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Final Report on

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

(Project #270)

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Abstract

The elusive ghost particles known as neutrinos are a subject of exciting ongoing research prospects that could enhance our understanding of the universe. This project focuses on using the **CERN open data portal** to analyze data from the OPERA experiment, which studied neutrino interactions and properties during their flight from CERN to the INFN underground laboratory in Gran Sasso (LNGS). The unique OPERA hybrid apparatus unambiguously proved muon to tau neutrino oscillations in appearance mode through the direct observation of tau neutrinos in a muon-neutrino beam produced at CERN.

We analyze data samples published on the Portal in CSV format using C++ or Python programs then display the results using the ROOT data analysis framework in various histograms.

We also work on HTML, CSS, and JavaScript code to create a web-application which visualizes 3D neutrino event topologies. This project deepens our understanding of neutrinos and shows how open data platforms can advance scientific studies and researches.

Acknowledgements

I would like to express my deep gratitude to Dr. Sergey Dimitrievsky, who never hesitated to provide help, advice or guidance, for his enthusiasm and unwavering continuous help. It has been an honor to work under his supervision for these last few weeks.

Thanks to the INTEREST team and to JINR for providing aspiring students from all over the world with the chance to learn valuable skills for academia and to be trained under such inspiring and enthusiastic supervisors. It has been an incredible learning opportunity.

Contents

1 Introduction

A neutrino (ν) is a neutrally charged, spin-1/2 fermion (elementary particle) belonging to the lepton group. Leptons are further categorized into three generations or flavors, as shown in Table 1. As seen below, there are three flavors of neutrinos, each associated with its corresponding charged lepton.

Charged Lepton	**Corresponding Neutrino**
Electron (e)	Electron neutrino (ν_e)
Muon (μ)	Muon neutrino (ν_μ)
Tau/Tauon (τ)	Tau neutrino (ν_τ)

Table 1: Charged leptons and their corresponding neutrinos.

Despite being the most abundant particle (with mass) in the universe, forming in the billions within nearly every high-energy object, neutrinos remain one of the most mysterious particles. Their elusive and "ghost-like" behavior is mainly because of their lack of electric charge. They interact only via the weak nuclear force and weakly interacting gravity force, both very weak compared to the electromagnetic force that governs interactions between most other particles that are easier to study. The specific interaction of neutrinos through weak forces makes them incredibly difficult to detect.

Another key characteristic contributing to their elusiveness is their extremely small, but non-zero, mass. The tiny mass of neutrinos contributes to making detection challenging since for interactions to occur, there needs to be some energy transfer between the neutrino and the detector particle. A heavier neutrino would impart more momentum and energy during an interaction, increasing the chance of a detectable signal.

Neutrinos were long thought to be massless, but the discovery of neutrino oscillation in 1998 conclusively demonstrated that they possess a finite mass, however tiny. Understanding the properties of neutrinos, is crucial for a complete picture of the Standard Model of particle physics. Neutrino oscillations themselves hint at physics beyond the Standard Model, as they require neutrinos to have mass, a property not predicted by the initial creation of the Standard Model.

1.1 Neutrino Production and Interaction

Neutrinos are mainly produced in high-energy fusion reactions in astrophysical settings as well as through the leptonic channel decay of a W boson.

The W boson, existing in a positively or negatively charged state ($W^{\pm}$), is the mediator of the weak force. It's inherently unstable, usually lasting for less than a trillionth of a second before decaying. The boson is usually created in high-energy particle collisions like Proton-Proton or Electron-Positron collisions. The W boson has two primary modes of decay, leptonic and hadronic. For our neutrino purposes we will focus on the leptonic channel decay[14].

As seen in Figure 1 When a W boson decays leptonically shortly after its creation, it transforms into a charged lepton (Muon, Electron or Tauon) and its corresponding neutrino flavor

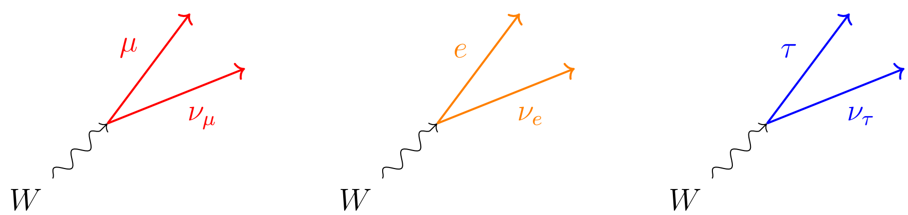


Figure 1: Decay of W boson into a charged lepton and its corresponding neutrino

The main way neutrinos interact with matter and how we -rarely- detect them is through a Charged Current (CC) or a Neutral Current (NC) interaction. CC interactions represent a fundamental process in which the W boson serves as a bridge between the incoming neutrino and the target particle (usually a nucleon within an atom)[12]. After a neutrino of a specific flavor collides with a nucleon it transforms into its corresponding charged lepton along with the exchange of a W boson as seen in figure 2.

