JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

Analysis and Interactive Visualisation of Neutrino Event Topologies Registered in the OPERA Experiment

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1 Abstract

Neutrino oscillation, first predicted by Bruno Pontecorvo in 1957, is a quantum mechanical phenomenon which manifests primarily as a neutrino created in one flavour and later interacting as another. This phenomenon implies that the neutrino has a non-zero mass which calls for a modification to the Standard Model of Particle Physics. The OPERA experiment was designed to detect tau neutrinos from muon neutrino oscillations. This project is concerned with examining data of neutrino event topologies registered in the OPERA experiment. The data set is accessed from CERN Open Data Portal. The data is analysed through programs written in C++ and the results of the analysis are displayed in ROOT data analysis framework. Moreover, JavaScript, HTML, and CSS were used to create a visualisation of typical topologies of neutrino interaction events.

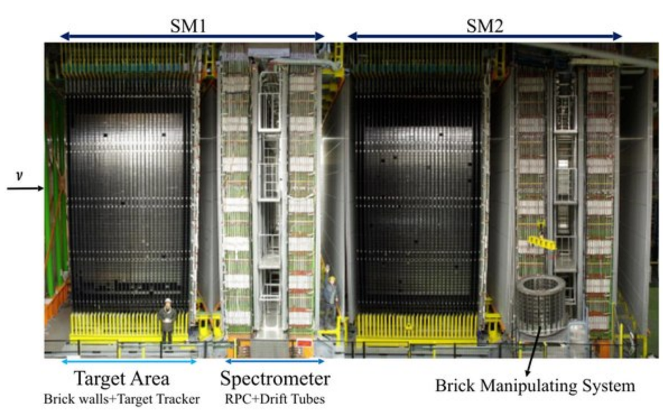
2 Introduction

2.1 Neutrino Oscillation

In 1930, Wolfgang Pauli hypothesised the existence of a particle, called neutrino, in order to solve the problem of the apparent disappearance of energy in the decay of certain atomic nuclei. A neutrino is a subatomic particle very similar to an electron in many ways but differs in that it is electrically neutral and has a very small mass that was long thought to be zero. It's one of the most abundant particles in the universe. However, it's very difficult to detect since it does not interact with other matter much at all. The only known forces a neutrino experiences are gravity and the weak force. A neutrino can come in one of three flavours. As far as we know, when a neutrino of a given flavour interacts and produces a charged lepton, the charged lepton will be of the same flavour as the neutrino. Although, it has been observed that neutrinos' flavour can change, known as neutrino oscillation, suggesting that neutrinos have non-zero masses which is inconsistent with the Standard Model of Particle Physics. This phenomenon, first proposed by Bruno Pontecorvo in 1957, has been studied since its discovery mostly in disappearance mode. Nonetheless, it is also important to observe the appearance of neutrino oscillations in compatibility with the disappearance results.

2.2 The OPERA Experiment

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) was designed to prove that through neutrino oscillation muon neutrinos can turn into tau neutrinos. It was a collaboration between CERN and the Laboratori Nazionali del Gran Sasso. The OPERA was a hybrid detector consisting of an emulsion target with a large mass and a high spatial resolution complemented with electronic detectors. Our project aims to analyse the data of the OPERA collaboration provided through the CERN Open Data Portal. We will learn how to read csv files and analyse the neutrino event topology features through C++ programs. Moreover, we will use HTML and CSS languages and JavaScript graphic libraries to visualise typical neutrino interaction event topologies.



