Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

Analysis and interactive visualization of neutrino event topologies registered in the OPERA experiment.

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Once again, thank you for this wonderful opportunity. I will always be grateful for the valuable lessons and experiences that I have gained during my time at JINR.

Abstract

Neutrinos are elusive particles that are difficult to detect and can pass through matter almost undisturbed. In our project, we will discuss phenomenon of neutrino oscillation, which implies that neutrinos have non-zero mass and can change their flavor as they move through space. The OPERA experiment, designed to study neutrino oscillations, was based on a hybrid technology combining electronic detectors and nuclear emulsions. This report presents an analysis of several OPERA datasets collected during the experiment, which are available on the CERN Open Data Portal. The presented results were obtained with help of C++ programs using the CERN ROOT data analysis framework. In addition, JavaScript, HTML, and CSS were used to visualize typical topologies of OPERA tau-neutrino interaction events in a web browser.

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Chapter 1

Introduction

Apart from photons, Neutrinos are subatomic particles that are like electrons but have no electric charge and a very small mass. They are produced in a variety of nuclear reactions and are abundant in the universe, with billions of them passing through your body every second without you even noticing.

Neutrinos are challenging to detect because they interact very weakly with matter, but specialized detectors have been developed to study their properties. These detectors have helped scientists learn more about the fundamental nature of the universe, including the behavior of matter at very high energies and the composition of the sun's core.

It has been discovered through multiple experimentation that neutrinos change their flavor as they move through space. There are three types of neutrino flavors: muon, tau, and electron, which are related to the interactions in which they participate. This flavor switching is a quantum mechanical phenomenon, and the term "neutrino oscillation" describes how the probability of a neutrino changing from flavor $\nu\alpha$ to flavor $\nu\beta$ oscillates with the distance traveled, whether in a vacuum or through matter.

Experiments conducted in the late 1990s confirmed the existence of neutrino oscillations, and this discovery led to the realization that neutrinos must have mass, which was previously thought to be zero. The study of neutrino oscillations is an active area of research, as scientists seek to better understand the mechanisms that drive these changes in flavor and the implications for our understanding of the universe.

Chapter 2

OPERA Experiment

One of the key experiments to study neutrino oscillations phenomenon was OPERA experiment, which is the phenomenon where a neutrino changes from one flavor to another as it travels through space.

OPERA was a long baseline experiment, designed to perform the first observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode.

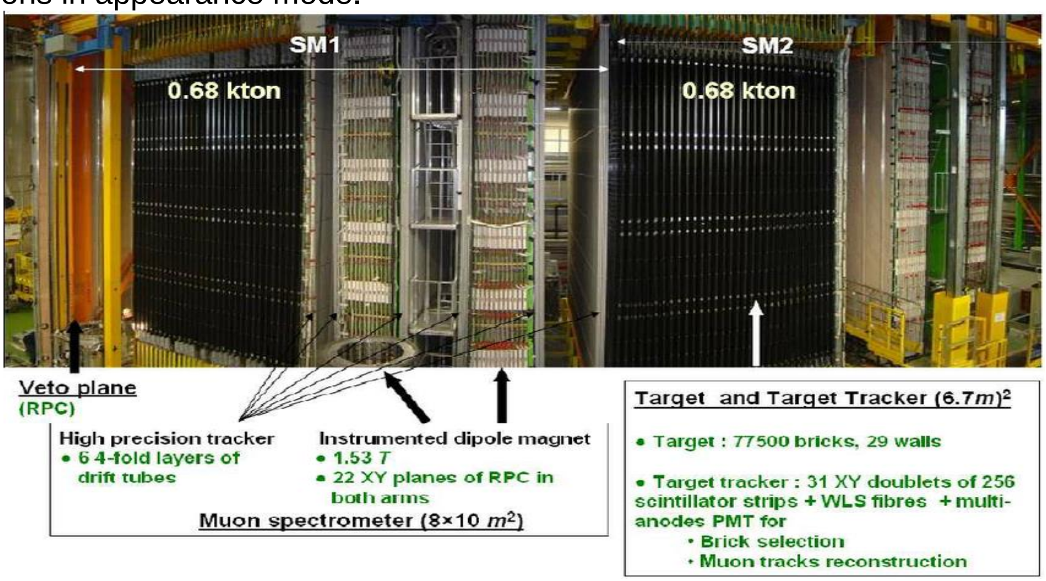

Figure 2.1: OPERA detector

The experiment used a high-intensity and high-energy beam of muon neutrinos generated at the CERN SPS in Geneva, which was sent through the earth to the LNGS underground laboratory in Gran Sasso, located 730 kilometers away in central Italy.

