Joint Institute for Nuclear Research

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

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Abstract

Nowadays, neutrino oscillations are one of the main challenges in particle physics. Experimental evidence suggests the possibility of new physics beyond the standard model, where neutrino oscillations can be understood. One of the main ideas is that neutrino oscillations are a consequence of the effects of a higher energy scale. OPERA experiment (Oscillation Project with Emulsion-Tracking Apparatus) is one of the projects that has studied this phenomenon at the Gran Sasso National Laboratory in Italy. The aim of this experiment was to directly observe ν_τ appearance within a pure ν_μ beam using nuclear emulsion techniques. This work analyzes several OPERA datasets collected during the experiment, which are available on the CERN Open Data Portal. This training aims to develop skills in data processing related to nuclear emulsion techniques and to become familiar with the advantages of the OPERA Experiment in understanding $\nu_\mu \to \nu_\tau$ neutrino oscillation.

Introduction

In the early 20th century, the phenomenon of beta decay was being studied, which at that time was described by the nuclear reaction ${}^A_Z X \rightarrow {}^A_Z X' + e^-$. It was expected that the emitted electron would have an energy equal to the difference in energy between the parent and daughter nucleus, however, a continuous energy spectrum was observed. To conserve energy, Wolfgang Pauli proposed the emission of a second particle (neutrino) in addition to the electron, which would be difficult to detect and would be assigned most of the energy released in the reaction: ${}^A_Z X \rightarrow {}^A_Z X' + e^- + \nu_e$. This particle was supposed to be a fermion with zero electric charge.

The issues related to neutrinos began in the 1960s with the Homestake experiment, carried out by Raymond Davis Jr. and John N. Bahcall. The goal was to detect solar neutrinos produced in fusion processes in the core of the Sun. There were notable discrepancies between the observed quantity of electron neutrinos and those predicted by the theory. Some hypotheses attempted to explain this disparity, such as rethinking the processes occurring in the Sun's core or analyzing the nature of neutrinos.

Subsequently, in 1957, Bruno Pontecorvo postulated the neutrino oscillation mechanism [Pontecorvo, 1957b, Pontecorvo, 1957a]. This model suggests that the left-handed neutrino fields ν_{lL} with $l = e, \mu, \tau$ participating in the electroweak interaction are linear combinations of orthogonal states of defined mass. This leads to the coherent mixing of flavors, and therefore neutrinos cannot be described as massless particles, contradicting the predictions of the standard model. Recent experimental data is conclusive regarding the mass bounds for different flavors of neutrinos ($m_{\nu_e} < 0.8\, eV/c^2$, $m_{\nu_\mu} < 0.17\, MeV/c^2$, $m_{\nu_\tau} < 18.2\, MeV/c^2$) [Aker et al., 2022, Collaboration and Barate, 1998].

It is important to note that the electroweak model cannot explain the mass of neutrinos because they only have left-handed helicity. Therefore, after the spontaneous breaking of electroweak symmetry, neutrinos remain as massless particles [Weinberg, 1967, Glashow, 1961, Salam, 1959].

Various experiments with solar, atmospheric, and nuclear reactor neutrinos have provided evidence of neutrino oscillations. One of the major projects is the Super-Kamiokande experiment, built to detect neutrinos emitted by supernovae, solar neutrinos, and atmospheric neutrinos. In 1998, it announced the first evidence of neutrino oscillation [Fukuda, 1998]. On June 18, 2001, the team at the Sudbury Neutrino Observatory (SNO) in Canada revealed evidence of flavor change in neutrinos traveling from the Sun's core to the Earth [Collaboration et al., 2001]. The observation of the complete flux of neutrinos predicted by the theory was reported.

In the quest to explain the very small values of neutrino masses, two models are important to highlight: the "Seesaw" mechanism and radiative corrections [Cortez Jr, 2005]. The "Seesaw" mechanism justifies the presence of mass at an energy scale higher than the values of standard model phenomena, but it presents the significant disadvantage of being experimentally inaccessible.

The importance of neutrinos for astrophysical scenarios is a fact. They provide the opportunity to study supernovae; being produced in the core of these events, they provide detailed information about collapse and explosion mechanisms. Furthermore, the diffuse background of neutrinos from supernovae is used to conduct studies on a cosmological scale [Mirizzi et al., 2016]. It is believed that, similar to the cosmic microwave background radiation from the Big Bang, there also exists a background of low-energy neutrinos in the universe, constituting one of the possible candidates for dark matter [Huerta Salas et al., 2020].

