JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problem

FINAL PROJECT REPORT ON THE INTEREST PROGRAMME

# Analysis and Interactive Visualization of Neutrino Event Topologies Registered in The OPERA Experiment


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# Abstract

In this project, we discussed a previous long-running mystery of solar neutrinos which was explained by a phenomenon called neutrino oscillation. And the OPERA experiment, which studied the neutrino oscillation in appearance mode, i.e. studied the data only about the neutrinos which had changed their flavor, which in this case was $\nu_\mu \longrightarrow \nu_\tau$. We have used the dataset for the OPERA experiment from CERN open data portal and developed consequent C++ codes for analysis of the data. We have further used CERN's ROOT library to plot the analyzed data. Further, we have also used JavaScript, HTML, and CSS to create a web browser-based visualization of results from the OPERA emulsion and electronic detector data.

# Acknowledgement

I would like to extend my gratitude towards my project supervisor **Dr. Sergey Dmitrievsky**, who guided and helped me undertake this project, especially during these difficult times. I would like to take this opportunity to thank him for his invaluable guidance, constant encouragement, and comments, which help sustained my efforts at all stages of this project work.

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A sincere thanks to **JINR INTEREST Team** also, to introduce this program and for providing me and students all around the globe with this opportunity, and for the smooth overseeing of the program. Throughout our project work, I have gained immense knowledge which would help us in the coming years.

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# Chapter 1

# Introduction

## 1.1 Neutrinos

In the collection of elementary particles, lies a family of particles called leptons. Which consist of electron(e), muon particle($\mu$) and tau particle($\tau$). and their corresponding electron neutrino($\nu_e$), muon neutrino($\nu_\mu$) and tau neutrino($\nu_\tau$).

neutrino is an elementary particle with no electric charge, very less mass, and $1/2$ unit of spin. Neutrinos are one of the most abundant particles in the universe. As they have very little interaction with matter, they are incredibly difficult to detect. To detect neutrinos, very large and very sensitive detectors are required. Typically, a neutrino will travel through many light-years through the normal matter before interacting with anything. Consequently, all terrestrial neutrino experiments rely on measuring the tiny fraction of neutrinos that interact in reasonably sized detectors. [1] [2] [3]

## 1.2 Solar Neutrino Problem

The flux of neutrinos at Earth should be several tens of billions per square centimeter per second, produced mostly at the sun's core. Neutrinos are very hard to detect because they interact very weakly with matter. Out of the three types (flavors) of neutrinos known in the Standard Model of particle physics, the Sun produces only electron neutrinos. When neutrino detectors measured the flow of electron neutrinos from the Sun, the number detected was much lower than the theoretically predicted value. Various experiments were conducted but the results were similar, the number deficit was between $1/2$ to $2/3$ of the expected value.

The solar neutrino problem concerned a large discrepancy between the flux of solar neutrinos as predicted from the Sun's luminosity and as measured directly. The discrepancy was first observed in the mid-1960s and troubled physicists till the early 2000s. However, in 1968 Pontecorvo proposed that if neutrinos had mass, then they could change from one flavor to another. Thus, the ”missing” solar neutrinos could be electron neutrinos which changed into other flavors along the way to Earth, rendering them invisible to the detectors.

Several experiments were conducted and with advancements in technology, acceptable results which align with the proposed theory started to appear. Various scientists involved in these experiments received the Nobel Prize in Physics. [4]

## 1.3 Neutrino Oscillations

Neutrino Oscillation is a phenomenon of the change of flavor of a neutrino into another while traveling long distances. It is an important phenomenon in particle physics as it provides that neutrinos have a finite mass which is in disagreement with the Standard Model of Particle physics. The Standard Model defines three flavors of neutrinos $\nu_\alpha$, $\alpha$ = e, $\mu$ and $\tau$. The proposed theory of neutrinos undergoing a change in flavor on propagating long distances has been experimentally confirmed. This phenomenon of transition between different neutrino flavors is termed Neutrino Oscillations. The first compelling data for the same came from Super-Kamiokande Collaboration, Japan, and was further verified by other experiments as well, like SNO collaboration, Canada, the Sudbury Neutrino Observatory, OPERA collaboration, and many more.

