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

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Abstract

In this project there were three main programming tasks and one optional task. C++ scripts have been developed to plot several distributions for comparison to the ones obtained in the OPERA experiment. In tasks 3 and 4, CERN Open Data Portal has been used to visualize vertices and tracks reconstructed in OPERA nuclear emulsions as well as electronic detector hits registered in three OPERA ν_τ-candidate events.

Acknowledgment

I would like to express my gratitude for working in this fourth wave under the supervision of Dr. Sergey Dmitrievsky, who was always keen to help us and present his best to make this project understandable. He was always helping us with no hesitation and provide additional sessions like Root Histogram fitting, so I appreciate his effort. In addition, thanks to the INTEREST Project @ JINR committee for giving students from all over the world this opportunity to be trained under the guidance of supervisors who are such kind.

1 Introduction

Neutrinos are neutral elementary particles (fermions) which can be classified into: ν_e, ν_μ and ν_τ, in addition to their anti ones. Neutrinos are very weakly interacting with matter, so they interact via the weak force and they have a spin of $\frac{1}{2}\hbar$. In this project, we will depend only on the dataset of **OPERA Experiment** obtained from **CERN Open Data Portal**, as we intend to study the work done in OPERA related to neutrino oscillation and detection.

1.1 CERN Open Data Portal

In the CERN Open Data Portal [3] there is a lot of information and data stored of approximately two petabytes about experiments done in the field of particle physics such as **OPERA**, ALICE, ATLAS, CMS, and LHCb.The set of data files that will be used from this site:

- Emulsion Data for Neutrino-Induced Charmed Hadron Production Studies (48.5 kB).
- Emulsion Data for Track Multiplicity (456.1 kB).
- Emulsion Data for ν_τ Appearance Studies (34.6 kB).
- Electronic Detector Data for ν_τ Appearance Studies (51.0 KB)

1.2 OPERA Experiment

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) [4, 5, 6] is designed to study the neutrino oscillations, and to observe ν_τ from ν_μ oscillation, through τ lepton decay in the emulsion detector [7]. It is constructed underground of Gran Sasso Laboratory, Italy lies about 732 kilometers from CERN. The neutrinos' interactions in this experiment are reconstructed through a technique called "Emulsion Cloud Chamber" and the electronic detection system.

1.2.1 Neutrinos Production at CERN

Figure 1 shows how muon neutrinos ν_μ were obtained in CERN to make their way to Gran Sasso laboratory, starting with a proton beam of 400 GeV [8] produced by the Super Proton Synchrotron (SPS) at CERN. As a result of interactions of the protons with a graphite rod (shown in the very left side of the Figure 1 pions and kaons were produced and focused by the horn and reflectors which were two focusing magnets. Finally, passing through the one-kilometer decay pipe, pions and kaons decayed to muons and muon neutrinos. These μ neutrinos were then traveling to Gran Sasso and part of them oscillated to tau neutrinos. For 1.8×10^{20} protons sent on target in CERN there were 19×10^3 interactions of neutrinos registered by the OPERA electronic detectors in Gran Sasso [9].

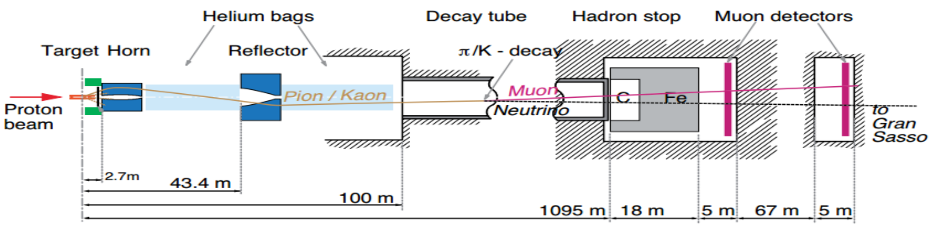


Figure 1: CERN Neutrinos to Gran Sasso (CNGS) beam line

1.2.2 Oscillation of Neutrinos

The meaning of oscillation here means the change of neutrinos from one flavor into another one such as $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$. This is technically possible by making the neutrino travel for a long distance such as in the case of the OPERA experiment.

1.3 OPERA Detector

Figure 2 [7] shows a side view of the whole Opera detector at Gran Sasso, while Figure 3 [5] gives a closely view of the emulsion film components.

