STUDY OF PI-MESONS (PIONS) PRODUCTION IN PROTON-PROTON COLLISION AT ULTRA-RELATIVISTIC ENERGIES

BY

MUHAMMAD AAMIR SHAHZAD

SESSION 2010-2012

DEPARTMENT OF PHYSICS
INTERNATIONAL ISLAMIC UNIVERSITY
ISLAMABAD, PAKISTAN

(2012)

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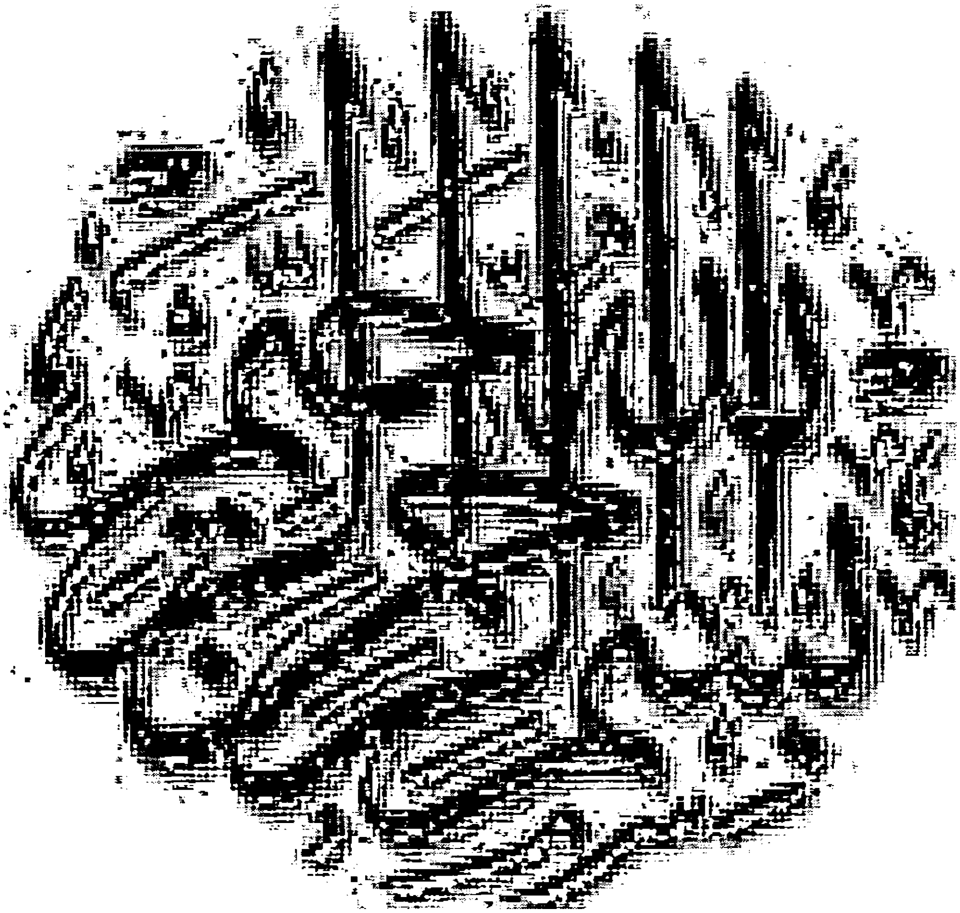

IN THE NAME OF
ALLAH

THE MOST BENEFICENT

THE MERCIFUL

O-MY LORD

INCREASE ME IN KNOWLEDGE

(Al QURAN SURA TAHA SECTION 16, 114)

International Islamic University, Islamabad
Faculty of Basic and Applied Sciences
Department of Physics
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Study of Pi-Meson (Pions) Production in p-p Collisions at Ultra-Relativistic Energies

By

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A thesis submitted to **Department of Physics**, International Islamic University Islamabad for the award of degree **MS Physics.**

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Approval

It is Certified that the work presented in this thesis entitled **"Study of Pions Production in p-p Collisions at Ultra-relativistic Energies"** is carried out by **Mr. Muhammad Aamir Shahzad,** Registration No. 22-FBAS/MSPHY/F10 under my supervision and that in my opinion, it is fully adequate, in scope and quality, for the award of degree of MS Physics from International Islamic University, Islamabad.

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MY AFFECTIONATE PARENTS,

BELOVED BROTHERS AND SISTERS

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All the praises and thanks for Almighty **ALLAH:** Who guides us in darkness, helps us in difficulties and is the entire source of knowledge & wisdom endowed, to mankind and for equipping His humble creatures with mental faculty. I firmly believe that **ALLAH:** never spoils any effort. Every piece of work is rewarded according to the nature and degree of devotion put in. It is with the grace of **ALLAH:** the most Benign and Compassionate that I have been able to undertake and execute this research work.

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AUTHOR

(MUHAMMAD AAMIR SHAHZAD)

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LIST OF ABBREVIATIONS

ACORDE	A Cosmic Radiation Detector
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
CERN	European Organization for Nuclear Research
CMS	Compact Muon Solenoid
EMCAL	Electromagnetic Calorimeter
FMD	Forward Multiplicity Detector
GEANT	GEomatry ANd Tracking
GUI	Graphical User Interface
HMPID	High Momentum Particle Identification
IP	Interaction Point
ITS	Inner Tracking System
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
MC	Monte Carlo
PAW	Physics Analysis Works
Pb-Pb	Plumbus-Plumbus (Lead-Lead)
PHOS	Photon Spectrometer
PID	Particle Identification
PMD	Photon Multiplicity Detector
p-p	proton-proton
QCD	Quantum Chromodynamics
QGP	Quark Gluon Plasma
SDD	Silicon Drift Detectors
SPD	Silicon Pixel Detectors

SPS	Super Proton Synchrotron
SSD	Silicon Strip Detectors
TOF	Time of Flight
TPC	Time Projection Chamber
TRD	Transition Radiation Detector
ZDC's	Zero Degree Calorimeters

ABSTRACT

In the present work the production of pions in proton-proton collisions at ultra-relativistic energies has been studied. Two different techniques have been used for this analysis. First one is the ALICE (A Large Ion Collider Experiment) offline framework to observe the pions as production signals of Quark Gluon Plasma (QGP). Main components of offline framework are virtual Monte Carlo, a set of collaborating classes for primary particle simulation and base classes for fast simulation. The experimental setup of this study has been developed at European Organization for Nuclear Research (CERN) in Geneva, Switzerland. Large Hadron Collider (LHC) is the highest energy particles accelerator, working at CERN to test the production of various fundamental particles and to explore the origin of mass. Analysis of the research work is done by the ROOT software. This is offering equivalent platform of computing for analysis at large scale in combination with the PROOF system. I have also discussed in detail about ALICE and its other sub-detectors used in ALICE. The second technique is the study of pions using FLUKA code. FLUKA is general purpose software for use in different areas of science and technology. FLUKA can simulate both the fixed target as well as the colliding beams. The overall trend of pion production is similar in both techniques.

CHAPTER 1

INTRODUCTION

The theoretical prediction about the existence of pion was given by a Japanese scientist H. Yukawa in 1935 [1]. After his prediction, these particles were experimentally observed by C.F. Powell with his collaborators in 1947 by using photographic emulsion technique [2]. In attempting to explain the fact that nucleons hold together in-spite of the mutual electrostatic repulsion of the protons within them, Yukawa invoked an analogy with electrostatic forces. He argued that the forces which hold nucleon together might be the result of the creation and annihilation of new particles, knowing that the forces are effective over very short distance. By invoking the Heisenberg's uncertainty principle, Yukawa was able to calculate the approximate masses of such particles, to be nearly two hundred times than that of an electron. These particles are now-a-days known as pi-mesons (π-mesons) or pions.

Mesons are strongly interacting particles. The term meson was coined to describe the particles with mass intermediate between the mass of electron and the proton. The experimental studies of cosmic ray events showed that there were other mesons with masses larger than those of the pi-mesons. These newly observed mesons were, individually, about one thousand time massive than that of an electron. These mesons were later on called pi-mesons. There are some other types of mesons known as k-mesons, D-mesons and rho-mesons etc. Clearly not all these mesons could be classed as fundamental particle, but a way had to be found to understand these in terms of excitation in a more fundamental system. The founding of the constituent-quark model by Gell-Mann and Zweig showed excitation in a more fundamental system could indeed be done. According to this model, combinations of three or more quarks are known as baryons and quark and antiquark pair form mesons. There are six flavors of quarks, which are up, down, charm, strange, top and bottom. Up, charm and top quark carry charge (2/3)e while down, strange and bottom quark carry (−1/3)e and each quark carry a baryon number (1/3). Bound state combinations can be formed from these quarks and the antiquarks. Quark carry spin 1/2 and also carry a quantum number called color and the color dependent forces are such that only color neutral (color-singlet) combinations manifest as mesons.

Like other nucleons, pions are also buildup of quarks and gluons. There are three kinds of pi-meson i.e. $\pi^{\pm}$-meson and π^{0}-meson. π^{+}-meson and π^{-}-meson are antiparticles of each other while π^{0}-meson is its own antiparticle and called neutral pion. This neutral pion was, not found until it was produced in the accelerators in 1950. Pions are buildup of quark-antiquark pair and are combination of two of the lightest quarks (up and down quarks). Pions are bosons with zero spin and do not obey Pauli-Exclusion principle. In terms of mass of electron (m_e), the rest mass of π^{+} is 273.3m_e, π^{-} is 272.74m_e and that of π^{0} is 264.20m_e. The rest mass energy of the charged pion is 139.58 MeV and that of π^{0} is 134.98 MeV. Pions are widely been used for induced nuclear reactions due to their interaction ability with the nuclei of the atom by imparting all energy to the target nuclei.

In p-p collision, large numbers of particle are produced, having transverse momenta (p_t) below 1 GeV/c at ultra-relativistic energies. By using first principles of perturbative QCD (Quantum Chromodynamics) the production of these particles is not computable. It is significant to observe the production of these particles ensuing as a result of interaction which depends upon both p_t and nature of particle groups. Evolution of the particle production in p-p interactions, at various incident energies has been considered by comparing statistics from prior experiments. To meet the contemporary needs of experimental high energy particle physics and to test the validation of theoretical predictions about the basic constituents of particles, their masses and the forces holding them together, a huge collider is built at CERN (European Organization for Nuclear Research) known as large Hadron Collider (LHC) at Switzerland. Among the experimental setups of LHC, two huge experiments, ALICE (A Large Ion Collider Experiment) and CMS (Compact Muon Solenoid) are being used to collect the experimental data of p-p and Pb-Pb collisions to test the theoretical predictions and expectations of Standard Model [3-4]. With the operation of p-p collision at LHC, a new energy range (upto 7 TeV) is explored where the production of particles from strong interactions are predominantly gluonic in nature and estimated to play growing role. The production of pions is identified by numerous independent techniques and information from the ITS (inner tracking system) and TPC (time projection chamber) of the detector [5-6].

ALICE is a multipurpose detector use to study proton-proton collision and is especially dedicated to study the heavy ion interactions. Sequentially to cope with the challenges, the

ALICE offline project has developed a coherent simulation framework as integral part of the AliRoot object oriented (C++) framework for simulation, reconstruction and analysis based on Root. Its main components are the virtual Monte Carlo, a set of collaborating classes for primary particle simulation and base classes for fast simulation. The virtual Monte Carlo interface has been developed by the ALICE offline project in order to make the user code for detector simulation, independent from the underlying transport Monte Carlo [7-8].

The purpose of this project is to study the pions produced in primary interactions, different production and decay channels of π-mesons, using Monte Carlo simulation technique for ALICE set-up and FLUKA (particle transport code) to identify the pions as production signals of Quark Gluon Plasma (QGP).

The introductory chapters (1-2) contain some basic concepts of pions, their production modes in the p-p collision using Monte Carlo simulation method. In chapter (3) necessary steps for experimental work and data collections have been described. The results of these studies have been discussed in the chapter (4). References of each chapter are given at the end of the corresponding chapter.

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CHAPTER 2

LITERATURE REVIEW

2.1 THE STANDARD MODEL OF PARTICLE PHYSICS

In 1960 Sheldon Glashow's discovery about combining electromagnetic and weak interactions led to the foundation of Standard Model [1]. In 1967, Abdus Salam and Steven Weinberg worked together to include the Higgs mechanism into electroweak theory which gives it a present form [2-6]. Masses of elementary particles are described in Standard Model through Higgs mechanism. This consists of $W^{\pm}$, Z^{0} bosons and fermions masses, i.e. leptons and quarks. In 1973, after the discovery of neutral weak currents caused by the exchange Z^{0} boson, the electroweak theory developed and extensively accepted. Glashow, Salam, and Weinberg shared the Nobel Prize for discovering electroweak theory in 1979 [7-8]. The $W^{\pm}$,Z^{0} bosons were exposed experimentally in 1981with same masses as predicted by the Standard Model.

Development in the Standard Model of particle physics continued from mid to the end of 20th century. The Standard Model achieved further confidence, after the sighting of the bottom quark in 1977, the top quark in 1995 and the tau neutrino in 2000. This Model is occasionally considered as the "theory of almost everything", due to its achievement in simplifying a wide range of experimental consequences. On the other hand, the Standard Model is not an absolute theory of basic interactions as it does not clarify the physical significance of dark mass, dark energy and full theory of gravitation as described by general relativity. The oscillations of neutrino and their non-zero masses are not correctly accounted in this model. This model is rather theoretical explanation of interactions of quarks and leptons. Quarks and leptons are the basic constituent of all the matter in the universe. Fundamental forces such as strong, weak and electromagnetic forces are responsible to bind the quarks and leptons together. A typical example of QFT (Quantum Field Theory) is Standard Model which reveals a vast variety of physics, containing spontaneous symmetry breaking etc. It is used as a basic theory for building several models which include hypothetical particles and symmetries. Experimentalists have integrated the Standard Model for the search of new physics beyond it. Some properties of so called elementary particles estimated by the Standard Model are specified in the table 2.1.

