JOINT INSTITUTE FOR NUCLEAR RESEARCH
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Analysis and Interactive Visualization of Neutrino Event Topologies Registered in The OPERA Experiment

Final Report of INTEREST Program

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Abstract

This final report presents the analysis and visualization of neutrino interaction events registered in the OPERA experiment, conducted within the framework of Wave 13 of the JINR INTEREST Program. The primary objective was to study the topology of neutrino events using the CERN Open Data Portal. The analysis focused on Charmed Hadron Production and Muon identification, utilizing the ROOT data analysis framework and C++. Key kinematic variables, including flight lengths and impact parameters of charmed decay daughter particles, were reconstructed and found to be in agreement with published OPERA results. Additionally, a specific analysis of charged hadron multiplicity and muon track angles led to the successful identification of a dimuon event within the dataset. Furthermore, to enhance the interpretability of these complex events, a web-based interactive 3D visualization tool was developed using the THREE.js library. This tool allows for the rendering of tau neutrino candidate events, providing a visual correlation to the statistical data. The project successfully demonstrates the application of high-energy physics analysis techniques to real experimental data

1 Introduction and Theoretical Background

1.1 Introduction to Neutrinos

Neutrinos are among the most enigmatic and fundamental particles in the Standard Model of particle physics. Their feeble interaction with matter, only through the weak force and gravity, makes them extraordinarily difficult to detect, yet their study offers profound insight into the nature of the universe. Historically, neutrinos were postulated to preserve conservation laws in beta decay, and since then, experiments such as those studying the solar neutrino problem, atmospheric neutrinos, and reactor neutrinos have gradually unveiled their surprising behavior. Neutrinos are among the most mysterious and fundamental particles in the universe. First proposed by Wolfgang Pauli in 1930 to explain the apparent violation of energy and momentum conservation in beta decay, neutrinos have since become essential to our understanding of both particle physics and astrophysics. These particles are electrically neutral, have extremely small masses, and interact only via weak nuclear force and gravity, making their detection extremely difficult. Despite their elusive nature, neutrinos are the second most abundant particles in the universe after photons, streaming through every square centimeter of Earth in vast numbers each second, almost without any interaction.

In the Standard Model of particle physics, there are three types (or flavors) of neutrinos:

- the electron neutrino (ν_e),

- the muon neutrino (ν_μ),

- the tau neutrino (ν_τ).

Each flavor of neutrino is associated with a corresponding charged lepton; the electron, muon, and tau, respectively. For decades, neutrinos were believed to be massless, as originally postulated by the Standard Model. However, experimental observations starting in the late 20th century challenged this view.

One of the most profound discoveries in modern physics is the phenomenon of neutrino oscillation. This process describes how a neutrino created with a specific flavor can change into another flavor as it propagates through space. Neutrino oscillation arises from the quantum mechanical mixing between mass eigenstates and flavor eigenstates, which are not identical. The relationship between them is described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, analogous to the CKM matrix in the quark sector. This matrix contains three mixing angles and one CP-violating phase, which together govern the oscillation probabilities between flavors. The discovery of neutrino oscillation implies that neutrinos have non-zero mass, marking a clear indication of physics beyond the Standard Model and leading to the 2015 Nobel Prize in Physics awarded to Takaaki Kajita and Arthur B. McDonald.

Among the experiments that provided direct evidence for neutrino oscillations, the OPERA experiment (Oscillation Project with Emulsion-tRacking Apparatus) stands as a milestone. Conducted at the Gran Sasso National Laboratory (LNGS) in Italy, OPERA

aimed to observe the appearance of tau neutrinos (ν_τ) in a beam originally composed of muon neutrinos (ν_μ) generated at CERN. The CERN Neutrinos to Gran Sasso (CNGS) beam traveled approximately 730 km through the Earth's crust from CERN to LNGS. If neutrino oscillations occur, a fraction of the ν_μ beam should transform into ν_τ neutrinos during this journey. Detecting even a few ν_τ events in such a long-baseline experiment would thus serve as a direct proof of flavor oscillation.

