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Analysis and Interactive Visualization of Neutrino Event Topologies Registered in the OPERA Experiment

Final Report

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Abstract

The OPERA (Oscillation Project with Emulsion-tRacking Apparatus) experiment was conducted at the Gran Sasso National Laboratory in Italy. It was designed to demonstrate the oscillation of muon neutrino into tau neutrino using nuclear emulsion technique. The experiment observed 10 tau neutrino candidate events, confirming the transmission of muon neutrino into tau neutrino during their flight from CERN to Gran Sasso.

The transmission of muon neutrino into tau neutrino as seen during the experiment is due to the phenomena of neutrino oscillation which describes the change of flavour of the neutrino as it moves through space. We made use of the C++ and ROOT libraries to analyse experimental data gathered from the CERN Open Data Portal. For visualization of tau neutrino event, JavaScript, HTML and C++ were used.

Chapter 1:

Theoretical Background

The Standard Model outlines the classification of particles into fermions and bosons, with fermions further categorized into quarks and leptons. Neutrinos, belonging to the lepton category and denoted as νe, νμ, and ντ, are challenging to detect as they do not interact with matter at all due to their electric neutrality and interactions limited to weak nuclear forces and gravity. The concept of neutrino oscillation, indicating flavour changes during movement, emerged through experiments challenging the Standard Model's assumption of zero neutrino mass.

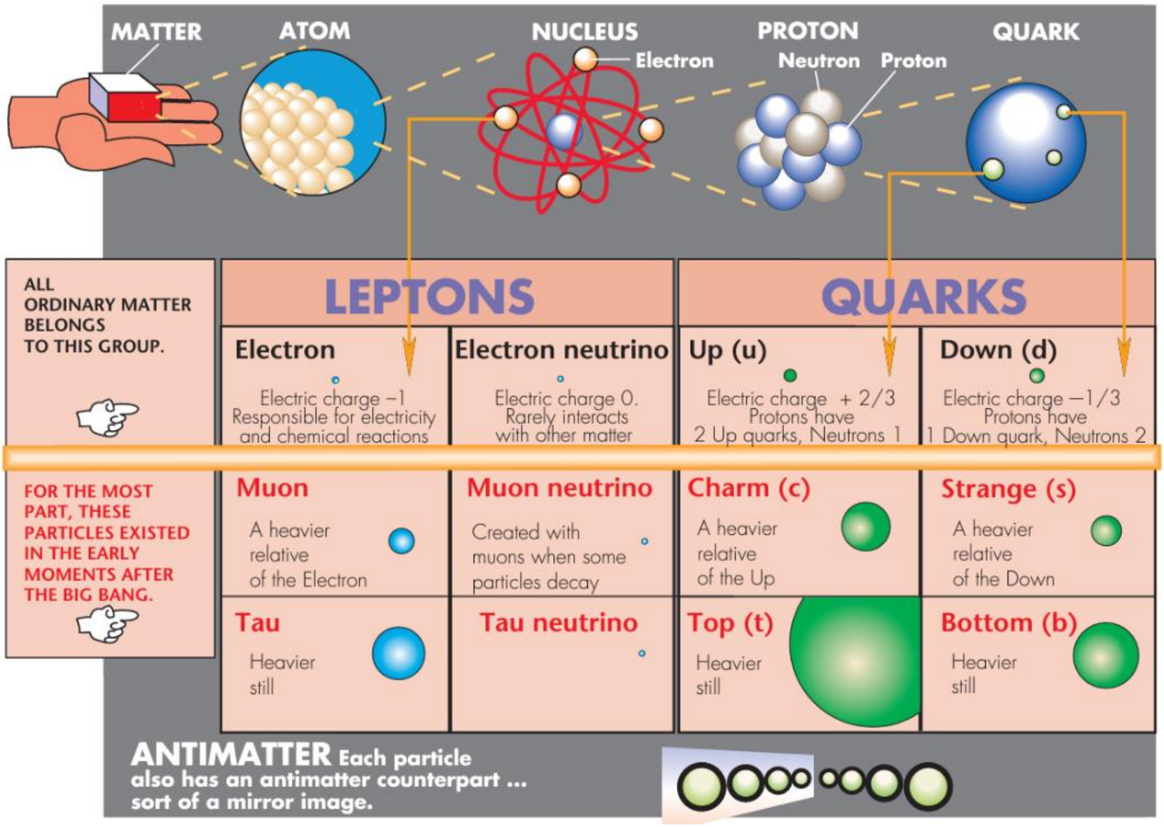


Figure 1 – The Standard Model [1]

