So more W^+ bosons will be formed in case of pb-pb collision. More W^+ means more antimuons. Therefore, for the case of pb-pb collisions the ratio of muon and antimuon will be more than 1 whereas in the case of pp collisions. Such type of deviation was observed in the events produced using pythia program and can be seen in the figure 3.1 .

So by analysing this asymmetry in p_T it can be said that the events generated contains W boson production and can be used for further analysis.



(a) muon antimuon p_T ratio in pp collisions



(b) muon antimuon p_T ratio in pb-pb collisions

Figure 3.1: Verification of events produced using pythia program

Chapter 4

Reconstruction of W bosons

The measured mass of Higgs boson is 125.35 GeV/c^2 with a precision of 0.15 GeV/c^2 [13]. The branching ratio of Higgs decaying into a pair bosons is more when higgs is having mass around 160 GeV/c^2. It can be referred from the graph shown in figure 4.1. The mass of W bosons is around 80 GeV/c^2 for both $W^-\&W+$ boson. So if Higgs were to decay via this process than Higgs boson should be having mass around 160 GeV/c^2 having bandwidth spread from 100 GeV/c^2 to 180 GeV/c^2. For the reconstruction of W bosons the lepton and neutrino is used in which the W bosons further decayed. Since it is hard to detect the neutrino's the events with large MET (Missing Transverse Energy) are selected. Because of the MET the spectrum of reconstructed mass of W boson is very spread. Consequently the spectrum of reconstructed mass of Higgs boson is also wide spread.

But these are the effects that are observed at the detectors. These results were compared

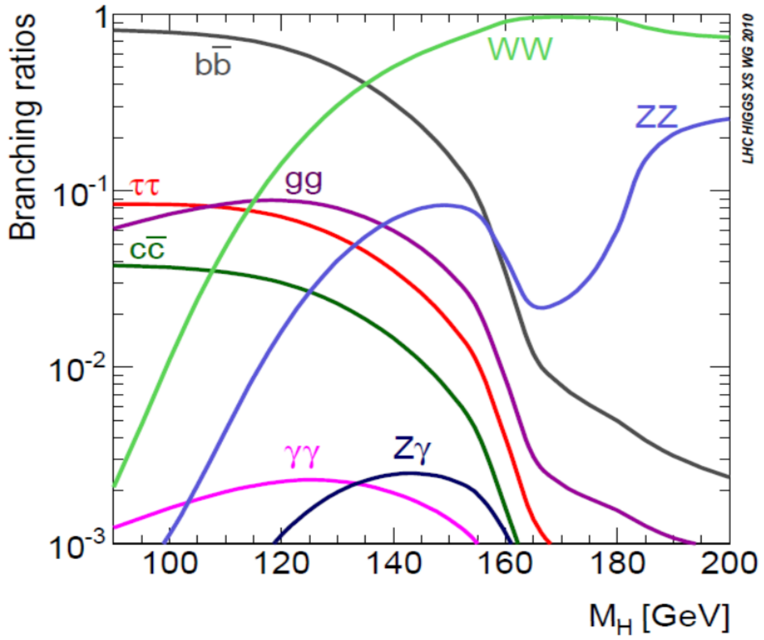
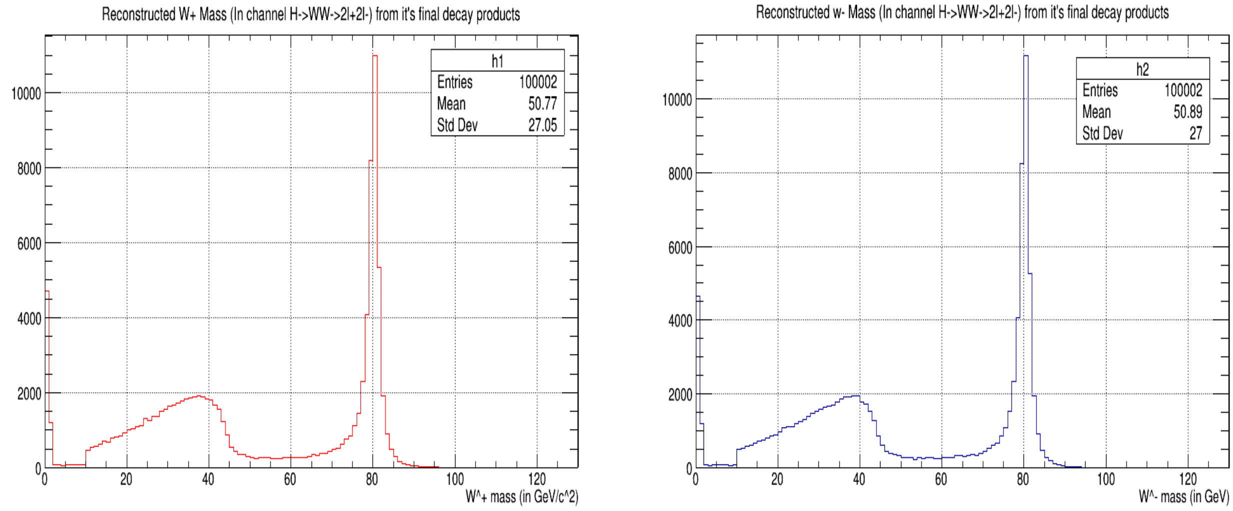


Figure 4.1: Mass of Higgs with branching ratio in different process

with the pythia model. Pythia produces Higgs with mass around 125 GeV/c^2, therefore the reconstructed mass of W bosons have a wide spectra varying from around 40 GeV/c^2 to around 80 GeV/c^2 to make energy conserved. In some events W^- boson were produced with mass around 40 GeV/c^2 and W^+ with mass around 80 GeV/c^2 and in some events the W^+ boson were produced with mass around 40 GeV/c^2 and W^- with mass around 80 GeV/c^2.

