Study of kaon production at lower energy levels

by

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Major Professor
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Abstract

Isaac Newton famously wrote, “It is inconceivable that inanimate brute matter should, without the mediation of something else which is not material, operate upon and affect other matter without mutual contact” (Newton, Isaac). This philosophical query ties into the mysteries that the Deep Underground Neutrino Experiment (DUNE) seeks to address. DUNE aims to explore fundamental questions such as the imbalance of matter and antimatter, supernova dynamics, and physics beyond the Standard Model. At its core, DUNE studies neutrinos, abundant subatomic particles with minimal mass and weak interactions, thus making them extremely difficult to detect. By examining how neutrinos interact and decay, DUNE aspires to deepen our understanding of the universe’s evolution and the underlying laws of physics.

I am interested in looking at how DUNE’s project focuses on the cross sections of low-energy kaon particles, with the goal of improving their detection and calibration in liquid argon. Since DUNE is still under construction, I have been looking at how to use data from the prototype that will aid in identifying kaon decay and reducing confusion with similar particles. I am interested in learning more about refining kaon cross-section measurements to an accuracy of less than one percent and evaluating whether their detailed analysis significantly enhances particle research. Additionally, I have been researching how to combine the thin-slice and energy methods to produce a more accurate histogram of low-energy kaon production, thus contributing to DUNE’s broader mission of advancing particle physics.

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Acknowledgements

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The ProtoDUNE-SP detector was constructed and operated on the CERN Neutrino Platform

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URA Visiting Scholars program

Introduction

Particle physics is the branch of science that seeks to understand the fundamental components of matter and the forces that govern their interactions. At its core, particle physics investigates the building blocks of the universe, including quarks, leptons, bosons, and their interactions as described by the Standard Model of particle physics. This framework successfully explains a wide range of phenomena, from the behavior of subatomic particles to the underlying principles of forces such as electromagnetism, the weak force, and the strong force. However, significant mysteries remain, such as the nature of dark matter, the dominance of matter over antimatter in the universe, and the possibility of particles and forces beyond the Standard Model.

Neutrinos, nearly massless particles that rarely interact with matter, play a pivotal role in particle physics. Their unique properties, such as flavor oscillations and potential connections to sterile neutrinos, make them a key area of focus for research. Experiments like DUNE are designed to address unanswered questions about neutrinos, offering insights into their behavior and their implications for the evolution of the universe. By exploring the fundamental nature of these particles and their interactions, particle physics not only deepens our understanding of the cosmos but also lays the groundwork for technologies and theories that extend far beyond the current standard model (Dune at LBNF).

The Deep Underground Neutrino Experiment (DUNE) is a cutting-edge project created to advance our understanding of particle physics through the study of neutrino interactions, proton decay, and other rare phenomena. Central to DUNE's mission is the detailed investigation of

neutrino interactions using a comprehensive setup that includes near and far detectors. The experiments near detector, located downstream of the neutrino source in South Dakota, measures cross sections to study neutrino interactions, while the far detector at the Sanford Laboratory records signals over long distances. This effort represents a collaborative push within the scientific community to refine detection methods and deepen our understanding of neutrino behavior.

A significant focus within DUNE is the study of kaon particles, particularly their behavior at lower energy levels. These efforts, including preliminary findings during the construction phase, aim to enhance particle calibration and reduce confusion with other similarly acting particles. By analyzing kaon decays in liquid argon, researchers seek to improve detection accuracy and refine cross-section sensitivity to within one percent. This precision is critical for understanding particle interactions and for developing advanced methods to track kaon production using combined mathematical approaches, such as the thin-slice method and energy method, to construct more accurate histograms.

At the heart of DUNE's detection technology is the liquid argon time projection chamber (LArTPC), a detector that leverages liquid argon's high density and advanced electric and magnetic field configurations. The LArTPC enables detailed three-dimensional reconstruction of particle trajectories, making it an effective tool for neutrino interaction studies (Dune at LBNF). DUNE's prototypes, ProtoDUNE-HD and ProtoDUNE-VD, validate the experiment's methodologies and ensure reliability for large-scale operations. These detectors are essential for calibrating particle identification systems, developing event reconstruction techniques, and refining sensitivity analysis (Dune at LBNF).

In the context of the Deep Underground Neutrino Experiment (DUNE), kaons in the final state are a key signature for proton decay searches, particularly the mode Reconstructing kaons' final states is complicated by interactions with liquid argon. Therefore, studying the cross sections of kaon argon interaction is important. These particles are also produced in high-energy collisions, such as those in cosmic-ray interactions. By focusing on kaon cross-section measurements and incorporating mathematical modeling techniques, researchers aim to advance DUNE's capacity for particle analysis.

DUNE also explores broader aspects of neutrino physics, including flavor oscillations and the possibility of sterile neutrinos. Neutrino flavor changes, governed by the mixing of mass eigenstates, challenge the traditional three-flavor model and hint at new physics beyond the Standard Model. The inclusion of sterile neutrinos in theoretical frameworks highlights the experiment's potential to uncover groundbreaking insights. Through its multifaceted research goals, DUNE represents a significant leap in the field of particle physics, combining state-of-the-art technology, advanced computational methods, and innovative theoretical approaches

So where does matter come from? Why is there so much matter and so little antimatter? These are the questions the Deep Underground Neutrino project hopes to answer. The Deep Underground Neutrino project is dedicated to working on understanding the preferred amounts of matter to antimatter, dynamics of a supernova, and to better understand the evolution of the universe and physics beyond the standard model. To better understand the universe DUNE is

specifically researching neutrinos, a subatomic particle, which has a half-integral spin and only interacts through a weak interaction (Detectors and Computing

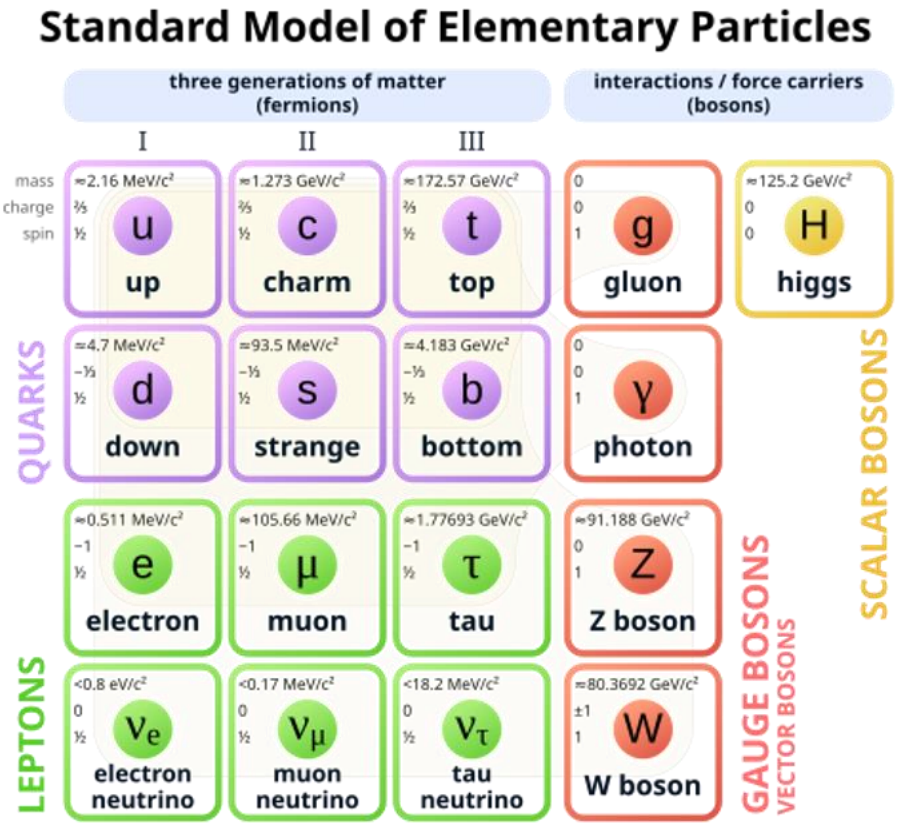
Background

Fundamental Particles and the Standard Model

The Standard Model is a collection of theories deployed over the years to describe how the 17 fundamental particles interact with each other. Particles are organized into categories based on properties and interactions. There are two main types of particles, fermions and bosons. Fermions include quarks and leptons; electrons and muons that combine to produce protons and neutrinos they create matter. Bosons on the other hand are force carrying particles like photons which mediate the electromatic force or the gluon which mediates the strong force.

Altogether there are 17 fundamental particles, 12 fermions and 4 force caring bosons and the Higgs boson which give particles mass. The three main fundamental forces include electromagnetic force, strong force, and weak force. However, the standard model, considered incomplete even though it has been useful explaining many experimental results, doesn't account for dark matter, dark energy, gravity, or the matter / antimatter asymmetry. These are some of the questions DUNE hopes to research to discover what goes beyond the standard model.

Figure 1 Standard Model of Elementary Particles (*standard model of elementary particles + gravity.svg*)



Neutrinos

The neutrino is electrically neutral and because its rest mass is so small it was until recently that it was considered zero. Neutrinos are the most common and abundant particles with mass in the universe. They are produced by nuclear processes such as fusion, fission, and radioactive decay specifically when particles decay. Neutrinos typically pass through normal matter unimpeded and

undetected because they have such weak interactions. They are extremely hard to detect. The Standard Model describes how different types (flavors) of neutrinos (electron, muon, and tau neutrinos) mix into one another as they propagate through space.