Neutrinos are also used in studies that seek to explain the asymmetry between matter and antimatter through models proposing the existence of heavy neutrinos. The decays of these particles in the early universe could be responsible for the asymmetry between particles and antiparticles through a process known as leptogenesis [Davidson et al., 2008].

The experimental evidence of neutrino oscillations and the prediction of a mass for them indicate that the neutrino sector in the standard model requires modifications.

OPERA Experiment

The OPERA Experiment was designed to perform the first observation of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode through the detection of the τ leptons produced in ν_τ charged current interactions with the final state τ particle decaying in one (muon, electron or hadron) or three prongs. This entailed directing a beam of muon neutrinos from CERN to the Gran Sasso National Laboratory in Italy at the distance of 730 kilometers. At Gran Sasso was located a system of detectors specifically designed to capture distinct characteristics indicative of tau neutrino interactions.

At the Gran Sasso National Laboratory, the detector was able to register all types of neutrinos 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 Super Proton Synchrotron proton beam. Thanks to the excellent spatial resolution of nuclear emulsions, interleaved with lead plates to form a compact modular target, and using the complementary information provided by electronic detectors, event topology and kinematics could fully reconstructed.

The OPERA neutrino detection system was based on nuclear emulsion films. These consisted of multiple layers of a photographic emulsion containing silver halide crystals. Charged particles, such as tau leptons produced by neutrino interactions, caused ionization within these crystals, leaving distinct tracks. The emulsion films was 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 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. In addition to nuclear emulsion, OPERA incorporated electronic detectors, such as drift tubes and resistive plate chambers to complement the emulsion-based tracking. The electronic detectors provided additional information, such as the time of the interaction, which helped to identify distinct tracks in the nuclear emulsion layers.

Nuclear emulsions, historically called Emulsion Cloud Chamber (ECC) are tracking detectors well suited for the study of short-lived particle decays. They have been successfully used in the DONUT experiment at FNAL, providing the first experimental evidence of the τ neutrino [Kodama et al., 2001]. They also have been used in studies of ν_μ-induced charm production. Charmed hadrons have masses and lifetimes similar to those of the τ lepton and constitute one of the main background sources for oscillation experiments like OPERA. At the same time, charm production represents the most powerful tool to directly test the experiment capability of detecting τ decays, given the alike topology characterising ν_μ CC events with a charmed particle in the final state and oscillated ν_τ induced CC interactions.

Two distinct decay topologies can be identified, depending on the relative positions of the interaction and decay vertices (Fig. 1). If the decay occurs in the same lead plate as the neutrino interaction or in the first 45 µm-thick downstream emulsion layer, it is defined as short decay and daughter tracks can be detected as particles showing a large impact parameter with respect to the neutrino vertex. Otherwise, it is defined as long decay and daughter tracks typically appear as extra-tracks, not attached to the reconstructed neutrino interaction point and starting downstream of the vertex film.

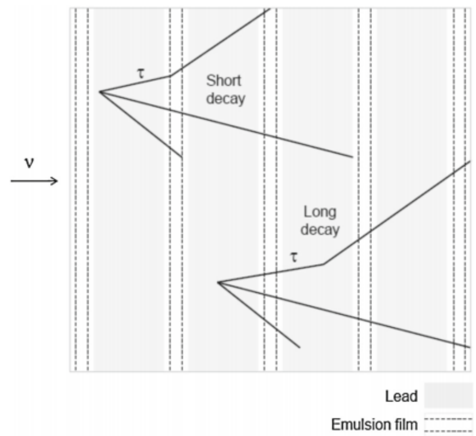


Fig. 1: Sketch of short and long τ decay topologies.

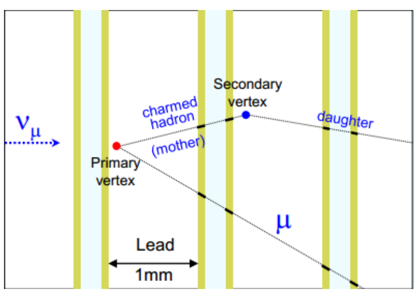
Results

Task 1

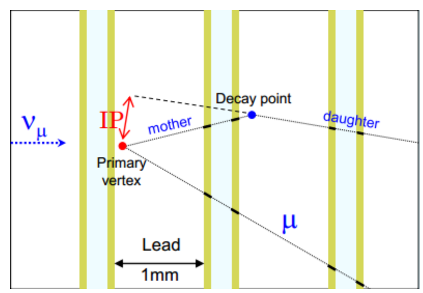
In this task we used the OPERA emulsion dataset for the neutrino-induced charmed hadron production studies from the Open Data Portal and developed a C++ code for the analysis of this dataset. In the first part it is determined the flight length of the 50 events of ν_μ decay, which is defined as the distance traveled by the charmed hadron (the mother particle) between the primary vertex of decay and the secondary vertex of interaction as it's shown in Fig. 2.a. For this we read the positions in the files "Vertices.csv" and compute the flight lengths using the formula,

