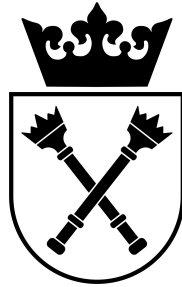


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Development of track reconstruction for the upgraded NA61/SHINE Vertex Detector

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Master's thesis
in the field: Experimental physics

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Oświadczenie autora pracy

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Kraków, 25.07.2023

Mateusz Ludwik Bajda

*This thesis I want to dedicate
to my parents, **Teresa** and **Jerzy**.
For their unconditional love, support and faith in me.*

„Studenci innych wydziałów dostają często do wykucia materiał z kilkuset stron na za trzy dni, podczas gdy studenci fizyki uczą się nieraz zawartości kilku stron na za miesiąc. Jednak w ten sposób dowiedziałem się kolejnej ważnej rzeczy: że nieodłącznym towarzyszem w nauce fizyki jest ciągła f r u s t r a c j a”

prof. dr hab. Andrzej Dragan, *Kwantechizm, czyli klatka na ludzi*.

First of all, I would like to thank my supervisor, **Dr Hab. Paweł Staszek**, for his knowledge, and patience, and for introducing me to the world of experimental physics, the part related to the analysis of physical phenomena as well as hardware and its software. I also want to thank the entire NA61/SHINE experiment collaboration, especially **Ivan Pidhurskyi** for many discussions on software improvements and simulations.

I am also very grateful to my friends. Especially to **Szymon Gamrat**, **Konrad Pawlik**, and **Milena Czubak**. Thank you for the various discussions, and especially for your help during our academic adventure so far.

Finally, I would like to thank my whole family, mother **Teresa**, father **Jerzy**, and sister **Dominika** for their support. In particular, I want to thank my girlfriend, **Agnieszka Karpl**, for her understanding, perseverance, substantive assistance, and forbearance of my nightly analyses.

Abstract

This thesis is dedicated to the upgraded Vertex Detector used in the NA61/SHINE experiment, i.e. its hardware and software. The performance of the improved software is demonstrated on simulation of D^0 mesons generated in Pb+Pb central collisions at $150A\text{ GeV}/c$. Moreover, an analysis of the acceptances and reconstruction efficiencies of the upgraded Vertex Detector for single particles (kaons and pions) and two particles (charm mesons D^0). The analysis was based on selected decay channel of the D^0 meson:

$$D^0 \rightarrow K^- + \pi^+ \tag{1}$$

The thesis is divided into 12 chapters. In the first chapter (chapter 1) there is a physical description of heavy ion collisions and the formulation of the Standard Model. The next chapter (chapter 2) describes the NA61/SHINE experiment and a detailed explanation of the so-called open charm measurements which is the main physics program in the NA61/SHINE experiment.

To carry out such studies, a specialized device is required, the so-called Vertex Detector (VD). The chapter 3 contains the description of the pilot version of VD used in the NA61/SHINE experiment, while the chapter 4 describes the reconstruction chain.

During Long shutdown 2 (LS2), the Vertex Detector detector has been upgraded as described in the chapter 5. This required an upgrade of the VD software, which is described in the chapter 6.

In the next two chapters (chapter 7 and 8) an analysis of acceptances and reconstruction efficiencies of single particles (kaons and pions) and D^0 mesons for the upgraded Vertex Detector are presented. The obtained results are presented in the chapter 9, while the conclusions are provided in the chapter 10.

A final summary of the thesis and description of further steps are given in the chapter 11, while some additional figures used in this thesis are collected in the appendix (chapter 12).

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Chapter 1

Introduction

1.1. The Standard Model

The first major breakthrough in elementary particle physics was the discovery of the electron by J. J. Thompson in the 19th century [1]. This discovery has changed our understanding of how matter around us is built. The atom was believed to be the elementary particle of matter. Along with the next experiments, e.g. experiment by Rutherford [2] and others, it turned out that atoms are not elementary particles. From the experiments carried out, it was established that an atom consists of an atomic nucleus, made of protons and neutrons with electrons circulating around (Figure 1.1).

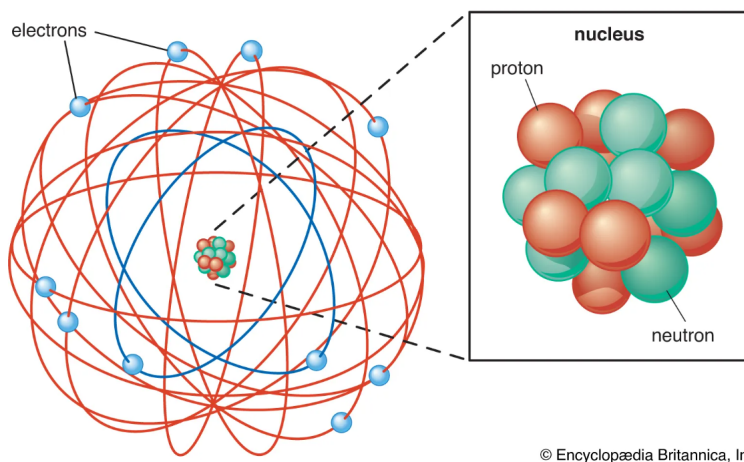


Figure 1.1: Rutherford, after interpreting the results of the experiment, compared the atom to the solar system, in which light electrons circulate in a large empty space around a massive atomic nucleus. [3]

During the next decades, mainly in cosmic rays, more and more particles and antiparticles were discovered in particular the first discovered antiparticle was the positron discovered by Anderson in 1932 [4]. In order to continue systematic studies of particles and the nature of their interactions, the construction of the first devices accelerating ions has begun [5].

As the matter was bombarded using different beams of hadrons and ions at higher and higher energies, more and more new particles were discovered. So, the question was, do

particles consist of certain elementary objects? The consensus was reached in the second half of the 20th century, after analyzing the results of many experiments and comparing them with many theoretical predictions.

The theoretical model that can explain the discovery of subsequent particles and describe the interactions between them is the Standard Model (MS). According to that model, all matter surrounding us consists of 12 fundamental particles (divided into quarks and leptons) and their corresponding antiparticles. These particles are called fermions and they have a half-integer spin. This model also describes three of the four fundamental interactions between particles that take place by means of the boson exchange, i.e. particles with integer spin. The classification of elementary particles and the exchange bosons that are described by MS is presented in figure 1.2.

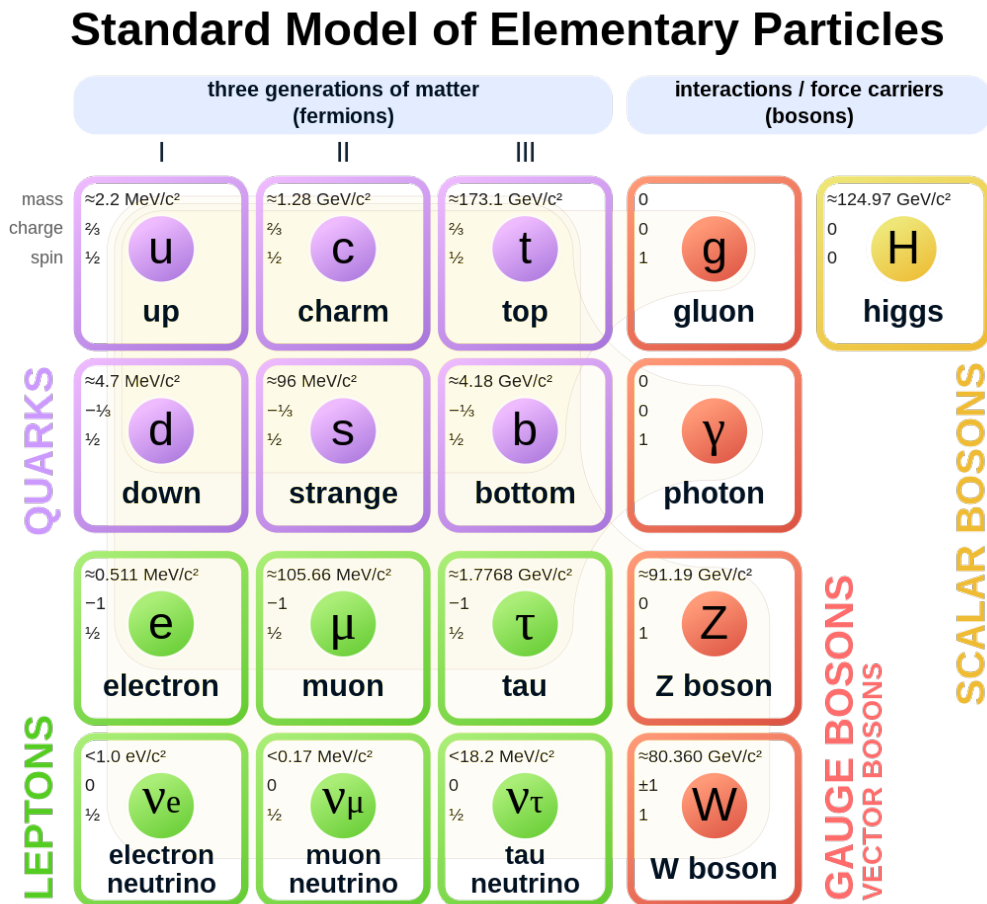


Figure 1.2: Table presenting the division of elementary particles and the exchange bosons in the Standard Model. [6]

Fermions have been divided into three generations, each containing a pair of quarks and a pair of leptons. Most of the universe around us is made up of particles belonging to the I generation. Heavier particles from II and III generations decay very quickly and can not form stable objects [7].

1.1.1 Forces and the exchange particles (bosons)

There are four types of fundamental interactions in the universe: the gravitational interaction, electromagnetic interaction, the weak interaction, and the strong interaction. They differ in distance range and strength. The gravitational interaction acts between all types of particles and forms of matter. Although the interaction distance is infinite, this interaction is the weakest. The electromagnetic interaction is responsible for the largest number of phenomena in physics on micro and macroscopic scales. For example, it binds electrons in atoms or intermolecular interactions in liquids and solids. Although the weak interaction is weaker than the electromagnetic and strong interaction, it is still much stronger than the gravitational interaction. It is mainly responsible for the decay in slow nuclear processes, e.g. β decay [8]. The strong interaction is responsible for the binding quarks in hadrons, i.e. particles made of three quarks, or mesons (particles made of a quark-antiquark pair).

The Standard Model describes three of the four fundamental forces in terms of the exchange bosons:

- Z^0 , W^+ , W^- - bosons carry the weak interaction and have a mass about 100 times that of a proton,
- gluons, g - carry the strong interaction, which is described by a new quantum number „color”,
- photon, γ - carry the electromagnetic interaction.

It is worth noting, that the Standard Model gives us not only a description of already known particles or interactions but also allows us to predict further physical phenomena. An example is the prediction of a new exchange boson (the Higgs boson), which is the carrier of the interaction with the Higgs field responsible for the generation of particle masses. In 2012 independently CMS [9] and ATLAS [10] discovered the Higgs boson.

1.1.2 Mathematical formulation of the Standard Model

The Standard Model of particle physics is a gauge quantum field theory [11, 12]. The mathematical description is based on symmetries that are around us in nature. There are space-time symmetries and also internal symmetries. Electromagnetic, strong, and weak interactions are established on internal symmetry by the local gauge theory:

$$G_{\text{local}} = \text{SU}(3)_{\text{color}} \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \quad (1.1)$$

where:

- $\text{SU}(3)_{\text{color}}$ - non-abelian color gauge group describes the strong interactions (QCD - *Quantum Chromodynamics*).
- $\text{SU}(2)_L \otimes \text{U}(1)_Y$ - electroweak gauge group where $\text{SU}(2)_L$ is a non-abelian group which describes the left-handed weak isospin and $\text{U}(1)_Y$ represents the weak hypercharge. This gauge group is broken to the abelian electromagnetic group $\text{U}(1)$ of Quantum Electrodynamics (QED). [13, 14]

All information about interactions, energies, or masses is encoded in the Lagrangian, which provides a very compact description of the theory [12]. All the formalism contained in the mathematical description of the Standard Model can be described by one simple Lagrangian (more specifically, the Lagrangian density):

$$\mathcal{L} = \underbrace{-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}}_{\textcircled{1}} + \underbrace{i\bar{\psi}\not{D}\psi + \text{h.c.}}_{\textcircled{2}} + \underbrace{\psi_i y_{ij} \psi_j \phi + \text{h.c.}}_{\textcircled{3}} + \underbrace{|D_\mu \phi|^2}_{\textcircled{4}} - \underbrace{V(\phi)}_{\textcircled{5}} \quad (1.2)$$

where:

- ① This is the scalar product of field strength tensor $F_{\mu\nu}$. It includes the existence of all elementary particles in the Standard Model and also describes all possible interactions. Figure 1.3 shows Feynman diagrams that are included.
- ② The first term contains a formalism that describes how particles interact with matter. The fields here (ψ and $\bar{\psi}$) describe quarks (antiquarks) and leptons (antileptons). On the other hand, the covariant derivative ($\not{D}$) contains the exchange bosons (except the Higgs boson), which do not interact with each other at this point. The second term (h.c.) is the „hermitian conjugate” of the first term.
- ③ This expression describes how particles receive mass by interacting with the Brout–Englert–Higgs (BEH) field ϕ . For this purpose, the elements y_{ij} of the Yukawa matrix represent the coupling parameters with the BEH field that are used. [15]
- ④ A term describing how the exchange bosons decay into a pair of particles. For example, in the presence of an atomic nucleus, a photon (with high energy), by interacting with an electric field, will vanish for creating a pair of particles: an electron and a positron:

$$\gamma \rightarrow e^- + e^+$$

- ⑤ The last term describes the potential of the Brout–Englert–Higgs (BEH) field ϕ . It is worth pointing out, that this potential infinite number of minima. This is why a spontaneous symmetry breaking can occur in the model.

Quantum chromodynamics (QCD)

This theory is one of the most important parts of the Standard Model. It introduces a new degree of freedom, the so-called color. This quantity is not a color in the optical sense but is responsible for the strong interactions. It can be treated as a charge, like in QED (Quantum electrodynamics), but in QED there are only two (positive and negative) but in QCD there is three (r - red, b - blue, g - green). The intermediary bosons that carry the color are the gluons. The Lagrangian density fully describing QCD has the form:

$$\mathcal{L}_{QCD} = \underbrace{\sum_{f=1}^6 [\bar{q}_f i \gamma^\mu \partial_\mu q_f - m_f \bar{q}_f q_f]}_{\textcircled{1}} - \underbrace{g_s (\bar{q}_f \gamma^\mu T^a q_f) A_\mu^a}_{\textcircled{2}} - \underbrace{\frac{1}{4} F_{\mu\nu}^a F_a^{\mu\nu}}_{\textcircled{3}} \quad (1.3)$$

where:

- ① This term describes the „kinetic energy” of quarks (q_f) with their masses (m_f).
- ② It is representing the interaction of quarks (q_f) with gluons field (A_q^a) by strong coupling constants g_s (index a is gluon color).
- ③ The scalar product of field strength tensor $F_{\mu\nu}^a$:

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

It includes the interaction of gluons and their „kinetic energy”. The exchange bosons in the strong field (gluons) are specific because they interact with each other. Due to QCD is non-abelian group SU(3). [16]

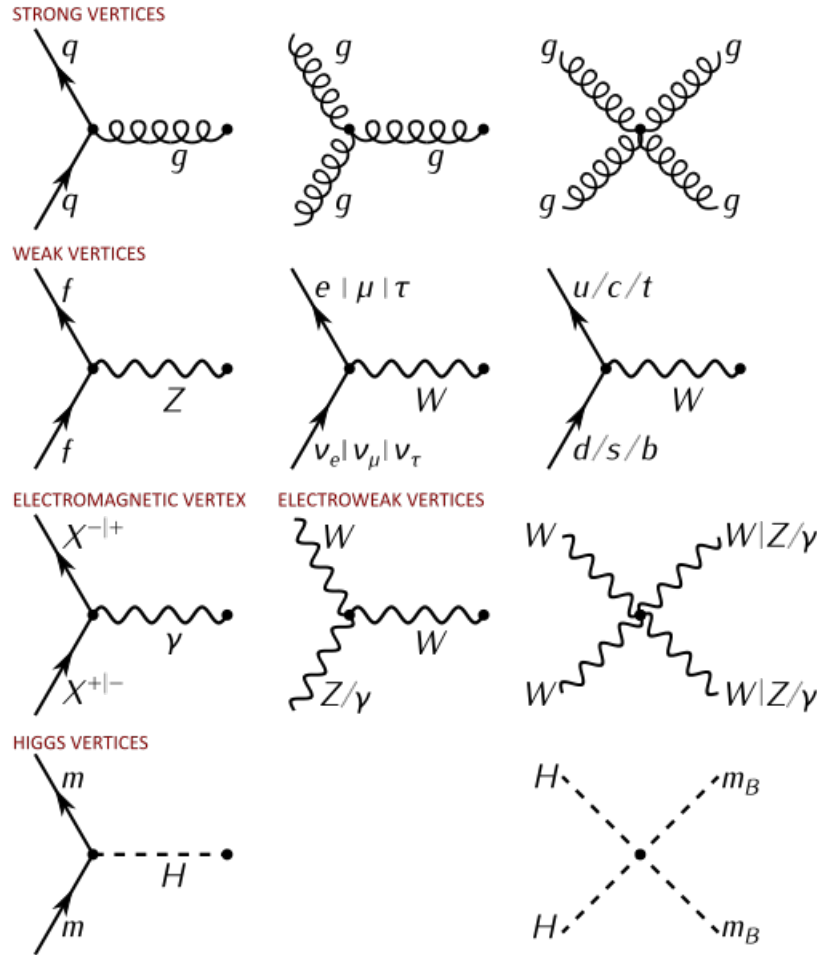


Figure 1.3: Feynman diagrams that are included in term $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ of all fields. [17]

1.2. High energy collision

With the development of technology, more and more advanced experimental techniques are used to detect new particles in order to study nuclear matter. Such studies focus on hadron-hadron, nucleus-hadron, and nucleus-nucleus collisions. These collisions are classified according to the projectile energy per nucleon in the laboratory frame [18, 19]:

- low energies - up to about $20A \text{ MeV}/c$,
- medium energies - from $20A \text{ MeV}/c$ to $100A \text{ MeV}/c$,
- relativistic energies - from $100A \text{ MeV}/c$ to $10A \text{ GeV}/c$,
- ultra-relativistic energies - above $10A \text{ GeV}/c$.

In a collision, different mechanisms occur depending on the energy [19]. For beam energies below $20A \text{ MeV}/c$, direct nucleon-nucleon collisions are forbidden by the Pauli exclusion principle. For medium energies, the important mechanism occurring during the collision is multifragmentation. Phenomena such as the creation of particles and the transparency of matter occur in relativistic collisions, i.e. for energies above $100A \text{ MeV}/c$. The primary insight into the relativistic collisions is described by the participants-spectator model.

1.2.1 The participants-spectator model

In this model, the nucleons included in colliding nuclei are divided into two parts:

- participants – the nucleons that are directly involved in the collision.
- spectators – nucleons that are not involved in the collision.

A schematic representation of the participants-spectator model is shown in figure 1.4. Collision centrality is defined by the impact parameter b . The lower the impact parameter value, the centrality of collision and the number of participants increases.

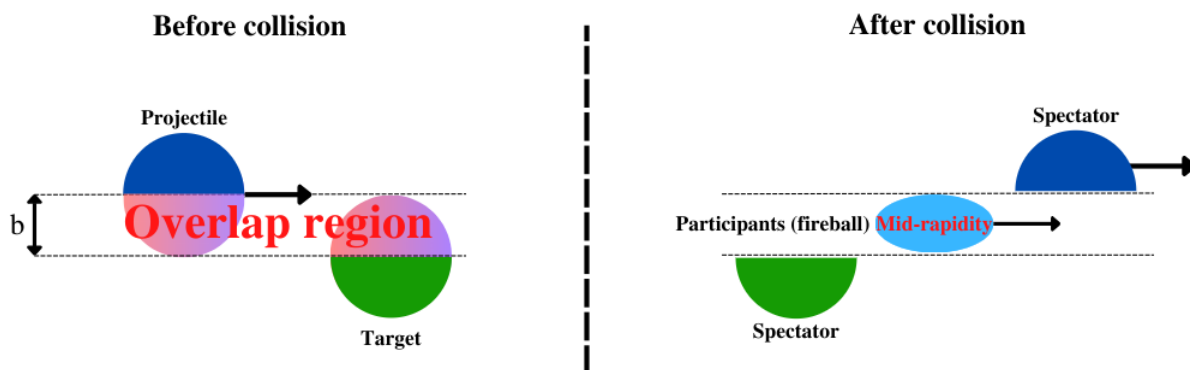


Figure 1.4: A schematic explanation of the participants-spectator model concept.

Assuming that a gas of massless quarks and gluons was formed in the overlapping area, the energy density of the formed system is proportional to the fourth power of the temperature according to the Stefan Boltzmann distribution [20]:

$$\mathcal{E} \simeq gT^4, \quad (1.4)$$

where T is temperature, and g is the number of degrees of freedom.

There are two ways to determine the energy density of matter [20]:

1. By quantum electrodynamics (QED):

$$\mathcal{E}_{QED} = \frac{\pi^2}{30} \left[\underbrace{2}_{\textcircled{1}} + \frac{7}{8} \times \underbrace{2}_{\textcircled{2}} \times \underbrace{2}_{\textcircled{3}} \right] T^4 \approx 2T^4, \quad (1.5)$$

where:

- ① the number of photon spins,
- ② electron and positron,
- ③ the number of electron spins.

2. By quantum chromodynamics (QCD):

$$\mathcal{E}_{QCD} = \frac{\pi^2}{30} \left[\underbrace{2}_{\textcircled{1}} \times \underbrace{8}_{\textcircled{2}} + \frac{7}{8} \times \underbrace{2}_{\textcircled{3}} \times \underbrace{2}_{\textcircled{4}} \times \underbrace{3}_{\textcircled{5}} \times \underbrace{3}_{\textcircled{6}} \right] T^4 \approx 15T^4, \quad (1.6)$$

where:

- ① the number of gluon spins,
- ② the number of colors,
- ③ quark and anti-quark,
- ④ the number of quark spins,
- ⑤ the number of quark color,
- ⑥ the number of quark flavors (u, d, s).

1.2.2 The Quark-Gluon Plasma

One of the states of nuclear matter predicted by the theory which can be formed in high-energy nucleus-nucleus collisions is the quark-gluon plasma (QGP). In this state, quarks and gluons are not confined to hadrons. In high-energy collisions of atomic nuclei, it is possible to create a quark-gluon plasma. The entire process of creating QGP can be presented in a few steps:

- ① Two heavy atomic nuclei that have been accelerated to a speed close to the speed of light are centrally colliding with each other.
- ② As a result of the collision, a hot, dense system called a fireball is formed in the overlapping area (see figure 1.4). If the energy density in the formed system is above about $1 \text{ GeV}/fm^3$ then a quark-gluon plasma is formed.
- ③ Formed QGP expands which leads to a decrease in its energy density. After a while, the hadronization process takes place, i.e. quarks and gluons combine into hadrons. Hadronic gas is formed.
- ④ After a longer period of time, the chemical composition of the system is fixed, i.e. chemical freeze-out. This is due to disappearing the inelastic interactions between the hadrons.
- ⑤ Over time, the system cools down and expands, further reducing the interaction between the created particles. This leads to the stabilization of the energy and momentum of the particles. This system evaluation stage is called kinetic freeze-out.

Studying the quark-gluon plasma formed in the heavy-ion collision is very difficult. This is due to the fact that the detected particles were formed in the hadronization processes. However, the phenomena related to the QGP state occur in the early stages of the collisions. Those only observables weakly sensitive to the hadronization and the following stages of the collision can be used to study QGP. The following observables (**quark-gluon plasma signatures**) has been proposed as a signature for the QGP creation [21]:

- The size of the fireball measured particle interferometry.
- The non-continuous ratio of strangeness and charm production to entropy QGP.
- The change in the medium proportion of heavy mesons (J/ψ , ψ' , Υ , Υ') that results from the color charge screening in QGP (Debye screening length λ_D).
- Suppression of high p_T by high p_T partons interaction with QGP.
- The elliptic flow scaling with the number of constituents quarks.

Chapter 2

The NA61/SHINE experiment

2.1. The experiment overview

SPS Heavy Ion and Neutrino Experiment (SHINE) [22] is a fixed-target experiment located on the H2 beamline of the CERN SPS (Super Proton Synchrotron) accelerator (figure 2.1). It was optimized to study hadron production in hadron-proton, hadron-nucleus, and nucleus-nucleus collision. This experiment is a successor to the NA49 experiment [23] from which several components are used. About 140 physicists from 28 institutions in 15 countries participate in the NA61 experiment.

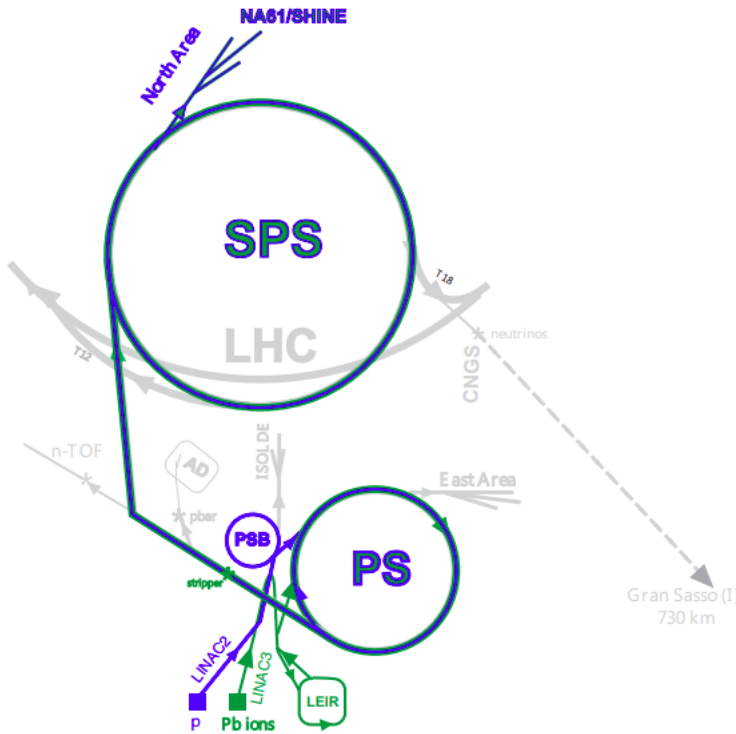


Figure 2.1: A scheme of the accelerators important in delivering the beam (marked with a bold blue line) of ions and protons to the NA61/SHINE experiment [24].

2.2. The physics programme

The main goal of the experiment is to study the diagram of strongly interacting matter [25], including i.a. charm hadron production, quark-gluon plasma signature, and location of the critical point.

