JOINT INSTITUTE FOR NUCLEAR RESEARCH

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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Abstract

Neutrino Oscillation (phenomenon of the change of flavour of a neutrino into another while travelling longer distances) has been discussed. An overview of the CERN Open Data Portal, which provides access to an increasing range of data generated by CERN research, has been presented. Several datasets of the OPERA experiment from CERN Open Data Portal have been analyzed using C++ codes. Precisely, neutrino-induced charmed hadron production sample, ν_μ sub-sample used in charged particle multiplicity analysis, and $\nu_\mu \to \nu_\tau$ sample have been processed and analyzed. To create web browser-based visualization of the final OPERA results JavaScript, HTML and CSS have been used. Analyzed data has been plotted using the CERN's ROOT library.

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Chapter 1

Introduction

1.1. Neutrino Oscillation

Neutrinos are the universe's second most numerous elementary particles (after photons). Understanding the neutrino sector is one of the top objectives for scientists all across the world. It has the potential to produce a fundamental theory beyond the Standard Model of particle physics, which states that the fundamental particles are Leptons and Quarks. It has been proven experimentally that neutrinos change flavour when they travel large distances. Neutrino Oscillations is the phenomenon of transitioning between distinct neutrino flavours (Fig. 1.1).

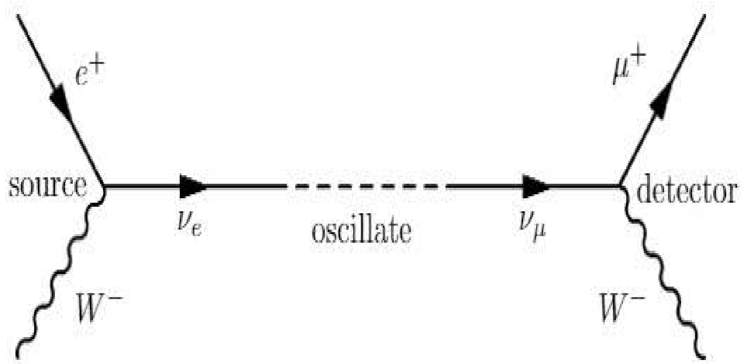


Figure 1.1: Neutrino Osillation

1.2. CERN Open Data Portal

The CERN open data portal provides access to a variety of data generated as a result of experiments performed at CERN. It disseminates the numerous outcomes from diverse research initiatives, as well as the software and documentation required to comprehend the data analysis. To make the portal's products citable, they are released under open licences