Classification			Name	Symbol	Charge	Mass (MeV/c^2)	Life Time (seconds)
Fermions	Leptons		Electron	$e^{\pm}$	±e	0.5110	∞
Fermions	Leptons		Muon	$\mu^{\pm}$	±e	105.7	2.20×10^{-6}
Fermions	Leptons		Tau	$\tau^{\pm}$	±e	1784	3.04×10^{-13}
Fermions	Leptons		Neutrino	ν_e, $\bar{\nu}_e$ ν_μ, $\bar{\nu}_\mu$ ν_τ, $\bar{\nu}_\tau$	0 0 0	0 0 0	∞ ∞ ∞
Fermions	Hadrons	Mesons	Pion	$\pi^{\pm}$ π^{o}	±e 0	139.6 135.0	2.60×10^{-8} 0.87×10^{-16}
Fermions	Hadrons	Mesons	Kaon	$K^{\pm}$ K^{o}, ($\bar{K}^{o}$)	±e 0	493.7 497.7	1.24×10^{-8} 0.89×10^{-10}
Fermions	Hadrons	Mesons	D meson	$D^{\pm}$ D^{o}, ($\bar{D}^{o}$)	±e 0	1869 1865	10.7×10^{-13} 4.3×10^{-13}
Fermions	Hadrons	Baryons	Proton	p, $\bar{p}$	±e	938.3	> 10^{39}
Fermions	Hadrons	Baryons	Neutron	n, $\bar{n}$	0	939.6	896
Fermions	Hadrons	Baryons	Lambda	Λ^{o}, $\bar{\Lambda}^{o}$	0	1116	2.63×10^{-10}
Fermions	Hadrons	Baryons	Sigma	Σ^{+}, $\bar{\Sigma}^{+}$ Σ^{o}, $\bar{\Sigma}^{o}$ Σ^{-}, $\bar{\Sigma}^{-}$	±e 0 ±e	1189 1193 1197	0.80×10^{-10} 7.40×10^{-20} 1.48×10^{-10}
Fermions	Hadrons	Baryons	Xi	Ξ^{o}, $\bar{\Xi}^{o}$ Ξ^{+}, $\bar{\Xi}^{+}$	0 ±e	1315 1321	2.90×10^{-10} 1.64×10^{-10}
Fermions	Hadrons	Baryons	Omega	Ω^{-}, $\bar{\Omega}^{-}$	±e	1672	0.82×10^{-10}
Bosons			Photon	γ	0	0	∞
Bosons			Graviton	2	0	0	Not Yet
Bosons			Gluon	1	0	0	Indirectly (not observed singly)
Bosons			W^{+}	1	+1	80	Yes
Bosons			W^{-}	1	-1	80	Yes
Bosons			Z^{0}	1	0	91	Yes
Bosons			Higgs	H	0	125.06	Not Yet

Table 2.1 Classification of atomic particles and their properties e.g. charge, mass etc.

2.2 QUARK-GLUON PLASMA (QGP)

After the Big Bang in millionth of a second, the universe was like dense plasma, under extreme condition that is, at extremely high temperature and density that neither nuclei nor even nucleons could exist. The plasma made up of quarks (the particles that compose nucleons), some other elementary particles and gluons (the massless particles which carry force between quarks). As quarks interact through strong interaction they exchange gluons or in the modern physics language, strong force is mediated by gluons between quarks. Since hadrons are made up of quarks which leads to the force that holds nucleons together in the nucleus. Unlike atomic plasma, above mentioned quark-gluon plasma is a mixture of exotic particles [9].

Quark–Gluon Plasma (QGP) is a probable state of QCD which contains free quarks and gluons that are some of the essential basic constituents of matter. Moreover, the interaction of quarks and gluons are different from other particles. As they are separated, they attract each other more strongly at low temperatures and densities which explain why existence of free quarks does not occur in nature. Quarks and gluons give contribution in the composition of baryonic matter [10]. In ordinary matter, quarks are confined where as in the QGP, quarks are free to move. The color charge of quarks and gluons is observed in Quark–gluon plasma. The color electric field is not displayed outside a finite volume of QGP, so that Quark-Gluon Plasma must be color-neutral. Therefore it will have integer electric charge like a nucleus.

Quark-Gluon plasma can be produced experimentally in the laboratory at high temperatures and densities. The behavior of ensuing matter does not resemble with the quasi-ideal condition of deconfined quarks and gluons, but it is more like an ideal intense fluid [11]. In fact the QGP state will not be free at temperature range attained at present colliders, was estimated in 1984 as a result of the residual effects of confinement [12-13]. First attempt which was made to generate QGP was in 1980s and 1990s at CERN's Super Proton Synchrotron (SPS). These results directed CERN to declare indirect confirmation for a new state of matter in the year 2000 A.D [14]. Existing experiments at the Brookhaven's National Laboratory, Relativistic Heavy Ion Collider (RHIC) in USA and at Large Hadron Collider (LHC) at CERN in Switzerland, are continuing this effort by smashing relativistically accelerated gold ions and lead ions respectively into each other [15-16].

2.3 LARGE HADRON COLLIDER (LHC)

A collider is a category of particle's accelerator which involves confined beams of elementary particles. Colliders are used as exploring machines in Particle Physics, to accelerate particles at high kinetic energies, allowing them to interact with more particles. Analysis of the by-products as a result of these interactions provides fine evidences about the composition of subatomic world and the natural laws. At high energies, these become noticeable only for small intervals of time and therefore may be tough or unfeasible to study in other ways.

European Organization for Nuclear Research (CERN) built the world's largest and highest energy particle accelerator known as Large Hadron Collider (LHC) from 1998 to 2008. The aim of LHC is to analyze the estimations of various theories regarding particle physics, high energy physics and predominantly for the survival of the theorized Higgs boson and the large family of new particles which were forecasted by supersymmetry [17-18]. Large Hadron Collider hopefully addresses various basic questions of physics and enhances the understanding of the fundamental laws of nature. The LHC is situated in a circular tunnel of 27 kilometers in circumference and 9 kilometers in radius, as deep as 100 meters beneath across the France and Switzerland border near Geneva, Switzerland. Different experimental setups comprising of various detection techniques have been deployed in the LHC tunnel and all of them are designed for particular type of investigation. The synchrotron of LHC is designed for the collision of opposed beams of protons up to 7 TeV [19-20]. More than 15,000 scientists and engineers from different laboratories and universities, over 100 countries took part in the construction of LHC [21]. The main purpose of LHC physics plan is proton–proton collisions. However, for short intervals of time, normally one month in a year, heavy-ion interactions are incorporated in this program [22]. Six detectors are located at the intersection points of LHC's tunnel. A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) are gigantic setups which are designed to detect the particle ensuing from p-p and Pb-Pb interactions [23]. A Large Ion Collider Experiment (ALICE) and LHCb possess more particular tasks and remaining two very small detectors, TOTEM and LHCf are designed for specific research. A graphical representation of LHC tunnel is drawn in figure 2.1.

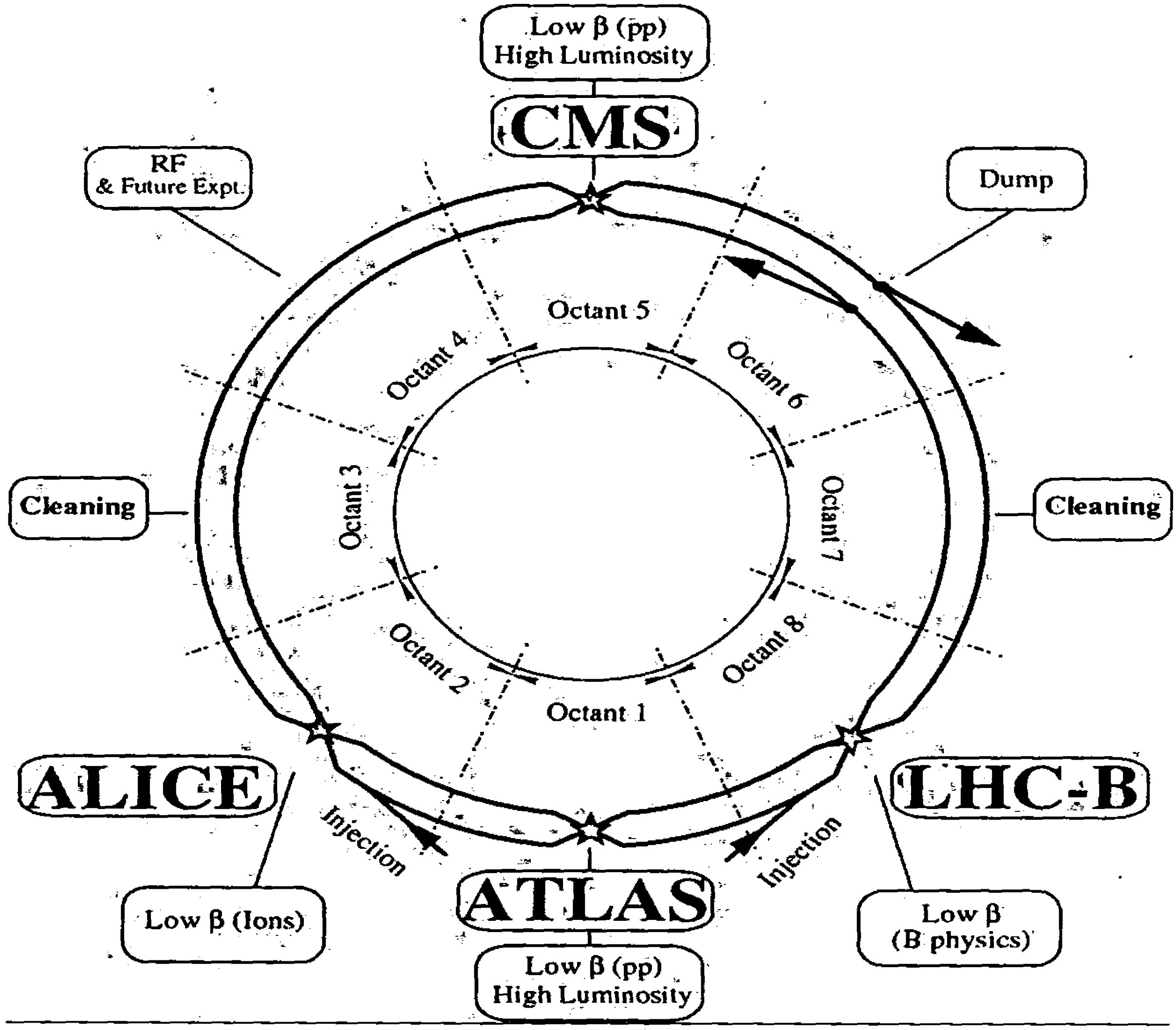

Figure 2.1 Schematic representation of LHC tunnel and the experimental setups to carry out the studies of HEP.

The circulation of proton beams was successfully made in the central ring of LHC tunnel on 10 September 2008 for first time. After 9 days, the operations were stopped because of magnetic quench arising from an electrical error [24]. More than 50 superconducting magnets and their mountings were infected by the explosions of helium gas [25-26]. Again proton beams were circulated successfully on 20 November 2009 and recorded first p–p collisions [27-28]. The first collision was made between two beams of proton having energy 3.5 TeV on 30 March 2010. This collision sets the world record for highest energy and the LHC started its deliberated research program [29]. Until the end of 2012, the LHC will function at 4 TeV per beam which is

0.5 TeV advance than 2010 and 2011. After that, for 22 months it will be shut down and then again functional at the end of 2014, allowing full energy operation with the energy of 7 TeV per proton beam [30].

Scientists look forward that LHC will answer several basic questions of physics, regarding the fundamental laws of forces and interactions among the elementary constituent of matter, particularly the connection of general relativity and quantum mechanics where present theories and information are uncertain.