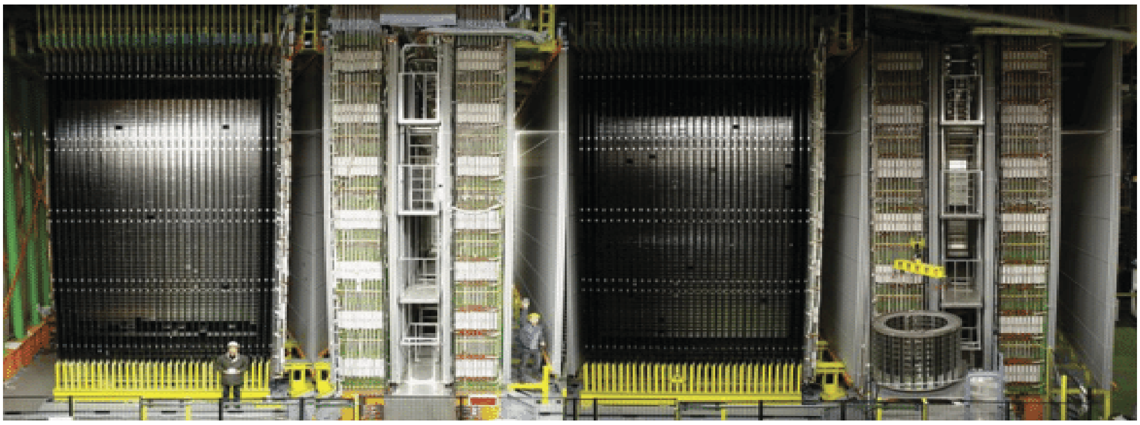


Figure 2: OPERA Detector: a side view

1.3.1 Emulsion Cloud Chamber

Neutrinos detection is enhanced according to the mass of the detector itself. In Emulsion Cloud chamber [10, 7, 8] the main unit composing it is called "brick". Each brick is manufactured with 1 millimeter-thick 56 lead plates, with area of $12.5 \times 10.2\ cm^2$ [9, 8] and weighs about 8.3 kilograms with 57 emulsion films. In 2009, the mass of the detector reached about 1250 tons, due to a large number of added bricks to the detector. In the end, the bricks are arranged together to form a wall with dimensions of $6.7 \times 6.7\ m^2$ [8].

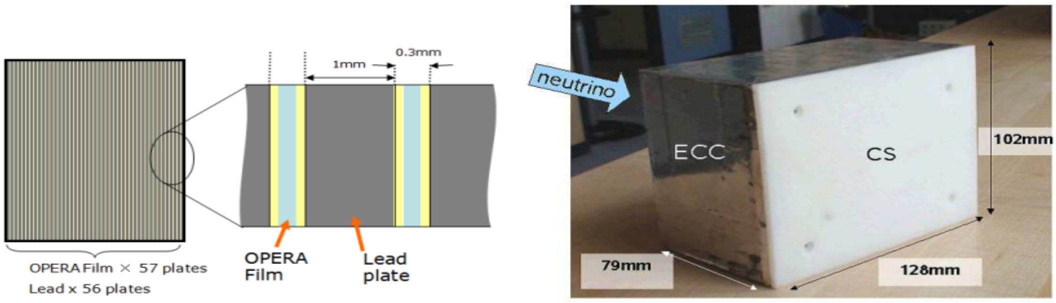


Figure 3: Opera Emulsion Film Components

1.3.2 Electronic Detection System

OPERA electronic detectors included Target Tracker system following by magnetic spectrometers. It was used to trigger neutrino interactions with the detector's target. Also it helped in identifying the positions of bricks that contained neutrino interaction vertices, by reconstruction of muon tracks and/or hadron shower axes using hits of the electronic detectors.

1.4 Tasks of Project

First of all, the four tasks are performed with C++ and JavaScript files that were mainly obtained from Dr. Sergey and then modified. There were three main tasks plus one optional task for this project are ordered as:

1.4.1 Task (1)

1. Downloading OPERA "emulsion dataset for the neutrino-induced charmed hadron production studies" from the Open Data Portal
2. Developing a C++ program for analysis of the dataset.
3. Reading the positions of the primary and the secondary interaction vertices as well as the parameters of the charm decay daughter particle tracks.
4. Obtaining the histograms for the flight lengths of charmed hadrons and impact parameters of the daughter particle tracks concerning the primary neutrino interaction vertices.
5. Comparing these histograms and those published in the paper [1] by the OPERA collaboration.

1.4.2 Task (2)

1. Downloading the OPERA emulsion dataset for the charged hadron multiplicity studies from the Open Data Portal.
2. Developing a C++ program for analysis of the dataset.
3. Reading the positions of the primary neutrino-lead interaction vertices as well as the parameters of the secondary charged particle tracks.
4. Obtaining the histograms of multiplicities of all produced charged particles and angles of the muon tracks.
5. Comparing these histograms and those published in the paper [2] by the OPERA collaboration.

1.4.3 Task (3)

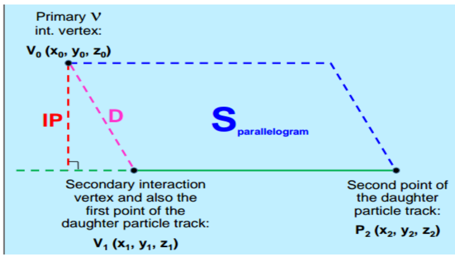
1. Downloading OPERA emulsion dataset for the tau neutrino appearance studies from the Open Data Portal site.
2. Editing and filling the missed parts in the provided java script files.
3. Displaying of 3D tracks of charged particles as well as primary and secondary interaction vertices, reconstructed in nuclear emulsions, using the THREE.js graphics library.

1.4.4 Task (4)

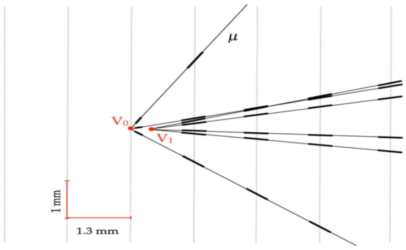
1. Downloading OPERA electronic detectors dataset for the tau neutrino appearance studies from the Open Data Portal for visualization [11].
2. Editing and filling the missed parts in the provided java script files.
3. Displaying of two 2D event views of the electronic detector hits registered in XZ and YZ projections, using the D3.js graphics library.

