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

FINAL REPORT OF INTEREST PROGRAMME

Joint Institute for Nuclear Research (JINR), Russia
Dzhelepov Laboratory of Nuclear Problems
INTEREST Programme, Wave 14

Supervisor:
Dr. Sergey Dmitrievsky

Student:
Md Majid Hussain
Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India

Participation Period:
March 02 – April 19, 2026
INTEREST Programme, Wave 14

Abstract

The Standard Model of particle physics originally predicts neutrinos to be massless; however, the observation of neutrino oscillations demonstrates that neutrinos change flavor and therefore possess non-zero mass, indicating physics beyond the Standard Model.The OPERA (Oscillation Project with Emulsion tRacking Apparatus) experiment was designed to provide direct evidence of tau-neutrino appearance in a muon-neutrino beam produced at CERN and detected at the Gran Sasso Laboratory.

This report presents the analysis and visualization of neutrino interaction events recorded by OPERA using datasets from the CERN Open Data Portal, within the framework of the JINR INTEREST Program. The study focuses on reconstruction of charmed hadron decay topologies, analysis of charged hadron multiplicities and muon track angular distributions, and development of an interactive 3D event display.

Using C++ and the ROOT framework, key observables such as flight lengths, impact parameters, and particle multiplicities were extracted. The results show qualitative agreement with published OPERA analyses. Additionally, a web-based 3D visualization using Three.js was developed to enhance interpretation of tau-neutrino candidate events.

Contents

1. Introduction and Theoretical Background

Neutrinos are among the most fundamental and elusive particles in nature. They are electrically neutral, interact only through the weak interaction and gravity, and possess extremely small masses. Their weak coupling to matter makes them difficult to detect, yet precisely for this reason they provide powerful insight into the microscopic structure of the universe.

Historically, the neutrino was proposed by Wolfgang Pauli in 1930 to explain the apparent non-conservation of energy and momentum in beta decay. In the Standard Model of particle physics, neutrinos appear in three flavours:

- electron neutrino (ν_e),
- muon neutrino (ν_μ),
- tau neutrino (ν_τ).

Each flavour is associated with a corresponding charged lepton: the electron, muon, and tau.

One of the most important discoveries in modern particle physics is neutrino oscillation. A neutrino produced in a definite flavour state can later be observed as a different flavour after propagation. This occurs because flavour eigenstates are quantum superpositions of mass eigenstates, and their relation is described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix. The observation of neutrino oscillations implies that neutrinos have non-zero mass and therefore provides direct evidence for physics beyond the original Standard Model formulation.

Among the landmark experiments in this field, the OPERA experiment (*Oscillation Project with Emulsion-tRacking Apparatus*) played a decisive role by targeting the direct observation of tau neutrino appearance in a muon neutrino beam. Unlike disappearance experiments, OPERA sought to identify the flavour transformation explicitly through the observation of tau-lepton decay topologies.

2. The OPERA Experiment

The OPERA detector was installed at the INFN Gran Sasso National Laboratory (LNGS) in Italy, approximately 730 km from CERN. It was exposed to the CNGS beam (CERN Neutrinos to Gran Sasso), a beam initially dominated by muon neutrinos. If oscillations occur during propagation through the Earth's crust, a fraction of these ν_μ should convert into ν_τ before reaching Gran Sasso.

The OPERA apparatus was a hybrid detector that combined:

1. **Emulsion Cloud Chambers (ECCs)** made of lead plates interleaved with nuclear emulsion films, providing micrometric spatial resolution.

2. **Electronic detectors** for event triggering, timing, muon identification, and detector-level topological information.

A typical OPERA brick consisted of 57 emulsion films interleaved with 56 lead plates. The lead served as a dense target for neutrino interactions, while the emulsion layers acted like photographic detectors that recorded charged-particle trajectories with very high precision. In addition, Changeable Sheets (CS) were used as interface emulsion films to reduce scanning load and guide the scan-back procedure toward the interaction vertex.

The distinctive signature of a tau-neutrino charged-current interaction is the production of a short-lived tau lepton, which decays after a very short flight distance. This decay often appears as a visible kink or displaced secondary vertex in the emulsion data. By reconstructing such topologies, OPERA achieved the direct observation of $\nu_\mu \to \nu_\tau$ oscillation. Over the course of the experiment, ten tau-neutrino candidate events were identified, providing statistically significant evidence of flavour appearance.

Beyond its primary oscillation result, OPERA also generated high-quality datasets for charm production, charged hadron multiplicity, muon and electron neutrino interactions, and tau-neutrino appearance. These datasets are now available through the CERN Open Data Portal, making them highly valuable for education and open-data-based research.

3. Project Objectives

The combined objective of the uploaded reports is to analyze and visualize neutrino interaction events from the OPERA experiment using public datasets from the CERN Open Data Portal. More specifically, the work aims to:

1. Study charmed hadron production and reconstruct decay-related observables such as flight length and daughter-track impact parameter;

2. Analyze charged hadron multiplicities in neutrino–lead interactions and investigate the angular distribution of muon tracks;

3. Reconstruct and visualize tau-neutrino candidate event topologies in an interactive browser-based environment;

4. In the most extended implementation, integrate emulsion-based 3D visualization with electronic-detector 2D hit displays for a unified detector-wide event interpretation.

These tasks build practical skills in C++, ROOT, computational geometry, browser-based visualization, and interpretation of real high-energy physics data.

4. Scope of Work and Methods

4.1 Task 1: Charmed Hadron Analysis

The charm-production dataset contains 50 muon-neutrino charged-current interactions in lead in which a charmed hadron was reconstructed. These events are especially important because charm decays can mimic tau-like decay topologies and therefore serve as a valuable control sample for validating the detector and the analysis procedure.

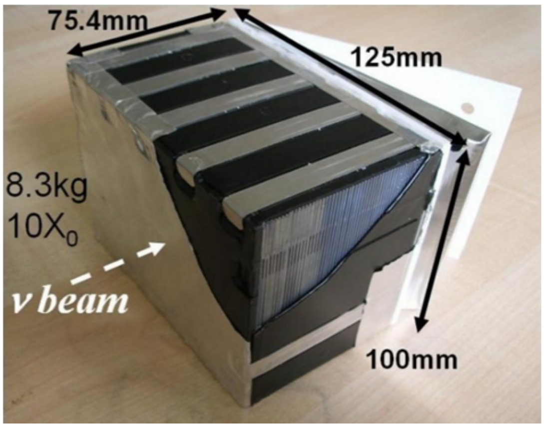


Figure 1: Emulsion Cloud Chamber (ECC)