$$d = \overline{V_0 V_1} = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2}, \tag{1}$$

where (x_0, y_0, z_0) are the coordinates of the primary vertex and (x_1, y_1, z_1) the coordiantes of the secondary vertex.



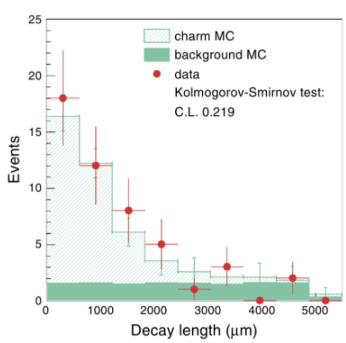
(a) Flight length of a charmed hadron.



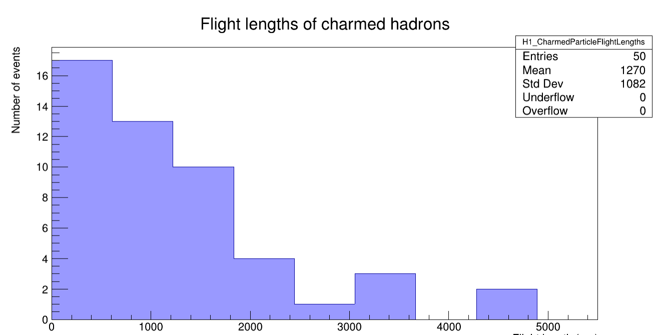
(b) Impact parameter of a daughter particle track.

Fig. 2:

The calculated values are stored in a histogram that was created using the CERN ROOT C++ framework and is compared with the histogram obtained in [Agafonova et al., 2014] as it's shown in Fig. 3.



(a) Decay length distribution obtained with OPERA experiment dataset in [Agafonova et al., 2014].



(b) My results of the decay length distribution using OPERA dataset.

Fig. 3:

As second part of the task is determined the distribution of impact parameter of the daughter particle tracks with respect to the primary neutrino interaction vertex. This is defined as the distance between the primary vertex and the daughter's path, which is determined by the distance between a line and a point in 3D space as in Fig. 2.b. The coordinates of the primary vertex were obtained from the EventID "Vertices.csv" file, while the coordinates for the daughter tracks were obtained in the EventID "TrackLines.csv". Impact parameter can be calculated using the formula,

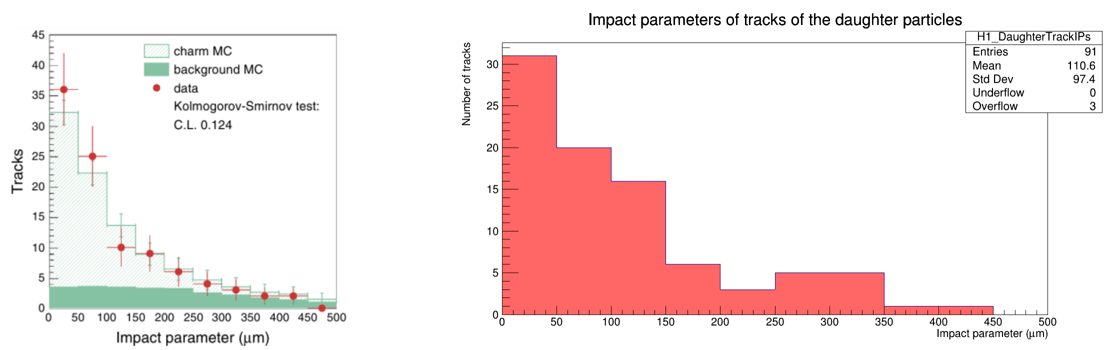
$$IP = \frac{|\vec{X}_1 \times \vec{X}_2|}{|\vec{X}_2|}, \tag{2}$$

where $\vec{X}_1$ is the vector that goes from the primary vertex to the secondary interaction vertex and $\vec{X}_2$ is the vector that goes from the secondary interaction vertex to the second point of the daughter particle track. Writing this expression in terms of the coordinates we have

$$IP = \sqrt{\frac{\sum_{cyc}^{x,y,z}(y_0z_2 - y_0z_1 + y_1z_0 - y_1z_2 - y_2z_0 + y_2z_1)^2}{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2}}, \tag{3}$$

where the indices $1, 2, 3$ correspond to the aforementioned vertices.

