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

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Wave 8 Project Report

Joint Institute For Nuclear Research, Dubna, Russia
April 7, 2023

Contents

Abstract

Understanding neutrino ν oscillations better was the goal of the scientific experiment known as OPERA. As a neutrino travels through space, its flavor changes due to the phenomenon of neutrino oscillation. This report uses C++ code and the ROOT library to examine several OPERA data sets that are accessible on the CERN Open Data Portal. Also, JavaScript, HTML, and CSS have been utilised for visualisation of OPERA tau neutrino sample. A simplified version of the OPERA browser-based event display was used to visualise interesting neutrino event topologies.

1 Introduction

The studies done on the neutrino go as far back as to 1930s in an era where the interest in nuclear physics was at a peak with many of the worlds most renowned physicists fixating their focus on subjects like decays and model explaining the nature of the nucleus and from them one of the most important interactions was the Beta decay. The Beta decay is the decay of one type of nucleon into the other type in order to stabilize the radioactive nuclei, however, in the first attempts to describe it, it left open alot of loose ends like the conservation of Energy, Momentum and Angular Momentum (Spin angular momentum in particular). It was Wolfgang Pauli who first postulated in 1930 in his very famous letter to about the existence of a neutral, one half spin particle of very small mass, it was later coined neutrino by Enrico Fermi, This solved many pending issues with the conservation laws written above. Itremained only to observe this particle, and indeed, this was done by Cowan and Reines in 1956,which was the first of many discoveries in the neutrino field. Calculations led the neutrino to be one of the most a bund antparticles in the universe, it has very littlemass which is not yet calculated with great accuracy and was determined to be less than .12 eV, anatural source for neutrinos is the fusion nuclear reactions which is quite common as it is the main energy source for all ordinary stars, as an example of that 2% of the suns energy carried by neutrinos from fusion reactions which is a greatmagnitude.Due to the very small mass of the neutrino and the energy it carries, it can move with extremely relativistic velocities.

Neutrinos are leptons, which means they can't interact via the strong nuclear force, they arealso electrically neutral which means they can't interact with electromagnetic force as well, due to thevery small mass they have, their gravitational interaction is pretty insignificant and negligible.What this means is that the only significant way neutrinos can interact is via the weak nuclear forcewhich for the most part is 'weak' in magnitude compared to the strong nuclear force and theelectromagnetic forcetoo. The weak interaction has a very short effective range (around 10^{-17} to10^{-16} m). At distances around 1018 meters, the weak interaction has a strength of a similar magnitudeto the electromagneticforce, but this starts to decrease exponentially with increasing distance.Scaled up by just one and a half orders of magnitude, at distances of around $3 \times 10^{17} m$, the weak interaction becomes 10,000 times weaker. All the aforementioned reasons lead the neutrinos to very rarely interact with matter, very much so that it would require 3 Light Years of Lead in order to interact with a single neutrino with a 50/50 probability.

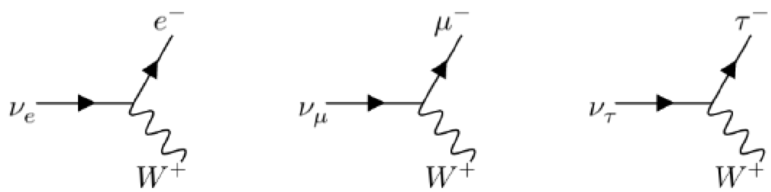


Figure 1.1

It was later found out that there were more than one type of neutrino which was the electron neutrino and its antimatter sibling, there were also two other flavors of the neutrino corresponding to the muon and the tau particles, and that a certain neutrino when interacting with matter it will produce its corresponding 'Flavor' and only it, which means an electron neutrino can't produce a muon or a tauand vice versa.

2 Neutrino Oscillation

A neutrino interacts with matter only by the weak nuclear force, which has a very small range, and very weak gravity force, which makes them very difficult to detect. Neutrinos participate in the charged current (CC) and neutral current (NC) weak interactions, and it has been demonstrated through experimentation that there are three different types or flavours of neutrinos: electrons (ν_e), muons (ν_μ), and tauons (ν_τ). The distinctive signature of their CC interaction serves as the basis for classifying neutrinos into flavours, with μ_e denoting a neutrino produced with an energy of e^+ or e^- during the CC interaction, ν_μ denoting a neutrino produced with an energy of μ^+ or μ^-, and ν_τ denoting a neutrino produced with an energy of τ^+. It is also clear that a certain flavour of neutrino will always result in a charged lepton of that flavour, never a different flavour, when it decays in the CC interaction.

