International Remote Student Training Program

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

Dzhelepov Laboratory of Nuclear Problems
Joint Institute for Nuclear Research

Egemen Gover
B.Sc. (Physics)
Middle East Technical University
Ankara
Turkey

Supervisor
Dr. Sergey Dmitrievsky
Joint Institute for Nuclear Research
Dubna
Russia

Abstract

Perhaps one of the oddest outcomes of particle physics is the neutrino oscillations. Standing in the region of "beyond Standard Model" (as Standard Model does not predict neutrino oscillations, let alone predicting them acquiring any mass), it gives new insights into new physics. As such, studying such topic will or may lay the foundations for new models of particle physics. In this project, we examine the data extracted directly from CERN Open Data Portal, in which we specifically study and analyze the OPERA experiment that took data from 2008 to 2012. Our work focuses on implementation of data analyzing methods. Throughout the work schedule, we extensively worked with C++ and the ROOT framework provided by CERN to extract, analyze, and plot the OPERA open data, as well as with JavaScript project to visualize interesting topologies of OPERA neutrino events.

Acknowledgment

It has been such an honor to have the opportunity to work with JINR. These valuable weeks that I have spent upon this project have improved me in various topics immensely. Knowing that with each project JINR provides sets me ready for a career in nuclear and particle physics more than ever, it compels me to go further into the field. Moreover, I especially thank Dr. Sergey Dmitrievsky for his extraordinary passion for helping and lecturing. His enthusiasm never perished and drove us to do more. I am forever indebted.

Contents

1 Introduction

The story begins with solar neutrino problem. The nuclear reactions that take place in the sun, produce ν_e (electron neutrinos) as a byproduct. Born from the nuclear reactions, their journey starts from the sun to the earth. They travel nearly at the speed of light, but not quite exactly c. In the late 1960s, Homestake experiment (also known as solar neutrino experiment) detected something rather unusual. The expected number of electron neutrino particles were inconsistent with the theoretically predicted number that was produced in sun beforehand. As such, there was some deficit that currently lacked any feasible explanation provided by any existing theories, including the Standard Model. This problem gave birth to neutrino oscillation and paved the way to deeper dive into *beyond the Standard Model.*

Neutrino oscillation theory states that the deficiency in neutrino problems, arises from the fact that neutrinos have what is called *flavors.*

1.1 Neutrino Flavors

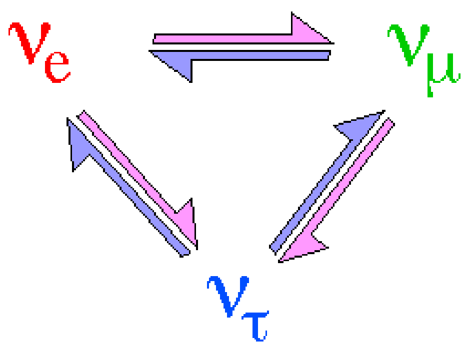


Figure 1: Here we see the three flavors of neutrino. Electron, muon, and tau neutrino (clockwise) [1]

At the core of the neutrino oscillations, lies the neutrino flavor property. As such, the deficit of electron neutrinos detected in Homestake experiment turned out to be a solid proof of oscillating flavors. For simplicity, consider each of the particle represented by a sinusoidal wave. Of course, in reality it is not really a sine wave, but it will give us a good imaginative framework to work upon. In figure 2 we see the graph of probability function with respect to L/E, where L is the distance and E is the energy in GeV scale.

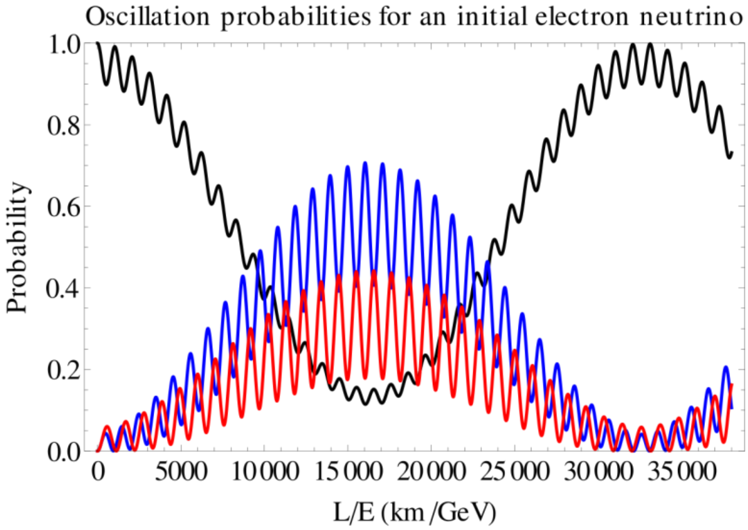


Figure 2: Here we see the probabilities of each flavor, starting from the electron neutrino. Black represents, electron neutrino, blue muon neutrino and finally red for tau neutrino.[2]

Probability function of each flavor seems to be varying accordingly to the distance. Before measuring (or capturing) a neutrino, the particle is in superposition of exactly three states, no more or no less. Any disturbance in its wave function causes the neutrino to choose a flavor, and interestingly a mass.

