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

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I am writing this letter to express my deepest gratitude for the opportunity to be a part of JINR. I feel extremely honored to have been selected and to have had the chance to learn and grow under the guidance of such a supportive and knowledgeable team. During my time at JINR, I had the chance to work on challenging projects, engage in insightful discussions, and observe the inner workings of a successful organization. I have gained invaluable knowledge, skills, and experience that will undoubtedly benefit me in my future endeavors. I would like to extend my sincere appreciation to all the individuals who have contributed to making my internship experience a memorable and enriching one. I am especially grateful to my mentor, who took the time to share their expertise and provided me with guidance and feedback throughout my internship. Once again, thank you for this wonderful opportunity. I will always be grateful for the valuable lessons and experiences that I have gained during my time at JINR.

ABSTRACT

Neutrinos are elusive particles that are difficult to detect and can pass through matter almost undisturbed. In our project, we will discuss the phenomenon of neutrino oscillation, which implies that neutrinos have non-zero mass and can change their flavor as they move through space. The OPERA experiment, designed to study neutrino oscillations, was based on a hybrid technology combining electronic detectors and nuclear emulsions. This report presents an analysis of several OPERA datasets collected during the experiment, which are available on the CERN Open Data Portal. The presented results were obtained with help of C++ programs using the CERN ROOT data analysis framework. In addition, JavaScript, HTML, and CSS were used to visualize typical topologies of OPERA tau-neutrino interaction events in a web browser.

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INTRODUCTION

Apart from photons, Neutrinos are subatomic particles that are like electrons but have no electric charge and a very small mass. They are produced in a variety of nuclear reactions and are abundant in the universe, with billions of them passing through your body every second without you even noticing.

Neutrinos are challenging to detect because they interact very weakly with matter, but specialized detectors have been developed to study their properties. These detectors have helped scientists learn more about the fundamental nature of the universe, including the behavior of matter at very high energies and the composition of the sun's core.

It has been discovered through multiple experimentation that neutrinos change their flavor as they move through space. There are three types of neutrino flavors: muon, tau, and electron, which are related to the interactions in which they participate. This flavor switching is a quantum mechanical phenomenon, and the term "neutrino oscillation" describes how the probability of a neutrino changing from flavor $\nu\alpha$ to flavor $\nu\beta$ oscillates with the distance traveled, whether in a vacuum or through matter.

Experiments conducted in the late 1990s confirmed the existence of neutrino oscillations, and this discovery led to the realization that neutrinos must have mass, which was previously thought to be zero. The study of neutrino oscillations is an active area of research, as scientists seek to better understand the mechanisms that drive these changes in flavor and the implications for our understanding of the universe.

NEUTRINOS

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_c), muon neutrino (ν_μ), and tau neutrino (V_T),. These flavors are distinguished by their interactions with other particles, particularly the charged leptons (ℓ) produced in their weak interactions [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].

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. where the creation of a new flavor is 6 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]

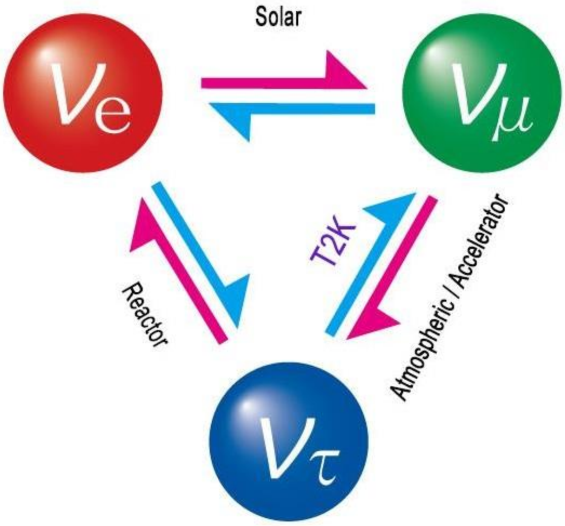


Figure 3: Neutrino oscillation between three generations [7]

OPERA

The Oscillation Project with Emulsion-Tracking Apparatus (OPERA) experiment was one such experiment that observed neutrinos in the appearance mode, providingexperimental proof for $\nu_{\mu} \rightarrow \nu_{c}$ 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_{c} in the detector, the experiment studied the phenomenon of neutrino oscillation and the properties of neutrinos in greater detail.

2.1 OPERA DETECTOR

The Oscillation Project with Emulsion-Tracking Apparatus (OPERA) experiment studied neutrinos in the appearance mode, and provided experimental proof for $\nu\mu \rightarrow \nu\tau$ oscillation.

$$\nu c \text{ ---> } \nu\tau$$

By observing the appearance of νc in the detector, the experiment studied the phenomenon of neutrino oscillation and the properties of neutrinos in greater detail.