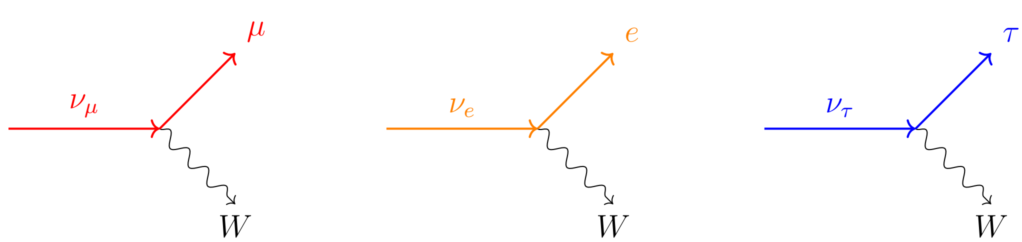


Figure 2: Decay of neutrinos to their respective leptons during a CC interaction

1.2 Neutrino Oscillation

Neutrino oscillation describes the process of neutrinos changing or transforming from one flavor state to another as they travel through space or matter. The phenomenon of neutron oscillation was first proposed by Bruno Pontecorvo in the 1950s[8]. Pontecorvo's idea was initially met with doubt and skepticism. However, as more and more experimental evidence started to accumulate, his idea began to gain credibility and support.

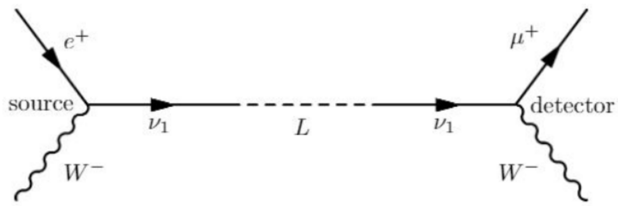


Figure 3: A diagram showing the oscillation of an electron neutrino (ν_e) to a muon neutrino (ν_μ) after travelling a distance L from source.

The concept of neutrino oscillation finally gained enough support with the emergence of the solar neutrino problem. The solar neutrino problem was a subject of many debates between physicists as it found a large dissimilarity between the number of flux of solar neutrinos expected from the sun's brightness and the number of solar neutrinos measured. The leading experiment that first detected the effects of the solar neutrino problem was The Homestake Experiment led by Ray Davis[6] in South Dakota, USA. Davis and Bahcall observed a large deficit in the flux with respect to the prediction of the Standard Model.

Solar neutrinos are mainly created by chains of fusion reactions in the sun. In the so-called p-p chain, the primary reaction (which takes place with frequency 86%) that creates the most solar neutrinos is [7]

$$p \ + \ p \longrightarrow (^2H)^+ \ + \ e^+ \ + \ \nu_\mathrm{e}$$

A similar problem also emerged a couple of decades later in Gifu, Japan after a group of physicists struggled with atmospheric neutrinos detected being less than originally expected. Atmospheric neutrinos are produced after cosmic rays strike the atmosphere and go through a chain of reactions and decays. There was expected to be 2 ν_μ for each ν_e produced but the resulting spectrum was incredibly different than the one originally expected[11]

Neutirno oscillations were finally proven experimentally at the turn of the century. First, by the Super-Kamiokande Collaboration in Japan in 1998 which presented the first conclusive strong evidence of ν oscillation[9], which solved the atmospheric neutrino anomaly. The second compelling evidence came shortly thereafter in 2001 from the Sudbury Neutrino Observatory (SNO) in Ontario, Canada, which finally solved the long standing solar neutrino problem[5].

1.3 OPERA Experiment

The **O**scillation **P**roject with **E**mulsion-t**R**acking **A**pparatus, or **OPERA** for short, was an experiment that was mainly designed to detect $\nu_\mu \rightarrow \nu_\tau$ oscillation during their journey to the detector. The experiment took data for about five years, from 2008 to 2012, but data analysis continued even after the experiment officially ended.

OPERA aimed to study the behaviour of neutrinos travelling from a CERN-based accelerator to a detector deep underground at the Gran Sasso National Laboratory (LNGS) in Gran Sasso, Italy 732 Kilometers away which is a baseline long enough for oscillation to occur[13].