Neutrino Flavor States are described mathematically with the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix. The flavor states are not the same as the mass states, and neutrinos produced in one flavor state can evolve into a different flavor state as they travel, driven by differences in the masses of the neutrino eigenstates. The observable consequence of this mixing phenomenon is Neutrino Flavor Change. (Aksel)

Weak Interactions

The weak force operates over very short distances its range is limited to approximately 10^{-18} meters and is responsible for changing the flavor of quarks for example, turning a down quark into an up quark during neutron decay. This interaction is crucial for many astrophysical phenomena such as the synthesis of elements in stars, illustrating its significance despite its relatively weak strength compared to other fundamental forces. (*Review of Particle Physics* Particle Data Group*)

During this process, a W boson is emitted as a down quark transforms into an up quark. The W boson then quickly decays into an electron and an electron antineutrino, which are emitted from the nucleus. This emission of a W boson allows the neutron to change into a proton, creating an electron and an antineutrino as byproducts. Z bosons, while also mediators of the weak force, are only involved in neutral weak interactions, where particles interact without changing type. These bosons are essential for the weak force's unique ability to cause particles to change identity, a feature that is not present in other fundamental forces.

Kaons, a type of meson, are particles composed of a quark and an antiquark—specifically, a strange quark paired with either an up or down quark. In kaon decay, the weak interaction enables a strange quark to transform into an up quark through the exchange of a W boson. This quark change allows the kaon to transition into other particles, with each decay pathway determined by the specific quark configuration and quantum states involved. The weak interaction's role in neutral kaon decay also leads to an intriguing phenomenon called CP violation (charge-parity violation). CP violation occurs because kaons decay into matter and antimatter states at slightly different rates, which has profound implications for the observed imbalance of matter and antimatter in the universe. (*Review of Particle Physics* Particle Data Group*)

Cp Violation

CP violation was discovered in in 1964, then later in the early 2000s experiments studied CP, violation in more detail, such as the NA48 experiment at CERN and the KTeV experiment at Fermilab High-Energy Collisions in Particle Accelerators: CERN's Large Hadron Collider (LHC) and Fermilab's accelerators accelerate particles to high energies and then collide them. Kaons can be produced in these collisions when the energy is sufficient to create the necessary quark and anti-quark pairs. CP violation is a violation of charge conjugation parity symmetry. This is when the combination of C-symmetry which is charge conjugation symmetry and parity symmetry noted as P-symmetry in physics are interchangeable states of particles and antiparticles. However, this is violated when it comes to some mesons. Large CP Violation could explain why the universe has an abundance of matter compared to antimatter. Currently we know that quark CP violation is not big enough but there are hints from T2K and Nova (both long-baseline neutrino oscillation

experiments) that the CP violation in the neutrino section could be large. This is a major investigative point for DUNE. (*Review of Particle Physics* Particle Data Group*)

Neutrino flavor changes and Lepton Mixing

A neutrino can change between flavors as it moves through space. A neutrino that starts out as an electron neutrino can turn into a tau neutrino or a muon neutrino, or a mixture of the two. It can then turn back into its original electron neutrino. (*Giunti and Kim 260-266*). It is important to note that while we have a unitary 3 by 3 matrix to represent these flavor changes, there are experimental results that suggest there could be more than 3 neutrino mass eigenstates and therefore more than three flavors. These hypothetical flavors without corresponding lengths are known as Sterile neutrinos. They do not interact with the W boson standard model but are believed to interact with gravity (*Giunti and Kim 260-266*). However, when looking at the matrix form of the Lagrangian, we see how there is an allowance for this (as denoted below). Lepton mixing refers to the mathematical framework to allow neutrino flavors to mix As previously denoted (V_i) is represented in the Lagrangian for the lepton charged current interactions in the mass basis. Lepton mixing mathematical representation is noted below from chapter 14 of the Review of Particle Physics equations 14.25-14.27 (*14. Neutrino Masses, Mixing, and Oscillations)*

$$-L_{cc} = \frac{g}{\sqrt{2}}(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L)\gamma^{\mu}U(V_1, V_2, V_3.....V_n)W_{\mu}^{+} + h.c$$

The Lagrangian Shows (U) that satisfy the unitary condition

$$\text{U is } 3 \times n \rightarrow UU^{\dagger} = I_{3x3}$$

$$-L_m = [[(\bar{e}_L^I, \bar{\mu}_L^I, \bar{\tau}_L^I)M_{\ell}(e_R^I, \mu_R^I, \tau_R^I) + h.c] - L_{M\nu}$$

M_{ν} can be diagonalized with two 3 × 3 unitary matrices. This can be done given that $L_{M\nu}$ is the standard model extended with the addition of m number of sterile neutrinos renormalized operators, to two types of mass terms. This is noted in more detail chapter 14 of the Review of Particle Physics equations 14.6 and 14.8.

Figure 2 Lepton mixing mathematical representation (*Giunti and Kim 260-266*)

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix indicates that the flavor states are not the same as the mass states, and neutrinos produced in one flavor state can evolve into a different flavor state as they travel, driven by differences in the masses of the neutrino eigenstates. The observable consequence of this mixing phenomenon is Neutrino Flavor Change.

Pions

Pions are a common interaction product in a neutrino interaction. For precise modeling of neutrino event generators, it is essential to understand the pion-argon interaction. Pion-argon cross section measurement serves as an important input for neutrino interaction models. The many studies carried out in the ProtoDUNE-SP experiment will be useful for current and future neutrino experiments using LArTPC technology including ICARUS, MicroBooNE, and DUNE. Pions play a crucial role in neutrino interactions, particularly in deep inelastic scattering and resonance production. When a neutrino interacts with a nucleon (proton or neutron) inside a nucleus, it can excite the nucleon into a higher energy state, leading to the production of a pion. This process, known as resonant pion production, is a dominant interaction channel at intermediate neutrino

energies (typically in the range of hundreds of MeV to a few GeV). Additionally, pions can be produced through coherent scattering, where a neutrino interacts with an entire nucleus, producing a pion without breaking the nucleus apart. It does not significantly alter the nucleus's quantum state due to its small transfer momentum as a recoil. Understanding pion production in neutrino interactions is essential for neutrino oscillation experiments since pions contribute to the final-state particles that must be properly identified and reconstructed to determine the neutrino's original energy.

Kaons

Kaons are produced in high-energy particle collisions and decays involving other particles. They can be created through various processes in particle accelerators and in cosmic-ray interactions with the Earth's atmosphere(*Giunti and Kim 260-266*). Kaons, are also known as K mesons. They are a type of meson—composite particles made up of a quark and an anti-quark that play a crucial role in the study of particle physics. Mesons appear as short-lived products of very high energy collisions between particles. These particles are mesons they belong to the hadron family, which includes both mesons and baryons. Kaons come in four different types based on their quark content. This relates to their quantum number also known as strangeness.

While both kaons and pions are mesons composed of quark-antiquark pairs, their lifetimes are dictated by the interactions that govern their decay. Charged pions, decay exclusively via the weak interaction. A charged pi+ consists of an up quark and a down antiquark, while a charged K+ consists of an up quark and a strange antiquark. which introduces additional constraints in decay processes. The involvement of the strange quark means kaons are more affected by the suppression of certain decay modes.

In liquid argon detectors, such as LArTPCs, the differences in lifetimes and decay products of kaons and pions are critical for their detection and characterization. Liquid argon provides an ideal medium due to its high density and ionization properties, enabling precise tracking and energy deposition measurements. π^0 decay shortly after being produced, traveling only a short distance. In contrast, charged pions and kaons travel farther—though the charged kaon has a *shorter* lifetime, it still doesn't make it as far. This allows their decay vertices to be spatially separated from their production points, which is an important signature for identifying kaons in experiments.

Additionally, kaons can undergo interactions such as elastic or inelastic scattering with argon nuclei before decaying, resulting in distinctive secondary particle production patterns. The ability of LArTPCs to reconstruct particle interactions is a powerful tool for studying kaon and pion behavior. Understanding these interactions is crucial for neutrino physics, as kaons often contribute to neutrino production in beamlines, and for exploring rare processes, such as kaon decays that could reveal physics beyond the Standard Model.

In a LArTPC, kaons produce distinctive signatures due to their relatively long lifetime and unique decay channels. The precise tracking and high-resolution imaging of LArTPCs allow reconstruction of the decay vertex, which is crucial for identifying kaon decays.

Neutral kaons K^0 $\overline{K}$ can oscillate between $K^0$and $\overline{K}$ states before decaying. From kaon results in a LArTPC, you can expect precise measurements of kaon decay rates and branching ratios. These detailed reconstructions of decay kinematics contribute to neutrino beam

characterization and rare decay searches, potential evidence of physics beyond the standard model, and unexpected decay modes or deviations in predicted lifetimes or interaction rates.

Methods

Track Characteristics

Overall, LArTPCs help explore kaon decay modes as well as other particles aiding both Standard Model validation and the hunt for new phenomena. A displaced decay vertex (a point separated from the initial interaction vertex) indicates a particle with a longer lifetime, such as a kaon. LArTPCs are excellent tools for studying rare kaon decay modes. Some things that can be observed are as follows.

Shorter Travel Distance: Charged kaons typically have a shorter path in the detector before decaying or interacting. compared to pions. The LArTPC can identify this extended track.

I**onization Profile**: As kaons move through the liquid argon, they ionize the medium, leaving tracks that can be reconstructed. The energy deposition along the track (dE/dx) can help distinguish kaons from other particles like pions, muons, and protons especially at lower momenta where stopping kaons exhibit unique ionization patterns.

Secondary Interactions Before decaying, kaons can interact with argon nuclei

Elastic Scattering: Produces small-angle deflections, observable as a kink in the kaon track.

I**nelastic Scattering**: Results in nuclear excitation or the production of secondary particles, leaving more complex interaction patterns in the detector.