2 First Task: Emulsion Data for Neutrino-Induced Charmed Hadron Production Studies

In the first task, distributions of the decay lengths and the impact parameters are presented: on the left sides of Figures 5 and 6 the distributions were build using the dataset taken from the Open Data Portal [3]; on the right sides - the distributions taken from [1] both for simulated and for experimental data.



(a) Calculation Method



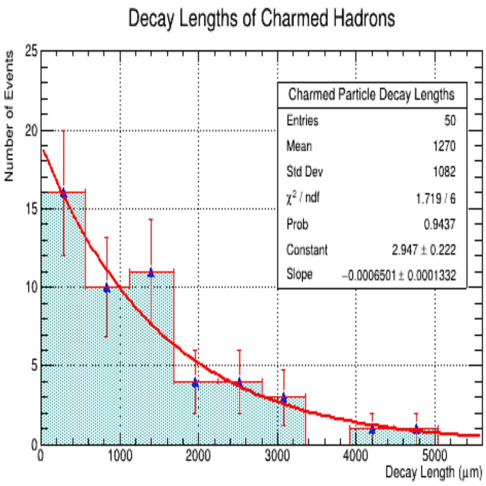
(b) Reconstruction of ν Interaction

Figure 4: Vertices of Neutrino Representation

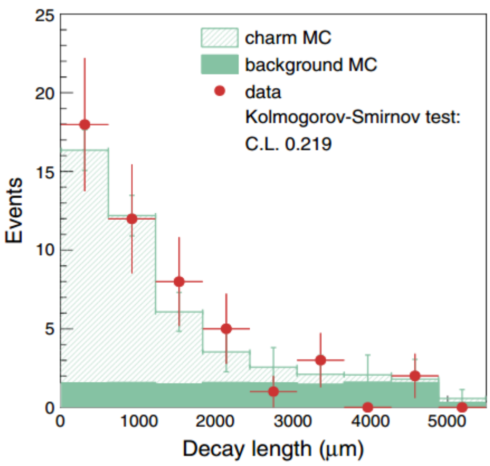
2.1 Calculation of Decay Lengths

The decay length is obtained by calculation of the distance between the two, starting and ending, points in 3D space as in Figure 4, we need to calculate interval between points V_0 and V_1. This is given by:

$$D = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2} \tag{1}$$



(a) Theoretical



(b) Experimental

Figure 5: A Comparison of the Decay Length Distribution Obtained from the Dataset with the One Taken from the OPERA Paper [1]

2.2 Calculation of Impact Parameters

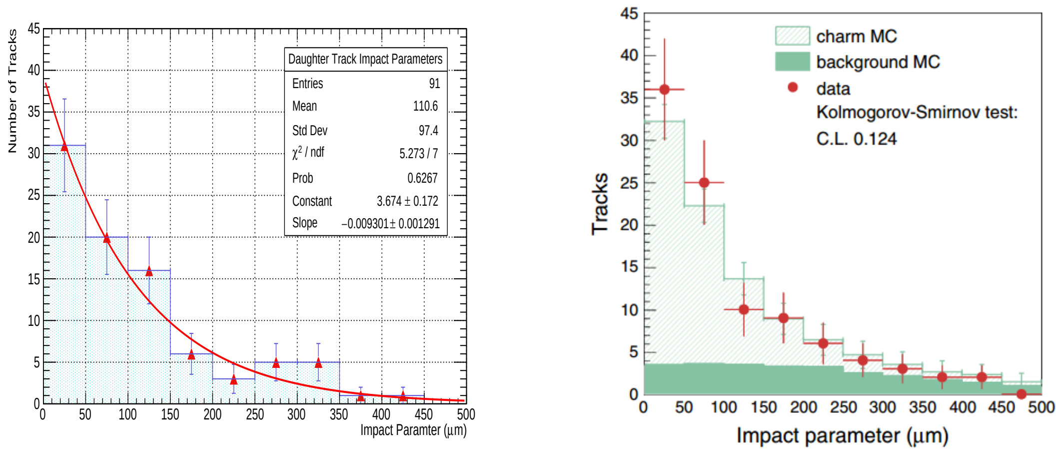
Impact Parameter (IP) of the Track:It is a distance in 3D space between the primary neutrino interaction vertex and the track's line.

$$IP = \frac{|\overline{V_0V_1} \times \overline{V_1P_2}|}{\overline{V_1P_2}} = \frac{\begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ dx_{10} & dy_{10} & dz_{10} \\ dx_{21} & dy_{21} & dz_{21} \end{vmatrix}}{\sqrt{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}} \tag{2}$$

Hence the final formula of the impact parameter is given by:

$$IP = \sqrt{\frac{(dy_{10}dz_{21} - dy_{21}dz_{10})^2 + (dx_{10}dz_{21} - dx_{21}dz_{10})^2 + (dx_{10}dy_{21} - dx_{21}dy_{10})^2}{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}} \tag{3}$$

In previous equations, it should be noted that $dA_{ij} = A_j - A_i$. Where $A = x$ or y or z and $i, j = 0, 1, 2$.



