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ANALYSIS AND INTERACTIVE VISUALIZATION OF NEUTRINO EVENT TOPOLOGIES REGISTERED IN THE OPERA EXPERIMENT

Student:

Ayomide Olalekan Ajayi

University of Debrecen, Hungary

Supervisor:

Dr. Sergey Dmitrievsky

Dzhelepov Laboratory of Nuclear Problems, JINR, Russia

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Abstract

The OPERA experiment was a project designed to demonstrate the oscillation of muon neutrinos into tau neutrinos using nuclear emulsion technique. To achieve this goal, the experiment required high intensity neutrino beam, underground location, and a hybrid detector with a large target mass and micrometric resolution.

The purpose of this project is to study the tools for analyzing and visualizing the OPERA experiment data obtained from the CERN Open Data Portal. To process the experimental data, C++ programs have been developed using the CERN ROOT libraries. The use of the Three.js graphics library and HTML has made it possible to create a 3D interactive visualization of interesting topologies of neutrino events in a web browser, which allows sharing the results with the wider scientific community.

1 Introduction

1.1 Neutrino

Neutrinos (ν) are incredibly elusive particles that possess a distinct set of properties. These fundamental particles have no electric charge and a negligible mass, and they interact only through weak nuclear force and gravity. As a result, they have very weak interactions with matter, making them extremely difficult to detect and study [1]. There are three known types or flavors of neutrinos: electron neutrino(ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ). These flavors are distinguished by their interactions with other particles, particularly the charged leptons (ℓ) produced in their weak interactions [2]

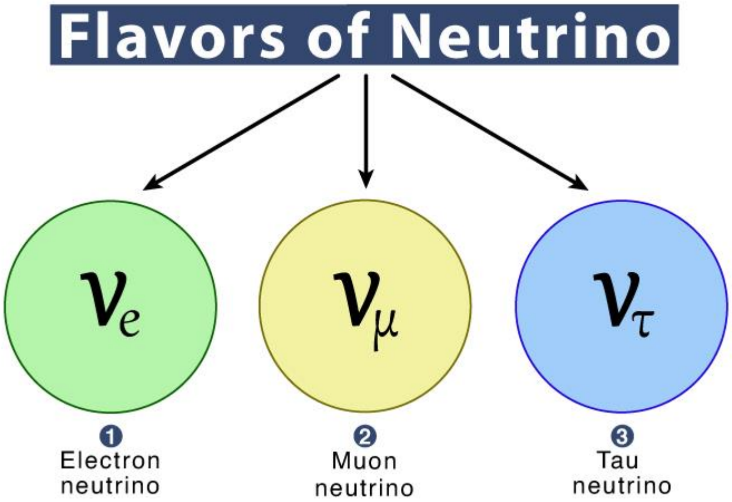


Figure 1: Flavors of Neutrinos [3]

1.2 Neutrino Oscillations

The phenomenon of neutrino oscillation, in which a neutrino of one flavor can change into another flavor as it propagates through space, has been extensively studied since its discovery in the late 20th century. This phenomenon implies that neutrinos have mass, which is not predicted by the Standard Model of Particle Physics [4].

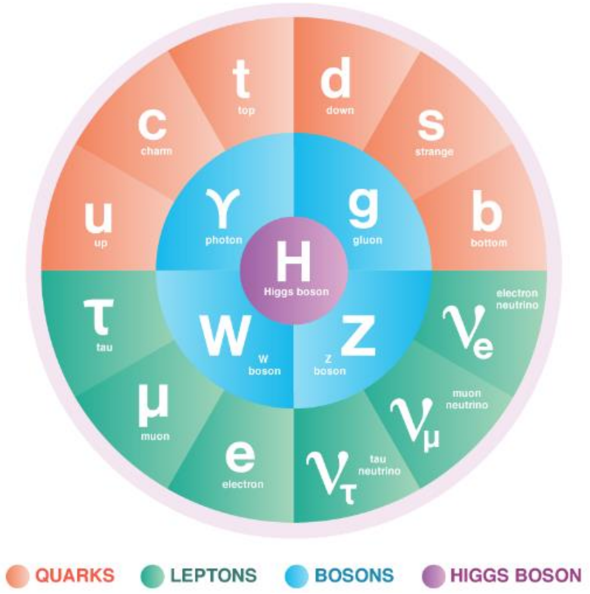


Figure 2: Standard model of the particle [5]

Neutrino oscillation has been observed mostly in disappearance mode, where a beam of neutrinos of a particular flavor is created and the disappearance of that flavor is measured [2]. This mode of detection provides information about the probability that a neutrino of a given flavor will transition to a different flavor, but it does not provide any direct information about the new flavor that is created. Hence, is important to study the appearance mode, where the creation of a new flavor is observed. In the appearance mode of detection, a beam of neutrinos is created with a specific flavor, and the detection of a different flavor at the detector indicates the presence of neutrino oscillation [2][6].

