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

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Abstract

The Standard Model treats neutrinos as chargeless and massless fermions. The existence of neutrino oscillations requires that neutrinos have some mass. The OPERA experiment registered ten tau neutrino candidate events, and thus confirmed the transmutation of muon neutrinos into tau neutrinos during their flight from CERN to LNGS (Italy). Some distributions regarding the production of charmed hadrons and the multiplicity of charged particles were constructed based on OPERA datasets extracted from CERN Open Data Portal. The visualization of tracks and vertices reconstructed in nuclear emulsion detectors was also performed as a result of the analysis of neutrino candidate events.

Chapter 1

Theoretical Framework

1.1 Neutrinos

The Standard models describes two kinds of particles fermions and bosons. Fermions are of two types quarks and leptons. The spin statistics theorem states that fermions are spin half particles while bosons are integral spin. There are 6 types of leptons that come in three generations. The neutrinos (ν_e, ν_μ and ν_τ) are leptons. The three generations are divided based on increasing masses.

Neutrino is electrically neutral. Their interactions are limited to very short-range weak nuclear and gravitational forces, making their detection difficult. The neutrinos participate in charged current and weak current interactions. The flavors are classified based on how the neutrinos decay into corresponding leptons.

Neutrino oscillation requires neutrinos to have mass, thus leading to the modification of the Standard Model (New Physics Beyond the Standard Model).

1.2 Neutrino Oscillation

Neutrino oscillation refers to the possibility of a neutrino flavor change. Neutrino of a given flavor can interact(be detected) after some time in a different flavor state. Flavor states are the neutrinos that interact to produce electrons, muons, and tauons. Neutrino Oscillation arises from quantum mechanical phenomenon due

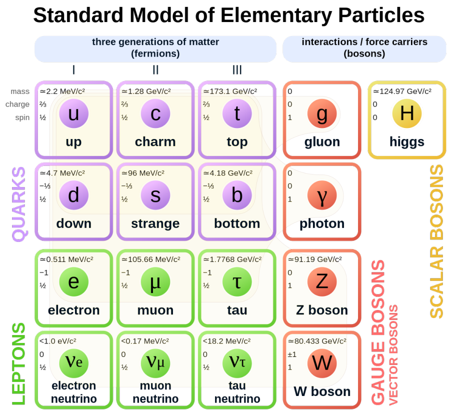


Figure 1.1: Standard Model of Particle Physics

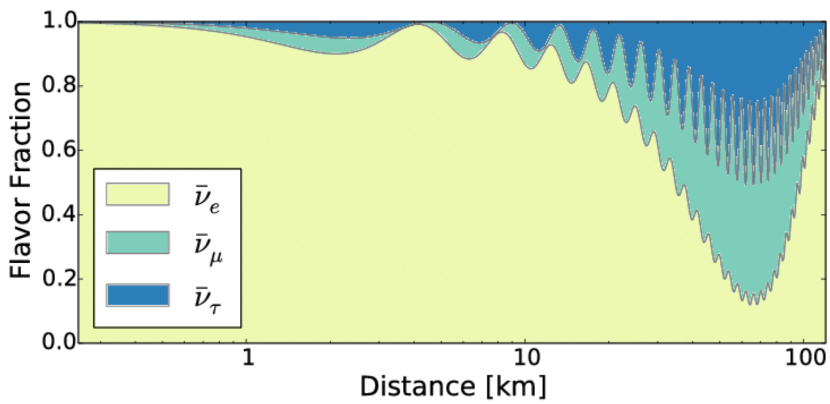


Figure 1.2: Neutrino Oscillation.

to the neutrino mass. The superposition principle allows the three neutrinos flavor states to be written as a linear combination of three neutrino states having definite masses(orthogonal). The mass eigenstates evolve at different rates, so at later times, the flavor state is different from the initial one.

The PMNS matrix relates the flavor and mass states.

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_e1 & U_e2 & U_e3 \\ U_\mu 1 & U_\mu 2 & U_\mu 3 \\ U_\tau 1 & U_\tau 2 & U_\tau 3 \end{pmatrix} \cdot \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Experimentally neutrino oscillation has been studied primarily via disappearance mode. However, its study in appearance mode is also essential, like the OPERA experiment.