1.2 OPERA Experiment

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) was an instrument used in a scientific experiment for detecting tau neutrinos from muon neutrino oscillations. The experiment is a collaboration between CERN in Geneva, Switzerland, and the Laboratori Nazionali del Gran Sasso (LNGS) in Gran Sasso, Italy and uses the CERN Neutrinos to Gran Sasso (CNGS) neutrino beam.

The process started with protons from the Super Proton Synchrotron (SPS) at CERN being fired in pulses at a carbon target to produce pions and kaons. These particles decay to produce muons and neutrinos. The beam from CERN was stopped on 3 December 2012, ending data taking, but the analysis of the collected data has continued.

The OPERA detector was a hybrid system that combined electronic detectors for real-time event tracking and nuclear emulsion films for high-precision spatial measurements of charged particle trajectories. These emulsions act like photographic plates, capable of recording particle tracks with micrometric resolution. The detector's structure was divided into "bricks" composed of lead plates (serving as dense targets for neutrino interactions) and emulsion films (recording the resulting particle tracks). When a tau neutrino interacts with the detector material, it produces a tau lepton, which quickly decays into other charged particles. The distinctive topology of this decay—typically characterized by a kink in the track—serves as a signature of a ν_τ interaction. By reconstructing such topologies, physicists can statistically confirm the appearance of tau neutrinos in the originally pure muon neutrino beam.

The first ν_τ candidate event was reported by OPERA in 2010, and over the subsequent years, additional events were identified, reaching a statistically significant observation. This provided direct evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation, complementing earlier results from Super-Kamiokande, SNO, and KamLAND, which had established the existence of oscillations using disappearance measurements rather than appearance modes.

The OPERA experiment thus played a crucial role in confirming that neutrino oscillation occurs not only through the disappearance of one flavor but also via the appearance of another, offering a comprehensive picture of neutrino mixing phenomena. Moreover, the OPERA data and reconstruction techniques have continued to provide valuable educational and research opportunities, allowing students and researchers to analyze neutrino topologies, track reconstructions, and kinematic parameters using real experimental data.

2 Project Objectives

The objective of this project is to analyze and visualize neutrino interaction events from the OPERA experiment using data provided by the CERN Open Data Portal. Students will learn how to read and process OPERA CSV files containing information from both electronic detectors and emulsion films, and how to study the topology of neutrino events

using C++ and the ROOT data analysis framework. The project also includes developing elements of interactive 2D and 3D event visualization in a web browser with HTML, CSS, and JavaScript graphics libraries such as THREE.js and D3.js, allowing a deeper understanding of neutrino detection and event reconstruction.

3   Tasks

This section presents the task-wise work carried out for the analysis and visualization of neutrino topologies registered in the OPERA Experiment.

3.1   Charmed Hadron Production:

The primary objective of this study was to analyze charmed hadron production utilizing the OPERA emulsion dataset. The analysis involved extracting the spatial coordinates of both primary and secondary interaction vertices, along with the track parameters of the charm decay daughter particles. A C++ framework coupled with the ROOT library was employed to process the dataset, compute kinematic variables, and generate histograms, which were subsequently validated against published OPERA results. Specifically, the flight length was determined by calculating the three-dimensional Euclidean distance between the primary and secondary vertices.

