JOINT INSTITUTE FOR NUCLEAR RESEARCH

Dzhelepov Laboratory of Nuclear Problems

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Final Report

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

Ossama W. Abdelwahed (B.Sc Physics)

Alexandria University

Alexandria, Egypt

supervisor

Dr. Sergey Dmitrievsky

Dzhelepov Laboratory of Nuclear Problems, JINR

Dubna, Russia

Abstract

Neutrinos are neutral fermions with very little mass, they are the most abundant particle in the universe after photons and they represent a promising opportunity for developing physics beyond the Standard Model. In our project, we will be studying one of the most important phenomena involving neutrinos which is flavor oscillation. We will access the data of the OPERA experiment published on the CERN Open Data Portal, we will then analyze some event topology features by developing computer programs using C++ and will use the ROOT framework to display our results. Also, we will develop 2D and 3D interactive visualization in a web browser using HTML, CSS, and JavaScript.

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1 Introduction

A neutrino (ν) is an electrically neutral lepton, fermion that interacts only via the very short ranged weak nuclear force and the very weak gravitational force making them very hard to detect. Neutrinos take part in the charged current (CC) and neutral current (NC) weak interactions and it is established experimentally that they are of three varieties or flavors, electron ν_e, muon ν_μ, and tauon ν_τ. The basis on which the neutrinos are classified into flavors is the distinctive signature of their CC interaction, where ν_e is the neutrino produced with e^+ or produces e^- during the CC interaction, ν_μ is the neutrino produced with μ^+ or produces μ^-, and ν_τ is the neutrino produced with τ^+ or produces τ^-. It is also evident that when a neutrino of a specific flavor decays in the CC interaction it will always produce a charged lepton of the corresponding flavor and not a different flavor.[1]

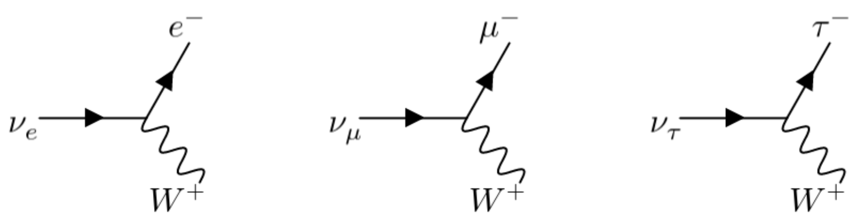


Figure 1: Decay of neutrinos to their respective leptons during a CC interaction

Neutrinos were long thought to be massless 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, propelling the neutrino sector to be one of the most sought to understand due to the promising potential for development of physics beyond the Standard model.

1.1 Neutrino Oscillation

The phenomenon of oscillation is the transformation of a neutrally charged particle into a different neutrally charged particle. Such oscillations are observed in neutral mesons oscillating between the particle and its antiparticle ($K^0 \leftrightarrows \bar{K}^0$). In the case of neutrinos, they oscillate between the three neutrino flavors. Neutrino oscillation entails that if a specific flavor neutrino, say ν_μ, is produced during weak interaction, at a sufficiently large distance L from the source, there is a probability of detecting a different flavored neutrino.[1]

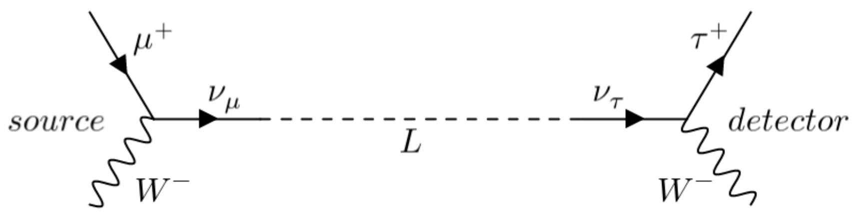


Figure 2: Muon neutrino to tauon neutrino oscillation

Experiments with solar, atmospheric, reactor, and accelerator neutrinos have produced and are still producing evidence for the existence of neutrino flavor oscillation. There exist two different methods to investigate neutrino oscillation. As mentioned earlier with ν_μ there exists a probability for neutrinos to transition $P(\nu_\mu \to \nu_\tau) \neq 0$ which can be investigated by observing the appearance of ν_τ at the detector, this method is known as appearance mode; it then follows that the probability of a neutrino to preserve its flavor $P(\nu_\mu \to \nu_\mu) < 1$ which can be investigated by observing the disappearance of ν_μ on the way from the source to the detector, this is called disappearance mode. An example of an experiment that was set up in disappearance mode is the Sudbury Neutrino Observatory collaboration that detected the disappearance of solar ν_e solving the famous Solar Neutrino Problem.[2] An example of an experiment that was set up in appearance mode is OPERA which we will discuss in more detail.