The calculated values are stored in a histogram that was created using the CERN ROOT C++ framework and is compared with the histogram obtained in [Agafonova et al., 2014] as it's shown in Fig. 4.



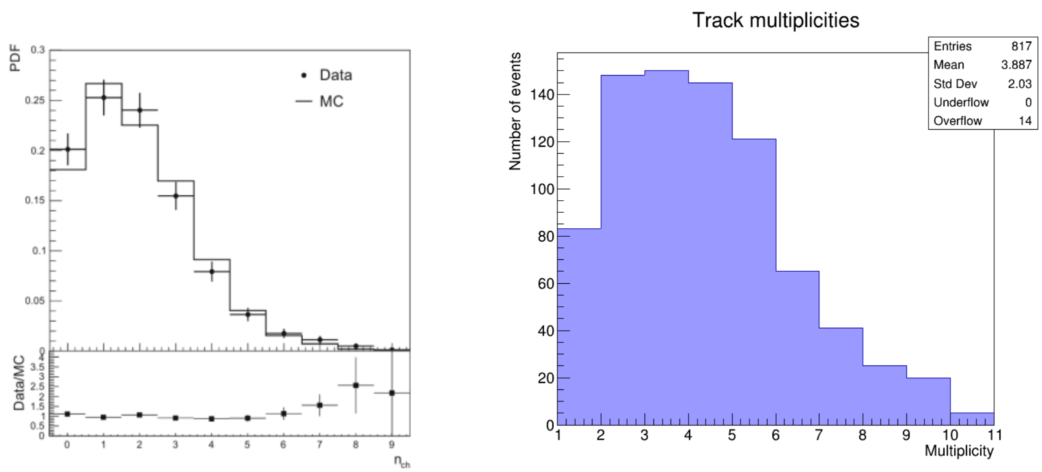
(a) Impact parameter distribution obtained with OPERA experiment dataset in [Agafonova et al., 2014].

(b) My results of the impact parameter distribution using OPERA dataset.

Fig. 4:

Task 2

In this task we reproduced the track multiplicitie distribution of 817 events of ν_μ decay. Track multiplicity of a vertex is the number of charged particle tracks associated with the vertex. 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. A comparison of the charged particle multiplicity distributions obtained from the OPERA data analysis and the obtained in [Agafonova et al., 2018] is shown in Fig. 5.



(a) Track multiplicity distribution obtained with OPERA experiment dataset in [Agafonova et al., 2018].

(b) My results of the track multiplicity distribution using OPERA dataset.

Fig. 5:

In the second part is determined to the two-dimensional distribution of the XZ and YZ slopes, which helps understanding the probability of specific topologies to occur. 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 angles with the Z axis in ZX and ZY views, respectively, as it's shown in Fig. 6.

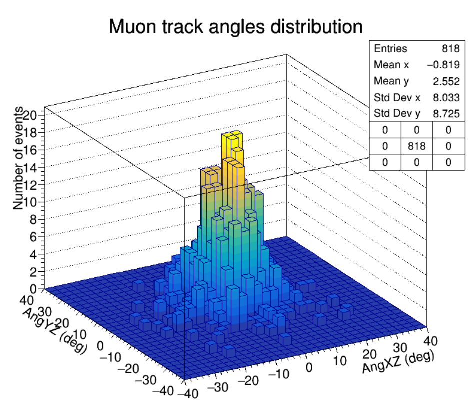


Fig. 6: 2D representation histogram of the muon track angle distribution.

Task 3

In this task we create a browser-based 3D event display focusing on tau neutrino appereance studies. For this is used the THREE.js graphics library in a simplified version of the OPERA browser-based event display with some missing sections that need to be recovered. The objective is to reconstruct and visualize tracks and vertices in nuclear emulsions related to 10 ν_τ candidate events. Some examples of our results are shown in Fig. 6. and can be compared with results obtained by [Agafonova et al., 2021].