Neutrinos are the second most abundant known elementary particles in the universe. The first idea (of neutrino-antineutrino oscillations) was considered by

B. Pontecorvo in 1957. Neutrino flavour mixing and flavour oscillations were introduced at the beginning of the ‘60 by Z. Maki, M. Nakagawa, and S. Sakata.

Specialized detectors have revealed the quantum phenomenon of neutrino oscillation, where flavour probability oscillates as neutrinos traverse space. The three known flavours of (nu_e, nu_mu, and nu_tau) are defined by W boson decays. There are three flavours of charged leptons: e(electron), m(muon), and t(tau lepton). When a neutrino of given flavour interacts and turns into a charged lepton, that charged lepton will always be of the same flavour as the neutrino as the week interaction couples the neutrino of a given flavour only to the charged lepton of the same flavour.

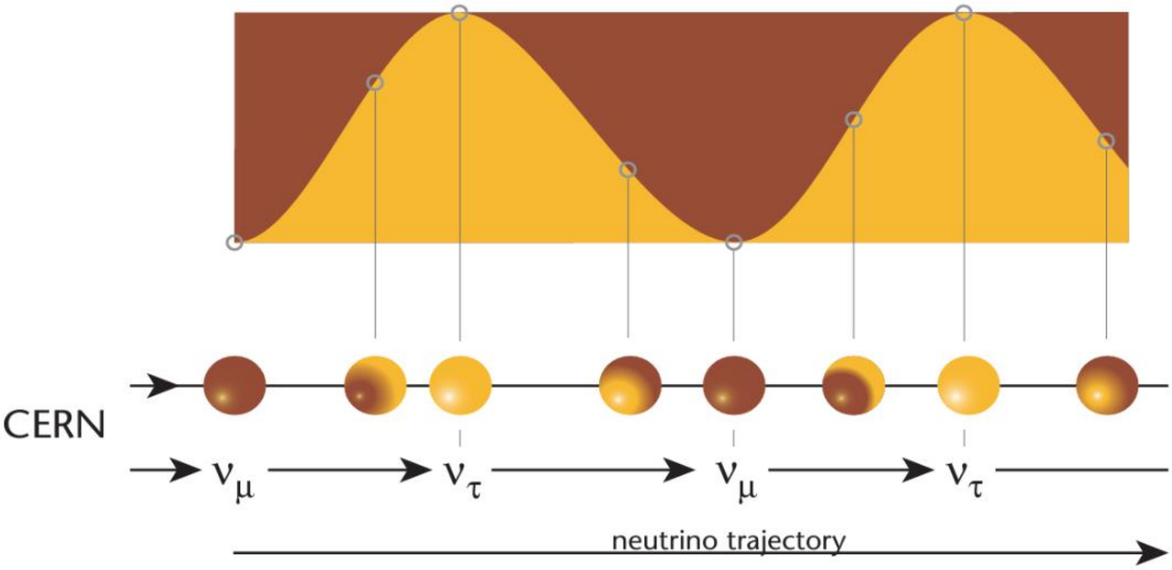


Figure 2 - νμ, and ντ oscillations (a pure ντ beam produced at CERN directed towards Gran Sasso) [1]

Late 1990s experiments confirmed oscillations, challenging the previously held belief in zero neutrino mass and prompting ongoing research into the underlying mechanisms governing these flavour changes. The study distinguishes neutrino flavours based on interactions with charged leptons, contributing to our evolving comprehension of the universe.

