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FINAL REPORT
ON THE INTEREST PROGRAMME

Analysis and interactive visualization of neutrino event topologies registered in the OPERA experiment

Supervisor:
Dr. Sergey Dmitrievsky

Student:
Cecilia Romero Rodríguez, Cuba
Higher Institute of Technologies and Applied Sciences (InSTEC)

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Abstract

The Standard Model of particle physics initially predicts that neutrinos have no mass. However, it has been experimentally demonstrated that neutrinos spontaneously change flavor, which implies that neutrinos do have mass. It is therefore believed that these particles may be a gateway to a more general physical theory.

The long baseline neutrino experiment OPERA (Oscillation Project with Emulsion tRacking Apparatus) aimed to provide the first direct proof of tau neutrino appearance in a pure muon neutrino beam (CERN Neutrinos to Gran Sasso beam), which is part of the phenomenon that goes beyond the Standard Model. In this project, the neutrino event topologies registered in the OPERA experiment will be analyzed and visualized.

Introduction

Main Problem

The Standard Model of Particle Physics, the theory describing fundamental particles and their interactions, originally predicts that neutrinos are massless. However, the phenomenon of neutrino oscillations - where a neutrino spontaneously changes flavor (e.g., from muonic to tauonic) during propagation - experimentally demonstrated, directly implies that neutrinos do possess mass. This fundamental discrepancy between theory and experimental observation indicates that the Standard Model is incomplete, pointing to the need for a more complete physical theory.

Background

The OPERA experiment (Oscillation Project with Emulsion tRacking Apparatus) was specifically designed to provide direct and conclusive proof of neutrino oscillations in the appearance mode. Using a pure beam of muon neutrinos generated at CERN and directed towards the underground Gran Sasso laboratory (Italy), 730 km away, OPERA sought to detect the appearance of tau neutrinos, a direct consequence of oscillation. Its hybrid detector, unique of its kind, combined a massive target mass ($\sim$1.2 kt) of nuclear emulsions and lead plates - capable of providing micrometric resolution - with electronic detectors. This configuration allowed not only for the unambiguous identification of the ten tau neutrino candidates that confirmed its main discovery but also for detailed studies of the interactions of all neutrino flavors.

Findings

OPERA successfully achieved the first direct observation of the transformation of muon neutrinos into tau neutrinos, confirming the oscillation phenomenon in the appearance mode. Furthermore, throughout its operation, it generated a rich and precise dataset on neutrino interaction topologies. The publication of this data on the CERN Open Data Portal has democratized access to this invaluable resource, allowing the global scientific community to validate, analyze, and learn from these pioneering results.

Project Goals

The main objective of this project is to use the public data from the OPERA experiment to reproduce and validate some of its key results, while simultaneously developing skills in high-energy physics data analysis and scientific visualization. The specific goals are:

1. **Charmed Hadron Analysis:** To study the production of charmed hadrons in neutrino interactions, analyzing flight lengths and impact parameters (IP) to characterize their decays.

2. **Hadronic Multiplicity Study:** To analyze the multiplicity of charged particles produced in neutrino-lead interactions, as well as the angular distribution of the resulting muons, to understand the dynamics of these collisions.

3. **Tau Neutrino Candidate Event Visualization:** To develop and implement an interactive 3D event viewer within a web browser, capable of representing the interesting topologies of the tau neutrino candidate events discovered by OPERA.

Scope of Work and Methods

The work carried out in this project has been delimited to the following specific tasks, aligned with the objectives:

Task 1: Charmed Hadron Analysis

- Download the OPERA emulsion dataset for the study of charmed hadron production.
- Develop a C++ program to read the CSV files, extracting the positions of the primary and secondary interaction vertices and the parameters of the daughter particle tracks from the decay.
- Calculate and generate histograms of: a) the flight lengths of the charmed hadrons, and b) the impact parameters of the daughter tracks relative to the primary vertex.
- Save the histograms and qualitatively compare the results with those published in the official OPERA documentation.

Task 2: Charged Hadron Multiplicity Analysis

- Download the OPERA emulsion dataset for the study of hadron multiplicity.
- Develop a C++ program to analyze the neutrino-lead interaction vertices and the parameters of the secondary charged particle tracks.
- Calculate and generate histograms of: a) the multiplicity of all produced charged particles, and b) the angles of the muon tracks.
- Save the histograms and perform a critical comparison with the results published by the OPERA Collaboration.