Construction of Proto DUNE- SP

ProtoDUNE-HD is the prototype for one of the first two 12,000 kiloton LArTPC modules to be installed in the DUNE experiment. The prototype is currently operating at CERN, where they are testing the event reconstruction algorithms by finding interaction vertices for particle identification. Mainly ProtoDUNE is used to help reduce systematic uncertainties for the DUNE far detector. TPC/imaging aid the calorimetric measurements that are used in DUNE to help produce 3D images of particle interactions. Each Anode Plane Assemblies (APA) consists of a frame that holds three parallel planes; the wires of each plane are oriented at different angles with respect to those on the other planes to enable 3D reconstruction. See the image below. The components of Proto DUNE-SP are as follows and seen in the diagram below: time projection chamber (TPC), cold electronics (CE), and photon detection system (PDS). The six APAs are arranged into two APA planes, each consisting of three side-by-side APAs. Between them splits the central cathode plane, composed of 18 CPA modules, the TPC volume into two electron-drift regions, one on each side of the cathode plane. A field cage (FC) completely surrounds the four open sides of the two drift regions to help maintain that the electric field is uniform and unaffected by the cryostat walls and other nearby conductive structures. The detector elements, consisting of the time projection chamber (TPC), the cold electronics (CE), and the photon detection system(PDS), are housed in a cryostat that contains liquid argon. (Abi et al. *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, volume I: Introduction to dune*)

Figure 3 ***Far Detector*** **((Abi et al.** ***Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, volume I: Introduction to dune pg 13*** **image914893168)**

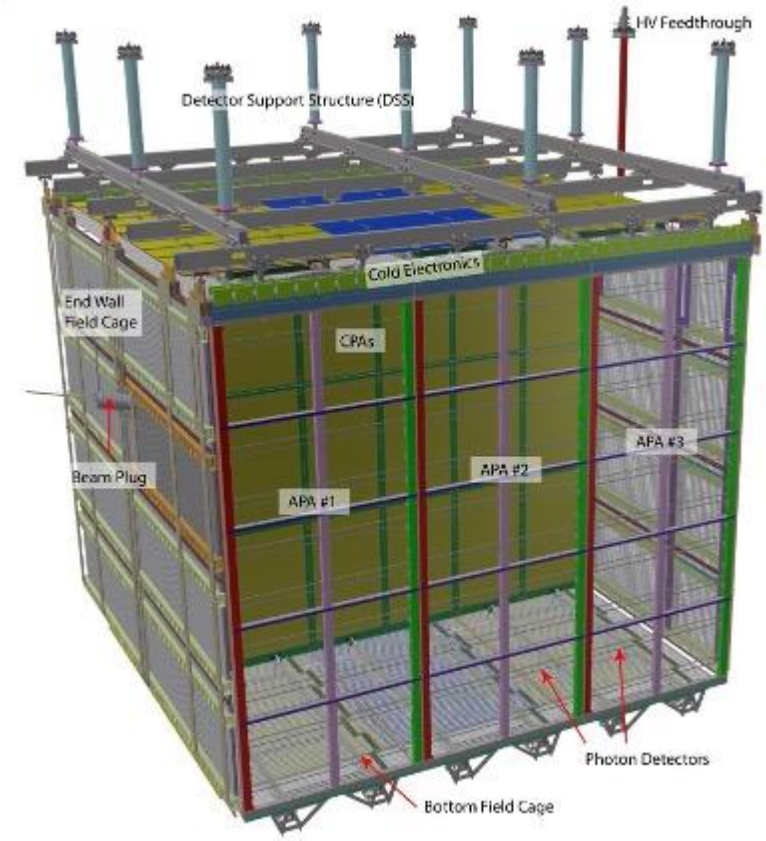
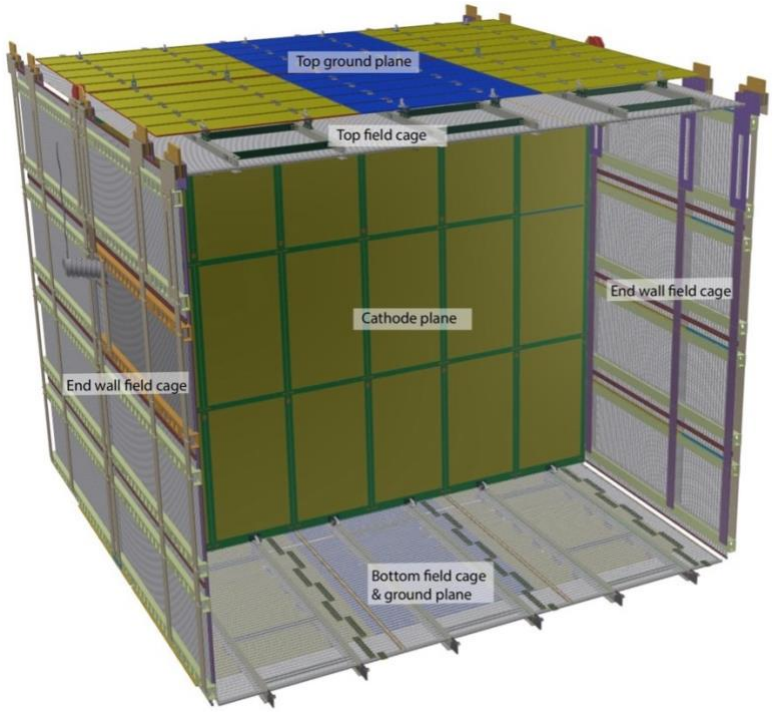


Figure 4 *Far Detector* (Abi et al. Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, volume I: Introduction to dune pg 13 image914893168)



Identifying Particles

ProtoDUNE has conducted simulations using the Monte Carlo simulator alongside real data from its initial runs. We can extract data based on our specific interests and create various graphs using this simulator, which can then be compared with real data. ProtoDUNE-SP utilizes the arrival time of ionization electrons at each wire to produce 3D reconstructions. Ionization helps determine energy deposition for calorimetry. By combining spatial and calorimetric information, we can accurately identify particles.

Cross-sections play a crucial role in particle physics and high-energy physics, serving as a fundamental tool for understanding interactions. A cross-section is defined as the effective area of interaction between particles, measuring the likelihood of a specific reaction occurring when two particles collide. Cross-sections provide a quantitative framework that aids in comprehending and

predicting the outcomes of particle interactions, thus guiding experimental designs. The probability that a particle with cross section $\sigma\sigma$ will penetrate a distance z into a material (like a detector) without interacting is given by the exponential attenuation formula: $P_z = e^{(-n\sigma z)}$

Future Research for Kaon Cross Sections

Understanding kaon cross-section sensitivity and improving documentation of energy reconstruction methods are crucial for future research. Additionally, I am beginning to investigate how integrating two mathematical approaches—the thin-slice method and the energy method—could help create more accurate algorithms for reconstructing lower-energy kaon production. This, in turn, will enhance our understanding of fundamental particles and their interactions. This section of my report focuses on how this theoretical process could be beneficial for future reconstruction attempts of lower-energy Kaon productions.

This understanding is crucial for optimizing particle accelerators and detectors, particularly in projects like the Deep Underground Neutrino Experiment. In the context of DUNE, where preliminary outlines are being developed to refine cross sections, a common approach involves employing the "thin slice method" to generate histograms. Statistical projection techniques are employed to extract cross section values, contributing to more precise experimental designs. As part of my research for this report I will focus on exploring our understanding of kaon cross sections. Improvements to the kaon cross section analysis will enhance ProtoDUNE's sensitivity and produce more accurate particle identification results for DUNE. Identifying which specific cross sections have the most significant impact on DUNE's sensitivity is valuable in eliminating outliers and noise in the data. Identifying these Kaon cross sections are of particular importance for researchers working on oscillation reconstruction, energy reconstruction, momentum

reconstruction, and flavor analysis, as it can significantly influence the accuracy and effectiveness of these reconstruction processes. However, we have not identified specifically how these estimated cross sessions sensitivity affects DUNE's potential specifically at lower energy.

Researchers want to know what the oscillation parameters are at lower energies so that they can have more accuracy in recognizing the oscillation and interaction patterns of neutrinos, specifically. The more isolated analysis produced provides a better-defined cross section for each particle which then can be used by DUNE to compare to real data While previous experiments have done similar work, such as CERN's Large Hadron Collider, the medium of liquid argon provides more reactions with which to work.

Thin slice method to E-slice method

The thin slice Method was used by Francesco Pietropaolo, Stefania Bordoni, and Francesca Stocker. They have adjusted this method for Lar TPC'S in 2021 (Collaboration et al.). And later updated by T. Yang in 2022 (Yang) which was then used by Heng-Ye Liao to produce the 5 GeV/c p-Ar inelastic cross-section used in his research from 2022-2023 (Yang). This method is what I propose to use to find cross sections for Kaon production. The thin slice method is a technique used in particle physics to determine differential cross sections by dividing a detector medium into many small, virtual slices and analyzing particle interactions within each slice independently. The thin slice method estimates the interaction cross section of a particle with a target material by treating each virtual slice as a "thin target," assuming that the probability of interaction in each slice is small and interactions are statistically independent.

Kaons interacting with argon nuclei primarily undergo strong interactions, leading to the production of secondary particles. Kaons traversing a detector lose energy continuously and may interact with argon atoms. To measure the cross-section, we divide the detector into thin virtual slices. Each slice corresponds to a small step in energy loss and position. We define two histograms in which each bin corresponds to a virtual slice. One histogram counts only kaons interacting in the slice; the other counts all kaons entering the slice regardless of whether they interact or not. This produces a Histogram where the x-axis represents the slice ID or "bin" and dl/dx is represents kaons traveling through the detector; they lose energy continuously, so each slice corresponds to a lower average kaon energy. This approach allows us to extract the interaction cross-section as a function of energyection as a function of energy, by using the interaction probability, the known thickness of the slice, and the number density of argon atoms in the slice.

Looking at how Proto DUNE beam particles are affected by space charge distortions and variations in energy loss with distance, the cross section calculations are affected which is why the geometrical thin slice has some discrepancies at the end of the track. The E-Slice Method works in the energy phase space, so there are no spatial distortions in the cross section measurement. The uncertainties due to SCE can be avoided by using energy slices. However, there is a distortion at the beginning of the track, which is where most of the particles are seen, so the thin slice method is preferred currently

The main energy value used in the thin slice method has been the Mean Energy Loss at each Bin Energy E from Bethe Bloch so the cross section produced is where the ratio of Interaction to incident histogram is represented by (N). As Tingjun noted the slab thickness is affected by SCE uncertainty. However, this is mainly while the field is not uniform on the edges. After a certain

section this works itself out, yet the beginning data is repeatedly uncertain. Thus, using this mean energy works well to adjust for this but when particles are less abundant the energy is not as well defined as a mean average and the very end calculations have an uncertainty. Due to this being at the end of the track and not as many particles reach this point it has be deemed that we can live with vast uncertainty.