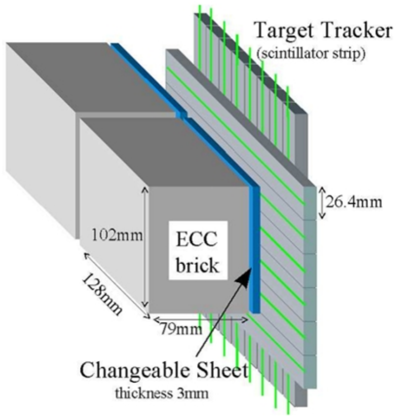


Figure 2: Changeable Sheets with target tracker

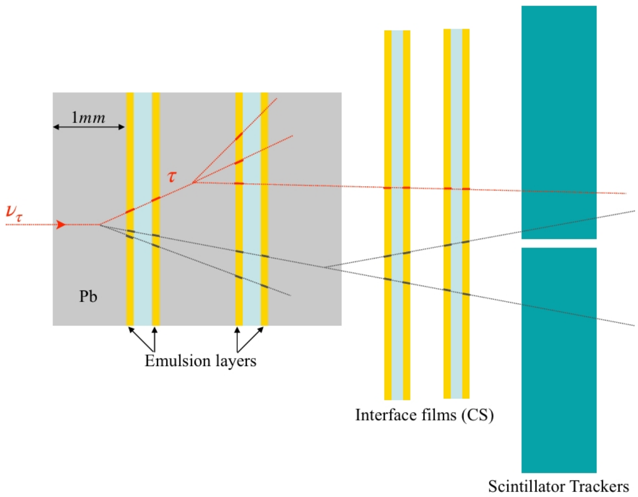


Figure 3: Schematic view of a v_τ CC interaction and the decay-in-flight of the final state τ lepton as it would appear in an OPERA brick, in the interface emulsion films (Changable Sheets), and in the scintillator trackers (Target Trackers)

The analysis workflow consisted of:

- Reading the CSV files containing the primary interaction vertex, the secondary decay vertex, and daughter-particle track information;

- Reconstructing the decay geometry using C++ and the ROOT framework;
- Calculating the charm flight length from the primary and secondary vertex co-ordinates;
- Calculating the impact parameter of daughter tracks relative to the primary vertex;
- Generating ROOT histograms and comparing them qualitatively with published OPERA distributions.

If the primary vertex is at (x_1, y_1, z_1) and the secondary vertex is at (x_2, y_2, z_2), the charm flight length is

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}. \tag{1}$$

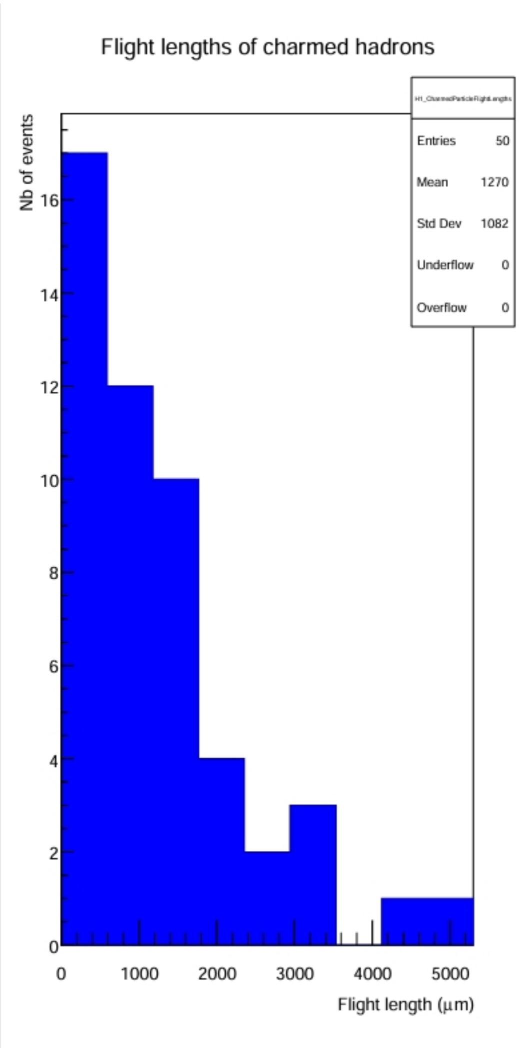


Figure 4: Analysis Result

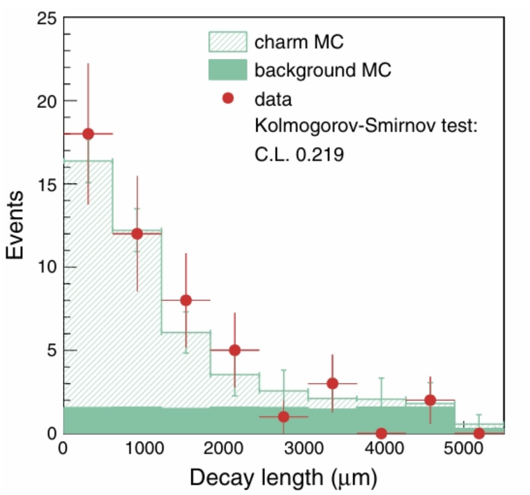


Figure 5: OPERA Paper Result

To compute the impact parameter, consider the primary vertex $P_1(x_1, y_1, z_1)$ and the daughter track defined by the secondary vertex $P_2(x_2, y_2, z_2)$ and another point on the same track $P_3(x_3, y_3, z_3)$. The impact parameter is the perpendicular distance from the primary vertex to the daughter track:

$$IP = \frac{\left\| \overrightarrow{P_2P_1} \times \overrightarrow{P_2P_3} \right\|}{\left\| \overrightarrow{P_2P_3} \right\|}. \tag{2}$$