Chapter 2

OPERA

Oscillation Project with Emulsion-tRacking Apparatus(OPERA) experiment was designed as the most straightforward way of detecting neutrino oscillations. The objective of the OPERA experiment was the direct observation of ν_τ, in a pure ν_μ (CNGS) beam produced at CERN. In OPERA, τ leptons were produced from the decay of τ neutrinos due to charge current(CC) interactions.

2.1 Detector

OPERA detector required high density, large mass, micrometric resolution, and low background noise(underground location). It comprised of target units, bricks made of nuclear emulsion films with lead plate interleaving [1].

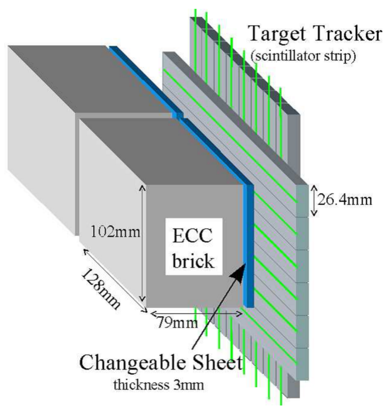


Figure 2.1: Schematic view of the brick with changeable sheet in the detector

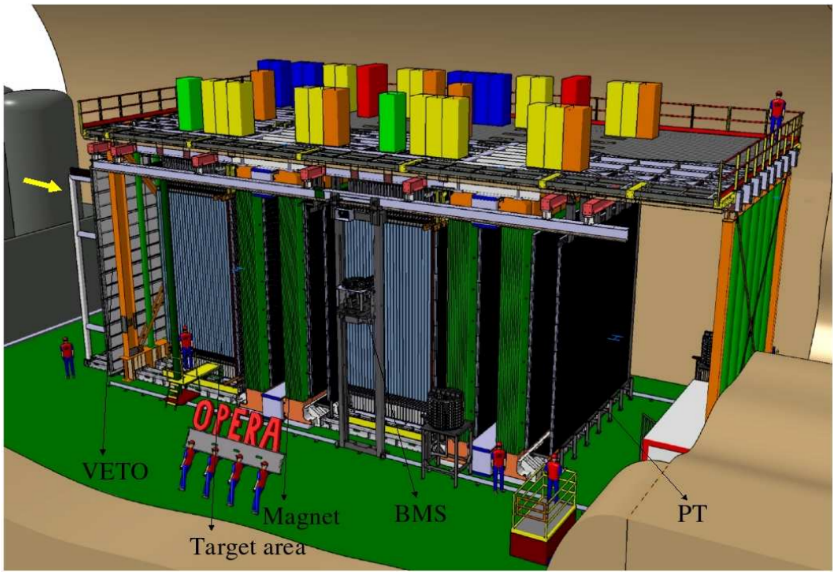


Figure 2.2: Artistic View of OPERA detector [1]

The OPERA target contained 150000 such bricks (total mass 1.25 kton) arranged into walls interleaved with plastic scintillators. The detector was divided into two identical supermodules. Each supermodule consisted of a target section followed by a magnetic spectrometer for measurement of the charge and momentum of the penetrating particles. They provided real-time identification of the brick where the neutrino interaction had occurred. The corresponding brick was extracted from the wall, X-ray marked, and exposed to cosmic rays for alignment. The emulsion films developed were subjected to emulsion scanning to scan the event accurately.

2.2 Neutrino Beam

OPERA required an intense and energetic beam that traveled a distance of hundreds of kilometers to seek the presence of ν_τ. The beam was produced by collisions of accelerated protons with a graphite target after focusing the particles in the desired direction. Generally, the product of collisions (muons and neutrinos) traveled undeviated from their parent trajectory. Muon neutrinos produced at CERN cross the earth's crust and reach OPERA (732 km).

Chapter 3

Neutrino Induced Charmed Hadron production studies

The objective was downloading the OPERA emulsion dataset for the neutrino induced charmed hadron production from the CERN Open Data Portal [7]. A C++ program was developed for the analysis of the dataset. The positions of the primary and the secondary interaction vertices and the parameters of the charm decay daughter particle tracks were read. The flight lengths and impact parameters of the daughter particle tracks with respect to primary neutrino vertices were saved to a histogram.

3.1 Decay Lengths

The decay(flight) length of a charmed hadron is the distance between the primary and secondary vertices of a neutrino interaction event, i.e., the distance between two points in 3D space.

The positions of the primary and secondary vertices are given in `.CSV` file in the form of `eventID_Vertices.csv` here `event_id` varies across 50 observed events in the emulsion data for neutrino-induced charmed hadron production.