In order to study and observe the oscillations, large distances are needed for experimental setups, generally in the order of a few hundred kilometers. Luckily, LNGS (Laboratori Nazionali del Gran Sasso) was specifically designed and engineered for neutrinos initially created in CERN. The 732 km distance between two of the facilities allows us to study the distance effect on neutrino oscillations.

1.2 OPERA

The Oscillation Project with Emulsion-tRacking Apparatus, or OPERA for short, was dedicated to neutron oscillation process. This setup mainly focused on tau neutrinos (ν_τ) that would result from the oscillation of muon neutrinos (ν_μ). Our project focuses on the data provided by CERN Open Data Portal. Neutrinos created at CERN with production energies at the order of 400 GeV [3] were then directed towards LNGS positioned in Italy. Such production of neutrinos is achieved by colliding protons with a graphite target.

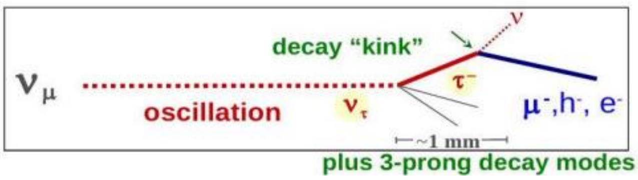


Figure 3: The main goal OPERA is demonstrated above. Here, tau neutrino arising from oscillation can be seen [4].

The nuclear reaction produces pions and kaons, which later decay into muon neutrinos. Mean value of energy ($< E_{\nu_\mu} >$) of such particles are 17 GeV [4].

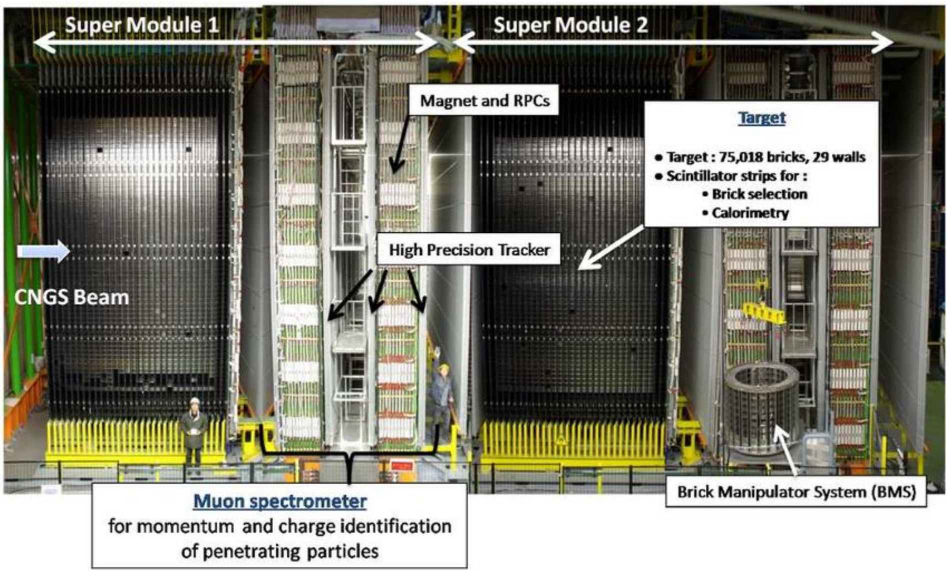


Figure 4: The OPERA detector [5]

Although we are more concerned about muon neutrinos, it should be noted that there is a small amount of contamination resulted by the byproduct of the nuclear reaction. Proton-proton reactions result in creation of $\bar{\nu}_\mu$ with a percentage of $\approx$0.9% and $\bar{\nu}_e$ with $\approx$2.0% [5]. LNGS had a relatively simple setup to detect neutrinos, as shown in figure 4. It is composed of two identical super-modules and they both include electronic and emulsion detectors. Each layer of the module

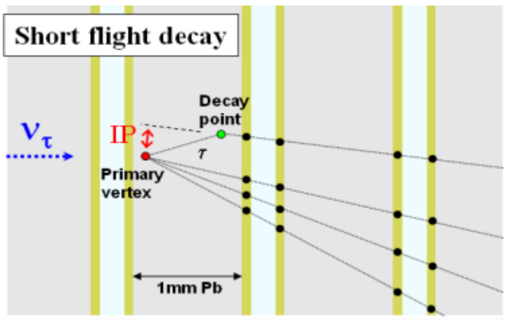


Figure 5: Here the blue line represents a muon neutrino. At the vertex point, we observe a tau particle between emulsion layers. [6]

contained an ECC brick, namely called *Emulsion Cloud Chamber*. These blocks were capable of registering neutrino events, as they had emulsion films. In fact, every single one of these blocks had a total of 57 emulsion films. With the total brick number amounting to 150,000, we end up with immense amount of data to read. Luckily, breakthroughs in emulsion readout techniques help us analyze the data in a relatively short amount of time. Emulsion scanning stations used in OPERA had spatial resolution of 0.3 μ and angular resolution of 2.0 mrad, with a reading speed up to 75 cm^2/h