3 Data Analysis and Results

3.1 Emulsion Data of Neutrino-induced Charmed Hadron Production Studies

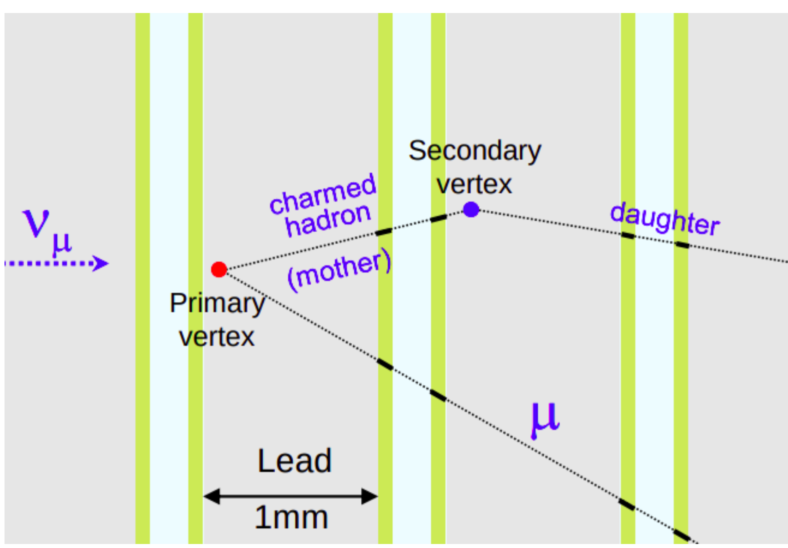
We developed a C++ program to analyse the emulsion data set of neutrino-induced charmed hadron production. The study of charm production was performed in OPERA in order to prove the possibility of registration of tau neutrino, since short-lived charmed hadrons showed similar decay topologies as the tau lepton. The data set contains the observed 50 muon neutrino interaction events over a sample of 2925 muon neutrino charged-current events fully analysed. It contains the information of the primary neutrino interaction vertices and the secondary vertices produced by charmed hadron decays, as well as the parameters of the charm decay daughter particle tracks.

3.1.1 Flight Length

We first calculated the flight lengths (decay lengths) of the charmed hadrons. Flight length of a charmed hadron is just the distance between the primary and the secondary vertices of the neutrino interaction event. To calculate the flight length, we can use the formula

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

where D is the flight length, x_1, y_1 and z_1 are the coordinates of the primary vertex, and x_2, y_2 and z_2 are the coordinates of the secondary vertex.



We saved the flight lengths of charmed hadrons into a histogram and saved the histogram to an image file.

