JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

Final Report presented for :

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

INTEREST PROGRAM WAVE 12

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Project Webpage

Abstract

This report describes the work carried out under the INTEREST Programme at the Joint Institute for Nuclear Research (JINR), focusing on the analysis and interactive visualization of neutrino interaction topologies measured by the OPERA experiment. The OPERA detector, based on a hybrid apparatus of nuclear emulsions and electronic tracking, was built to detect the appearance of tau neutrinos in a muon neutrino beam ,direct evidence of neutrino oscillation effects.

Using publicly available datasets from the CERN Open Data Portal, this research replicated important published findings by examining neutrino-induced charm hadron production and charged hadron multiplicities. ROOT based C++ programs were created to extract flight lengths and impact parameters from emulsion data, as well as angular and multiplicity distributions of secondary tracks, with results in agreement with those of the OPERA Collaboration.

In addition, this project included reviving and expanding a 3D event display system for browser based visualization of neutrino events with JavaScript and the THREE.js library. The visualization environment facilitates examination of tau neutrino candidate interaction spatial topology, with increased understanding of complex decay signatures. In general, this project provides an end-to-end workflow for utilizing open experimental data in high-energy physics, combining quantitative analysis with interactive visualization to investigate rare neutrino events at high spatial resolution.

Contents

1 Theoretical Background

1.1 Neutrinos and Neutrino Oscillations

Neutrinos are fundamental fermions that belong to the lepton family according to the Standard Model of particle physics. They are characterized by their lack of electric charge, small mass, and their sole interaction forces being the weak nuclear force and gravity, making them among the most hard to find particles in the universe. There are three known flavors of neutrinos: electron (ν_e), muon (ν_μ), and tau (ν_τ), each associated with a corresponding charged lepton.

The phenomenon of neutrino oscillation refers to the ability of a neutrino created in a given flavor state to transform into another flavor state as it moves through space. This behavior, first proposed by Bruno Pontecorvo and later supported by the PMNS mixing matrix, means that the flavor eigenstates are superpositions of distinct mass eigenstates. Consequently, the observation of oscillations provides direct evidence that neutrinos possess non zero mass,a fact not accounted for in the original explaination of the Standard Model.

Experimental confirmation of neutrino oscillation came through observations of both solar and atmospheric neutrinos, notably in the Super-Kamiokande and Sudbury Neutrino Observatory (SNO) experiments. These findings not only solved long-standing anomalies but also opened new avenues for understanding physics beyond the Standard Model, such as the role of neutrinos in baryogenesis via leptogenesis, and their potential connection to dark matter.

1.2 OPERA Experiment

The OPERA (Oscillation Project with Emulsion-tRacking Apparatus) experiment was a long-baseline neutrino oscillation experiment designed to provide the first direct observation of tau neutrino (ν_τ) appearance in a muon neutrino (ν_μ) beam. Conducted between 2008 and 2012, the experiment utilized the CNGS beam from CERN to the Gran Sasso National Laboratory (LNGS), spanning a baseline of 730 km.

The OPERA detector employed a hybrid architecture consisting of electronic detectors and Emulsion Cloud Chambers (ECCs). Each ECC “brick” was composed of alternating layers of high-resolution nuclear emulsion films and lead plates, enabling precise spatial reconstruction of particle tracks and interaction vertices. This configuration was essential for identifying the short-lived leptons produced in (ν_τ) charged-current interactions.

The experiment successfully recorded 10 tau neutrino candidate events, thereby providing unambiguous evidence of (ν_μ) $\rightarrow$ (ν_τ) oscillations in appearance mode—a milestone in experimental neutrino physics. Additionally, OPERA investigated charm production as a control sample due to the similar lifetimes and decay topologies of charmed hadrons and τ leptons, thereby validating the detector's sensitivity and reconstruction algorithms.

OPERA's achievements not only confirmed fundamental aspects of neutrino physics but also demonstrated the feasibility of using hybrid detectors for rare event searches, combining real-time event tagging with submicron-resolution tracking. The experiment represents a critical chapter in the broader effort to explore the neutrino sector and its implications for new physics.

2 My Tasks

Here I present the task wise work I carried out for the Analysis and Visualization of Neutrino Topologies registered in OPERA Experiment.

