Exotic Particle Searches with ALICE at the LHC

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

Master of Science

by

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under the guidance of

Prof. Raghunath Sahoo

DISCIPLINE OF PHYSICS

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"Exotic Particle Searches with ALICE at the LHC"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE** and submitted in the **DISCIPLINE OF PHYSICS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2019 to June 2020 under the supervision of Dr. Raghunath Sahoo, Associate Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Vaibhav

(Vaibhav Lohia)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

M.Sc. Thesis Supervisor

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Vaibhav Lohia

Dedicated to my friends

&

family

ABSTRACT

Exotic particles such as *"tertaquarks"* and *"pentaquarks"* were predicted very long ago (1964) but the trend to find their experimental evidence is recent. One such pentaquark was discovered recently in the STAR experiment but due to the less statistical significance the results were not promising enough. Now, the tracks which go through the ALICE experiment are way higher in number than the STAR experiment. So, the higher number of tracks signifies much higher statistics to deal with and to get a much larger statistical significance.

The pentaquark which we are dealing with decays in the following manner $\boldsymbol{N^0} \rightarrow \Lambda + K_s^0$. Now, talking about the daughters. These daughter particles are called "V0 Particles" because of their decay shape. Then those decayed particles can be identified by PID method which uses the Bethe-Bloch formula. This can be done either directly or by their decayed products using the invariant mass reconstruction. We have tried both the approaches to find the invariant mass of both Λ and K_s^0. Then the invariant mass plots were fitted with Gaussian curve to get the particle's mass and width.

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Chapter 1

Introduction

Humans have always been obsessed with symmetry, weather it is in art, or in science, we are highly attracted to patterns and the reason behind them. In physics this is highly noticable in theories and models that physicists make because as we notice that, just like us, the universe is also obsessed with symmetries and patterns and as we got to the bottom of this mystery of symmetries in our nature, we found that they are somehow associated with some conserved quantities, for example translatory motion gives rise to conservation of linear momentum and rotatory motion gives rise to conservation of angular momentum. This was first observed by Emmy Noether and this theorem is called Noether's theoerem [10]. Now, some symmetries are more fundamental than others like our fundamental forces in nature also follow this pattern such as the electromagnetic force results in the conservation of charge and so on. Now, there are other building blocks such as fundamental particles that make up this universe along with our 4 fundamental forces and their corresponding carriers.

1.1 Quarks and Leptons

1.1.1 Family with 3 generations

The building blocks of matter are divided into two groups, quarks and leptons. Now, we have 6 different quarks and 6 different leptons. Electron, which is quite famous in the particle world is a member of the lepton family along with its neutrino called the electron neutrino as you can see in Fig. 1.1 along with other members in the lepton family, which are quite new for example we have muon and it's neutrino which are 2nd generation leptons and finally we have our 3rd generation leptons called the tau and of course, it's neutrino. So, to explain the fundamental blocks of proton and neutron we have to dig a little deeper. Other family that I mentioned is the family of quarks, this family also have 3 generations with 2 members in each generation. We have our first generation quarks called up and down quarks, then comes the second generation quarks, the strange and charm quarks and lastly we have top(truth) and bottom(beauty) quarks which are third generation quarks. But story is not over yet.

1.1.2 Baryons and Mesons

Now, due to some phenomena such as quark confinement and asymptotic freedom, it is impossible for quarks to be in an isolated state. To make matter particles we need combination of quarks. There are some set of rules must be followed in order to make possible combinations of quarks. As per Dirac's theory for every particle there exists an antiparticle. Hence, the family of leptons and quarks have their own opposite copies called anti-leptons and anti-quarks. So, if we combine a quark and an anti-quark we have particle called a meson and since all the matter particles are fermions (particles with non-intergral spin) adding one quark and one anti-quark makes a meson acts like a boson. Furthermore, if we join three quarks or three anti-quarks we have what's called a baryon or an anti-baryon and they are fermions and mesons and baryons are together called hadrons.

1.1.3 Interactions

Now, just like the charge and mass there are other properties of each particles which are associated to them are known as quantum numbers. These include spin (s), Baryon number (B) , Lepton number (L), Isospin (I) and

HyperCharge (Y) etc . Further more, these particles interact with each other with some force carriers, such as photon is the force carrier particle of the electromagnetic force and for weak force we have W and Z vector bosons, for strong force we have gluons (8 in number) and finally we have graviton which is associated with none other than the gravitational force. Although, there is no such experimental verification for the existence of graviton, every other force carrier bosons have been discovered experimentally.

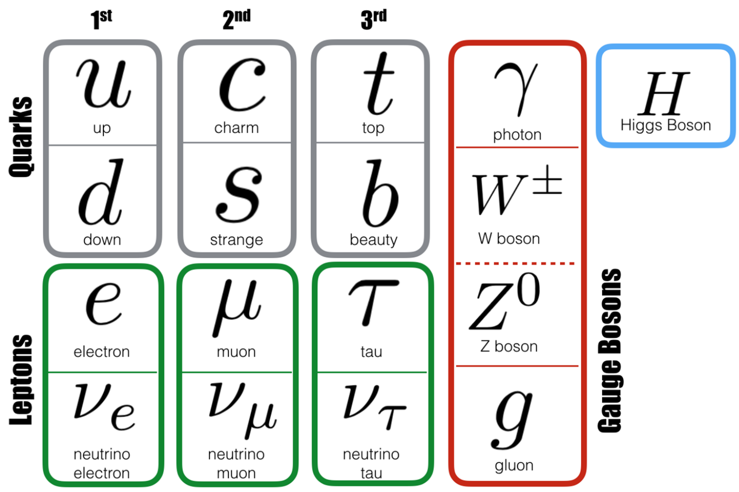

Figure 1.1: Standard table for Standard Model with both Quarks and Leptons [1].

1.2 Quark model of Quantum Chromodynamics

The theory of QCD states that quark feels the strong interaction and come in three colours *red*,*blue* and *green* (r, b, g). These are just labels, there is no such connection with the colours of electromagnetic spectrum, and only colourless combination of quarks are observed as particles called *hardrons*. The QCD colours are equivalent to the charges of *QED*, just like positive and negative charges colours cancel themselves out. A combination of $r + b + g$ is colourless.

Antiquarks carry anticolour such as *antired*, *antiblue* and *antigreen* ($\bar{r}$, $\bar{b}$, $\bar{g}$). Combimation of colour and anticolour is also colourless. The *"gluons"* which are called the guage bosons of QCD also have colour combinations. The fact that only colourless particles exists in nature, we can make simple combinations such as 3 quarks of different colours known as *baryons* and 3 antiquarks known as *antibaryons*, also a combinations of a quark and an antiquark known as *mesons* [11].

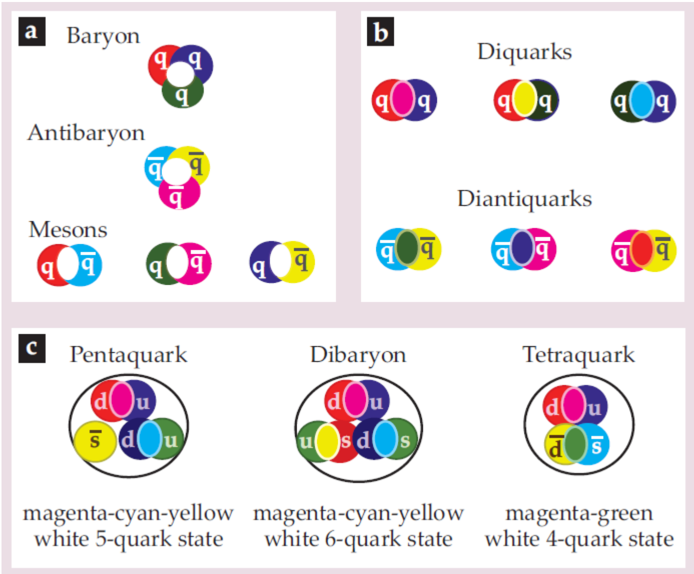

Figure 1.2: Colour combinations of different Hadrons [12]

1.3 Heavy Ion Collisions and the formation of QGP

In High energy interaction the energy densities are at maximum when the two highly Lorentz contracted nuclei collide. Each incident nucleus in heavy ion collision is lorentz contracted disc. For large nuclei such as Pb or Au, the diameter of the disc is about 14 fm (femtometer, or Fermi) and its thickness is about $14/\gamma$ fm, where, at the highest beam energies attainable at RHIC and LHC, the relativistic γ factors are approximately 100 and 2500 respectively, corresponding to beam rapidities of y = 5.3 and 8.5 [3].

