JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE
INTEREST PROGRAMME

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

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Abstract

This report presents the analysis and visualization of neutrino interaction topologies recorded by the OPERA experiment and published through the CERN Open Data Portal. The study consists of three tasks: (1) reconstruction and analysis of charmed hadron decay topologies, (2) analysis of charged hadron multiplicities and muon track angular distributions, and (3) restoration of an incomplete JavaScript-based 3D event display to visualize tau neutrino candidate events in nuclear emulsions.

Using C++ and the ROOT framework, key physical observables such as charmed hadron flight lengths, impact parameters, charged particle multiplicities, and muon track angles were reconstructed and plotted. Additionally, a fully functional interactive 3D visualization was implemented using HTML, CSS, and THREE.js. The results qualitatively agree with previously published OPERA analyses and demonstrate the educational value of the OPERA Open Data Portal.

1. Introduction

The study of neutrino interactions provides unique insight into weak interactions, oscillation phenomena, and lepton-flavour transformation. The OPERA experiment (Oscillation Project with Emulsion-tRacking Apparatus) was designed to perform a direct observation of muon-to-tau neutrino oscillations by identifying the short-lived τ-lepton produced in charged-current interactions of tau neutrinos.

In 2010, OPERA reported the first candidate tau neutrino event, and by 2018 the Collaboration had observed **ten tau neutrino candidates**, providing significant evidence for the appearance of tau neutrinos in a muon neutrino beam.

The CERN Open Data Portal now hosts a substantial portion of OPERA's emulsion and electronic detector data. This enables students and researchers to analyze real neutrino events, reconstruct topologies, and explore particle interactions with micrometric precision.

The present work focuses on three main tasks involving data analysis and event visualization, demonstrating the workflow of handling emulsion detector CSV files, extracting physics observables, and constructing interactive 3D displays.

2. The OPERA Experiment

The OPERA detector was located in the INFN Gran Sasso underground laboratory in Italy, 730 km away from CERN. Muon neutrinos from the CNGS (CERN Neutrinos to Gran Sasso) beam traversed the Earth's crust and arrived at the detector, where some oscillated into tau neutrinos.

OPERA's hybrid detection apparatus consisted of:

1) **Emulsion Cloud Chambers (ECCs)** composed of:
   a) Lead plates serving as neutrino interaction targets
   b) Nuclear emulsion films with ~1 μm spatial resolution
2) **Electronic detectors** used for:
   a) event triggering
   b) muon identification
   c) timing information

This combination enabled OPERA to identify the τ-lepton decay topology:
short decay length (~mm), kink angle, impact parameter, and associated daughter tracks.

OPERA also provided high-quality datasets for:

   I.   charm production
   II.   charged hadron multiplicities
   III. muon and electron neutrino interactions
   IV.   tau neutrino appearance

These datasets are available as CSV archives through the CERN Open Data Portal.

3. Project Description

This project explores how OPERA open data can be processed, analyzed, and visualized.

The work is divided into three tasks:

1. **Charm decay topology analysis**
2. **Charged hadron multiplicity analysis**
3. **3D visualization of tau neutrino candidate events**

Each task includes reading raw CSV files, reconstructing event features, and generating analysis plots or interactive displays.

4. Charm Hadron Decay Analysis (Task 1)

4.1. Objective.
To read OPERA charm production datasets and reconstruct measurable quantities, specifically:

- Charm flight lengths
- Impact parameters of daughter tracks

4.2. Methodology.
C++ code was developed to: Parse vertex CSV files (primary and secondary vertices), Identify charm daughters, Compute flight distance as:

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

Compute impact parameter (IP) of a daughter track using line-to-point distance formula:

$$IP = \frac{|\overrightarrow{V_0V_1} \times \overrightarrow{V_1P_2}|}{|\overrightarrow{V_1P_2}|}$$

where

- $\overrightarrow{V_0V_1} = (dx_{10}, dy_{10}, dz_{10})$ is the vector from the primary vertex to the daughter point,
- $\overrightarrow{V_1P_2} = (dx_{21}, dy_{21}, dz_{21})$ is the direction vector of the daughter track.

Expanding the cross-product and magnitudes explicitly:

$$IP = \sqrt{\frac{(dy_{10}dz_{21} - dy_{21}dz_{10})^2 + (dx_{10}dz_{21} - dx_{21}dz_{10})^2 + (dx_{10}dy_{21} - dx_{21}dy_{10})^2}{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}}$$

