JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

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

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Abstract

This report presents a comprehensive study of neutrino interaction events obtained from the OPERA experiment, carried out as part of the INTEREST Program at the Joint Institute for Nuclear Research. The primary objective of this work was to investigate the topology of neutrino interaction events using datasets available through the CERN Open Data Portal and to extract meaningful physical insights through computational analysis.

The study focuses on key aspects such as charmed hadron production, charged hadron multiplicity, and muon identification. The analysis was performed using C++ in conjunction with the ROOT data analysis framework, enabling the computation and visualization of important kinematic parameters. Quantities such as decay (flight) lengths, impact parameters, and angular distributions of particle tracks were evaluated to understand the spatial and geometric characteristics of neutrino-induced interactions within the detector.

Particular attention was given to the reconstruction of event topologies from raw detector data. By analyzing the distribution of muon track angles and charged particle multiplicities, the internal structure of interaction events was examined in detail. These observations help in understanding the behavior of particles produced during neutrino interactions and validate the effectiveness of computational methods in extracting physical meaning from experimental data.

In addition to quantitative analysis, a three-dimensional visualization tool was developed using THREE.js to represent complex interaction geometries. This visualization enabled intuitive interpretation of particle trajectories and decay patterns, providing a bridge between numerical results and physical understanding. Overall, the project demonstrates the successful integration of data analysis, computational techniques, and visualization methods in studying real high-energy physics data.

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1 Introduction and Theoretical Background

1.1 Introduction to Neutrinos

Neutrinos are among the most fundamental yet weakly interacting particles in the Standard Model. Due to their interaction only via the weak force and gravity, they can traverse matter with minimal interaction.

Originally proposed to explain energy conservation in beta decay, neutrinos are now essential in both particle physics and astrophysics.

There are three flavors:

- Electron neutrino (ν_e)
- Muon neutrino (ν_μ)
- Tau neutrino (ν_τ)

Neutrino oscillation, where neutrinos change flavor during propagation, confirms that they possess mass and indicates physics beyond the Standard Model.

1.2 OPERA Experiment

The OPERA experiment was designed to detect the transformation of muon neutrinos into tau neutrinos.

Neutrinos produced at CERN traveled approximately 730 km to the Gran Sasso detector. The detector utilized electronic systems for online detection of neutrino events and lead-emulsion modules for high-precision particle tracking.

A characteristic signature of tau neutrino interaction is a kink in the particle track due to tau decay.

2 Project Objectives

Analyze OPERA datasets

Perform computations using C++ and ROOT

Study charmed hadron production

Analyze muon track distributions

Develop visualization tools

3 Tasks

3.1 Charmed Hadron Production

3.1.1 Detailed Theory

Charmed hadrons are particles containing at least one charm quark and are produced in high-energy neutrino interactions with matter. In experiments such as OPERA, neutrinos interact via the weak force with nuclei in the detector, producing secondary particles including charmed hadrons.

These particles are highly unstable and decay via weak interactions with very short lifetimes (typically of the order of 10^{-13} seconds). Due to relativistic effects, they travel a measurable distance before decaying, which allows experimental detection through track-ing systems.

The decay of charmed hadrons produces a characteristic secondary vertex, distinct from the primary interaction vertex. The identification of this secondary vertex is crucial for:

- Studying charm quark production mechanisms
- Understanding neutrino interaction dynamics
- Identifying rare events such as tau neutrino interactions

Two key observables are used in this analysis:

Decay Length The decay length represents the spatial distance between the production point and the decay point of the particle. It provides insight into the lifetime and relativistic motion of the particle.

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

In relativistic terms, decay length is related to intrinsic particle properties:

$$L = \gamma\beta c\tau \tag{2}$$

where γ is the Lorentz factor, $\beta = v/c$, τ is the proper lifetime, and c is the speed of light. This relation shows how time dilation increases the observed decay distance.

Impact Parameter The impact parameter is defined as the minimum perpendicu-lar distance between the extrapolated particle trajectory and the primary vertex. It is a critical parameter for distinguishing between particles originating from the primary interaction and those from secondary decays.

$$d_0 = \frac{|r \times p|}{|p|} \tag{3}$$

In two-dimensional geometry:

$$d_0 = \frac{|Ax_0 + By_0 + C|}{\sqrt{A^2 + B^2}} \tag{4}$$

A large impact parameter indicates that the particle track does not point back to the primary vertex, suggesting a decay process. This is a key signature of charmed hadron decay.

3.2 Charged Hadron Multiplicity and Muon Track Angle

3.2.1 Charged Hadron Multiplicity: Detailed Theory

Charged hadron multiplicity refers to the number of charged particles produced in a single neutrino interaction event. It is an important observable in high-energy physics as it reflects the complexity and energy of the interaction.

