Joint Institute for Nuclear Research

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

International Remote Student Training at JINR

Instructor

Dr. Sergey Dmitrievsky

Student

Macari Magdy Fayez

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Introduction

The enigmatic nature of neutrinos, which are fundamental particles with low interaction cross-sections, has long intrigued physicists. Their significance in elucidating the fundamental structure of the universe and their potential to unveil new physics beyond the Standard Model serve as ongoing motivations for scientific investigation.

This study explores the captivating realm of neutrinos using an innovative approach: leveraging the extensive dataset available on the CERN Open Data Portal and employing sophisticated programming techniques. The OPERA experiment achieved noteworthy outcomes by observing the oscillation of muon neutrinos into tau neutrinos.

The experiment's meticulous data collection and preservation are now accessible through the CERN Open Data Portal, providing a distinctive resource for further exploration. This study specifically focuses on analyzing these datasets, particularly the detailed CSV files containing information on registered neutrino events. To examine the intricacies of these events, we utilized the robust capabilities of the C++ programming language. By designing tailored programs, we extract and analyze crucial features of neutrino event topology, revealing concealed patterns and relationships within the data.

Subsequently, we employ the powerful ROOT data analysis framework to visualize these findings, transforming abstract data points into interactive histograms and graphs. However, our exploration extends beyond static visualizations[3]. This study also explores the potential of web technologies for dynamic event display. By harnessing the power of HTML, CSS, and JavaScript libraries such as THREE.js and D3.js, we develop interactive 2D and 3D visualizations that breathe life into neutrino events.

This innovative approach holds the promise of enhancing comprehension and fostering deeper engagement with the data. This study transcends mere technical exercise; it represents a journey to the forefront of neutrino research. By amalgamating open data, advanced programming techniques, and creative visualization methodologies, our objective is to illuminate the mysteries surrounding these enigmatic particles and contribute to our comprehension of the fundamental building blocks of the universe.

Abstract

The elusive nature of neutrinos, subatomic particles barely interacting with matter, has captivated physicists for decades. This report delves into their secrets through a unique approach: analyzing the OPERA experiment's rich data from CERN's Open Data Portal using advanced programming and visualization techniques.

We leverage the meticulously collected OPERA data, stored in detailed CSV files, to extract and analyze crucial features of neutrino events. Custom C++ programs will unlock hidden patterns and relationships within the data, while the powerful ROOT framework will transform them into interactive histograms and graphs.

But our exploration transcends static visualizations. We harness the power of HTML, CSS, and JavaScript libraries like THREE.js and D3.js to develop dynamic 2D and 3D visualizations, bringing neutrino events to life in an immersive and engaging way.

OPERA Experiment

3.1 About Opera Experiment

Revealing the Secrets of Neutrinos: An In-Depth Exploration of the OPERA Experiment at CERN

Neutrinos, enigmatic particles with weak interactions with matter and potential implications beyond the Standard Model, have captivated physicists for a considerable time. At the forefront of this pursuit, the OPERA experiment conducted at CERN has pushed the boundaries of neutrino physics.

Initiated in 2001, the primary objective of OPERA was to make definitive observations of tau neutrinos, a rare and elusive variant of the more prevalent muon neutrinos. This entailed directing a beam of muon neutrinos from CERN in Switzerland to the Gran Sasso National Laboratory in Italy, spanning a distance of 730 kilometers. At Gran Sasso, an advanced detector was awaiting deployment, specifically designed to capture distinct characteristics indicative of tau neutrino interactions.

The OPERA detector represented a remarkable feat of engineering. It employed a combination of lead plates and photographic emulsion film, forming a composite structure capable of accurately recording the tracks left by charged particles generated from neutrino interactions. This unique design facilitated unprecedented resolution, enabling precise differentiation between various types of neutrinos.

Following years of meticulous data collection and analysis, OPERA achieved a seemingly insurmountable feat: in 2013, the experiment announced the first-ever observation of oscillation from muon neutrinos to tau neutrinos. This groundbreaking discovery corroborated a long-standing theory, affirming that neutrinos can alter their "flavor" during their journey.

Beyond this seminal observation, the impact of OPERA extends far and wide. The experiment's extensive dataset, now accessible through the CERN Open Data Portal, presents a valuable resource for further scientific investigations. Researchers continue to delve into this data, aiming to uncover novel insights into the behavior of neutrinos and the fundamental nature of the universe.