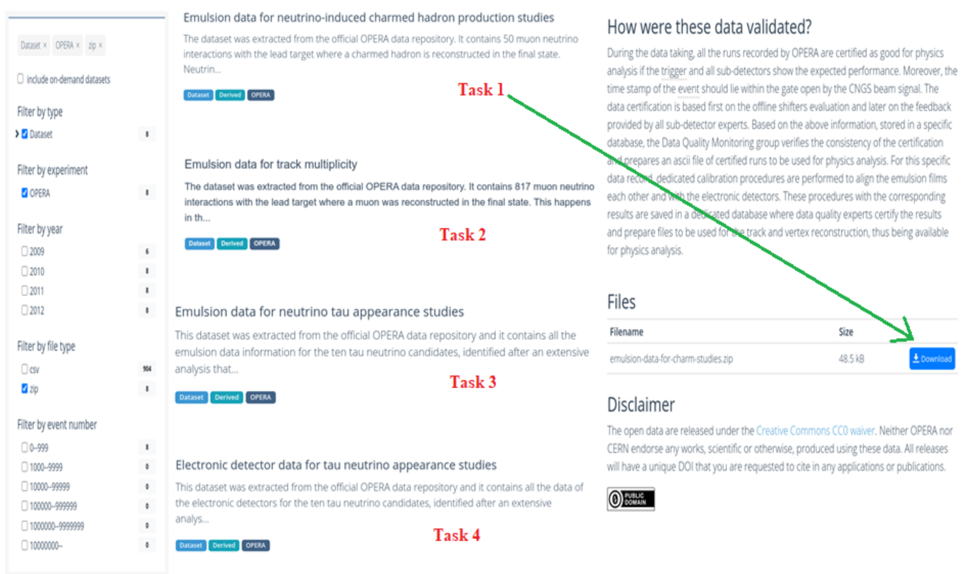


Figure 1.2: Visualization of a search tool on the CERN Open Data Portal

and given a unique DOI (Digital Object Identifier).
Experimental information includes data and additional figures and tables, simplified data formats for outreach and analytical training, level experiment-specific software, reconstructed collision and simulated data, and basic raw data with associated reconstruction and simulation software. Excess link for the CERN Open Data portal is:- “opendata.cern.ch”. Way to download the data from the same is very much emergent from Fig. 1.2.

1.3. OPERA experiment

Oscillation Project with Emulsion tRacking Apparatus.

OPERA was a research project aimed at understanding neutrino oscillations. It was a long baseline experiment with the goal of detecting the appearance of ν_τ from the oscillation of ν_μ during their 3 millisecond journey from Geneva to Gran Sasso.
The experiment was a collaboration between the European Organization for Nuclear Research (CERN), Switzerland and LNGS (Laboratori Nazionali del Gran Sasso) of INFN, the world’s largest underground physics laboratory. The neutrino source and a neutrino detector were 732 km apart (Fig. 1.3).
To produce pions and kaons, accelerated protons from CERN’s super proton synchrotron (SPS) were shot in two cycles at a carbon target. Muons and neutrinos were produced as a result of the decay of these particles. OPERA was designed with the goal of identifying the neutrino by observing its decay topologically. This was accomplished by combining real-time detection techniques (electronic detectors) with the Emulsion Cloud Chamber (ECC) facility in a hybrid setup (Fig. 1.4). This setup had a total volume of 2000 m^3 $(10 \times 10 \times 20)$ m^3,

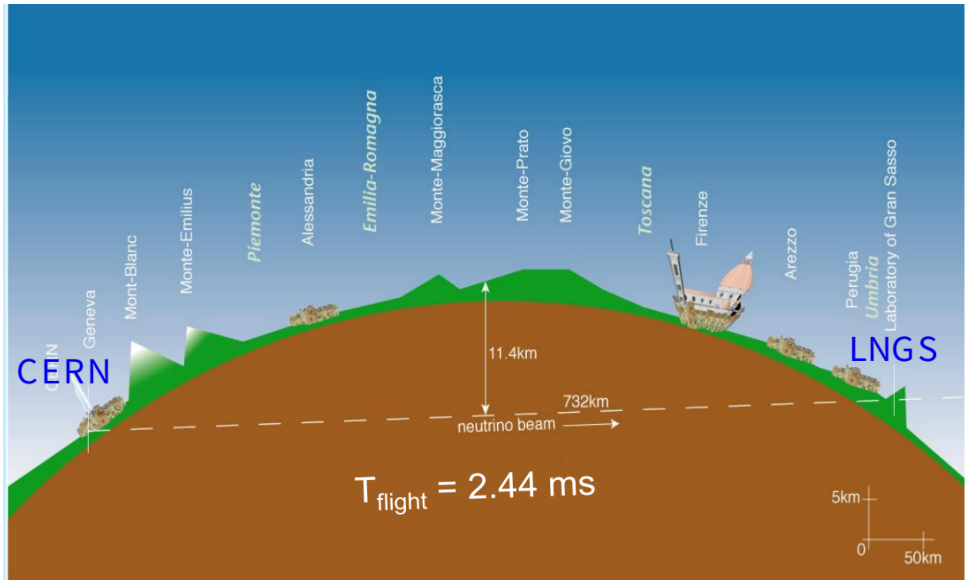


Figure 1.3: CNGS experiment

and was composed of two identical Super-Modules (namely SM1 and SM2) each with 31 walls and 31 double layers of scintillator planes, followed by a magnetic spectrometer. A passive material plate was employed as a target, and nuclear emulsion films were used as tracking devices with sub-micrometric accuracy in an ECC detector. The DONuT experiment, which

