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Project Report

ProtoDUNE BSM searches: Signal Simulations & Trigger Emulation from the Simulated Data

Submitted by

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I am also deeply grateful to CERN for providing this once-in-a-lifetime opportunity, which has exceeded my expectations in every way.

Lastly, I want to thank everyone who supported me throughout this journey, including my family and friends, whose constant encouragement kept me motivated.

Abstract

This project involves a comprehensive analysis of simulated Beyond the Standard Model (BSM) signals on the CERN neutrino platform (NP04) of ProtoDUNE. Exploring BSM physics remains a critical frontier in particle physics, and the ProtoDUNE experiment is at the forefront of this pursuit. A significant part of this study includes Heavy Neutral Lepton (HNL) signal simulations, trigger emulation, and determining the threshold cut value for triggering using trigger primitive information. Signal simulations and trigger emulation were successful, yielding the expected trends. The next step involves obtaining the threshold value for triggering by comparing the efficiencies with the background, which will be pursued as an extension of this work. These efforts aim to enhance the scope for the detection of neutrinos and BSM signatures, contributing to the broader goals of the ProtoDUNE experiment.

ProtoDUNE BSM searches:
Signal Simulations and Trigger Emulation from the Simulated Data

1 Introduction and Background

1.1 Introduction

The search for BSM physics is one of the most compelling and challenging endeavors in contemporary particle physics. The ProtoDUNE experiment, an integral part of the Deep Underground Neutrino Experiment (DUNE) located at CERN, aims to explore these areas by leveraging its sophisticated detectors and data acquisition systems. My project focuses on analyzing trends in various parameters such as momentum, position, and track length using simulations of BSM signals (HNL) in ProtoDUNE (NP04), which is located at the CERN neutrino platform. Additionally, it aims to obtain an optimum threshold value for triggering the signals using the trigger primitive information. Throughout the project, I gained proficiency in LArSoft software and managed job submissions via HTCondor. Most of the coding was done in C++, with plotting done using PyROOT.
Apart from the project, I attended workshops of ROOT, cloud chamber detector and silicon pixel sensors. I attended the summer student lectures and took part in the visits to ATLAS, synchrocyclotron, ProtoDUNE, SPS beam test centre, antiproton decelerator and data centre.

1.2 The ProtoDUNE

The ProtoDUNE experiment is a large-scale prototype of the DUNE and is located at the CERN research facility. Its primary objective is to validate the design and performance of the liquid argon time-projection chambers (LArTPCs) which are pivotal for detecting neutrinos with high precision.

The **single-phase LArTPC** (ProtoDUNE-SP) detector constructed and tested at the NP04 experiment at CERN, serves as a test bed and a prototype for components of the first far detector module of DUNE. The detector constitutes two parallel planes (cathode and anode) separated by the drift gap. The sense-wire assemblies, known as Anode Plane Assemblies (APAs), contain three planes of readout wires on both faces, with the sense wire readout amplifiers and analog-to-digital converters (ADCs) placed inside the LAr close to the wires to improve the signal-to-noise ratio[3].

Figure 1: Layout of the EHN1 experimental area. The Dual Phase cryostat is on the left, and the Single Phase cryostat is on the right. Image source:[1]

The **dual-phase LArTPC**, in turn, utilizes the gaseous phase of argon, apart from the liquid phase, for better signal amplification. It uses Large Electron Multipliers (LEMs) to produce larger signals. The charged particles ionize the liquid argon, producing electrons that drift upwards towards the liquid-gas interface under an electric field. These electrons are then extracted into the gas phase, where a stronger electric field induces secondary scintillation light, which is detected by photodetectors.
The Dual-phase LArTPC developments have been stopped and is now rebuild as a vertical drift (single-phase) LArTPC.

1.3 Liquid Argon Time Projection Chamber (LArTPC)

The DUNE experiment proposes four massive Liquid Argon Time Projection Chambers (LArTPCs), with a total fiducial mass of 40 kilotons (kt) [4]. In an LArTPC, when neutrinos enter the detector, a small percentage of them interact with argon nuclei. In charged-current (CC) interactions, a neutrino can collide with an argon atom, resulting in the ejection of a charged lepton (electron or muon) from the nucleus. This charged lepton, being highly energetic, will create a significant ionization trail as it travels through the liquid argon.

