JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

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 results of the study conducted during the tenth wave of the JINR Interest Programme, focused on the analysis of data from the OPERA experiment, available on the CERN open data portal, with the aim of investigating the appearance of tau neutrinos. Using languages such as Python, C++, and JavaScript, the analyses encompassed the investigation of charmed hadron decays and the analysis of track multiplicity, providing insights into the dynamics of particles produced in neutrino interactions in the OPERA experiment. Additionally, the detailed reconstruction of particle vertices and trajectories in emulsion films allowed for a profound understanding of the topology of tau neutrino candidate events. These results significantly contributed to deepening knowledge in neutrino physics, especially in neutrino oscillation mechanisms and neutrino detection techniques.

1. Introduction

1.1 Neutrinos in the Standard Model

The theory of neutrinos emerged in 1930 to elucidate the continuous behavior of the beta decay spectrum. According to the principles of energy conservation, the electrons emitted in this process should possess a specific energy, determined by the masses of the isotopes before and after decay. However, it was observed that the emitted electrons exhibited a variety of energies, often lower than those predicted for a two-body decay. Pauli then postulated the existence of a massless, electrically neutral particle (to preserve electric charge) with weak interaction with matter. This particle would be emitted alongside the electron, explaining the observed spectrum. Later, it was confirmed that this particle is the electron antineutrino.

$$n \rightarrow p + e^- + \bar{\nu}_e. \quad (1)$$

The experimental detection of neutrinos occurred through inverse beta decay, made possible in 1956 by the use of liquid scintillators associated with a nuclear reactor. In this process, a proton in the liquid absorbed the neutrino, generating an electron-positron pair. Shortly afterward, the positron annihilated with an electron, resulting in the emission of two gamma rays in opposite directions, detected by the scintillating liquid. Within about 5 microseconds, the neutron was captured by the cadmium nucleus, producing more gamma rays. The temporal correlation of the light flashes revealed the indirect detection of the neutrino.

Neutrinos have been incorporated into the Standard Model of particle physics, which is a theory derived from the combination of principles from Group Theory, Spontaneous Symmetry Breaking, and Gauge Invariance. In the Standard Model, there are four groups of elementary particles: leptons, quarks, gauge bosons, and the Higgs boson. Leptons and quarks are the fermions of the Standard Model, meaning particles with half-integer spin, while gauge bosons and the Higgs boson are particles with integer spin, with gauge bosons being vector bosons and the Higgs being a scalar particle. Within this framework, neutrinos are classified as leptons, and their interactions with physical gauge bosons must be described through the fermion Lagrangian.

1.2 Neutrino Oscillation

The study of solar neutrinos has become a significant approach to understanding their characteristics. By analyzing the flux of neutrinos coming from the Sun, a reduction in electron neutrinos at the surface is observed compared to the expected value. Bruno Pontecorvo proposed, in 1957, the existence of neutrino oscillations, meaning a change in the leptonic flavor of these particles as they propagate a certain distance from their source, later confirmed by the Super-Kamiokande experiment.

According to neutrino oscillation, there is a neutrino flavor eigenstate, produced in the weak interaction with a charged lepton of the same flavor, which oscillates quantumly in its propagation. This effect is due to the fact that it is a linear combination of mass eigenstates with amplitudes proportional to the Pontecorvo-Maki-Nakagawa- Sakata mixing matrix. A consequence of neutrino oscillation is that, unlike what was proposed by Pauli and assumed by the standard model, neutrinos have mass. However, oscillation experiments are not capable to provide information about the magnitude of the neutrino mass, but only provide information about the quadratic mass difference.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \tag{2}$$

At an appropriate distance from the source, neutrinos produced in a specific flavor state can, therefore, be detected as a different flavor state. The appearance of a different neutrino flavor from the original one is the clearest signature of oscillations.

2. OPERA Experiment

The OPERA experiment was conceived during a period when neutrino oscillations were predominantly studied through the disappearance of the original flavor. Its main mission was to make the first direct observation of tau neutrinos (ν_τ) originating from the oscillation of muon neutrinos (ν_μ) to tau neutrinos (ν_τ) in the long-distance beam from the CNGS at CERN to the Gran Sasso underground Laboratory (LNGS), situated at a distance of 730 km. The experiment also had the capability to observe electrons, which would also enable the investigation of the $\nu_\mu \rightarrow \nu_e$ oscillation channel.