Figure 1.4: OPERA hybrid detector

had first observed the ν_τ was an application of the ECC technology at a mass scale of 100 kg. The ECC had demonstrated the unique capability of combining an exceptionally accurate tracker with the ability to do kinematical variable measurements. In OPERA, the ECC technology was significantly larger in scale. The “brick”, which was a basic unit, was made up of 56 plates of lead (1 mm thick) combined with industrially produced nuclear emulsion films for a total weight of 8.3 kg. To reach the total mass of 1.25 kton, around 150000 target units were built. The bricks were organised in 62 vertical walls that were perpendicular to the beam direction and were separated by plastic scintillator planes.

Main goal of the OPERA experiment was to observe ν_τ appearance in a pure ν_μ beam through the detection of the short-lived tau leptons produced in ν_τ charged-current (CC) interactions. The physics programme also included:

Oscillation physics:

- $\nu_\mu \rightarrow \nu_e$ study
- sterile neutrino analysis

Non-oscillation physics:

- charged particle multiplicity analysis
- cosmic ray physics

Requirements for this experiments were as follows:-

For ν beam: high energy for τ production, high intensity, long baseline for oscillation at the atmospheric scale.

For detector: high density and large target mass, micrometric resolution, low background (underground location).

Chapter 2

Project tasks and results

This project contains three tasks as described below, and this is to be noted that, the data required for calculations has been obtained from the CERN Open Data Portal.

2.1. Task 1

Aim
To study the Emulsion data for neutrino-induced charmed hadron production and analyze it by:-
(I) Calculating the Flight Length of the charmed hadron.
(II) Calculating the Impact Parameter of the daughter tracks with respect to the primary vertex.
Theoretical formulation
If (x_1, y_1, and z_1), and (x_2, y_2, and z_2) are the co-ordinates of the primary vertex and secondary vertex respectively, the F.L. (flight length) can be determined by:-

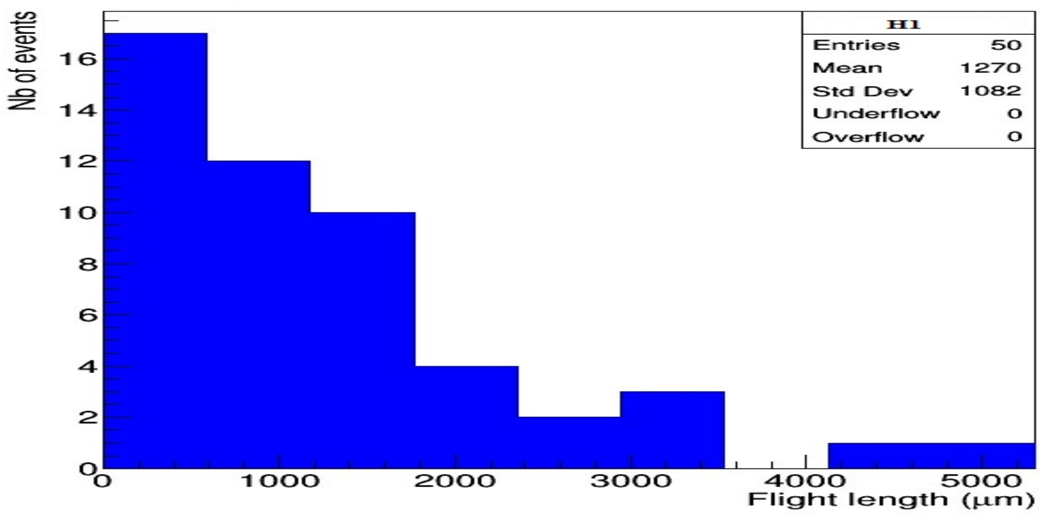
$$F.L. = \sqrt{\left((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\right)}. \tag{2.1}$$