The ionization caused by the lepton generates free electrons, which drift through the liquid argon under the influence of an electric field and are eventually collected by anode planes. As these ionization electrons move, they lose energy and produce scintillation photons in the process. These scintillation photons are detected by photomultiplier tubes (PMTs), where they are absorbed and trigger the emission of photoelectrons from the photocathode.

The emitted photoelectrons are then accelerated through a dynode chain in the PMT, amplifying the signal to produce a measurable current. This current can be recorded and analyzed to reconstruct the event.[4].

1.4 Heavy neutral leptons (HNL)

Neutrinos have been instrumental in deepening our understanding of the Standard Model. Initially, the SM proposed that neutrinos are massless particles. However, experimental observations revealed that neutrinos possess a small but non-zero mass. This discrepancy has led to the exploration of HNLs, which are hypothetical, heavier counterparts to the known neutrinos. So, the searches for these additional neutrinos help to answer the fundamental questions in particle physics, and have the potential to provide evidence for BSM.

1.4.1 HNL production

From a phenomenological perspective, HNLs can, through mixing with the SM neutrinos, appear in any final state where kinematics permit, in place of neutrinos with a production rate that scales as $|U_{\alpha 4}|^2$. This allows for their creation in meson decays, i.e, the two-body decays of charged mesons into a lepton and either a neutrino or an HNL[6]. Figure 2 illustrates the decay process $K \to \mu^+ \nu_\mu$ (or HNL).

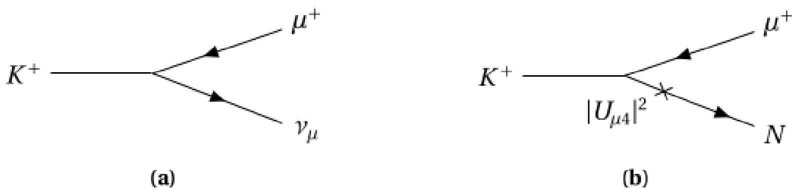

Figure 2: Diagrams for the (a) production of active neutrinos and of (b) HNLs. Image source:[6]

1.4.2 HNL decays

HNLs can have macroscopic lifetimes that depend in detail on the mass of the HNL and the mixing with the SM neutrinos. Although HNLs are long-lived, they are unstable particles, and eventually decay via mass mixing, similar to its production.

The decay modes involving a W boson produce detectable leptons. It can also decay weakly to a quark pair, lepton pair, or neutrino pair via Z boson exchange, or it can decay to two quarks or a neutrino and a lepton via a W boson[5].

As specific examples, an HNL might decay into a muon and a pion ($N \to \mu^\pm \pi^\mp$), or into muons and neutrino ($N \to \mu^\pm \mu^\mp \nu$). These specific decay channels are particularly useful for experimental searches, as they provide clear signatures that can be detected in the experiment, which I will be focusing upon, in my project.

1.5 LArSoft

The Liquid Argon Software (LArSoft) Collaboration develops and supports a shared base of simulation and reconstruction software across liquid argon time projection chamber (LArTPC) neutrino experiments[2]. The LArSoft code base is written in C++ and is built on the Art event processing framework, which is supported by the Fermilab Computational Science and AI Directorate for intensity frontier experiments. The software facilitates experiment-independent simulation, reconstruction and analysis software for neutrino and test beam experiments that use liquid argon time projection chambers.

2 Signal Simulations

Signal simulations involve the simulations of potential BSM signals that ProtoDUNE might detect, which help in understanding the detector's response to various hypothesized BSM phenomena.
I was given a set of HNL signals along with the decay products to simulate inside the protoDUNE detector, and observe the trends in momentum, position, energy loss and track lengths. I compared these parameters for two types of HNL decays, and for different masses: 1405MeV, 1003MeV and 601MeV. I could successfully obtain the plots, and could get valid explanations for each of them.

