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Production of Neutral Pions in Pb+Au collisions at 158 AGeV/c

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Abstract in English

Abstract in German
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In any subject which has principles, causes, and elements, scientific knowledge and understanding stems from a grasp of these, for we think we know a thing only when we have grasped its first causes and principles and have traced it back to its elements.

Aristotle, Physics

1

Introduction

1.1 The Standard Model

The laws of physics governing the world of elementary particles are now very well described by what we call the Standard Model of particle physics fruit of major theoretical and experimental advances of the twentieth century. To describe and understand Nature, physicists have worked to determine the basic constituents (elementary particles) which it is made and to define the interactions that govern theirs fundamental interactions.

In nature there are 12 matter particles and the 4 particles interactions of the standard model. It also provides that for every particle there is an antiparticle same mass but an opposed charge and parity. All these building blocks are grouped into three families growing masses. The stable matter particles composed of the first family whose members are the lightest.

Today, physics is understood through a series of elementary particles, which are classified into two main families: the fermions (particles of half-integer spin) and bosons (integer spin). The fermions follow the Pauli Exclusion Principle and they are the constituent particles of the ordinary matter—the proton, neutron and electron belong to this family. The bosons are the particles carrying the information exchanged between fermions during an interaction.

Among the fermions, six of them are classified as quarks (up, down, charm, strange, top, bottom), and the other six as leptons (electron, muon, tau,

\[1\] is a particle of half integer spin.
and their corresponding neutrinos). The quarks do not feel the strong interaction, and leptons are insensitive to it. Leptons are directly observable in nature. Quarks, however, are not directly observed in that they do not appear to exist by themselves as free particles. We can model each fundamental interaction between elementary particles by the exchange of bosons, namely particles integer spin, obeying the Bose-Einstein statistics which allows them to accumulate in the same condition. These particles "carry" the interaction of a particle to another and are thus called vector bosons. Four interactions have been identified:

*Electromagnetic interaction* where the photon is the intermediate vector boson. The photon does not have itself an electric charge, it is neutral, and particles exchanging photons retain their electric charge unchanged after the exchange. The mass of the photon is zero; the electromagnetic interaction length is infinite.

*The weak interaction* with three vector bosons: $Z^0$, electrically neutral, and $W^\pm$ have an electric charge $\pm 1$. It deals with all fermions through two charges, where one of these two charges is laid by the left handed fermions. *The strong interaction*, the gauge bosons are the gluons and they form an octet. Among the fermions, only quarks have a known color, which may take three values appointed by agreement "red", "green" and "blue". The gluons also have this feature, a combination of colors and anti-colors, and can thus combine them. They have zero mass.

The standard model thus encompasses all known particles and the three interactions with a wide effect of the particle. This is done through the quantum field theory that constitutes the mathematical framework of the model. The standard model allows us to explain all natural phenomena except gravity, which is for the moment, resists the theorists for a quantum theory and which can be neglected during the interaction between elementary particles, because of the weakness of the gravitational intensity force compared to the previous forces.

The structure of each interactions included in the Standard Model is dictated by the group of symmetry which leaves the action invariant. The model introduces the group symmetry gauge following:

\[ SU(2)_L \otimes U(1)_Y \otimes SU(3)_C \]  

(1.1)

The $SU(2)_L \otimes U(1)_Y$ gauge group combined both the electromagnetism and weak interaction theories into a single unified theory of electroweak theory of Glashow-Weinberg-Salam with the gauge group. It contains four quanta of radiation, one for the $U(1)$ part and three for $SU(2)$. The term $SU(3)_C$ is the color gauge group which describes the strong interactions. The Gluons are its 8 quanta of radiation.
1.2. The Strong Interactions

The Quantum ChromoDynamique (QCD) is the general accepted gauge theory [1, 2] used to reflect the strong interactions [4, 5] between basic constituents of nuclear matter. This approach to standard model is certainly its most complicated component insofar as its Lagrangian uses only quarks and gluons to describe the confined states (hadrons). Quarks do not interact with each other directly; they do so through the gluons as intermediated agents. We can only refer to there presence in objects which are color singlets. A colored quark can be bound with an antiquark with corresponding anticolor to form a meson. Three quarks of different colors can be bound to form baryon. Mesons and baryons are collectively called hadrons to be distinguished from the leptons and filed bosons as the "particles" which can be directly measured.

1.2.1 The QCD Lagrangian

The QCD is a Yang-Mills theory of colored quarks and gluons introduced by Gell-Mann [9] and Zweig[10] in the 60’s. It required the introduction of a new hidden quantum number in order to do not violate the Fermi Statistics for the particle $\Delta^{++}(uuu)$: color. All baryons (set of three quarks) and all mesons (pair of quark-antiquark) are singlets colors. Theirs symmetry properties are described by the $SU(3)_c$. We can define a local transformation gauge as the form:

$$U = \exp(g_3 \sum_a \alpha_a(x) T_a), a = 1, 8$$

(1.2)

here the $g_3$ is the QCD coupling constant, the matrices $T_a$ represent the generators of the $SU(3)_c$ gauge group and $\alpha_a$ are an arbitrary phases dependent on the space-time coordinates. The QCD Lagrangian involve a bosonic part and fermionic part, it takes the following form:

$$L_{QCD} = \frac{1}{4} F_{\mu \nu}^a F_{\mu \nu}^a + \sum_{q=1}^6 (i \bar{\psi}_q \gamma^\mu D_\mu \psi_q - m_q \bar{\psi}_q \psi_q)$$

(1.3)

With the field strength tensor:

$$F_{\mu \nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c$$

(1.4)

and the covariant derivative:

$$D_\mu = \partial_\mu + ig_s \frac{\lambda_a}{2} A_\mu^a$$

(1.5)
The last term in Eq.(1.4) contain the fundamental difference between QED and QCD which describes the self coupling of gluons. This approach allows interaction between gluons giving rise to the definition of a vertex 3 or 4 gluons while in QED, the interaction between photons is not permitted. The six quarks $q$ are represented by the spinors $\psi_q$ which are the 4-component Dirac spinors associated with each quark field of (3) color $i$ and flavor $q$, the $A^a_\mu$ are the (8) Yang-Mills (gluon) fields as well as the associated covariant derivatives $D_\mu$ and $f_{abc}$ are the structure constants of the $SU(3)$ algebra. The very limited length scale of the strong interaction, of the order of $10^{-15}$ meters, is due to the gauge bosons self-coupling. This also particularly implies that the interaction strength between two quarks increases with their relative distance. The interaction between quarks grows weaker as the quarks approach one another more closely. This important properties of the strong interaction and its physics can be divided into two regimes: asymptotic freedom and confinement [12].

### 1.2.2 Asymptotic freedom

One of the striking properties of QCD is asymptotic freedom which states that the interaction strength between quarks becomes smaller as the distance between them gets shorter so that quarks behave almost as free particles. Similarly to the QED, the coupling constant of QCD is defined by

$$\alpha_s = \frac{g_s}{2\pi\hbar c}$$

(1.6)

The $\alpha_s$ value shows a strong dependence on the momentum transfer $Q^2$ in a collision. The $\alpha_s(Q^2)$ evolution is governed by theory through the differential equation of renormalization group[2]:

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s)$$

(1.7)

If we consider only the first order of $\alpha_s$, the function is calculated by a perturbative treatment of QCD as a development of the strong coupling:

$$\beta \alpha_s = -b \alpha_s^2(1 + \vartheta(\alpha_s^3))with b = \frac{33 - 2n_f}{12\pi}$$

(1.8)

For the leading order perturbative approximation the solution of this equation gives the variation of the coupling constant to the scale of the momentum transfer at large momentum:

$$\alpha_s(Q^2) = \frac{\alpha_0}{1 + \alpha_0 \frac{33 - 2n_f}{12\pi} \ln \frac{Q^2}{\mu^2}}$$

(1.9)
1.2. THE STRONG INTERACTIONS

Where $\alpha_0$ is the coupling constant for $n_f$ number of active quark flavors with the momentum transfer $\mu$.

From equation (..) we conclude that for a number of flavors less than 17, the coupling constant decreasing slowly to zero when $Q^2 >> \mu^2$, i.e. precisely where the asymptotic freedom is. Therefore the quarks behave as they were free inside the hadrons. At this stage when the momentum transfer is large, the strong interaction physics can be calculated in perturbative theory. The variation of the coupling constant diverges for small values of $Q^2 < \mu^2$ bear the application of perturbative treatment to calculate the physical observable inaccurate. In this prevailing order a new phenomenon, coming directly from the non-abelian propriety of the theory. The Fig. 1.1 illustrate the decreasing of the strong interaction constant coupling depending on the momentum transfer. The QCD is therefore perturbative and calculable at short distance (large $Q$): the asymptotic freedom. However, long-distance (low $Q$), the coupling constant becomes too big and the perturbatif calculations are no longer valid. Another approach can be done, in order to estimate the evolution of the coupling constant by introducing directly in the definition of the coupling a new parameter $\lambda_{\text{QCD}}$ which sets the scale at which the coupling constant becomes large and the physics becomes nonperturbative. The $\Lambda_{\text{QCD}}$ value can be determined experimentally and it is on the order of 200 MeV:

$$\alpha_s(Q^2) = \frac{1}{\left(\frac{33-2n_f}{12\pi}\right) \ln\left(\frac{Q}{\Lambda_{\text{QCD}}}\right)^2}$$  \hspace{1cm} (1.10)

It remains to solve the problem of formulating the QCD theory in a non-perturbatif when the strong interaction coupling becomes hard for large distances between quarks (upper than fm) or for small energy scale energy (less than GeV). A solution is provided by the Lattice QCD method.

1.2.3 The quarks confinement

One of the prominent prosperities of QCD is the formation of color singlet objects. This feature is called the color confinement of quarks in hadrons. In the same way as the electric charges of the opposite sign attraction, the color charge attracts quarks with different colors. The QCD explains, in particular, the formation of hadrons. When the quarks moves away from each other (the energy put into play decreases), more gluons are exchanged. These gluons themselves can interact with each other or a couple of new pairs virtual quark-antiquark. Beyond a typical distance of 1 fm ($10^{-15} m$), quarks can no longer spread freely and remain confined within hadrons. This phase of hadronization taken over the non-perturbative QCD regime is generally described by phenomenological models. In general, if the potential between two
quarks is proportional to the distance between them, then the two quarks can never be separated. To illustrate this character, a classic parameterization [7, 8, 9] of potential inter-quarks is proposed in the equation:

\[ V(r) = V_0 - \frac{\pi}{12} \frac{1}{r} + \sigma r \]  

(1.11)

The second term of this equation shows the Colombian interaction for short distances, the confinement is represented by the last term where \( \sigma \) is called the string tension. One may try to separate the quarks by pulling them apart, then the restoring force of the linear potential between them grows sufficiently rapidly to prevent them from being separated. The interaction between the quarks gets stronger as the distance between them gets larger. The form of the potential results of these two terms is shown in Figure 1.1 depending on the separation distance \( r \). The potential between the two quarks becomes linear and is growing to infinity with the inter-quarks distance.

Figure du potential quark anti-quark.
1.2. Deconfinement and the Quark Gluon Plasma

It is believed that the universe consisted of quark and gluons transforming to
hadronic matter just a few microseconds after the Big Bang. Theories also
predict that it may still exist in the universe that we see today since the cores
of dense neutron stars and the supernova supply extreme astrophysical envi-
ronments which favor the creation and the existence of this state. Among the
goals of current nuclear researches is the observation of this new undiscovered
state called Quark Gluon Plasma (QGP) \([10]\) in which its building blocks
(quarks and gluons) act in like free particles. The search for a such phase
transition from the confined hadronic matter to the deconfined QGP matter
is a fascinating subject to study the dynamics of this interface. The nature
of the strong interaction has been described as in the case of the hadrons
ordinary matter. However, it is crucial to be able to describe the behavior of
the matter under conditions of temperature and density, particularly when
one or both of these two quantities are extremely high.

The challenge is to understand the substance of the Universe during its first
moments, but also of existing forms such as inside the compact stars formed
by the gravitational collapse of the supernovae nucleus. We can talk about
phase transition when certain properties of nuclear matter undergo a radic-
al change for that reason the system can be well described using statistical
mechanics description which provides global variables and other conserved
quantities. The grand canonical ensemble is therefore used to describe the
whole system allowing the variation of the particles number. The parameters
of the control are then the temperature \(T\), the volume \(V\) and the chemical
potential $\mu$. The latter represents the necessary energy to provide to the system in order to add a quark. Generally the diagram of phases depending on the temperature ($T$) and potential chemical baryonic, as shown in Figure: By increasing $T$ or $\mu_b$, a phase transition is possible to occur. The evolution of the universe can be traced from its earliest moments, where the temperature was well above $T_c$ and at low chemical potential. The bottom left of this diagram correspond to a low temperature and low potential baryonic, the behavior of QCD thermodynamics can be described in terms of hadron gas (states composed of related quarks and gluons): If we increase the temperature of the system, this state can not exist as it is. There is a small area where this matter is undergoing a transition considered as cross over, from which the degrees of freedom are not the hadrons but quarks and gluons themselves. The high $\mu$ and small $T$ on the right of the diagram, corresponds to a region accessible by compressing the system. This state of matter is a matter of quarks that can be found in the hearts of neutron stars [12].

![Figure 1.3: The phase transition diagram of hadronic matter [11].](image_url)


1.2. **THE STRONG INTERACTIONS**

1.2.5 **The Lattice QCD**

The estimations of the preceding paragraph are based on very rough approximations. At large distances (i.e. small scales); it becomes impossible to use the perturbative theory to achieve results. Indeed, the interactions between quarks and gluons are too strong and perturbative approach can not work. In particular, the QGP can not really be considered as gas particles without interaction. To take in account these interactions we should use the QCD to model all the interactions existing in the system. In this framework, Lattice simulations of QCD thermodynamics have made significant progress in the last decade. The method of Lattice QCD allows a statistical approach of the strong interaction for complex systems. It gives access to the thermodynamic characteristics of a quarks and gluons system at the equilibrium. The rapid rise in computational power and implementation of better algorithms authorize the simulation of the behavior of matter by the QCD equations, which describes the strong interaction suffered by the quarks and gluons. The whole technic is based on the discretization of space-time on the finite domain. The particles involved in the simulation are located on the nodes of the Lattice. An introduction to the used lattice QCD methods and its technical details could be founded in [13].

*Figure 1.4:* The lattice QCD [14].

Initially, the developments were limited to $\mu_b = 0$ and they can calculate the evolution of pressure depending on the temperature. Figure 1 shows the evolution predictions of the energy density (left) and pressure (right) depending on the temperature. This method of studying deconfinement take into account 3 assumptions: two light quark (u and d), three light quarks (u, d or s), or two light flavors (u and d) and a heavy flavor(s). A transition from the hadronic phase to partonic phase is clearly visible. The energy density undergoes a rapid change near a critical temperature $T_C$, enhanced by almost
CHAPTER 1. INTRODUCTION

an order of magnitude, as indicated in Figure 1. The temperature $T_c$ depends on the number of flavors ($n_f$) considered: $T_c = 175$ MeV for two light quarks (2 flavors), $T_c = 155$ MeV for three light quark (3 flavors).[flavours]. The reported error is the statistical error only and therefore it does not take into account the engendered systematical error by the discretization of the lattice. The Lattice QCD confirms the sharp increase, already estimated by the equations 8 and 10, of the number of degrees of freedom of the system to the temperature of the phase transition. This rapid change is an indication that the fundamental degrees of freedom are different above and below the critical temperature.