4.3. Results.

Charm Hadron Flight Length

Entries	50
Mean	1270
Std Dev	1082
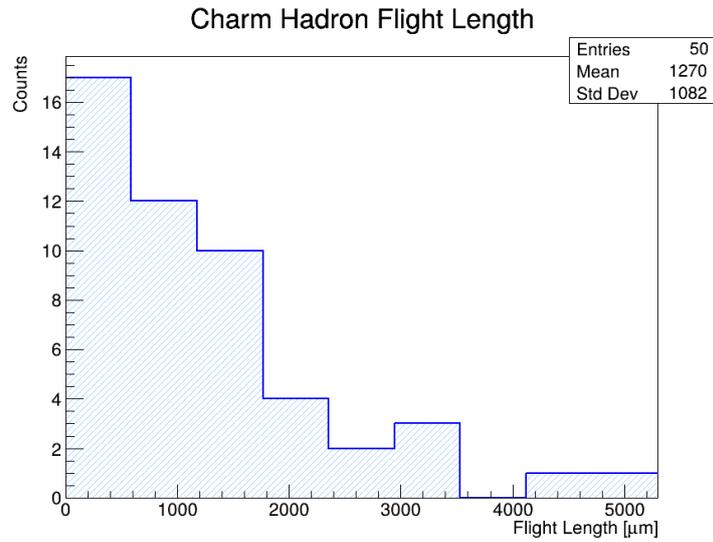
Figure 4.1 *Flight Length Distribution*

Impact Parameter

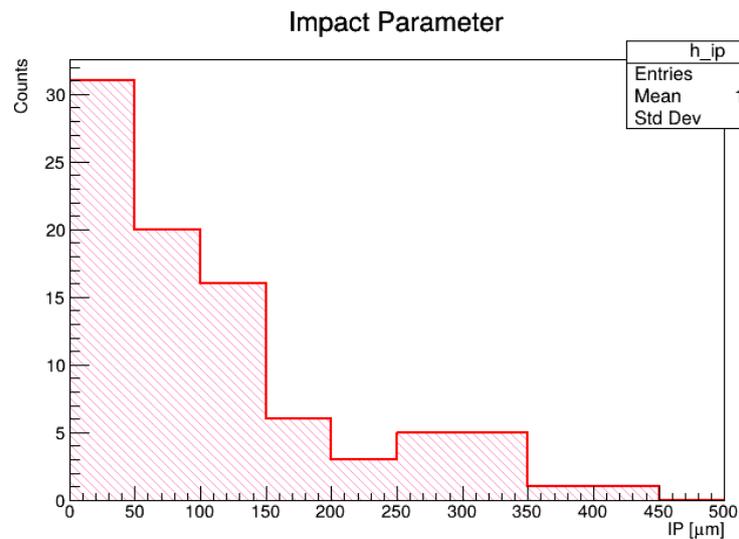| h_ip | |
Entries	91
Mean	110.6
Std Dev	97.4

Figure 4.a *Impact Parameter Distribution*

The distributions reproduce the qualitative features reported in OPERA publications: exponential flight-length behavior and a characteristic impact-parameter tail.

5. Charged Hadron Multiplicity & Muon Angle Analysis (Task 2)

5.1. Objective. To analyze neutrino-lead interactions and extract:
- **Charged particle multiplicity distribution**
- **Muon track angular distribution**

5.2. Methodology. A C++/ROOT program was written to:
- Read primary vertices and all associated secondary tracks
- Extract track slopes (slope$_{XZ}$, slope$_{YZ}$)
- Convert slopes to angle through:

$$\theta_x = \arctan(slope_{xz}), \theta_y = \arctan(slope_{yz})$$

- Fill:
  - A **1D multiplicity histogram** (0–10)
  - A **2D muon angle histogram** (θx vs θy) with ranges −0.5 to 0.5 rad
  - A **3D isometric angular histogram** (optional visualization)

5.3. Results
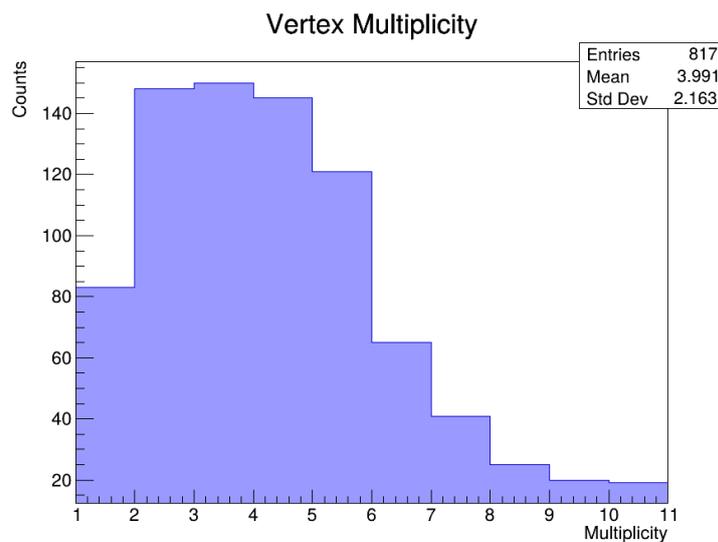
Figure 5.1 Track Multiplicity Distributions

Muon Track Angles (Isometric Projection)
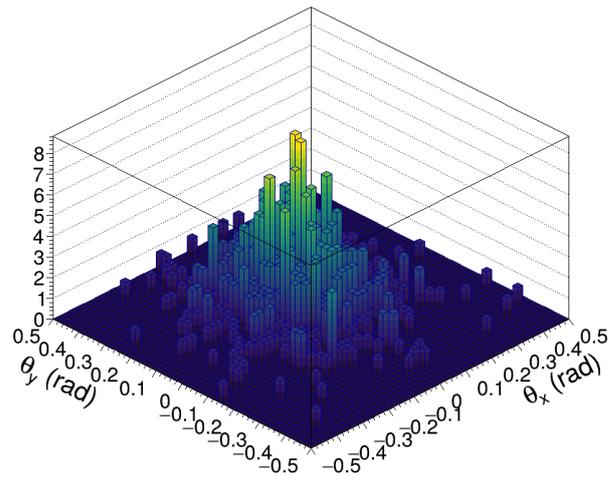
Figure 5.2 Muon Track Angles Distribution (Isometric Projection)