Here are some key takeaways from the OPERA experiment:

First observation of muon neutrino to tau neutrino oscillation. Pioneering detector technology with unmatched resolution. Open data sets fuel further research and discovery. Contributions to understanding neutrino properties and the Standard Model. OPERA's legacy is a testament to the power of collaboration and cutting-edge technology in advancing our understanding of the universe's fundamental mysteries. By peering into the world of neutrinos, OPERA has opened doors to exciting new avenues in physics research, paving the way for future discoveries that may rewrite our understanding of the cosmos.

3.2 Neutrino Production

Muon Neutrino Production

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) is a particle physics experiment designed to study neutrino oscillations. Neutrinos are elusive subatomic particles that come in three flavors: electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ). Neutrino oscillation is the phenomenon where neutrinos change from one flavor to another as they travel through space, which implies that they have mass.

Muon neutrinos (ν_μ) are one of the three types of neutrinos. They are produced in various astrophysical processes and particle interactions. To explain the process of muon neutrino production, we need to consider some of the sources and interactions where muon neutrinos are generated.

1. **Muon Decay**: One of the most common sources of muon neutrinos is the decay of muons. Muons are unstable particles with a relatively short lifetime. When a muon decays, it can produce a muon neutrino and an electron or antimuon and electron antineutrino pair. The decay process can be represented as:

$$\mu^- \to e^- + \nu_\mu + \nu_e \quad \text{(muon decay)}$$

$$\mu^+ \to e^+ + \nu_\mu + \nu_e \quad \text{(antimuon decay)}$$

   In these processes, muon neutrinos (ν_μ) are produced.

2. **Pion Decay**: Muon neutrinos can also be generated in the decay of charged pions (π^+ and π^-). Pions are mesons, and their decay can produce muon neutrinos and antineutrinos:

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\pi^- \to \mu^- + \nu_\mu$$

   In both cases, muon neutrinos are created along with muons.

Detection at Gran Sasso

The journey culminates at the Gran Sasso National Laboratory, where a specialized detector is located. This detector was able to register all types of neutrinos in real time using nuclear emulsions and electronic detectors. Precise (100 nanoseconds and even better) time synchronization system between CERN and Gran Sasso laboratory allowed to associate registered neutrino events with the corresponding pulses of the SPS proton beam. Collected statistics of neutrino events and precise study of neutrino topologies allowed us to distinguish different neutrino flavors, better understand neutrino properties and discover

$$\nu_\mu \to \nu_\tau$$

3.3 The Detector at Gran Sasso

The primary goal of the OPERA experiment was to investigate the phenomenon of neutrino oscillations, a phenomenon that implies neutrinos changing from one type to another as they travel through the crust of the earth. Specifically, OPERA aimed to observe the transformation of muon neutrinos into tau neutrinos, providing essential insights into neutrino properties and behavior.

Detector Components

The core of the OPERA neutrino detection system relied on *nuclear emulsion films*. These specialized films consist of multiple layers of a photographic emulsion containing silver halide crystals. Charged particles, such as tau leptons produced by neutrino interactions, cause ionization within these crystals, leaving distinct tracks after development and analysis.

The emulsion films were meticulously arranged in *target modules*, forming a series of finely segmented layers. These modules were strategically interspersed with lead plates to enhance the probability of neutrino interactions

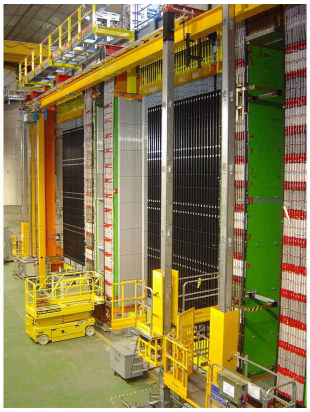


Figure 3.1: Detector at Gran Sasso

within the target material. Neutrino interactions in the target could produce tau leptons, which subsequently decay, generating secondary charged particles that traverse the emulsion layers. These particles leave characteristic tracks, allowing for identification and detailed analysis.

