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NuMI BEAM MUON MONITOR DATA ANALYSIS AND SIMULATION FOR IMPROVED BEAM MONITORING*

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Abstract

Following the decommissioning of the Main Injector Neutrino Oscillation Search (MINOS) experiment, muon and hadron monitors have emerged as essential diagnostic tools for the NuMI Off-axis ν_e Appearance (NOvA) experiment at Fermilab. This study uses a combination of muon monitor simulation and measurement data to study the monitor responses to variations in proton beam and lattice parameters. We also apply pattern-recognition algorithms to develop machine-learning-based models to establish correlations between muon monitor signals, primary beam parameters, and neutrino spectra at the detectors.

INTRODUCTION

The NOvA (NuMI Off-axis ν_e Appearance) experiment [1] aims to study neutrino oscillations using a long-baseline setup. It comprises two tracking calorimeters: the Near Detector and the Far Detector. These detectors are strategically positioned at baselines of 1 km and 810 km to maximize the probability of oscillations with respect to the Fermi National Accelerator Laboratory's NuMI (Neutrinos at the Main Injector) beam [2]. The NuMI beam can be configured to generate a primary ν_μ or $\bar{\nu}_\mu$ neutrino/anti-neutrino beam.

By analyzing the disappearance of ν_μ neutrinos and the appearance of $\bar{\nu}_e$ antineutrinos in the beam, NOvA investigates and quantifies neutrino oscillations. These measurements provide crucial insights into the fundamental properties of neutrinos and their interactions.

NuMI BEAMLINE

NOvA uses Fermilab's NuMI neutrino beam [2]. The beam is created by 120-GeV protons from the Main Injector striking a 1.2-m-long graphite target. Two magnetic horns focus charged pions and kaons produced in the target. The focused mesons decay in a 675-m-long decay pipe to produce muons and muon neutrinos. The muon neutrino beam is delivered to neutrino experiments such as NOvA. Muons are monitored by the muon monitors (MM) located at the end section of the beamline and absorbed by the rock between and downstream of the monitors. The horns can be operated with "forward horn current" (FHC), focusing π^+ and K^+, which decay to muon neutrinos, or "reverse horn current" (RHC), producing muon antineutrinos. The beamline layout is shown schematically in Fig. 1.

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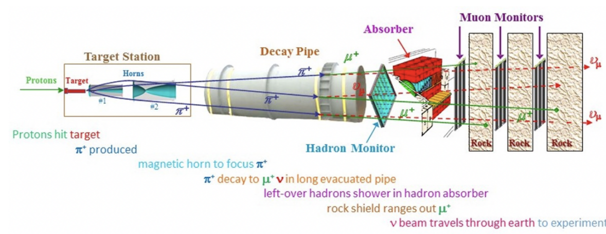

Figure 1: NuMI beamline: target, magnetic horns, decay pipe hadron monitors, hadron absorber, and muon monitors.

MUON MONITORS

The muon monitors are designed to detect muons of various energy ranges. The three muon monitors (MM1, MM2, MM3) [2] are located downstream of the hadron absorber and separated by 12 and 18 m of rock, hence sensitive to muons of different momentum. Each MM consists of a 9×9 array of ionization chambers. Each ionization chamber consists of two parallel-plate electrodes separated by a 3-mm gap. The chambers are filled with He gas. The ion chambers are designed to measure the fluence of charged particles. The charged particles ionize the helium gas within the chambers; the liberated ions and electrons are collected on electrodes. The perfect ion chamber gives a current reading that matches the charge produced when a high-energy particle deposits its energy. With high-energy particles, the amount of ionization per distance is almost the same regardless of the type or energy of the particle. So, by counting up the charge deposited, one can figure out how many particles passed through. A typical muon signal on MM1 is shown in Fig. 2.

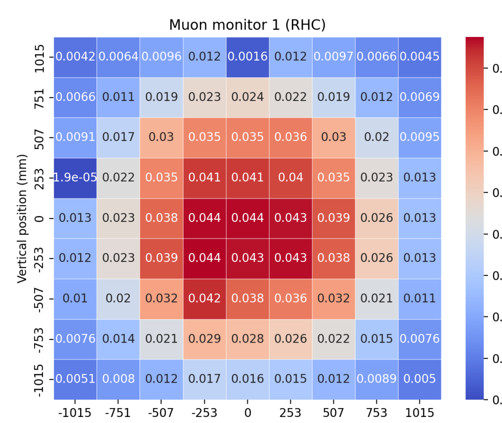

Figure 2: 81 pixels of signal readout at MM1. The number shown in each pixel is the voltage signal in that pixel. The two pixels with abnormally low signals are unreliable and were excluded from the analysis.