2.4 PI-MESONS (PIONS)

Significant development in the field of theoretical physics occurred in 1935 when Yukawa attempted to find the field theory of nuclear force patterned after the theory Fermi had developed for β-decay [31]. In the Fermi theory, the basic transformation taking a neutron into a proton involves the emission of the electron-neutrino pair with a certain assumed coupling. Using the virtual emission and absorption of electron-neutrino pair between the neutron and proton, Yukawa tried to generate the strong nuclear force between the nucleons. He based his considerations on an analogy with electromagnetic forces between charged particles which are generated by exchange of photons between them. The basic electric force, the coulomb force has an infinite range of interaction because the exchanged photons are mass less. He showed that exchange of massive quanta between nuclear particles would give rise to a short range force, the range being inversely proportional to the mass of the exchanged particles. He found the strength of β-decay coupling to be too weak to generate the strong nuclear force. Yukawa thus put forward another idea of transformation of the neutron into a proton involves emission of another particle with a new coupling. To fit the short range nature of the nuclear force, he realized that this new particle cannot be mass less, for it was known that exchange of mass less photon give rise to the long range Coulomb force. He introduced the mass of new particle and fitted its value to obtain the right range of the nuclear force, i.e. about 10^{-13}cm. He needed about three hundred electron masses to achieve this [32]. Here was the new prediction on the existence of particles of mass intermediate between electron and proton. Such particles were later found in nature and are called mesons. Yukawa then proposed a mathematical form for strong nuclear force. His potential energy (P.E) function has the mathematical form [33].

$$P.E = -K \frac{e^{-\alpha r}}{r} \qquad 2.1$$

where the constant 'α' has the dimensions of reciprocal length and 'K' is the positive constant that must be determined from experiments. For pions as exchanged particles the force corresponding to the Yukawa's potential has a much shorter range than that of Coulomb force. It has appreciable magnitude only over a distance comparable to nuclear dimension i.e. about 10^{-15}cm. At that time such particles could not be produced in the laboratory because no accelerators were available with enough energy to produce these particles. Cosmic rays were the only source known at that time which had high energy particles among them. The search for particles with mass intermediate between those of the electron and the proton were undertaken by a number of researchers working on cosmic rays in the early periods using cloud chambers and later by using photographic emulsion plates. A particle now called the 'muon' was the first to be found in such studies. For a number of reasons it turned out that, it was not the particle which could be the mediator of strong forces. In this scenario, Powell and collaborators exposed photographic plates to cosmic rays at high altitudes [34]. When the plates were developed, they found them to contain tracks of new particles, which had not been seen before and were named as π-mesons. They saw events, which they interpreted as decay of π-meson coming to rest in the emulsion and decaying into a muon. The decay muon was always found to have the same range in the emulsions, about 600 μm. This is consistent with the kinematics of two body decay in which the decay products will have monochromatic energies. The other member of the two body decay product did not have a track in the emulsion, probably because it was neutral. The kinematics was consistent with the neutral particle having zero mass and they considered it to be the neutrino. There were also events recorded where, in addition to the π decay to μ, they saw the μ decay to e. A pion interacts with the target nucleus via strong interactions and is freely absorbed on complex nuclei. The pion is absorbed in the target nuclei and deposits its kinetic energy and rest mass energy which leads to high nuclear excitations. Therefore, even a nucleus having high fission barrier can be subjected to collapse under shower with pions. There are two main characteristics of pion induced fission studies. Firstly, the reactions of pion with nucleus offer a condition, in which high nuclear excitations are attained. Thus the effects of interior agitation on fission prospects, with and without high angular momentum can be evaluated. Secondly, for nuclear excitations by projectiles like photons and antiprotons, the pion serves as an intermediate step particle. By using charged pions of different energies, measurement of fission cross-sections in various targets are made which is an important step to understand behavior of nuclear many body system at high temperatures [35]. Studies of the interaction of the pions have been of great interest for the last many years. Some systematic experiments have been carried out for the measurement of parameters such as binary fission cross-sections and angular distributions of track length of the reaction products [36].

In the early years of discoveries, progress of such work with cosmic rays was slow but with the building of high energy accelerators at various institutions, rapid progress have been made in this field. This fueled the growth of an era of good measurements with which one could find precise values for the mass, lifetime, spin, parity etc.There are three generations of pions i.e. π^+ π^- and π^0. The quark combination of π^+ is $u\bar{d}$ The mass and mean life time of the π^+ has been measured in a variety of experiments since it was discovered. The modern values are $m_{\pi+}$ = (139.56995 ± 0.0004) MeV and lifetime $\tau_{\pi}+$ = (2.603 ± 0.0005) x 10^{-8} s. The dominant decay mode is $\pi^+ \rightarrow \mu^+ + \nu_\mu$ with a branching ratio of (99.98770 ± 0.0004) %. The spin of π^+ has been determined by using a reaction $p + p \rightarrow \pi^+ + d$. There is no direct experimental determination of the spin of π^-. However, the spin of π^- must be zero because, it is just the antiparticle of π^+. The internal structure of π^- is $d\bar{u}$ The mass and the lifetime of π^- is same as that of π^+. The neutral π has been detected by its decay mode, $\pi^0 \rightarrow \gamma + \gamma$. It is made up of $(u\bar{u} - d\bar{d})/\sqrt{2}$. The mass and mean life time of π^0 is $m_\pi{}^0$ = (134.9764 ± 0.0006) MeV and $\tau_\pi{}^0$ = (8.4 ± 0.6) x 10^{-17} s respectively [37]. The $e^+ e^- \gamma$ decay mode of π^0 has branching ratio (1.198 ± 0.032) %. It also has spin zero because it is proven theoretically that a system with spin one cannot decay into two gammas while a system with spin zero can. Quarks are the elementary particles, properties of quarks are given in the table 2.2.

Generations	Quarks	Symbol	Rest mass (GeV/c^2)	Electric charge	Strange	Charm	Top	Bottom
1	Up	u	$\leq 3 \times 10^{-3}$	$\frac{2}{3}$	0	0	0	0
	Down	d	$\approx 7 \times 10^{-3}$	$-\frac{1}{3}$	0	0	0	0
2	Charm	c	≈ 0.12	$\frac{2}{3}$	0	1	0	0
	Strange	s	≈ 1.2	$-\frac{1}{3}$	-1	0	0	0
3	Top	t	≈ 4.2	$\frac{2}{3}$	0	0	1	0
	Bottom	b	$\approx 175 \pm 5$	$-\frac{1}{3}$	0	0	0	-1

Table 2.2 Classifications and properties of quarks in to different generations i.e. charge and rest mass etc.

2.4.1 PRODUCTION OF PIONS

Hadron production measurements in proton-proton collision at high energies opened a new novel and previously unexplored domain in particle physics which allows tests and validations of the predictive power of quantum chromodynamics [38]. Theoretical estimates predict that fraction of pions originating from gluon fragmentation stays above 75% in p_t range upto 30 GeV/c. Here the measurements of π production cross-section at ultra-relativistic energy provide constraints on the gluon to pion fragmentation in a new energy regime [39-40]. Significant fraction of hadrons is produced in pp-collision at high energies via soft parton interactions, which cannot be well described within the framework of perturbative quantum chromodynamics.

Using a 380 MeV α-particles beam incident on a carbon target, a team of researchers produced π^+-mesons in the laboratory for the first time in 1949 and detected them by the nuclear emulsion method in 1950. Using a synchrotron with 330 MeV gamma-rays incident on various targets such as hydrogen, beryllium and carbon, Steinberges and colleagues reported finding that multiple gamma-rays are emitted. By studying the angular correlation of the produced gamma-rays, they showed that they come in pairs from the decay of a neutral meson. An estimate of the cross-section for the production of neutral mesons showed that it is similar to that for the charged mesons. The cross-section in hydrogen and the cross-section in beryllium and carbon were found to be comparable. The meson they found was the neutral counterpart π^0, of the charged π-mesons. The neutral π-mesons were also found in cosmic rays through the study of the spectrum of gamma-rays in atmosphere at height of 70,000 feet, using the nuclear emulsion technique. Some of the production modes of the π-mesons are stated as follows.

If two nucleons collide, with initial kinetic energy in MeV range, they can create a π-meson [41-42]. Thus for proton-proton collision some possible reactions are,

$$p + p \rightarrow p + p + \pi^{o} \tag{2.2}$$

$$p + p \rightarrow p + n + \pi^{+} \tag{2.3}$$

$$p + p \rightarrow p + p + \pi^{-} + \pi^{+} \tag{2.4}$$

Since the rest mass of π^+ is 139.58 MeV, so it is the minimum initial kinetic energy in the 'center of mass' system which is needed to create a π^+-meson. Some reactions that might occur for a proton-neutron collision are,

$$p + n \rightarrow p + n + \pi^{o} \tag{2.5}$$

$$p + n \rightarrow n + n + \pi^{+} \tag{2.6}$$

$$p + n \rightarrow p + p + \pi^{-} \tag{2.7}$$

The occurrence of processes such as given in equations 2.2, 2.3 & 2.4 and equations 2.5, 2.6 & 2.7 shows that there is no conservation law for meson number. Pions are also produced by proton (p), antiproton ($\bar{p}$) annihilation and neutron (n), antineutron ($\bar{n}$) annihilation.

$$p + \bar{p} \rightarrow \pi^{+} + \pi^{-} + \pi^{\circ} \quad (2.8)$$

$$n + \bar{n} \rightarrow \pi^{+} + \pi^{-} + \pi^{\circ} + \pi^{\circ} \quad (2.9)$$

The charged pions can also be produced by following reactions.

$$p + p \rightarrow \pi^{+} + d \quad (2.10)$$

$$p + p \rightarrow \pi^{+} + (d + n) \quad (2.11)$$

$$p + n \rightarrow \pi^{\circ} + d \quad (2.12)$$

$$p + d \rightarrow He^{3} + \pi^{\circ} \quad (2.13)$$

$$p + d \rightarrow H^{3} + \pi^{+} \quad (2.14)$$

Pions can also be produced when a nucleon is exposed to γ-ray photon, such as

$$\gamma + p \rightarrow \pi^{+} + n \quad (2.15)$$

$$\gamma + n \rightarrow \pi^{-} + p \quad (2.16)$$

The neutral pions can also produced by bombarding hydrogen (protium and deuterium) with high energy photon.

$$\gamma + p \rightarrow \pi^{\circ} + p \quad (2.17)$$

$$\gamma + d \rightarrow \pi^{\circ} + (n + p) \quad (2.18)$$

$$\gamma + d \rightarrow \pi^{\circ} + d \quad (2.19)$$

Charged pions can also be produced from photons and from heavy ion collisions.

2.4.2 DECAY OF PIONS

Charged pions are unstable and primarily decay with a half life ($T_{1/2}$) of about 2.6×10^{-8} second. This decay process is as follows:

$$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu \quad (2.20)$$

and further

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_e \quad (2.21)$$

Equation 2.20 shows that the μ^+ (positively charged muon) subsequently decays into a positron and a neutrino pair. Pions may also decay according to the reaction [43]:

$$\pi^+ \rightarrow e^+ + \nu_e \quad (2.22)$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu + \gamma \quad (2.23)$$

$$\pi^+ \rightarrow \pi^\circ + e^+ + \nu_e \quad (2.24)$$

Similarly the possible decay processes with negative pions are as follow [10]:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu + \gamma \quad (2.25)$$

$$\pi^- \rightarrow e^- + \nu_e^- \quad (2.26)$$

$$\pi^- \rightarrow \pi^\circ + e^- + \bar{\nu}_e \quad (2.27)$$

The most likely decay mode of the π° meson is

$$\pi^\circ \rightarrow \gamma + \gamma \quad (2.28)$$

The mean life of π° is about 0.87×10^{-16} second [44]. π°cannot decay into only one photon because the momentum could not be conserved. In fact, in all these decays at least two particles must be produced in order to conserve momentum.

Rare decay modes are also possible e.g.

$$\pi^\circ \rightarrow \gamma + e^+ + e^- \quad (2.29)$$

$$\pi^\circ \rightarrow 2e^+ + 2e^- \quad (2.30)$$

2.4.3 THEORETICAL ESTIMATE OF PION REST MASS ENERGY

Yukawa's theory of nuclear force formulate theoretical estimate of pion rest mass energy. Looking at the exchange reactions which are specified in section 2.3, in each reaction, violation of law of energy conservation takes place to the extent of uncertainty principle i.e.

$$\Delta E \, \Delta t \cong \hbar \qquad (2.31)$$

where

ΔE = Energy of the pion mass,

Δt = Time between the ejection of pion by one nucleon and its capture by the other nucleon

$\hbar = h/2\pi$ and

h = Planck's constant

Considering the range of nuclear force $=1.5 \times 10^{-13}$ cm and pion velocity as velocity of light

$$\Delta t = 1.5 \times 10^{-13} / 3 \times 10^{10}$$

$$\Delta t = 0.5 \times 10^{-23} \text{ second.}$$

$$\Delta E = h/(2\pi \times \Delta t)$$

$$\Delta E = 6.63 \times 10^{-34} /(2 \times 3.142 \times 0.5 \times 10^{-23}) \text{ Joules}$$

$$\Delta E = 6.63 \times 10^{-34} /(2 \times 3.142 \times 0.5 \times 10^{-23} \times 1.6 \times 10^{-19}) \text{ eV}$$

$$\Delta E = 131.88 \text{ MeV.}$$

This value of the rest mass energy of pion is close to the measured value i.e. 139.6 MeV ($\pi^{\pm}$) and 135 MeV (π°) [45]. This proves that the exchange particle involved in the nuclear force is π-meson, as predicted by Yukawa's theory.

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CHAPTER 03

METHODOLOGY

Apart from the experimental studies of π included nuclear reactions using online, offline frameworks and SSNTDs (Solid State Nuclear Track Detectors), these studies can also be carried out using simulation techniques. There are a number of computation programmes for simulation studies, such that GEANT3, GEANT4 and FLUKA etc.

3.1 MONTE CARLO SIMULATION TECHNIQUE

A class of computational algorithms which is based upon repetitive random number sampling to calculate results have been named as Monte Carlo Methods. Physical and mathematical systems can be simulated with the help of Monte Carlo methods. If it is difficult to deduce a scientific result with a deterministic algorithm than it is more suitable to derive it by a computer using these methods [1]. John von Neumann, Nicholas Metropolis and Stanislaw Ulam invented the method of Monte Carlo Simulation in 1940, while working on the project of nuclear weapon designing and after that it was named as Monte Carlo Casino [2].

With the use of Monte Carlo Methods, the systems involving many degrees of freedom, like fluids, strongly coupled solids, disordered materials, and cellular structures can easily be simulated. These are widely used in mathematics and physics to evaluate complex problems that cannot be solved by using deterministic algorithms. When Monte Carlo methods are being applied in the exploration of space and oil, their forecast of failures are routinely better than other alternative methods [3]. Monte Carlo Methods have a lot of applications in engineering, electronics and geostatistics etc. Giving different levels of uncertainty, energy outcome of wind farm during its lifetime can also be simulated. Effects of pollution by diesel and petrol can also be simulated with the help of Monte Carlo Methods [4-5]. Numerical optimization approach is a dominant and well-known purpose of arbitrary numbers in numerical simulation. In this context, it is used to minimize or maximize some vector functions having large number of dimensions. Metropolis algorithm is the best recognized sampling technique which can be comprehensive and give methods which allow the analysis of inverse problems with complicated information and data having arbitrary distribution [6-7].