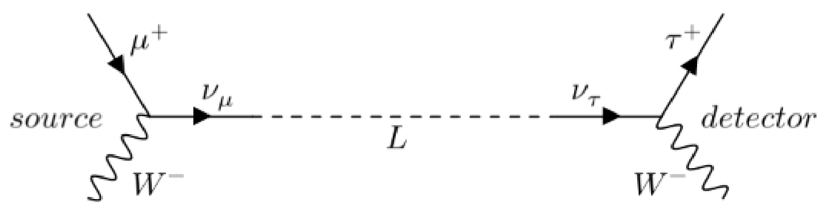


Figure 2.1

The neutrino sector has become one of the most sought-after to understand due to the promising potential for development of physics beyond the Standard Model. Neutrinos were long believed to be mass-less particles in the Standard Model, but the experimental discovery of the neutrino oscillation implied that neutrinos have mass, which required modification to the Standard model. The oscillation phenomenon involves the conversion of one neutrally charged particle into another neutrally charged particle. Neutral mesons oscillating between the particle and its antiparticle exhibit these oscillations. Neutrinos, in this situation, alternate between the three neutrino flavours. According to neutrino oscillation, there is a chance of discovering a distinct flavour of neutrino if a certain flavour neutrino, such as ν_μ, is created via weak interaction at a distance L from the source that is sufficiently great Fig 2.1.

3 OPERA Experiment

A long-baseline neutrino beam from CERN to Gran Sassa Laboratory (LNGS), located 730 kilometres apart, was used in the experiment known as the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) to identify the first direct observation of ν_μ -> ν_τ oscillation. ν_μ with an average energy of 17 GeV made up the majority of the CNGS beam. 2.1%of $\bar{\nu}_\mu$ and 0.9% of ν_e , $\bar{\nu}_e$ were also present in the beam.

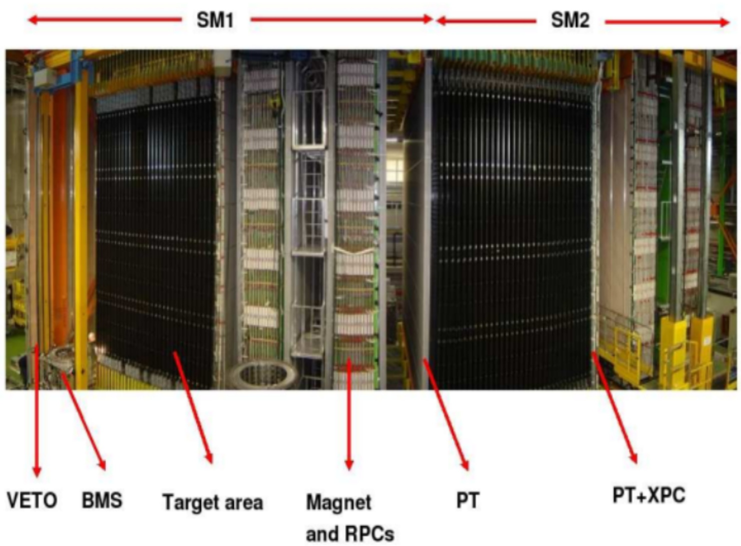


Figure 3.1

The European Organization for Nuclear Research (CERN), located in Switzerland, and Laboratori Nazionali del Gran Sasso (LNGS), located in Italy, collaborated on the experiment. The CERN Neutrinos to Gran Sasso (CNGS) neutrino beam hit the OPERA detector with high intensity (2.4 1013 protons on target per pulse) and high energy (400 GeV). In the Super Proton Synchrotron at CERN, a beam of this kind was created by the collision of accelerated protons with a graphite target. The generated secondary particles, in particular the pions and kaons, were focussed in the desired direction. These particles continue to decay into muons and ν_μ, which move in the same direction as the original particles.The Gran Sasso Underground Laboratory (LNGS), located 730 kilometres distant, hosted the

OPERA detector, which was the target of this high-energy ν_μ beam createdat CERN SPS.TheOPERA detector was a hybrid one. Its two identical Super-Modules made up its 2000m^3 (10 1020m^3) overall volume. In order to track the interactions taking place in the rock around the experimentalsetup, a Resistive Plate Chamber (RPC) was positioned in front of the first super module.EachSuper-Module has around 75000 bricks in it, with 31 Target Trackers that connect the verticallyplaced bricks into the shape of a wall (6.7 6.7 m^2), which together make up the Target Section.