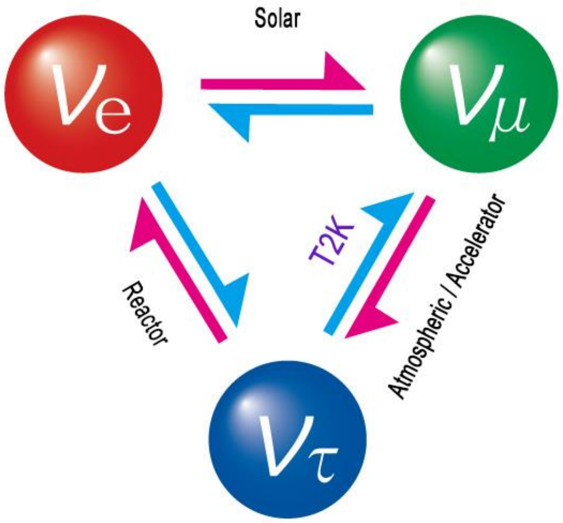


Figure 3: Neutrino oscillation between three generations [7]

2 OPERA

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) experiment was one such experiment that observed neutrinos in the appearance mode, providing experimental proof for $\nu_\mu \rightarrow \nu_\tau$ oscillation. In the experiment, a beam of muon neutrinos was created at European Organization for Nuclear Research (CERN) in Geneva and directed towards the Gran Sasso National Laboratory (LNGS) in Italy, where a detector was located [6] [8]. By observing the appearance of ν_τ in the detector, the experiment studied the phenomenon of neutrino oscillation and the properties of neutrinos in greater detail.

2.1 CNGS Neutrino Beam

OPERA used long-baseline CERN Neutrinos to Gran Sasso (CNGS) high-intensity and a high-energy beam of muon neutrinos. The beam consisted mainly of ν_μ with a mean energy of about 17 GeV, with a $\overline{\nu_\mu}$ contamination of 4% and $\nu_e + \overline{\nu_e}$ contamination of ~ 0.9%. The high energy of the beam and the fact that the ν_τ prompt contamination was totally negligible made the beam suitable for the study of $\nu_\mu \rightarrow \nu_\tau$ transitions in appearance mode [6]. The beam energy was optimized to maximize the τ rate at the detector site and resulted from a compromise between two opposite requirements: a significant charged-current (CC) interaction cross-section of the oscillated ν_τ which occurs at high energy values, and a large oscillation probability favoring low energies [9].

2.2 OPERA Detector

The detection of τ lepton produced in the CC interaction of a ν_τ requires two conflicting requirements: a large target mass to collect enough statistics and an extremely high spatial accuracy to observe the short-lived τ lepton (cτ = 87.11 μ m). The τ lepton was identified by the detection of its characteristic decay topologies either in one prong (electron, muon, or hadron) or in three prongs. Short track of τ lepton was measured with a large mass target made of lead plates (target mass and absorber material) interspaced with thin nuclear emulsion films (high-accuracy tracking devices). This detector is historically called Emulsion Cloud Chamber (ECC). Among past applications, it was successfully used in the DONUT experiment for the first direct observation of the ν_τ [10].