The detection of τ lepton produced in the CC interaction of a $\nu\tau$ 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 ($c\tau = 87.11\ \mu$ 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 $\nu\tau$ [10].

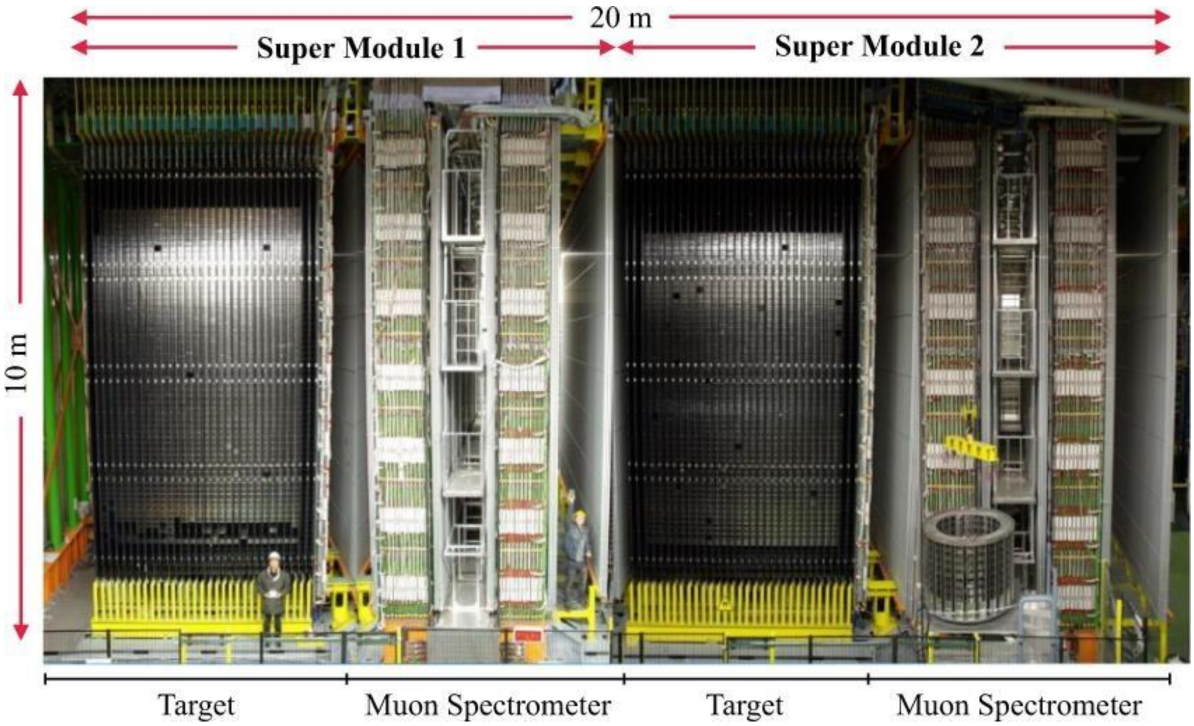
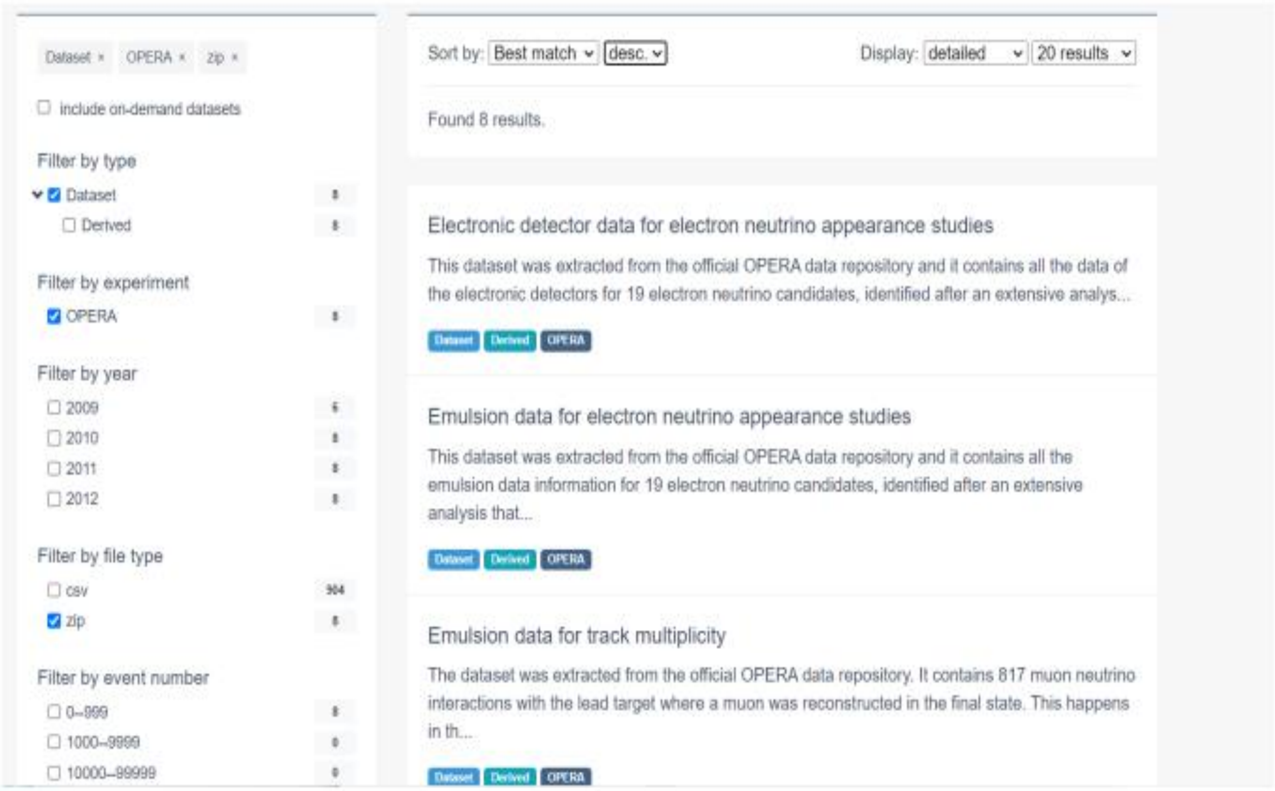