(a) Obtained from the Dataset

(b) Taken from the OPERA paper

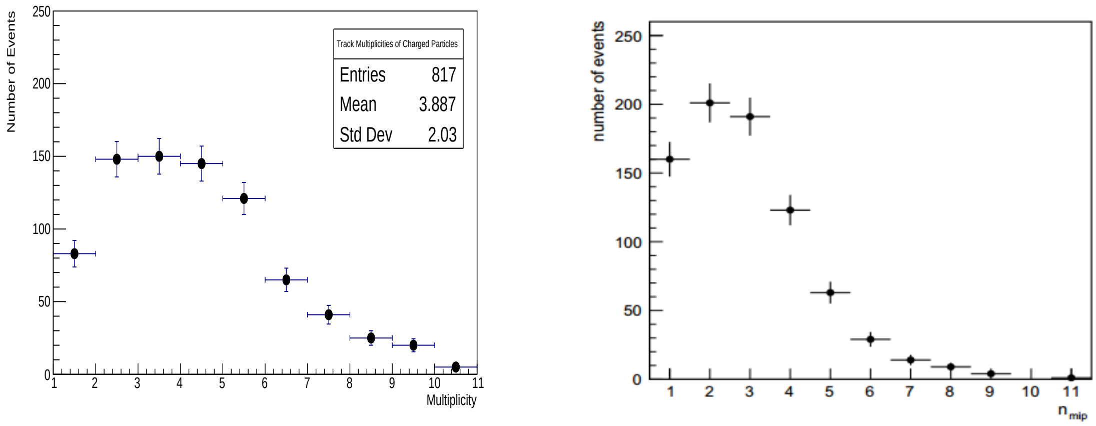
Figure 6: A Comparison of the Impact Parameter Distribution Obtained from the Dataset with the One Taken from the OPERA Paper [1]

2.3 Programming Work

The mathematical equations for decay length and the impact parameter should be written in C++ form and added to the C++ compilation file. Then using this file we can analyze data from the "Emulsion Data for Neutrino-Induced Charmed Hadron Production Studies" folder which contained .csv files used for doing the analysis needed.

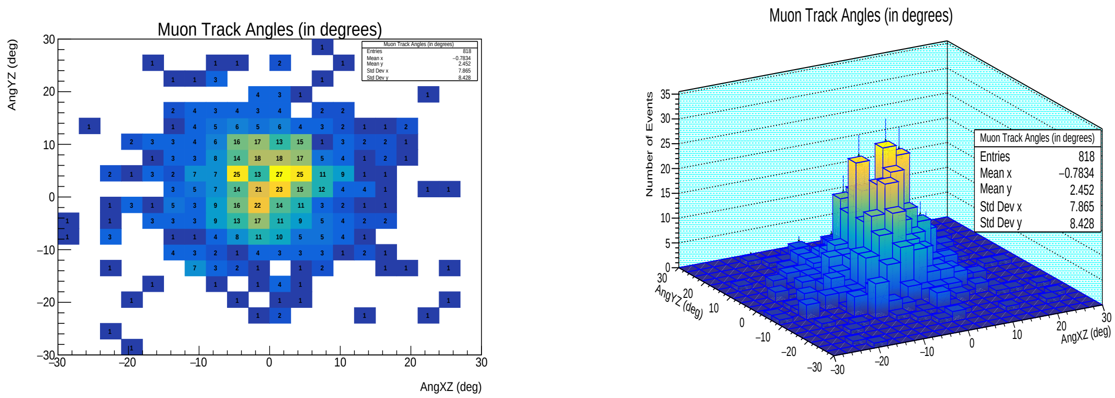
3 Second Task: The Charged Hadron Multiplicity Studies

In the second task, distributions of the track multiplicities are presented: on the left side of Figure 7 the distribution was build using the dataset taken from the Open Data Portal [3]; on the right side - the distribution taken from [2] both for simulated and experimental data. In Figure 8 two different representations of the same 2D histogram with distribution of the muon track angles obtained from the dataset are shown.



(a) Obtained from the Dataset (b) Taken for OPERA Paper

Figure 7: A comparison of the Track Multiplicity distribution obtained from the Dataset with the One Taken from the OPERA Paper [2]



(a) 2D Representation ("colz" Option) (b) 3D Representation ("lego2" Option)