Chapter 2:

OPERA Experiment

The OPERA experiment was conducted in collaboration between the European Organization for Nuclear Research (CERN) in Switzerland and the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, explored the intricate process where a neutrino transitions between different Flavors during its journey through space.

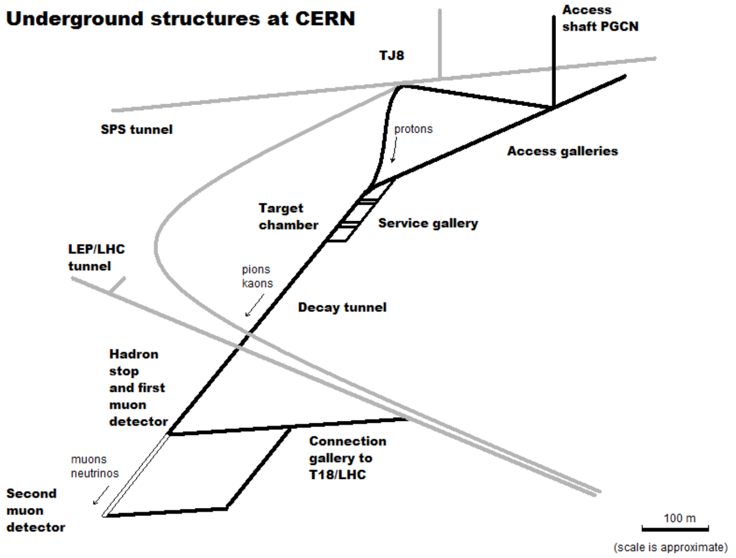


Figure 3 – CERN Neutrinos to Gran Sasso Underground Structures [2]

The experimental setup involved generating a beam of muon neutrinos at CERN in Geneva, directed towards the OPERA detector [3] situated at LNGS in Italy. The CERN Neutrinos to Gran Sasso (CNGS) neutrino beam, characterized by high intensity (2.4 x 10^{13} protons on target per pulse) and energy (400GeV), was produced in the Super Proton Synchrotron through the collision of accelerated protons with a graphite target. $\nu\mu$ neutrinos are produced as a decay product of the collision of two protons. Produced secondary particles, particularly pions and kaons, were precisely focused in the desired direction, subsequently decaying into muons. These particles maintained their trajectory towards the OPERA detector located 730 kilometres away in the Gran Sasso Underground Laboratory.