Deterministic algorithms work fine in small dimensions. When the function have several variables, these algorithms encounter troubles such as, if the number of assessment needed to enlarge quickly with increasing dimensions or the boundary of a multidimensional region is complicated then these algorithms cannot provide fast and efficient results. Monte Carlo methods offer a way out of this exponential increase in calculation time [8]. The use of Monte Carlo Simulation technique is remarkable in the field of physics research. Many accelerators and colliders at various energies with a variety of projectile-target combinations which are used in the experiments of High Energy Physics and other fields of science and technology, all over the world can be simulated using these methods.

3.2 THE ALICE EXPERIMENT

A Large Ion Collider Experiment (ALICE) is one out of the six detectors of Large Hadron Collider (LHC), situated at European Organization for Nuclear Research (CERN) in Geneva, Switzerland. ALICE is dedicated for the study of heavy ion interactions, however, it can also be used to study the proton-proton collision with great precision at ultra-relativistic energies. More than 1500 physicists and scientists from 100 institutions are currently carrying out the research in high energy physics in collaboration with ALICE. It was initially designed as an inner detector in 1993, later on balanced by an additional muon spectator designed in 1995 [9-10]. It is a broad spectrum detector which is being used for measurement of majority of known observables like hadrons, electrons, muons and electromagnetic radiations etc [11]. Some more technical modules with specifications and detector features of ALICE are shown in figure 3.1 [12].

- Design: Central barrel plus single forward muon spectrometer.
- Size: 16 meter high, 16 meter wide and 26 meter long.
- Weight: 10,000 tonns

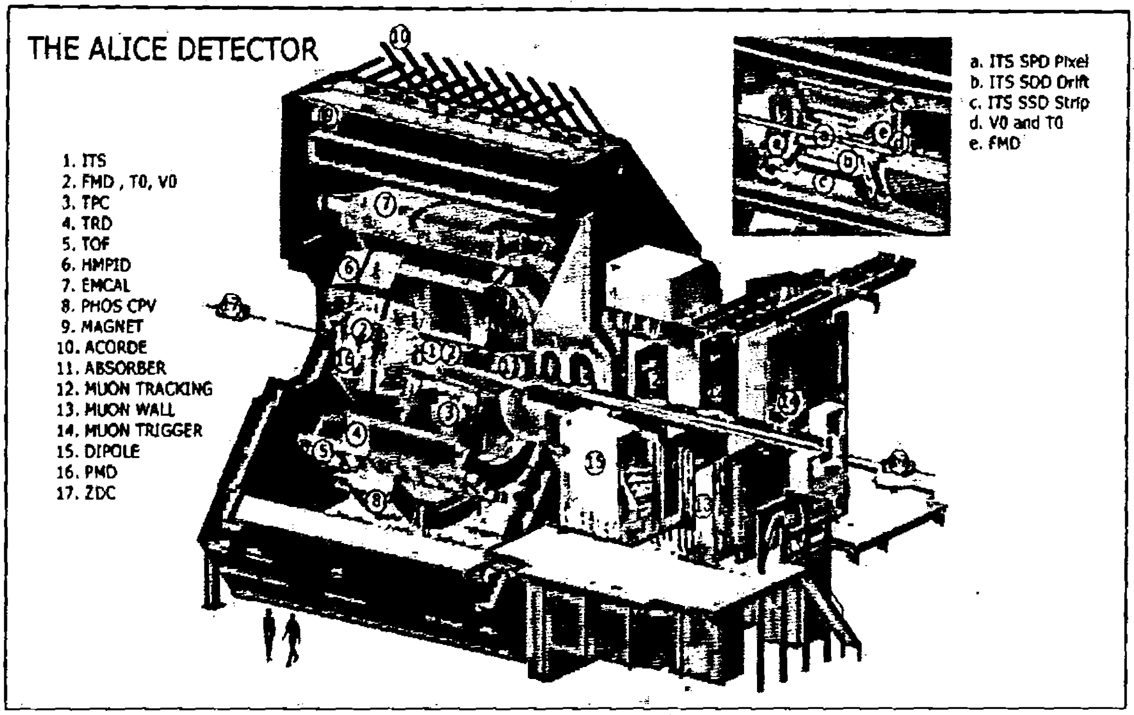

Figure 3.1 Schematic diagram of ALICE Experiment, indicating the position of its different detectors

3.3 OVERVIEW OF DETECTORS USED IN ALICE

The inner part of the ALICE detector is implanted in a big magnet with a weak solenoidal field (0.5 Tesla). It consist of Inner Tracking System (ITS) having six sheets of high resolution silicon detectors which are used for tracking, Time Projection Chamber (TPC) and a large area Particle Identification System (PID) arrangement of Time Of Flight (TOF) counters. Additionally, two small area single arm detectors, an electromagnetic calorimeter (EMCal) and selection of optimized counters for high momentum wide range particle identification (HMPID) composed of Time of Flight counters. The forward muon spectrometer is made up of multipart absorber's arrangement of, huge dipole magnet and twelve channels of triggering chambers and tracking. With the help of Zero Degree Calorimeters (ZDCs) this setup is accomplished which are positioned in the tunnel of machine and a Forward Multiplicity Detector (FMD) covering a significant portion of phase space. These detectors are used to identify the tracks of hadrons and electrons. The main barrel of ALICE is the combination of following components and particle detection modules.

> *Magnet*

The best possible option for the experiment is a huge solenoid having weak field. The choices of weak solenoidal field with continuous tracking in the Time Projection Chamber significantly simplify the task of pattern recognition. The magnet has enough large inner radius to accommodate Electromagnetic Calorimeter for photon which is situated 5 meter away above the vertex. The L3 magnet is a solenoid at room temperature having eight sided aluminum spiral which is cooled by demineralised water through external routes. In 1988, the magnet become operational for L3 Linear Electron-Positron Collider (LEP) Experiment [13]. The drift fields in the surrounding area of magnet satisfy relatively below 50 Gauss [14].

> *Inner Tracking System (ITS)*

The vital function of ITS is to reconstruct the hyperon decay, tracking and identification of particles with low momentum. This feature is attained with six barrels detectors having high resolution. Due to high particle density, the four inner most layers are purely made up of Silicon Drift and Silicon Pixel Detectors. The outer layer's cooling system of the ITS is planned to fulfill the necessities of the TPC in terms of uniformity and stability of temperature [15]. Additionally, for particles with momentum greater than 3 GeV/c, the spatial correctness of ITS is critical component for the resolution of momentum [16-17].

The Silicon Pixel Detector (SPD) is made up of hybrid silicon pixels. It is an essential aspect to determine the location of the principal vertices and calculations of the impact parameter of secondary particle tracks originating from the weak decays of strange, charm, and beauty particles [18-19]. Two transitional layers of ITS is composed of Silicon Drift Detectors (SDD), where the density of charged particle is 7 cm^2. On the planes of both detectors in every drift region, the cathode strips with 120 mm pitch are placed in order to fully diminish the volume of detector [20]. Two sided Silicon Strips Detectors (SSD) are used on the both outer layers of ITS. The detection modules have one sensor which is linked to two hybrids having six chips each [21-22]. Aluminum on polyimide micro cables is used in making connections among the sensors in the detection module [23]. The technology of every section was selected according to the environment of radiation and magnetic field in which they function.

➢ *Time Projection Chamber (TPC)*

The TPC is most important detector used for tracking in the inner barrel region and optimized to offer measurements of charged particle momenta with good capability of two track separation, particle recognition and the calculation of vertices [24]. The inner radius of TPC is 90 cm which is the maximum suitable hit density of 0.1 per cm^2. The outer radius is of 250 cm, designed for dE/dx resolution less than 7 percent. A special setup with an inner readout chamber was designed to perform beam tests before embedding of TPC in ALICE in 2007 [25]. The complete detector was deployed in parts and than all the designed features go through a serious test [26]. TPC cylinder is instrumented at the end plates of the readout chambers plates covering entire area of 32.5 m^2 [27–29].

➢ *Transition Radiation Detector (TRD)*

The main objective of TRD is the identification of electron having momentum above 1 GeV/c in the central barrel region [30]. Through specific energy loss measurement, the identification of electrons having momentum below 1 GeV/c can be recognized in the Time Projection Chamber. The recognition of electron offered by TPC and TRD having $p_t > 1$ GeV/c can be utilized, in combination with the determination of impact parameter tracks of electron in the ITS, to measure charm and the bottom quarks which produced in the interactions. The addition of the TRD, appreciably enlarge the objectives of ALICE physics [31-33].

➢ *Time-Of-Flight (TOF) Detector*

The TOF detector is an array of large area used for identification of particle having intermediate range of momentum below 2.5 GeV/c for pions and kaons and up to 4 GeV/c for protons [34]. This offers large models of charge particles such as protons, pions and kaons for event by event classification. Furthermore, studies of invariant mass particularly for detection of heavy flavored and vector meson is permitted by recognized kaons [35]. A gaseous detector was selected to cover large area and the best way out for the Time of Flight detector is the Multi gap Resistive Plate Chamber [36-37]. High and consistent electric field more than complete gaseous level of detector is the main characteristic of these chambers.

➢ *High Momentum Particle Identification Detector (HMPID)*

The HMPID, is devoted for the evaluation of recognized hadrons at $p_t > 1$ GeV/c [38]. The main function of HMPID is to improve the particle identification ability of ALICE which enables the detection of charged hadrons outside momentum interval is achievable through loss of energy in Inner Tracking System, Time Projection Chamber and Time Of Flight dimensions. The detector's structure is optimized to observe the yield of particles at very high energies in p-p and heavy ion collisions [39]. Light nuclei with high transverse momentum in mid rapidity region, can be identified using HMPID [40].

➢ *Photon Spectrometer (PHOS)*

This is basically an electromagnetic spectrometer with high resolution which covers a partial recognition at mid rapidity region [41-42]. Its basic objective is to investigate the thermal and dynamical features of primary stage of the interactions which take out the measurements of straight photon having low transverse momentum. High discrimination is required for the identification of hadrons, neutrons and anti-particles. TOF observations in the electromagnetic calorimeter, provides discriminating criteria for the investigation of shower improvement [43]. The high energy resolution is desired to identify π^0 via invariant mass analysis of photons which are decayed, is achieved with the help of scintillator matter of sufficient thickness and provides high photon electron products.

➢ *Electromagnetic Calorimeter (EMCAL)*

The construction of Electro-Magnetic Calorimeter (EMCal) was started in 2008. It was designed to make ALICE capable to discover the jet quenching interaction physics of energetic quark and gluons produced during Pb-Pb collisions at the LHC with matter [44-45]. EMCal was designed to calculate the energy of emitted charged particles at forward rapidities, basically photons which are produced by the decays of π^0. The basic designed calorimeter's parameter was selected to achieve the necessary physics objectives of high transverse momenta [46]. Simulations of the EMCal reaction have exposed that the energy deposit have large background, primarily from delayed neutrons formed in the secondary interactions in adjacent equipment of the ALICE [47].

➢ *Alice Cosmic Ray Detector (ACORDE)*

The ACORDE is a collection of scintillators which is located on the top L3 magnet. Two roles are offered by it in ALICE, it offers quick trigger signals for commissioning and also provides procedures of arrangement and calibration of other detectors. In alliance with TPC, TRD and TOF typical actions of muons and multi muons can also be detected, allowing the discovery of cosmic rays possessing high energy in the region which lies at the bottom of cosmic rays spectrum [48]. The average threshold energy for atmospheric muons is nearly 15 GeV which cuts all the hadronic and electromagnetic mechanism, while upper energy limit for reorganized muons will be less than 2 TeV which depends upon the intensity of magnetic field up to 0.5 T.

➢ *Muon Spectrometer*

The comprehensive variety of heavy quark vector mesons resonances and the ϕ meson can be calculated in $\mu^+\mu^-$ decay channel with the assistance of Muon Spectrometer. Synchronized dimension of the quarkonia groups with the identical equipment permits a direct assessment of their creation rate based upon different parameters like p_t and collision centrality. It contains passive front absorbers which absorb photons and hadrons at the collision vertices. For fast interaction trigger, it is essential to note that the muon spectrometer depends on V0 detector to enhance its efficiency during the p-p collision at insignificant beam intensity [49]. Simulations were carried out with FLUKA and GEANT3 to optimize the arrangement of the spectrometer [50-52].

➢ *Forward Detectors*

Spectator nucleons are identified in ALICE, with the help of detectors known as Zero-Degree Calorimeters (ZDC). By using magnetic elements of the LHC beam line, neutrons are separated from protons. Each set of ZDC is made by two detectors, one for spectator neutrons (ZN) and one for spectator protons (ZP). These are installed on lifting platforms. The mark of observer proton has a wide distribution for the proton calorimeter [53-55]. To measure the multiplicity and spatial distribution of photons, Photon Multiplicity Detector (PMD) is used in pseudo rapidity range of $2.3 \leq \eta \leq 3.7$ [56]. To study the simulations of central collision, the design parameters of FMD in the section of mid rapidity region were used [57].

3.4 ALICE OFFLINE FRAMEWORK

In heavy ion collisions enormous data is produced and it was a big challenge for the physicists to handle such a large amount of data. Therefore, to get precise and accurate simulation results of data produced by ALICE detector, physicists have developed unique algorithms which are used for the analysis of data. The combination of these algorithms is commonly known as ALICE offline framework. To investigate and renovate data which comes from real interactions is the main purpose of the offline framework. Object-Oriented products had been used to restore the FORTRAN CERN library, which includes PAW and GEANT3 in the early 1990s [58-60]. When the offline framework of ALICE decided to shift to C++ in 1998, none of these products were entirely developed for production. To estimate the performance of ALICE detector, the team of offline framework and the scientists had started to develop software which sets a lot of stress on the developers, to offer working apparatus while developing the offline framework system. In this perspective a whole conversion to Object Oriented C++ with distinct progress line was sustained by the ALICE physics society, to provide an efficient working environment at least comparable with GEANT3 and CERNLIB. Different particles transport packages have been produced through virtual machine by using Monte-Carlo technique, to allow control at run time between packages. The ROOT framework was adopted after an intense evaluation period in November 1998 and immediately the improvement of the ALICE offline Framework was started [60-61]. ROOT frame work is an important part of the Offline framework which is used to handle at applications at large scale.