Neutrinos are generally produced in high-energy nuclear reactions and decay processes of heavy nuclei. After production as neutrino travels, wave function and eigenstates associated with it evolves and due to these quantum effects, the flavor of a neutrino can change. The mathematics behind this phenomenon has been well explained [5], The expression for the probability of $\nu_e$ to be detected as or changed into $\nu_\mu$ in a vacuum is

$$P\left(\nu_e \longrightarrow \nu_\mu\right) = \sin^2(2\theta)\sin^2\left(\frac{m_1^2 - m_2^2}{4E}L\right) \tag{1.1}$$

Where, L is the distance traveled, E is the energy of the neutrino, $m_i, i \in 1,2$ are the mass eigenstates and $\theta$ is the mixing angle.

# Chapter 2

# OPERA Experiment

## 2.1 The OPERA Experiment

In this project, we aim at analyzing the data provided by the OPERA experiment. The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) [6] was a scientific experiment designed to detect the first observation of a $\nu_\tau$ from a $\nu_\mu \rightarrow \nu_\tau$ oscillation by implementing a long-baseline beam from CERN to Gran Sassa Laboratory (LNGS), 730 km away. The CNGS beam consists mainly of $\nu_\mu$ with an energy of 17 GeV. The beam also contain a very small amount of contamination of 2.1% of $\nu_\mu$ charged current events and 0.9% of $\nu_e$ [7].

The experiment was a collaboration between the European Organization for Nuclear Research (CERN), Switzerland, and Laboratori Nazionali del Gran Sasso (LNGS), Italy. The OPERA detector was exposed to the high intensity ($2.4 * 10^{13}$ protons on target per pulse) and high energy (400 GeV) CERN Neutrinos to Gran Sasso (CNGS) neutrino beam. A beam of this type was generated in the Super Proton Synchrotron, CERN by the collision of accelerated protons with a graphite target. The secondary particles produced (pions and kaons in particular) were focused in the desired direction. These particles further decay into muons and $\nu_\mu$ which in turn travel in the direction identical to the parent particle. This high-energy $\nu_\mu$ beam produced at SPS, CERN was then directed towards the OPERA detector situated in Gran Sasso underground laboratory (LNGS), 730 km away.

The OPERA detector 4 was a hybrid type detector. It had a total volume of 2000 m3 ($10 \times 10 \times 20 m^3$) and was composed of two identical Super-Modules. A Resistive Plate Chambers, (RPC) was placed in front of the first super module to tag the interactions occurring in the rock surrounding the experimental setup. Each Super-Module consists of approximately 75000 bricks along with 31 Tar-