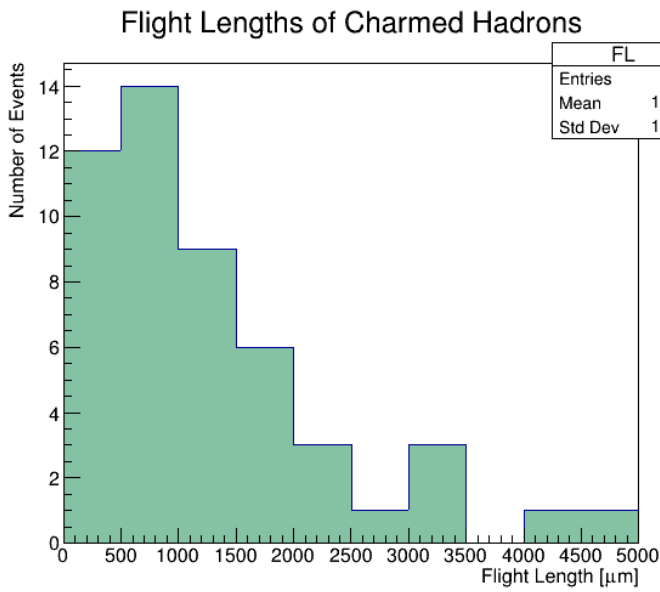


Figure 1

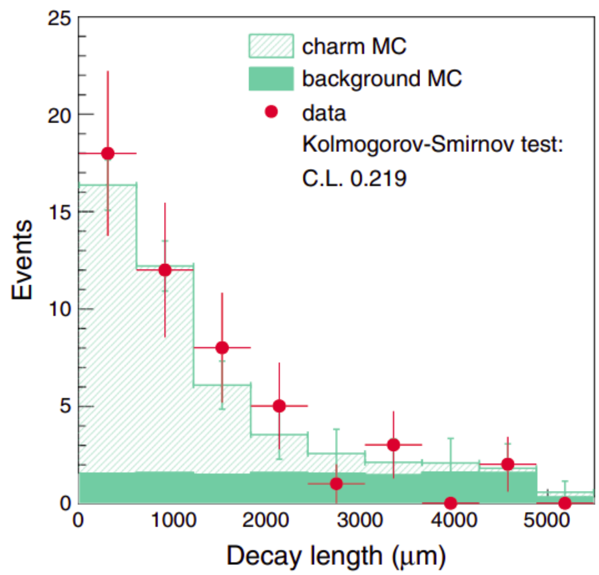


Figure 2

Comparing our results, Figure 1, with the one, Figure 2, published in the OPERA paper [1], we can see that the distributions are very similar.

3.1.2 Impact Parameter

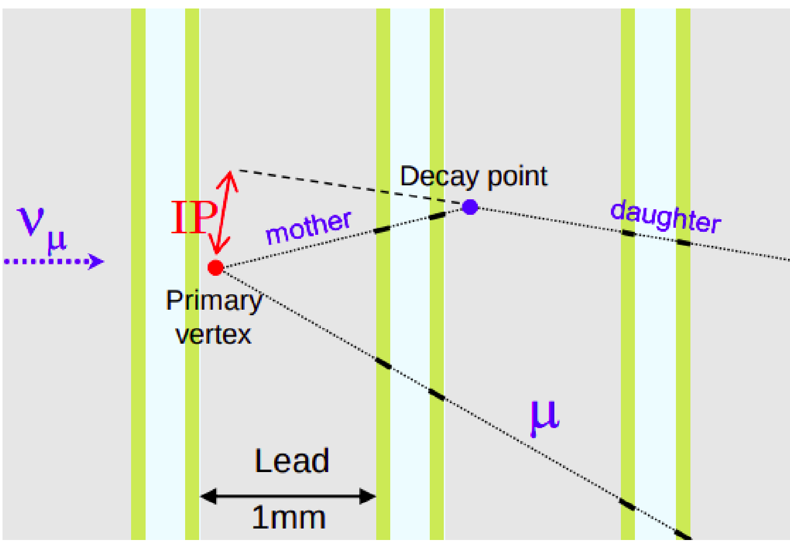
We calculated the impact parameter of the daughter tracks which is the shortest distance between the daughter particle track and the primary neutrino interaction vertex. This was calculated using the formula:

$$\mathrm{IP} = \frac{|\overline{V_0V_1} \times \overline{V_1P_2}|}{|\overline{V_1P_2}|} = \frac{\begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ x_1 - x_0 & y_1 - y_0 & z_1 - z_0 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \end{vmatrix}}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_2)^2 + (z_2 - z_1)^2}}$$

$$= \sqrt{\frac{(dy_{10}dz_{21} - dy_{21}dz_{10})^2 + (dx_{10}dz_{21} - dx_{21}dz_{10})^2 + (dx_{10}dy_{21} - dx_{21}dy_{10})^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}},$$

$$\begin{aligned} dx_{ij} &= x_i - x_j, \quad i, j = 1, 2, 3, \\ dy_{ij} &= y_i - y_j, \\ dz_{ij} &= z_i - z_j, \end{aligned}$$

where IP is the impact parameter, V_0 is the primary interaction vertex, V_1 is the secondary interaction vertex and the first point of the daughter particle track, and P_2 is the second point of the daughter particle track.



The results were saved into histogram and then into an image file as seen below.

