CERN Summer Student Internship Report
Uncertainties and Biases in Neutrino-Nucleus Interactions at DUNE Far Detector
A Machine Learning Approach

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December 20, 2023

Abstract

This report presents an analysis performed at CERN, focusing on specific biases and uncertainties in neutrino-nucleus interactions that affect the determination of neutrino oscillation in view of the upcoming DUNE experiment. Utilising the GENIE event generator, the study assesses several interaction models, particularly in regard to their handling of Final State Interactions (FSI). The impact of these models on energy prediction discrepancies and cross-section measurements is quantified. A significant portion of the study is dedicated to the statistical evaluation of FSI model performances. Additionally, the report details the quality control work performed for the ERAM TPC detector modules, crucial for the T2K experiment. These findings provide actionable insights to refine detection methods. The insights gained from this work contribute to a more precise understanding of neutrino interactions, supporting ongoing research in the field.

Introduction

Neutrinos are subatomic particles that are integral to our understanding of particle physics and the universe. They are electrically neutral and interact with matter via the weak nuclear force, making their detection extremely challenging [5]. Despite being one of the most abundant particles in the universe, produced by nuclear reactions in stars and during supernova explosions, their elusive nature has made the study of neutrinos a complex field within particle physics [5]

Neutrinos exist in three flavors: electron (ν_e), muon (ν_μ), and tau (ν_τ). Each flavor is a quantum superposition of three mass eigenstates (ν_1, ν_2, ν_3) with different masses. The phenomenon of neutrino oscillations is a quantum mechanical effect where a neutrino created with a specific lepton flavor (e.g., electron, muon, or tau) can later be measured to have a different flavor. This can only occur if neutrinos have mass and if the flavors are quantum superpositions of mass eigenstates.

The probability P of a neutrino changing flavor is given by:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2) \cdot L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

where:

- $\nu_\alpha \to \nu_\beta$ denotes the change from one neutrino flavor to another,
- θ is the mixing angle,
- Δm^2 is the difference in the squares of the masses of the mass eigenstates (in eV^2),
- L is the baseline, or the distance the neutrino travels (in km),

- E is the neutrino energy (in GeV).

The factor 1.27 in the formula is a product of constants that allows the oscillation probability to be conveniently expressed in terms of the baseline L in kilometers and the neutrino energy E in GeV. This factor arises from converting the units of the physical constants involved in the formula to match these units, ensuring the formula's practical applicability to experimental measurements.

It's important to note that this is a simplified version of the oscillation formula and it assumes only two neutrino flavors are involved, but it captures the essence of the phenomenon [5].

1 Neutrino Oscillations

Neutrino oscillations represent one of the most intriguing phenomena in particle physics. This process, whereby a neutrino changes its flavor while in transit, directly indicates that neutrinos are not massless, contrary to the initial postulations of the Standard Model.

Neutrinos are produced through weak decays as specific flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$. However, these flavor states are not eigenstates of the Hamiltonian governing their propagation, which are the mass eigenstates (ν_1, ν_2, ν_3). The flavor eigenstates are quantum superpositions of mass eigenstates, and the mass eigenstates propagate differently because they have different masses.

The relationship between the flavor and mass eigenstates can be expressed through the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix, a unitary matrix that describes the probability of a neutrino changing its flavor [2]. The PMNS matrix is defined as:

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} \\ U_{e3} & U_{\mu 3} & U_{\tau 3} \end{pmatrix}$$

Here, $U_{\alpha i}$ denotes the amplitude for a neutrino of flavor α to be found in mass state i. The PMNS matrix can also be parameterized in terms of three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and a CP-violating phase. The oscillation probability can then be expressed in a more detailed form considering all three neutrino flavors.

Neutrino oscillations are of immense importance because they imply new physics beyond the Standard Model. The precise measurements of the oscillation parameters, especially the differences in neutrino masses and the mixing angles, are crucial for understanding the nature of neutrinos and their role in the universe. These measurements are conducted in various neutrino experiments worldwide.

2 DUNE Experiment

The Deep Underground Neutrino Experiment (DUNE) is a cutting-edge international research project focused on studying neutrinos and unraveling their mysteries. Located at the Sanford Underground Research Facility, DUNE aims to provide groundbreaking insights into neutrino oscillations, mass hierarchy, and CP violation [2]. The project, involving collaboration from scientists from over 30 countries, is set to begin taking physics data with the Fermilab neutrino beam in 2031. The primary goals of DUNE are to study neutrino oscillations in unprecedented detail, investigate the asymmetry between matter and antimatter in the universe, and observe neutrinos from supernovae.