To achieve its goals, OPERA adopted an innovative approach, combining real-time detection techniques (using electronic detectors) with the Emulsion Cloud Chamber (ECC) technique. The ECC consists of plates of passive material, such as lead, interleaved with nuclear emulsion films, which act as submicrometrically precise tracking devices. This technology had already been successfully used in the DONUT experiment, which was the first to directly observe tau neutrinos.

The OPERA experiment significantly expanded the scale of this technology, using "bricks" composed of 56 lead plates interleaved with nuclear emulsion films, totaling a mass of 1.25 kilotons. These "bricks" were arranged into 62 vertical "walls," transverse to the beam direction, between layers of plastic scintillators. The detector was divided into two identical units (supermodules), each containing 31 walls and double layers of scintillators followed by a magnetic spectrometer.

The electronic detectors played an important role in the experiment, triggering data acquisition, identifying and measuring the trajectory of charged particles, and locating the "brick" where the interaction occurred. The trajectory of muons was tracked back to the originating "brick" through the scintillator planes. When no muon was observed, the scintillation signals produced by electrons or hadronic showers were used to predict the location of the "brick" containing the primary neutrino interaction vertex.

After identifying the "brick" of interest, the emulsion films at the interface were developed to search for tracks related to the neutrino interaction. The analysis of the event topology selected potential tau neutrino candidates, which were confirmed through kinematic analysis at the primary and decay vertices.

The modularity of the target structure allowed for nearly real-time analysis of neutrino-target interactions, minimizing target mass reduction during the experiment execution. Each wall of "bricks" was followed by a double layer of plastic scintillators for real-time detection of charged particles. The instrumented target was followed by a magnetic spectrometer to measure the deflection of charged particles and to remove ambiguities in trajectory reconstruction.

Finally, two glass RPC planes mounted in front of the first target enabled the rejection of charged particles originating outside the fiducial region of the target, minimizing interference from neutrino interactions in the surrounding rock material and other nearby experiments.

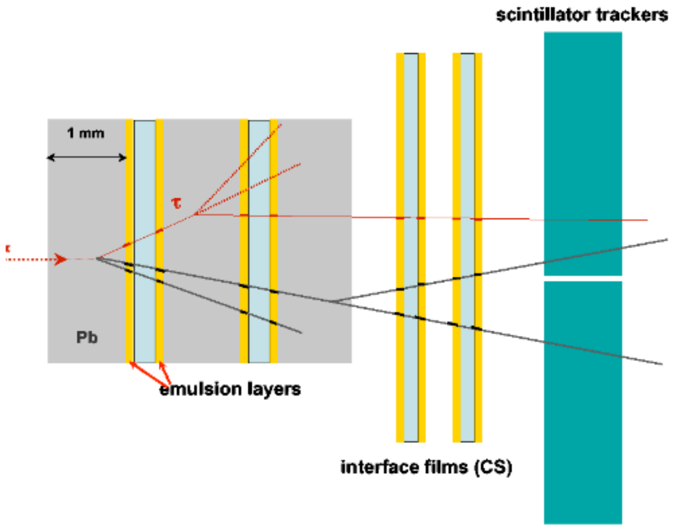

Fig 1. Schematic representation of a charged-current interaction of the ντ, as it would appear in an OPERA "brick," in the emulsion films, and in the scintillator trackers.

3. Data Analysis and Results

3.1 Charmed Hadrons

As mentioned, the OPERA experiment aims to observe muonic neutrino oscillations to tau neutrinos through the detection of tau leptons produced in charged-current interactions of tau neutrinos. The same procedure was applied in the search for charm hadrons, which exhibit decay topologies similar to tau leptons. Fifty candidate events for charmed hadron decays were observed, and their data will be used in this analysis.

The detection of charmed hadrons follows a carefully developed procedure to identify the decays of these particles, as depicted in Figure 2, which occur at distances on the order of 1 mm from the neutrino interaction point.

