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

The objective of the scientific experiment known as OPERA was to better understand the phenomenon of neutrino oscillations. The phenomenon of neutrino oscillation is the transformation of one neutrino's flavour into another as it travels longer. In this report, several OPERA data sets have been analyzed which is available on CERN Open Data Portal using C++ code along with ROOT library. Also, Visualization of neutrino topology events have examined from the OPERA tau neutrino sample with a simplified version of the OPERA browser-based event display. For creating web browser-based visualization of OPERA results JavaScript, HTML and CSS have been used.

Contents

Chapter 1

Introduction

Apart from photons (particles of light), neutrinos are the most abundant particles in the entire universe and the Earth is being constantly bombarded by them. A neutrino is a sub-atomic particle that resembles an electron in many ways, but differs in that it is electrically neutral and has a very tiny mass that was once believed to be zero. Neutrinos are produced during the nuclear reactions inside the Sun and also as a result of interactions of cosmic radiations with the Earth's atmosphere. 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.

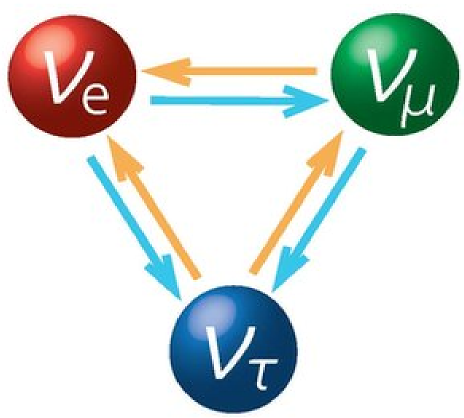

Figure 1.1: Neutrinos can oscillate between their different flavours.

It has been demonstrated through experimentation that as neutrinos travel over large distances, their flavour changes. There are three different types, known as flavours: muon, tau and electron, relating to what interactions they partake in. Neutrino oscillations are the name given to this phenomenon of switching between several neutrino flavours. It is a quantum mechanical phenomenon, and the name "neutrino oscillation" is used to describe how the probability of ν_α to ν_β conversion in a vacuum or in matter oscillates with the distance travelled.

Chapter 2

OPERA Experiment

One of the experiments to study the phenomenon of neutrino oscillations was OPERA. This experiment used the LNGS underground laboratory in Gran Sasso, located 730 kilometres distant in central Italy, and the CNGS high-intensity and high-energy beam of muon neutrinos generated at the CERN SPS in Geneva.