1.3 The ultra relativistic heavy ion collisions

1.3.1 Machines

The goal of research in the ultra relativistic heavy ions is studying the possible formation of a new state of nuclear matter called Quark and Gluon Plasma (QGP). It is believed that this state of matter can be reached at ultra relativistic heavy ions collisions with targets to achieve sufficient energy density and temperature. Under these circumstances, the nuclear material undergoes a deconfined phase transition leading to the formation of the QGP. To simulate such extreme conditions here on earth, Ultra relativistic heavy ion collisions between two nuclei were performed and an experimental campaign has therefore launched since 1986 to prove its existence and to study it. The program of this campaign used to study the dense matter. The different used machines for this subject are presented in Table 1: the Alternating Gradient Synchrotron (AGS) and the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) and the Super Proton Synchrotron (SPS), the future Linear Hadron Collider (LHC) at CERN. The main objective of these accelerators (red circles in Fig) is to draw a detailed description for the path of the universe in the opposite direction by raising the temperature in the area where the nuclei are collided.

1.3.2 The Geometry of the collision

A nucleus-nucleus collision at very high energy produces a large number of hadrons near the center of mass. The attained energy density during the collision depends on the energy of the incident nucleus, their longitudinal size (atomic mass) and the fireball volume that is big enough to explore the QGP. The corresponding Lorentz contraction is important since it is already
1.3. THE ULTRA RELATIVISTIC HEAVY ION COLLISIONS

<table>
<thead>
<tr>
<th>Name</th>
<th>Mode</th>
<th>Beam</th>
<th>$E$ (AGeV)</th>
<th>$\sqrt{S_{NN}}$ (GeV)</th>
<th>$\epsilon$ (GeV/fm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$U^{238}$</td>
<td>1</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>AGS</td>
<td>fixed target</td>
<td>$Pb^{208}$</td>
<td>12</td>
<td>4.9</td>
<td>1.0</td>
</tr>
<tr>
<td>SPS</td>
<td>fixed target</td>
<td>$Pb^{208}$</td>
<td>158</td>
<td>17.3</td>
<td>2.5</td>
</tr>
<tr>
<td>RHIC</td>
<td>collider</td>
<td>$Au^{197}$</td>
<td>100</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>LHC</td>
<td>collider</td>
<td>$Pb^{208}$</td>
<td>2750</td>
<td>550</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1.1: Number of events and beam particles before and after cutting on the time of the start counter and the vertex $v_z$ of the CDC.

$\gamma_1 = 10$ for the SPS and it make also sure that the deformation is in the direction of movement. The centrality of the collision or the recovery degree of two nuclei at the collision time is usually given as a percentage of the total cross section. We might define then from these measurements an important variable at this stage: the impact parameter $b$, which gives the distance between the axes of the two nucleuses. This description can be illustrated by figures 1.

![Figure 1.5: The geometry.](image)

Here we describe the case of the most central collisions as they permit to get the higher energy density and they are essentially in the form of a hadrons gas. When a collision occurs at low impact parameter $b$, the measured number of particles will be big, and the collision will be central. In
contrast, a collision at high impact parameter is peripheral. One can underline
the principal observables which characterize the dynamic of the collision
that are expressed in term of rapidity:

\[ y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} \] (1.12)

where \( E \) is the total energy of the particle and \( P_L \) is its longitudinal momentum. When the energy density is important to the mass of the particle, we prefer to use the pseudo-rapidity variable:

\[ \eta = \frac{1}{2} \ln \frac{|p| + p_L}{|p| - p_L} = -\ln(\tan \theta_0) \] (1.13)

where \( \theta \) is the angle between the particle momentum and the beam axis. The energy density initial \( E_{Bj} \) produced in the collisions can then be calculated using the formula 1 [Bjorken 1]: (write the one in the paper draft)

\[ E_{Bj} = \frac{1}{A_T \tau_0} \frac{dE_t}{dy} \] (1.14)

This equation takes into account the overlapping transverse surface between the nucleons \( A_T \) (depends on \( B \)), \( \tau_0 \) the proper time of the partons thermalisation (estimated at around \( 1 \text{ fm/c} \)) and the measurement of the total transverse energy, for such particle \( i \) emitted by an angle \( \theta_i \), is defined by:

\[ E_T = \sum_{i=1} E_i \sin(\theta) \] (1.15)

The energy densities at CERN-SPS energy is on the average of \( 3.9 GeV/fm^3 \). From the equation 1 we conclude also that the more energy density is high the more we have the possibility to create the QGP.

1.3.3 The evolution of the QGP: Scenario of Bjorken

To reach the Quark-Gluons Plasma, extreme scenarios must be re-created by colliding heavy ions with velocities close to the speed of light: enormous temperatures, pressure and densities of those first few microseconds. The framework of the space-time evolution of ultra-relativistic heavy ion collisions is defined qualitatively and even quantitatively in terms of the reached energy density. This scenario of evolution was proposed by Bjorken in 1983 [Bjorken 2] and is represented in Figure 1.

The system presents a succession of several phases. In the pre-equilibrium phase, about typical time of \( T_0 \) of \( 1 \text{ fm/c} \), the system is thermalised and led
to the formation of QGP in total lifetime of the order of 5 to 7 fm/c. The quark-gluon states created in collisions will expand and cooled down very rapidly, $t = 10^{-23}$ s till reaching the critical temperature $T_c$ transition. That means that the quarks are grouped into hadrons and the cooling system will be gradually transformed into a hadronic phase. The hadronic matter keeps expanding and cooling off. The hadrons undergo elastic and inelastic collisions that change the production rate and the momentum spectrum of different particles. They finally stopped when the system expansion reached its limit. This ultimate step is called chemical freeze-out where eventually all inelastic interactions are stopped and the particles species are no longer changed by collisions but only by decays. The nature of particles and their energies are then frozen. These will disintegrate to provide stable particles that eventually end up their course in the detector. Such scenario raises some questions about the possibilities to probe the partonic phase since the short lifespan of the QGP for a few fm make it more difficult to be observed directly by the detectors. However the manifestation of the QGP probes at various moments during the evolution is the only way to find its evidence by the remnants of the collisions.
1.3.4 The experimental observations of the QGP

Such a scenario raises some questions about the possibilities to probe the partonic phase. The plasma would have a very short lifetime, typically $10^{-23}$ s are expected. Moreover, how to ensure that the observed gap does not come from a purely hadronic or nuclear, and thus is really deconfined phase? In reasonable manner, the detection of a set of signatures might be really a clear way to discard any ambiguity [ambiguity]. The predicted signatures for the QGP can be roughly divided into 3 categories: electromagnetic signatures which are based on the detection of dileptons and photons, signatures associated with the measurement of the hadron production, and the signature coming from the deconfined phase which enhance the production of strange quarks and the $J/\psi$ suppression. Among these various probes, photons and dileptons are know to be advantageous as these signals examine the entire volume of the plasma. We will concentrate only on the electromagnetic signatures. The reader is referred to [signature] for more detailed review about the other probes.

**Electromagnetic probes**  Together with dileptons, photons constitute electromagnetic probes which are believed to reveal the history of the evolution of the plasma. Dileptons are produced in a QGP phase by quark-antiquark annihilation, which is governed by the thermal distribution of quarks and antiquarks in the plasma. The examination of photons provides a tool to study the different stages of a heavy ion collision. They are believed to originate from quark-gluon Compton scattering ($q(q)g \rightarrow q(q)$) and quark-antiquark annihilation ($q(\bar{q}) \rightarrow gg$) processes as well as from bremsstrahlung processes ($q\bar{q}(g) \rightarrow q\bar{q}(g)$) [p1,p2].

**Direct photons:** Photons have various origins with rather different sources. There are three subprocess decribed previously which dominate the photons emission from the fireball. They can be obtained by extracting the decay photons where in this case one have to deal with formidable background problems because of the hadronic decays into photons most notably the $\pi^0$ (into gg) and the $\eta$ (into gg or $\pi^0\pi^0\pi^0$). All these process are schematically shown in Figure 1.

**Thermal photons:** All the photons radiated from thermalized matter the quark-gluon plasma phase are named Thermal photons. They can be produced during the whole history of the evolution of QGP and Hadron gas.
1.3. THE ULTRA RELATIVISTIC HEAVY ION COLLISIONS

\[ \pi \]

\[ h! \]

\textbf{Figure 1.7:} Fey.Diag
1.3. THE ULTRA RELATIVISTIC HEAVY ION COLLISIONS
To my self I seem to have been only like a boy playing on the seashore, and diverting myself now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

Sir Isaac Newton

2

The CERES Experiment

2.1 Experimental setup overview

CERES/NA45 (Cherenkov Ring Electron Spectrometer) is the only experiment at the CERN Super Proton Synchroton (SPS) dedicated to the study of $e^+e^-$ pairs produced in nucleon-nucleus and nucleus-nucleus collisions in a fixed target geometry in the low mass range of up to $1\ GeV/c^2$. It is axially symmetric around the beam and it has $2\pi$ azimuthal coverage. It was set-up in 1990, went into service 1991 and started to take data 1992. The original setup included two Silicon Drift Detectors (SDD), two Ring Imaging CHerenkov Detectors detectors (RICH) for the electron identification. It was upgraded twice, once from 1994 to 1995 with an additional multiwire proportional chamber with pad readout (the Pad Chamber) to improve the momentum resolution and to allow operation in the environment of the multiplicity of lead on gold collisions [15]. A second time it was upgraded with an additional magnet and new tracking detector a cylindrical Time Projection Chamber (TPC) with radial drift filed which replaced the pad chamber [16]. This was done to improve the mass resolution.
Figure 2.1: The CERES experimental setup.
2.2. THE TARGET REGION

The $dE/dx$ signal in the TPC provides also electron identification in addition to the identification by the RICH detectors. The new experimental setup, with the TPC, reaches a mass resolution $\delta m/m \sim 3.8\%$ at the $\phi$-peak in the electron decay channel. The addition of the TPC opens the possibility to study hadronc observables. The following sections of this chapter describe the main features of subdetectors. They have a common acceptance in the polar range $8^\circ < \theta < 14^\circ$ which corresponds to pseudorapidity range of $2.1 < \eta < 2.65$ at full azimuthal coverage. The upgraded experiment is shown in figure 2.1.

2.2 The target region

CERES used during the last data taking in 2000 a target system consisting of 13 fixed gold disks of 25$\mu$m thickness, and 600$\mu$m diameter, spaced uniformly by 1.98 mm in the beam direction. The distance between the disks was chosen such that particles coming from a collision in a given target disc and falling into the spectrometer acceptance do not hit any other disc. The reason behind this geometry is to minimize the conversion of the $\gamma$'s into $e^+e^-$ pairs. A tungsten shield is installed around the target to absorb particles emitted backwards in order to protect the UV-counters of RICH detectors from a long background signals.

![Figure 2.2: The Target area: 1 - The vacuum pipe, 2 - The entrance window, 3 - BC2 4 - BC2’s PMT, 5 - Au target, 6 - BC3’s PMT, 7 - MC’s PMT, 8 - BC3, 9 - MC scintillator, 10 - Al-mylar light guide, 11 - SiDC1(down), 11 - SiDC2(up), 13 - Gas radiator.](image-url)
2.3 The trigger system

Triggers are essential to optimize the quality and quantity of the physics events and to keep the same time, the background events very low. The CERES experiment trigger system starts the read-out sequence of the detectors if the occurrence of a collision has been detected. This is done with system of beam/trigger detectors shown in figure 2.3. The Beam Counters (BC1, BC2 and BC3) are the Cherenkov-counters with air as radiator. These detectors are used to detect collisions happened between projectile and target nuclei.

\[ T_{\text{BEAM}} = BC_1 \times BC_2 \]  
\[ T_{\text{MinB}} = BC_1 \times BC_2 \times BC_3 \]  
\[ T_{\text{central}} = T_{\text{MinB}} \times MC \]

**Figure 2.3:** Schematic view of trigger detectors.

The beam trigger (BEAM) is defined by the coincidence of the two beam counters (BC1 and BC2) located in 60\(\text{mm}\) and 40\(\text{mm}\) in front of the target respectively:

The minimum bias trigger (MinB) is defined as beam and no signal in the beam counter (BC3) which is located 69\(\text{mm}\) downstream the target system.

To select the centrality of the collisions based on charged particle multiplicity a Multiplicity Counter (MC or MD) located 77\(\text{mm}\) downstream the target was used. Its output signal is approximately proportional to the number of charged particles passing through it. The central collision trigger is defined as:

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\[ T_{\text{central}} = T_{\text{MinB}} \times MC \]
The veto detectors VW and VC are plastic scintillators. They are used to reject interactions which happened before the target. The main trigger detectors BC2, BC3 and MC are located in the target area followed by the Silicon Drift Detectors (SDD’s), they form a vertex telescope which is a central part of the event and track reconstruction.

### 2.4 The Silicon Drift Detectors

The doublet Silicon Drift Detectors(SDD’s) are placed approximately 10cm behind the target. Each of them consists of a circular 4-inch silicon wafer with a thickness of 250µm which has a central hole of about 6mm diameter for the passage of the beam. The sensitive area covers the region between the radii 4.5mm and 42mm with full azimuthal acceptance and cover the pseudorapidity range [1.6,3.4]. The 4” SDD used in CERES is designed using the principle of the sideward dileption [17]. A charged particle traversing the detector creates a cloud of electron-hole pairs which then drifts along radially in the electric field towards the outer rim of the silicon wafer (Fig. 2.4) where they are collected by an array of 360 anodes distributed equally over its surface and connected with a read-out chain.

![Working mode of the Silicon Detectors](image)

**Figure 2.4:** Working mode of the Silicon Detectors.
Schematic view of the anode structure used in the SDD detectors is shown in Fig. 2.5 where its design guarantees optimal charge sharing and provides an accurate azimuthal position resolution [18]. The charge of one hit is detected by several anodes and a more exact position measurement can be done by calculating the center of gravity of this distribution. When a charged particle passed through the detector plane, the radial coordinate $r$ (or the polar angle $\theta$) of a point is calculated knowing the drift velocity and measuring the drift time FADC (Flash Analogue to Digital Counters) with sampling frequency of $50MHz$. An example of an event in the SiDC detector is shown in Fig. 2.6.

The two SDD’s detectors provide a very precise vertex reconstruction, determine the pseudorapidity density of charged particle $dN/d\eta$, coordinates of hundreds charged particles with high spatial resolution and interaction rate in addition to the suppression of $e^+e^-$ pairs coming from conversions. This feature of the SDD is extremely necessary for the rejection of photon conversions before the RICH2.
2.5. THE RICH DETECTORS

The Ring Imaging Cherenkov Detectors (RICH) are used to identify the electrons and to measure the particle velocity $\beta$. They are the heart of the electron spectrometer. The two RICH detectors were invented by J.Séguinot and T.Ypsilantis [17]. If the momentum of the particle is known the mass can be determined. Particles pass through radiator and the radiated photons are collected by a position-sensitive photon detector by focusing mirror. The simplest method to discriminate particles with Cherenkov radiation utilizes the existence of a threshold for radiation; thus providing a signal whenever $\beta$ is above the threshold $\beta = 1/n$. The RICH detectors in the CERES experiment operated with $CH_4$ at atmospheric pressure as radiator gas. An illustrated view of the CERES RICH detector principle of operation is shown in Fig.(2.7).