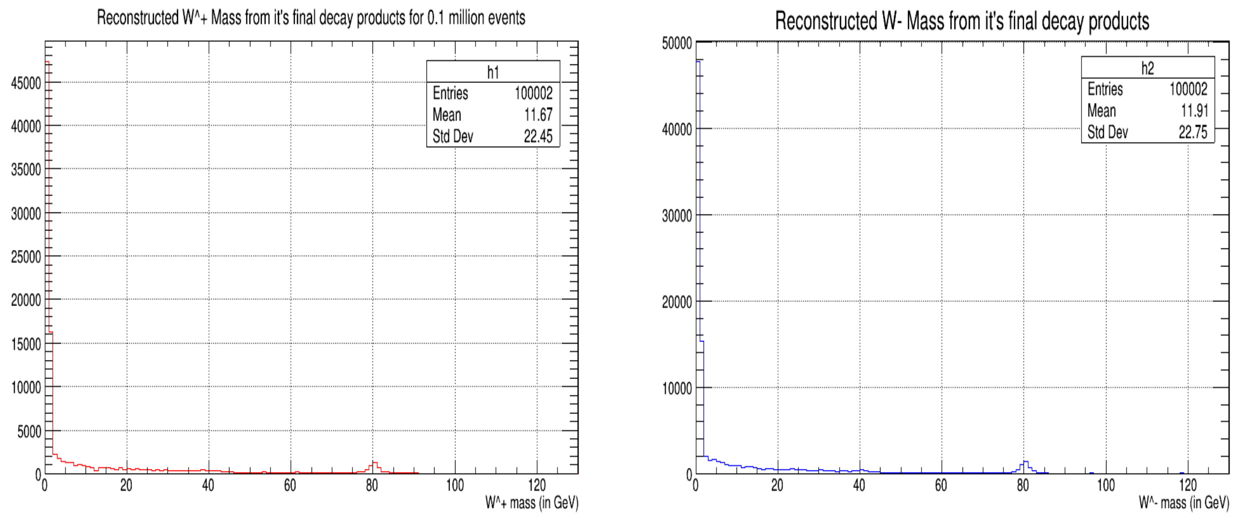
The mass of W bosons was reconstructed using the muons and neutrinos dynamical variables. The energy and momentum were obtained from the pythia program of muon and neutrino for every event. Then the energy and momentum of muon and neutrino were added followed by the use of energy mass relationship ($E^2 = (pc)^2 + (mc^2)^2$) to reconstruct the mass of W bosons. First events were generated in which Higgs was only allowed to decay into the pair of W bosons



(a) reconstructed mass of W^+ boson (b) reconstructed mass of W^- boson

Figure 4.2: Reconstructed mass of W bosons for events in which Higgs was allowed to decay into pair of W bosons only and W bosons were allowed to decay into muon and muon neutrino only

and W bosons were forced to decay into muon and antimuon neutrino. Such events are classified as events containing signal only. 4.2 . The mass of W bosons and Higgs were generated using

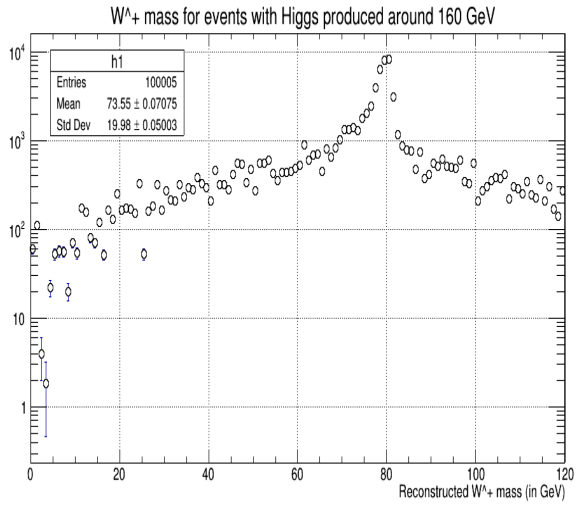


(a) reconstructed mass of W^+ boson (b) reconstructed mass of W^- boson

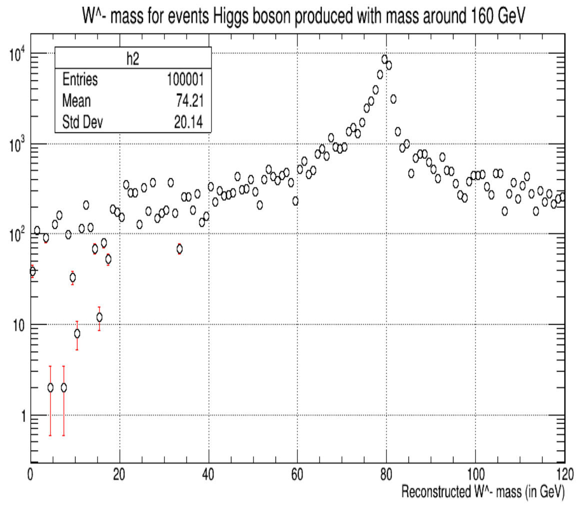
Figure 4.3: Reconstructed mass of W bosons for events in which Higgs and W bosons were not forced to decay via a specific channel