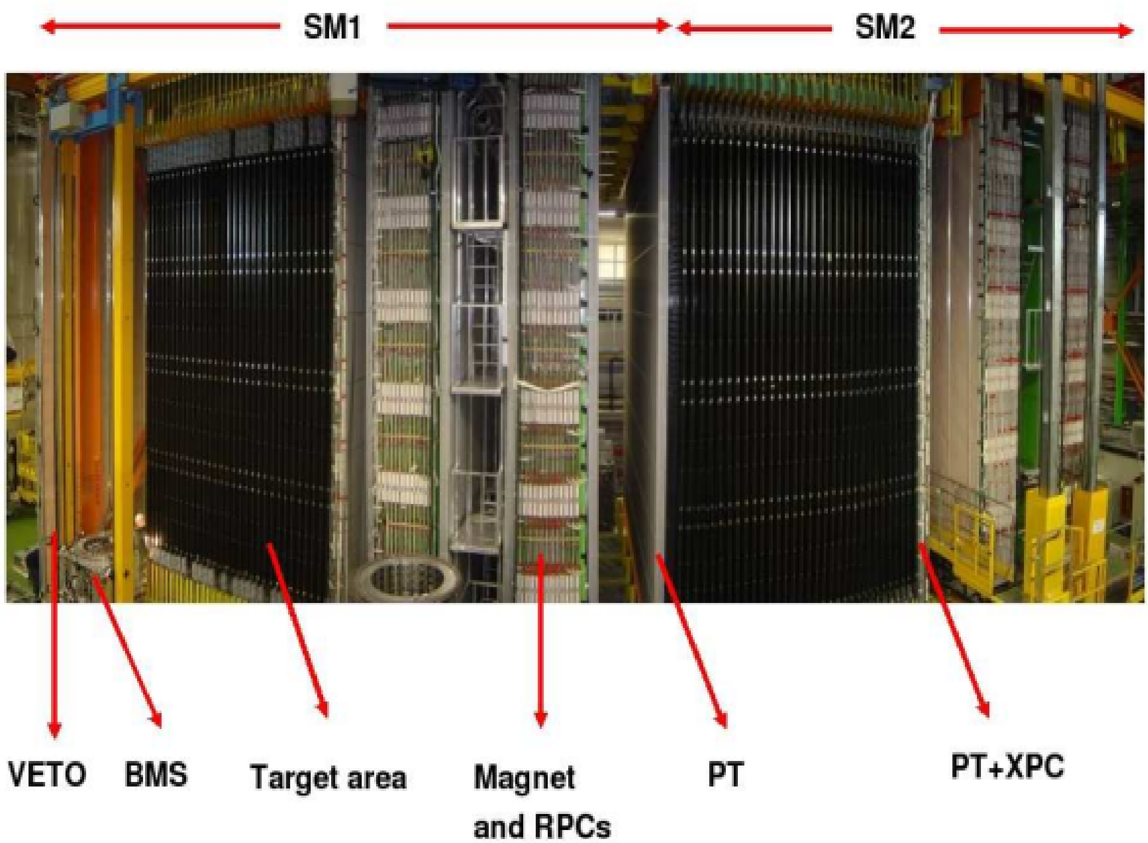

Figure 2.1: OPERA detector

The CERN Neutrinos to Gran Sasso (CNGS) beam was mostly made up of ν_μ particles with a mean energy of around 17 GeV, 2.1 percent $\bar{\nu_\mu}$ CC event contamination, and 0.9 percent electron (anti-)neutrino contamination.
Figures 2.1 and 2.2 show the structure of the OPERA detector. Each brick wall, which consists of 2912 bricks and is supported by a thin stainless steel framework, has a double layer of plastic scintillators (called Target Trackers, or TT), which allow for the real-time identification of the charged particles that are emitted from the wall. It was made up of two identical Super-Modules and has a total volume of 2000 m^3.