According to electromagnetism, a charged particle emits photons in a medium when it moves faster than the speed of light in that medium (Cherenkov radiation). The speed of light in a medium with reflecting index $n$ is given by:

$$v = \frac{c}{n}$$ (2.4)

where $c$ is the velocity of light in a vacuum. When the velocity of charged particle exceeds the threshold, Cherenkov lights are emitted under a constant angle $\theta_c$ with respect to particle trajectory.
\[ \theta_c = \cos \left( \frac{1}{n \beta} \right) \]  
\[ (2.5) \]

From the asymptotic angle \( \theta_c \), the Lorentz threshold for a charged particle to radiate can be expressed as:

\[ \gamma_{th} = \frac{1}{\sqrt{1 - \frac{1}{n^2}}} \]  
\[ (2.6) \]

The methan-gas has \( \gamma_{th} \approx 32 \) and very high transmission in the U-V region. Therefore, only electrons and positrons emit Cherenkov light. Charged pions need a momentum of 4.5 GeV in order to reach the threshold. Whereas most of hadrons (95%) pass without creating any signal. The RICH detectors are therefore practically hadron blinded. The relativistic particles pass through a radiator, and the emitted photons are optically focused by a spherical mirror onto a position-sensitive photon detector, on which Cherenkov photons are detected on a ring with radius:

\[ R = R_\infty \sqrt{1 - \left( \frac{m \gamma_{th}}{p} \right)^2} \]  
\[ (2.7) \]

where \( R_\infty \) is the the asymptotic radius of particles with \( \gamma >> \gamma_{th} \).
2.6. **THE TIME PROJECTION CHAMBER (TPC)**

As the ring radius, the number of the Cherenkov photons depends also on particles momentum and its mass:

\[ N = N_{\infty} \left[ 1 - \left( \frac{m.\gamma_{th}}{p} \right)^2 \right] \]  
(2.8)

where \( N_{\infty} \) is the asymptotic number of the reconstructed photons with \( \gamma >> \gamma_{th} \). In order to minimize the numbers of photons conversions in the spectrometer and to reduce the loss of momentum resolution due to the multiple scattering, the amount of material within the acceptance is kept as small as possible. For this reason, RICH1 mirror is based on thin carbon fibre structure with 1 mm thickness whereby the radiation length is about 0.4%. The RICH2 mirror is built of 6 mm glass with radiation length of 4.5% at comparable U-V reflectivity [18]. The UV detector used for position sensitive measurement of the photons are gas counters consisting of three amplification stages, two Parallel-Plate Avalanche Chambers (PPAC) and a Multi-Wire Propotional Detector (MWPD), with a gas composition of 94% helium and 6% methane and saturated vapor pressure of TMAE (Tetrakis-di-Methyl-Amino-Ehtylen). The incoming photons are converted into electrons by adding TMAE as a photo-sensitive agent. In order to achieve a sufficient particle pressure, the TMAE is heated to 40\(^\circ\)C. For the purpose of prevention from gas condensation and the avoidance of temperature gradients the whole spectrometer is operated at 50\(^\circ\)C. The produced ion cloud in the last step induces a signal on a pad plan of 53800 pads in RICH1 and 48400 pads in RICH2. The pad sizes are 2.7 \(\times\) 2.7 and 7.6 \(\times\) 7.6 mm\(^2\) respectively which corresponds to 2 mrad per pad in both cases.

2.6 **The Time Projection Chamber (TPC)**

The Time Projection Chamber in a soleind magnet is a powerful device for the hadron spectrometer that has been implemented for relativistic heavy ion experiments. We will introduce briefly how TPC’s in general work and later in the next subsections, the CERES TPC will be described in much more detail. The TPC comprises a cylinder filled with gas (typically a mixture of argon and methane). Uniform electric and magnetic fields are applied parallel to the axis of the cylinder. Charged particles created in the collisions pass through the chamber and ionize the chamber gas along the trajectories. Electrons produced by the ionization drift toward the end cap of the TPC due to the electric field. The electron trajectories follow the magnetic field in a tiny spirals. On each end cap, the drifting electrons are amplified by a grid of anode wires, and signals are read out from small pads behind the anode.
wires. The TPC’s are designed to provide a three-dimensional picture of all charged particles emitted in a large aperture surrounding the beam axis with a minimal disturbance to the original trajectories [19].

2.7 The CERES Time Projection Chamber

2.7.1 The geometry

The cylindrical geometry of the CERES TPC extends 2 m in length and 1.3 m in radius. In the center of the TPC there is a cylindrical electrode with radius of 48.6 cm. It is located at a distance of 3.8 m downstream the target. The TPC is divided into 20 planes around the beam axis, each of them with $16 \times 48 = 768$ readout channels on the circumference. In total, 15360 (20 planes×48 pads×16 chambers) individual channels with 256 time bins allowing a three-dimensional reconstruction of particle tracks. A perspective view of CERES TPC is shown in Fig.(2.8) [20].

The ionization region or active volume of the TPC is 9 $m^3$ filled with 80\% Ne and 20\% CO$_2$ gas mixture. This composition was chosen as an optimum compromise between small diffusion, sufficient primary ionization, long radiation length and reasonable fast drift velocity [21]. The new spectrometer system had to preserve the polar angle acceptance range which corresponds to $8^\circ < \theta < 15^\circ$ and the full azimuthal symmetry of the original CERES setup. The electric field is radial and it is define by the inner electrode which is an aluminum cylinder at a potential of $-30kV$ and the cathode wires of the read-out chambers at ground potential. In order to cancel rim effects of the electric field which should be parallel to \( \vec{r} \), two voltage dividers consists of 50 $\mu$m thick capton foils enclose the drift volume at the end caps of the TPC.

2.7.2 The coordinate system

The global coordinate laboratory system used in the CERES experiment is shown in Figure ??.. Its origin located in the middle of the target area. The z-axis is defined by the beam axis. The event polar coordinates are the polar angle $\theta$, the pad coordinate which is translated to the angle $\phi$ given by the read-out channel and the distance $z$ to the center of the target area.
2.7. THE CERES TIME PROJECTION CHAMBER

2.7.3 The read-out system: principle of operation

Before building the trace of a charged particle, a read-out system is needed for that purpose. The TPC is filled with a gas mixture (see previous section), which is ionized by the passage of a particle and the resulting charges are collected on the electrodes (pads) at the ends of the TPC cylinder. Signals originate from electrons that are freed when moving charged particles ionize the gas in the TPC. The electrons drift along the path given by the drift velocity vector in Eq. (2.9) and reach one of the sixteen read-out chambers which are installed in the outer circumference of the TPC. At close distance to the anode wires, the electric field rises very sharply so drift electrons create ionized avalanches (electrons are multiply by factor $10^4$) as they accelerate towards the anode wires where they are absorbed. Ions created
in these avalanches produce image charge on the pad plane; the anode wires are close to the pad plane and are on $1.3 \, kV$ in potential. The gating grid is furthest from the pad plane and it is operated at an offset voltage of $-140 \, V$. In the opened case, after an external trigger-signal, the electrons are allowed to pass through the gating grid which is switched to transparent mode at $U_{bias} = 0 \, V$. In the closed state, adjacent gating grid wires alternate from $-70 \, V$ and $+70 \, V$ then potentials differences set up electric fields between the wires that are perpendicular to the drift direction. By this way, stopping non-triggered electrons extends the life of the TPC by preventing unnecessary ionization from occurring in the read-out chambers.

The experimental arrangement for the electric field is calculated using the simulation package GARFILED \[17\] from NIM paper. The electric potential map performed for a read-out chambers with the gating grid during the open mode is drawn and shows in Figure 2.10. The electric field lines helps to visualize the electric field near the charges. Field lines define the direction of the force that a positive charge experiences near other charges. The slowly drifting ions created near to the anode wires are neutralized in a very short time and captured by the cathode-pads. The analogue signals on the TPC pads are amplified, sharped and digitize in Front End Electronics (FEE). Measuring the drift time and knowing the drift velocity enables the
reconstruction of the radial coordinates of the tracks. Due to the chevron geometric shape of the pads the charge cloud reconstructed presisely and shared between the adjacent pads in the azimuthal direction [20]. The radial drift field strength is proportional to $1/r$. The electric field and the magnetic field in the CERES TPC are not constant along the drift path of the electrons.

Therefore the drift velocities is not either [22]. In the presence of magnetic field $\vec{B}$ and an electric field $\vec{E}$ the drift velocity can be calculated using the following formula [23]:

$$\vec{v}_d = \frac{\mu}{1 + (\omega \tau)^2} \left( \vec{E} + \omega \tau \frac{\vec{E} \times \vec{B}}{B^2} + (\omega \tau)^2 (\vec{E} \cdot \vec{B}) \frac{\vec{B}}{B^2} \right)$$  \hspace{1cm} (2.9)

In this equation: $\mu = e\tau/m$ is the mobility of the electrons, $\tau$ is the mean time between two collisions, and $\omega = \beta \mu$ is the cyclotron frequency. The angle between the drift velocity $\vec{v}_d$ and the electric field $\vec{E}$ is $\alpha_L$ the Lorentz angle given by:
CHAPTER 2. THE CERES EXPERIMENT

\[
\alpha_L = \left( \vec{E}, v_D \right)
\]  \hspace{1cm} (2.10)

Given a precise knowledge of \( \mu, \vec{B} \) and \( \vec{E} \) the actual drift path can be calculated. The drift velocities range from 0.7 cm/\( \mu s \) to 2.4 cm/\( \mu s \) with a maximal drift time of about 71 \( \mu s \). The avalanche process produced close to the anode wires induces a signal in the chevron-type cathode pads [14]. This specific geometry of the cathode pads in Figure 2.11 represents schematic view of the read-out chambers in the TPC where in Figure 2.12 we see the chevron structure which has been taken for the CERES TPC.

![Diagram of TPC readout chambers](image)

**Figure 2.11:** Cross section of the TPC readout chambers.

The TPC is operated in an inhomogeneous magnetic field, indicated in Figure 2.1 by red dotted lines, generated by two warm coils with current flowing in opposite directions. The radial component of the magnetic field is maximal between the two coils and the deflection of charged particles is mainly in the azimuthal direction. The magnetic field \( \vec{B} \) has a radial \( B_r \) and longitudinal \( B_z \) components with strength up to 0.5\( T \). The field integral is 0.18 Tm at 8° and 0.38 Tm at \( \theta = 15° \). Figure 2.13 shows the radial and longitudinal components of the magnetic field at the inner and the outer center end of the angular acceptance in \( \theta \).

### 2.7.4 TPC track reconstruction

In this section, we introduce firstly the algorithms (hit finding, track finding and track fitting) used to reconstruct the tracks in the radial drift TPC, then we describe the particle identification procedures by measuring its ionization
2.7. THE CERES TIME PROJECTION CHAMBER

Figure 2.12: Four single chevron pads of the cathode pads compose one readout chamber.

Figure 2.13: The magnetic field in the CERES TPC.
CHAPTER 2. THE CERES EXPERIMENT

energy loss \( (dE/dx) \). A schematically event display of the TPC after track reconstruction is shown in Figure 2.14.

![Schematic event display of the TPC.](image)

**Figure 2.14:** Schematic event display of the TPC.

**TPC hit finding**

The particle trajectories are reconstructed from hits in the tracking detectors using a tracking finding algorithm. As mentioned before (see section 2.7.1) the CERES TPC has 20 planes with 768 pads along the azimuthal direction. The data of each channel consists of linear amplitude from 8-bit ADC in 256 time bins in radial direction. In total the \( 20 \times 768 \times 256 \approx 4 \) million pixels make up the pixel grid. When a charged particle passes the counter gas of the detector the crossing point in each plane give a definition of the hit. It is described by a local maximum the adjacent pads and time bins [16]. Hit coordinates are defined and encoded as pad amplitudes in two-dimensional array of pad versus time coordinates. The hit finding procedure starts to examine the pixel grid of the TPC in all the twenty planes searching the local maxima in the time direction for each pad. A local maximum corresponds to a hit only if the local maxima in time and pad directions are at the same location. The procedure is illustrated in Figure 2.15. The spatial coordinates of the individual hits \( (x,y,z) \) are calculated from \( (pad,time,plane) \) coordinates knowing the complete geometry of the chamber, the drift velocity of the TPC, which itself depend on the electric and magnetic field (Eq.2.9) and the gas proprieties. An area of 3 pads \( \times 5 \) time-bins around the local maximum is assigned to a hit. After finding all the maxima, the positions of all the individual hits are determined by calculating the center of gravity in
pad and time directions for each of them. They are define as:

\[
\bar{p} = \frac{\sum_i A_i A_{\text{max}} f_i p_i}{\sum_i A_i}
\]

and

\[
\bar{t} = \frac{\sum_i A_i A_{\text{max}} f_i t_i}{\sum_i A_i}
\]

(2.11)

where the index \( i \) represent the pixels in the area of 15 pixels around the local maximum, \( A_i \) is the amplitude which corresponds the the pixel \( i \), \( A_{\text{max}} \) is the absolute maximum, \( f_i \) is counter variable to each pixel. This method memorizes the the sum amplitudes of absolute maxima from those hits which share the same pixel. Thus the overlapping hits problem is solved. A detailed procedure and reconstruction of overlapping hits is schematically shown in Figure 2.16.

Figure 2.15: The TPC hit finding procedure.
The Track finding

Once the different hits are all identified and provided, it is possible to proceed to the combination of the reconstructed hits and then associate these into tracks. Depending on the polar angle, a TPC track consists of up to 20 hits. The track finding routine begins from taking a hits candidates in the middle planes of the TPC (5 to 15) along the Z-direction, where the hit density is lowest [24], and combine them with their closest neighbors in the two upstream and downstream planes in Z-direction to determine the sign of the track curvature in φ-direction. Within a window of $\Delta \phi = 5.3$ mrad and $\Delta \theta = 1.4$ mrad, further hits in both directions are searched around the predicted φ position done with a linear extrapolation using the two previous hits. If no hits were found, the procedure stops at this point. In the next step, the tracking software uses a second order polynomial with Tukey Weights [25] fit to find missing hits and to collect all the hits which are possibly assigned to the track in several iterations. Again the tracking stops in that direction if no additional hits are found.

Figure 2.16: The TPC overlapping hit reconstruction. The absolute maximum of the considered hit is stored by the counter variable. It will be increases by the the absolute maxima of the overlapping neighbors whenever a founded pixel is shared to several hits.