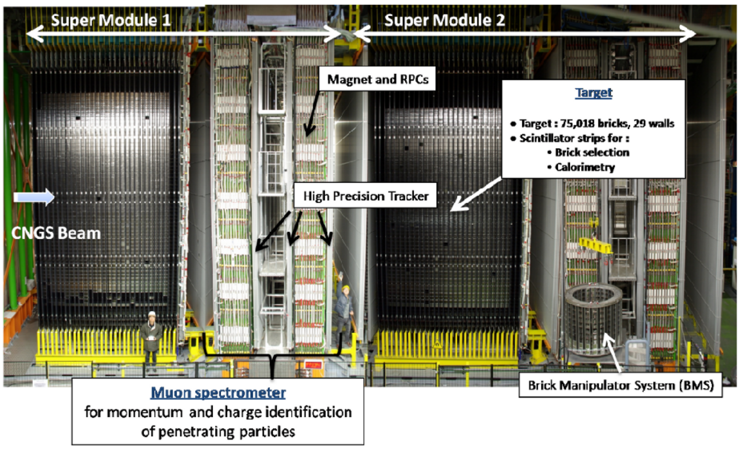



Figure 2.1: The OPERA Detector

get Trackers which couple the bricks arranged vertically in the form of a wall ($6.7 \times 6.7m^2$) which collectively forms the Target Section. An individual emulsion brick was composed of 57 thin emulsion films arranged consecutively with 56, 1 mm thick lead plates. This forms the fundamental unit of the Emulsion Cloud Chamber of the Detector. Below each brick, there was a box containing two changeable emulsion sheets. These sheets form an interface between the Target tracker and the tracks recorded in the bricks. The target section was followed by a magnetic spectrometer for the momentum and charge measurement of muon particles [8].

## 2.2 CERN Open Data Portal

The CERN Open Data portal [**?**] is the access point to a growing range of data produced through the research performed at CERN. It disseminates the preserved output from various research activities and includes accompanying software and documentation needed to understand and analyze the data. The portal adheres to established global standards in data preservation and Open Science: the products are shared under open licenses, they are issued with a Digital Object Identifier (DOI) to make them citable objects. Data levels Data produced by the LHC experiments are usually categorized in four different levels (DPHEP Study Group (2009)):

1. Level 1 data provides more information on published results in publications, such as extra figures and tables.

2. Level 2 data includes simplified data formats for outreach and analysis train-

ing, such as basic four-vector event-level data.

3. Level 3 data comprises reconstructed collision data and simulated data together with analysis-level experiment-specific software, allowing to perform complete full scientific analyses using existing reconstruction.

4. Level 4 data covers basic raw data (if not yet covered as level 3 data) with accompanying reconstruction and simulation software, allowing the production of new simulated signals or even re-reconstruction of collision and simulated data.

The CERN Open Data portal focuses on the release of event data from levels 2 and 3. The LHC collaborations may also provide small samples of level 4 data.

# Chapter 3

# Analysis of Emulsion Data from CERN Open Data Portal

## 3.1 Task 1: Analysis of Emulsion Data of neutrino-induced charmed hadron production

We analyzed emulsion data for neutrino-induced charmed hadron production to assess the validity of the $\nu_\tau$ appearance by studying the production of charmed hadron due to $\nu_\mu$ interactions. Charmed Hadrons have similar masses and a life-time similar to that of  leptons. Thus, they are considered as one of the most possible contamination background resources in the OPERA experiment.

In this article [9] a procedure for short-lived particle detection and selection criteria is described. The selected data sample contained 50 candidate muon neutrino interaction events which were collected in 2008, 2009, and 2010 runs. The data provided the track-lines coordinates of daughter particles, interaction vertices coordinates, and impact parameters of the daughter particles. The data obtained from the CERN Open Data Portal contained the Tracklines and Vertices files corresponding to the 50 neutrino interaction events candidates.

### 3.1.1 Flight Length of Charmed Hadrons

To calculate the Flight Length of the charmed hadron, we need to find the distance between the primary and the secondary interaction vertices. flight length can be easily obtained by using the following equation:

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

Where, d is the flight length, x1, y1 and z1 are the co-ordinates of the primary vertex and, x2, y2 and z2 are the co-ordinates of the secondary vertex.

The local coordinates for primary and secondary vertices given in the *EventIDVertices.csv* file. Using a C++ program, the primary and secondary vertices were read for each file and using the mathematical formula stated above, the flight length for each event was calculated and stored in the a vector object. ROOT was used to plot the histogram for the flight length, which is given below 7.