In figure 5, we see a 2D cross section of a single layer of ECC brick. In a short flight decay, decay occurs without passing second emulsion layer. As we know the distance between the primary vertex (where we observe the creation of a tau particle due to tau neutrino) and the decay point (where the lepton decays into daughter products), we can then calculate flight length and impact parameter. Our task one will primarily focus on calculating such properties. Moreover, to know the exact position, slope, and number of events to draw our histograms and graphs, we need to write a sophisticated C++ code to analyze hundreds of event logs. This project mainly focuses on the construction of such code.

2 Tasks

2.1 Task 1: Calculation of Impact Parameters and Flight Lengths of Charmed Hadrons

In our first task, we are going to be focusing on the calculation of impact parameters and flight lengths of particles induced and produced by neutrinos. We first begin with downloading the required data files from CERN, namely called *Emulsion Data for Neutrino-Induced Charmed Hadron Production Studies.*

We can define impact parameter as the shortest 3D distance between the primary vertex and a continuation of a daughter track line. Therefore, cross product for such calculation is needed. We can then proceed to the calculation as:

$$Impact\ Parameter(IP) = \frac{|\overrightarrow{V_0 V_1} \times \overrightarrow{V_1 V_2}|}{|\overrightarrow{V_1 V_2}|} = \frac{\left| \begin{matrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ dx_1 - dx_0 & dy_1 - dy_0 & dz_1 - dz_0 \\ dx_2 - dx_1 & dy_2 - dy_1 & dz_2 - dz_1 \end{matrix} \right|}{\sqrt{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}}$$

Where V_0 *and* V_1 are primary and secondary vertex points respectively. Daughter particle track line is defined by two points: V_1, (the daughter production point), and V_2. Using the vertex points that were available in acquired data .csv files, we used the above equation as our starting point. The code we have written specifically identifies vertex point coordinates, and then stores them in a vector to do the necessary calculations. After various steps we get:

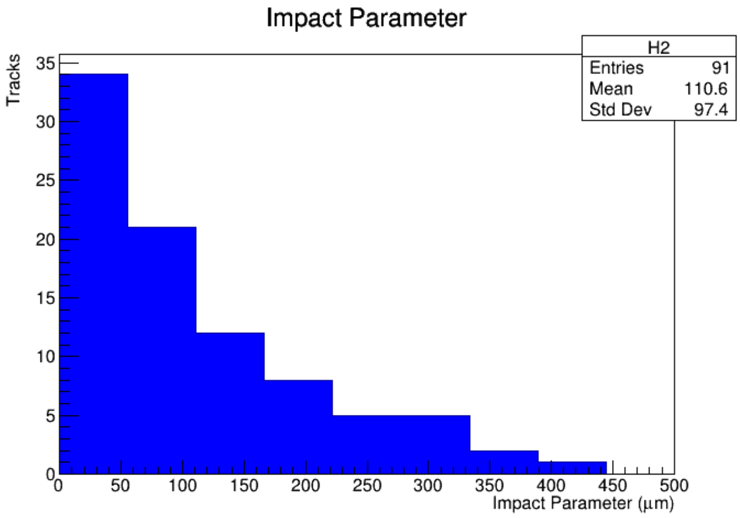


Figure 6: Number of tracks that correspond to each impact parameter

The histogram in figure 4 shows distribution of daughter track IP parameters. Furthermore, we can use the same data to obtain flight lengths of daughter particles. The decay length can be calculated as:

$$|\overrightarrow{V_0 V_1}| = \sqrt{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}$$

And by using C++ and ROOT framework we then conclude:

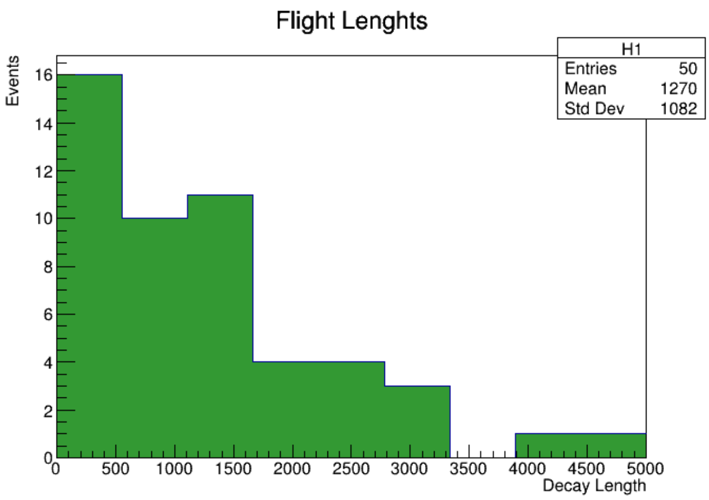
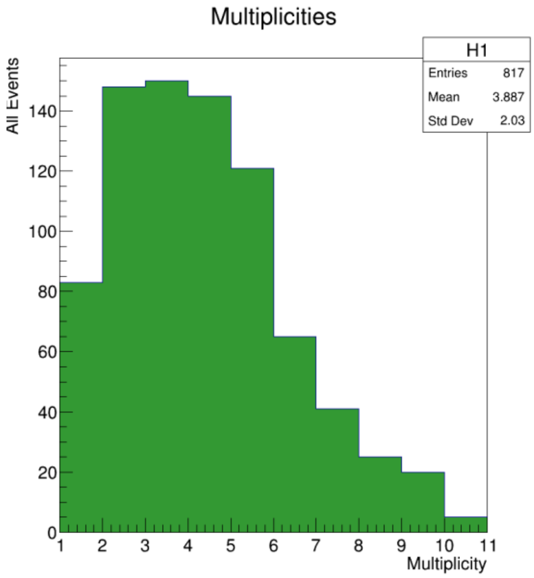


