Experimental Techniques in Intermediate-Energy Physics for Identification and Reconstruction of Particles

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I would like to dedicate this thesis to my loving parents...
Abstract

As particle physics was evolving, new and improved particle identification techniques have been developed, and data analysis with computers became important. The use of high energy accelerators allowed the production and measurement of a diversity of particles unknown formerly, making it necessary the development of a set of techniques in order to be able to distinguish them. The work presented in this thesis is a study of the available methods, usually employed, to identify and reconstruct particles; the experimental data come from Thomas Jefferson National Accelerator Facility, and were taken with the CLAS detector system. The experiment employed a photon polarized tagged beam with energies between 0.8 and 2.3 GeV and a liquid deuterium target. The analysis requires a review of the most important physics and mathematics concepts supporting particle identification techniques.

The work will be focused in two scenarios: Direct and indirect identification. The former is helpful when the particle mean decay path is comparable with the detector size such that, on average, they do not decay before reaching the corresponding detector; in this case, there exist some methods to perform the data analysis such as mass cuts, time of flight and energy loss. The latter is related to either particles decaying on its way through the detectors or slow particles that cannot surpass the detection threshold; in this case, it is necessary to reconstruct the particles using methods based on the conservation laws of energy and momentum such as invariant mass and missing mass.

The analysis will be performed with the help of the data analysis framework ROOT [4] and a package for the analysis and conversion of CLAS bos format data called ROOTBEER (ROOT Bank Event Extraction Routines) [14]. The above mentioned particle identification methods are implemented from the analysis of two reaction channels associated with the same initial state (Photon-Deuteron):

\[ \gamma d \rightarrow \pi^+ \pi^- pn \]

\[ \gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+ [\pi^- p]n \]
The first channel produces four different particles in the final state: one positive pion \( (\pi^+) \), one negative pion \( (\pi^-) \), one proton \( (p) \) and, one neutron \( (n) \). Using this reaction two different methods of direct identification will be shown: mass cuts and the time of flight.

The second channel produces, initially, three different particles: one positive kaon \( (K^+) \), one lambda particle \( (\Lambda) \) and, one neutron \( (n) \). The square brackets represent the decaying particle \( [\Lambda] \) and the corresponding decay products of it \( [\pi^- p] \). Using this reaction, two methods of indirect identification will be shown: invariant mass and missing mass; this can be done since lambda particles have a short lifetime, and decay (in about 63.9\%) into a proton and a negative pion, being difficult to detect it directly.
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Chapter 1

What Is Matter Made Of?

1.1 Greek Philosophers

The idea that matter consists of very small particles began more than 2000 years ago, from the time of ancient Greek philosophers as Democritus or Leucippus, who thought of matter as composed of smaller particles called atoms [1], hidden for human eyes. The atomistic idea was based on the interpretation of reality which philosophers made through their senses. Empedocles tried to explain how was the structure of matter, proposing four types of atoms which comprised all the matter that was known, using what he thought were the principal substances: stone-stuff, water-stuff, air-stuff and fire-stuff [7]. Empedocles explained matter was a composition of these substances in different amounts and combinations, depending on the properties of the substance. The model can be described with the idea of iron composition, it was believed iron was the result of holding together stone atoms and fire atoms; in the case of soil, he believed it was the combination of stone atoms and water atoms [8]. In addition, Democritus tried to explain which was the way matter could hold together; he believed particles had hooks, staples and cavities useful to interlace and create different materials; it was basically a mechanical approach, probably the only one by the epoch.
1.2 The Classical Approach

For years, those ideas were avoided by scientists because they were based on philosophical theories without any experimental verification. Physics science, based on the works of scientist as Galileo, Kepler and Newton, supports all theories on experiments which could predict the behaviour of nature. Unfortunately, by that time, there was not the appropriate technology to defend the atomic theory; some couple of years were necessary until the first experiments arose, showing the existence of particles constituents of matter.

When Maxwell wrote the electromagnetic equations, the nature of electricity was a mysterious [1]; there was not knowledge about electrons, protons, or any individual particle; in nineteenth century, there were many scientists who worked trying to give an explanation about cathode rays and their pass through rarefied gases; scientist as Jean Perrin, Philipp Lenard, William Crookes and Arthur Shuster gave different contributions to the explanation related to the phenomena behind electricity; however, none of these attempts led to any significant progress since different experiments showed results that were contradictory; researches showed cathode rays could pass through different screens without making holes in them; that fact led Lenard to establish cathode rays were waves; on the other hand, Crookes tube experiment showed cathode rays could not pass through a strong material, such as a target made of zinc, so that the object would emit a definite shadow, leading Crookes to take on cathode rays as a beam of particles.

The explanation about the behaviour of cathode rays came with the works and experiments made by J.J. Thomson, who not only believed in the atomic theory but also showed atoms were composed by smaller particles. The atomic theory had been retaken with the researches about chemical elements. Boyle proposed matter was composed of an irreducible units of matter (that he called corpuscles) based on the chemical elements that were known as copper, iron, mercury and gold; Boyle (1661) defined element as “certain Primitive and Simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the Ingredients of which all those called perfectly mixt Bodies are immediately compounded, and into which they are ultimately resolved" (p.350) [2].
Thompson developed several experiments in order to show that atoms were an array of two kind of charges, negative and positive ones. He conceived the atom as a positively charged sphere with enough number of negatively charged particles in order to have the whole atom as neutral; additionally, he assumed cathode rays were formed by fast-flying charged particles [8] and designed an experiment to prove it, finding the relation among the mass and the electric charge of the particles. Broadly, the experiment was based on the deflection of cathode rays due to an electric and magnetic field. Cathode rays were extracted from a material such as hot electric plates and were accelerated by a strong electric field; while the beam was passing through two parallel plates, it was deflected by an electric field and an array of coils which created a magnetic field helpful to get information about the beam velocity. Thomson was able to calculate the mass and electric charge ratio by measuring the deflection distance of cathode rays, the electric current passing through the coils, and the electric potential.

![Thomson's atomic model](image)

Fig. 1.1 Thomson’s atomic model: The model shows a body uniformly positive charge with enough number of electrons inside to have it neutral. Figure taken from [7].

The results obtained in the experiment led to conclude atoms can be broken into smaller particles and a new atomic model was proposed. The Figure 1.1 shows an image of Thomson’s atomic model; it was nearly close to the atomic model that is accepted nowadays. His view about a cloud of negative particles moving inside the atom match with the conception we have now about electrons, but his notion about a uniform distribution of positive charge inside the atom was far away from the actual idea.
1.3 The Modern Approach

The discovery related with atomic nuclei came between 1908 and 1913 with the works and experiments made by Ernest Rutherford who showed most of the atomic mass and positive charge was concentrated in an small central nucleus. In order to prove the theory, Rutherford designed an experiment using a beam of positively charged particles and a target of a very thin gold foil. The beam was composed of alpha particles, which have positive charge and with mass comparable with the mass of atoms; this particles are generated in radioactive decay processes in nucleus of unstable atoms; nowadays, it is known alpha particles are composed of two neutrons and two protons bound together. The golden foil experiment was based on the way alpha particles scattered when they were passing through the gold foil. Rutherford and his colleagues, Hans Geiger and Ernest Marsden, published at least five papers about the experiments they made about scattering of alpha particles. The remarkable result they got it was the fact that most of the particles that came from the beam went straight through showing no interaction with the target, while occasionally, some of the alpha particles seemed to interact with the target evidencing a significant scattering.

![Nuclear scattering: Model of the way Rutherford conceived alpha particles scattered due to the electromagnetic interaction with atomic nucleus. Figure taken from [7].](image)
Scattering of alpha rays indicate that about 1 particle in 20,000 were turned through an average angle of 90 degrees [20]; something that would have been impossible with the atomic model of Thomson. The fact that the majority of the particles went straight ahead without interacting with the foil led Rutherford to think most of the atom is empty space; on the other hand, the evidence that some particles scattered led Rutherford to proposed that atoms must have a compact nucleus. The results of the experiments led to a new atomic model described by Rutherford; Figure 1.2 shows an outcome of what he interpreted was happening in the experiment, Rutherford showed the atom was not uniformly charged as Thomson thought, but it was composed by a strong and positive charged nucleus and a cloud of electrons revolving around it.

Rutherford’s atom was the atomic model for a while, however, one important correction had to be made. In the periodic table, elements have their own atomic number depending on the number of charged particles concentrated in the nucleus; in the case of oxygen, it is the eighth element in the table sequence, meaning it that oxygen should have eight positive charged particles concentrated in the nucleus. Assuming oxygen has eight particles in the nucleus of the atom, a correct value of charge was gotten but a wrong mass, since oxygen was heavier; however, if oxygen was supposed to have eighteen particles concentrated in the nucleus, a correct value of mass was gotten but a wrong charge [7].

This situation led to consider there were some particles in the nucleus which do not have charge, positively charged particles were called protons and chargeless particles were called neutrons; the experimental verification of the new theory was provided by James Chadwick in 1932.

Chadwick performed an experiment using a source of alpha particles in order to impinge a light element as beryllium. Chadwick realized that rays got released after alpha particles smashed the element; he did not know what the nature of the ray was, he was sure it did not have charge but it had the enough energy to eject protons from a target of an element as paraffin or other matter containing hydrogen. Chadwick mentioned the experimental results were difficult to explain on the first hypothesis, which assumed the radiation was quantum
radiation as gamma rays, while the best description was supposed the radiation consisted of particles of mass nearly equal to that of a proton and with not net charge. This kind of particles were called neutrons [5].