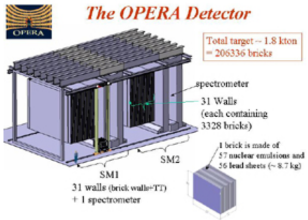


Figure 3.2: Nuclear Emulsion

Electronic Detectors

In addition to nuclear emulsion, OPERA incorporated electronic detectors to complement the emulsion-based tracking. Electronic detectors, such as drift tubes and resistive plate chambers, were placed in alternate layers with the emulsion films. These detectors helped provide precise timing information and improved the overall tracking accuracy.

Using a huge amount of nuclear emulsion and registering neutrino events in real-time with the help of electronic detectors allowed OPERA to achieve its main goal. The high spatial resolution of emulsion films made it possible to accurately reconstruct particle tracks, which contributed to a better understanding of the dynamics of neutrino interaction.

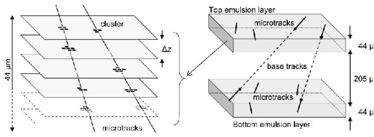


Figure 3.3: Tracking particles

Detector Operation

The OPERA experiment primarily focused on the detection of tau neutrinos produced by a muon neutrino beam generated at CERN (European Organization for Nuclear Research) in Geneva, Switzerland. The neutrinos traveled through the Earth to the Gran Sasso Laboratory, a distance of about 730 kilometers.

When a muon neutrino interacted with the OPERA detector, it could produce a tau neutrino through the process of neutrino oscillation. The tau neutrino, in turn, could create a tau lepton, which left distinct tracks in the nuclear emulsion layers. The electronic detectors provided additional information, such as the time of the interaction.

The sophisticated design of the OPERA detector allowed for the identification and reconstruction of rare tau neutrino events, providing valuable data for the study of neutrino oscillations.

Successful Detection of Tau Neutrinos

Despite the significant technical challenges associated with manipulating and analyzing nuclear emulsion films, the OPERA experiment successfully achieved the pioneering result of directly detecting tau neutrinos produced in $\nu_\mu \to \nu_\tau$ oscillations. This triumph was further highlighted by the experiment's ability to accurately identify and reconstruct the characteristic decay topologies of tau leptons in the emulsion layers.

Task 1

4.1 Calculation of the flight lengths of charmed hadrons

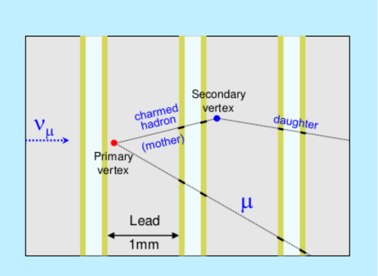


Figure 4.1: Decay Length illustration

In neutrino interaction events involving charmed hadron decays, the decay length measures the distance between the initial interaction point (primary vertex) and the point of final particle production (secondary vertex). This distance, representing the decay path in 3D space, is recorded in a .CSV file with unique event identifiers for each observed decay in the emulsion data. Figure 4.2 presents our analysis of these decay lengths, while Figure 4.3 represents the histogram of the OPERA paper [1]. The minor differences can be attributed to gradual data updates by the involved laboratories.

4.1.1 Impact Parameter Analysis of Daughter Tracks

Definition and Calculation

The impact parameter (IP) is an important parameter in neutrino interactions, quantifying the distance between a daughter particle track and the primary neutrino interaction vertex. It's calculated as the shortest

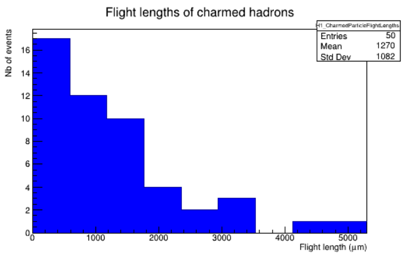


Figure 4.2: Our result

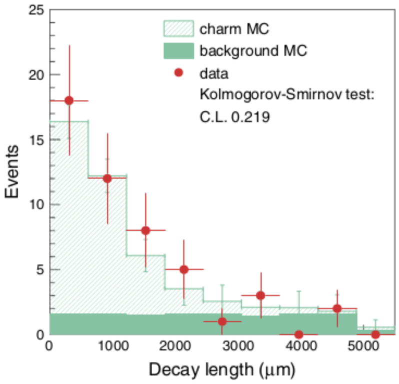


Figure 4.3: Opera results

distance between a point (primary vertex) and a line (daughter track) in 3D space. The formula for IP is:

$$\text{IP} = \frac{|(\overrightarrow{X_0} - \overrightarrow{X_1}) \times (\overrightarrow{X_1} - \overrightarrow{X_2})|}{|\overrightarrow{X_1} - \overrightarrow{X_2}|} \tag{4.1}$$