Muon Track Angles (Top Projection)
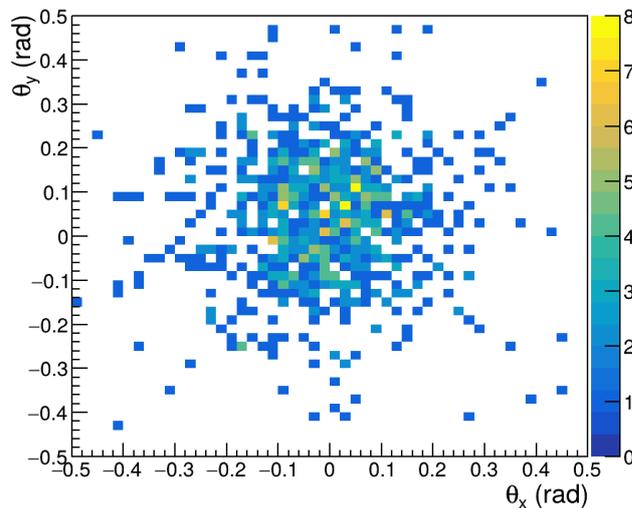
Figure b.3 Muon Track Angles Distribution (Top Projection)

Multiplicity distributions follow the expected OPERA charged-hadron multiplicity patterns, with most events yielding a small number of charged tracks. The muon angle distributions are centered near zero, consistent with forward-boosted CNGS muon neutrino interactions.

The charged-particle multiplicities obtained agree with the distributions published by the
OPERA Collaboration. (2015). Study of charged hadron multiplicities in charged-current neutrino interactions in the OPERA detector. Eur. Phys. J. C.

6. Combined Visualization of Emulsion and Electronic Detector Event Topologies (Task 3 and 4)

6.1. Objective

The objective of this part of the project is to restore, complete, and integrate two interactive visualization systems:

1. **A 3D THREE.js event display** showing emulsion-reconstructed vertices and particle tracks.
2. **A 2D D3.js event display** showing electronic detector (ED) hits in XZ and YZ projections with amplitude-based colour maps.

Both visualizations are synchronized to show the ten OPERA τ-neutrino candidate events.
This integrated system enables a unified, detector-wide interpretation of neutrino interactions by visually linking emulsion track topologies with electronic detector response patterns (see Figure 6.1 and Figure 6.2).

6.2. Methodology

6.2.1. Restoration of the 3D Emulsion Event Display (Task 3)

The provided THREE.js event viewer lacked full implementations of:

- `dm3D.drawVertices()`
- `dm3D.drawTracks()`

We reconstructed this functionality by:

(a) Vertex reconstruction

- Parsing vertex positions from the `loadEvent*.js` files.
- Rendering each vertex using `THREE.SphereGeometry`.
- Applying transformations relative to the primary interaction vertex.
- Ensuring the correct hierarchy in the scene graph.

(b) Track rendering

- Extracting start and end points using `Track3D.pos1()` and `Track3D.pos2()`.
- Implementing 3D tubular tracks via `THREE.TubeGeometry`.
- Applying track categories and colours (legend described in Section 6.3).
- Ensuring proper removal and redrawing when switching events.

This reveals τ-lepton decays, hadron and muon trajectories, and electro-magnetic showers.

6.2.2. Restoration of the 2D Electronic Detector Display (Task 4)

The D3.js ED event viewer was missing critical rendering logic. We restored:

(a) Hit mapping

- Correct mapping of detector channels to their physical XZ and YZ projection geometry.
- Rendering each scintillator hit as an SVG rectangle.
- Providing consistent scaling between events.

These results can be seen in *Figure 6.1*

(b) Heatmap colour encoding

- Implemented amplitude-based colours using OPERA Target Tracker detector hits.
- colours transition through:
  blue → cyan → green → yellow → orange → red
  (with >20 photo-electrons saturating red).

Hit intensities correspond directly to this gradient (see *Figure 6.2*).