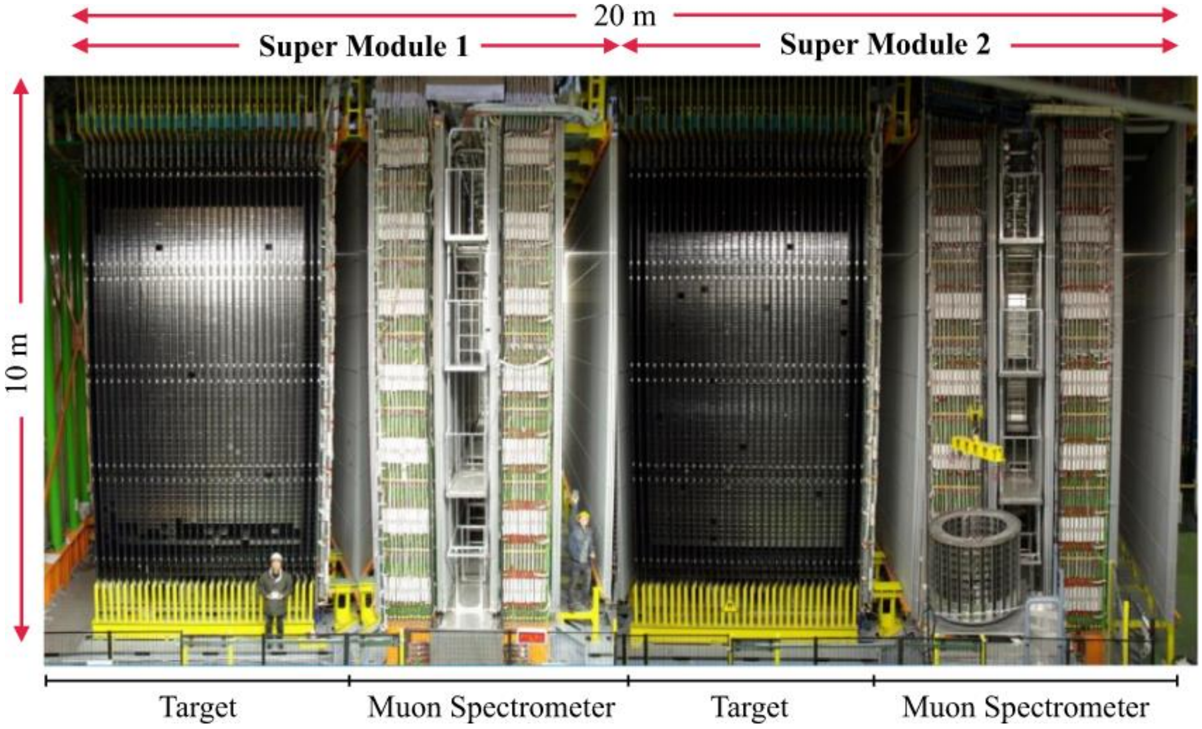


Figure 4: Side view of the OPERA detector (20 × 10 × 10) m^3*.. The CNGS beam come from the left side of the detector. Two identical Super Modules* [11]

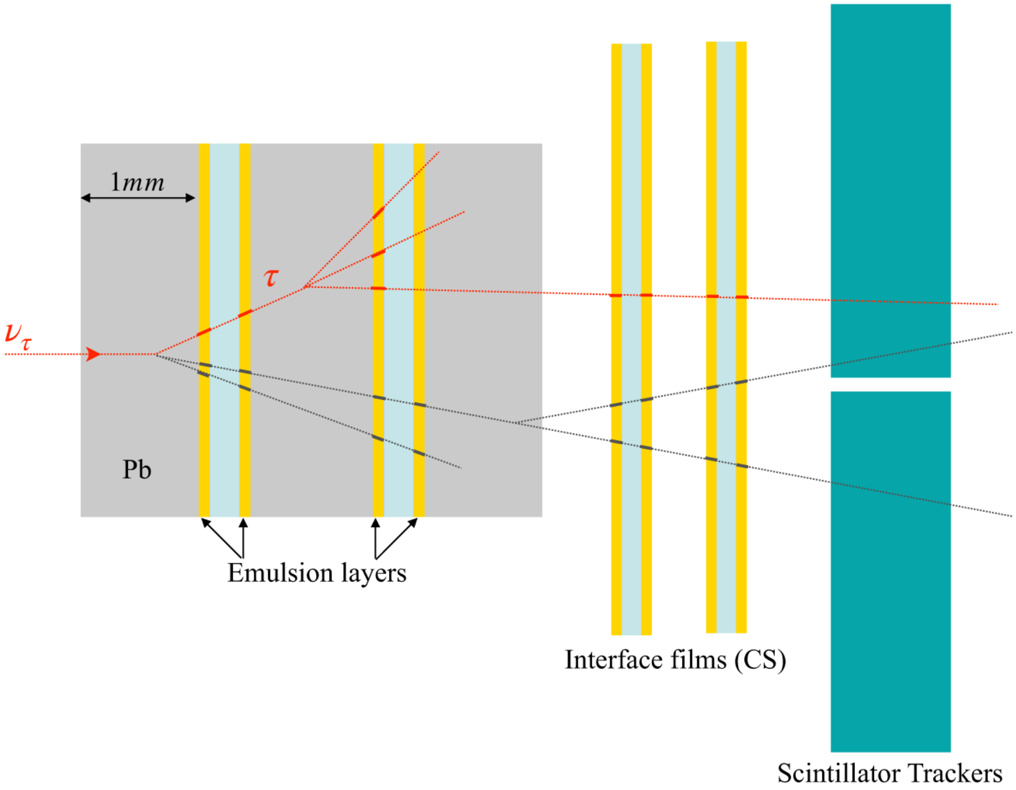


Figure 5: Schematic view of a ντ CC interaction and the decay-in-flight of the final state τ lepton as it appeared in an OPERA brick, in the interface emulsion films (Changeable Sheets), and in the scintillator trackers (Target Trackers) [11]

3 Analysis of Emulsion Data for the study of Neutrino-induced Charmed Hadron Production

Charmed hadrons have masses and lifetimes like those of the τ lepton and constitute one of the main background sources for oscillation experiments like OPERA. At the same time, charm production represents the most powerful tool to directly test the experiment's capability of detecting τ decays, given the analogous topology characterizing ν_μ CC events with a charmed particle in the final state and oscillated ν_τ - induced CC interactions [12].

Therefore, in this study, we assess the validity of ν_τ appearance by studying the production of charmed hadron due to ν_μ interactions.