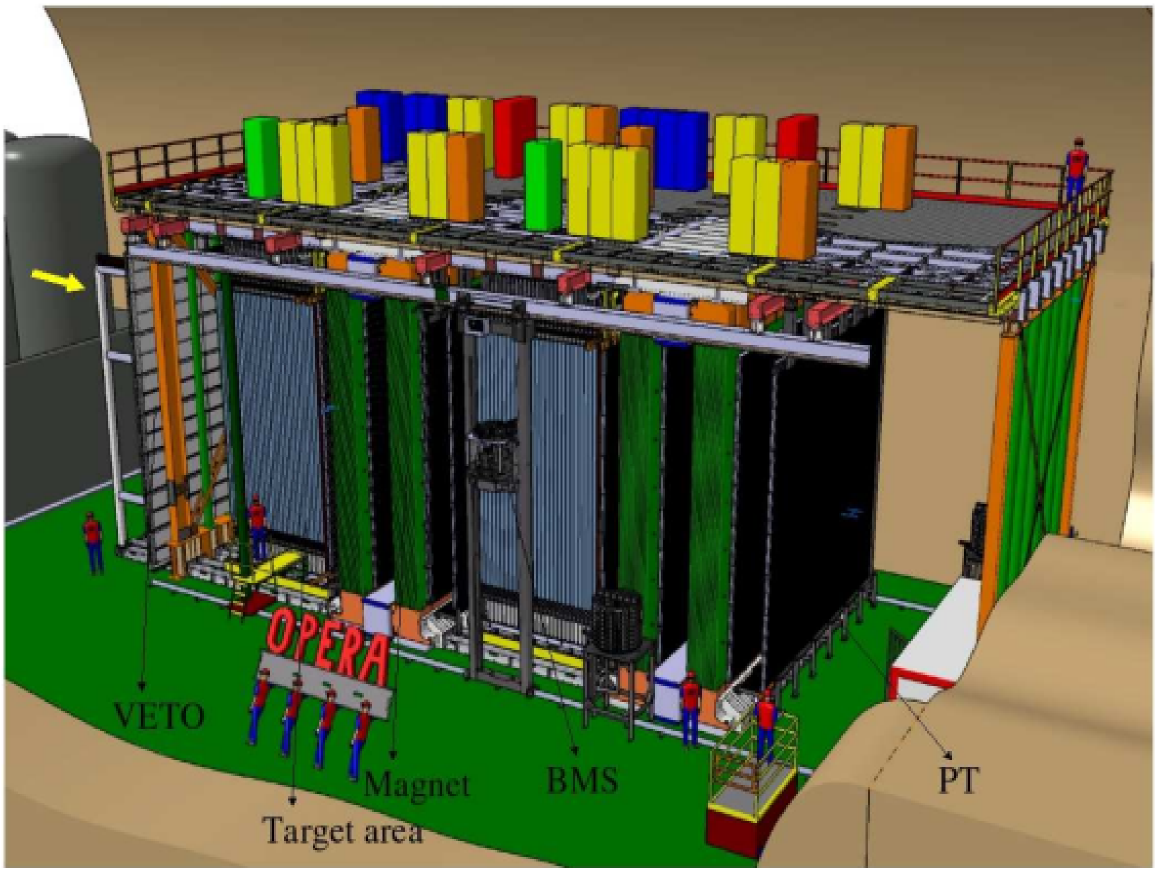

Figure 2.2: Artistic view of the OPERA detector.

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 set up. The Target Section was made up of the approximately 75000 bricks that make up each Super-Module and the 31 Target Trackers that connect them into vertical walls.

2.1. CERN Open Data Portal

In close coordination with the experiments, CERN IT and the CERN Scientific Information Service jointly created the CERN Open Data Portal in 2014. A variety of data produced as a result of CERN investigations are accessible through the open data portal at CERN. It disseminates the various findings from various research projects as well as the software and documentation necessary to understand the data analysis.

Chapter 3

Results and discussion

3.1. Task 1

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

3.1.1 Flight Length of the charmed hadron

Flight length (or decay length) of a charmed hadron is just a distance between the primary and the secondary vertices of the neutrino interaction event, i.e., the distance between two points in 3D space.