Figure 8: Different Representations of the Muon Track Angle Histogram

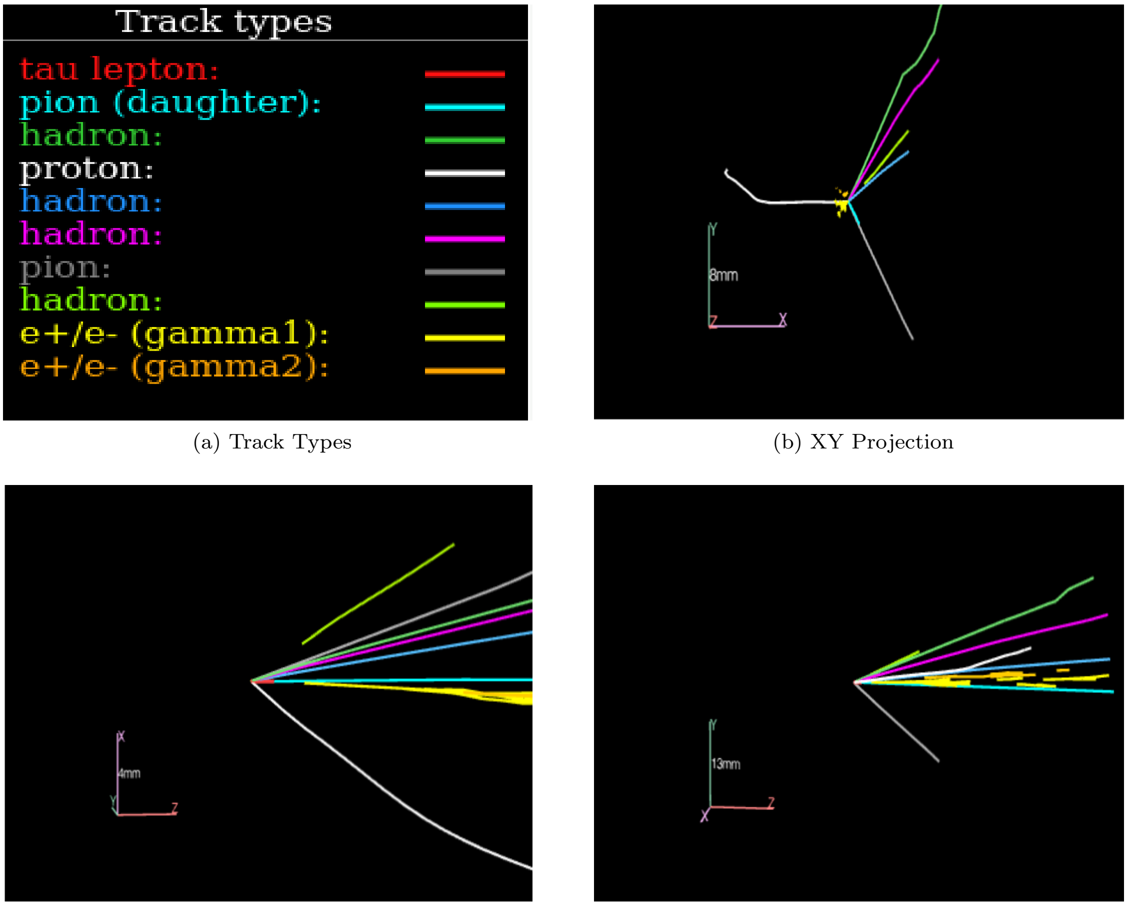
4 Third Task: Emulsion Data for The ν_τ Appearance Studies

In this task we had 10 ν_τ appearance studies in events with IDs of (9190097972, 9234119599, 10123059807, 11113019758, 11143018505, 11172035775, 11213015702, 12123032048, 12227007334, 12254000036).

In my case, I will mention only the following three events:

- **9234119599** in Figure 9
- **10123059807** in Figure 10
- **12254000036** in Figure 11