1.2 OPERA

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA), was an experiment designed to investigate $\nu_\mu \to \nu_\tau$ oscillation in appearance mode. The appearance of ν_τ is observed through the detection of the short-lived tauon τ produced in the CC ν_τ interaction utilizing the nuclear emulsion technique. The experiment used a detector that was located at the underground Gran Sasso Laboratory (LNGS) in Italy, 730km away from the neutrino source, a suitable distance to observe neutrino oscillation. The detector was exposed to CERN Neutrino to Gran Sasso (CNGS) ν_μ beam produced at CERN SPS accelerator with very small contamination.[3]

$\langle E_{\nu_\mu} \rangle$	17GeV
$\bar{\nu_\mu}/\nu_\mu$	0.02
$(\bar{\nu_e} + \nu_e)/\nu_\mu$	0.001
$(\nu_\tau + \bar{\nu_\tau})/\nu_\mu$	negligable

Table 1: Charectarsics of CNGS beam

The OPERA detector was a hybrid apparatus composed of two identical Super Modules (SM) each composed of a target wall with a mass of 0.63 kton and a magnetic spectrometer complemented with electronic detectors. The target wall is composed of Emulsion Cloud Chamber units (ECC) called bricks, each brick is made up of 57 nuclear emulsion films, which are a type of photographic films that can detect three-dimensional tracks of charged particles with submicron spatial resolution, 300

μm thick, interleaved with 56 lead plates, 1 mm thick, with a 12.7 cm by 10.2 cm cross-section, a thickness of 7.5 cm corresponding to about 10 radiation lengths and a mass of 8.3 kg.[4]

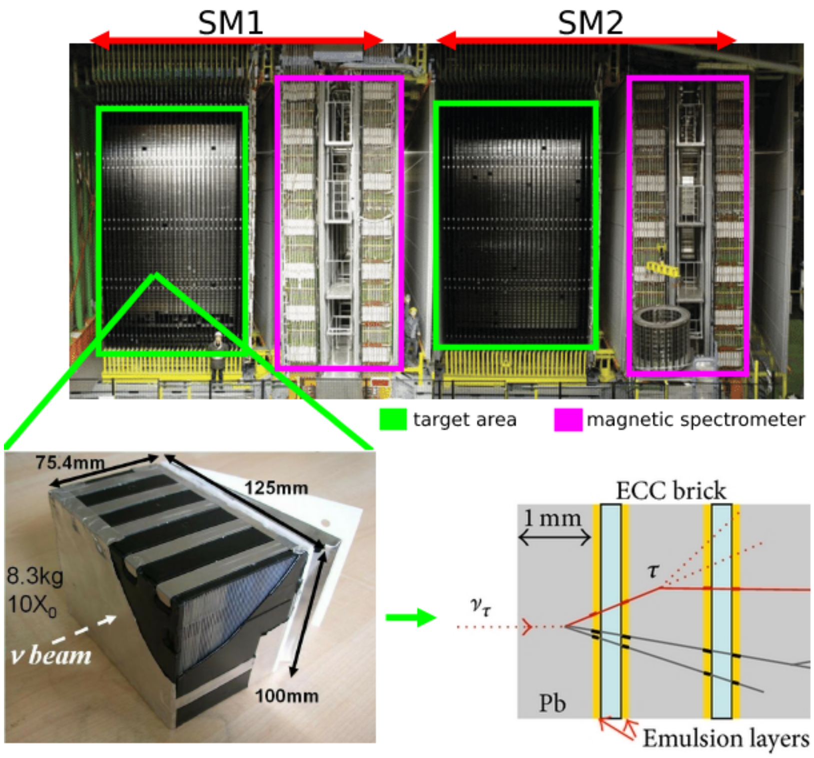


Figure 3

The electronic detectors reconstruct the interactions to help identify the most probable brick containing the interaction vertex, the most probable brick is then extracted and its films are analyzed. The τ lepton is identied by the detection of its characteristic decay topologies either in one prong (electron, muon, or hadron) or in three-prongs.[4]

2 Tasks

2.1 Task 1: Charm Decay Topology Study

The appearance of ν_τ in the OPERA detector was observed through the distinctive signature of the ν_τ interaction where the τ lepton decays in one or three prongs. Charmed hadrons have similar masses and lifetimes to those of the τ lepton and constitute one of the main background sources, and also the CC interaction of ν_μ with charmed hadrons in the final state has a similar topology to that of oscillated ν_τ which makes it a great tool for background check and a powerful test for the experimental capabilities of the detector.[5]

In this task we use the emulsion dataset for the neutrino-induced charmed hadron production studies from the Open Data Portal for calculating some topological characteristics the charmed hadron decay, specifically the impact parameter and the flight length. A code was developed using Python and C++ with the Root framework in reading, analysing, and visualising the data.

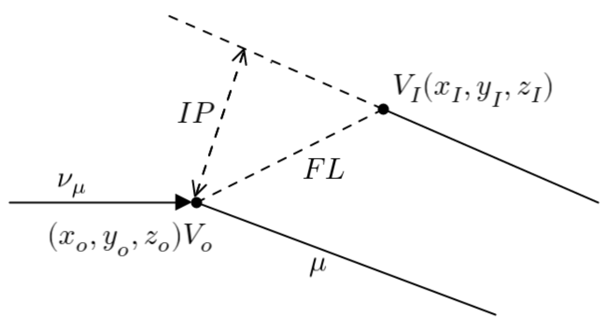


Figure 4: Schematic view of one-prong decay topology. The primary vertex V_o is where the ν_μ CC interaction occurs producing a muon and a charmed particle that has a flight length FL and decays at the secondary vertex V_I. IP is the impact parameter.

the flight length can be calculated from the primary and secondary vertex positions provided in the data.