In neutrino-nucleus interactions, higher energy transfers typically result in the production of more secondary particles, increasing the multiplicity. Therefore, multiplicity is often used as an indirect measure of:

- Interaction energy
- Hadronization processes
- Event topology complexity

Mathematically:

$$N_{ch} = \text{number of charged particles per event} \tag{5}$$

The statistical behavior of multiplicity is studied using distributions:

$$P(N_{ch}) \tag{6}$$

These distributions are useful for comparing experimental results with theoretical models and Monte Carlo simulations.

3.2.2 Muon Track Angle: Detailed Theory

Muons are commonly produced in neutrino interactions, especially in charged-current interactions involving muon neutrinos. Since muons are relatively penetrating and minimally interacting, their tracks are easier to reconstruct in detectors.

The angle of the muon track provides valuable information about the kinematics of the interaction, including momentum transfer and scattering behavior.

The track angle is calculated using the slope of the trajectory:

$$\theta = \tan^{-1}(m) \tag{7}$$

where m is the slope of the track.

From a momentum perspective, the angle is related to transverse and longitudinal momentum components:

$$\tan\theta = \frac{p_T}{p_L} \tag{8}$$

This relation is crucial in detector physics, as it helps in reconstructing the momentum vector and understanding the angular spread of particles.

A narrow angular distribution suggests forward scattering, while a broader distribution indicates complex interaction dynamics.

3.3 Interactive Visualization

3.3.1 Detailed Theory

Visualization of neutrino interaction events in three dimensions is essential for interpreting complex detector data. Tools such as THREE.js are used to render particle trajectories and interaction points in a spatial framework.

Each event typically consists of:

- A primary vertex where the neutrino interaction occurs
- Multiple particle tracks emerging from the vertex
- Possible secondary vertices from decays (e.g., charm decay)

The visualization allows researchers to:

- Identify decay topologies (e.g., kinks in tracks)
- Analyze spatial correlations between particles
- Understand detector geometry and reconstruction accuracy

Such tools bridge the gap between raw numerical data and physical interpretation, making it easier to detect patterns and validate theoretical expectations.

Charmed Hadron Production

The decay length is calculated as:

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

The impact parameter is also evaluated to study track displacement.

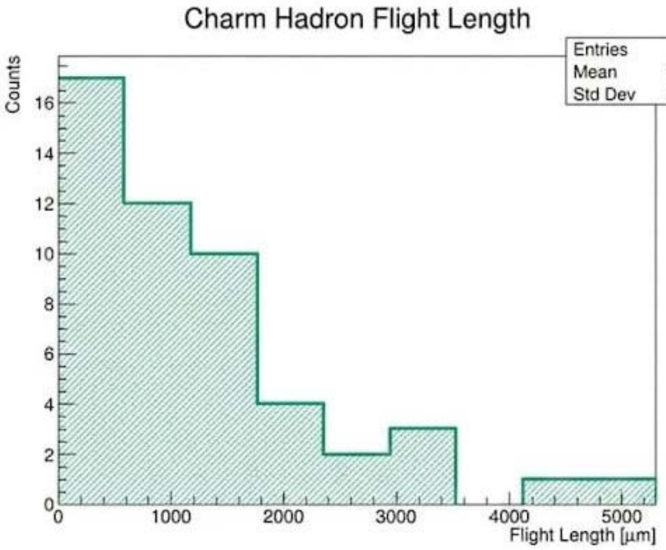

Figure 1: Decay Length Distribution

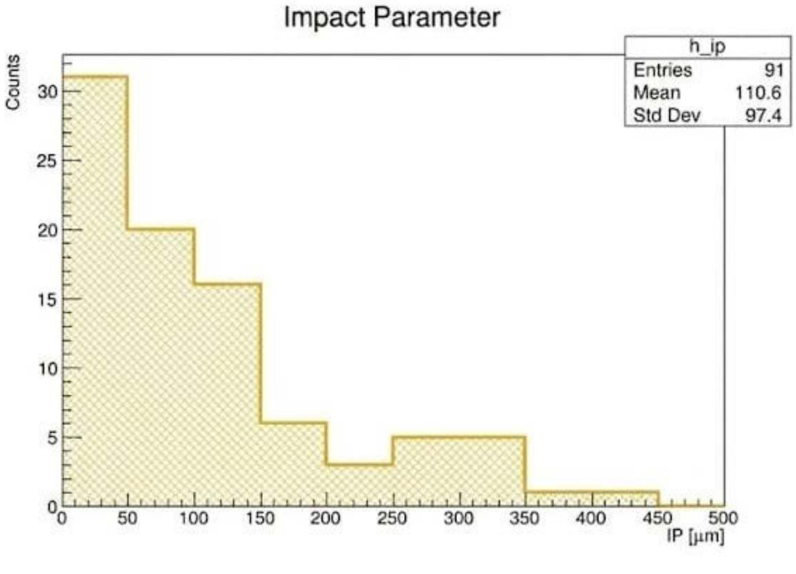

Figure 2: Impact Parameter Distribution

Charged Hadron Multiplicity and Muon Track Angle Distribution

The track angle is calculated as:

$$\theta = \tan^{-1}(m) \tag{2}$$

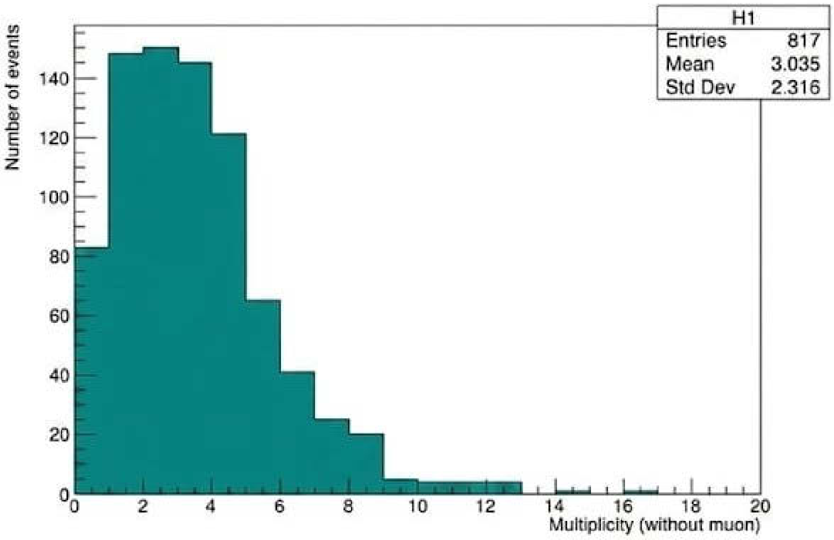

Figure 3: 2D Histogram of Muon Angles

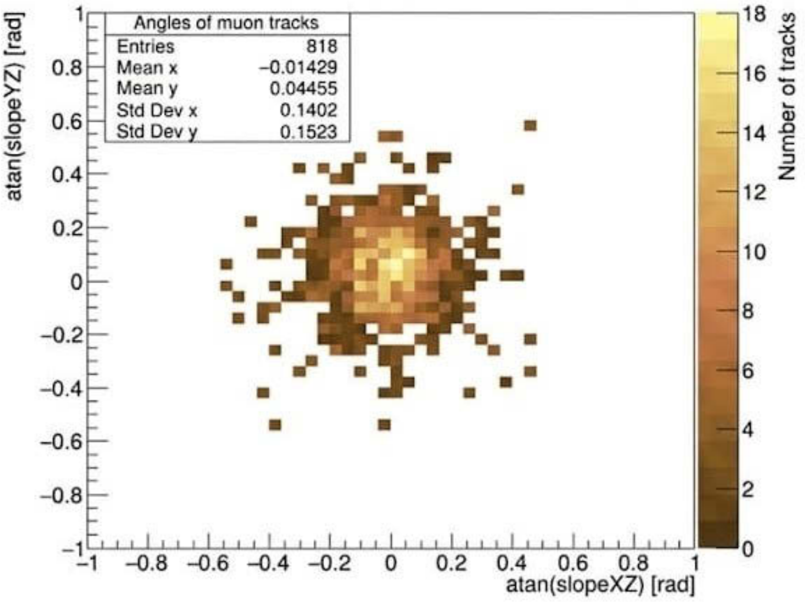

Figure 4: 1D Projection

Interactive Visualization

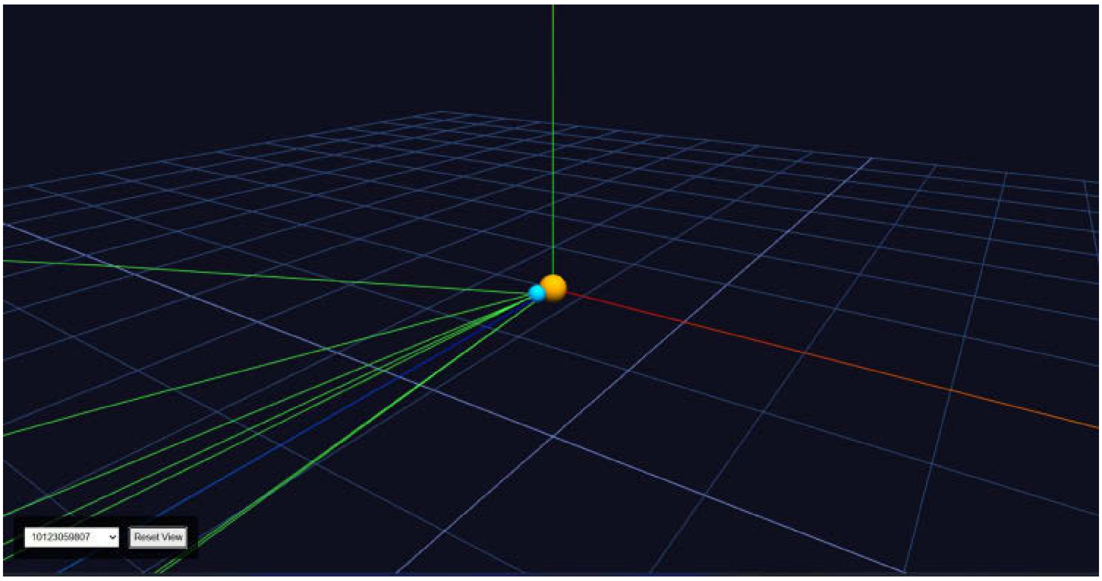

Figure 5: 3D Event 1

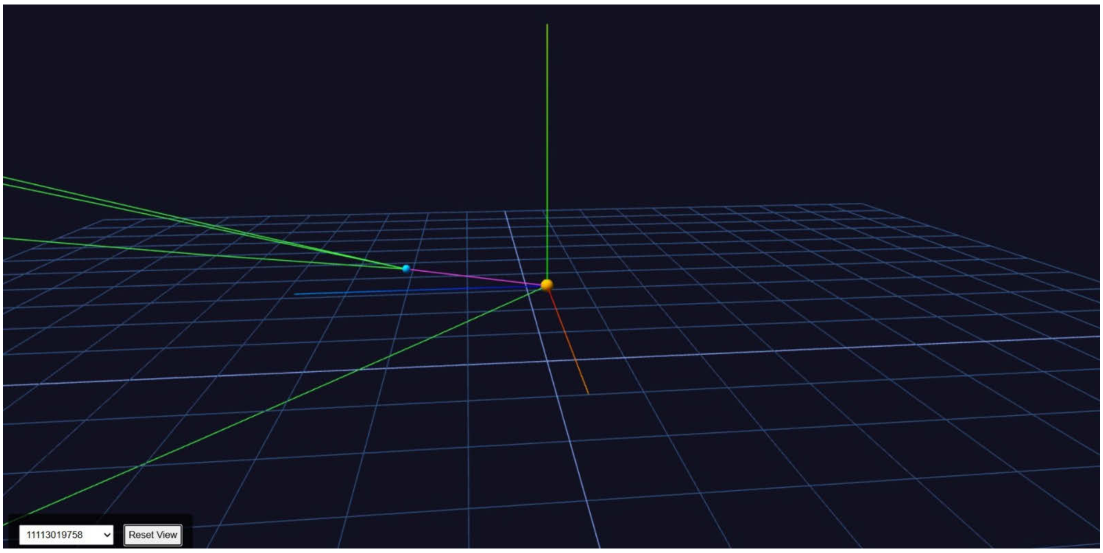

Figure 6: 3D Event 2

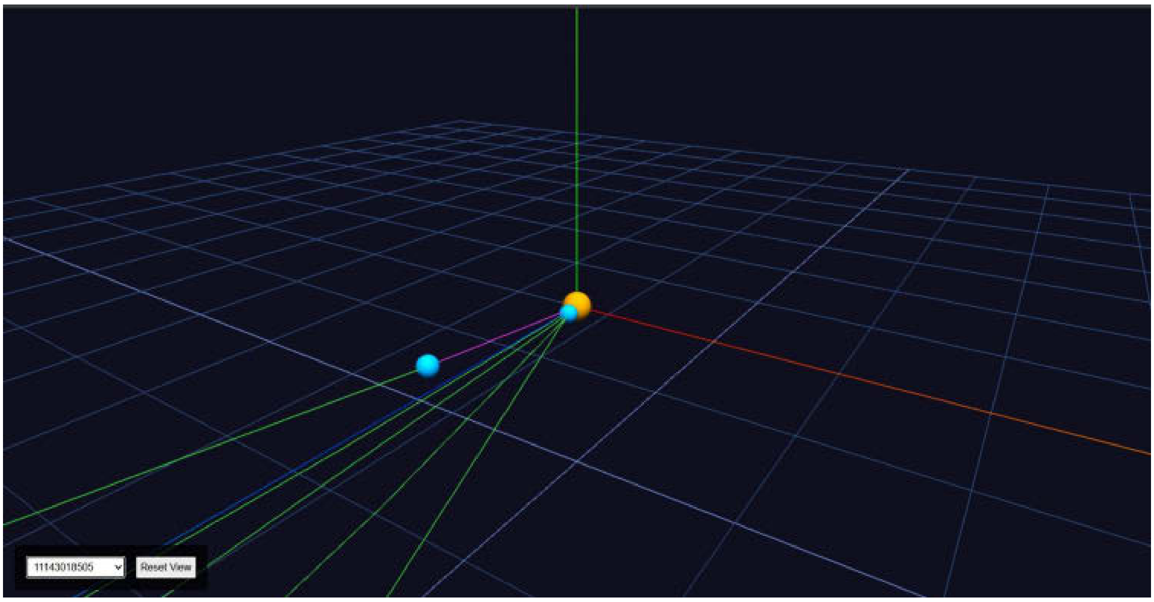

Figure 7: 3D Event 3

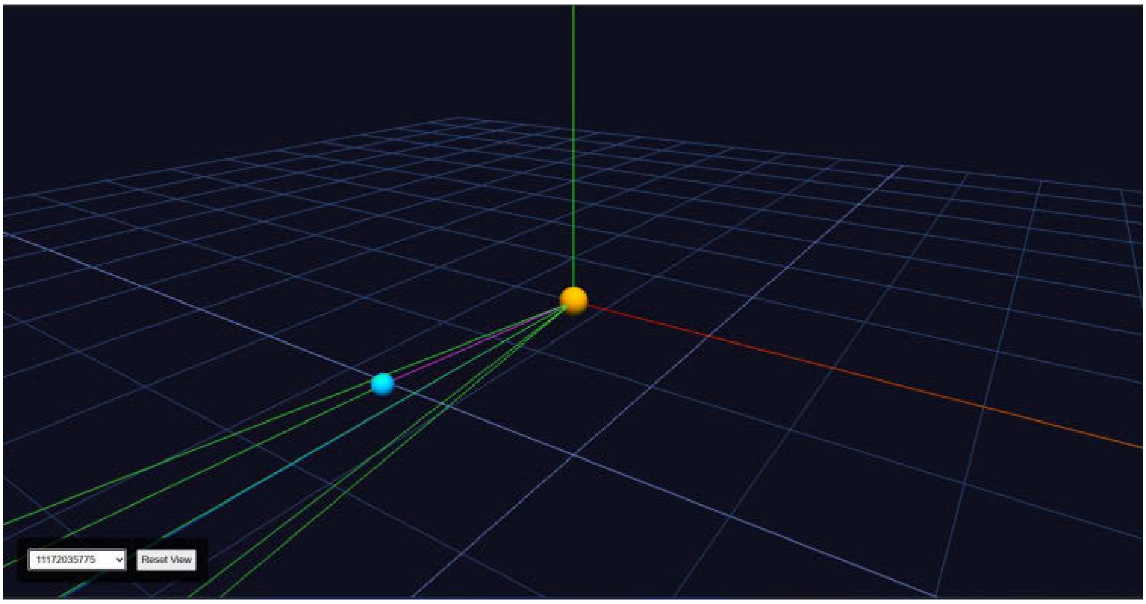

Figure 8: 3D Event 4