2.1 Steps of signal simulations

Signal simulation was done with the help of a detailed documentation of Dr. Ciaran Hasnip which is given in this repository.

1. I was given a set of simulated signals of different decays and masses, with which I propogated 1000 HNL events for each, within the detector. The histograms thus obtained were used to plot different parameters to observe the trends for the given decays and masses.
2. I used LArSoft modules and .fcl files for simulating Geant4 particle propagation.
3. I modified the analyser module to get the required information and histograms from the output of the above step, and plotted them to obtain the trends in track lengths of exiting and contained particles.
4. I run the code for Geant4 detector simulation and reconstruction.
5. The output root files thus obtained are used for the trigger part.

2.2 The distribution of parameters with respect to masses and decays

All the plots can be viewed from this repository.

2.2.1 The x, y, z components of the momentum and energy for different decays

The trends observed on plotting the momentum and energy for different decays, i.e, $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$ and $HNL \rightarrow \mu^{+} + \mu^{-}$ are:

- The mean value of total energy for the $HNL \rightarrow \mu^{+} + \mu^{-}$ is lower than that of $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$. The reason for this is that the first one is a three-body decay, and therefore, the missing energy will be that of the neutrino produced with it.
- Since the boost is taken in the z-direction, the z component of momentum is higher and x and y components are nearly zero.

2.2.2 The x, y, z components of the momentum and energy for different masses

The trends observed on plotting the momentum and energy for different masses (601MeV, 1003MeV and 1405MeV) are:

- Heavier the HNL mass, higher are the mean values of momentum and energy.

- It was expected that if the HNL mass is larger, then it would have less kinetic energy for the same flux, resulting in a lower z-momentum. But the plots showed the reverse (see Figure 4), and Salvador Urrea explained this theoretically, that the boost is stronger when the HNL mass increases, and this increase is responsible for a larger z-momentum for larger masses.

- On plotting the parameters for pion and muon individually, the same trends were followed.

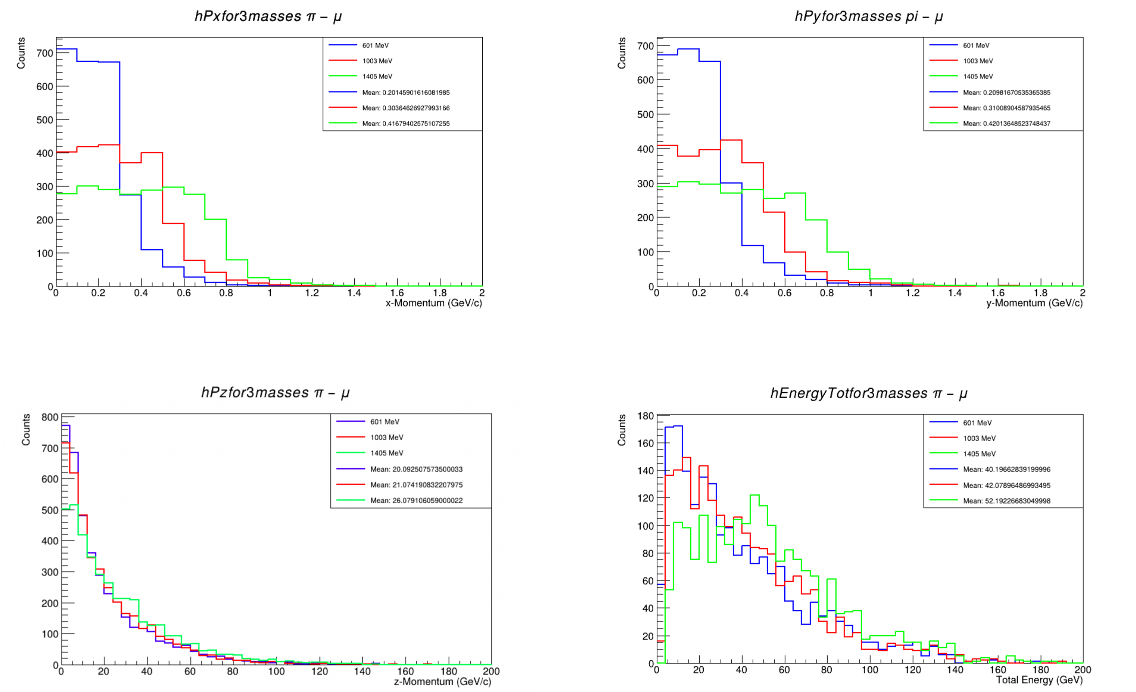

Figure 4: The momenta in the x, y, z directions and energy plots for the primary muon and pion in $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$ decay