4.1 For Event of ID = 9234119599

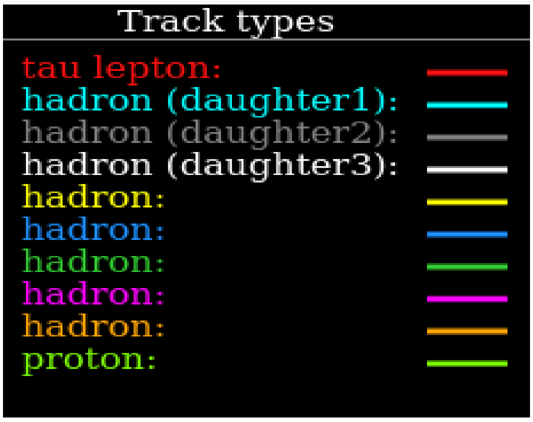


(a) Track Types (b) XY Projection

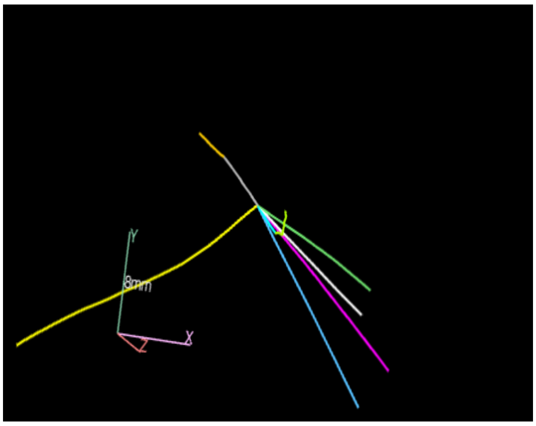
(c) XZ Projection (d) YZ Projection

Figure 9: Reconstructed Tracks in emulsion for Event 9234119599

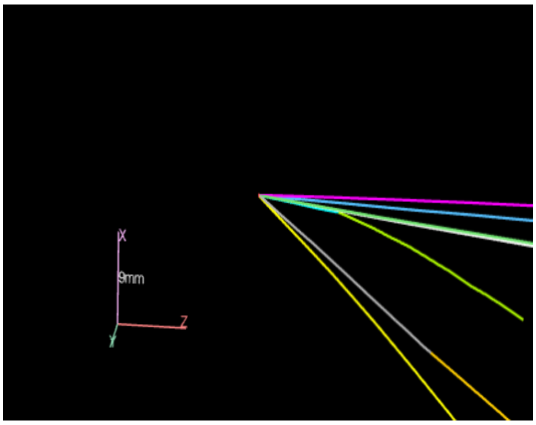
4.2 For Event of ID = 10123059807



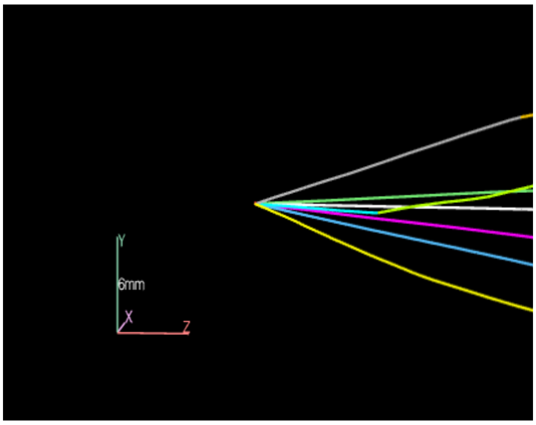
(a) Track Types



(b) XY Projection



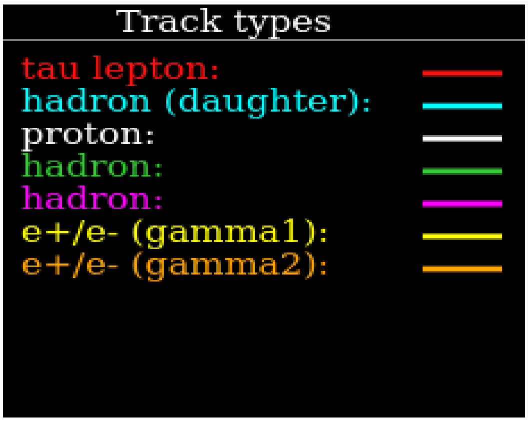
(c) XZ Projection



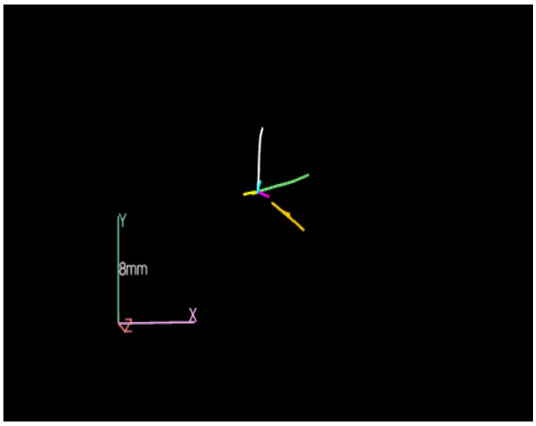
(d) YZ Projection

Figure 10: Reconstructed Tracks in emulsion for Event 10123059807

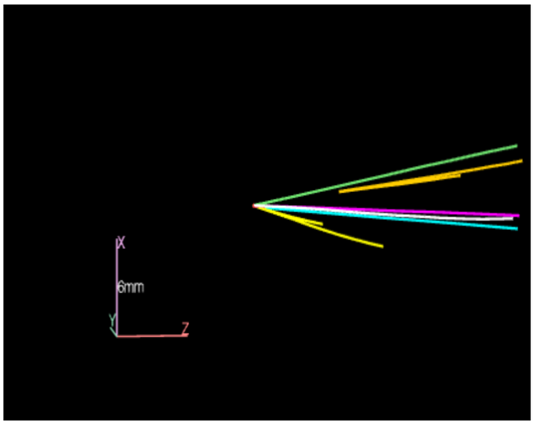
4.3 For Event of ID = 12254000036



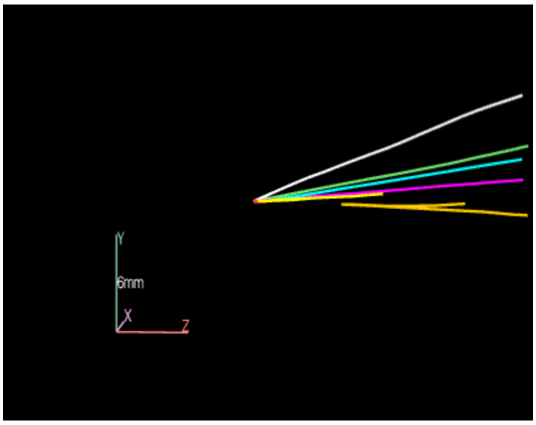
(a) Track Types



(b) XY Projection



(c) XZ Projection



(d) YZ Projection

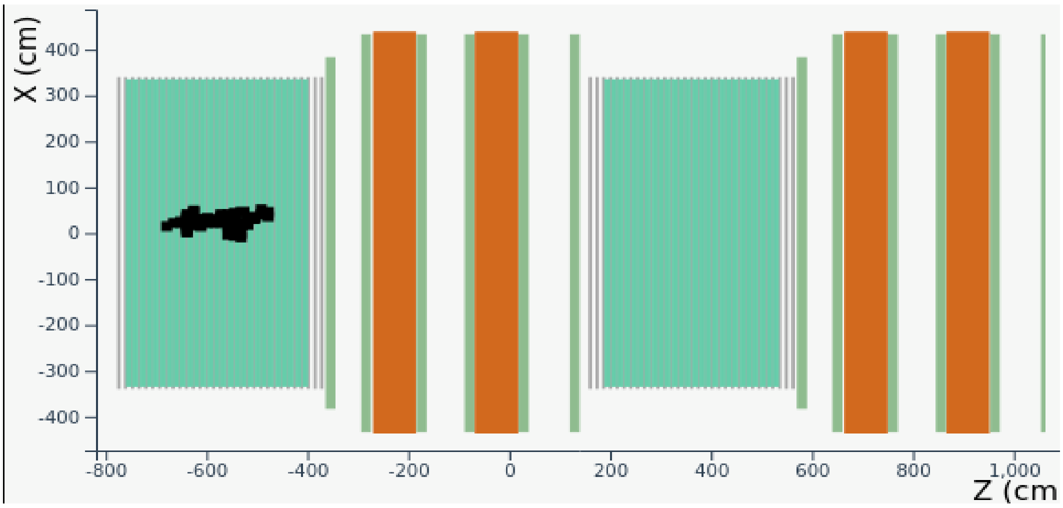
Figure 11: Reconstructed Tracks in emulsion for Event 12254000036