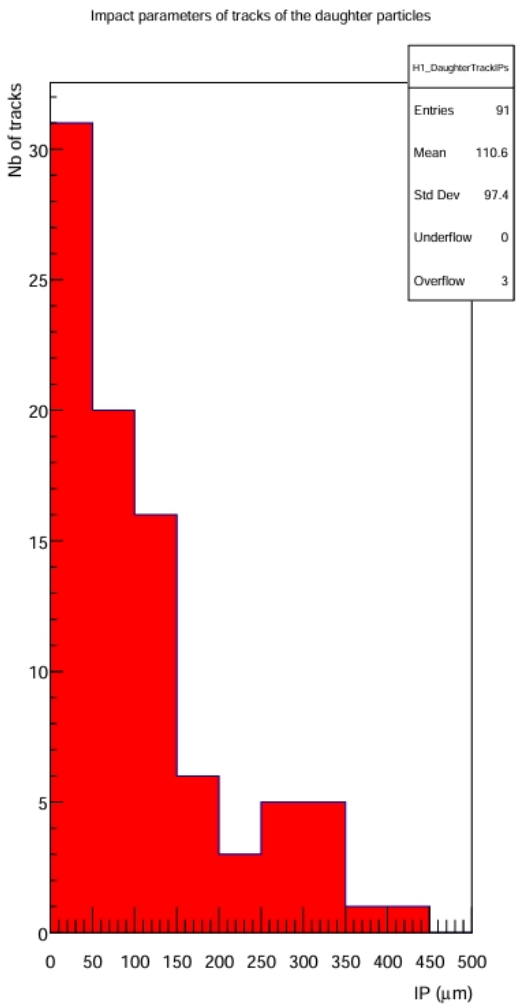


Figure 6: Analysis Result

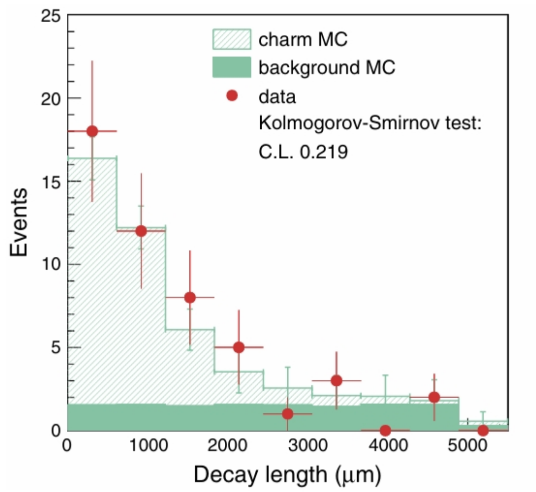


Figure 7: OPERA Paper Result

The generated flight-length and impact-parameter distributions reproduce the qualitative features reported by the OPERA Collaboration: an approximately exponential behaviour for the decay-length spectrum and an impact-parameter distribution with the expected non-trivial tail.

4.2 Task 2: Charged Hadron Multiplicity and Muon Track Angles

The hadron-multiplicity dataset contains 817 muon-neutrino charged-current interactions with a lead target in which a muon was detected. The purpose of this task is to characterize the topology of the hadronic final state and to study the geometry of the muon tracks.

The C++/ROOT analysis included:

- identifying the primary neutrino interaction vertex;
- counting the number of charged secondary particles to construct multiplicity histograms;
- extracting track slopes from the XZ and YZ projections;
- converting slopes to angular variables;
- constructing one-dimensional and two-dimensional histograms for multiplicity and muon-angle distributions.

If a track has slope m with respect to the z-axis, the corresponding angular variable is obtained from

$$\theta = \tan^{-1}(m). \tag{3}$$

In practice, the two projected angular coordinates are written as

$$\theta_x = \arctan(\text{slope}_{XZ}), \qquad \theta_y = \arctan(\text{slope}_{YZ}). \tag{4}$$

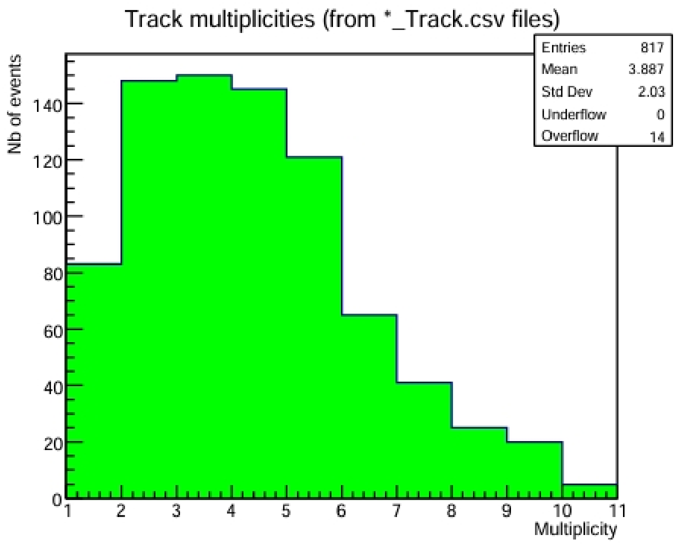


Figure 8: Track multiplicity of all produced charged particles.

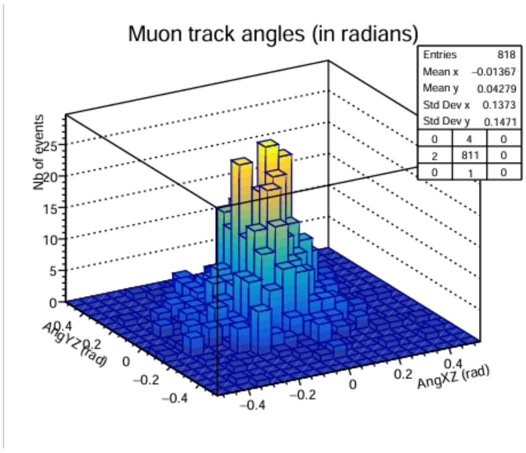


Figure 9: 2-D Angular distribution of muon tracks

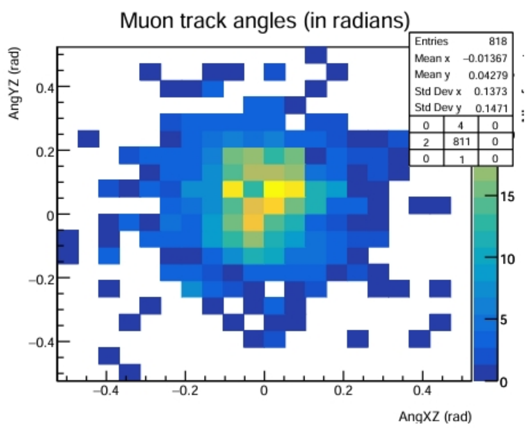


Figure 10: 1-D Angular distribution of muon tracks

The multiplicity distribution shows that most events produce only a small number of charged hadrons, consistent with the behaviour reported in OPERA publications. Likewise, the muon-angle distributions are centered close to zero, as expected for forward-going muons in CNGS beam interactions.

An interesting feature of this event sample is the presence of 818 reconstructed muon tracks for 817 neutrino interaction vertices. Further study of the sample revealed that one event contains two tracks identified as muons, making it a dimuon event.

4.3 Task 3: Interactive 3D Visualization of Tau-Neutrino Candidate Events

A major goal of the project was to develop an interactive visualization environment for the ten tau-neutrino candidate events observed by OPERA. The 3D visualization is based on browser technologies and the THREE.js graphics library.

The visualization uses two principal data sources:

- `EventID_Vertex.csv`, containing interaction-vertex coordinates,
- `EventID_Lines.csv`, containing points along each reconstructed particle trajectory.

The development process involved restoring or completing missing parts of an existing source code base. In the 3D display, vertices are drawn as geometric objects placed relative to the primary interaction point. Tracks are reconstructed by determining their 3D endpoints and then rendering them as lines or tubes in the scene.