Task 3: Tau Neutrino Candidate Event Visualization

- Use the OPERA emulsion dataset for the tau neutrino appearance study.
- Work with a provided codebase for a 3D event viewer based on the browser and the THREE.js library.
- Complete the missing parts of the source code to achieve a functional visualization that displays the reconstructed tracks and vertices in the 10 tau neutrino candidate events.
- Ensure that the visualization clearly and intuitively represents the characteristic topology of these rare events.

The OPERA detector

As shown in Fig. 1, the OPERA detector was composed of two identical super-modules (SM). Each of them had a target section composed of 31 target walls filled with the lead/emulsion bricks alternated with walls of scintillator strips that constitute the electronic target tracker (TT), as we can see in Fig.2.
A brick was made of 57 emulsion films interleaved with 56 lead plates, each 1mm thick (Fig.3). The bricks are housed in a light support structure placed between consecutive TT walls. In total, about 150000 bricks were assembled, amounting to about 9 million emulsion films, corresponding to an area of 110000 m^2, the largest amount of nuclear emulsion films ever produced for a single project.

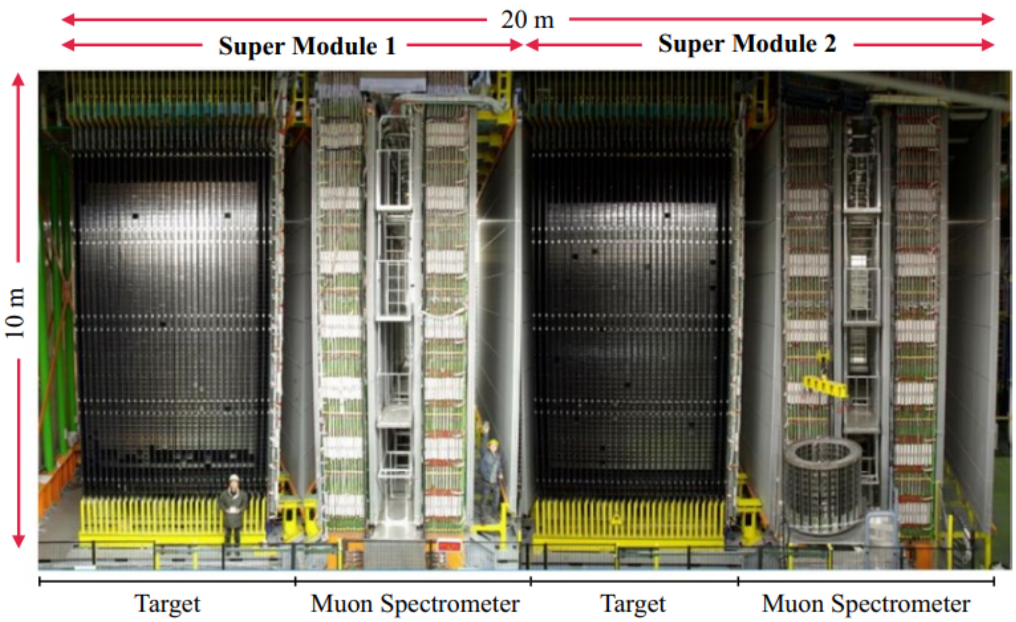

Figure 1: OPERA detector $(20 \times 10 \times 10)\text{m}^3$

In order to reduce the emulsion scanning load, Changeable Sheets (CS) film interfaces was used in OPERA. Charged particles from a neutrino interaction in the brick cross the CS and produce a signal in the TT scintillators. Fig. 2 can help us to understand the process. The corresponding brick is then extracted and the CS developed and analyzed. The information of the CS is then used for a precise prediction of the position of the tracks in the most downstream films of the brick, hence guiding the scan-back vertex finding procedure. To a better understanding of the detector and the physics behind it, see [2], [3].