2.1 TASK 1 : Charmed Hadron Flight Length and Impact Parameter Extraction using OPERA Data

We had two sub tasks to achieve in this task. We aimed to extract the coordinates of the primary and secondary interaction vertices and the parameters of Charm decay Daughter Particle Tracks. These were then used to calculate the Flight Length and Impact Parameter, using the calculations as presented below. We then used ROOT Software to plot histograms for the obtained Flight Lengths and Impact Parameters and compared them to the histograms in the paper.

The Data used can be found here : Open_Data_Portal_T1

In my case, I used Python to extract the relevant fields of data from the .csv files and then used C++ for the ROOT Histograms.

The code I wrote can be found in the github repository linked below.

Code : Repo_for_Task1

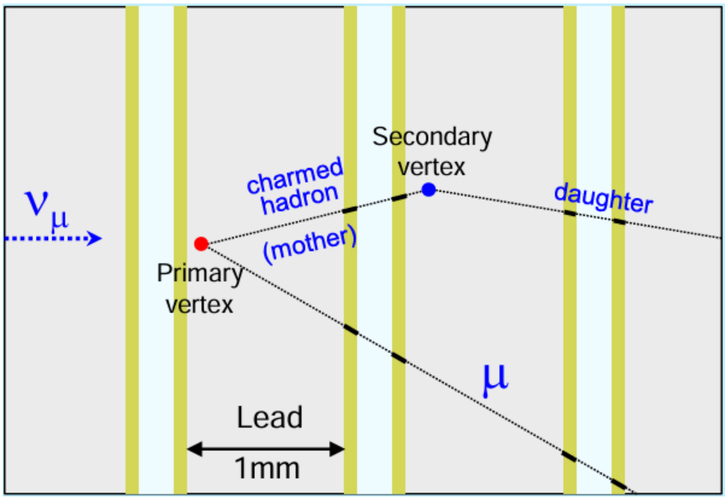
2.1.1 Sub Task 1 : Calculation of Flight Lengths/ Decay Lengths

Once we obtained the 3 dimensional coordinates of the Primary and secondary vertices, then it was simple Coordinate Geometry at play to calculate the Flight Length. Mathematically, the Flight Length is just the 3D Distance between the primary and secondary vertices. It was calculated as :

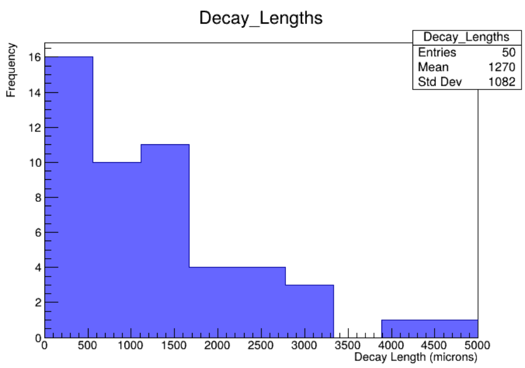
$$Flight\_Length = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

where (x_1, y_1, z_1) represents the primary vertex and (x_2, y_2, z_2) represents the secondary vertex.

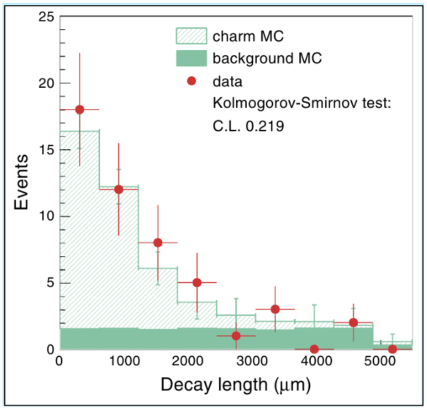
Then I used ROOT to construct a 1D Histogram for the obtained Flight Lengths, which are also called Decay Lengths.The histogram obtained by analysis and the histogram as in the original paper are presented below.