Data Extraction and Analysis

To analyze the IP distribution, the following steps were performed:

Data Extraction:

Primary vertex coordinates were obtained from the EventIDVertices.csv file. Daughter track coordinates were extracted from the EventIDTrackLines.csv file, specifically selecting rows where trType equals 10. IP Calculation:

For each daughter track, the IP was calculated using the formula above.

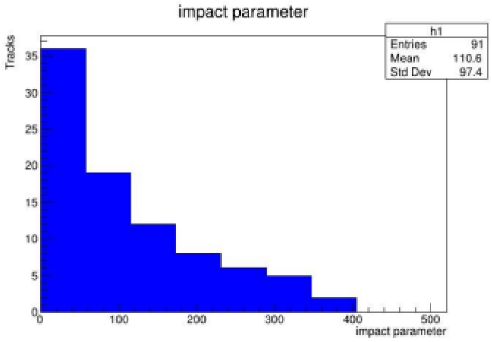


Figure 4.4: Our result

Task 2

5.1 Analysis of Charged Particle Multiplicity in Pb Interactions with OPERA emulsion data

5.1.1 Introduction

This section studies the multiplicity of charged particles produced in neutrino interactions using the OPERA emulsion dataset downloaded from the CERN Open Data Portal. A dedicated `C++` code was developed to analyze the dataset, focusing on extracting the positions of primary interaction vertices and the parameters of secondary charged particle tracks. Analyzed quantities include multiplicities of all produced charged particles and angles of muon tracks. The results are presented and compared with existing literature data to evaluate the accuracy and effectiveness of the analysis approach[3].

5.1.2 Methodology

Track Definition and Multiplicity Extraction

In this analysis, a charged particle track is defined by its starting point (x,y,z) and two slopes, XZ and YZ , representing the tangents of the track's angles with the Z axis in ZX and ZY views, respectively. The `C++` code reads the multiplicity associated with each eventID from the "Vertex.csv" file and stores it in a histogram created using ROOT libraries. An important consideration is that since multiplicity is an integer, the histogram cell width must also be an integer to avoid misinterpretations.

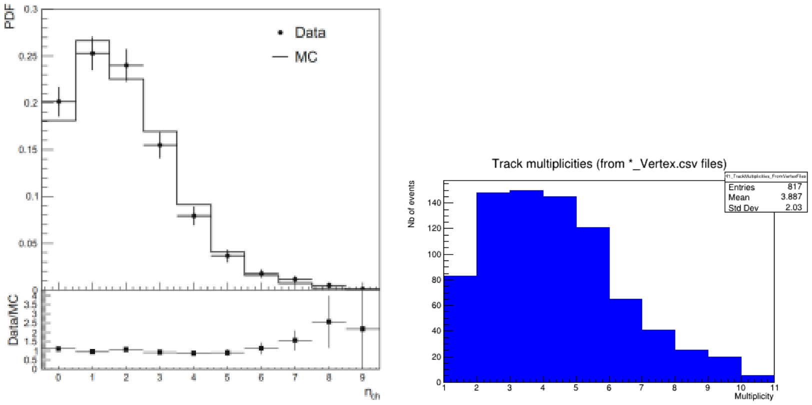
Data Processing and Analysis

The analysis procedure involves the following steps:

Data Loading: The OPERA emulsion dataset is loaded into the `C++` environment. Vertex Identification: Primary Neutrino interaction vertices are identified based on specific criteria. Track Reconstruction: Tracks of secondary charged particles are reconstructed using their starting points and slopes. Multiplicity Counting: The number of charged particles associated with each event is counted and stored. Muon Track Angle Extraction: Angles of muon tracks are extracted and analyzed separately. Histogram Generation: Histograms are created to visualize the distributions of charged particle multiplicities and muon track angles.