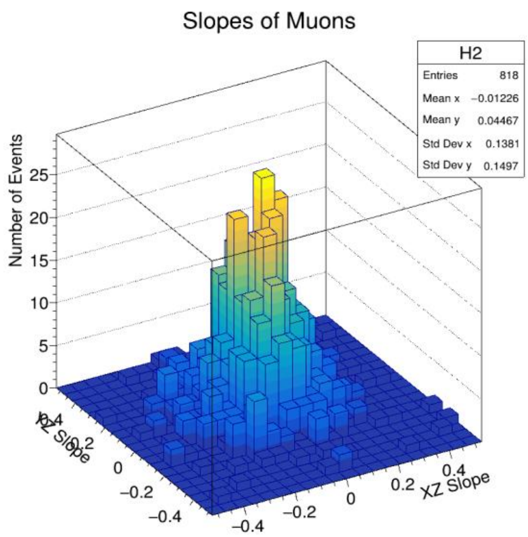
Figure 7: Different flight lengths corresponding to different events

2.2 Task 2: Extraction of Charged Hadron Multiplicities and Muon Track Slopes

In this part of our research we mainly focused on muon productions due to muon neutrino induction on the lead target. The data set we worked with registered 817 υ_{μ} interactions. Notice that in figure 8, there is an inconsistency between the number of entries in multiplicity histogram, and number of muons in muon-slope 2D plot. Our code revealed an event with an ID number of "11093039862", in which we observe a dimuon topology.



(a) Multiplicities



(b) Slopes of muons with respect to global coordinates

Figure 8: Using emulsion data for track multiplicity, we can see the constructed multiplicity histogram and global slopes of induced muons with respect to XZ and YZ.

In dataset semantics, we see the variables corresponding to slopes, namely labeled as slopeXZ, which accounts for the track angle in XZ view, and slope YZ, corresponding to track angle in YZ view. By using C++ string library, we specifically extract the data corresponding to such values. Exact angle can be calculated by:

$$\theta = \tan^{-1}(slopeXZ) \quad \Phi = \tan^{-1}(slopeYZ)$$

Another variable type we included in our code is the *trType* that preexisted in Vertex.csv and Tracks.csv files. This variable is crucial, as it represents the type of particle we are dealing with. OPERA dataset categorized each type of tracks with an integer number that follows as

- 1 - Muon
- 2 - Hadron
- 3 – Electron
- 4 - Black
- 5 - Back Black
- 6 - Gray
- 7 – Back Gray

For the calculation of muon slopes, our program was coded specifically to target trType =1 by using *istringstream* constructor.

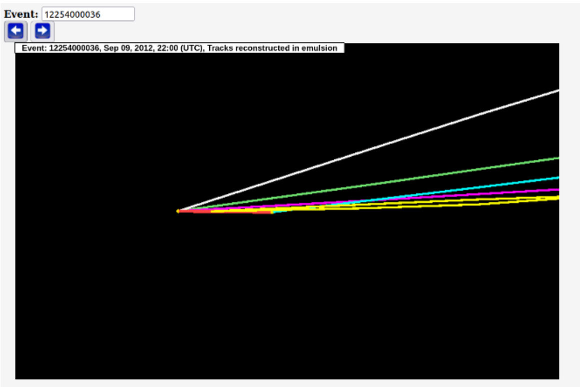
The multiplicity calculation was done by using *mult* variable. This value represents the number of ECC tracks attached to a vertex. The track multiplicity in each event can also be calculated as a number of tracks stored in the corresponding Tracks.csv file, i.e., the tracks coming from the primary neutrino interaction vertex.