If the vector distance between the primary vertex and the daughter track is $\vec{A}$, and e_r, is the direction vector of the daughter track, I.P. (impact parameter) is given by:-

$$I.P. = \frac{|\vec{e_r} \times \vec{A}|}{|e_r|} \tag{2.2}$$

Calculations
(I) For flight length:
Specifically, EventIDVertices.csv file was used. Vertices have been read for each file computationally using a C++ code. Flight lengths for each event have been calculated from Eq. 2.1, and stored in the form of a data file.
(II) For impact parameter:
Vertices obtained from the EventIDVertices.csv have used, and the coordinates corresponding

to the daughter track have been taken from the EventIDTracklines.csv. Impact parameters for each event have been calculated from Eq. 2.2, and stored in the form of a data file.
Histogram for the flight length and impact parameter have been plotted with the help of ROOT software.
Results



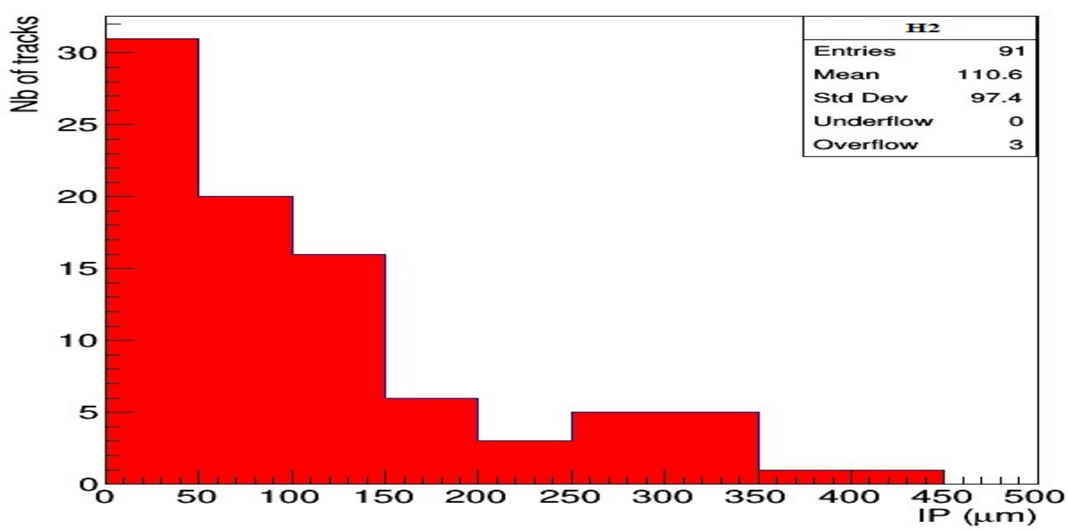


Figure 2.1: Task 1 results (a) Flight length (b) Impact parameter

2.2. Task 2

Aim

To evaluate the emulsion data for track multiplicity of charged hadrons. This data set only included events in which a neutrino interaction with a lead target resulted in a muon in the final state. This task is divided in two parts:-
(I) Plotting the histogram for multiplicities of all produced charged particles.
(II) Calculating the angles of the muon tracks.

Theoretical formulation

The angle of muon track (θ) can be determined with the help of slope of the tracks with respect to the Z- axis. The required relation is as follows:-

$$\theta = \tan^{-1}(slope). \tag{2.3}$$

Calculations

Interaction of a 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.