This visualization makes it possible to inspect characteristic tau-decay signatures directly in a browser. The resulting event display provides an intuitive understanding of the observed kinks, displaced vertices, and the spatial relationship among daughter particles.

An interesting feature of this event sample is the presence of 818 reconstructed muon tracks for 817 neutrino interaction vertices. Further study of the sample revealed that

one event contains two tracks identified as muons, making it a dimuon event. This observation demonstrates that the reconstruction procedure is capable of identifying rare topologies beyond the simplest charged-current signature.

4.4 Task 4: Integrated Visualization with Electronic Detector Data

The visualization task can be extended by combining the emulsion-based 3D display with a 2D representation of the electron detector (ED) responses using the D3.js library. In this integrated system, the electronic detector is displayed through XZ and YZ projections, while emulsion-reconstructed vertices and tracks are simultaneously shown in 3D.

The restored ED visualization includes:

- mapping detector channels to their physical geometry,
- rendering scintillator hits as SVG objects,
- amplitude-based colour encoding of detector response,
- synchronization of the ED view with the emulsion-based event display.

A representative colour legend is given in Table 1 and Table 2.

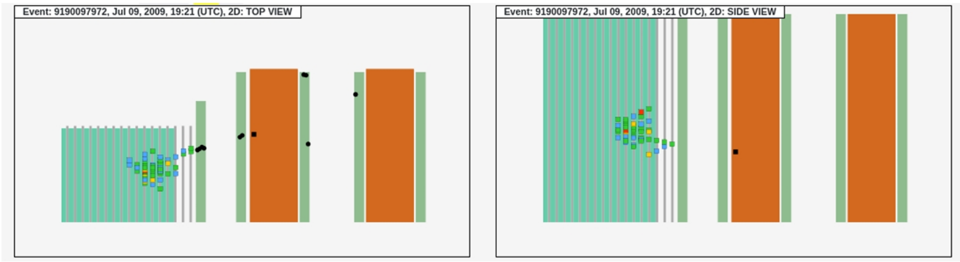
Table 1: Track colour legend for the 3D emulsion display.

Colour	Track type
Red	Parent τ track (reconstructed or restored)
Yellow	Hadron track or electromagnetic shower segment
Cyan	τ-lepton daughter track
White	Hadron track
Magenta	Hadron track or electromagnetic shower segment

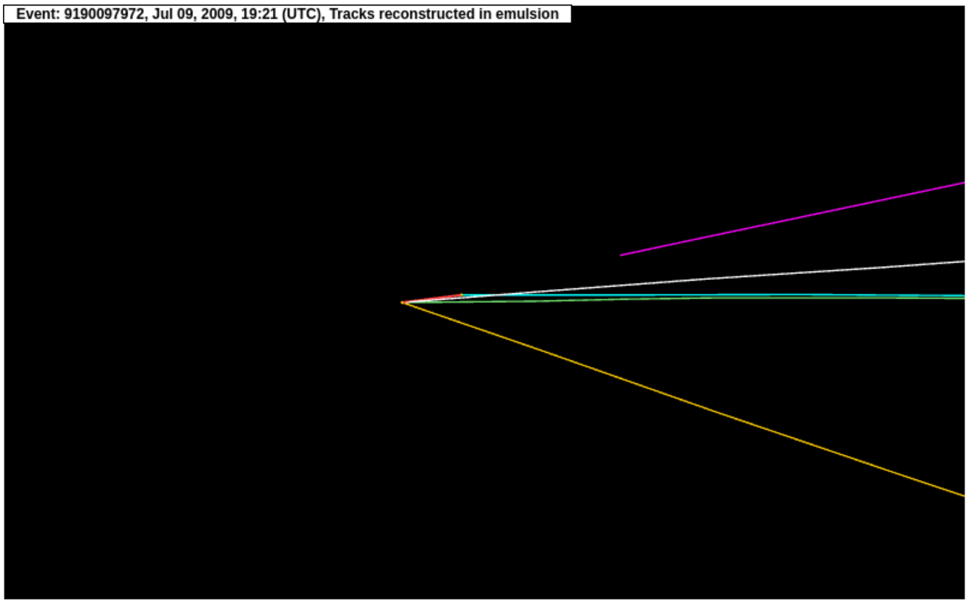
Table 2: Amplitude colour legend for the 2D electronic detector display.

Colour	Amplitude
Deep blue	0
Cyan	5
Green	10
Yellow	15
Orange	20
Red	> 20

The integrated display produces a richer detector-wide interpretation of neutrino interactions by correlating emulsion-track topology with electronic-detector hit patterns. This enhances the educational and interpretive value of the open data considerably.

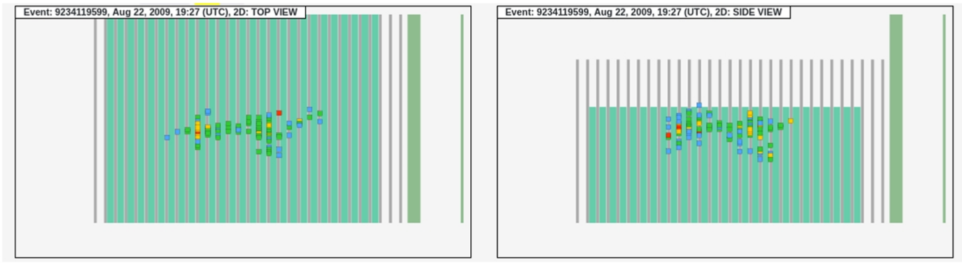


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 9190097972,



(b) Event displays for nuclear emulsion films

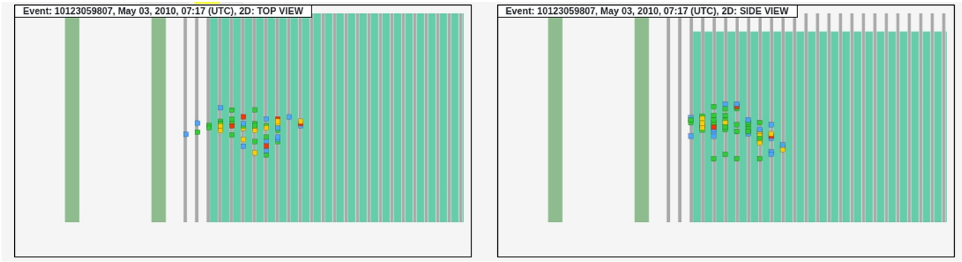
Figure 11: Combined figure with (a) and (b)