2.7.5 TPC Track fitting

In order to obtain the parameters defining a particle trajectory, the path of the track must be known as function of these parameters. The task is to to provide $\vec{p}$, $\theta$ and $\phi$ angles of the particles. The presence of the strong inhomogeneous magnetic field in the TPC make the analytical description of the particle trajectory not possible. Therefore, the momentum of the particle is calculated using a two-dimensional momentum fit in the $\phi - z$ and
r – z planes based on reference tables. These tables were produced by Monte Carlo simulations of the CERES TPC using the GEANT software package [26]. Applying several iterations, the retained hits are close to the fitted track and those with large residuals $\Delta r > 0.4 \text{ cm}$ and $r \Delta \theta > 0.2 \text{ cm}$ are abolished from the fit.

It is assumed that the deflection in the magnetic filed is in first order only in $\phi$-direction. The momentum is determined from the $\phi$-deflection. The $\theta$ angle is obtained by fitting a straight line through the hits in the $r - z$ plane. A second-order corrections in $\theta$ is applied to improve the quality of the fit. The track fitting performs two type of fitting, one is the 2-parameters (pco2) fit and the other one the 3-parameters(pco3) fit. A better resolution is obtained by using a weighted combination of these two fits variables (pcomb), where their weights depend on the momentum resolution over the whole momentum range presented in Figure 2.17. During all these three types of fitting we are able to determine the charge of the track by looking to the sign of the momentum. The two-parameter fit supply better results for high momentum tracks. The multiple scattering competes with the detector resolution whereby the three-parameter fit absorbs their effect for low momentum. The magnitude of the momentum and the angles $\theta$ and $\phi$ of the track are the whole output information of the fitting function. Another parameterization is presented by taking the assumption that the track is originating from the target area, which permit to determine the local angles for the polar ($\theta$ or $\theta_{R2M}$) and azimuthal ($\phi$ or $\phi_{R2M}$) angles. This can be done and recorded by the projection of the TPC track corresponding to the second RICH mirror. Then making the TPC reconstructed track extrapolation to the target area. To accomplish this variables storing step, two further parameters are used to measure the TPC track local angles:

$$\theta_{local} = \arctan \left( \frac{Y\ Line_1}{X\ Line_1} \right)$$

$$\phi_{local} = \arctan \left( \sqrt{X\ Line_1^2 + Y\ Line_1^2} \right)$$

where $X\ Line_1$ is the slope in the xz plane and $Y\ Line_1$ is the slope in the yz plane of the TPC track.

The relative momentum resolution $dp/p$ as a function of the momentum $p$ is determined by the resolution at high momentum of the detector (res.det) and the multiple scattering (ms) in the detector material at low momentum [27]:

$$\left( \frac{dp}{p} \right)^2 = \left( \frac{dp}{p} \right)^2_{\text{res.det}} + \left( \frac{dp}{p} \right)^2_{\text{ms}}$$

(2.14)
with

\[
\left( \frac{dp}{p} \right)_{\text{res.det}} \propto p \tag{2.15}
\]

\[
\left( \frac{dp}{p} \right)_{\text{ms}} \propto \frac{1}{B} \sqrt{\frac{1}{L.x_0}} \tag{2.16}
\]

where: \( L \) is the the measured track length and \( x_0 \) is the radiation length. From the combined momentum fit, the relative momentum resolution of the CERES TPC is expressed by:

\[
\frac{dp}{p} = \sqrt{(1\%)^2 + (2\%)^2}. \tag{2.17}
\]
2.7.6 Particle identification using dE/dx measurement

Using the TPC, a particle identification of charged particles can be achieved by measuring their energy loss dE/dx. This works very well for particles having low momentum, however in the opposite case, when their energy rises, the energy loss of a particle become less mass-dependent and since it is a function of its velocity, it will be hard to separate particles with velocities \( v > 0.7c \). The dE/dx of particles is described as the Bethe-Bloch formula in Eq.(3.6). The energy loss of a particle with charge \( Z \) and speed \( \beta = \frac{v}{c} \) passing through a medium with the density \( \rho \) is given by:

\[
dE/dx = K q^2 Z \frac{1}{A} \beta \left( \frac{1}{2} \frac{12m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right)
\]

(2.18)

where \( K = 4\pi N_A r_e c^2 \), \( N_A \) the Avogadro number, \( r_e \) the electron radius, \( Z \) the atomic number of the absorber, \( A \) the atomic weight of the absorber, \( \gamma = 1/\sqrt{1-\beta^2} \), \( T_{\text{max}} \) the maximum kinetic energy in a single collisions, \( I \) the mean excitation energy and \( \delta \) is the Bethe-Bloch correction factor.

Figure 2.18 shows the energy loss of the observed charged particles in the CERES TPC as a function of the momentum particles and compared with the Bethe-Bloch formula described above.
This chapter described in greater details the neutral pion analysis with emphasis on the proof and justification for making various cuts. Applying set of selection criteria to track candidates to reject combinatorial background. These choices and the obtained results for the electron/positron selection, the photon reconstruction and then reconstruction of the neutral pion from the converted photons in the RICH2 mirror will be discussed in this chapter.

### 3.0.7 Event data base

The data presented here were taken in the year 2000. The CERES/NA45 experiment has recorded on tape a large data samples consisting of 30 million good event in Pb-Au collisions of heavy nuclei at beam energy 158 GeV/c having a centrality of the top 7%(20%) of the total geometric cross section with an average multiplicity of $< dN_{ch}/d\eta > = 321$ and the pseudorapidity range $\eta = 2.1 - 2.65$. The typical Pb beam intensities delivered to CERES from the SPS was $\sim 1 \times 10^6$ ions per burst corresponding to a total interaction rate of $300 \sim 500$ event/burst. The highly compressed raw data on tape coming from the detectors and written by the Data Acquisition System (DAQ) have to be unpacked and converted into a suitable format for the subsequent data analysis. The events are grouped into 415 units, each unit consisting of about 200 bursts.

The analysis is/was performed in the framework of the C++ software package COOL (Ceres Object Oriented Library) with all the functionality needed to handle and analyze a large amount of data in a very efficient way. Having the
data defined as ROOT Tree format specialized storage methods are used to get direct access and process. A complete particle trajectories reconstructed once all data has been processed into meaningful physical information (i.e. for each particle track a necessary information from each detector is stored like hit amplitudes and number of hits ..).

### 3.1 The reconstruction chain

The different steps of the reconstruction chain to get the signal In describing this, we shall keep the chronological order of the analysis program which can be represented by the following scheme:

- Hit reconstruction and tracking.
- Electron identification.
- Pairing $e^+e^- \rightarrow \gamma$.
- Identification of $\gamma$ conversions.
- Pairing $\gamma$.
- Invariant mass of $\pi^0$ in the same event.
- Mixed event and background substraction.
- Invariant mass of $\pi^0$ as a function of $p_t$ and $y$.
- Efficiency and acceptance determination.
- Efficiency and acceptance correction.
- Transverse momentum spectrum of $\pi^0$.

The first point is common to all physics analysis done with CERES data. The other steps are specific for the analysis presented here. Therefore, they will be described in chapter 4 and 5.
3.2 The Electron and Positron selection

The particle identification (PID) in the TPC using the energy loss $dE/dx$ of the charged particles, provide a powerful tool to select electrons, positrons and to separate them from kaons, pions and protons. As we’ve seen in the previous chapter, what we called $dE/dx$, a function of mass and momentum of the charged particle which passes through the medium. The momentum is determined by the curvature of the track due to the magnetic field. This operation of particles identification in the TPC is measured from the electrons collected at the ends caps of the TPC.

The energy loss inside the TPC gas which interest us here is essentially due to the ionization and to inelastic collisions (gas atoms excitation). The energy transfers which taking place during the Colombien shock have a statistical character (Landau (ref A) and Vavilov (ref B) distribution). Precise measurement of each point (hit) of track which contains a record of 3 charges adjacent pads is therefore a sample of the energy loss. If the transferred energy to the electron is sufficient, the freed electron thus ionizes other atoms of the gas.

Figure 3.1: The energy loss of the charged particles.
Figure (3.1) shows evident points concentration distribution (bands), each corresponding to a specific mass of particle. This function that was expressed within the equation (2.18) gives a curve as a function of the particle energy that is characterized by a decrease leading to a minimum which is then followed by a rapid increase that cap. This means that the resolution is good at low momentum and it became gradually deteriorated when the momentum increasing. In order to optimize the efficiency and significance, tighter selection criteria are imposed to select only the provided dE/dx information for the electron and the positrons events. The right of the figure (dEdx figure) represents all the accepted charged particles after taking the dE/dx band in the region $308 - 2\sigma_{dEdx} < dEdx < 440$ and along the momentum interval. However, this cut prevent the contamination of the charged pions when theirs energy loss overlap. This contamination is clearly visible on the left of the figure. An extra condition on the momentum is then needed. The new cut $dEdx > 260 + 10\log p$ is included and represented by the the black incline line which allow the suppression of the $\pi^\pm$ contaminations and beyond these values.

The effect of the previous cuts is showen on the righ side of the figure. The electron/positron band are well seperated from the other hadrons, therfore the contaminations can be easily rejected by imposing all the cuts described above.

### 3.3 The mixing event method

Experimentaly we are dealing some times with instabilities particles which have a very short life time, or discussing the statistical analysis od data which direct to the final event analysis, in these cases we are beyond multiple paths that lead from the detection digitizings to physics information. During the an ultra-relativistic collosion, a pair of electrons/positrons (i.e the same signs) do not come from the same photon, however they might issued from a coincidence events.

Figure ( 3.9) shows the reconstructed electron (positron) numbers in each event can reach of 32 electron(positron). Each electron (positron) combine with with positron (electron) of opposit charge to form one photon. However the extraction of photon signal is reproduced by building invariant mass distribution using electrons and positrons hits taken from different event of similar multiplicity.

This approach of the substraction of combinatorial background is called the mixed event method. The idea of mixed event method is based on the com-
### 3.3. THE MIXING EVENT METHOD

Figure 3.2: The multiplicities of electrons and positrons in each event. The selection was obtained by using the energy loss information provided from TPC detector.

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Positrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>$2.804705 \times 10^7$</td>
<td>$2.804705 \times 10^7$</td>
</tr>
<tr>
<td>Mean</td>
<td>30.03</td>
<td>32.47</td>
</tr>
<tr>
<td>RMS</td>
<td>7.725</td>
<td>8.02</td>
</tr>
</tbody>
</table>

**Figure (3.2)** shows the principle of the mixed event technique. The applied track selection is the same for all the recorded events in order to reproduce correctly the combinatorial background. Each combination for a certain event $i$ between $X_i$ and $Y_i$ is taken into account after passing all the global criteria cuts. The yield will form the real distributions needed later to extract the signal. This step is repeated over all the number of events ($n$).

Another correlation of $X$ and $Y$ particles which can be happened numerically but it will not be taken into account physically since it is considered as background. All the combinations $X_i$ and $Y_i, Y_{i-1}, Y_{i-2}, ..., Y_{i-n}$ or $Y_i$ and $X_i, X_{i-1}, X_{i-2}, ..., X_{i-n}$ are counted by the mixing between the different events. Chronologically, after each event, the selected $X-Y$ combinations are stored in an array.
Event = $i$

$X_i$, $Y_i$

$X_i \leftarrow Y_{i-1} Y_{i-2} Y_{i-4} \cdots Y_{i-n}$

$Y_i \leftarrow X_{i-1} X_{i-2} X_{i-3} \cdots X_{i-n}$

Selection of the lepton pairs

Real distribution

Selection of the lepton pairs

Mixing event distribution

Figure 3.3: The principal operation of the mixing event method.
3.4  The standard Quality cut

The track quality criteria is used to accept only the well defined tracks and reject the fake tracks. The track quality cuts depend essentially on the number of the hits on the track. The main requirement is that the track must have a minimum number of associated hits. Furthermore, the geometry of the TPC detector provide the acceptance range for the whole track finding process.

![Scatter plot of the used track quality cut](image)

**Figure 3.4:** The scatter plot of the used track quality cut. The black line indicates the placed criteria dependence on the polar angle and the number of the fitted hits.

The recorded number of hits on the TPC segment Only the tracks which they have more than 10 hits will be kept for the analysis performed later. We apply an angular cut on the polar angle as function of the number of fitted hits to have the full coverage of the TPC detector. This can be summarized by suspecting the black line indicated in the Figure (3.4). It illustrates the \( \theta \) of the TPC Vs number of the fitted hits on the stored track. These cuts, on the number of the fitted hits and the polar angle of the TPC collectively referred to the total TPC geometrical acceptance.
3.5 The study of the unlike and like sign pairs

In our case, as first step from the reconstruction scheme, we start firstly by the electron/positron combinations and the same procedure will be applied to $\gamma\gamma$ invariant mass distributions.

Let’s now reformulate the mixed event method explained above to study the photon reconstruction case. As first point, the $X - Y$ combination which basically represents the phase spaces of the associated particles, will be the electron-positron combination. This latter ensemble of the opposed signs represents the signal of a ”good” photon(from the event).

Before going to discuss the photon reconstruction part, we have to keep in mind that we are concerned with the reconstruction of photons that convert(shortly) before the TPC spectrometer into $e^+e^-$ via the measurement of the electron pair in the TPC.

The opening angle distribution of the unlike sign pairs ($e^+e^-$) and the like signs pairs ($e^+e^+ + e^-e^-$) for different $P_t$ have been investigated in order to optimize the definition of the photon for efficiency and significance.

The opening angle between the the electron and the positron can be expressed by the equation:
\[ \cos \theta = \frac{p_{x1}p_{x2} + p_{y1}p_{y2} + p_{z1}p_{z2}}{|p_1||p_2|} \]  

(3.1)

where the \( P_1 \) and \( P_2 \) are the Lorentz vector for the electron (positron) and the positron respectively.

The variation of the opening angle between the unlike signs pairs \((e^+e^-)\) and the like-sign pairs\((e^+e^+ + e^-e^-)\) is shown in figure (3.6).

The peak in each momenta window indicates clearly the existence of photons converted before the the Time Projection Chamber. The peak became narrower and the number of the photons is decreasing when we go at high momentum regions.
Figure 3.6: The variation of the opening angle between the unlike sign $e^+e^-$ (blue line) and the like signs $e^+e^+, e^-e^-$ (red line) corresponding to their momentum from 0 to 8 GeV, each window represents 1 GeV.
3.5. \textit{THE STUDY OF THE UNLIKE AND LIKE SIGN PAIRS}

At this stage, the conversion signal and the background distribution have different shapes, this can be observed by inspecting the unlike and like signs distributions where the unlike and like signs distributions are not comparable at each other at low opening angle regions. Further and detailed investigations should reveal for a better precision and determination of the opening angle. The ratio of the unlike-signs and like-sign pairs in different momentum bins is displayed in the the set of figure (3.7) then it is fitted by a sum of a constant and exponential functions which take the form:

\[ f(\text{ratio}) = p_0 + \exp(p_1 + p_2x) \quad (3.2) \]

The vertical lines in each momentum bin was calculated as the opening angle points where the ratio is 10\% higher than the constant level \((p_0)\). This lead us to what we call it the \textit{cross-point}, where the unlike and like sign distributions starts to converge and meet each other. Thereby, bringing the signal to background ratio to probe the conversion signature gives us the Crosspoint definition expressed by the following equation:

\[ \text{Cross-point(momentum)} = 1/p_2.(\ln(0.1.p_1) - p_1) \quad (3.3) \]

where \(p_1\) and \(p_2\) refers to the fit function parameters metioend previously. Most interestingly, we shall see that the calculation of the Cross-point values as function of momentum direct us to new physical picture by applying new cut on the opening angle between the the \(e^+e^-\) as function of theirs momentum. From these considerations, we can define the \textit{ThetaEP cut}. It is shown in figure (3.8)..... and it can be expressed by:

\[ \text{ThetaEP}(p) = f_1 + f_2 \quad (3.4) \]

where:

\[ f_1 = \exp(a_0 + a_1p + a_2p^2 + a_3p^3) \quad \text{with} \quad p \in [0, 8.5] \quad (3.5) \]

and

\[ f_2 = 3.5 \quad \text{(mrad)} \quad (3.6) \]

\(f_1\) function corresponds to the curved line and \(f_2\) is the horizontal line at the opening angle 3.5\textit{(mrad)} and larger than 8.5\textit{(GeV/c)}. 