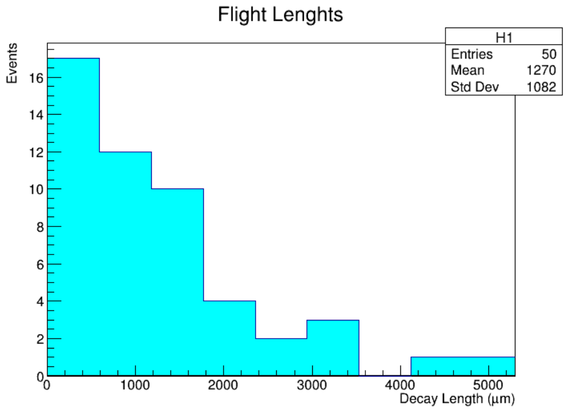



Figure 3.1: Flight Lengths

### 3.1.2 Impact Parameter

For calculation of the Impact Parameter (IP) of the daughter tracks with respect to the primary vertex, we need to find the shortest distance between the primary vertex and the daughter track. To calculate this, we have used the following formula:

$$\mathrm{IP} = \frac{\left\|V_0\vec{V_1} \times V_1\vec{V_2}\right\|}{\left\|V_1\vec{V_2}\right\|} = \frac{\begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ x_1 - x_0 & y_1 - y_0 & z_1 - z_0 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \end{vmatrix}}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}}$$

Where, $V_0(x_0, y_0, z_0)$ are the co-ordinates of the primary vertex, $V_1(x_1, y_1, z_1)$ are the co-ordinates of the secondary vertex, also the first point of the daughter particle track and $V_2(x_2, y_2, z_2)$ second point of the daughter particle track.

Similar to flight length calculation, the coordinates corresponding to the daughter track were given in the *EventIDTracklines.csv* file under the *trtype = 10*, while the local coordinates for the primary vertex were given in the *EventIDVertices.csv* file. Using a C++ program, all the data points were read from the files and using above formula, the Impact Parameter was calculated and stored in the form of a data file. ROOT was used to plot the histogram for the Impact Parameter which is given below 8.

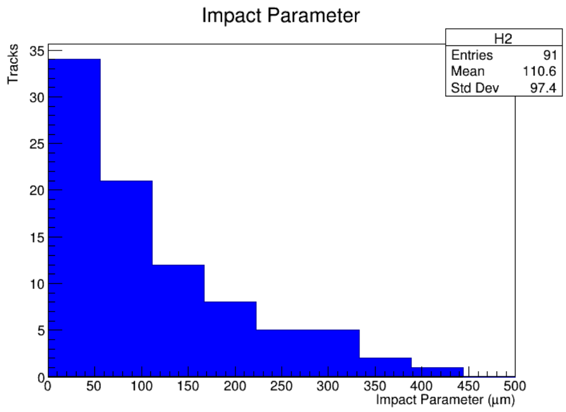



Figure 3.2: Impact parameter

The obtained histograms have been compared with the ones from the original OPERA papers [9] [10] and found to be in a good agreement with the published results.

## 3.2 Task 2: Analysis of charged hadron multiplicities

The multiplicity distribution of charged hardons reflects the dynamics of the interaction. In this task, the emulsion data for track multiplicity of charged hadron was examined. Events stored in this data set were specifically the ones in which a neutrino interaction with a lead target produces a muon in the final state. This data record contains the information on the neutrino interaction vertices including all the emulsion tracks produced in the interactions. [11]

### 3.2.1 Multiplicities of Produced Charged Particles

The interaction of a muon neutrino with the lead nucleus target produces different hadrons and the multiplicity of the hadrons corresponding to a certain event is given in the *EventIDvertex.csv* file. Using a C++ code, the multiplicity was read for each event. The extracted multiplicities were stored in a single data file. Further ROOT was used to plot the histogram for the multiplicities.

The multiplicities can also be calculated using the number of tracks, which were extracted from *EventIDTracklines.csv* file. A similar method was used to obtain the multiplicities and plotting. The plots obtained from both of the methods were the same. Moreover, the results were comparable with the ones published in the OPERA paper 9.