5.1.3 Results and Discussion

Figure 5.1a presents the histogram of charged particle multiplicities obtained from the OPERA emulsion data analysis [2]. This is compared with the results of our analysis shown in Figure 5.1b. Both histograms exhibit a similar distribution, demonstrating decent agreement between the multiplicities extracted from the OPERA data and the published ones.



(a) OPERA emulsion data analysis (b) Our Analysis

Figure 5.1: Comparison of charged particle multiplicity distributions obtained from the OPERA data analysis and the reference paper

5.1.4 Muon Track Angle Analysis

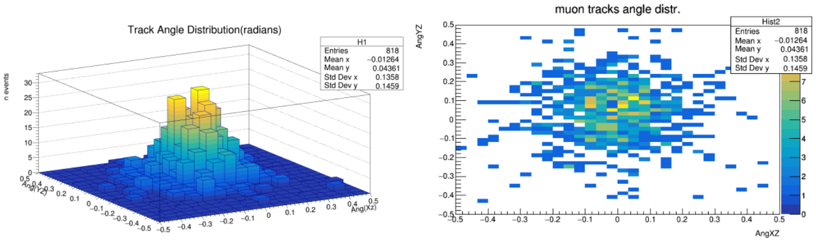
In addition to multiplicity, the angles of muon tracks were also analyzed to provide further insights into the interaction properties . This section details the methodology, results, and observations related to muon track angles.

Track Parameter Extraction

The file eventID Tracks.csv contains primary vertex coordinates and track slopes in XZ and YZ planes for each of the 817 events. These slopes were used to calculate the corresponding angles with the X or Y axis.

A C++ code was developed to extract these angles from the files and generate visualizations to analyze their distribution.

Visualization of Track Angles



(a) 2D histogram of muon track angles (b) Track Angle distribution

Figure 5.2: Visualizations of muon track angles from the OPERA emulsion data analysis.

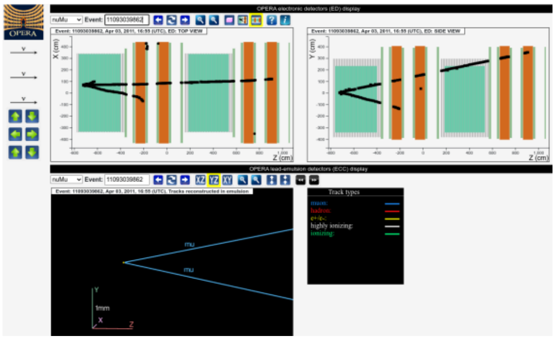


Figure 5.3: Visualization of the dimuon event 11093039862 from the OPERA emulsion data (source: Open Data Portal

Task 3

Introduction

In this task, the OPERA emulsion dataset focusing on tau neutrino appearance studies is utilized. The goal is to create a browser-based 3D event display using the THREE.js graphics library. The provided code is a simplified version, but some sections are missing and need to be recovered. The objective is to reconstruct and visualize tracks and vertices in nuclear emulsions related to 10 tau neutrino candidate events.

Dataset Overview

The dataset consists of information related to tau neutrino interactions recorded by the OPERA experiment. This includes data on particle tracks and interaction vertices within nuclear emulsion layers. The tau neutrino candidates are crucial for studying neutrino oscillations and advancing our understanding of fundamental particle physics.

THREE.js Graphics Library

The THREE.js graphics library is employed to create an interactive 3D visualization of the events. THREE.js is a powerful tool for rendering three-dimensional graphics in web browsers, making it suitable for displaying complex particle interaction events.

Task Steps

(a) **Understanding the Provided Code**: Review the existing codebase to understand its structure, functions, and the specific parts that are missing.

(b) **Recovering Missing Sections**: Identify the missing sections in the code responsible for crucial functionalities. This may include sections related to event loading, track reconstruction, vertex positioning, and camera controls.

(c) **Implementing Track and Vertex Reconstruction**: Enhance the code to reconstruct tracks and vertices based on the dataset. Utilize the information available in the dataset to accurately position and visualize particle tracks and interaction vertices in the 3D space.

(d) **Ensuring Interactivity**: Implement interactive features to allow users to explore and manipulate the 3D visualization. This may involve adding controls for zooming, panning, and rotating the view.