Exploring the unification of the energy and thin slice method by using our histogram data to help locate where the field has become uniform using the thin slice method to set up the first half of our data could be beneficial for future analyst. Then rerunning the end data of each track and applying the energy method for the end of the track when particles are scarce and therefore are not predicting a less defined mean energy. Then adjusting the uncertainty using the information gained by separately analyzing the end of the track using the energy slice method. This change to the current methodology compared to previous cross section data analysis could better define the energy range of lower energy kaon productions over an extended time, allowing for a more defined number of tail-end energy of the track. Hopefully this will help define the overall energy of the kaon particles.

Part of my research for this report involves defining the E-slice method for combining the thin slice method with the E-slice method. Previously, the slice thickness had to be adjusted, leading to variations near the TPC front face due to Spatial Charge Effects (SCE). The E-slice method assumes that all pions traverse roughly the same amount of liquid Argon (LAr) in each slice, resulting in a relatively constant beam angle. Additionally, since all pions have approximately the same energy upon reaching a specific slice, both the beam momentum and the

energy loss per unit length (dE/dx) are also roughly constant. Slice thickness and particle energy in each slice are properties that can be computed using a substantial number of particles. For this method to be effective, E-slices will need to maintain an average thickness, allowing for more precise definitions of data based on the midway range. This will involve measuring energy as a specific value rather than a mean to help reduce uncertainties.

Preliminary Work - Study Thin Slice Method and Kaon Particle Selection

This summer, I secured a grant through The Universities Research Association (URA) and collaborated with Dr. Tingjun Yang and his graduate students to access relevant data and deepen my understanding of kaon cross-section analysis at lower energies. As part of the Visiting Scholars Program, I submitted a proposal for funding to cover travel expenses for visits to Fermilab. The visits to Fermilab were of significant importance for two reasons. First, they provided opportunities for face-to-face discussions and deliberations, which were essential for advancing scientific discourse. Second, the interactions focused on refining my understanding of kaon cross-section sensitivity and improving documentation related to energy reconstruction methods. Additionally, my research aimed to combine two mathematical approaches, the thin slice method and the energy method for cross-section analysis. This integration created a more precise histogram for recording lower-energy kaon production. A significant challenge was determining whether the current tracks were sufficient for analysis. While at Fermilab, I developed histograms using Monte Carlo simulations. During my attempt to use the time-of-flight (TOF) method to identify kaons at 1 GeV

and 2 GeV, I discovered that an initial cut at 115 ns of the overall TOF graphs eliminated protons, as their values extended past 115 ns.

The graphs below compare Monte Carlo and real data time-of-flight results. We see very clear definitions in the Monte Carlo data, while the real data are muddled, which is expected. The Monte Carlo simulations are well-defined because the program knows what particles are being sent in, whereas the real data reveal that some particles are not as clearly defined. When we extend the graph to 160 ns, we notice that it includes all the protons, indicating that we can use TOF to make a cut to eliminate them.