A single target brick was made up of 57 emulsion films interlieved by 56 lead plates that were each 1 mm thick. Such a sandwich structure of the detector is conventionally called Emulsion Cloud Chamber. Each brick had an additional outer compartment with two interchangeable emulsion sheets inside. These sheets acted as an interface between the Target Tracker and the bricks. A magnetic spectrometer for measuring momentum and charge of muons was located behind the target section.

4 Result and Discussion

4.1 Analysis of Emulsion Data of neutrino induced charmed hadron production

We analyzed emulsion data for neutrino-induced charmed hadron production to assess the validity of the ν_τ appearance by studying the production of charmed hadron due to ν_μ interactions. Charmed Hadrons have similar masses and a life-time similar to that of leptons. Thus, they are considered as one of the most possible contamination background resources in the OPERA experiment.

4.1.1 Decay Length

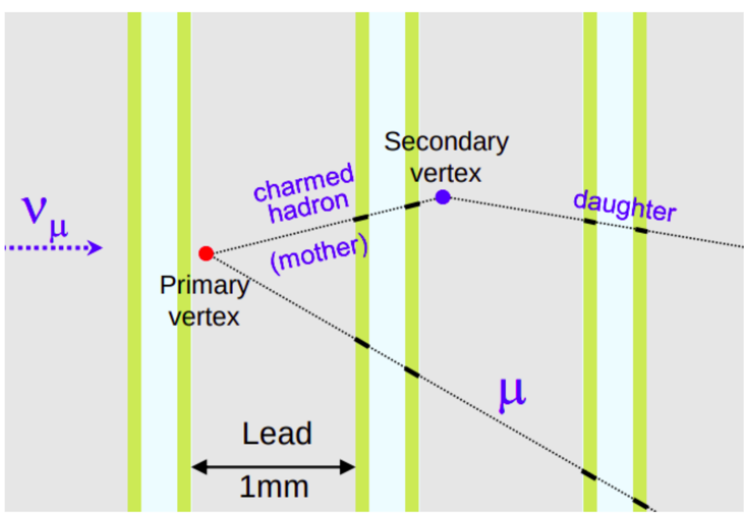


Figure 4.1

We first calculated the flight lengths (decay lengths) of the charmed hadrons. Flight length of a charmed hadron is just the distance between the primary and the secondary vertices of the neutrino interaction event as shown in figure 4.1 . To calculate the flight length, we can use the formula

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{4.1}$$

where D is the flight length, x_1, y_1 and z_1 are the coordinates of the primary vertex, and x_2, y_2 and z_2 are the coordinates of the secondary vertex.

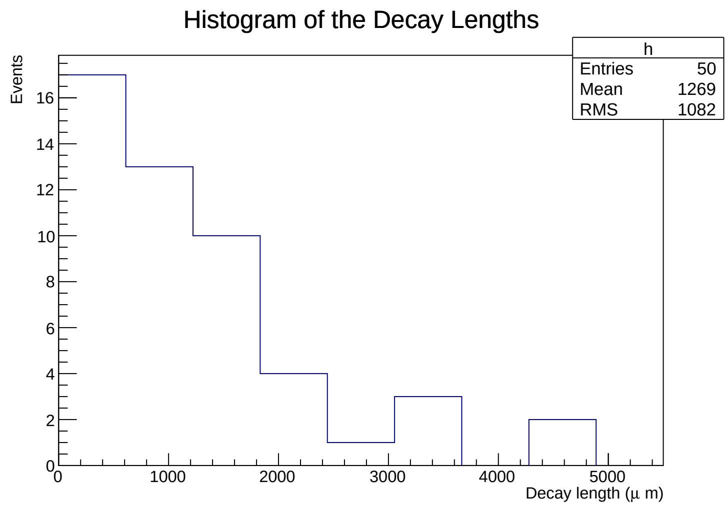


Figure 4.2

The results obtained are shown in the Root histogram in Figure 4.2.

4.1.2 Impact Parameter

We calculated the impact parameter of the daughter tracks which is the shortest distance between the daughter particle track and the primary neutrino interaction vertex.

This was calculated using the formula:

$$IP = \frac{|\bar{V_0 V_1} \times \bar{V_1 P_1}|}{\bar{V_1 P_2}} \tag{4.2}$$

where IP is the impact parameter, V_0 is the primary interaction vertex, V_1 is the secondary interaction vertex and the first point of the daughter particle track, and P_2 is the second point of the daughter particle track. The results obtained are shown in the Root histogram in Figure 4.4.