muons and neutrinos available in the events. Since the W bosons were decaying into the 2 particles, muon and antimuon neutrino they should carry momentum approximately half to that of W boson. So a cut on the transverse momentum of muon and neutrino was used for the mass reconstruction of W bosons. Thus p_T of muons and neutrinos should ideally should be $M_W/2$. So the applied cut contains only those neutrinos and muons containing p_T in the range 30 MeV$/c^2$ to 50 MeV$/c^2$ as the mass of W bosons is about 80.39 MeV$/c^2$. Using this mass of $W^{\pm}$ bosons Higgs mass was reconstructed. The reconstructed mass of W bosons are shown in figure Later events were produced with no particular constraint on decay channel of Higgs.

It means later Higgs was allowed to decay through all feasible processes based on the event characteristics. This time the events contains both signal plus background. Then the ratio of reconstructed mass using signal events were taken with the events containing both signal and background. Same number of events were produced for both signal and signal+background. The ratio of signal upon signal+background should come out less than 1 as the later also contains background in addition to the signal. But this was not the case. It's because as stated earlier same number of events i.e 1 million events were produced for both analyses. Since signal contains all the events in which Higgs decayed into a pair of w bosons then to 2 muons and 2 neutrinos. The reconstructed mass of W bosons are shown is shown in figure 4.3 .
The mass of Higgs produced in pythia is by default around 125 GeV/c^2. This default was changed and set to 160 GeV/c^2 with bandwidth from 140 GeV/c^2 to 180 GeV/c^2. Then reconstruction of the Higgs and W bosons were done. The reconstructed mass of W bosons is shwon in figure 4.4 .



(a) reconstructed mass of W^+ boson

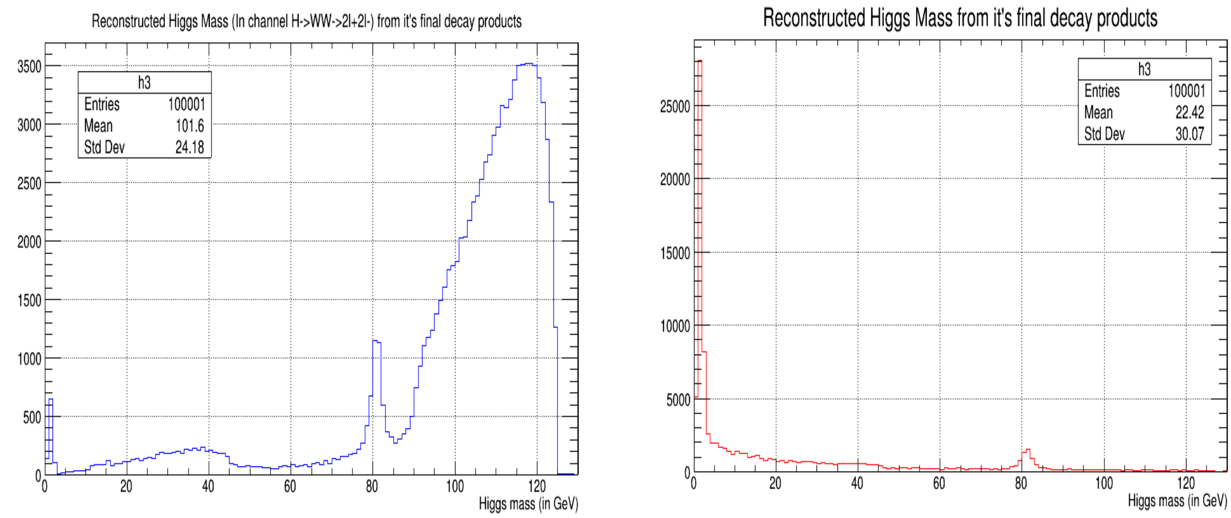


(b) reconstructed mass of W^- boson

Figure 4.4: Reconstructed mass of W bosons for events in which Higgs bosons were produced with mass around 160 GeV/c^2.

Chapter 5

Reconstruction of Higgs bosons



(a) Reconstructed mass of Higgs boson in events containing signal only

(b) Reconstructed mass of Higgs bosons for events containing both signal and background

Figure 5.1: Reconstructed mass of Higgs bosons

Using the reconstructed mass of W^- and W^+, the mass of Higgs boson can be reconstructed by simply adding the mass of both W^- and W^+. Higgs boson mass was also reconstructed for both type events i.e events containing signal only and events containing signal and background events. The reconstructed mass of Higgs for events containing signal is shown in figure 5.1 and for events containing both signal and background is shown in figure 5.1

