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

Submitted by

Athar Ahmad

M. Sc. (Physics)

Aligarh Muslim University

India

Under the guidance of

Dr. Sergey Dmitrievsky

Joint Institute for Nuclear Research

Dubna, Russia

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

Dzhelepov Laboratory of Nuclear Problems

Joint Institute For Nuclear Research

6 Joliot-Curie St., Dubna, Moscow region, Russia 141980

Abstract

Neutrino Oscillation is a phenomenon of the change of flavour of a neutrino into another while travelling longer distances. It is an important phenomenon in High-Energy Physics as it provides that neutrinos have a finite mass which is in disagreement with the Standard Model of Particle physics. In the OPERA experiment, we have studied the Neutrino Oscillation in appearance mode, i.e. it studies the data only about the neutrinos which have changed their flavour, which in this case is $\nu_\mu \to \nu_\tau$. In this project we have used the dataset for the OPERA experiment from CERN open data portal and developed consequent C++ codes for the bifurcation of data and its analysis. We have further used the CERN's ROOT library to plot the analysed data. In the later part of the project we have also used JavaScript, HTML and CSS to create web browser-based visualization of the final OPERA results.

Acknowledgment

I would like to express my gratitude to my supervisor for this opportunity and the support that I received during the 6 weeks of the project.I want to thank him for his valuable assistance, time and help through the whole program period. I would also like to thank the Organizing Committee of the INTEREST program for allowing me to be part of this program and giving me this great opportunity of learning.

Contents

Chapter 1

Introduction

According to the Standard Model of Particle Physics, Neutrinos are defined as the massless neutral leptons that come in three generations namely the electron neutrino, muon neutrino and the tau neutrino (Table. 1). As the name suggests they are neutral(neu) and massless (-ino). Its discovery dates back to 1930 when Wolfgang Pauli postulated the existence of this neutral particle in order to theoretically explain the continuous -spectrum. In the year 1956, Clyde Cowan and Frederick Reines of the Los Alamos National Laboratory confirmed the detection of electron type anti -neutrinos at the Savannah River Nuclear site [1]. These neutral leptons because of their small interaction cross section participate only in weak interactions (and very weakly in gravity) , hence are difficult to detect. Recent experiments indicate that neutrinos have a non- zero rest mass and multiple mass eigenstates unlike the flavour states, thereby indicating mixing. As an evidence of mixing, neutrinos have been observed to change from one flavour to another during their propagation – a phenomenon called neutrino oscillation.

I Generation	II Generation	III Generation
ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

Chapter 2

Neutrino Oscillations

The Standard Model defines three flavors of neutrinos ν_α, $\alpha=$ e,μ,τ. It has been experimentally confirmed that neutrinos undergo a change in flavor on propagating long distances. This phenomena of transition between different neutrino flavors is termed as Neutrino Oscillations. It is a quantum mechanical effect and the probability of conversion of ν_α to ν_β in vacuum or in matter has an oscillatory dependence on the distance travelled and hence the term neutrino oscillation is used. The idea of neutrino oscillations was first coined by Bruno Pontecorvo in 1957, he proposed the idea of matter antimatter oscillations analogous to the oscillations in mixed neutral particles (specifically neutral kaon mixing) [2]. This assumption was further investigated by Z. Maki, M. Nakagawa and S. Sakata in 1962 to postulate the neutrino flavour mixing angle thus defining specific mass eigenstates for neutrinos which led to the concept of neutrino oscillations [3]. Experiments conducted in the past have reportedly confirmed the deficit in the solar neutrino flux a similar anomaly in the atmospheric neutrino flux was also reported. After several years, the experimental confirmation of the neutrino oscillations was presented by the Super-Kamiokande Collaboration, Japan (atmospheric neutrino anomaly) [4] and SNO collaboration, Canada [5] as a solution to the long-lived solar and the atmospheric neutrino puzzle. The experimental confirmation of neutrino oscillations thus justified the existence of non-zero neutrino rest mass, which laid the foundation of physics beyond the Standard Model.