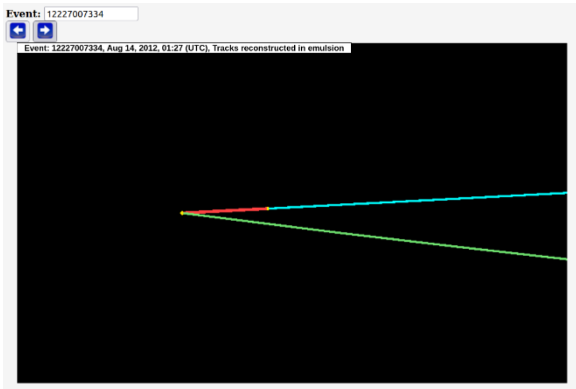
2.3 Task 3: Browser Based Visualization of Interesting Neutrino Event Topologies with JS and HTML

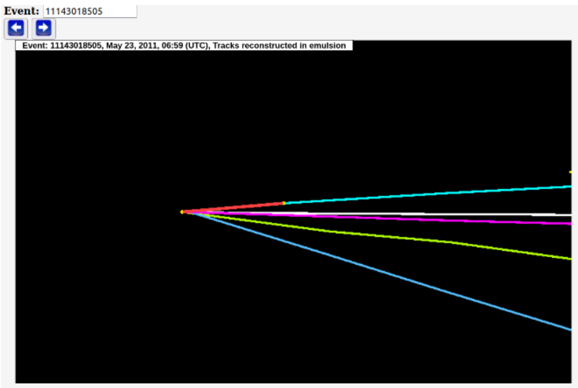
Although histograms come in handy when we are dealing with numeric values, it becomes almost indispensable to visualize the occuring decays and trajectory paths. In this section, we dealt with the construction of a program to model the interactions. The sole purpose was to reconstruct the previously available CERN Open Data OPERA electronic detector display (ED). Such visualization of topologies helps to understand how the registered (or searched for) tau neutrino interactions look like. While the OPERA experiment registered a total of 19,905 neutrino interactions, only 10 of them were confirmed τ leptons [7]. In 2018 OPERA announced the discovery of ν_τ appearance in a muon neutrino beam, with a significance of 6.1 σ [8].

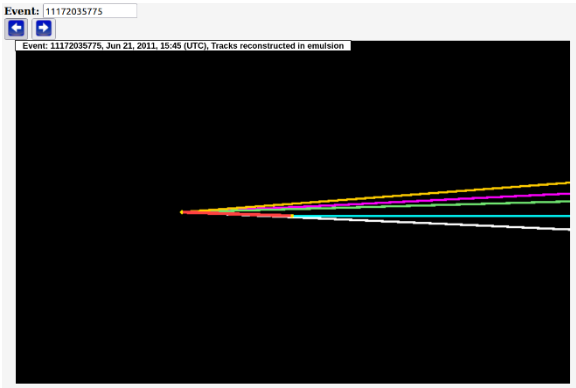
The method of this task was different from the previous two. Instead of using C++ and ROOT framework, we worked with JavaScript and HTML.