6.3. Results

Table 1. Track Colour Legend (3D Emulsion Display)

Colour	Track Type
Red	Parent τ track (reconstructed or restored)
Yellow	Hadron track or EM shower segments (e+/e-)
Cyan	τ-lepton daughter track
White	Hadron track
Magenta	Hadron track or EM shower segments (e+/e-)

Table 2. Detector Amplitude Colour Legend (2D Detector Display)

Colour	Amplitude (photo-electrons)
Deep Blue	0
Cyan	5
Green	10
Yellow	15
Orange	20
Red	>20

3D Visualization (Emulsion)

- All vertices and tracks successfully displayed
- τ-decay kinks visible
- Clear colour-coded identification of particle categories
- Example in *Figure 6.1*

2D Visualization (Electronic Detector)

- XZ and YZ hit projections restored
- Correct geometrical mapping
- Dynamic amplitude-based colour coding
- Example in *Figure 6.2*

Integrated Display

- Both detector subsystems synchronized per event
- Enhanced understanding of the event topology by correlating:
  - emulsion kink topology
  - ED hit distribution
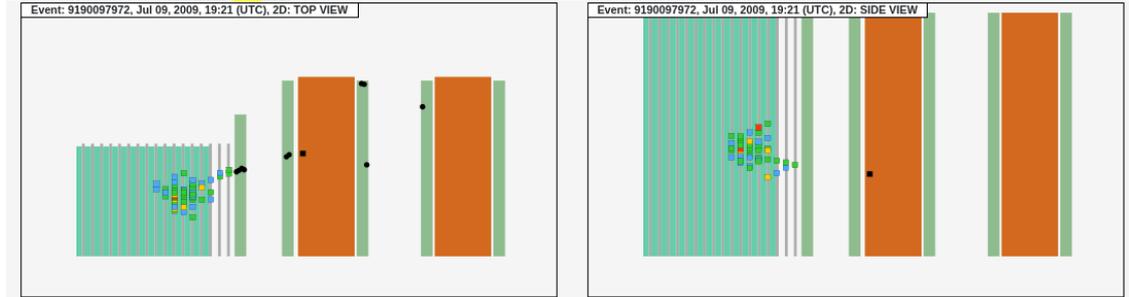
(a)
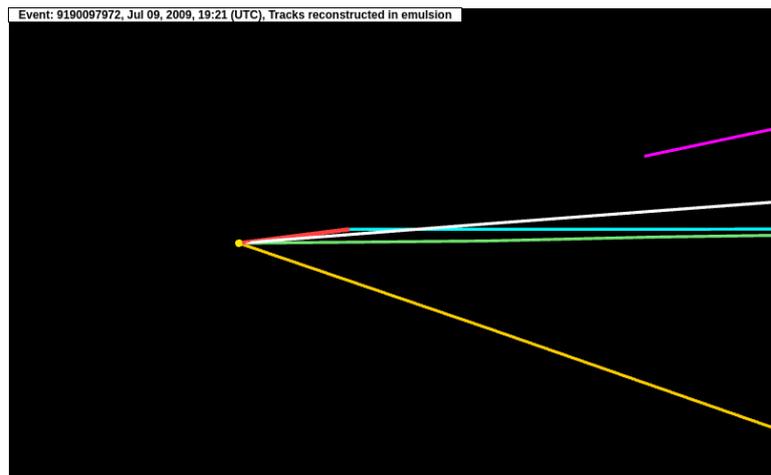
(b)

Fig. 6.1. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the v_τ candidate event 9190097972, (b) for nuclear emulsion films
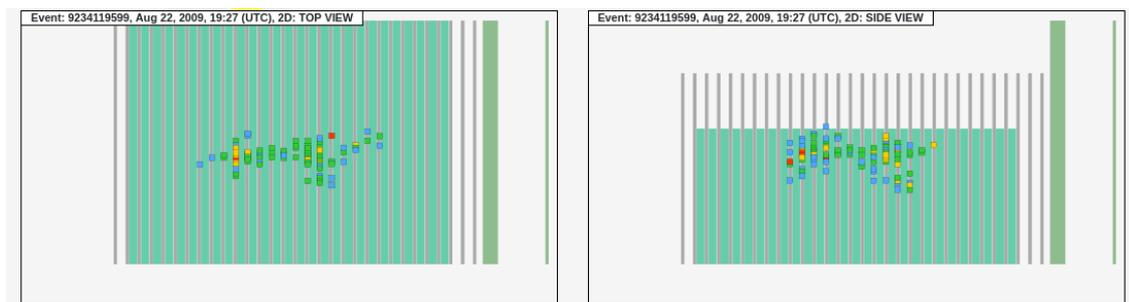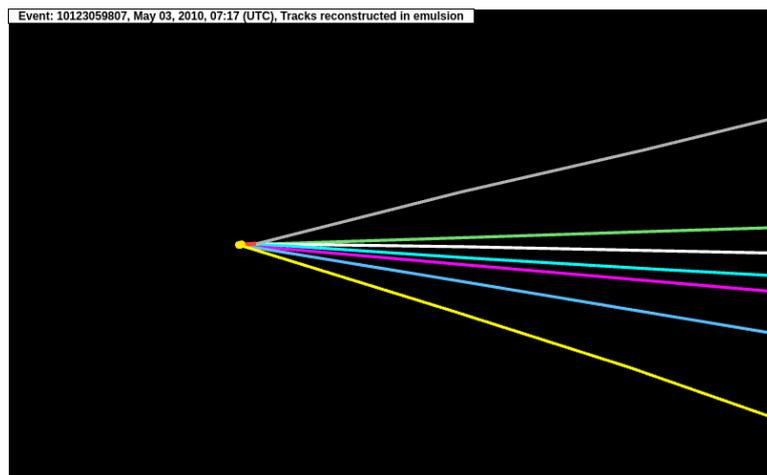