Figure 3.2b shows the results of our analysis. Figure 3.2a shows the analysis done on actual data and its comparison with MC simulation. Our histogram is in good agreement with the published result [2]. Minor differences arise due to small updation of the data by corresponding laboratories over due course of time.

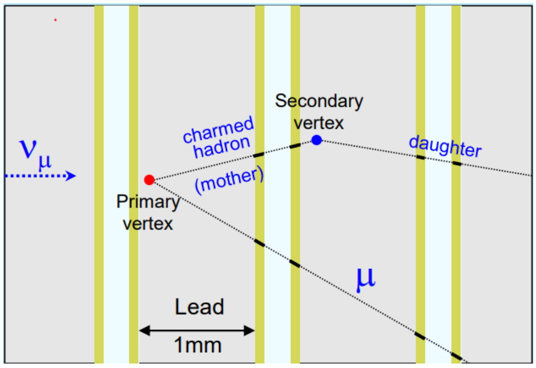
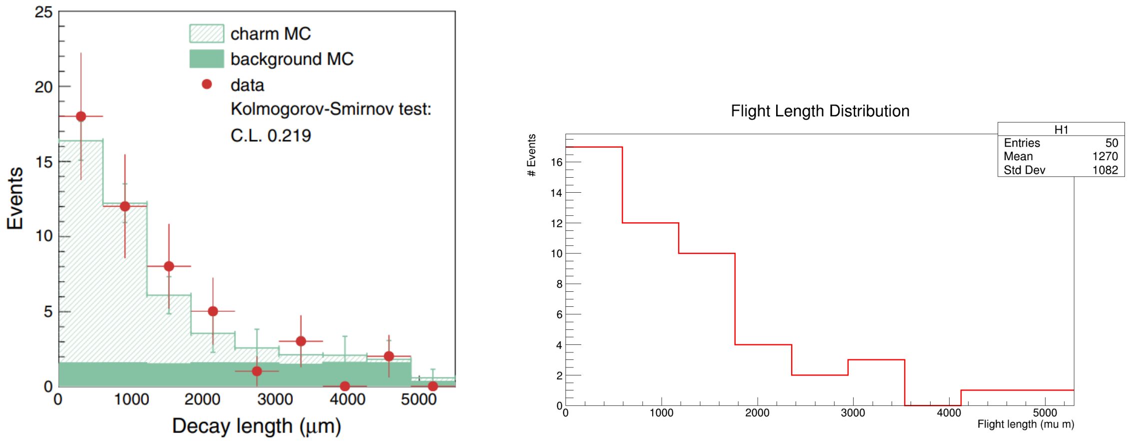


Figure 3.1: Charmed Hadron decay in ν_μ CC interaction



(a) Published

(b) Analysis

Figure 3.2: Decay Length Histograms

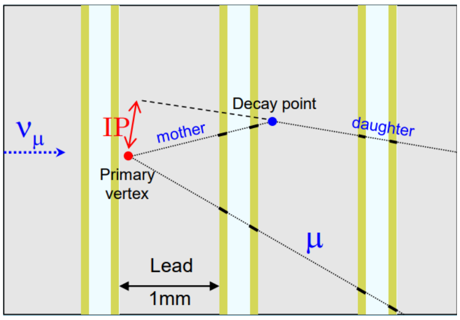


Figure 3.3: Charmed Hadron decay in ν_μ CC interaction

3.2 Impact Parameter

Impact Parameter(IP) is the distance between the daughter particle track and primary neutrino interaction vertex, the distance between line and point in 3D.