Chapter 3

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) is a scientific experiment designed to study the phenomena of neutrino oscillations. It is a long baseline experiment aiming to detect the appearance of ν_τ (tau neutrinos) from the oscillation of ν_μ (muon neutrinos) during their 3 milli-second travel from Geneva to Gran Sasso [6]. The experiment is a collaboration between the European Organization for Nuclear Research (CERN), Switzerland and Laboratori Nazionali del Gran Sasso (LNGS), Italy. The OPERA detector is exposed to the high intensity (2.4 $\times 10^{13}$ protons on target per pulse) [7] and high energy (400 GeV) [7] CERN Neutrinos to Gran Sasso (CNGS) neutrino beam. A beam of this type is 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) are focused in the desired direction. These particles further decay into muons and ν_μ which in turn travel in the direction identical to the parent particle. This high energy ν_μ beam produced at SPS, CERN is then directed towards the OPERA detector situated in Gran Sasso underground laboratory (LNGS), 730 km away.

The OPERA detector (fig 3.1) is a hybrid type detector. It has a total volume of 2000 m^3 (10 x 10 x 20 m^3) [7] and is composed of two identical Super-Modules. A Resistive Plate Chambers, (RPC) is placed in front of the first super module to tag the interactions occurring in the rock surrounding the experimental set up. Each Super-Module consists of approximately 75000 bricks along with 31 Target Trackers which couple the bricks arranged vertically in the form of a wall (6.76.7m^2) [7] which collectively forms the Target Section. An individual emulsion brick is 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 is 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 is followed by a magnetic spectrometer for momentum and charge measurement of muon particles.
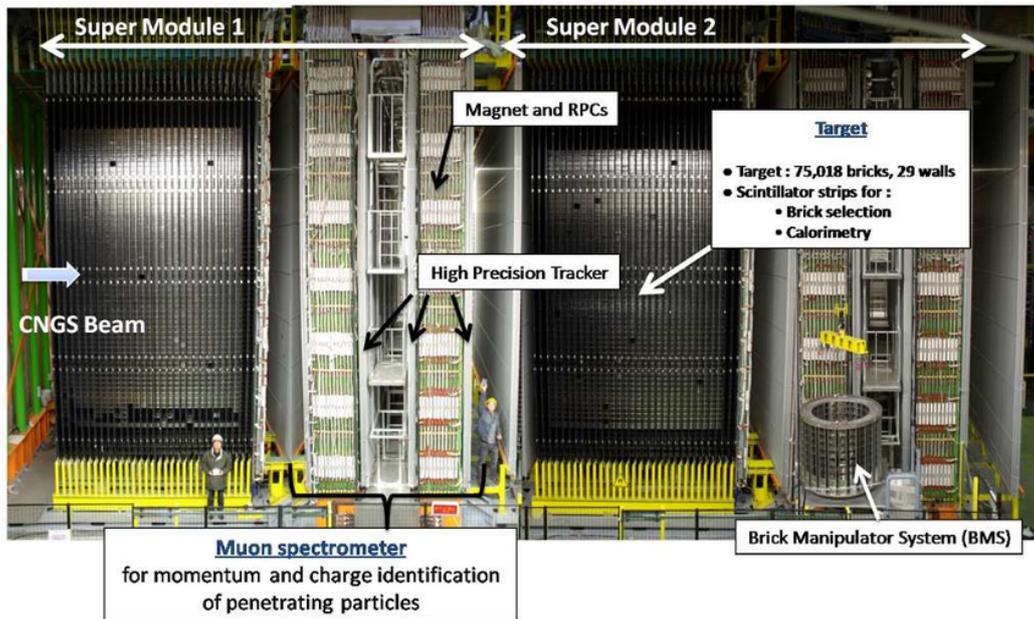

Figure 3.1: A picture of the complete OPERA detector at LNGS.