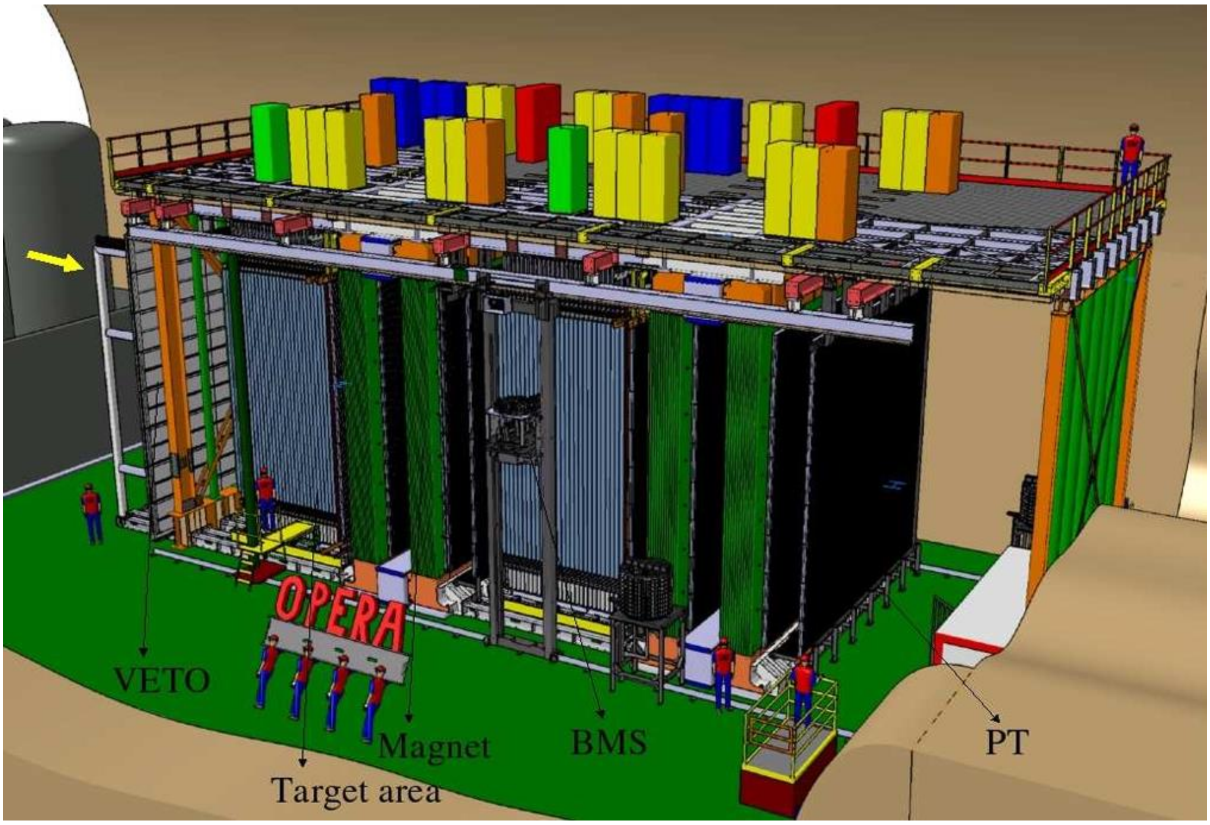


Figure 4 – Artistic view of the OPERA detector [3] yellow arrow indicates the direction of the incoming CNGS neutrino beam.

The experimental setup included magnetic spectrometers, plastic scintillator strips, and arrays of target bricks with a total mass of 1.2 ktons, arranged in the form of walls. Each target brick composed of 57 emulsion films interleaved with 56 lead plates, each 1 mm thick.

Chapter 3:

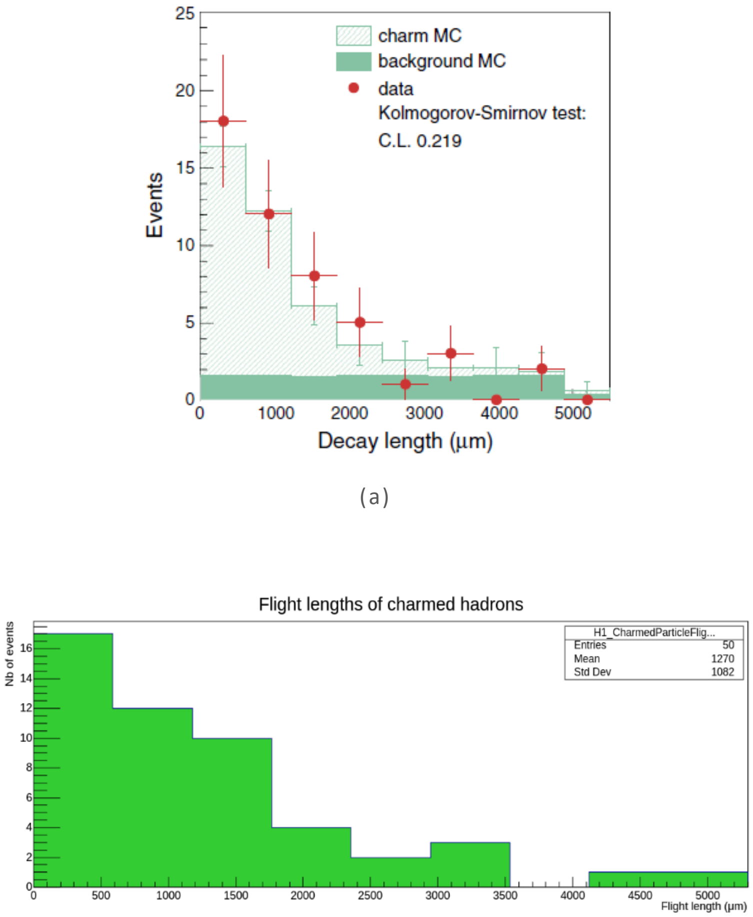
Task 1 – Neutrino Induced Charmed Hadron production studies