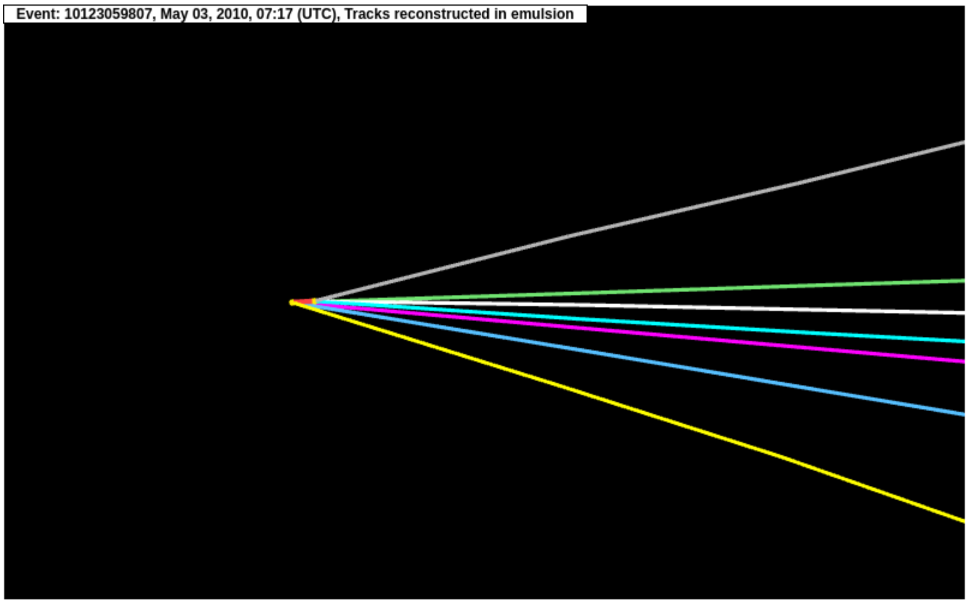
(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 9234119599,

(b) Event displays for nuclear emulsion films

Figure 12: Combined figure with (a) and (b)

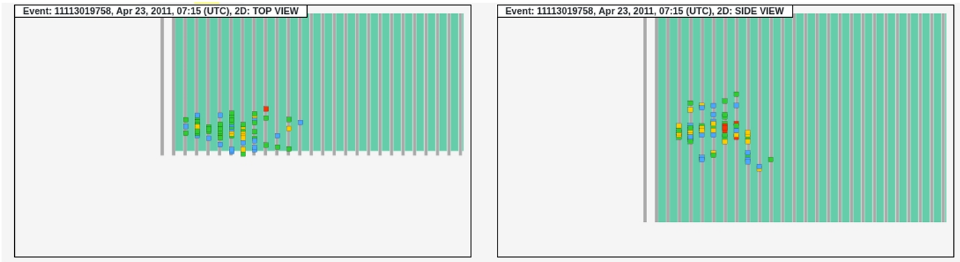


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 10123059807,

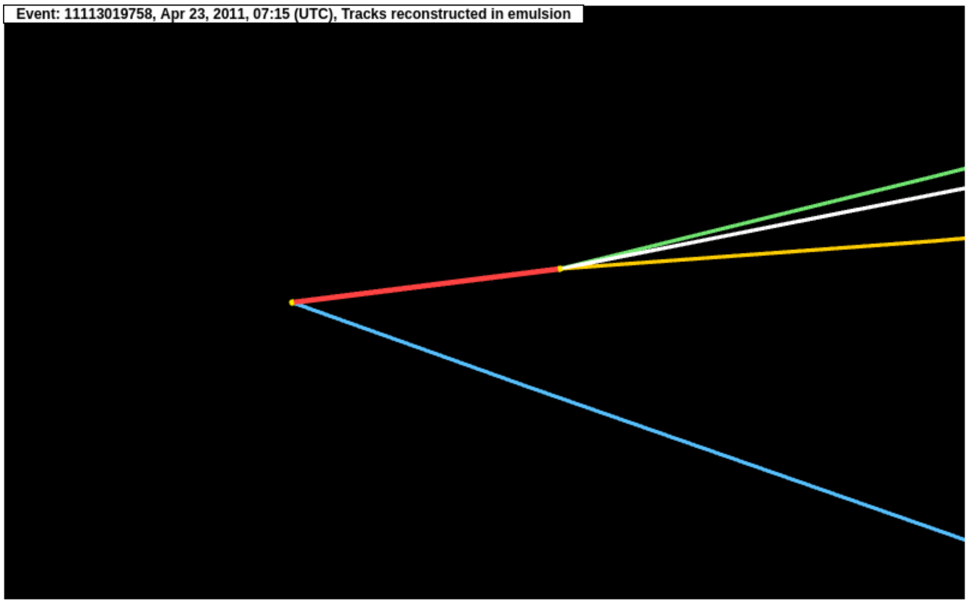


(b) Event displays for nuclear emulsion films

Figure 13: Combined figure with (a) and (b)

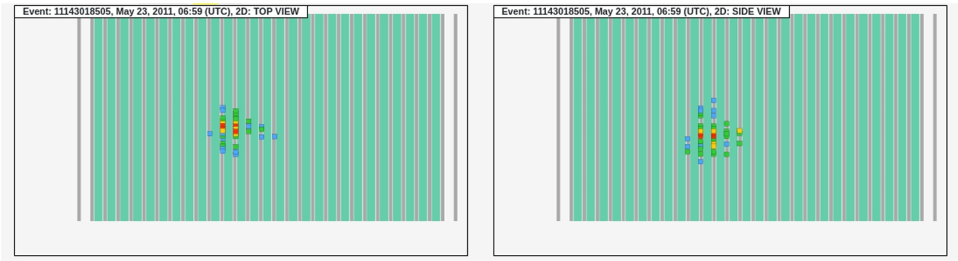


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 11113019758,

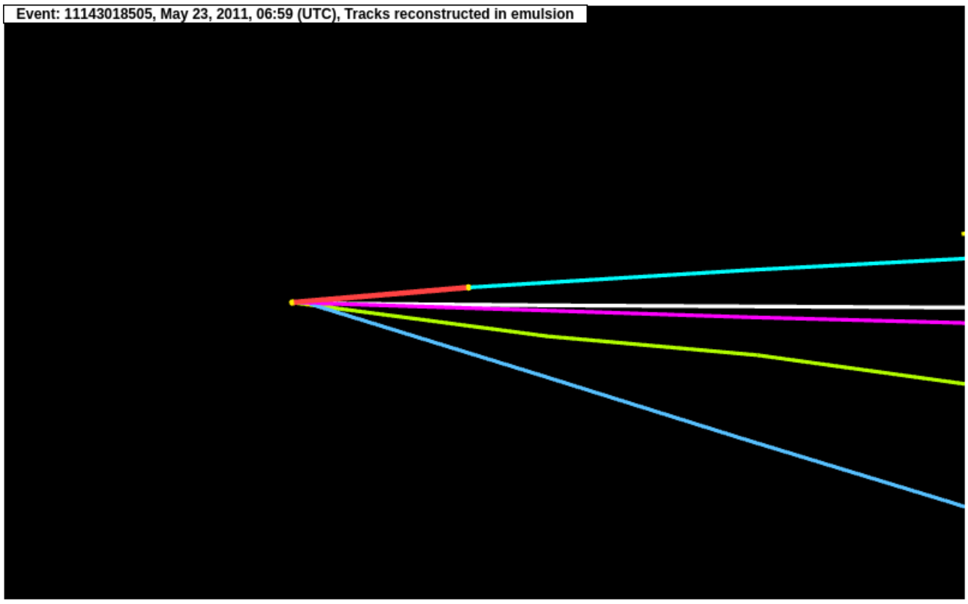


(b) Event displays for nuclear emulsion films

Figure 14: Combined figure with (a) and (b)