The move to C++ was successfully accomplished and ALICE users have now a framework which is exclusively in C++. With the help of AliRoot software all the scientific design information have been quoted which permit developers to deal with, both the instant requirements and the lasting objectives in the same framework with the help of contribution to all users of ALICE.

3.4.1 ROOT FRAMEWORK

Number of significant elements is offered by the ROOT. A whole framework of data analysis containing all the PAW properties, an advanced Graphics User Interface (GUI), a large set of valued functions involving mathematics, generation of arbitrary numbers, minimization methods and a complete set of object containers and documentation tools. With user classes and libraries the ROOT system can be comprehensive which makes the parts of system effective. These libraries are overloaded vigorously and can contribute the identical services of inhabitant ROOT classes. CINT C++ interpreter is one of the major parts of ROOT. CINT is used by the ROOT system which is used for execution C++ scripts and C++ line input command. The main benefit of C++ interpreter is to allow fast prototyping and to minimize the threshold for new users of C++.

ROOT is generally being used in Particle and Nuclear physics, particularly United States, in most of the European laboratories and also in other fields of science and technology [62]. The ALICE-developed AliEn system and the ROOT system are currently linked with each other. This is offering equivalent platform of computing for analysis at large scale in combination with the PROOF system.

3.4.2 ALIROOT FRAMEWORK

There is a central module in AliRoot framework called STEER. It offers routing, base classes, interface classes and run management. Every detector has independent modules which include simulation code, reconstruction and the analysis code is added effectively. To perform simulations of detector output, an abstract interface and various transport codes can be loaded. In many cases, every module requires the data of other module which results in the further difficulty of data possession. To overcome this issue, a whiteboard approach is developed where the shared data is placed to ROOT memory which is then available to all modules. This overcomes the dependence of modules and swaps them with respect to the whiteboard approach. The interactive browsing of data and object models are allowed by the grouping of class dictionary with folders. For the class methods, this function is normally misplaced. To prevent this problem the concept of tasks was introduced by the ROOT system to ensure general programming and browsing. With the help of tasks for interactive browsing, common and repeated methods could be raised. In AliRoot, reconstruction and analysis procedures are done by tasks.

An abstract interface called AliGenerator is developed to make possible the use of different generators. Study of full events, event by event analysis, single processes and a mixture of both, can be done with this interface. By applying this theoretical foundation class, numerous codes of Monte Carlo simulations such as PYTHIA, HERWIG and HIJING are available from the classes of AliRoot [63-65]. Another interface is developed with FLUKA, using Virtual Monte-Carlo to provide another substitute to GEANT3. The geometrical model of various packages is replaced which is free from some explicit simulation engine, for being used in analysis and in reconstruction of tracks. The AliRoot framework can offer data at different stages of the simulation process and evolution of the detector design, in order to offer the nearly consistent simulation of detector response.

3.5 INTRODUCTION TO FLUKA: A VIRTUAL MACHINE FOR MONTE CARLO SIMULATION

FLUKA is a broad function tool for the computation of particle transportation which covers a comprehensive range of applications. It is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications i.e. proton and electron accelerator shielding, target design, dosimetry and radiation protection, neutronics, calorimetry, tracking and detector simulation, detector design, Accelerator Driven Systems (e.g., Energy Amplifier), cosmic ray research, space radiation (space related studies partially funded by NASA), neutrino physics, hadron therapy and beam dump etc. It is a fully integrated Monte Carlo simulation package for the interaction of particles and nuclei in matter [66-68]. With the help of FLUKA, we can simulate the transportation of nearly 60 different particles in matter.

- Proton-proton and proton-nucleus interactions up to 10000 TeV.
- Heavy ion interactions up to 10000 TeV/n.
- Electromagnetic and μ interactions from 1 keV to 10000 TeV.
- Energy loss and transport of charged particle.
- Transport in magnetic fields.
- Transport and interactions of multi-group neutrons up to 20 MeV.
- Neutrino interactions up to 100 TeV.

We can also transport Synchrotron radiation and optical photons using this program. Tracking of emitted radiation from unstable residual nuclei and time evolution can be performed online. Premature versions of the FLUKA hadronic event generator were implemented in other codes particularly in GEANT3. The hadronic FLUKA generator in GEANT3 is no more developed since 1993 and cannot be compared with the present stand-alone FLUKA [69]. Improvement of sound and modern physical models is the highest priority of design and development of FLUKA. While developing FLUKA, microscopic models are used on every possible occasion, reliability among all the reaction types, conservation laws are mandatory at every step and results are verified with the experimental data [70]. Systematic use of double accuracy had a vast impact on overall precision which makes this code very efficient. These qualities are achieved by making cautious choice of the algorithms used. A reasonable flexibility is attained by minimizing the need for user-written code and provides a large number of choices to the user.

FLUKA package has dual capability. It can be utilized in fully analogue mode as well as biased mode in contrast with any other software. It can be used to forecast fluctuations, signal coincidences and other associated events, an enormous variety of arithmetical techniques are also accessible to examine other rare events in association with attenuations by several orders of magnitude. The performance and development of sound and contemporary physical models is an extraordinary characteristic of FLUKA. It can hold even very difficult geometries, using an enhanced version of the well known Combinatorial Geometry (CG) package. The FLUKA Combinatorial Geometry has been deliberated to observe correctly charged particles tracks even in the presence of magnetic or electric fields. A part of the code where effectiveness, precision, reliability and flexibility have combined and offering very valuable results is the FLUKA geometry. It is derived from the Combinatorial Geometry package and it has been completely revised. An entirely new, quick tracking approach has been developed with special consideration to charged particle transport, particularly in magnetic fields. New bodies have been launched; ensuing improved rounding precision, speed and with easier input preparation. A variety of visualization and debugging tools are also obtainable. In many purposes, no programming is required from the user. However, a number of user interface routines (in Fortran 77) are offered for users with particular necessities.

Efficiency has been achieved by having a frequent recourse to table look-up sampling and efficient use of dual precision has a great impact on overall accurateness. Both of these qualities have benefited from a cautious selection of the algorithms adopted. To manage a logical flexibility while minimizing the need for user written code, this package has been provided with a variety of choices accessible to the user. FLUKA uses a unique transport algorithm for charged particles together with a multiple Coulomb scattering treatment, giving the accurate imaginative displacement even near a boundary. A unique handling of multiple Coulomb scattering and of ionization fluctuations allows the code to manage precisely some complicated tasks, such as electron backscattering and energy deposition in thin layers even in the few keV energy range.

3.5.1 FLAIR FOR FLUKA

An advance and user friendly interface of FLUKA is known as flair. This interface makes easy edit of the input file, run codes and observe the output. It is based exclusively on Python. Flair offers following functionalities:

- An almost error free and easy editing interface known as front-end interface which is used for correction of errors of the user input during editing.
- During a run, it provides compiling, debugging and scrutinizing of the status.
- Processing of output files and generation of plots is done by an interface known as 'gnuplot' which is a back-end interface.
- It geometrical objects for easier editing, accumulating and sharing among projects of other users.
- Python is used for operating the input files, processing of the outcomes and for interfacing to 'gnuplot'.

Flair mechanism is direct with the FLUKA input file and is capable to read/write all suitable FLUKA input setups. The user is interacting instantly with the FLUKA cards inside the flair editor, having a small conversation with every card which displays the information in human understandable format. Flair is capable to read and write all layouts recognized by FLUKA, but internally it works always in the names format and tackles the input as a list of comprehensive cards. The built-in format for saving is constantly fixed with names for the input and free with names for the geometry. The user can dominate the default exporting format either by the appropriate FLUKA cards (like **FREE, GLOBAL, GEOBEGIN**) or by overriding the format in the project definition. Future developments of FLUKA include the enhancement of physics models for new ions, such as oxygen and helium, with a view to their possible use in hadron therapy. The code is also progressively in use to simulate the secondary radiation produced during treatment by the beam interacting with the patient. This feature is crucial as secondary radiation is being studied as a very powerful tool to perform monitoring during treatment. A general FLUKA input file is shown in figure 3.2.

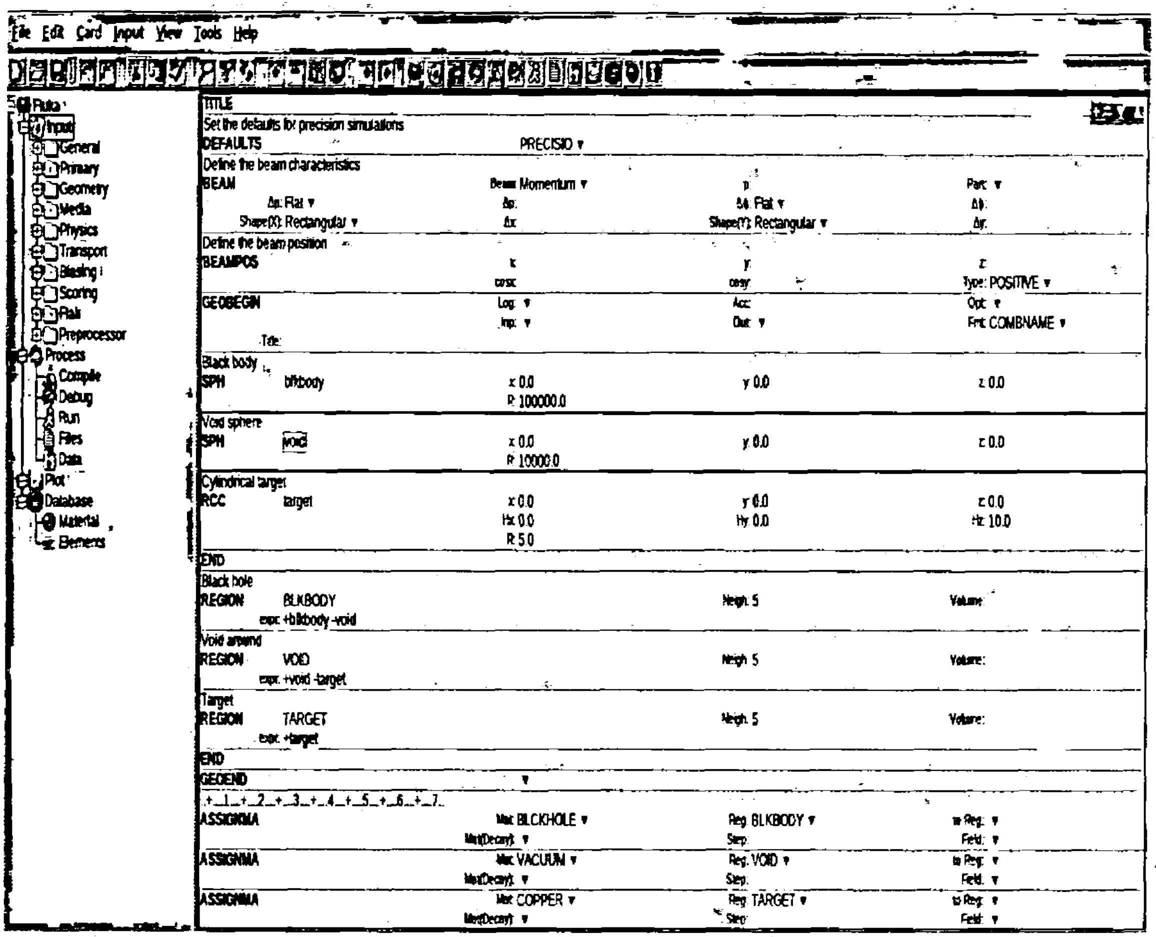

Figure 3.2 Schematic print out of general FLUKA input file

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CHAPTER 4

RESULTS AND DISCUSSIONS

The simulated results regarding production of pions in p-p interactions at various collision energies are presented in this chapter. These results are obtained by using two different Monte Carlo Simulation techniques i.e. with FLUKA software and then by using the ALICE offline framework. The energy distribution and spectral fluence of produced secondary particles during the collision are observed by these Monte Carlo Simulation packages. The data collected by using both of these softwares is then compared, analyzed and demonstrated in a broad way. The illustration of data analysis is essential because in just few graphs it could not be explained.

4.1 PIONS PRODUCTION IN p-p COLLISIONS USING ALICE OFFLINE FRAMEWORK

Large Hadron Collider (LHC) energy range provides exclusive information regarding measurement of the transverse momenta (p_t) spectrum of charged particles produced in p-p collisions. In this section the measurement of p_t spectrum of total charged particles and pions in p-p collisions is offered. Pions are the particles observed in the collisions or decay products of those particles which are produced from weak decays of strange mesons. This offline framework contains the complete simulation of the ALICE detector and the analysis of the p-p collision to observe the production of pions has been done by using Root software. The framework of AliRoot has been used to execute the study of simulation for the Technical Design Reports of all detectors of ALICE. The ultimate purpose of the offline framework is to reconstruct and analyze data which comes from real and simulated interactions. Additionally, this method allows us to review the working framework towards the final ambition of emerging physics from data. The event merging approach, in which a signal event before finishing the digitization process producing digits which contain the information of raw data is combined with principal signal free event. The significance of this process for simulation of heavy-ion collision lies in the fact that one principal event can be used for various signal events thus minimizing the time of computation and data storage space. Simulated result obtained by using ALICE offline framework and Root analysis software is placed here and the observed pattern of pion has been classified on the basis of p_t and at the end, results of the p_t spectrum are discussed in figure 4.1.