2.2.3 Track length comparison

Track length refers to the length of the path that a charged particle travels. The track lengths for different decays and masses were compared, by obtaining histograms as a result of modifying analyser modules. I could obtain the track lengths of both contained and exiting particles separately, and could make distinct plots for the track length until the particle exits the detector, and the track length beyond the detector length.
From the plots, it was observed that when the HNL mass increased, track length also increased. I could also compare the track lengths of individual particles, which obviously shows that the heavier particle (pion in our context) with the same initial kinetic energy will have shorter track lengths because they lose energy at a higher rate due to their larger mass.
By analyzing track lengths and energy deposition patterns, we can identify particle types, estimate their masses, and reconstruct the dynamics of particle interactions, which are essential in the search for new particles!

3 Reconstruction

I am also able to run the reconstruction for the simulated data for all the masses and decays given. This can serve as a comparison for the truth produced my Monte Carlo, and the reconstructed variables. Also, this ensures that the reconstruction algorithms are accurately interpreting the detector data and helps to identify and correct systematic errors and biases.
For the analysis of reconstructed variables, I am required to create an analyser module, which I will be doing in the upcoming weeks. All the files generated, are saved in the CERNBox.

4 LArSoft Trigger

Particle detectors generate an immense amount of data, as they are bombarded with high-energy particles at very high rates. Recording every single event would be impractical due to the limitations of data storage and processing capabilities. Triggering allows to select and record only those events that are likely to be of interest and filtering out the background events. It also helps to identify different types of events based on expected signatures, such as a specific energy deposition pattern, timing information, or particle tracks. Here, I am working to develop a method for real-time triggering, by finding an optimum threshold value for the ADC integral sum, such that we are able to select the events of our interest.

4.1 Trigger emulation from the simulated data

I could generate trigger primitive (TP) information from the signals that I simulated till detector simulation level. Thanks to the detailed documentation provided by Hamza Amar, which can be viewed through this link. The trigger information was generated from the output of detector simulations, using the `run_tpalg_taalg_tcalg.fcl` file and the analysis is done using run_offlineTriggerTPCInfoDisplay.fcl file.
The trigger primitives provide the hit information recorded by a detector when a particle interacts with it. The information about the trigger (TPs or 'hits'), thus obtained include:

- **Analog-to-Digital Converter (ADC) integral** The analog signal generated on a particle detection is digitized by an ADC, converting the continuous analog signal into discrete digital values. The integral of this ADC signal corresponds to the total charge collected by the detector element, which is proportional to the energy deposited by the particle.
- **ADC peak** is the maximum value of the signal from the ADC.
- **Channel ID** identifies the specific detector channel that recorded the signal.
- **Start time** is the timestamp indicating when the signal first rises above a certain threshold. This marks the beginning of the detected interaction.
- **Time peak** refers to the time at which the ADC signal reaches its maximum value.
- **Time over threshold** refers to the duration for which the signal remains above a predefined threshold value, which is analogous to energy deposition by the particle.

From this information, further analysis were initiated, which helps in triggering the events online by providing a threshold for the ADC integral.

4.2 Comparison of the sum of ADC integral and corresponding total energy, by events

For each event, I computed the sum of ADC integral, and compared that with the total energy, i.e, the sum of the energy of the daughter particles. The energy is obtained from the truth by Monte Carlo simulation at the Geant4 simulation level.