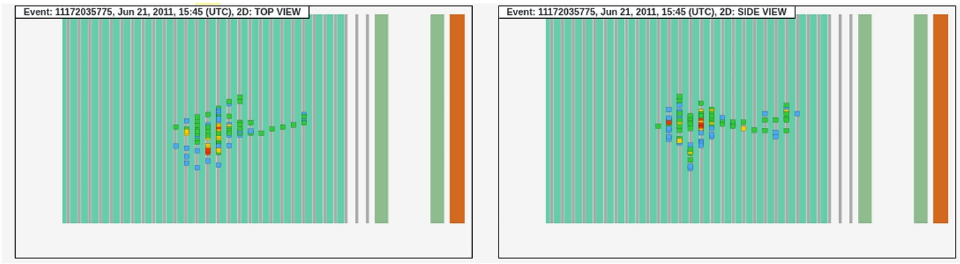


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 11143018505,

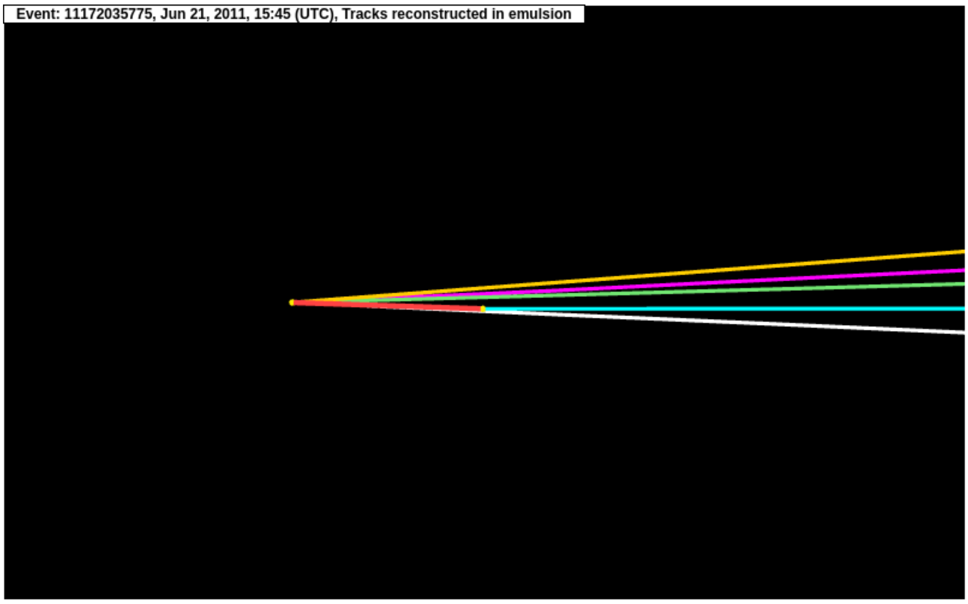


(b) Event displays for nuclear emulsion films

Figure 15: Combined figure with (a) and (b)

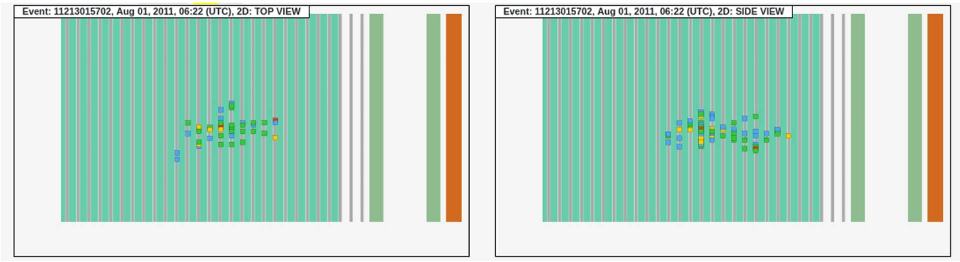


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 11172035775,

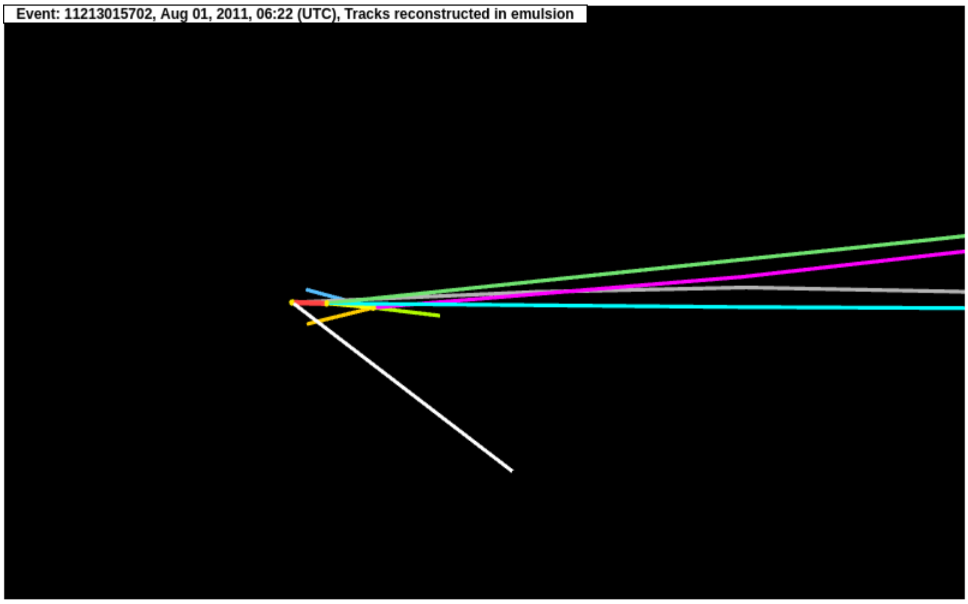


(b) Event displays for nuclear emulsion films

Figure 16: Combined figure with (a) and (b)