Rutherford experiment is considered the starting point of particle physics; since then, improving scattering experiments have shown matter is really composed of smaller particles, changing the concept of atom as an elementary particle. Nowadays, it is well known that atoms consist of smaller composite particles as protons and neutrons, referred to as nucleons, and a cloud of structureless particles called electrons [7, 6]. The interest generated by those nuclear researches led to a development of particle accelerators around the years 1926 and 1935 [8], allowing the production of a diversity of particles unknown by that time such as pions, kaons, neutrinos, among others. All above produced the development of new and improved particle identification techniques.
Chapter 2

Physics and Mathematical Fundamentals

2.1 Special Relativity

The theory of special relativity play an important role in the explanation of phenomena related with particle physics; it describes known features such as relativistic mass, mass-energy equivalence, length contraction and time dilation; a classical example is the paradox presented in the average lifetime of subatomic particles like pi mesons; the average lifetime for these particles is $1.8 \times 10^{-8}$ s [13] for an observer in rest, it means that particles with a velocity $v$ could travel a distance determined by $d = v \times t$; nevertheless, from different experimental sets, the observations have shown that pions have a lifetime greater than the one predicted and they can, therefore, reach longer distances. The explanation arise from special relativity and the time dilation.

Formulated by Albert Einstein, the theory is based on two postulates:

- The laws of physics are the same in all the inertial frames, including mechanics and laws of electromagnetic interaction [13].

- The speed of light is a universal constant, the same for all observers [13].
Classical Galilean transformations appeared to satisfy the fact that the laws of physics are the same in all the inertial frames, taking into account that in classical physics the time measured by different observers is considered the same, assuming that measurements are made simultaneously. Figure 2.1 shows two observers, $s$ and $s'$, moving with relative velocity to each other; the system $s'$ is moving at constant speed $v$ along the $x$ axes.

![Fig. 2.1 System $s'$ with relatively motion][26].

In classical physics the equations which relates position and time as seen by both observers are given by the expressions:

\begin{align*}
    x' &= x - vt \\
    y' &= y \\
    z' &= z \\
    t' &= t
\end{align*}

(2.1) (2.2) (2.3) (2.4)

These equations show the way space-time coordinates for both inertial systems, moving with relative speed $v$, are related; one can show that Newton laws are invariant for these sets of transformations, differentiating the coordinate transformations two times with respect the time, obtaining that $a_x = a'_x$, which implies that $F = F'$; in addition, it is important to show the expressions for kinetic energy $E_{\text{kinetic}}$ and momentum $P$ of a particle in classical physics [22], since they will have some important changes before the development of special relativity.
\begin{align*}
E_{\text{kinetic}} &= \left(\frac{1}{2}\right)mv^2 \quad (2.5) \\
\mathbf{P} &= mv \quad (2.6)
\end{align*}

A consequence of these sets of transformations is the fact that the speed of different bodies in motion is relatively; talking about a light beam, it also implies that an observer with relative motion with respect to a light signal will measure a speed different to the one obtained by experiments and theoretically; this situation was incompatible with Maxwell’s equations which predict that the speed of light is always \( c = 3 \times 10^8 \text{ m/s} \) regardless the reference system or the relative motion of it. Galilean transformations thus fail to satisfy both postulates of relativity, since their use imply that electromagnetic laws are not invariant and the speed of light is not an universal constant. it was then necessary to rely on other rules called Lorentz transformation in order to guarantee Einstein postulates \cite{22}.

\begin{align*}
\mathbf{x}' &= \gamma(x - vt) \quad (2.7) \\
\mathbf{y}' &= y \quad (2.8) \\
\mathbf{z}' &= z \quad (2.9) \\
\mathbf{t}' &= \gamma(t - \frac{vx}{c^2}) \quad (2.10)
\end{align*}

Being \( \gamma = \sqrt{\frac{1}{1 - \frac{v^2}{c^2}}} \). The Lorentz transformations satisfy the fact that mechanical and electromagnetic laws are invariant in all inertial frames, as well as, the speed of light is the same for all observers \cite{22}; in addition, Lorentz transformation became identical to Galilean transformation in the limit when \( v \ll c \), and where the gamma factor can be approximated to one. A deduction of these equation can be found in \cite{13}. Lorentz transformations have an important impact in the classical perspective one have of natural laws:

1. The speed of light will always be the same, nonetheless if the observer has relatively motion with respect to the light beam.
2. An event occurring simultaneously in an inertial frame are not simultaneous to another observer in a different inertial frame.

3. The length contraction appears as a consequence of Lorentz transformation; it predicts a difference in the length measured of an object by two observers; one in rest compared with another moving with relative motion. The measurement of the length is shorter for the moving observer by the \( \gamma \) factor.

4. Time dilations, similar to length contraction, arise from Lorentz transformation. It predicts a difference in the time period measured by two observers. The measurement of the time interval is longer by the gamma factor for the observer in motion.

5. The mathematical expressions lead to the fact that nothing can travel faster than the speed of light \( c \); likewise, the addition of velocities shows that a beam of light traveling with speed \( c \) in a reference frame also travels with speed \( c \) in another reference frame with relative motion.

The effects predicted by the theory have been demonstrated through many experiments and measurements that confirm such predictions; the study of mass, momentum and energy will give more support to the theory.

### 2.2 Relativistic Dynamics

Taking into account the first postulate of special relativity, it is necessary to check the laws of conservation related to momentum and energy for isolated systems. When the conservation of momentum is studied for some specific situation, e.g. a collision in one inertial frame, one use the transformation of velocities to study the same phenomena in another inertial frame, finding that the momentum is not conserved. This situation leads to do some necessary changes in the Newton laws in order to satisfy the first postulate. The generalization of momentum (a demonstration can be found in [13, 24]) is given from this equation:
The momentum depends on the gamma factor, the mass, and the velocity. This equation guarantees the conservation law of momentum in any inertial frame; in addition, it occurs the same as with the Lorentz transformation in relativistic kinematics; in the limit when the gamma factor becomes to zero, the expression reduces to the classical result. The term of the mass multiplied by the gamma factor is often considered as the relativistic mass, while the term $m$ is referred to the rest mass. One of the implications of the Lorentz transformation is the fact that anything can travel faster than a beam of light.

### 2.3 Relativistic Energy

Similar to the relativistic momentum, it is necessary to restating the classical expression for the energy in order to guarantee the conservation laws. The change in kinetic energy $K$ of a particle as it moves from $r_a$ to $r_b$ due to a force $F$ is:

$$K_b - K_a = \int_{a}^{b} F \cdot dr$$

$$K_b - K_a = \int_{a}^{b} \frac{dp}{dt} \cdot dr$$

Taking into account the relativistic expression for momentum one have:

$$K_b - K_a = \int_{a}^{b} v \cdot \left[ \frac{m v}{\sqrt{1 - \frac{v^2}{c^2}}} \right]$$

Solving the integration and letting the point $a = 0$, one gets:

$$K = (\gamma - 1)mc^2$$
Similar with the Lorentz transformation and relativistic momentum, this expression turns into its classic expression in the case when \( v \ll c \). The kinetic energy arises from the work done on the particle to bring it from rest to speed \( v \) [13]. Finally, rearranging the above equation one gets:

\[
E = K + mc^2
\]  

(2.16)

It is assumed that the term \( E \) is the total energy of a particle, and it is equal to the addition of the kinetic energy, due to the external work, and the “rest energy”. This assumption implies an equivalence between mass and energy; something that never was developed in classical physics theories; in addition, the equation shows that a body hold energy only because of its mass.

### 2.4 Energy-Momentum Relation

When the conservation laws of physics are studied, one never find a law of the conservation of kinetic energy; the general law of conservation is applied for momentum. This situation leads to express the total energy of a free particle in terms of momentum:

\[
E = \left( \frac{1}{2} \right) mv^2 = \frac{p^2}{2m}
\]

(2.17)

Working with these expressions and using the theory of relativity studied above, it is possible to show the relationship between energy and momentum. The result of the process is given by the equation:

\[
E^2 = (pc)^2 + (mc^2)^2
\]

(2.18)

This equation shows the relation of the total energy of a particle with its momentum and rest energy; furthermore, in the case of photons which does not have mass and can not be found at rest, the energy is expressed by:
This expression shows evidence that a particle without mass can carry momentum and energy.

2.5 Four-Vectors

The study of special relativity lead one to consider expressing the physics magnitudes in terms of a mathematical object called four-vector, this tool is more convenient to make calculus and manage, in a compact form, the algebra of special relativity. A four-vector, different to the usual three vector, is a expression with fourth components: three related to space and one related to the time, creating a four-dimensional space-time in special relativity. The fourth dimension arises from the fact that there is not an absolute measurement of time for two observers, making it necessary to know the specific time measured for each one. To simplify equations it is useful to use the expressions:

\[ x^0 = ct \]
\[ \beta = \frac{v}{c} \]

The first equation allows to express the time coordinate in terms of length without modify the result, since speed of light is an invariant; in addition, the beta term reduces in one expression the ratio between the speed of the body and the speed of light. On the other hand, one has the other three component of space:

\[ x^1 = x \]
\[ x^2 = y \]
\[ x^3 = z \]
The use of the argument $x$ with its superscript is with the aim of reducing mathematical equations and expressing it in a simplest way. Writing again the Lorentz transformations one gets the components of the four-vector position:

\[ x^0' = \gamma (x^0 - \beta x^1) \quad (2.20) \]
\[ x^1' = \gamma (x^1 - \beta x^0) \quad (2.21) \]
\[ x^2' = x^2 \quad (2.22) \]
\[ x^3' = x^3 \quad (2.23) \]

Using the properties of matrix operations one can express the last equations as:

\[
\begin{pmatrix}
  x^0' \\
  x^1' \\
  x^2' \\
  x^3'
\end{pmatrix} = \begin{pmatrix}
  \gamma & -\gamma \beta & 0 & 0 \\
  -\gamma \beta & \gamma & 0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  x^0 \\
  x^1 \\
  x^2 \\
  x^3
\end{pmatrix} \quad (2.24)
\]

The above product of matrices can be expressed as a sum; letting Greek indices run from 0 to 3 one gets the four-vector positions as:

\[ x^{\mu'} = \sum_{\nu=0}^{3} (\Lambda^{\mu}_{\nu}) x^{\nu} \quad (2.25) \]

where $\Lambda$ is the Lorentz transformation matrix.