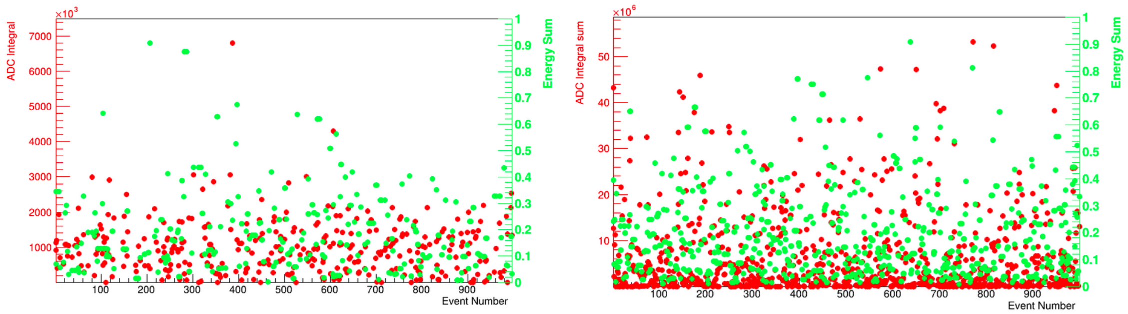

Figure 5: Plots for ADC integral sum and Energy from truth corresponding to events, for both the decays: $HNL \rightarrow \mu^{\pm} + \mu^{\mp}$(left) and $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$(right)

This event-by-event comparison helps to get an idea to see how the ADC integral is related to the energy deposition. The plots obtained for 1000 events of both decays are given in the Figure 5. Here, $HNL \rightarrow \mu^{\pm} + \mu^{\mp}$ has less TPs, than that of $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$, the reason being the minimum ionising property of muon, which deposits uniform energy, independent of its energy. Also, I plotted ADC integral sum versus total energy for both decays(see Figure 6), and individual energies of the daughter particles of 601MeV $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$ decay (see Figure 7).
All these plots clearly depicts that the muon being minimum ionising particle, shows less number of TPs even at high energies, unlike pion. This helps us to choose the $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$ decay for our experiments requiring higher threshold cut values.

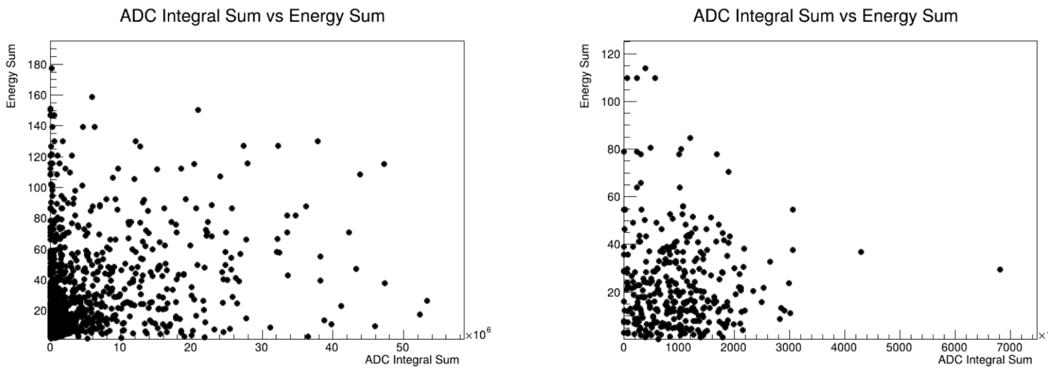

Figure 6: Plots for ADC integral sum versus Energies obtained from the simulation for 601 MeV comparing both the decays: $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$(left) and $HNL \rightarrow \mu^{\pm} + \mu^{\mp}$(right)