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

the results are then filled in a root histogram and compared to that of the OPERA paper cited above.

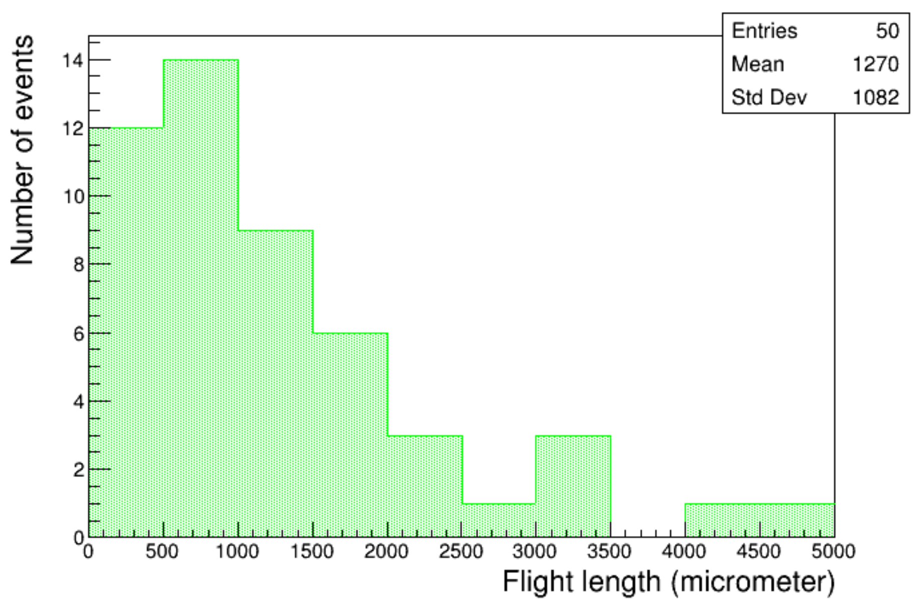


Figure 5

The impact parameter of each daughter track is the shortest distance between the primary vertex and the track line in three dimension space. This can be calculated from the coordinates of the primary vertex and two points on the track line. Utilizing vector analysis, the formula for calculation of the impact parameter is

$$IP = \frac{|(\vec{X_o} - \vec{X_1}) \times (\vec{X_o} - \vec{X_2})|}{|(\vec{X_1} - \vec{X_2})|} \quad (2)$$

where $X_o = (x_o, y_o, z_o)$ is the position vector of the primary vertex, and X_1 and X_2 are position vectors of two points on the line, the analysis resulted in the following histogram.

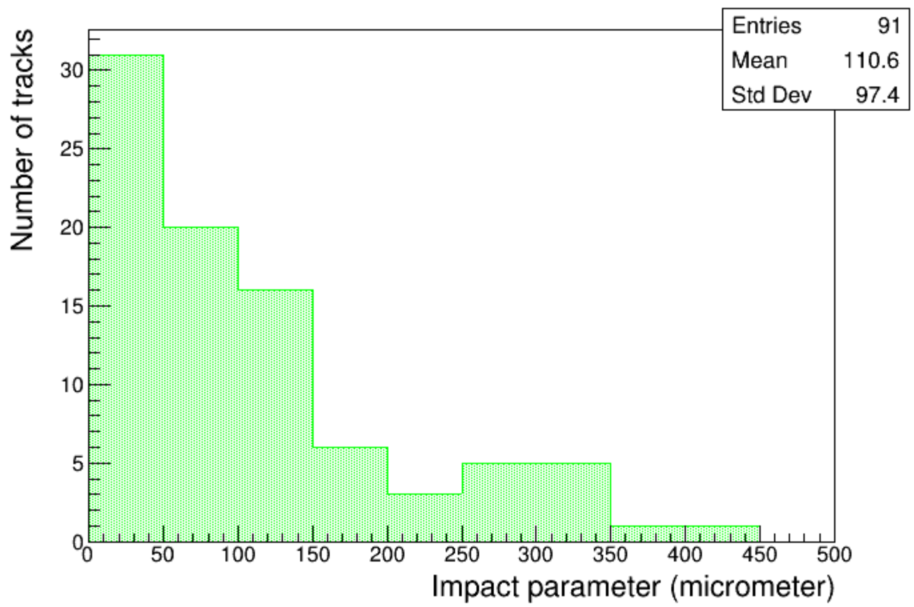


Figure 6

2.2 Task 2: Track multiplicity study

The multiplicity distribution of charged hadrons is an important characteristic of the CC interaction which is useful to improve models of particle production which in turn are used in Monte Carlo event generators.[6]

In this task, we study the track multiplicity distribution of charged particles resulting from the CC interaction of ν_μ in the OPERA target and compare our results to the paper cited above.