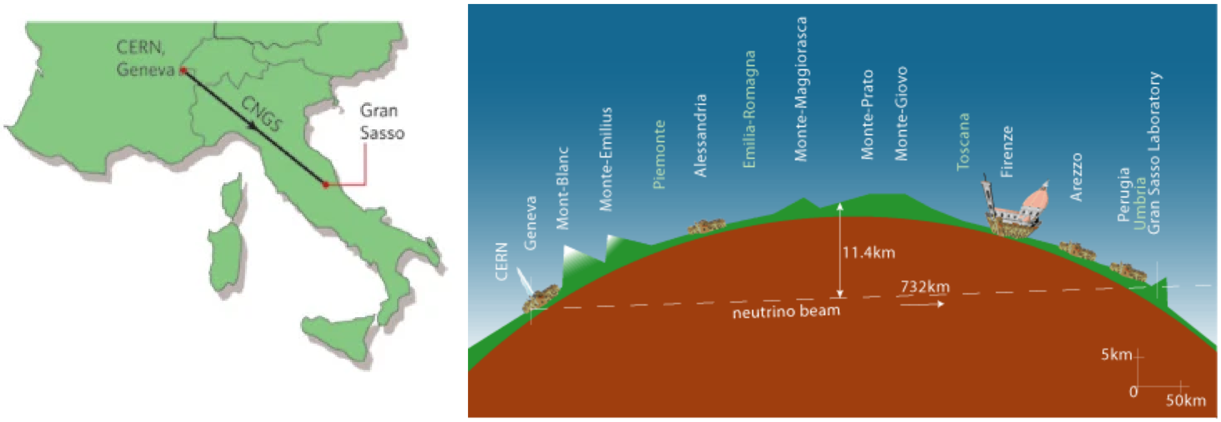


Figure 4: Images showing the positioning of the beam source in Geneva and the detector in Gran Sasso

The neutrino source was the CERN Neutrinos to Gran Sasso (CNGS) beam that mainly emit Muon neutrinos (ν_μ) -as seen in table 2- that were produced by the CERN Super Proton Synchrotron (SPS) accelerator[4] from a 400 GeV/c proton beam. By colliding the protons with a graphite target, pions and kaons were produced that further decayed into muons and muon neutrinos. In total, 1.8×10^{20} protons were directed toward the target. This resulted in the registration of 19×10^3 neutrino interactions by the electronic detectors of the OPERA experiment at Gran Sasso[15].

$\langle E_{\nu_\mu} \rangle$	17 GeV
$\bar{\nu}_\mu / \nu_\mu$	0.02
$(\bar{\nu}_e + \nu_e)/\nu_\mu$	0.01
$(\nu_\tau + \bar{\nu}_\tau)/\nu_\mu$	negligible

Table 2: CNGS beam properties

The OPERA detector was a hybrid instrument that consisted of two identical Super Modules (SM), each made up of a massive target wall (625 tons in mass) paired with a magnetic spectrometer along with electronic detectors. The target wall was constructed

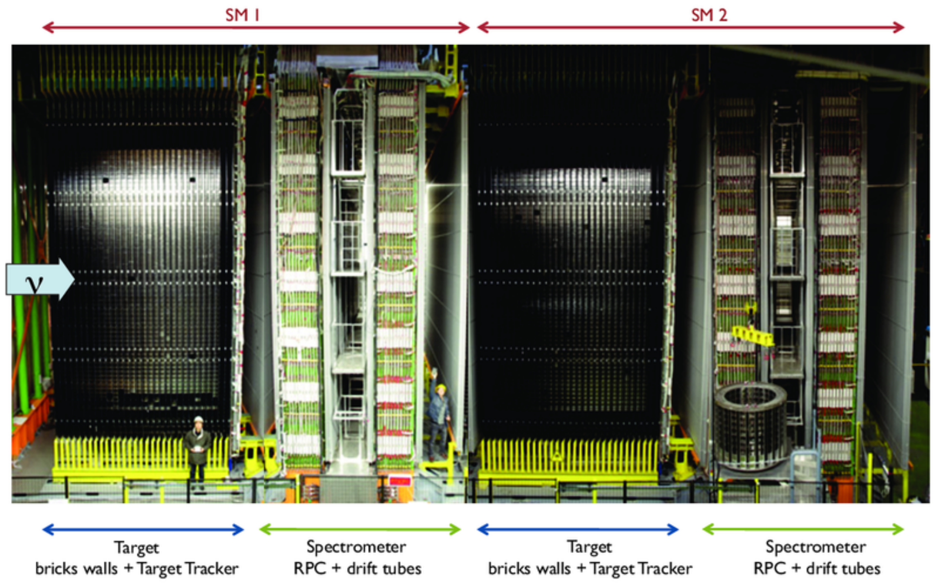


Figure 5: Side view of the OPERA detector showing the two SMs and their paired magnetic spectrometer.

using blocks called Emulsion Cloud Chamber units (ECC), also known as bricks. Each SM contained about 75,000 bricks[10].