The CNGS beam was composed mostly of muon neutrinos, with a mean energy of around 17 GeV and 2.1% electron (anti-)neutrino contamination. The experiment detected neutrinos using a large hybrid detector that consisted of two identical Super-Modules, each made up of 29 target walls interleaved with a double layer of plastic scintillators (called Target Trackers or TT) that allowed for the real-time identification of charged particles emitted from the target.

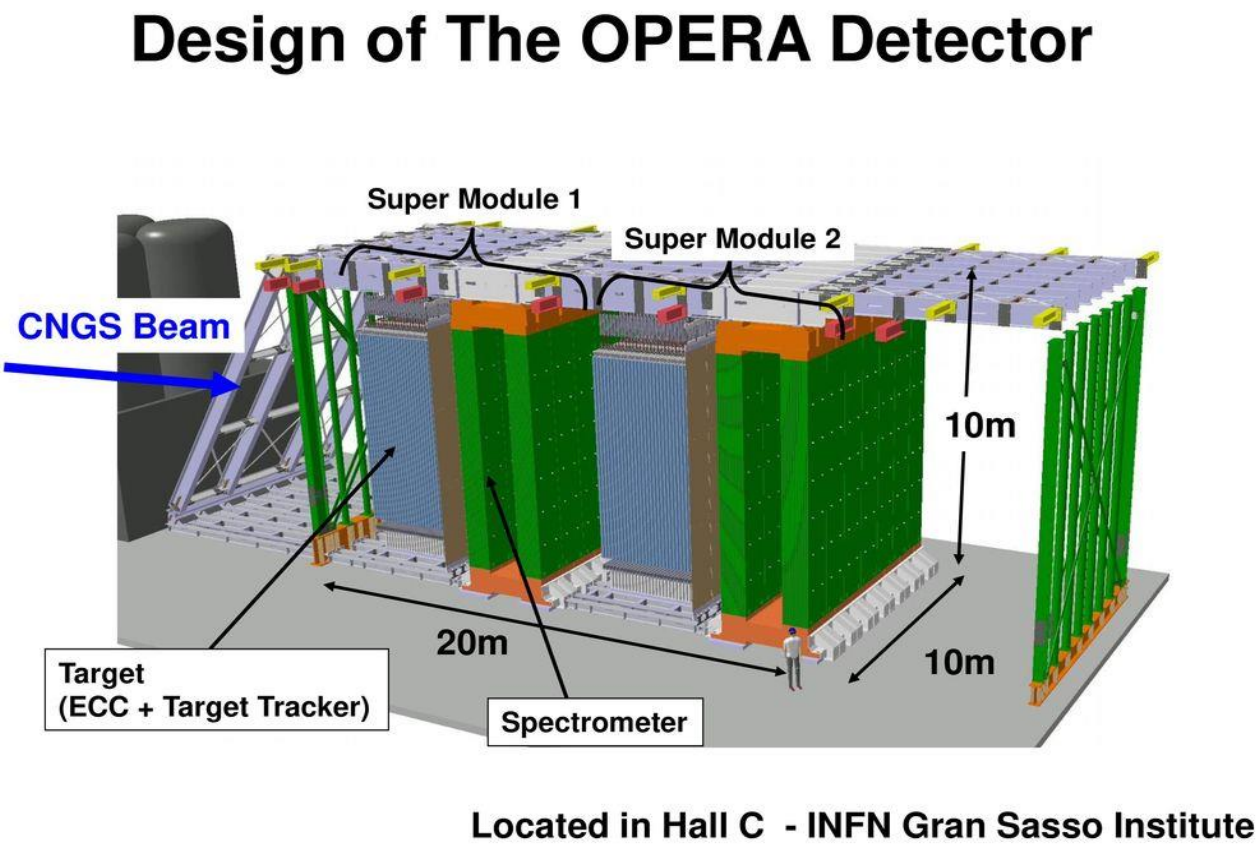

Figure 2.2: Design of the OPERA detector

In addition to the Target Trackers, the detector also included a Resistive Plate Chamber (RPC), placed in front of the first super module to tag the interactions occurring in the rock surrounding the experimental set up, and a magnetic spectrometer. The Target Section of each Super-Module included approximately 75,000 target units (called bricks).

2.1. CERN Open Data Portal

The CERN Open Data Portal is an online platform that provides free and open access to scientific data generated by CERN's experiments. The portal was created in 2014 in collaboration with CERN IT and the CERN Scientific Information Service, and its purpose is to promote transparency, collaboration, and scientific progress by making CERN's research data widely available to the public. The portal offers various types of data, such as experimental results, detector performance, and simulation data, along with the software and documentation needed to understand and analyze the data. The CERN Open Data Portal is a valuable resource for scientists, researchers, students, and anyone interested in exploring the mysteries of the universe.