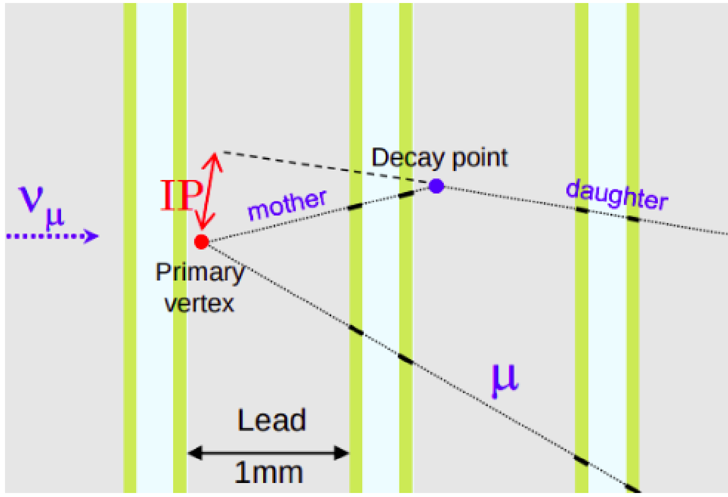


Figure 4.3

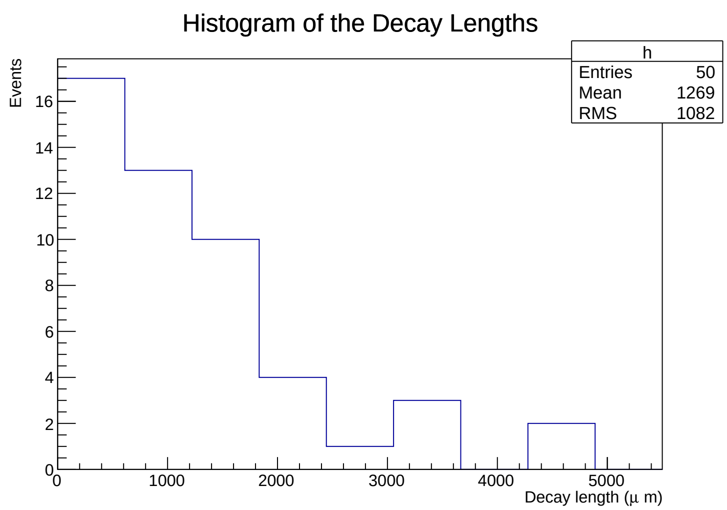


Figure 4.4

4.2 Emulsion Data for Track Multiplicity

We analysed the emulsion data set of the charged hadron multiplicity studies. The data set contains 817 muon neutrino interactions with a lead target in which a muon was reconstructed in the final state. It contains the information of the positions of the primary neutrino-lead interaction vertices as well as the parameters of the secondary charged particle tracks.

4.2.1 Track Multiplicity

Track multiplicity is the number of tracks of charged particles associated with a given vertex in our case it is associated with the muon neutrino primary interaction vertex.