Each ECC brick consisted of 57 nuclear emulsion films, which were specially built photographic films capable of detecting the tracks of charged particles in three-dimensions with exceptional detail, with resolution down to a submicron scale. These films were each 300 µm thick and were layerd with 56 lead plates, each 1 mm thick. The cross-section of each brick measured 12.7 cm by 10.2 cm, with a thickness of 7.5 cm, corresponding to approximately 10 radiation lengths. The total mass of each brick was 8.3 kg [10].

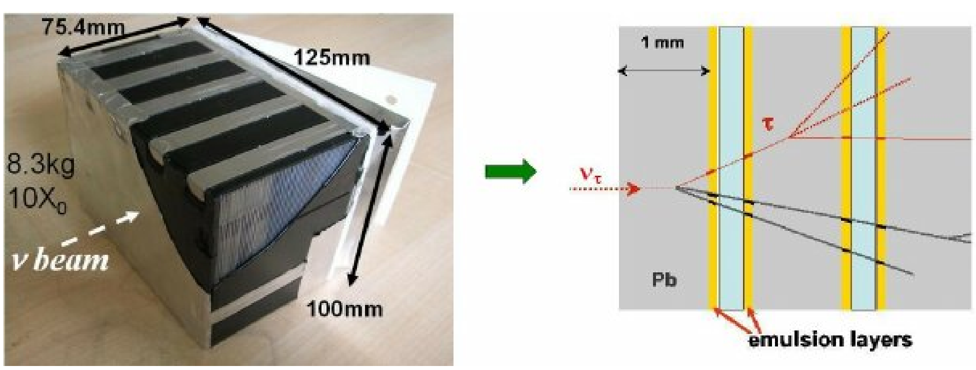


Figure 6: ECC Brick structure (left) and a scheme of the internal structure with a typical ν_τ detection topology (right).[10]

The target has been split into bricks so when an interaction gets recorded, the most probable brick can be selectively taken out from the target wall, then get its films extracted, developed and analyzed soon after the interaction occurrence. The analysis of the events was performed by automated microscopes in laboratories all around the world that were part of the OPERA Collaboration. Half of the events were analyzed in Japan, the other half in Europe.

For accurate event analysis, a very precise film-to-film alignment was needed, which was achieved by exposing a brick to cosmic muons for 24 hours soon after the brick extraction. Then the irradiated brick was disassembled, and its films were shipped for development.To reduce the noise from the cosmic ray tracks recorded by the brick over its lifetime (from assembly to development), the use of Changeable Sheets (CS) was integrated into the detector. The Changeable Sheet (CS) acted as a bridge between the electronic detectors and the ECC bricks, the CS consists of a pair of emulsion films that were assembled in LNGS. While the films used in the CS were identical to those in ECC bricks, many processes were applied to the CS in their assembly to mitigate the effect of background noise. The usage of the CS proved useful as there was a reduction of background cosmic rays affecting the bricks by 100 tracks/cm^2 per film[1].

2 Tasks

2.1 Task 1: Neutrino-Induced Charmed Hadron Production Analysis

In the first task of the project we were assigned with utilizing the **OPERA emulsion dataset for neutrino-induced charmed hadron production studies** from the Open Data Portal. A final state reconstruction of a charmed hadron is obtained from 50 muon neutrino interactions with the primary target in the dataset. The so-called charged-current (CC) interactions of a muon neutrino are where neutrino-induced charm generation occurs.

The detection process of Tau neutrinos (ν_τ) in the OPERA detector presented a unique challenge. While the distinctive signature of ν_τ interaction in the OPERA detector became apparent through the observation of τ lepton decays, characterized by the emergence of one or three prongs, charmed hadrons which share similar masses and lifetimes with the τ lepton, made them a significant background noise source in the detector. However, the final state resulting from charged current interactions of ν_μ with charmed hadrons exhibits a topology resembling that of oscillated ν_τ interactions. Leveraging this similarity, the detector's experimental capabilities underwent rigorous testing, providing a vital tool for background validation.[2]

Our analysis here focused on calculating some topological properties, two of which were the impact parameter (IP) and the decay length (DL) of the interaction.