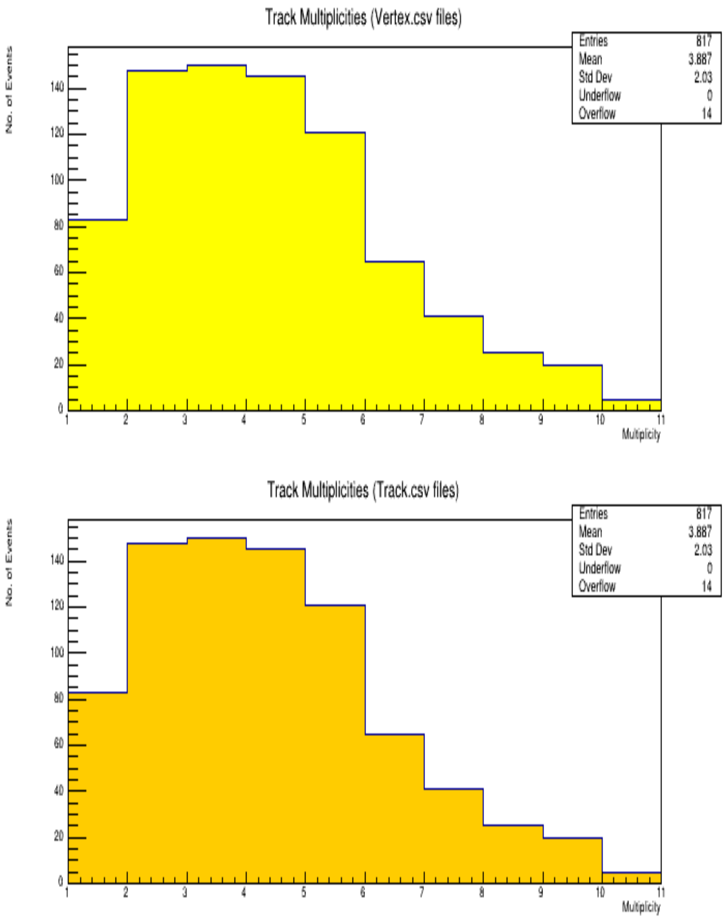



Figure 3.3: Track Multiplicities obtained 1) using vertices 2) using track lines

### 3.2.2 Angles of the Muon Tracks

The angle of the muon tracks was calculated by given the slope of the track using the formula:

$$\theta = Tan^{-1}(slope)$$

Where $\theta$ is the angle of the muon track in radians. Additionally, the distribution of XZ and YZ track angles of the produced muons, with respect to the Z-axis, was plotted in a 2D histogram. The slope of the tracks with respect to the Z-axis was read from the *EventIDTracks.csv* file. The histogram was drawn in two different styles, "lego2" and "colz". Two sets of histograms were obtained with angles in radians and degrees, as shown below 10.