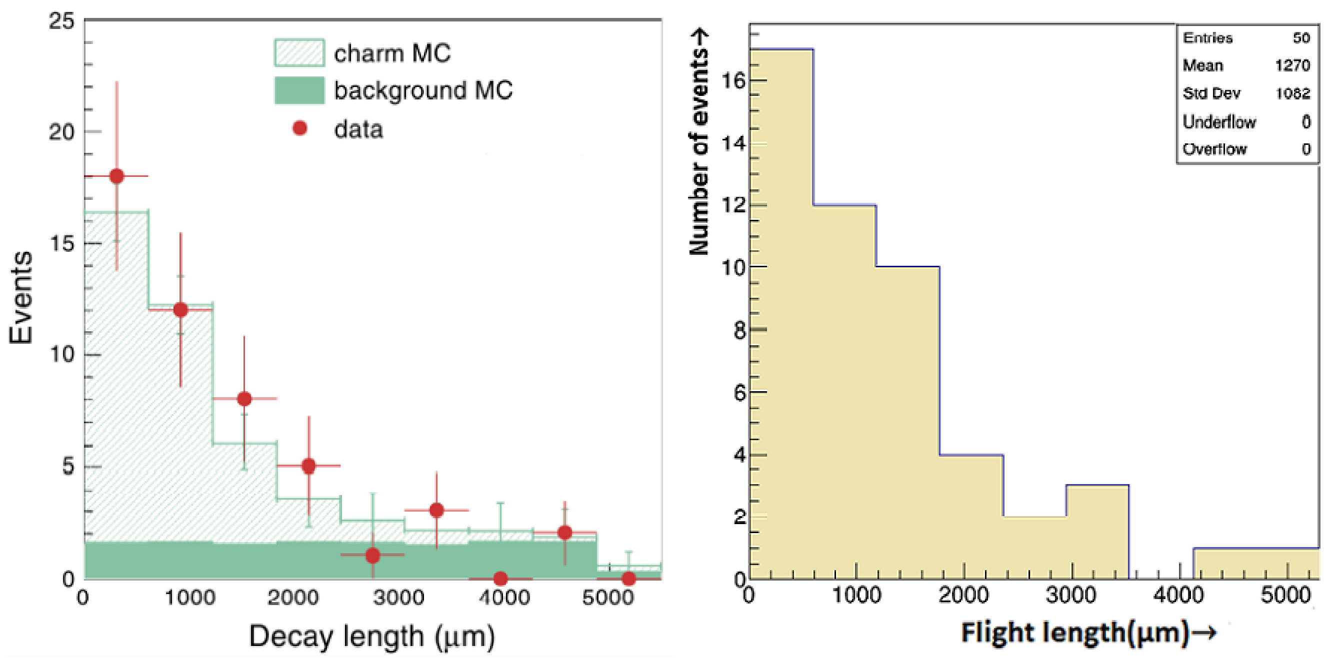

Figure 3.1: Flight Length of the charmed hadron

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:

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

The local coordinates for primary and secondary vertices given in the EventIDVertices.csv file were used. Each file's vertices have been computationally read using a C++ program. Flight lengths for each event have been calculated using above formula, and stored in the form of a data file. Here in the Figure 3.1, the data which is obtained from OPERA has been compared with the reference paper of Agafonova et al. Histograms for flight length has been plotted using ROOT software.

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

Impact parameter (IP) is a distance between the daughter particle track and the primary neutrino interaction vertex, i.e., the distance between a line and a point in 3D space.