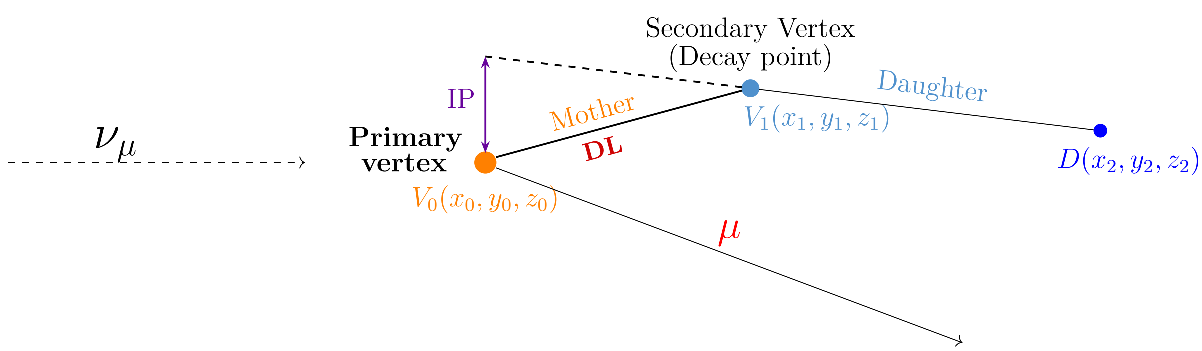


Figure 7: Illustration of ν_μ decay topology. The primary vertex V_0 is where the main ν_μ CC interaction occurs, producing a muon and a charmed particle that has a decay length DL and further decays at the secondary vertex V_1 into a daughter particle ending at a vertex D. IP is the impact parameter defined below.

We can define the decay length as the distance between the primary vertex where the main CC interaction occurs and the secondary vertex as the vertex at which the secondary decay occurs.

The impact parameter of the event is the shortest 3D distance between the primary neutrino vertex and the extension of the daughter decay track line. We can see a visualization of the event topology in the illustration above.

The decay length can be calculated after analyzing the dataset and extracting the primary and secondary vertex points provided in the data using the formula.

$$DL = \sqrt{(x_o - x_I)^2 + (y_o - y_I)^2 + (z_o - z_I)^2} \tag{1}$$

the results are then inserted into the ROOT framework and filled into a histogram (Figure 5) which provided similar results as the paper published about the Aforementioned events[2].

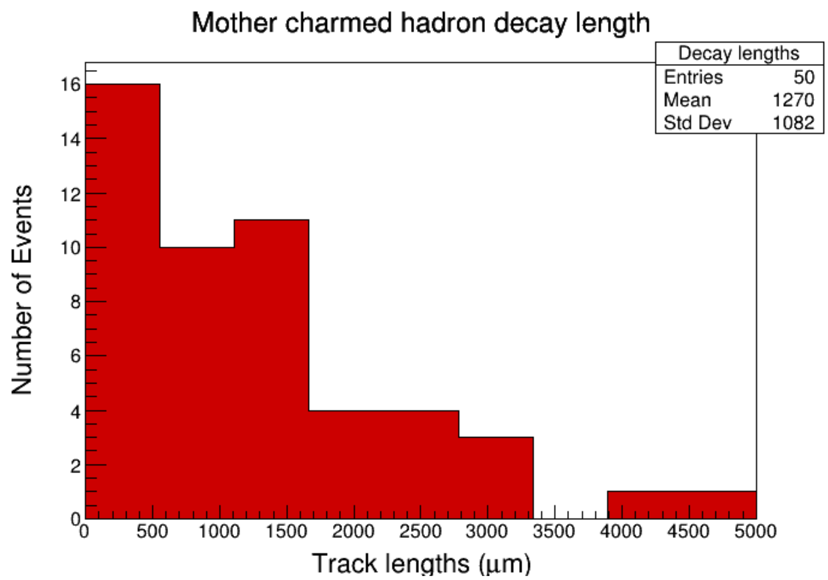


Figure 8

Afterwards, we calculated the IP using the coordinates of the primary vertex (V_0), the secondary vertex (V_1) and a point D on the daughter track line. Using vector analysis, the following formula can be used to calculate the impact parameter.

$$IP = \frac{|(\vec{r}_{\mathrm{V}_0} - \vec{r}_{\mathrm{V}_1}) \times (\vec{r}_{\mathrm{V}_1} - \vec{r}_{\mathrm{D}})|}{|\vec{r}_{\mathrm{V}_1} - \vec{r}_{\mathrm{D}}|} \tag{2}$$

where $\vec{r}_{\mathrm{V}_0}, \vec{r}_{\mathrm{V}_1}, \vec{r}_{\mathrm{D}}$ denote position vectors for V_0, V_1, D respectively.