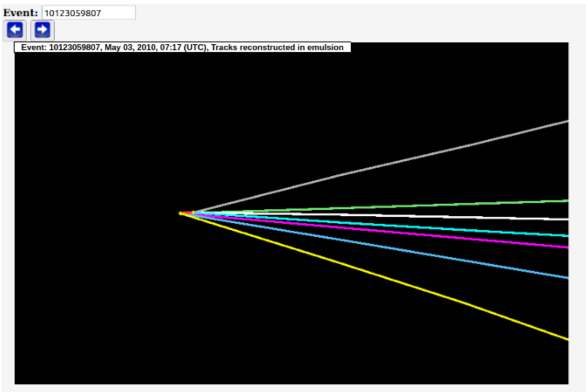
2.4 Emulsion Detector Track Display

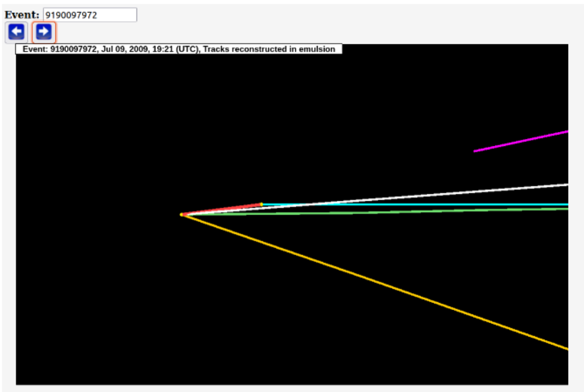