In the first part of the task, we developed a code to analyze the emulsion data for track multiplicity dataset from CERN open data portal. First of all, we produced a histogram to represent the multiplicity distribution of all produced charged particles.

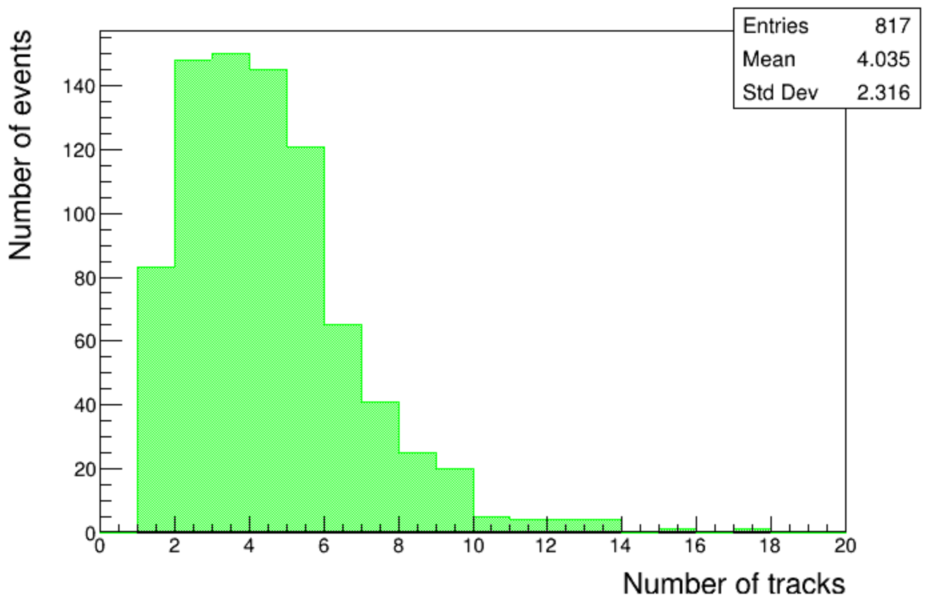


Figure 7

In the second part of the task we found the slope distribution of muon tracks. We can notice that the number of entries in the histogram for the muon slopes is more than that of the total number of events. This is because in one case we have a di-muon CC event.

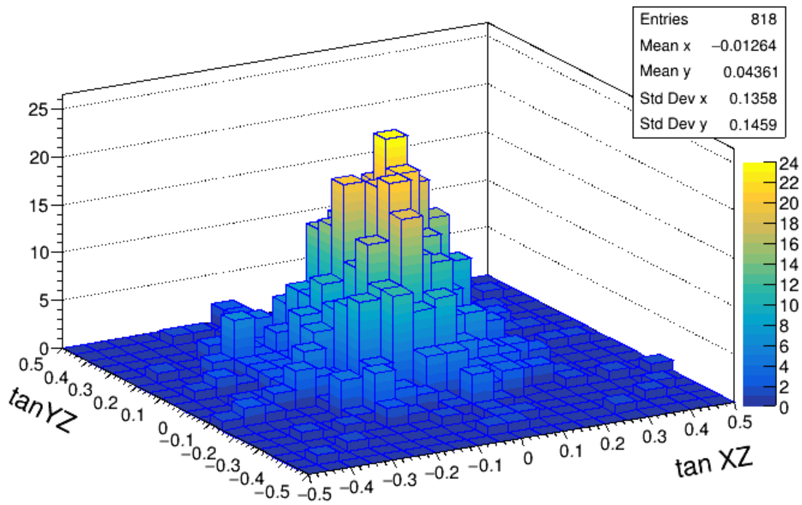
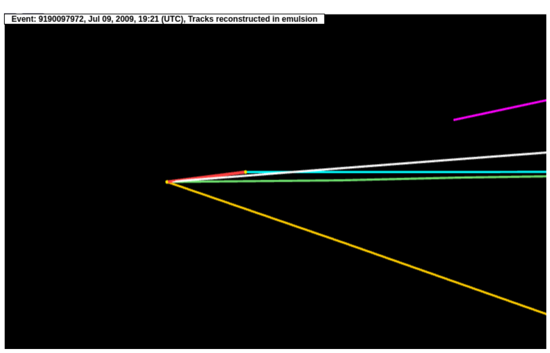
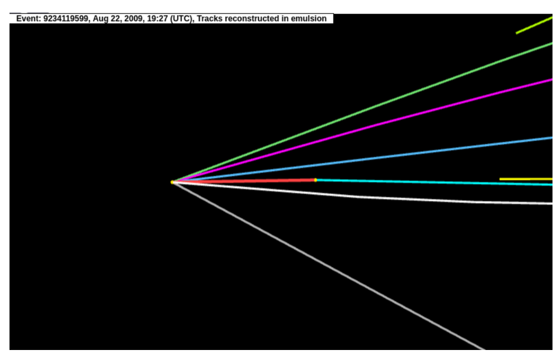