3.1 Flight Length of the Charmed Hadron

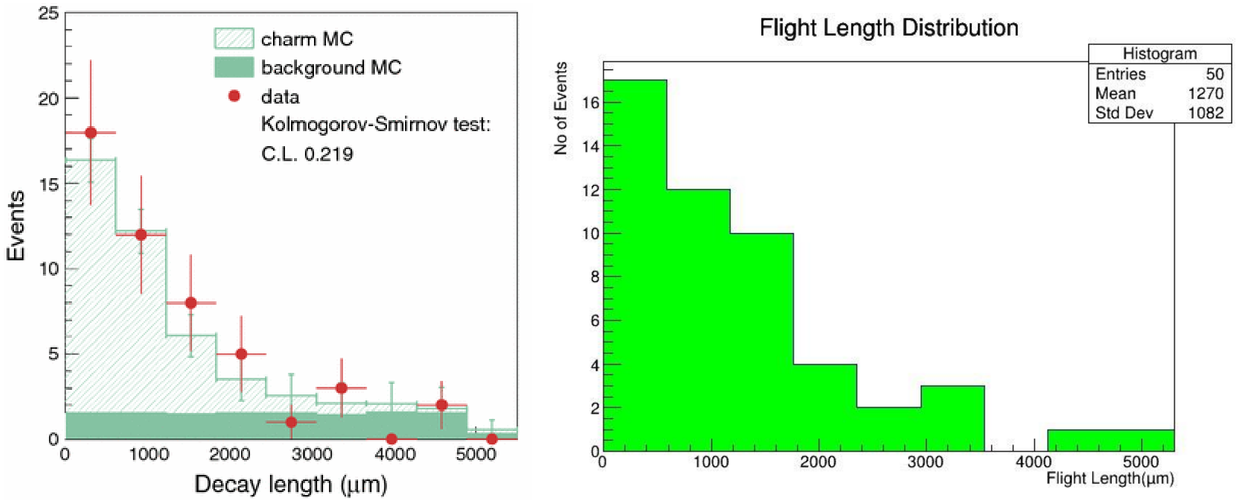
The flight length is the distance traveled by a charmed hadron before decay. The charmed hadron is created at the primary vertex of the ν_μ CC interaction and decay takes place at the secondary vertex. The dataset used for analysis was extracted from the official OPERA data repository. It contains 50 muon neutrino interactions with the lead target where a charmed hadron is reconstructed in the final state. Neutrino-induced charm production happens in the so-called charged-current (CC) interactions of a muon neutrino [13].

C++ code is used to compute the flight lengths (decay length) and the data used was obtained exactly from files named EventID_Vertices.csv. The Flight length for each event was calculated using the formula:

$$\text{Flight Length} = \sqrt{(x2 - x1)^2 + (y2 - y1)^2 + (z2 - z1)^2}$$

x1, y1 and z1 are the coordinates of the primary vertex, and x2, y2 and z2 are the coordinates of the secondary vertex.

The values are stored in a data file and compared with the appropriate paper. The CERN ROOT C++ framework was used to plot the Histogram.



a: Taken from the OPERA paper *b: Obtained from the Dataset*

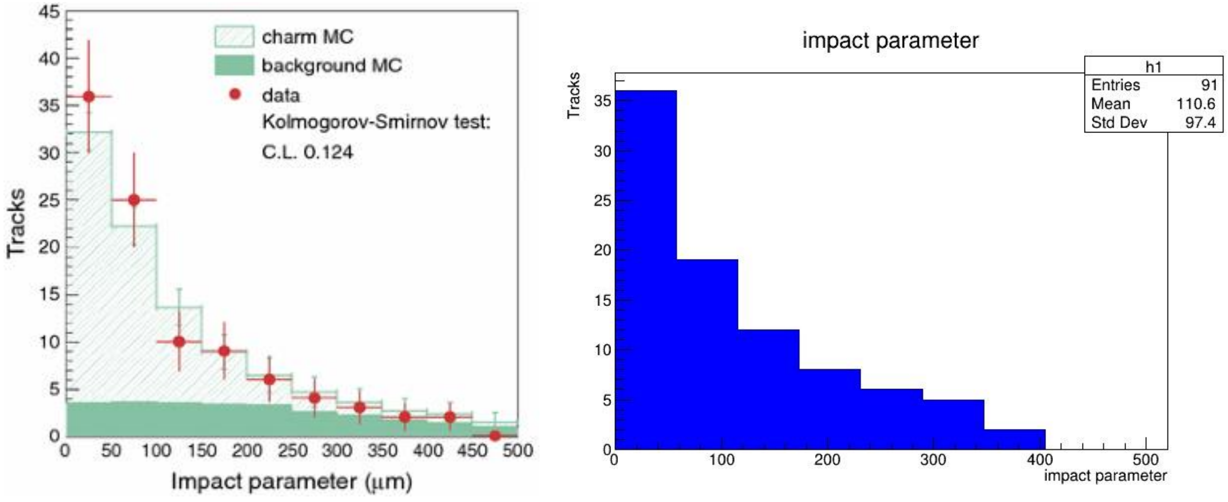
Figure 6: Comparing the Flight Length Distribution Acquired from the Dataset to the One Presented in the OPERA Paper.