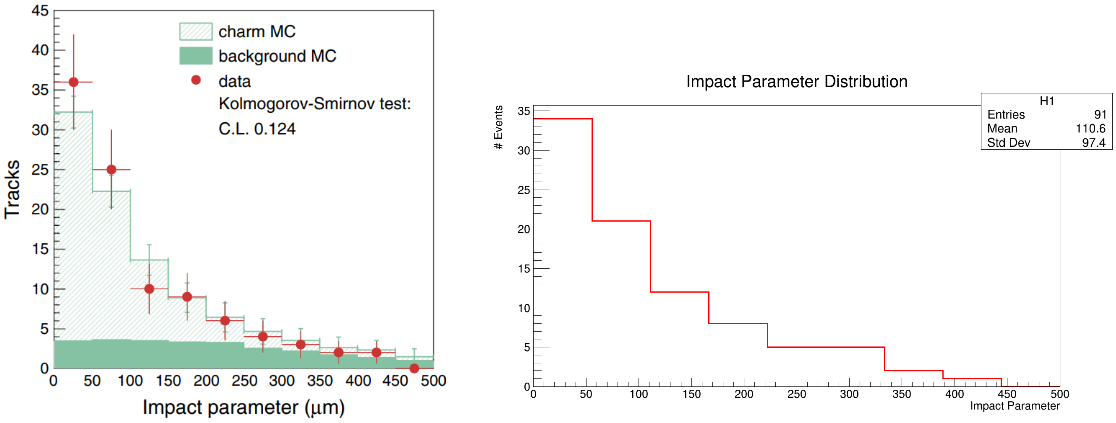
The impact parameter can be calculated as

$$\mathrm{IP} = \frac{\left|\vec{e_r} \times \vec{A}\right|}{|\vec{e_r}|}$$

Here, $\vec{A}$ is the vector distance between the daughter track and the primary interaction vertex, $\vec{e_r}$ is any vector in the direction of the daughter track.

The charmed hadron decays into daughter particles, and each daughter track is stored by two sets of coordinates in 3D, in the file `eventID_Tracklines.csv`; here `event_id` varies across 50 observed events in the emulsion data. The vertex coordinates of primary and secondary particles are stored in the corresponding `eventID_Vertices.csv`. The daughter particle track type is 10. The C++ program extracts the daughter vertex and the track line coordinates. The impact parameter was then computed using the above formula(in component form).

Figure 3.4b shows the results of our analysis. Figure 3.4a shows the analysis done on real data in the publication. Our histogram for the impact parameters is in good agreement with the published result [2]. Minor differences arise due to small refinements in the data by corresponding laboratories over due course of time.



(a) Published

(b) Analysis

Figure 3.4: Impact Parameters Histograms

Chapter 4

Track multiplicity studies in CC ν - Pb interactions

OPERA emulsion dataset for the charged hadron multiplicity has been downloaded from the CERN Open Data Portal. A C++ code was developed to analyze the dataset. The positions of primary neutrino-lead interactions vertices and parameters of secondary charged particle tracks have been read. Histograms of the multiplicities of all produced charged particles and muon track angles have been stored.

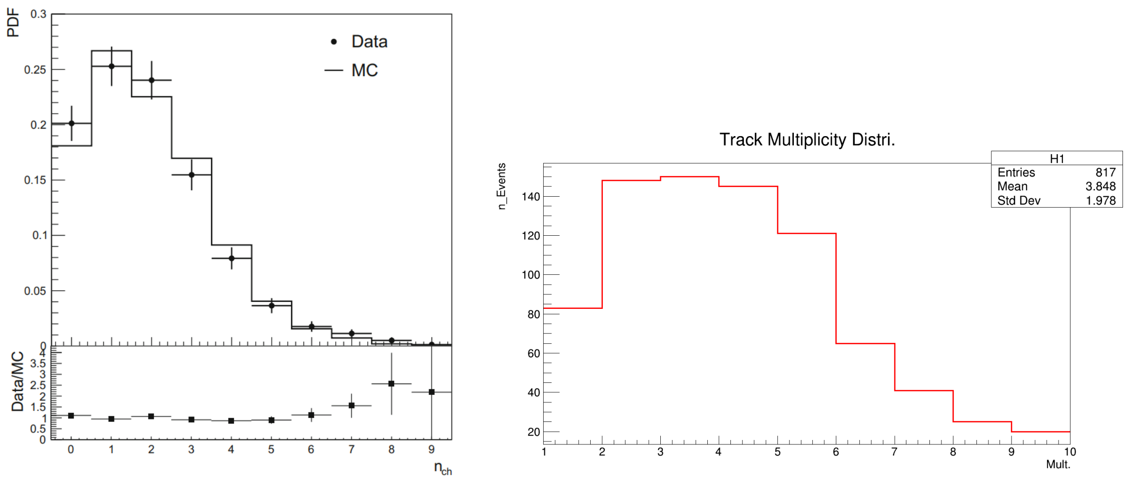
Histograms of the multiplicities of all produced charged particles and muon track angles have been stored.

4.1 Multiplicity distribution of charged particles

Track multiplicity is the number of charged particles produced by the ν_μ interaction with the lead nucleus(target). Each track in our sample is defi ned by its starting point(3D) and two slopes, slope XZ and YZ. They are the tangents of angles with the Z axis in ZX and ZY views.