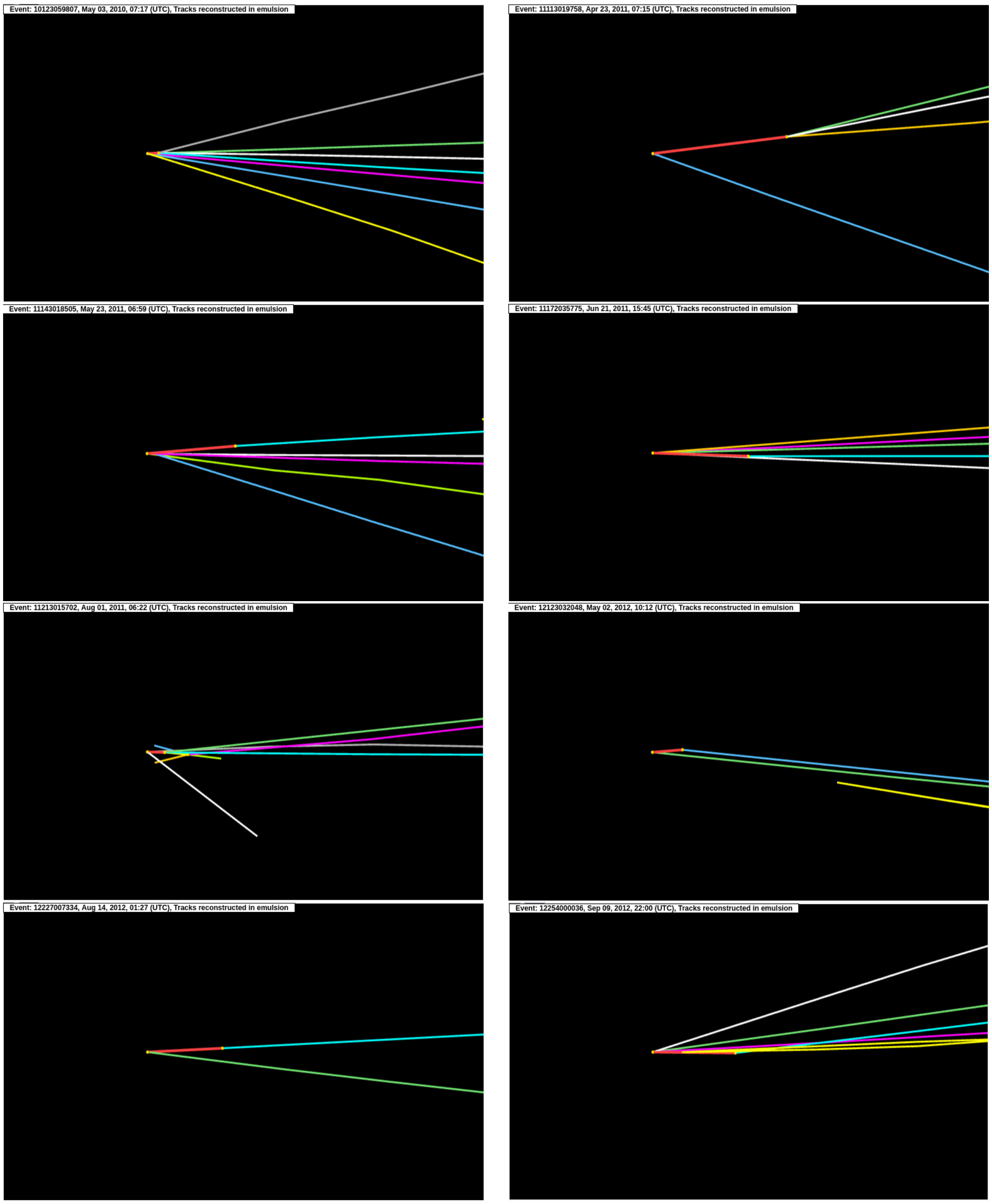
Figure 8

2.3 Task 3: Display of Tracks in Emulsion Detector

In this task a simplified version of a browser based 3D event display that uses the THREE.js library was provided with incomplete source code. We were able to complete the code in order to display tracks and vertices reconstructed in the OPERA emulsion dataset (10 ν_τ-candidate events) for the tau neutrino appearance studies.