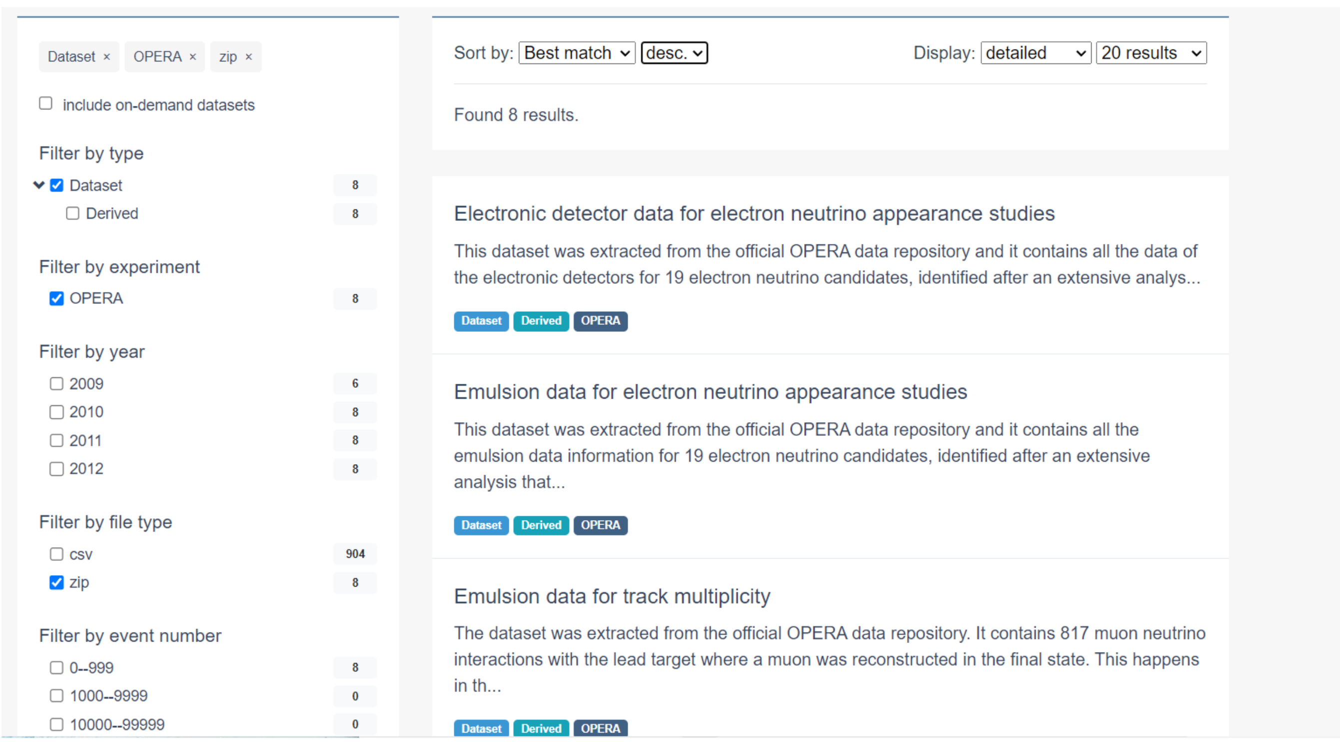

Fig 2.1.1: Interface of CERN Open Data Portal

Chapter 3

Results and discussion

3.1. Task 1

The objective of Task 1 was to analyze the emulsion data for the study on neutrino-induced charmed hadron production.

3.1.1 Flight Length of charmed hadron

Flight length (or decay length) of a charmed hadron is just a distance between the primary and the secondary vertices of neutrino interaction event, i.e., the distance between twopoints in 3D space before the particle decays into other particles.

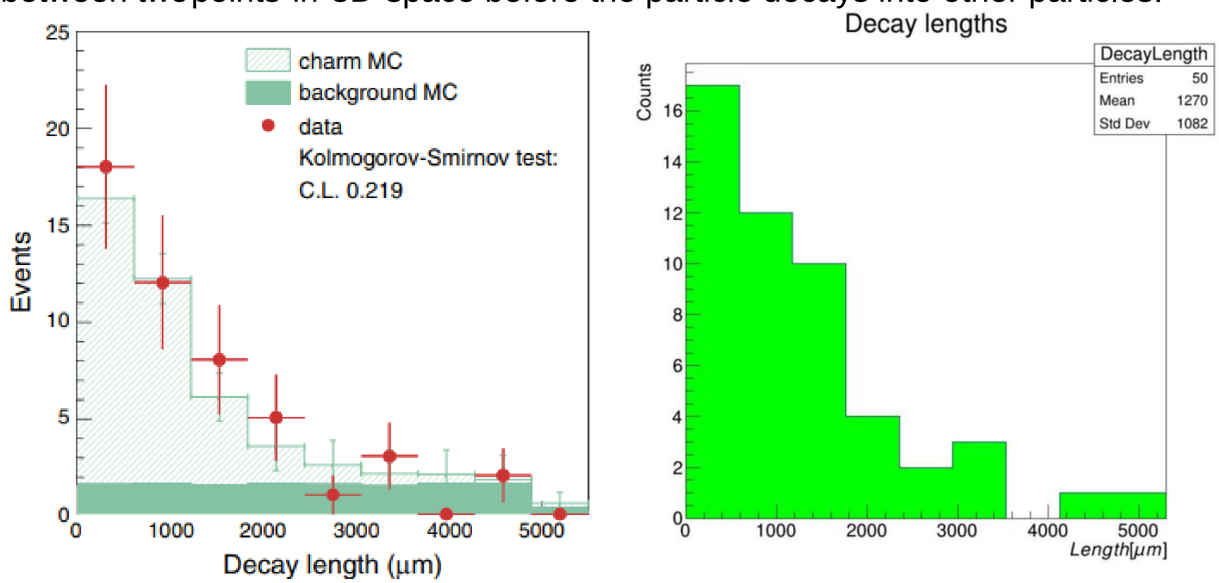

Figure 3.1: Flight Length of the charmed hadrons

If the primary vertex's coordinates are (x_1, y_1, and z_1) and the secondary vertex's coordinates are (x_2, y_2, and z_2), respectively, the flight length may be calculated as follows:

$$Flight\ Length = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

The EventIDVertices.csv file from the CERN Open Data Portal was utilized to obtain the local coordinates of the primary and secondary vertices, and a C++ program was used to extract this information from each file. Using the formula, the flight lengths were computed for each event and subsequently saved to a histogram. The histogram has been plotted using ROOT software. In Figure 3.1, the obtained histogram (right) is compared with the one published by OPERA (left) [1].