Figure 2: Side view of the OPERA detector (20 × 10 × 10) m^3*.. The CNGS beam come from the left side of thedetector. Two identical Super Modules* [11]

CERN OPEN DATA PORTAL

The CERN Open Data Portal is an online platform that provides free and open access to scientific data generated by CERN's experiments. The portal was created in 2014 in collaboration with CERN IT and the CERN Scientific Information Service, and its purpose is to promote transparency, collaboration, and scientific progress by making CERN's research data widely available to the public. The portal offers various types of data, such as experimental results, detector performance, and simulation data, along with the software and documentation needed to understand and analyze the data. The CERN Open Data Portal is a valuable resource for scientists, researchers, students, and anyone interested in exploring the mysteries of the universe.



Dataset × OPERA × zip ×

☐ include on-demand datasets

Filter by type

- ☑ Dataset 8
  - ☐ Derived 8

Filter by experiment

- ☑ OPERA 8

Filter by year

- ☐ 2009 5
- ☐ 2010 8
- ☐ 2011 8
- ☐ 2012 8

Filter by file type

- ☐ csv 904
- ☑ zip 8

Filter by event number

- ☐ 0–999 8
- ☐ 1000–9999 0
- ☐ 10000–99999 0

Sort by: Best match desc.

Display: detailed 20 results

Found 8 results.

Electronic detector data for electron neutrino appearance studies

This dataset was extracted from the official OPERA data repository and it contains all the data of the electronic detectors for 19 electron neutrino candidates, identified after an extensive analys...

Dataset Derived OPERA

Emulsion data for electron neutrino appearance studies

This dataset was extracted from the official OPERA data repository and it contains all the emulsion data information for 19 electron neutrino candidates, identified after an extensive analysis that...

Dataset Derived OPERA

Emulsion data for track multiplicity

The dataset was extracted from the official OPERA data repository. It contains 817 muon neutrino interactions with the lead target where a muon was reconstructed in the final state. This happens in th...

Dataset Derived OPERA

Fig 3: Interface of CERN Open Data

ANALYSIS OF EMULSION DATA 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 $\nu\mu$ CC events with a charmed particle in the final state and oscillated $\nu\tau$ - induced CC interactions [12].

Therefore, in this study, we assess the validity of $\nu\tau$ appearance by studying the production of charmed hadron due to $\nu\mu$ interactions.