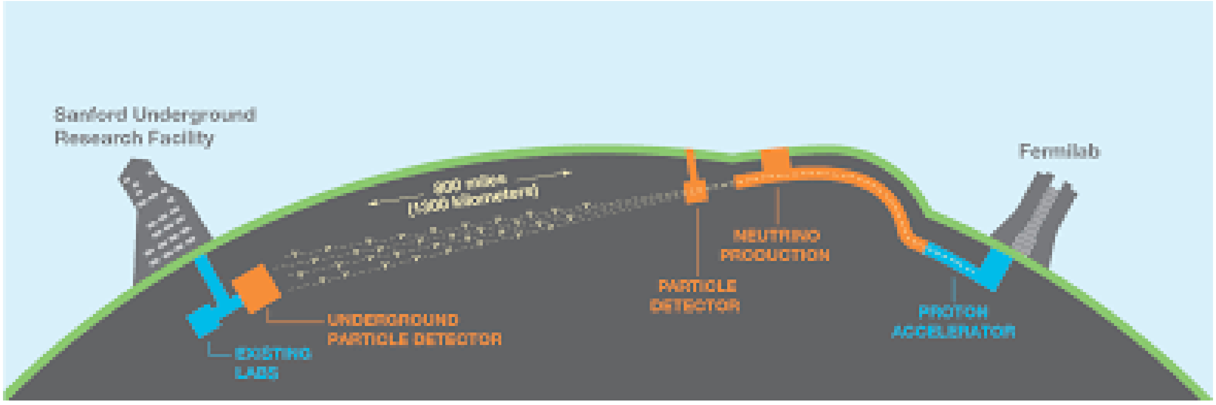

Figure 1: Deep Underground Neutrino Experiment

2.1 Motivation and Goals

- **Understand Neutrino Oscillations:** With its finely-tuned detectors, DUNE aims to measure neutrino oscillations with greater precision than ever before, providing more stringent tests of the PMNS matrix and potentially revealing new physics.

- **CP Violation:** One of the most anticipated goals of DUNE is to determine whether Charge-Parity (CP) violation occurs in neutrino oscillations. Observing CP violation outside of the quark sector, particularly among leptons, would have profound implications for our understanding of the matter-antimatter asymmetry in the universe, potentially explaining why the universe is composed mostly of matter, rather than containing equal parts matter and antimatter.

- **Proton Decay and Supernova Neutrinos:** DUNE is also designed to search for rare physics phenomena such as proton decay and to detect neutrinos from supernovae. The observation of proton decay would provide insight into the Grand Unified Theory (GUT), while capturing neutrinos from supernovae would offer valuable information about these stellar explosions and the role of neutrinos in astrophysical processes.

2.2 Detector Technologies

DUNE's experimental setup is composed of two primary components: the far detector located at the Sanford Underground Research Facility (SURF) in South Dakota, and the near detector complex at Fermilab in Illinois. The distance between these two detectors allows for the study of neutrino oscillations over a long baseline, providing a unique environment to observe the nuances of neutrino behavior.

2.2.1 Far Detector

The far detector, situated 1.5 kilometers underground to minimize cosmic ray interference, comprises four massive liquid argon time-projection chambers (LArTPCs). LArTPCs are cutting-edge in neutrino detection technology, allowing for precise tracking and energy measurements of the final state particles produced in neutrino interactions. Liquid argon is employed due to its stability and high electron density, making it an effective medium for a time projection chamber. When a neutrino interacts with an argon nucleus, it produces charged particles that ionize the argon atoms in their path. The ionization electrons are subsequently drifted through the liquid argon by an electric field to the anode planes, producing a signal that can be analyzed to reveal the energy deposited by the particles and thus allow us to reconstruct the incoming neutrino energy.[2].

2.2.2 Near Detector

The near detector, located at Fermilab, performs complementary measurements to understand the properties of the neutrino beam and the physics of neutrino interactions at higher energies. This detector is crucial for interpreting the data from the far detector accurately, as it provides necessary information about the initial composition and energy of the neutrino beam before the neutrinos undertake their 1,300-kilometer journey to the far detector and before oscillations have occured.

3 Uncertainties and Biases in Neutrino-Nucleus Interactions

The study of neutrino-nucleus interactions, particularly at the energies relevant for DUNE, stands at the frontier of our understanding of weak interaction physics. However, extracting fundamental neutrino properties from these interactions necessitates navigating a labyrinth of complex phenomena and intricate theoretical models, each contributing its own set of uncertainties and potential biases [3].

3.1 Theoretical Framework and Model Uncertainties

The theoretical landscape for neutrino-nucleus interactions is a tapestry of quantum mechanics, nuclear physics, and particle interactions, with the overarching framework provided by the Standard Model of particle physics. Neutrino interactions are principally modeled through Quantum Chromodynamics (QCD) and electroweak theory, incorporating the dynamics of quarks, leptons, and force carriers (W and Z bosons).

3.1.1 Cross-section Calculations

Neutrino interaction cross-sections, pivotal for any neutrino experiment, are derived from a convolution of the neutrino flux, the interaction probability, and the nuclear structure functions. The latter, embodying the probability distributions of quarks and gluons in a nucleon, introduce substantial uncertainties due to the complex, many-body nature of atomic nuclei.

3.1.2 Nuclear Medium Effects

The nuclear environment significantly modifies the free-nucleon cross-sections. Modeling these effects requires accounting for nuclear form factors, Fermi motion, binding energies, and nucleon correlations. Discrepancies in these parameters between different models lead to variations in predicted cross-sections and reconstructed neutrino energies.