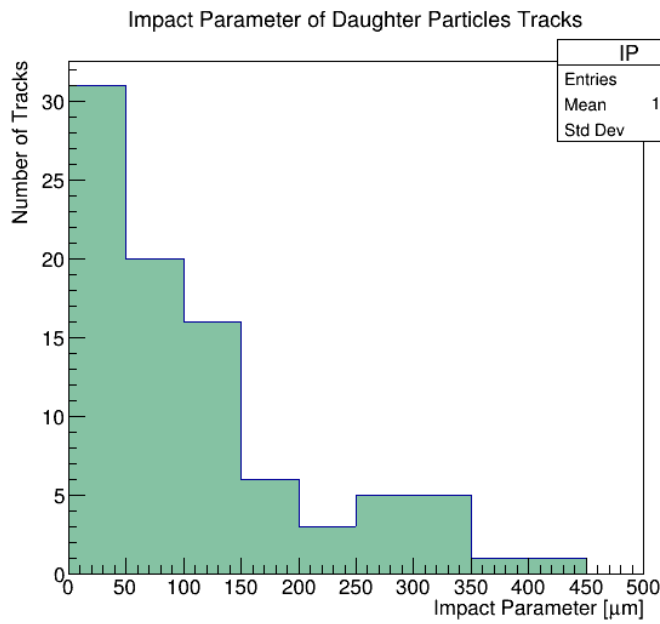


Figure 3

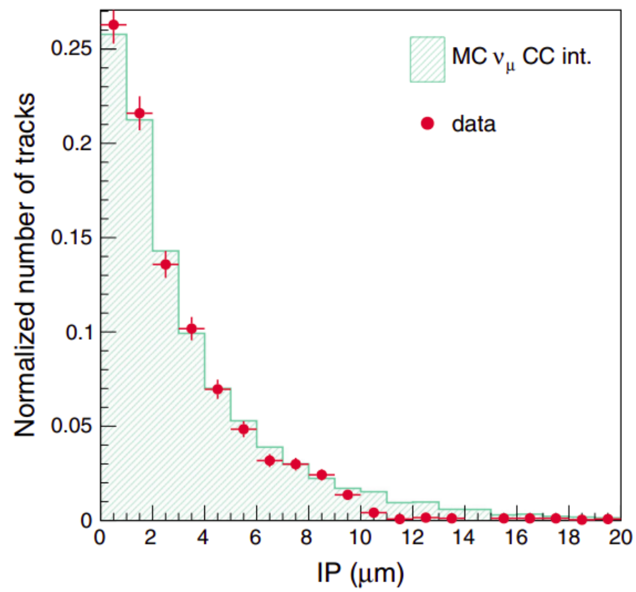


Figure 4

The histogram we obtained, Figure 3, is reasonably similar to that, Figure 4, from the OPERA published paper [1].

3.2 Emulsion Data for Track Multiplicity

In this task, we developed a C++ program to analyse the emulsion data set of the charged hadron multiplicity studies. The data set contains 817 muon neutrino interactions with a lead target in which a muon was reconstructed in the final state. It contains the information of the positions of the primary neutrino-lead interaction vertices as well as the parameters of the secondary charged particle tracks.

3.2.1 Track Multiplicity

Track multiplicity is the number of tracks of charged particles associated with a given vertex; in our case it is associated with the muon neutrino primary interaction vertex. We searched for the multiplicities of all the produced charged particles, saved them to a histogram and to an image file, as seen below on the left.