Figure 3.7: The ratio of the unlike sign $e^+e^-$ and the like signs $e^+e^+, e^-e^-$ Vs the opening angle corresponding to their momentum from 0 to 8GeV, each window represent 1GeV. The vertical line indicates the angular cut.
3.6 THE PHOTON RECONSTRUCTION

The geometrical $\Theta_{EP}$ cut has its main support at small opening angles and low momenta. In what follows, the $\Theta_{EP}$ cut will be kept during the whole analysis scheme described later.

![Theta(e+e-) Vs P](image)

**Figure 3.8**: The electron-positron opening angle Vs the momentum, the curved and the horizontal line indicates the applied cut values to define photons.

3.6 The photon reconstruction

3.6.1 Photon-Matter interaction

Photons are electromagnetic radiations with zero mass, electrically neutral and travelling with a constant velocity that is always the speed of light $c$. A photon passing through matter interact in different ways. There are four important mechanisms of interactions between the photon and matter. In all these mechanisms of the process, the photon gives up some or all of its energy to a matterial particle. This is usually happening in the vicinity of an atomic nucleus. The Compton effect where the photon can
be diffused by an electron (or a nucleus) and lose some of its energy. Note that the photon don’t slowdown. It is still travelling with the velocity $c$, but its frequency is reduced. At lower energies the dominant process is the photoelectric effect.

The photon collide with the electron and ionizes the atom of the matterial by kicking out one electron.

Other process equivalent to the previous one but in this case the photon energy is not enough to free the electron. Thereby, the photon is captured by the atom and excites the state of the hitted electron in the shell to higher energy level. Again, the photon disappears and transmits all its energy to the atom. The Last common process, which is the formation or the materialization of two electrons, one negative (electron) and the other one positive (positron). This process is called Pair production. It is a direct conversion of radiant energy to matter.

### 3.6.2 Photon conversions ($\gamma Z \rightarrow e^+e^- Z$)

The CERES/NA45 experiement measures photon yields by conversion method. For Pair Production to occur, the electromagnetic energy, or the photon energy, must be at least equivalent to the mass of the two electrons. When the photon energy is greater than $2m_e c^2$, which corresponds to $1.022 \text{MeV}$, the photon can be materialized by the creation of electron-positron pair. For photon energies above the threshold energy, the surplus energy appears as kinetic energy to the two electrons.

An additional condition which must be satisfied during the Pair Production process because it can not be occur in the vacuum. The energy and the momentum can not be simultaniusly conserved. Something must participate in the interaction and absorb the momentum of the initial photon to balance the equations. The presence of a charged particle like an atomic nucleus, which should be more massive than the electron/positron, during the interaction can absorb a fraction of the photon mometum. The Pair Production is the dominant process at high energies.

Since the photons are masseles, they are not detected directly. Theirs state is displaced as neutral vertex. The converted electrons are identified by the searching for oppositely charged track near the electron track, then we do the extrapolatation to a common target point. Tracks found in this way are subsequently used as starting point for track combinations and a converted photon is created for each valid pair. We have to remember that our our goal is to reconstruct the photons through conversions happening mainly in the RICH2 mirror location.
3.6. THE PHOTON RECONSTRUCTION

3.6.3 The reconstructed photon mapping

So far we have concentrated on the description of the unlike and like sign pairs as building blocks for the photon by using the TPC information. The number of photons per each event is displayed in figure (3.9). Our next task is to define and determine the photon by scanning theirs spatial map inside the detector.

![Graph showing photon distribution](image)

**Figure 3.9:** The number of the reconstructed electrons and positrons in each event by using the dEdx information provided from TPC detector.

Figure (3.11) illustrates the azimuthal and the polar angles distributions for the primary photon selection based on the data collected previously. In the X-Y plane, the photons are measured for the whole azimuthal acceptance. However, a radiant cut $0.135 \leq \theta \leq 0.25$ was used to select only the phase-space where the photons are supposed to come from the decay of the neutral pions. Thus, by applying this polar cut we exclude the photons yielded from the multiple scattering or the Bremsstrahlung processes which are mainly happening at lower polar angles. The measured transverse momentum of the reconstructed primary photon from the unlike and like sign pairs is shown in Figure (3.10). The transverse momentum distribution has sharp peak near zero and broader peak at high transeverse momentum. This behaviour can be understood from the fact that photon conversion is characterised by very small electron-positron opening angle.

The measured transverse momentum vector for the primary photon

For the preceding considerations, the plan for the start-up should therefore be two-pronged. The first one is the sophisticated reconstruction of the sec-
CHAPTER 3. THE DATA ANALYSIS

Figure 3.10: Schematic event display of the TPC.

3.7 The Secondary vertex fit algorithm

The Secondary vertex technique provide a very clean and well measured photons which can be used in the reconstructed of the neutral pions represented in the next section. Opposite charged trackes are combined to obey the physical process \( \gamma \rightarrow e^+e^- \) candidates. The method will be expanded to provided the option to fit the charged tracks. Each of the two tracks is assumed to point out to a common position. This constraint take into acount that the verticies are parallel to each other at the conversion point as a general assumption. Consequently, an implicit "zero mass" on the invariant mass for the displaced vertices is yielded at the RICH2M region.

The principle of the Scondary Vertex fit algorithm is to calculate the 3D distance between the two tracks. The used alogorithme calculates the point of the opposit sign track pairs which have assigned to the electron and to the positron. This method is performed on the Least Square Method. It was used by HADES collaboration, and it is also described in [HADES reference]. For further details and all the characteristic features about it the reader is advised to consult [reference].

The study of the vertexing and kinematic fitting withing the Secondary Ver-
3.7. THE SECONDARY VERTEX FIT ALGORITHM

Figure 3.11: The mapping of the reconstructed photons in the phase-space. The top window represents the bidimensional distribution of the azimuthal and polar angles for the reconstructed photons. The middle and the bottom windows show the projection of the $\theta_\gamma$ and the $\phi$ angles respectively.

text algorithm will be divided into two subsections. The first part will be
intended to provide the mathematical framework of the vertex fitting. This is handled generally by solving analytically the closest approach point equations of the two opposite sign tracks. Then we will examine in more details and explicitly the practice calculation of the closest approach point occurring from the latter subsection.

3.7.1 The mathematics of the Secondary Vertex fit

The general way of the Secondary Vertex consists of the following prescription. All the charged tracks are parametrized as straight lines and used as input to the algorithm. Assuming that there are $N$ detected tracks that means for each input candidate $i \in [1, N]$ and from the linearity hypothesis, we write the definition of the $i^{th}$ track in the form:

$$\vec{x}_i = \vec{r}_i + \vec{u}_i t, \quad t \in \mathbb{R} \quad (3.7)$$

such that $\vec{r}_i$ refers to the position vector, $\vec{u}_i$ its direction vector, i.e. $\vec{u}_i = \vec{r}_i / |\vec{r}_i|$ and $t$ is the track parameter or the so-called controlled variable. We will attempt to determine the unknown coordinates in space of the position vector $\vec{r}_{sv}$ which is assigned to the point of conversion. The distance of the conversion point to a given $i^{th}$ track which is basically expressed in the equation (3.7) can be calculated as:

$$D_i = |(\vec{r}_i - \vec{r}_{sv}) \times \vec{u}_i| \quad (3.8)$$

Equation 2 is a result from the fact that $\vec{r}_i$ vector set are the measured data points and the $D_i$ represents the deviations from the given set of data in the base $|\vec{u}_i|$. According to Least Square method, the fitting proceeds by finding the sum of the squares of the deviations $D_i$ for all the detected tracks. There are a given uncertainties for all the measured data point; for that reason these points can be weighted differently in order to give the high-quality points more weight. Based on this, the squares deviations are therefore summed and minimized to find the best fit line. This can yields the following:

$$M^2 = \sum_{i=1}^{N} \frac{D_i^2}{\sigma_i^2} = \sum_{i=1}^{N} |(\vec{r}_i - \vec{r}_{sv}) \otimes \vec{u}_i| \quad (3.9)$$

By taking the uncertainties $\sigma_i^2$ constant, the minimization of $M^2$ is thus equivalent to the determination of the space coordinates of the closest approach between the $N$ tracks. The minimization of $M^2$ is simply done by making the the partial derivatives of $M^2$ with respect to the unknown parameters and set these value to zero. The $M$ quantity defined in Equation 3 has a property
3.7. THE SECONDARY VERTEX FIT ALGORITHM

which can be used to carry out a $\chi^2$ test. We now write this consequence, the analogous expression of 3, in the form:

$$\chi^2 = \sum_{i=1}^{N} \frac{D_i^2}{\sigma_i^2}$$  \hspace{1cm} (3.10)

The condition for the $\chi^2$ to be minimum is that:

$$\frac{\partial \chi^2}{\partial x_{sv}} = 0, \quad \frac{\partial \chi^2}{\partial y_{sv}} = 0, \quad \frac{\partial \chi^2}{\partial z_{sv}} = 0$$  \hspace{1cm} (3.11)

To determine the equation (3.11), we first have to get the distance between the two selected charged tracks $D_i^2$, i.e.:

$$D_i^2 = [(y_i - y_{sv})a_{zi} - (z_i - z_{sv})a_{yi}]^2 + [(z_i - z_{sv})a_{xi} - (x_i - x_{sv})a_{zi}]^2 + [(x_i - x_{sv})a_{yi} - (y_i - y_{sv})a_{xi}]^2$$  \hspace{1cm} (3.12)

Expanding the equation system (3.11), this leads to:

$$\frac{\partial \chi^2}{\partial x_{sv}} = \sum W_i \left\{ [(z_i - z_{sv})a_{zi} - (x_i - x_{sv})a_{zi}]a_{zi} - [(x_i - x_{sv})a_{yi} - (y_i - y_{sv})a_{zi}]a_{yi} \right\} = 0$$

$$\frac{\partial \chi^2}{\partial y_{sv}} = \sum W_i \left\{ [(x_i - x_{sv})a_{yi} - (y_i - y_{sv})a_{zi}]a_{xi} - [(y_i - y_{sv})a_{zi} - (z_i - z_{sv})a_{yi}]a_{zi} \right\} = 0$$

$$\frac{\partial \chi^2}{\partial z_{sv}} = \sum W_i \left\{ [(y_i - y_{sv})a_{zi} - (z_i - z_{sv})a_{yi}]a_{yi} - [(z_i - z_{sv})a_{zi} - (x_i - x_{sv})a_{zi}]a_{zi} \right\} = 0$$  \hspace{1cm} (3.13)

where the $W_i$ is the weighting factor $2/\sigma_i^2$. The equation (3.13) is linearized in the unknown parameters of the space coordinates. Involving matrix manipulations and especially matrix inversions, the equation system in (3.13) can be summarized in three main matrices labeled as $A$, $B$ and $C$ which satisfy the equation:

$$C = A^{-1}B$$  \hspace{1cm} (3.14)

The expressions of these specific matrices are written in the matrix form and obtained as follow:

$$A = \sum_{i=1}^{N} W_i \begin{pmatrix} a_{yi}^2 + a_{zi}^2 & -a_{yi}a_{zi} & -a_{xi}a_{yi} \\ -a_{yi}a_{xi} & a_{xi}^2 + a_{zi}^2 & -a_{yi}a_{zi} \\ -a_{zi}a_{xi} & -a_{zi}a_{yi} & a_{yi}^2 + a_{zi}^2 \end{pmatrix}$$  \hspace{1cm} (3.15)
\[ B = A \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}, \] (3.16)

and the wanted matrix:

\[ C = \begin{pmatrix} x_{sv} \\ y_{sv} \\ z_{sv} \end{pmatrix}, \] (3.17)

One this problem is handled by solving analytically the point of closest approach of the two charged tracks (the two candidates), we could then determine the \( A, B \) and \( C \) matrices. The latter \( C \) matrix is a 1-column matrix which offers the space coordinates values of the conversion point.

It may be, however, that the uncertainties \( \sigma_i \) are not normally distributed and their expectation values are different from zero. This constraint implies dependency of the \( \sigma_i \) uncertainties on the \( D_i \) distances (i.e. \( \sigma_i^2 = \sigma_i^2(D_i) \)).