Results

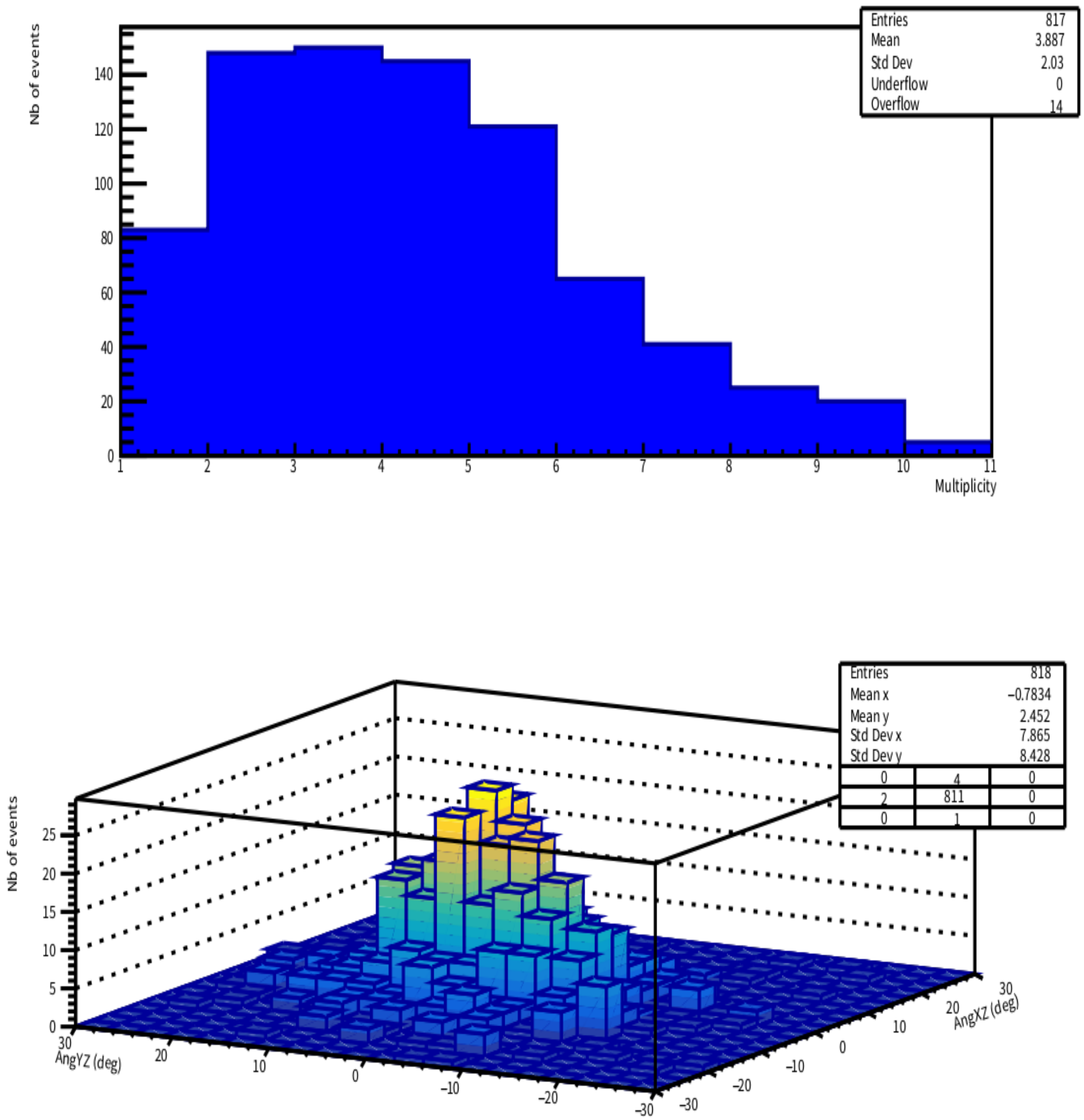


Figure 2.2: Task 2 results (a) Multiplicity distribution (b) Angle of muon tracks (in degrees)

2.3. Task 3

Aim

There were 5603 fully reconstructed neutrino interactions in the OPERA nuclear emulsion detectors. After analysis of neutrino event topologies it was found 10 ν_τ-candidate events satisfying final kinematical cuts. The corresponding OPERA dataset contains information of the neutrino interaction vertices and tracks reconstructed in the emulsion. The aim of this task was to visualise topologies of the 10 tau neutrino candidate events. This has been done using THREE.js (JavaScript) graphical library.