**Four-Vector Energy and Momentum**

It is possible to obtain a relationship among the proper time (the one in the reference frame at rest) and the time measured by moving systems [10]. The equation gotten is:

\[ t' = \gamma t \quad (2.26) \]
Where $t'$ is time measured by the moving system and $t$ is the proper time. In particle physics the difference between the time measured at the laboratory and the proper time of the particle (the time measured if one could travel in the same way as the particle) is important, (being the proper time better to work because it is an invariant). Based on both measures of time one can define two types of velocities, the first one using the time measured at the laboratory and a second one using the proper time of the particle [10]. The common velocity is given by the equation:

$$v = \frac{dx}{dt}$$  \hspace{1cm} (2.27)

The vector velocity is the derivate of the vector position with respect of the time; the change in the position and time is taken from the laboratory reference frame; on the other hand, and using the proper time of the particle, one can define another velocity which is named proper velocity and is given by the equation:

$$\eta = \frac{dx}{d\tau}$$  \hspace{1cm} (2.28)

This velocity is the change of the vector position, taken from the laboratory system, respect to the proper time of the particle; it is important to add that position is a four-vector, as was represented above; therefore, proper velocity is also a four-vector which can be expressed as:

$$\eta^\nu = \frac{dx^\nu}{d\tau}$$  \hspace{1cm} (2.29)

Thus:

$$\eta^\nu = \gamma(c, v_x, v_y, v_z)$$  \hspace{1cm} (2.30)

As it is known, momentum is the product of mass with velocity; then, now one is able to express the four-vector momentum using the proper velocity:

$$p^\mu = m\eta^\mu$$  \hspace{1cm} (2.31)
being the spatial components:

\[ \mathbf{p} = \gamma m \mathbf{v} = \frac{m \mathbf{v}}{\sqrt{1 - \frac{v^2}{c^2}}} \]  \hspace{1cm} (2.32)

and the time component:

\[ p^0 = \gamma mc \]  \hspace{1cm} (2.33)

In the first section when it was studied special relativiy, it was shown that relativistic energy is given by:

\[ E = \gamma mc^2 = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}} \]  \hspace{1cm} (2.34)

Working with the above equations it is found an expression which relates energy and momentum in a unique four-vector [10]:

\[ \mathbf{p}^\mu = \left( \frac{E}{c}, p_x, p_y, p_z \right) \]  \hspace{1cm} (2.35)

As it is shown in the above equation the relativistic momentum is a four-vector with three components of spatial momentum and one component of energy.

The theory developed in this section has useful implications in experimental particle physics; since, similar to classical mechanics, in every closed system, the total relativistic energy and momentum are conserved [11].

### 2.6 Implication of Conservation Laws

It is possible to recognize two phenomena that are consequences of conservation laws: The missing mass and invariant mass. In particle physics experiments, as mentioned before, one have a series of detectors which measure particle magnitudes directly, then, this magnitudes are used to identify specific particles; on the other hand, one have short-living particles which decaying on its way through the detector being difficult to detect directly (or neutral particles which do not interact with detectors), this kind of particles can be reconstructed using
the methods of missing mass and invariant mass. It is important to realize the distinction between the concepts of invariant and conservative; the former applies for magnitudes that has same value in all inertial frames, an example of this is the mass; the later applies for magnitudes which has the same value before and after a process, an example of this is the total energy [11].

2.6.1 Missing Mass Method

In this work the process of missing mass has an important role; it will be used to reconstruct particles which do not have charge. The reactions that will be studied are:

\[ \gamma d \rightarrow \pi^+ \pi^- pn \]

\[ \gamma d \rightarrow K^+ [\Lambda] n \rightarrow K^+ [\pi^- p] n \]

As one can notice, both reactions has in their final states charged particles, which can be detected by detectors, and neutral particles (neutrons), which can not be detected by the available detectors for this work. After the reactions one can identify directly charged particles using the information provided by detectors; in the case of neutrons, it is necessary to use conservations laws to reconstruct them, since they do not have charge and were not detected. As it was presented, the four-vector momentum has to be conserved before and after a process; it means that the momentum four-vector of the incoming beam and the target has to be equal to the addition of the momentum four-vectors of each of the final state particles. An example with the first reaction is shown here:

\[ \gamma d \rightarrow \pi^+ \pi^- pn \]

Using four-vectors notation

\[ P_{\mu \gamma} + P_{\mu d} = P_{\mu \pi^+} + P_{\mu \pi^-} + P_{\mu p} + P_{\mu n} \quad (2.36) \]
The accelerator provide information about the four-vectors of the photon-beam and the deuteron target; on the other hand, detectors provide information about the four-vectors of the charged particles (positive pion, negative pion and proton), with these information one is able to clear the four-vector related to the neutron:

\[ P_{\mu n} = (P_{\mu \gamma} + P_{\mu d}) - (P_{\mu \pi^+} + P_{\mu \pi^-} + P_{\mu p}) \]  \hspace{1cm} (2.37)

Using this way, the detection of neutrons was made for both reactions.

### 2.6.2 Invariant Mass

One can apply the relativistic relation between energy and momentum to deduce that a pair of particles come from decays of an unstable particle. It is necessary to compute the invariant mass of both particles in their final state in order to determine the rest mass of the particle which they come from. An example of this method is shown for the second reaction of this work:

\[ \gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+[\pi^- p]n \]

One can divide the reaction in two times; first of all, just before the reaction, three particles are obtained, a positive kaon, a lambda particle, and a neutron \((K^+[\Lambda]n)\); then the lambda particle decays into two particles (a negative pion, and a proton). Due to the mean lifetime of lambda particles \((2.632 \pm 0.020) \times 10^{-10} \text{s}\) \[18\], they decay on their way through the detectors and they can not be measured directly, meaning this that detectors just obtain information about the final state \(K^+[\pi^- p]n\). One can calculate the four-momentum of the initial particle, in this case lambda, from the four-momentum components of the decaying products with this method:

\[ P_{\mu \Lambda} = P_{\mu \pi^-} + P_{\mu p} \]  \hspace{1cm} (2.38)

Using this way, the reconstruction of lambda particles was made in the reaction.
Chapter 3

Experiment: CEBAF and The CLAS Detector

The data used for this analysis were taken as part of the g13b run period at the Thomas Jefferson National Accelerator Facility, in Newport News, Virginia. The reactions and production of particles, which are going to be studied in this work, were achieved by using the CEBAF (Continuous Electron Beam Accelerator Facility) and the CLAS (CEBAF Large Acceptance Spectrometer) detector located in the Hall B experimental area. This chapter describes the main features of the experimental setup for g13b.

3.1 The CEBAF

CEBAF is a particle accelerator which uses superconductor technology to accelerate electrons at high velocities; being able to reach energies between 1.2 and 6 GeV, the electrons are then sent into a fixed target in one of the three end halls (A, B, C) for simultaneous researches; each hall owns specific conditions for the beam current, the target and the physics reaction. The Figure 3.1 shows a scheme of CEBAF.

The main components of CEBAF are the injector, five linear accelerators, the magnets, the refrigeration plant, and the experimental halls where the reaction is analysed. The main
property of LINACS is their capacity of delivering a continuous beam buckets separated by 2 ns with a duty cycle of 100% [9]; it is due to the use of radio frequency cavities made of an element called Niobium; when currents travel through metals, most of them offers resistance but Niobium behaves as a superconductor when it is cool with super cold temperatures, that reach -271 °C, losing almost all resistance. LINACS have strong magnets in order to accelerate and focus the electron beam, as electrons are negatively charged they would tend to repeal each other making necessary the use of dipoles and quadrupoles to control them. On the other hand, recirculating arcs are composed with magnets which bend the electron beam in the loop from one straight section to the next for up to five orbits.

**HOW CEBAF WORKS**

![Diagram of how CEBAF works](image)

The electron beam begins its first orbit at the injector. At nearly the speed of light, the electron beam circulates the 7/8 mile track in 24 millionths of a second.

Each linear accelerator uses superconducting technology to drive electrons to higher and higher energies.

Magnets in the arcs steer the electron beam from one straight section of the tunnel to the next, for up to five orbits.

A refrigeration plant provides liquid helium for ultra-low-temperature, superconducting operation.

The electron beam is delivered to the experimental halls for simultaneous research by three beams of physicists.

Fig. 3.1 Outline of the accelerator and the three end halls. Figure taken from [3].

The experiment starts at the injector; electrons are produced by photoemission, illuminating a photo cathode of GaAs with a laser source; the first bucket of electrons is accelerated to 67 MeV and directed to the linear accelerators (LINACS) [17]; each LINAC can boost electrons by 0.6 GeV; therefore a complete loop around the track increase the electron beam energy up to 1.6 GeV; the electron beam is allowed to make a total of five passes through both LINACS for a total energy of 6 GeV. Finally, getting the enough energy, depending on the experiment, the beam is sent to one of the three end halls in order to study the
properties of matter. Since data were taken in Hall B, with a large-acceptance detector for multi-particle detection, some of its principal features will be described.

3.2 Hall B

The three halls placed in the laboratory are labeled with the letters A, B and, C; halls A and C house two spectrometers capable of making high-precision measurements but over a limited area; in contrast, hall B, through the use of the CLAS detector, allows one to make measurements in almost $4\pi$ solid angle but with a lower precision [16]. There are a series of experimental detectors located in Hall B, being the main equipment the CLAS; Hall B also houses the photon tagger system, beam-line, and a suit of beam diagnostic tools.