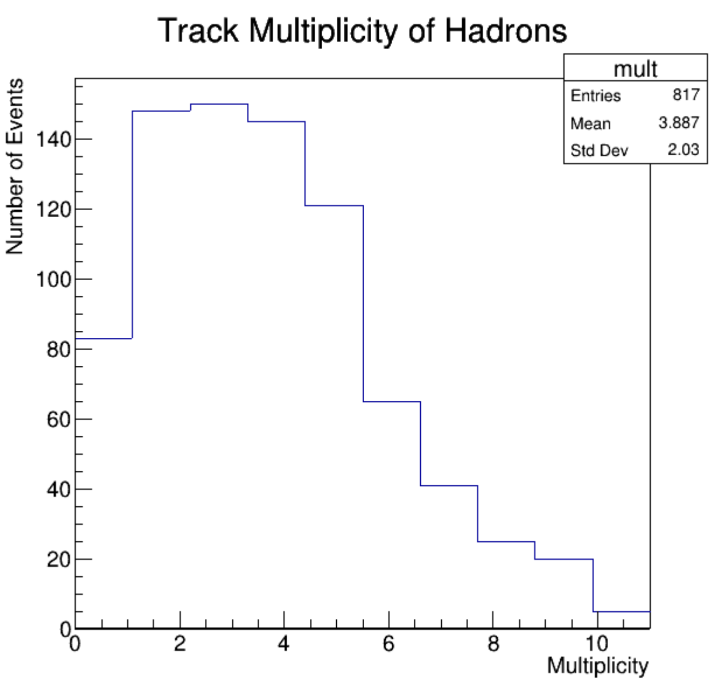


Figure 5

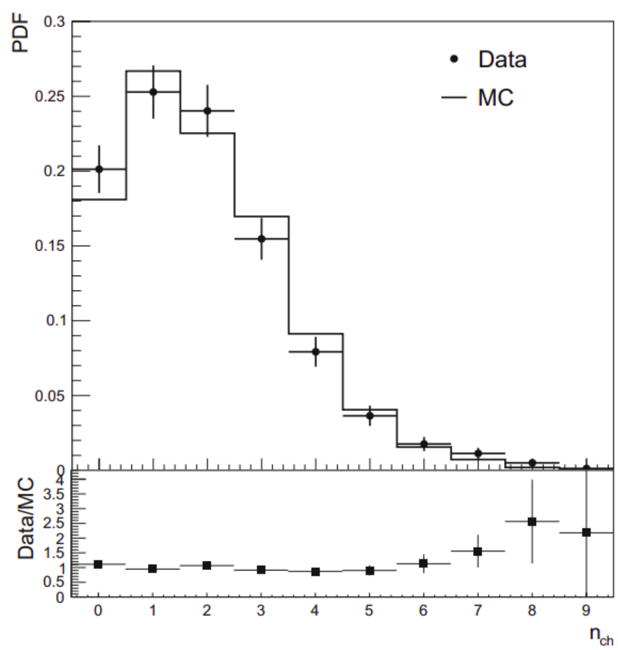


Figure 6

The histogram we obtained, Figure 5, is comparable to a reasonable extent to the one, Figure 6, from the corresponding published OPERA paper [2].

3.2.2 Track Angle

Each track is defined by its starting point, a 3D point near the vertex, and two slopes, i.e., tangents of angles with respect to the Z-axis in the XZ and YZ views. We obtained the muon track angles, Figure 7, by the equation

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

where θ is the angle of the muon track in radians, and s is the slope.