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With the MINOS [2] Near Detector shut down since February 2019, MM now provide essential information to monitor the beam and target, maintain the beam quality, and identify issues with the beamline alignment early. The MINOS Near Detector was previously used to monitor the quality of the neutrino beam. The off-axis NOvA Near Detector cannot be used for the same purpose because its spectrum has insufficient sensitivity to beam configuration changes to provide useful monitoring [3]. MM have certain advantages over neutrino detectors. With the MINOS detector, gathering enough statistics to isolate an issue with the beamline could take weeks. In contrast, MM gather sufficient statistics in a single pulse, so any issues that occur can be identified and mitigated much more efficiently.

Muon Monitor Data and Beam Scans

Data for the MM analysis are obtained through a series of dedicated beam scans conducted after each significant change in the beamline configuration or a long shutdown. The raw data [4] include proton beam position and size, horn current, and MM signals. Each parameter has an associated timestamp [5] so that the correlation among the beam parameters can be studied spill by spill. A sample of raw data is shown in Fig. 3. Beam scans involve controlled variations in the beam position on the target, beam spot size, and focusing horn currents. This process that changes the proton beam position on the target horizontally and vertically is called a "target scan."

On top of that, another set of scans is performed where the horn current is varied during the target scan. These are referred to as "horn current scans." Beam scans provide insight into how MM signal changes with the primary beam and optics parameters change. However, beam simulation studies are required to address the changes in the optics configuration that cannot be measured directly (e.g., magnetic horn and target alignment).

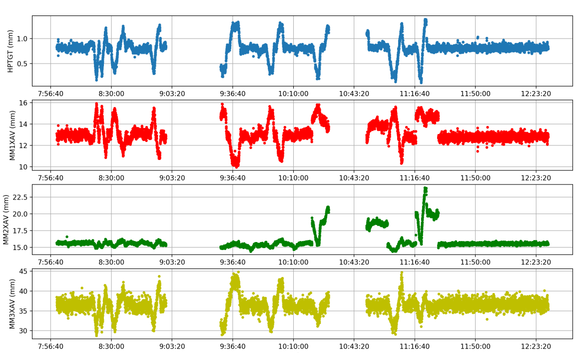

Figure 3: Raw data visualization: HPTGT (primary proton beam horizontal position on target), MM1XAV (horizontal muon beam centroid at muon monitor 1), MM2XAV (horizontal muon beam centroid at muon monitor 2), and MM3XAV (horizontal muon beam centroid at muon monitor 3) parameters.

Muon Monitor Simulation Improvements

NuMI beam simulations for neutrino studies are performed using a Geant4-based Monte Carlo (MC) simulation package called `g4numi` [6, 7]. Geant4 [8] is a software toolkit for the simulation of the passage of particles through electromagnetic fields and matter. It is widely used in high energy physics, nuclear physics, space science, and medical physics. `g4numi` provides information about the location and kinematics of each decay into a neutrino. The output of the `g4numi` simulation is stored in the ROOT [9] files containing ntuples with neutrino production and MM information for specific beam and horn current settings. Generating high-statistics samples for individual MM pixels is computationally demanding and time-consuming. To simulate a large number of protons on target (typically 1000 grid jobs with 500k protons on target each), OpenScienceGrid [10] was used.

Two new approaches were developed to improve the efficiency of muon simulations:

- multiple decay (where muon parent particles were forced to decay multiple times, producing up to 50 muons) and
- uniform beam simulation (starting with a single large uniform proton beam distribution and selecting the subsample in postprocessing by applying Gaussian weights covering a range of proton beam positions in a single simulation).

The two approaches were combined and demonstrated to be consistent with the original simulation. Large MC samples were produced for variations in the proton beam position and size, magnetic horn beam current, position and orientation of target and horns. These samples were then used to train machine learning models and establish connections between MM signals, primary beam parameters, lattice parameters, and neutrino spectra at Near and Far Detectors.

MACHINE LEARNING FOR BEAM MONITORING

Machine Learning (ML) algorithms offer the ability to analyze vast datasets and identify intricate patterns and correlations that might be challenging for conventional analysis methods. By training ML models on experimental data and simulation results, we can develop predictive models capable of associating specific changes in the muon monitor pixels with particular variations in primary beam parameters. This provides a more comprehensive way to detect parameter changes using muon monitor signal patterns and check how the neutrino flux changes due to these parameter changes.

The advantage of using machine learning based on muon monitor simulation is that it helps study situations that are not easily accessible in measurement. For example, one can explore scenarios with very low horn current or target and horns being offset or tilted. However, one of the challenges is the need to produce a sufficient number of high-statistics data samples. Thanks to the modified simulation approach (uniform beam + multiple decays), there are enough Monte

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Carlo (MC) data points for algorithm training and validation. Table 1 shows the structure of the MC samples. Each point corresponds to a spill in the measurement data. The simulation took 133 seconds to generate 100 training samples, showcasing the efficiency of the process. By leveraging the existing large-scale uniform beam simulation results, one can generate various MC samples to investigate a wide range of primary beam parameters and their impact on the MM responses.