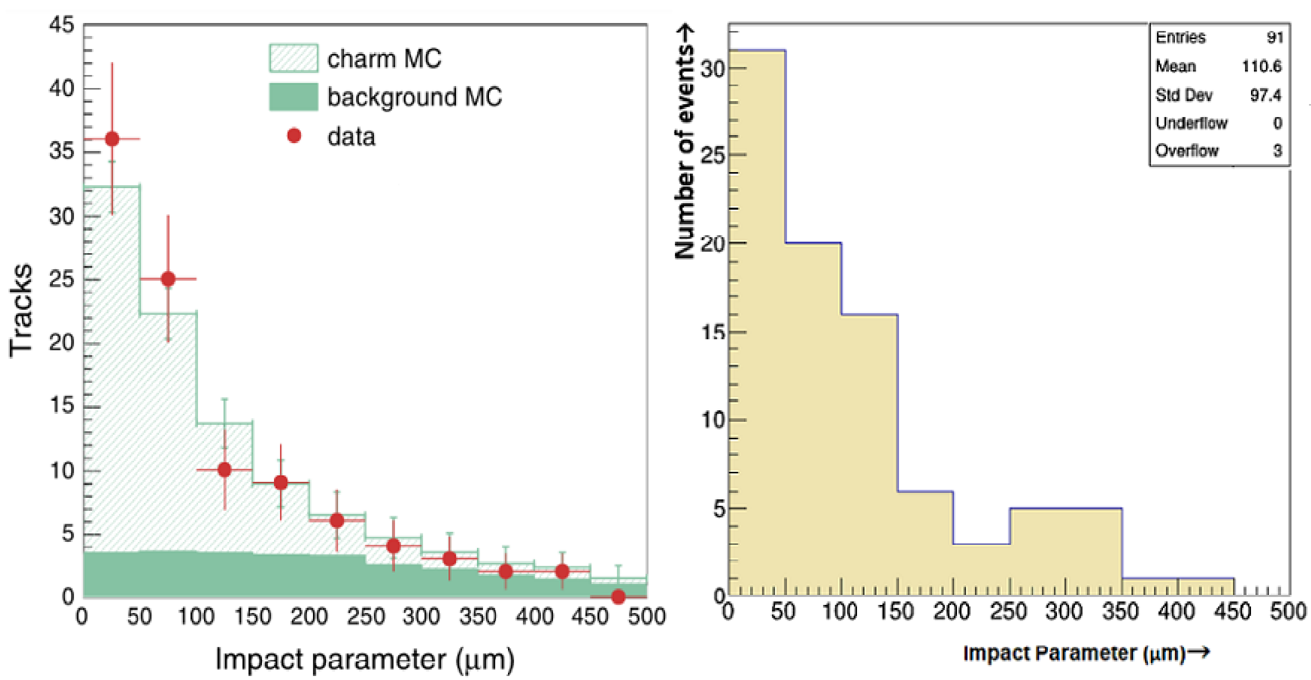

Figure 3.2: Impact Parameter of the daughter tracks with respect to the primary vertex

Impact parameter can be calculated using below mentioned formula:

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

Where, $\vec{A}$ is the vector distance between the primary vertex and the daughter track and e_r, is the direction vector of the daughter track. The local coordinates for the primary vertex were provided in the EventIDVertices.csv file, the coordinates for the daughter track were provided in the EventIDTracklines.csv file under the trtype 10 designation. The unit direction vector for the daughter track (e_r) was computed using a C++ code. Vector distance $\vec{A}$ was calculated, then impact parameter can be obtained from above formula. In the Figure 3.2 the obtained data from OPERA has been compared with he published data, Impact parameter histogram has been plotted using ROOT software

3.2. Task 2

In this Task emulsion dataset for the charged hadron multiplicity has been studied using Open Data Portal.

3.2.1 Multiplicities of all produced charged particles

Track multiplicity, which is related to the muon neutrino primary interaction vertex in our scenario, is the number of charged particle tracks associated to a specific vertex.

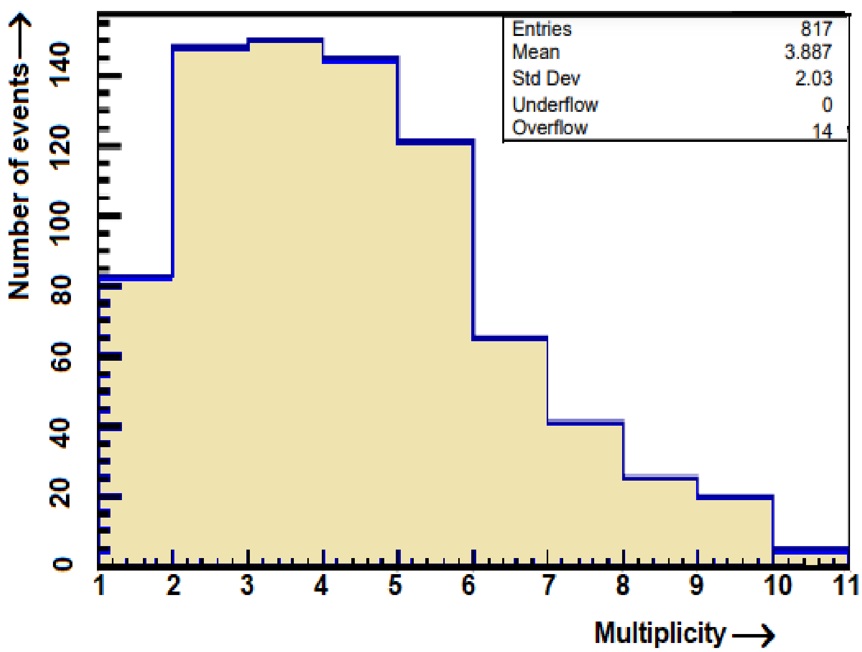

Figure 3.3: Track multiplicity distribution

The number of hadrons produced by a neutrino's interaction with the lead nucleus target varies depending on the event, and this information is provided in the EventIDvertex.csv file. The multiplicity for each event was read using a C++ code. In one data file, the extracted multiplicities were stored. Histogram for Track multiplicities which is plotted using ROOT has been 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 mathematical formula:

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

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

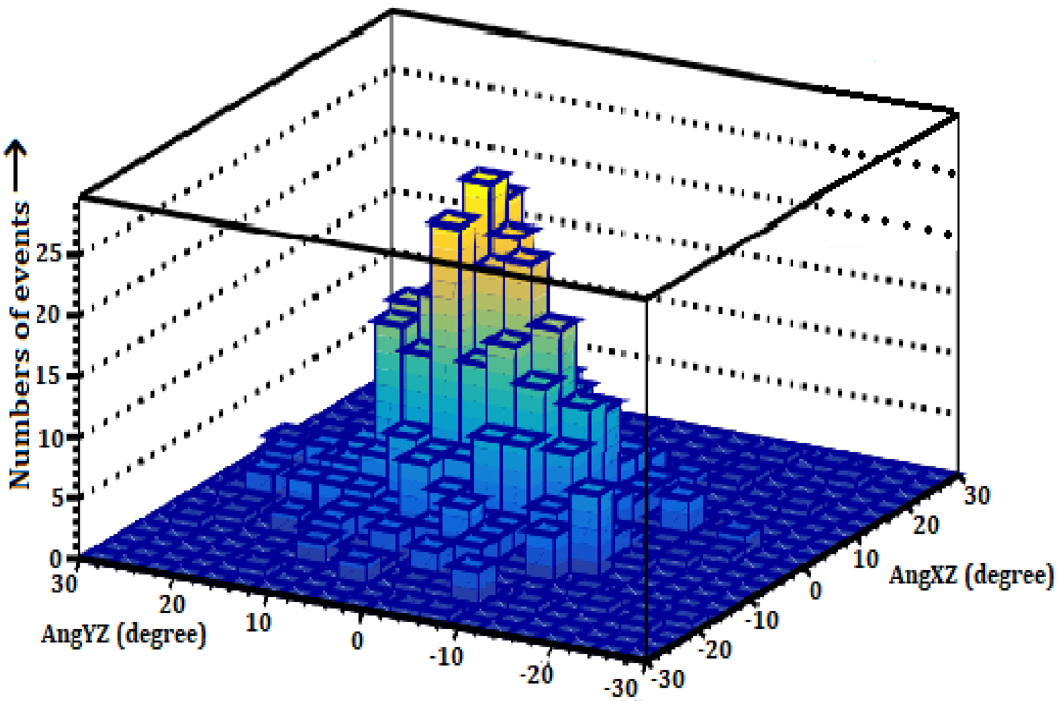

Figure 3.4: Muon track angles

Entries		818
Mean x		−0.7834
Mean y		2.452
Std Dev x		7.865
Std Dev y		8.428
0	4	0
2	811	0
0	1	0

The XZ and YZ views' slopes were read using the C++ code. For each event, the angle of the muon track was computed using the above mentioned mathematical formula. The plot for Muon track angles has been shown in Figure 3.4 which is plotted using ROOT software.

3.3. Task 3

3.3.1 Emulsion Data for Neutrino Tau Appearance Studies

In this Task, a 3D visualisation was produced using the OPERA emulsion data set for the tau neutrino appearance study. After final kinematical cuts, the electronic detectors' collection of 5603 completely reconstructed neutrino interactions was reduced to 10 successful τ neutrino candidates. The THREE.js JavaScript (JS) library was used to visually reconstruct the whole set of data. Here in the figure 3.5 Tracks and Vertices which is reconstructed in nuclear emulsion has been shown for 6 tau neutrino candidate events out of 10 tau neutrino candidate events.