Figure 5 Time of Flight 1 GeV Real Data

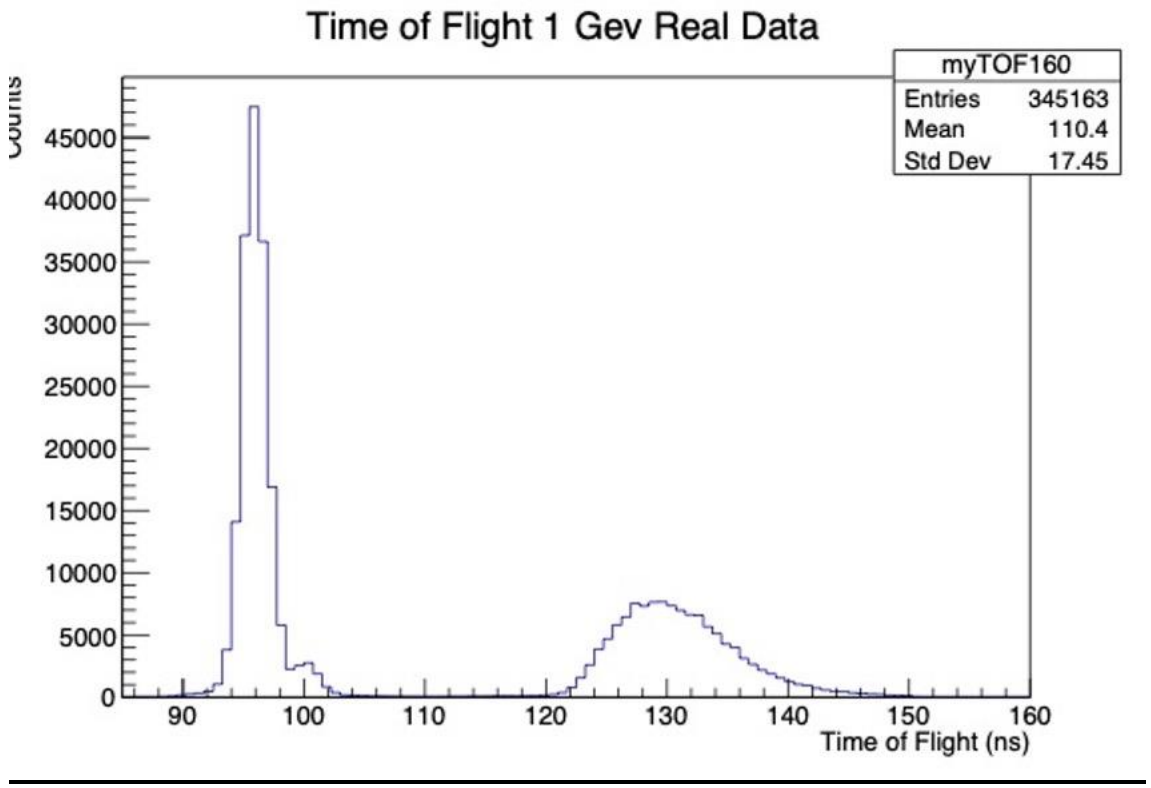


Figure 6 Time of Flight 1 GeV Real Data

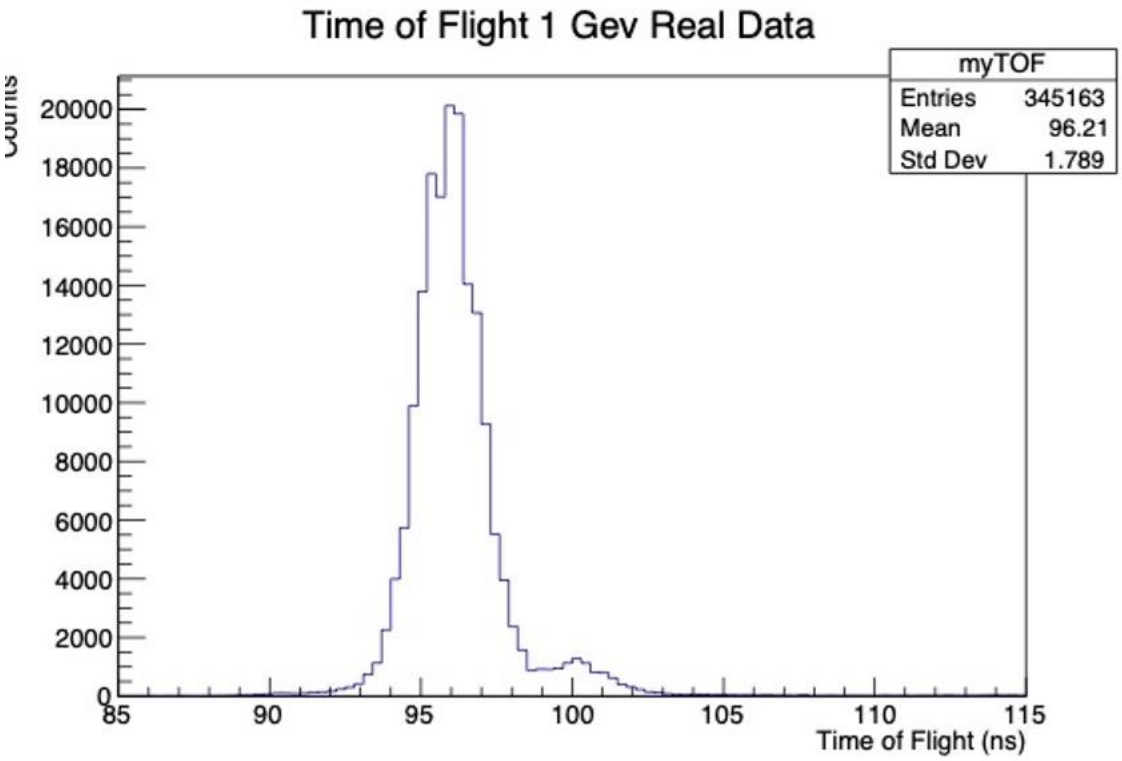


Figure 7 Time of Flight 1 GeV Monte Carlo

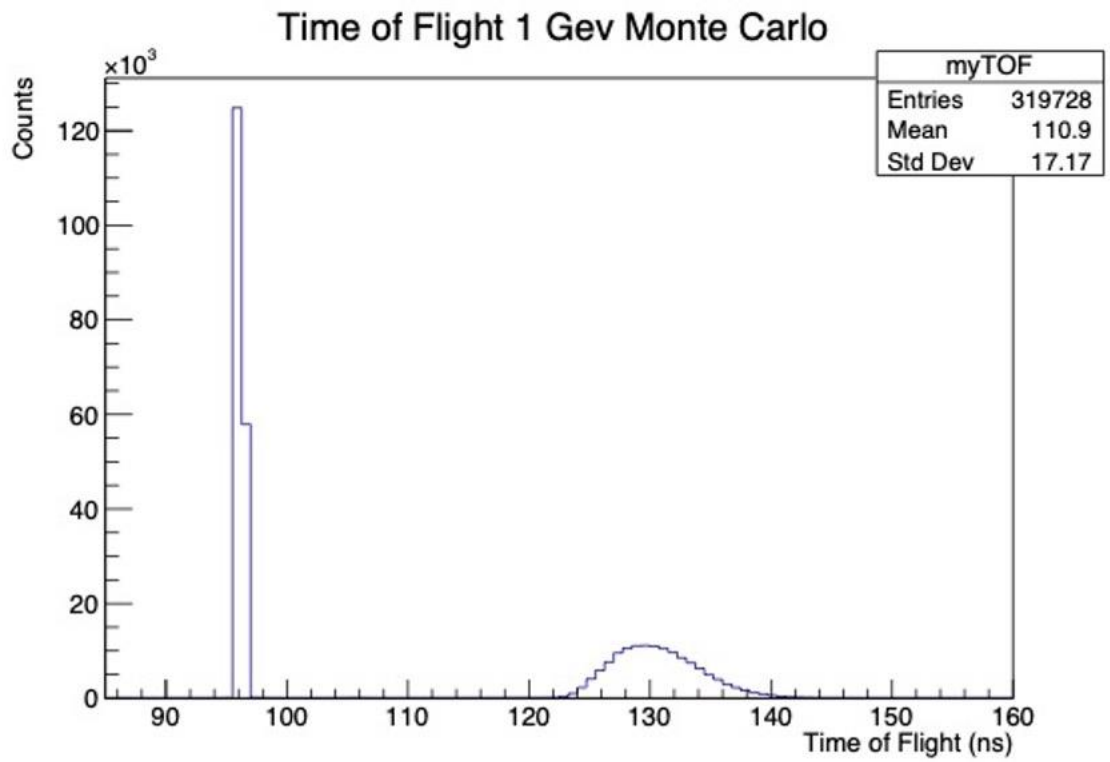


Figure 8 Time of flight 1Gev Real Data

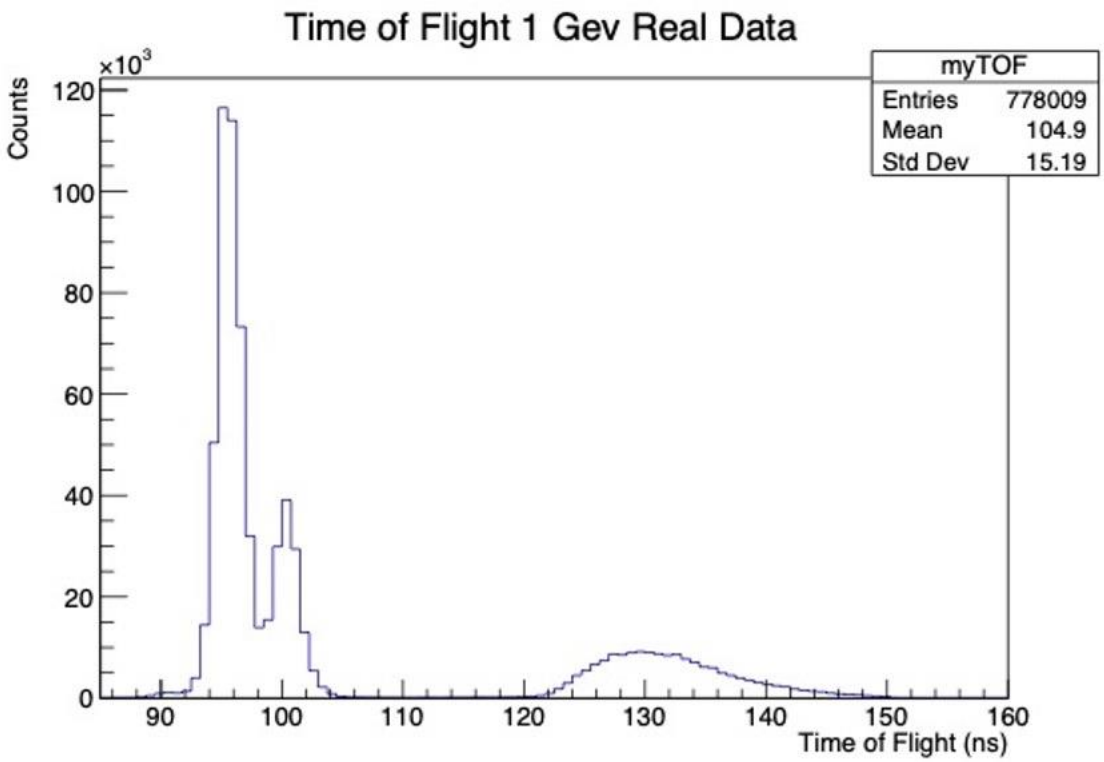


Figure 9 Time of Flight 1 GeV Monte Carlo

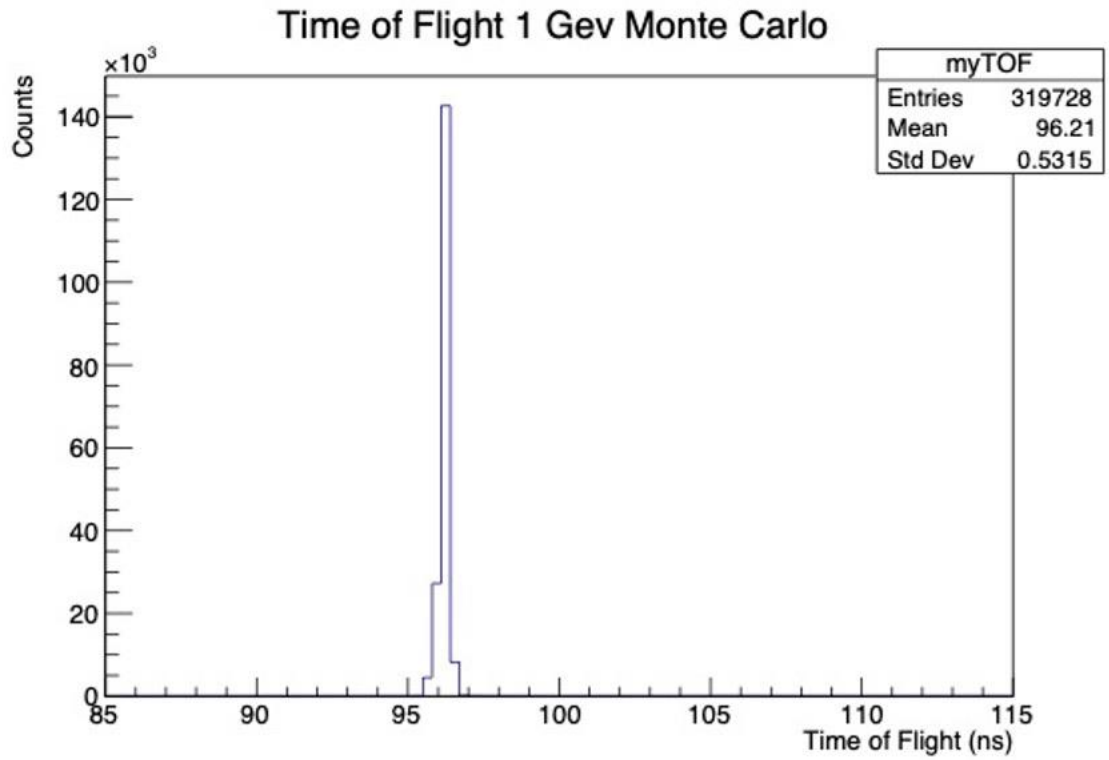


Figure 10 Time of Flight GeV Real Data