After the ultra-relativistic nuclear collisions, very high energy density and temperature is created, making the nucleons melt to form a soup of the fundamental particles called partons. These partons, which are usually

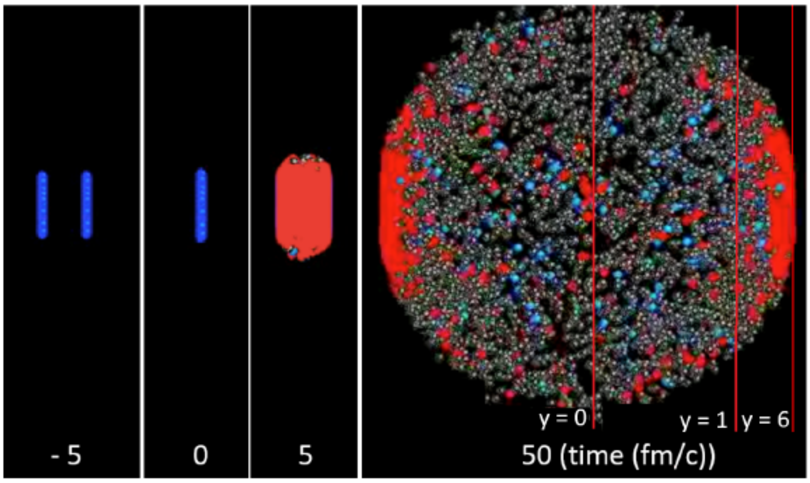

Figure 1.3: A schematic diagram of Heavy Ion Collision [3]

confined inside hadrons, now move in a spatial volume of the nuclei. The system, because of very high initial energy density expands hydrodynamically and cools down.
Now, if we talk about the quarks and gluons which are present in this high energy density system, which do not look free. In fact, they are strongly coupled to each other that they kind of form a medium that flows as well as expands as a hydrodynamic fluid with a low viscosity and high entropy. This system has a life span of 1 fm/c or even shorter. This system or matter is known as Quark Gluon Plasma or QGP. It is believed that after the big bang the QGP was formed just for a few microseconds.

The spacetime evolution of heavy-ion collisions is a complex process involving different degrees of freedom at different times, which makes a theoretical description difficult. The formed QGP during the spacetime evolution, goes through a confinement transition, making composite hadrons. This point is called hadronization. There may be a mixed phase of partons and hadrons, which should be reflected as a first order phase transition. The hypersurface at which the particle producing inelastic collisions stop, is called chemical freeze-out. Later the mean free path of the system becomes higher than the system size and the elastic collision between the particles stop. This is called kinetic freeze-out. The final state particles then free stream.

Chapter 2

ALICE (A Large Ion Collider Experiment)

ALICE is one of the 4 main detectors at LHC. As you can guess by it's name that it is meant mainly for the heavy ion collisions such as Pb+Pb collisions at extremely high energy densities and temperatures where matter interacts strongly with each other and the state of that matter is what we call a Quark Gluon Plasma or simply (QGP).

It addresses many observables, such as multiplicity and rapidity distribution of events, also some specific QGP signals such as direct photons, charmonium and bottomonium.

The two main parts of the detectors are the central barral detectors and the forward detectors [4].

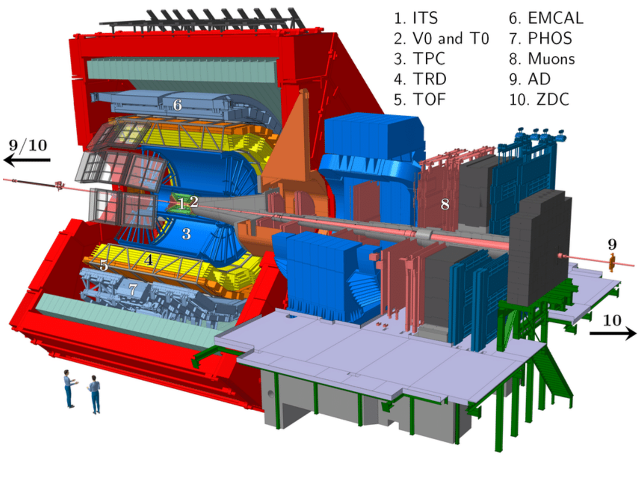

Figure 2.1: ALICE detector [4].

2.1 Components of ALICE

- **Cental Barral Detectors :** These are the detectors which are integrated inside the solenoid magnet and are mainly used to identify charged particles and photons. This category includes ITS, TPC, TRD, TOF and HMPID for identifying charged particles and PHOS and EMCAL for identifying photons. TPC is the main tracking detector in ALICE.

- **Forward Detectors :** This category includes Muon Spectrometer, FMD, PMD, T0, V0 and are mainly used for triggering, luminosity measurements and event characterization.

We will only be discussing the central barrel detectors mainly ITS, TOF and TPC, which are used for this work.

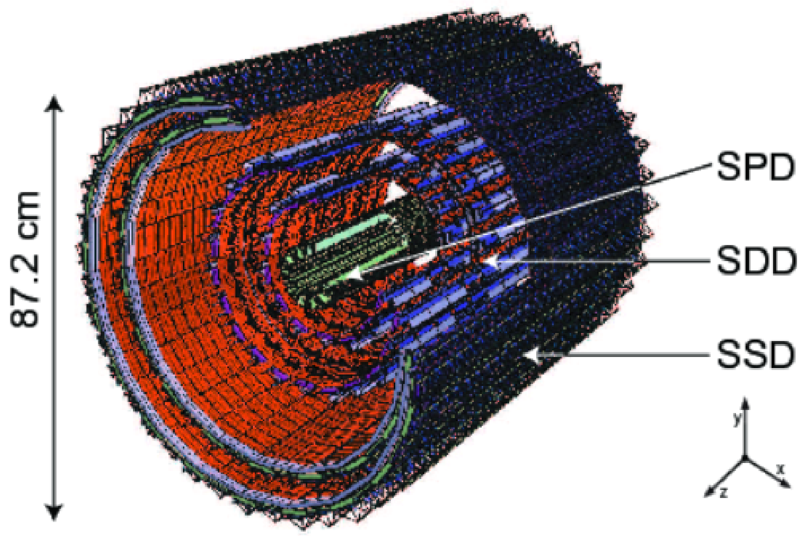

Figure 2.2: Inner Tracking System (ITS) [5].

2.2 ITS (Inner Tracking System)

The detector which is closest to the beam pipe and the interaction point is the Inner Tracking System as shown in Fig 2.2 . The purpose of ITS is to reconstruct the primary and secondary vertices. SSD (Silicon Strip Detectors) is the innermost part of the ITS after that there is SDD (Silicon

Drift Detectors). They both are called Silicon Pixel Detectors (SPD) which makes the ITS.

2.2.1 Particle Identification (PID) in ITS

The particle identification in the central barrel detectors is done by using the specific energy loss of a charged particle which is traversing in the medium. The radiation is emitted by the charged particles when they cross the boundary between two materials.
Measurement of specific energy loss of dE/dx are provided by the last four layers of the ITS detector which are SDD (Silicon Drift Detectors) and SSD (Silicon Strip Detectors). Then , a truncated mean is applied to the measurements. The PID in ITS is performed in a very low p_T region of about 1 GeV/c. [7].