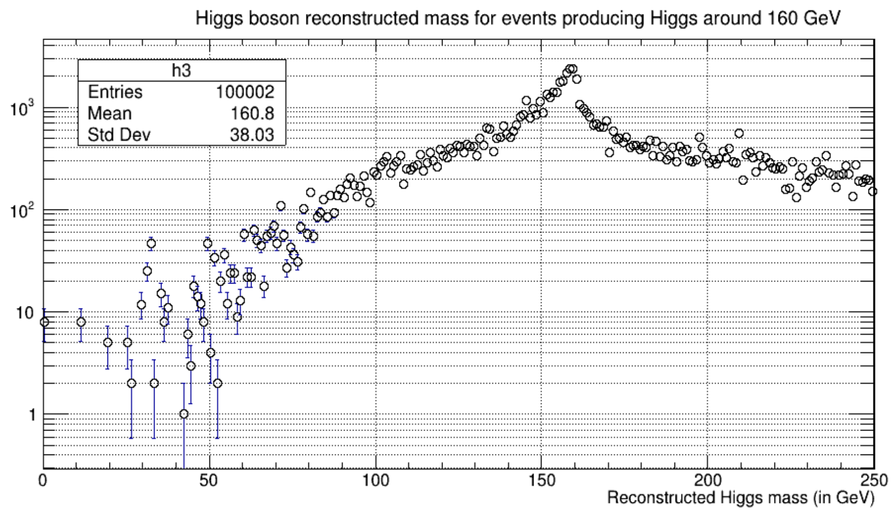


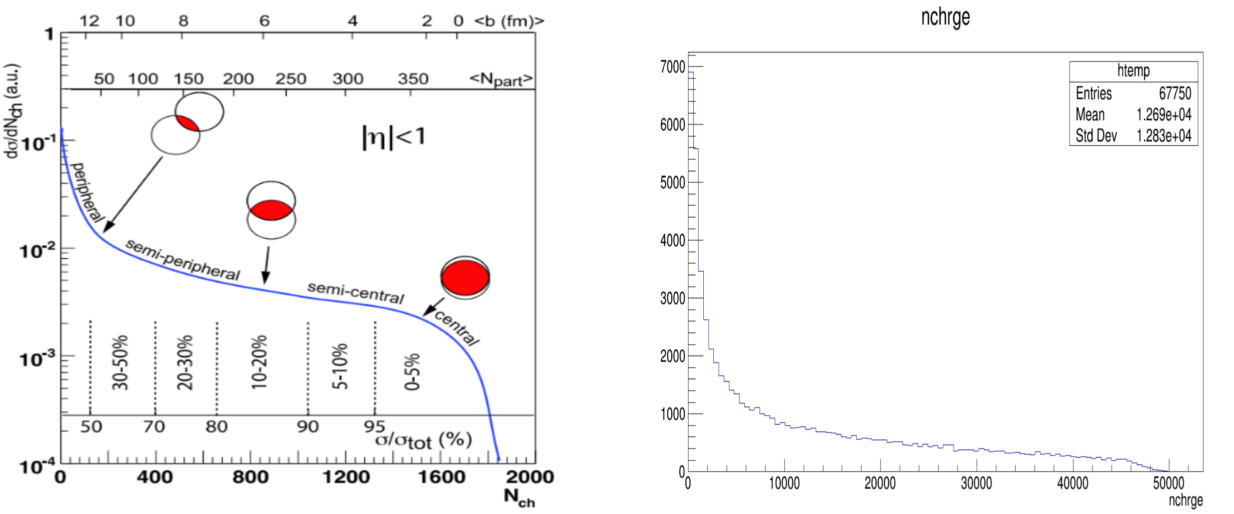
Figure 5.2: Reconstructed Higgs mass for events producing higgs with mass around 160 GeV/c^2.

Higgs mass was also reconstructed for the case when events were generated in which Higgs boson were produced with mass 160 GeV/c^2 with bandwidth from 140 GeV/c^2 to 180 GeV/c^2. The result of reconstruction is shown in figure 5.2. For this briet wigner distribution can be seen varying from 100 GeV/c^2 to 180 GeV/c^2.

Chapter 6

Event centrality

In pb-pb collisions there is an additional factor which needs to be taken into account during analysis. It's the centrality of the event. In case of heavy ion collisions, centrality is the measure of overlap of a nucleus with another nucleus or the measure of number of participating nucleons from one nucleus in a collision. When the collision is head on that is complete overlapping of one nucleus with another or all the nucleons of both the nucleus participate in collision then centrality of the event is 0% . When the two nucleus crosses each other without even touching then the centrality is 100% . Thus events are classified if they are 60% central , 40% central ,head on or peripheral. Peripheral events are those in which colliding nucleus overlap less than 50% . Production of particles depends on the centrality of the event. And our measuring the production of particles is one of the fundamental observable, more specially charge particle, in analysis purposes. Nuclear modification factor is also observed with respect to the centrality. So defining centrality is a crucial task for the events in data analysis. Centrality of the events is calculated by measuring the production of the charged particle in all events. The production of charge particles is shown in figure 6.1 . The centrality of events will be defined by observing this graph. The event in which maximum number of charged particles are produced will be the most central and those events will be 0% central. Taking the production of number of charged particles in this event as reference other event's centrality will be defined. Like, the events which produced 60% charged particle of the complete central event will be marked as having centrality 60% . Similarly centrality of events will be defined and then if an analysis is to be done on events with 40% centrality then only those events which has produced 40% charged particles of the most central event will only be used in the analysis.