The C++ code reads multiplicity from each `eventID Vertex.csv` file and stores it in a histogram created using ROOT libraries. The critical point is that the multiplicity is an integer, so the histogram cell width must be an integer as well.

The result is shown in Figure 4.1b for comparison with the analysis performed in the paper [3] shown in Figure 4.1a. The two histograms show decent agreement with actual and MC data.



(a) Published

(b) Analysis

Figure 4.1: Charged Multiplicity Histograms

4.2 Muon Track Angles

Another way of identifying a track in 3D is by specifying one point(primary vertex) and the 2 angles the track makes with 2 of the axes keeping one axis fixed. The file `eventID_Tracks.csv`, where `eventID` is varied across the 817 events, contains coordinates of the primary vertex[1] as well as the slopes of the track in XZ and YZ planes.

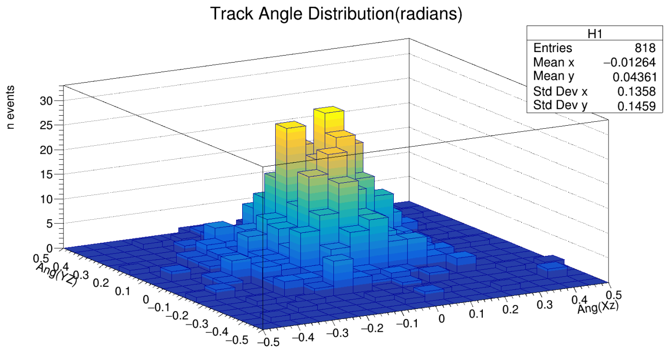
Corresponding angles with the X(or Y) axis can be computed as

$$\theta = \tan^{-1}[\text{slope } XZ(\text{or } YZ)]$$

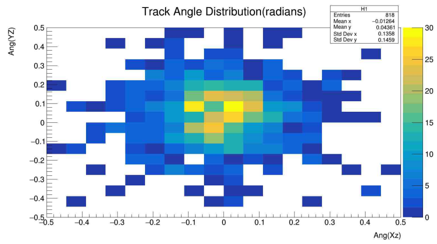
The C++ code was developed to read the slopes from all files, convert them to corresponding angles, and plot them on a 2D histogram shown in Figure 4.2b. A `lego` plot was also created using ROOT [6] libraries shown in Figure 4.2a.

From the Figure 4.2 we can see that the total number of entries is 818 while the total number of events is 817. This points to the fact that one of the events is a dimuon event; it contains 2 tracks. Further analysis revealed that the event `11093039862` contains 2 muons tracks. In Figure 4.3 a visualization of that event is shown, which is taken from the Open Data Portal [7].

[1]Due to experimental uncertainity, the point may be near to the primary vertex.



(a) 3D



(b) 2D Projection

Figure 4.2: Muon Track Angle Histograms for ν_μ CC interactions

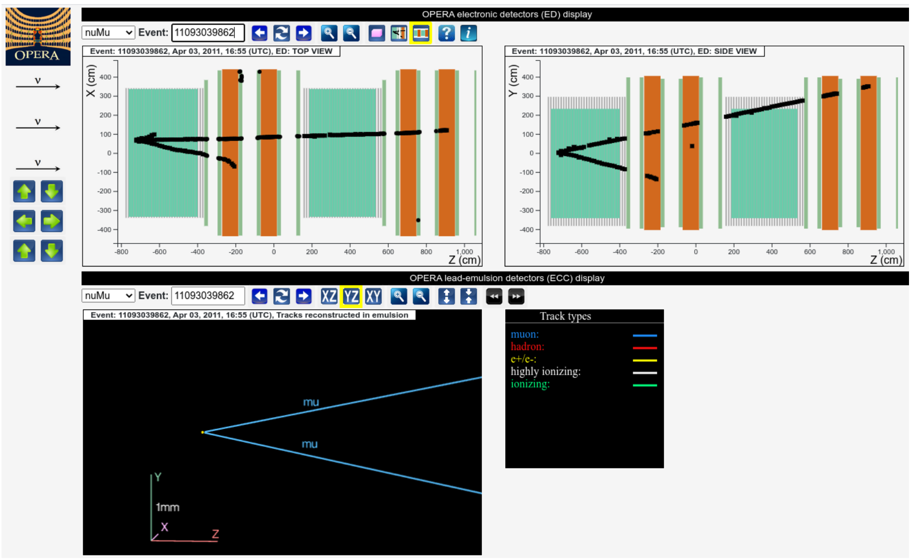


Figure 4.3: Visualization of the dimuon event

Chapter 5

Visualization of the events from the OPERA emulsion dataset

The task objective was to display tracks and vertices reconstructed in nuclear emulsions in 10 ν_τ candidate events. The emulsion dataset for ν_τ appearance studies was downloaded from the CERN Open Data Portal.