Chapter 4

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 analyse 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 categorised 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 training, 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 5

Project Tasks and Observation

5.1 Task 1

Emulsion data for neutrino-induced charmed hadron production studies This task aimed at analyzing the emulsion data for the neutrino induced charmed hadron production studies. The theory behind this task was that when the decays in the same lead plate where the neutrino interaction occurred, the candidates are selected on the basis of the Impact Parameters (IP) of the daughter tracks with respect to the interaction vertex [1]. The data obtained from the CERN Open Data Portal contained the Tracklines and Vertices files corresponding to 50 possible neutrino interaction events. The task was divided into two parts:

1. Calculation of the Flight Length of the charmed hadron: Flight Length is defined as the distance between the primary and the secondary interaction vertices. Mathematically, flight length is calculated as,

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

where, 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 were used. 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 form of a data file. ROOT was used to plot the histogram for the flight length which is given in fig.5.1.
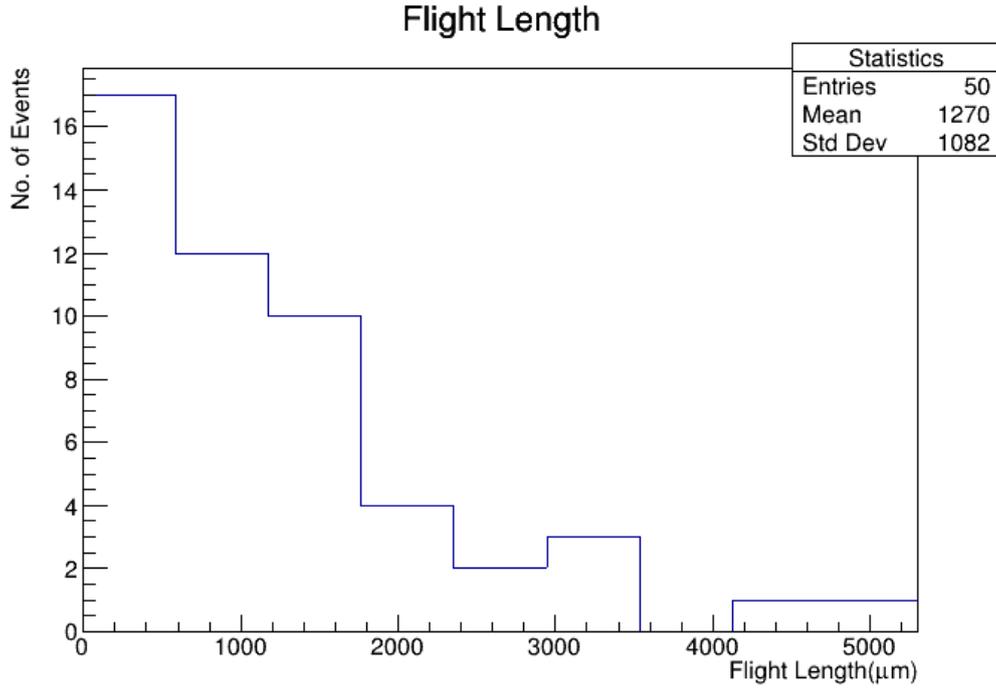
Figure 5.1:

2. Calculation of the Impact Parameter (IP) of the daughter tracks with respect to the primary vertex: It is the shortest distance between the primary vertex and the daughter track. Mathematically, the IP is calculated as,

$$Impact\,Parameter = |\,\vec{e_r} \times \overrightarrow{PD}\,|\,/\,|\,\vec{e_r}\,|$$