(a) Classification of event's centrality

(b) Charge production obtained from pb-pb collision at 5 TeV

Figure 6.1: Defining centrality of events

Chapter 7

Nuclear modification factor (R_{AA})

The internal structure of proton was studied by deep inelastic scattering [14] . A leptonic particle was bombarded on proton to study it's internal structure. Thus, using DIS (Deep inelastic scattering) the parton distribution was determined. Various models were made to explain the internal structure of protons and hadrons. It was also found that the momentum fraction that the partons were carrying also depends upon the centre of mass energy. The functions that defines the parton distribution are also known as parton distribution function (PDF). PDF's can also be determined using pp collisions [15] .
In heavy ions collisions nucleus contains more than one nucleon. Initially it was assumed that the parton distribution function in case of nucleus having many nucleons is just the superposition of each nucleon's parton distribution function. Later the measurements of ratio between the structure function of various nucleus and the structure function of deuterium were taken. The ratio was found different from one. This means that the parton distribution function of heavy ions were not simply the superposition of all it's nucleons PDF rather there was a nuclear modification in the parton distribution function of PDF . The deviations from unity in PDF's were described by including nuclear effects in the PDF, today known as nuclear parton distribution function (nPDF) . Now the production of charged particle is an observable which is used to study string interaction governed by the quantum chromodynamics.
In LHC charged particles are produced in soft interactions and hard interactions. Soft interactions involves the process in which low momentum is transferred between the interacting particles. While in hard interactions large momentum transfer is there. Soft particles (particles carrying low momentum) are mainly produced via secondary decays. Hard particles (particles carrying high momentum) are mainly produced directly from the collision of the beam particles. Out of the mentioned two categories of particles hard interactions are of utmost importance as they contains most of the physics [16] . Soft interactions are hard to account for. Hard interactions can be described by perturbative QCD and can be better understood compared to the soft interactions [17] [18] . Observables like production of charge particles modifies if instead of pp collisions pb-pb collisions are done. These effects arises due to the presence of other nucleons in the nucleus. These effects are explained by formation of QGP [19] . For charged particles modifications of this type are modelled in the parameterised in nPDFs (nuclear parton distribution functions) [20] [21]. Modifications in observables like production of charged particles are measured using a factor named as nuclear modification factor. The nuclear modification factor is calculated by

$$R_{pbpb} = \frac{1}{A} \frac{d^2\sigma^{ch}_{pbpb}(\eta, p_T)/dp_T d\eta}{d^2\sigma^{ch}_{pp}(\eta, p_T)/dp_T d\eta} \tag{7.1}$$

Here A is 208 for pb (lead). σ^{ch} is production cross-section for charged particles. p_T and η is the transverse momentum and rapidity of the charged particles. The term numerator or denominator without A in eq-(1) is called the double differential cross section of number of charged particles produced in a given rapidity and transverse momentum range. The double differentiation cross-section is defined as below:

$$\frac{d^2\sigma^{ch}(\eta, p_T)}{dp_T d\eta} = \frac{1}{\mathcal{L}} \frac{N^{ch}(p_T, \eta)}{\Delta p_T \Delta\eta} \tag{7.2}$$

Here, $\mathcal{L}$ is the integrated luminosity of the beam. Luminosity [22] [23] is defined as the number of interactions taking place inside the detector per unit area per unit time. When the luminosity is integrated over the whole time interval then it becomes the integrated luminosity which gives a measure of the total number of interactions that took place due to the crossing of two beams. Basically, integrated luminosity [22] is the measure of the data that is obtained at the detectors due to the crossings of beams. N^{ch} is number of charge particles produced in the range Δp_T & $\Delta\eta$. Thus the nuclear modification factor can be measured. If their is no modifications due to the change of nucleus, then the value of R_{AA} comes out to be 1. If there are effects due to change in the nucleus of colliding particles then the value of R_{AA} is found to be deviated from 1. The nuclear modification factor for production of charge particles at 5 TeV for pb-pb collision is calculated and plotted at different centrality events and is shown in figure 7.1 .

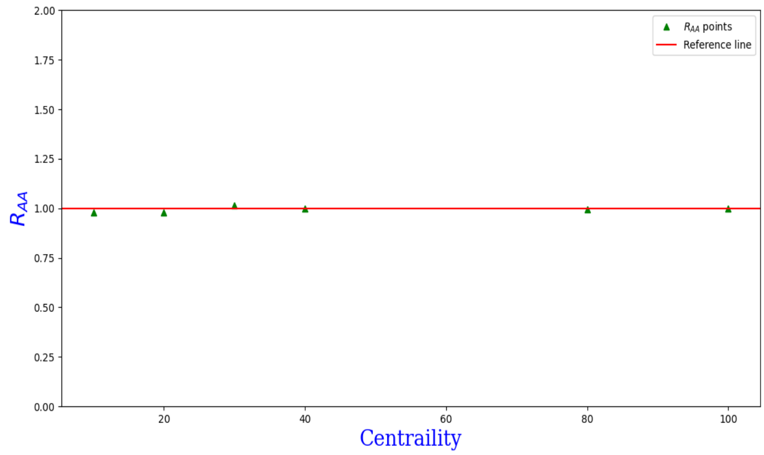


Figure 7.1: Nuclear modification factor for pb-pb collisions at 5 TeV for production of charged particles.