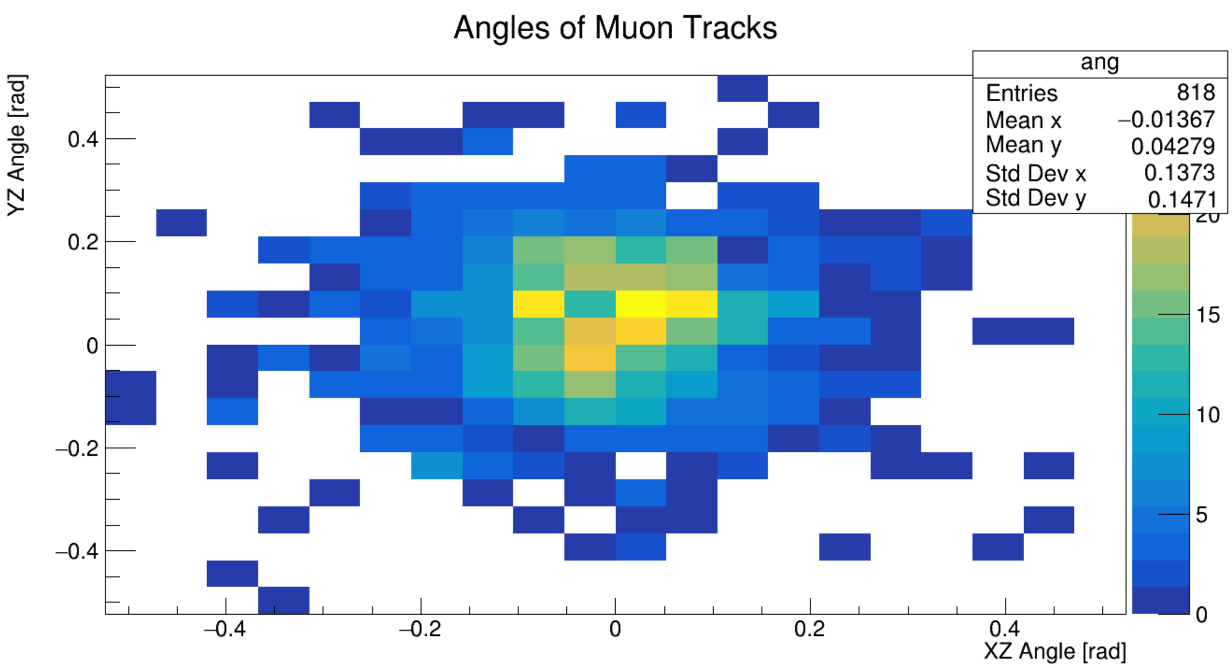
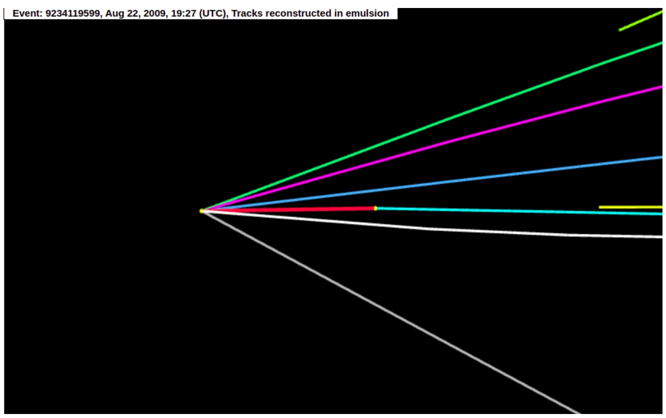
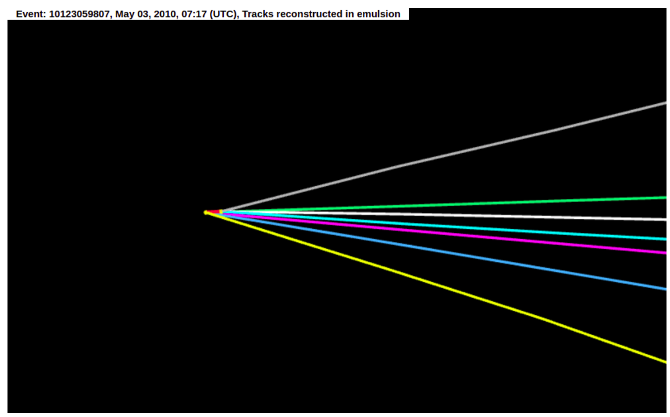