where, (e_r) is the direction vector of the daughter track and, (PD) is a distance between the primary vertex 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, the unit direction vector for the daughter track $(\vec{e_r})$ was calculated and stored in a vector. Further the distance between the primary vertex and the daughter track was calculated as $(\overrightarrow{PD})$ and then the Impact Parameter was calculated using the mathematical formula given above and stored in the form of a data file. ROOT was used to plot the histogram for the Impact Parameter which is given in fig. 5.2.
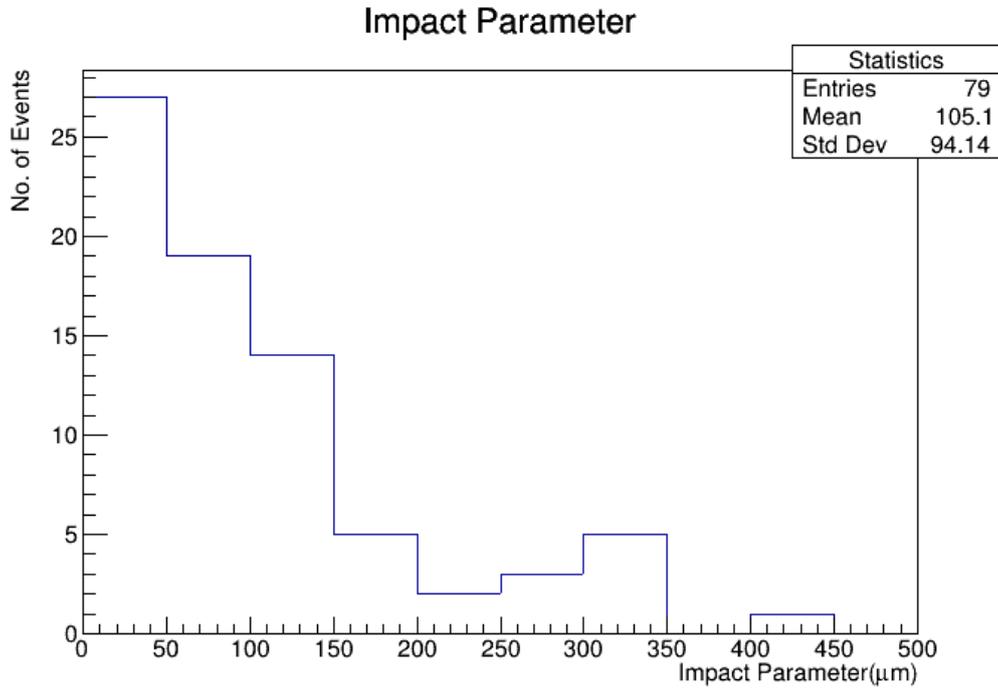
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Figure 5.2:

5.2 Task 2

In this task the emulsion data for track multiplicity of charged hadron is 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 of the neutrino interaction vertices including all the emulsion tracks produced in the interactions. Randomly 800 events were selected out of the three runs in 2010, 2011 and 2012. The data obtained from the CERN Open Data Portal contained the Track and Vertex files corresponding to 800 events in which a muon was detected in the final state. The task was divided into two parts:

1. Plotting the histogram for multiplicities of all produced charged particles: The interaction of a 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

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plot the histogram for the multiplicities which is given in fig.5.3
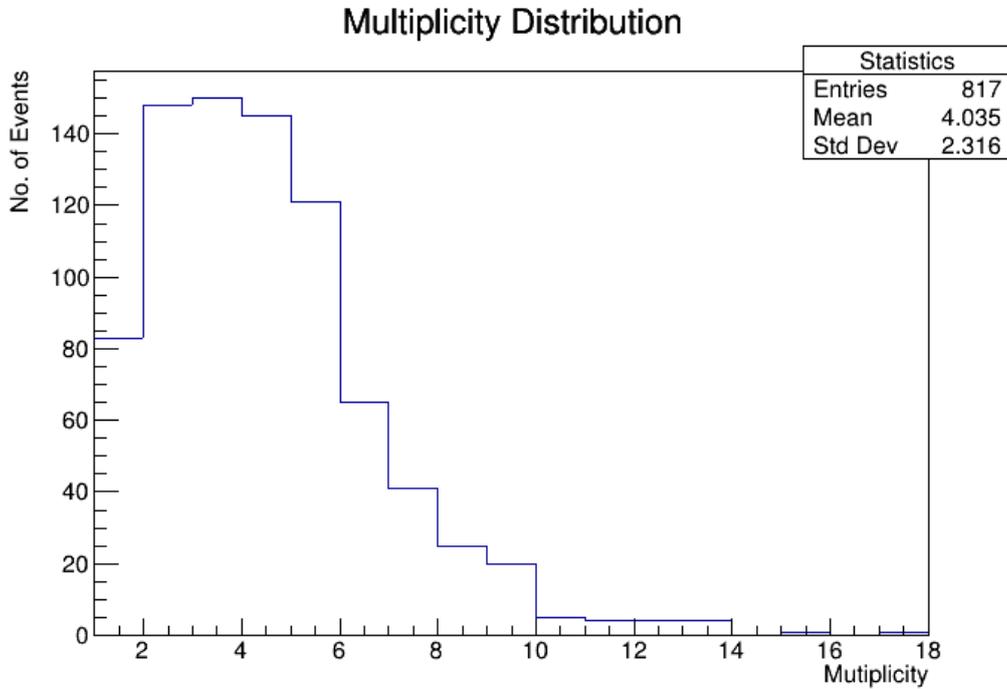.