Primary and Secondary Vertices



Decay Lengths Histogram that I obtained



Decay Lengths Histogram in the Paper[3]

2.1.2 Sub Task 2 : Calculation of Impact Parameters

Once we obtained the 3 dimensional coordinates of the Primary and secondary vertices, then it was simple Coordinate Geometry at play to calculate the Impact Parameters.Impact Parameter is nothing but the perpendicular distance from Primary Vertex $P_1(x_3, y_3, z_3)$ to the Daughter Track through the Secondary vertex $P_2(x_1, y_1, z_1)$ and another point in space $P_3(x_2, y_2, z_2)$ is given by:

$$I_p = \frac{\left\| \vec{P_2 P_1} \times \vec{P_2 P_3} \right\|}{\left\| \vec{P_2 P_3} \right\|},$$

where $\vec{P_2 P_3} = (x_3 - x_2,\ y_3 - y_2,\ z_3 - z_2)$ is the direction vector of the Daughter Track, and $\vec{P_2 P_1} = (x_1 - x_2,\ y_1 - y_2,\ z_1 - z_2)$ is the vector from the Track to the Primary Vertex.

Then I used ROOT to construct a 1D Histogram for the obtained Impact Parameters.The histogram obtained by analysis and the histogram as in the original paper are presented below.

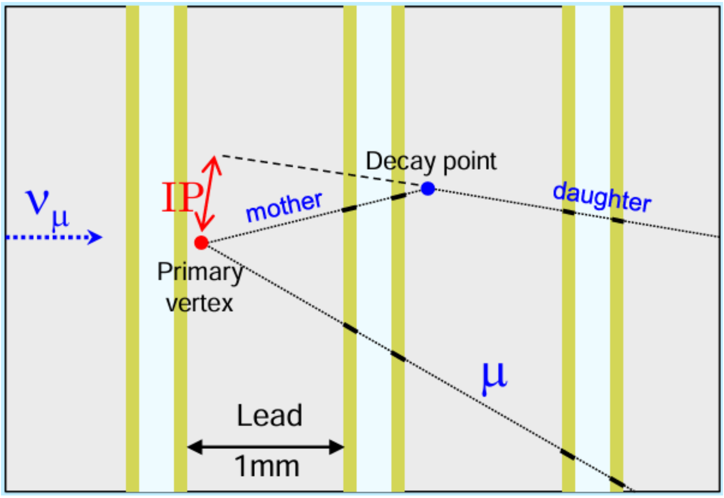
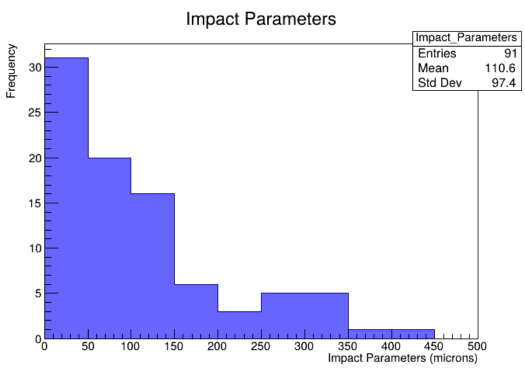
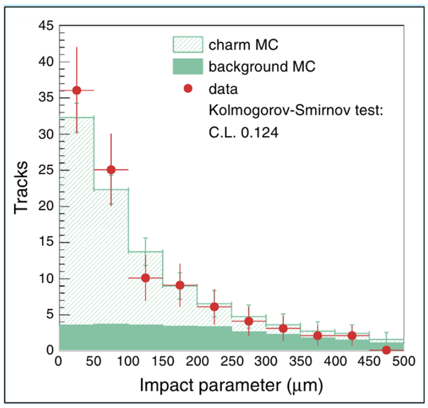


Image Depicting Impact Parameter



Impact Parameters Histogram that I obtained



Impact Parameters Histogram in the Paper[3]

2.2 TASK 2 :

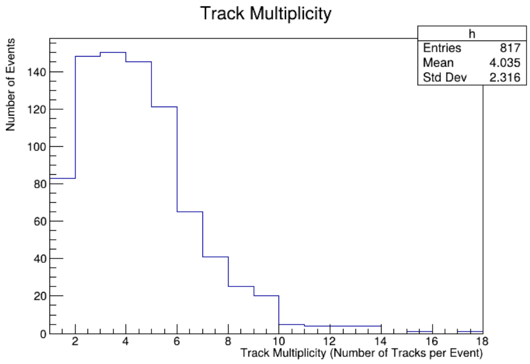
For this Task, my contribution was to calculate and plot track multiplicity distribution for 817 (ν_μ) interaction events. Also, it was required to produce two-dimensional distribution of XZ and YZ muon track slopes, which is critical in determining the probability of certain topologies occurring in these interactions. The code I wrote can be found in the github repositorysitory linked below.