2.3 TPC (Time Projection Chamber)

TPC is one of the main tracking detectors in the central barrel region. It has a pseudorapidity coverage of $|\ \eta\ |< 0.8$. It reconstructs each and every track using 159 space points at max. The TPC in ALICE consists of gas volume barrel divided into two equal halves by a 30μm high-voltage electrode which is use to generate the drift field. The outer and inner radius of the barrel are 280 and 80 cm respectively and has an overall length of 500 cm towards the direction of the beam [6]. The layout of ALICE TPC is given in Fig. 2.3 .

2.3.1 Working of TPC

- Firstly, the charged particles that reach the ALICE detector begin to enter into the gas volume barrel of TPC and then the tracks ionizes the gas molecule.

- Then the ionized electrons goes to the readout chamber or in other words, they drift towards the readout chamber because of the electric

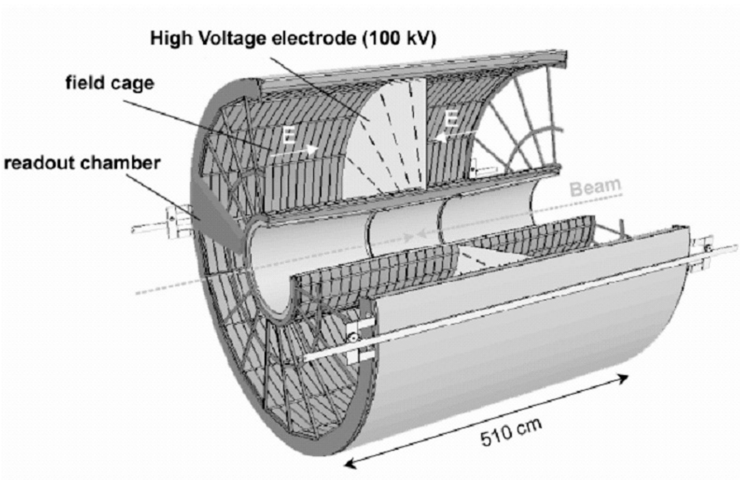

Figure 2.3: Main Components of ALICE Time Projection Chamber (TPC) [6].

field.

- Finally, it measures the position of the charged particle by finding the x and y coordinates by the help of pad planes and the third coordinate is calculated as a function of time i.e z = time **x** drift velocity [7].

2.3.2 Particle Identification (PID) in TPC

If we talk about the PID information which is added through TPC, it is also done using specific energy loss measurements. The truncated mean however is applied to over a maximum number of 159 cluster information. It is not only capable of adding PID information of charged hadrons upto p_T 1 - 2 GeV/c. The bigger dynamic range of TPC also allows us to identify light nuclei [7]. And also, when it is in the Bethe-Bloch region of the dE/dx distribution, PID for individual tracks is also available.

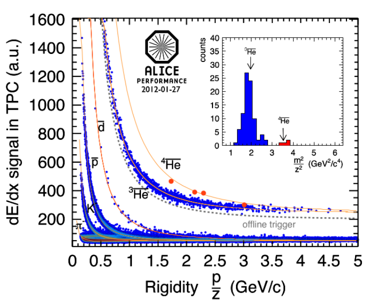

Figure 2.4: PID of different particles using TPC [7].

Chapter 3

Exotic Particles

Particles that are eerie to us and not so familiar with the nature are typically called exotic particles. There are several types of exotic particles such as combination of gluons are called glueballs and particles made with four quarks are called tetraquark which are mesons. The type of particle that I worked with is a pentaquark which is a baryon made up of five quarks. Much more exotic particles are out there in the nature to explore.
Baryons and *mesons* are not the only combination of quarks and gluons. Other particles such as *"tetraquark"*, containing two quarks and two antiquarks and *"pentaquark"*, containing four quarks and one antiquark. Two or three gluons can potentially also form a colourless object, referred to as a *"glueball"*.
According to QCD, it is expected that to produce these exotic particles in high energy physics experiment. But there was no clear evidence of these hadrons. After 2003, however there has been an increase in the rate of observations of new hadronic states which are of at least four or five quarks and antiquarks.
X(3872) was the first exotic state that was observed in 2003 by the Belle experiment. The mass was not in match with any predicted $c\bar{c}$ state. It is believed that X(3872) is a bound state of four quarks (tetraquark). The binding mechanism of the particle is still unknown which brings us to our next section which is different types of hadronic models for exotic particles.

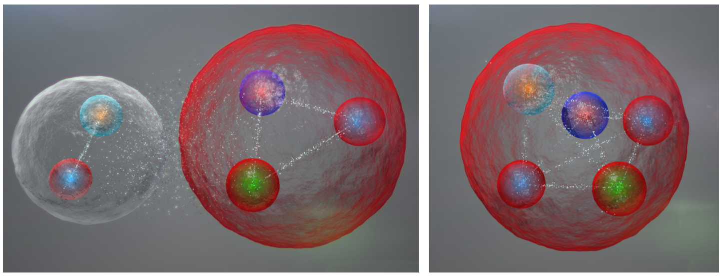

Figure 3.1: Some quark combinations to make mesons, baryons and pentaquarks [2]

3.1 Exotic Hadron Models

Among different models that have been proposed so far, the two that recieve most attention are those which involves *molecule of hadrons* and *multiquark states*. [11]

3.1.1 Molecule of Hadrons

The first hadron molecule, the *deuteron*, was discovered in the 1930s and is now used in a wide range of applications. It is possible that if *neutron* and *proton* can bind together through *pion* exchange, why can't we find other *hadrons* doing the same ? If we talk about *pentaquarks*, the molecule picture of it, will contain a *baryon* and a *meson*. This bound state will have a mass lower than the threshold which is required to decay strongly into it's components which is a *baryon* and a *meson* for a pentaquark and a combination of two *mesons* for a tetraquark. Therefore, due to this at least one of the quarks must change their states in which they are confined with their other partners before the molecule can decay, and this results in long-lived states [13]. Now, due to low binding energies to form them it is assumed that the large production in colliders are not accounted for such particles.

3.1.2 Multiquark states

In QCD, for a particle to be physical, the total content of a hadron must be colourless, so it is not surprising that we can have a multiquark states of four and five quarks for example. The compact multiquark picture, predicts a plethora of exotic states. The predicted masses tend to have fairly large uncertainties, but expectations for certain mass differences between related states are more precise. However, the experimental limits present a significant challenge to the compact multiquark model. The multiquark model also fails to describe the narrow width observed in many exotic states and also no isospin partner has ever been found [13].

3.2 Pentaquarks

Hadrons which are made up of 4 quarks and one anti-quark are called pentaquarks. They are the heavier cousins of protons and neutrons. The name was coined by Claude Gignoux and Harry J. Lipkin in 1987. However, it was predicted long ago by Murray Gell-Man back in 1964 when he first postulated the existence of quarks. The first pentaquark discovery was claimed by Laser Electron Photon Experiment (LEPS) in 2003 along with several others but they were not accepted because of less statistical significance. Recently, in 2015 the LHCb collaboration at CERN discovered a new pentaquark which decayed into a proton and a J/Ψ $(c\bar{c})$ particle [2].

$$\boldsymbol{P_c(4312)}^+ \rightarrow p \, + \, J/\Psi$$

This discovery has a statistical significance of 7.3 sigma which is beyond 5 sigma threshold that is needed to claim a discovery of a new particle.