The analysis resulted in the following histogram, which also was similar to the published results[2]

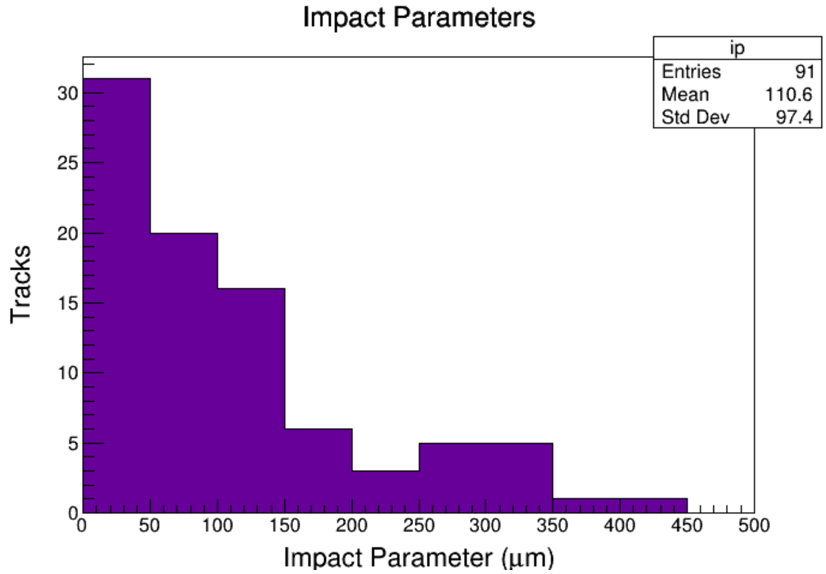


Figure 9

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

In the second task, we focus on studying the **Emulsion dataset for track multiplicity**. We study the track multiplicity distribution of charged hadrons produced in the CC ν_μ interaction events. The data set contains 817 ν_μ CC interactions with the lead target.

We first developed a code to analyze the data and extract the multiplicity distribution of the charged hadrons produced in the interaction events, after filling it in a histogram we can see that it's comparable to the results in the published paper about the events[3].

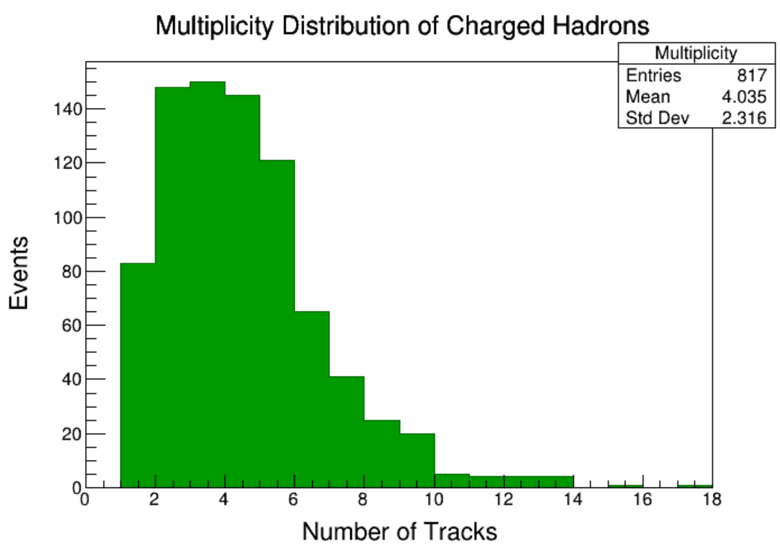


Figure 10

In the second part of the task we developed a program that extracted the slope distribution of the Muon (μ) tracks (trType=1) from the dataset and then calculated the angles of the muon tracks by using the arctan (tan^{-1}) geometrical calculation. Interestingly we noticed in the histogram below that the number of entries is one more than the total number of events. Turns out that is because there's one event with di-muon tracks (di-muon event), further analysis of the dataset showed that the di-muon event number was the event "11093039862".