3.1 FLIGHT LENGTH OF CHARMED HADRON

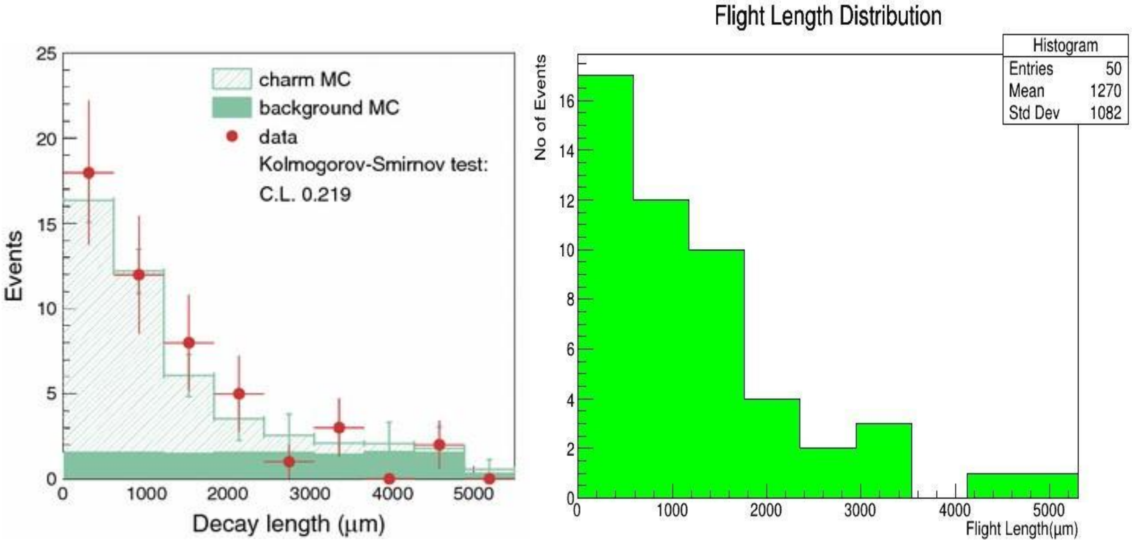
The flight length is the distance traveled by a charmed hadron before decay. The charmed hadron is created at the primary vertex of the $\nu\mu$ CC interaction and decay takes place at the secondary vertex. The dataset used for analysis was extracted from the official OPERA data repository. It contains 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:

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

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

The calculated values are stored in a histogram that was created using the CERN ROOT C++ framework and compared with the corresponding histogram from the OPERA paper [3].



a: Taken from the OPERA paper

b: Obtained from the Dataset

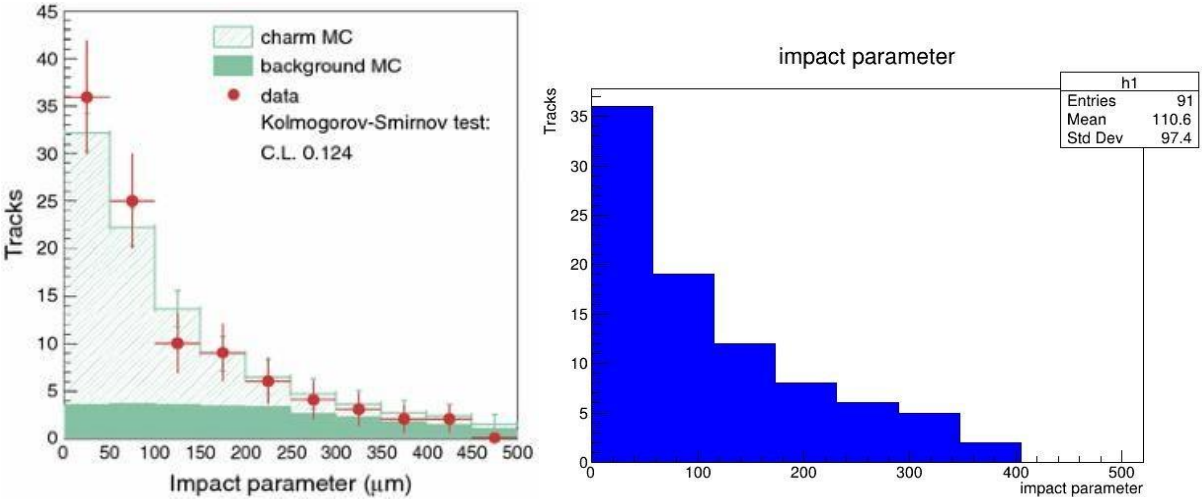
Figure 4: Comparing the Flight Length Distribution Acquired from the Dataset to the One Presented in the OPERAPaper.

3.2 THE IMPACT PARAMETER OF THE DAUGHTER TRACKS WITH RESPECT TO THE PRIMARY VERTIX:

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].

$$\frac{|X0 - X1| \times |X1 - X2|}{|(X1 - X2)|}$$

where $X0 = (x0, y0, z0)$ is the position vector of the primary vertex, and $X1$ and $X2$ 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 5: Comparing the Impact Parameter Distribution Acquired from the Dataset to the One Presented in the OPERA Paper

TASK 2

In this task an OPERA emulsion dataset related to the study of charged hadron multiplicity was used, which is available on the Open Data Portal

4.1 Multiplicities of all produced charged particles

In our scenario, track multiplicity refers to the number of charged particle tracks that are linked to a particular vertex, which is associated with the primary interaction vertex of the muon neutrino.