They are based on the study of hadrons in hadron-proton, hadron-nucleus, or nucleus-nucleus collisions (e.g. p+p or Pb+Pb) at different beam momentum: for heavy ions, the momentum is in the range from $13A$ GeV/c to $158A$ GeV/c (where A is the mass number), while for protons it can be up to 400 GeV/c (figure 2.2).

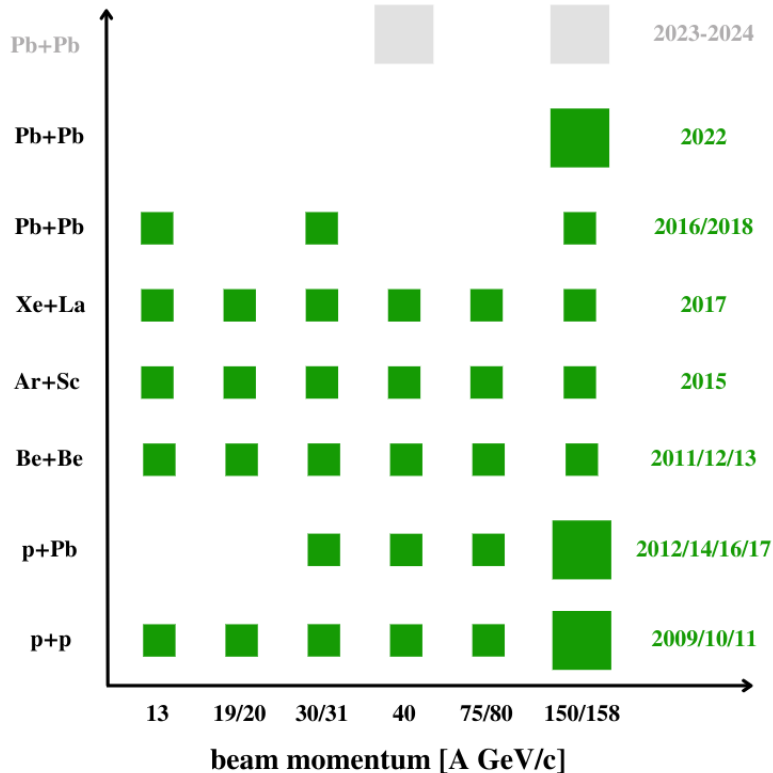


Figure 2.2: Data collected as part of the NA61/SHINE experiment (green) in space and planned measurements (gray).

It is expected that by carrying out the above measurements it will be possible to determine the location of the critical point on the phase diagram by studying system fluctuations. From theoretical considerations (using Lattice QCD calculations) it is predicted, that the critical point is located at temperature $T = 162 \pm 2$ MeV and baryon chemical potential $\mu_B = 360 \pm 40$ MeV [26]. The measured values of temperature T and baryon chemical potential μ_B during the chemical freeze-out phase in the NA49 (blue) and NA61 (green) experiments are shown in figure 2.3.

In the NA61/SHINE experiment, in addition, to study the phase diagram of strongly interacting matter, the following measurements are carried out:

- hadron production in hadron-induced reactions (e.g. p + C) related to the T2K [27] experiment, which measures artificial neutrino fluxes,

- nuclear fragmentation cross-sections for cosmic ray physics in Pierre-Auger Observatory and experiment KASCADE [27].

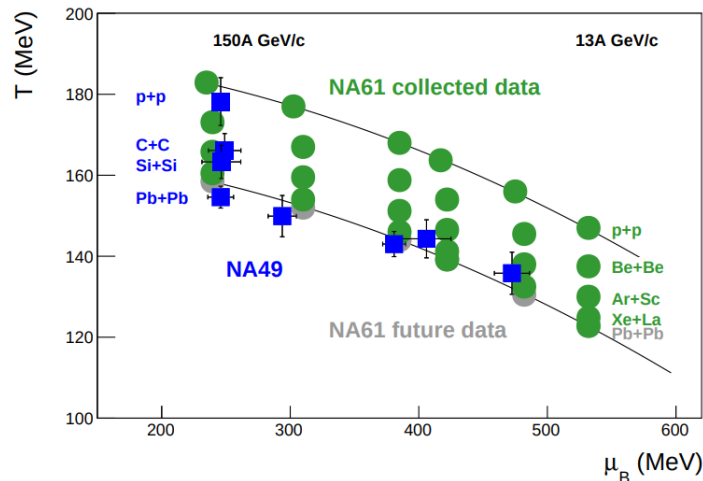


Figure 2.3: The measured values of temperature T and baryon potential μ_B during the chemical freeze-out phase in the NA49 (blue) and NA61 (green) experiments. [28].

2.3. The mechanism of charm production

One of the possible extensions of the research on the phase transition to the quark-gluon plasma is the study of the mechanism of charm production, which is an important issue in relativistic collisions of heavy ions. It will allow us to discriminate between models that contain different mechanics of charm production like statistical and dynamic models.

Direct measurement of open charm mesons (D mesons) has been added to the NA61/SHINE experiment scientific program. The motivation for open charm measurements was to find answers to the following questions [29]:

- ◆ What is the mechanism of charm production?
- ◆ How does the onset of deconfinement in the nucleus-nucleus collision impact charm production?

In order to answer the above questions, it is necessary to know the average multiplicity of the $\langle c\bar{c} \rangle$ pair (charm quark and charm antiquark) which is created in collisions of heavy ions in full space. For this purpose, measurements of hadrons (mainly mesons) made of charm quarks are required. The detectors in the NA61/SHINE experiment have sufficiently good acceptance and high precision to perform measurements in a wide range of phase space.

2.3.1 Theoretical predictions

Estimated results of dynamic and statistical models for the average multiplicity of pairs $\langle c\bar{c} \rangle$ created in Pb+Pb collisions at 158A GeV/c momentum are presented in the figure 2.4.

They have quite large uncertainties, which result mainly from the uncertainty of e.g. system temperature and modeling of the charm production in nucleon-nucleon collisions [30].

It is worth noting, that the predictions differ by up to two orders of magnitude. So, it will be possible to narrow down the theoretical scenarios as well as to understand the mechanism of the formation of charm quarks thanks to the precise measurements of the average multiplicity $\langle c\bar{c} \rangle$ in a wide range of phase space.

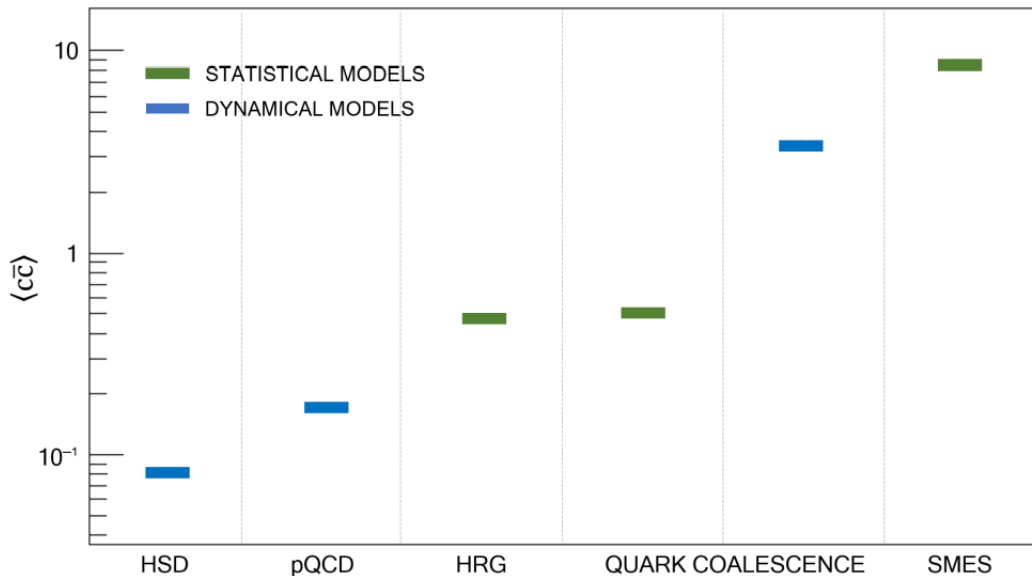


Figure 2.4: Mean multiplicity of charm quark pairs produced in the full phase space in central Pb+Pb collisions at 158A GeV/c calculated with dynamical models (blue bars): HSD [31], pQCD-inspired [32], and Dynamical Quark Coalescence [33], as well as statistical models (green bars): HRG [34], Statistical Quark Coalescence [34], and SMES [35]. Figure from [29].

2.3.2 The signal of deconfinement

From theoretical models, it is predicted that the mechanism of charm production will vary depending on the phase of the strongly interacting matter. This means that the mechanism of charm production in the confined matter will be different from the mechanism of charm production in the quark-gluon plasma (QGP). This is due to the difference in the carriers of charm that exist in both of these phases.

In the QGP the charm quarks alone are carriers of charm but in the confined matter, the lightest carriers of charm are D mesons. Despite the fact that the effective number of degrees of freedom in both phases is the same [36], the energy needed to create a pair of charm carriers i.e. $D\bar{D}$ in the confined state ($2m_D \approx 3,7$ GeV/c) is about 1 GeV/c higher compared to the energy needed in QGP to create $c\bar{c}$ pair ($2m_c \approx 2,6$ GeV/c). Thus as in the case of strangeness [37], the production of charm is predicted to increase at the transition of strongly interacting matter for the hadronic state to the QGP state (figure 2.5).

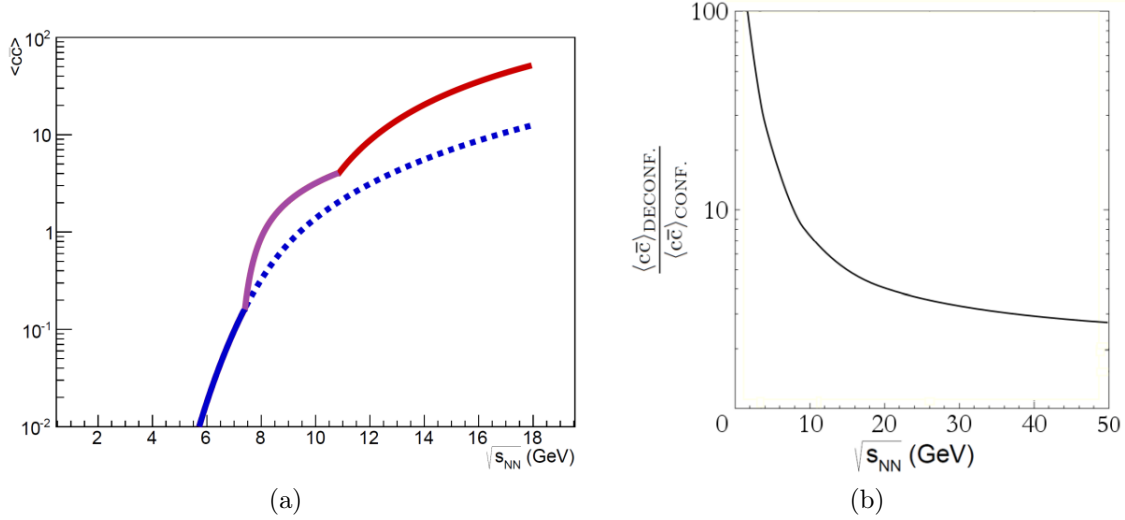


Figure 2.5: a) The dependence of the number of created pairs $\langle c\bar{c} \rangle$ in the Pb+Pb central collision depending on the available energy per nucleon ($\sqrt{s_{NN}}$) predicted by the SMES model [35]. The blue line corresponds to confined matter and the red line corresponds to deconfined matter. The visible dashed line corresponds to the absence of a phase transition. b) The dependence of the $\langle c\bar{c} \rangle$ ratio (the number of pairs formed in confined matter to the number of pairs formed in the deconfined matter) depending on the available energy ($\sqrt{s_{NN}}$) calculated by pQCD model [32]. Figures from [29].

The $c\bar{c}$ pairs created in the nucleus-nucleus collision can hadronize in two ways (figure 2.6):

- **open-charm** - a pair of **charm hadrons** (usually mesons) will be formed, e.g. a charm quark will bond with a light antiquark ($D^0(c\bar{u})$ or $D^+(c\bar{d})$) and a charm antiquark will bond with a light quark ($\bar{D}^0(\bar{c}u)$ or $D^-(\bar{c}d)$).
- **hidden-charm** - a bound $c\bar{c}$ system called **charmonium** (J/ψ) will be formed.

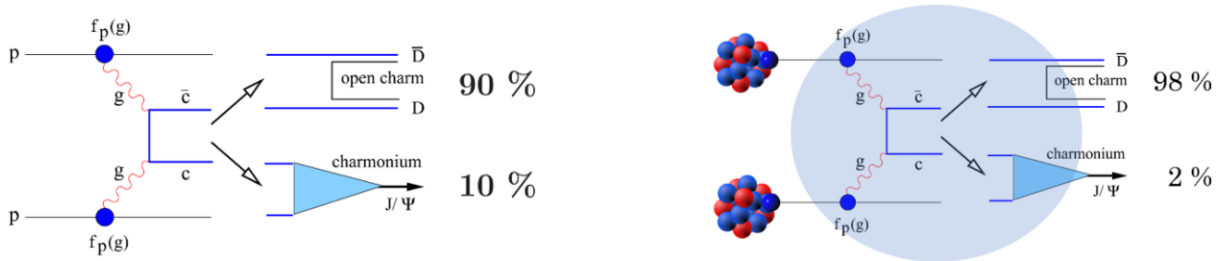


Figure 2.6: The $c\bar{c}$ pair possible transformation scenarios depending on the collision (p+p or heavy ions central collision). Figure from [38].

It is seen in figure 2.6 that the amount of open charm created is increased in heavy ion collisions (A+A) as compared to p+p. The explanation for this is as follows:

1. The generated $c\bar{c}$ pairs form the pre-charmonium state in the QPG,

2. The produced pair interacts with the surrounding deconfined matter,
3. Due to the color screening, the likelihood of creating an open-charm increases.

Thus, by measuring the ratio of the hidden charm to the open charm, we are able to study the interaction of the created $c\bar{c}$ pair with the deconfined matter. The goal of open charm measurement in the NA61/SHINE experiment is to provide reference data for the study.

2.4. The idea of measurement open charm

To study the multiplicity of $c\bar{c}$ pairs created in the collisions, it is necessary to measure as many formed charm hadrons as possible. The table 2.1 presents the properties of several charm hadrons, e.g. their lifetime and decay channel.

Table 2.1: Charm particles produced in a nucleus-nucleus collision. [39].

Charm hadron	Mass [MeV]	Channel decay	$c\tau$ [μm]	Branching ratios [%]
D^0	1864.83 ± 0.05	$\pi^+ + K^-$	122.9	3.950 ± 0.031
$\bar{D}^0$	1864.83 ± 0.05	$\pi^- + K^+$	122.9	3.950 ± 0.031
D^+	1869.65 ± 0.05	$\pi^+ + \pi^+ + K^-$	311.8	9.38 ± 0.16
D^-	1869.65 ± 0.05	$\pi^- + \pi^- + K^+$	311.8	8.22 ± 0.28
D_S^+	1968.34 ± 0.07	$\pi^+ + K^- + K^+$	151.2	5.39 ± 0.15
Λ_c	2286.46 ± 0.14	$p + \pi^+ + K^-$	60.7	6.28 ± 0.32

According to the predictions of the Parton Hadron String Dynamics model, the largest amount of charm is carried by the D mesons [31]. However, due to the short lifetimes (or the distance to decay) of these mesons, their measurements are very challenging and require specialized detectors.

Note that the NA61/SHINE experiment is a fixed-target experiment. Thus, the particles created from the collision will have a Lorentz boost along the direction of the beam (the z-axis). For example, for a beam with a momentum of 150 GeV/c, due to the Lorentz boost the typical γ factor is on the level of 10. So then, the average distance traveled by the D^0 meson will be:

$$c\tau \cdot \gamma > 1 \text{ mm} \quad (2.1)$$

Thanks to the Lorentz boost, the measurement of charm hadrons will be easier as compared to the collider experiment.

Despite the Lorentz boost, measuring short-lived particles is still a challenging task. Charm mesons can be measured by their decay channels into kaons and pions. However, heavy ion collisions produce a large number of kaons and pions at the point of nucleus-nucleus interaction called **the primary vertex**. A specialized device called the Vertex Detector is needed to distinguish the particles formed at the decay point of the charm mesons (called **the secondary vertex**) from the particles formed at the primary vertex. A measurement of the D meson is shown in figure 2.7.

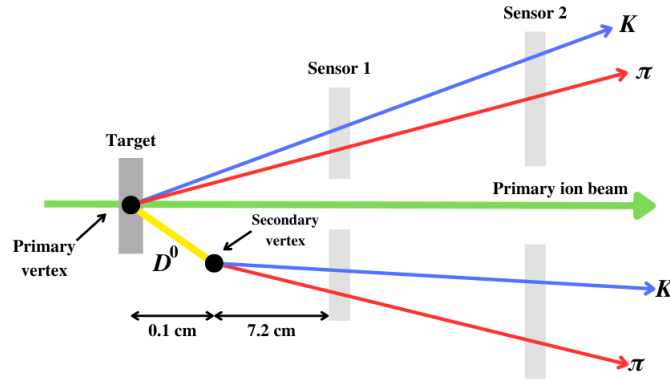


Figure 2.7: The concept of measuring the charm hadron D^0 using a Vertex Detector (VD).

2.5. NA61/SHINE detectors

Numerous components of the NA61/SHINE set-up (figure 2.8) were inherited from the NA49 experiment [24, 40]:

- four Time Projection Chamber (TPCs),
- two Time of Flight (ToF) walls,
- superconducting magnets.

The entire detection system can be divided into two parts: devices in front of and behind the target.

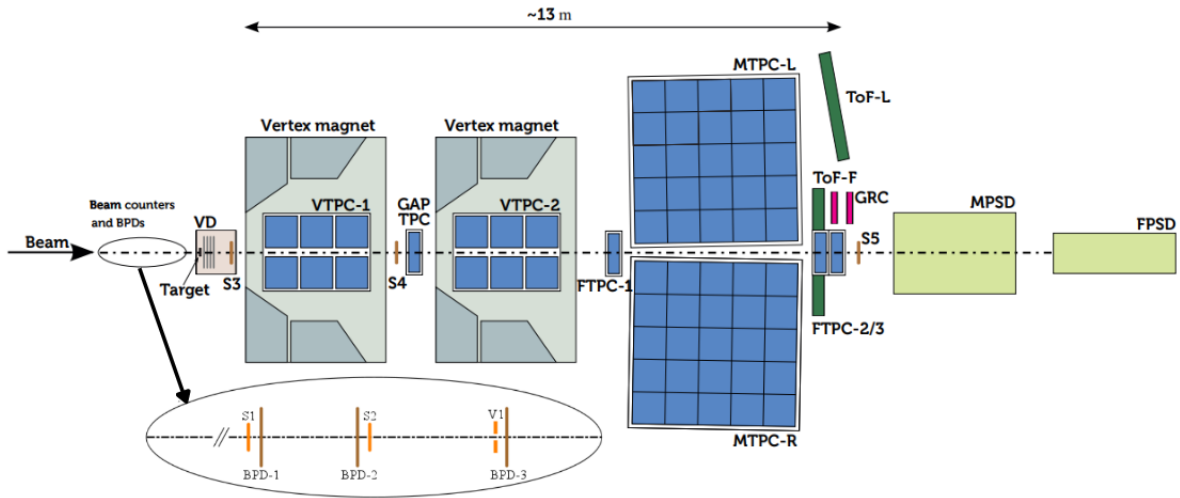


Figure 2.8: Scheme of the NA61/SHINE experiment with marked detectors. The target is placed in the Vertex Detector located in front of the four Time Projection Chambers. The direction of the incoming beam is along the z -axis. [41].

2.5.1 Upstream devices

The final acceleration of the beam takes place in the SPS (figure 2.1). Then the beam is transported by the H2 beamline to the northern area where the detection system of the NA61/SHINE experiment is located. Before it collides with the target, the parameters of the beam including beam position, beam profile, and intensity are measured by the detection system shown at the bottom of the figure 2.8. The system includes [40]:

- Two scintillation detectors S1 and S2 located on the beam along z axis. They detect beam particles and they are part of the precise timing reference for the trigger system.
- Three Beam Position Detectors (BPDs) measuring the beam particle trajectories on an event-by-event basis.
- A veto scintillation counter (V1) with a hole (radius of 1 cm) provides active beam focus by rejecting beam halo particles.

2.5.2 Target and downstream devices

The beam hits the target, which is located in the front part of the Vertex Detector (VD). As a result of the collision, the created particles (and partly also the beam particles that did not interact with the target) pass through the VD and then fly onto the next part of the detection system.

Time Projection Chambers (TPCs)

The TPCs are tracking detectors providing 3D particle trajectories and also inform on dE/dx for particle identification (PID) as well as inform on particle charges and momenta. The TPCs consist of Multi-Wire Proportional Chambers (MWPC) which are built from a gating grid, cathode, and pad planes [40]. The two TPC detectors (VTPC1 and VTPC2) are located closest to VD. They are inside the superconducting magnets which are oriented vertically to bend the charge particles' trajectories in the x - y plane. The magnetic field is directed from top to bottom, so positive charged particles' trajectories are bent to the left (looking downstream to the beam). The maximum value of the generated magnetic field is in the range of 1 to 1.5 T.

Between VTPCs there is located the GAP TPC not used for heavy ion measurements and behind them are the two main TPC chambers: MTPC-L and MTPC-R.

Time-of-flight (ToF)

Behind the entire TPCs system, there is the Time of Flight detector system, which includes: ToF-L, ToF-R, and ToF-F. These detectors allow to identify particles having the same mass by measuring the time of flight of the particle (with a precision of a few tens ps).

Projectile Spectator Detector

Last but not least detection system is the Projectile Spectator Detectors (PSDs): MPSD and FPSD. These are calorimeters that measure the energy which is carried by the projectile spectators. The PSD measurements are used to determine the centrality of the nucleus-nucleus collision.

Chapter 3

Vertex Detector

3.1. The concept of SAVD

Most of the registered particles intersect at one main point, i.e. the primary vertex of interaction. However, some of the reconstructed tracks intersect in a well-defined secondary vertex, which results from the occurrence of various types of decays.

The main idea behind using the Vertex Detector was to measure short-lived particles (mainly D^0 mesons), which decay into kaons and pions (table 2.1). However, many kaons and pions are produced in a nucleus-nucleus collision, especially in the primary vertex. So to separate the kaons and the pions coming from the secondary, and primary vertexes, the Vertex Detector is needed (figure 3.1).

To perform measurements of open charm in a nucleus-nucleus collision, a **S**mall **A**cceptance **V**ertex **D**etector (**SAVD**) [42] was added to the experimental setup (figure 2.8) in October 2016.

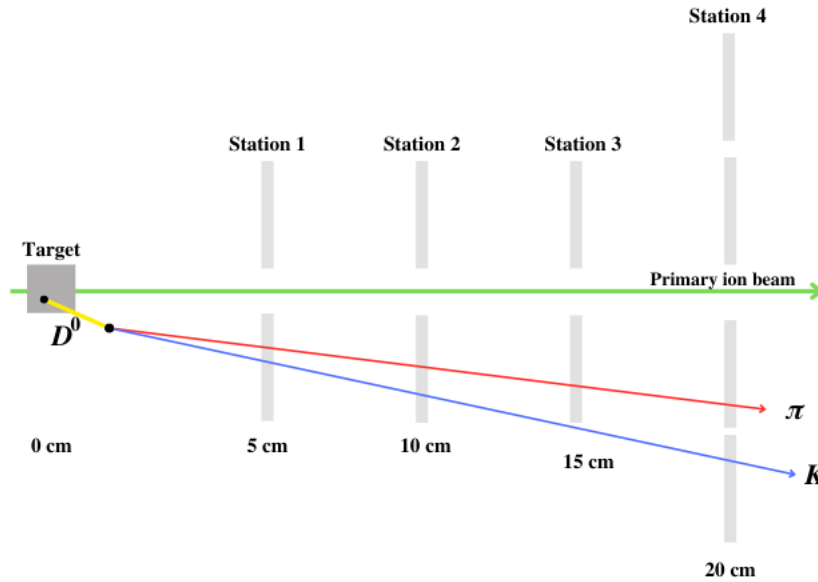


Figure 3.1: The idea of D^0 meson measurement in SAVD by reconstructing particles formed as a result of decay: kaon (K^-) and pion (π^+).

3.2. The detector configuration

For the data-taking configuration, the location of SAVD was about 80 cm upstream of VTPC1 (see figure 2.8). This detector consists of two arms (Jura and Saleve), whose names correspond to the names of the mountains surrounding the CERN area. Each of the arms has 4 stations located respectively 5, 10, 15, and 20 cm downstream (figure 3.1). On each arm are located eight MIMOSA-26AHR Monolithic Active Pixel Sensors (MAPS) pixel detectors based on CMOS (Complementary Metal-Oxide-Semiconductor) technology. The computer model of SAVD is shown in figure 12.1.

The sensitive area of a single MIMOSA sensor is $1.06 \times 2.13 \text{ cm}^2$. It consists of 1156 columns and 576 rows of pixels. This gives a total of approximately 663.5 thousand pixels per sensor. A very good spatial resolution of $3.5 \text{ }\mu\text{m}$ both on x and y direction results from a small pixel pitch of $18.4 \text{ }\mu\text{m}$ in each direction.

All thin sensors are placed on durable but very light carbon fiber ladders. The integrating procedure of the sensors with ladders was entrusted to the Institute of Nuclear Physics (IKF) of the Goethe-University Frankfurt am Main. In addition, pipes have been attached to the back of the carbon fiber ladders, which are used for sensor cooling by cold water.

Carbon fiber ladders are located on four C-shape aluminum supports. At the first and second stations (figure 3.1), in each of the arms, there is one sensor, while at the third and fourth stations, there are two and four sensors, respectively. The location of the sensors is shown in the picture 12.2. In front of the first station, a target is placed at a distance of about 5 cm. The whole system is enclosed in a pixel-glass box. Before taking measurements, the back and front of the detector are closed with thin mylar foils, while the inside is filled with helium to minimize beam and particle interactions in the gas surrounding the detector elements. The photo of the SAVD is shown in the figure 3.2. Downstream to SAVD the VTPC1 is located in the large dipole magnet. The remnant magnetic field generated by the magnet extends to the volume occupied by SAVD and ranges from 0.13 T (most upstream station) to 0.25 T (most downstream station).