In this case special care on the calculation of \( \sigma_i \)'s values because we are dealing with non-negligible values of errors. It can be redefine and one gets the alternative expression as:

\[ \sigma_i^2(D_i) = \begin{pmatrix} \frac{\partial D_i}{\partial x_1} & \frac{\partial D_i}{\partial y_1} & \frac{\partial D_i}{\partial x_2} & \frac{\partial D_i}{\partial y_2} \\ \sigma_{x_1x_1} & 0 & 0 & \sigma_{x_1y_1} \\ 0 & \sigma_{y_1y_1} & 0 & \sigma_{y_1y_2} \\ \sigma_{x_2x_1} & 0 & 0 & \sigma_{x_2y_2} \\ 0 & \sigma_{y_2y_1} & 0 & \sigma_{y_2y_2} \end{pmatrix} \begin{pmatrix} \frac{\partial D_i}{\partial x_1} \\ \frac{\partial D_i}{\partial y_1} \\ \frac{\partial D_i}{\partial x_2} \\ \frac{\partial D_i}{\partial y_2} \end{pmatrix} \] (3.18)

With the definition written in equation (3.18), \((x_1, y_1)\) refers to the track space coordinates by requiring \( z = 0 \). \((x_2, y_2)\) are the corresponding slopes in the X-Z plane (for \( x_2 \)) and Y-Z plane (for \( y_2 \)). Thus, that reads:

\[
\begin{cases}
    x_2 = \frac{u_x}{u_z} \\
    y_2 = \frac{u_y}{u_z}
\end{cases}
\] (3.19)

where \((u_x, u_y, u_z)\) are the coordinates of the unit direction vector \( \vec{u} \). The \( \sigma_{mn} \) refers to covariance if \( m \neq n \) and in the opposite case \( m = n \) it corresponds to the variance of the \( m \) and \( n \) parameters. In what follows, we will use a short notations to simplify the complication of the equations. Let:
3.7. THE SECONDARY VERTEX FIT ALGORITHM

\[
\vec{\Delta}_i = \Delta_x \vec{r} + \Delta_y \vec{j} + \Delta_z \vec{k}.
\]  

(3.20)

and

\[
\vec{\Delta}_i = \vec{r}_i - \vec{r}_{sv}.
\]  

(3.21)

from the equations (3.20) and (3.21) one can get:

\[
\begin{aligned}
\Delta_x &= x_i - x_{sv} \\
\Delta_y &= y_i - y_{sv} \\
\Delta_z &= z_i - z_{sv}
\end{aligned}
\]  

(3.22)

Furthermore, the unit vector property provides us:

\[
u_z^2 = 1 - u_x^2 - u_y^2
\]  

(3.23)

which leads to:

\[
\begin{aligned}
\frac{\partial u_x}{\partial x} &= -u_x \\
\frac{\partial u_x}{\partial u_x} &= u_z \\
\frac{\partial u_z}{\partial u_y} &= u_y \\
\frac{\partial u_y}{\partial u_z} &= u_z
\end{aligned}
\]  

(3.24)

From these formulas, the equation 3.12 can be re-written in the following compact form:

\[
D_i^2 = (\Delta_{zi}^2 - \Delta_{xi}^2)u_{xi}^2 + (\Delta_{zi}^2 - \Delta_{yi}^2)u_{yi}^2 - 2(\Delta_{yi} \Delta_{zi} u_{yi} u_{zi}) + \Delta_{xi} \Delta_{zi} u_{xi} u_{zi} + \Delta_{xi} \Delta_{yi} u_{xi} u_{yi} + \Delta_{zi}^2 + \Delta_{yi}^2
\]  

(3.25)

and the partial derivatives in equation 3.18 will be computed with respect to \(u_x\) and \(u_y\) and not for the \(x_2\) and \(y_2\) cases (this step will be done later). Thus, the results of the updated partial derivatives of the distance \(D_i\) are and obtained as:
\[ \frac{\partial D_i}{\partial x_1} = \frac{(1 - u_{z_1}^2)\Delta_{x_1} - u_{x_1}(\Delta_{x_1}u_{z_1} + \Delta_{y_1}u_{y_1})}{D_i} \]

\[ \frac{\partial D_i}{\partial y_1} = \frac{(1 - u_{y_1}^2)\Delta_{y_1} - u_{y_1}(\Delta_{x_1}u_{z_1} + \Delta_{x_1}u_{x_1})}{D_i} \]

\[ \frac{\partial D_i}{\partial u_{x_1}} = \frac{\Delta_{x_1}^2 - \Delta_{x_1}^2 u_{x_1}^2}{D_i} \]

\[ \frac{\partial D_i}{\partial u_{y_1}} = \frac{\Delta_{y_1}^2 - \Delta_{y_1}^2 u_{y_1}^2}{D_i} \]

\[ Q = x_2^2 + y_2^2 + 1 \]  

Using the equations in 3.19, \( Q \) can be expressed in the form:

\[ Q = \frac{1}{u_z^2} \]  

Finally, once all the parameters have been found, the error propagation with the no-negligible values of \( \sigma_i \) is obtained by simply implementing all of them in the equation (3.18).

The complete procedure is re-iterated until convergence is reached. Before each iteration track parameters and error matrices are translated to current vector position. It should be noted that the procedure of the charged track selection for the conversion criteria is iterated till a displacement of the order 0.01\( \mu \)m or less is seen on the computed slope of the secondary vertex position.

As a conclusion, the method is based on maximizing the Secondary vertex probability (or minimizing the \( \chi^2 \)) derived from the vertex fits for a permutation of possible two track associations. Within the mathematical framework, the position of the conversion point is then given by the equation (3.14).
3.7.2 Application of the Secondary vertex method

The determination of the Secondary vertex point manifest through the mathematical configuration presented above. As a consequence, here we make a direct application for the photon conversion point which is identified by the following sequence.

Assume we have the two electrons vectors expressed as:

\[
\begin{align*}
\vec{p}_1 &= \vec{a}_1 + t \cdot \vec{b}_1 \\
\vec{p}_2 &= \vec{a}_2 + s \cdot \vec{b}_2
\end{align*}
\] (3.31)

we consider the distance vector \( \vec{d}_i \) between \( \vec{p}_1 \) and \( \vec{p}_2 \), that means:

\[
\vec{d}_i = u(\vec{b}_1 \times \vec{b}_2) \leftrightarrow \vec{d}_i \perp \vec{b}_1 \quad \text{and} \quad \vec{d}_i \perp \vec{b}_2
\] (3.32)

In additon one can get (see Figure ..):

\[
\begin{align*}
\vec{p}_1 + \vec{d}_i &= \vec{p}_2 \\
\vec{a}_1 + t \cdot \vec{b}_1 + u(\vec{b}_1 \times \vec{b}_2) &= \vec{a}_2 + t \cdot \vec{b}_2
\end{align*}
\] (3.33) (3.34)

which yields:

\[
\vec{a}_1 - \vec{a}_2 = s \cdot \vec{b}_2 - t \cdot \vec{b}_1 + u(\vec{b}_1 \times \vec{b}_2)
\] (3.35)
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By re-writing the equation (3.35) in the matricial form:

\[
\begin{pmatrix}
  b_{2x} - b_{1x} & (\vec{b}_2 \times \vec{b}_1)_x \\
  b_{2y} - b_{1y} & (\vec{b}_2 \times \vec{b}_1)_y \\
  b_{2z} - b_{1z} & (\vec{b}_2 \times \vec{b}_1)_z \\
\end{pmatrix}
\begin{pmatrix}
  s \\
  t \\
  u \\
\end{pmatrix}
= 
\begin{pmatrix}
  a_{1x} - a_{2x} \\
  a_{1y} - a_{2y} \\
  a_{1z} - a_{2z} \\
\end{pmatrix}
\]

The goal is to determine \((s, t, u)\) vector compound. The system of linear equations in (3.36) can be solved by using Cramer’s rule in terms of determinants. That read,

\[
s = \frac{\text{det} S}{\text{det} A}, \quad t = \frac{\text{det} T}{\text{det} A}, \quad u = \frac{\text{det} U}{\text{det} A}
\]

with:

\[
\text{det} A = 
\begin{vmatrix}
  b_{2x} & - b_{1x} & (\vec{b}_2 \times \vec{b}_1)_x \\
  b_{2y} & - b_{1y} & (\vec{b}_2 \times \vec{b}_1)_y \\
  b_{2z} & - b_{1z} & (\vec{b}_2 \times \vec{b}_1)_z \\
\end{vmatrix}
\]

\[
\text{det} S = 
\begin{vmatrix}
  a_{1x} & - a_{2x} & b_{1x} & (\vec{b}_2 \times \vec{b}_1)_x \\
  a_{1y} & - a_{2y} & b_{1y} & (\vec{b}_2 \times \vec{b}_1)_y \\
  a_{1z} & - a_{2z} & b_{1z} & (\vec{b}_2 \times \vec{b}_1)_z \\
\end{vmatrix}
\]

\[
\text{det} T = 
\begin{vmatrix}
  b_{2x} & a_{1x} & - a_{2x} & \vec{b}_2 \times \vec{b}_1)_x \\
  b_{2y} & a_{1y} & - a_{2y} & \vec{b}_2 \times \vec{b}_1)_y \\
  b_{2z} & a_{1z} & - a_{2z} & \vec{b}_2 \times \vec{b}_1)_z \\
\end{vmatrix}
\]

\[
\text{det} U = 
\begin{vmatrix}
  b_{2x} & - b_{1x} & a_{1x} & - a_{2x} \\
  b_{2y} & - b_{1y} & a_{1y} & - a_{2y} \\
  b_{2z} & - b_{1z} & a_{1z} & - a_{2z} \\
\end{vmatrix}
\]

Consequently, the Secondary vertex point is just pointed out by the vector \(\vec{p}_{12}\) expressed by the following equation:

\[
\vec{p}_{12} = \vec{p}_1 + \frac{1}{2} \vec{d}_i
\]

\[
= \vec{p}_1 + \frac{1}{2}(\vec{p}_1 - \vec{p}_2).
\]

Any vector of the electron/postion detected by the TPC and expressed by the equation (3.33) is then computed by the coordinates \((X_{line0}, Y_{line0}, 0)\). The \((x_2, y_2)\) slopes that are defined in the previous section with \(z = 0\) are equivalent to the \(\vec{s}\) slope in the X-Z plane (for \(x_2\)) and Y-Z palne (for \(y_2\)). They are obtained by the \(X_{line1}\) and \(Y_{line1}\) values of the TPC track. The latter two parameters are used to measure the local angles defined in the equations (2.12) and (2.13).
3.7.3 Secondary vertex cut (SV)

Since our concern is to reconstruct the photons that converts in the RICH2 mirror position, we select them by making a cut on the converted photon. It was possible to enhance the extracted photon signal by the $\theta_{EP}$ cut described in Section (3.5). It has a powerful support to reduce the background and to compensate the resolution and the significance.

![Secondary Vertex distributions of the photons candidates.](image)

**Figure 3.13:** The Secondary Vertex distributions of the photons candidates. The reconstructed photons from the unlike sign pairs ($e^-e^+$) are in blue and the like sign pairs ($e^-e^- + (e^-e^+)$) in red. The top two plots correspond to Secondary Vertex distributions on the X axis before and after the $\theta_{EP}$ cut while on the bottom two plots, the same distributions on the Y axis before and after the $\theta_{EP}$ cut.
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This can be seen by checking the reconstructed secondary vertices distributions in the X, Y and Z axis. It is explicitly verified on the X and Y axis shown in figure (XY) after and before the \( \text{ThetaEP} \) cut. Additionally, a more server check can be observed corresponding the projection of the distribution on the X-Y plane illustrated in figure (3.14). The highly concentrated distribution represents the photons location in the phase-space.

This method reinforce the suppression of the contamination of different hadrons and distinguish between them.

![Figure 3.14](image)

**Figure 3.14:** The projection of the Secondary Vertex distribution on the X-Y plane. The most populated area indicates the positions of the reconstructed photons.

A similar situation along the Z axis is presented separately, where the most significantly photons distribution are very clear. This is shown in figure 3.15. From this one finds that reconstructed photons are concentrated in the RICH2 mirror region. This is expected since the RICH2 mirror is main converter and leads to acceptable situation.

By following the previous steps discussed above, More precise tuning is now needed and may give further improvement to select the photons at the RICH2M position. The Secondary Vertex cut (SV) can be comfortably performed at \( 2\sigma \). After extensive verification that no photons information was being originated from other locations, by keeping the SV cut in all the accumulated analysis, the Secondary Vertex distributions from the contribu-
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Figure 3.15: The Z direction of the Secondary Vertex distributions of the photon candidates before (left) and after (right) imposing the ThetaEP cut.

...tions of the unlike and like sign pairs investigated as function of the photon momentum (see figure (3.18)). This requirement is a major benefit from the SV cut which has been studied depending on the momentum of the photons. This study can be explored in figure (3.17). The location of the extracted photon signal is substantially present at the RICH2 converter and fitted with Gaussian function. This confirms that the used technique to determine the photons is equivalent to our expectations where they should be occurring.

The mean of the Gaussian fit refers to converted photons as function of their momentum. The stability of the mean values indicates the well reconstructed photons candidates which will be used next to the neutral pion reconstruction. The width of the distributions is dominated by the angular resolution of the opposed charged tracks.
Figure 3.16: The measured Z direction of the Secondary Vertex distributions after the ThetaEP cut as function of the photon momentum.
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Figure 3.17: The extracted signal distribution of the converted photons Vs the momentum of the photon.
3.8 The $\pi^0$ reconstruction

This section is dedicated to describe the reconstruction of $\pi^0$ from $\gamma\gamma$ decay. The produced $\pi^0$ decays into a pair of photons with branching ratio 98.7% making it the most convenient decay channel for $\pi^0$ reconstruction. The procedure to determine the reconstruction is similar to the one for the photons described in Section (3.6).

3.8.1 Invariant mass analysis

The invariant mass of a particle is given by the absolute value of its 4-momentum. As photons are massless particles this reduces to the determination of the energy and the opening angle between the two photons. For photon pair originating from $\pi^0$ decay the invariant mass is identical to the $\pi^0$ rest mass of 134.9766 MeV [19]. The reconstruction of $\pi^0$ is twofold problem. The first one was the reconstruction of the $\gamma$. Then $\pi^0$’s are found. $\gamma$’s were reconstructed by combining the two opposed charged traks of $e^+$ and $e^-$ using the TPC information. The invariant mass of particle pair is given by the absolute value of its 4-momentum.

$$p_{12} = p_1 + p_2 \quad (3.44)$$

The invariant mass expression of $\pi^0 \rightarrow \gamma\gamma$ is found by taking the
3.8. THE $\pi^0$ RECONSTRUCTION

$p = (p_0, p_1, p_2, p_3) = (E, p_x, p_y, p_z)$ and taking the metric base diag $g_{\mu\nu} = (1, -1, -1, -1)$. The $E = p$ for the photons. This reads:

$$
\begin{align*}
M_{\pi^0}^2 &= 2E_{\gamma_1}E_{\gamma_2}(1 - \cos \theta) \\
&= 2|\vec{p}_{\gamma_1}| |\vec{p}_{\gamma_2}| (1 - \cos \theta) \\
\Rightarrow M_{\pi^0} &= \sqrt{2|\vec{p}_{\gamma_1}| |\vec{p}_{\gamma_2}| (1 - \cos \theta)}
\end{align*}
$$

(3.45)

The Mixing event

Once the "good" photons are identified, the invariant mass analysis of $\pi^0$ cannot be identified uniquely since all possible photon-photon combinations have to be considered. The procedure of event mixing method is widely used to determine the combinatorial background. The mixed event is determined by taking all photon candidates from an event and combine it with the photons from different events. This straightforward to what have been discussed in Section (3.3). By this way the mixed event distribution is determined in the case of the $\pi^0$ invariant mass

The Armenteros Podolanski plots

In order to try to verify if there is any cross decay channels with the $\pi^0$ peak which can be misidentify the mass, we study the Armenteors-Podolanski plot [20].

*Figure 3.19:* The mean and the width of the fitted secondary vertex distribution Vs the photon momentum.
The variables of the Armenteros-Podolanski technique are the $p_{TA}$ which is the projection of one of the two photon momentum (daughters) on the flight direction of the neutral pion (parent). The second used parameter is $\alpha$ that can define by the momentum projections of the photons on the direction of the $\pi_0$ meson. This can be simply expressed as:

$$\alpha = \frac{p_L(\gamma_1) - p_L(\gamma_2)}{p_L(\gamma_1) + p_L(\gamma_2)} \quad (3.46)$$

In the $(p_{TA}, \alpha)$ plane, a good reconstruction of the parent particle mass should appears as an elliptic concentration. This can be seen in figure 3.19. This method reinforce the suppression of the contamination of different hadrons and distinguish between them. A clear signal of the neutral pion mass is seen and there is no decay channel which can misidentified the reconstruction of the $\gamma\gamma$ invariant mass.

**The Opening angle cut (OpG1G2)**

The opening angle between the two photons have been studied as function of the neutral pion transverse momentum. This is shown in figure (3.20). An opening cut $\text{OpG1G2}$ between the two reconstrcuted photons is implemented in order to reduce the combinatorial background whi are coming from small opening angle photons. The magenta line indicates the implemented cut as function of the neutral pion momenta, this can be expressed as: $\text{OpG1G2} = 0.2 \exp(-5p) + 0.02$, where $p$ represents the momenta of the neutral pion.