3.1.2 Impact Parameter of the daughter particle tracks with respect to the primary vertex

The term impact parameter comes from the physics of high-energy particle collisions. This is a measure of how close the track of a given particle comes to the primary neutrino interaction vertex.

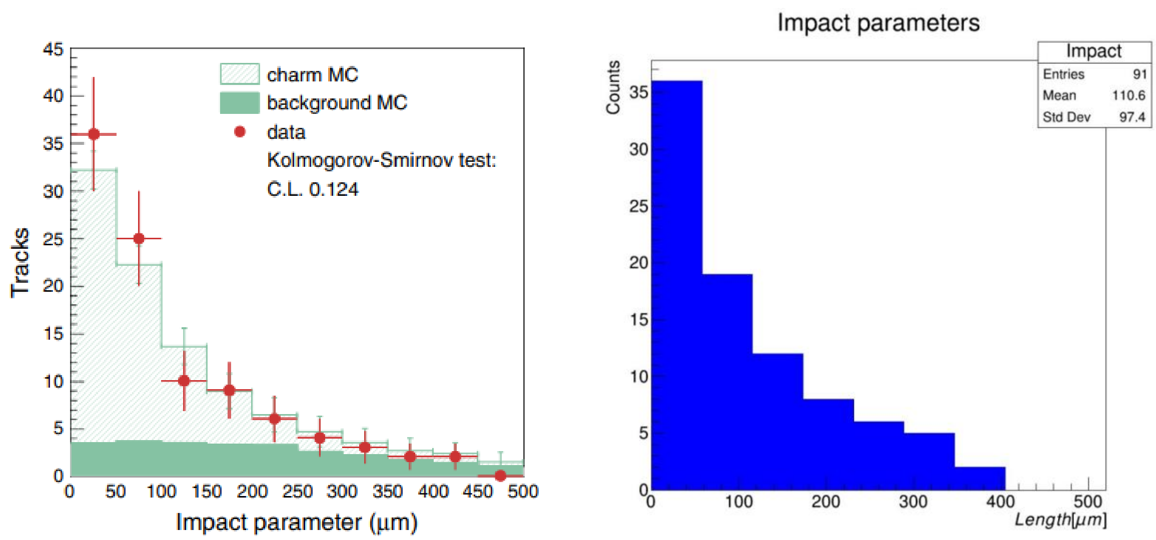

Figure 3.2: Impact Parameter of daughter tracks in reference to primary vertex

Impact parameter can be calculated using below mentioned formula:

$$I.P. = \frac{\left|\vec{e_r} \times \vec{A}\right|}{|e_r|}$$

To calculate the impact parameter, we need to first obtain the vector distance $\vec{A}$ between the primary vertex and the daughter track, as well as the direction vector e_r of the daughter track. The coordinates for the primary vertex can be found in the EventIDVertices.csv file, while the coordinates for the daughter track can be found in the EventIDTracklines.csv file. Once we have calculated the vector distance $\vec{A}$, we can use the formula mentioned above to obtain the impact parameter. In Figure 3.2 the obtained data from OPERA has been compared with the published data; Impact parameter histogram has been plotted using ROOT software.

3.2. Task 2

In this task an OPERA emulsion dataset related to the study of charged hadron multiplicity was used, which is available on the Open Data Portal.

3.2.1 Multiplicities of all produced charged particles

In our scenario, track multiplicity refers to the number of charged particle tracks that are linked to a particular vertex, which is associated with the primary interaction vertex of the muon neutrino.

