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

Mostafa Reda Helmy
B.Sc. (Physics)
Cairo University
Cairo
Egypt

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

Participant in Wave 12 (03 March - 20 April, 2025)

Abstract

One of the most fascinating and unexpected discoveries in particle physics is the phenomenon of neutrino oscillations. Sitting firmly in the realm of beyond the Standard Model, since the Standard Model neither predicts neutrino mass nor their ability to oscillate between flavors, this effect opens the door to entirely new physics. Exploring such a topic doesn't just expand our understanding, it could help lay the groundwork for future extensions of the Standard Model.

In this project I've delved into real experimental data from CERN's Open Data Portal, with a particular focus on the OPERA experiment which collected data between 2008 and 2012. My work centered on developing and applying data analysis techniques to uncover and study neutrino interactions hidden within the OPERA dataset.

Throughout the project I worked extensively with C++ and CERN's ROOT framework, handling everything from data extraction and analysis to plotting and interpreting the results. On top of that I also developed a JavaScript-based visualization tool designed to bring the intriguing topologies of OPERA neutrino events to life, making the hidden patterns of these rare interactions both intuitive and engaging.

Acknowledgment

I would like to express my sincere appreciation to the Joint Institute for Nuclear Research (JINR) for offering me the invaluable opportunity to be part of this project. Being involved in this work has not only strengthened my technical and scientific understanding but has also deepened my passion for the field of nuclear and particle physics. Every step throughout this experience has given me new perspectives, both theoretically and practically, and has helped me grow as both a researcher and a learner.

I am especially grateful to Dr. Sergey Dmitrievsky for his outstanding mentorship and support throughout the project. His remarkable dedication to teaching, his willingness to guide us through challenges, and the energy he brings to every discussion have been nothing short of inspiring. His enthusiasm was contagious and consistently motivated me to strive for a deeper understanding and to push the limits of my own work.

This experience has reinforced my eagerness to continue exploring the fascinating world of particle physics and has prepared me with both the mindset and the tools to take on future challenges in the field. I am truly thankful to everyone who contributed to this enriching journey.

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1 Introduction

The story begins with the solar neutrino problem. Deep within the core of the sun, nuclear reactions produce electron neutrinos (νe) as a natural byproduct. From the moment they are born, these neutrinos begin a long journey, traveling from the heart of the sun all the way to Earth. Their speed is close to the speed of light, although not exactly c.
In the late 1960s, the Homestake experiment widely known as the solar neutrino experiment revealed something rather unexpected. The number of electron neutrinos detected on Earth was significantly lower than the number predicted by theoretical models of the sun's nuclear processes. This discrepancy could not be explained by any existing framework, including the Standard Model.
The solar neutrino problem marked the beginning of an entirely new chapter in particle physics. It led to the realization that neutrinos might not be the simple, massless particles they were once thought to be, and ultimately introduced the concept of neutrino oscillation a phenomenon that opened the door to physics 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 [1]

At the heart of neutrino oscillations lies the concept of neutrino flavor. The deficit of electron neutrinos observed in the Homestake experiment would later stand as strong evidence for the idea that neutrinos can change their flavor as they travel through space.

To visualize this phenomenon, one can imagine each neutrino as being represented by a sinusoidal wave. While in reality neutrinos are not simple sine waves, this analogy offers a helpful way to build intuition around the concept and to follow the logic behind their oscillating behavior.

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.

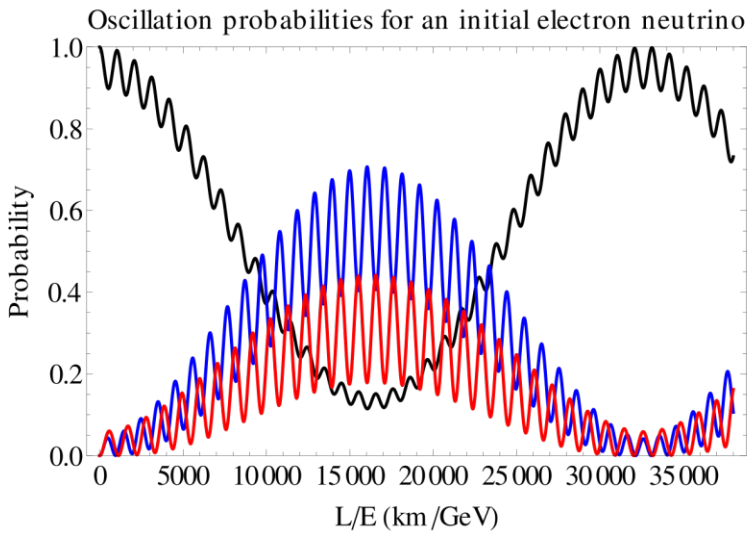


Figure 2 illustrates the probability distribution for each neutrino flavor, starting from an initial electron neutrino. In this plot, black represents the electron neutrino, blue the muon neutrino, and red the tau neutrino [2].
As the neutrino travels through space, the probability of detecting each flavor changes with distance. Until the moment of measurement (or detection), the neutrino exists in a superposition of exactly three possible states no more, no less. one neutrino with some specific flavor has an effective mass which is a linear combination of three different masses and vice versa, one neutrino with some specific mass can be seen as a mix of three different flavors.