3.2.1 In search for a new Pentaquark

Now, the quest continues for finding new pentaquarks. In my case, one such pentaquark which has a mass range of 1650-1780 MeV was discovered first with STAR experiment at RHIC which decayed into two strange particles one is a baryon Λ and the other one is a meson K_s^0.

$$\boldsymbol{N^0} \rightarrow \Lambda \, + \, K_s^0$$

This analysis was done in minimum bias Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with a narrow peak at about 1734 MeV as we can see in Fig. 3.2 in the ΛK^0_s invariant mass plot [8]. The statistical significance can be qualified between 3σ and 6σ where the higher significance is mainly for semi-peripheral events. My job is to look for this same *pentaquark* with

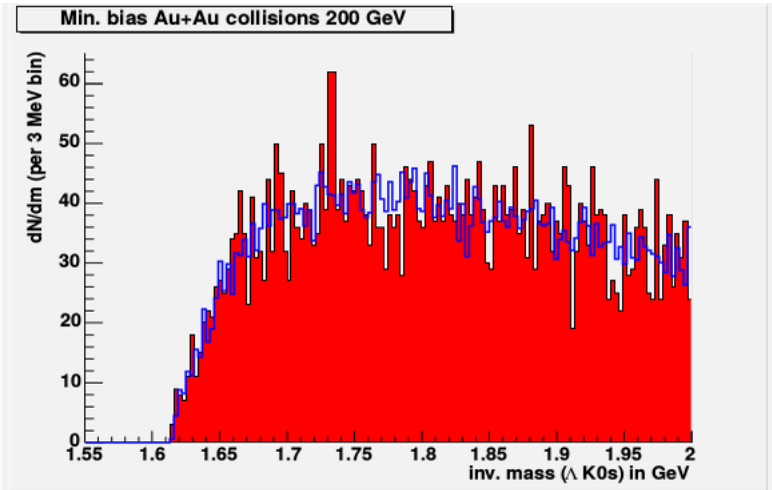

Figure 3.2: Invariant mass distribution ΛK^0_s (in GeV) in minimum bias Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV measured with the STAR experiment (red) together with the estimated background using the mixed events technique (line) [8].

ALICE experiment in Pb+Pb collisions, possibly at $\sqrt{s_{NN}}$ = 5.02 TeV and compare the results with STAR. Due to high energy available at the LHC for the collisions, the number of tracks generated are huge as compared to RHIC. The huge amount of statistics increases the possibility of finding pentaquark manifolds.

Chapter 4

Analysis Method & Framework

In HEP, a framework is a set of software tools that enables data processing. For example the old CERN Program Library was a toolkit to build a framework. PAW was the first example of integration of tools into a coherent ensemble specifically dedicated to data analysis. [14]

4.1 AliROOT Framework

ALICE uses ROOT framework, which is a scientific software framework. ROOT primarily uses C++, while other languages such as python and R are also integrated into it. It includes all the functionality required for statistical and data analysis, big data processing and storage of physics analysis. In addition to the package for physics analysis, the software for the simulations of events and detector is required. To fulfill all the requirements necessary AliROOT framework was born, which is obviously based on ROOT. AliROOT also uses different Monte-Carlo softwares like GEANT3 [15], GEANT4 [16] and Pythia [17] to simulate the interaction of particles with detector material. [18]

4.1.1 Local Run

To complete an analysis task in AliROOT, we must write four seperate codes and then add them later. This is the standard procedure [19]. Those files are

- Header file (AliAnalysisTask.h).
- Implementation file (AliAnalysisTask.cxx).
- Macro file (AddTask.C).
- Run analysis file (runAnalysis.C).

Now, to run locally we simply make an alice environment in our bash terminal and open AliROOT to run our runAnalysis task.

4.1.2 GRID Run

There are two options in runAnalysis task weather to run our task locally (Offline) or on the GRID. The Worldwide LHC Computing Grid, or simply known as Grid, is a global collaboration of computer centers. It is used to provide resources to store, distribute and analyse the petabytes of data that are generated by the LHC.

The GRID distibutes the work to different computing centers that are working for the ALICE collaboration to run our analysis on a big scale which is way more than our local systems can provide [20].

4.2 V0 Particles

Λ and K_s^0 both are strange particles with quark composition *(uds)* and *($d\bar{s}$ - $s\bar{d}$)/*$\sqrt{2}$ respectively but their decayed particles are not strange. Strange particles are hadrons containing at least one strange quark. This is characterized by the quantum number of particle called *"strangeness"*. K_s^0 is the lightest neutral strange meson *($d\bar{s}$ - $s\bar{d}$)/*$\sqrt{2}$ and Λ is the lightest neutral strange baryon *(uds)*.

Neutral strange particles, such as K_s^0 and Λ, decay giving a characteristic decay pattern, called *V0*. The mother particle disappears some cm away from the interaction point and two oppositely charged particles appear in its place , which are bent in opposite directions as represented in Fig. 4.1. We observe that for a pion-pion final state the decay pattern is quite symmetric whereas in the pion-proton final state the radius of curvature of the proton is somewhat bigger than that of the pion: due to the higher mass of proton, hence it also carries most of the initial momentum. [9]

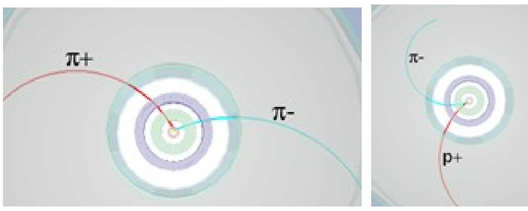

Figure 4.1: decay of $\boldsymbol{K_s^0} \rightarrow \pi^+ + \pi^-$ and $\boldsymbol{\Lambda} \rightarrow p + \pi^-$ in V shape, so called *V0 particles* [9]

4.3 Data Analysis Techniques

Analysis is done using ALICE classes by filtering out data of our desired particles using event selection and track cuts.

4.3.1 Event Selection

We use event selection to get minimum noise and maximum useful data. In some analysis, event selection is done on the basis of centrality i.e analysis is done based on the collision dynamics. In simple words, if the collision is head to head, the centrality is high and if it is peripheral the centrality is lower. Here we are using data from every collision, irrespective of it's centrality. The production of Λ and K_s^0 is measured at mid rapidity ($|y| < 0.5$) in minimum bias Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the ALICE detector. The data were collected with a minimum bias trigger (Trigger is an electronic system which makes the decision whether the data should be saved or not) which requires a hit in VZERO detectors (kINT7).

This data is extracted from the Run 2 operation at LHC.

4.3.2 Approach 1

In our Approach 1, we used a class called "AliAODTrack" [21] which has all the information about each and every track of the events, from that class we can then identify our desired tracks by using "AliPIDResponse" which is a class based on the PID response of the TPC. It identifies particles based on the Bethe-Bloch formula. We have written more on that in sec. 2.2.3 . Now, as we know Λ decays into p and π^-. Also K_s^0 decays into π^+ and π^-. So, what we did is that after identifying those particles we simply stored their information such as momentum, energy, DCA(Distance of closest approach) and etc. And then using the invariant mass reconstruction, we simply reconstructed the masses of our neutral particles i.e Λ and K_s^0.

Methodology

Now, first we consider the decay of the neutral baryon Λ into a proton and a negatively charged pion, $\boldsymbol{\Lambda} \rightarrow p\pi^-$.