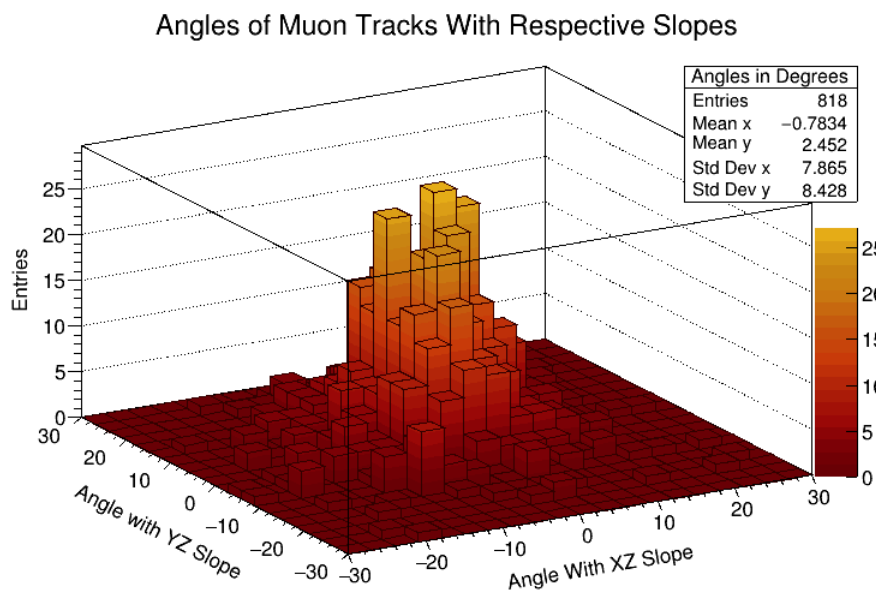


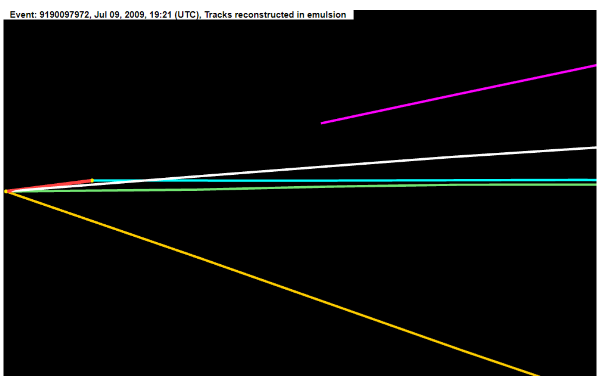
Figure 11

2.3 Task 3: Browser-based Interactive Visualization and display of ν_τ events

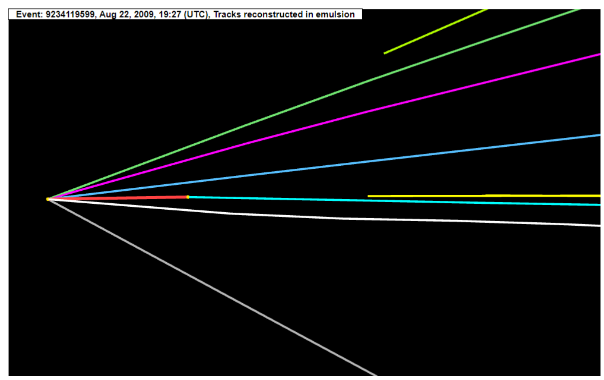
In this task we utilized JavaScript and its **THREE.js** graphics library along with HTML and CSS code to make a basic version of a browser-based 3D interactive visualization of the 10 ν_τ events in the OPERA experiment. We displayed their topologies by completing the provided code in the task to correctly reconstruct the vertices in the OPERA emulsion dataset for the ν_τ candidate events and edit their absolute position to make it relative to the primary vertex.

Figure 12: Each color shown above corresponds to a different type of track detected in the emulsion events

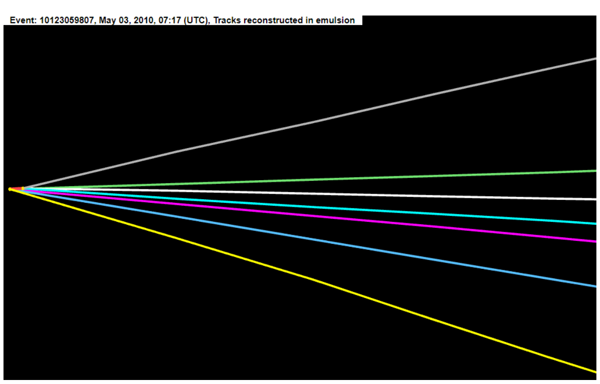
We can see the sideways visualization of all 10 events below



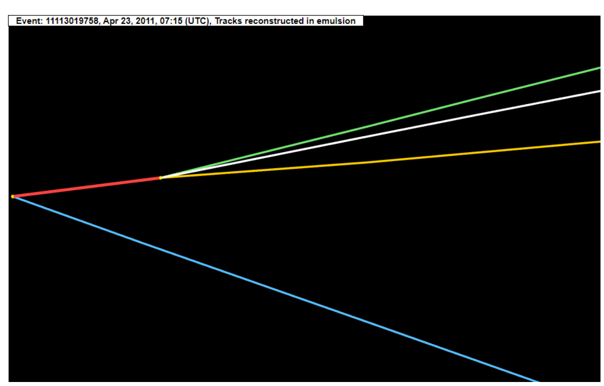
(a) Tracks reconstructed in emulsion for event 9190097972