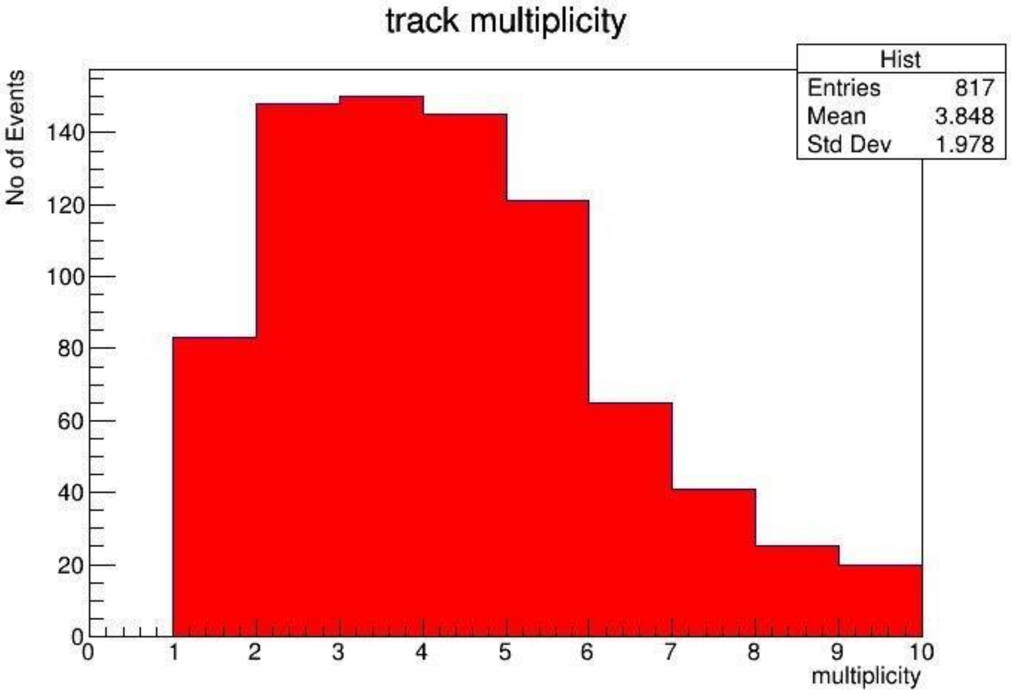


Figure 6 : Track multiplicity distribution

The EventIDvertex.csv file contains information on the number of charged particles produced in a neutrino interaction with lead target. A C++ code was used to read the track multiplicity associated with each event, and the extracted values were saved to a ROOT histogram. The resulting plot is shown in Figure 3.3.

THE ANGLES OF MUON TRACKS

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.