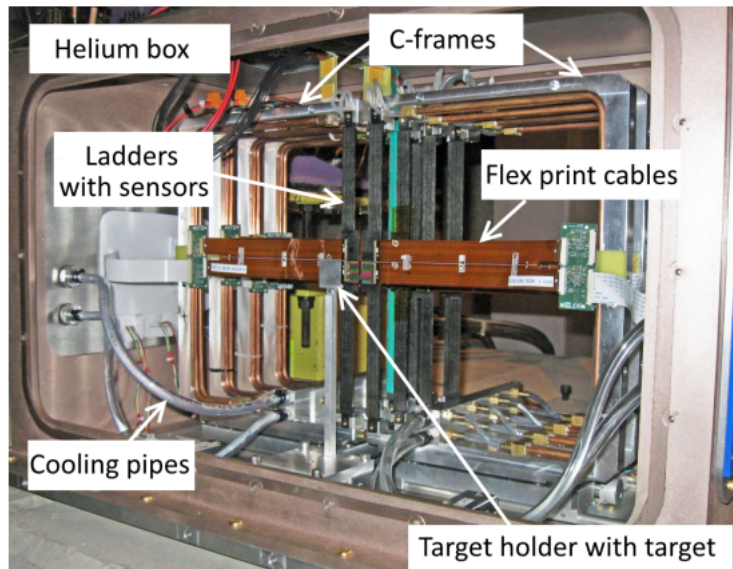


Figure 3.2: A photo showing the inside of SAVD with selected elements. [42]

Chapter 4

Reconstruction chain in SAVD

A dedicated shine module handles the whole chain of reconstruction used in the Vertex Detector of the NA61/SHINE experiment. In the first stage, the so-called "cluster" objects are formed. Several pixels of which the sensor is built can be fired as a result of the passage of a charged particle. Such a complex object is called a "cluster". A specialized computer algorithm identifies such clusters. It takes each pixel and then searches for adjacent pixels in two dimensions that contain a signal above the imposed threshold. The found fired pixels are used to determine the center of gravity, which is treated as the center of the cluster. The whole procedure is called "clusterization" [42]. The clusters are then provided as input to the tracking procedure which is divided into five modules.

The description of the reconstruction chain presented in this chapter is based on the data collected in 2018 in a collision Xe beam with a momentum of 150A GeV/c on a 3 mm La target.

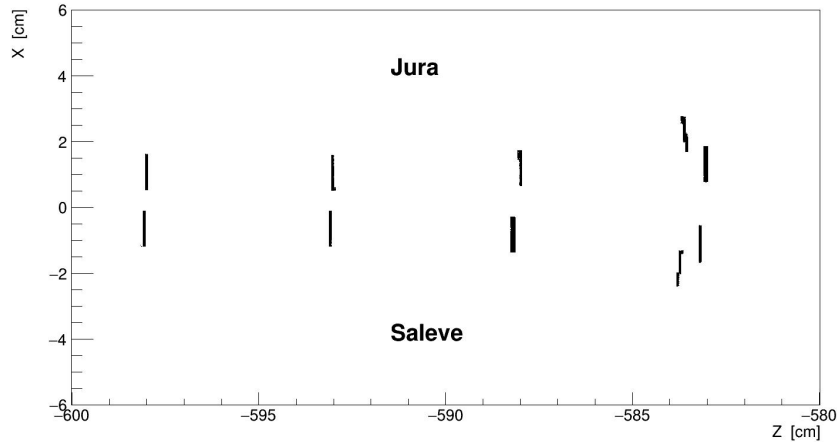


Figure 4.1: Clusters distribution in SAVD. Coordinate in the global NA61 coordinate system (see figure 2.8).

4.1. Combinatorial tracking procedure

The purpose of this procedure is realized by VdTrackingInitModule. In the first step, it is assumed that the clusters that have been fired by the passing particle form a straight line

both in the x - z plane and in the y - z plane:

$$x(z) = a_x z + x_0 \quad (4.1)$$

$$y(z) = a_y z + y_0 \quad (4.2)$$

Using the above parameterization, all possible combinations of three-cluster tracks are created. Then, using the χ^2 criterion, only accepted tracks that lie on a straight line are used for further analysis.

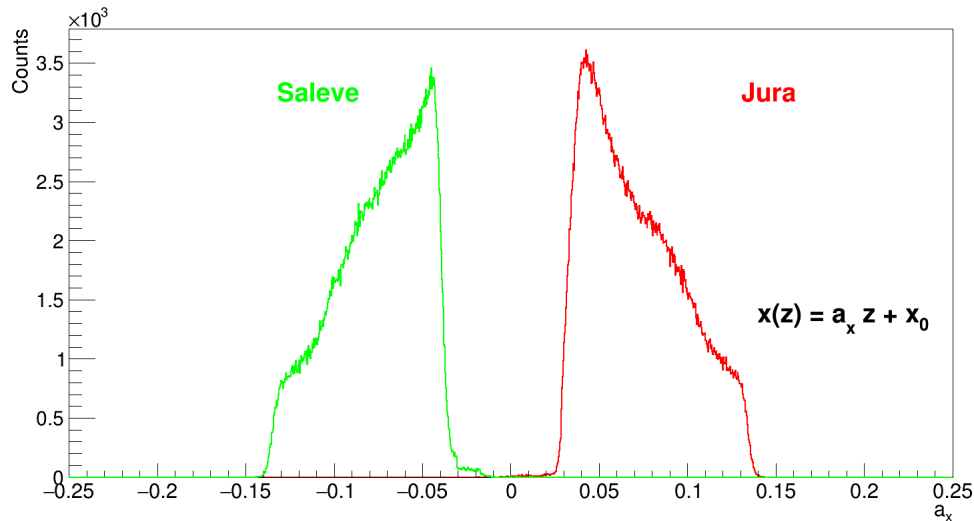


Figure 4.2: Slope distribution of reconstructed line tracks for Jura (positive a_x values) and Saleve arm (negative a_x values) - see figure 4.1.

However, the SAVD is not far from the magnet, so the particle tracks are slightly curved, especially at the third and fourth stations, due to the vertical component B_y of the magnetic field. Therefore, in the next step of tracks reconstruction, a second-order polynomial function is fitted for x , and a linear function for y :

$$x(z) = \alpha_2 z^2 + \alpha_1 z + x_0 \quad (4.3)$$

$$y(z) = \beta z + y_0 \quad (4.4)$$

But to clearly define a track we need (at least) 4 cluster combinations. Therefore, the accepted three-cluster tracks are divided into two groups: A and B (see table 4.1). The procedure of creating fourth-cluster tracks is very simple: 3 cluster tracks belonging to two different groups should share the same cluster on stations where the overlap occurs.

Table 4.1: Groups of three cluster tracks. Overlapping stations are marked in red.

Group	Station 1	Station 2	Station 3	Station 4
A	+	+	+	
B		+	+	+

The distribution of all recognized clusters in the x - z plane is shown in figure 4.1. Figure 4.2 shows the distribution of slope (a_x) in the x - z plane of reconstructed tracks in this module.

4.2. The primary vertex position

The next step is to find the primary interaction point the so-called **primary vertex**. It is defined as the point of closest approach of all reconstructed tracks. For this purpose, a module - PrimaryVertexReco - was created, to which reconstructed tracks (from VdTrackingInitModule) are provided as input.

To determine the longitudinal component z_{prim} of the primary vertex, the minimum of the following expression is performed [30]:

$$D(z) = \sum_{i < j} [(\alpha_i z + x_{0_i} - \alpha_j z - x_{0_j})^2 + (\beta_i z + y_{0_i} - \beta_j z - y_{0_j})^2] \quad (4.5)$$

The x and y components of the primary vertex, x_{prim} and y_{prim} , are determined as the averages of x and y tracks coordinate at location z_{prim} .

The location of the primary vertex is determined for all reconstructed tracks but also can be determined separately for tracks reconstructed in the Jura and Saleve arms. The differences between the Jura and Saleve components of the primary vertex are shown in figure 4.3. It is worth noting a small difference in the case of the y component. On the other hand, there may be a larger difference in the x component due to the vertical component B_y of the magnetic field acting on x - z plane. Moreover, the huge difference in the z component is due to the small opening angle of SAVD. For this reason, it was decided to increase the accuracy of the reconstruction of the original vertex mainly by increasing the opening angle - which will be discussed in the following chapters. The coordinates of the determined primary vertex are presented in figure 4.4.

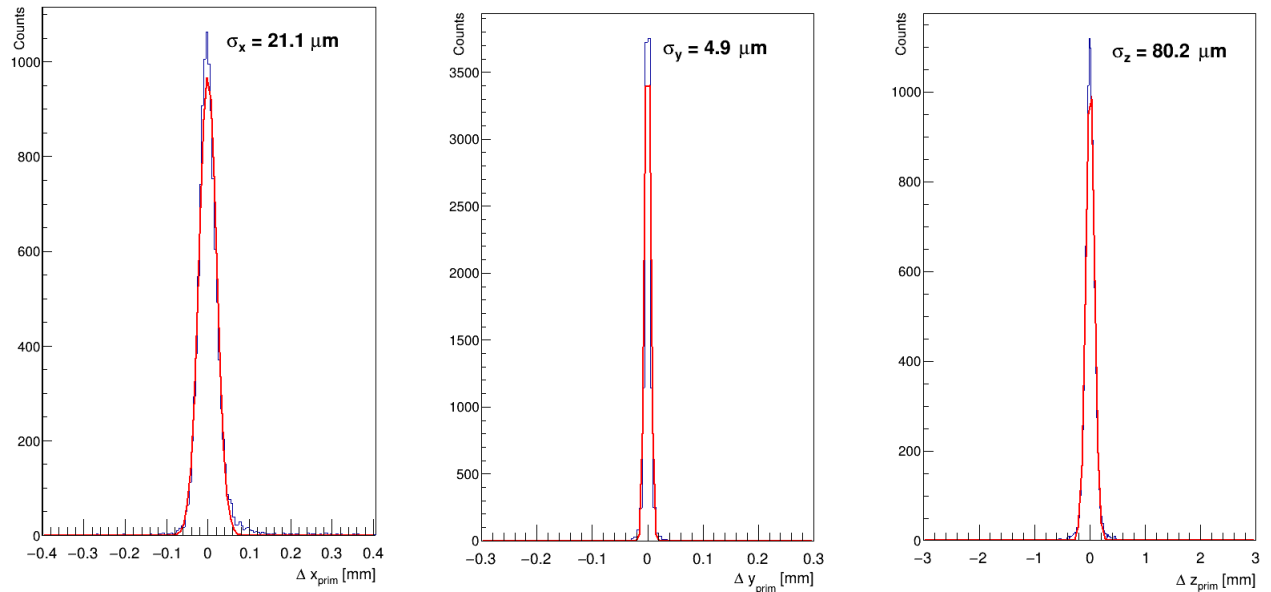


Figure 4.3: Distribution of differences between coordinates (x , y , and z) of the determined primary vertex in Jura and Saleve arms. The red lines correspond to Gaussian fits of the distributions.

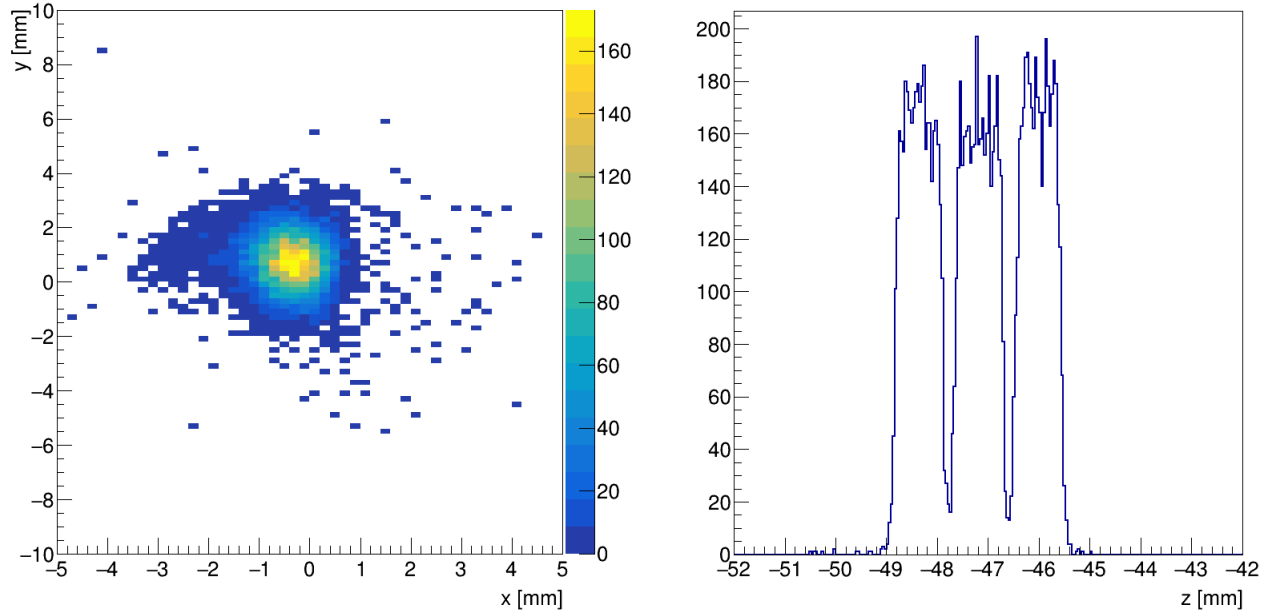


Figure 4.4: Left: x vs y distribution of determined locations of the primary vertex. Right: The z component of the primary vertex relative to the location of the first station. As a result of the high-precision reconstruction of the original vertex, it is seen the structure of the used La target.

4.3. Hough Transform method

The next module (called VdTrackingHTModule) is based on the Hough Transform (HT) method [43]. The HT procedure is based on transformation tracks to HT space where all clusters are transformed to one point (a_x, a_y) . This procedure is used information of the primary vertex and allows to reconstruct tracks detected only in 3 or 4 stations in VD (the combination method requires detection in 4 stations). The procedure consists of several steps:

1. The Hough space parameters (a_x, a_y) of each cluster (at each station) relative to the primary vertex is calculated in x - z plane:

$$a_x = \frac{x_{\text{cluser}} - x_{\text{prim}}}{z_{\text{cluser}} - z_{\text{prim}}} \quad (4.6)$$

and in y - z plane:

$$a_y = \frac{y_{\text{cluser}} - y_{\text{prim}}}{z_{\text{cluser}} - z_{\text{prim}}} \quad (4.7)$$

2. The determined point (a_x, a_y) for a given cluster is added to the 2D histogram of (a_x, a_y) represent the Hough space (figure 4.5).
3. If the points in Hough space are close enough, we connect them into one cluster. We call it "clusterization". The binning in the Hough space was optimized based on simulation to maximize the track reconstruction efficiency.

4. Tracks can be recognized as the peaks in the Hough space. If the "clusters" have hits frame at least 3 different stations a track can be formed. If there are more than four clusters in one peak, three- and four-cluster tracks are created from all possible combinations. For three-cluster tracks, a straight line is fitted in both x and y . On the other hand, in the case of four-cluster tracks, a straight line is fitted in y , and in x a second-order polynomial is used. Only tracks that passed χ^2 criteria are then accepted.
5. In the last step, tracks reconstructed in the combinatorial tracking procedure (chapter 4.1), and in this module are combined. In case the same track is reconstructed the procedure kept only one track.

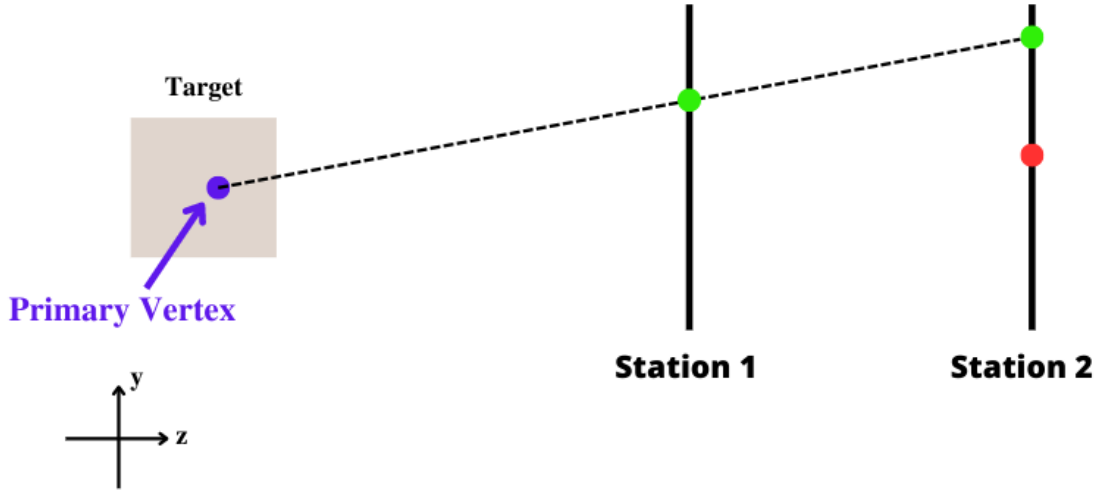


Figure 4.5: Scheme of determining clusters in Hough space. Points marked in green form a cluster, while a point in red will not create a track with them.

4.4. Secondary vertex tracks

The main purpose of the Vertex Detector in the NA61/SHINE experiment is to determine decay points of short-lived particles (for example D^0) called **secondary vertex**. To reconstruct tracks of the secondary vertex the Hough Transform method is used, but with the location of the primary vertex shifted along the z axis. An explanation of why shift along the z axis is sufficiently provided will be discussed in chapter 9 and chapter 10.

For example, D^0 lifetime multiplied by the speed of light ($c\tau$) is equal to $122.9 \mu\text{m}$. However, due to the Lorentz boost ($\gamma \sim 10$), the average distance is about 1 mm. Therefore in this module (called VdTrackingHTPackage), to find tracks of particles formed as a result of decay, the Hough Transform method is executed several times, but for the primary vertex shifted along the z axis. This allows covering decay range up to 1 cm downstream from the primary vertex which is sufficient to account for the reconstruction of D^0 mesons. The procedure of shifting the primary vertex along the z axis is shown 4.6.

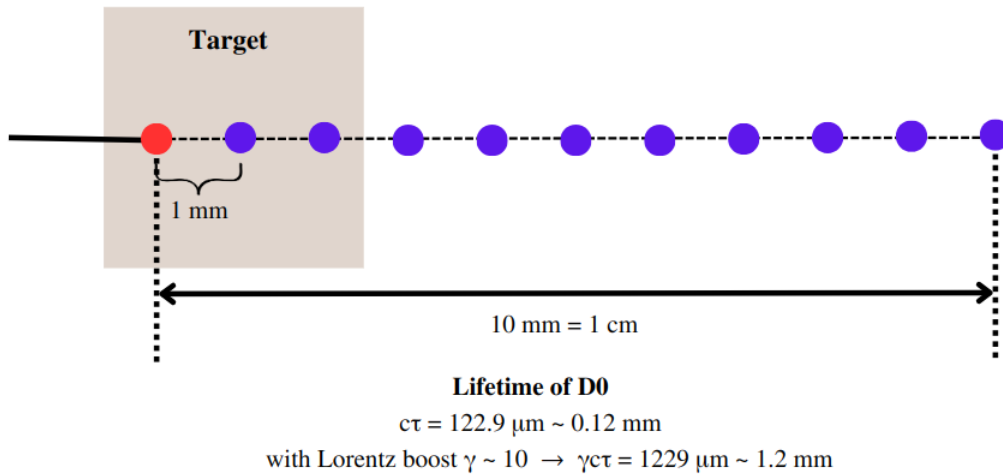


Figure 4.6: Scheme of the primary vertex shift procedure. The primary vertex calculated in the PrimaryVertexReco module is marked in red, while the predicted locations of the secondary vertex are marked in blue.

4.5. Corrected the primary vertex position

The last step of track reconstruction in a Vertex Detector is the correction of the primary vertex, taking into account additional track determined using the Hough Transform method. The purpose of this procedure is realized by PrimaryVertexRecoHT. The distributions of track slope in x - z plane (a_x) for all reconstructed tracks are shown in figure 4.7. The corrected positions of the primary vertexes are shown in figure 4.8.

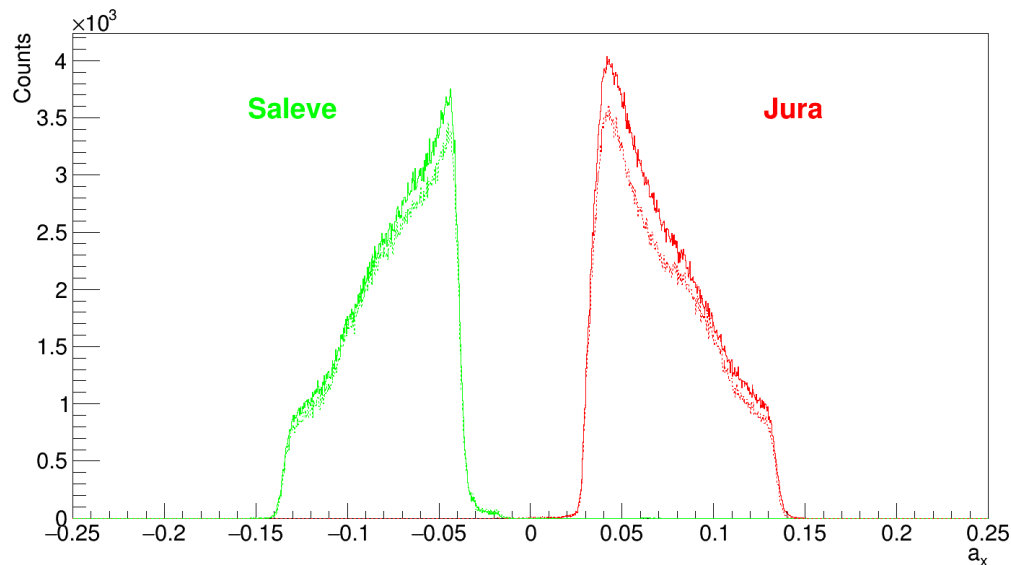


Figure 4.7: Slope distribution in x - z plane (a_x) of all reconstructed tracks for Jura (positive a_x values) and Saleve arm (negative a_x values) - see figure 4.1. The dashed line shows the distribution before the HT method was applied, and the solid line after.

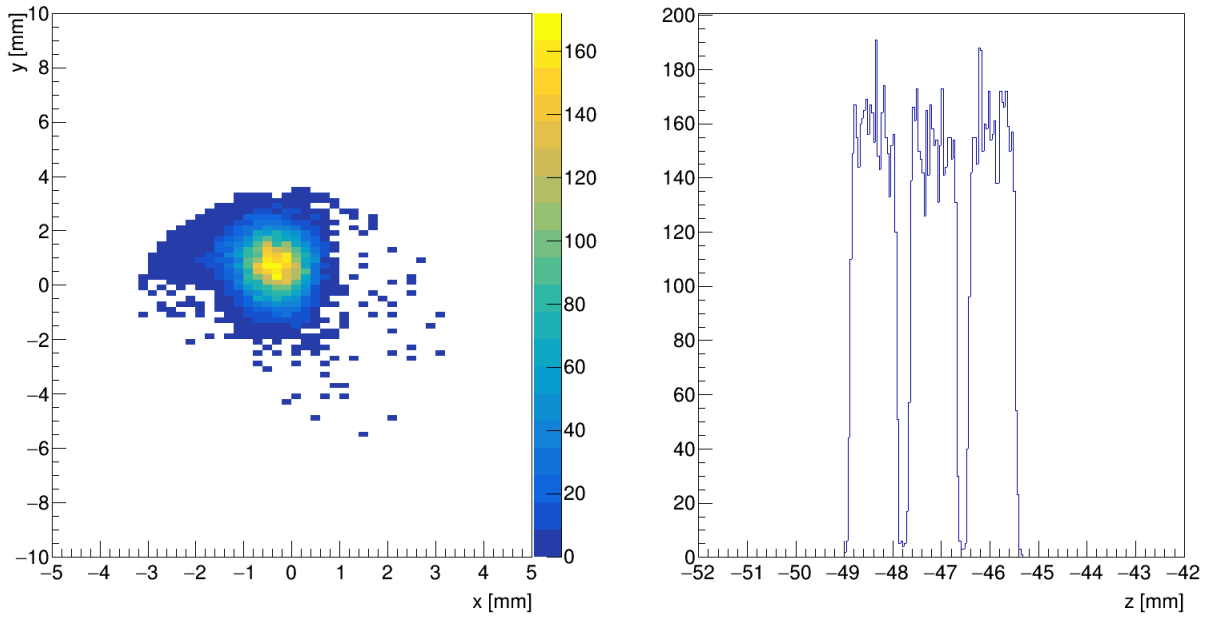


Figure 4.8: Left: x vs y distribution of determined locations of the corrected primary vertex. Right: The z component of the corrected primary vertex relative to the location of the first station. As a result of the high-precision reconstruction of the original vertex, it is seen the structure of the used La target.

Chapter 5

Upgraded Vertex Detector

During the Long Shutdown 2 (LS2) at CERN the detection system of NA61/SHINE was significantly upgraded [44]. The main improvements are:

- Exchange of the Vertex Detector (VD) configuration by employing ALPIDE silicon sensors [45] to increase geometrical acceptance (the opening angle) and also to mount up the speed of data readout,
- Replacement of TPC (Time Projection Chamber) readout electronics to increase the speed of data readout and reduce the noise,
- Construction of the new Geometry Reference Chamber (GRC) to support drift velocity measurements in the TPCs,
- Construction of the new Beam Position Detectors (BPD) and new Time of Flight (ToF) detectors.

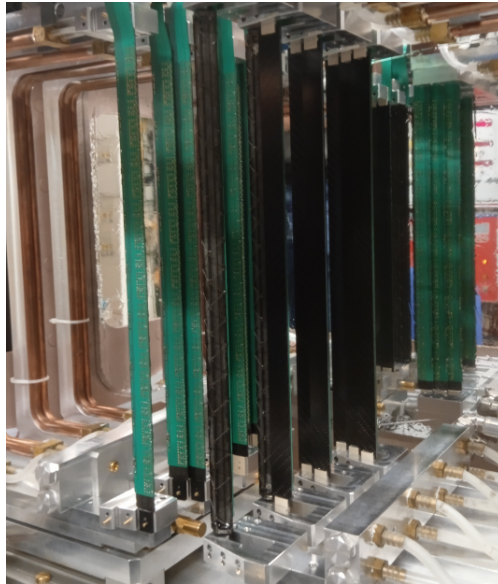


Figure 5.1: Picture of ALPIDE staves after their installation inside VD in April 2022.

5.1. The VD setup

The upgraded Vertex Detector (VD), like SAVD, is located between the target and VTPC-1 (see figure 2.8). The detector consists of two arms: Jura and Saleve. Each arm comprises four stations (station 1 — station 4) which are located respectively at distances of 7, 12, 17, and 22 cm from the target. The main components of the stations are vertically oriented carbon fiber "staves" on which there are 9 ALPIDE silicon sensors. However, not all sensors are used. The number of staves installed in stations and the number of sensors used in each station are shown in table 5.1.

Table 5.1: Number of staves and used sensors in each station.