Code : Repo_for_Task2

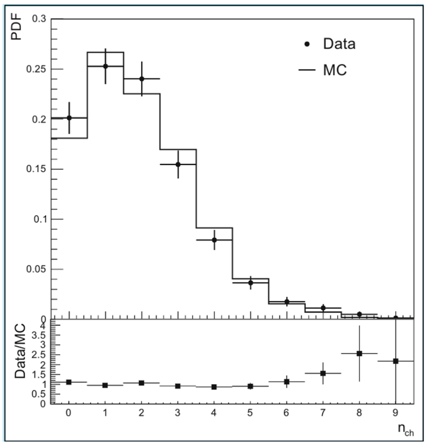
2.2.1 Sub Task 1 : Track Multiplicities in Muon Neutrino Interactions

Track multiplicity is defined as the number of charged particle tracks to a given vertex, normally to the primary interaction vertex of a muon neutrino. Data from the EventIDvertex.csv file, with the number of charged particles created in each neutrino-lead interaction,was used in this analysis to investigate patterns of multiplicity.

Python was used to read this data, calculate the track multiplicity for each event, and save the results in a ROOT histogram with C++. This histogram gives a visual representation of charged particle multiplicity distribution over all events. The resulting plot is shown below.



Charged track Multiplicity Histogram that I obtained



Hadron track Multiplicity Histogram from the Paper[4]

2.2.2 Sub Task 2 : Muon Track Angle Distribution

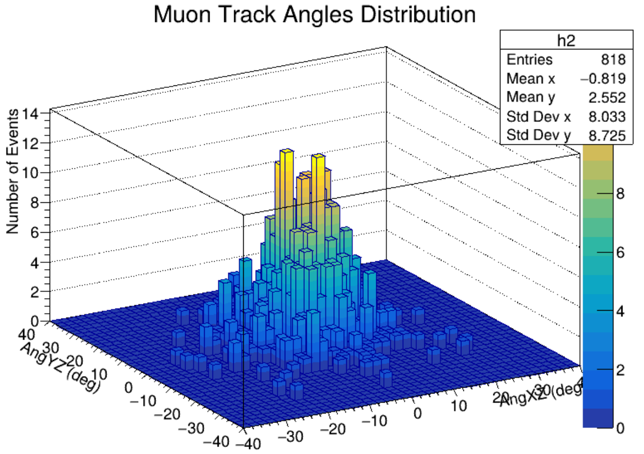
The direction of muon tracks can be measured by determining their angles through the following relation:

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

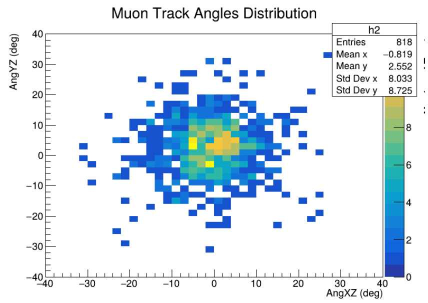
Where, m = Slope and θ = the angle of the muon track in radians. The slopes along the XZ and YZ projections, being the tangents of the track against the Z-axis, were extracted for each event using Python. These values of slopes were subsequently utilized to calculate the respective angles of the muon tracks.

The data of interest was taken from the EventID_Tracks.csv file, where muon tracks were identified by trType = 1. For each muon track found, the angle was computed and saved in a 2D ROOT histogram to plot the angular distribution. The histogram resulting from this is presented below.

Every muon track is characterized by a point close to the original vertex and its corresponding slopes in the XZ and YZ planes, allowing exact reconstruction of the geometry of the track in three-dimensional space.



