Convolutional Neural Network in application to Slow Magnetic Monopole in the NOvA Experiment

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October 15, 2024

Abstract

The NOvA experiment, primarily focused on neutrino oscillation studies [1], provides an excellent platform for the search for slow-moving magnetic monopoles—hypothetical particles predicted to carry magnetic charge. In this analysis, the focus is on detecting slow magnetic monopoles with velocities corresponding to a beta (= v/c) in the range of 10^{-4} to 10^{-2}. Existing analysis is based on linear fit algorithm to the slow magnetic monopole tracks reconstruction and selection [2, 3]. In this project it is suggested to cross-check and possibly improve the analysis within convolutional neural network approach.

1 Introduction

Magnetic monopoles are hypothetical particles that carry isolated magnetic charge, either north or south, and their existence would have far-reaching implications in fundamental physics. While originally proposed by Dirac in 1931 to explain the quantization of electric charge, monopoles are also predicted by various grand unified theories (GUTs) and could have been produced in the early universe during phase transitions.

Of particular interest in this analysis are slow magnetic monopoles, with velocities much smaller than the speed of light ($\beta \simeq 10^{-4}$–10^{-2}). These slow monopoles would lose energy primarily through ionization as they pass through matter, leaving quite highly ionizing tracks that can be distinguished from the signals produced by other particles in the NOvA (far) detector.

1.1 Existing Analysis and Track Fitting

Current work by our group, we developed methods to identify magnetic monopole candidates by fitting linear trajectories (tracks) of particles passing through the NOvA far detector. Due to their highly ionizing nature and expected straight-line paths, magnetic monopoles produce tracks distinct from background particles such as muons, which typically has less deposit energy and $\beta = c$. Additionally, we employed robust algorithms to separate monopole-like signals from electronic noise and other non-muon backgrounds. This linear fitting method provided a reliable approach to isolate potential monopole events while reducing background contamination, enabling stringent limits to be placed on the flux of magnetic monopoles.

1.2 Proposed Neural Network-Based Cross-Check and Improvements

Building upon this foundational analysis, we aim to enhance the monopole search by incorporating a neural network-based reconstruction and particle identification (PID) approach. This new analysis will act as a cross-check to the existing work, leveraging modern machine learning techniques to improve the identification of slow magnetic monopole tracks. The neural network will be trained on simulated monopole events and known backgrounds, allowing for more sophisticated pattern recognition and better discrimination between signal and background. By introducing this method, we seek to improve sensitivity to slow monopoles, reduce false positives, and ultimately provide a more robust validation of our findings, contributing to the overall search for magnetic monopoles within the NOvA experiment.

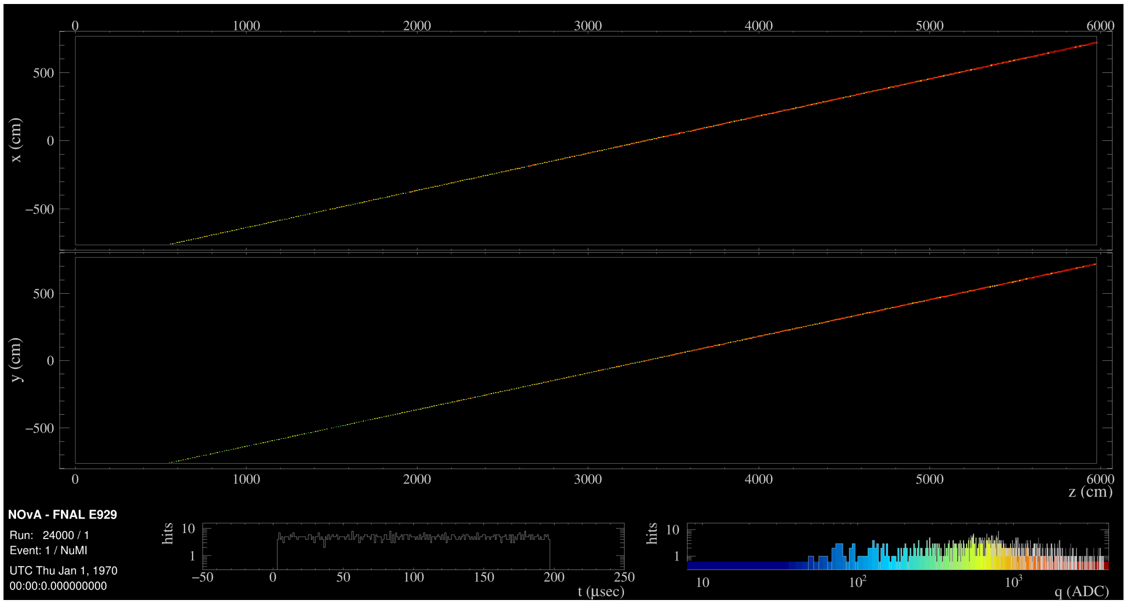

Figure 1: An example of the simulated slow magnetic monopole track in the NOvA far detector.