Station number	Number of staves	Number of sensor in each stave
Station 1	1	3
Station 2	2	3
Station 3	2	5
Station 4	3	5

The ALPIDE is a large MAPS (Monolithic Active Pixel Sensor) chip based on CMOS (Complementary Metal-Oxide Semiconductor) technology with a length of 1.5 cm and a height of 3 cm. Each sensor has a sensitive area covered by approximately 525,000 pixels (1024 columns and 512 rows) with dimensions of $26.88 \mu\text{m} \times 29.24 \mu\text{m}$ [46]. Such design provides high spatial resolution on the level of $5 \mu\text{m}$. Figure 5.2 shows the schematic layout of staves with active sensors drawn in red (Jura) and green (Saleve).

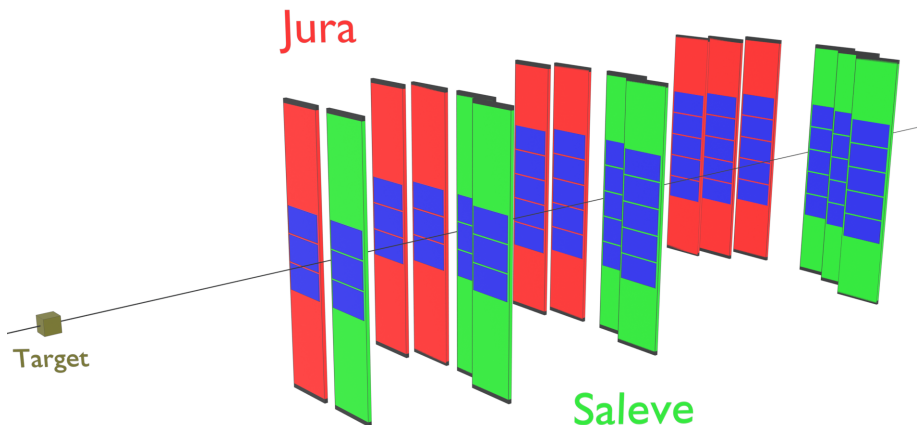


Figure 5.2: The structure of the used sensors (blue rectangles) located on staves. The corresponding arms (Jura and Saleve) are marked in red and green.

Most of the SAVD components are used for the upgraded device, which are:

- C-shape frames,
- colling system,

- the helium enclosure box,
- mechanical support for staves,

However, the improvement of the sensor layout also involved an improvement in data readout, which was based on the ALICE-ITS DAQ software. This software was modified and adapted to the NA61/SHINE experiment requirements. The readout system was based on a **MO**dular **S**ystem for **A**cquisition, **I**nterface, and **C**ontrol (**MOSAIC**) board [47]. The data read from the sensors are sent to MOSAIC using specialized "Firefly" cables [48]. Figure 12.3 shows a picture of a top view inside the detector with Firefly cables marked with white arrows.

The entire system inside the detector consists of 18 staves that require power. For this purpose, a Low-Voltage (LV) Power Supply Unit (PSU) consisting of 48 low-voltage channels was constructed [41]. The Raspberry PI 4 hosted inside the device provide the external control PSU via an Ethernet connection. Moreover, for each channel, the LV power supply enables:

- current and voltage monitoring,
- setting current limits,
- latch up protection check.

Figure 12.4 shows pictures of the inner volume and front panel of the LV PSU, while figure 12.5 shows a picture of the rack with a MOSAIC's boards and LV PSU. Finally, figure 5.3 shows the inner section of the detector with a 3 mm Pb target.

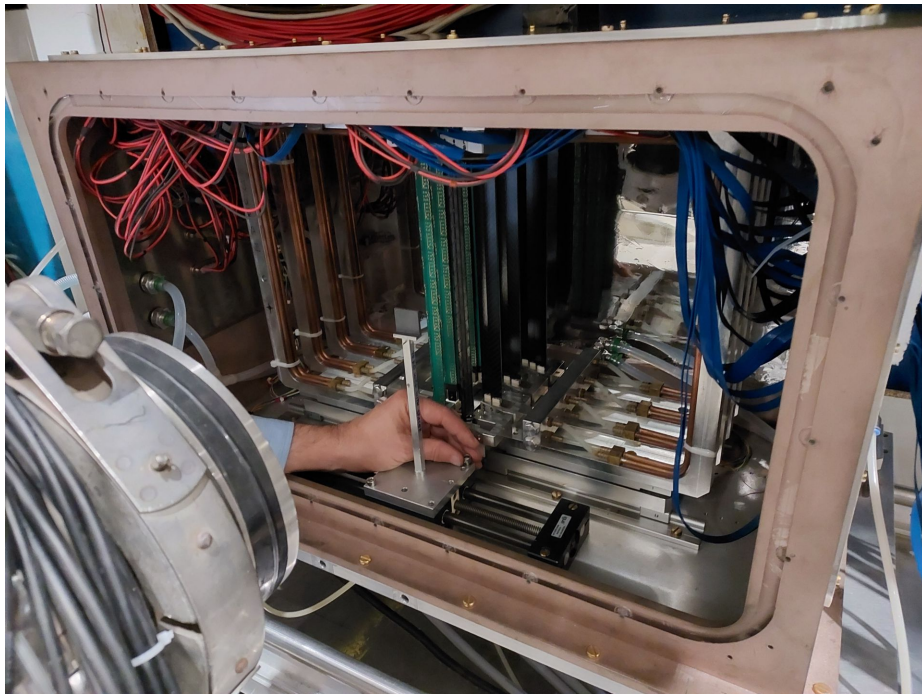


Figure 5.3: Picture of VD inner volume with Pb target - the picture was taken in November 2022 after installation.

Chapter 6

Upgraded reconstruction chain in VD

The upgraded hardware part of VD (described in chapter 5) requires an upgrade to the VD track reconstruction software. The software upgrade was performed sententially for each reconstruction module, keeping however the same structure of the reconstruction chain. We invented the naming convention of the new modules by adding "Al" in front of the original SAVD name referring to the ALPIDE sensors used.

The improvements of the reconstruction chain presented in this chapter were tested and optimized on simulations of the collision of a Pb beam with a momentum of 150A GeV/c on a 3 mm thick Pb target. Figures 6.1, 12.7 and 12.8 show the distribution of clusters for each station. The visible peaks in the distribution for the x coordinate are due to the overlap of the sensors in stations 2, 3, and 4.

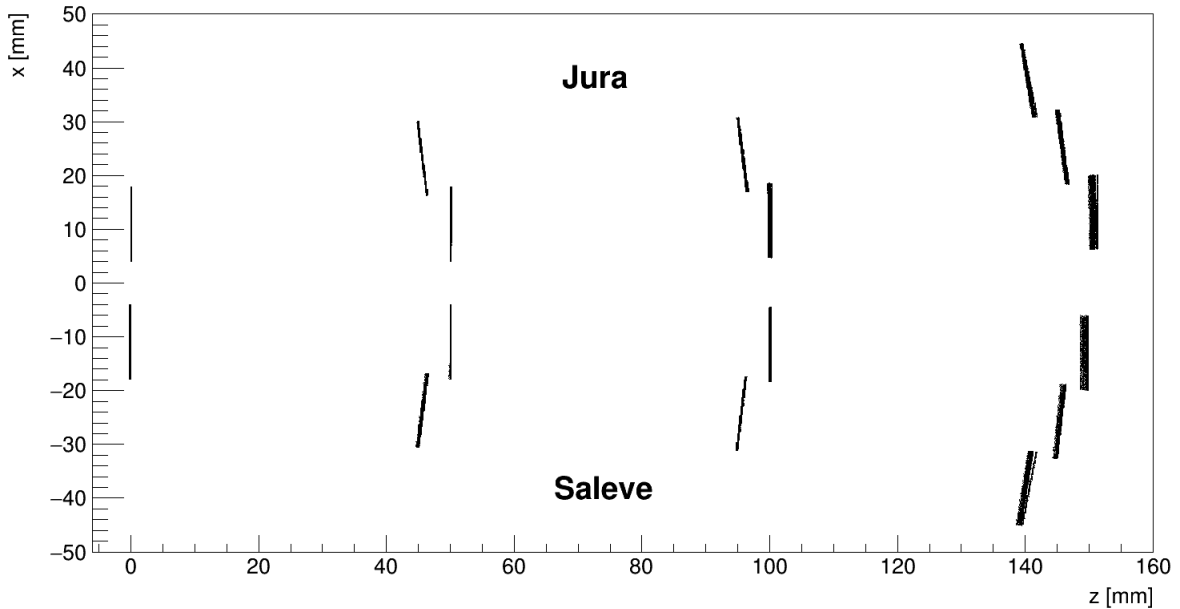


Figure 6.1: Clusters distribution in upgraded Vertex Detector.

The clusterization procedure used for upgraded VD utilizes the same method as in SAVD. The main upgrade refers to the modification of a number of sensors and naming conventions.

6.1. Combinatorial tracking procedure

In the first step (in module `AlVdTrackingInitModule`) three cluster tracks are created from all possible combinations of clusters: from 3 first stations (group A) and 3 last stations (group B), see table 4.1.

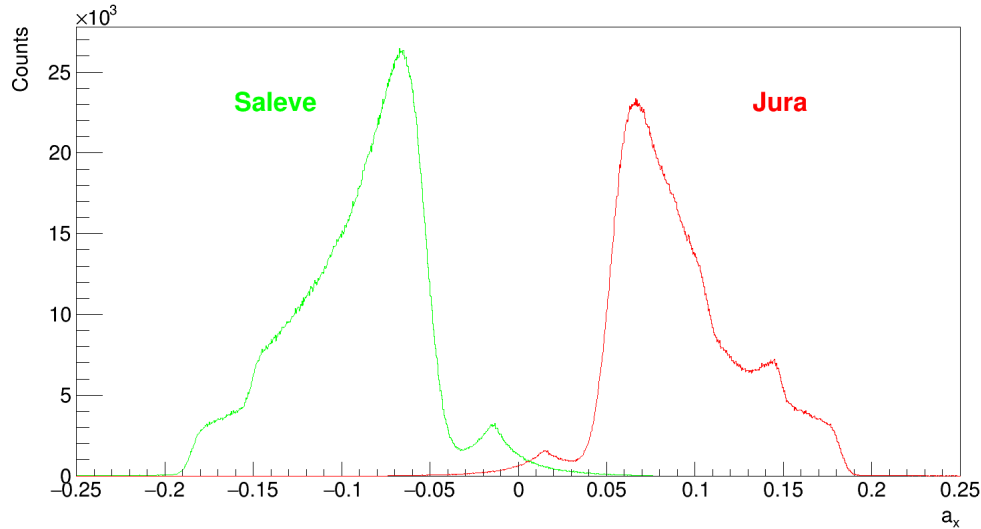


Figure 6.2: Slope distribution of reconstructed line tracks for Jura (positive a_x values) and Saleve arm (negative a_x values) - see figure 6.1.

However, each station has a different number of staves with a different number of sensors (see table 5.1). For this purpose, a dedicated naming convention for three cluster tracks was adopted. It is based on station number, stave number, and sensor number (see figure 6.3).

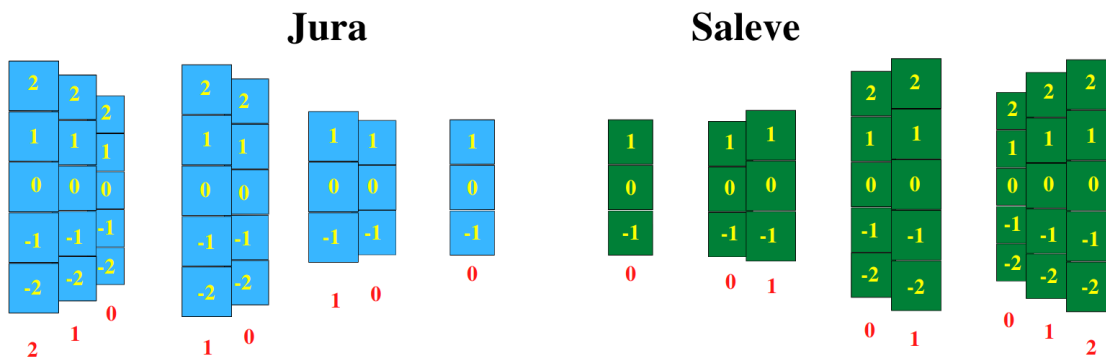


Figure 6.3: The numbering used in creating the three-cluster tracks. The stave number is marked in red, where the number 0 corresponds to the stave closest to the beam. The sensor number is marked in yellow.

For example:

■ **B_0-1_1-1_1-1** — this combination means that we have clusters in:

➤ station 2 (stave nr 0 and sensor nr -1),

- station 3 (stave nr 1 and sensor nr -1),
- station 4 (stave nr 1 and sensor nr -1).

For each combination of the three-cluster track, the deviation (see figure 6.4) is determined according to the formula [42]:

$$\text{dev}_x = \frac{(z_3 - z_2)x_1 + (z_2 - z_1)x_3}{z_3 - z_1} - x_2, \quad (6.1)$$

$$\text{dev}_y = \frac{(z_3 - z_2)y_1 + (z_2 - z_1)y_3}{z_3 - z_1} - y_2, \quad (6.2)$$

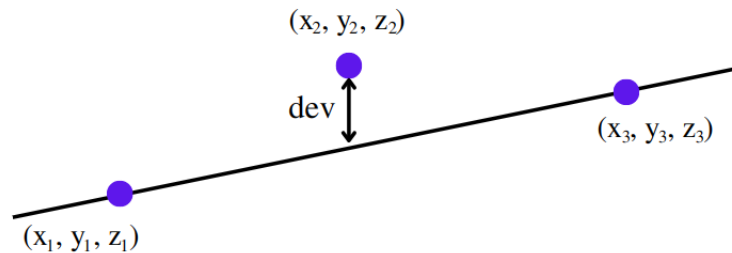


Figure 6.4: Definition of deviation (dev) for the combination of three clusters.

An example of the distribution of calculated deviation for clusters combination name **B_0-1_1-1_1-1** is shown in figure 6.5. It is worth noting the large combinatorial background and the visible structure of two peaks in x which is due to the vertical component B_y of the magnetic field acting on particles with different charges on x - z plane.

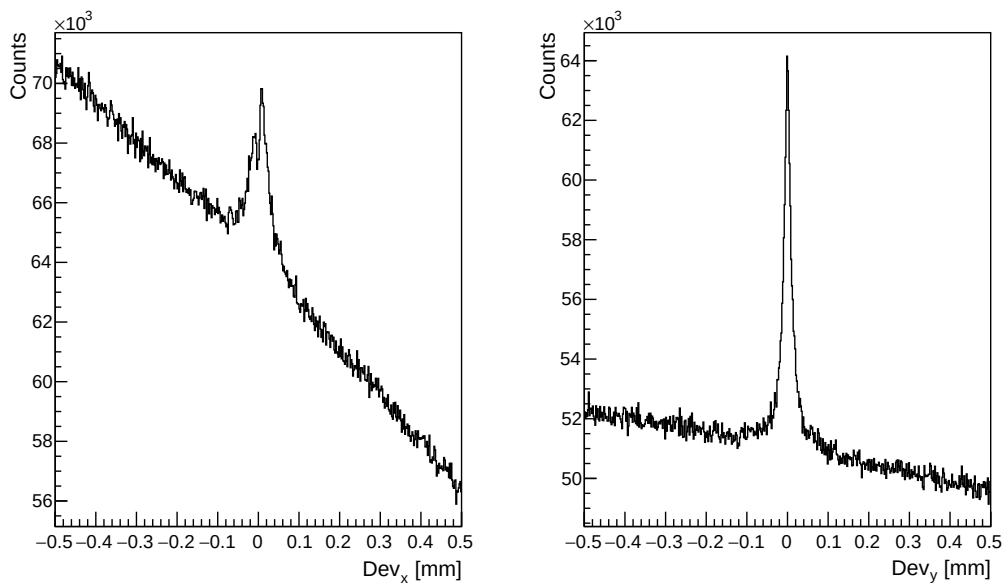


Figure 6.5: The distributions of calculated deviation for all possible three-cluster tracks in combination **B_0-1_1-1_1-1** in the Jura's arm.

After the determination of the deviation value, cuts are applied that allow to select the desired tracks. An example of the distribution of deviation values after applying the cuts is shown in figure 6.6. The next step is to combine the three-clustered tracks into four-clustered tracks. The example of group combination A+B is shown in figure 6.7.

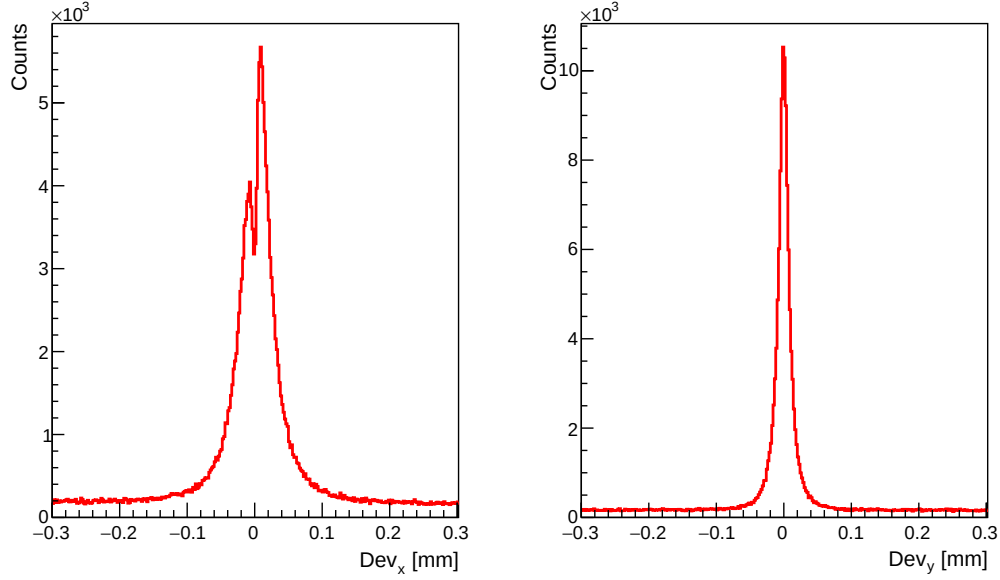


Figure 6.6: The distributions of calculated deviation for accepted three-cluster tracks in combination B_0-1_1-1_1-1 in the Jura's arm.

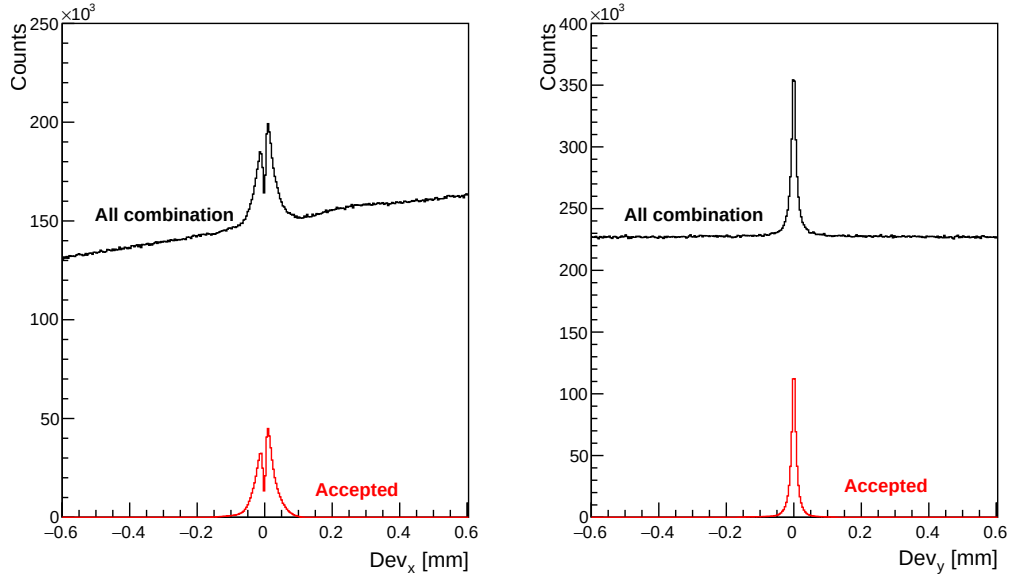


Figure 6.7: The distributions of calculated deviation for four-cluster tracks in combination A_00_00_00+B_00_00_10 in the Jura arm. Accepted fourth-cluster combinations are marked in red.

6.2. Hough Transform method

The performance of this module for SAVD data was already described in section 4.3. In principle, the module allows the reconstruction of 3 cluster tracks using the information on the primary vertex positions which increases SAVD acceptance. The upgraded Vertex Detector tracks may consist not only 3 or 4 clusters but even 5, 6, or 7. This is due to the overlap of stations 2, 3, and 4. For this reason, in the module AlVdTrackingHTModule, the term "layer" has been introduced to allow for the description of more than one cluster detection in a given station. For the reconstructed tracks number of layers is equal to the number of all clusters generated in the detector by the passing particle and it ranges from 3 to 7. The examples of particle track passing the detector are shown in figure 6.8 and the way how the variable "layer" is illustrated.

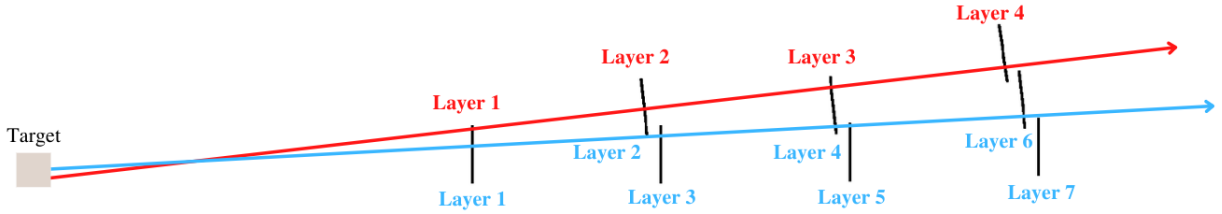


Figure 6.8: The scheme shows the case of 4 and 7 cluster tracks that can be reconstructed in the upgraded Vertex Detector.

For three layers in the track, the deviation is determined according to the formula 6.1 and 6.2 (see figure 6.4). But for more than three layers in the track residuals are determined according to the following steps:

1. A combination of N clusters is created. Then a second-order polynomial function is fitted for x (in x - z plane), and a linear function for y (in y - z plane):

$$x(z) = a_x z^2 + b_x z + c_x \quad (6.3)$$

$$y(z) = a_y z + b_y \quad (6.4)$$

2. For each cluster in the combination (with the position (x_i, y_i, z_i)) the residual res_{x_i} is determined according to the formula:

$$\text{res}_{x_i} = x_i - (a_x z_i^2 + b_x z_i + c_x) \quad (6.5)$$

$$\text{res}_{y_i} = y_i - (a_y z_i + b_y) \quad (6.6)$$

The distributions of residuals of all possible layers are constructed and shown in the figure 12.10, 12.11, and 12.12 as a black line. The red residual distributions in the same plots refer to residual distribution for accepted tracks. In figure 6.9 the black line shows the distribution of the number of layers associated with the reconstructed tracks but the red line shows the distribution of the accepted number of layers associated with the reconstructed tracks. It is seen that most tracks are three- and four-clustered, but it is worth noting the large distribution of five- and six-clustered tracks.

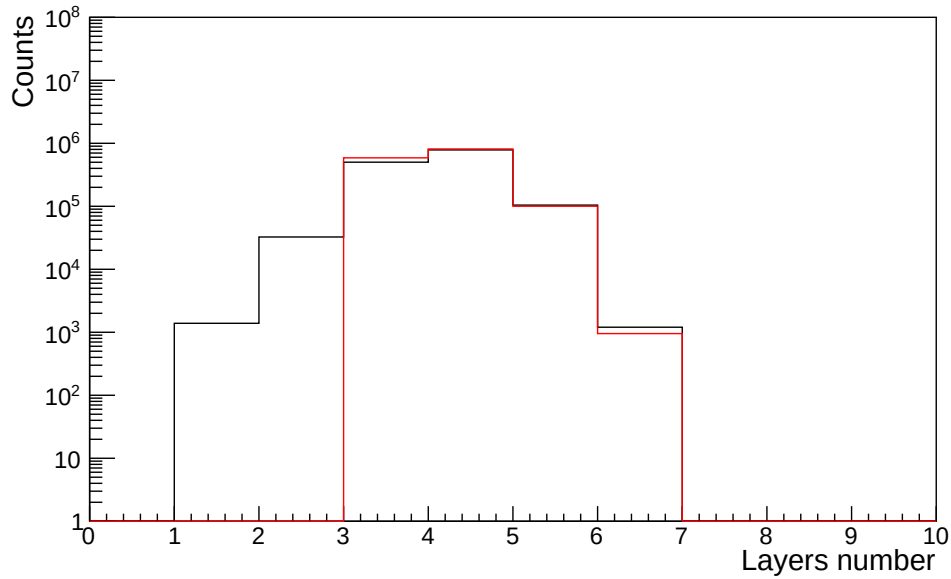


Figure 6.9: The distribution of the number of layers in reconstructed tracks from the Hough transform method. The red line represents the distribution of the number of layers associated with the reconstructed and accepted tracks.

As in the case of SAVD tracks reconstruction the combination method and HT module are used to reconstruct final primary vertex positions. The distribution of primary vertex position in simulated Pb+Pb 150A GeV/c most central events is shown in figure 12.9 and 6.10 which is calculated in the last module (AlPrimaryVertexRecoHT).

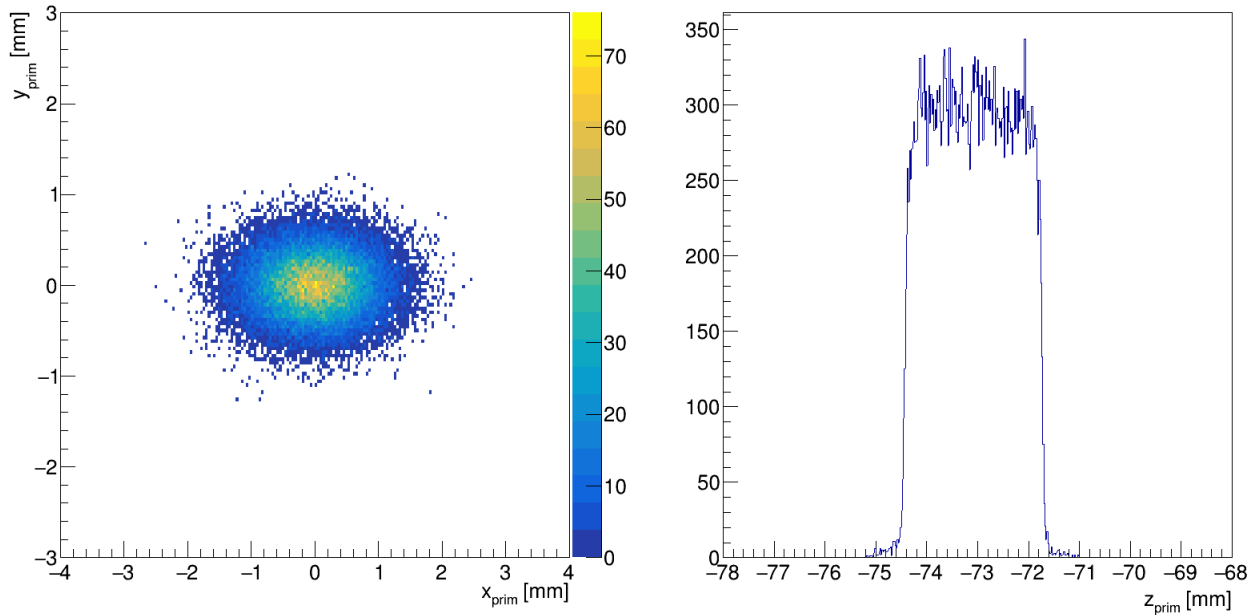


Figure 6.10: Left: x vs y distribution of determined locations of the corrected primary vertex. Right: The z component of the corrected primary vertex relative to the location of the first station.