Multiplicity Distribution

Figure 5.3:

2. Calculating the angles of the muon tracks: The angle of the muon tracks is calculated given the slope of the track by the mathematical formula

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

where θ is the angle of the muon track. The slope of the tracks with respect to the Z- axis were given in the *EventIDTracks.csv* under the *trType 1*. Using the C++ code, the slope for the XZ and YZ views were read from each file and using the mathematical formula above the angle of the muon track was calculated for each event. The angles were then stored in the form of a data file. ROOT was used to plot the two-dimensional histogram for the two angles of muons fig. 5.4.
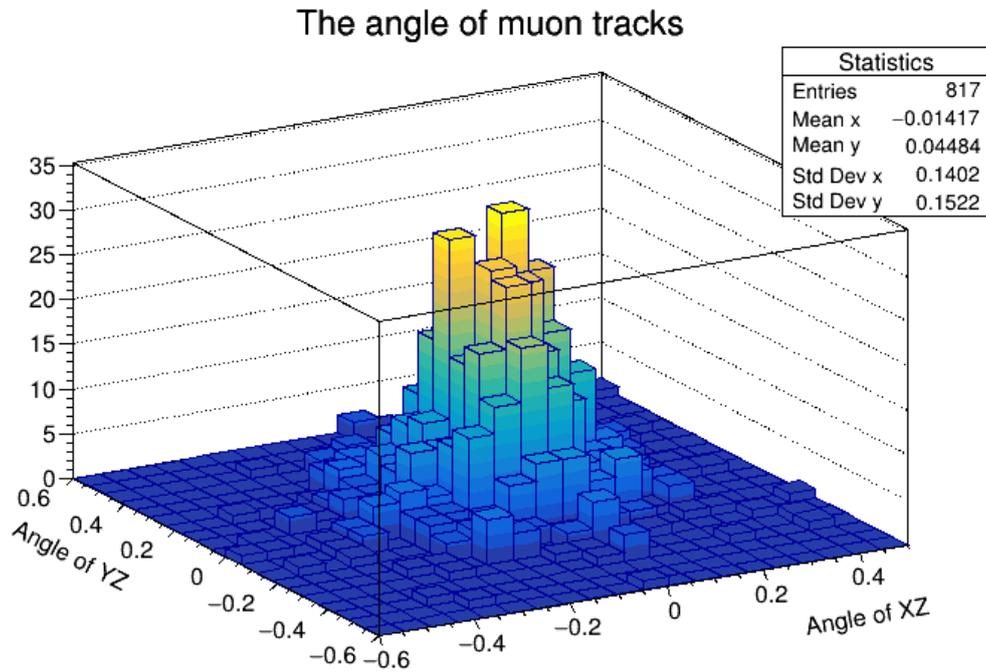
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The angle of muon tracks

Statistics	
Entries	817
Mean x	−0.01417
Mean y	0.04484
Std Dev x	0.1402
Std Dev y	0.1522

Figure 5.4:

5.3 Task 3

This task aims at visualising the final data detected by the electronic detectors involved in the OPERA Experiment. The electronic detectors had obtained 5603 fully reconstructed neutrino interactions which after final kinematical cuts were reduced to 10 successful τ neutrino candidates. The complete data was than reconstructed visually using D3 JavaScript (JS) library.