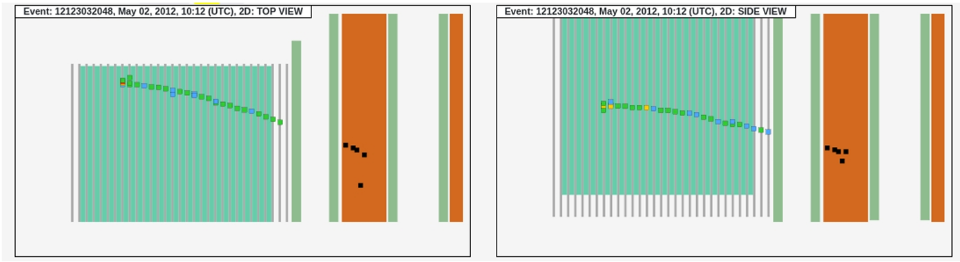


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 11213015702,

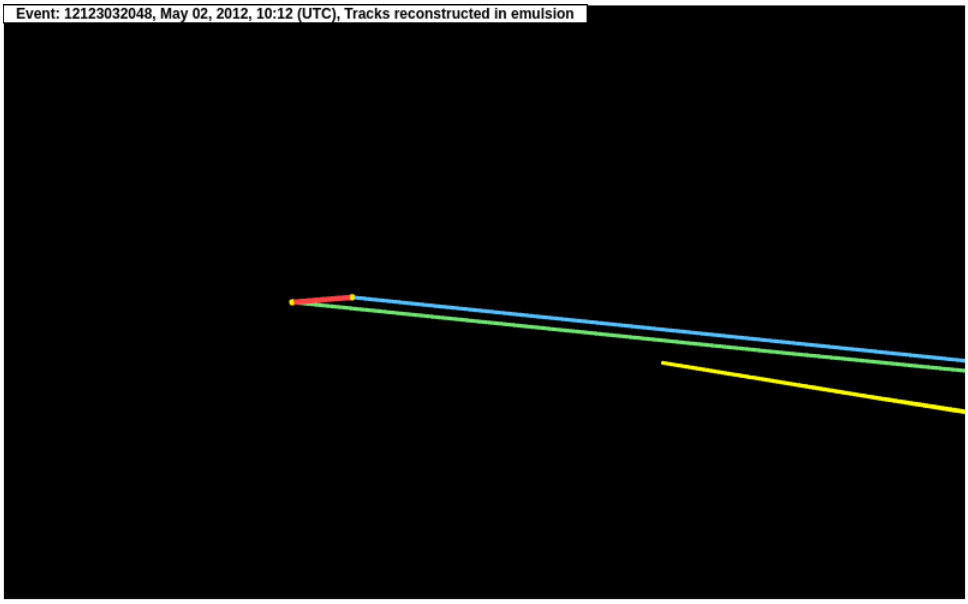


(b) Event displays for nuclear emulsion films

Figure 17: Combined figure with (a) and (b)

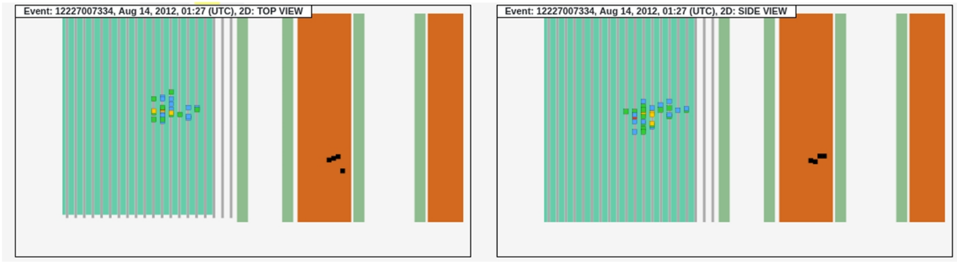


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 12123032048,

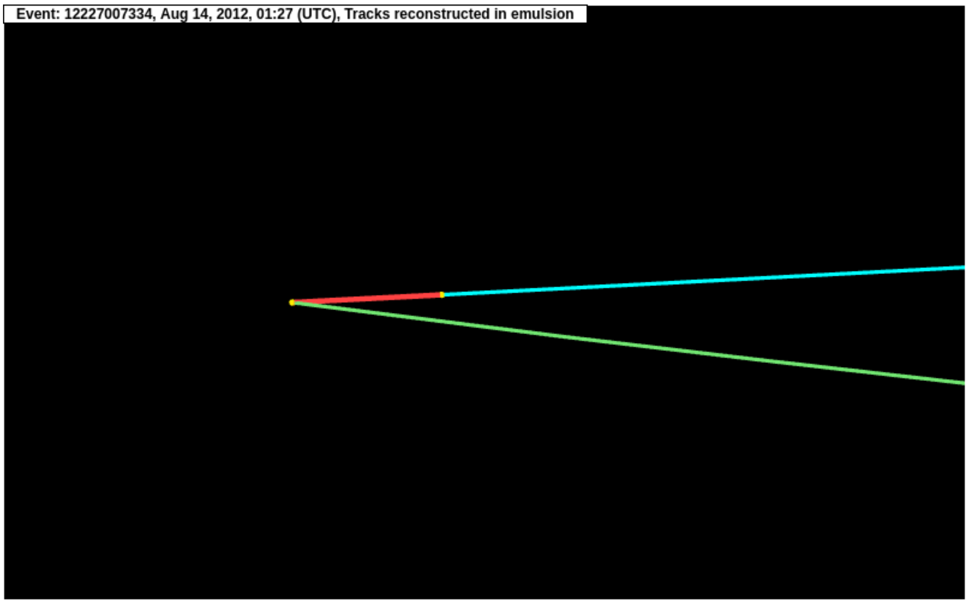


(b) Event displays for nuclear emulsion films

Figure 18: Combined figure with (a) and (b)