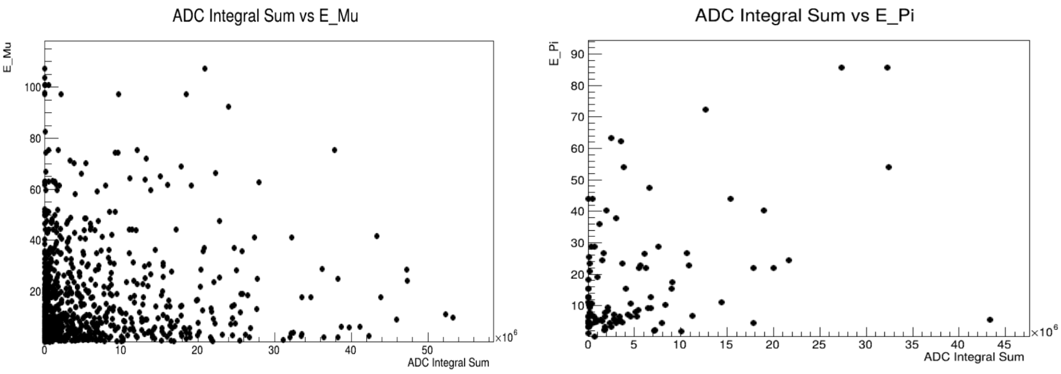

Figure 7: Plots for energies of Pion and Muon seperately for 601MeV HNL decay to pion and muon

4.3 Efficiency versus cut values of ADC integral sum

To get an optimum threshold value for ADC integral sum, we need to compare the efficiencies for different cut values for cosmic, neutrino and HNL signals. So I plotted the efficiency versus cut value plots for HNL signal with 1000 events for 601MeV mass, which is shown in the Figure 8. Efficiency is calculated as:

$$\text{Efficiency} = \frac{\text{Number of events passing the threshold value}}{\text{Total number of events with TPs}}$$

From the plots, it is evident that for $HNL \rightarrow \mu^{\pm} + \mu^{\mp}$ decay, muon TPs are less likely to be above the ADC integral sum threshold, which is due to its minimum ionising property. On comparing these plots, with that of cosmic and neutrino events, we will be able to obtain an optimum value of cut, which might help in facilitating a real-time triggering.

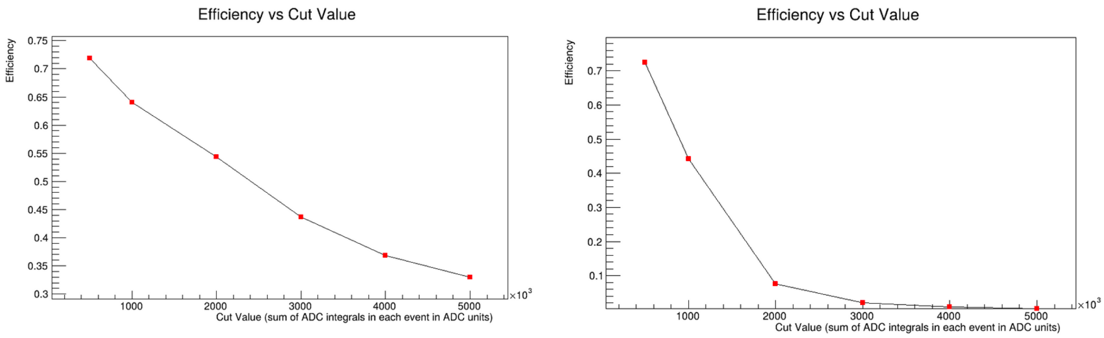

Figure 8: Plots for efficiencies versus threshold values of ADC integral sum for both decays: $HNL \rightarrow \pi^{\pm} + \mu^{\mp}$(left) and $HNL \rightarrow \mu^{\pm} + \mu^{\mp}$(right)

5 Conclusion

The project primarily dealt with HNL signal simulations and trigger emulation from simulated signals to obtain trigger primitive information. Analysis of various parameters such as momentum, energy, and track lengths across different decay modes and masses aligned with theoretical expectations. The trigger emulation is done using the simulated data and efficiency versus threshold values of ADC integral sum were plotted, in the end.
Further analysis on this, will be the comparison the efficiencies of different threshold values of the ADC integral sum for various events, including cosmic, neutrino, and HNL signals, to determine an optimal threshold value that facilitates real-time triggering.
The invaluable support from my supervisors, along with the passion I developed during this project, has inspired me to continue this work as my master's thesis. My future works will focus on the reconstruction of both simulated and real data, which will be pivotal in studying neutrino interactions within ProtoDUNE. I am hopeful that this work will contribute to the successful detection and confirmation of neutrinos in the detector!

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