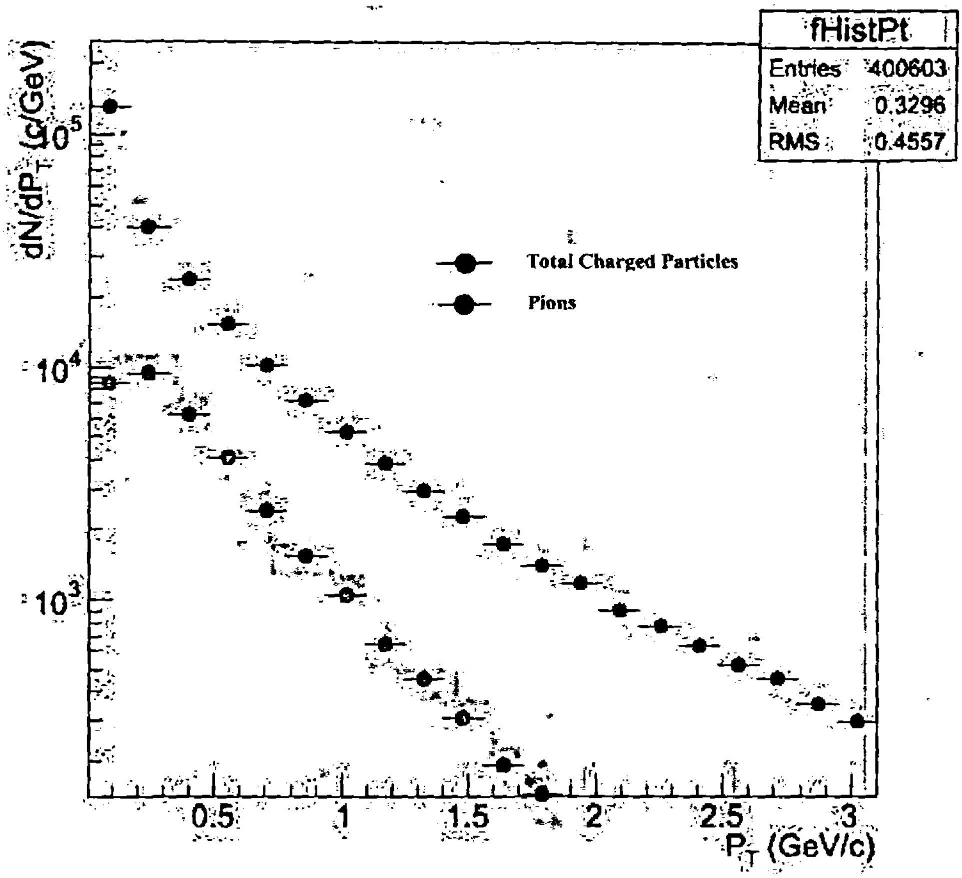

Figure 4.1 Monte Carlo Simulation results for the production of total charged particles and pions in p-p collision using ALICE Offline Framework at 900 GeV energy.

4.1.1 RESULTS AND DISCUSSIONS OF p_t SPECTRUM

The figure 4.1 is drawn by using ALICE offline framework which is based on the Monte Carlo technique. Data of p-p collisions at ultra-relativistic energy (900 GeV) is used for the demonstration of this graph and is analyzed with the help of Root software.

- Black dots in the p_t spectrum represent the total number of primary charged particles produced as a result of p-p collisions.
- Red dots in the p_t spectrum represent the production of pions as a result of p-p collisions.

This graph shows the curves of total charged particles as well as pions produced as a result of p-p collisions. Pions are the particles, observed in the collisions which are produced from weak decays of strange mesons. In this distribution pattern, transverse momentum p_t of the particles produced is taken on x-axis having p_t range $0.5 < p_t < 3$ in GeV/c while the number of pions and total charged particles produced as a function of transverse momentum p_t is taken on y-axis. This graph shows behavior of total charged particles produced as well as pions on the basis of transverse momenta i.e. how the abundance of total charged particles and pions vary with the increasing transverse momenta. Graph illustrate clearly that in start the abundance of pions produced increases with the increase in p_t but after sometime it goes on decreasing and at a certain value it becomes very low. It is clear from the graph that the abundance of pions is goes on decreasing and after a certain value the curve shows saturation. At this level the p-p collision is responsibly demonstrated by perturbative QCD in terms of the hard parton-parton scattering where large momentum transfers. The production of pion is maximum at 0.2 GeV/c. The curve of total charged particles also evolve the same results i.e. the particles production increase with increase in p_t and started decreasing with time and become saturated after 3 GeV/c as shown in figure 4.1. The p_t distribution of pions shows that the pions produced in p-p collisions have been emerged from the QGP phase produced just after the interaction take place. This trend of p_t also represents the QCD behavior domain in particle physics.

4.2 PIONS PRODUCTION IN p-p COLLISIONS AT VARIOUS ENERGIES USING FLUKA SOFTWARE

In p-p collisions, the behavior of energy spectrum of pions production can precisely and accurately be measured at Large Hadron Collider (LHC) energy range. The observed patterns of energy spectrum of pions in p-p collisions at different energies by using FLUKA package are presented and discussed here in this section. In FLUKA, Monte Carlo simulation technique is used for the recording of results which is called scoring. Some graphs are placed which are plotted with the help of FLUKA and at the end of this section, results of the energy spectra are discussed.

In present research work, the projectile (protons) of different energies strike with the target material. As a result of these interactions, very large number of pions is produced. The beam position is fixed at (0, 0, -1) and the radius of target material is 0.000000001cm (1×10^{-9}). The thickness of the target material is 2×10^{-8}cm (0.00000002). LAMBIAS card is added in the code which controls the inelastic collision of the particles and in this case $\lambda_{inelastic}$ is 0.00000000001cm (1×10^{-11}). To control the fluence of particles at boundary USERBDX card is added. The energy range of the scattered particles is 0.001 to that level at which we have to discuss the behavior of the graph. The data is preceded for 3 cycles having number of events 100000 (1×10^5). At the end we get the number of pions produced per cm^2 which are represented in different graphs.

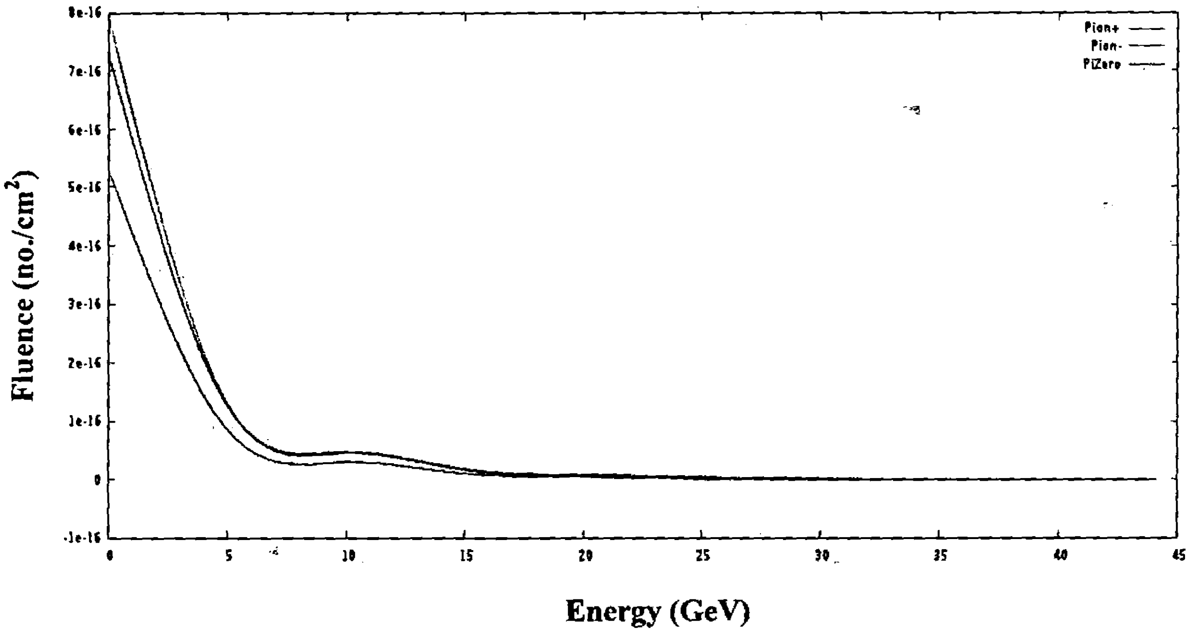

Figure 4.2 Figure shows the FLUKA results of pions production in p-p collisions at 50 GeV

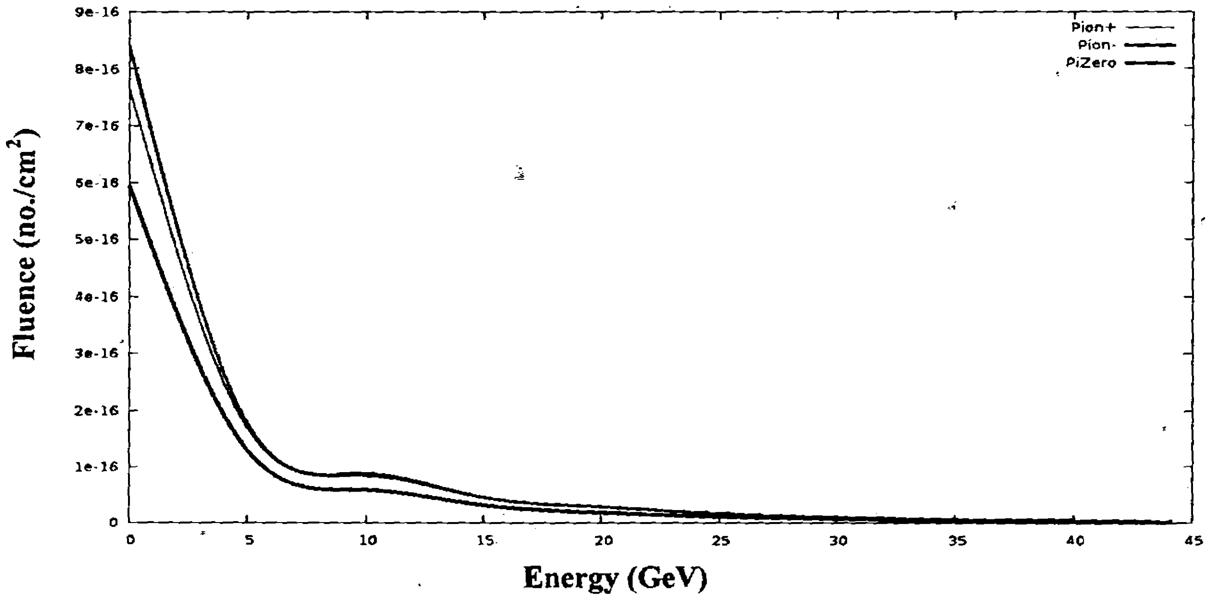

Figure 4.3 Figure shows the FLUKA results of pions production in p-p collisions at 100 GeV

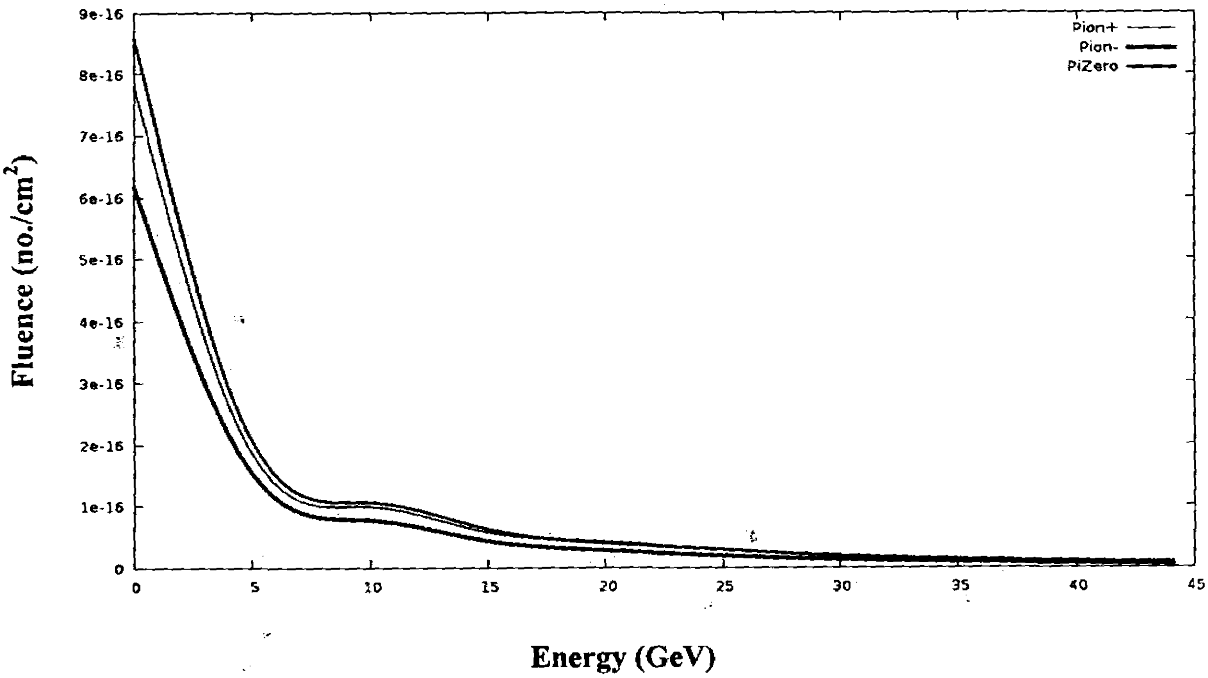

Figure 4.4 Figure shows the FLUKA results of pions production in p-p collisions at 150 GeV