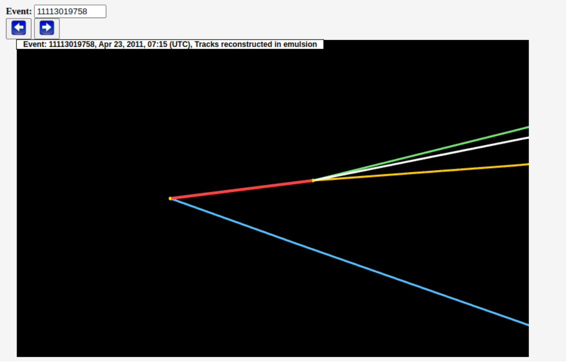
(e) **Testing and Validation**: Thoroughly test the recovered and implemented sections to ensure the correctness of the 3D event display. Validate the results against known events and expected outcomes.

Importance of the Task

(a) **Visualization for Analysis**: The 3D event display serves as a valuable tool for researchers to visually analyze and interpret tau neutrino interaction events. It provides a comprehensive view of particle tracks and their spatial relationships.

(b) **Scientific Discovery**: Understanding tau neutrino appearance is fundamental to unraveling mysteries in neutrino physics. The visual representation aids scientists in gaining insights into the behavior of these elusive particles.

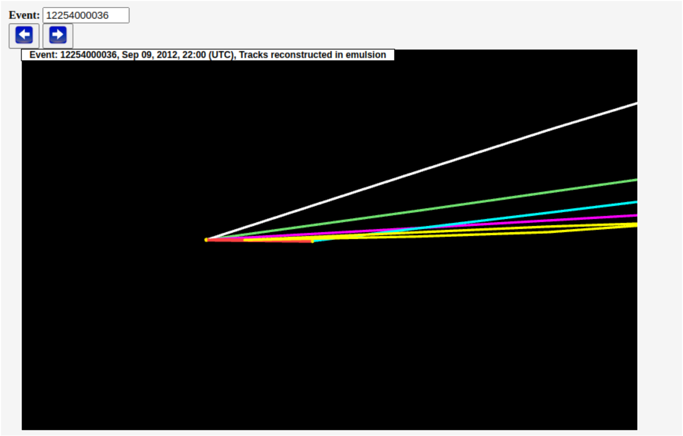
(c) **Educational Tool**: The 3D event display can also serve as an educational tool, allowing students and enthusiasts to explore and learn about particle interactions in an engaging manner.