To study and observe neutrino oscillations, experiments require neutrinos to travel over large distances typically on the scale of several hundred kilometers. Fortunately, the Laboratori Nazionali del Gran Sasso (LNGS) was specifically designed and constructed to detect neutrinos produced at CERN. The 732 km baseline between these two facilities provides the perfect setup to investigate how neutrino oscillations evolve as a function of distance.

1.2 OPERA

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) is centered around studying neutrino oscillations, specifically focusing on tau neutrinos ($\nu\tau$) produced by the oscillation of muon neutrinos ($\nu\mu$). My project delves into the data provided by the CERN Open Data Portal. At CERN, a 400 GeV proton beam from the

Super Proton Synchrotron (SPS) is directed onto a graphite target, producing secondary particles that decay into neutrinos. The resulting CNGS neutrino beam has an average energy of about 17 GeV, as used in the OPERA experiment [3], and these neutrinos are then directed toward the Gran Sasso National Laboratory (LNGS) in Italy for further study.

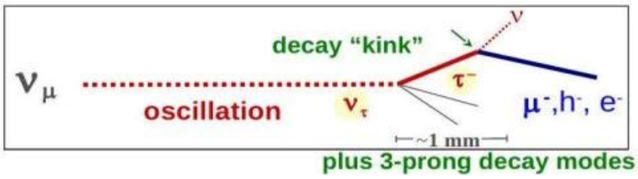


Figure 3: The main goal of OPERA was to search for events with a characteristic decay topology of short-lived tau leptons, which were produced in interactions of tau neutrinos arising from $\upsilon\mu \rightarrow \upsilon\tau$ oscillations.

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

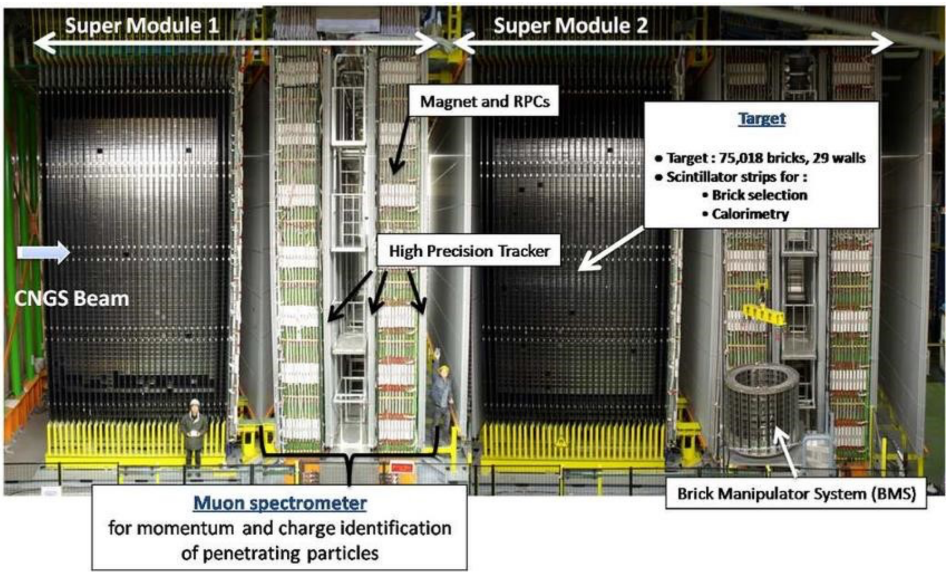


Figure 4: The OPERA detector [5]

While our primary focus is on muon neutrinos, it's important to note that there is a small amount of contamination from the byproducts of the nuclear reaction. Proton-proton interactions lead to the creation of $\bar{\upsilon}\mu$ with a contamination of approximately 0.9% and $\bar{\upsilon}e$ with around 2.0%

[5]. The Gran Sasso National Laboratory (LNGS) employed a relatively straightforward setup for neutrino detection, as depicted in Figure 4. This setup consists of two identical super-modules, each containing both electronic and emulsion detectors. Each component of the detector plays an important role in the detection process.

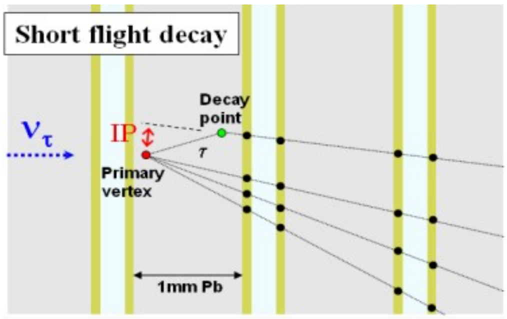


Figure 5: The blue line in this diagram represents a tau neutrino which interacts in a lead plate between emulsion films [6].