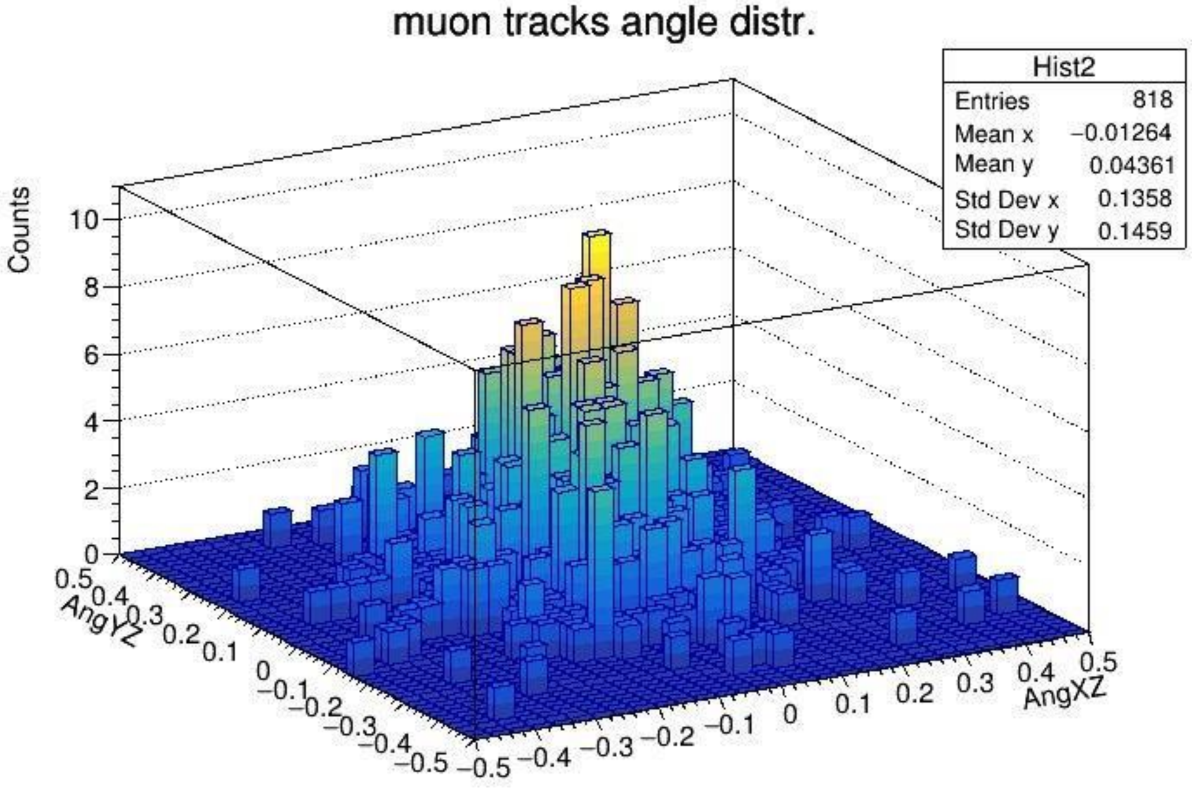


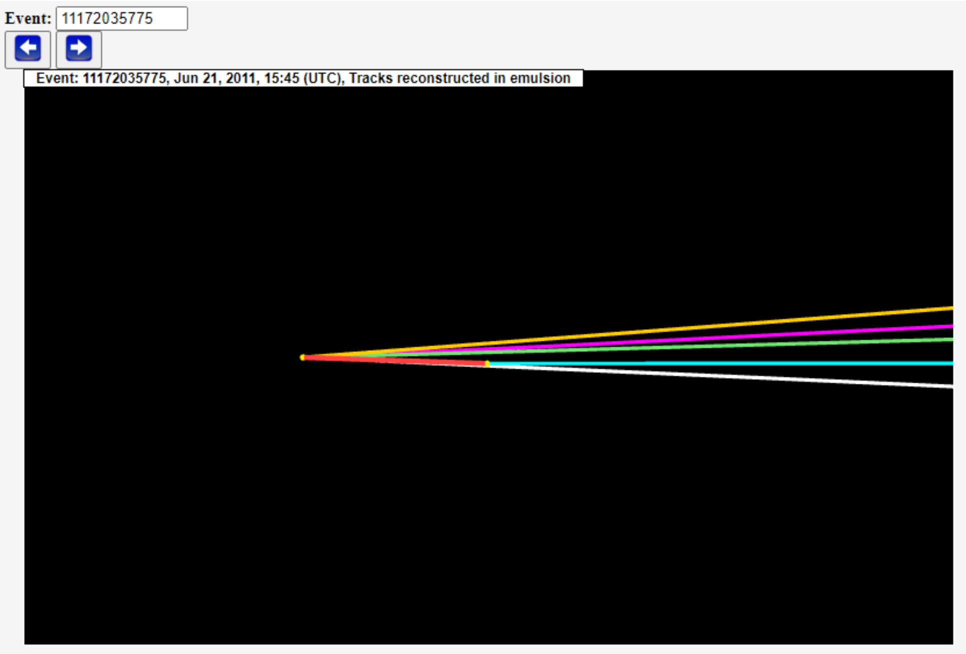
Figure 7: 2D representations of the Muon Track Angle Histogram

The slopes of muon tracks in XZ and YZ views were read using the C++ code. For each event, the angle of the muon track was computed using the above-mentioned mathematical formula and saved to a ROOT histogram. The obtained plot for Muon track angles is shown in Figure 7.