3.2 The impact parameter of the daughter tracks with respect to the primary vertex

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 [14]. This can be calculated from the coordinates of the primary vertex and two points on the track line [15].

$$\text{IP} = \frac{\left|(\vec{X}_0 - \vec{X}_1) \times (\vec{X}_0 - \vec{X}_2)\right|}{\left|(\vec{X}_1 - \vec{X}_2)\right|}$$

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.



a: Taken from the OPERA paper [12]

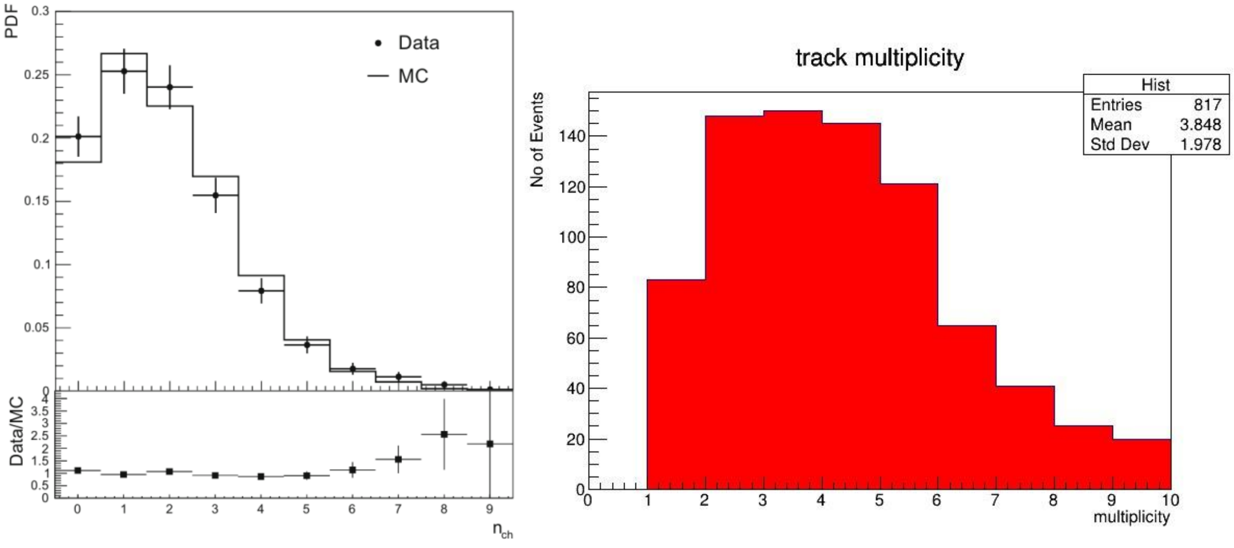
b: Obtained from the Dataset

Figure 7: Comparing the Impact Parameter Distribution Acquired from the Dataset to the One Presented in the OPERA Paper.

4 Analysis of the νμ CC interactions

4.1 The multiplicity distribution of charged hadrons in hard scattering processes

The multiplicity distribution of charged hadrons is an important characteristic of the hadronic final states in hard scattering processes. Since it reflects the dynamics of the interaction, it has been extensively studied in cosmic rays, fixed targets, and collider experiments [16]. Track multiplicity is defined as the number of track lines emerging from a given vertex, like in this case, the primary vertex of the ν_μ CC interaction. The appropriate emulsion data can be found in the files EventID_Vertex.csv.



a: Taken from the OPERA paper *b: Obtained from the Dataset*

Figure 8: Comparing the Track Multiplicity Distribution Acquired from the Dataset to the One Presented in the OPERA Paper.

4.2 Angles of the muon tracks emerging from the primary vertices of νμ CC interactions.

Tracks are defined using a point near the vertex and two slopes, which are the tangents with respect to the Z-axis in the XZ and YZ plane. Muon track lines can be identified in the EventID_Tracks.csv file as the rows with trType = 1. Muon track angles in radians were calculated using the formula:

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

A 2D histogram of the angle distribution was drawn as well as a 3D projection.