1. First the tau neutrino event data from the electronic detectors were manually loaded into separate .js files under the alias loadEventEventID.js as it is difficult to load files from a local computer to a JS program.

2. Then, an index.html file was created which allows the reassembling of all the JS, CSS, Graphics files and JS libraries. The external JS libraries native to the JS language were downloaded and loaded in to the index file. The internal libraries were first created as .js files according to the functions required in the programs and inserted in the index.html files.

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3. Next, the JS file to define the various required classes like HitTT, HitRPC and HitDT were defined.

4. Next the browser window which will show the required visualisation is defined with the alias Display2d-def.js and the various elements like the text box to display the eventid, the buttons for switching to the next and previous events, the buttons for switching between the detector view and the event region view are defined.

5. Further, a program named MgrDraw2D-def.js is created to define the classes required to draw the visualisation.

6. Finally, a file named MgrDraw2D-funcAdd.js is created to link each event and its corresponding classes created in D3.js for the Target Tracker Hits, RPC Hits and DT Hits to the Browser based 2D display to show the final visualization of the detector hits (fig. 5.5(a)).

5.4   Task 4

This task aims at analysing and visualising the final data derived from the emulsion dataset used in the OPERA Experiment. The electronic detectors had obtained 5603 fully reconstructed neutrino interactions which after final kinematical cuts were reduced to 10 successful τ neutrino candidates. The complete data was than reconstructed visually using 3 JavaScript (JS) library. Here, we have used the same procedure as used in Task 3 but instead of a 2D view, we have created a 3D visualisation of all the tracks and vertices obtained in the 10 successful τ neutrino candidates in a browser window.

1. First the tau neutrino event data from the electronic detectors were manually loaded into separate .js files under the alias loadEventEvenID.js.

2. Then, an index.html file was created which allows the reassembling of all the JS, CSS, Graphics files and JS libraries. The external JS libraries native to the JS language were downloaded and loaded in to the index file. The internal libraries were first created as .js files according to the functions required in the programs and inserted in the index.html files. Further the toolbars and buttons like the textbox used to display the eventID and the buttons for switching to the next and previous events are defined in the Display3d-def.js file were loaded into the index.html file.

3. Further, a JS file named Event-def.js to define the various required classes like id, date, vertices3D, tracks3D was created.

4. Next, a Vertex-def.js file for the definition of the required vertex parameters was created.

5. A Track3D-def.js file was created to define the various parameters related to the tracks like the line colours, and various classes like id, partID, pos1, pos2 and Axy.

6. Further, a program named MgrDraw3D-def.js is created to define the classes required to draw the visualisation.

7. Finally, a file named MgrDraw3D-funcAdd.js is created to link each event and its corresponding classes created in 3.js to the Browser based 3D display to show the final visualization of the neutrino decay topologies in the emulsion dataset (fig. 5.5(b)).

Figure 5.5:

(a)   (b)