Event: 11113019758

Event: 11113019758, Apr 23, 2011, 07:15 (UTC), Tracks reconstructed in emulsion

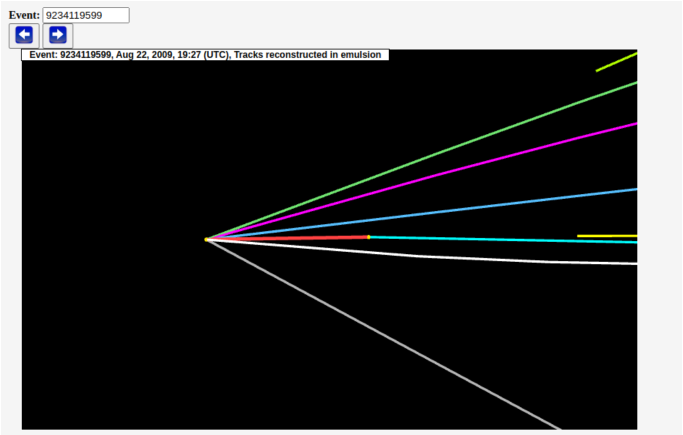
Figure 6.1: Event with ID 11113019758



Event: 12254000036

Event: 12254000036, Sep 09, 2012, 22:00 (UTC), Tracks reconstructed in emulsion

Figure 6.2: Event with ID 12254000036

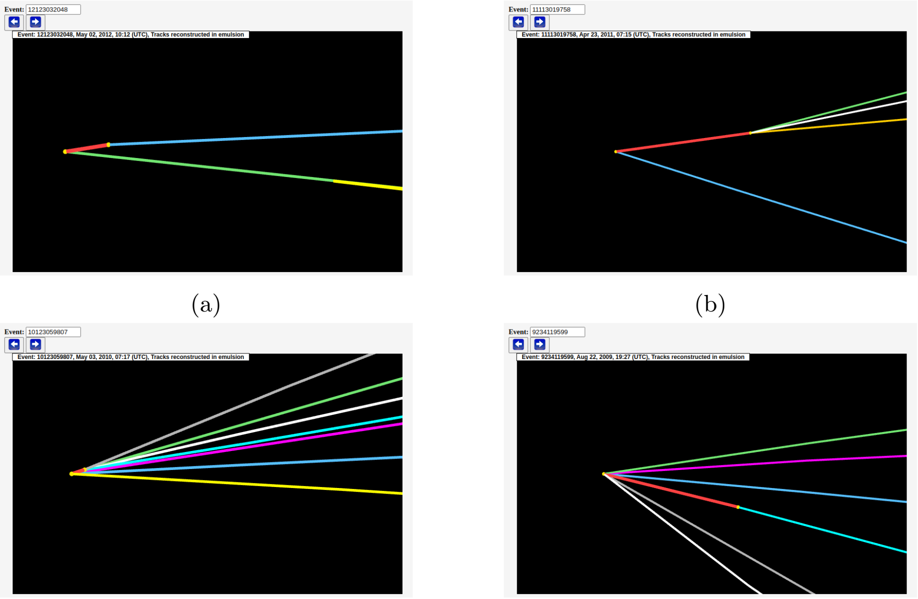


Event: 9234119599

Event: 9234119599, Aug 22, 2009, 19:27 (UTC), Tracks reconstructed in emulsion

Figure 6.3: Event with ID 9234119599

Some extra Visualizations



Event: 12123032048

Event: 12123032048, May 02, 2012, 10:12 (UTC), Tracks reconstructed in emulsion

(a)

Event: 11113019758

Event: 11113019758, Apr 23, 2011, 07:15 (UTC), Tracks reconstructed in emulsion

(b)

Event: 10123059807

Event: 10123059807, May 03, 2010, 07:17 (UTC), Tracks reconstructed in emulsion

(c)

Event: 9234119599

Event: 9234119599, Aug 22, 2009, 19:27 (UTC), Tracks reconstructed in emulsion

(d)

Figure 6.4: Extra Visualizations.

Aknowledgment

The successful completion of this project would not have been possible without the invaluable guidance and support of Dr. Sergey Demetrevesky. His expertise in particle physics. provided a crucial foundation for our research, and his willingness to share his knowledge and insights throughout the process proved instrumental in navigating the complexities of the project. We are deeply grateful for his patient mentorship, insightful critiques, and unwavering encouragement. This work stands as a testament to Dr. Demetrevesky's dedication to his students and his commitment to furthering knowledge in scientific writing.

Bibliography

[1] N. Agafonova, et al., “Procedure for short-lived particle detection in the OPERA experiment and its application to charm decays,” Eur. Phys. J. C **74**, 1 (2014).

[2] N. Agafonova, et al., “Study of charged hadron multiplicities in charged-current neutrino–lead interactions in the OPERA detector,” Eur. Phys. J. C **78**, 1 (2018).

[3] N. Agafonova, et al., “Final results of the OPERA experiment on ν_τ appearance in the CNGS neutrino beam,” Phys. Rev. Lett. **120**, 211801 (2018).

[4] OPERA Collaboration, “The OPERA Experiment: Detection of Neutrino Oscillations,” Journal of High Energy Physics, 2008. `https://link.springer.com/article/10.1007/JHEP06(2015)069`

[5] N. Agafonova, et al., “Recent Developments in Neutrino Physics,” Progress in Particle and Nuclear Physics, 2016. `https://www.sciencedirect.com/science/article/pii/S0146641016300705`

[6] C. Gustavino, et al., “OPERA: A Precision Experiment for Atmospheric Neutrino Oscillations,” Journal of Physics: Conference Series, 2016. `https://iopscience.iop.org/article/10.1088/1742-6596/718/6/062038`

[7] M. Dracos, et al., “Neutrino Physics with OPERA in the CNGS Beam,” Physics Procedia, 2015. `https://www.sciencedirect.com/science/article/pii/S1875389215026843`

[8] N. Mauri, et al., “OPERA: Highlights and Results,” Journal of Physics: Conference Series, 2020. `https://iopscience.iop.org/article/10.1088/1742-6596/1342/1/012036`