One OPERA target module, called an Emulsion Cloud Chamber (ECC) brick, was capable of recording neutrino events due to the presence of emulsion films. Specifically, each block contained 57 emulsion films interleaved with 1mm thick lead plates. OPERA detector contained ~150,000 such bricks With a total mass of 1.2 ktons. OPERA's electronic detectors registered neutrino interactions in real time and allowed the extraction of bricks that were most probably to contain neutrino interaction vertices. A total of ~10000 bricks were extracted over the course of the experiment for their emulsion analysis. Additionally, advancements in emulsion readout techniques allowed physicists to efficiently process and analyze huge amount of data.

The data from OPERA were processed in a relatively short time thanks to powerful emulsion scanning stations with impressive specifications: a spatial resolution of 0.3 µm, an angular resolution of 2.0 mrad, and a reading speed of up to 75 cm^2/h.

Figure 5 illustrates a 2D cross-section of an ECC brick. In cases of so called "short flight" decay, the decay of tau lepton occurs before passing through the second emulsion layer. By knowing the distance between the primary neutrino interaction vertex (where the tau lepton is produced) and the decay point (where the tau lepton decays into daughter particles), we can calculate the decay length and impact parameter. The first task of our project will primarily focus on calculating these characteristics. Additionally, to determine the exact vertex positions, track slopes, and the number of events needed to create our histograms and graphs, we must write an advanced C++ code capable of analyzing hundreds of event logs.

2 Tasks

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

For our first task, we'll be calculating the impact parameters and flight lengths of particles produced in neutrino interactions. To start, we'll need to download the relevant data files from CERN, specifically the Emulsion Data for Neutrino-Induced Charmed Hadron Production Studies.

The impact parameter (IP) of a daughter track is the 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. This can be calculated from the coordinates of the primary vertex and two points on the track line.

$$\boldsymbol{IP} = \frac{|\boldsymbol{X_0} - \boldsymbol{X_1}|\ \boldsymbol{x}\ |\boldsymbol{X_1} - \boldsymbol{X_2}|}{|\boldsymbol{X_1} - \boldsymbol{X_2}|}$$

where $X_0 = (x_0, y_0, z_0)$ is the position vector of the primary vertex, and $X_1 and\ X_2$ are position vectors of two points on the line. The analysis resulted in the following histogram. The coordinates of the primary vertex were obtained from the EventID_Vertices.csv file, while the coordinates for the daughter tracks were obtained in the EventID_TrackLines.csv file in the rows where trType equals 10.

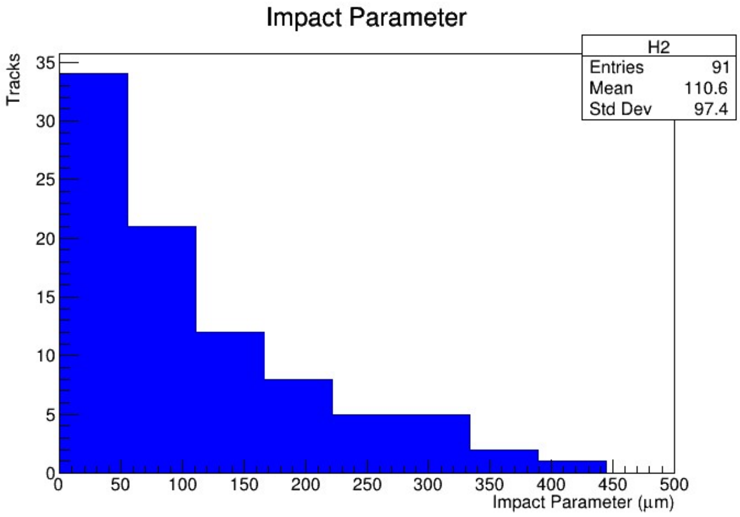


Figure 6: Number of tracks that correspond to each impact parameter

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:

$$\boldsymbol{DL = \sqrt{(X_0 - X_1)^2 + (Y_0 - Y_1)^2 + (Z_0 - Z_1)^2}}$$

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

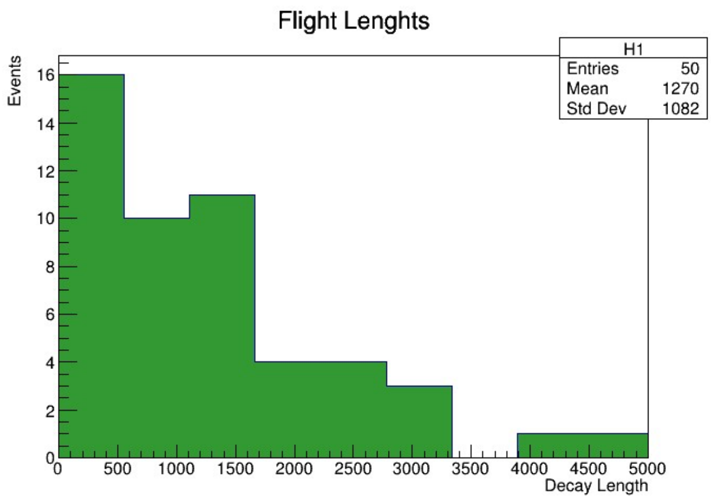
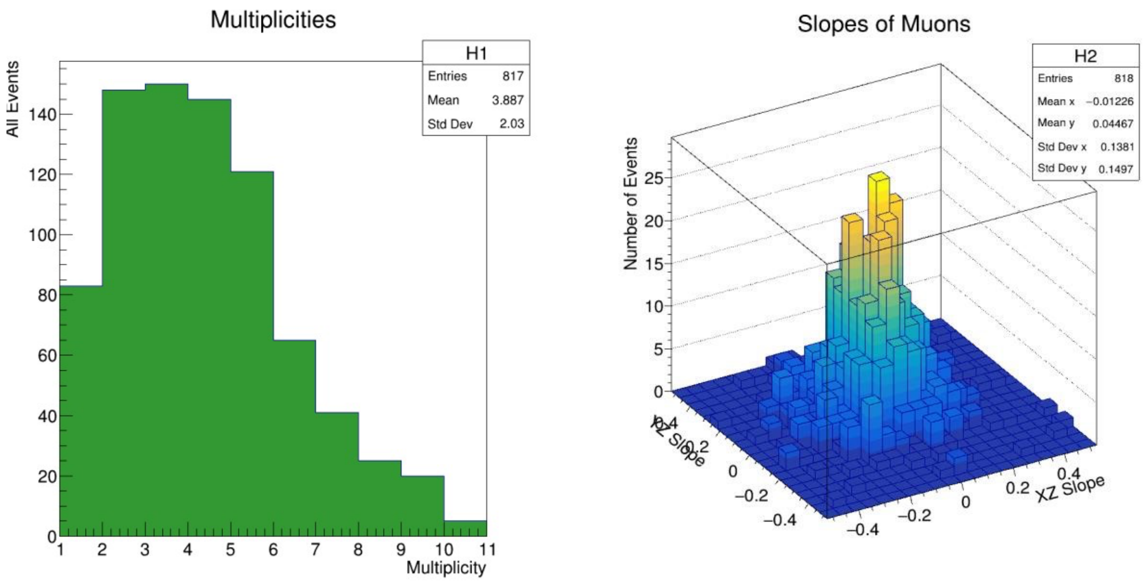


Figure 7: Different flight lengths corresponding to different events

These results are consistent with those published by the OPERA Collaboration [9]

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

In this section of our research, we focused primarily on muon production resulting from muon neutrino interactions with the lead target. The dataset we analyzed recorded 817 $\upsilon\ \mu$ interactions. It's important to note that in Figure 8, there is a discrepancy between the number of entries in the multiplicity histogram and the number of muons shown in the muon-slope 2D plot. Our code identified an event with the ID number "11093039862", in which we observed a dimuon topology.



(a) Multiplicities

(b) Slopes of muons with respect to global coordinates

Figure 8: Using emulsion data for track multiplicity, we can plot histograms of charged track multiplicity 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 included in our code is the trType, which was already present in the Vertex.csv and Tracks.csv files. This variable is essential, as it indicates the type of particle under consideration. The OPERA dataset categorizes each track type with an integer value, which is as follows:

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

To calculate the muon slopes, our program was specifically coded to target trType = 1 using the istringstream constructor.

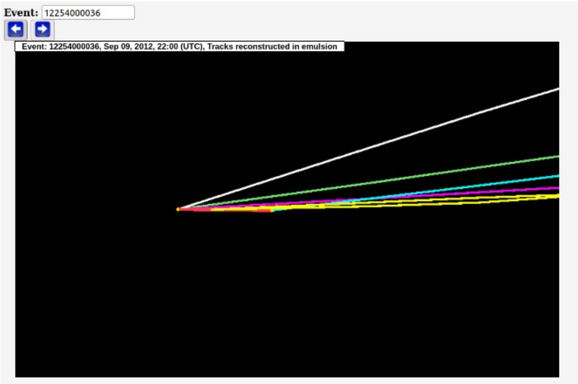
The multiplicity calculation was performed using the mult variable, which represents the number of ECC tracks associated with a vertex. Track multiplicity in each event can also be determined by counting the number of tracks stored in the corresponding Tracks.csv file, specifically those tracks originating from the primary neutrino interaction vertex.