(a)

(b)

Fig. 6.2. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the ν_τ candidate event 9234119599, (b) for nuclear emulsion films
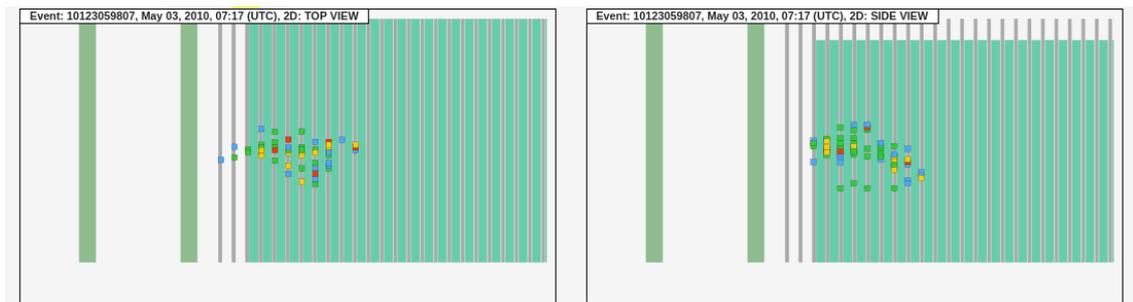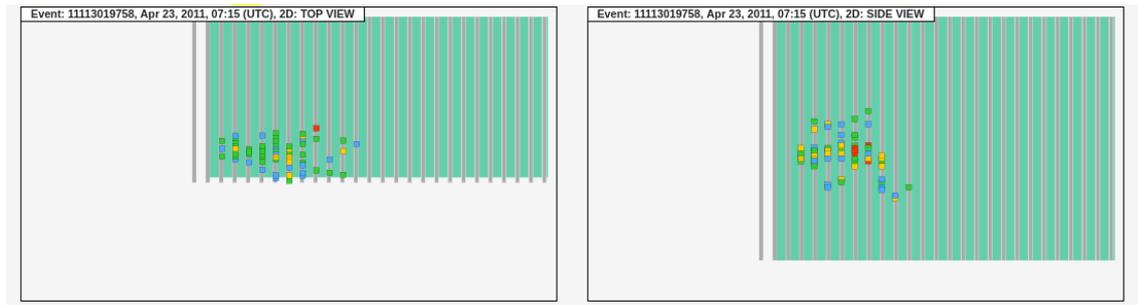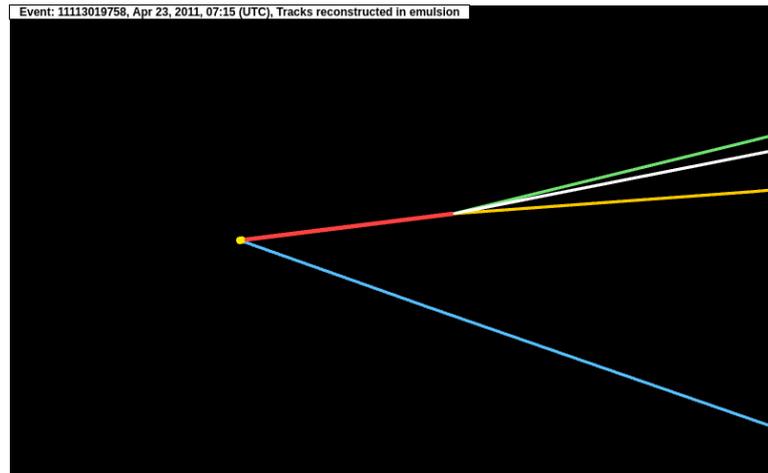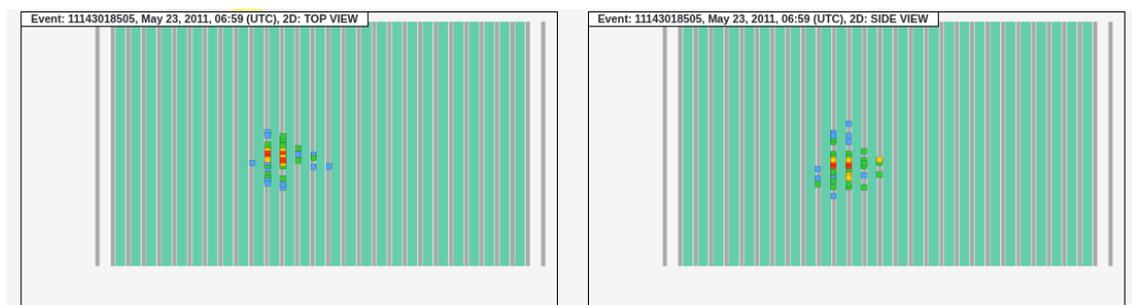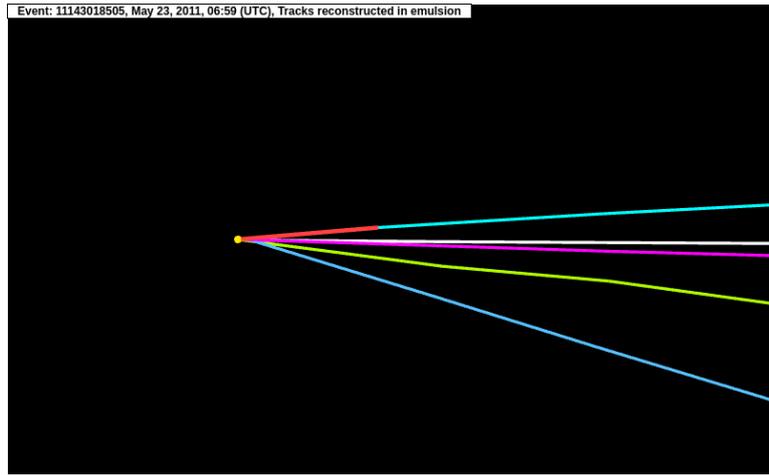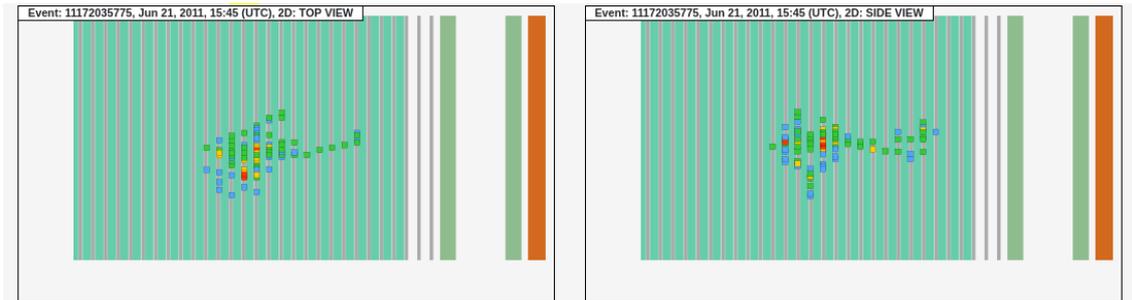