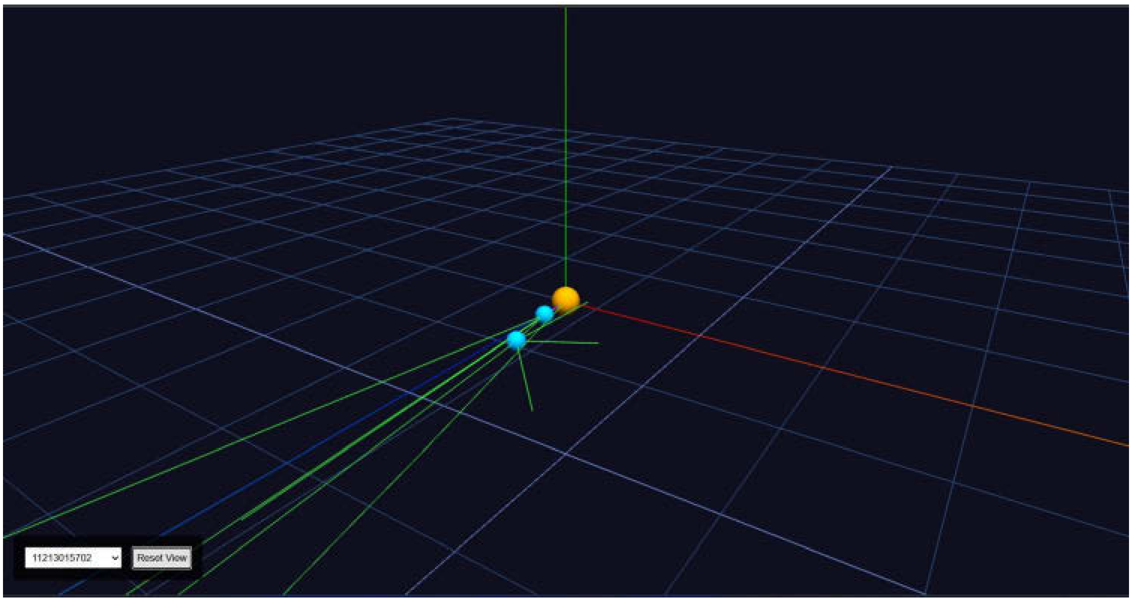

Figure 9: 3D Event 5

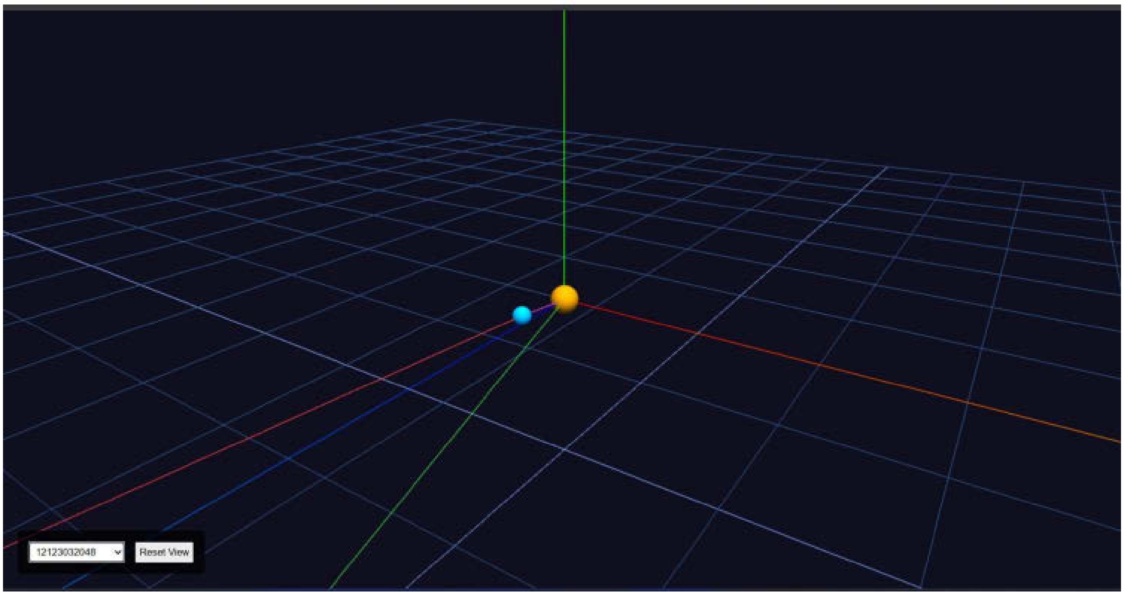

Figure 10: 3D Event 6

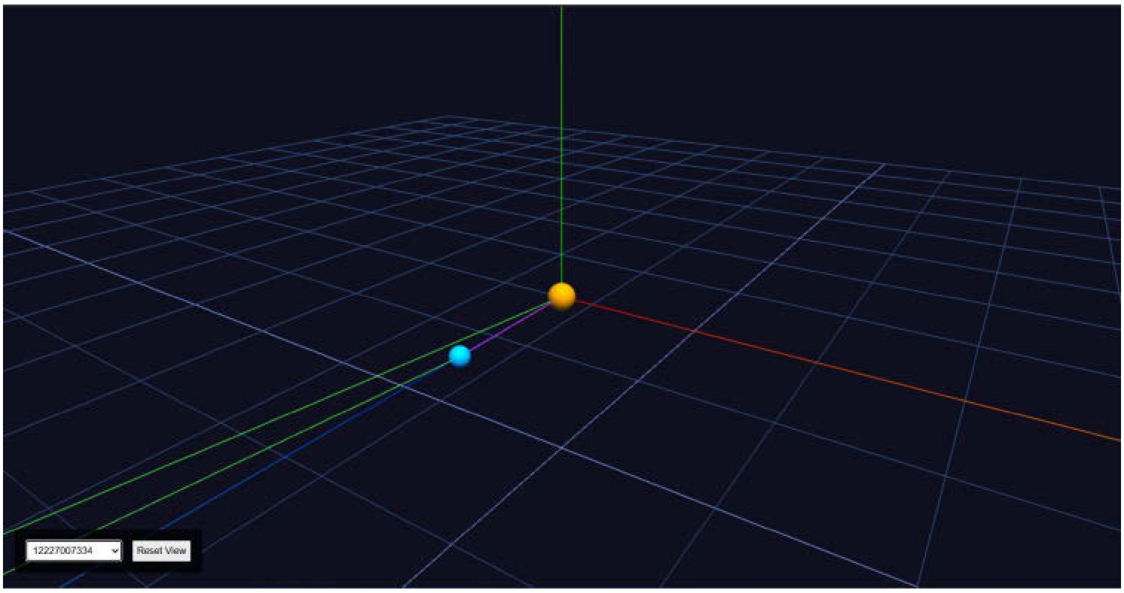

Figure 11: 3D Event 7

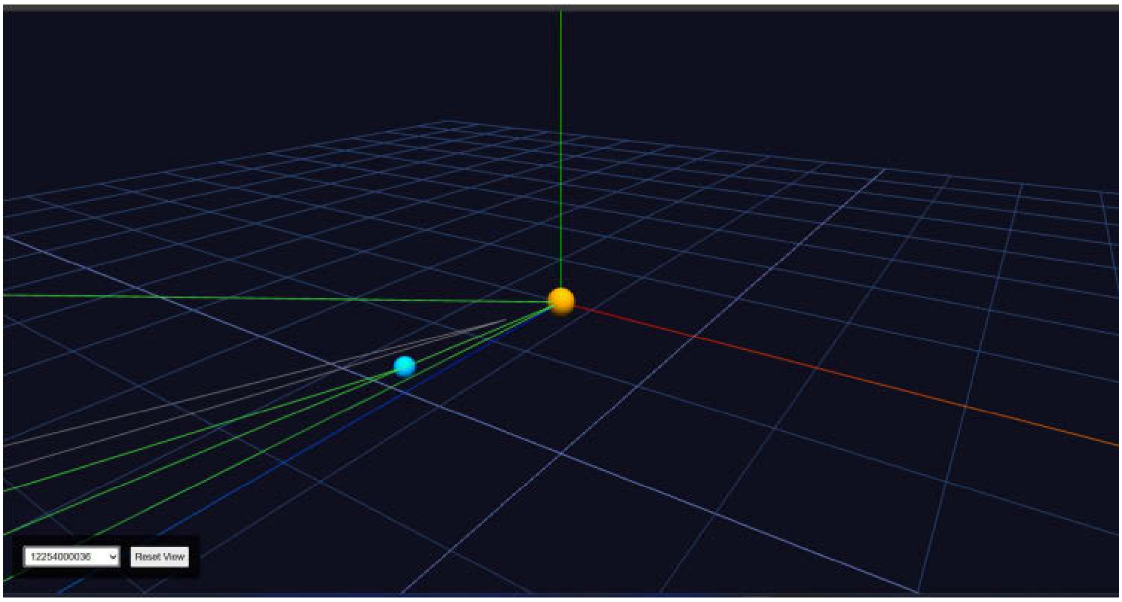

Figure 12: 3D Event 8

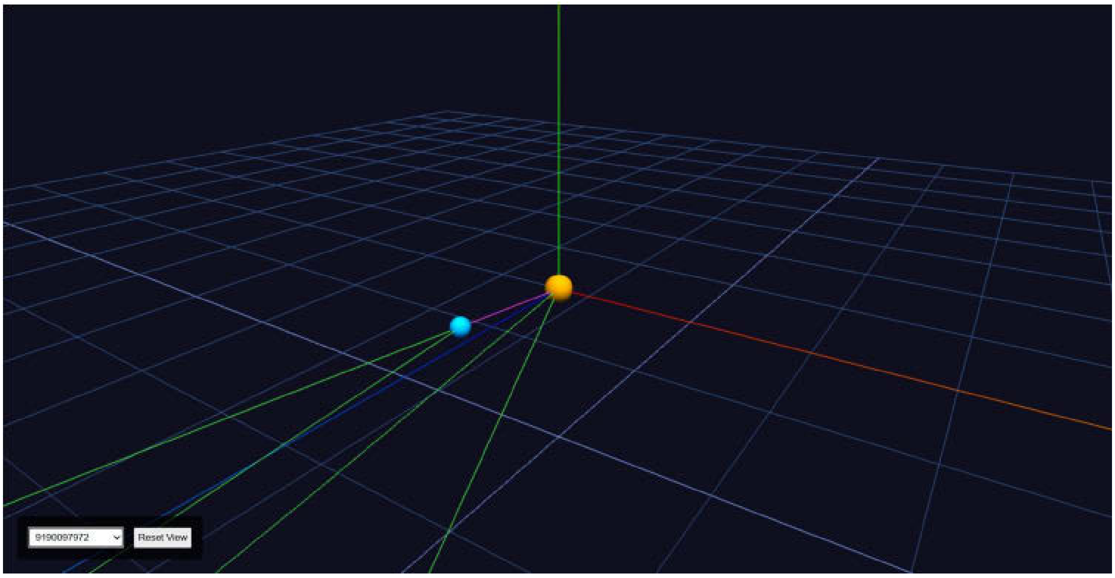

Figure 13: 3D Event 9

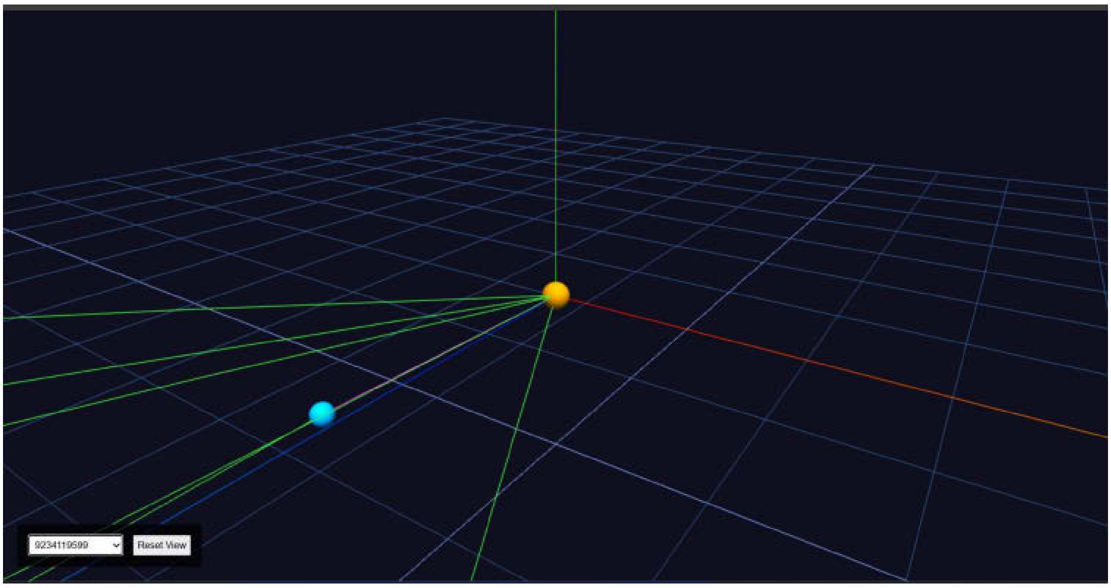

Figure 14: 3D Event 10

4 Results and Conclusion