Results

Task 1: Charmed Hadron Analysis

The dataset used for this task contains 50 muon neutrino charged-current (CC) interactions with a lead target [4], where a charmed hadron was reconstructed. These events are a key back-

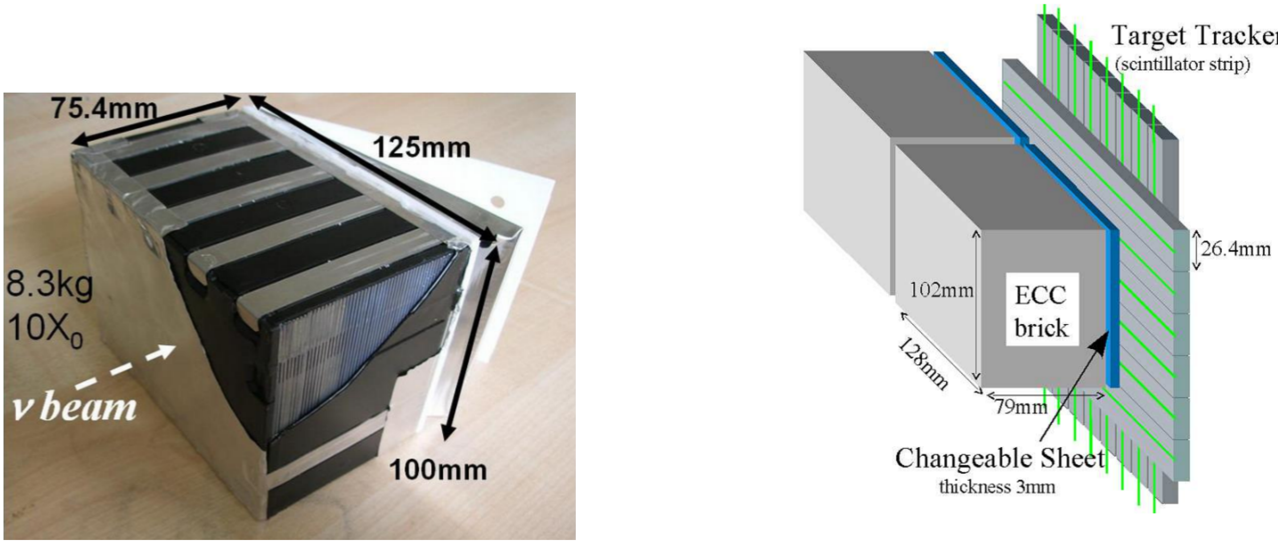

Figure 2: Emulsion Cloud Chamber (ECC) brick (left). The bricks have a transverse size of 12.8× 10.2 cm^2, a thickness of 7.5 cm and a mass of 8.3 kg. We can also see (right) an schematic view of two bricks with their Changeable Sheets and target tracker planes.

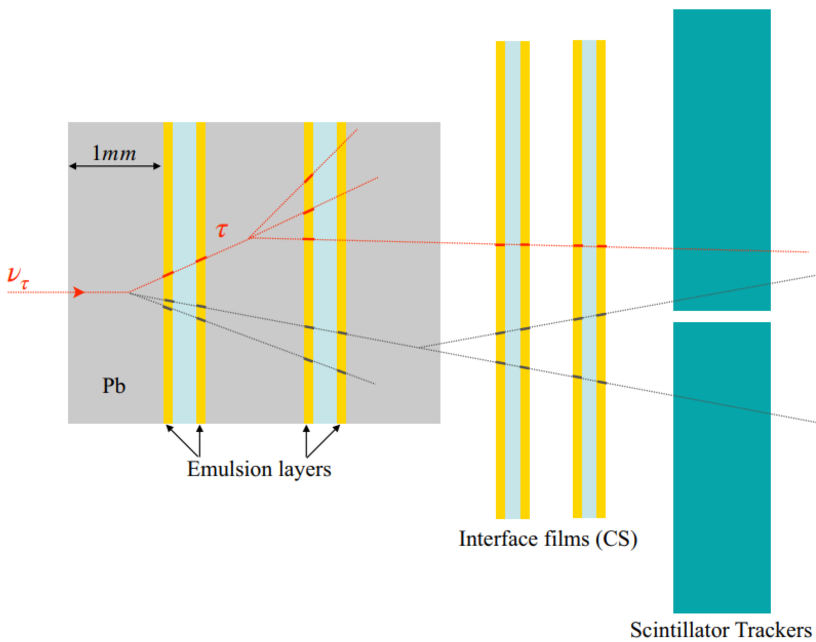

Figure 3: Schematic view of a ν_τ CC interaction and the decay-in-flight of the final state τ lepton as it would appear in an OPERA brick, in the interface emulsion films (Changable Sheets), and in the scintillator trackers (Target Trackers). Each emulsion film consisted in a pair of 44 μm thick nuclear emulsion layers coated on each side of a μm thick plastic base.