Chapter 7

Simulation

After the adaptation of the reconstruction modules to the upgraded Vertex Detector, the next goal of my work was to establish the acceptance and reconstruction efficiency of events containing only D^0 charmed meson. To obtain this goal the D^0 decay products (pions and kaons) were transported through the Vertex Detector modeled in the GEANT4 package. The hits produced in the sensitive layers of detectors during particle transport were then converted to cluster objects and used as input to the reconstruction chain. In the executed analyses, one decay of the D^0 meson was considered (see table 2.1):

$$D^0 \rightarrow \pi^+ + K^- \quad (7.1)$$

7.1. Generating D^0 mesons

The D^0 phase-space distribution was obtain according to D^0 rapidity (y) and transverse momentum (p_T) distribution predicted by PHSD (Parton-Hadron-String Dynamics) event generator. The p_T distribution from the model was fitted with the Boltzmann function:

$$\rho(p_T) \sim p_T \cdot \exp\left(\frac{-\sqrt{p_T^2 + m^2}}{T}\right) \quad (7.2)$$

and y distribution was fitted with the Gaussian distribution:

$$\rho(y) \sim \frac{1}{\sqrt{2\pi}\sigma_y} \cdot \exp\left(-\frac{(y - \mu)^2}{2\sigma_y^2}\right) \quad (7.3)$$

For the symmetric system colliding with the beam momentum of 150A GeV/c:

$$\mu = 2.91, \quad (7.4)$$

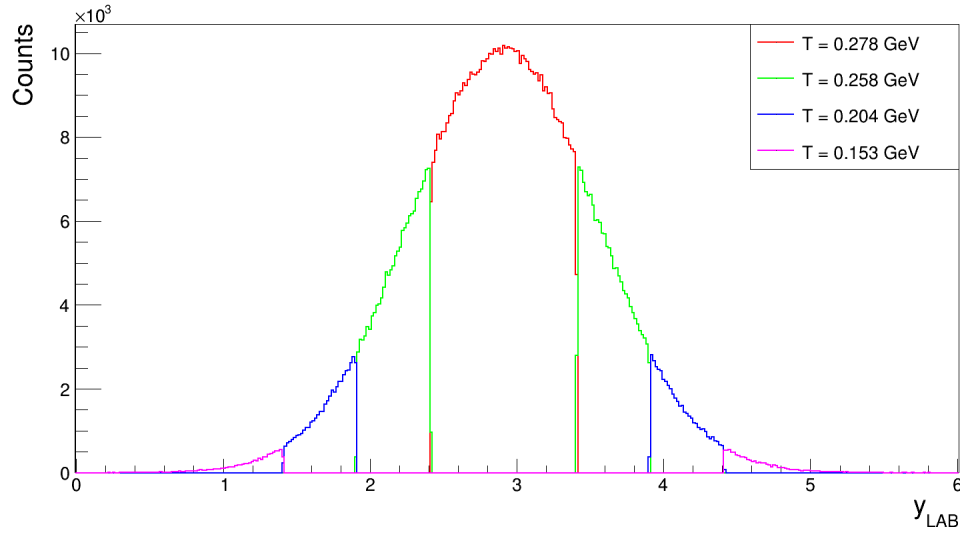
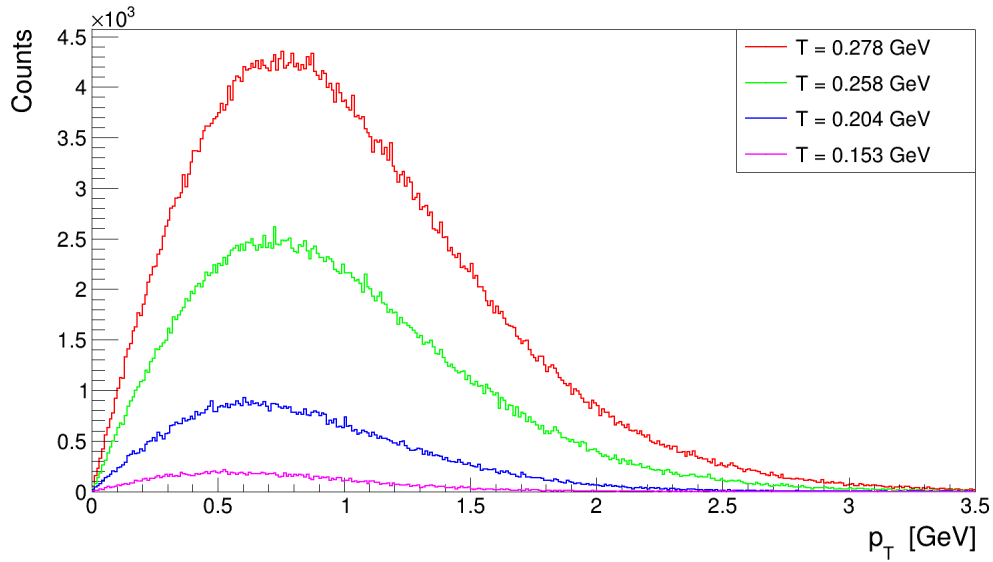
where μ refers to the center of mass rapidity in the LAB frame, and σ_y obtain from the fits to model distribution shown in figure 7.1:

$$\sigma_y = 0.63. \quad (7.5)$$

However, it was found that the inverse slope parameter (T) in formula 7.2 depends on rapidity [49]. To account for this effect the rapidity distribution was split into several bins and the transverse momentum distributions were constructed and fitted for each bin, separately. The bins of rapidity and the values of inverse slope parameter T_y are shown in table 7.1 and also shown in figure 7.1. The p_T distribution for the rapidity bins is shown in figure 7.2.

Table 7.1: The rapidity bins and T_y parameters used for generation D^0 .

Rapidity bin	Value of T [MeV]
$ y_{CM} \leq 0.5$	278
$0.5 < y_{CM} \leq 1$	258.1
$1 < y_{CM} \leq 1.5$	204.3
$0.5 < y_{CM} \leq 1$	152.9

Figure 7.1: The rapidity distribution for generated D^0 with marked bins.Figure 7.2: Transverse momentum distribution of generated D^0 with marked bins.

Using the parametrization 7.2 and 7.3 with identical parameter values large statistics of D^0 mesons (y_{LAB}, p_T) by PHSD for central Pb+Pb collision at beam momentum 150A GeV/c were generated, and plotted in figure 7.3.

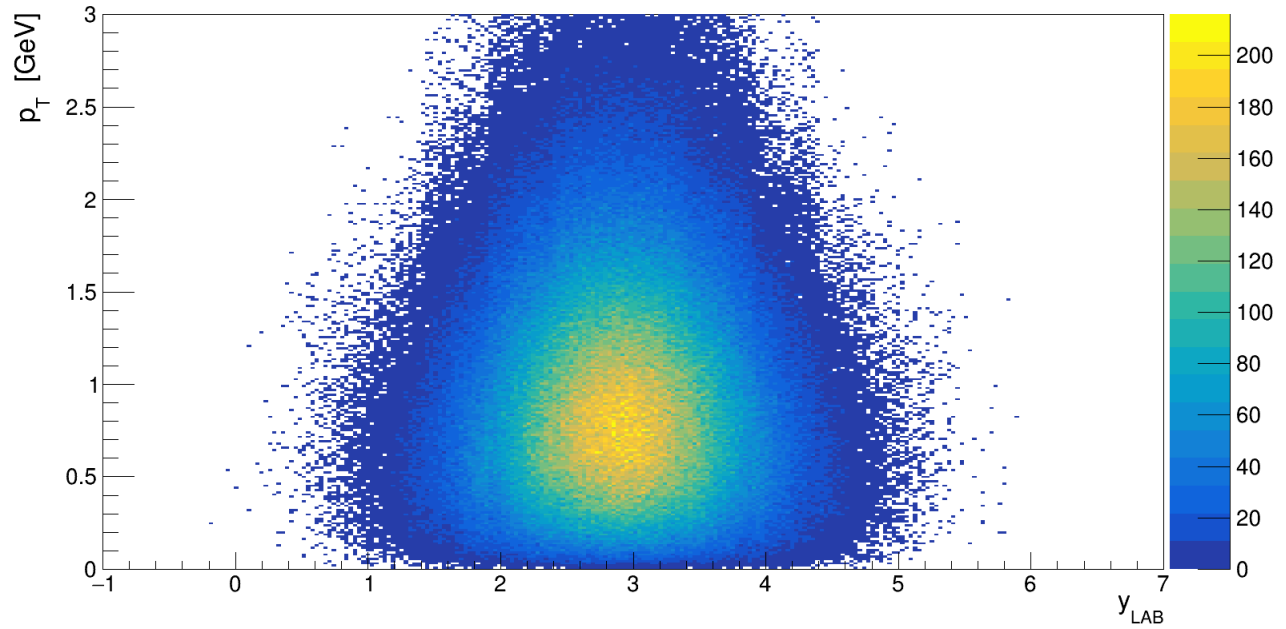


Figure 7.3: The distribution of rapidity in LAB (y_{LAB}) versus the distribution of transverse momentum (p_T) for generated D^0 .

The following expressions were used to determine the parameters needed as an input to the GEANT4 simulation, i.e. the momentum components p_x, p_y, p_z in LAB frame:

$$p_x = p_T \cos(\alpha), \quad (7.6)$$

$$p_y = p_T \sin(\alpha), \quad (7.7)$$

$$p_z = m_T \sinh(y_{LAB}), \quad (7.8)$$

where $m_T = \sqrt{p_T^2 + m_{D^0}^2}$ and $m_{D^0} = 1.86484$ GeV [39].

The values of the α angle were randomly chosen from a uniform distribution in the range from 0 to 2π . The distributions of x, y , and z momentum components are shown in figure 7.4 on the next page.

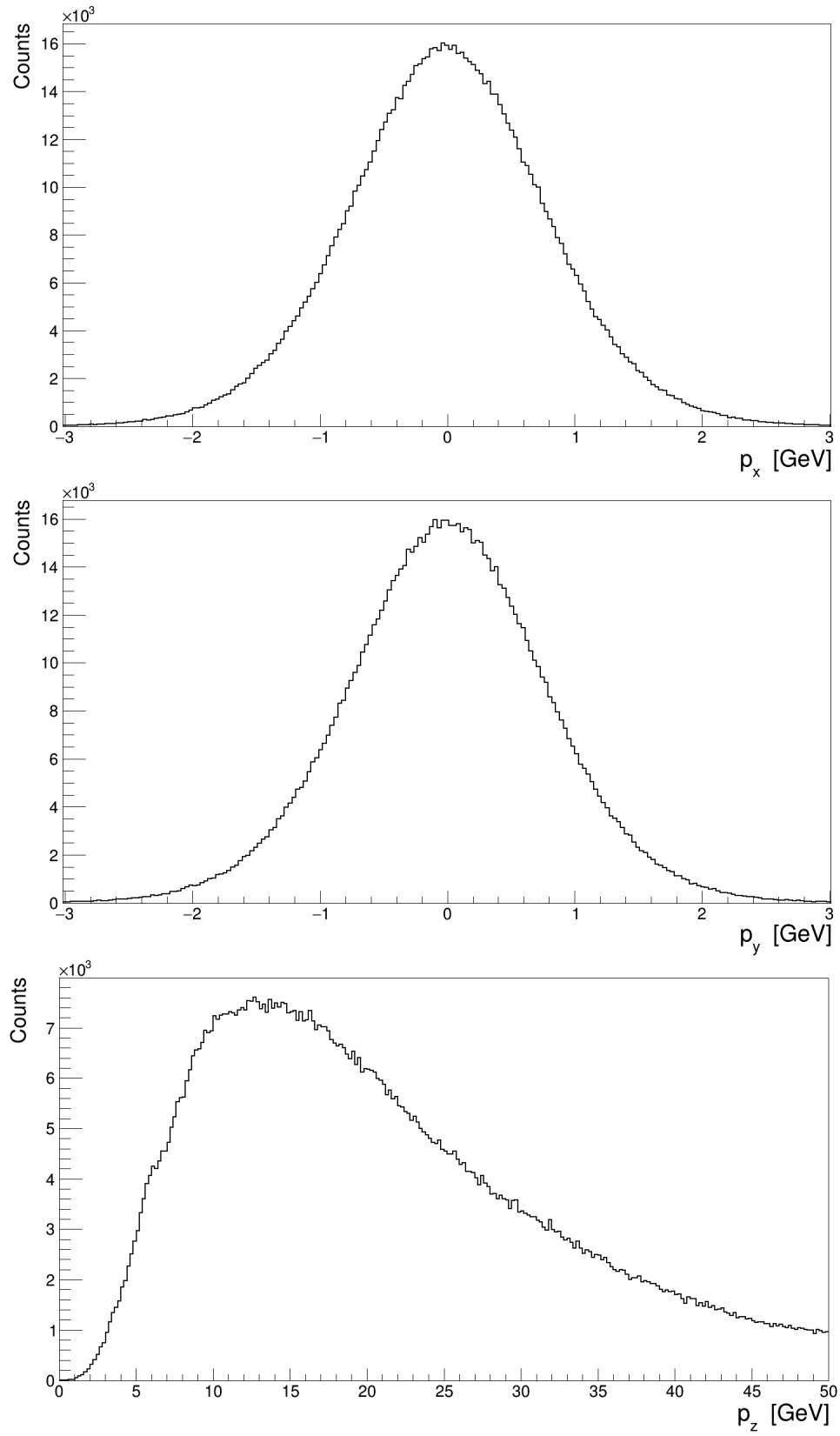


Figure 7.4: Distributions of x , y , and z momentum components of the generated D^0 mesons.

7.2. Simulation of D^0

Generated D^0 mesons were used to determine the acceptance and reconstruction efficiency of the upgraded Vertex Detector. The whole procedure was based on several steps:

- ① Defining geometry of the upgraded Vertex Detector in GEANT4, e.g. the position of the arms, sensors size as well as their position and rotate angle, and position of the target.
- ② Choosing a D^0 emission point inside the 3 mm Pb target volume according to a uniform distribution in z coordinate and Gaussian distribution in x, y coordinate where:

$$\mu_x = 0, \quad \sigma_x = 0.06 \text{ cm}, \quad \text{for range : } x \in (-0.25, 0.25) \text{ cm}, \quad (7.9)$$

and:

$$\mu_y = 0, \quad \sigma_y = 0.03 \text{ cm}, \quad \text{for range : } y \in (-0.15, 0.15) \text{ cm}. \quad (7.10)$$

- ③ Shooting D^0 from the emission point and transporting its decay products through the experimental setup.
- ④ The reconstruction from GEANT4 hits of the transported particles using the VD reconstruction chain.
- ⑤ Associating reconstructed tracks (so-called *recoTrack*) with the generated tracks in GEANT4 simulation (so-called *simTrack*).

The last step ⑤ is performed by comparing the location of reconstructed and simulated track hits at the given detection layer.

Because of the inability to determine the primary vertex in the reconstruction chain, the location of the primary vertex is entered into the reconstruction procedure directly from the simulation. Moreover, it is possible to overlap several *recoTracks* into one *simTrack*. In this case, the track with the most common hits was selected.

Acceptance and reconstruction efficiency were determined for different arm distances based on the layout of the first station and different positions of the target locations relative to the first station. The position of the arms and the width of the stave at the first station are shown in figure 7.5. The distance between the arms is described by the formula:

$$d = |x_{\text{Jura}}| + |x_{\text{Saleve}}| - 15 \text{ mm} \quad (7.11)$$

It is worth noting, according to [50], that on each of the 15 mm wide staves on the outside of the beam, there is a stripe about 1.2 mm wide that corresponds to the data readout (more specifically: Digital Periphery [50]). So ultimately about 13.8 mm of stave width is a sensitive area. The definition of the distance d between the arms Jura and Saleve based on the layout of the first station and the marking of the inactive part of each stave is shown in figure 7.5. On the other hand, in figure 7.6 there is a scheme of the Pb target position r relative to the first station in local coordinates.

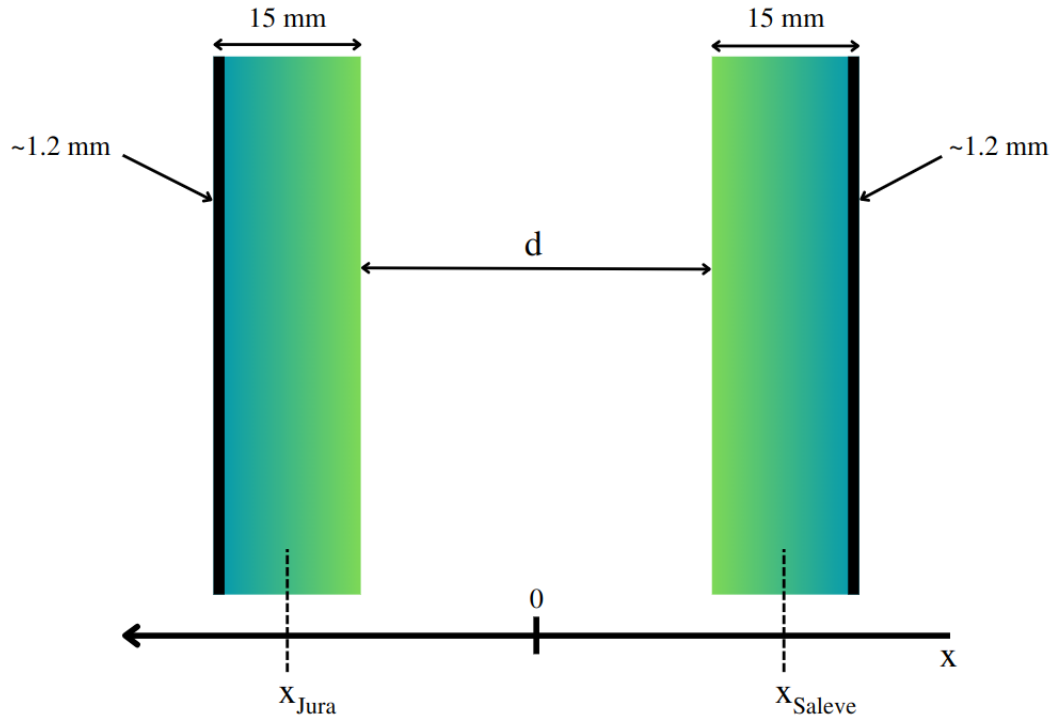


Figure 7.5: The definition of the distance d between the arms Jura and Salve is based on the layout on the first station. The inactive areas are marked in black.

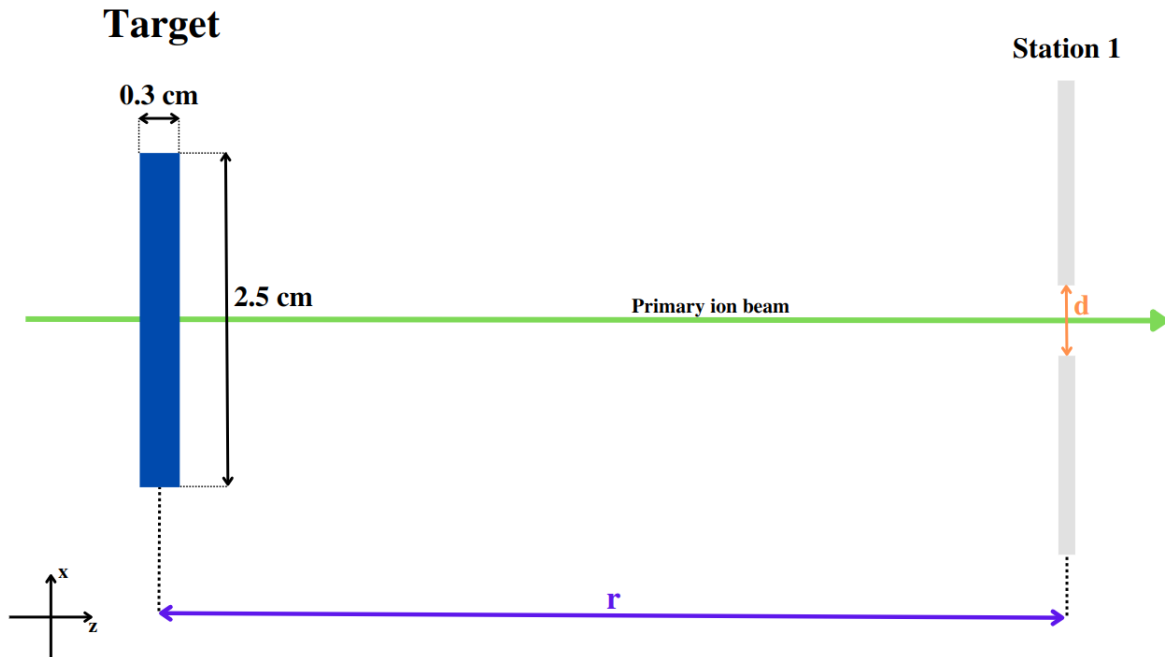


Figure 7.6: The definition of the distance r , i.e. the position of the Pb target relative to the first station.

Chapter 8

Analysis

As described in the section 7.2, the reconstruction of D^0 mesons was simulated for different arm positions and different positions of the target locations relative to the first station. Arm positions considered in the analysis are provided in table 8.1. The positions of the lead target are shown in table 8.2.

Table 8.1: The positions of the Jura and Saleve arms and the respective distances d (gap) between the arms.

Case number	Jura position x_{Jura} [mm]	Saleve position x_{Saleve} [mm]	Distance d [mm]
1	9.5	-9.5	4
2	10	-10	5
3	10.5	-10.5	6
4	11	-11	7
5	11.5	-11.5	8
6	12	-12	9

Table 8.2: Lead target positions relative to the first station included in the analysis.

Case number	Distance r [cm]
1	5
2	6
3	7
4	8
5	9
6	10

A description of the analysis scheme is provided on the following pages.

8.1. Acceptance

In the first step, the single particle acceptance for K^- and π^+ , that were created in D^0 decay, was calculated. The single particle acceptance was defined as:

$$\text{Acc}_i = \frac{N_{\text{sim}_i}^{(A)}}{N_{\text{sim}_i}} \cdot 100 \%, \quad (8.1)$$

where $i = K^-, \pi^+$ and where:

- $N_{\text{sim}_i}^{(A)}$ - is the number of K^- (or π^+) that passed the detector and produced 3 (or more) hits,
- N_{sim_i} - is the number of all simulated K^- (or π^+) that were created in D^0 decay.

Information about hits was taken from the GEANT4 track (so-called simTrack). After determining the single particle acceptance, the next step was to determine the D^0 acceptance as a situation when both D^0 daughters were accepted. Thus, the two particles acceptance was defined as:

$$\text{Acc}_{D^0} = \frac{N_{\text{sim}}^{(A)}}{N_{\text{sim}}} \cdot 100 \%, \quad (8.2)$$

where:

- $N_{\text{sim}}^{(A)}$ - is the number of D^0 s having both daughters accepted, i.e. both daughters passed the detector and produced at least 3 hits,
- N_{sim} - is the number of all simulated D^0 s.

8.2. Reconstruction efficiency

In the second step I calculated the single particle reconstruction efficiency. The whole procedure can be explained in a few steps:

- ① For each reconstructed track (recoTrack), a loop over clusters was performed.
- ② For each of the clusters, the associated hit from the simulated track was searched. Tracks (recoTrack and simTrack) with related hits have been linked.
- ③ The particle was reconstructed if the number of associated hits was greater than 3.

Thus, the definition of the single particle reconstruction efficiency is as follows:

$$\text{Eff}_i = \frac{N_{\text{reco}_i}}{N_{\text{sim}_i}^{(A)}} \cdot 100 \%, \quad (8.3)$$

where $i = K^-, \pi^+$ and where:

- N_{reco_i} - is the number of K^- (or π^+) that were reconstructed,

- $N_{\text{sim}_i}^{(A)}$ - is the number of K^- (or π^+) that passed the detector and produced 3 (or more) hits.

After determining the single particle reconstruction efficiency, the next step was to determine the D^0 reconstruction efficiency as a situation when both D^0 daughters were reconstructed. The two particle reconstruction efficiency was defined as:

$$\text{Eff}_{D^0} = \frac{N_{\text{reco}}}{N_{\text{sim}}^{(A)}} \cdot 100 \%, \quad (8.4)$$

where:

- N_{reco} - is the number of D^0 s having both daughters reconstructed,
- $N_{\text{sim}}^{(A)}$ - is the number of D^0 s having both daughters accepted, i.e. both daughters passed the detector and produced 3 (or more) hits.

8.3. Secondary vertex position

During the D^0 simulation, an additional element of the analysis was the study the location of the D^0 meson decay point, i.e. the so-called secondary vertex. For this purpose, for each simulated D^0 event, the distance of the secondary vertex from the primary vertex was determined as a vector:

$$\vec{s} = \vec{p}_{\text{sec}} - \vec{p}_{\text{prim}} = (x_{\text{sec}} - x_{\text{prim}}, y_{\text{sec}} - y_{\text{prim}}, z_{\text{sec}} - z_{\text{prim}}), \quad (8.5)$$

where:

- $\vec{p}_{\text{prim}} = (x_{\text{prim}}, y_{\text{prim}}, z_{\text{prim}})$ - the position of primary vertex,
- $\vec{p}_{\text{sec}} = (x_{\text{sec}}, y_{\text{sec}}, z_{\text{sec}})$ - the position of secondary vertex.

Chapter 9

Results

In this chapter, an analysis of the data produced in simulations will be presented. The main goal of this work was to determine VD acceptances and reconstruction efficiencies defined in chapter 8. Due to the large number of cases (as many as $6 \times 6 = 36$), below is a detailed description of the analysis and results for case:

$$r = 7 \text{ cm}, \quad d = 6 \text{ mm} \tag{9.1}$$

9.1. The single particle acceptance and reconstruction efficiency

The total momentum distributions of the all simulated, accepted and reconstructed π^+ are shown in figure 9.1, while K^- distributions are shown in figure 9.5. The acceptance and reconstruction efficiency (see chapter 8) calculated as a function of total momentum are shown in the figure 9.2, 9.3, (for π^+) 9.6, and 9.7 (for K^-).