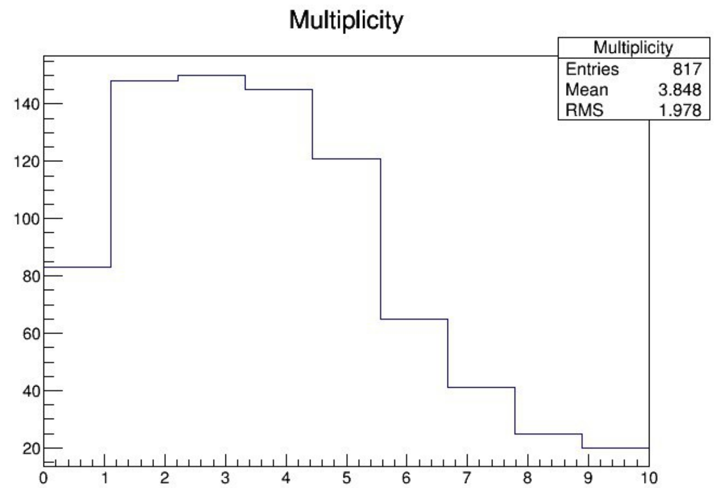


Figure 4.5

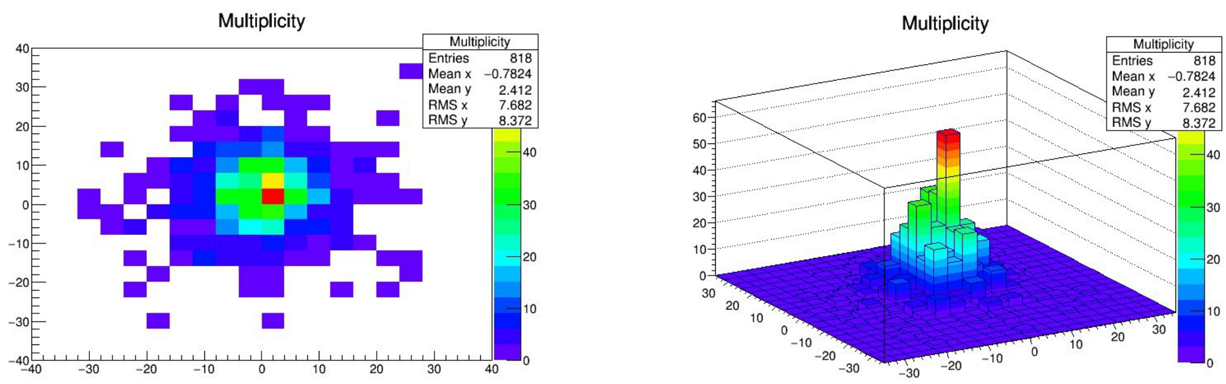
We searched for the multiplicities of all the produced charged particles, saved them to a histogram, as shown in Figure 4.5.

4.2.2 Muon Track Angles

Each track is defined by its starting point, a 3D point near the vertex, and two slopes, i.e., tangents of angles with respect to the Z-axis in the XZ and YZ views. We obtained the muon track angles, Figure 4.6, by the equation.

$$\theta = tan^{-1}(s), \tag{4.3}$$

where θ is the angle of the muon track in radians, and s is the slope.

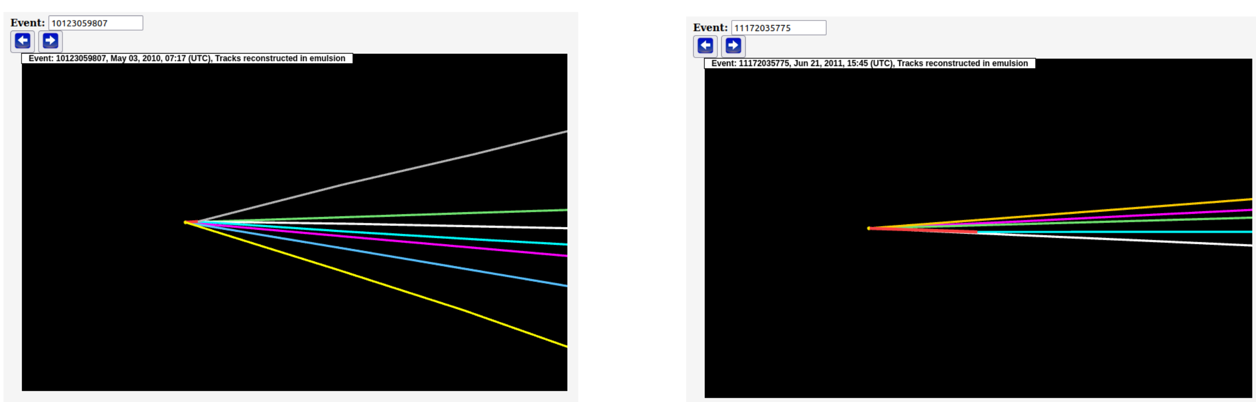


(a) (b)

Figure 4.6

4.3 Emulsion Data for Tau Neutrino Appearance Studies

We used the OPERA emulsion data set for the tau neutrino appearance studies to create a 3D visualisation of two tau neutrino candidate event topologies. We implemented a simplified version of a browser-based event display using the JavaScript THREE.js graphics library.



(a) (b)

Figure 4.7

The primary and secondary vertices along with the track positions reconstructed in the nuclear emulsion in the candidate events were displayed by recovering the code of the corresponding JavaScript data structure program. HTML/CSS files were implemented to display the characteristic event topologies in a browser window.

Conclusions

In this project, thanks to experimental data on the CERN open data portal, we got acquainted with the phenomenon of neutrino oscillation. In particular, we considered two ν_τ candidate events registered in the OPERA experiment, which prove the existence of ν_μ->ν_τ oscillations. Inaddition to investigating various topological events characteristics that are useful for improving event generators and selecting candidate events of substantial interest, we were able to see reconstructed tracks of charged particles produced in neutrino interactions. We gained a lot of hands-on experience working with the ROOT framework, learned about some of its features, became familiar with the use of the CERN open data portal for data retrieval and learned about several interactive visualization tools made using JavaScript graphics libraries.

Acknowledgments

I would like to thank Joint Institute for Nuclear Research for this great opportunity, which is based on mixing with real projects and dealing with them to gain experience.

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