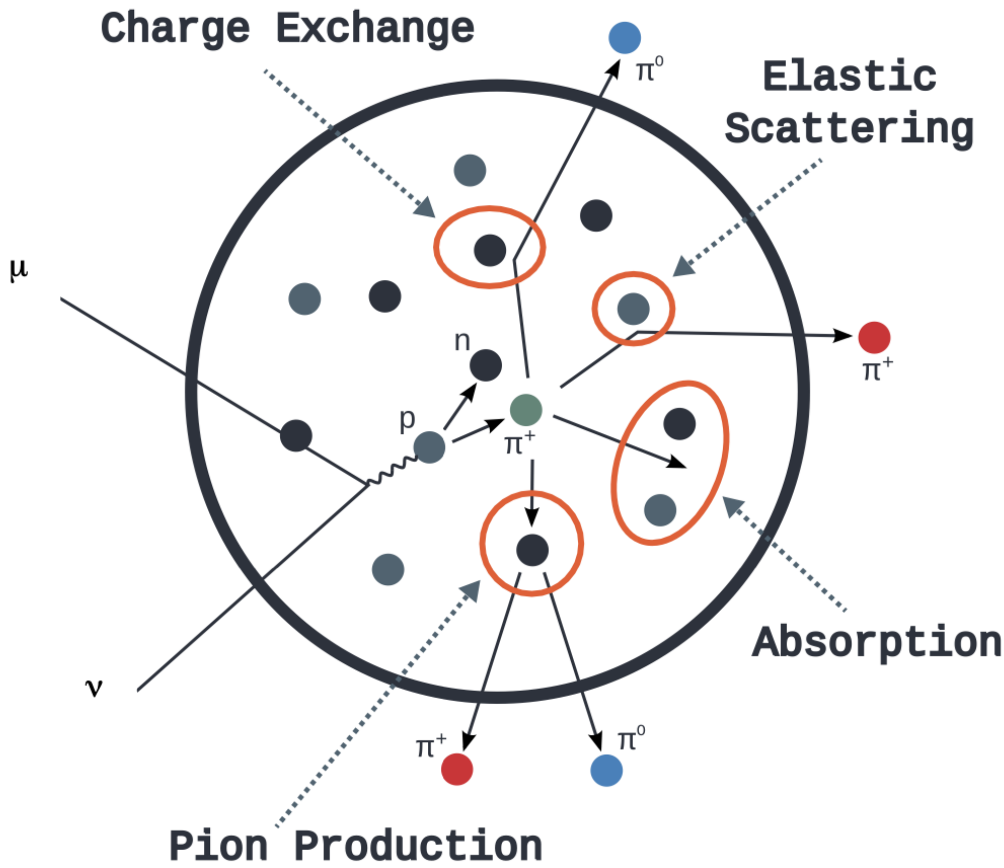

Figure 2: The illustration underscores the convoluted journey of hadrons generated in a neutrino-nucleus collision. The initial interaction, governed by weak force exchange, creates a cascade of secondary particles that undergo numerous Final State Interactions (FSIs) within the nuclear environment before they are detectable. These FSIs, involving re-scattering, absorption, and charge exchange, drastically alter the observable particle energy and composition, complicating back-tracing to the original neutrino characteristics[3].

3.1.3 FSI Complexity

As depicted in the figure 2, FSIs play a critical role in the energy transfer and particle production in neutrino interactions. Models must contend with the probabilistic nature of these interactions, involving inelastic scattering, pion production, and absorption processes, each influenced by the nuclear potential and the quantum states of nucleons.

3.2 Experimental Challenges and Data Interpretation

The exploration of neutrino-nucleus interactions presents unique experimental challenges. One significant hurdle is the inherent limitation of detectors in accurately capturing low-energy neutrino interactions [2]. The sensitivity and resolution of detectors are crucial in this aspect. Additionally, the complexity of data acquisition systems, which must handle high data rates and require sophisticated algorithms for data analysis, adds to the experimental challenges [4].

Interpreting data from these experiments involves a meticulous process of comparing experimental results with theoretical models and analyzing discrepancies. This comparison is crucial for refining models and improving future experiments. The use of tools like the GENIE event generator helps in understanding the impact of neutrino interactions on various detector materials [5].

Reliability in model predictions is a critical aspect of neutrino-nucleus interaction studies. Different models offer varied interpretations of neutrino interactions, constrained by our current understanding of nuclear physics and computational limits for simulating complex interactions [3]. Discrepancies between model predictions and experimental data necessitate a careful approach to data interpretation, ensuring that uncertainties are adequately accounted for.

4 Addressing Uncertainties for neutrino oscillation analyses

The field's advancement hinges on a symbiotic relationship between theoretical developments, experimental advancements, and advanced data analysis techniques.

Neutrino-nucleus interaction studies are inherently riddled with uncertainties, arising from both experimental setups and theoretical models. These uncertainties, if not properly understood and managed, can alter the measurements we perform of neutrino oscillation parameters. The process of identifying and quantifying these uncertainties is a complex yet vital aspect of neutrino physics. For instance, the discrepancies in cross-section measurements and their impact on neutrino flux predictions are critical areas where uncertainties play a major role [3]

Experimental uncertainties often stem from detector limitations, data acquisition challenges, and the interpretation of signals. Improving detector technologies and refining data analysis methods are essential steps in minimizing these uncertainties [2]. The advancements in detector design, as seen in the ProtoDUNE project, provide a blueprint for future developments in neutrino detection technologies. ProtoDUNE, a prototype for the DUNE far detectors, serves as a testbed for the technologies and methodologies to be employed in DUNE. It measures critical parameters such as neutrino interaction rates and energy spectra, playing a pivotal role in fine-tuning the detector design and data analysis techniques for the main DUNE experiment [2].