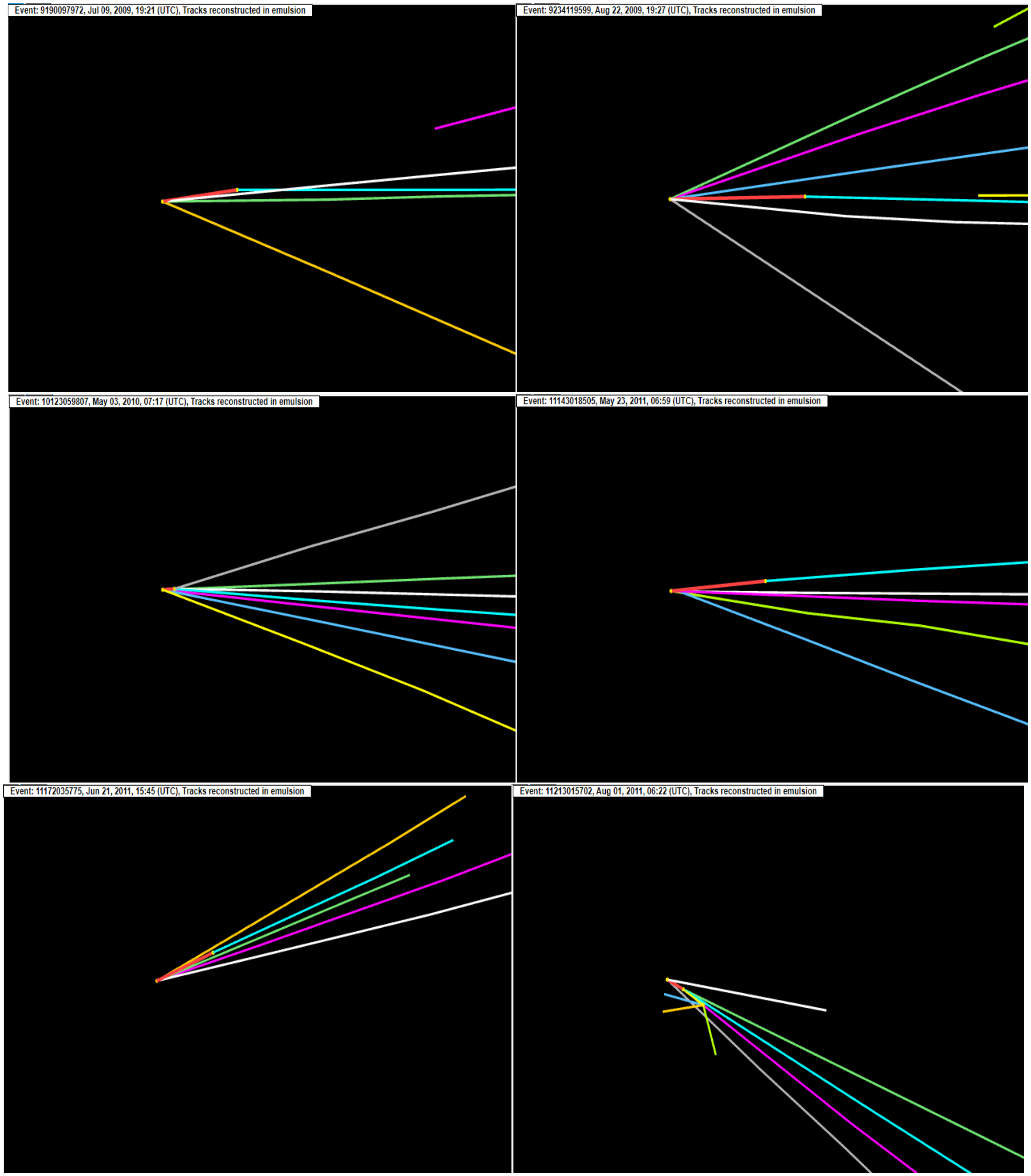

Figure 3.5: Tracks reconstructed in emulsion

Chapter 4

Summary and conclusion

Several OPERA datasets accessible on the CERN Open Data Portal have been subjected to qualitative and quantitative analysis using C++ applications utilising CERN's ROOT libraries. In this project the work has divided in three parts. In Part 1 (Task 1), flight lengths of charmed hadrons and impact parameters of their daughters with respect to primary neutrino interaction vertex have been calculated. In Part 2 (Task 2), the distributions of track multiplicities of charged particles and angles of the muon tracks have been obtained. The obtained distributions have been found to be in good agreement with the published results. And lastly, In part 3 (Task 3), 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. The images of the neutrino events that were acquired can be compared to those on the Open Data Portal.

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