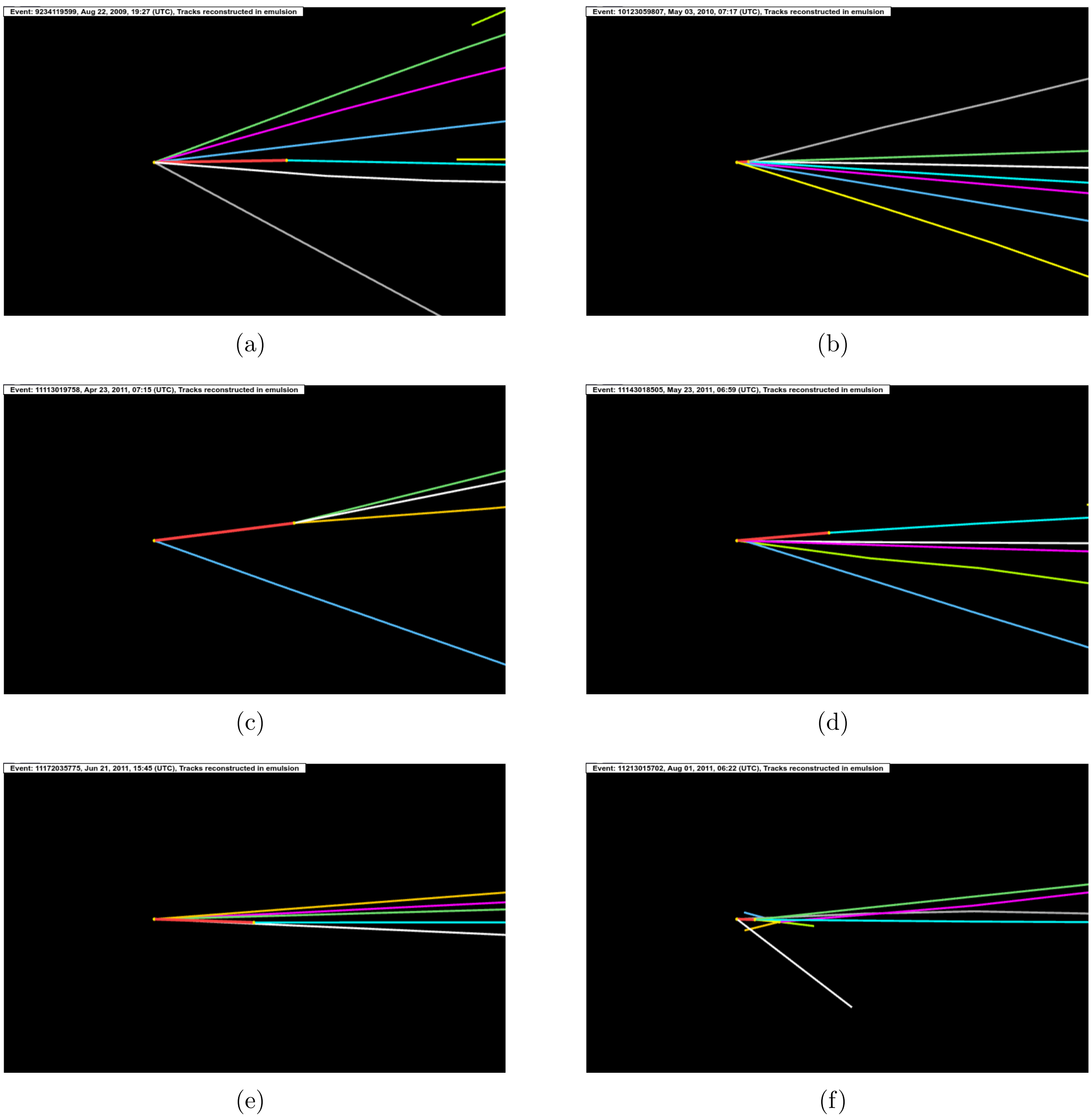


Fig. 7: Examples of the 10 ν_τ candidate events obtained in our simplified browser-based 3D event display.

Conclusions

Through this project, skills for processing experimental data have been developed using the data obtained from the OPERA Experiment. To achieve this, it was necessary to study and understand C++ codes for analyzing the dataset corresponding to the reported events. This also served as an introduction to using ROOT as a tool for data processing and interpretation, enabling us to compare our results with those obtained from the literature. This involved studying decay length distributions, impact parameters, multiplicity and track slopes, which provided insight into the information extracted by particle detectors and how to use it to reconstruct neutrino events using nuclear emulsion data. This project also requested to understand and modify a HTML, CSS, JS project to visualize the topology of interesting neutrino interaction events in the OPERA detector, a simplified version of event display with an interactive interface was created using the Three.js graphics library. This information can help to comprehend the production and decay of charmed hadrons in neutrino interactions and is also of considerable interest for understanding the behavior of charged particles produced in neutrino interactions, as well as for studying the muon production in these interactions.