On the theoretical front, enhancing the accuracy of neutrino interaction models is paramount. This involves integrating the latest experimental data, refining model parameters, and improving computational techniques for simulation [5].

5 Objective 1: Studying the reconstructed energy bias due to mismodeling of neutrino-nucleus interactions

5.1 Theoretical Framework and Research Rationale

The focus of this research was an exploration into the uncertainties and biases inherent in neutrino-nucleus interactions, with a specific emphasis on the role of secondary particles like neutrons and pions in the final state, and how their production influences the overall uncertainties in energy measurements[5].

The reconstruction of neutrino energy is a cornerstone of neutrino physics experiments, particularly in large-scale endeavors such as the DUNE experiment. The calorimetric method of energy reconstruction plays a pivotal role in these experiments due to its comprehensive approach in capturing the energy of particles produced in neutrino interactions.

In calorimetric methods, the reconstructed neutrino energy $E_{\nu,\text{rec}}$ is derived from the sum of the visible energies of all detectable particles produced in a neutrino interaction. This method is represented by the equation:

$$E_{\nu,\text{rec}} = E_{\text{lep}} + \sum T_p + \sum T_{\pi^\pm} + \sum E_{\pi^0/\gamma}$$

The key components contributing to this energy sum are:

- E_{lep}, the energy of the lepton, which is usually the most easily identifiable and measurable product of a neutrino interaction.
- $\sum T_p$, the sum of the kinetic energies of protons, which are often detectable in modern neutrino detectors.
- $\sum T_{\pi^\pm}$, the sum of the kinetic energies of charged pions. Detecting these particles and measuring their energies contribute significantly to the accuracy of the reconstructed neutrino energy.
- $\sum E_{\pi^0/\gamma}$, the sum of energies of neutral pions and photons. While challenging to detect, advancements in detector technology have improved the capture and measurement of these particles' energies.

The challenge in this approach lies in accounting for particles that are not detectable or have energies below the detection threshold, such as neutrons. The inability to detect certain particles introduces a bias in the estimated neutrino energy. This bias is crucial for experiments like DUNE, where precise energy measurements are vital for investigating phenomena such as neutrino oscillations and CP violation.

To mitigate these biases, advanced detection technologies and analysis techniques are employed. For example, the DUNE experiment uses Liquid Argon Time Projection Chambers (LAr-TPCs), which offer high-resolution tracking and energy measurements.

1. Model 1: No Final State Interaction (FSI), providing a baseline scenario focusing on uncertainties intrinsic to the initial interaction.
2. Model 2: Introduction of FSI, single step cascading effect, highlighting the impact of particle re-scattering and absorption in the nucleus.
3. Model 3: Integration of both FSI and multi-step , offering a comprehensive view of the multi-stage interactions.

In the context of neutrino-nucleus interactions, a "cascade" refers to the series of subsequent interactions that occur after the initial neutrino collision with a nucleus. These cascading events can involve a variety of subatomic processes, including the creation and interaction of secondary particles like pions and neutrons. The complexity of these cascades can significantly impact the final observable outcomes in neutrino detection experiments.

- E_{avail}: Caloriemetric sum of the outgoing hadronic state, indicative of the energy observed in a detector with a high tracking threshold.

Figure 3 illustrates the relationship between detected neutrino energy and the influence of final state particles in neutrino-nucleus interactions. The plot notably shows that the reconstructed neutrino energy is often below the true generated neutrino energy, primarily due to the invisible energy carried away by neutrons. This depiction highlights the impact of secondary particles, such as neutrons and pions, on the accuracy and reliability of neutrino energy measurements. The presence and behavior of these particles are critical factors in the calibration and interpretation of neutrino detection experiments.

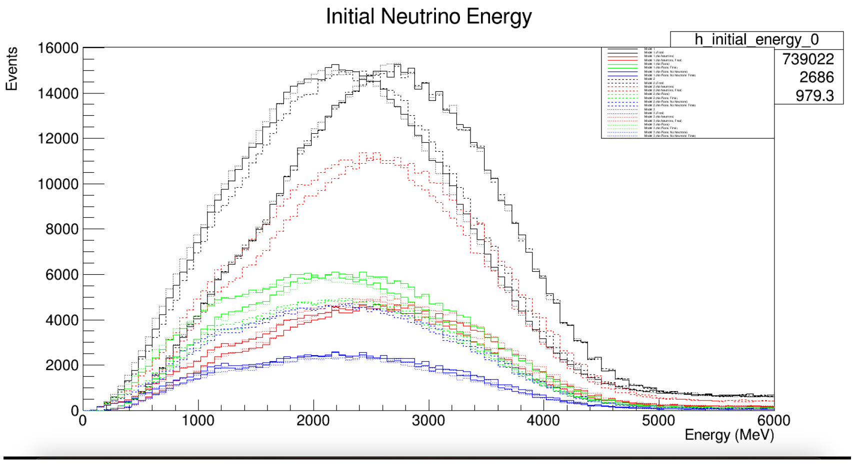

Figure 3: True vs Detected Neutrino Energy.