The acceptances and reconstruction efficiencies for all cases (see table 8.1 and 8.2) of π^+ from the decay of the D^0 meson are presented in table 9.1 and in figure 9.4, and for K^- are presented in table 9.2 and in figure 9.8.

9.1.1 Pions (π^+)

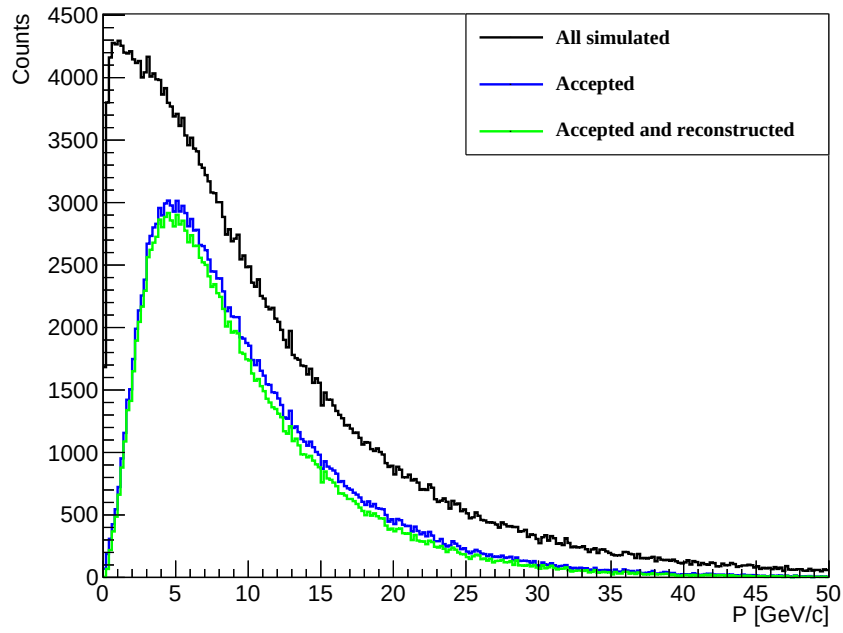


Figure 9.1: The total momentum distribution of π^+ produced from D^0 decays.

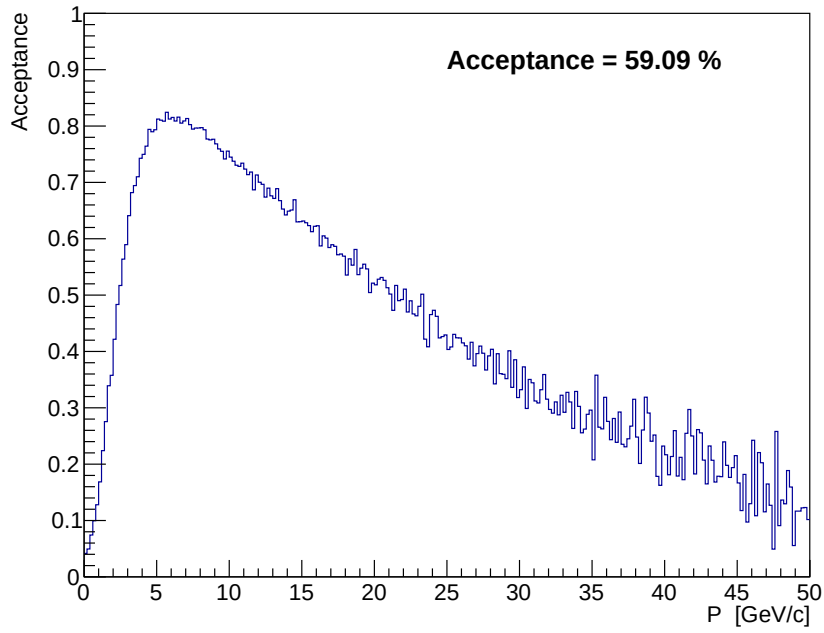


Figure 9.2: Acceptance of π^+ from D^0 decays plotted as a function of the total momentum. The integrated acceptance is marked in black.

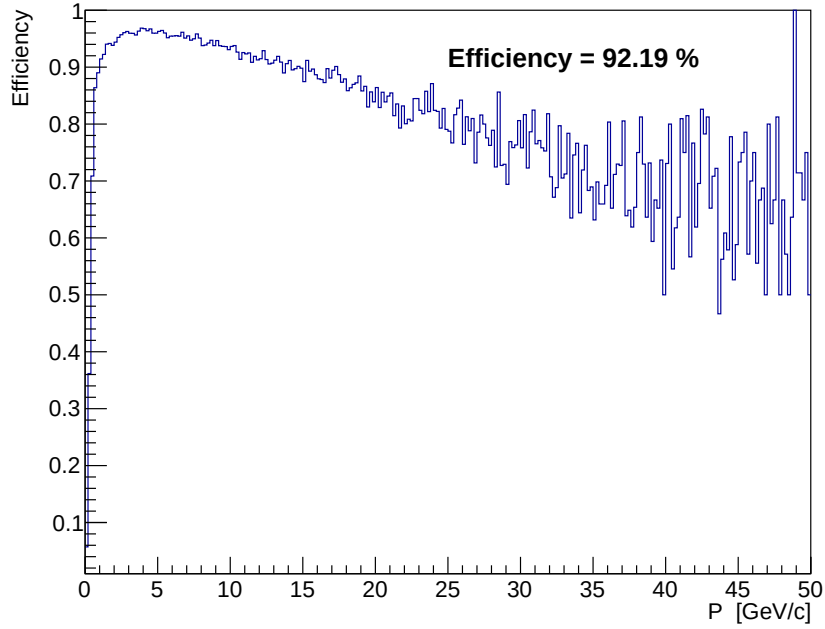


Figure 9.3: Reconstruction efficiency of π^+ from D^0 decays plotted as a function of total momentum. The integrated reconstruction efficiency is marked in black.

Table 9.1: The acceptance and reconstruction efficiency in % of π^+ from the D^0 decays for all considered cases (see table 8.1 and 8.2).

Distance r	Distance d											
	4		5		6		7		8		9	
	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff
5	64.4	91.6	61.2	90.9	57.3	90.5	53.5	90.4	50	90.4	46.5	90.4
6	64.6	92.8	61.8	91.9	58.4	91.5	54.9	91.2	51.6	91.2	48.5	91.2
7	64.8	93.5	62	92.8	59.1	92.2	56	92	52.8	91.8	49.8	91.7
8	64.3	94.2	62.1	93.4	59.6	92.8	56.8	92.5	53.8	92.3	51	92.4
9	63.7	94.1	61.7	93.6	59.5	93.1	57.1	93	54.4	92.8	51.9	92.7
10	62.1	94	60.5	93.7	58.7	93.1	56.9	92.7	54.7	92.6	52.3	92.6

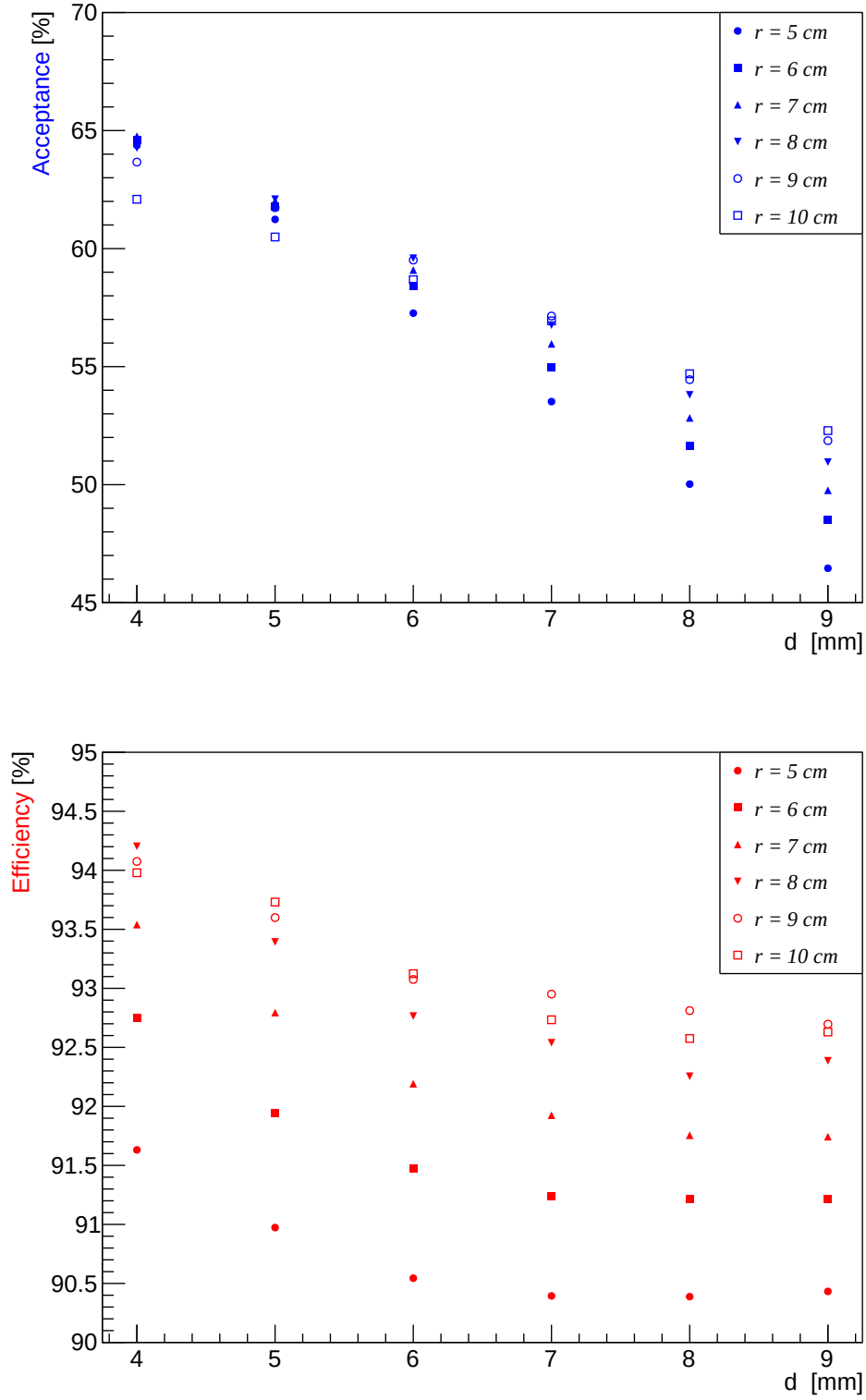


Figure 9.4: The integrated acceptance (blue) and reconstruction efficiencies (red) of π^+ from the decay of the D^0 mesons for all considered cases (see table 8.1 and 8.2).

9.1.2 Kaons (K^-)

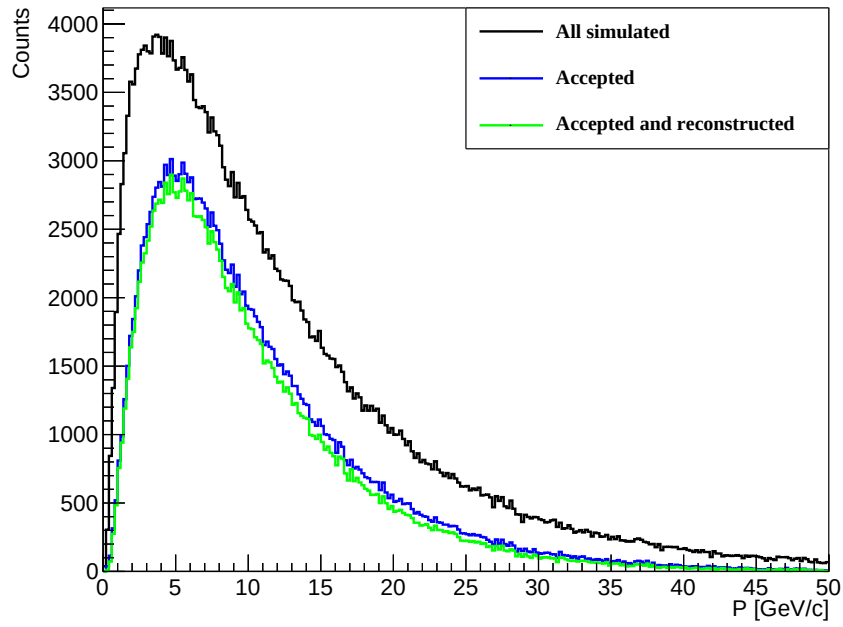


Figure 9.5: The total momentum distribution of K^- produced from D^0 decays.

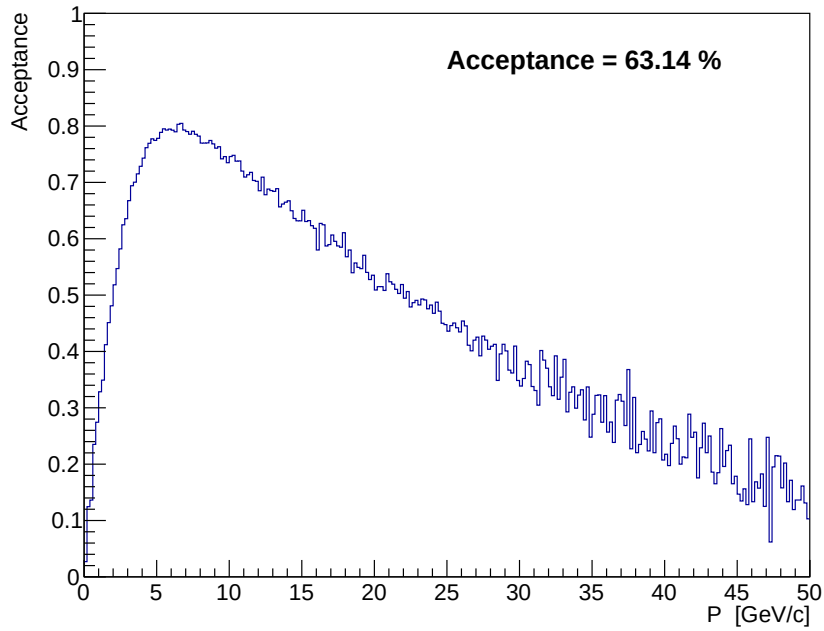


Figure 9.6: Acceptance of K^- from D^0 decays plotted as a function of total momentum. The integrated acceptance is marked in black.

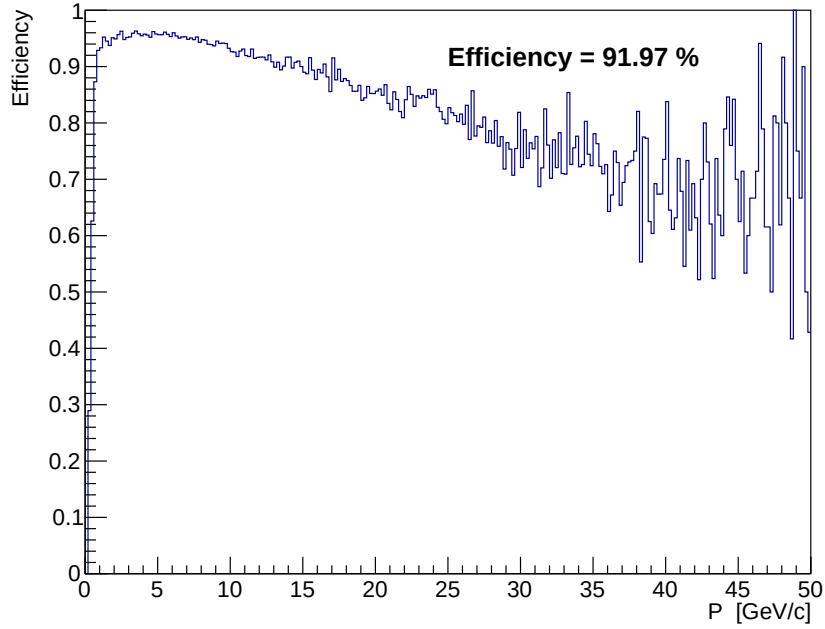


Figure 9.7: Reconstruction efficiency of K^- from D^0 decays plotted as a function of total momentum. The integrated reconstruction efficiency is marked in black.

Table 9.2: The acceptance and reconstruction efficiency in % of K^- from D^0 decays for all considered cases (see table 8.1 and 8.2).

Distance r	Distance d											
	4		5		6		7		8		9	
	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff
5	68.2	91.5	64.5	90.7	60	90.4	55.5	90.2	51.4	90.3	47.6	90.2
6	69	92.5	65.5	91.7	61.8	91.1	57.8	91.1	53.9	90.9	50.1	91.1
7	69.4	93.4	66.4	92.4	63.1	92	59.3	91.7	55.7	91.7	52.2	91.5
8	69.6	93.9	66.8	93.2	63.7	92.5	60.5	92.3	57.2	92.1	54	92
9	69.1	94	66.9	93.4	64.5	92.9	61.4	92.6	58.4	92.6	55.3	92.4
10	68	94	66	93.5	64	93	61.6	92.6	59	92.4	56.4	92.5

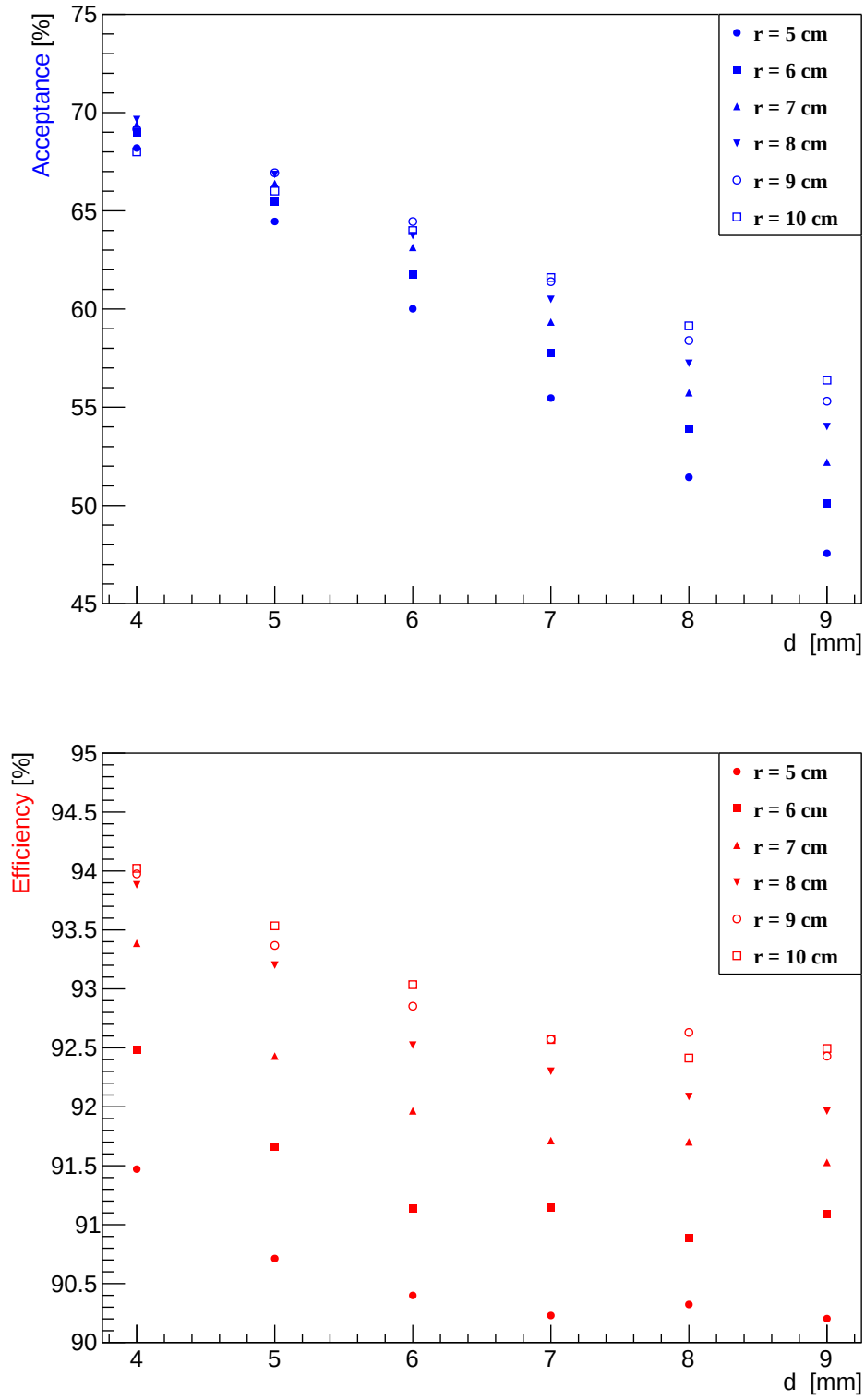


Figure 9.8: The integrated acceptance (blue) and reconstruction efficiencies (red) of K^- from the D^0 decays for all considered cases (see table 8.1 and 8.2).

9.2. Acceptance and reconstruction efficiency of D^0 mesons

The total momentum distributions of the all simulated, accepted and reconstructed D^0 s are shown in figure 9.9. The acceptance and reconstruction efficiency (see chapter 8) calculated as a function of total momentum are shown in the figure 9.10, and 9.11.

The D^0 meson acceptance and reconstruction efficiencies for all considered cases (see table 8.1 and 8.2) are presented in table 9.3 and on figure 9.12.

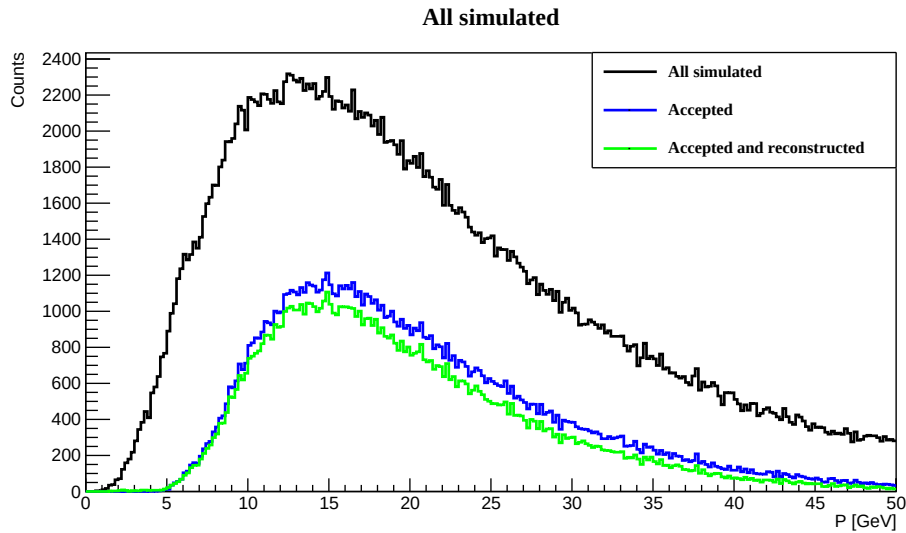


Figure 9.9: Total momentum distributions of all generated D^0 s (black line), accepted D^0 s (blue line), and reconstructed D^0 s (green line).

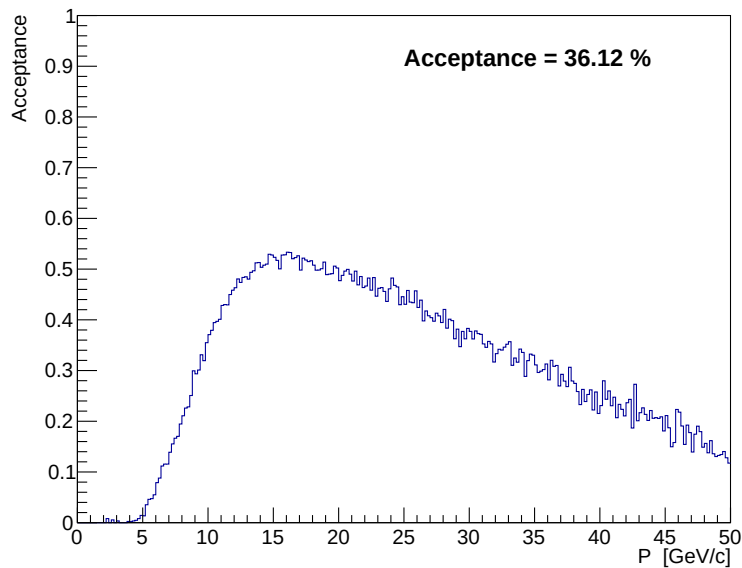


Figure 9.10: Acceptance of D^0 plotted as a function of total momentum. The integrated acceptance is marked in black.

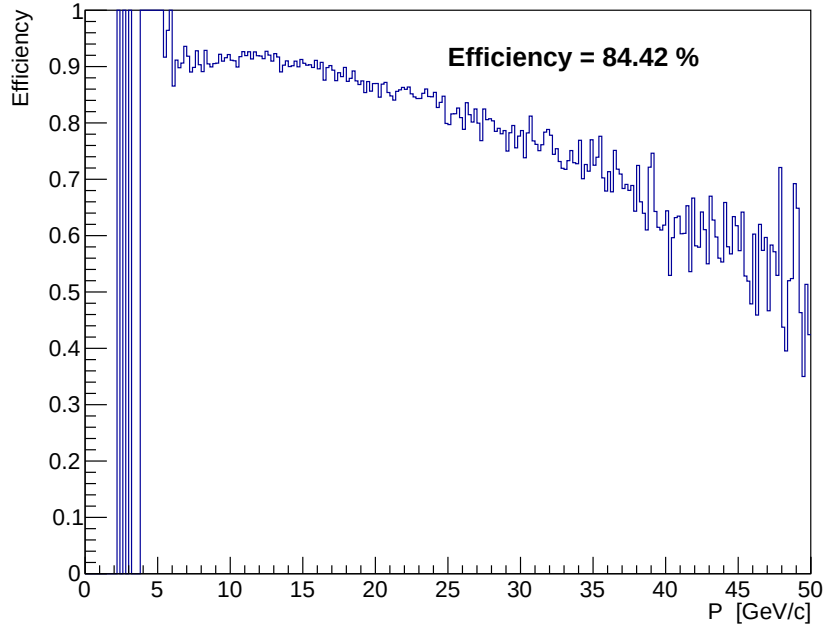


Figure 9.11: Reconstruction efficiency of D^0 plotted as a function of the total D^0 momentum. The integrated reconstruction efficiency is marked in black.

Table 9.3: The D^0 acceptance and reconstruction efficiency for all considered cases (see table 8.1 and 8.2).