$$\text{Flight\_Length} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Where (x_1, y_1, z_1) represents the primary vertex and (x_2, y_2, z_2) represents the secondary vertex. Then ROOT was used to construct a 1D Histogram for the obtained Flight Lengths, which are also called Decay Lengths. The histogram obtained by analysis and the histogram in the original paper are presented below.
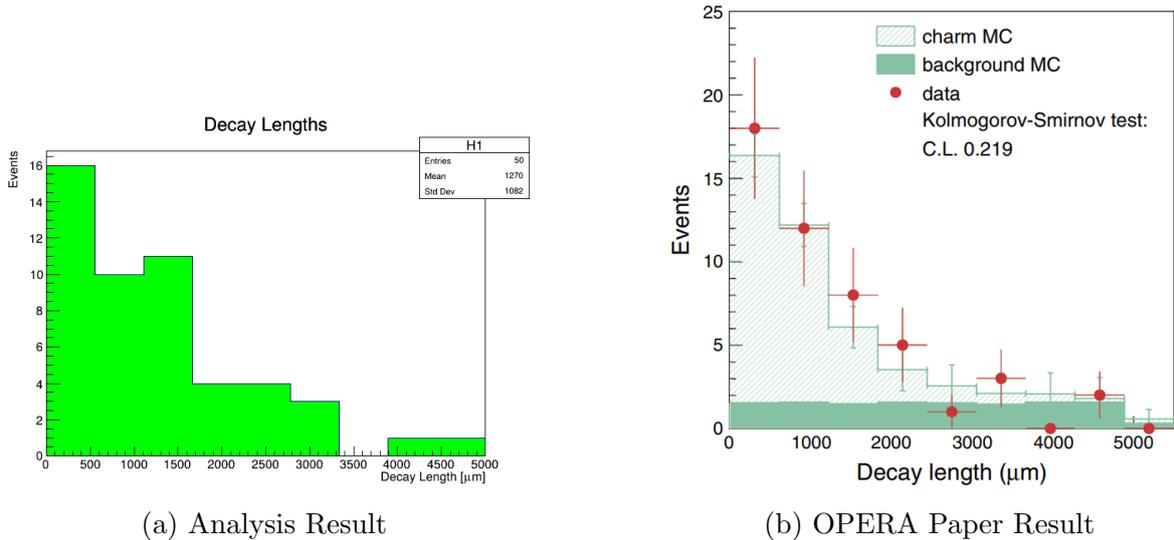

(a) Analysis Result   (b) OPERA Paper Result

Figure 1: Comparison of the Decay Lenght Histogram. (a) The histogram obtained from my analysis using ROOT. (b) The reference histogram from the OPERA paper.

Upon acquiring the three-dimensional coordinates of the Primary and Secondary vertices, we applied 3D coordinate geometry principles to compute the Impact Parameters (I_p). The Impact Parameter is defined as the perpendicular distance from the Primary Vertex

$P_1(x_1, y_1, z_1)$ to the daughter particle track, which passes through the Secondary Vertex $P_2(x_2, y_2, z_2)$ and another point in space $P_3(x_3, y_3, z_3)$. This relationship is mathematically expressed as:

$$I_p = \frac{\left\| \vec{P_2P_1} \times \vec{P_2P_3} \right\|}{\left\| \vec{P_2P_3} \right\|} \tag{1}$$

In this equation:

- $\vec{P_2P_3} = (x_3 - x_2, y_3 - y_2, z_3 - z_2)$ represents the direction vector of the Daughter Track.

- $\vec{P_2P_1} = (x_1 - x_2, y_1 - y_2, z_1 - z_2)$ represents the vector connecting the Secondary Vertex to the Primary Vertex.