The relative energy bias is a critical quantity in the evaluation of neutrino energy reconstruction methods. It is defined as the fractional discrepancy between the reconstructed neutrino energy $E_{\nu,\text{rec}}$ and the true neutrino energy $E_{\nu,\text{true}}$, normalized to the true neutrino energy:

$$\text{Relative bias} = \frac{E_{\nu,\text{rec}} - E_{\nu,\text{true}}}{E_{\nu,\text{true}}}$$

As depicted in Figure 4, the distributions show a trend towards negative values, indicating that the reconstructed neutrino energy tends to be underestimated. This systematic underestimation can be observed in the relative bias distribution, which is primarily composed of contributions from unaccounted pion masses and missed neutron energy. Understanding and correcting for this bias is essential for accurate neutrino energy measurements.

Figure 5 highlights a few distinctive features which impact the neutrino energy reconstruction. The plot exhibits distinct peaks at integral multiples of the rest mass of pions (135 MeV), indicative of significant pion production at these energy levels. In calorimetric analysis, where only kinetic energy deposits are recorded, the rest mass of undetected pions is not accounted for. Consequently, these undetected pions introduce notable uncertainties in the measurement of neutrino energy, as the missing rest mass energy contributes to the discrepancy between the true and detected energy.

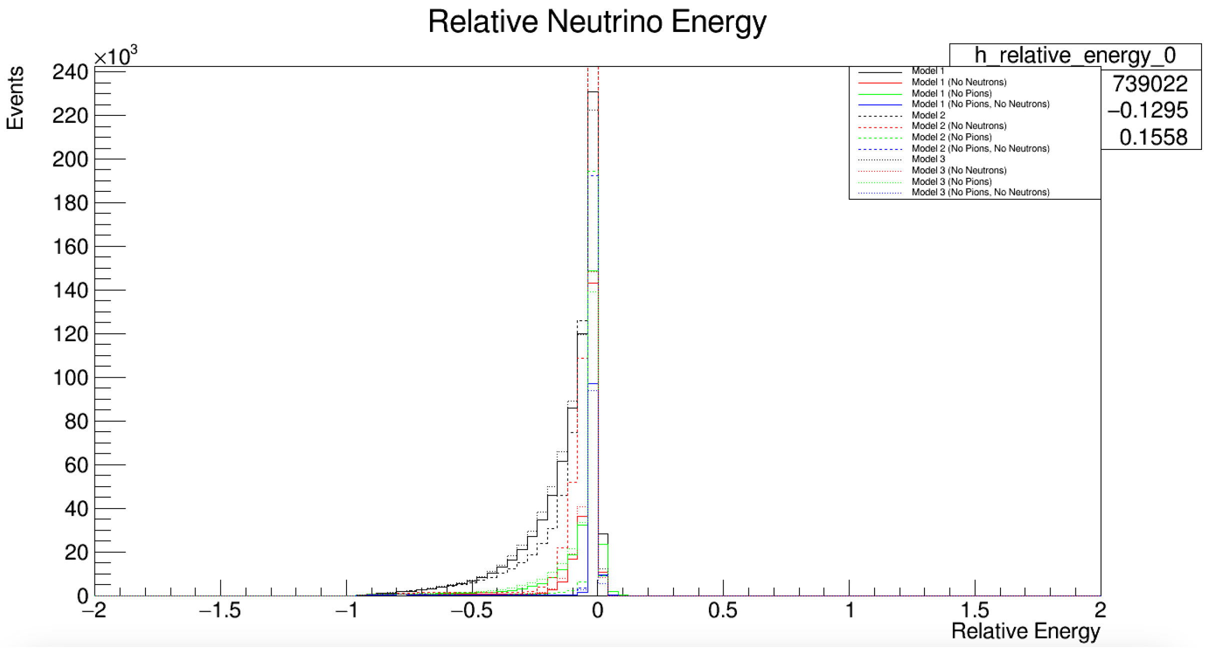

Figure 4: Relative energy bias distribution. Negative values indicate an underestimation of the neutrino energy, with the bias being predominantly due to the unaccounted energy of missed pions and neutrons.

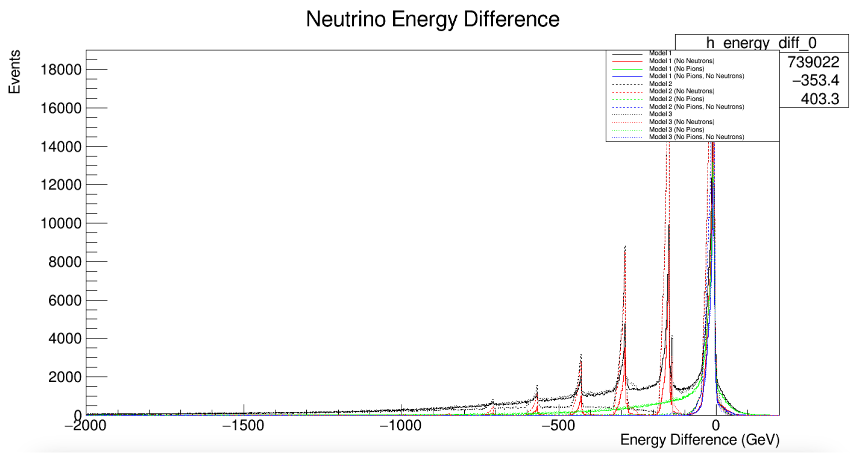

Figure 5: Uncertainties and biases with respect to production of different final state products .