Distance r	Distance d											
	4		5		6		7		8		9	
	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff	Acc	Eff
5	42.5	83.4	38.1	82.2	33	81.6	28.4	81.5	24.6	81.5	21.1	81.5
6	43.2	85.3	39.1	83.8	34.7	83.1	30.4	82.9	26.7	82.8	23.2	82.9
7	43.8	86.9	39.9	85.5	36.1	84.4	31.9	83.9	28.1	83.8	24.8	83.8
8	43.6	88.1	40.4	86.6	36.8	85.5	33.1	85.1	29.5	84.6	26.4	84.7
9	43	88.2	40.2	87.1	37.1	86.2	33.9	85.7	30.5	85.5	27.4	85.4
10	41.3	88	38.9	87.3	36.4	86.4	33.9	85.5	31.2	85.3	28.3	85.3

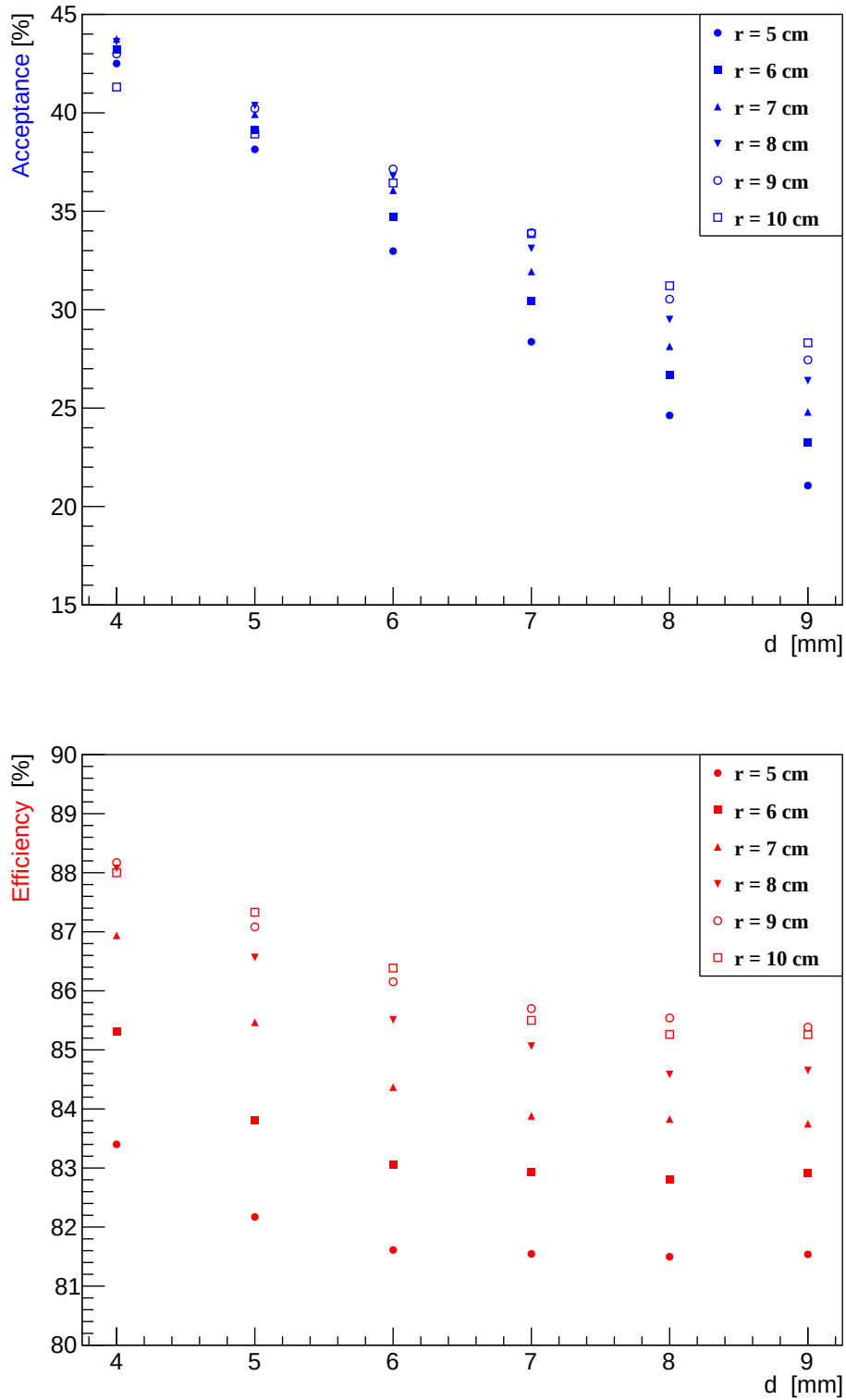


Figure 9.12: The integrated acceptance (blue) and reconstruction efficiencies (red) of D^0 mesons for all considered cases (see table 8.1 and 8.2).

9.3. Distributions of the secondary vertex position

The distribution of the z component (z_{reco}) of the secondary vertex relative to the target location is shown in figure 9.13. In addition, distributions of three quantities were constructed:

- The relative distance between primary and secondary vertex (see equation 8.5) :

$$s = \sqrt{(x_{\text{sec}} - x_{\text{prim}})^2 + (y_{\text{sec}} - y_{\text{prim}})^2 + (z_{\text{sec}} - z_{\text{prim}})^2}, \quad (9.2)$$

The definition of s is also explained in figure 9.14.

- The z component of $\vec{s}$ (see equation 8.5):

$$s_z = z_{\text{sec}} - z_{\text{prim}}, \quad (9.3)$$

The definition of s_z is also explained in figure 9.15.

- The transverse component of $\vec{s}$ (see equation 8.5):

$$s_T = \sqrt{(x_{\text{sec}} - x_{\text{prim}})^2 + (y_{\text{sec}} - y_{\text{prim}})^2}, \quad (9.4)$$

which is shown on figure 9.16.

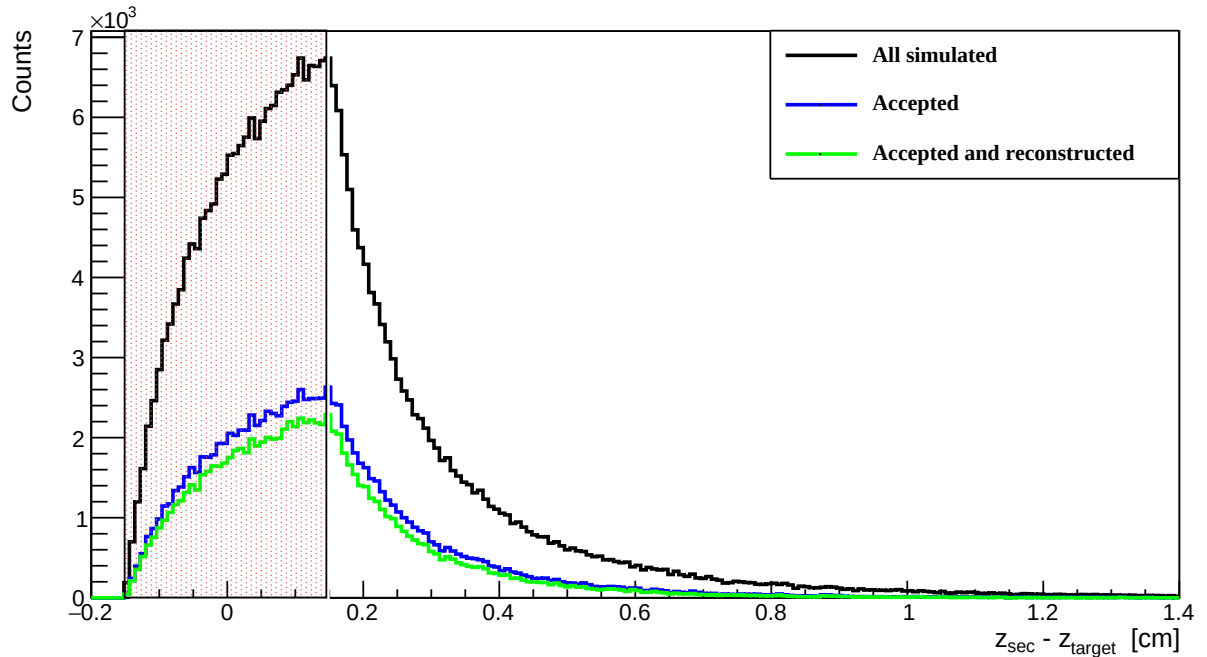


Figure 9.13: The distribution of the z component (z_{reco}) of the secondary vertex relative to the target position. The shaded of z_{sec} occupied by target.

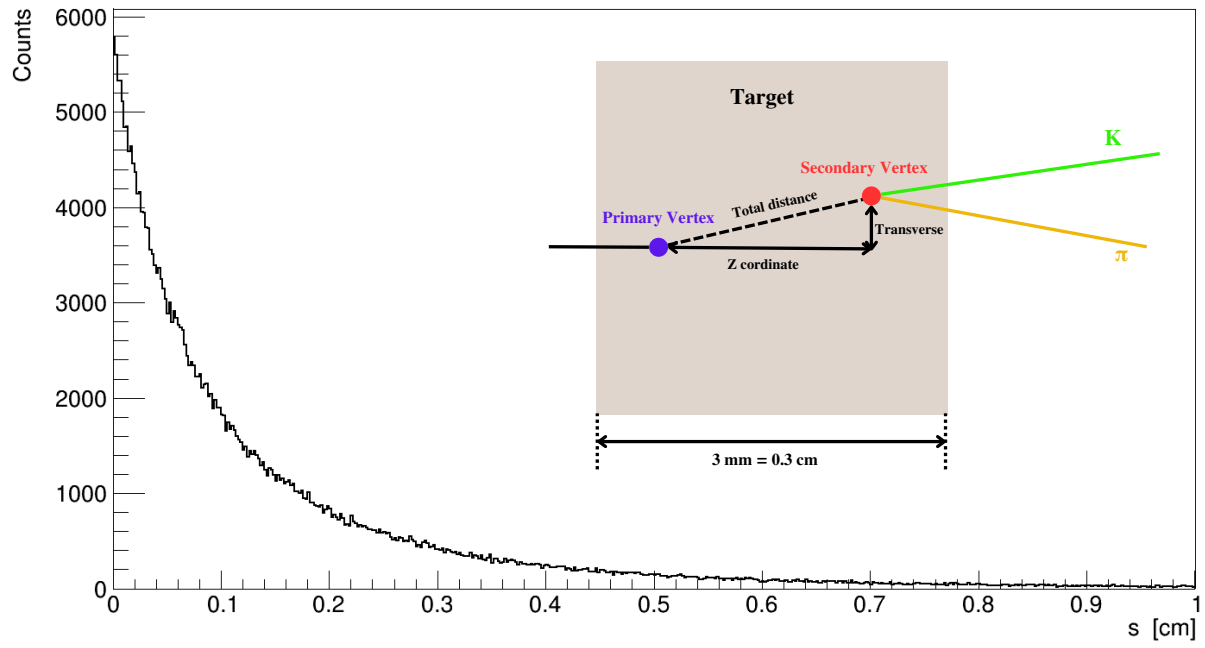


Figure 9.14: The distribution of relative distance between primary and secondary vertex $\vec{s}$ (see equation 9.2).

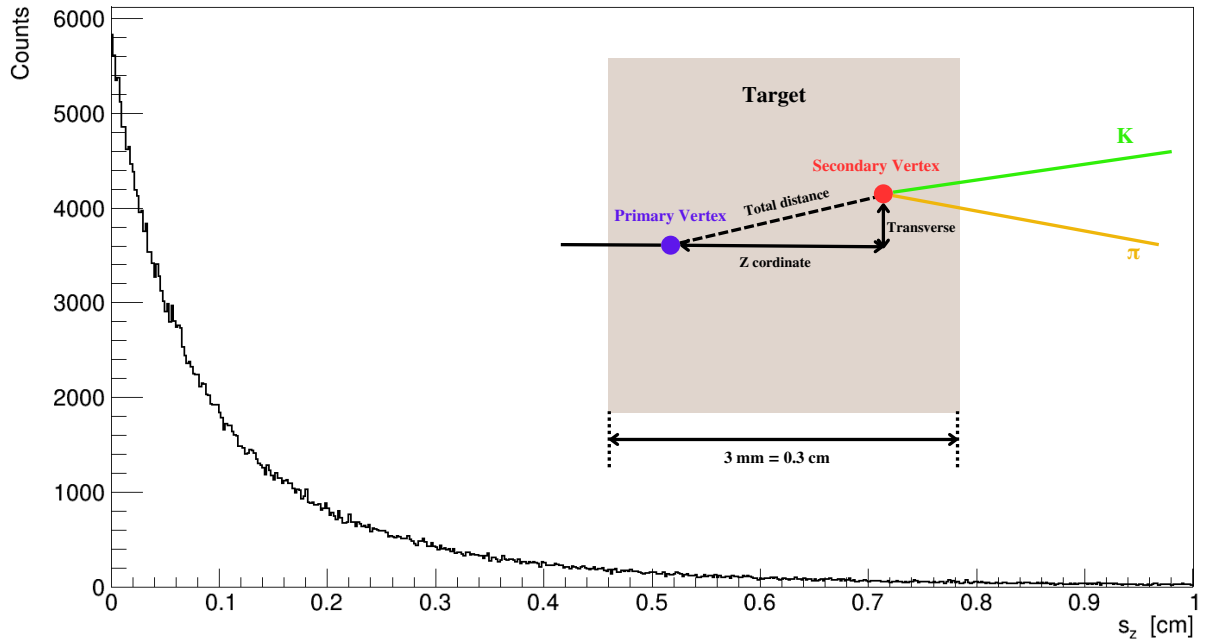


Figure 9.15: The distribution of the z component of $\vec{s}$ (see equation 9.3).

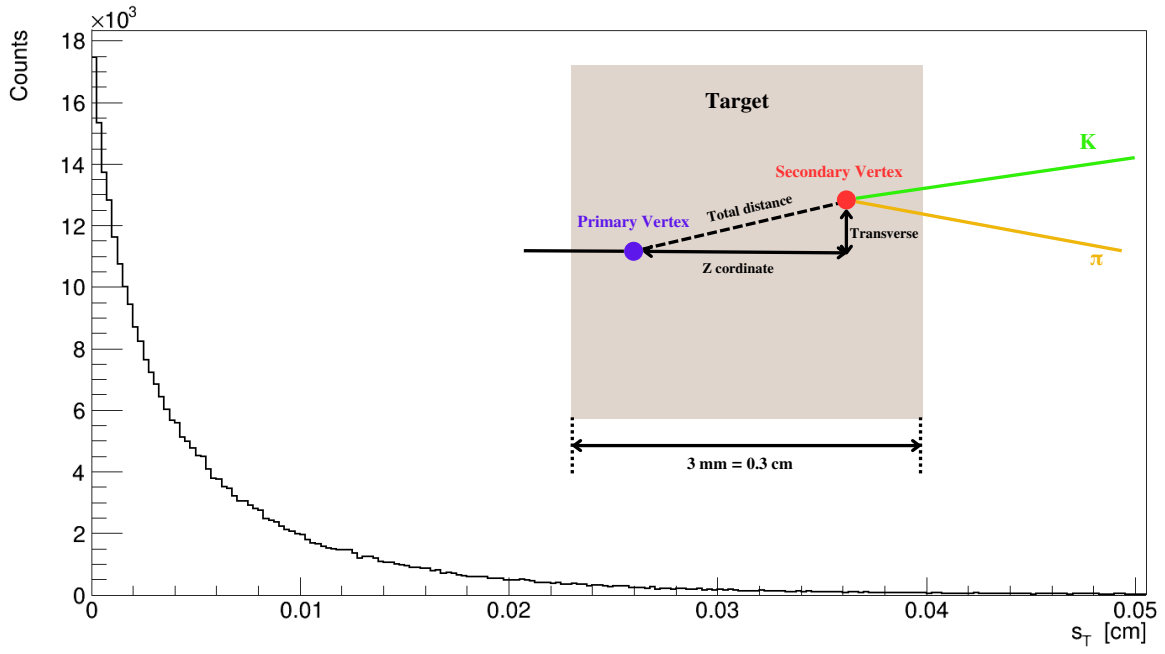


Figure 9.16: The distribution of the transverse component of $\vec{s}$ (see equation 9.4).

Chapter 10

Discussion and outlook

Based on the analysis of simulated D^0 mesons, the following conclusions can be drawn:

- ① Increasing the distance of the target position from the first station leads to increase of the single particle acceptances and reconstruction efficiencies (see figure 9.4 and figure 9.8).
- ② Lorentz boost in the fixed-target experiment makes the z axis the most important for the procedure of distinguishing the secondary vertex from the primary vertex. It is caused by the fact that the transversal position of the secondary vertex relative to the primary vertex is much smaller compared to the distance along z (compare figures 9.15 and 9.16). The average values of distances for simulated D^0 are:

$$\bar{s} = 1.43 \text{ mm}, \quad (10.1)$$

$$\overline{s_z} = 1.428 \text{ mm}, \quad (10.2)$$

$$\overline{s_T} = 0.065 \text{ mm}. \quad (10.3)$$

- ③ Most of the accepted D^0 mesons decay inside the target (see figure 9.13, 10.1, and 10.2).
- ④ A significant number of kaons and pions with large total momenta have a limited reconstruction efficiencies in the Vertex Detector. See figure 9.1, 9.3, and 9.5, 9.7.

An explanation for ④ may be that: most of kaons and pions with large total momenta pass between the arms (which can be seen as an increase in acceptance with a smaller distance d between the arms in the figure 9.4 or figure 9.8). Thus, these particles are not accepted in the first station, generating 3 hits only. According to chapter 6, the 3 hit tracks are considered differently i.e. different cut formulas are used compared to 4 or more hit tracks. Using narrow cuts for 3 hit tracks can cause poor reconstruction efficiency. This is visible in the layers distribution of simulated tracks (simTracks) for accepted and reconstructed kaons in the figure 10.3. The scope of this analysis allows to perform optimization of these cuts however the optimisation is not part of this thesis.

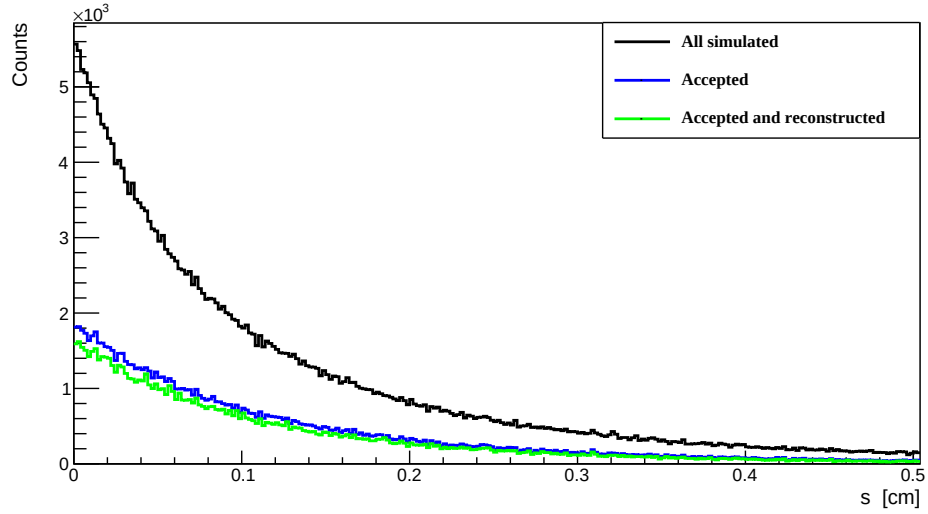


Figure 10.1: Example of the total distance distribution of the secondary vertex from the primary vertex s for accepted and reconstructed D^0 s.

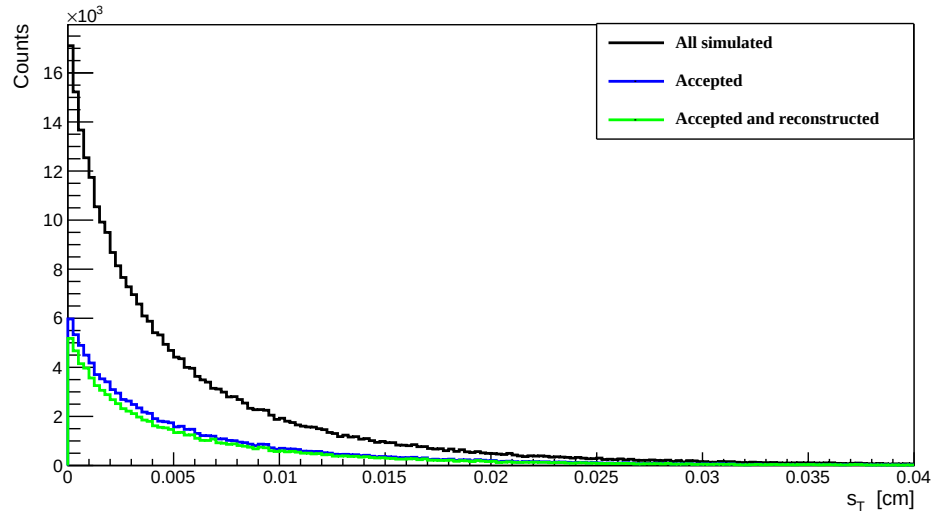


Figure 10.2: Example of the transverse component (s_T) of $\vec{s}$ distributions for accepted and reconstructed D^0 s.

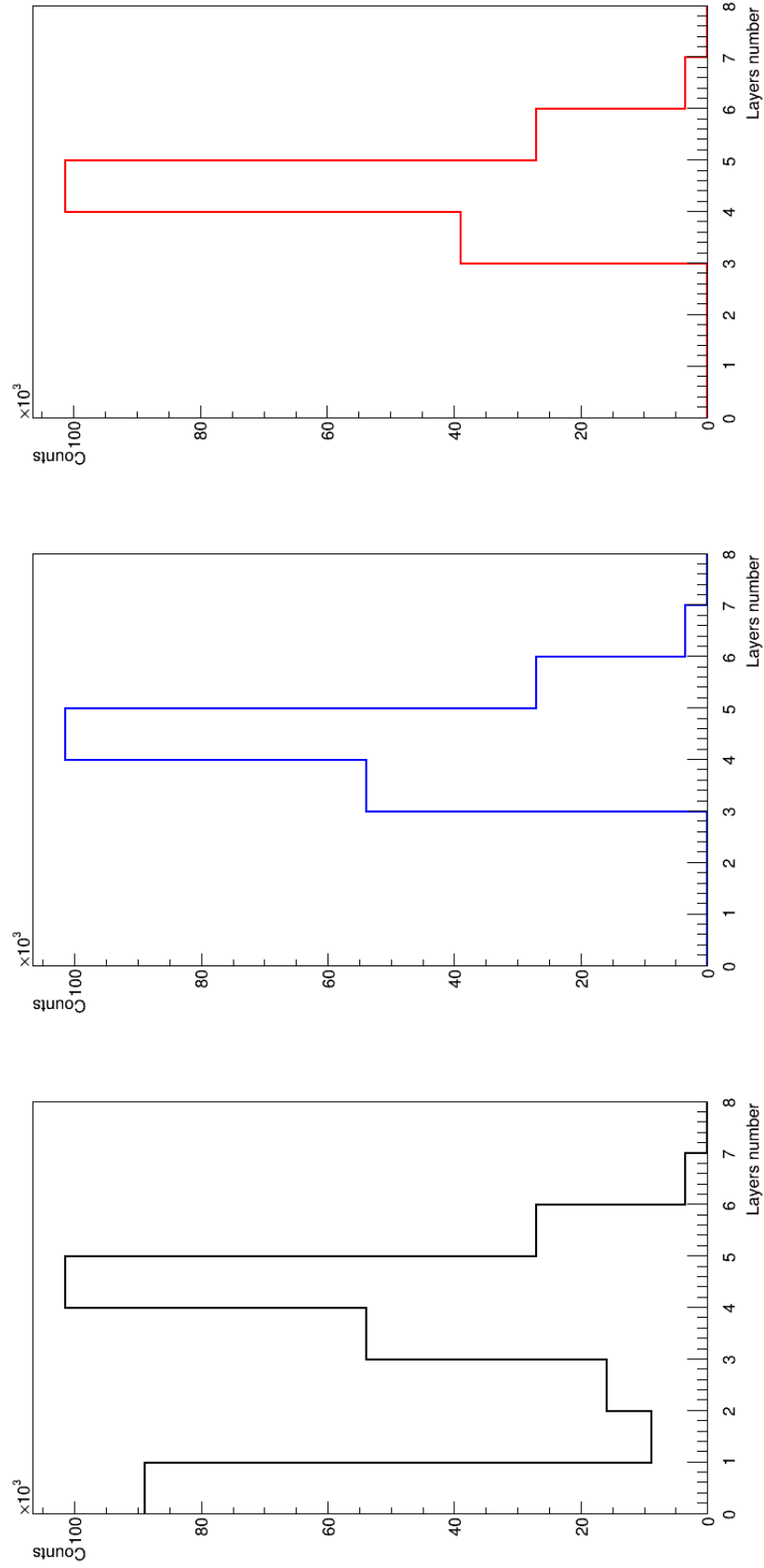


Figure 10.3: The distributions of the number of layers for simulated (black), accepted (blue) and reconstructed (red) kaons.

Chapter 11

Conclusion

The main program of the NA61/SHINE experiment is dedicated to the study of the charm production mechanism based on the measurement of open charm mesons (D mesons). An important aspect of performing such measurements is the use of a specialized device, the so-called Vertex Detector.

The Vertex Detector is required to distinguish the location of the decay point of short-lived charm mesons (so-called secondary vertex) from the location of the primary interaction point (so-called primary vertex).

This thesis contains a description of the hardware improvements of the Vertex Detector in the NA61/SHINE experiment as well as a description of the software used to reconstruct the particle tracks. This work also covers an analysis of the single particle acceptance and reconstruction efficiency (based on kaons and pions) and an analysis of the two particle acceptance and efficiency (based on one of the D^0 meson decays).

I managed to come to some interesting conclusions, which are presented in the chapter 10. The obtained results will allow to make a decision regarding the position of the VD arms and the position of the target relative to the first station during data taking foreseen in 2023 and 2024. The obtained results based only on simulation of particle transport through VD. However, to carry out a full analysis of the acceptance and reconstruction efficiency of the NA61/SHINE experimental setup, it is necessary to include TPCs in the simulation as well.

In conclusion, the performed analysis gave a better understanding of the upgraded Vertex Detector and showed areas of the reconstruction chain that need to be fine-tuned.

The further analyzes will be dedicated to simulations of the full detection system, i.e. including TPCs. This will allow us to find the optimal values of some quantities such as the position of the arms in Vertex Detector, which will be used in measurements in years 2024-2025. However, the most important part of my future work on simulations with the full detection system (VD and TPCs) will be the demonstration of D^0 meson reconstruction in the particle background utilizing background suppression cuts using topological information provided by the Vertex Detector.