ground for tau neutrino detection but also serve as a crucial tool for validating the experiment's ability to identify tau-like decay topologies.
The analysis searched for secondary decay vertices. The observed number of charm candidates (50) was consistent with expectations, and the agreement between data and simulation validated

the detector performance and the analysis chain for tau neutrino appearance. The data record provides information on:

- The primary neutrino interaction vertex.
- The secondary vertex from the charmed hadron decay.
- All emulsion tracks produced at both vertices.

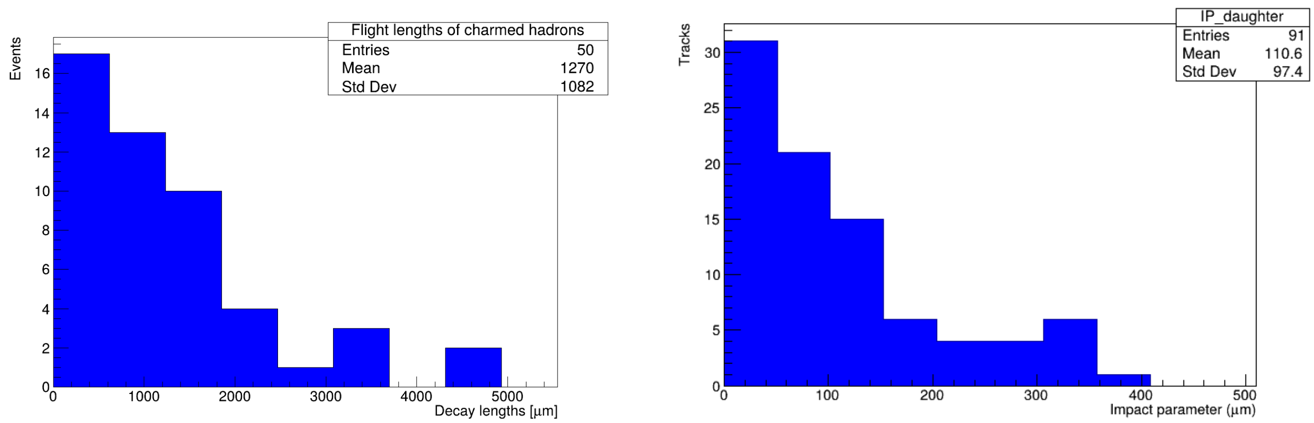

Figure 4: The charmed hadron flight lenghts (left), and the impact parameter of the daughter particle tracks with respect to the primary neutrino interaction vertices (right).

When comparing to [1], we can see that the histograms are not exactly the same, but emulsion scanning and analysis in OPERA was made in several different laboratories around the world, Europe or Japan, for example. Sometimes the results of decay lengths and IP measurements provided in the OPERA datasets were obtained in different laboratory (not the one where the measurements of vertices and tracks were taken from). So, some small disagreement could exist. Anyways, the results are very similar.

Task 2:

This dataset details 817 muon neutrino charged-current interactions with a lead target [5], where a muon was detected. The core of the study is the analysis of hadron multiplicity to understand how hadronic showers form. It provides complete information on the neutrino interaction vertex and the trajectories of all emitted particles, which is the final step of the event analysis. The recorded tracks include:

- Minimum ionizing tracks from the hadronic shower.
- Heavily ionizing particles from nuclear break-up and evaporation.
- Nuclear fragments moving both forward and backward.

Fig.5 shows the vertex multiplicity for all charged particles, excluding muons. This histogram is also very similar to [6]. In Fig.6 angular distribution of all reconstructed muon tracks is shown.