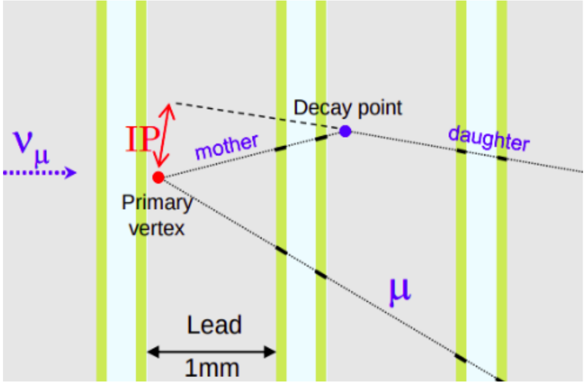

Fig 2. Represents the decay of a charmed hadron.

The first step in charmed hadron detection is to define the primary vertex, which is determined by extrapolating the trajectory to the center of the lead plate just above the point where the trajectory disappears. This point indicates the position where the neutrino interacts with the detector, giving rise to new particles. Identifying the primary vertex enables the characterization of possible produced charmed hadrons. Additionally, it is necessary to determine the secondary vertex, which is the point where the charmed hadron produced decays into other particles, and the distance traveled before the particle decays is the decay length of the particles, calculated using equation 4.

$$\overline{V_0V_1} = (x_1 - x_0, y_1 - y_0, z_1 - z_0) = (dx_{10}, dy_{10}, dz_{10}) \tag{3}$$

$$D \equiv |\overline{V_0V_1}| = \sqrt{dx_{10}^2 + dy_{10}^2 + dz_{10}^2} \tag{4}$$

The first analysis conducted with the data from the 50 candidate events for charmed hadron decays, obtained by the OPERA experiment, was the plotting of the distribution of the decay length of the charmed particles.

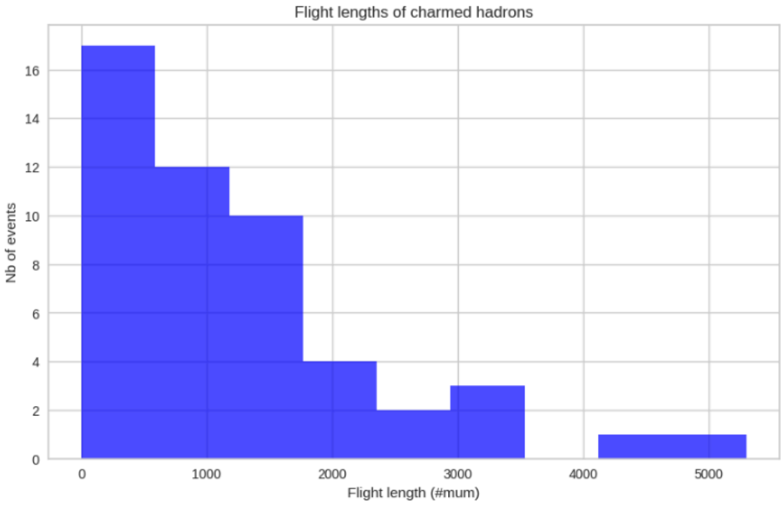

Fig 3. Distribution of decay length of candidate charmed hadrons.

For the detection of charmed hadrons, the search for additional tracks, known as "extra tracks," is conducted. These tracks cross at least three emulsion films and have an impact parameter with respect to the vertex smaller than 300 μm (or 500 μm, depending on the longitudinal distance z relative to the vertex). These additional tracks are important for confirming the presence of charmed particles and for distinguishing the events of interest from other background noise. The impact parameter is calculated using the following equation:

$$IP = \frac{|\overline{V_0 V_1} \times \overline{V_1 P_2}|}{|\overline{V_1 P_2}|}$$

The second analysis conducted with the data from the 50 candidate events for charmed hadron decays, obtained by the OPERA experiment, was the plotting of the distribution of the impact parameters of the daughter particles resulting from the decay of charmed hadrons.