Chapter 12

Appendix

12.1. The SAVD setup



Figure 12.1: The computer model of Vertex Detector in NA61/SHINE. [25]

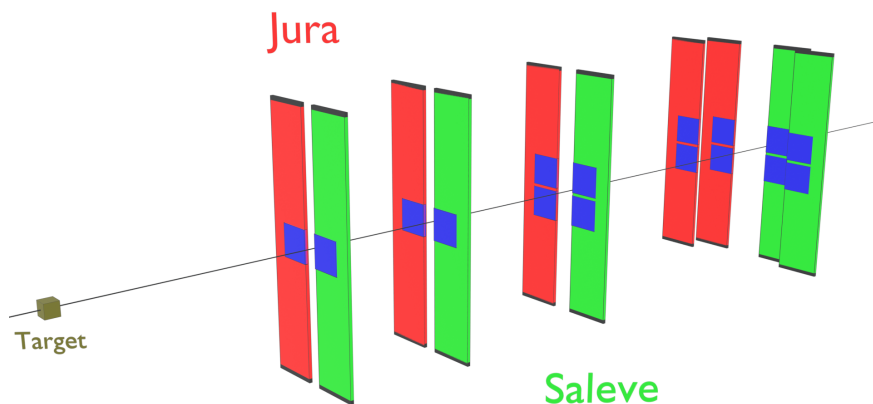


Figure 12.2: Layout of sensors used in SAVD (blue rectangles). The corresponding arms (Jura and Saleve) are marked in red and green.

12.2. The upgraded VD setup

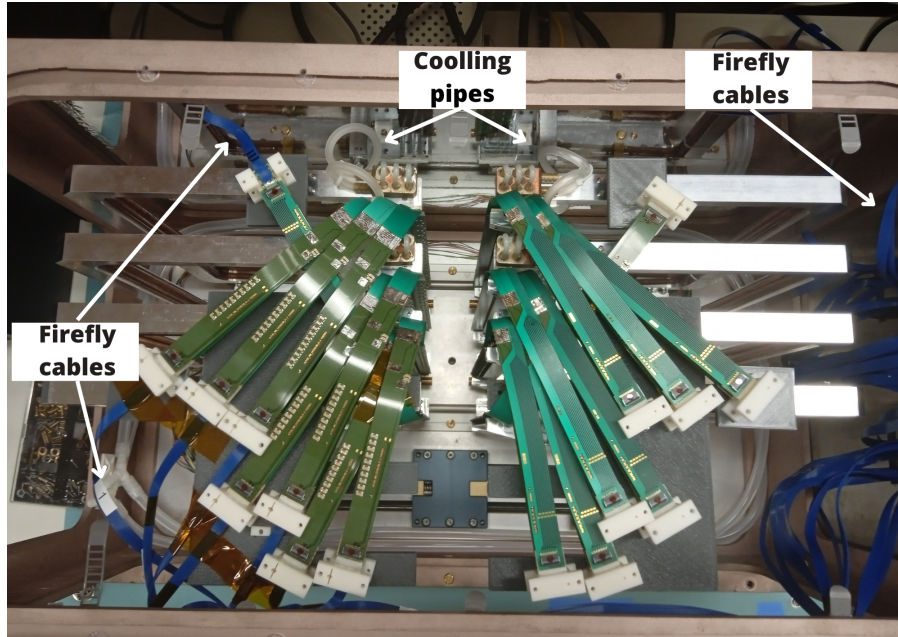


Figure 12.3: Photo shows the inner section of the VD detector with marked components. The picture was taken in April 2022.

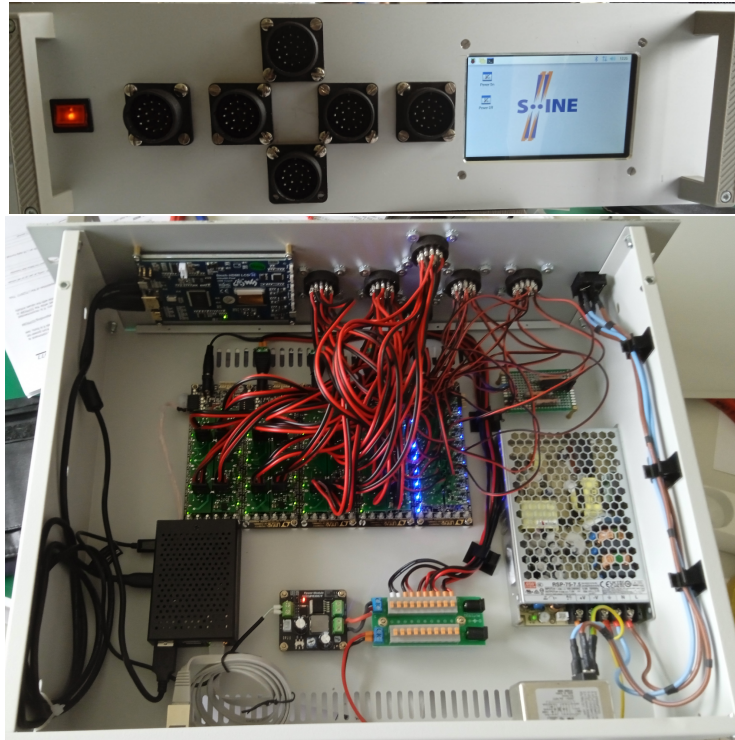


Figure 12.4: Top picture shows the front pannel, while the bottom picture shows the inside of the LV PSU. The pictures were taken in April 2022.

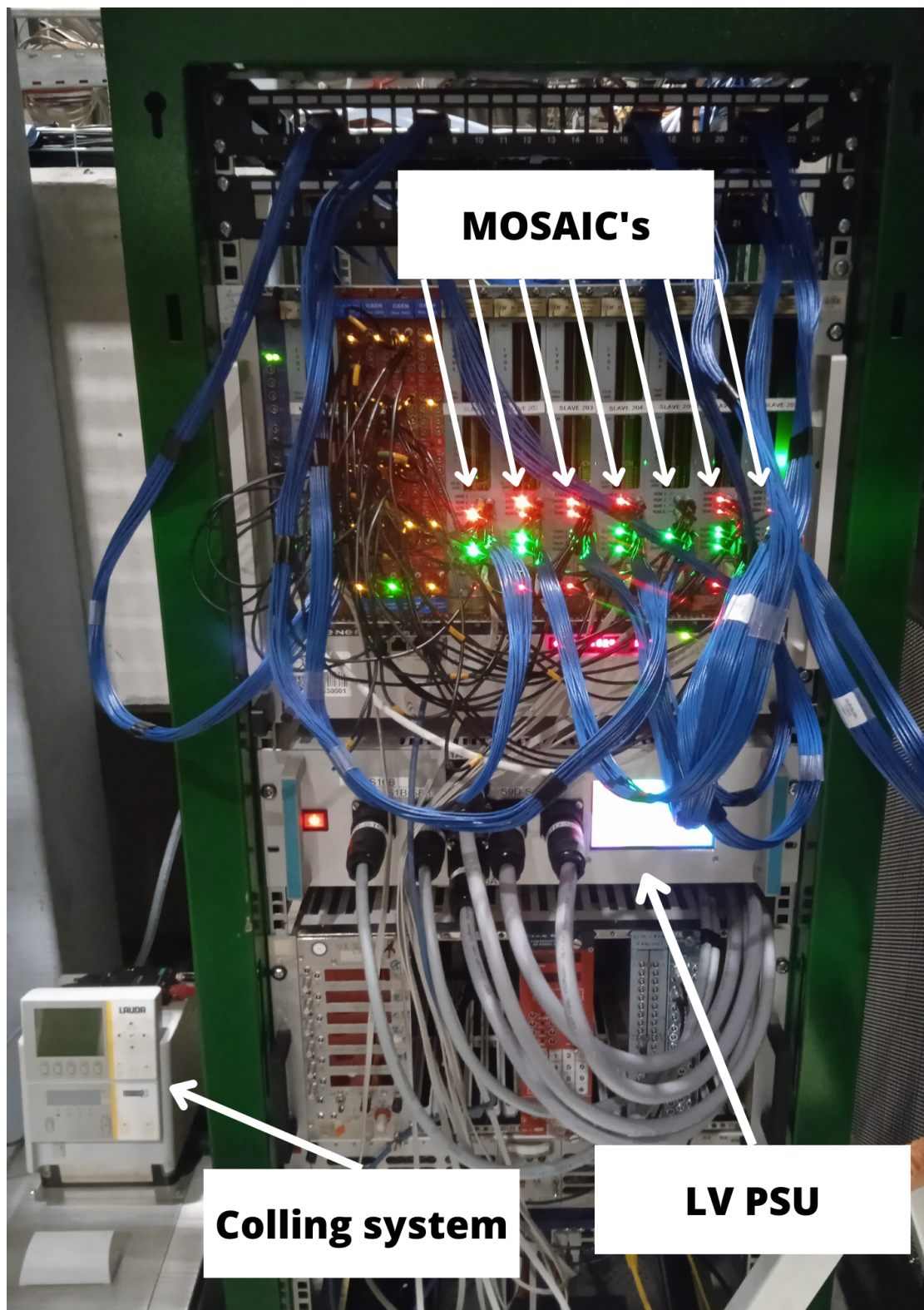


Figure 12.5: The picture shows the rack with marked components: colling system, MOSAIC boards, and LV PSU. The picture was taken in April 2022.

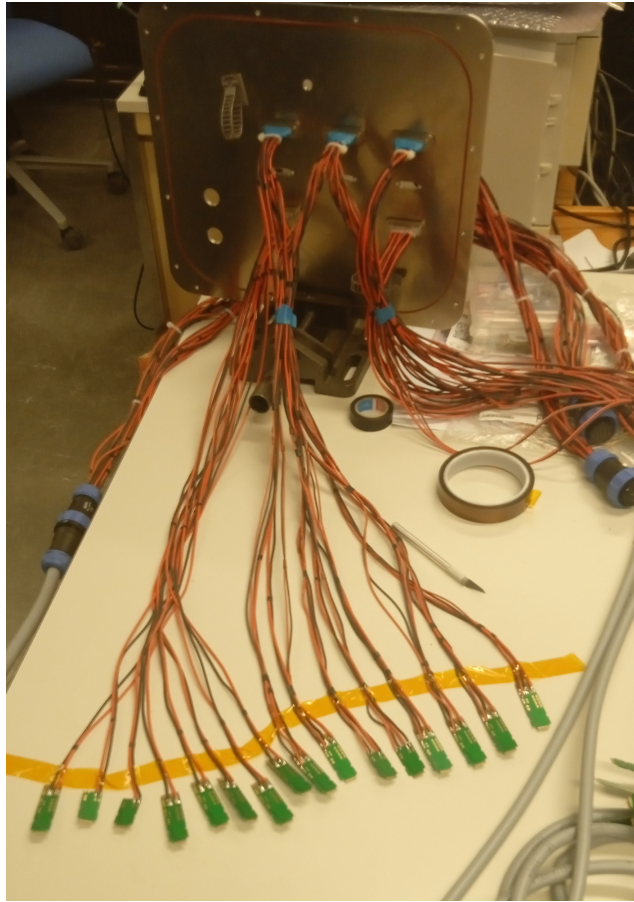


Figure 12.6: The photo shows one of the electrical tests of LV cabling for APLIDE staves installed in MAVD. The picture was taken in April 2022.

12.3. The upgraded reconstruction chain in VD

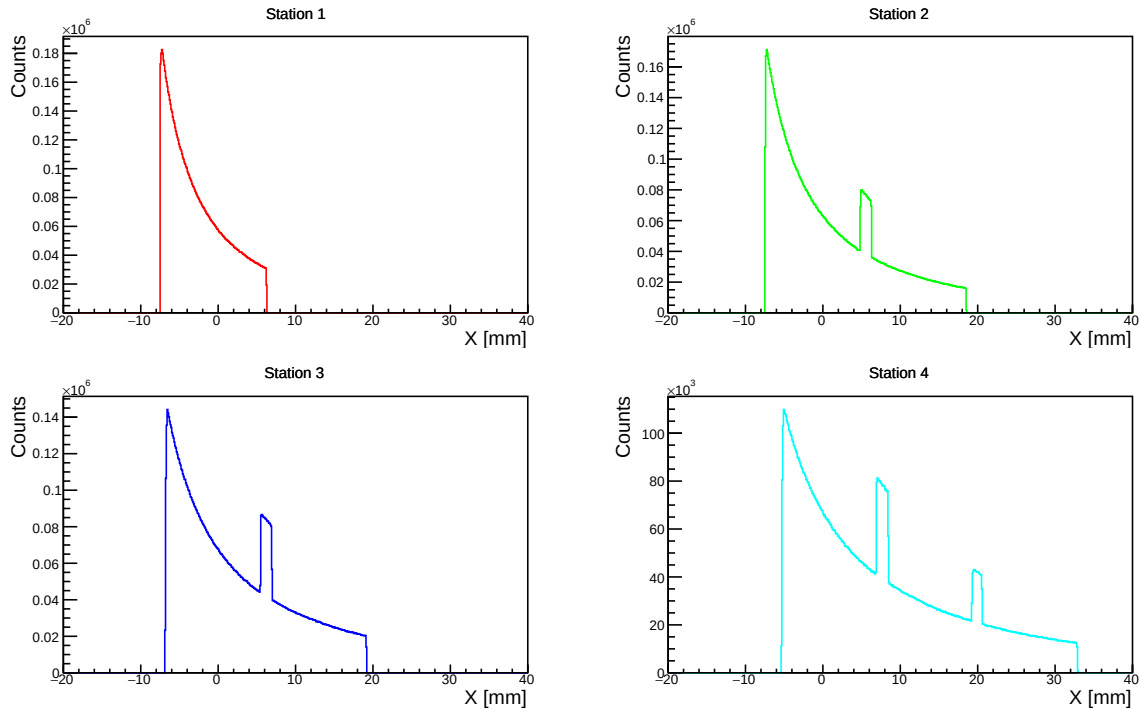


Figure 12.7: The x component of clusters distributions in the Jura arm stations.

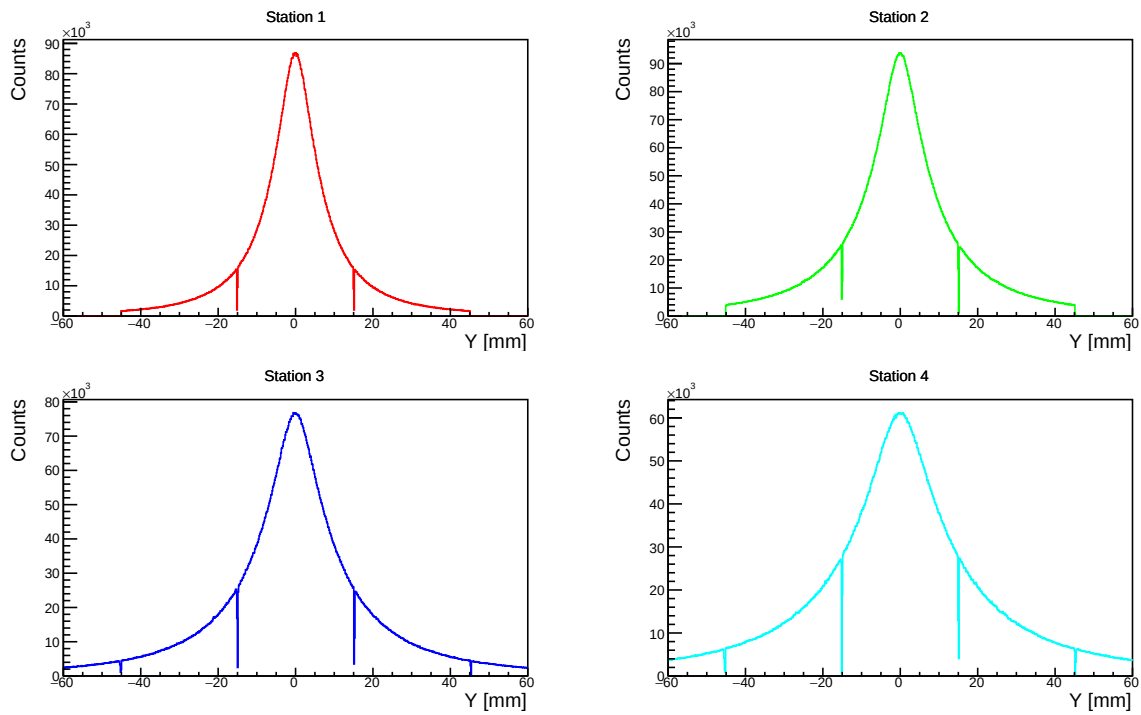


Figure 12.8: The y component of clusters distributions in the Jura arm stations.

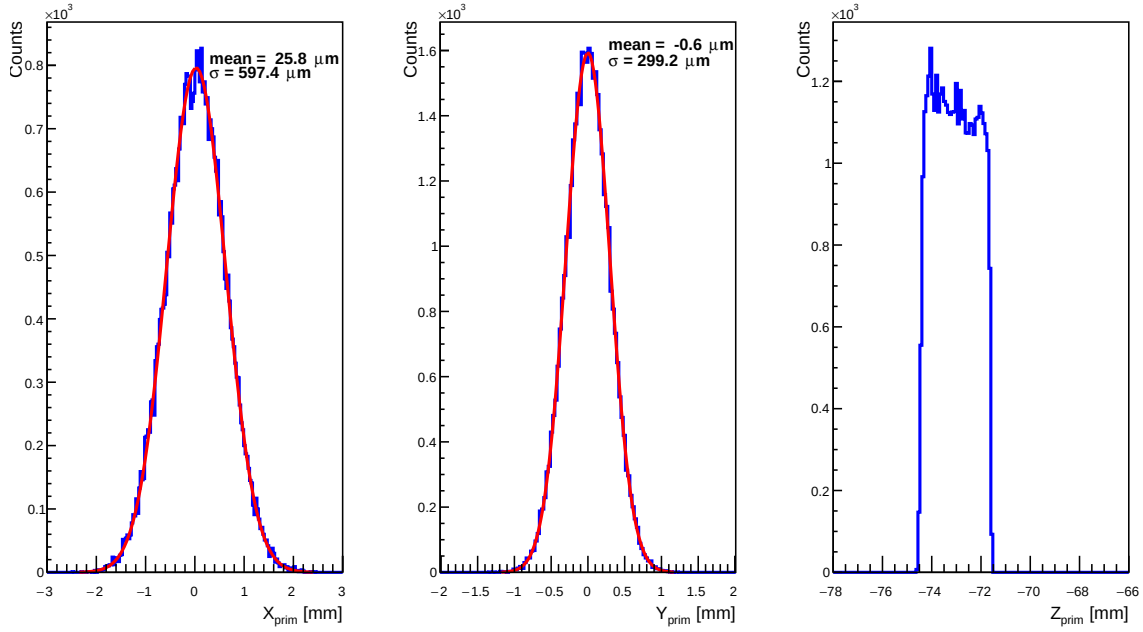


Figure 12.9: The x , y , and z components of the primary vertex. The z component is relative to the location of the first station.

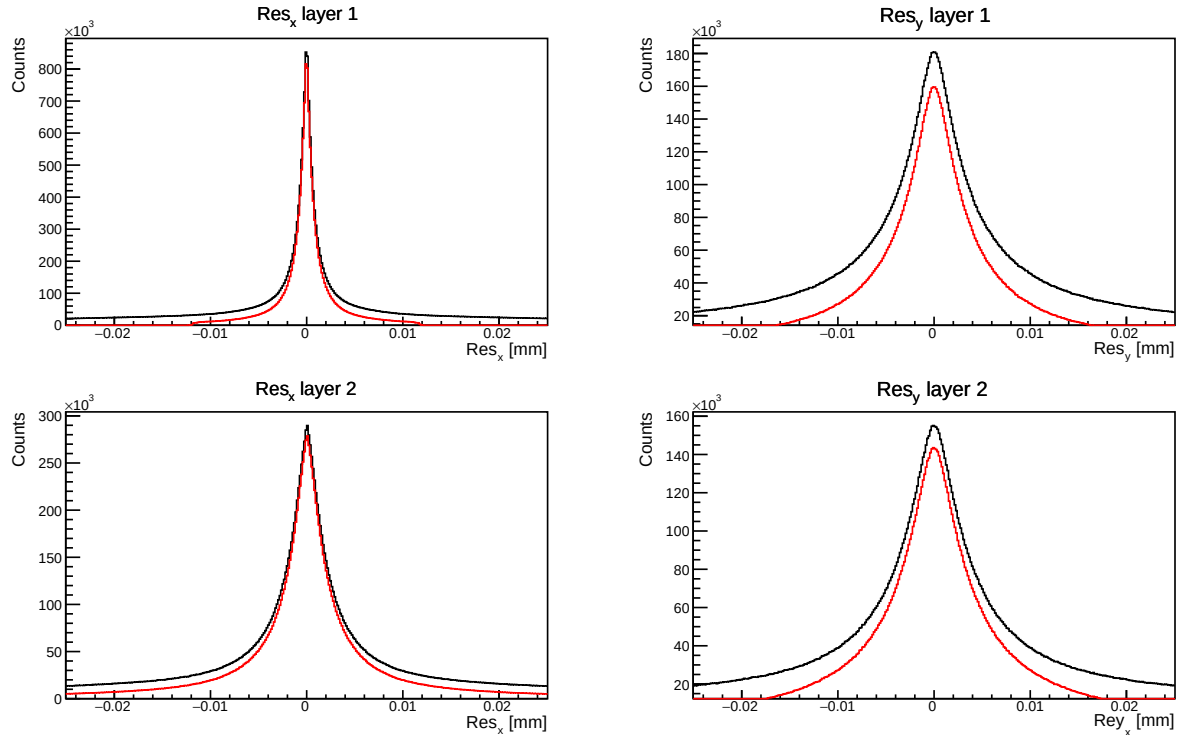


Figure 12.10: The residual distributions of layers constructed in the AIVdTrackingHTModule. The red line represents distributions after cuts. Part 1.

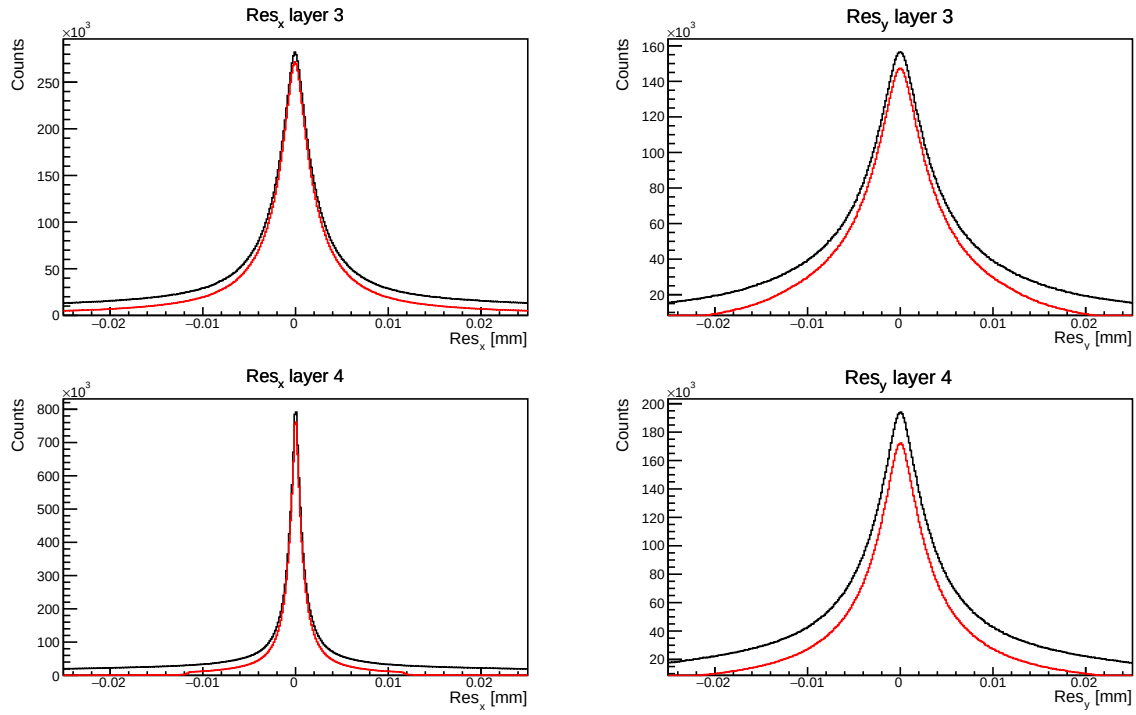


Figure 12.11: The residual distributions of layers constructed in the AIVdTrackingHTModule. The red line represents distributions after cuts. Part 2.

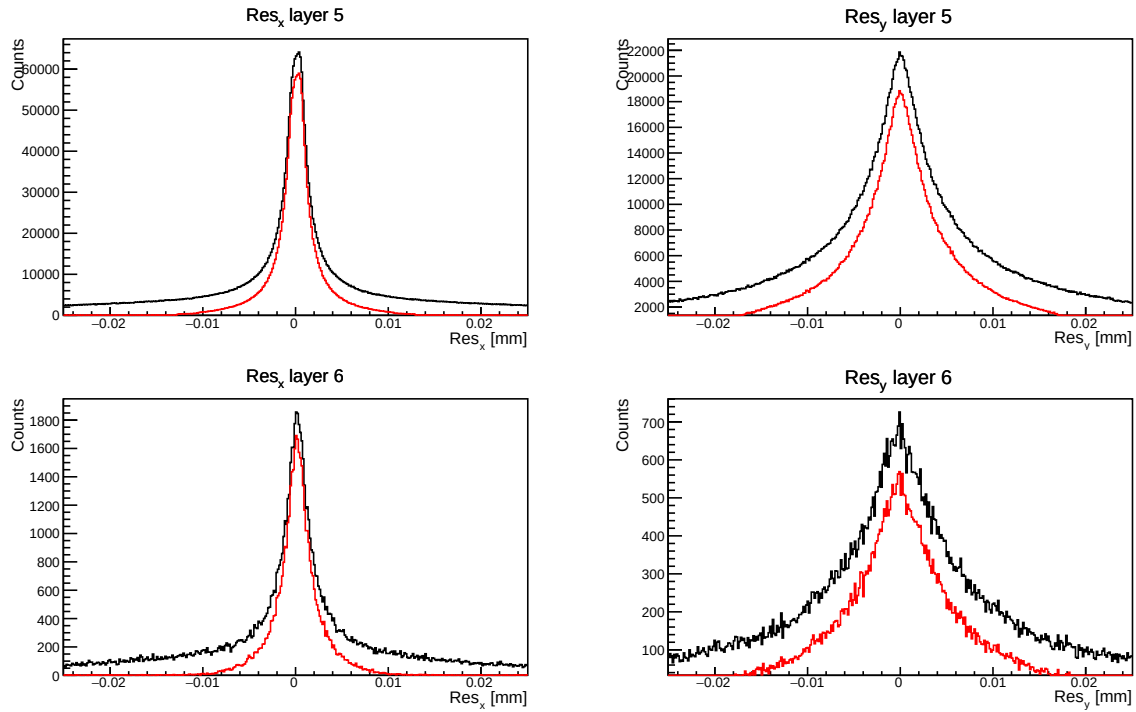


Figure 12.12: The residual distributions of layers constructed in the AIVdTrackingHTModule. The red line represents distributions after cuts. Part 3.

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