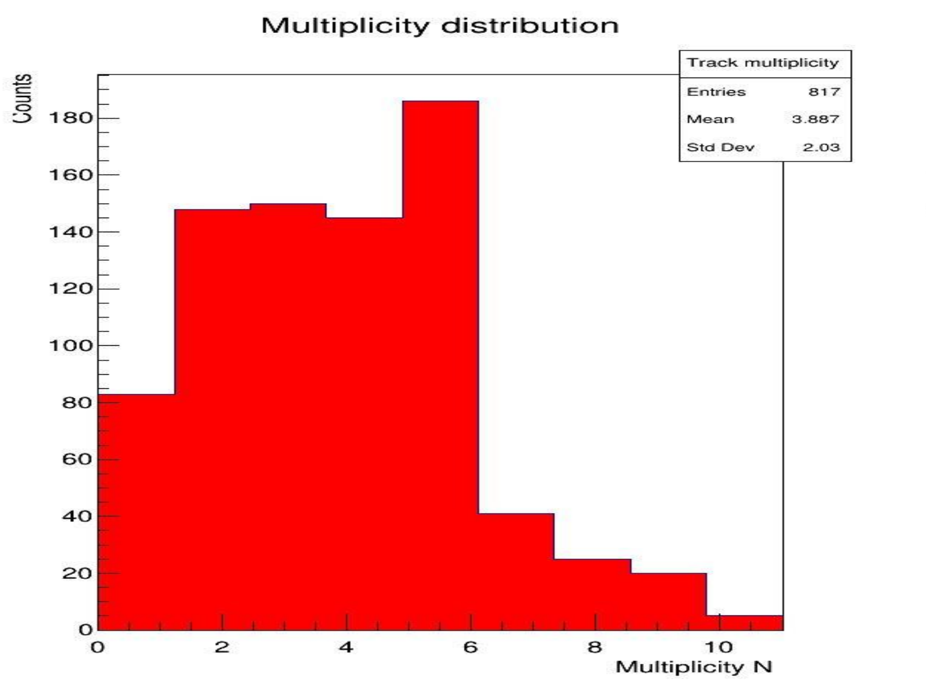

Figure 3.3: Track multiplicity distribution

The EventIDvertex.csv file contains information on the number of charged particles produced in a neutrino interaction with lead target. A C++ code was used to read the track multiplicity associated with each event, and the extracted values were saved to a ROOT histogram. The resulting plot is shown in Figure 3.3.

3.2.2 The angles of the muon tracks

The angle of the muon tracks can be calculated using the below mentioned mathematicalformula:

$$\theta = \tan^{-1}(m)$$

Where, m = Slope and θ = the angle of the muon track in radians.