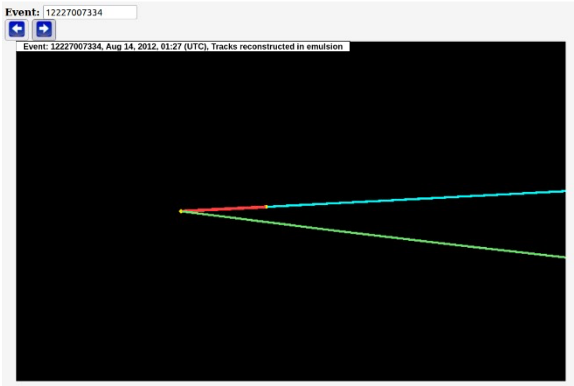
These results are consistent with those published by the OPERA Collaboration [10]

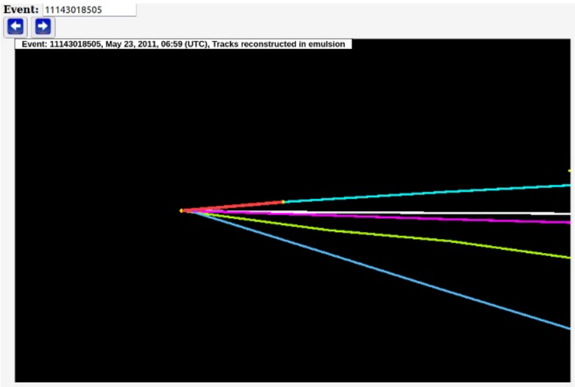
2.3 Task 3: Browser Based Visualization of Interesting Neutrino Event Topologies with JS and HTML

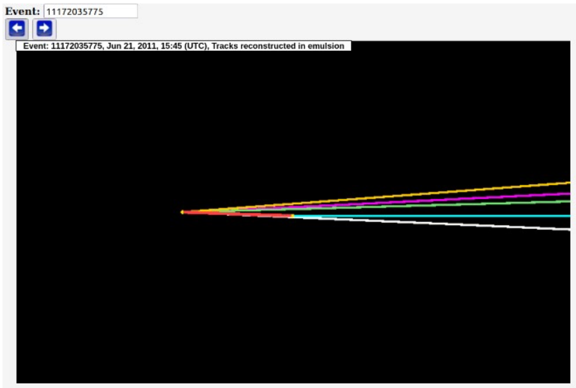
While histograms are useful for handling numeric values, visualizing decays and trajectory paths becomes almost essential for understanding the interactions. In this section, we focused on developing a program to model these interactions, with the primary goal of reconstructing the CERN Open Data OPERA electronic detector display (ED). This visualization of topologies is crucial for comprehending how the registered (or targeted) tau neutrino interactions appear. Although the OPERA experiment recorded a total of 19,905 neutrino interactions, only 10 of these were confirmed as τ leptons [7]. In 2018, OPERA announced the discovery of $\nu\tau$ appearance in a muon neutrino beam, with a significance of 6.1 σ [8].
The approach for this task differed from the previous ones. Instead of utilizing C++ and the ROOT framework, we employed JavaScript and HTML for the visualization.