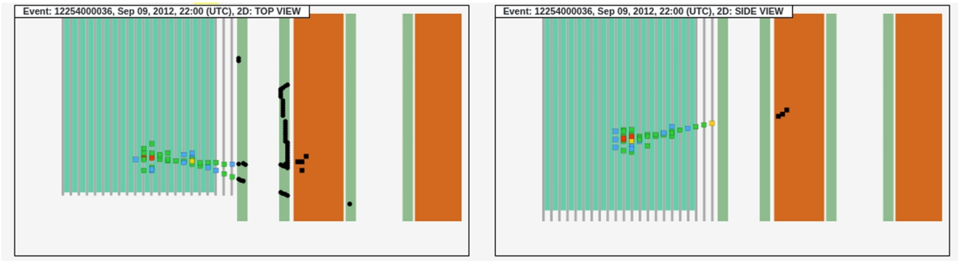


(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 12227007334,

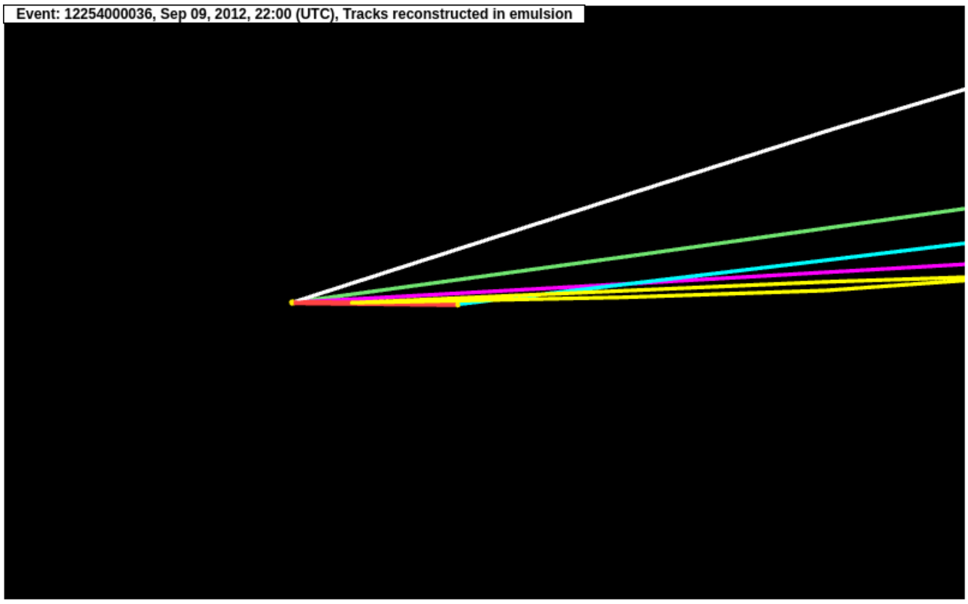


(b) Event displays for nuclear emulsion films

Figure 19: Combined figure with (a) and (b)



(a) Event displays for electronic detector data (top view on the left and side view on the right) for the ν_τ candidate event 12254000036,



(b) Event displays for nuclear emulsion films

Figure 20: Combined figure with (a) and (b)

5. Results and Discussion

5.1 Charm topology reconstruction

The charm analysis successfully reconstructs the decay geometry from publicly available emulsion datasets. Both flight-length and impact-parameter histograms show strong qualitative agreement with OPERA reference plots. Small discrepancies are expected because parts of the original emulsion scanning and subsequent measurements were distributed across different laboratories. Nevertheless, the reproduced shapes validate the reconstruction method and demonstrate the consistency of the public data.

5.2 Multiplicity and muon-angle analysis

The charged-hadron multiplicity distribution follows the expected pattern of neutrino–lead charged-current interactions, with low multiplicity dominating the sample. The muon angular distributions are concentrated near the beam direction, reflecting the forward-boosted geometry of the CNGS beam. The discovery of a dimuon event through the comparison of 817 interaction vertices and 818 reconstructed muon tracks is a particularly notable internal consistency check and highlights the physics richness of the dataset.

5.3 Visualization of tau-neutrino candidate events

The visualization tasks were successful in reconstructing the ten tau-neutrino candidate events in a browser environment. The event displays reveal the characteristic short-lived tau decay topology and allow the user to examine the spatial arrangement of daughter tracks, displaced vertices, and, in the most advanced implementation, the corresponding detector hits in the electronic subsystem.

The combined visualization approach is important not only as a graphical complement to statistical analysis but also as a physics tool. In neutrino experiments based on emulsion detectors, the direct visual interpretation of decay kinks and prong structure remains crucial for understanding how the oscillation signal emerges from complex event topologies.

6. Conclusion

The analysis of charmed hadron production confirms that secondary decay vertices can be reconstructed reliably from emulsion data and that derived observables such as flight length and impact parameter agree qualitatively with published OPERA results. The charged-hadron multiplicity study reproduces the expected distributions and shows that muon tracks are predominantly aligned with the beam geometry. The appearance of a dimuon event further demonstrates the sensitivity of the analysis chain to rare and interesting event structures.

The visualization component adds a powerful qualitative dimension to the project. By restoring and extending interactive browser-based displays, the work makes the topology of tau-neutrino candidate events directly observable. In the most advanced version, the integration of 3D emulsion reconstruction with 2D electronic detector views produces a unified representation of the event, strengthening the link between detector response and reconstructed particle trajectories.

Taken together, these results validate the educational and scientific value of the OPERA Open Data Portal. The project provides practical training in high-energy physics data analysis, detector reconstruction, computational geometry, and scientific visualization. More broadly, it illustrates how open-data initiatives can bridge the gap between theoretical particle physics and real experimental practice.

Acknowledgements

I would like to sincerely thank the JINR INTEREST Programme for providing the opportunity to work on real experimental data from the OPERA experiment. I am especially grateful to my supervisor, Dr. Sergey Dmitrievsky, for his guidance, support, and valuable discussions throughout the project.

I also acknowledge the CERN Open Data Portal for making the OPERA datasets publicly available, enabling this analysis and visualization study. This project has been an invaluable experience in developing practical skills in high-energy physics data analysis and scientific visualization.

References

[1] CERN Open Data Portal, https://opendata.cern.ch.

[2] N. Agafonova *et al.* (OPERA Collaboration), "The OPERA experiment," *Journal of Instrumentation* **4** (2009) P04018.

[3] N. Agafonova *et al.*, "The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment," *Journal of Instrumentation* **4** (2009) P06020.

[4] S. Dmitrievsky, "Status of the OPERA Neutrino Oscillation Experiment," *Acta Physica Polonica B* **41** (2010).

[5] N. Agafonova *et al.*, "OPERA tau neutrino charged current interactions," *Scientific Data* **8** (2021) 218.

[6] OPERA Collaboration, "Emulsion data for neutrino-induced charmed hadron production studies," CERN Open Data Portal, DOI: https://doi.org/10.7483/OPENDATA.OPERA.R5MW.SEFX.

[7] OPERA Collaboration, "Emulsion data for track multiplicity," CERN Open Data Portal, DOI: https://doi.org/10.7483/OPENDATA.OPERA.BVC1.UI85.

[8] OPERA Collaboration, "Study of charged hadron multiplicities in charged-current neutrino interactions in the OPERA detector," *European Physical Journal C* (2015); see also arXiv:1706.07930.

[9] OPERA Collaboration, "Final results of the OPERA experiment on ν_τ appearance in the CNGS beam," *Physical Review Letters*.

[10] ROOT Data Analysis Framework, CERN, https://root.cern.

[11] THREE.js Documentation, https://threejs.org.

[12] D3.js Documentation, https://d3js.org.