(a)

(b)

Fig. 6.3. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the ν_τ candidate event 10123059807, (b) for nuclear emulsion films

(a)

(b)

Fig. 6.4. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the ν_τ candidate event 11113019758, (b) for nuclear emulsion films
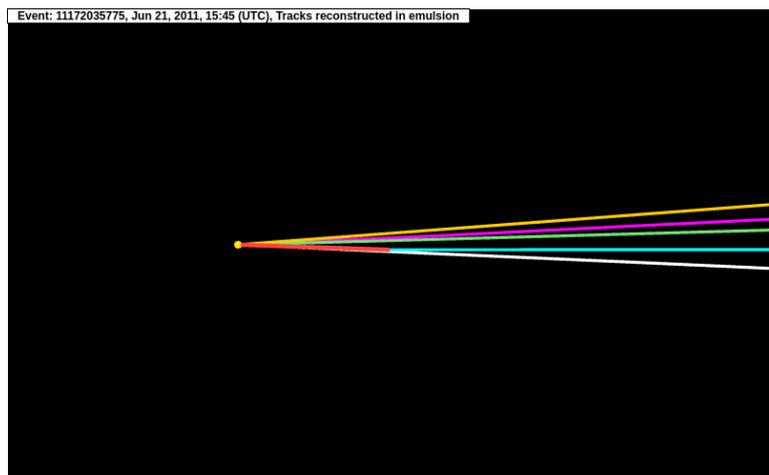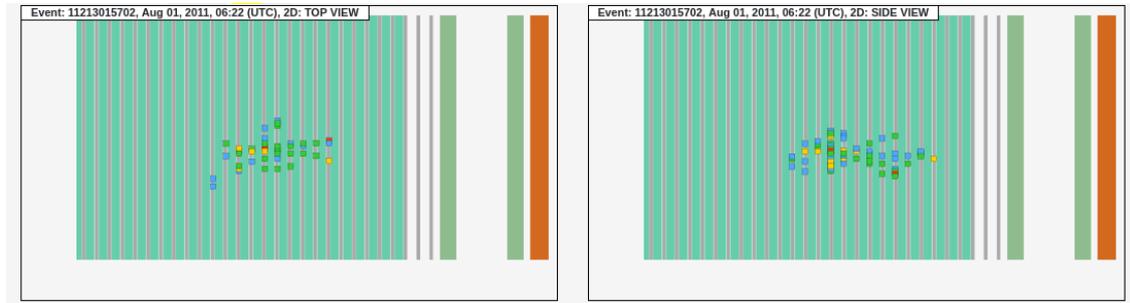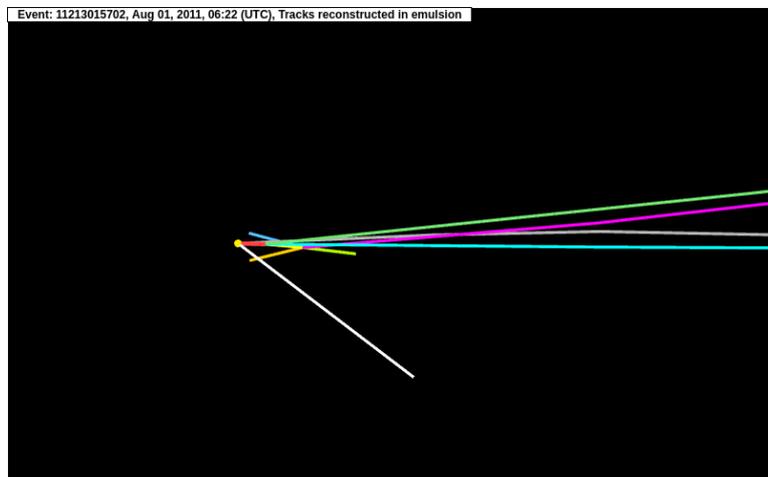