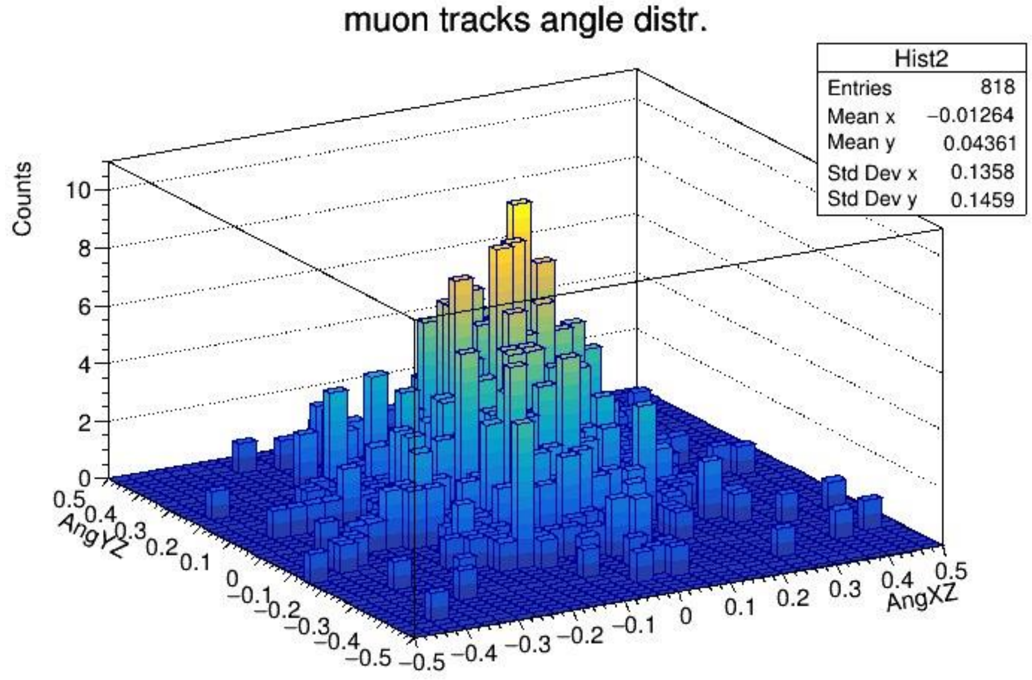


Figure 9: 2D representations of the Muon Track Angle Histogram

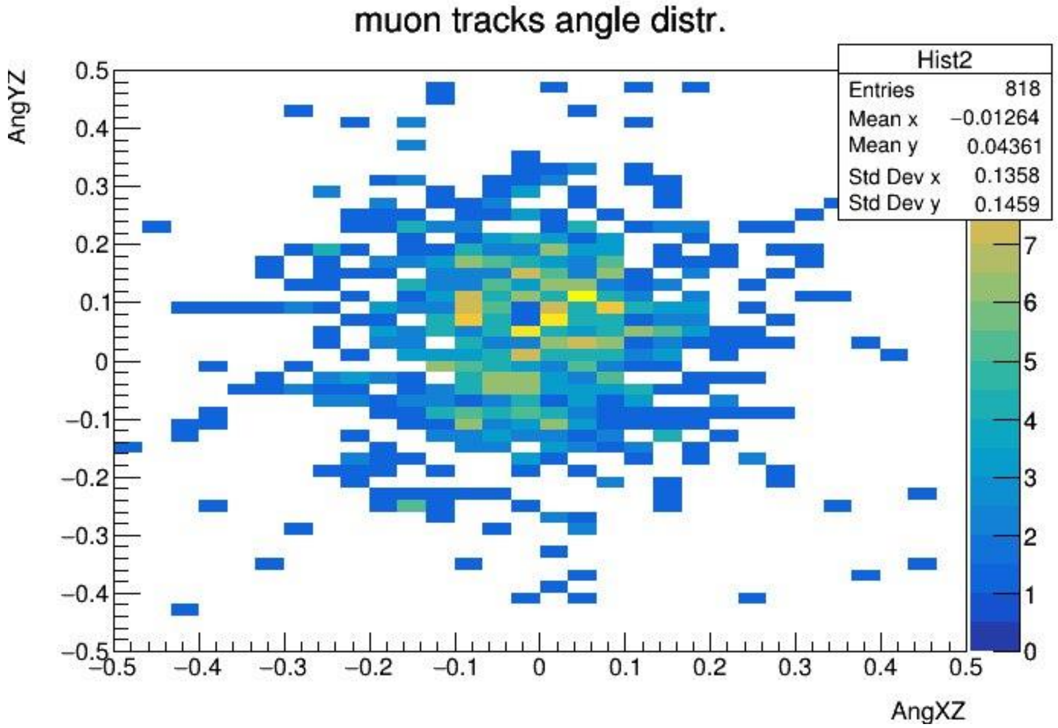
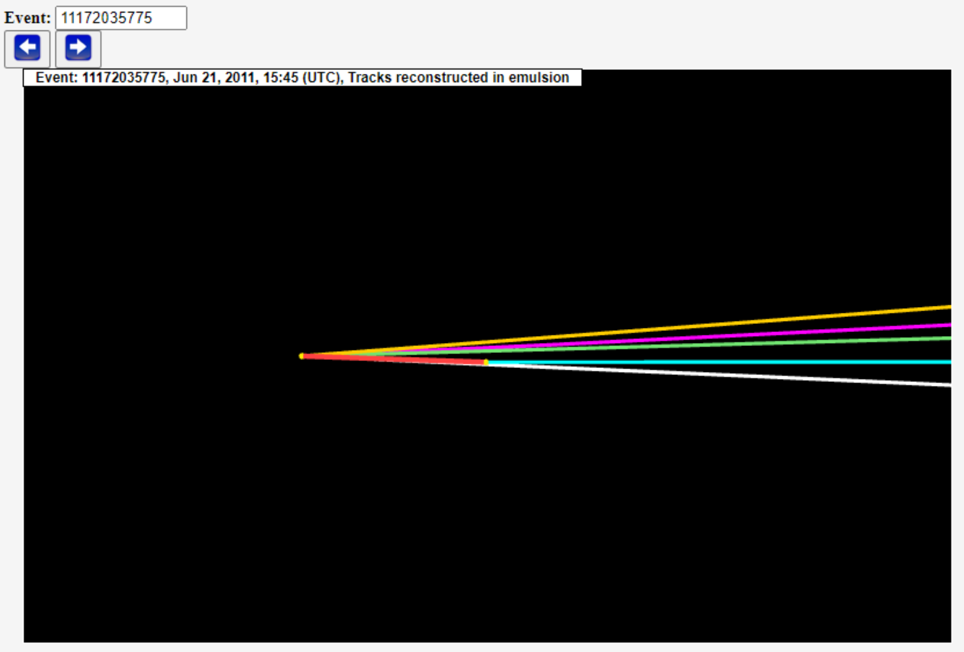