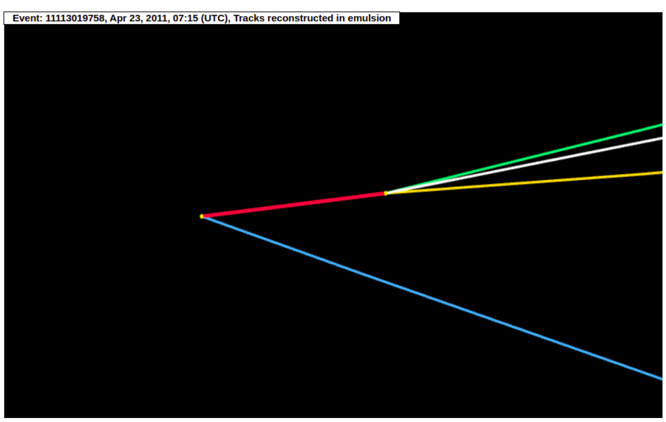
Figure 7

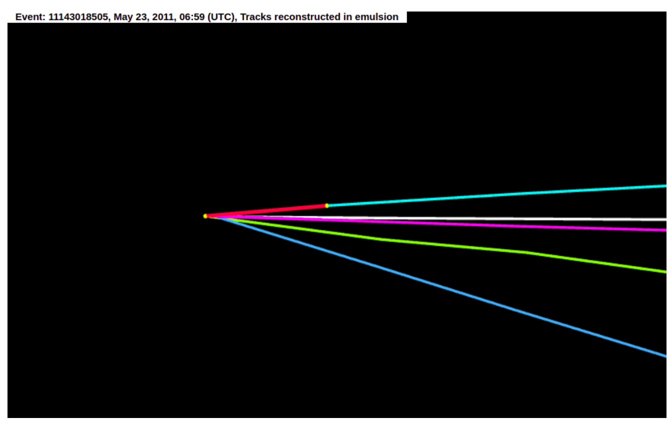
3.3 Emulsion Data for Neutrino Tau Appearance Studies

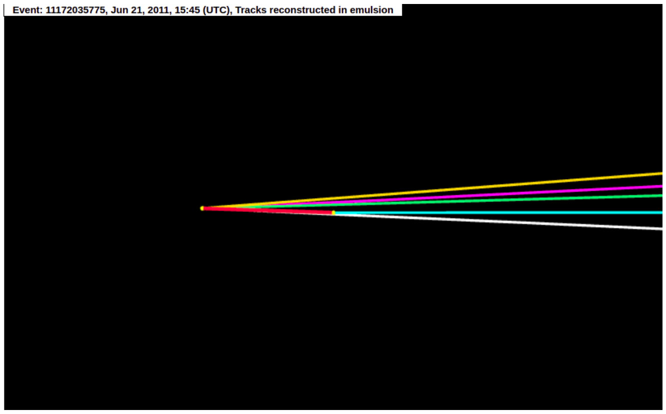
In this task, we used the OPERA emulsion data set for the tau neutrino appearance studies to create a 3D visualisation of 10 tau neutrino candidate event topologies. We implemented a simplified version of a browser-based event display using the JavaScript THREE.js graphics library. The primary and secondary vertices along with the track positions reconstructed in the nuclear emulsion in the candidate events were displayed by recovering the code of the corresponding JavaScript data structure program. HTML/CSS files were implemented to display the characteristic event topologies in a browser window.