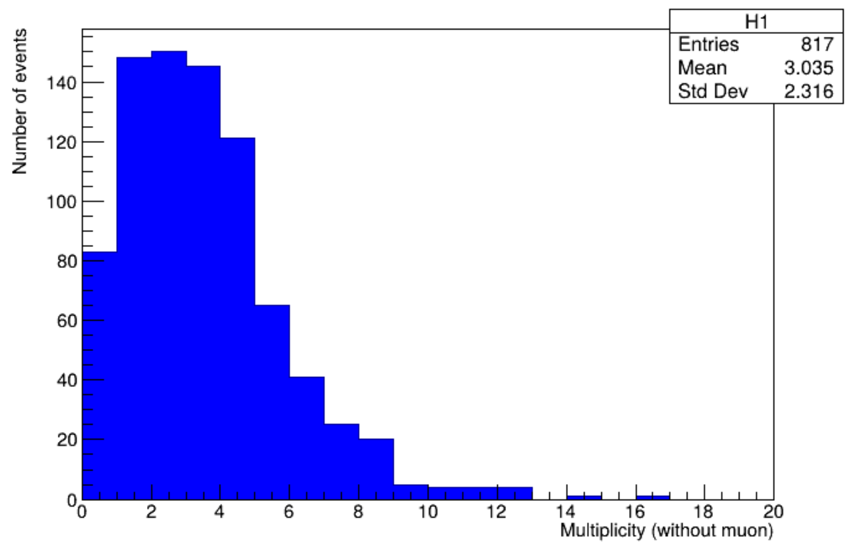

Figure 5: Track multiplicity of all produced charged particles.

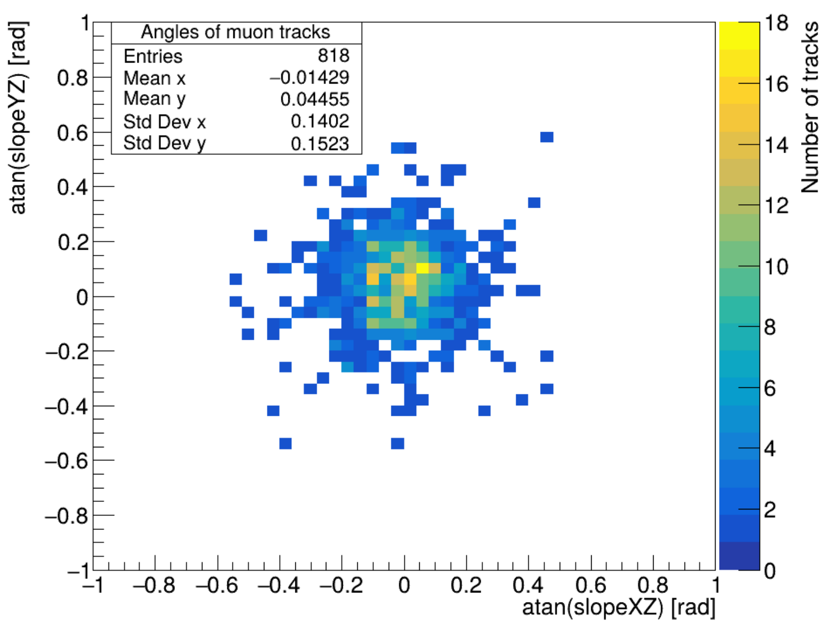

Figure 6: Angular distribution of muon tracks.

There are 818 entries in the histogram, because there was one dimuon event in the analyzed sample. In CC quasi-elastic events direction of produced muon is usually very close to the original direction of muon neutrino. In one particular (not quasi-elastic) event, probably, a hadron was produced togheter with the first muon and then it decayed and the second muon was born. The tilt of the tracks in the YZ view was close to the tilt of the CNGS neutrino beam relative to the horizontal direction of the OPERA detector (approximately 3 degrees), according to the fact that, at Gran Sasso, the beam came from beneath the Earth's surface.

Task3:

The observation of the tau neutrino appearance in a muon neutrino beam was the main goal of the OPERA experiment. This dataset contains all the emulsion data information for the ten tau neutrino candidates [7], identified after an extensive analysis that includes data from both electronic detectors and nuclear emulsion films after their digitization with fully automated optical microscopes. This data record contains in particular the information of the neutrino interaction vertices including all the emulsion tracks produced in the observed interactions and decay. The location of the neutrino interaction and the measurement of the trajectories of all the particles produced is the final step of the event analysis.