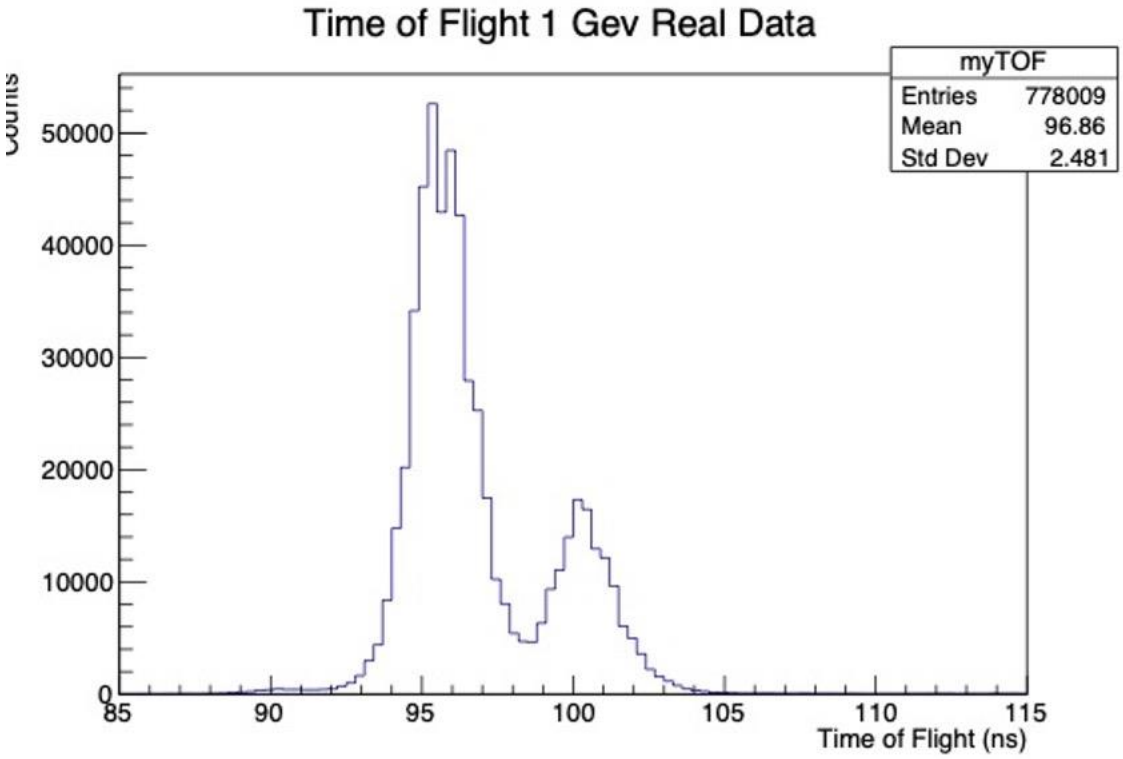


Figure 11 time of flight 2 GeV Monte Carlo

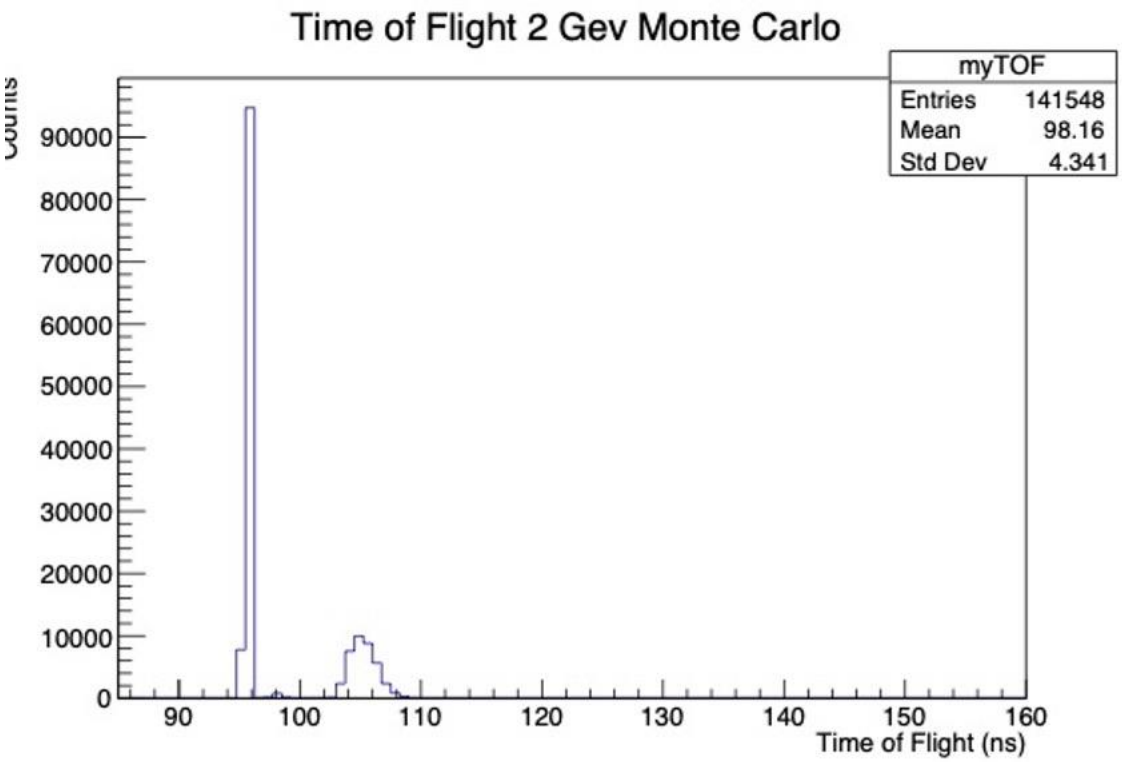


Figure 12 Time of flight 2 GeV Real Data

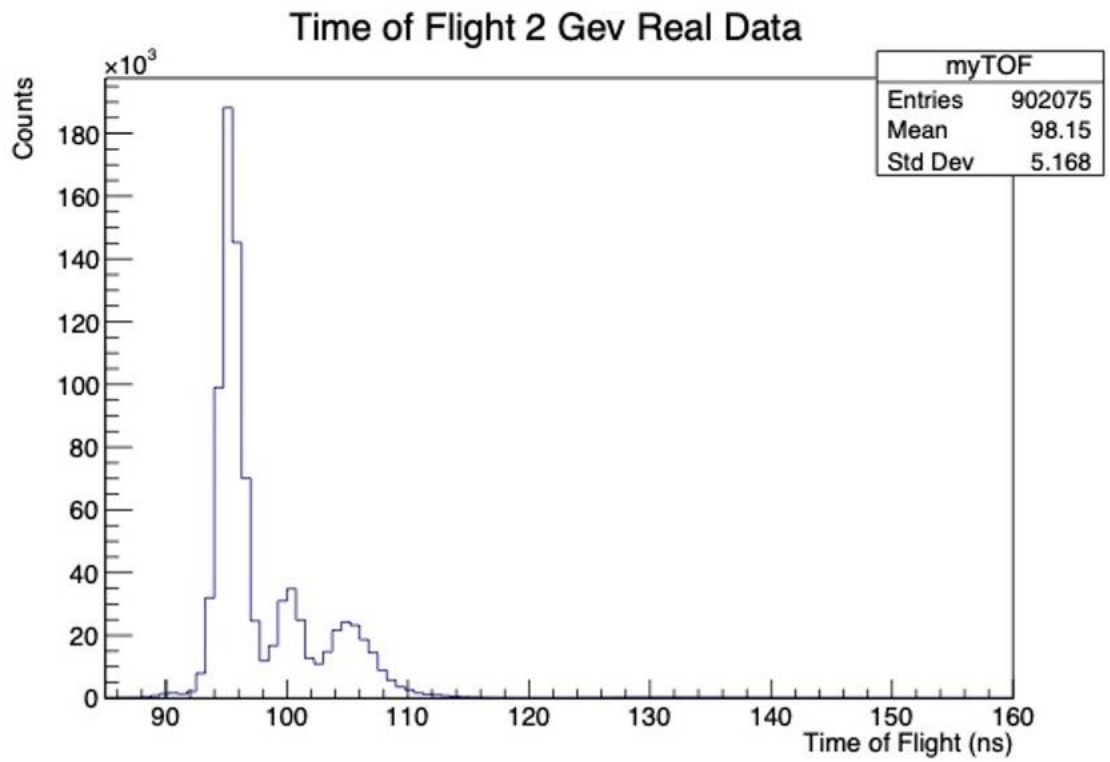


Figure 13 Time of Flight 2 GeV Monte Carlo

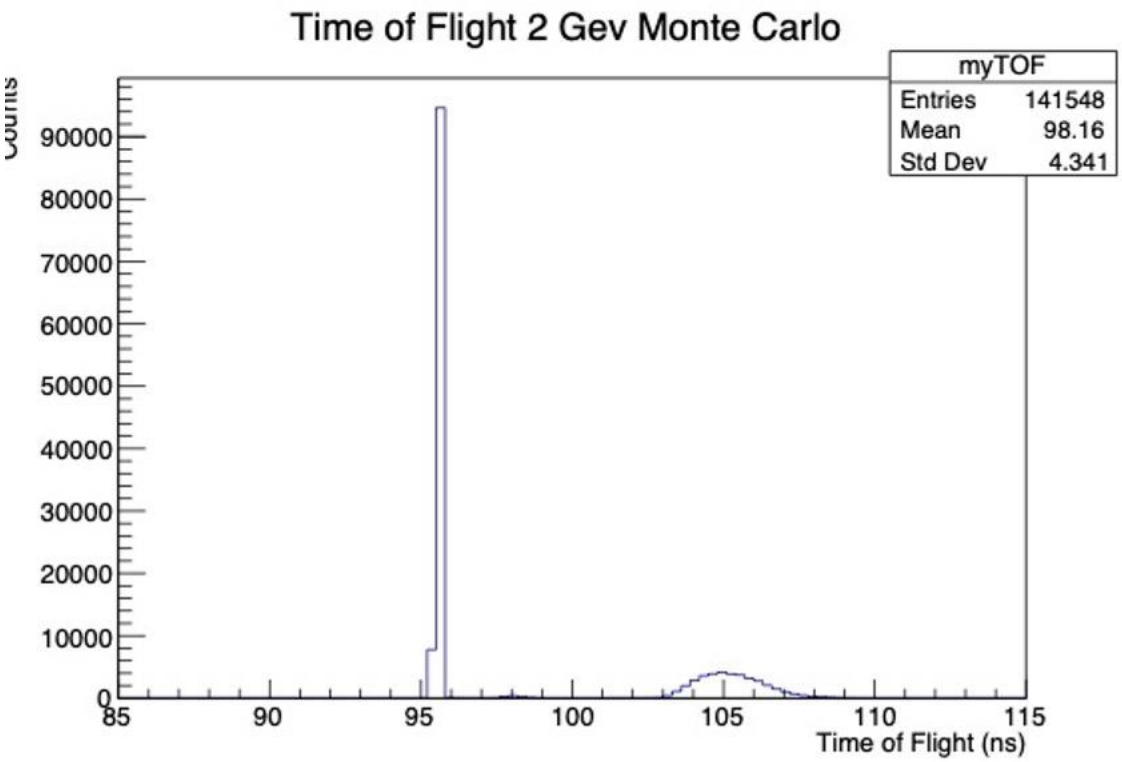


Figure 14 Time of Flight 2 GeV Real Data

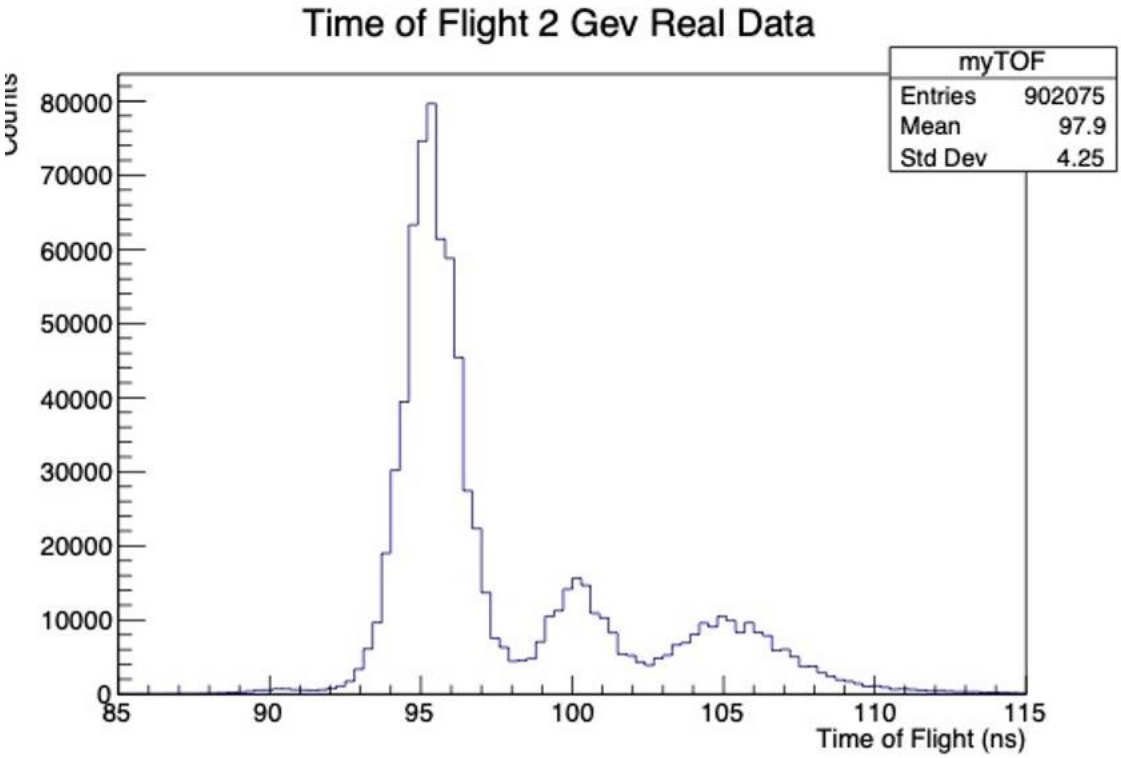


Figure 15 Time of Flight 2 GeV Real Data

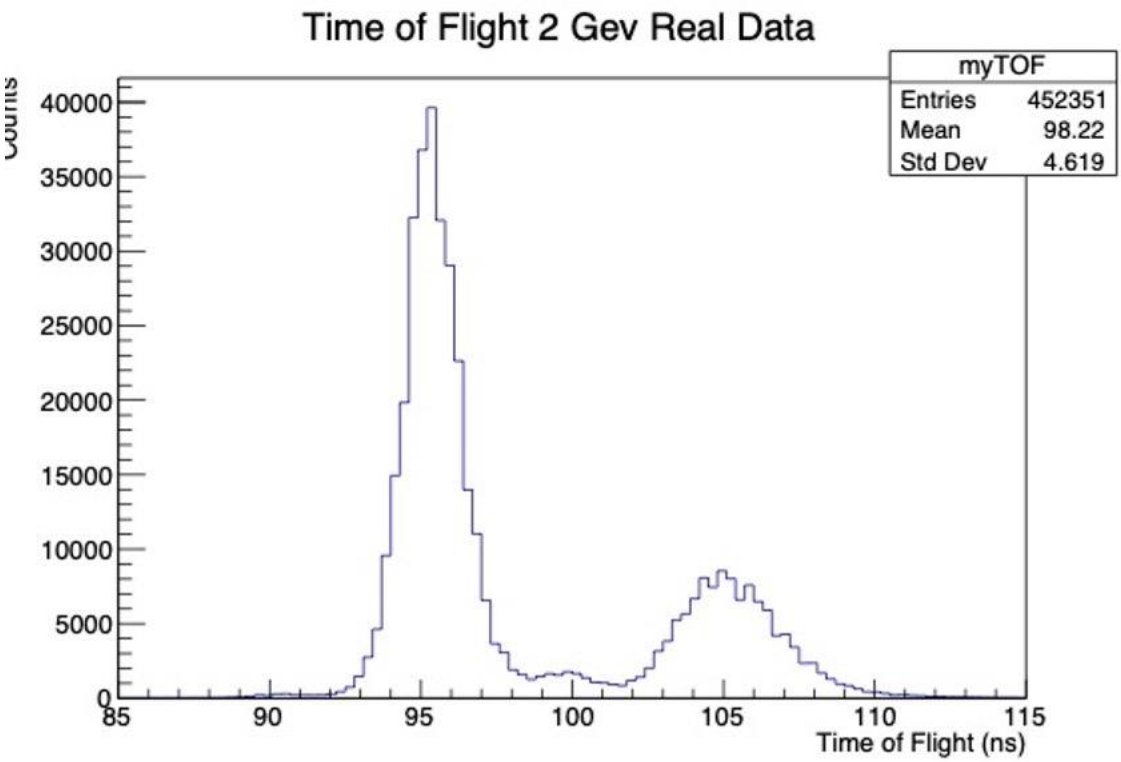