Task 1 focused on emulsion data related to studies of neutrino-induced charmed hadron production. These studies aimed to confirm the ability to detect vt by investigating the production of charmed hadrons from nµ interactions. Due to the comparable characteristics (mass and lifetime) of tau leptons and charmed hadrons, the latter were identified as a potential source of background in the OPERA experiment.

3.1 Flight length

The term "flight length" is defined as the distance between production and decay points of a particle in 3d space. In the context of charmed hadron decay, it specifically signifies the distance between the primary neutrino interaction vertex and a secondary interaction vertex where the charmed particle undergoes decay into other particles. The dataset utilized for examination originates from the official OPERA data repository, encompassing 50 instances of muon neutrino interactions with the lead target, wherein a charmed hadron is reconstructed in the final state. For a neutrino interaction event with primary vertex coordinates (x1, y1, z1) and secondary vertex coordinates (x2, y2, z2), the calculation of flight length involves determining the spatial separation between these points in 3D space.

$$\textbf{Flight length} = \sqrt{(\mathbf{x}_2 - \mathbf{x}_1)^2 + (\mathbf{y}_2 - \mathbf{y}_1)^2 + (\mathbf{z}_2 - \mathbf{z}_1)^2}$$



(a)

(b)

Figure 4 – Fight lengths of charmed hadrons (a) published [4] (b) calculated

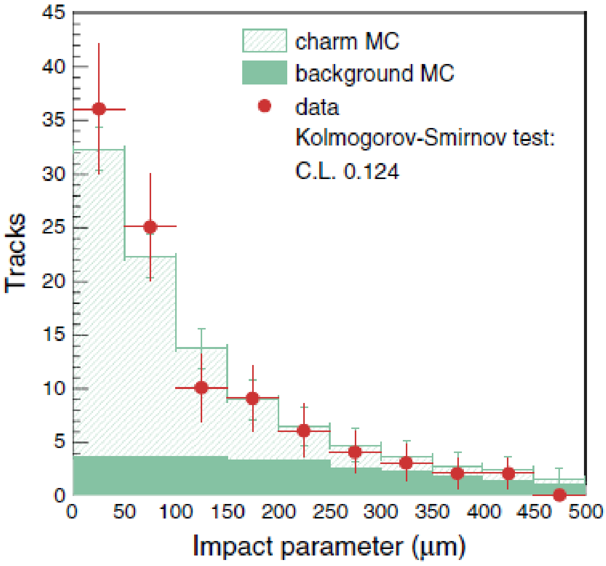
3D positions of primary and secondary vertices are stored on the CERN Open Data Portal in .CSV files named eventIDVertices.csv, where the event ID varies across the 50 observed events in the emulsion dataset related to neutrino-induced charmed hadron production. Local coordinates for these vertices were acquired from a set of .CSV file with help of a C++ program. Flight lengths for each event were then computed using a specified formula and saved into a histogram. The resulting histogram, depicted in Figure 4 (b), is compared with the one published by OPERA (a) [4], with all visualizations generated using ROOT software.