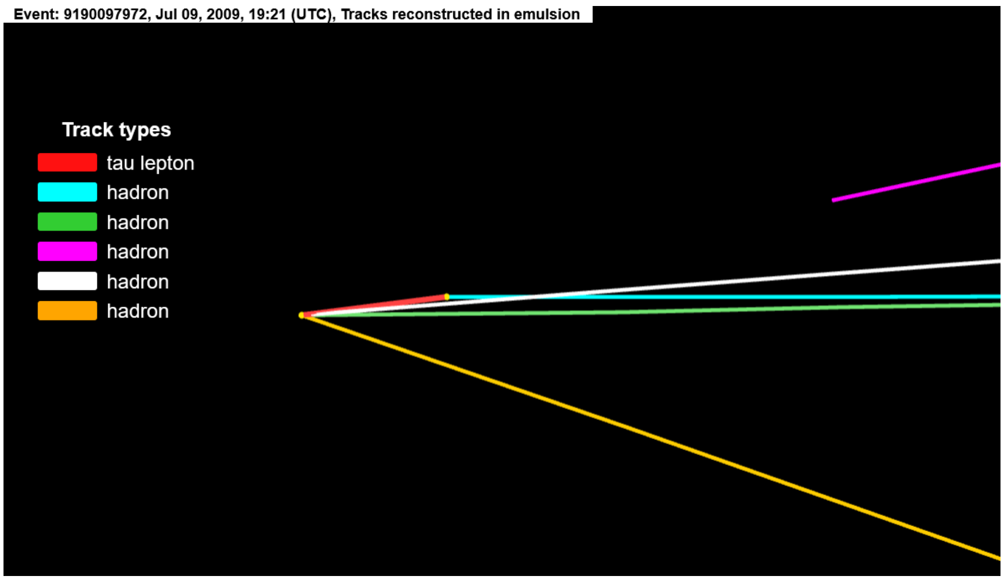

Figure 7: Event display of the neutrino candidate event 9190097972. This one occurred on July 9, 2009 in the first SM.

The analysis of the CS emulsion films in Fig.7 revealed a converging pattern of five tracks. From the analysis of their impact parameters, all tracks could not originate from the same vertex: one of the tracks (highlighted in light blue) must come from a secondary vertex, located 10 μm upstream from the downstream face of the vertex lead plate. In the same way, in the event of Fig.8 At the vertex location seven tracks were found, and the analysis of the CS emulsion films revealed a converging pattern of three tracks. There are 10 examples like this below that will also be commented; for more information, see [3].

In Fig.9, the analysis of the CS emulsion films revealed a converging pattern of four and three tracks respectively. In Fig.10, converging patterns were of 27 tracks for the left one, the most probable interpretation for this event is a ν_τ charged-current interaction with a tau lepton and a charmed hadron decaying respectively into one prong and two prongs. The other one presented a converging pattern of seven tracks, this event was interpreted as a ν_τ charged-current interaction with the tau lepton decaying into a single hadron.

In Fig.11, (left) the analysis of the CS films revealed a converging pattern, at the vertex location three tracks were found; this event was interpreted as a ν_τ charged-current interaction with the tau lepton decaying into three hadrons. In the right event display, a converging pattern of six tracks and two tracks at vertex lacation were found; this event was interpreted as a ν_τ charged-current interaction with the tau lepton decaying into a muon.

Figure 8: Event display of the neutrino candidate event 9234119599, which occurred on August 22, 2009, also in the first SM.