We let E_Λ, $\boldsymbol{p_\Lambda}$ and m_Λ be the total energy, momentum and mass of the mother paricle Λ.
Let E_p, $\boldsymbol{p_p}$ and m_p be the total energy of proton p and similarly let E_{π^-}, $\boldsymbol{p_{\pi^-}}$ and m_{π^-} be the total energy, momentum and mass of the negative pion π^-.
Now, from conservation of energy and momentum, we get

$$E_\Lambda = E_p + E_{\pi^-} \tag{4.1}$$

$$\vec{p_\Lambda} = \vec{p_p} + \vec{p_{\pi^-}} \tag{4.2}$$

and from the relativistic equation of Einstein (we are taking c = 1)

$$E_\Lambda^2 = p_\Lambda^2 + m_\Lambda^2 \tag{4.3}$$

where, $p_\Lambda = |\vec{\boldsymbol{p_\Lambda}}|$ is the magnitude of the vector $\vec{p_\Lambda}$. Now, the relativistic equation also applies for the daughter particles.

$$E_p^2 = p_p^2 + m_p^2 \tag{4.4}$$

$$E^2_{\pi^-} = p^2_{\pi^-} + m^2_{\pi^-} \tag{4.5}$$

where, $p_p = |\vec{p_p}|$ and $p_{\pi^-} = |\vec{p_{\pi^-}}|$ are the magnitudes of $\vec{p_p}$ and $\vec{p_{\pi^-}}$.
From the above equations, we find that

$$m^2_\Lambda = E^2_\Lambda - p^2_\Lambda = (E_p + E_{\pi^-})^2 - (\vec{p_p} + \vec{p_{\pi^-}})^2 \tag{4.6}$$

$$= E^2_p + E^2_{\pi^-} + 2E_p.E_{\pi^-} - p^2_p - p^2_{\pi^-} - 2\vec{p_p}.\vec{p_{\pi^-}} \tag{4.7}$$

where,

$$\vec{p_p}.\vec{p_{\pi^-}} = p_{1x}.p_{2x} + p_{1y}.p_{2y} + p_{1z}.p_{2z} \tag{4.8}$$

$$\vec{p_p}.\vec{p_p} = p^2_{1x} + p^2_{1y} + p^2_{1z} = p^2_1 \tag{4.9}$$

$$\vec{p_{\pi^-}}.\vec{p_{\pi^-}} = p^2_{2x} + p^2_{2y} + p^2_{2z} = p^2_2 \tag{4.10}$$

$$m^2_\Lambda = (E^2_p - p^2_p) + (E^2_{\pi^-} - p^2_{\pi^-}) + 2E_p.E_{\pi^-} - 2p_p.p_{\pi^-} \tag{4.11}$$

and finally, we get the invariant mass formula for Λ baryon.

$$m_\Lambda = \sqrt{(E^2_p - p^2_p) + (E^2_{\pi^-} - p^2_{\pi^-}) + 2E_p.E_{\pi^-} - 2\vec{p_p}.\vec{p_{\pi^-}}} \tag{4.12}$$

Now, we would repeat the same procedure to calculate the invariant mass of $K^{,0}_s$. After, calculating the invariant masses of both the strange particles, we made some plots for both $m_{K^0_s}$ and m_Λ which are in the results section.

Track Cuts

For both Λ and $K^{,0}_s$ we applied several cuts for the analysis of their daughter charged tracks.

- Positive charge cut for π^+ and p.
- Negative charge cut for π^- and $\bar{p}$.
- TPC Sigma (σ) cut : σ should be less than 3.
- Pseudorapidity cut : $|\ \eta\ |$ should be less than 0.8
- Rapidity cut : $|\ y\ |$ should be less than 0.5
- Distance of closest approach cut : (DCA) should be less than 0.8

4.3.3 Approach 2

In this approach, we will use another class from AliROOT called "AliAODv0" which contains the information about the V0 candidates and can find their invariant mass without reconstructing it from their decayed particles. Here, we have used a simple algorithm with increase in number of cuts to make our invariant mass plots of V0 candidates (which are Λ and K_s^0) look sharp so that we can identify the signal from the background easily.
The class "AliAODv0" also contains information about their daughter particles which we can access by using our old "AliAODTrack" class. This would become helpful for us as we have to apply cuts to the daughter paricles as well to filter out other unnecessary tracks.

Methodology

The method is fairly simple for this approach. Not much mathematics is going on here. As "AliAODv0" class contains most of the required information about the tracks [22]. We simply, filter out the unnecessary tracks from the events from various cuts on both V0 candidates and their corresponding daughter particle and just take the invariant mass information and plot it as a histogram.

Track Cuts

There are several cuts for our V0 candidates (Λ and K_s^0) and their daughters which are as follows.

- Get on fly status.
- Pseudorapidity cut : $\mid \eta \mid$ should be less than 0.8
- Rapidity cut : $\mid y \mid$ should be less than 0.5
- V0 Radius cut : 5 < R < 100.

V0 Daughters cuts.

- Positive and negative charge cuts for each daughter.

- TPC Sigma (σ) cut : σ should be less than 3 for K_s^0 daughters and less than 5 for Λ daughters.

- Distance of closest approach to primary vertex cut for both positive and negative daughters : DCA_{Pos} and DCA_{Neg} should be less than 0.1.

- DCA cut : $DCA_{Daughters}$ should be less than 0.8.

- X rows TPC cut : DauXrowsTPC should be less than 70.

Chapter 5

Results and Discussions

The results that came throughout the project were mostly focused on the invariant mass of V0 particles because for the Pentaquark that desire to find decays into those V0 particles. So, in order to find the mother, we must find their daughters first. At the end of the project, I successfully found those V0 particles (Λ, K_s^0 and $\bar{\Lambda}$ and fitted them with a gaussian curve to calculate it's mean, sigma and etc. I also want to show you some PID response for different particles using TPC signal.

All the plots are given below.

5.1 PID response for different particles

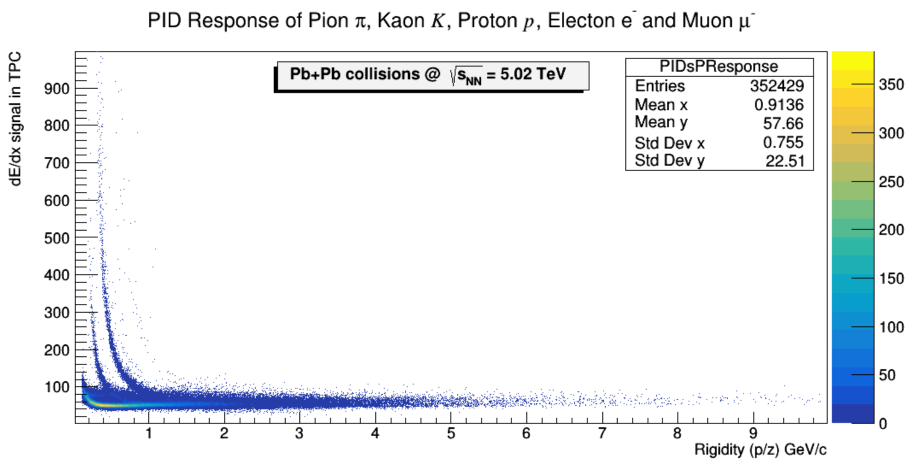

Figure 5.1: This analysis was done locally in minimum bias Pb+Pb collisions. This is a 3D plot where the colour represents the number of charged particle in particular bins.

5.2 Lambda (Λ)

The observed invariant mass of Λ is approximately 1.1156 GeV.