3.2 Impact Parameter

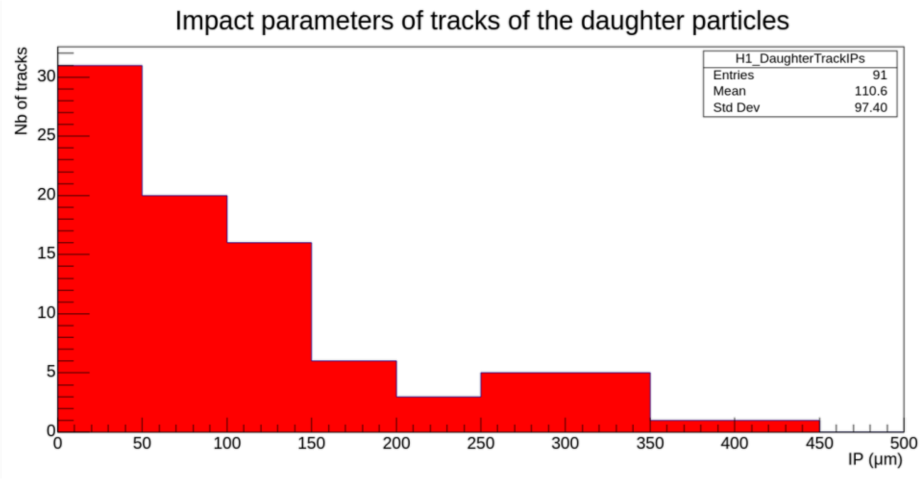
The impact parameter (IP) of a daughter track is the distance between the daughter particle track and the primary neutrino interaction vertex, i.e., the distance between a line and a point in 3D space. This can be calculated from the coordinates of the primary vertex and two points on the track line.

$$IP = \frac{|(\vec{x}_0 - \vec{x}_1) \times (\vec{x}_1 - \vec{x}_2)|}{|(\vec{x}_1 - \vec{x}_2)|}$$

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.



(a)



(b)

Figure 5 – Impact parameters of charmed hadrons (a) published [4] (b) calculated

The obtained Impact Parameter distribution is shown in Figure 5 (b). The histogram was plotted using ROOT libraries. 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.

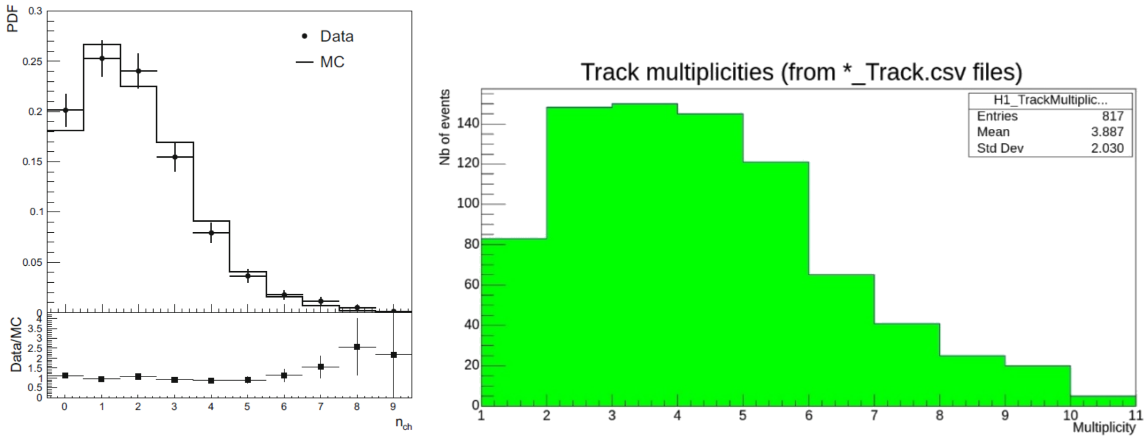
Chapter 4:

Task 2 – Track multiplicity studies in νμ CC interactions

Track multiplicity is defined as the number of tracks attached to a given vertex, like in this case, the primary vertex of the $\nu\mu$ CC interaction. In this task an OPERA emulsion dataset related to the study of charged hadron multiplicity [5] was used, which is available on the Open Data Portal.

4.1 Multiplicities of all produced charged particles

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. 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 6.