2D Histogram of Track Angles



1D Projection of the Distribution

2.3 TASK 3 : Interactive Visualization of Tau Neutrino Events

To be able to see and comprehend the fascinating shapes of the tau neutrino events that were present in the emulsion data of the OPERA experiment, we created a web based visualizer of these events . We used THREE.js Library extensively.

In order to create these illustrations, we used data from two files. One of the files, titled "EventID_Vertex.csv," informed us about the precise location (the vertex) at which particles collided. From another file, titled "EventID_Lines.csv," we extracted two points on each particle's trajectory (the track). Based on these two points, we were able to determine the entire track of the particle. We took this information and saved it in a way that JavaScript could understand. Then, we used the THREE.js library and some web page code (HTML) to build a visualizer of all the interaction spots (vertices) and particle paths (tracks) for each of the ten tau neutrino events.

The code I wrote can be found in the github repository linked below.

Code : Repo_for_Task3

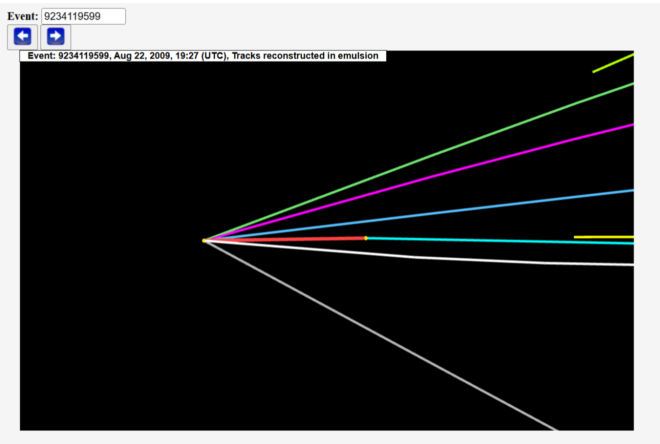
2.3.1 Drawing the Interaction Spots (Vertices)

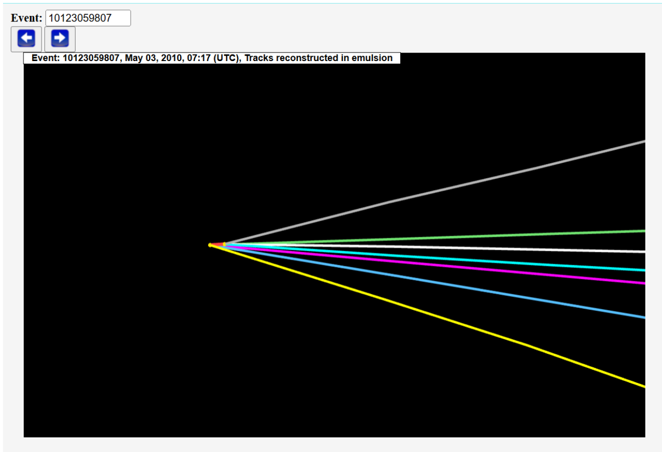
We had to determine exactly where to plot the various interaction points (such as where a particle had decayed) on the screen in relation to the primary starting point of the interaction (the main vertex). To accomplish this, we added the screen position where we plotted the main starting point and the difference between the actual location of the other interaction spot and the actual location of the main starting point. We did this independently for the left-right, up-down, and forward-backward directions (x, y, and z coordinates) to obtain the proper position on the canvas.

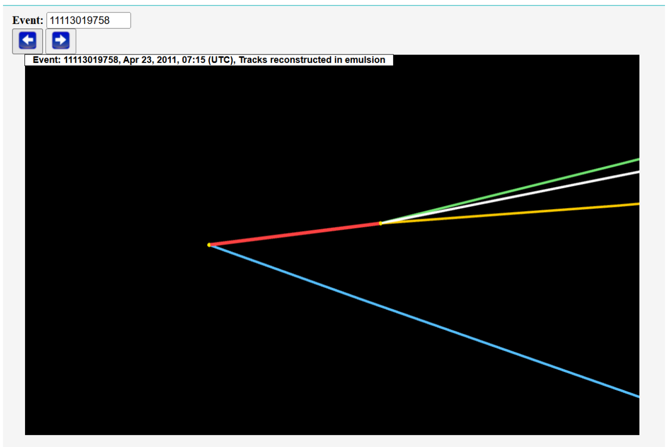
2.3.2 Drawing the Particle Paths (Tracks)