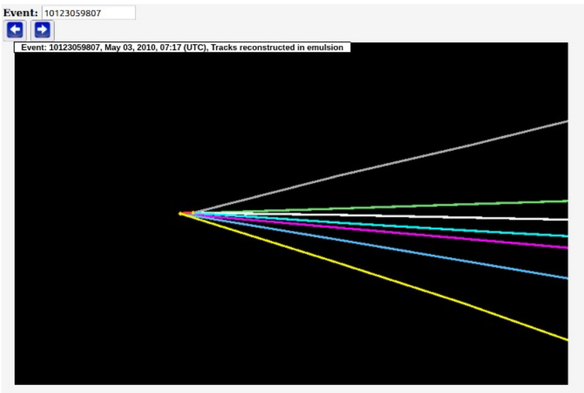
2.4 Emulsion Detector Event Display

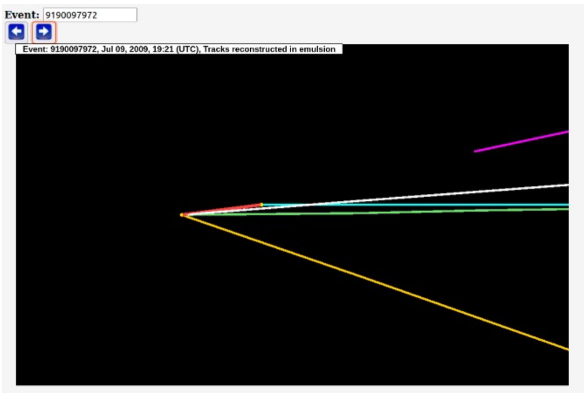