(a) (b)

Figure 6 – Track multiplicity distribution (a) published [5] (b) calculated

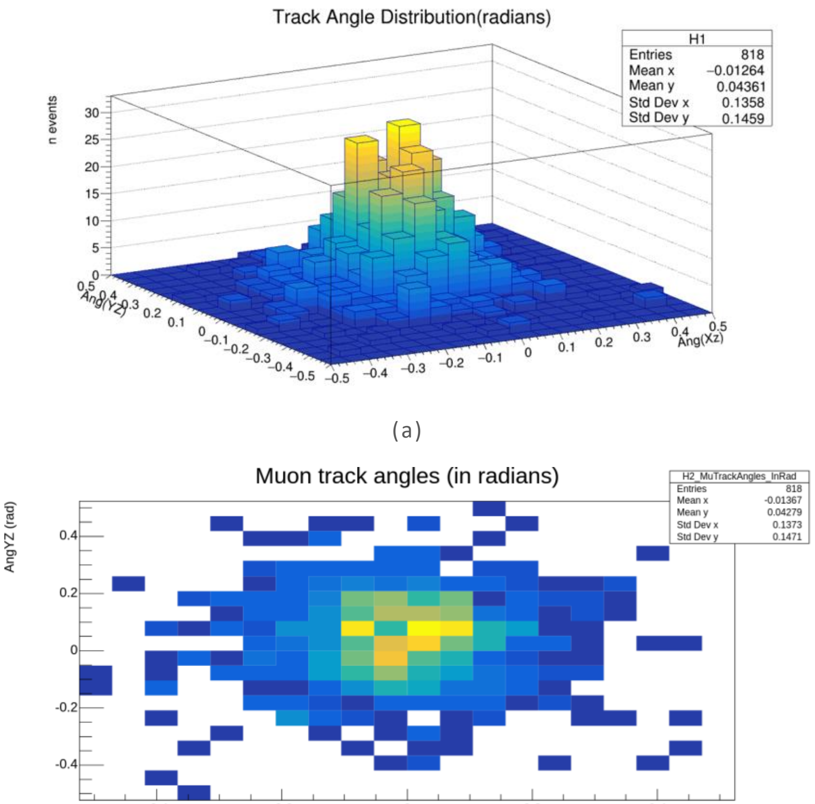
4.2 - The angles of the muon tracks

The angle of the tracks can be calculated using the below mentioned mathematical formula:

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

Where, m = Slope and θ = the angle of the muon track in radians. 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.

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.



(a)

(b)

Figure 7 – Muon track angle (a) 3D distribution (b)2D projection

Chapter 5:

Task 3 - Emulsion Data for Tau Neutrino Appearance Studies

For OPERA emulsion dataset related to tau neutrino appearance study [6], a 3D visualization was created. To visually represent interesting topologies of the found events in a web browser, the THREE.js JavaScript library was used. Figure 9 shows reconstructed Tracks and Vertices for 2 out of the 10 tau neutrino candidate events.

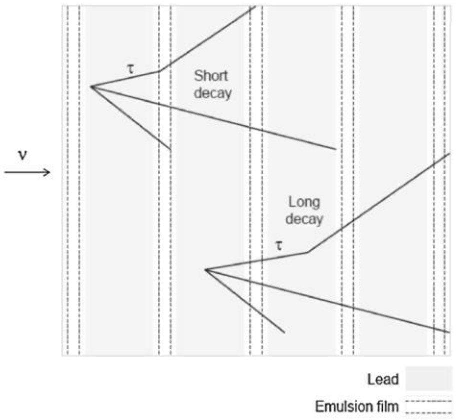


Figure 8 - Sketch of short and long τ decay topologies [2]