Subsequent to the calculation, the ROOT framework was utilized to generate a 1D histogram for the obtained Impact Parameters. The histogram resulting from our analysis, alongside the reference histogram from the original paper, is presented below.
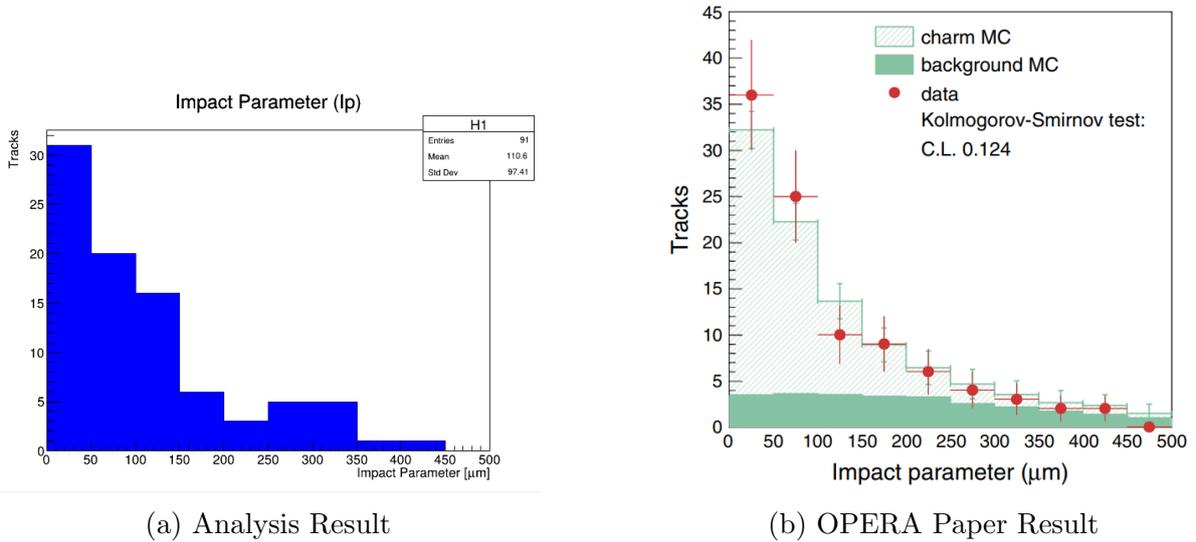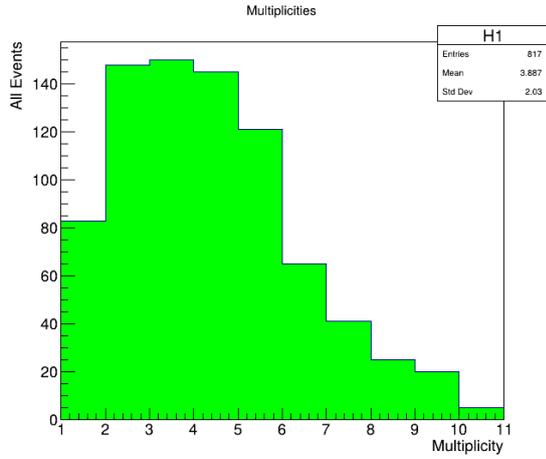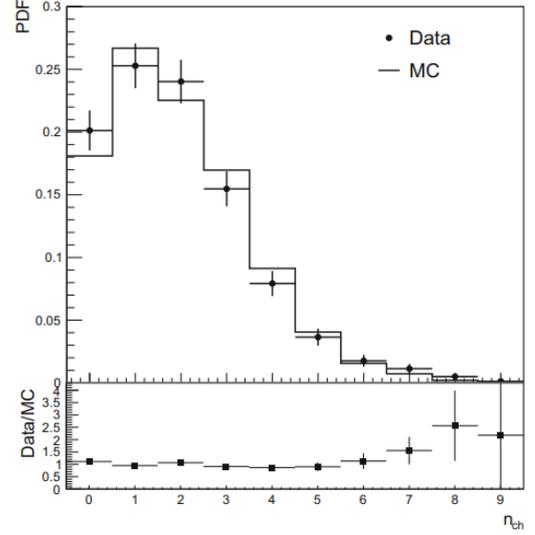

(a) Analysis Result

(b) OPERA Paper Result

Figure 2: Comparison of the Impact Lenght Histogram. (a) The histogram obtained from my analysis using ROOT. (b) The reference histogram from the OPERA paper.