CLAS is suitable to work with reactions which involve both electron and photon beams; experimental data used to develop this analysis were ran with an incident photon beam. The goal of the experiment required a linearly polarized photon beam [17]. Having the enough energy, electrons leave the CEBAF system and enter in the experimental hall; the electron beam is driven to the radiator where by Bremsstrahlung a beam of photons is produced; the photon beam then goes directly towards the target (located inside the CLAS), interacting with it and producing a certain reaction; the resulting final-state particles travel through the CLAS sub-detectors, such as start counter, drift chambers, time of flight and the electromagnetic calorimeter, where they are detected and identified.

3.3 Photon Beam Production and Photon-Tagging System

High-energy photons can be generated by bremsstrahlung technique; the process begins when an electron beam interact with the electromagnetic field of an atomic nucleus (radiator); this interaction results in a deceleration of the electron, and the corresponding emission of a photon with an energy roughly the same as that lose by the electron; this assumes that the fraction of energy transferred to the nucleon is negligible [23]. A high-energy beam of
polarized photons can be found in two states: circular or linear. The former is generated when longitudinally polarized electrons are incident upon an amorphous radiator (typically gold is the most common material for the radiator). The later, the result of a collective effect, is generated when an unpolarized beam of electrons is incident upon a thin diamond radiator [23].

In order to know the emitted photon energy, it is necessary to measure the energy of the incident electron and the energy of the outgoing electron. Information about the energy of the incident photon comes from the accelerator; given that after the bremsstrahlung process the beam comes out from the radiator as a mixture of non-interacting electrons, scattered electrons, and photons, it is necessary to use a photon-tagging spectrometer. This system has two purposes: Removing the electrons from the beam axes, allowing photons to continue to CLAS detector, to later measure the energy of the outgoing electrons. Figure 3.2 shows an layout of the device.

Fig. 3.2 Photon tagging spectrometer with some of the components labeled [23].

The electrons are separated when passing through the tagger magnet; those which did not interact with the radiator are deflected into a beam dump below the floor of hall B,
while those which did interact are deflected at greater angles, by the magnet, towards a system of scintillator planes (hodoscope planes: “T-counters” and “E-counters” [17]), from which timing and energy measurements for the electrons are made. Timing information by T-counters is used to associate the correct photon with an event, dismissing other multiple photons per event, while the E-counters is used to get a measurement of the electron energy. Using the energy conservation it is possible to calculate the photon energy.

### 3.4 CLAS Detector

In order to measure and identify particles generated in a reaction by the photon beam and the target, several sensitive devices are located surrounding the target so that accurate measurements of different magnitudes such as time, momentum and path length can be perform.

#### 3.4.1 Target Cell

The experimental data studied in this work used a set of data from the g13 run period; for this period the target material was liquid-deuterium contained in a cell made from Kapton with thin aluminum windows.\(^1\)

![Cylindrical target cell](image)

Fig. 3.3 Cylindrical target cell. It was 40 cm long, and 4 cm in diameter at its widest point [3].

\(^1\)the many features of Kapton make this material an optimal option to hold the target; Kapton has high structural and thermal stability, while having low impedance to particles [23]
The cell was cylindrically shaped with a length of 40 cm. The target cell was located 20 cm upstream from the center of CLAS in order to maximize acceptance. Figure 3.3 shows a schematic view of the target.

### 3.4.2 Start Counter

The first device is the Start Counter (SC) which is used to detect charged particles leaving the target and setting the “zero” for time-of-flight measurements. The start counter is composed of a set of scintillators paddles distributed in six sectors surrounding the deuterium target as shown in Figure 3.4; paddles are useful to measure time by detecting the radiated photons induced from particle ionization. The main function of the start counter is to determine which bucket of photons were responsible for each event, based on a difference with the time measured by the photon tagger; the difference can not exceed the 2 ns [21].

![Fig. 3.4 Start counter: Schematic view and cross-sectional view [17].](image)

### 3.4.3 Torus Magnet

The torus magnet is a device useful to identify if the particles produced in a reaction are negatively or positively charged as well as to determinate the momentum of the particles with the help of the tracking system. Torus magnet is divided in six different sectors Figure 3.5; it consists of six iron-free superconducting coils symmetrically arranged in a toroidal-like
shape. Each coil is 5 m long and has a kidney shape with 216 turns of aluminum-stabilized NbTi/Cu [17]; the kidney shape guarantees a free field region around the target, and produces a toroidal magnetic field almost pure azimuthal and perpendicular to the photon beam [21]. The magnetic field in g13 was set with negative polarity by passing a current of -1500 A. Consequently, positively charged particles bent toward the beam line, and negatively charged particles bent away from the beam line [17].

### 3.4.4 Drift Chambers

The drift chambers were designed in order to accomplish two important goals; they determine the particle trajectories and provide key information about particle identification by the determination of the particle momentum. Drift chambers are located in three regions of CLAS:

- Region one: it is closest to the beam line; this chambers are located in a sector almost free field surrounding the target, and provide information about the momentum and the trajectory of particles produced before entering the region of the magnetic field.
• Region two: it is placed in between the torus coils; the high magnetic field in this region allows to obtain a good resolution in the curvature of the particles track, making it possible to achieve better measurements of particles momentum.

• Region three: it is located outside the torus magnet; this region, like the first one, is almost free field and allow to get information about particles trajectory which follow a straight line towards the outers detectors.

Fig. 3.6 View of the relative position of the drift chambers regions. The section of the picture with zoom is a representation of the tracking reconstruction. [17].

Besides the three regions where drift chambers are located, they cover the six sectors of CLAS; furthermore, each region is separated and composed of two super layers: one axial to the magnetic field and the other tilted at a 6° which provide azimuthal information [17]. Likewise, layers are composed of two types of wires, field wires and sense wires, arranged in such a way that field wires, acting as a cathode at a high negative voltage, surround one sense wire which acts as an anode at a high positive voltage, forming a hexagonal pattern called cell; the voltage on the wires creates an electric field in the cells. Figure 3.6 shows an scheme of drift chambers and the relative positions they have with respect to the beamline and the torus magnet.

Drift chambers works because of the process of ionization (atoms or molecules gain or loss electrons); drift chambers are filled with high-purity gas mixture of 90% of argon
and 10% of CO2 [17]; the process of ionization occurs when high-energy charged particles, produced in the reaction, pass through the drift chambers, interact with the gas molecules, and create free electrons along their path; the principal reason of the particles energy loss is related to inelastic collision. After the interaction, the electrons that were produced by the collision are collected by the sense wires due to the electric field in the cell; in its way to the sense wire, the electrons interact with other gas molecules producing a cascade of electrons which reach the sense wires, this creates a measurable signal.

### 3.4.5 The Time-of-Flight System

The time of flight system plays an important role in the process of particle identification; it is used to measure the time it takes the charged particles to travel from the interaction vertex to the time-of-flight counters. Using this information (along with the path length) with the momentum as given by drift chambers, one is able to find the identities of the particles. The time of flight system is a six-sector arrangement which covers the CLAS between 8° and 142° in polar angle, and 80% of the azimuthal angle; the device is composed of 57 scintillator paddles distributed over the six sectors [23]. The way it works is by ionization; the ionized radiation from a charged particle going through a scintillator excites the material radiating photons which then are guided to the photo-multipliers to finally produce a signal. Figure 3.6 shows the location of the time-of-flight system in the detector.
Chapter 4

Particle Reconstruction and Analysis

This chapter describes the available methods, usually employed, for direct and indirect identification of particles. In the case of direct identification, two methods are developed: The first one will be the simplest method, which is supported on direct mass-cut over the data; then, it is explained a more elaborate method based on the time-of-flight and momentum of the particles, taking into account the energy-loss of the particles when they interact with matter. In the case of indirect identification two methods are developed: The missing-mass and the invariant-mass.

The experimental data is from Thomas Jefferson National Accelerator Facility, taken with the CLAS detector system. The experiment employed a photon polarized beam with energies between 0.8 and 2.3 GeV and a liquid deuterium target. In the Lab, the data is acquired by detectors in form of electronic readouts that are recorded in Bos format files [21]; formerly, data was processed using the CLAS reconstruction and data analysis package RECSIS [17], which takes the electronic information and translates them into physical variables such as position, time, charge, momentum etc. Finally, RECSIS sorts the information by "events" into multiple banks such as EVNT, TAGR, and SCPB; to know more about the information contained in each bank read appendix 1.
4.1 Initial Event Filter

Two reactions will be studied in this work in order to implement each one of the particle identification methods:

\[ \gamma d \rightarrow \pi^+ \pi^- pn \]

\[ \gamma d \rightarrow K^+ [\Lambda] n \rightarrow K^+ [\pi^- p] n \]

For both reactions one have as a final state three charged particles, and one neutral particle (2pos 1neg 1neu). With the first reaction, three methods will be developed, two for direct identification and one for reconstruction of particles (in the case of the neutron). With the second reaction, the last method will be presented in order to reconstruct the lambda particles from their decaying products [\pi^- p].

4.2 $\gamma d \rightarrow \pi^+ \pi^- pn$ Analyses. Mass-Cut Technique.

The mass-cut technique could be considered as the simplest form to identify particles, but also it is the less accurate. It was express before detectors provide information about different physics magnitudes among which is the mass of the particles; due to the impossibility of measuring it directly, mass information is generated by the detector based on the particle’s
momentum. Figure 4.1 illustrates the momentum dependence for mass values of the particles; the graph was implemented in a range of mass which match with the proton mass.

![Mass Distribution](image)

**Fig. 4.2** Mass of all the particles after the first skim, five remarkable peaks show evidence about a set of different particles mixed in this distribution. The y axes is in logarithmic scale.

Before getting specific information about the mass of the particles, it is necessary to apply some parameters to the data; the filtering processes in the analysis of the $\gamma d \rightarrow \pi^+ \pi^- pn$ reaction, initially, required at least one good tagger hit (from TAGR bank), it means that the analysis will start taking into account all the particles generated in a reaction which match with, at least, one photon. With this first condition completed, one can get the mass of the particles calculated by the system, using data from the drift chambers and the time-of-flight detectors (from EVNT bank). The Figure 4.2 shows the mass distribution for all the particles (positive, negative, and neutral ones), related with a good photon; as can be visualized, there are at least, five different particles represented by the five peaks in the graph; note the logarithmic scale on the vertical axes and the mass ranges on the horizontal axes. The information obtained about the mass distribution is useful in order to implement the first PID method based on direct mass-cuts over the data.