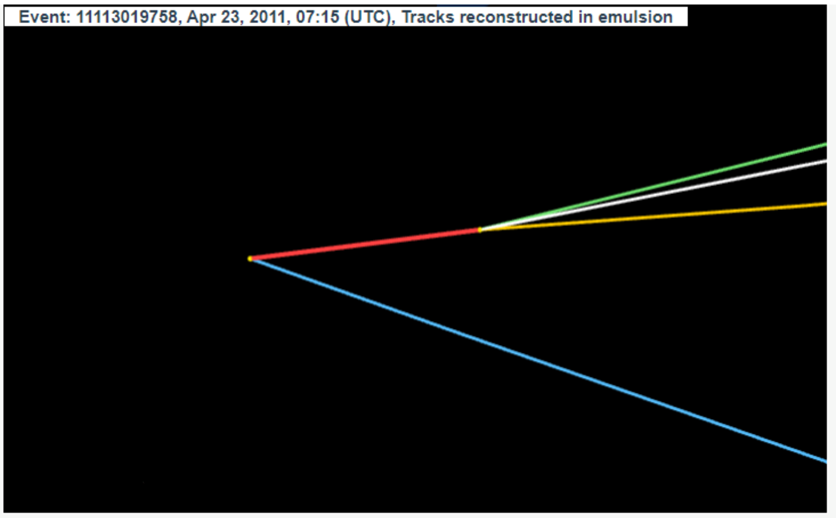
In the file EventID_Vertex.csv we obtain the position of a vertex and using the file EventID_Lines.csv we obtain two points along the track lines to be able to obtain the whole track. These values were saved into a JavaScript object, then Three.js graphics library and HTML were used to build a browser-based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

Drawing vertices

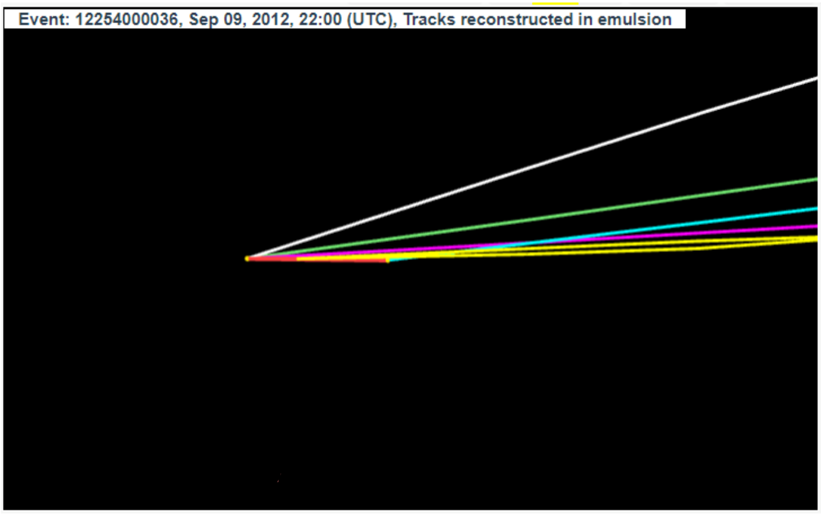
The missing parts of the JavaScript code pertained to relative vertex position concerning the primary interaction vertex. The new positions were computed by adding the on-screen drawing position, primVertDrawPos(), of the primary vertex to the difference between the real position of the secondary vertex, vertRealPos(), and the real position of the primary vertex, primVertRealPos(). This process is reiterated for the x, y, and z coordinates.

5.1.2 Drawing Tracks

The missing parts of the JavaScript code pertained to the relative track positions concerning the primary interaction vertices. This information was obtained by incorporating the coordinates of the drawing position, primVertDrawPos(), of the primary vertex into the difference between the coordinates on a track point and the actual position of the primary vertex, primVertRealPos(). This calculation is performed for each of the two points on every track, each having three coordinates.



(a)



(b)

Figure 9 – Tracks reconstructed in emulsion (a) Event ID: 11113019758 (b) Event ID: 12254000036

Conclusion

The OPERA experiment has played a substantial role in advancing our comprehension of neutrino oscillations, as extensively documented in prior research. This project conducted processing and analysis of several OPERA datasets accessible through the CERN Open Data Portal, leveraging the C++ and ROOT libraries. The results obtained are consistent with those published in the original OPERA papers. To visualize the topology of interesting neutrino interaction events in the OPERA detector, a simplified version of event display with an interactive interface was created using the Three.js graphics library.

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