3.2 Charged Hadron Multiplicity and Muon Track Angle Distribution: A C++ program was developed to analyze the OPERA emulsion dataset for charged hadron multiplicity studies. The analysis involved reconstructing primary vertices, calculating muon angles, and comparing the generated histograms with the corresponding OPERA publication.

(a) Analysis Result   (b) OPERA Paper Result

Figure 3: Muon Multiplicity Analysis. (a) The histogram obtained from my analysis using ROOT. (b) The reference histogram from the OPERA paper.

To reconstruct the geometry of the events, determining the directionality of the muon tracks was essential. The spatial angle (θ) of each muon track was derived from its slope (m) using the following trigonometric relation:

$$\theta = \tan^{-1}(x) \tag{2}$$

In this analysis, x represents the slope of the track relative to the Z-axis. The tangent values in both the XZ and YZ projections were extracted for each event using Python algorithms. These slope values were subsequently utilized to calculate the respective spatial angles.

Muon candidates were specifically isolated by filtering for tracks with the identifier `trType = 1`. For every identified muon track, the calculated angle was populated into a 2D ROOT histogram to visualize the angular distribution. This approach allowed for an exact reconstruction of the track geometry in three-dimensional space. The resulting 2D histogram and its corresponding 1D projection are presented below.

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(a) 2D Histogram of Track Angles
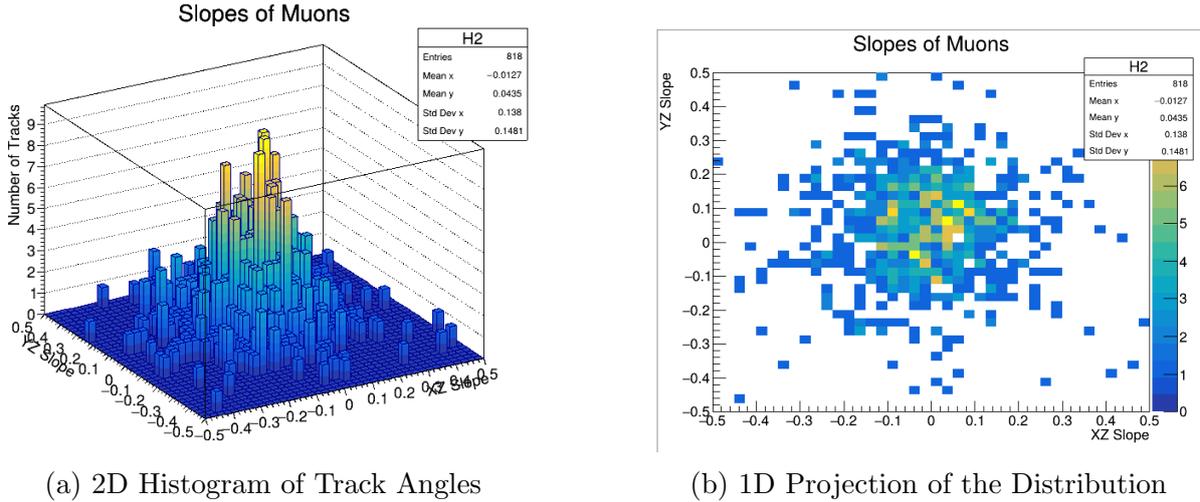

(b) 1D Projection of the Distribution

Figure 4: Muon Track Angle Analysis. (a) The 2D histogram showing the angular distribution of muon tracks. (b) The 1D projection of the angular data.

During the compilation of the angular distribution data, a discrepancy was observed between the total number of interaction events and the number of reconstructed muon tracks. While the dataset contained 817 distinct interaction vertices (multiplicities), the analysis yielded 818 muon tracks.

To investigate this anomaly, a specific algorithm was developed to scan the dataset for events containing multiple tracks identified as muons (trType = 1). This validation process revealed that the event file $11093039862-Tracks.csv$ contained two distinct muon tracks. This observation confirms the presence of a **dimuon event** within the dataset, where a single neutrino interaction produced two muon candidates, thereby accounting for the extra track in the total count.