**The $\pi^0$ signal extraction**

The combinatoric background is define as the background level in mass distributions after imposing all the requierements on the kinematic quantities. Besides the discussed cuts, more stringent requirements are used to observe the $\pi^0$ signal. The combinatorial background depends upon the $p_T$ distribution of the reconstructed photons. The obtained $\gamma\gamma$ invariant mass distributions for the photons yielded from the same event and the mixing event is scanned as function of transverse momentum and rapidity ranges. This has been checked for 10 $p_t$ bins. Each signal templates represents $0.25(GeV/c)$. We expand also the study as function of rapidity splited in three interval, $2.2 \leq y_1 < 2.4$, $2.4 \leq y_2 < 2.6$ and $2.6 \leq y_3 < 2.7$. In all what follows we will measure the $\gamma\gamma$ invariant mass as function of these two variabels ($p_t, y$). Additional constraint on the second $p_t$ bin $0.25-0.5 \ (GeV/c)$, the third $p_t$ bin $0.5-0.75(GeV/c)$ and along all the rapidity intervals. This cut have been imposed where we require for all the
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Figure 3.20: The scatter plot of the $\pi^0$ transverse momenta vs the opening angle between the two photons. The OpG1G2 cut is indicated by the magenta line.

 photons opening angles to be larger than 0.11 rad and 0.07 rad in the transverse momentum interval 0.25 – 0.5 GeV/c and 0.25 – 0.5 GeV/c respectively, and for all the rapidity $2.2 < y < 2.7$.

All photons that survived the previous cuts were taken in combination with each other. The resulting $\gamma\gamma$ mass distributions was used to define the $\pi^0$ signals. As it is illustrated in figures (3.21), (3.22), (3.23) the signal is well separated from the background and the $\pi^0$ mass is pointed out by the vertical line. The background in blue is below the peak in all the transverse momenta bins and rapidity. In the first $p_t$ window we do not measure photons, therefore no signal is obtained.

The scale factor obtained from the ratio (real/mixed) of the invariant mass distribution will be used to normalize the mixed event background and subtract it from the real event invariant mass distributions. The normalization is done with the purpose to have equal width of the mixed to the real candidates.

The normalization region for each $p_t$ and rapidity is obtained by fitting the ratio of the $\gamma\gamma$ mass distribution of the real to the mixed events. The used fit function for this purpose is gaussian function and a constant. The constant factor was obtained from the ratio of the two distributions. The range of the fit is $0.08 - 0.25 (GeV)$. (see figures (3.24), (3.25), (3.26) )
Figure 3.21: The invariant mass distribution for all the photons coming from the same event (blue histogram) and the mixing event (red histogram) for the rapidity range $2.2 \leq y < 2.4$ and 8 $p_t$ bins of 0.25$GeV$
Figure 3.22: The invariant mass distribution for all the photons coming from the same event (blue histogram) and the mixing event (red histogram) for the rapidity range $2.4 \leq y < 2.6$ and $8 p_t$ bins of $0.25 GeV$.
Figure 3.23: The invariant mass distribution for all the photons coming from the same event (blue histogram) and the mixing event (red histogram) for the rapidity range $2.4 \leq y < 2.7$ and 8 $p_t$ bins of 0.25 GeV
Figure 3.24: The ratio of the same and mixed events mass distributions for the
rapidity range $2.2 \leq y < 2.4$ and 8 $p_t$ bins of 0.25$GeV$
Figure 3.25: The ratio of the same and mixed events mass distributions for the rapidity range $2.4 \leq y < 2.6$ and 8 $p_t$ bins of 0.25GeV
Figure 3.26: The ratio of the same and mixed events mass distributions for the rapidity range 2.6 ≤ y < 2.7 and 8 $p_t$ bins of 0.25GeV
The distributions of the invariant mass are obtained by the subtraction of the mixed event distributions from the real event distributions. To normalization factor is calculated to have an equal number of entries around the expected $\pi^0$ peak between the real and the mixed event. The normalization factor value is given by the direct observation of the stable invariant mass region where the real and the mixed distribution have the same form. Figure (3.27) shows the $\gamma\gamma$ invariant mass for the three rapidity ranges and the sum of them. The signal is clearly visible and located at the $\pi^0$ mass mentioned in [19].

The invariant mass $\gamma\gamma$ spectrum is then investigated as function of the transverse momentum and rapidity. This can be seen for each template fits for the first rapidity range $2.2 - 2.4$ in figure (3.28), for the second rapidity interval $2.4 - 2.6$ in figure (3.29) and for the last rapidity

![Figure 3.27: The mean and the width of the fitted secondary vertex distribution Vs the photon momentum.](image-url)
2.6 – 2.7 in (3.30). In the last rapidity set, the \( p_t^0 \) yields are too smaller.

The peak position and the width for each rapidity range of the \( \gamma \gamma \) invariant mass distribution are illustrated in figure (3.31). The Mean of the Gaussian fit for the first two rapidities is stable along the transverse momentem, however for the last range is not stable. This can been seen also in the width. The statistical uncertainties for the last rapidity is high, This is due to the limited statistics which is not sufficient to maintain a fit with free parameters.
Figure 3.28: The real mass distribution of $\pi^0$ after subtracting the normalized mixed event distribution in the range $2.2 < y < 2.4$ and 8 $p_t$ bins of 0.25GeV
Figure 3.29: The real mass distribution of $\pi^0$ after subtracting the normalized mixed event distribution in the range $2.2 < y < 2.4$ and 8 $p_t$ bins of 0.25 GeV
Figure 3.30: The real mass distribution of $\pi^0$ after subtracting the normalized mixed event distribution in the range $2.2 < y < 2.4$ and 8 $p_t$ bins of 0.25 GeV.
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Figure 3.31
Monte Carlo Simulations

4.1 Introduction

A CERES Monte Carlo simulation is used for numerous purposes to determine the detector response to the production of the Neutral pions and possible backgrounds. The full Monte Carlo simulation described in this chapter is used for the efficiency evaluation for the neutral pion reconstruction. The CERES Monte Carlo simulation can provide predictions at three different levels: at the level generator (partons), the particle level and the reconstructed photons and neutral pions by using a simulation of the detector. Raw data generated by the Monte Carlo is processed by the same tracking, vertexing, and filtering programs used for the actual data. An important aspect of these programs is that they must be applied at both the Monte Carlo programs used for theoretical predictions, the level detector for the experimental measurements in order to be able to compare the Monte Carlo generation and data. The main Monte Carlo implementations which were used to simulate the CERES spectrometer response are listed below, each step will be discussed in much more details within the next sections.

1. The CERES Event Generator (user-input).

2. The CERES Detector simulation with Geant software.

3. The Conversion from Step2 to Step3c.

4. The reconstruction of the final analysis.
4.2 The Event Generator

This step is called also the user-input. A standard physics generator, to generate the partons in the whole phase-space and impose a certain requirements corresponding to the geometry of the collision. The kinematic Event generator generates particle spectra where the main input parameters are particle types, numbers of the produced particles per each event or the requested total number in the full collision, the momentum distribution, the detector acceptance range and the corresponding temperature of the generated particles. The goal is to define some reasonable cuts to maximize the significance of the results.

To let the $\pi^0$ s ejectile in the GEANT software (see Section 4.3), the main characteristics of the the physical process $\pi^0 \rightarrow \gamma\gamma$ and those of their decay products are studied via the TGenPhaseSpace class found in the ROOT package [21]. This the input parameteres of the package are: number of decay particles, masses of particles, betas of decaying particle, total energy in the C.M. minus the total mass, and the kinematics of the generated particles.

The important kinematical parameters which have to be investigated for the generated $\pi^0$ and the decayed photons are:

- The phase-space initial parameters.
- The rapidity.
- The transverse momentum $p_t$.
- Polar and azimuthal angles in the laboratory reference frame.

Owing short mean life time $\tau = 8.4 \pm 0.6 \times 10^{-17}$ s [19] which is typically of electromagnetic decays, the $\pi^0$'s decay before getting free from the collision region.

The neutral pions are generated with Boltzmann distribution for the transverse momentum. The corresponding temperature (the inverse slope) of $\pi^0$ is 190 $MeV/c^2$, [22]. The rapidity obey a Gaussian distribution with a mean $y = 2.95$ and width $\sigma_y = 1.2$. [23]. The $p_t^0$s are generated in the center of mass frame, but later the photons which are the decay products are finally boosted using the betas of the $p_t^0$ original particle. For the 158 AGeV energies, the beam beat is 2.913 with the the rapidity interval [1.5-3.0].

Substantial computations are required to generate high statistics samples for the studied physical process. For that reason we generate 9900 events per
Figure 4.1: The $m_T$ spectra inverse slopes $T$ on the particle mass $m$ at CERN-SPS Pb-Pb collisions

output file and each file contain 50 $\pi^0$ per each event. This prescription is the generation stage. The second stage consists of the operation of the generated neutral pions and photons within a new requirement. The generated photon in the whole phase space are filtered with the geometrical acceptance cut which is $0.135 (rad) < \theta(\gamma) < 0.25 (rad)$, and it is imposed once all the photons were being generated within the phase space configuration described above. This criteria is chosen to cover the CERES spectrometer.

The scatter plot in figure (4.2) illustrates the generation and acceptance stages of the rapidity versus the transverse momentum distribution of the neutral pion. On the left, before applying the geometrical cut, and on the right side of the figure, after fulfilling the geometrical acceptance require-
ment. We see clearly that that we have large acceptance for the bulk of the π⁰ in 0 < p_t < 2 and rapidity of y ∈ [2.2 – 2.7]. An additional check is needed and performed to verify the opening angle between the two photons as function of the π⁰ transverse momentum. This is shown in figure (4.3).

So far, all the kinematic proprieties of the generated/accepted π⁰ and their yields, the photons, are known. The 4-momentum vectors of the mother particles (π⁰) and the daughters (γγ) are recorded. The full decay/production history is stored in dat format files. The produced π⁰s by the Kinematic Event generator were used for studies that required larger statistics. The number of the generated neutral pion used for the complete Monte Carlo simulations is about 7 millions of π⁰. An another aspect of using the the Event generator and its output, which bear an estimation of how we could achieve the reconstruction of the neutral pion decaying into two photons, will be used and discussed in more details in Chapter 5.

### 4.2.1 Expected number of π⁰ mesons

As mentioned in Chap.2 the CERES experiment recorded 30 million good events in collisions of heavy nuclei during the running period in the year
Figure 4.3: The ($\gamma\gamma$) opening angle distribution versus the transverse momentum of the neutral pion. The projection of the opening angle is plotted on the right panel.

200. Before to perform an analysis, we use a quantitative method to explore the expected number of $\pi^0$ and ($\eta$) yields after the analysis to check if such analysis is feasible. The number of $\pi^0$ mesons produced per event is approximately about 500 neutral pion at the CERN-SPS energy of 158 AGeV/c [24]. Getting the output parameters of the $\pi^0$ from the kinematic generator described above, we can recapitulate these complete information in order to offer an estimation of the $\pi^0$ expected number.

\[
N_{\pi^0} = \text{BR} \times 500\pi^0 \times \text{acceptance} \times N_{\text{event}} \times \text{efficiency}. \tag{4.1}
\]

where:

- $N_{\pi^0}$ is the $\pi^0$ expected number.
- BR: the branching ratio of $\pi^0 \rightarrow \gamma\gamma$ (98.7\% [19]).
- The acceptance (for 1 output file) $= \frac{n\text{Acc}_{\pi^0}}{n\text{Gen}_{\pi^0}} = \frac{495000}{3802554} = 0.13$
- $N_{\text{event}}$: the total number of the recorded events ($30.10^6$ events).
If we take the efficiency for detecting a neutral pion \( \approx (0.04)^2 \), from the radiation length as an approximation, this reads:

\[
N_{\pi^0} = 3.06 \times 10^6 \pi^0 \text{s} \quad (4.2)
\]

This number is an upper limit because it assumes that conversions are reconstructed with 100% efficiency.

**Figure 4.4:** The comparison between the Thermal model [25] and the experimental data particle ratios.

In relativistic heavy ion collisions, the analysis performed on the ratios of the produced hadrons shows that they are well described by a statistical model. The hadron production is described using thermal models enabling to encounter the yield particles. In this way, the ratio \( \eta/\pi^0 \) is obtained from the thermal model [25] which is in very good agreement with the experimental data. It states the particle ratios as they were measured by several experiments at the SPS in Pb-Pb collisions. In figure (4.4), the particle ratios of different hadrons are illustrated.
4.3 The detector simulation

The complete CERES detector setup is implemented GEANT simulation [26]. The output information of the Event Generator (user-input) contained in the dat files (see Section 4.2) are propagated through the CERES detector volume. The GEANT software simulates the passage of the generated elementary particles ($\pi^0$s and $\gamma$s) by the Event generator through the matter. It provides a full data base passage of the standard geometrical shapes and materials used to model the CERES spectrometer.

All the essential physical interactions between the generated $\pi^0$ and photons with the detector material are computed. Every propagated particle is simulated with GEANT independently. At the final stage the particle trajectory can be traced and thus saved in RWAMC format files. The digits in the RAWMC files include all energy deposits (hits) recorded during the particle trajectory during its passage through the individual elements of the detector. This means each hit is assigned to a track number to where it is originating from.

The digitization framework of the RAWMC output files is performed to build a mapping between the location of sensitive detectors within GEANT, and the subsequent front-end electronics functionality. This step is accomplished by using the CERES Step2 Analyzer.

However, before to proceed the digitization process of the simulation output, a setup.analyzer file is used to set one of the two options: Clean Monte Carlo (CMC) or Overlay Monte Carlo (OMC) simulations. The CMC is used basically for fast simulations of the CERES spectrometer. The CMC option allows us to gain additional insights into the detector effects in less computing time with low disk space storage. It allows very flexible runtime configuration once every check have been checked. The OMC operation is done by overlaying the simulated Monte Carlo tracks on top of the real raw data event. The association is made accurately only between the GEANT tracks as an input and The OMC tracks as output.

The output of the Step2 Analyzer during the digitization process are written in ROOT format files. They are accessible and can be checked at any stage of the GEANT simulation engine. This ability is an important aspect to ensure that the Monte Carlo faithfully reproduce the truth detector manifestations. This simulation chain was performed to produce about 7 million $\pi^0$ events. This task is time consuming and have to be handled in very large volume of disk space.
4.3.1 The Conversion from Step2 to Step3c

After the Step2 Analyzer simulation chain, the output of this simulation has to be processed through the same reconstruction treatment used in the experimental data analysis softwares described in Chapter 3 (Step3c). This means that once this step is reached all the track finding, track fitting operations are applied in the same way as in the data analysis.

The Purity

For each reconstructed track, we associated simulated track with the largest common number of hits. This can be expressed as the purity of the reconstructed track. The Purity can be defined as the fraction of hits having same MC parent among hits attached to the track. It can be written for \(i^{th}\) track as:

\[
Purity = \frac{NHits(MC,(i^{th}\text{track}))}{NHits(All,(i^{th}\text{track}))}
\]

where:

- \(NHits(MC,(i^{th}\text{track}))\) represents the number of hits for the \(i^{th}\) Monte Carlo track and
- \(NHits(All,(i^{th}\text{track}))\) is the total number of the associated hits of the \(i^{th}\) Monte Carlo track. The distribution of the Purity for reconstructed tracks is shown in figure (4.5).