TASK 3

EMULSION DATA OF TAU-NEUTRINO APPEARANCE STUDIES

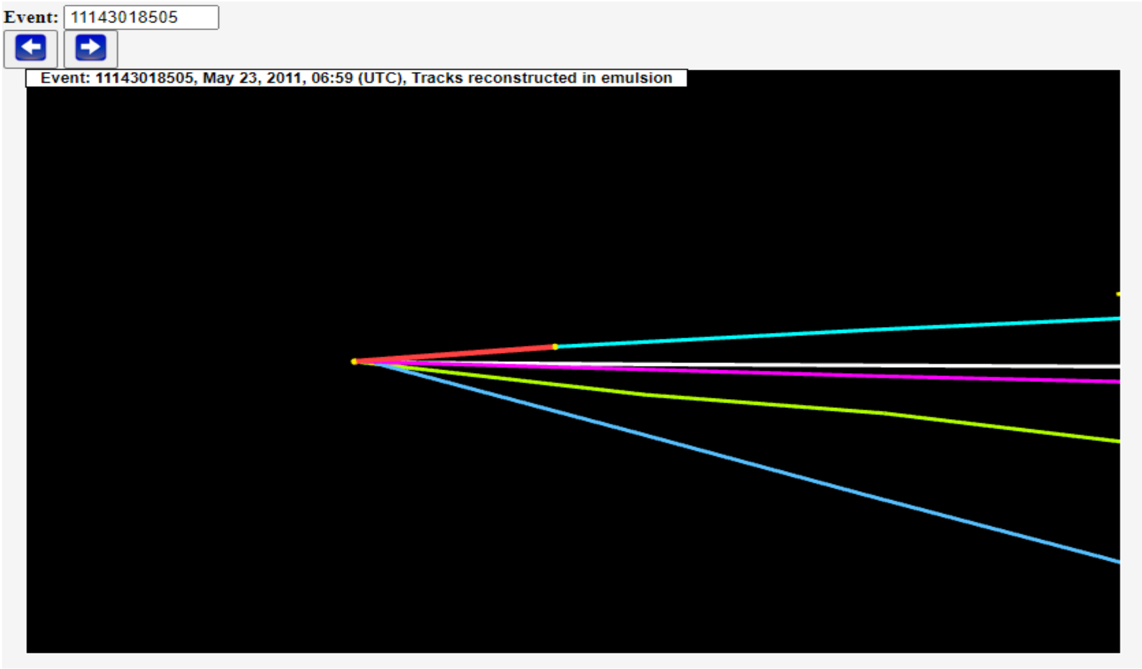
For OPERA emulsion dataset related to tau neutrino appearance study, a 3D visualization was created. As it was said in the OPERA publication [3] topological and kinematical cuts were applied to a sample of 5603 reconstructed neutrino interactions, and 10 ντ candidate were selected. To visually represent interesting topologies of the found events in a webbrowser, the THREE.js JavaScript library was used. Figure 8 to 11 shows reconstructed Tracks and Vertices for 4 out of the 10 tau neutrino candidate events.



Event: 11172035775

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

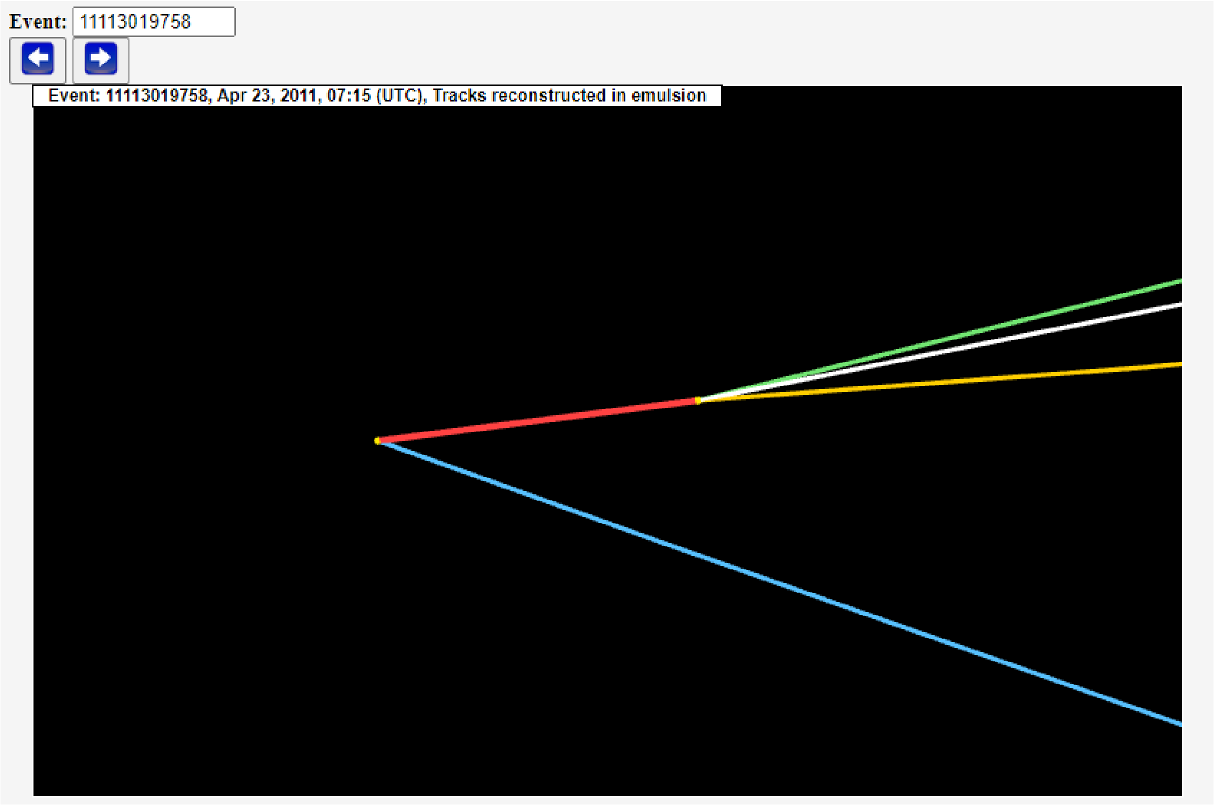
Figure 8: Reconstructed Tracks in emulsion for Event 11172035775