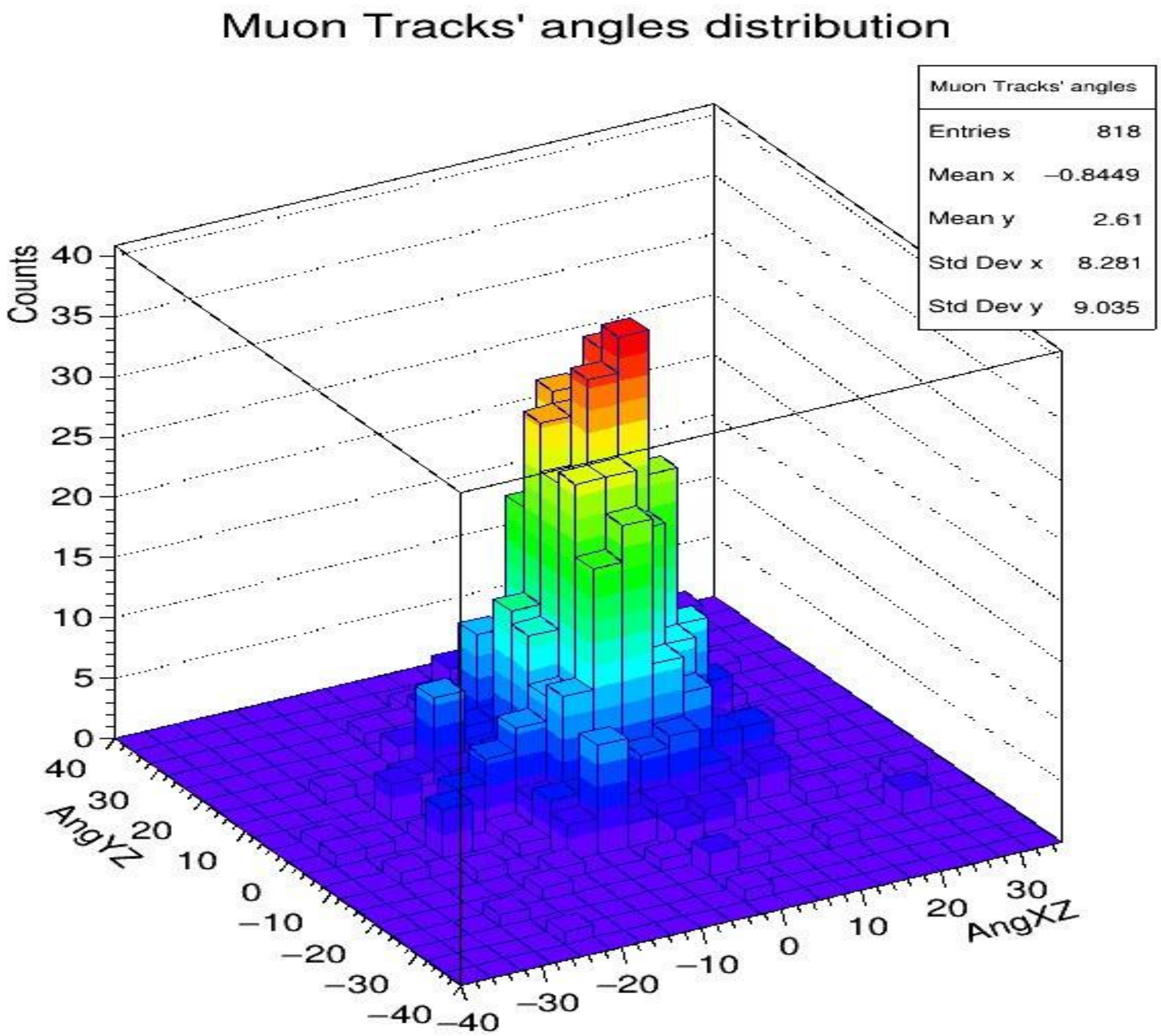

Figure 3.4: Muon track angles

The slopes of muon tracks in XZ and YZ views were read using the C++ code. For each event, the angle of the muon track was computed using the above-mentioned mathematical formula and saved to a ROOT histogram. The obtained plot for Muon track angles is shown in Figure 3.4.

3.3. Task 3

3.3.1 Emulsion Data for Tau Neutrino Appearance Studies

For OPERA emulsion dataset related to tau neutrino appearance study, a 3D visualization was created. As it was said in the OPERA publication [3] topological and kinematical cuts were applied to a sample of 5603 reconstructed neutrino interactions, and 10 ν_τ candidate were selected. To visually represent interesting topologies of the found events in a web-browser, the THREE.js JavaScript library was used. Figure 3.5 shows reconstructed Tracks and Vertices for 4 out of the 10 tau neutrino candidate events.