Table 1: Structure of the Monte Carlo (MC) Data Samples, Including Various Parameters: horn current (HornI), spot size, proton x and y positions (denoted “hptgt” and “vptgt”), number of muons at each of the 81 pixels (e.g., mm1pixel1), and neutrino spectra split into bins (e.g., nuray1 for the flux in the first bin, 0–0.2 GeV)

Parameter	Meaning
ID	Index of data point
HornI (kA)	Horn current (kA)
spot_size (cm)	Proton beam spot size (cm)
hptgt (cm)	Proton x position (cm)
vptgt (cm)	Proton y position (cm)
mm1pixel1–81	# muons, pixel1–pixel81 at MM1
mm2pixel1–81	# muons, pixel1–pixel81 at MM2
mm3pixel1–81	# muons, pixel1–pixel81 at MM3
nuray1–50	# ν_μ or $\bar{\nu}_\mu$, NOvA ND location bins from [0–0.2] to [9.8–10] GeV

A relatively simple neural network structure was used consisting of 243 input nodes (muon counts recorded at the 3×81 pixels of MM1, MM2, and MM3; these counts provide information about the spatial distribution of muons detected by the monitors), 100 nodes in the middle layer, and 54 in the output layer (horn current, horizontal and vertical proton beam position, spot size and neutrino spectrum at the NOvA Near Detector location split into 50 bins over the energy range from 0 to 10 GeV). Ten thousand samples from the multiple decay/uniform beam simulation were used for training and validating the ML model.

Examples illustrating the ML model performance are shown in Figs. 4 and 5. The two lines in both figures are virtually indistinguishable. The ratio of the two neutrino spectra is practically flat in the region of interest between 1 and 3 GeV.

CONCLUSION

We analyzed the results of the muon monitor beam scan measurements, improved the performance of the existing `g4numi` simulation by implementing a more efficient simulation technique (multiple decay) and employing another technique developed within the group (uniform beam), used the resulting MC simulations to train the ML model, and compared the outcomes of the ML algorithm and MC simulation. The next step is to combine measurement data and MC simulation to improve ML training predictive power and reduce beam-focusing-related uncertainty on the neutrino flux in the detectors.

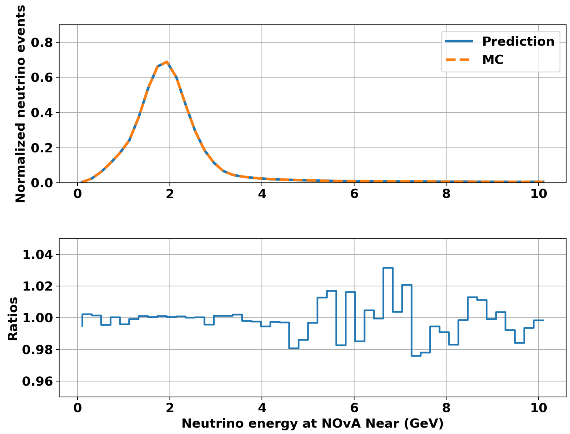

Figure 4: MC and ML output comparison. Top plot: neutrino spectra at the location of the Near Detector, bottom plot: ratio of ML prediction to MC.

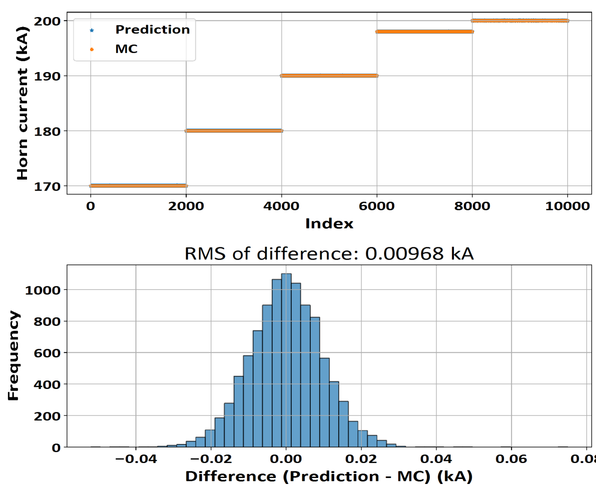

Figure 5: MC and ML output comparison. The top plot is a magnetic horn current within the 170 to 200 kA range (multiple samples for the same horn current include different proton beam positions and sizes), and the bottom plot is the difference between ML prediction and MC (kA).

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