5.2.1 Results from Approach 1

Local Run

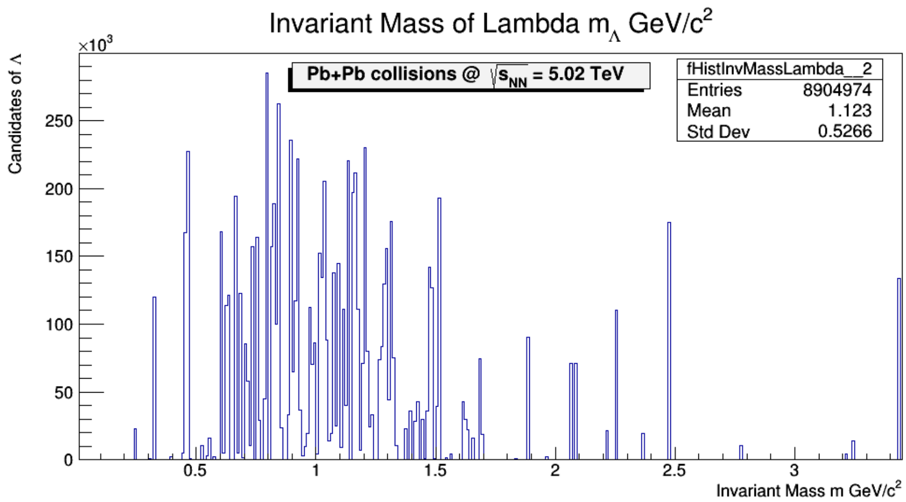

Figure 5.2: The local mean of this plot is around 1.123

GRID Run

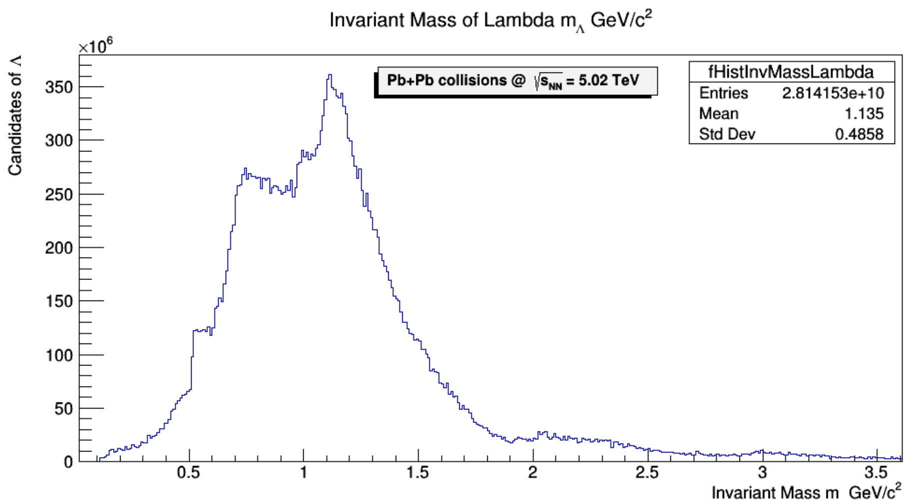

Figure 5.3: The GRID mean of this plot is around 1.135

5.2.2 Results from Approach 2

In this we included only the plots from the GRID Run because after so many cuts the local tracks were negligible and were not good for any interpretation. The table below has parameters of the Gaussian fit that we did on the plot. The mean of the Gaussian comes out to be 1.11513 with an error in the orders of 10^{-5} which is a very promising result as compared to the approach 1.

GRID Run

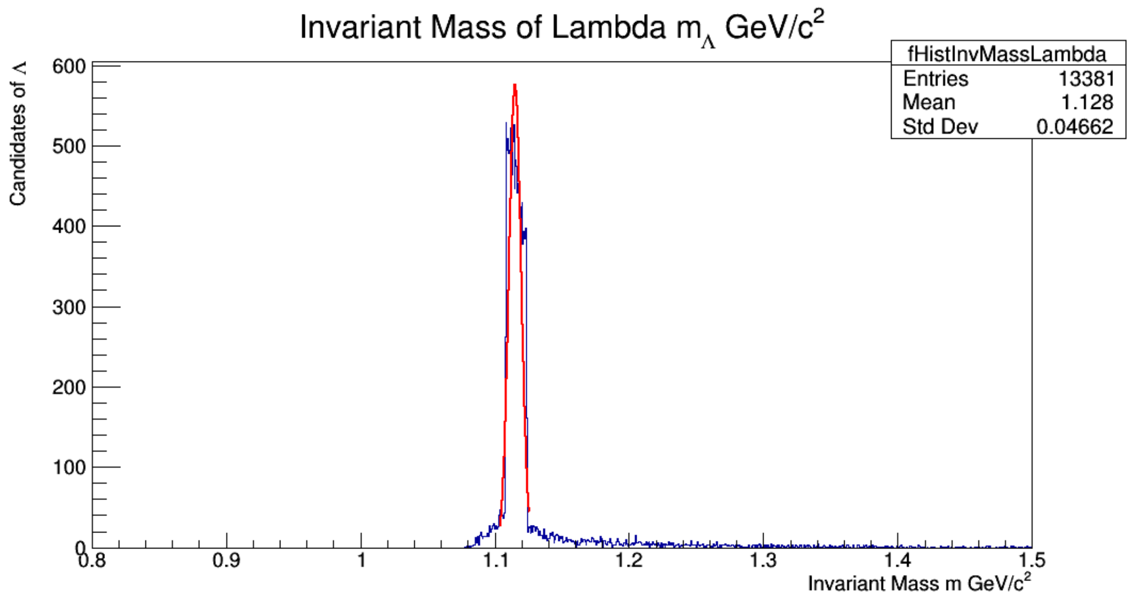

Figure 5.4: The mean of this plot is around 1.128 without the Gaussian fit

Parameter	Value	Error	Stepsize
Constant	5.760×10^2	7.084	1.1510×10^{-7}
Mean	1.11513	5.05×10^{-5}	9.651×10^-7
Sigma	4.5471	3.5384×10^{-5}	3.87×10^-5

5.3 K-Short (K_s^0)

The observed invariant mass of K_s^0 is approximately 0.4976 GeV.