Figure 10: 3D representations of the Muon Track Angle Histogram

5 Visualization of OPERA ν_τ-candidate event topologies

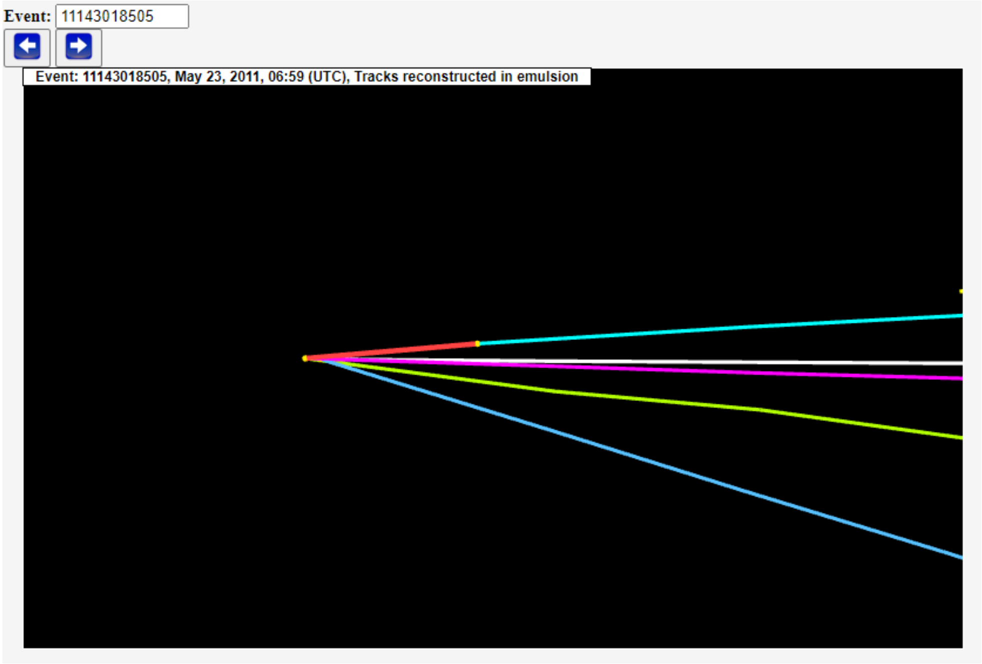
In the file EventID_Vertex.csv we obtain the position of a vertex and using the file EventID_Lines.csv we obtain two points along the track lines to be able to obtain the whole track. These values were saved into a JavaScript object, then Three.js graphics library and HTML were used to build a browser-based 3D event display of vertices and track lines of each of the 10 tau neutrino candidate events. Some candidates are shown below [11].



Event: 11172035775

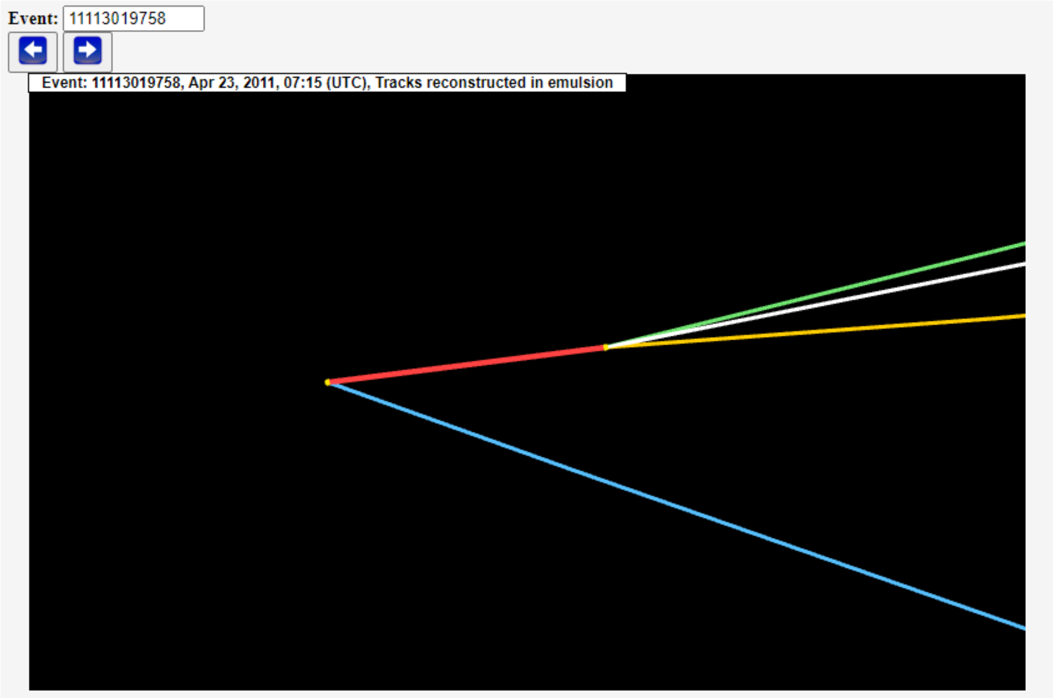
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), Tracks reconstructed in emulsion