Acknowledgment

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Bibliography

[Agafonova et al., 2014] Agafonova, N., Aleksandrov, A., Anokhina, A., Aoki, S., Ariga, A., Ariga, T., Bender, D., Bertolin, A., Bozza, C., Brugnera, R., et al. (2014). Procedure for short-lived particle detection in the opera experiment and its application to charm decays. *The European Physical Journal C*, 74:1–9.

[Agafonova et al., 2018] Agafonova, N., Aleksandrov, A., Anokhina, A., Aoki, S., Ariga, A., Ariga, T., Bertolin, A., Bodnarchuk, I., Bozza, C., Brugnera, R., et al. (2018). Study of charged hadron multiplicities in charged-current neutrino–lead interactions in the opera detector. *The European Physical Journal C*, 78:1–8.

[Agafonova et al., 2021] Agafonova, N., Alexandrov, A., Anokhina, A., Aoki, S., Ariga, A., Ariga, T., Bertolin, A., Bozza, C., Brugnera, R., Buonaura, A., et al. (2021). Opera tau neutrino charged current interactions. *Scientific data*, 8(1):218.

[Aker et al., 2022] Aker, M. et al. (2022). Direct neutrino-mass measurement with sub-electronvolt sensitivity. *Nature Physics*, 18(2):160–166.

[Collaboration and Barate, 1998] Collaboration, A. and Barate, R. (1998). An upper limit on the neutrino mass from three-and five-prong tau decays. *The European Physical Journal C-Particles and Fields*, 2(3):395–406.

[Collaboration et al., 2001] Collaboration, S. et al. (2001). Measurement of the rate of nu_e+ d–¿ p+ p+ eˆ-interactions produced by 8b solar neutrinos at the sudbury neutrino observatory. *arXiv preprint nucl-ex/0106015*.

[Cortez Jr, 2005] Cortez Jr, Nelson V y Tonasse, M. D. (2005). Calculable lepton masses, seesaw relations, and four neutrino mixings in a 3-3-1 model with an extra u (1) symmetry. *Physical Review D*, 72(7):073005.

[Davidson et al., 2008] Davidson, S., Nardi, E., and Nir, Y. (2008). Leptogenesis. *Physics Reports*, 466(4-5):105–177.

[Fukuda, 1998] Fukuda, Yoshiyuki y Hayakawa, T. y. I. E. y. I. K. y. I. K. y. I. H. y. I. Y. y. K. T. y. K. J. y. K. S. y. o. (1998). Evidence for oscillation of atmospheric neutrinos. *Physical Review Letters*, 81(8):1562.

[Glashow, 1961] Glashow, S. (1961). Glashow 1961. *Nucl. Phys*, 22:579.

[Huerta Salas et al., 2020] Huerta Salas, J., Huerta Salas, J., et al. (2020). Búsqueda de materia oscura ligera más allá del modelo estándar. B.S. thesis, Benemérita Universidad Autónoma de Puebla.

[Kodama et al., 2001] Kodama, K., Ushida, N., Andreopoulos, C., Saoulidou, N., Tzanakos, G., Yager, P., Baller, B., Boehnlein, D., Freeman, W., Lundberg, B., et al. (2001). Observation of tau neutrino interactions. *Physics Letters B*, 504(3):218–224.

[Mirizzi et al., 2016] Mirizzi, A., Tamborra, I., Janka, H.-T., Saviano, N., Scholberg, K., Bollig, R., Hüdepohl, L., and Chakraborty, S. (2016). Supernova neutrinos: production, oscillations and detection. *La Rivista del Nuovo Cimento*, 39:1–112.

[Pontecorvo, 1957a] Pontecorvo, B. (1957a). Inverse beta processes and nonconservation of lepton charge. *Zh. Eksp. Teor. Fiz.*, 34:247.

[Pontecorvo, 1957b] Pontecorvo, B. (1957b). Mesonium and anti-mesonium. *Sov. Phys. JETP*, 6:429.

[Salam, 1959] Salam, Abdus y Ward, J. C. (1959). Weak and electromagnetic interactions. *Il Nuovo Cimento (1955-1965)*, 11:568–577.

[Weinberg, 1967] Weinberg, S. (1967). Weinberg 1967. *Phys. Rev. Lett*, 19:1264.