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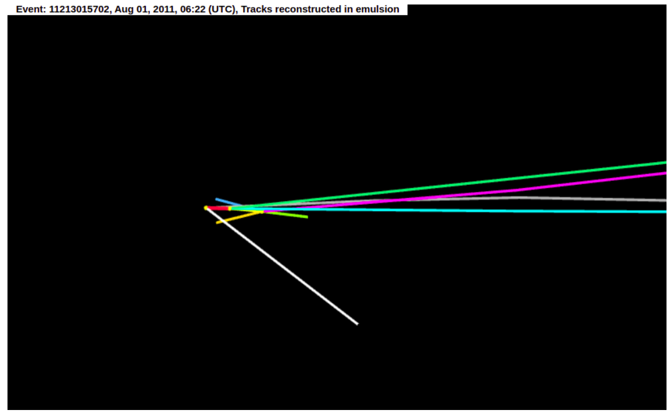
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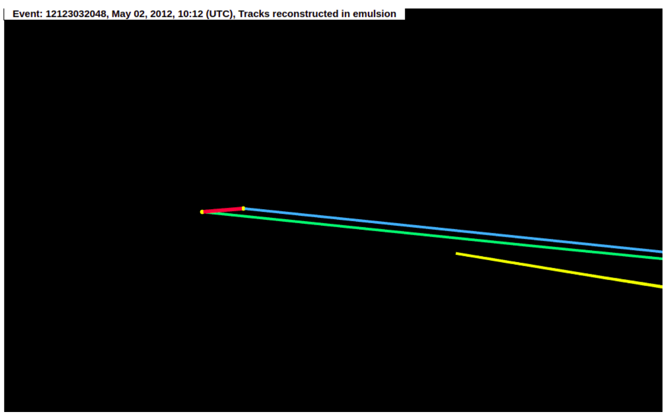
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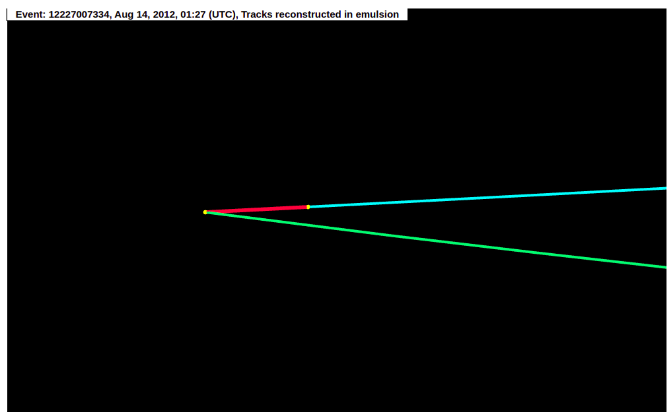
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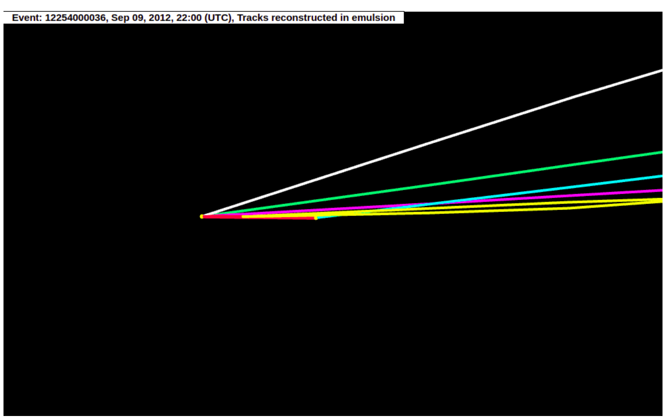
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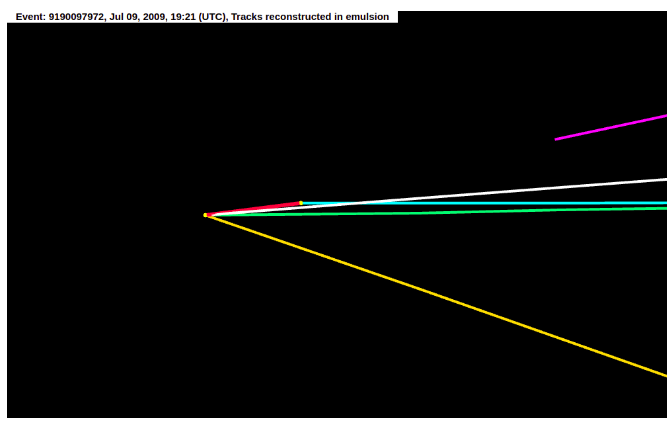
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4 Summary

Neutrinos are the second, after photons, most abundant known elementary particles in the universe and understanding them indicates a necessity to develop a fundamental theory beyond the Standard Model of Particle Physics. Accordingly, in this project, we worked on analysing several OPERA data sets available on CERN Open Data Portal using C++ programs along with ROOT library. The results we obtained were then compared with those in the original published OPERA papers and they were found to be in good agreement. We also created a visualisation of interesting neutrino topology events from the OPERA tau neutrino sample with a simplified version of the OPERA browser-based event display. We modified JavaScript code to draw 3D vertices and tracks reconstructed in the nuclear emulsion.

Bibliography

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[2] N. Agafonova et al. Study of charged hadron multiplicities in charged-current neutrino-lead interactions in the opera detector, 2017. https://arxiv.org/abs/1706.07930.

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