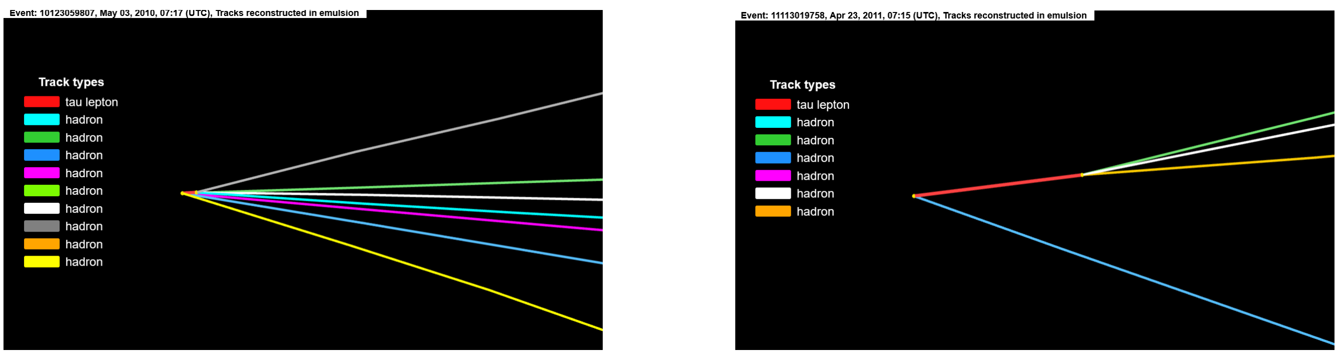

Figure 9: Events displays of the neutrinos candidates 10123059807 (left) and 11113019758 (right), occurred on May 3, 2010, in the second SM and on April 23, 2011, in the first SM, respectively.

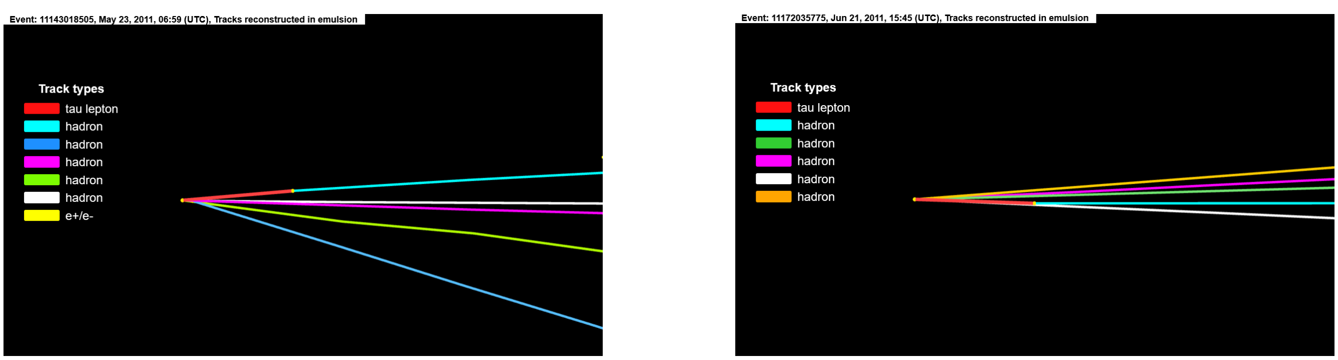

Figure 10: Events displays of the neutrinos candidates 10123059807 (left) and 11113019758 (right), occurred on May 3, 2010, in the second SM and on April 23, 2011, in the first SM, respectively.

In Fig.12, the analysis of the CS films (left) revealed 15 tracks, six of which showed a converging pattern, and at the vertex location two tracks were found. On the other hand, (right) it had a converging pattern of ten tracks; at the vertex location four tracks were found. Both events were