The association of a reconstructed vertex to a simulated vertex is successful if the Purity exceeded 50%. The reconstructed tracks which are not associated with a simulated track are called ghost tracks and they are not taken into account. By using the Purity condition we are rejecting the ghost tracks from the reconstruction chain.

Completely reconstructed tracks will be employed to perform the main analysis of the reconstruction efficiency of the neutral pion analysis.

4.3.2 The reconstructed tracks Comparison

The tracks which survived after the Purity condition, are compared in order to cross check the reconstruction chain provided by the Overlay Monte Carlo simulations.

The phase-space covered by the TPC is shown in Figure 4.6. It illustrates the polar and the azimuthal angles distributions from the reconstructed tracks which were determined by the Overlay Monte Carlo technique (similar
4.3. THE DETECTOR SIMULATION

The purity distribution of the reconstructed charged tracks from the assigned Monte Carlo tracks.

Figure 4.5: The Purity distribution of the reconstructed charged tracks from the assigned Monte Carlo tracks.

the Step3c) and the true tracks which are the output of the Step2 Analyzer. The polar angles are plotted in the range \(0 < \theta < 0.3\text{(rad)}\). The structure at high theta angles are not considered since we cut on \(0.135 < \theta < 0.25\). This point will be justified in the analysis section. The azimuthal angles distribution are scanned and plotted in the range \(-3.15 < \phi < 3.15\text{(rad)}\). The structure of the pad chambers and the 8 spokes of the TPC is clearly visible.
One can compare the singal track efficiency by evaluating the reconstruction efficiency. This is obtained by simply dividing the number of reconstructed embedded tracks, obtained from the Overlay Monte Carlo method, by the number of the true embedded tracks, obtained from the Monte Carlo simulations.

The angular Dependance in the TPC of the reconstruction efficiencies is shown in figure (4.7). On the right panel, the $\theta$ dependence obey a flat dis-
4.3. THE DETECTOR SIMULATION

Figure 4.7: The TPC reconstruction efficiencies as function of the polar and the azimuthal angles.

Figure 4.8: The comparison of the TPC fitted hits on the track for Overlay Monte Carlo simulation plotted in blue and for data in red, the vertical line at $N_{Hits} = 10$ indicates the minimum value for the reconstructed track taken in both cases.

Distribution along the theta range $[0.135 - 0.245](rad)$ whereas at low thea
angles, the efficiency starts increasing reaching the flat area. This effect returns to acceptance limit where the outer edge of the TCP is located. The Dependance on the azimuthal reconstruction of the tracks is shown on the second panel of the same figure (right).

A visible sign of hole is positioned at $\phi \approx -3$. (rad). This behavior refers to a dead region during data taking. Figure (4.8) shows the number of the TPC fitted hits on the track for Overlay Monte Carlo simulations plotted in blue and for data in red. One can notice that the taken cut for $NHits$ larger than 10, indicated by the black vertical line, applied in both Overlay Monte Carlo and data is a good estimation.

4.4 The unlike/like sign pairs comparison

The various selection criteria imposed on pair tracks (electrons and positions) events is based on those of data analysis with some adjustments for better signal to background (Here i have to say that the angles were smeared, if so , what is the smeared values of phi and theta.....). The subtracted signal to background distributions is studied in ten momentum bins $0 < p < 10$ (GeV/c). Figure (4.9) illustrates a shape comparison of photon signatures (unlike sign - like sign pairs) between the data (in red) and the Overlay Monte Carlo (in blue) distributions, each momenta window represents $1$ (GeV/c). The comparison in each momentum bin was made by the normalization of the maximum of the photon conversion signals in both Overlay Monte Carlo and data.

The photon conversion signatures are well pronounced in all the momentum bins and became narrower at high momentum. The Overlay Monte Carlo and data distributions reproduces both the same photon signal width. At large momentum, the signal to background in the data distributions exhibits an extra contributions at higher theta. It should be mentioned at this point this situation is happening in the region outside the real signal distribution where the photon conversion signature is well defined and known. Furthermore, this misidentified background is seen not seen in the Overlay Monte Carlo since the input particles to Event Generator are the neutral pions which decay to a pair of photons within the acceptance range. This can be interpreted by the flat distribution of the Overlay monte Carlo distributions.
4.4. THE UNLIKE/LIKE SIGN PAIRS COMPARISON

However, the presence of the effect would manifest itself by a question which arises part of the effect and if it has a different origin. It is therefore useful to look at the charged tracks of electrons and positrons selection criteria mentioned in Section 3.2. The observed structures in the signal to background distributions for $7(\text{GeV/c}) < p < 10(\text{GeV/c})$ are expected to come from of highly ionizing $\pi^\pm$. We optimized the ionization loss cuts by keeping the upper limit cut $dEdx < 440$ and settled on tight cut values of $dEdx > 290 + 2.\log(p)$ at energy loss low ionizing regions. This highly ionizing events which pass the tightened cut are illustrated by figure (4.10). The left panel represents the considered energy loss area for the electron/positron selection, and in the right panel, the performed dEdx check-cut. Thus, in order for a electron/positron leptons to fulfill the loose requirements, it must pass only the dEdx ionization cuts mentioned above. By inspecting figure (4.11), one can conclude that this approach explicitly minimize the uncertainties related to the suppression of the charged pions contributions. Consequently, these little bumps are originating from the charged pions and not from the electrons and positrons.
4.5 The Photon mapping comparison

The reconstruction procedure of the photons is based on the measured charged tracks of the electrons and the positrons from the Overlay Monte Carlo simulations. The reconstruction of final state photons requires a well measured photon candidate, where the combinatorial background is here estimated by the event-mixing technique, considering only events with similar multiplicities. The used criteria for the photon reconstruction are the same of those mentioned already in Section 3.6.2. One should, however, keep in mind that the photons has to be within a fiducial volume of $0.135 < \theta_{TPC} < 0.25$ and full azimuthal coverage. The comparison of the reconstructed photons candidates from the Overlay Monte Carlo method and the analyzed data can be done either via ratio or a difference of the two distributions. The first method reflects the scaling by the ratio of the two angular distribution maxima of the measured photons from Overlay Monte Carlo and data. This can be seen in figure (4.12). The second method consists by calculating the angular distribution integrals of the reconstructed photons, then performing the scaling by using the obtained ratio of the two integrals. This method can be illustrated by figure (4.13).

The key test of the Overlay Monte Carlo is its ability to predict the different distributions of the reconstructed photons in the detector at the level of RICH2 mirror. Although the Overlay Monte Carlo reproduce the photon distributions and agrees well with the data, a minor problem encountered here is related to small differences between the photon mapping described by Overlay Monte Carlo simulations and data. The difference is slightly seen by looking at the angular distributions comparison provided by the integration method, where in contrast if we consider the comparison performed by the maximum method. Following these investigations, this may affects the reconstruction efficiency by making a geometrical correction factor due to tiny differences between the photon topologies dependence of $\theta$ and $\phi$ in the simulation and data.

4.6 The Secondary Vertex Comparison

The postion of the photon decay vertex was reconstructed from opposed charger tracks detected in TPC and originated from the RICH2 mirror area. The z-vertex positions were determined using the same algorithm as detailed in our previous study described in Chapter 3. The combinatorial background has been substructed from the real photon signal for each momentum bin (shown in figure (4.14)) and then applying the Secondary vertex in the region
4.7. THE $\gamma\gamma$ INVARIANT MASS DISTRIBUTIONS

In order to evaluate the reconstruction efficiency for the neutral pion production, the $\gamma\gamma$ invariant mass distributions are studied and checked. All the following obtained invariant mass distribution are based on the same cut criteria used with data. We perform our study as function of transverse momentum in the range $0 < p_t < 2$ and rapidity splitted in three ranges expressed as: $2.2 < y_1 < 2.4$, $2.4 < y_2 < 2.6$ and $2.6 < y_3 < 2.7$. We have to keep in mind that we find that signal candidates in the regions: $0.25 < p_t 0.5 < 0.75 < 0.75$ are considerably contaminated by background events along all the taken rapidity range. This effect have been seen in data and Overlay Monte Carlo. therefore a special opening angles between the two photon candidates is needed. For this purpose we require a tighter conditions:

\[
\begin{align*}
  &\left\{ \begin{array}{ll}
    y_1 & \text{and } 0.25 < p_t < 0.5 \text{(GeV/c)} \Rightarrow \theta(\gamma\gamma) = 0.11 \text{(rad)} \\
    y_1 & \text{and } 0.5 < p_t < 0.75 \text{(GeV/c)} \Rightarrow \theta(\gamma\gamma) = 0.08 \text{(rad)} \\
    y_2, y_3 & \text{and } 0.25 < p_t < 0.5 \text{(GeV/c)} \Rightarrow \theta(\gamma\gamma) = 0.1 \text{(rad)} \\
    y_2, y_3 & \text{and } 0.5 < p_t < 0.75 \text{(GeV/c)} \Rightarrow \theta(\gamma\gamma) = 0.07 \text{(rad)} \\
  \end{array} \right. \\
\end{align*}
\]
CHAPTER 4. MONTE CARLO SIMULATIONS

The different subtracted invariant mass distributions obtained for this requirements is shown in figures (4.16),(4.17) and (4.18). We can summarize these investigation by looking to the mean and the width of the reconstructed $\gamma\gamma$ mass versus the transverse momentum shown in figure (4.19). The mean of real invariant mass distribution of the Overlay Monte Carlo and data agrees very well for the two first rapidity intervals $y_1$ and $y_2$, however in the third rapidity interval, due to low statistics and 0.1 rapidity step the invariant mass distribution is slightly different at high momentum. This can inspected also when looking to the width distributions illustrated in figure (4.20).

4.8 Acceptance and efficiency evaluation

The different of signal presented in the previous sections are not representative directly of the neutral pion production. All the measured quantities must be corrected by certain factors which take into account the geometrical acceptance and efficiency of the CERES detector. Therefore determining the detector acceptance and efficiency of the selection criteria of data is essential to obtain quantitative and properly calculated production. The acceptance is the phase-space region covered by the TPC detector. It is related to the detector geometry. However the efficiency evaluation depends on the reconstruction efficiency of tracks determinte by the reconstruction chain listed in Section 3.1. The multiplicity in the whole phase-space (0 to $2\pi$) is generated within the Boltzmann distribution for the transverse momentum and a Gaussian distribution for the rapidity distributions with a mean $y = 2.95$. The transverse momentum and rapidity distributions were studied in eight $p_t$ bins and in three rapidity intervals. The two first equidistant rapidity bins are $2.2 < y_1 < 2.4$ and $2.4 < y_2 < 2.6$. The last rapidity bin is $2.6 < y_3 < 2.7$. In all what follow, we will keep this phase-space divison as function of transverse momentum and rapidity.

As a first exploratory study, the acceptance calculation of the generated neutral pions which decay into two photons requires a number of conditions including the geometry of detector. These imposed requirements were explained in much more details within the the Event generator Section (See Section 4.2). The acceptance can be simply define by the ratio between the number of found particles $n_{Acc}$ within the geometrical limit and the number of generated particles $n_{Gen}$ in the full phase-space $4\pi$. It can be expressed
4.8. ACCEPTANCE AND EFFICIENCY EVALUATION

as:

\[ \text{Acceptance}(p_t, y) = \frac{n\text{Acc}(p_t, y)}{n\text{Gen}(p_t, y)} \] (4.5)

Under these circumstances the \( \pi^0 \) acceptance is illustrated in figure (4.21). The \( \pi^0 \) acceptance of the first two rapidities intervals \( y_1 \) in red squares, \( y_2 \) in blue circles and \( y_3 \) in light blue triangles. The acceptance is low at low transverse momentum regions for all the rapidity bins and starts to increase at high momentum. The acceptance of first two rapidity intervals is large in comparison with the last rapidity interval.

For more reliable approach, it was important to ensure, as far as possible, that the Monte Carlo simulation reproduces the experimental data correctly. This cross check is needed for the reconstruction efficiency evaluation by using the complete Overlay Monte Carlo simulation information. The reconstruction efficiency is the ratio of the reconstructed neutral pion yields by the simulated neutral pions which across the entire volume of the detector. It can be defined as:

\[ \text{Rec. Efficiency} = \frac{n\text{Rec}}{n\text{Sim}} \] (4.6)

where the numerator (\( n\text{Rec} \)) was explained and obtained from the reconstruction part of the overlay Monte Carlo which is similar to the experimental data analysis and the denominator(\( n\text{Sim} \)) is the number of the neutral pions passed through the detector simulation described by the GEANT software. the evaluated reconstruction efficiency for the three different rapidity bins indicated previously is shown in figure (4.22).

The equations (4.5) and (4.6) provide us two kind of efficiency which are assigned to the geometrical acceptance and the reconstructed efficiency. They are used to determine directly the correction factor. The total or the physical efficiency is then defined as the probability of neutral pion simulated within a geometrical acceptance and produced during 158 AGeV/c Pb-Au collisions at 7% centrality in the CERES spectrometer. Consequently, the physical efficiency of the simulated \( \pi^0 \)s which cover such available phase-space is then given by the product \( \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{rec}} \). This factor will be used later to correct the production rate of the measured neutral pions obtained from the experimental data analysis.
Figure 4.9: The Photon signal distribution comparison between the Overlay Monte Carlo simulations (red) and data (blue). Each momentum window represents 1(GeV/c).
Figure 4.10: The left panel represents the used energy loss of the charged particles measurement within the TPC, the black incline line and the upper cut at 440 refers to the electron/positron selection. The right panel shows the tighter energy loss in order to cross check the bumps shown in the photon signal at high momentum.
Figure 4.11: The Photon signal distribution comparison between the Overlay Monte Carlo simulations (red) and data (blue) after dappling the new $dE/dx$ condition. Each momentum window represents 1(GeV/c).
Figure 4.12: The Mean and Width of the Secondary vertex.
Figure 4.13: The Mean and Width of the Secondary vertex.
Figure 4.14: The Secondary Vertex distributions of the subtracted signal to background reconstructed in the Overly Monte Carlo simulations. Each window represents a 1 (GeV/c) photon momenta.
Figure 4.15: Left panel, the position of the photon vertex converting to $e^-e^+$ for Overly Monte Carlo (in blue) and data (in red). On the right panel, the corresponding width of the Secondary vertex distribution, the data are shown in magenta and Overlay Monte Carlo distribution in green.
Figure 4.16: The Mean and Width of the Secondary vertex.
Figure 4.17: The Mean and Width of the Secondary vertex.
4.8. ACCEPTANCE AND EFFICIENCY EVALUATION

Figure 4.18: The Mean and Width of the Secondary vertex.
Figure 4.19: The Mean and Width of the Secondary vertex.
Figure 4.20: The Mean and Width of the Secondary vertex.
Figure 4.21: The acceptance of the neutral pion as function of rapidity and transverse momentum.
Figure 4.22: The reconstruction efficiencies distributions versus the $\pi^0$ transverse momentum studied for different rapidity bins.
5

Results
Bibliography