Calculations

A missing section of the source code for a browser-based 3D event display that uses the THREE.js graphics package has been provided. The code was recovered and used to show the tracks and vertices rebuilt in nuclear emulsions for the 10 τ neutrino candidate events. Event Id's of these events are:

1)	9190097972	2)	9234119599
3)	10123059807	4)	11113019758
5)	11143018505	6)	11172035775
7)	11213015702	8)	12123032048
9)	12227007334	10)	12254000036

Information about interaction vertices and particle tracks is utilized in this operation as for previous ones. Data has been extracted from .csv files and stored as .js files (Fig. 2.3). Vertices and tracks of events have been stored in Vertex-def.js and Track3D-def.js respectively. Vertices are indicated as golden dotes whereas, track lines have been given different colours. Now, the object is to give a 3D view of the events. For that case, events have been stored in Event-def.js and a browser-based 3D event display has been enabled through Display3d-def.js file where all above mentioned events have been listed. Initialization of camera, vertex and track properties has been done with MgrDraw3D-funcAdd.js file.

From the 10123059807_Vertices.csv file

```
posX,posY,posZ,globPosX,globPosY,globPosZ,primary
112653,79333.3,24057,-219.336,121.595,192.288,1
112640,79344.7,24196.4,-219.337,121.596,192.301,0
111359,78992,34618,-219.465,121.561,193.344,0
100040,86241.7,47861.3,-220.597,122.286,194.668,0
```

From the loadEvent10123059807.js file

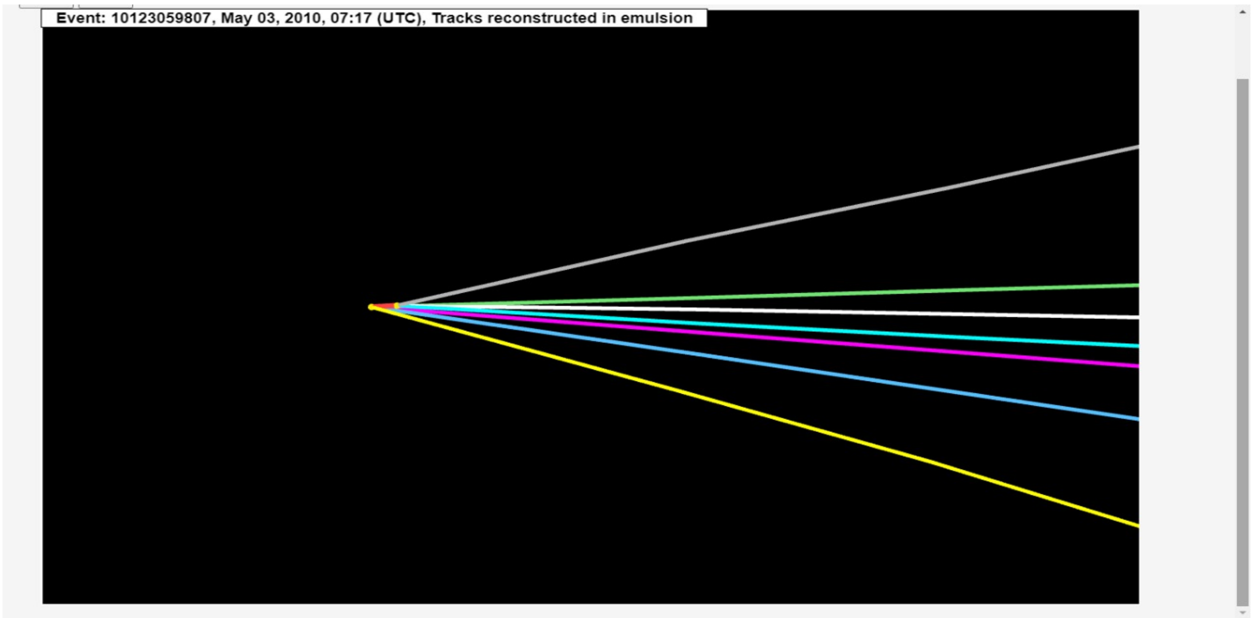
```
display3d.resetEvent();

display3d.event().id(10123059807);
display3d.event().date(1272871069000);

display3d.event().vertices3D([
  new Vertex([112653, 79333.3, 24057],   [-219.336, 121.595, 192.288]),
  new Vertex([112640, 79344.7, 24196.4], [-219.337, 121.596, 192.301]),
  new Vertex([111359, 78992, 34618],     [-219.465, 121.561, 193.344]),
  new Vertex([100040, 86241.7, 47861.3], [-220.597, 122.286, 194.668])
]);
```