The next step in the filtering consist in separating particles depending on the sign of the charge; then, based on the final products of the reaction, it was necessary to select events with only four particles in the final state. These first filters reduce the amount of data significantly and reduce the computer requirements for the analysis.
Fig. 4.3 Time-of-flight mass: (a) Positive particles. (b) Negative particles. Note the logarithmic scale on the vertical axes and the mass ranges on the horizontal axes.
Figure 4.3a shows the mass distribution for positive particles after the second filtering; here, the particles have been separated by the sign of the charge and events with four particles in the final state have been set. As it is possible to see, the proton can be identified at this stage selecting a window of values for the mass; in the case of the positive pion, there is not clear distinction between the mass of them and the positive kaons; this kaon-pion miss-identification provides one of the major difficulties with the analysis of CLAS data [19].

![Mass Distribution](image)

Fig. 4.4 Distribution of mass for protons.

Similar to the $\pi^+$ and the $k^+$, there is not clear distinction between the mass of the $\pi^-$ and the $k^-$; this is illustrated in Figure 4.3b which shows the mass distribution for negative particles, the highest peak represents the mass of negative pions while the other one is related with negative kaons. This matter is the principal reason why the mass-cut is a method with low accuracy, since the mass selection is performed selecting ranges in an arbitrary form, without having any physical condition. Assuming that a window of values for the mass of protons, positive pions, and negative pions need to be fixed in order to tag them individually, and implement the mass-cut method; the next criteria were used:

- $0.5 < M^2 < 1.4 GeV^2/c^4$ for protons.
- $0.0 < M^2 < 0.1 GeV^2/c^4$ for $\pi^+$.
- $0.0 < M^2 < 0.1 GeV^2/c^4$ for $\pi^-$. 
The final result for the proton mass distribution is shown in Figure 4.4, there are not significant changes compared with the range of values from Figure 4.3a; the difference are the cuts applied in the values of mass. On the other hand, Figures 4.5 show the distribution of mass for positive and negative pions after the mass-cuts, the graphs are like similar for both of them and present a small peak at about $0.01 \text{(GeV}^2/c^4\text{)}$, taking into account this mass value, it is possible that the information can be contaminated by muon particles or particles out of time.

The mass-cut method could be useful as a preliminary event filter; however, from the last analysis, it is evident the failures it has related with the differentiation of particles with close values of mass, due to the range for the selection of particles have to be large enough so that no good particle events are discarded. Better methods to discriminate particles arise.
as a necessity in order to achieve improving results. The next methods developed in this work will show better results in terms of the accuracy in the discrimination of particles.

### 4.3 Cutting on Delta-Beta vs Momentum and Missing Mass Method

In this section two useful methods, one for direct and one for indirect identification of particles, will be developed; the first one is the delta beta method, based on the difference of the experimental beta with the theoretical beta respect to the momentum; this method is used to identify particles directly; on the other hand; the missing mass method is developed, it is based on the conservation of energy and is useful to reconstruct particles which do not interact with the available detectors as neutrons.

#### 4.3.1 $\Delta \beta \nu p$

The event selection process was applied for the $\gamma d \rightarrow \pi^+ \pi^- pn$ reaction; in order to reduce the background on the data, the filters explained above (one good tagger hit, discrimination of particles by the sign and events with four particles at the final state) were implemented; it is important to be clear with the fact that every negative particle was tagged as a $\pi^-$; in the case of the difference between proton and positive pions, it was necessary to create a loop which discriminate the mass of all the positive particles per event and tagged the one with the greatest mass as proton and the other one as a $\pi^+$. Having done this, it is important to discriminate the particles using a method different to mass-cut technique, the Figure 4.3 shows again the mass distribution until this point. The next step in the particle identification is based on the relation that comes from special relativity between $\beta$ (velocity as a fraction of speed of light) and momentum $p$. Assuming that the experimental data should match with the theory; it is possible to compare the theoretical $\beta$ with the experimental one, as a function of the momentum $p$. Detectors provide information about the $\beta$ measured and from special relativity one is able to get information about the theoretical $\beta$ for each particle.
For the purpose of the cutting on the $\Delta \beta v s p$, histograms with such a distribution for protons, positive pions, and negative pions are shown in Figure 4.6.

The values of $\Delta \beta$ were obtained according to the expression:

$$\Delta \beta = \beta_{\text{measured}} - \beta_{\text{calculated}} = \beta_{\text{measured}} - \frac{p}{\sqrt{p^2 + m^2}}$$  \quad (4.1)

The $\beta_{\text{measured}}$ arises from the time-of-flight measurements and the tracking information whereby it is determined the path length of the particles; based on this information the system calculates their velocity and provide a value for the experimental $\beta$ [15]; all this information is located in the EVNT bank.

$$\beta_{\text{measured}} = \frac{\text{path}}{c(t_{\text{time-of-flight}} - t_{\text{start-counter}})}$$  \quad (4.2)

The $\beta_{\text{calculated}}$ comes from equation 3.32 which is:

$$p = \gamma mv = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

As it is known $\beta = \frac{v}{c}$, and rewriting the equation for $\beta$ one gets:

$$\beta_{\text{calculated}} = \frac{p}{\sqrt{p^2 + m^2}}$$  \quad (4.3)

The values used for the momentum were the ones measured by the detector while the values used for mass were the Particle Data Group (PDG) mass for protons, and pions [18].

The $\Delta \beta$ method is supported on the fact that the difference between the values of the $\beta_{\text{measured}}$ and the $\beta_{\text{calculated}}$ have to be small for the correctly tagged particles; for this reason the graphs 4.6 show intense bands centered at zero which correspond to the specific particle in each case.
Fig. 4.6 The graphs show the delta-beta distributions for protons (a), positive pions (b) and negative pions (c), the bands are centered around zero which correspond to each specific particle, the other bands are due to background or particles which do not match with the expected.
The good events were selected within a cut of $\pm 3\sigma$ established from a series of gaussian fits over the $\Delta \beta$, these fits were taken by different bins intervals of momentum. An example done for protons is shown in figure 4.7:

![Figure 4.7](image)

Fig. 4.7 Distribution of $\Delta \beta$ by momentum bins for protons, this example was determined for a range of momentum from 0.6 to 0.7(GeV/c).

Similar graphs were obtained for different bins of momentum starting from a value of 0.2(GeV/c) until a maximum value of 1.5(GeV/c); then values greater than 1.5(GeV/c) were fit by a zero-order polynomial. In the case of $\pi^-$'s and $\pi^+$'s the procedure was similar, particles were identified by cutting on the $\Delta \beta_{vsp}$. The fitting parameters related with the mean and sigma for each gaussian fitting were used to construct a function around the $\Delta \beta$ values for each one of the particles, in order to tagged them in a correctly way. All this procedure was done using root macros for fitting all the histograms and creating the function to fit the $\Delta \beta$ values. The results can be observed in the Figures 4.8, for protons and negative pions:

These cuts can be applied at the beginning of the code with just the initial event filters implemented, or at the final of the code, after all the event filters have been applied; the results are going to be similar and the variation of the parameters are not significantly [17].
Fig. 4.8 The graphs show the fitting cut on the $\Delta\beta vsp$ distribution for protons(a) and negative pions(b). The fitting function was established from the gaussian distribution parameters: the mean value and $\pm 3\sigma$. 
4.3.2 Vertex and Fiducial Cuts

The $\Delta \beta$ method allowed to identify, with more accurately results, the charged particles generated in the reaction; in addition to this, it is necessary to implement some additional cuts in order to clean the background which comes from different sources as events out of time, out of the detector geometry, and resolution issues. On the other hand, this cuts are going to improve the results at the end of the code when the neutron will be reconstructed. Based on the geometry of the target cell, it is necessary to add cuts on the z-vertex of the reaction for the $\pi^+$, $\pi^-$, and the proton. As was mentioned in the second chapter, the target cell is 40-cm long, and it is important to be sure all the particles come from that range of length. The results of this cuts for protons are sketched in figures 4.9. In the case of the $\pi^+$, $\pi^+$ the graphs obtained were similar.

Fig. 4.9 The graphs show the z-vertex distribution for protons before and after the cut based on the geometry of the target cell.
Other important slice, useful for cleaning the background, are the fiducial cuts, which are based on the geometry of the detector layers. As was mentioned in chapter two, the CLAS system is composed by a series of detectors located in six sectors. It is possible to get information about the distribution of the particles over each sector by graphing the angle distribution for the events. The figure 4.10 shows the distribution by sectors for all the particles, this graph was created with a small amount of data in order get a good delimited figure; as can be noticed, the six sectors of the detector are well defined; additionally, the regions with less events are the ones where the support frames of the detector are placed; this regions need to be removed since they are a source of background for the data.

In addition to the problem related with the support frames, the fiducial cuts are important since the detectors present low efficiency at the edges of them [15]; also, it was mentioned the magnetic field generated by the torus magnet is azimuthal, but it is non-uniform at the boundary regions close to the coils; this deficiencies of the detector produces uncertainty in the measure of momentum and failed track reconstruction, making it necessary to implement cuts on the azimuthal angles for each sectors. The $\theta$ vs $\phi$ distribution for negative pions is plotted in Figures 4.11, Figure 4.11a shows the angle distribution before the cuts; then, for Figure 4.11b cuts consisted of $\pm 5$ on the azimuthal angle were implemented.
Fig. 4.11 The graphs show the angle distribution for negative pions before (a) and after (b) the fiducial cuts.
This same cuts were applied for protons and positive pions for removing the background which comes from those particles. After the employed of these cuts, a better graph for each sector of the detector is obtained; Figure 4.12 shows the results.