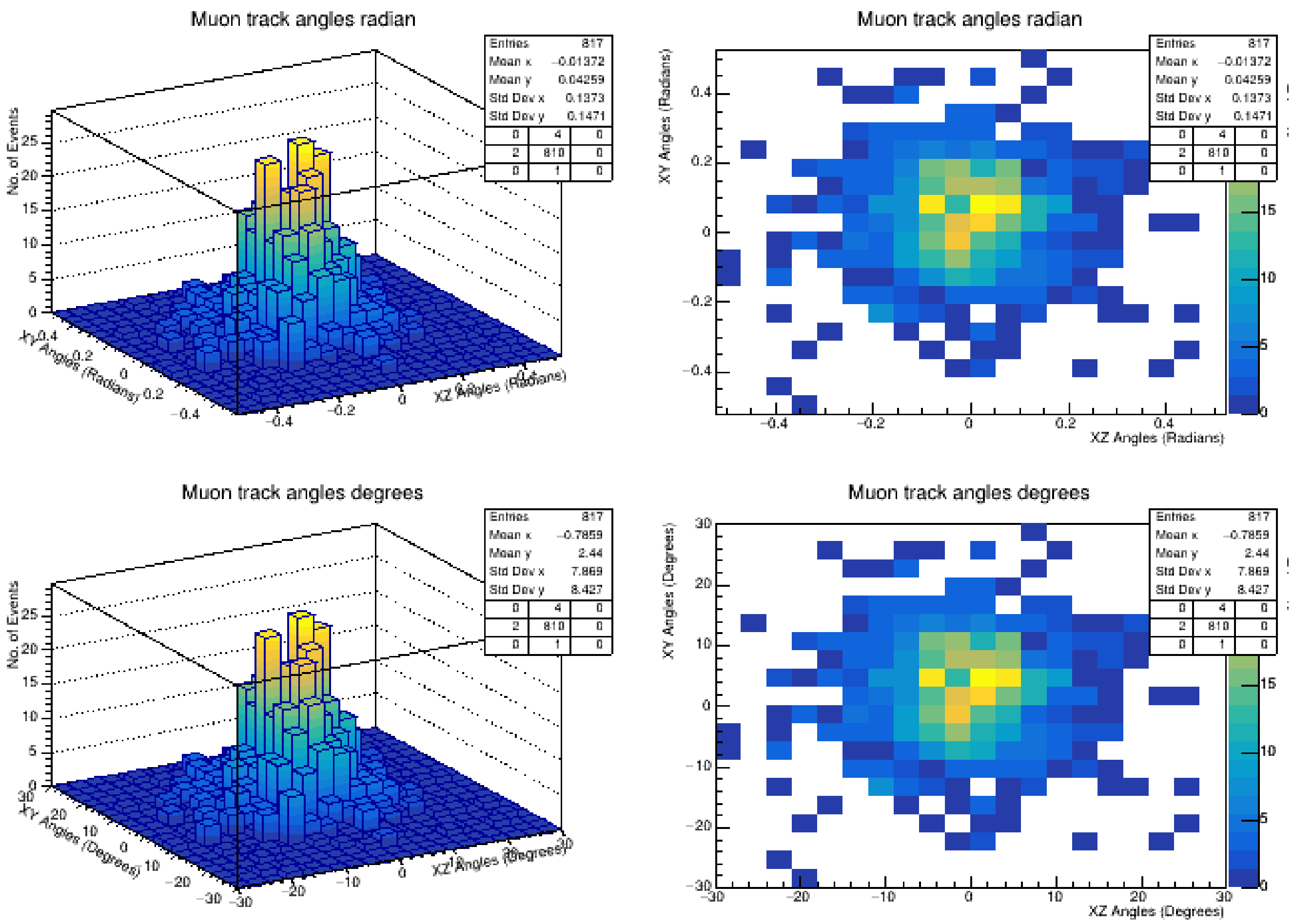



Figure 3.4: Muon Track Angles 1) in Radians 2) in Degrees

# Chapter 4

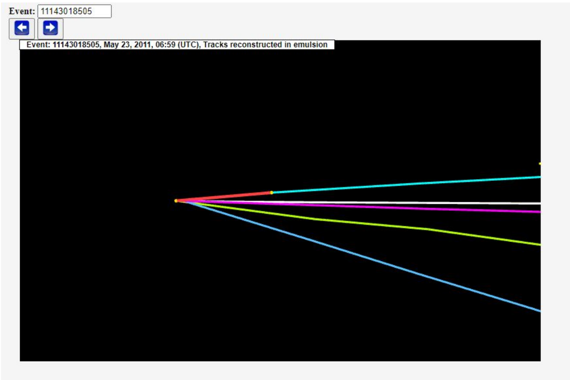
# Visualization of $\nu_\tau$ Candidate Events at OPERA Detector

## 4.1 Task 3: Visualization of Neutrino Event Topologies

In this task, we tried to implement a simple visualization of events from the OPERA $\nu_\tau$-candidate sample, where the tau lepton decay topology was reconstructed in the nuclear emulsion detectors. [12]