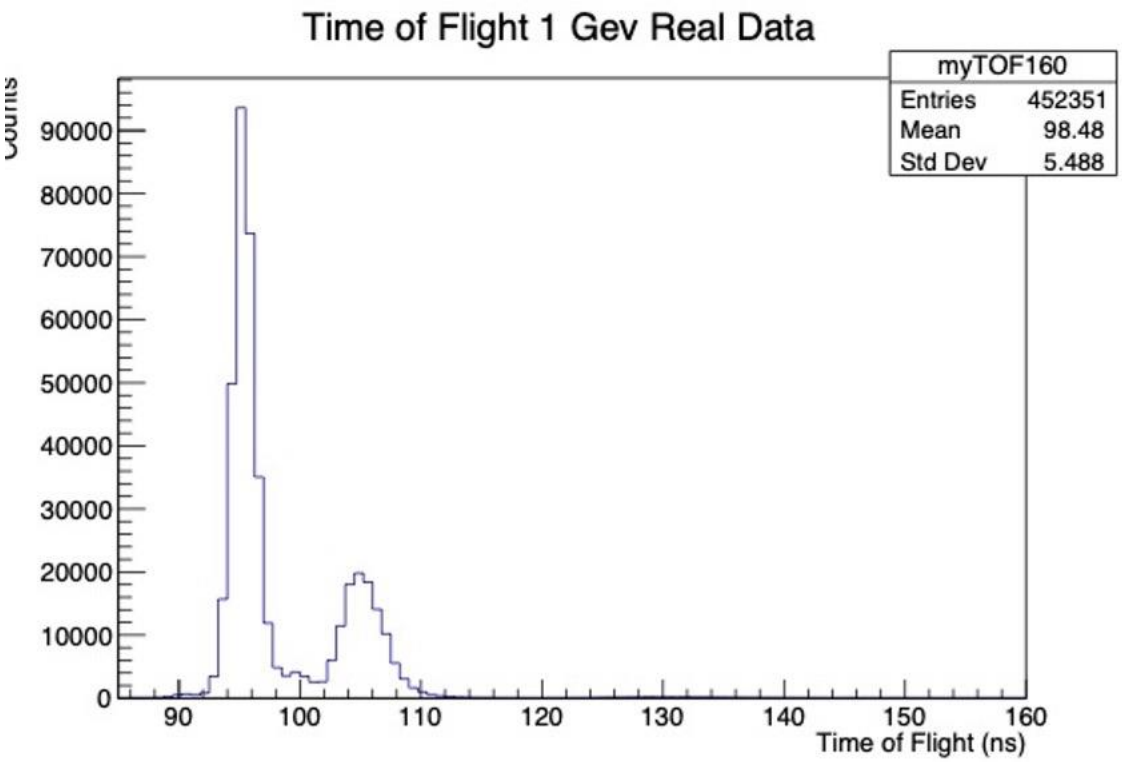


Figure 16 Time of Flight 1 GeV Real Data



After protons are removed, we utilize the track length to separate kaons and muons. By creating histograms for kaons and muons, we were able to enhance the kaon fraction based on track length. Looking at the histograms created, we observe that kaons show energy deposit (dE/dX) at distance z, which is closer to the start point compared to the muons, which continue further.