(b) Tracks reconstructed in emulsion for event 9234119599

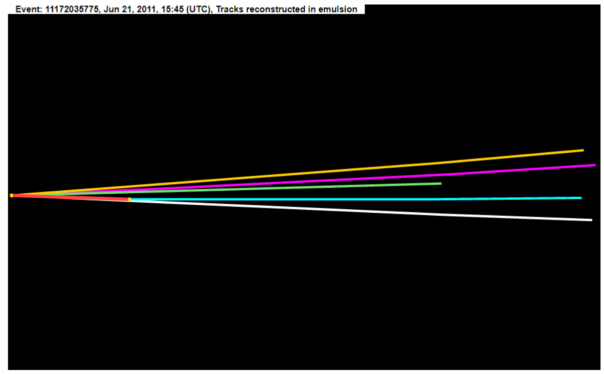


(a) Tracks reconstructed in emulsion for event 10123059807

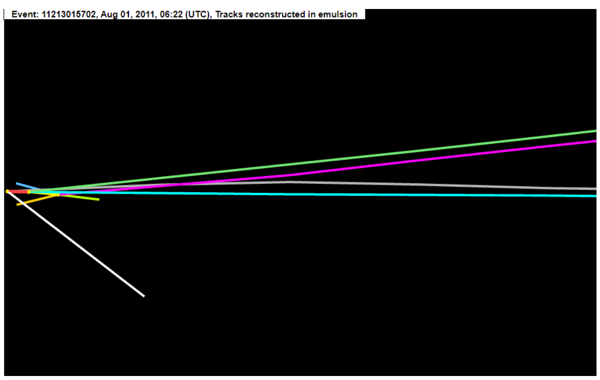


(b) Tracks reconstructed in emulsion for event 11113019758

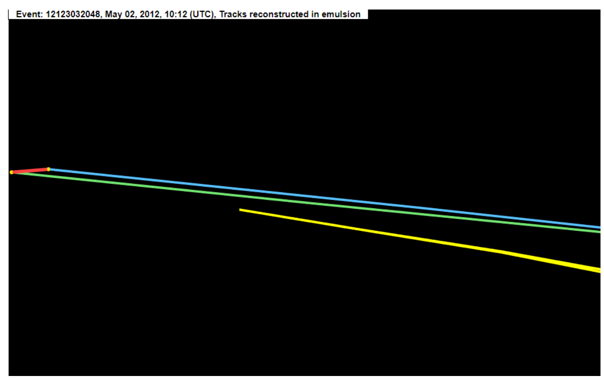
(a) Tracks reconstructed in emulsion for event 11143018505



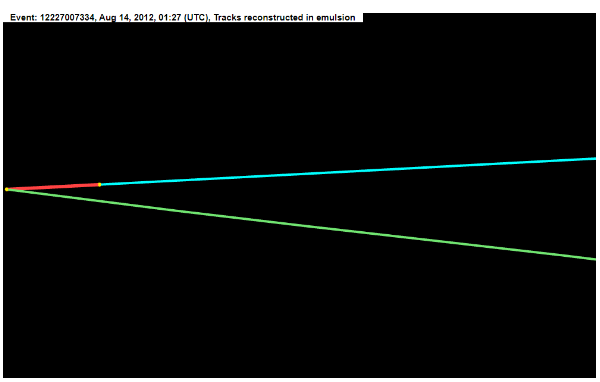
(b) Tracks reconstructed in emulsion for event 11172035775



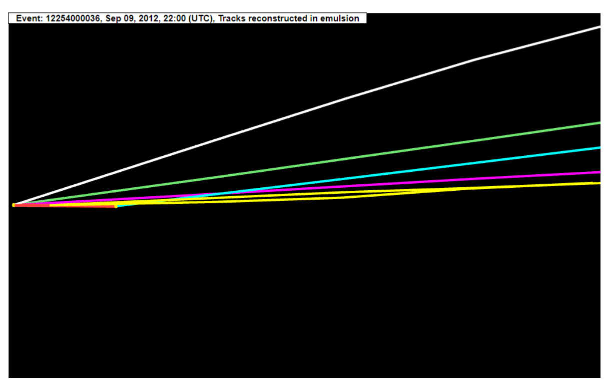
(a) Tracks reconstructed in emulsion for event 11213015702



(b) Tracks reconstructed in emulsion for event 12123032048



(a) Tracks reconstructed in emulsion for event 12227007334



(b) Tracks reconstructed in emulsion for event 12254000036

3 Conclusion

Our Work on this project introduced us to the world of open source data and taught us how to utilize it to get comprehensive scientific results. We also learned about the incredible phenomenon of neutrino oscillation through the experimental data obtained from OPERA on the CERN open data portal.

We gained a lot of practical experience using C++ and Python to extract and analyze data, we learned how to use ROOT to produce useful histograms and learned about its numerous features. By putting that knowledge into practice we produced results that are in good agreement with the results published by the OPERA collaboration team[2, 3]. Our participation in the project also introduced us to JavaScript and its graphic libraries, HTML and CSS which allowed us to create interactive 3D visualizations of ν_τ events detected by OPERA over the years of its operation. Further independent learning into the subjects we already got introduced to would allow us to integrate the skills we learned into our studies, research and future careers.

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