6 Objective 2: Reweighting between neutrino interaction models using Machine Learning

In the realm of high-energy physics, particularly in studies involving neutrino-nucleus interactions, the simulation of interaction events is a computationally demanding task. Each model encapsulates a unique set of physical parameters and assumptions, making the transposition of results between different models a challenge both in terms of computational resources and time. This objective explores the use of Boosted Decision Trees (BDT) to efficiently reweight interaction events between two nuanced models of neutrino-nucleus interactions. Model A introduces Final State Interactions (FSI) with a single step cascading effect, emphasizing particle re-scattering and absorption in the nucleus. Model B, on the other hand, incorporates FSI as multi-step processes. The use of machine learning techniques, such as BDT, to reweight between these two models is an appropriate tool, given that the degrees of freedom altered by each model can span a high dimensional parameter space. This approach allows for a more efficient exploration of the possible outcomes and their probabilities, providing a powerful method to understand and interpret the complex dynamics of neutrino interactions.

6.1 Methodology Overview

The approach involved training ML models on different interaction events sourced from simulations of neutrino-nucleus interactions. The crux of this methodology was the assignment of specific weights to each interaction event, achieved through reweighting technique. These weights, determined by the ML algorithm, were calibrated to reflect the variances between the interaction models, thereby facilitating the accurate transposition of results from one model to another.

6.2 Implementation of Machine Learning

Boosted Decision Trees (BDT), a robust ensemble learning technique known for its effectiveness in classification and regression tasks, was employed as the ML methodology. BDTs operate by converting a set of weak learners into a strong learner through an iterative process, making them particularly adept at managing complex datasets like those encountered in neutrino-nucleus interaction simulations.

The ML model was trained using a data set comprising different simulations and interaction events from Model A, with the algorithm learning to assign weights based on the events characteristics. These features included variables such as the neutrino energy, scattering angles, and the production of various particles. The complexity and diversity of these features were pivotal in enabling the BDT to understand and mimic the intricate features of Model B.

Critically, the output of the BDT training algorithm is a unique set of weights. These weights are key to the transposition process, effectively adapting the features of simulations from Model A into the framework of Model B. This approach dramatically minimized the computational load and time required for transposition from multiple weeks to produce a new detector simulation to 8-10 minutes, streamlining the process of comparing and analyzing results across different models of neutrino-nucleus interactions.

Post-training, the ML model could predict the appropriate weights for new interaction events from Model A, enabling the transposition of these events into the context of Model B. This was achieved by multiplying the results of each event in Model A by the predicted weight, effectively transforming the results to correspond with the expected outcomes in Model B.

This reweighting technique significantly reduced the computational load traditionally associated with direct simulations in high-energy physics. Instead of conducting extensive simulations for each model, this approach allowed for the efficient conversion of results between models, saving considerable computational resources and time.

Figures 6 and 7 display the 'Ratio to Target' distributions for the `eP (train)` and `Erecoil_minerva (train)` which is the recoil energy observed in neutrino interactions, as studied in the MINERvA experiment, respectively, comparing two distinct neutrino interaction models: ARi and ARj. In these figures, ARi delineates a model incorpo-

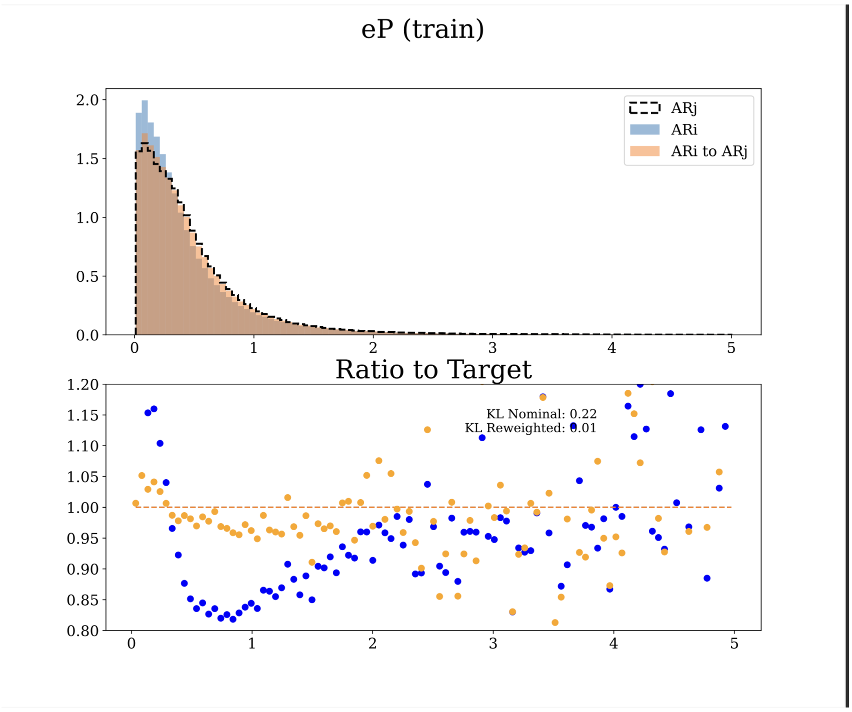

Figure 6: Energy of the proton in the final state for the training set.

rating Final State Interactions (FSI) with a single-step cascading effect, capturing the re-scattering and absorption events within the nucleus. ARj, by contrast, accounts for both FSI and multi-step processes.