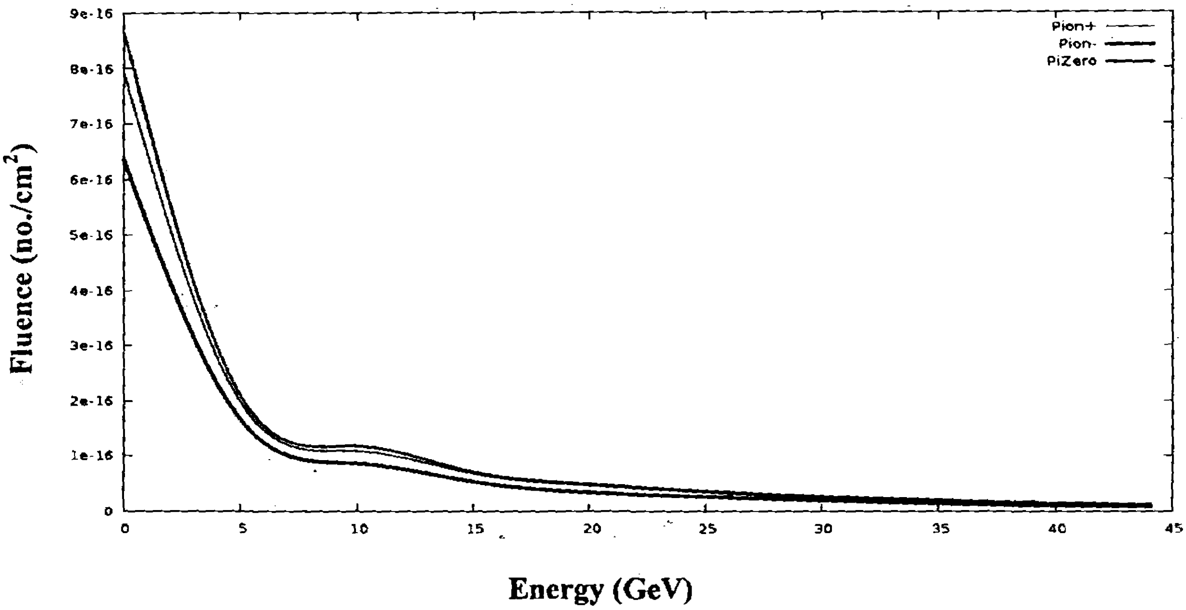

Figure 4.5 Figure shows the FLUKA results of pions production in p-p collisions at 200 GeV

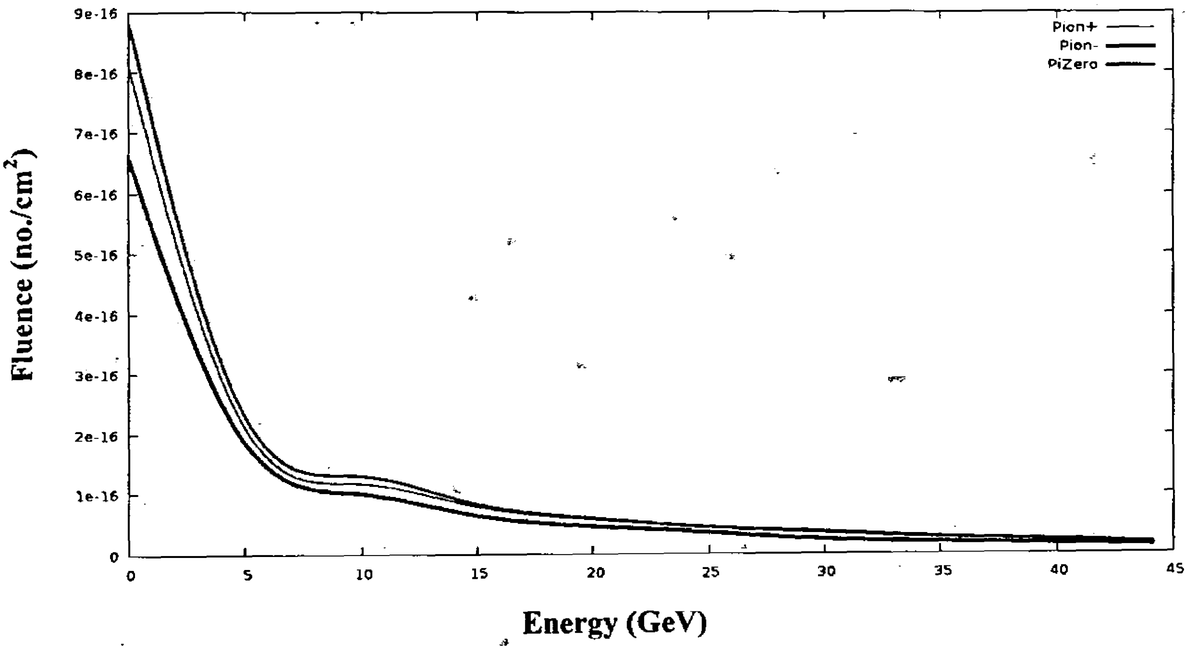

Figure 4.6 Figure shows the FLUKA results of pions production in p-p collisions at 300 GeV

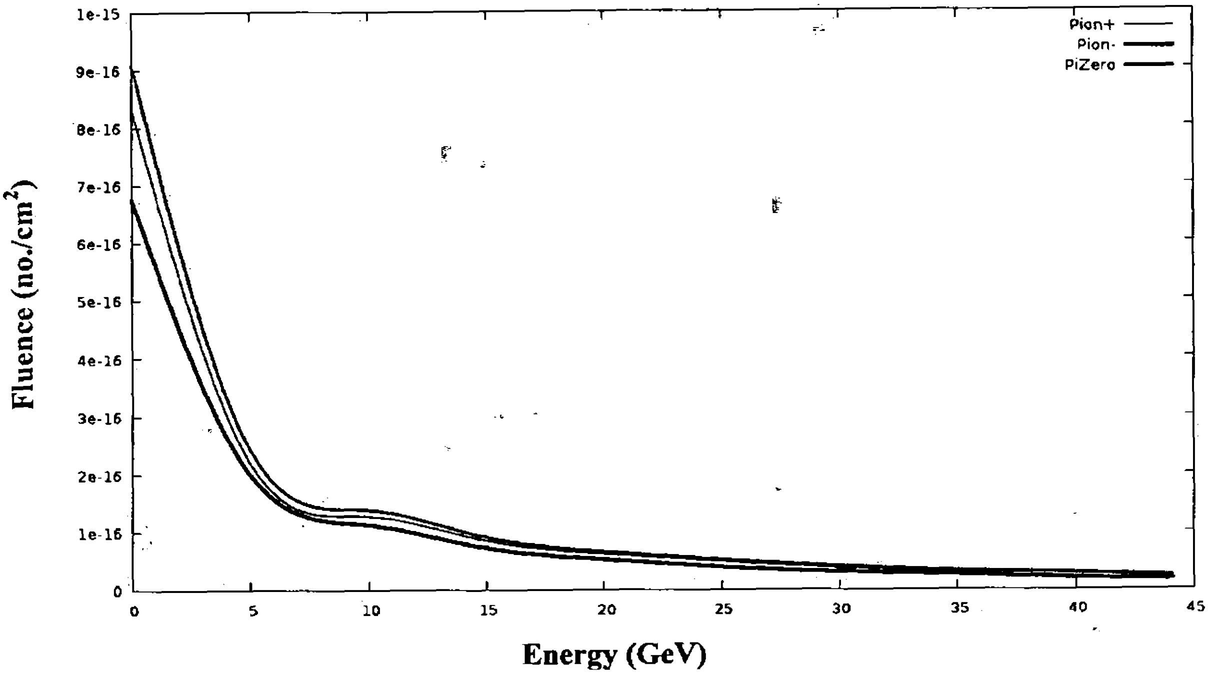

Figure 4.7 Figure shows the FLUKA results of pions production in p-p collisions at 400 GeV

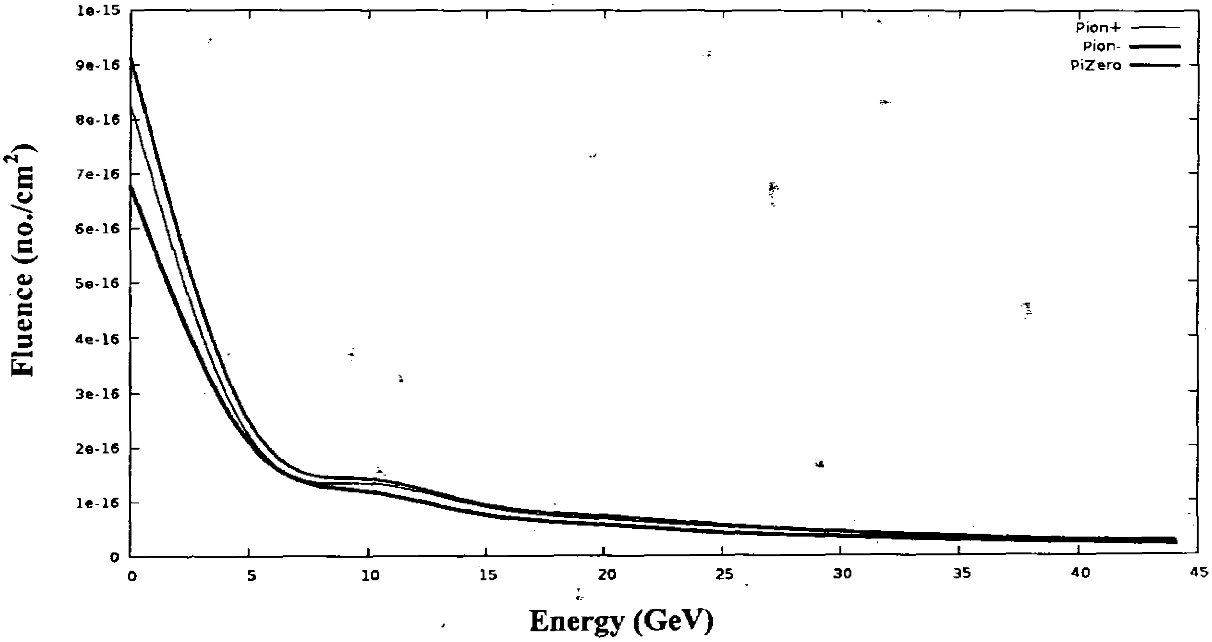

Figure 4.8 Figure shows the FLUKA results of pions production in p-p collisions at 500 GeV

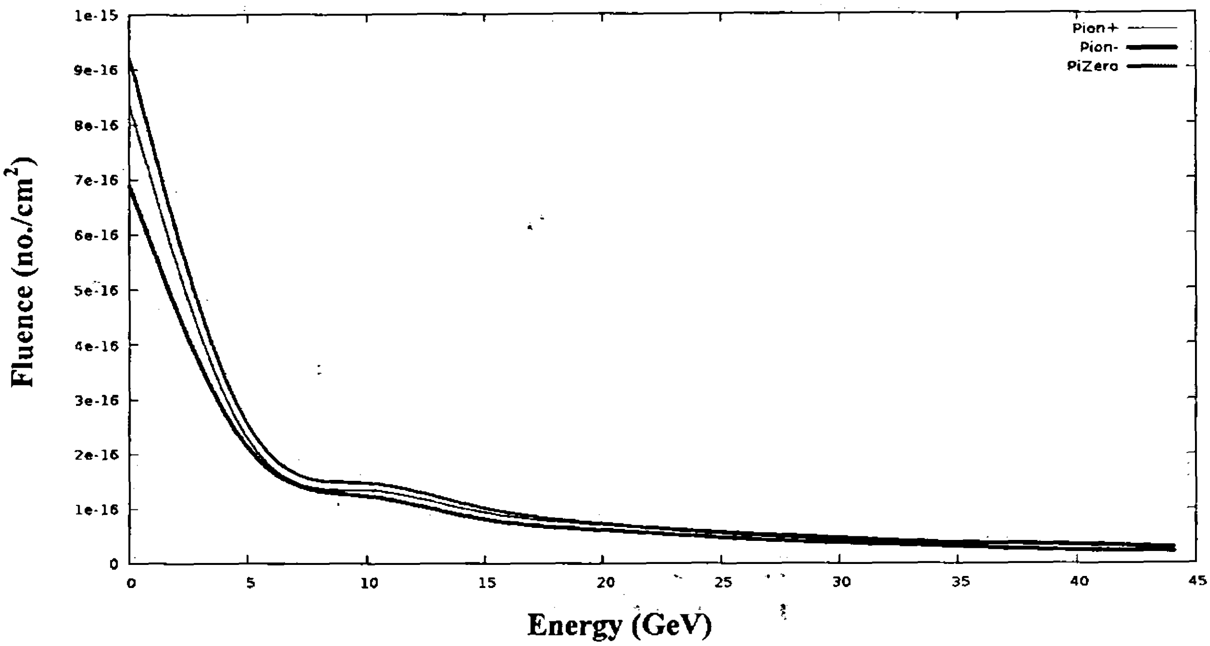

Figure 4.9 Figure shows the FLUKA results of pions production in p-p collisions at 600 GeV