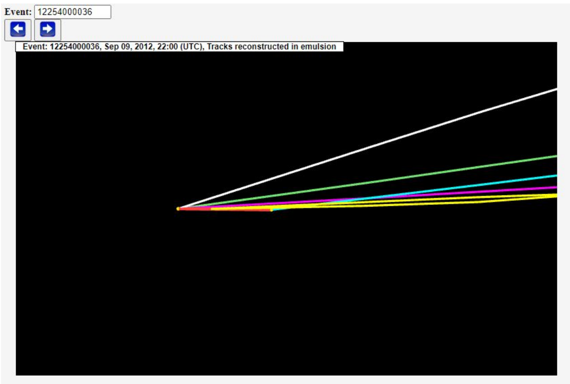
A web application for 3D visualization of OPERA events from the $\nu_\tau$ appearance data set has been implemented using a JavaScript (JS) THREE.js graphics library. Positions of tracks, as well as the primary and secondary interaction vertices reconstructed in nuclear emulsions, were inserted into the corresponding JavaScript data structures of the program. All components of HTML/CSS files were coherently implemented to display the characteristic topologies of the $\nu_\tau$ events in a browser window.

The display obtained is user interactive and hence the event can be viewed from a different perspective. Here, two of the events (*Event = 11143018505* and *Event = 12254000036*) have been attached with a side view and front view of each event track.

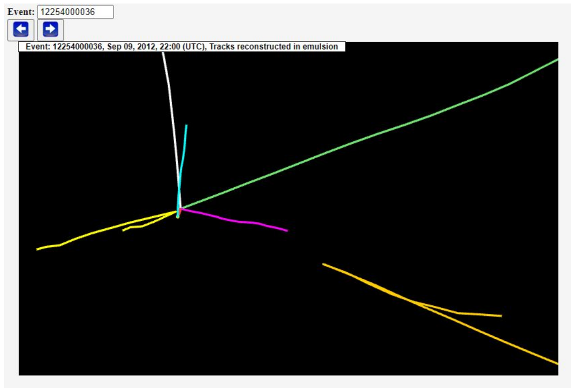



(a) Side view of Event = 11143018505


(b) Front view of Event = 11143018505




(c) Side view of Event = 12254000036




(d) Front view of Event = 12254000036


Figure 4.2: Visualization of $\nu_\tau$ Decay Tracks

## 4.2 Task 4: Visualization of OPERA Electronic Detectors

This task aims to analyze and visualize the data registered in the electronic detectors of the OPERA experimental setup. The electronic detectors had obtained

5603 fully reconstructed neutrino interactions which after careful consideration and study were reduced to 10 successful $\tau$ neutrino candidates. [13]

The complete data was then reconstructed visually using the D3.js JavaScript library.Here, we have used similar procedure as used in Task 3 but instead of a 3D view, we have created a two (side view and top view) 2D visualizations of Electronic Detectors hits registered in the 10 $\tau$ neutrino candidate events in a browser window. The results for events 11143018505 and 12254000036 have been attached below.