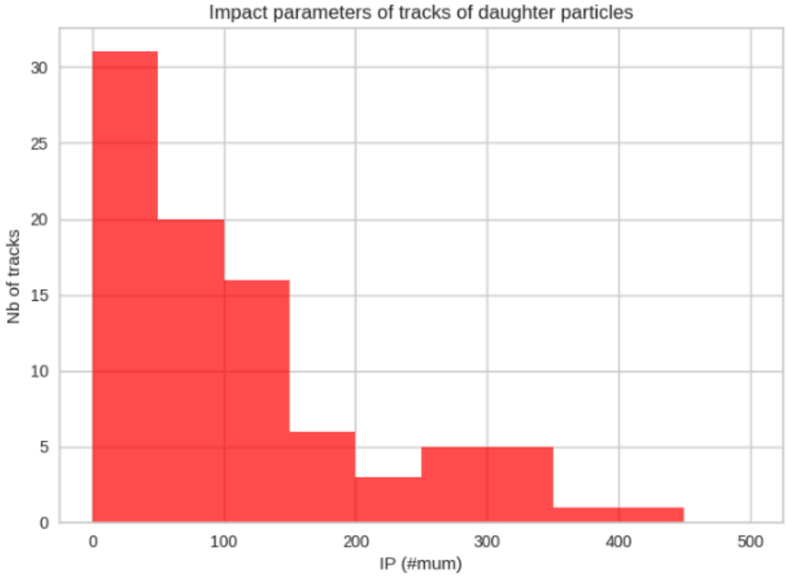

Fig 4. Distribution of impact parameters of daughter particles.

3.2 Track Multiplicity

The track multiplicity in neutrino-lead interactions in the OPERA detector is important for understanding the dynamics of charged particles produced during these interactions. The OPERA detector accumulated a sample of neutrino interactions with lead, where a negatively charged muon was identified by the muon spectrometer.

Track multiplicity refers to the number of individual particle trajectories detected in a specific event. In particle physics experiments, charged particles leave detectable tracks in detectors when they interact or decay. Therefore, track multiplicity is an essential measure for understanding the kinematics of produced particles, identifying interaction patterns, and validating theoretical models of collision processes.

During the track multiplicity data analysis in OPERA, the tracks associated with the primary vertex of muon neutrino interaction were identified. The goal was to determine the multiplicities of all charged particles produced during these interactions, and this data was recorded in a histogram, as shown in Figure 5.

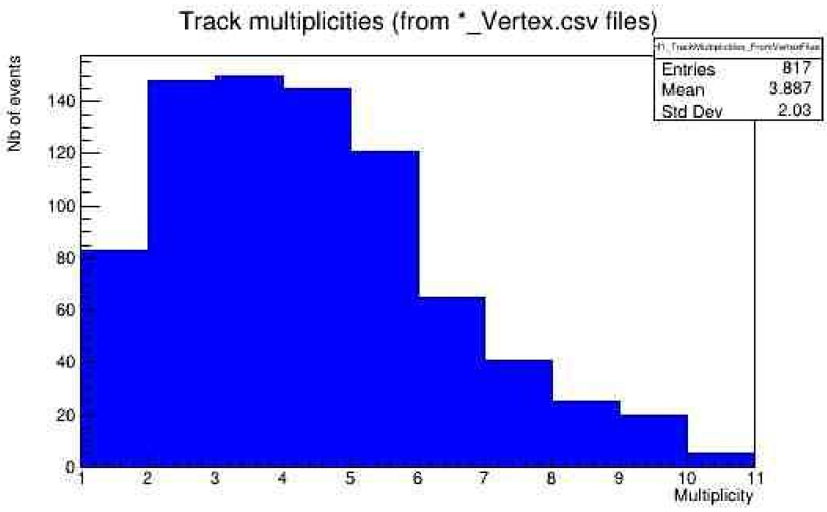

Fig 5. Distribution of track multiplicity.

Each track is defined by its starting point, a 3D point near the vertex, and two slopes, represented by the tangents of the angles with respect to the Z-axis in the XZ and YZ views. Additionally, during this analysis, the angles of the muon trajectories were obtained, as represented by Figure 6, using the equation $\theta = \tan^{-1}(s)$, where θ represents the angle of the muon trajectory in radians, and s is the slope.