(a)

(b)

Fig. 6.5. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the v_τ candidate event 11143018505, (b) for nuclear emulsion films

(a)

(b)

Fig. 6.6. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the v_τ candidate event 11172035775, (b) for nuclear emulsion films
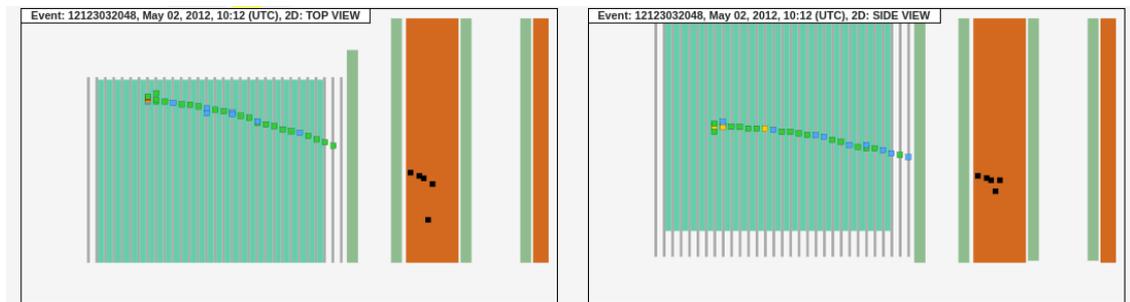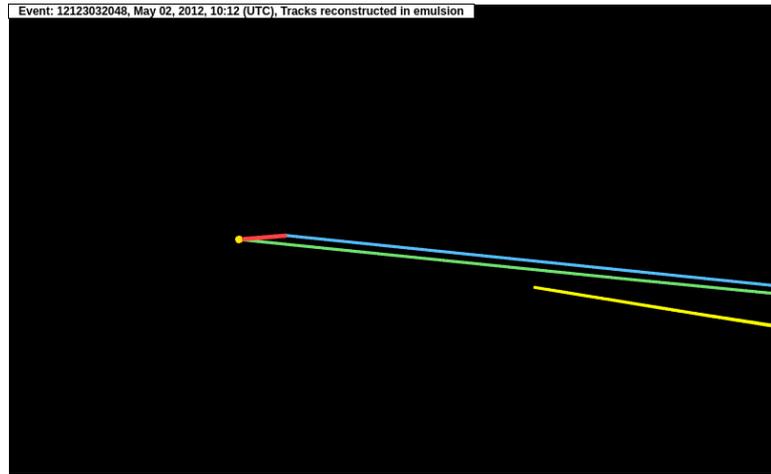

(a)

(b)

Fig. 6.7. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the v_τ candidate event 11213015702, (b) for nuclear emulsion films

(a)