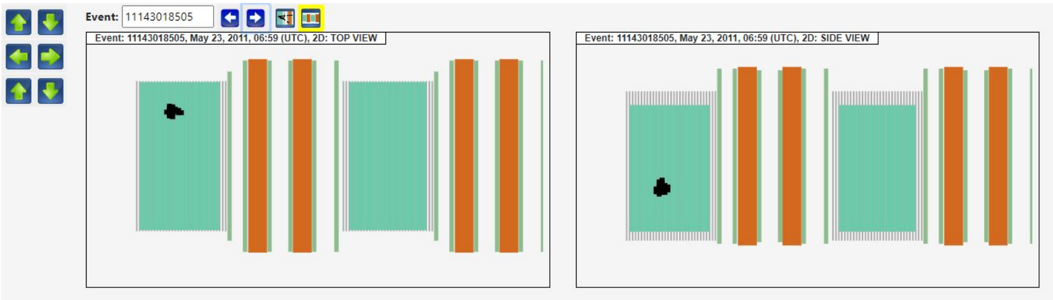



Figure 4.3: Event = 11143018505

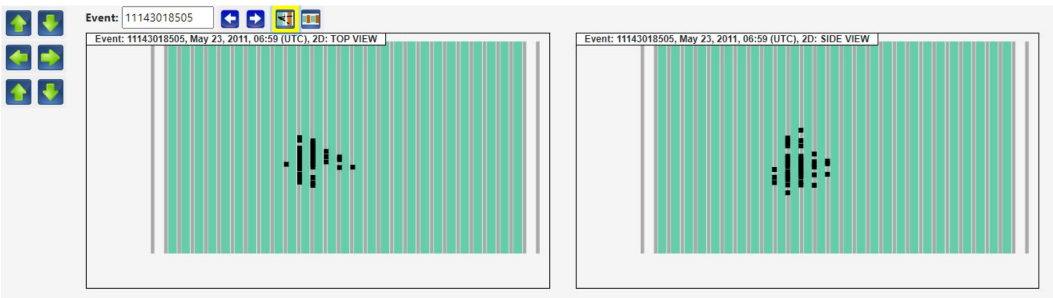



Figure 4.4: Zoomed in view Event = 11143018505

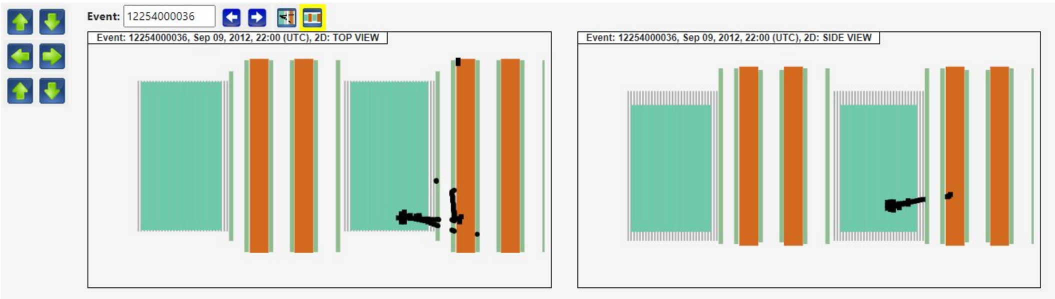



Figure 4.5: Event = 12254000036

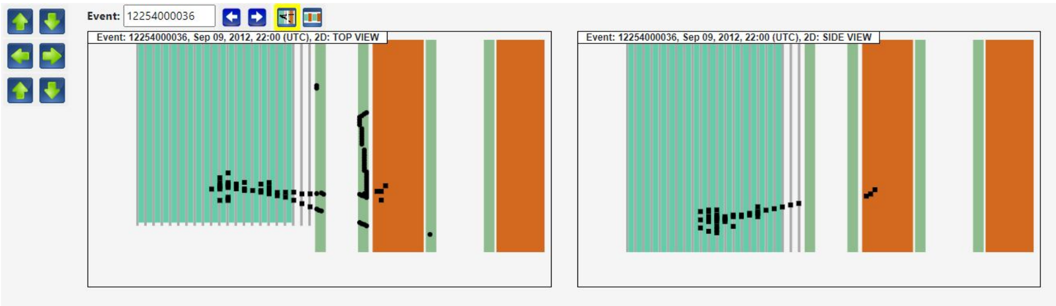



Figure 4.6: Zoomed in view Event = 12254000036

# Chapter 5

# Result and Discussion

After thoroughly studying, we got a better understanding of neutrino oscillation and related concepts. C++ programs using CERN's ROOT libraries have been developed for qualitative and quantitative analysis of several OPERA datasets available on the CERN Open Data Portal. The obtained results have been compared and found to be in good agreement with the ones published in the original OPERA papers. To visualize interesting topologies of neutrino interaction events from the OPERA $\nu_\tau$-candidate sample, a simplified version of the OPERA browser-based event display has been used and modified.

JavaScript code has been used to draw 3D tracks and vertices reconstructed in the nuclear emulsions and to draw Electronic Detectors hits in the side and top 2D views. The obtained images of the neutrino events are comparable with the ones available on the Open Data Portal [14].

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