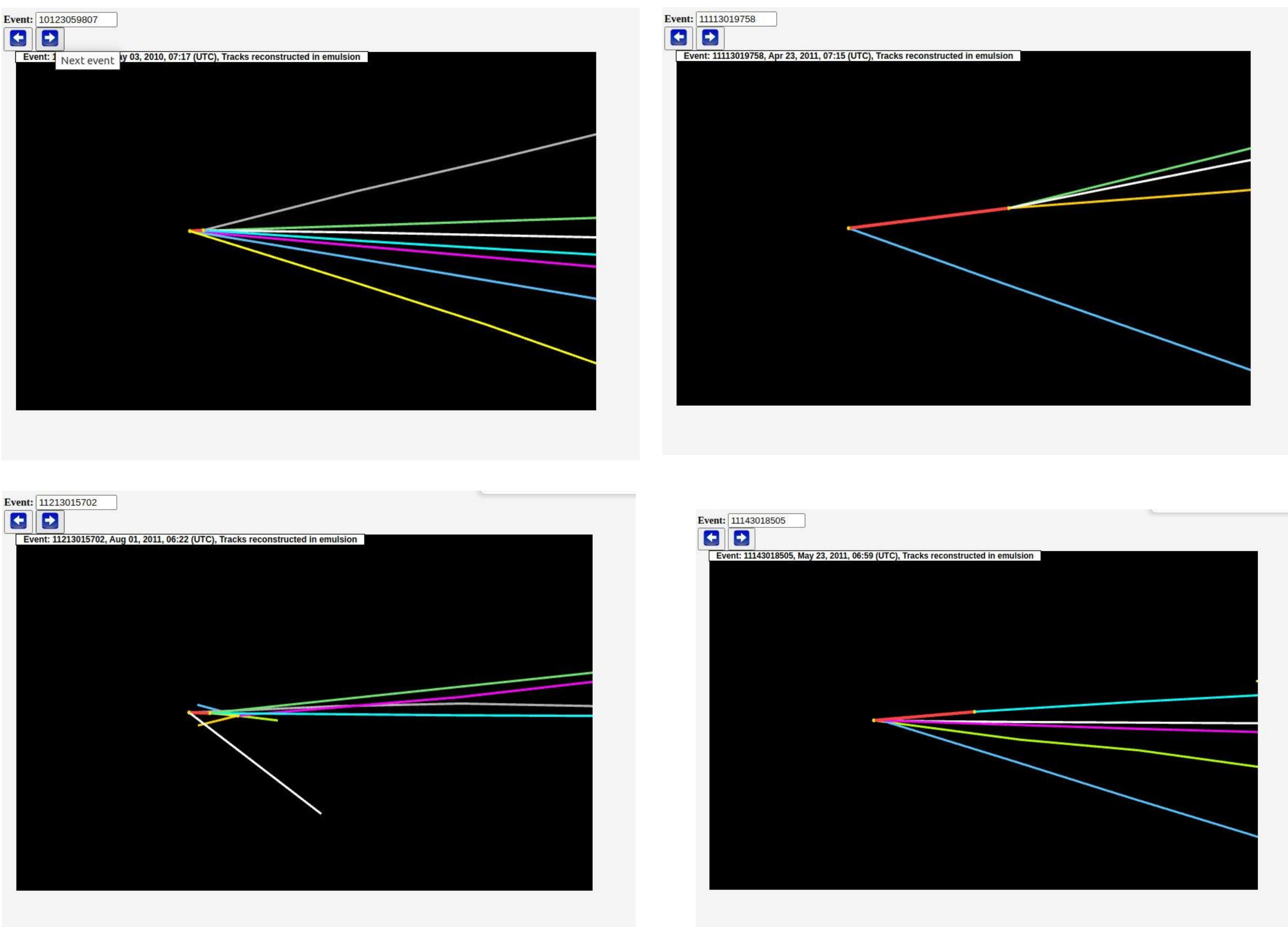

Figure 3.5: Tracks reconstructed in emulsion

Chapter 4

Summary and conclusion

This project involved analyzing several OPERA datasets available on the CERN Open Data Portal using C++ applications and CERN's ROOT libraries. The work was divided into three parts. In Part 1 (Task 1) of the project, the focus was on calculating the flight lengths of charmed hadrons and the impact parameters of their daughters relative to the primary neutrino interaction vertex. This information is important for understanding the properties and behavior of the charmed hadrons produced in neutrino interactions. To perform this analysis, C++ applications utilizing CERN's ROOT libraries were used. The results of this analysis can provide insights into the production and decay of charmed hadrons in neutrino interactions. In Part 2 (Task 2) of the project, the focus was on obtaining the distributions of the track multiplicities of charged particles and the angles of the muon tracks in the OPERA dataset. This information is of considerable interest for understanding the behavior of charged particles produced in neutrino interactions and for studying the properties of the muons produced in these interactions. To perform this analysis, C++ applications utilizing CERN's ROOT libraries were used. The obtained distributions were then compared to the published results, and it was found that they were in good agreement. This indicates that the analysis performed in this project is accurate and reliable. In Part 3 (Task 3) of the project, a simplified version of the OPERA browser-based event display was used and modified to visualize interesting topologies of neutrino interaction events from the OPERA nu_tau-candidate sample. Comparing the images obtained in this task with those on the Open Data Portal provides a deeper understanding of the neutrino interactions that took place in OPERA and deepens our understanding of particle physics.

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