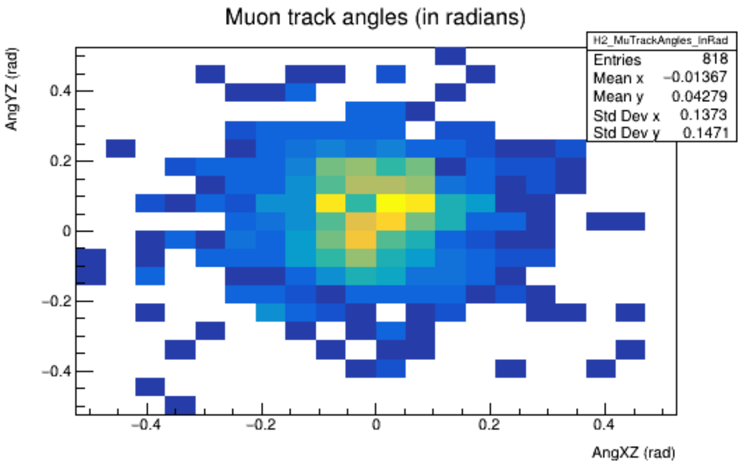

Fig 6. Ângulos das trajetórias dos múons

3.3 Vertex and Track Reconstruction

The emulsion data for tau neutrino appearance studies refer to the use of emulsion films in the OPERA experiment to detect tau neutrinos, extracting detailed information about the topology of neutrino interactions, including reconstruction of the primary interaction vertex and the associated particle tracks.

In this analysis, the OPERA emulsion data set was used for tau neutrino appearance studies with the aim of creating a three-dimensional visualization of 10 candidate tau neutrino event topologies. The primary and secondary vertices, along with the positions of the reconstructed tracks in the nuclear emulsion for the candidate events, were displayed in this analysis as shown in Figure 7. The tau lepton track is represented in red, the pion (daughter particle) in blue, the photon in white, the pion in gray, the gamma in orange and yellow, and finally, the tracks of the hadrons are represented in green, blue, and pink.

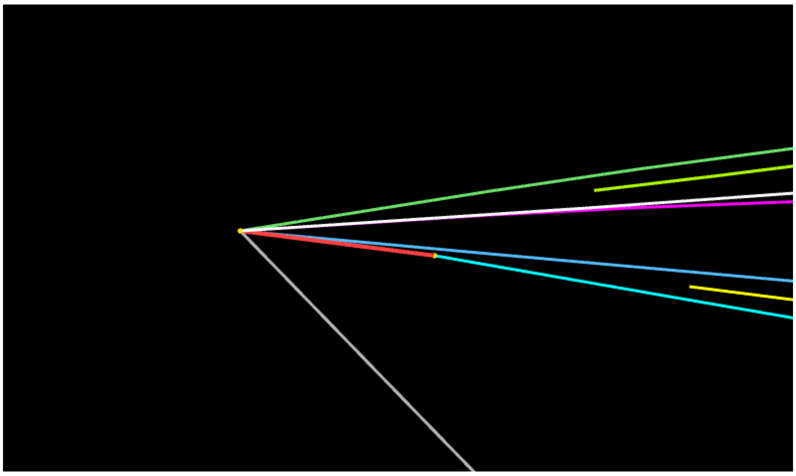

Fig. 7 An example of the topology of one of the tau neutrino candidate events.

4. Conclusions

The observation of 10 candidates for charged interactions ντ in the OPERA experiment represented a significant milestone in neutrino physics. This discovery was crucial for validating the three-flavor neutrino oscillation mechanism, specifically the νμ→ντ oscillations, with an impressive statistical significance of 6.1σ. The confirmation of these oscillations brought substantial contributions to the understanding of neutrino physics and the confirmation of related theoretical models.

The purpose of this work was to reproduce some of the analyses conducted in the OPERA experiment using languages such as Python, C++, and JavaScript. By replicating these analyses, the main goal was to achieve a deeper understanding of these events, the detection methods employed, and neutrino physics.

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