5.3.1 Results from Approach 1

Local Run

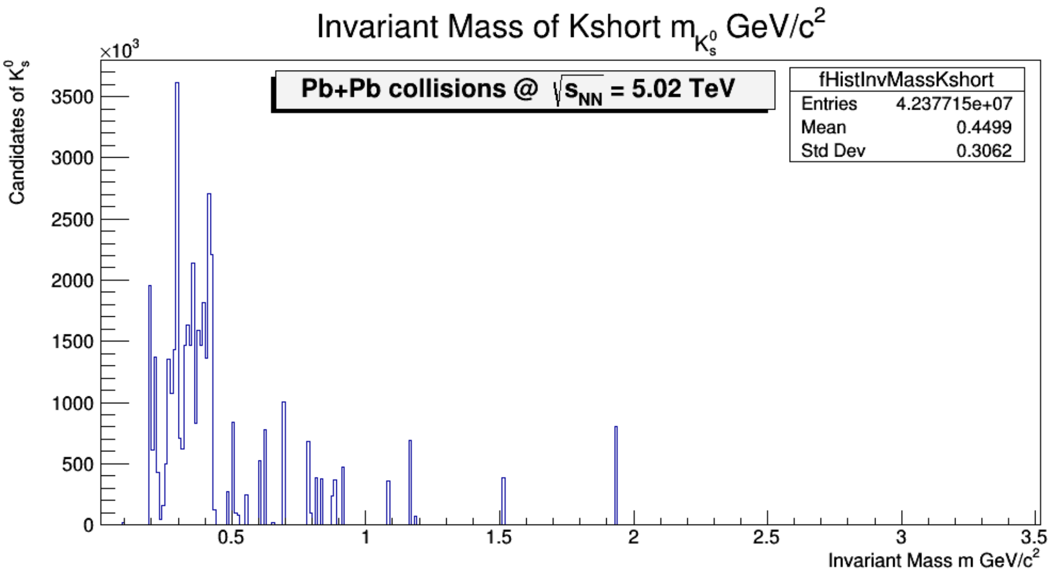

Figure 5.5: The local mean of this plot is around 0.4499

GRID Run

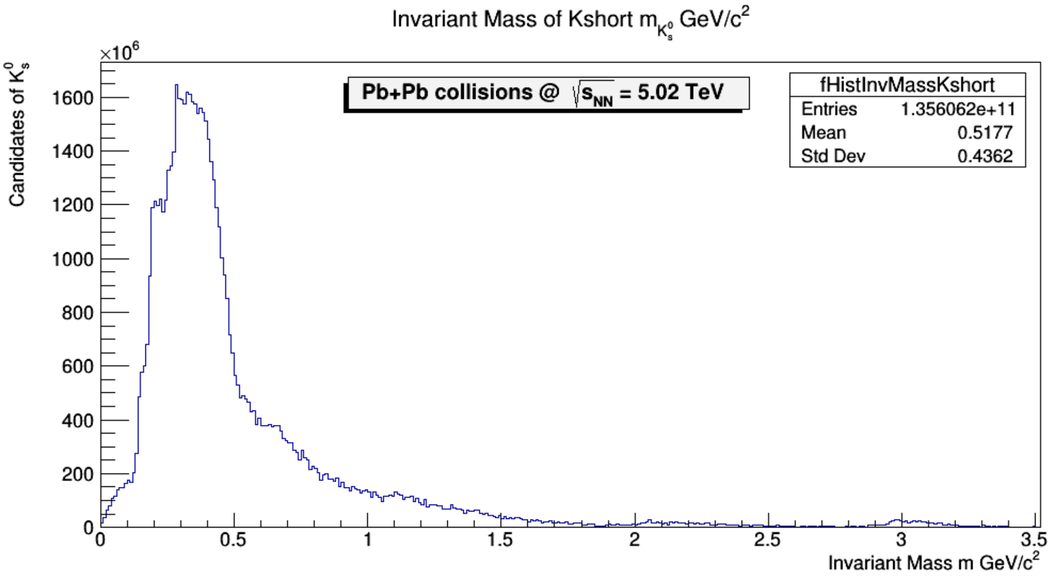

Figure 5.6: The GRID mean of this plot is around 0.5177

5.3.2 Results from Approach 2

In this we included only the plots from the GRID Run because after so many cuts the local tracks were negligible and were not good for any interpretation. The table below has parameters of the G fit that we did on the plot. The mean of the Gaussian comes out to be 0.4971 with an error in the orders of 10^{-3} which is also better from the approach 1.

GRID Run

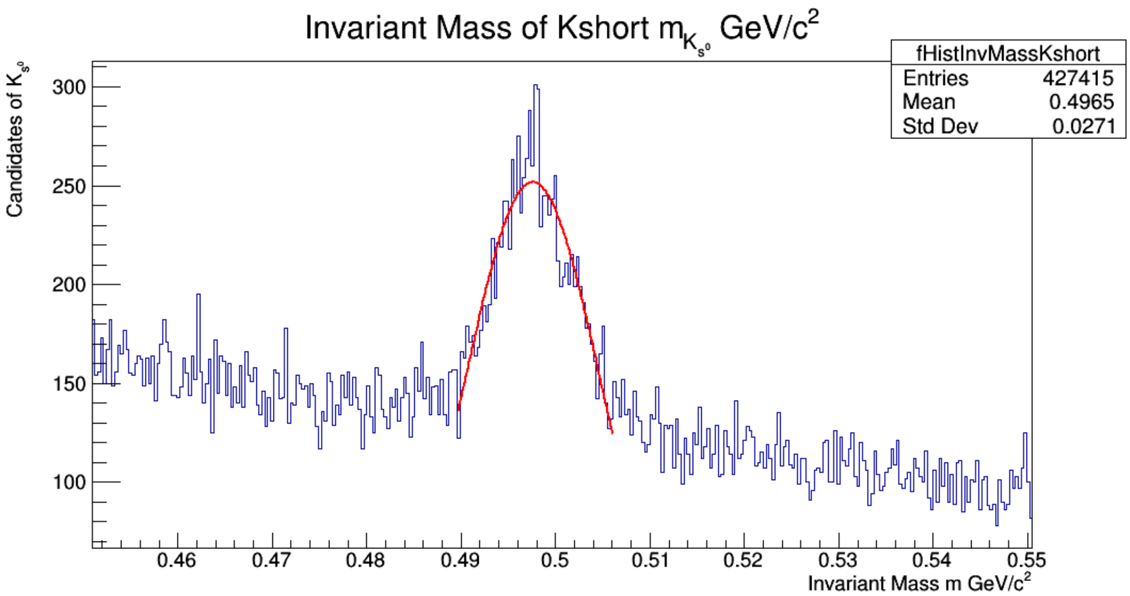

Figure 5.7: The mean of this plot is around 1.128 without the Gaussian fit

Parameter	**Value**	**Error**	**Stepsize**
Constant	10.345 x 10^2	9.014	4.1510 x 10^{-7}
Mean	0.4971	5.05 x 10^{-3}	3.651 x $10^{-}7$
Sigma	3.9652	3.5384 x 10^{-3}	8.245 x $10^{-}5$

5.4 Anti-Lambda ($\bar{\Lambda}$)

The observed invariant mass of $\bar{\Lambda}$ is approximately 1.1156 GeV.

5.4.1 Results from Approach 1

Local Run

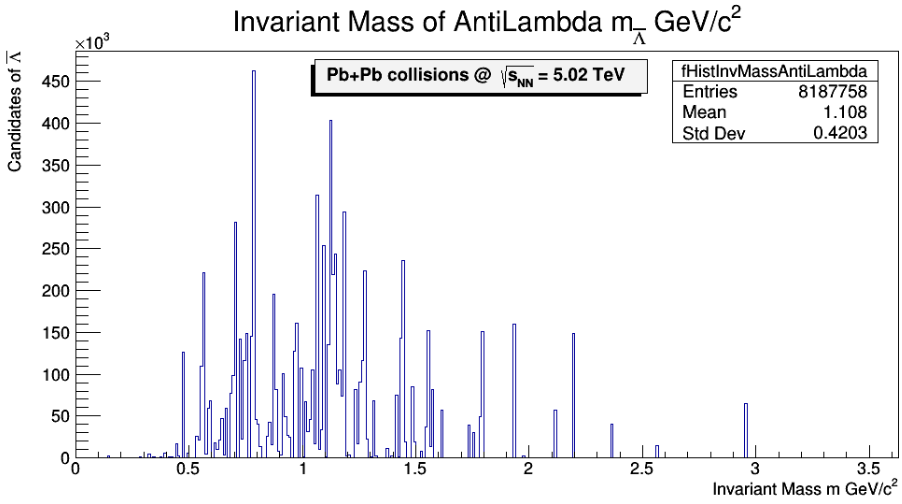

Figure 5.8: The local mean of this plot is around 1.108

GRID Run

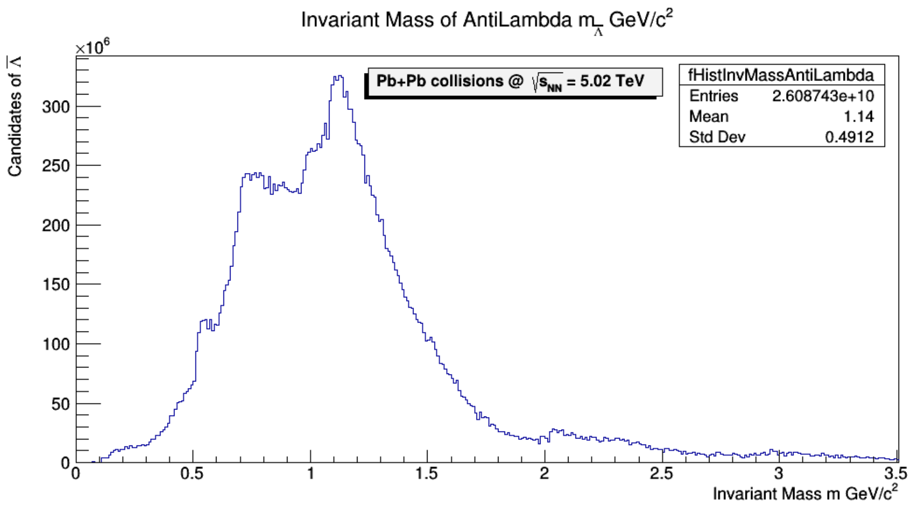

Figure 5.9: The GRID mean of this plot is around 1.140

5.4.2 Results from Approach 2

In this we included only the plots from the GRID Run because after so many cuts the local tracks were negligible and were not good for any interpretation. The table below has parameters of the guassain fit that we did on the plot. The mean of the gaussian comes out to be 1.11452 with an error in the orders of 10^{-5} which is again quite good.