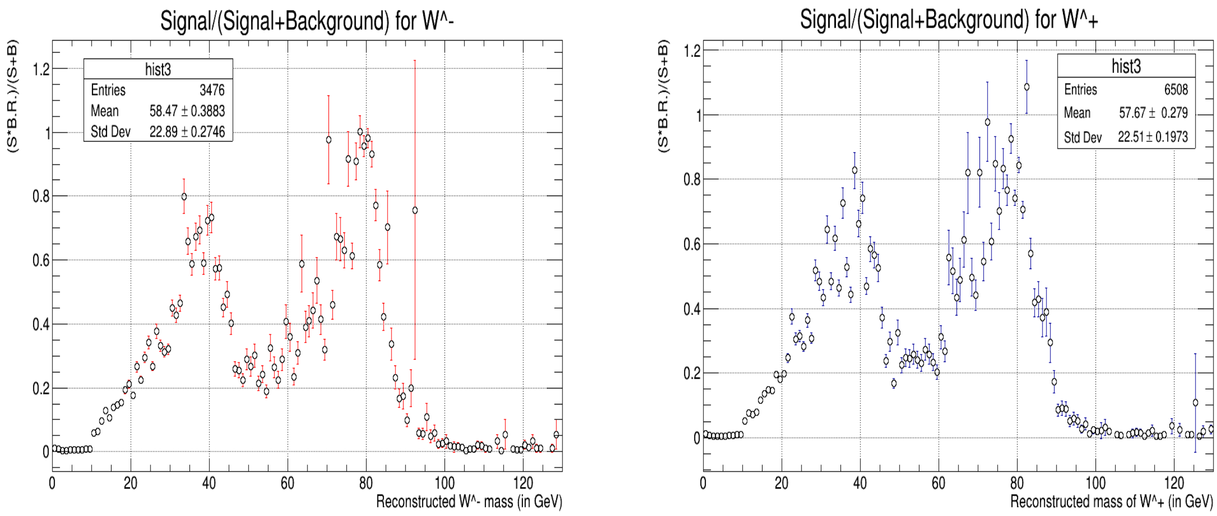
Chapter 8

Results

8.0.1 Signal background ratio

Events containing higgs with mass around 125 GeV/c^2

The reconstructed mass of Higgs and W bosons were calculated by taking the ratio of events containing only signal and both signal and background. For this same number of events were taken of signal and signal+background. But the signal contains all the events in which Higgs



(a) (S*B.R.)/(S+B) for W^- boson

(b) (S*B.R.)/(S+B) for W^+ boson

Figure 8.1: (S*B.R.)/(S+b) for W bosons. Here S means signal, B means background and B.R. means branching ratio.

decayed into a pair of W bosons which further decayed into muon & neutrino and the signal plus background contains only some events in which Higgs decayed via process of interest. Due to this while taking the ratio of events of both types the ratio was coming out to be greater than 1. But this should not be happening since signal plus background should be greater than signal only and the ratio should not exceed one. To take care of this anomaly the events containing signal were multiplied with the branching ratio. Then the ratio of both the histograms were taken and are shown in figure 8.1 . There are two peaks for W bosons one is around 80 GeV which is the actual mass of W bosons and another at around 40 GeV. The second peak arises due to the mass of Higgs with which the events were generated. Mass of W bosons each should be around 80 GeV and their sum add upto around 160 GeV which should be the mass of Higgs. In events obtained from detectors the Higgs is indeed found to have reconstructed mass around 160 GeV for the events in which it decayed into a pair of Higgs boson. But pythia generated events in which Higgs was produced with mass around 125 GeV. Because of which one of the two boson was produced with mass around 80 GeV and another with mass around 40 GeV.

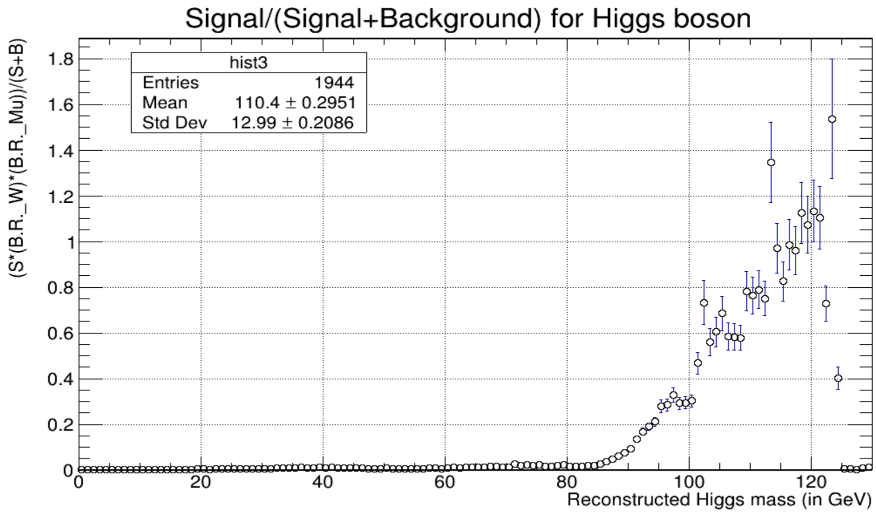
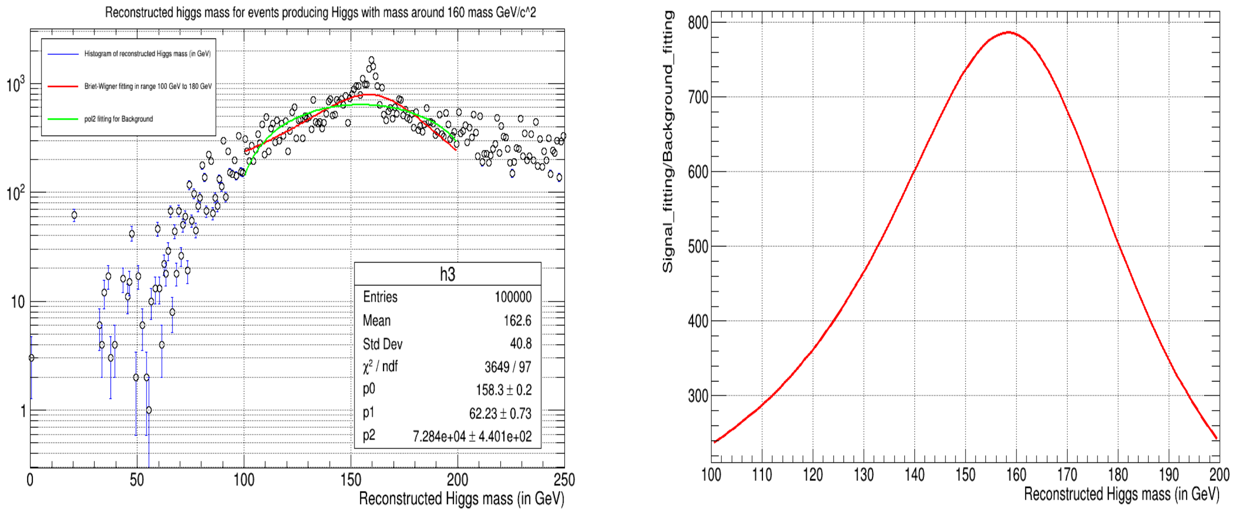