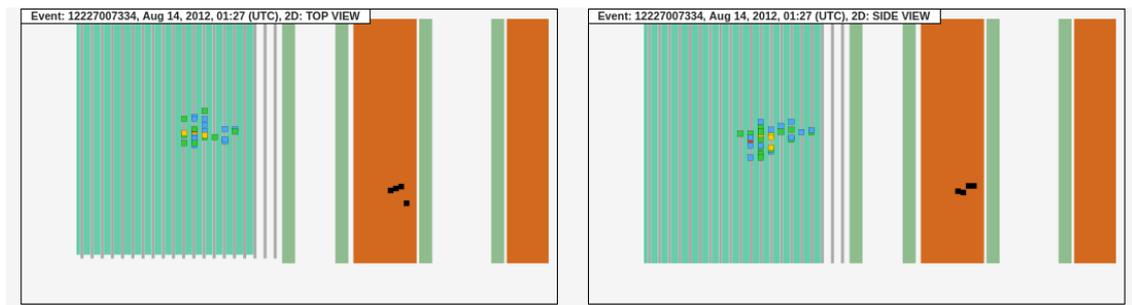*(b)*

Fig. 6.8. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the ν_τ candidate event 12123032048, (b) for nuclear emulsion films
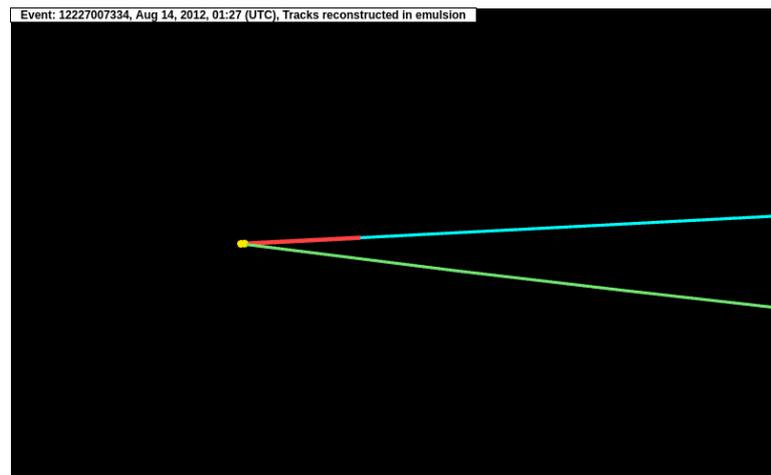

(a)

(b)

Fig. 6.9. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the ν_τ candidate event 12227007334, (b) for nuclear emulsion films
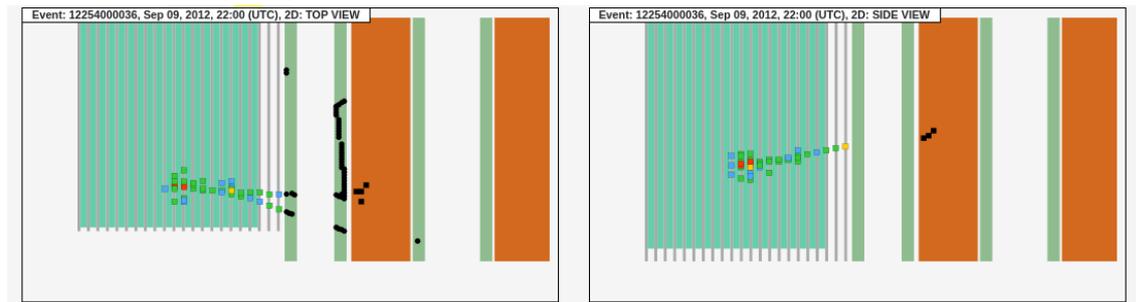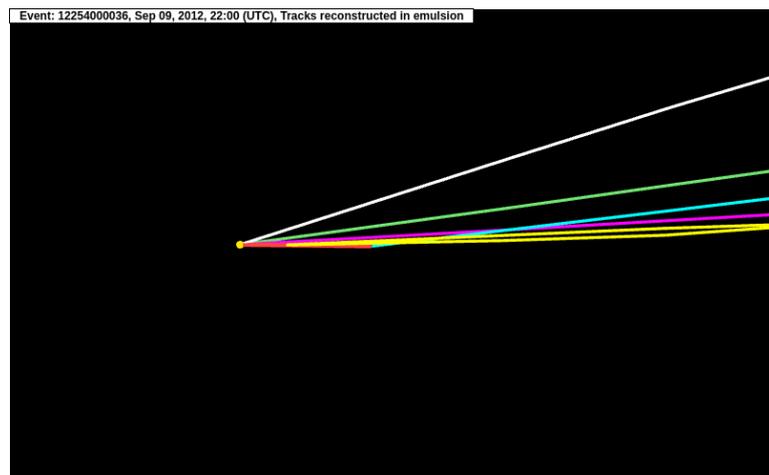
(a)

(b)

Fig. 6.10. Event displays (a) for electronic detectors data (top view on the left and side view on the right) for the v_τ candidate event 12254000036, (b) for nuclear emulsion films

6.6. Conclusion

A fully functional dual-detector visualization system was produced, demonstrating the complete interaction topology for each OPERA τ-neutrino candidate event. The integration of 3D track reconstruction with 2D detector response maps enables a richer and more comprehensive understanding of neutrino-induced interactions, consistent with OPERA's published results.

The restored 3D track reconstruction reproduces the topologies reported in the *OPERA Collaboration. (2018). Final results of the OPERA experiment on v_τ appearance in the CNGS beam. Phys. Rev. Lett.* Including the distinctive τ-decay kink signature.

7. Conclusion

This project demonstrates the full workflow of neutrino event analysis using real OPERA data. By working through the three tasks—charm decay reconstruction, charged hadron multiplicity analysis, and restoration of a 3D event display—it becomes clear how hybrid detectors and emulsion films enable high-precision particle tracking and vertex reconstruction.

The results match the qualitative behavior published in OPERA research articles, validating both the datasets and the implemented analysis code. Moreover, the development of a functional 3D browser-based event display highlights the importance of modern visualization techniques in neutrino physics education and outreach.

This project provides foundational experience in high-energy physics data analysis, detector reconstruction methods, and interactive event visualization tools.

8. References

[1] CERN Open Data Portal. https://opendata.cern.ch
[2] OPERA Collaboration, various publications
[3] N. Agafonova et al., "The OPERA experiment," JINST 4 (2009) P04018
[4] C++ ISO Standard
[5] ROOT Data Analysis Framework, CERN
[6] HTML5 Standard
[7] CSS3 Specification
[8] JavaScript Language Specification
[9] THREE.js Documentation
[10] D3.js Documentation