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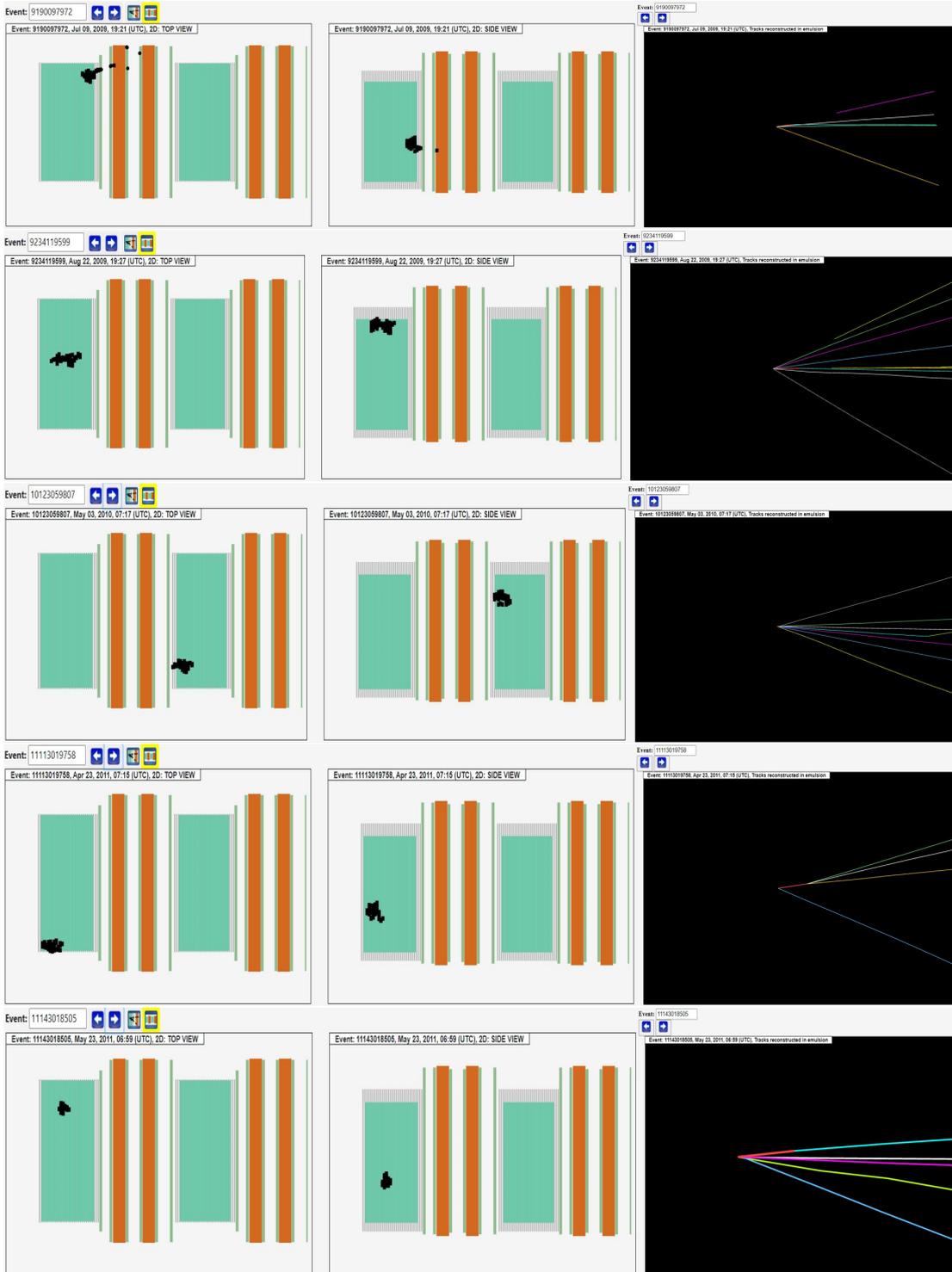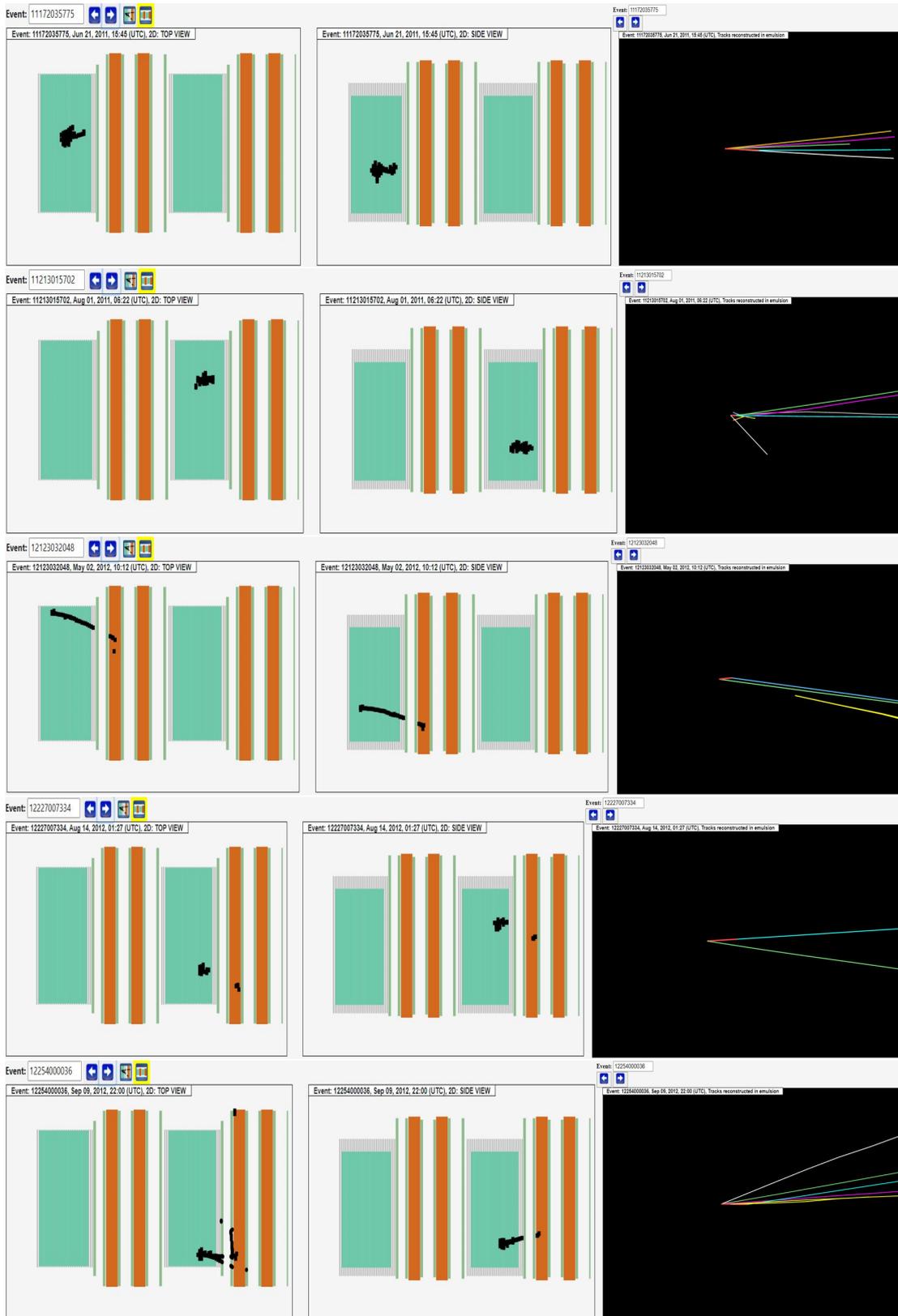
Chapter 6

Result

In this project analysis of the neutrino event topology is performed with the help of C++ programs. The result for the same is depicted in the ROOT data analysis framework. Further, the visualization of the neutrino interaction topologies is first done by using electronic detector data set in a browser based 2D display and then using the nuclear emulsion data set obtained from the OPERA detector in a browser-based 3D display.

Chapter 7

Conclusion

By studying the 10 successful τ neutrino candidates in the appearance mode, we have experimentally re verified the neutrino oscillation phenomenon for $\nu_\mu \to \nu_\tau$.This project has helped me to understand the experimental setup and the working of the Super Proton Synchrotron(SPS), the CNGS Beam and the OPERA Detector. Further, by the end of this project I have been acquainted with the CERN's Open data Portal for data acquisition and CERN's ROOT framework for data visualization along with the use of the 3.js and D3.js JavaScript libraries for 2D and 3D web-browser based program development.

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