Figure 8.2: S*B.R._W*B.R._Mu)/(S+b) for Higgs boson. Here S means signal, B means background and B.R._W (0.2158445) means branching ratio of Higgs decaying into a pair of W bosons. Likewise B.R._Mu (0.1081011) means branching ratio of W bosons decaying into lepton and neutrino.

The second peak came from these reconstruction of the signal of these particles. The signal to signal + background ratio for reconstructed mass of Higgs is shown in figure 8.2 .

Events containing higgs boson with mass around 160 GeV/c^2

For events containing Higgs boson with mass in bandwidth from 140 GeV/c^2 to 180 GeV/c^2 signal extraction was done by fitting signal events. First the events containing only signal were reconstructed to get the distribution of the reconstructed higgs boson mass. The distribution was Briet Wigner like. Then the Briet Wigner fitting was done with events containing both



(a) Reconstructed Higgs mass for events containing Higgs with mass around 160 GeV/c^2

(b) Signal extraction from ratio of signal to background fitting

Figure 8.3: Reconstructing Higgs mass

signal and background in range 100 GeV/c^2 to 200 GeV/c^2. Additionally, fitting was also done for background. The background events were best fitted by polynomial of 2nd order. This fitting was also done in the range 100 GeV/c^2 to 200 GeV/c^2. The figure containing the fitting is shown in the left figure 8.3. To extract the signal the fitting of signal and background were divide to and the result is shown in right figure of 8.3.

8.0.2 R_{AA} of W bosons for pbpb at 5 TeV

R_{AA} for W^+, W^- boson is calculated and shown in figure 8.4 for various centrality classes. It can be seen in the figure that for the production of $W^{\pm}$ boson is more for peripheral collisions and suppressed for most central collisions. This is because particles like Higgs are produced in initial state interactions via electromagnetic force. So Higgs is produced when colliding particles pass through barely touching each other or in events with mid peripheral centrality as in those events electromagnetic interactions are more there as compared to other interactions . For most central classes again the production is somewhat more as compared to partial overlapping collision events. In these events strong interactions are dominant.