The histograms compare the 'ARi' distributions (blue histograms) against the 'ARj' target distributions (dashed line histograms), indicating the initial variances between the models. The shaded areas represent the successful transposition from 'ARi' to 'ARj' after reweighting, effectively aligning ARi with the target ARj model.

Quantitatively, the lower scatter plots in both figures demonstrate the efficacy of the reweighting process using Kullback-Leibler (KL) divergence values. 'KL Nominal' denotes the divergence before reweighting, while 'KL Reweighted' reflects a significant reduction post-reweighting. This reduction, from 'KL Nominal: 0.22' to 'KL Reweighted: 0.01' in the `eP (train)` and from 'KL Nominal: 0.02' to 'KL Reweighted: 0.00' in the `Erecoil_minerva (train)`, validates the BDT's capability to harmonize the ARi model with the ARj model. The marked decrease in KL divergence underscores the successful adaptation of features from one simulation model to another, thus confirming the improved alignment and efficiency brought forth by the machine learning techniques.

By minimizing the need for extensive computational power, this approach not only accelerates the research process but also broadens the scope for conducting more intricate and diverse simulations.

Moreover, the successful implementation of ML in this context underscores the vast potential for further integration of advanced computational techniques in high-energy physics, Highlighting the way for more nuanced and sophisticated analyses in future research endeavors.

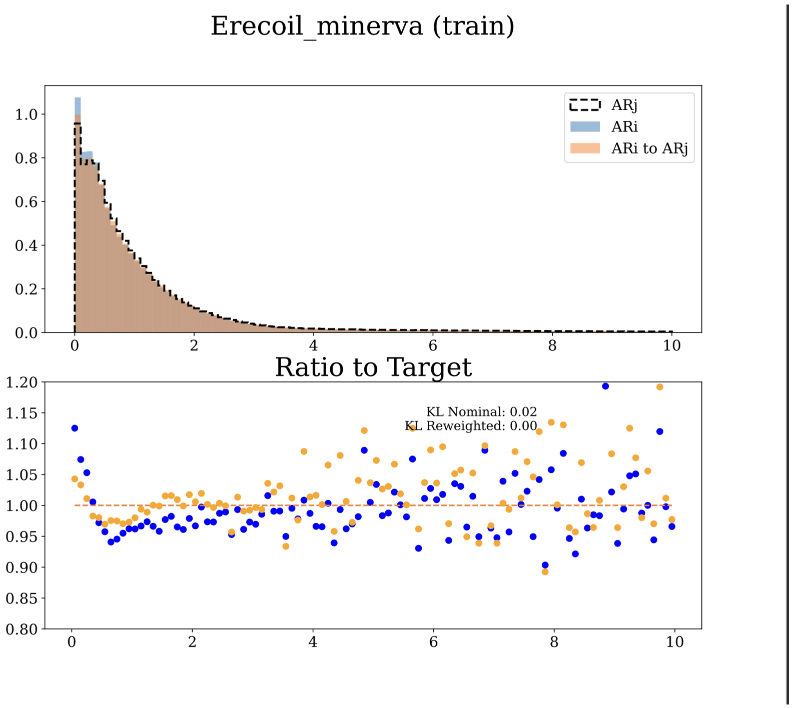

Figure 7: Recoil energy as recorded by the MINERvA detector for the training set.

7 Objective 3: Quality Control of ERAM TPC Detector Modules for T2K Experiment

The T2K (Tokai-to-Kamioka) experiment employs Micro-Pattern Gaseous Detectors (MPGDs), particularly Resistive Bulk Micromegas modules, for neutrino detection due to their high efficiency and resolution. These Micromegas modules are a core component of the ND280 Time Projection Chambers (TPCs), and since their installation in 2009, they have been performing impeccably, without response degradation or failures, demonstrating their robustness and long-term reliability [1].

The detector modules use bulk Micromegas technology, which allows for large detection areas with minimal dead zones and excellent gas gain uniformity [1]. A significant advancement in Micromegas technology is the development of resistive modules. These detectors enhance the spatial resolution by spreading the charge over multiple pads, even for small drift distances, ensuring that the spatial resolution is not compromised by the pad size. Our analysis focused on the performance of the resistive Micromegas, particularly their capability to maintain excellent spatial resolution due to the natural charge spreading over the pads [1].

Additionally, the resistive Micromegas detectors for the upgrade of the T2K near detector are produced at CERN. These detectors undergo quality control before their final installation in the experiment, ensuring their reliability and performance, as depicted in Figure 8.

7.1 Calibration and Testing

The calibration and hands-on testing of these modules were conducted using a dedicated test bench [?]. The test bench played a crucial role in evaluating the uniformity and gain of the detector modules. Through a scanning process using a robotic arm and an

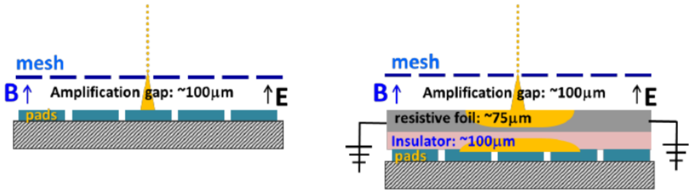

Figure 8: Schematic cross-section of a normal bulk Micromegas (left) and a resistive Micromegas (right). The pads are covered by a layer of insulating material and a layer of resistive material.[1]

^{55}Fe source, we confirmed the uniformity of the gain across the detector and assessed the energy resolution. This process ensured that any dead pads were identified and that a comprehensive gain map could be constructed for the detector modules [4].