![Angular Distribution](image)

Fig. 4.12 Direction of protons found by the detector (cosine y vs cosine x).

As can be noticed, after the fiducial cuts, the events registered in the edges of the detector and in the support frames were rejected, keeping just the events with more accurate measures of momentum.

## 4.3.3 Particles Vertex Time cuts

Cuts between the vertex time difference were implemented for \((t_{\pi^-} - t_{\pi^+})\), \((t_{\pi^-} - t_p)\), and \((t_{\pi^+} - t_p)\); these cuts were imposed on the basis that the three particles were generated in the vertex of the reaction, the figure 4.13 shows an scheme of the reaction; this fact lead to establish a difference between the vertex time for each particle of \(\pm 2ns\), particles out of this window of time were rejected. Using the time from the Time-Of-Flight detector, the time calculated with the path length and the \(\beta\) measured, one is able to find the reaction vertex time for each particle using the expression:

\[
p_{\text{Vertex-time}} = ((TOF)time_p) - ((TOF)path_p/c \times \beta_p)
\]  

(4.4)
Fig. 4.13 Graphical scheme for the reaction: By bremsstrahlung technique, photons are created; the photon beam interact with the deuterium target and generates a reaction with four particles at the final state. The four particles are generated at the same vertex.
Fig. 4.14 The graphs show the time difference between $\pi^+$ and $\pi^-$ before (a) and after (b) the $\pm 2ns$ cuts.

The same expressions apply for the $\pi^+$ and $\pi^-$. Finding the vertex time for each particle; then, the difference between them is calculated. Figures 4.14 show the results of these cuts.

From the delta-time graphs is possible to realise that the data is centered at zero, the $\pm 2ns$ cuts guarantee that events from other beam buckets were removed from the data. Similar graphs were obtained in the case of the $\pi^+$ with $p$ and $\pi^-$ with $p$; for both of them, the same cuts were implemented. With these conditions done, an accurately cut can be implemented comparing the particles delta-time as a function of momentum; Figure 4.15 shows information about the vertex time difference between the $\pi^+$ and $p$ as a function of the proton momentum. Similar to the delta-beta histograms; the fit was implemented using gaussian fits by momentum intervals. This cuts were also applied for the delta-time of both pions, and the negative pion with the proton.

Up to this point, the identification of the $\pi^+$, $\pi^-$ and proton have finished using the technique of cutting the delta-beta as a function of momentum; additionally, sources of background due to particles out time, sectors with low efficiency of the detector, and sections
Fig. 4.15 $\pi^+$ and $p$ delta-time as a function of proton momentum. Figure (a) shows the distribution obtained. Figure (b) shows the $\pm 3\sigma$ gaussian fit implemented on the graph.
with non-uniformly magnetic field were removed. The final steps in the analysis of the reaction $\gamma d \rightarrow \pi^+ \pi^- pn$ are related with the reconstruction of the neutron. Although there is a detector named electromagnetic calorimeter which is appropriate to detect neutral particles, for this work we did not use it; this lead one to use the conservations laws of special relativity and four vectors to reconstruct it. In order to do so, first of all, we need the information about the state of the system before the reaction with the photon and the deuteron target. Respecting to the target, as it is at rest, we just need mass of it to stablish its four-vector; in the case of the photon four-vector, it is necessary to determine its momentum and energy to have all the information. Finally, with the photon and deuteron four-vectors information along with the four-vectors of the charged particles, it is possible to reconstruct the neutron using the equation 3.36.

4.3.4 Photon Selection

The tagging system provide the information about the energy of all the photons which it detects; the main goal of this section, it is to find the "best" photon (the photon which generates the reaction per each event); similar with the cuts of the vertex time between particles, it is necessary to implement cuts on the vertex time between one of the charged particle versus photons using the expression:

$$Diff_{\pi^+ vs \gamma} = (\pi^+_{\text{vertex-time}}) - (\gamma_{\text{time}} + (20 + Z(\pi^+))/c)$$

(4.5)

where:

$\gamma_{\text{time}}$ = Event photon vertex time

$Z(\pi^+)$ = Z-vertex position of the positive pion

In the case of this work cuts on the vertex time for the photon was implemented compared, first of all, with the positive pion and then with the negative pion. It was necessary to implement this cuts two times in order to improve the selection of the best photon and be sure of having the correct values of energy for the reconstruction the neutron. The figure
4.16a show the delta-time information between the photon and the $\pi^+$; as it is possible to see, the graph is a little bit kilter to the left, this could be due to the particles out of time; the Figure 4.16b provide information about the number of photons which could generate the reaction.

Fig. 4.16 a) The reaction vertex time between all the detected photons and the $\pi^+$; the extra peaks are from events out of time and photons originated from other beam buckets. b) Number of photons per event after the first cut over the time difference; events with more than one photon were rejected.
Fig. 4.17 a) The reaction time vertex time between all the detected photons and the $\pi^-$; the extra peaks are from events out of time and photons originated from other beam buckets. b) Number of photons per event after the second cut over the time difference; events with more than one photon were rejected.

After this first cut over the reaction time vertex between the photon and $\pi^+$, another one was implemented in order to have an accurately selection of the photon which produced the reaction; the necessity of getting an accurately selection of the photon is for the reconstruction of the neutron; if the selected photon is not the correct one, it will give a wrong value of the energy of the system before the reaction; generating an incorrect value for the neutron four-vector. This cut was implemented using the reaction time vertex between photons and $\pi^-$s; Figure 4.17a shows the information about the delta-time between the $\pi^-$s and photons; Figure 4.17b provide information about the number of photons which could generate each event; events with more than one photon were rejected.
4.4 Particle Reconstruction: Energy Loss Corrections and Missing Mass method

The final steps in the analysis of the $\gamma d \rightarrow \pi^+ \pi^- pn$ reaction is the reconstruction of the neutron. As was mentioned in chapter 3, this process is possible due to the conservation of energy; the equation 3.37 shows the mathematical expression which will provide the complete information about the neutron:

$$ P_{\mu n} = (P_{\mu \gamma} + P_{\mu d}) - (P_{\mu \pi^+} + P_{\mu \pi^-} + P_{\mu p}) $$

From this equation we already know all the elements of the right side of the equal; the photon information was obtained from the cuts on the reaction time vertex and the energy is given by the accelerator; the information about the deuteron target consist just of the mass of it (as it is at rest); the information about the $\pi^+$, $\pi^-$, and $p$ was obtained from the delta-beta cuts. Base on all this information, the missing mass method for the neutron was implemented. Figure 4.18 illustrates the values of mass obtained for the neutron.

Based on Particle Data Group (PDG) the mass of the neutron has a value of $939.565379 \pm 0.000021 MeV$; if the graph is analysed, it is evident that the mean peak of the histogram is
moved to the right of the value $0.95\,\text{GeV}/c^2$ showing a small discrepancy with the theoretical value. This situation is due to a correction that is missed in the code, which is related with the energy loss by particles when they pass through matter. In order take into account this situation, there was the necessity of using the CLAS eloss software package, which perform a correction of the four-vectors (changing the momentum values) for charged particles, based on the energy deposited by them in each one of the different materials that they passed through.

Figure 4.19 illustrates the energy loss distribution for the $\pi^-$ and the proton. As can be seen in the graph, protons energy loss are most significant compared with the negative pions; this is due to protons have lower momentum values which produce this particles have higher interaction with matter.

After applying this correction, the missing mass method was implemented again showing more accurately results related with the mass of the neutron. Figure 4.20 shows the final histogram for the neutron mass with its respective fit, the graph was fit to a Gaussian plus a quadratic background. The missing mass illustrates a mean peak close to the theoretical value; showing evidence about the correct reconstruction of the neutron for the reaction.
Fig. 4.20 Mass distribution obtained using the missing mass method; the graph was fit to a Gaussian over a linear background.

4.5 $\gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+[\pi^- p]n$ Analyses. Invariant Mass Method.

The $\gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+[\pi^- p]n$ final-state events were selecting using a method similar to the one used for the $\gamma d \rightarrow \pi^+\pi^- p n$ analysis. The method for identifying charged particles $K^+$, $\pi^-$ and $p$ was the delta-beta cuts. The difference with respect to the first reaction lies in the fact that $\Lambda$ particles decay on its way through the detectors in $[\pi^- p]$ making it necessary to use the invariant mass method to reconstruct them. The cuts related with the vertex time of the particles, photons, and the fiducial cuts were applied too. The neutron was reconstructed using the missing mass method.

4.5.1 Loose Skim Cuts

In order to reduce the amount of data and background to a more manageable size for the analyses, the filters related with one good tagger hit, discrimination of particles by the sign and events with four particles at the final state were implemented; every negative particle was tagged as a $\pi^-$; in the case of the difference between protons and positive kaons, it was
Fig. 4.21 Graphic scheme for the reaction: By bremsstrahlung technique, photons are created; the photon beam interact with the deuterium target and generates a reaction with three particles; due to the $\Lambda$ particle decay on its way through the detector, it is not possible to measure it directly.

necessary to create a loop which discriminate the mass of all the positive particles per event and tagged the one with the greatest mass as proton and the other one as a $k^+$; then, events with four particles in the final state were selected. In addition, some of the detector-based cuts were applied for each particle such as Z-vertex cuts and fiducial cuts; for both cases, the results were similar compared with the first reaction, being not necessary to illustrate the analyses again.

Considering the fact that the proton and $\pi^-$ are the decaying products of the $\Lambda$ particle, a window of time within $\pm 2\text{ns}$ were required at the vertex time; Figure 4.21 illustrates an
scheme in which the reaction takes place. Respect with the Λ particles, the first invariant mass was required to be between 1.07\text{GeV}/c^2 and 1.2\text{GeV}/c^2, this window was selected to be enough based on the value of mass for Λ which is 1115.683 ± 0.006\text{MeV}; on the other hand, the first missing mass was required to be between 0.7\text{GeV}/c^2 and 1.2\text{GeV}/c^2, this window was selected to be enough based on the value of mass for the n which is 939.565379 ± 0.000021\text{MeV}; this methods are studied in the next sections when more rigorous cuts are implemented.