GRID Run

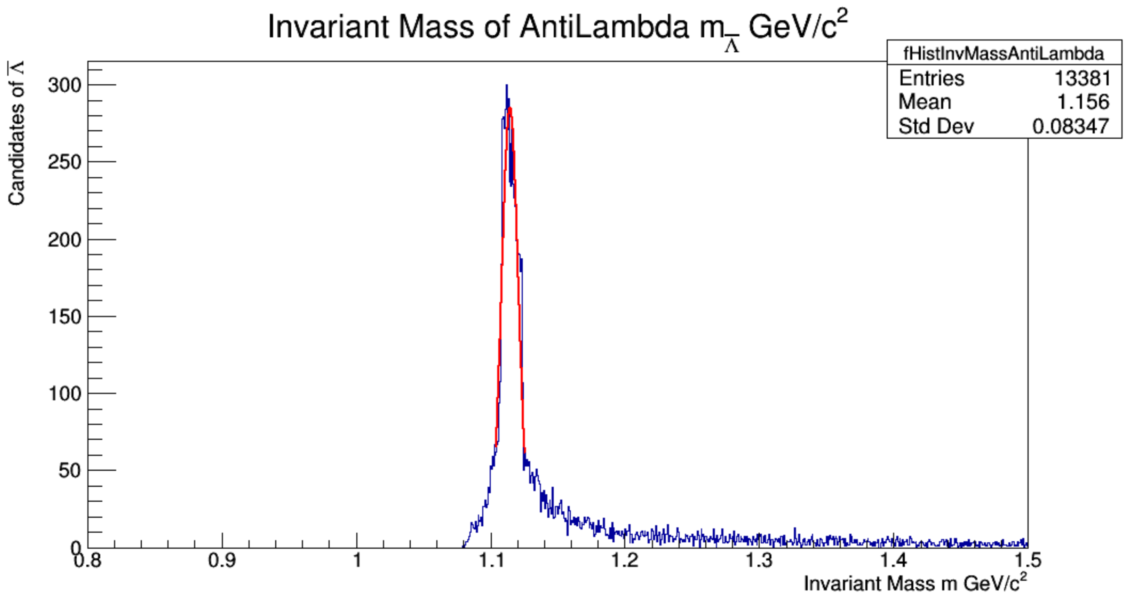

Figure 5.10: The mean of this plot is around 1.128 without the Gaussian fit

Parameter	**Value**	**Error**	**Stepsize**
Constant	2.8571 x 10^2	4.854	5.430 x 10^{-7}
Mean	1.11452	9.96 x 10^{-5}	8.214 x 10^-7
Sigma	6.18719	9.92 x 10^{-3}	6.74 x 10^-5

Chapter 6

Conclusion and Scope for Future work

In the present thesis, we made a brief introduction to the Standard Model of particle physics. This includes the classifications of fundamental particles, their composites in terms of baryons and mesons. The possibility of formation of exotic particles in accelerator experiments are discussed. Further, a discussion on the detectors used for the data analysis in ALICE experiment at the Large Hadron Collider is made, with special focus on the detectors used for the search of exotic particles. Using ALICE grid computing facility in C++ based ROOT and AliROOT framework, data are analysed. Some of the findings of the present work are mentioned below.

- The plots for the mass of V0 particles were achieved by doing the invariant mass reconstruction from using their daughter particles. The plots for the mass were made in both local and grid run with different statistics.

- After that, by using the class "AliAODv0" we got some more and better mass plots of the V0 particles.

- To know the actual calculated mass, we did a Gaussian fit and got the mean value and also the standard deviation of the plots.

The production cross section of the exotic particles is very less, because of their high mass. This warrants huge statistics and computing time.

An experimental case study is made through this project for the search of exotic particles in high energy heavy-ion collisions.

The main goal of this project is yet to achieve. However, getting these promising results above makes our job easier for finding our pentaquark. Here are some objectives for our future work

- We have to subtract background from the data by using the Event-mixing method.
- We will have to look for the mass range of the pentaquark which should be in between 1650-1780 MeV.
- For a signal to be qualified as a particle, it must have a significance of 5σ or above. Significance is nothing but the signal divided by the root of the background.

Moreover, unexpected outcomes is not uncanny in the search for pentaquarks, just like N^0, Ξ^0 is also a pentaquark with same isospin I = 1/2 [23]. This can also lead to the discovery of their isospin partners $N^+ \rightarrow \Lambda K^+$ and $\Xi^- \rightarrow \Lambda K^-$ and also for Θ^+.

Bibliography

[1] University of Zurich. Standard model of elemetary particles. *https://www.physik.uzh.ch/en/researcharea/lhcb/outreach/StandardModel.html*.

[2] LHCb experiment CERN. Lhcb experiment discovers a new pentaquark. *https://home.cern/news/news/physics/lhcb-experiment-discovers-new-pentaquark*.

[3] Wit Busza, Krishna Rajagopal, and Wilke Van Der Schee. Heavy ion collisions: the big picture and the big questions. *Annual Review of Nuclear and Particle Science*, 68:339–376, 2018.

[4] Alice Collaboration. Performance of the alice experiment at the cern lhc. *International Journal of Modern Physics A*, 29(24):1430044, 2014.

[5] G Dellacasa, X Zhu, M Wahn, FM Staley, V Danielian, TL Karavicheva, DP Mikhalev, N Carrer, M Gheata, G Stefanek, et al. Alice technical design report of the inner tracking system (its). Technical report, 1999.

[6] HJ Hilke. Time projection chambers. *Reports on Progress in Physics*, 73(11):116201, 2010.

[7] Chiara Zampolli. Particle identification with the alice detector at the lhc. *arXiv preprint arXiv:1209.5637*, 2012.

[8] Sonia Kabana. Exotic particle searches with STAR at RHIC. *Acta Phys. Hung.*, A24:321–328, 2005.

[9] ALICE Masterclass. Looking for strange particles in alice. *http://aliceinfo.cern.ch/public/MasterCL/MasterClassWebpage.html*.

[10] Willy Sarlet and Frans Cantrijn. Generalizations of noether's theorem in classical mechanics. *Siam Review*, 23(4):467–494, 1981.

[11] Greig Cowan and Tim Gershon. Tetraquarks and pentaquarks. *arXiv preprint arXiv:1808.04153*, 2018.

[12] Stephen Lars Olsen. Exotic particles with four or more quarks. *Physics Today*, 67(9), 2014.

[13] Lorenzo Capriotti. Pentaquarks. *arXiv preprint arXiv:1906.09190*, 2019.

[14] P Hristov. Aliroot primer. *The ALICE Collaboration*, 2006.

[15] René Brun, AC McPherson, P Zanarini, M Maire, and F Bruyant. Geant 3: user's guide geant 3.10, geant 3.11. Technical report, CERN, 1987.

[16] Sea Agostinelli, John Allison, K al Amako, John Apostolakis, H Araujo, P Arce, M Asai, D Axen, S Banerjee, G 2 Barrand, et al. Geant4—a simulation toolkit. *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, 2003.

[17] Torbjörn Sjöstrand, Stephen Mrenna, and Peter Skands. A brief introduction to pythia 8.1. *Computer Physics Communications*, 178(11):852–867, 2008.

[18] Sushanta Tripathy and Raghunath Sahoo. *Event and multiplicity dependence of O meson production in proton+ proton collisions with ALICE at the LHC and characterization of heavy-ion collisions using relativistic kinetic theory*. PhD thesis, Discipline of Physic, IIT Indore, 2019.

[19] ALICE Github. Writing an analysis task. *https://alice-doc.github.io/alice-analysis-tutorial/analysis/classes.html*.

[20] ALICE Github. Writing an analysis task. *https://alice-doc.github.io/alice-analysis-tutorial/analysis/rungrid.html*.

[21] AliROOT core. Aliaodtrack class reference. *http://alidoc.cern.ch/AliRoot/master/class_ali_a_o_d_track.html*.

[22] AliROOT core. Aliaodv0 class reference. *http://alidoc.cern.ch/AliRoot/master/_ali_a_o_dv0_8h.html*.

[23] Sonia Kabana. Review of the experimental evidence on pentaquarks and critical discussion. In *AIP Conference Proceedings*, volume 756, pages 195–200. AIP, 2005.