7.2 Test Bench Summary of TPC Detector Module ERAM27

Throughout my shift, I performed X-ray scans of an assigned ERAM27 detector using a remote setup enabled by the Windows PC at the CERN Test Bench. This task involved monitoring environmental conditions such as temperature, pressure, and humidity, which are critical for maintaining optimal detector performance and were tracked using a Python script [4]. Notably, the humidity levels were carefully observed to ensure they remained below 1% before raising the ERAM voltage above 100V, thereby safeguarding the detector's operational integrity. Each ERAM27 detector module consists of 32x35 pads or readout channels, and each of these channels was irradiated with an Fe55 source to characterize its performance, as detailed in Figure 9. The specific features and results of these tests will be described in detail in the following sections.

Top Left Panel - Gain from Gauss Fit (Fe peak): This panel showcases a color-coded gain distribution across the pads of the detector, obtained from Gaussian fits to the iron-55 peak. The variance in color intensity represents the variation in gain, indicating the detector's amplification uniformity. It is crucial for identifying regions of atypical gain which may necessitate further investigation or recalibration.

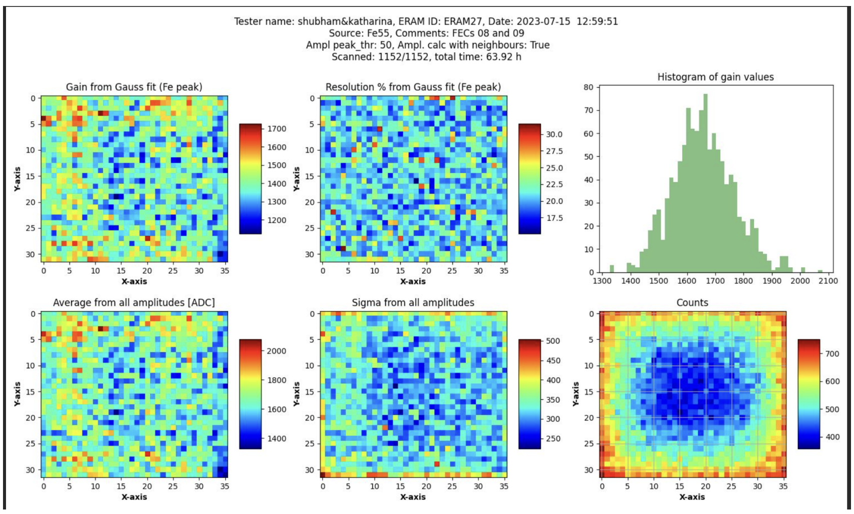

Figure 9: Summary of the performance metrics for ERAM27.

Resolution Percentage from Gauss Fit (Fe peak): The resolution percentage, derived from the Gaussian fit to the iron-55 peak, is illustrated in this panel. This map provides insights into the uniformity of the detector's resolution, with the color gradient reflecting the variability in resolution percentage across the detector surface. An ideal detector would show minimal variation, suggesting consistent performance across all pads.

Histogram of Gain Values: This histogram aggregates the gain values across all pads, offering a statistical representation of the gain uniformity. The distribution of counts versus gain values should ideally be narrow and peak-centered, indicative of uniform response across the detector.

Average from All Amplitudes [ADC The average amplitude for each pad, measured in Analog-to-Digital Converter (ADC) units, is depicted in this panel. The uniformity of average signal amplitudes is critical for ensuring consistent signal processing and interpretation across the entire detector array.

Sigma from All Amplitudes This panel displays the standard deviation (sigma) of the signal amplitudes for each pad, providing a measure of noise and signal fluctuation. A lower sigma value across the detector is preferred, highlighting stability and precision in the detected signals.

Counts from All Amplitudes The color map in this panel visualizes the counts of all signal amplitudes collected during the scan. A central concentration with a gradual fall-off towards the edges is expected. This observed pattern is actually attributed to the detector being shielded with a Mylar sheet, which extends under the gas pressure inside the detector. The Mylar sheet's presence and its interaction with the internal gas pressure produce this distinctive shape in the signal amplitude distribution.

Summary and Implications: The comprehensive analysis of ERAM27 reveals a consistent gain and resolution pattern, with only minor deviations, signifying the detector's readiness for deployment. The histogram of gain values further supports this by demonstrating a centralized gain distribution.

Acknowledgment

I would like to extend my deepest gratitude to my supervisors, Laura and Stephen. They have been more than just supervisors; their unwavering support and guidance throughout my internship have been invaluable. Their kind gesture of inviting me to a birthday party made me feel welcomed and at home. Their mentorship went beyond the professional realm, for which I am immensely grateful.

I would also like to express my heartfelt appreciation to Wissal and Nico. Their friendship and encouragement played a pivotal role in keeping my morale high during challenging times. Their presence as friends, offering support and camaraderie, made my internship experience even more memorable.

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