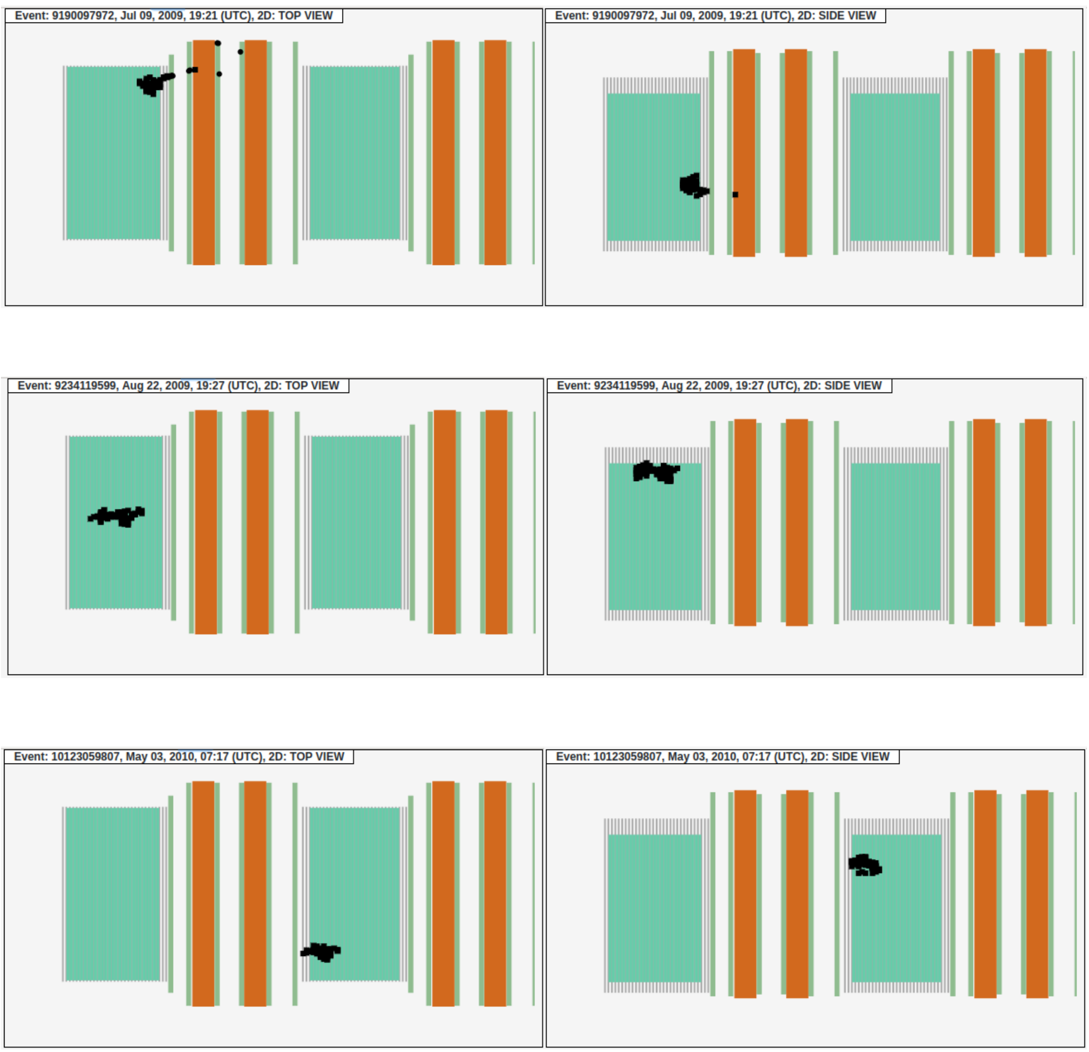


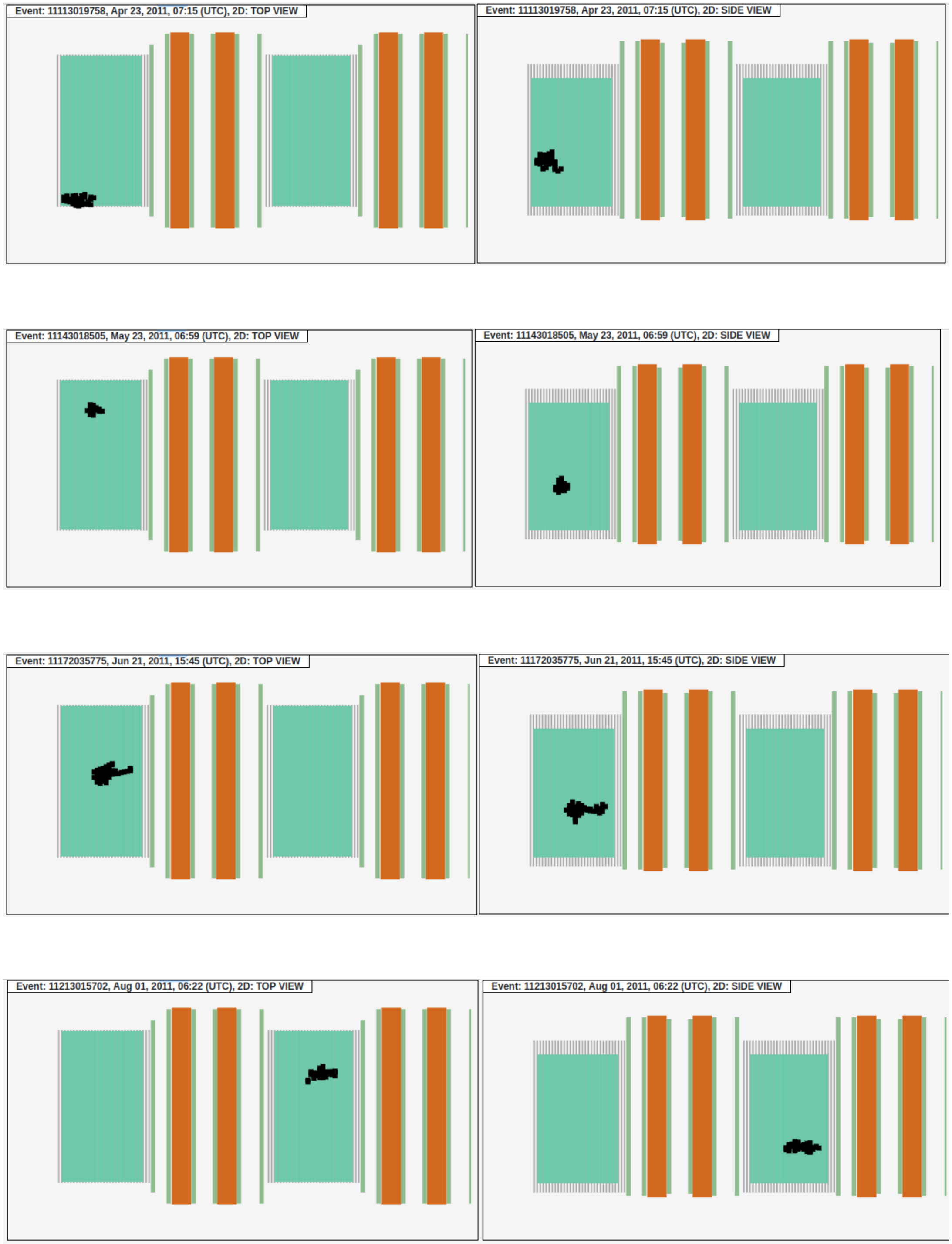



Event: 10123059807, May 03, 2010, 07:17 (UTC), Tracks reconstructed in emulsion
Event: 11113019758, Apr 23, 2011, 07:15 (UTC), Tracks reconstructed in emulsion
Event: 11143018505, May 23, 2011, 06:59 (UTC), Tracks reconstructed in emulsion
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), Tracks reconstructed in emulsion