### 4.5.2 Selecting the Λ events

The next step in the particle identification was the cuts on the delta-beta for each particle. For the purpose of these cuts, histograms with such a distribution for protons, negative pions, and positive kaons are shown in Figure 4.22; as it is possible to see in the figure, the delta beta values for protons and negative pions present a intense band centered at zero, corresponding these events with each specific particle; however, in the case of the positive kaons, there are two intense bands which do not correspond to the \textit{k}^+, since the bands are not centered at zero; this situation is due to the background presented at this stage of the analyses. With the main goal of eliminate a considerable amount of background; the Λ events were selected after the proton and positive pion, but prior to the the \textit{k}^+ identification.

The good events, in the case of the proton and \textit{π}^−, were selected within a cut of ±3\text{σ} established from a series of gaussian fits over the Δ\textit{β}, these fits were taken by different bins intervals of momentum. The fitting parameters related with the mean and sigma for each gaussian fitting were used to construct a function around the Δ\textit{β} values for each one of the particles, in order to tagged them in a correctly way. The results can be observed in the Figures 4.8, for protons and negative pions:

With the identification of the proton and the \textit{π}^− solved, the vertex time difference was implemented for both particles, taking into account that they come from the same root which is the lambda particles; a difference of ±2\text{ns} in the vertex time for both particles was established, particles out of this window of time were rejected. Next to the definition of the
Fig. 4.22 The graphs show the delta-beta distributions for protons (a), negative pions (b), and positive kaons (c). The bands are centered around zero which correspond to each specific particle, the other bands are due to background or particles which do not match with the expected.
Fig. 4.23 The graphs show the fitting cut on the $\Delta \beta \text{vs} p$ distribution for protons(a) and negative pions(b). The fitting function was established from the gaussian distribution parameters: the mean value and $\pm 3\sigma$. 
Fig. 4.24 Mass distribution obtained using the invariant mass method; the graph was fit to a Gaussian plus a linear function.

vertex time, the $p\pi^-$ invariant mass was implemented with the intention of reconstructing the $\Lambda$ particle. As was mentioned in chapter 3, this process is possible due to the conservation of energy; the equation 3.38 shows the mathematical expression which will provide the complete information about the neutron:

$$P_{\mu\Lambda} = P_{\mu\pi^-} + P_{\mu p}$$

From this equation we already know all the elements of the right side of the equal; the information about the $\pi^-$ and $p$ was obtained from the delta-beta cuts. Base on this information, the invariant mass method for the $\Lambda$ particle was implemented. Figure 4.24 illustrates the distribution of mass obtained for $\Lambda$ events. The distribution was fit to a quadratic background function and a lorenzian peak function, the cut was placed at $\pm 3\sigma$; the mean value of the graph match with the expected value for the $\Lambda$ mass ($1115.683 \pm 0.006 MeV$).

4.5.3 Final State Identification Cuts

Some important cuts were necessary to reduce the background before the identification of the $k^+$ and the reconstruction of the missing neutron for the $\gamma d \rightarrow K^+ [\Lambda] n \rightarrow K^+ [\pi^- p] n$
reaction. First of all, a cut on the vertex time between the $\pi^-$ and the photon was implemented imposing a window of difference of $\pm 2ns$. This cut was implemented before the identification of the $k^+$, with the main goal of reducing the extra bands that appears in Figure 4.22c, produced by particles from other beam buckets. The last cuts reduced the background presented in the $k^+ \Delta \beta$ distribution illustrated in Figure 4.22c; Figure 4.25 shows the new aspect of the same distribution after the above cuts(a) with its respective Gaussian fit(b), that was placed at $\pm 3\sigma$.

After identifying the positive kaon particles, a cut on the vertex time between the $k^+$ and the $\pi^-$ was implemented on a range of $\pm 2ns$ with the objective of eliminate the possible background which still remain in the reaction, Figure 4.26 illustrates the cutting results.

Next to the vertex time cut between $k^+$ and the $\pi^-$, it was necessary to select the photon which create the reaction (best photon); the vertex time cut was implemented between photons and the $k^+$, due to the $k^+$ is the only charged particle which come from the reaction vertex. The vertex time difference was required to be between $\pm 1ns$, Figure 4.27 shows the delta-time distribution.

The final steps in the analyses of the $\gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+[\pi^-p]n$ are the energy loss correction for the charged particles along with the reconstruction of the neutron via the missing mass method. The energy loss correction were applied in the same way as for the $\gamma d \rightarrow \pi^+\pi^-pn$ reaction. After correct the values of momentum for the $K^+$, $\pi^-$, and $p$, the reconstruction of the neutron was implemented using the missing mass method. Figure 4.28 illustrates the final result in the neutron reconstruction, the distribution was fit using two Gaussian functions.

With the reconstruction of the neutron the analyses for the $\gamma d \rightarrow K^+[\Lambda]n \rightarrow K^+[\pi^-p]n$ reaction was finished. As it is noticed in Figure 4.28 the mean peak of the graph matches with the expected value for the neutron mass.
Fig. 4.25 The graphs show the $\Delta \beta$ vs $p$ distribution after some cuts for kaons (a) and the fitting cut on the distribution (b). The fitting function was established from the gaussian distribution parameters: the mean value and $\pm 3\sigma$.
Fig. 4.26 Vertex time cut between $k^+$ and the $\pi^-$; the interval of time was required be between ±2ns.

Fig. 4.27 Vertex time cut between photons and the $K^+$; the interval of time was required be between ±1ns.
Fig. 4.28 Missing mass reconstruction of the spectator neutron. The signal was fit using two Gaussian function.
Chapter 5

Summary

In this analyses were studied two reactions, the $\gamma d \rightarrow \pi^+ \pi^- pn$ reaction and the $\gamma d \rightarrow K^+ [\Lambda]n \rightarrow K^+ [\pi^- p]n$ reaction, with which was illustrated four of the methods usually employed in physics laboratories to identify and reconstruct particles. The usefulness of the delta-beta, missing mass, and invariant mass methods, was evidenced when the process of direct and indirect identification of particles was done; additionally, it is important to take into account the advantages of using these methods since they depend only in the properties and values of the studied particles.

With the first reaction it was shown that the mass-cut method is useful as a preliminary event filter but it lacks of accuracy since the range of values for selecting the particles are implemented without any physical condition; this generates a selection of particles with a big uncertainty due to the background in the data. The delta-beta cut gave better results in terms of accuracy; in addition, this method take into account the fact that the measured and the theoretical relativistic beta must have similar values and also that they depend on the values of momentum of each particle. These facts offer reliability in the identification of the charged particles since the cuts has strong physical bases.

The theory of relativity provide the physical and mathematical bases for the implementation of the missing mass and invariant mass methods; both of them are supported in the law of conservation of energy; the reason of working with the values of energy and momentum
through the energy-momentum four-vector is that these quantities are conserved before and after an event. In the case of the missing mass, this mathematical tool allowed to balance the state of the system before and after the reaction in order to reconstruct the four-vector values for the neutron. In the case of the invariant mass, the addition of the four-vectors of the decaying particles $[\pi^- p]$ allowed to get the information related with the particle source $\lambda$.

The results obtained in this work were satisfactory, the identification of all the particles which were involved in both reaction was carried out; in addition, some additional cuts were well implemented in order to remove sources of background related with particles out of time and the geometry of the detector. The reconstruction of the $n$ and $\lambda$ particles evidenced the important of the law of conservation of energy and its impact in particle physics.
References


Appendix A

Bank Definitions

**EVNT bank**

ID: Particle Data Group ID  
Pmom: Particle momentum  
Mass: Mass squared (as a function of momentum)  
Charge: Particle charge  
Beta: Particle beta defined as $\beta = \frac{v}{c}$  
Cx: x cosine at track origin  
Cy: y cosine at track origin  
Cz: z cosine at track origin  
X: x coordinate of vertex  
Y: y coordinate of vertex  
Z: z coordinate of vertex  
DCstat: Information about the drift chambers  
CCstat: Information about the cherenkov counters  
SCstat: Information about the scintillator time-of-flight  
ECstat: Information about the electromagnetic calorimeter  
LCstat: Information about LCPB bank  
STstat: Information about the start counter  
Status: Status word (=0 out of time particles)
**TAGR bank**

- **ERG:** Energy of the photon in GeV
- **TTAG:** Time of the photon reconstructed in the tagger
- **TPHO:** Time of the photon after RF corrections
- **STAT:** Status (7 or 15 are good) other values should be discarded
- **T\_id:** T counter id
- **E\_id:** E counter id

**SCPB bank**

- **Time:** particle TOF time
- **Path:** particle path length to the TOF
Appendix B

Root Macros

Fitting The Invariant Mass

#include <fstream>

#include "TF1.h"
#include "TH1.h"
#include "TMath.h"
#include "TCanvas.h"

// Quadratic background function
Double_t bw(Double_t* x, Double_t* par){

    return par[0] + par[1]*x[0] + par[2]*x[0]*x[0];
}

// Lorentzian Peak function
Double_t lin(Double_t* x, Double_t* par){
return (0.5*par[0]*par[1]/TMath::Pi()) / TMath::Max(1.e-10, (x[0]-par[2])*(x[0]-par[2])+ .25*par[1]*par[1]);

} // Sum of background and peak function
Double_t total(Double_t* x, Double_t* par){
    return bw(x,par) + lin(x, &par[3]);
}

void invariant()
{
    TCanvas *c1 = new TCanvas("c1","c1"); //canvas to draw the distribution
    TFile *f = new TFile("/home/jeisson/rootbeer2.2/lambda.root"); //to call root file
    TH1F *hist = (TH1F*)f->Get("lambdamass2"); //to get the histogram from the root file
    hist->Draw(); // to draw the histogram
    // create a TF1 with the range from 1.09 to 1.14 and 6 parameters
    TF1 *func = new TF1("func",total,1.09,1.14,6);