2 Tasks

2.1 Reproducing Linear Fit Results Using Python

Student(s) is/are tasked with reproducing the results of the linear fits applied to particle trajectories (tracks) in the NOvA detector, particularly focusing on the distinction between slow monopole tracks and backgrounds like muons. Using Python, they implement algorithms to fit the straight-line trajectories of highly ionizing particles such as magnetic monopoles. This involves working with data sets that represent particle tracks in the detector, applying linear regression techniques, and comparing their results with established benchmarks. The exercise helps them solidify their understanding of data fitting techniques and gain experience in coding for scientific analysis.

2.2 Performing an Analysis with NOvA's Convolutional Neural Network

Student(s) is/are applying NOvA's convolutional neural network (CNN) framework [4] to analyze particle events. This task involves using 2D projections (XZ and YZ views) of detector data as input to the CNN, which is trained to distinguish between different particle types, including monopoles and backgrounds. Student(s) is/are learning to preprocess the data, configure the neural network parameters, and run the model to classify events based on their features. By engaging in this task, students are not only contributing to ongoing particle identification (PID) efforts but also gaining hands-on experience with deep learning in particle physics, enhancing their knowledge of Keras and TensorFlow.

2.3 Calculating Efficiency Plots and Presenting Results

In the final task, student(s) calculate(s) efficiency plots that represent the effectiveness of the detection and identification process for slow monopoles. This involves evaluating how well the analysis separates monopole-like events from the background, across different detection criteria. By calculating and plotting these efficiencies, student(s) measure(s) the performance of the algorithms they develop and refine, and quantify the experiment's sensitivity to slow magnetic monopoles. Presenting the results helps students develop critical communication skills, allowing them to explain their findings clearly in both written and oral formats, which is essential in research.

3 Preliminary schedule by topics/tasks

The duration of this project is 4-6 weeks. The work schedule will be agreed upon with the student(s).

4 Required skills

- Basic knowledge of Linux, Phyton (helpful to start).
- A personal laptop or computer with a Linux system installed. A Linux virtual machine will be provided to computentional jobs.
- English or Russian language for communication.

5 Acquired skills and experience

As part of the work on the Magnetic Monopole analysis within the NOvA experiment and that Project, the student(s) is/are developing valuable skills and practical experience in the following areas:

5.1 Particle Physics

Student(s) is/are gaining an introduction of fundamental particle physics concepts, especially those related to neutrino interactions and the search for exotic particles like (slow) magnetic monopoles. Through hands-on involvement in data analysis, they are learning about detector technologies, particle interactions, and the physics behind signal and background discrimination. This experience is equipping them with the ability to interpret experimental data, apply theoretical knowledge to real-world problems, and contribute to cutting-edge research in particle physics.

5.2 Python Programming

Python is used extensively in data analysis and scientific computing within many phisics projects. Student(s) is/are sharpening their skills in Python by writing scripts to automate data processing, analyze large datasets, and develop algorithms for event reconstruction. They are also using Python libraries such as NumPy, pandas, and matplotlib to manage and visualize data, which is essential for interpreting the results of their analyses. This experience prepares them for work in both academia and industry, where Python is a leading programming language.

5.3 Neural Networks

The student(s) is/are gaining practical experience in machine learning, particularly with the Keras and TensorFlow frameworks. These tools are being used to build and train neural networks for particle identification (PID) tasks, including recognizing monopole-like events in the NOvA far detector. They are learning how to design neural network architectures, preprocess input data (such as 2D image projections with charge information), and train models using labeled datasets. This skill set is increasingly valuable in scientific research and beyond, with applications in fields like data science, artificial intelligence, and engineering.

6 You are welcome and good luck!

We hope you find this material very INTEREST and wish you best practice in JINR.

References

[1] M. A. Acero *et al.*, "Improved measurement of neutrino oscillation parameters by the NOvA experiment," *Phys. Rev. D*, vol. 106, no. 3, p. 032004, 2022.

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[4] A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M. D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa, and P. Vahle, "A Convolutional Neural Network Neutrino Event Classifier," *JINST*, vol. 11, no. 09, p. P09001, 2016.