This study successfully demonstrated the application of computational and analytical techniques to real neutrino interaction data obtained from the OPERA experiment. Through the analysis of CERN Open Data, key physical characteristics of neutrino-induced events were investigated in detail, providing meaningful insights into particle interaction dynamics.

The evaluation of decay length and impact parameter enabled the identification of secondary vertices associated with charmed hadron production, highlighting the importance of spatial reconstruction in detecting short-lived particles. The analysis of charged hadron multiplicity provided information about the energy transfer and complexity of interaction events, while the study of muon track angles contributed to understanding the kinematic behavior and directional properties of particles produced in neutrino interactions.

Furthermore, the integration of computational tools such as C++ and the ROOT framework proved effective for handling and analyzing large datasets, allowing precise calculation of relevant parameters and generation of meaningful distributions. The development of three-dimensional visualization using THREE.js added significant value by enabling intuitive interpretation of interesting event geometries, bridging the gap between raw numerical data and physical understanding.

Overall, the project highlights the critical role of data-driven approaches in modern high-energy physics and demonstrates how computational analysis, combined with visualization techniques, can be used to extract detailed physical insights from experimental data. This work not only reinforces theoretical concepts related to neutrino interactions but also provides a strong foundation for further studies in particle physics data analysis and detector-based research.

Reference

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