Event: 11143018505

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

Figure 9: Reconstructed Tracks in emulsion for Event 11143018505



Event: 11113019758

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

Figure 10: Reconstructed Tracks in emulsion for Event 11113019758

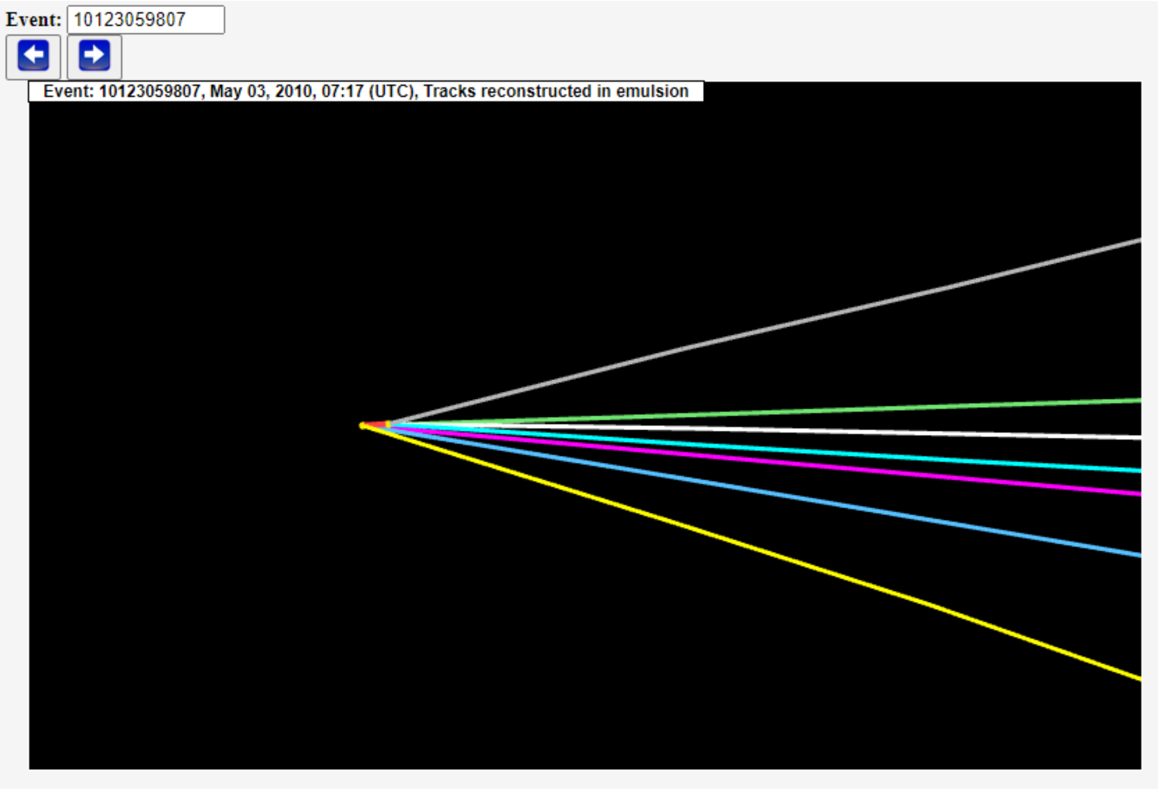


Figure 11: Reconstructed Tracks in emulsion for Event 10123059807

CONCLUSIONS:

This project involved analyzing several OPERA datasets available on the CERN Open Data Portal using C++ applications and CERN's ROOT libraries. The work was divided into three parts. In Part 1 (Task 1) of the project, the focus was on calculating the flight lengths of charmed hadrons and the impact parameters of their daughters relative to the primary neutrino interaction vertex. This information is important for understanding the properties and behavior of the charmed hadrons produced in neutrino interactions. To perform this analysis, C++ applications utilizing CERN's ROOT libraries were used. The results of this analysis can provide insights into the production and decay of charmed hadrons in neutrino interactions. In Part 2 (Task 2) of the project, the focus was on obtaining the distributions of the track multiplicities of charged particles and the angles of the muon tracks in the OPERA dataset. This information is of considerable interest for understanding the behavior of charged particles produced in neutrino interactions and for studying the properties of the muons produced in these interactions. To perform this analysis, C++ applications utilizing CERN's ROOT libraries were used. The obtained distributions were then compared to the published results, and it was found that they were in good agreement. This indicates that the analysis performed in this project is accurate and reliable. In Part 3 (Task 3) of the project, a simplified version of the OPERA browser-based event display was used and modified to visualize interesting topologies of neutrino interaction events from the OPERA nu-tau-candidate sample. Comparing the images obtained in this task with those on the Open Data Portal provides a deeper understanding of the neutrino interactions that took place in OPERA and deepens our understanding of particle physics.

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