Figure 2.3: *.csv to *.js conversion

Results



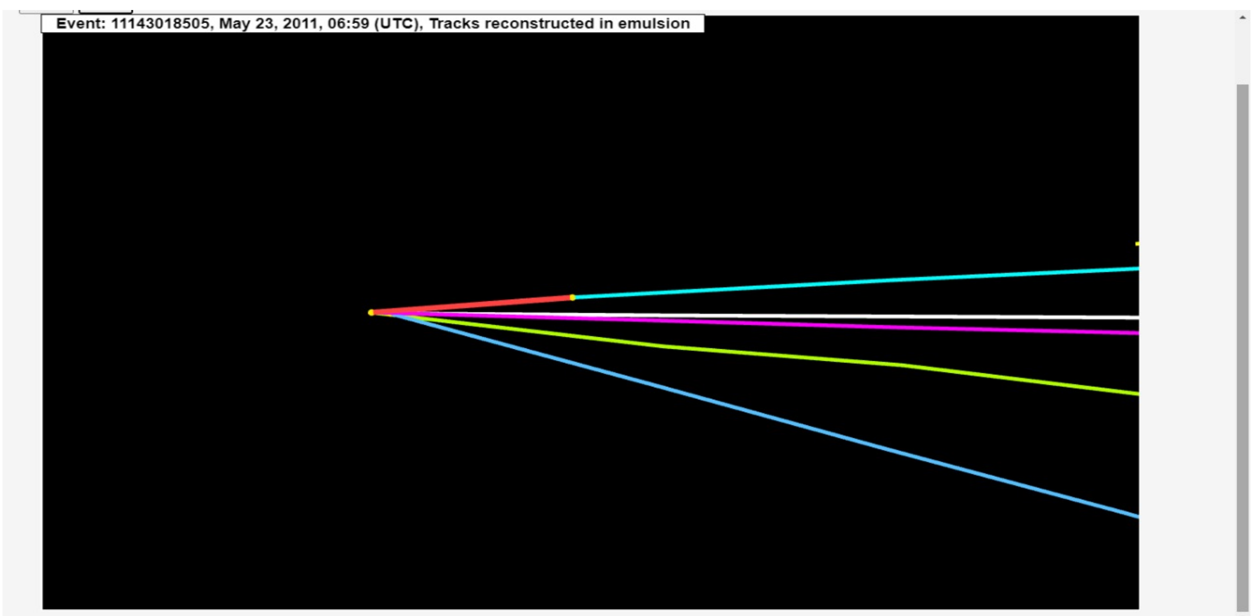


Figure 2.4: Task 3 results (a) Event Id: 10123059807 (b) Event Id: 11143018505

Chapter 3

Conclusions

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 a good agreement with the ones published the original OPERA papers. In order to visualize interesting topologies of neutrino interaction events from the OPERA ν_τ-candidate sample, a simplified version of the OPERA browser based event display has been used and modified. Missing parts of a JavaScript code have been inserted in the functions used to draw tracks and vertices reconstructed in the nuclear emulsions. The obtained images of the neutrino events are comparable with the ones available on the Open Data Portal.

Bibliography

[1] B. Pontecorvo, Zh. Eksp. Teor. Fiz. **33** (1957) 549.

[2] C. L. Cowan et al., Science **124** (1956) 103.

[3] Di Ferdinando, et at., Radiat **44** (2009) 840.

[4] R. Acquafredda, et al., J. Instrum. **4** (2009) 04018.

[5] CERN ROOT online manual (https://root.cern).

[6] CERN Open Data Portal (http://opendata.cern.ch/docs/about).

[7] HTML/CSS/JavaScript/... tutorials (https://www.w3schools.com/html/default.asp).

[8] THREE.js official web-site (https://threejs.org).