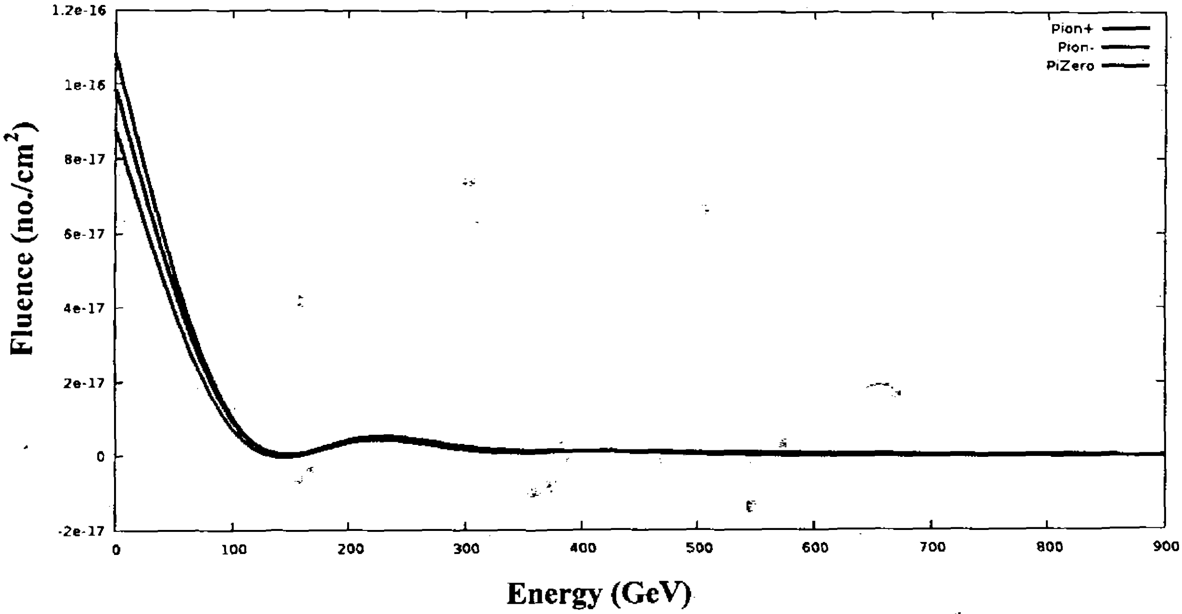

Figure 4.10 Figure shows the FLUKA results of pions production in p-p collisions at 2 TeV

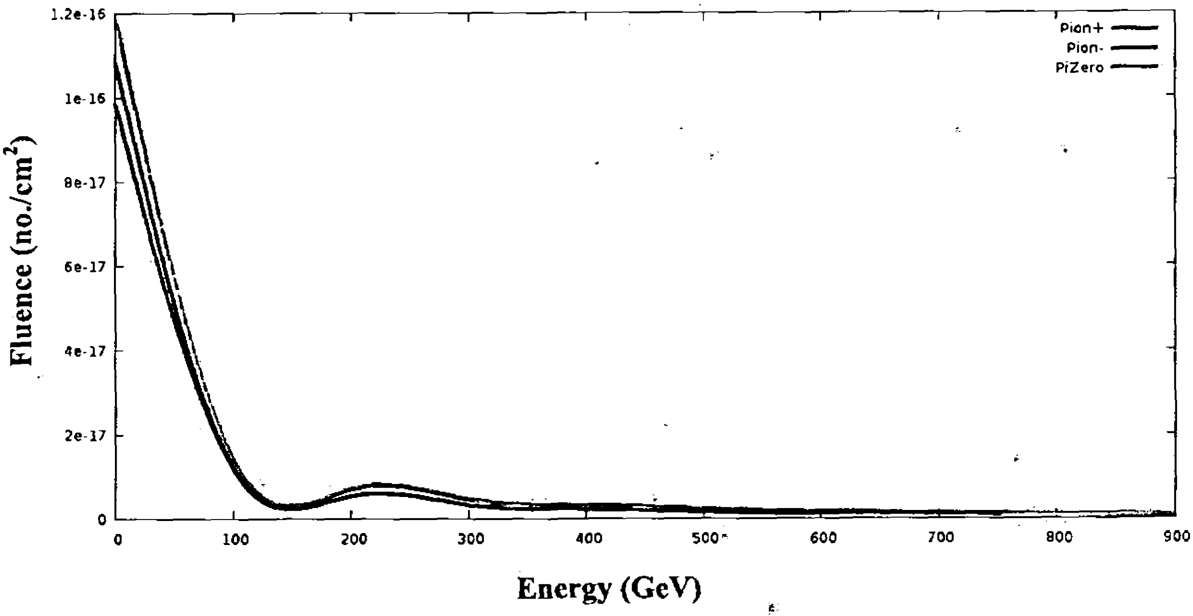

Figure 4.11 Figure shows the FLUKA results of pions production in p-p collisions at 5 TeV

4.2.1 RESULTS AND DISCUSSIONS OF ENERGY SPECTRUM

Figures 4.2-4.11 have been plotted by using Monte Carlo Simulation technique called FLUKA at different energy regimes. As a result of p-p collisions at very high energies, bulks of primary as well as secondary particles are produced. The objective of these graphs is to examine the production of pions ($\pi^{\pm}$ and π^{0}) which are secondary charged particles at different energy ranges. The energy spectrum of these charged particles is different at various energy levels. In this context, the energy spectrum of $\pi^{\pm}$ and π^{0} is made discretely which shows the consequences of FLUKA simulation of these charged particles at different energies. Figures 4.2 to 4.11 show the fluence of pions at different energy regimes. The kinetic energy of the produced particles is taken along x-axis and the range of energy is 0 to 45 GeV for first eight graphs. Last two graphs are plotted at 2 TeV and 5 TeV with kinetic energy range from 0 to 900 GeV, while the fluence (particles produced per cm^2) is taken along y-axis.

Figure 4.2 shows the energy spectrum of pions ($\pi^{\pm}$ and π^{0}) at 50GeV energy. From this figure, it is observed that the fluence of π^{0} is 8 e^{-16}, the fluence of π^{+} is approximately of 7.1 e^{-16} and for π^{-} fluence is 5.1 e^{-16}. It can be noticed that, at energy range of 0 to 2 GeV, maximum number of pions are produced while in range 2 to 40 GeV, comparatively less number of pions are produced. On the other hand, in the energy range of 40 to 45 GeV, very minute number of pions is produced and fluence curve shows saturation. It is clear from graph that fluence is the function of kinetic energy (scattered energy) of emerging particles and the pions fluence decreases with increasing kinetic energy.

Figure 4.3 shows that the fluence of π^{0} is 8.3 e^{-16}, for π^{+} the fluence is order of 7.6 e^{-16} and for π^{-} fluence is 6 e^{-16}. Figure 4.4 reveals that the fluence of π^{0} is 8.5 e^{-16}, for π^{+} the fluence is order of 7.8 e^{-16} and for π^{-} fluence is 6.2 e^{-16}. Figure 4.5 expose that the fluence of π^{0} is 8.7 e^{-16}, for π^{+} the fluence is order of 7.9 e^{-16} and for π^{-} fluence is 6.3 e^{-16}. After observing the behavior of these graphs, it can be noted that there is a small increase in the fluence of pions with increase in the energy of incident particles. It is measured that, in kinetic energy range of 0 to 2 GeV the maximum number of pions are produced while in range of 2 to 40 GeV, comparatively less number of pions are produced. On the other hand, in the energy range 40 to 45

GeV, very few pions are observed and the fluence curve become saturated. The relation between fluence and kinetic energy remains same as described in Figure 4.1.

In figures 4.6, 4.7, 4.8 and 4.9 same behavior is observed as in the above graphs i.e. the fluence is decreasing with the increase in the kinetic energy of scattered particles. In the energy range 40 to 45 GeV, the fluence of these particles becomes saturated. The fluence of figures 4.2-4.9 shows the dominance of hydro-dynamical behavior of the p-p collisions and is the representation of soft physical interactions phenomena. The decreasing trend of fluence of pion energy also represents soft and hard processes in hadronic formation.

Figures 4.10 and 4.11, the energy spectrum of produced pions is quite different from others because the energy of incident particles is very high i.e. 2 TeV and 5 TeV respectively. In the energy range 0 to 20 GeV, enormous numbers of pions are produced. As we move forward in the increasing kinetic energy range, a small bump is observed in the curve pions. This variation shows that pions are produced but they decay in the energy range 150 to 200 GeV. At further higher energy range i.e. from 320 to 500 GeV, the fluence curve shows saturation and after that the fluence becomes zero. In these two graphs, fluence is also function of kinetic energy of pions. These curves also show that fluence decreases with the increase of kinetic energy. The behavior of fluence with pion energy and the fluctuations in some particular energy ranges provide information that the pions reflect the perturbative QCD behavior in this energy regime. This trend is due to the mechanism of color confinement for which the physics is not fully understood.

Hence, these results of energy spectrum provide distinctive information to study the behavior of produced pions as a result of p-p collisions at different energy ranges.

CONCLUSIONS AND FUTURE RECOMMENDATIONS

In this research project the production of pions in p-p collisions at ultra-relativistic energies has been studied. It is observed that at these energies enormous numbers of particles are produced with varying properties. In the present research work, the transverse momentum spectrum and energy spectrums of pions produced as a result of p-p collisions has been studied, using ALICE offline framework and FLUKA software. As a result of this study, it is concluded that the abundance of produced pions increases with increase in the energy of colliding particles. It is also found that fluence of the produced pions decreases with increase in the kinetic energy of the particles.

In the extension of this work in future, one can measure the production cross sections of pions and other charged particles produced in p-p collisions at very high energies. The behavior of these charged particles with varying angles can also be studied. It is also possible to test out the performance of pions and other particles as a function of mass instead of energy. The measurement for the single and double differential cross-sections with respect to energy and angle can also be executed in the prolongation of this study.

SUMMARY

Large Hadron Collider (LHC) at CERN is the world's biggest particle accelerator. The presented study is based on one of the LHC detector called ALICE (A Large Ion Collider Experiment), which is a general purpose detector but particularly deliberated to study the heavy ion collisions and to observe a state of matter known as Quark Gluon Plasma (QGP). This phase of matter is supposed to be present in the early universe, about 10^{-5} second after the Big Bang. In this research work, production of pions in p-p collisions at various high energies has been studied, using two different Monte Carlo simulation packages i.e. ALICE offline framework and FLUKA. From the graphs, it is observed that huge numbers of particles are produced as a result p-p interactions. Firstly, the simulation is done by using ALICE offline framework for making transverse momentum (p_t) spectrum of pions. The analysis is done with the help of AliRoot package and observed that the production of particles significantly increases with the increase in the energy of colliding beams. Secondly, the simulation is carried out by using FLUKA software to make energy spectrums of pions at various high energies. FLUKA is the latest Monte Carlo code which provides very precise simulations. The results achieved with both packages are then discussed which shows that the production of pions and other charged particles in p-p collisions at various collision energies can be fine understood in the presented study. These results explicitly show that, large numbers of pions are produced in low kinetic energy range and the yield of pions decreases with increase in kinetic energy. As we move further along the x-axis, kinetic energy is increased and at a specific energy range the pions yield curve exhibits saturation.

APPENDIX-A

Input File

The input file of ALICE Offline Framework which is analyzed by Root software is given here as under

Include "TChain.h"

Include "TTree.h"

Include "TH1F.h"

Include "Tcanvas.h"

Include "AliAnalysisTaskPtMC.h"

Include "AliAnalysis Manager.h"

Include "AliESDEvent.h"

Include "AliESDInputHandler.h"

Include "AliMCEventHandler.h"

Include "AliMCEvent.h"

Include "TParticlePDG.h"

// example of an analysis task creating p_t spectrum

// Authors: Panos Cristakoglou, Jan Fiete Grosse-Oetringhaus, Christian Klein-Boesing

// Reviewd: A.Gheata (19/02/10)

Classinput (AliAnalysis TaskPtMC)

//____

```
AliAnalysisTaskPtMC::AliAnalysisTaskPtMC (const char*name)

:AliAnalysisTaskSE(name),fOutputList(0),

fHistPt(0), fHistPtPion(0)

{

        // Constructor


// DefineInput and Output slots here

// Input slot # 0 works with a TChain

Define Input (0, TChain::Class( ) );

// Output slot # 0 writes into a TH1 container

Define Output (1, TList::Class( ) );

}

//_______________________________________________________________

Void AliAnalysisTaskPtMC::UserCreatOutputObjects( )

{

        // Create Histograms

        // Called Once

fHistPtPion = new TH1F("fHistPtPion", "P_{T} distribution of Pions", 15, 0.1, 3.1);

fHistPt->GetXaxis( )->SetTitle ("P_{T}(GeV/c)");

fHistPt->GetYaxis( )->SetTitle ("dN/dP_{T}(c/GeV)");
```

```
fHist->SetMarkerStyle (KFullCircle);


fOutputList->Add(fHistPt);

fOutputList->Add(fHistPion);

}

//______________________________________________________________________

voidAliAnalysisTaskPtMC::UserExec(Option_t *)

{

// Main loop

//Called for each event

//Process MC truth


AliMCEvent*mcEvent = MCEvent ( );

//TParticlePDG*pion = new TParticlePDG (211);

if (track-> M( )>0.1395 && track-> M( )<0.1399)

fHistPtPion->Fill(track->Pt( ));

fHistPt->Fill(track->Pt( ));

} // track loop


// Post Output data

Post Data (1, fOutput List);
```

```
Post Data (2, fOutput List);

Post Data (3, fOutput List);

Post Data (4, fOutput List);

}

//______________________________________________________________________

voidAliAnalysisTaskPtMC::Terminate( Option_t*)

{

// Draw result to the screen

// Called Once at the end of query


fOutputList = dynamic_cast<TList*>(Get Output Data(1));

        if (!fOutputList)

{

Printf ("ERROR: Output list not available");

return;

}

fHistPt = dynamic_cast<TH1F*>(fOutputList->At(0));

        if (!fHistPt)

{

Printf ("ERROR: fHistPt not available");

return;
```

```
}
fHistPtPion = dynamic_cast<TH1F*>(fOutputList->At(1));
if (!fHistPtPion)
{
Printf ("ERROR: fHistPtPion not available");
return;
}
TCanvas*c1 = new TCanvas("AliAnalysisTaskPtMC","PtMC",10,10,510,510);
C1->cd(1)->SetLogy( );
fHistPt->DrawCopy ("E");
fHistPtPion->SetMarkerColor(2);
fHistPtPion->DrawCopy ("Esame");
```