    //give parameters
    func->SetParameters(100, 0.0,2.0,1.0,1.0,1.0,1.0);

    func->SetLineWidth(4);
    func->SetLineColor(kMagenta);
hist->Fit("func","V+","ep");

// improve the picture:
TF1 *backFcn = new TF1("backFcn",bw,1.09,1.14,3);
backFcn->SetLineColor(kRed);
TF1 *signalFcn = new TF1("signalFcn",lin,1.09,1.14,3);
signalFcn->SetLineColor(kBlue);
signalFcn->SetNpx(500);
Double_t par[6];

// writes the fit results into the par array
func->GetParameters(par);
backFcn->SetParameters(par);
backFcn->Draw("same");
signalFcn->SetParameters(&par[3]);
signalFcn->Draw("same");
}

Fitting The Missing Mass

//missing mass fit
#include <fstream>

#include "TF1.h"
#include "TH1.h"
#include "TMath.h"
#include "TCanvas.h"

Double_t bw(Double_t *v, Double_t *par)
{
    Double_t arg = 0;
    if (par[2] != 0) arg = (v[0] - par[1])/par[2];

    Double_t fitval = par[0]*TMath::Exp(-0.5*arg*arg);
    return fitval;
}

Double_t lin(Double_t *v, Double_t *par)
{
    Double_t arg = 0;
    if (par[2] != 0) arg = (v[0] - par[1])/par[2];

    Double_t fitval = par[0]*TMath::Exp(-0.5*arg*arg);
    return fitval;
}

Double_t total(Double_t* v, Double_t* par){
    return bw(v,par) + lin(v, &par[3]);
}

void missing()
{
}
TCanvas *c1 = new TCanvas("c1","c1"); //canvas to draw
TFile *f = new TFile("/home/jeisson/rootbeer2.2/lambda.root");
TH1F *hist = (TH1F*)f->Get("fnutralmass"); //get the histogram
hist->Draw();
// create a TF1 with the range from 0.8 to 1.2 with 6 parameters
TF1 *func = new TF1("func",total,0.8,1.2,6);
func->SetParameters(2.0,2.0,2.0,2.0,2.0,2.0);
func->SetLineWidth(4);
func->SetLineColor(kMagenta);
hist->Fit("func");

// improve the picture:
TF1 *backFcn = new TF1("backFcn",bw,0.8,1.2,3);
backFcn->SetLineColor(kRed);
TF1 *signalFcn = new TF1("signalFcn",lin,0.8,1.2,3);
signalFcn->SetLineColor(kBlue);
Double_t par[6];
// writes the fit results into the par array
func->GetParameters(par);
backFcn->SetParameters(par);
backFcn->Draw("same");
signalFcn->SetParameters(&par[3]);
signalFcn->Draw("same");
}
Appendix C

Classification of Particles

The study of particle physics through the history lead to the discovery of a diversity of particles which have its own properties in terms of mass, charge, interactions, spin, among others. These identified particles have been classified in different groups depending on the features named above. First of all, it is possible to divide the group into elementary particles and composite particles.

C.1 Elementary particles

Elementary particles are the ones that are fundamental in nature; it means that they are not composed with other particles. In this group it is found two different subgroups of particles: fermions and bosons. Fermions are particles which have half-integer spin and are characterized by Fermi-Dirac statistics; fermions can be from two types, quarks and leptons, the former are particles with half-integer charge and interact via strong interactions (up, down, charm, strange, top, bottom), the later are particles which may be charged or neutral (electron, electron-neutrino, muon, muon-neutrino, tau, tau-neutrino), charged leptons have electromagnetic as well as weak interactions, but they do not interact via the strong interaction. In the case of Bosons, they are particles with integer spin and are
considered as responsible of the four fundamental forces, in this group of particles it is found photons, bosons, and gluons.

## C.2 Composite particles

Composite particles are the particles which have an internal structure, it means that they are composed by more fundamental particles; this particles are called hadrons. Hadrons are divided into two groups: baryons and mesons. The former are particles with half-integral spin (proton, neutron, lambda, omega, xi, delta-baryon), the later are particle with integer spin (pion, kaon, phi, rho, eta, among others).
Appendix D

The Gaussian Distribution

Statistics focus its mathematical tools in solving problems with random results, it means there is no way to predict the final results after an experiment; throwing a dice, select a card from a deck, or predict the product of a particle decay are examples of random processes. On the other hand, in physics, the main goal of an experiment it is to measure the magnitudes that are involved, when a measuring is done, it has associated an error in the measuring due to different factors (instrumental errors). For this case, statistics and probability are important tools in order to work and interpret these kind of data. The Gaussian distribution is one of the most important probability distributions, there exist others as the binominal distribution or the Poisson distribution; measurement errors and in particular, instrumental errors are well described by this distribution [25]. In this theses most of the distribution functions were fit using the Gaussian distribution since it was the one that best fit the results. Moreover, even in cases where its applications is not strictly correct, the Gaussian often provides a good approximation for different distributions. [25]. The Gaussian distribution is given by:

\[ P(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \]

The values of \( \mu \) and \( \sigma \) correspond to the mean and variance of the distribution. In figure D.1 it is illustrated the effects of the \( \sigma \) values in the graph using a value of \( \mu = 0 \).
Fig. D.1 The Gaussian distribution for various $\sigma$ using $\mu = 0$.

As it is possible to see, the width of the graph depends on the values of $\sigma$. Additionally, the value of $\sigma$ also has an impact on the area under the Gaussian. When the fits for this work were implemented, the Gaussian were adjusted using a value of $\pm 3\sigma$, this is due to the areas defined by the intervals; these values are important in the analysis of the data:

- $1\sigma \rightarrow 68.3\%$
- $2\sigma \rightarrow 95.5\%$
- $3\sigma \rightarrow 99.7\%$

This area is represented in figure D.2.

In the case of $\pm 3\sigma$ that was the one used in this work, the $\mu \pm 3\sigma$ signifies that the true value has $\approx 99.7\%$ probability of laying between the limits of the graph [25].
Fig. D.2 The area contained between the limits of $\sigma$. Figure (a) shows the limited area using a sigma value of $\sigma = 0.5$. Figure (b) shows the area contained using sigma values of $1\sigma$, $2\sigma$, and $3\sigma$. Figure (b) taken from [25].
Appendix E

Conservation laws

The development of each physics branch has shown that there are some quantities that conserve before and after a process; conservations of energy, linear and angular momentum as well as the conservation of charged, are some important examples related with this fact. In the case of particles physics, it has been founded that such conservation laws hold; however, that conservation laws are not the only ones, researches in particle physics have shown other laws that conserve when a particle reaction or decay takes place.

E.1 Conservation of Baryon Number

The conservation of the baryon number says that the number of baryons before and after a process has to be the same. According to the classical notation $B = 1$ represents baryons, $B = -1$ for antibaryions, and $B = 0$ for everything else.

E.2 Conservation for Lepton Numbers

The conservation for lepton numbers, similar to the baryon number, says that the number of leptons before and after a reaction has to be conserved. According to the notation, it was assigned $L = 1$ to leptons, $L = -1$ for antileptons, and $L = 0$ for everything else.
With the discovery of the $\lambda$, $\sigma$, and $k$ particles, it was found that these particles behave strange since they were produced copiously by the strong interaction but decayed very slowly via the weak interaction [12]. The solution of this paradox came from the invention of a new quantum number called *strangeness* ($s$); particles with such behavior were assigned with strangeness values of $s = 1$, $s = -1$ and, $s = 0$; while their corresponding antiparticle gets the opposite value. It is important to say that the strangeness holds only for strong interactions, in the case of a decay occurs via weak interaction, the strangeness is not going to conserve [10].

In the case of the reactions studied in this thesis it is possible to evaluate the above conservation laws. First reaction:

$$\gamma d \rightarrow \pi^+ \pi^- pn$$

- Conservation of charge: It accomplish the conservation of charge, the deuterium target is composed by a proton and a neutron. it means that the system has an excess of one positive charge. After the reaction, both pions have opposite charge, meaning that the system has an excess of one positive charge due to the proton.

- Conservation of Baryons: Before the reaction the system has two baryons, proton and neutron. After the reaction the system has the same two baryons, which shows that they are conserved.

- Conservation of Leptons: There are no leptons before or after the reaction.

- Conservation of Strangeness: There are not strangeness particles before or after the reaction.

Second Reaction:

$$\gamma d \rightarrow K^+ [\Lambda] n \rightarrow K^+ [\pi^- p] n$$
• Conservation of charge: It accomplish the conservation of charge; initially, the system has an excess of one positive charge. After the reaction, in the first scenario, the system has two neutral particles ($\lambda$ and $n$) and one positive ($k^+$), which conserves the charge. In the second scenario, after the decay of the $\lambda$ particle, the system have again an excess of one positive particle since the final state has two positives ($K^+ and p$) and one negative ($\pi^-$) particles.

• Conservation of Baryons: It accomplish the conservation of baryons. Before the reaction the system has two baryons, proton and neutron. After the reaction, in the first scenario the system has two baryons with the $\lambda$ and the $n$; in the second scenario, the system presents two baryons again with the $p$ and the $n$.

• Conservation of Leptons: There are no leptons before or after the reaction.

• Conservation of Strangeness: Before the reaction, the system does not have strangeness particles. After the reaction, in the first scenario, it is presented the conservation of strangeness since the system has two strangeness particles: the $\lambda$ with $S = -1$ and the $K^+$ with $S = 1$. In the second scenario, the system has one strangeness particle which is the $K^+$, as was mentioned before, the strangeness is not conserved as the $\lambda$ particle decay via weak interaction.