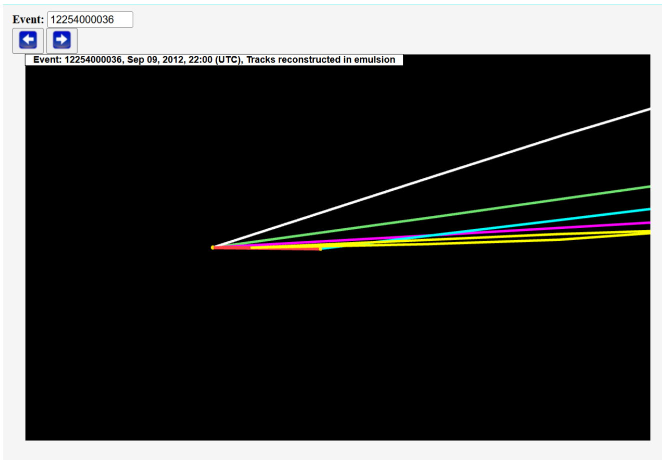
In the same way, in order to correctly draw the paths of particles (tracks) with respect to the main starting point, we utilized the screen location of the main starting point. We added this to the difference between a point on the path of the particle and the actual location of the main starting point. We performed this calculation for each of the two points we had along each particle's trajectory, and each point was three-dimensional (left-right, up-down, forward-backward). By doing this, we were able to plot the full particle traces in our canvas.

A few Event Visualizations are presented below.









Find the demo of the Neutrino Event Visualization here.

3 Concluding Remarks :

This project, carried out under the INTEREST Program at JINR, focused on analyzing and visually representing neutrino events captured by the OPERA experiment performed at CERN. We showcase a thorough approach to utilize open data in the field of high-energy physics. Not only did the study replicate significant findings from the OPERA collaboration, but it also created user friendly tools for delving into rare event topologies.

In the initial phase, the project calculated the flight lengths and impact parameters of charmed hadrons resulting from neutrino interactions. These measurements were derived using C++ and ROOT from emulsion data available on the CERN Open Data Portal. The findings, were compared with OPERA's published histograms.

The next steps were aimed at unraveling the kinematic structure of muon neutrino interactions. By analyzing track multiplicities and angular distributions, the research provided deeper insights into the intricate vertex structures and decay signatures found in OPERA's emulsion-targeted events.

The final part of the project went beyond conventional data analysis and ventured into visualization. By employing JavaScript and the THREE.js library, an interactive event display was created for web browsers, allowing for real-time 3D exploration of tau neutrino candidate topologies. This tool not only makes experimental data more accessible but also acts as a valuable educational resource for understanding complex decay geometries.

In summary, this work highlights the effectiveness of merging modern computational methods with experimental particle physics. It underscores the importance of open data platforms in science and illustrates the potential of hybrid approaches to replicate and expand upon significant findings in neutrino physics.

4 References :

The following papers were used as references:

[1] Acquafredda, R., and et al. The **OPERA** experiment in the **CERN** to gran sasso neutrino beam. Journal of Instrumentation 4, 4 (2009). (link).

[2] Dmitrievsky, S. status of the **OPERA** neutrino oscillation experiment. Acta Phys. Polon. B 41 (2010), 1539–1546. (link).

[3] N. Agafonova et al. Procedure for short-lived particle detection in the **OPERA** experiment and its application to charm decays. Eur. Phys. J. C, 74(8):2986, 2014. (link.)

[4] N. Agafonova et al. Study of charged hadron multiplicities in charged-current neutrino lead interactions in the **OPERA** detector, 2017. (link).

[5] N. Agafonova et al. Final results of the **OPERA** experiment on (ν_τ) appearance in the cngs neutrino beam. Phys. Rev. Lett., 120:211801, May 2018. (link).

5 Acknowledgement

I extend my deepest gratitude to my supervisor **Dr. Sergey Dmitrievsky**, for his unwavering support and insightful critiques throughout the project period. I am equally thankful to the **INTEREST Team at JINR, Dubna**, for this invaluable opportunity to engage in meaningful research remotely.