5 Fourth Task: Electronic Detector Data for ν_τ Appearance Studies

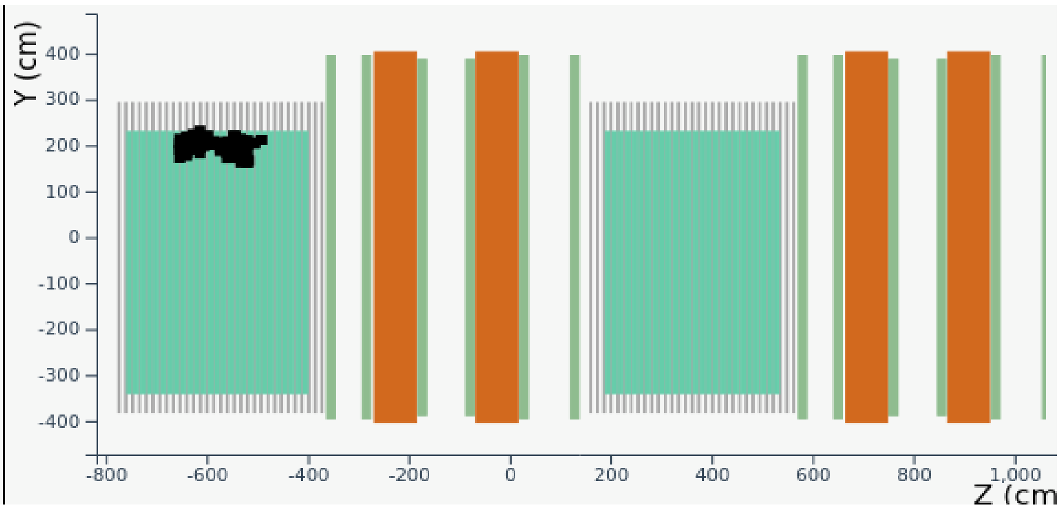
In this task the OPERA electronic detector hits are added for the same previous IDs as following:

- **9234119599** in Figure 12
- **10123059807** in Figure 13
- **12254000036** in Figure 14