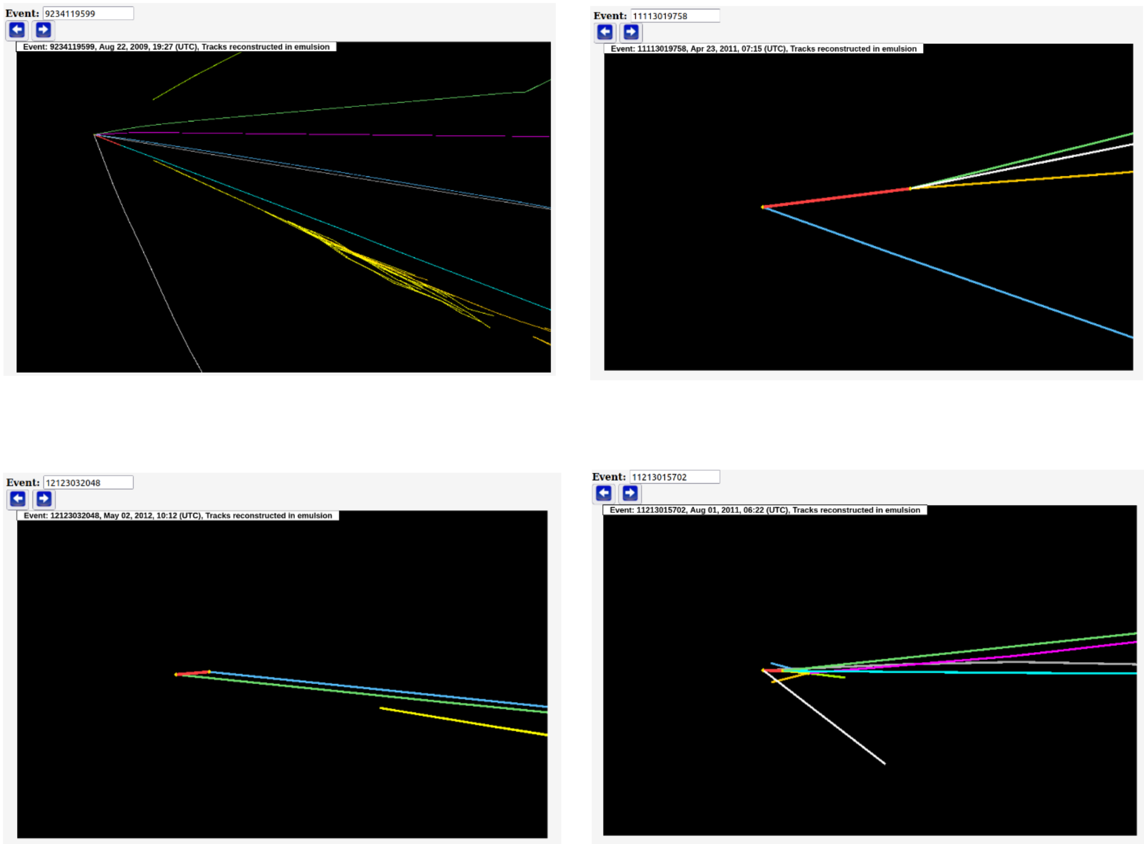
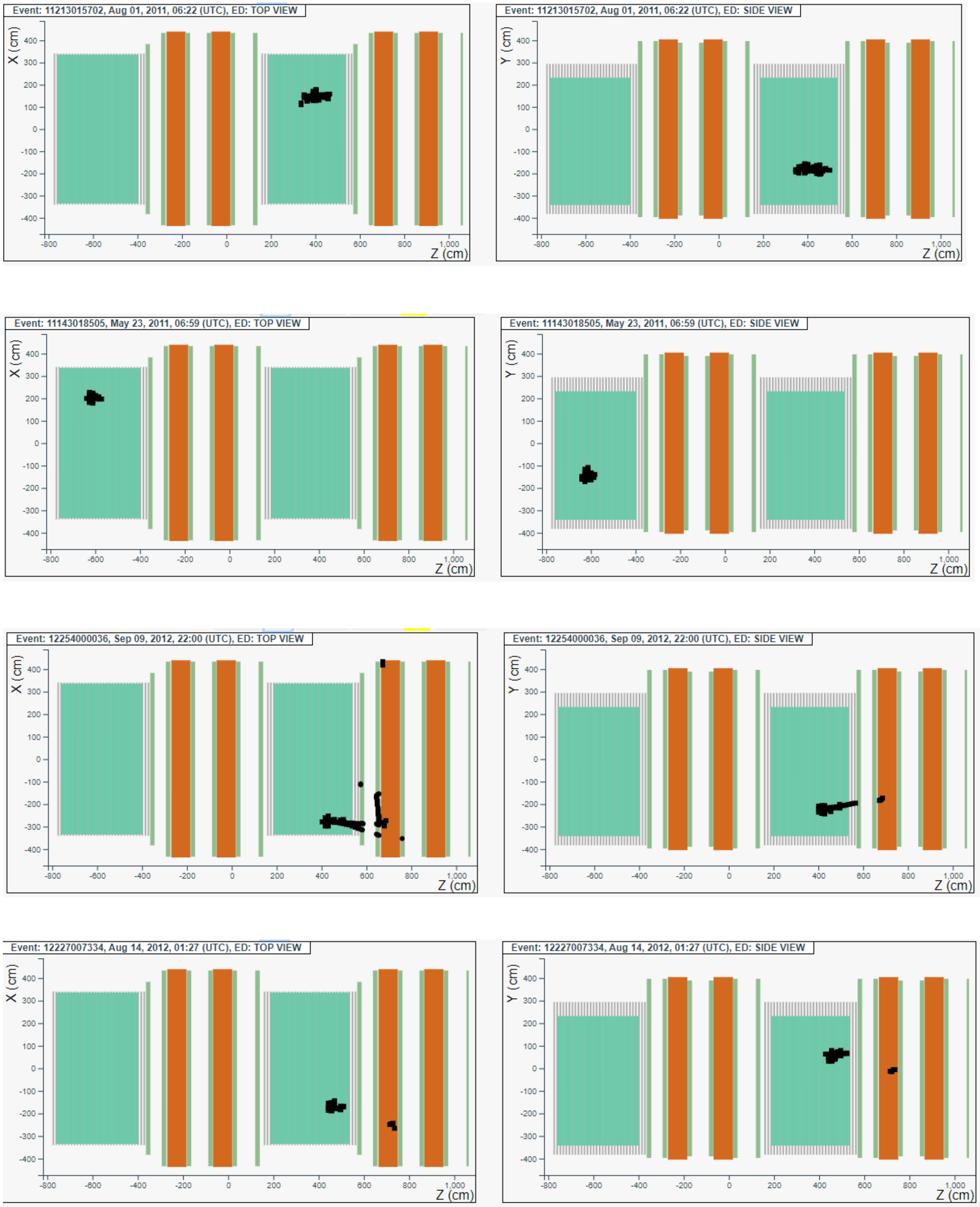
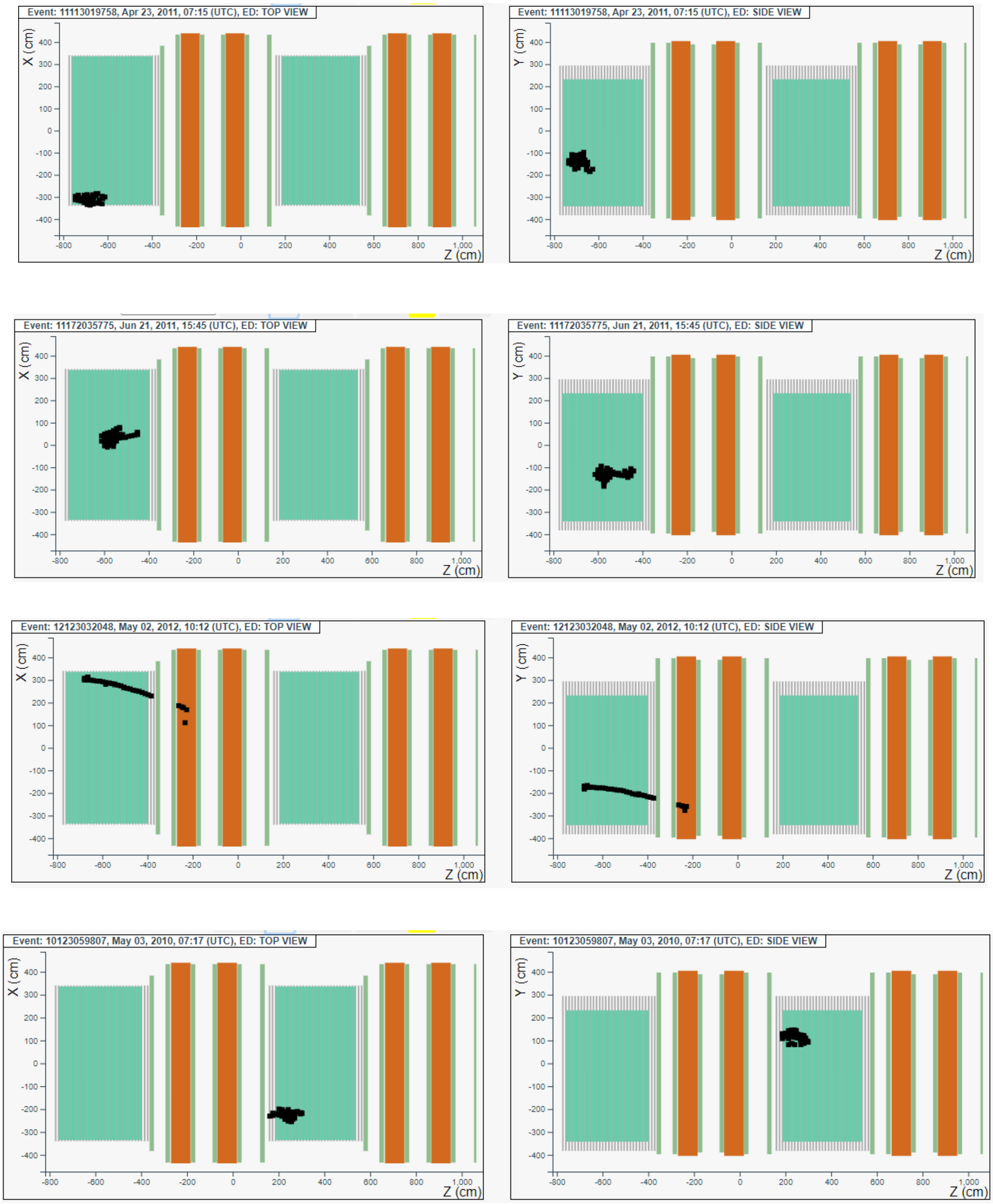