Event: 11213015702, Aug 01, 2011, 06:22 (UTC), Tracks reconstructed in emulsion
Event: 12123032048, May 02, 2012, 10:12 (UTC), Tracks reconstructed in emulsion
Event: 12227007334, Aug 14, 2012, 01:27 (UTC), Tracks reconstructed in emulsion
Event: 12254000036, Sep 09, 2012, 22:00 (UTC), Tracks reconstructed in emulsion

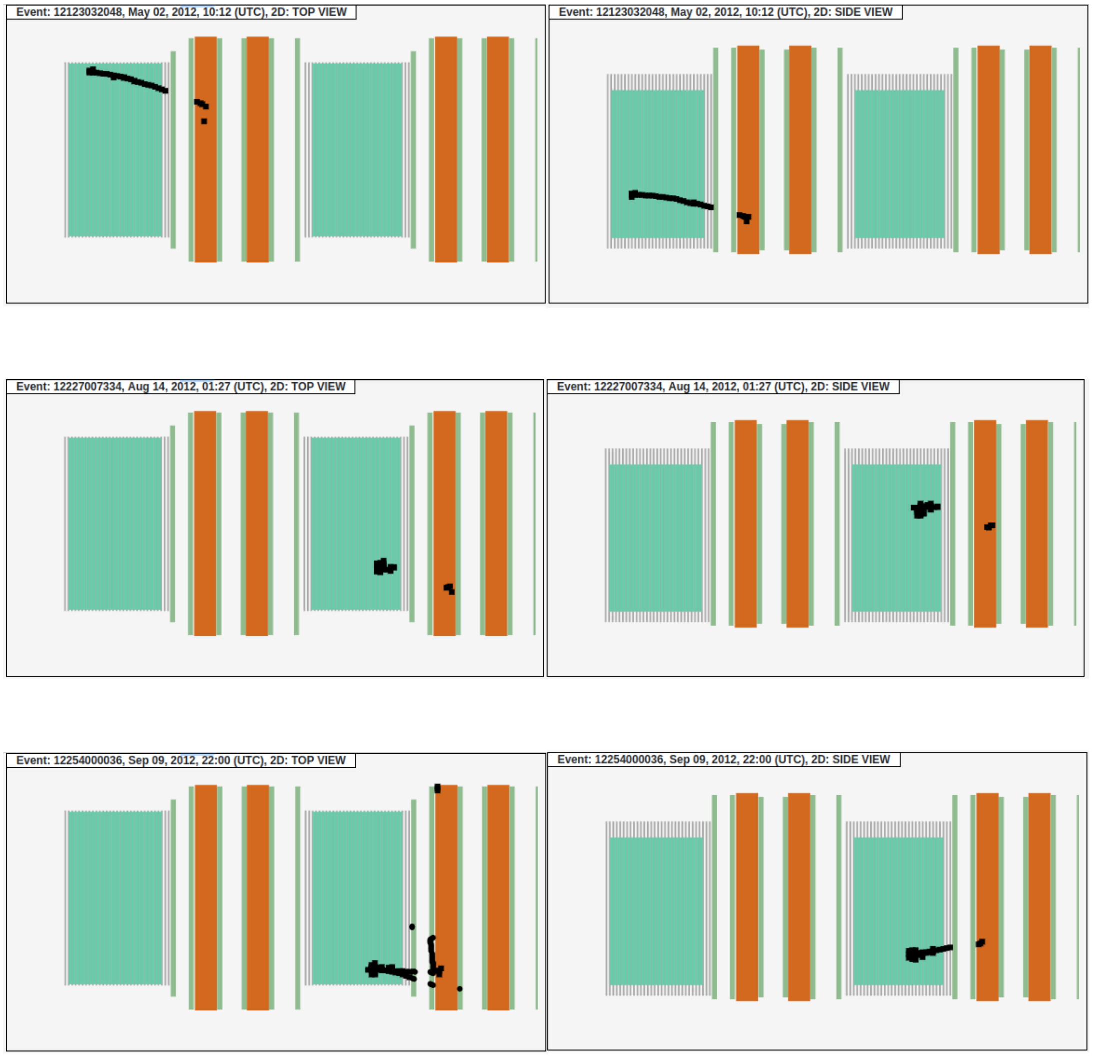
2.4 Task 4: Display of Hits in Electronic Detector