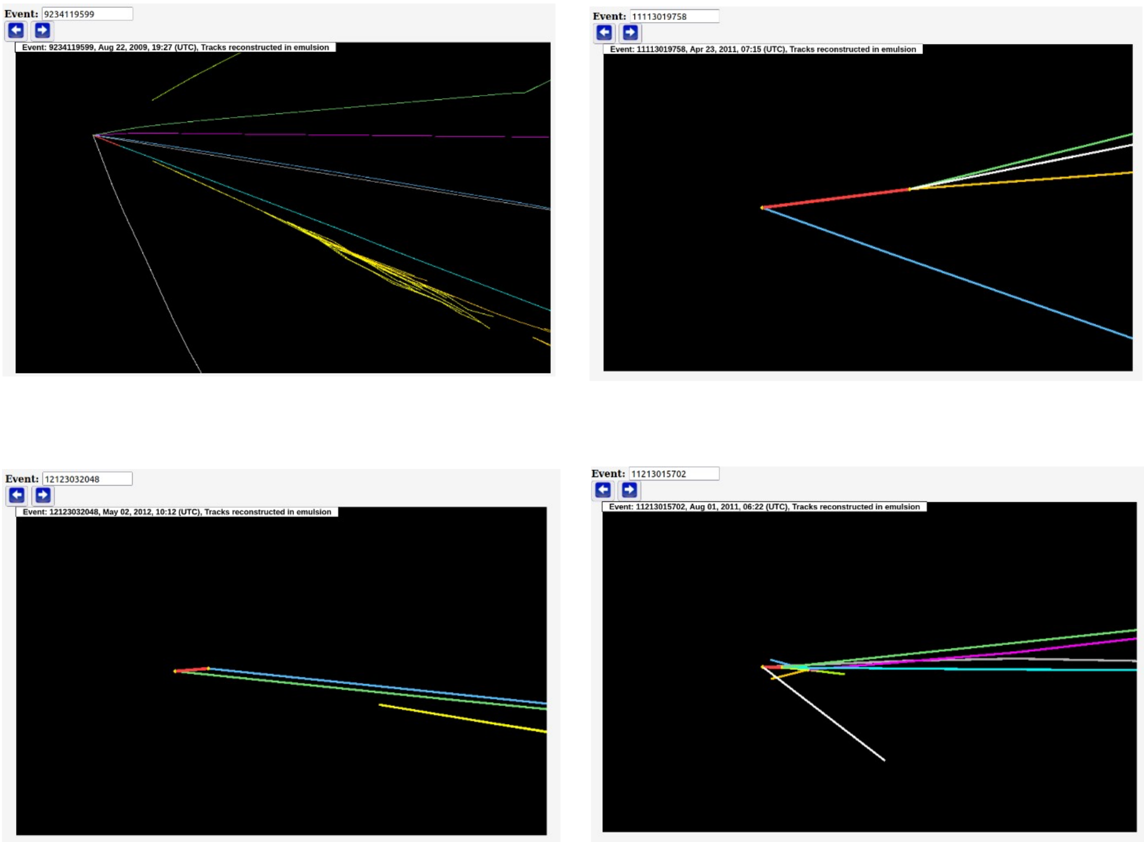
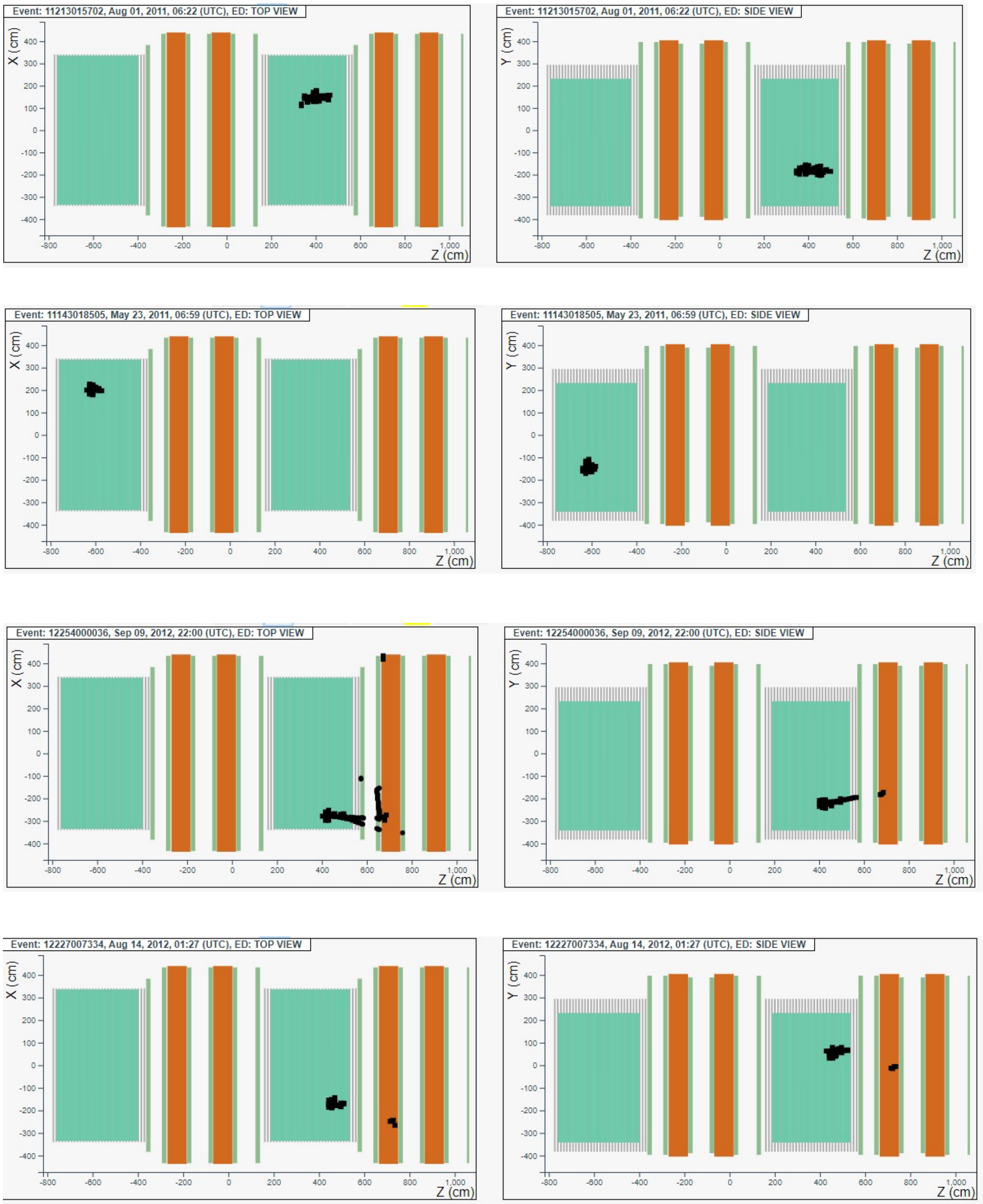
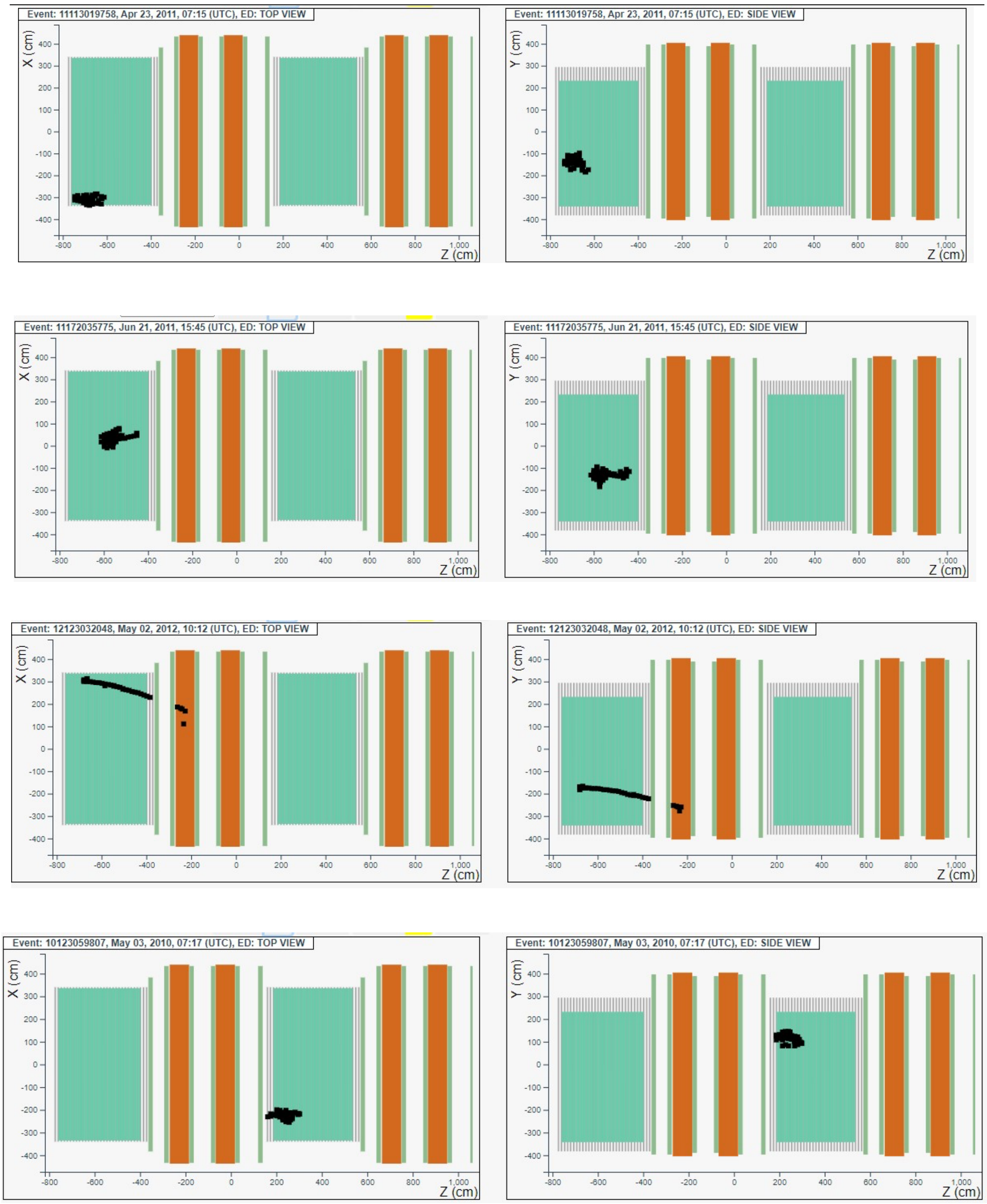