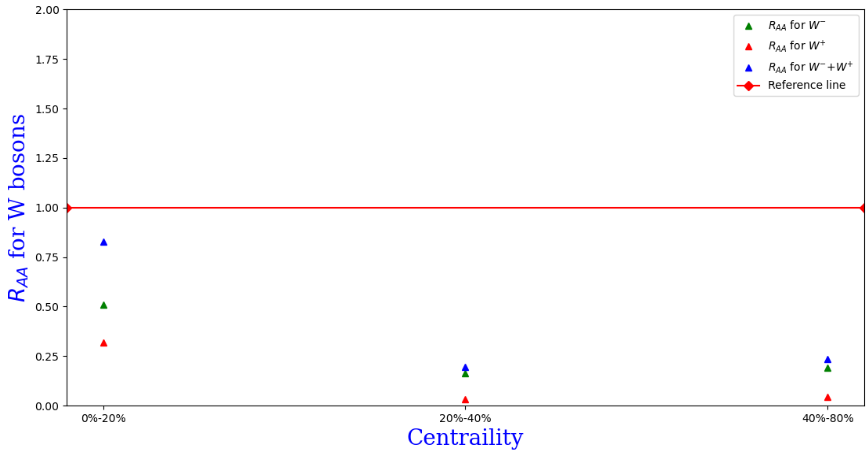


Figure 8.4: R_{AA} for W bosons

Chapter 9

Conclusion

From the analysis done in this report it was found that more μ_+ than μ_- are produced in pp collisions while in pb-pb collisions the production of μ_- was more as compared to μ_+ 3.1 . This is because of the different valence quark configuration in proton nucleus and the nucleons of lead nucleus. The reconstructed mass of W_- was peaked at 78.50 GeV/c^2 and the reconstructed mass of W_+ was peaked at 75.51 GeV/c^2 8.2 . The mass of W_- boson was calculated with an error 2.32% compared to it's mass measured with most precision till now [24] and for W_+ boson the error was 6.04% compared to it's standard mass [24] . The reconstructed mass of Higgs is peaked at 118.035 GeV/c^2 7.1 having error 5.83% with respect to mass of Higgs calculated with most precision by now [25]. The reconstructed mass for events in which Higgs were produced with mass around 160 GeV/c^2 were peaked at 158.03 GeV/c^2 and the distribution was Briet Wigner as expected. It was because the event in which Higgs decay into muon and neutrino contains large MET. The distribution for W bosons were also Briet Wigner and the sum of two Briet Wigner distribution (W^+_-) is also Briet Wigner. The nuclear modification factor for events obtained from pb-pb collisions referenced with events of pp collisions was calculated 8.1 and it was found that production of charge particles was more in the events with centrality were almost same for different centrality classes. Nuclear modification factor was also calculated for W bosons and found that the production was suppressed for intermediate centrality. This was because W bosons mostly came from the decay of Higgs and Higgs were produced in electromagnetic interactions which are dominant as compared to other interactions in peripheral events. The R_{AA} for W bosons was not normalised with p_T and η. Only production of W bosons were calculated. The R_{AA} for W bosons in that case was expected around 1.

References

[1] Cern. The higgs boson. https://home.cern/science/physics/higgs-boson.

[2] CMS collaboration Cern. Measuring the higgs boson decay to ww is 90% physics. the other half is teamwork! https://cms.cern/news/measuring-higgs-boson-decay-ww-90-physics-other-half-teamwork.

[3] Torbjörn Sjöstrand, Javira Altmann, Naomi Cooke, and Nishita Desai et. al. Pythia 8.310. https://pythia.org/pythia82/.

[4] Cern Accelerating Science Cern. Lepton. https://home.cern/tags/lepton.

[5] J. M. Campbell et. al. Event generators for high-energy physics experiments. https://arxiv.org/abs/2203.11110, 2024.

[6] University of Colorado Boulder. High energy physics. https://www.colorado.edu/physics/research/high-energy-physics#experimental_research-125.

[7] Cern. The standard model. https://home.cern/science/physics/standard-model.

[8] Wikipedia. Graviton. https://en.wikipedia.org/wiki/Graviton.

[9] Wikipedia. Beyond standard model. https://en.wikipedia.org/wiki/Physics_beyond_the_Standard_Model.

[10] Alice collaboration Cern. A ten-year journey through the quark–gluon plasma and beyond. https://home.cern/science/physics/higgs-boson.

[11] Wikipedia. Proton. https://en.wikipedia.org/wiki/Proton.

[12] Wikipedia. Lead. https://en.wikipedia.org/wiki/Lead#:~:text=Natural%20lead%20consists%20of%20four,lead's%20atomic%20number%20being%20even.

[13] CMS CERN. Cms precisely measures the mass of the higgs boson. https://cms.cern/news/cms-precisely-measures-mass-higgs-boson#:~:text=CMS%20physicists%20recently%20measured%20the,uncertainty%20of%20roughly%200.1%25!

[14] Thomas E. Balestri. W boson production in ultrarelativistic heavy-ion collisions at the cern lhc. https://www.star.bnl.gov/~jjiastar/Thesis/Thesis_Thomas.pdf.

[15] ATLAS Collaboration. Determination of the parton distribution functions of the proton using diverse atlas data from pp collisions at $\sqrt{s}$ =7, 8 and 13 tev. https://arxiv.org/abs/2112.11266.

[16] C. A. Salgado et al. Proton-nucleus collisions at the lhc: scientific opportunities and requirements. https://arxiv.org/abs/1301.3395.

[17] A. B. Kaidalov and K. A. Ter-Martirosyan. Multihadron production at high energies in the model of quark gluon strings. Sov.J.Nucl.Phys. 39 (1984) 979, Yad.Fiz. 39 (1984) 1545-1558.

[18] A. Capella, U. Sukhatme, C.-I. Tan, and J. Tran Thanh Van. Dual parton model. https://arxiv.org/abs/1101.2599.

[19] J. L. Nagle and W. A. Zajc. Small system collectivity in relativistic hadronic and nuclear collisions. http://arxiv.org/abs/1801.03477.

[20] K. J. Eskola, P. Paakkinen, H. Paukkunen, and C. A. Salgado. Epps16: Nuclear parton distributions with lhc data. http://arxiv.org/abs/1612.05741.

[21] D. de Florian, R. Sassot, P. Zurita, and M. Stratmann. Global analysis of nuclear parton distributions. http://arxiv.org/abs/1112.6324.

[22] Xabier Cid Vidal and Ramon Cid Manzano. Luminosity taking a closer look at lhc. https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.luminosity#:~:text=This%20value%2C%20L%20%3D%2010%2034,a%20leader%20in%20this%20field.

[23] Piotr Traczyk. Why precision luminosity measurements matter. https://home.cern/news/news/physics/why-precision-luminosity-measurements-matter.

[24] Atlas Cern. Improved atlas result weighs in on the w boson. https://home.cern/news/press-release/physics/improved-atlas-result-weighs-w-boson#:~:text=The%20W%20boson%20mass%20came,an%20uncertainty%20of%2019%20MeV.

[25] CMS Cern. Cms precisely measures the mass of the higgs boson. https://cms.cern/news/cms-precisely-measures-mass-higgs-boson#:~:text=CMS%20physicists%20recently%20measured%20the,uncertainty%20of%20roughly%200.1%25!