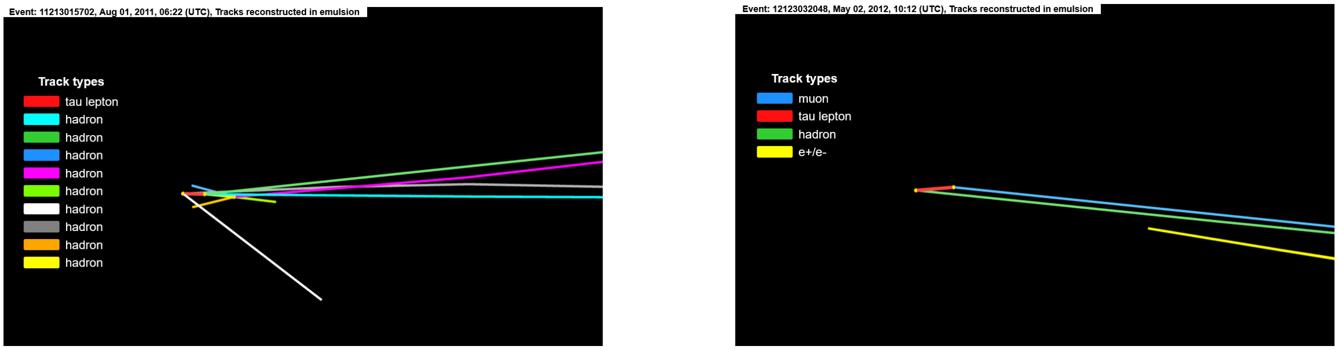

Figure 11: Events displays of the neutrinos candidates 11213015702 (left) and 12123032048 (right), occurred on August 1, 2011 in the second SM and on May 2, 2012 in the first SM, respectively.

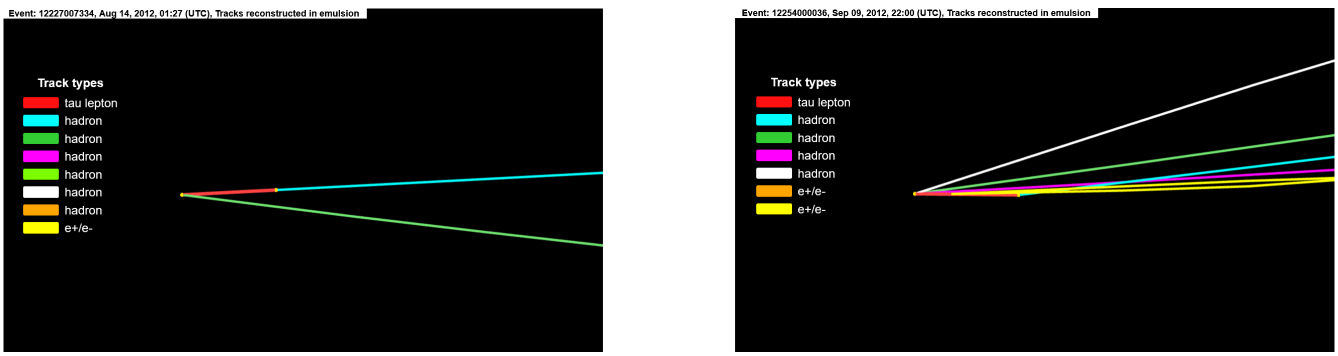

Figure 12: Events displays of the neutrinos candidates 12227007334 (left) and 12254000036 (right), occurred on August 14, 2012 in the second SM and on September 9, 2012 in the second SM, respectively.

interpreted as a ν_τ charged-current interaction with the tau lepton decaying into a single hadron.

Conclusions

All of the presented objectives were successfully accomplished, demonstrating the viability of using public data from high-energy physics experiments for educational and research purposes.

For Task 1, the analysis of charmed hadron production validated the detector's capability to identify secondary decay vertices, with flight length and impact parameter distributions showing good agreement with official OPERA results. The small discrepancies observed can be attributed to the distributed nature of emulsion scanning across multiple international laboratories.

In Task 2, the study of charged hadron multiplicity in neutrino-lead interactions revealed consistent patterns with published data, particularly the characteristic angular distribution of muon tracks aligned with the CNGS beam geometry. The analysis of 817 charged-current interactions provided valuable insights into hadronic shower development and collision dynamics.

The Task 3 visualization of experimental data component successfully achieved its goal of creating an interactive 3D event viewer capable of representing the complex topologies of tau neutrino candidate events in a web browser with help of advanced JavaScript graphics libraries (THREE.js). This visualization tool effectively illustrates the distinctive "kink" topology characteristic of tau neutrino events, where the short-lived tau lepton decays into secondary particles, providing an intuitive understanding of the experimental signatures that confirmed neutrino oscillations.

Collectively, this project not only reproduced key OPERA results but also developed essential skills in particle physics data analysis and scientific visualization. The successful completion of all tasks underscores the importance of open data initiatives in advancing scientific education and demonstrates that neutrino oscillation phenomena can be effectively studied and visualized using publicly available experimental data. The work contributes to bridging the gap between theoretical predictions and experimental observations in neutrino physics, supporting the evidence for physics beyond the Standard Model.

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