Figure 9: Visualization of the tracks. Each color corresponds to a different particle.

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 $(2.903\pm0.005)\times10^{-13}$ **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)

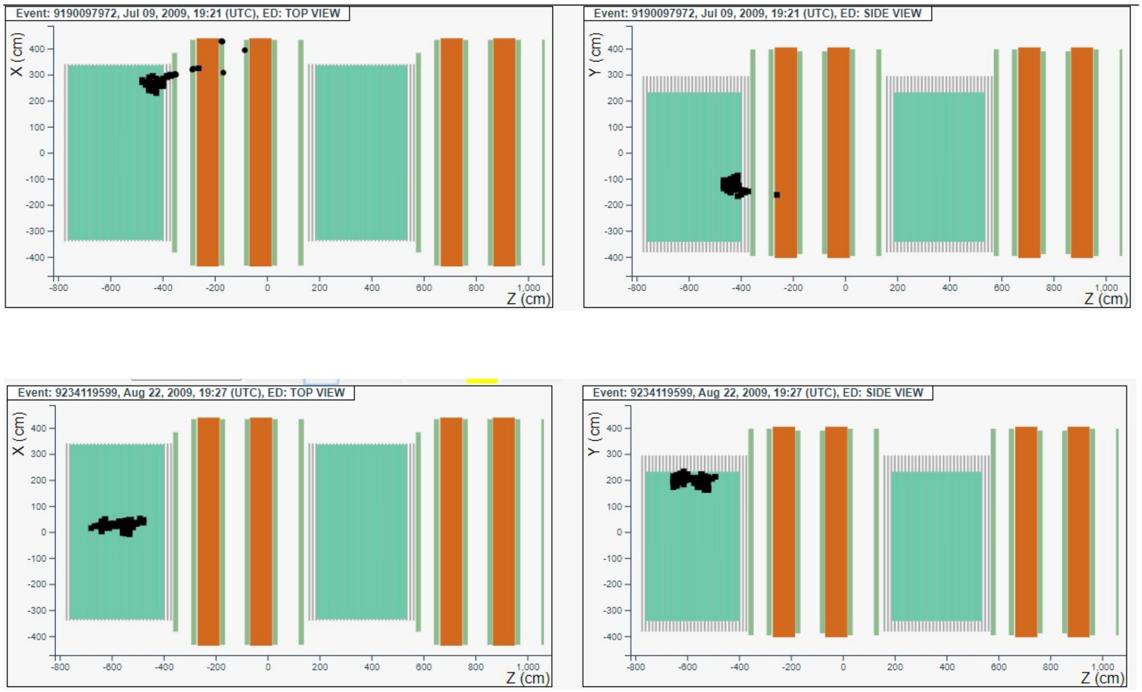


Figure 10: Side and top views of the OPERA detector. The black dots represent the positions of signals (hits) registered by the electronic detectors. These signals were crucial for pinpointing the locations of the target (lead-emulsion) modules, which were then extracted and analyzed. This process enabled the search for and high-resolution reconstruction of tau neutrino interaction event topologies near the primary vertices.

3 Results and Conclusion

Neutrino oscillations are a fascinating phenomenon to explore. Our work demonstrated and visualized the appearance of tau leptons, verified the $\upsilon\mu \rightarrow \upsilon\tau$ oscillation process, and provided us with a solid foundation in computational physics, particularly using C++ and ROOT. In addition to this, we gained a deeper understanding of the principles behind the Super Proton Synchrotron, the OPERA detector setup, and the theoretical aspects of neutrino detection.

Furthermore, we compared our results with those published by the OPERA Collaboration [9, 10], and found them to be in good agreement.
Our re-evaluation of this topic was also aimed at making it accessible for readers to learn from this report, without delving into complex quantum mechanical equations. As demonstrated by our histograms, ROOT provides simple solutions for effectively visualizing large data sets. By understanding and utilizing this framework, one can apply it to studies across various fields of physics and statistics.

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