Figure 11: Reconstructed Tracks in emulsion for Event 11172035775


Event: 11143018505

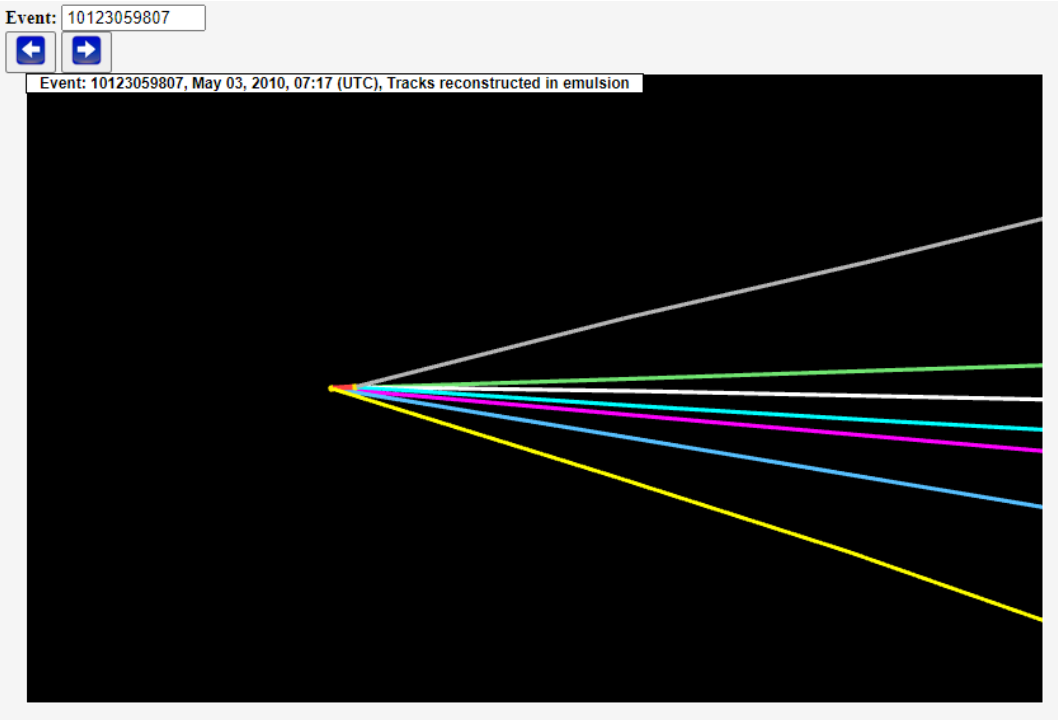
Event: 11143018505, May 23, 2011, 06:59 (UTC), Tracks reconstructed in emulsion

Figure 12: Reconstructed Tracks in emulsion for Event 11143018505


Event: 11113019758

Event: 11113019758, Apr 23, 2011, 07:15 (UTC), Tracks reconstructed in emulsion

Figure 13: Reconstructed Tracks in emulsion for Event 11113019758



Event: 10123059807

Event: 10123059807, May 03, 2010, 07:17 (UTC), Tracks reconstructed in emulsion

Figure 14: Reconstructed Tracks in emulsion for Event 10123059807

Conclusions

The OPERA experiment has contributed significantly to the study of neutrino physics, particularly in providing valuable insights into the behavior of neutrinos and their oscillation between different types, as documented in previous research. In this project, we conducted a rigorous analysis of the OPERA data available on the CERN Open Data Portal using the C++ ROOT library. The comparison of our results with those in the original published OPERA papers, which agreed, further expanded our understanding of fundamental physics. To help communicate our findings to a wider audience, we employed the Three.js graphics library to create an interactive event display that provides visual representation of the obtained results. All codes used for analysis and visualization can be found on GitHub [16].

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