3.3 Interactive Visualisation:

Interactive Visualization of Tau Neutrino Events To comprehend the complex topologies and distinct shapes of the tau neutrino events recorded in the emulsion data, a web-based 3D visualizer was developed. The **THREE.js** graphics library was utilized extensively to render the interaction geometries in a browser environment.

The visualization relied on parsing data from two primary files:

- `EventID_Vertex.csv`: Contained the precise coordinates of interaction vertices.

- `EventID_Lines.csv`: Provided two points along each particle's trajectory to define the tracks.

The objective was to recover missing segments of the provided source code to correctly interpret these coordinates and render the 10 candidate tau neutrino events. The primary challenge in drawing vertices was mapping the physical coordinates to the screen space relative to the primary interaction vertex. To achieve this, the screen position was calculated by taking the plotted position of the main starting point and adding the relative difference (offset) between the target vertex and the main vertex. This calculation was performed independently for the x, y, and z coordinates to ensure accurate placement on the 3D canvas. Similarly, to render the particle tracks, the trajectory data was

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normalized with respect to the main starting point. For every track, the two defining points extracted from the dataset were adjusted using the same offset logic applied to the vertices. By determining these 3D start and end points, `THREE.Line` objects were created to plot the full particle traces.

Representative visualizations of the reconstructed events are presented below.

(a) Reconstruction of Tau Candidate Event 11113019758

(b) Reconstruction of Tau Candidate Event 10123059807

Figure 5: Interactive 3D visualization of neutrino interactions using THREE.js. The lines represent particle tracks, and the spheres indicate interaction vertices. Red represents parent tau track, Cyan represents tau lepton daughter track, Green represents hadron tracks, Yellow represents Hadron track or EM shower segments (e+/e-), White and White Tones represents hadron track, Magenta represents Hadron track or EM shower segments (e+/e-)

4   Results and Conclusion

In this project, a comprehensive analysis of neutrino event topologies from the OPERA experiment was conducted using open-source data. The study was divided into three main tasks, covering statistical analysis, event reconstruction, and interactive visualization.

The analysis of **Charmed Hadron Production** yielded histograms for Flight Lengths (Decay Lengths) and Impact Parameters that showed a strong correlation with the reference distributions published by the OPERA collaboration. This validates the accuracy of the C++ algorithms developed for vertex reconstruction and Euclidean distance calculations. The ability to reproduce these kinematic variables confirms the reliability of the methods used to process the emulsion data.

In the study of **Charged Hadron Multiplicity**, the angular distribution of muon tracks was successfully mapped. A significant finding in this section was the discrepancy between the total number of interaction vertices (817) and reconstructed muon tracks (818). The subsequent algorithmic scan identified event `11093039862` as a **dimuon event**, verifying the capability of the analysis code to detect rare event topologies where a single neutrino interaction produces two muon candidates.

Finally, the development of an **Interactive 3D Visualizer** using THREE.js provided a crucial qualitative perspective to the quantitative analysis. By parsing raw vertex and track data, the tool successfully rendered the complex geometries of 10 tau neutrino candidate events directly in a web browser. This visualization is essential for understanding the "kink" topologies characteristic of tau lepton decays, which are the signature of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

The objectives of the INTEREST program project were successfully met. The work demonstrated that high-level physics analysis can be performed on open data using standard tools like ROOT and modern web technologies. This project not only reinforced the theoretical understanding of neutrino oscillations and the Standard Model but also provided practical experience in:

- Data processing of CSV datasets from particle detectors.

- Statistical analysis and histogram generation using the ROOT framework.

- Computational geometry for track reconstruction.

- Web-based graphical rendering for scientific visualization.

The combination of statistical validation and visual reconstruction offers a robust methodology for studying neutrino interactions, providing a solid foundation for future research in high-energy physics.

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