Figure 17 Kanons 1 GeV Monte Carlo

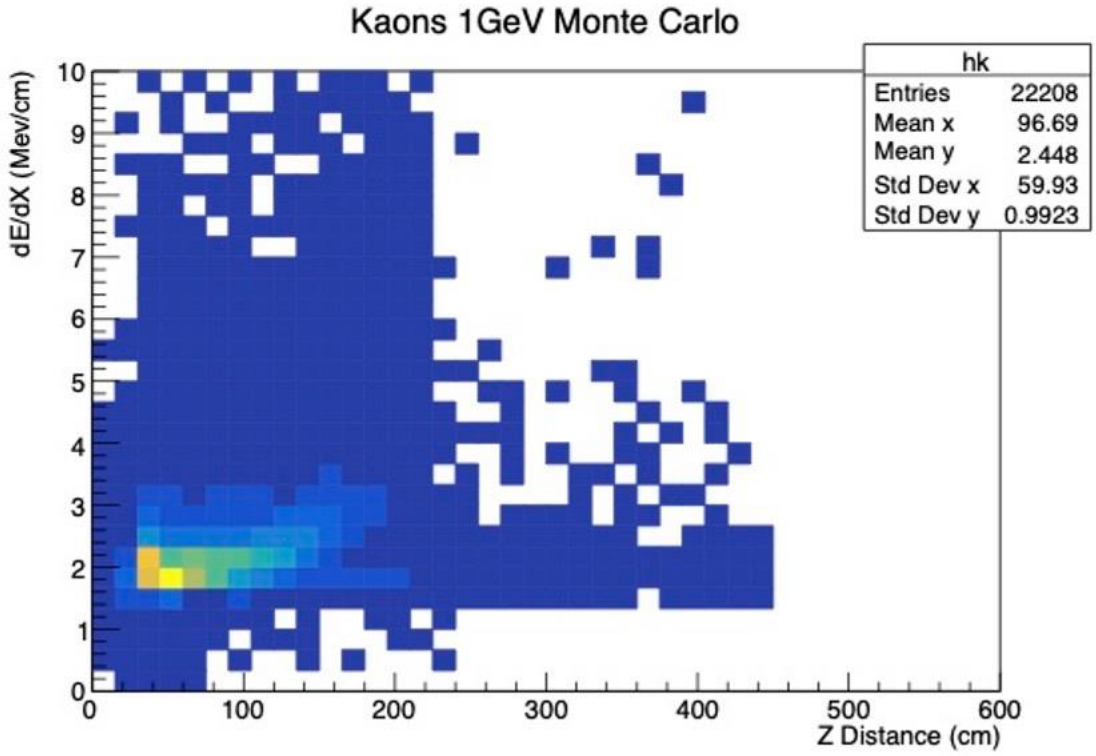


Figure 18 Muons 1 GeV Monte Carlo

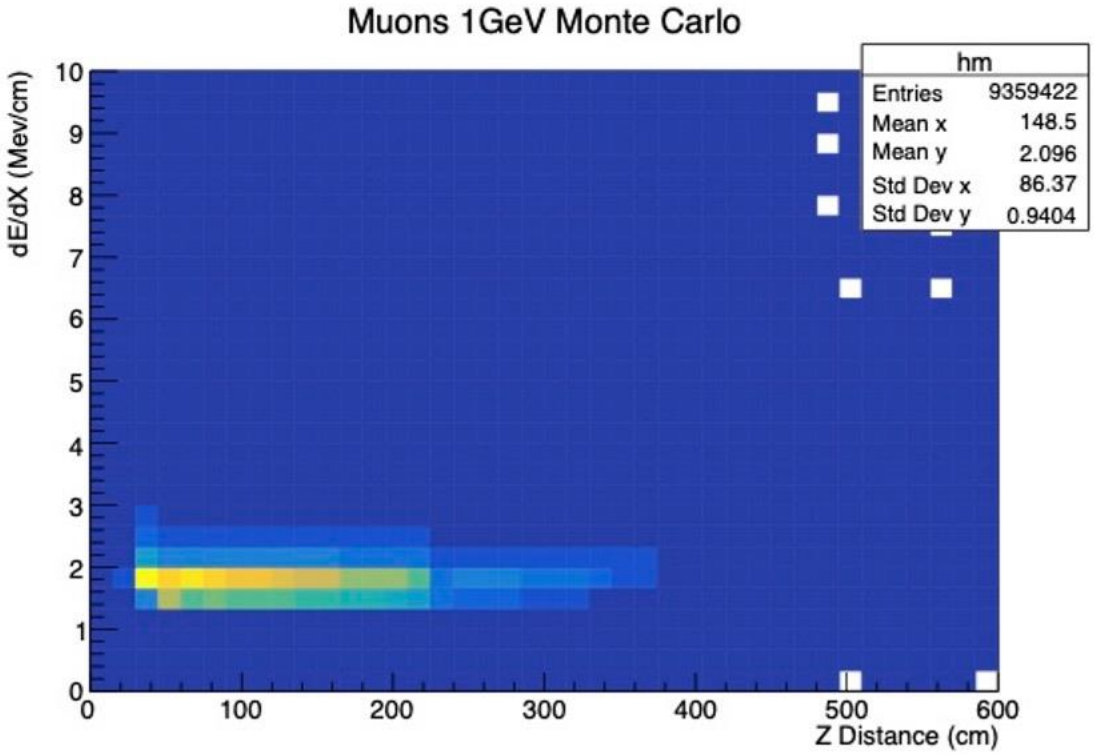


Figure 19 Kaons 2 GeV Monte Carol

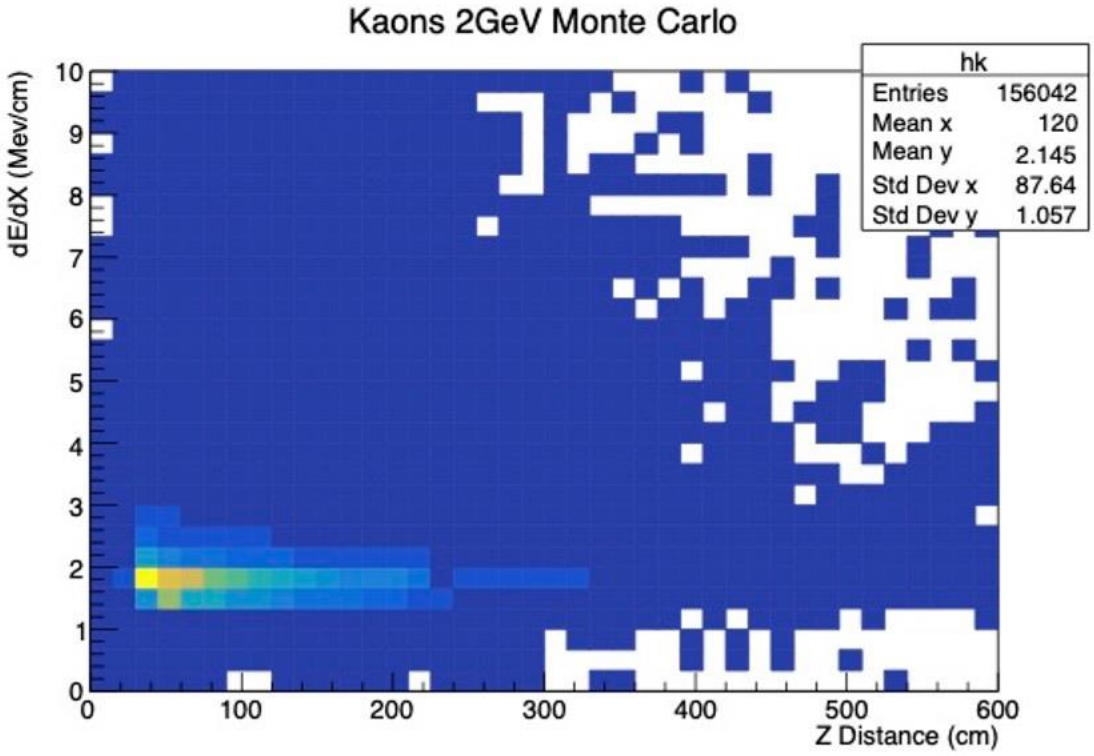
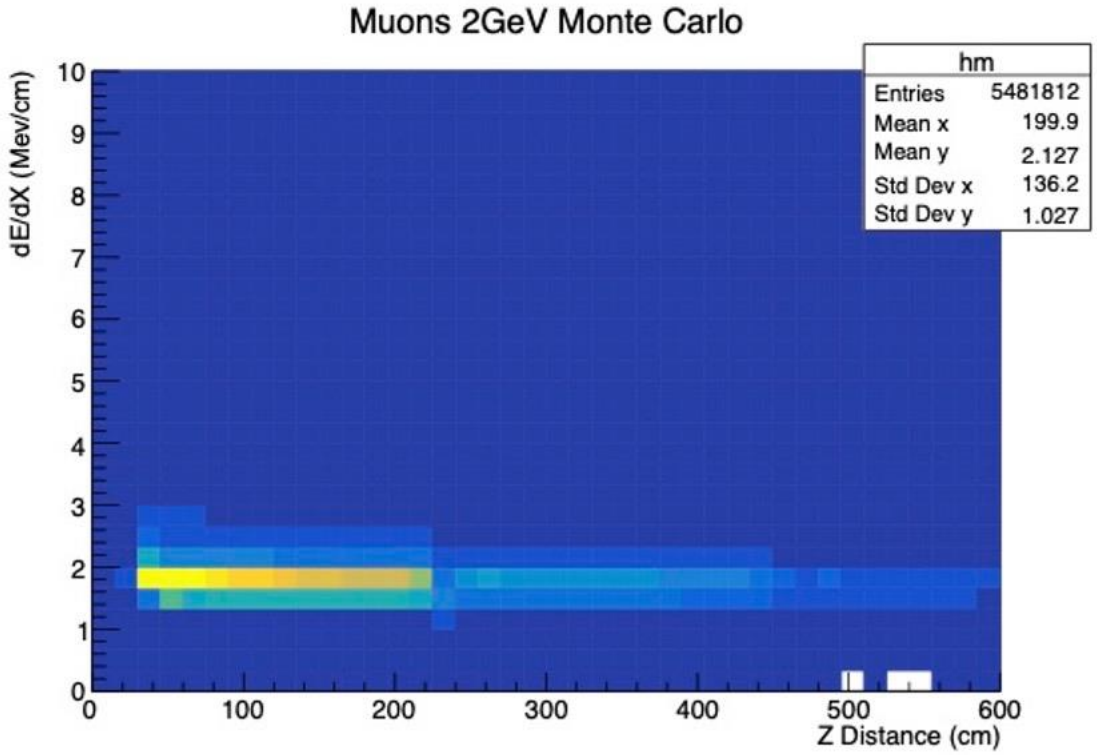


Figure 20 Muons 2 GeV Monte Carlo



Currently, this analysis can only be conducted with the Monte Carlo simulations, but it demonstrates how the Thin-Slice method, combined with energy and track length, can assist in identifying kaon cross sections using our preliminary data from ProtoDUNE's Monte Carlo simulation.

Applications

The techniques presented in this paper are currently being implemented at ProtoDUNE. Future applications will involve using this method to study kaons at lower energies, which can be applied to real data for the DUNE experiment. Understanding kaon production and decay enhances the modeling of neutrino interactions. Correctly identifying kaon interactions is crucial for reducing background noise and facilitating rare event searches. These particle identification methods will help track kaon production in neutrino interactions and refine cross-section models for simulations.

This advancement may lead to further kaon-focused studies that provide insights beyond the Standard Model, including research into CP violation.

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