Similar to task 3, a simplified version of a browser based 2D event display that uses the D3.js library was provided with incomplete source code, and we were able to recover the missing part of the code in order to display the electronic detector hits registered in XZ and YZ projections in the same 10 ν_τ-candidate events. As mentioned before the electronic detectors helped determine the most probable brick to contain the neutrino interaction vertex.





Event: 11113019758, Apr 23, 2011, 07:15 (UTC), 2D: TOP VIEW
Event: 11113019758, Apr 23, 2011, 07:15 (UTC), 2D: SIDE VIEW
Event: 11143018505, May 23, 2011, 06:59 (UTC), 2D: TOP VIEW
Event: 11143018505, May 23, 2011, 06:59 (UTC), 2D: SIDE VIEW
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), 2D: TOP VIEW
Event: 11172035775, Jun 21, 2011, 15:45 (UTC), 2D: SIDE VIEW
Event: 11213015702, Aug 01, 2011, 06:22 (UTC), 2D: TOP VIEW
Event: 11213015702, Aug 01, 2011, 06:22 (UTC), 2D: SIDE VIEW


Event: 12123032048, May 02, 2012, 10:12 (UTC), 2D: TOP VIEW
Event: 12123032048, May 02, 2012, 10:12 (UTC), 2D: SIDE VIEW
Event: 12227007334, Aug 14, 2012, 01:27 (UTC), 2D: TOP VIEW
Event: 12227007334, Aug 14, 2012, 01:27 (UTC), 2D: SIDE VIEW
Event: 12254000036, Sep 09, 2012, 22:00 (UTC), 2D: TOP VIEW
Event: 12254000036, Sep 09, 2012, 22:00 (UTC), 2D: SIDE VIEW

3 Results and Discussion

In this project we have been introduced to the phenomenon of neutrino oscillation through the experimental data of the CERN open data portal and, in particular, studied 10 CC interaction events that demonstrate $\nu_\mu \to \nu_\tau$ oscillation. We were able to visualize the track lines of the produced daughter particles and the electronic detector hits, in addition to studying some topological and multiplicity event characteristics that are useful in optimizing event generators and filtering candidate events of significant interest.

We have obtained a good deal of practical experience with the ROOT framework and discovered some of its features, got acquainted with accessing data through the CERN open data portal, and were introduced to some interactive visualization tools using JavaScript graphics libraries.

References

[1] K Nakamura, ST Petcov, et al. Neutrino masses, mixing, and oscillations. 2018.

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[3] N Agafonova, A Alexandrov, A Anokhina, S Aoki, A Ariga, T Ariga, A Bertolin, C Bozza, R Brugnera, A Buonaura, et al. Final results of the opera experiment on ν τ appearance in the cngs neutrino beam. *Physical review letters*, 120(21):211801, 2018.

[4] Sergey Dmitrievsky. status of the opera neutrino oscillation experiment. *Acta Phys. Polon. B*, 41:1539–1546, 2010.

[5] N Agafonova, A Aleksandrov, A Anokhina, S Aoki, A Ariga, T Ariga, D Bender, A Bertolin, C Bozza, R Brugnera, et al. Procedure for short-lived particle detection in the opera experiment and its application to charm decays. *The European Physical Journal C*, 74(8):1–9, 2014.

[6] N Agafonova, A Aleksandrov, A Anokhina, S Aoki, A Ariga, T Ariga, A Bertolin, I Bodnarchuk, C Bozza, R Brugnera, et al. Study of charged hadron multiplicities in charged-current neutrino–lead interactions in the opera detector. *The European Physical Journal C*, 78(1):1–8, 2018.