5.1 For Event of ID = 9234119599



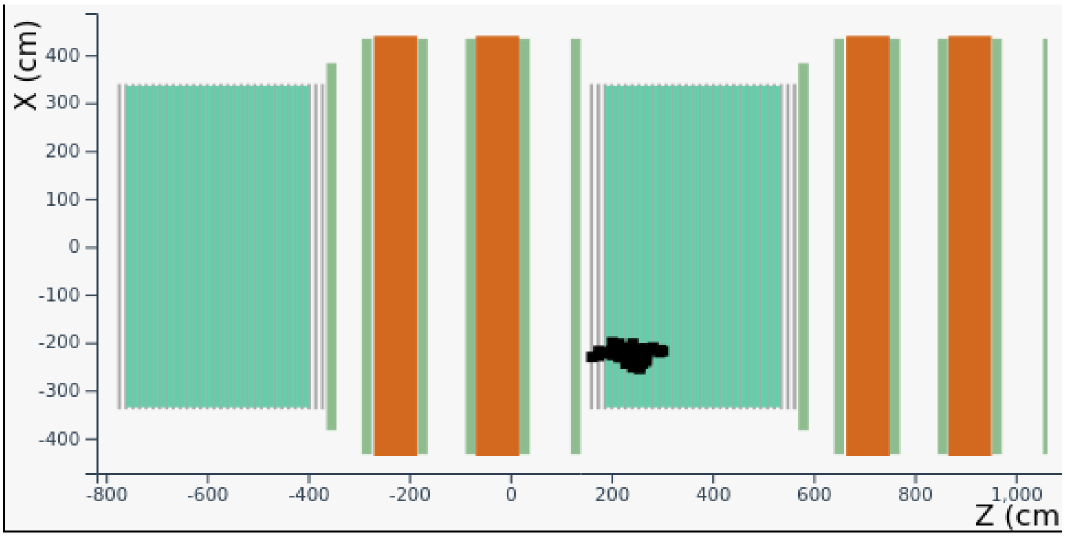
(a) Top View



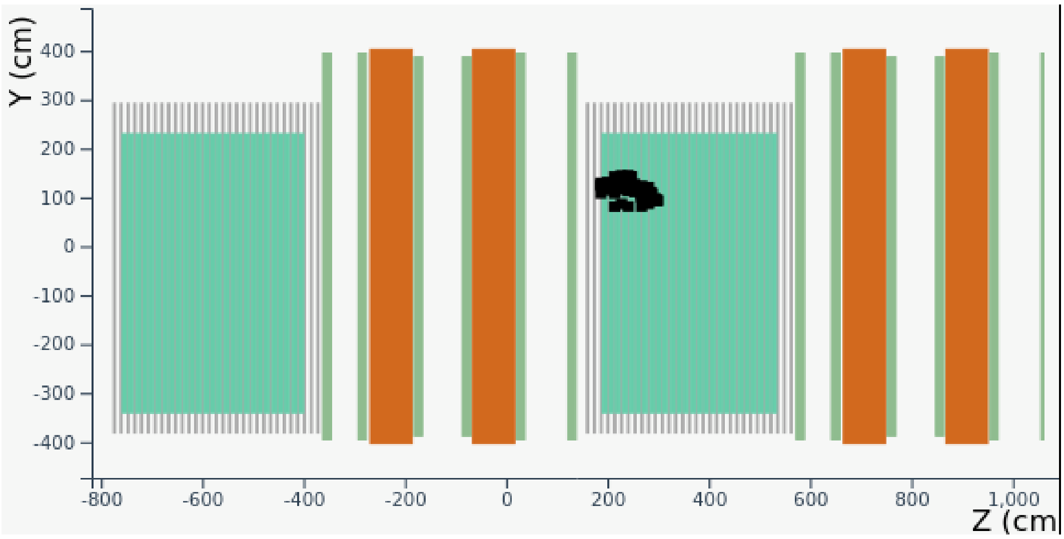
(b) Side View

Figure 12: Top and Side View for OPERA Electronic Detector Hits for Event 9234119599

5.2 For Event of ID = 10123059807



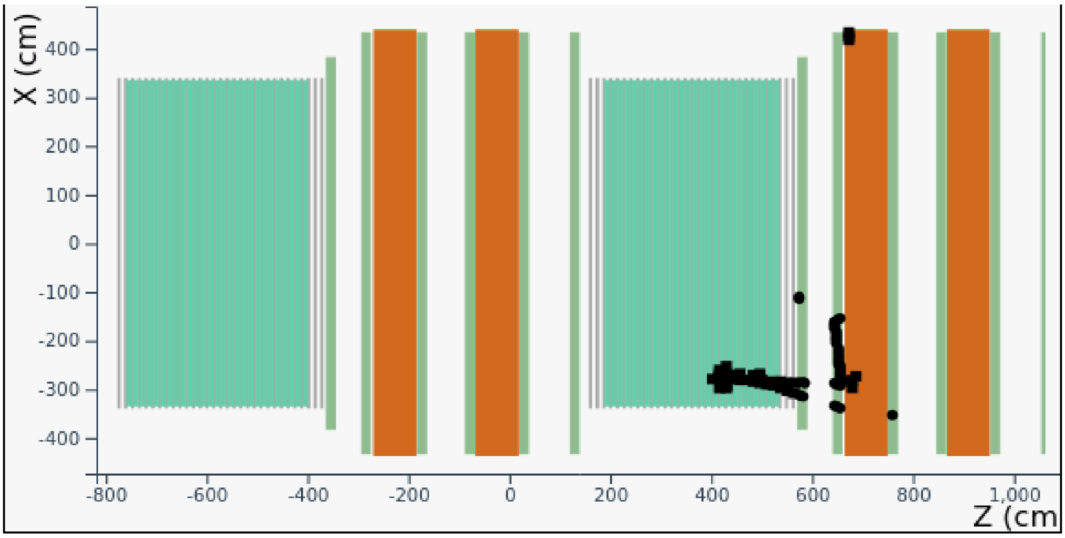
(a) Top View



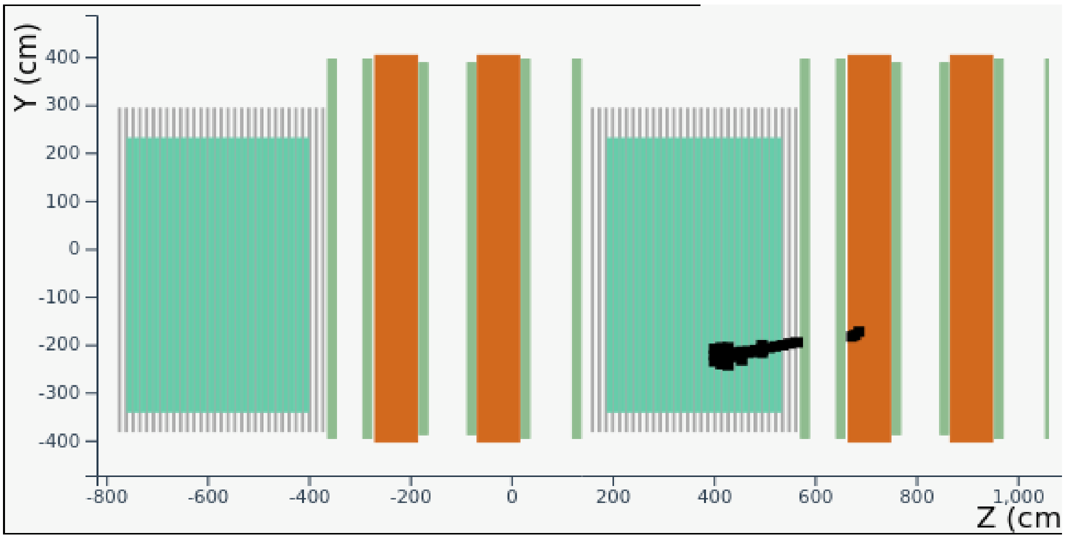
(b) Side View

Figure 13: Top and Side View for OPERA Electronic Detector Hits for Event 10123059807

5.3 For Event of ID = 12254000036



(a) Top View



(b) Side View

Figure 14: Top and Side View for OPERA Electronic Detector Hits for Event 12254000036

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