The electronic detector collection of 5603 completely reconstructed neutrino interactions was reduced to 10 possible ν_τ event candidates after applying the kinematical cuts [4] [5].

5.1 Visualisation

A simplified version of the browser based 3D event display that uses the THREE.js graphics library was provided with some missing source code. The tracks and vertices were visualized by recovering the code. Google Chrome web browser was used for running the `.html` file.

The primary vertex of each neutrino event was always drawn at the same point on the screen. Thus, the absolute coordinates of all tracks and vertices had been recalculated with respect to this reference point.

5.1.1 Drawing vertices

The missing information was the relative vertex position with respect to the primary interaction vertex.

The new positions were calculated by adding the drawing position `primVertDrawPos()` of primary vertex(on screen) to the difference between real position of secondary vertex `vertRealPos()` and real position of primary vertex `primVertRealPos()`. This is repeated for x, y and z coordinates.

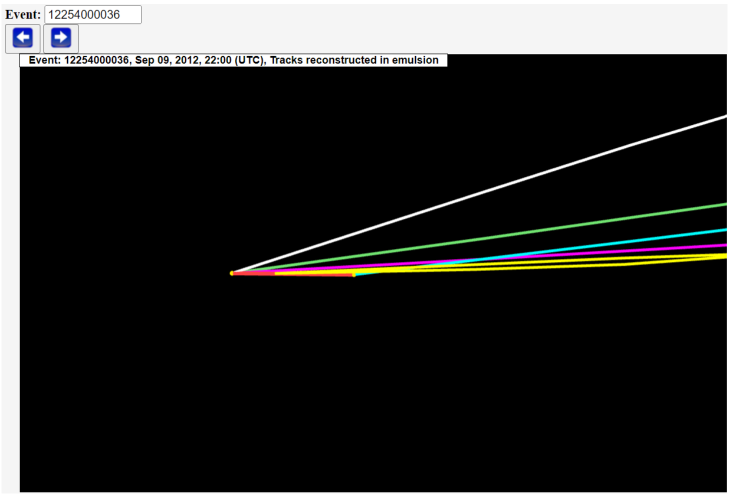
5.1.2 Drawing Tracks

The missing information was the relative track positions with respect to the primary interaction vertices.

The information was retrieved by adding the coordinates of drawing position `primVertDrawPos()` of primary vertex to the difference between the coordinates on a track point `iTrack.pos()` and the real position of the primary vertex `primVertRealPos()`. This is done for the two points(3 coordinates each) on every track.

Figures 5.1a and 5.1b shows the track and vertex display for two such events.

(a) eventID 9234119599



(b) eventID 12254000036

Figure 5.1: Track Reconstructed in nuclear emulsions

Conclusions

Neutrinos, one of the most abundant and undetected particles, require new physics beyond the standard model to account for their masses. The neutrino oscillation phenomenon is a testament to this fact. The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) experiment at the INFN Gran Sasso National Laboratory (LNGS) was designed to prove unambiguously muon to tau neutrino oscillations in appearance mode through the direct observation of tau neutrinos in a muon neutrino beam produced at CERN.

In this project, neutrino-induced charmed hadron production studies were performed wherein we obtained the distribution for flight length and impact parameters. Studies of CC neutrino interactions in lead involved obtaining the distributions of charged particle track multiplicities as well as distributions of muon track angles. The significance of such studies is twofold. It tells the interaction dynamics of the events and the removal of background noise (large scattering angles).

Next, the visualization of the track lines and the vertices of the tau neutrino candidate event was performed.

All the results achieved in this study agree well with the literature. Overall, this project provided us with an excellent opportunity to understand neutrino oscillation through experiments and also hand on experience in CERN ROOT, Open Data Portal and JavaScript graphics libraries.

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[7] CERN. Cern root. https://root.cern/.