Figure 9: Visualization of the tracks. Each color corresponds to a different particle.

In the figure above, we can observe each path of charged hadrons and leptons. Length of each line gives us an idea on its intrinsic lifetime property. Our main concern is a tau lepton which has a lifetime of $(2.903 \pm 0.005) \times 10^{-13}$ seconds, as it is represented by red color. In every single one of the decays, we see the induced tau lepton decaying further into daughter hadrons and leptons.

2.5 Event Display of Electronic Detectors




Event: 11113019758, Apr 23, 2011, 07:15 (UTC), ED: TOP VIEW
Event: 11113019758, Apr 23, 2011, 07:15 (UTC), ED: SIDE VIEW
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), ED: TOP VIEW
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), ED: SIDE VIEW
Event: 12123032048, May 02, 2012, 10:12 (UTC), ED: TOP VIEW
Event: 12123032048, May 02, 2012, 10:12 (UTC), ED: SIDE VIEW
Event: 10123059807, May 03, 2010, 07:17 (UTC), ED: TOP VIEW
Event: 10123059807, May 03, 2010, 07:17 (UTC), ED: SIDE VIEW
X (cm)
Y (cm)
Z (cm)

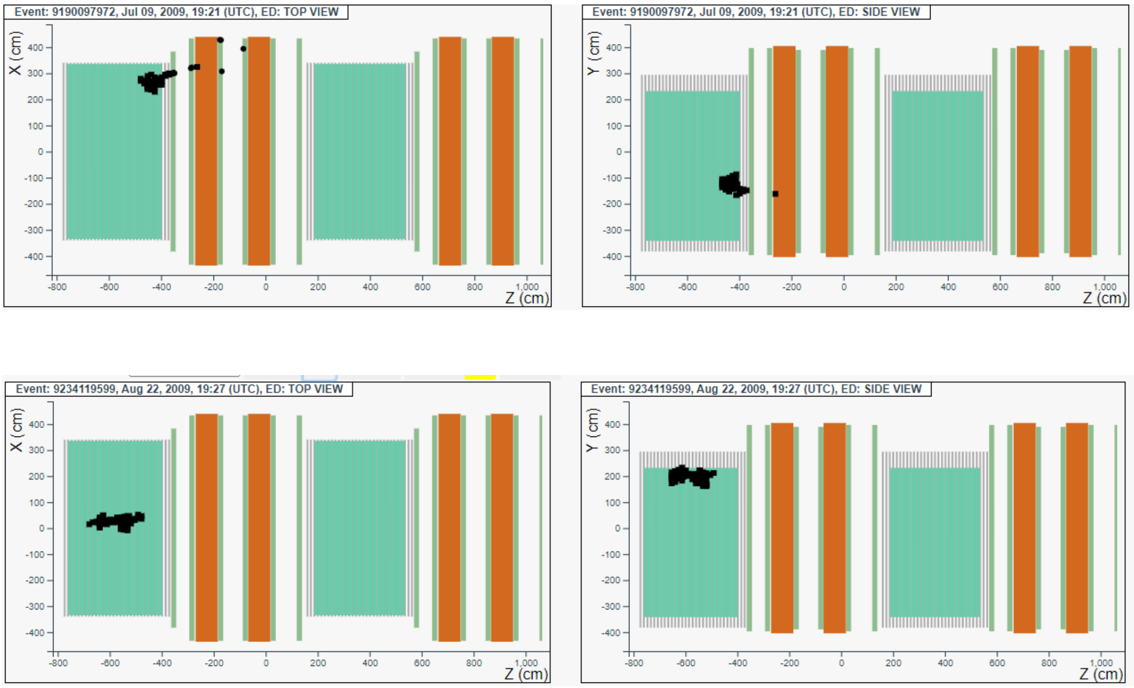


Figure 10: Side and top views of the OPERA detector. Black dots indicate the positions of signals (hits) registered in electronic detectors. Those signals helped to locate the target (lead-emulsion) modules to be extracted and analyzed in order to search for and reconstruct with a high resolution the tau neutrino interaction event topologies near the primary vertices.

3 Results and Conclusion

Neutrino oscillations are a remarkable phenomenon to study on. Our work demonstrated and visualized the appearance of tau leptons and muons, verified $\upsilon_\mu \rightarrow \upsilon_\tau$, and awarded ourselves with a solid background on computational physics, especially with C++ and ROOT. Apart from this, we learned the principles behind Super Proton Synchrotron, OPERA detector setup and theoretical aspects of neutrino detection. Furthermore, we compared our results with the papers published by the OPERA Collaboration (1,2) and witnessed a good agreement between the obtained results.

Our re-evaluation of this topic was also intended for people to read and learn from this report easily, without having to worry about the complex quantum mechanical equations. As shown in our histograms, ROOT offers simplistic solutions to better visualize large data files. By learning the aspects of this framework, one can further use it in their studies that govern different subjects of physics and statistics.

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