PROCEEDINGS OF SCIENCE

NuMI Beam Monitoring Simulation and Data Analysis Status and Progress

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With the Main Injector Neutrino Oscillation Search (MINOS) experiment decommissioned, muon and hadron monitors became an important diagnostic tool for the NuMI Off-axis ν Appearance (NOvA) experiment at Fermilab to monitor the Neutrinos at the Main Injector (NuMI) beam. The goal of this study is to maintain the quality of the monitor signals and to establish correlations with the neutrino beam profile. And we carry out a systematic study of the response of the muon monitors to the changes in the parameters of the proton beam and lattice parameters. We report here on the progress of the beam data analysis and comparison with the simulation results.

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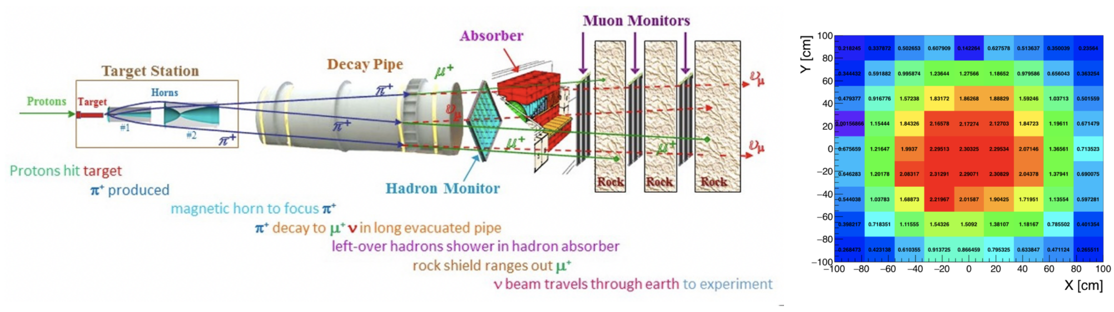


(a) **(b)**

Figure 1: (a) Schematics of the NuMI beamline. (b) 81 pixels of signal readout at MM1. The numbers in pixels are the voltage signal.

1. Overview of the NuMI beamline monitoring system

NOvA experiment [1] 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 pions and kaons produced in the target. The focused mesons decay in a 675-m-long decay pipe to produce mainly muons and muon neutrinos. The layout of the beamline is shown schematically in Fig. 1a. Three muon monitors (MM1, MM2, MM3) are located downstream of the hadron absorber. Muon monitors are identical 9×9 pixel arrays of ionization chambers. A typical muon signal on MM1 is shown in Fig. 1b. With the MINOS detector shut down since February 2019, the muon monitors now provide essential information to monitor the beam and target, maintain the highest quality beam, and identify issues with the beamline alignment early, which is crucial to achieving NOvA experiment goals. Other diagnostic tools include the hadron monitor upstream of the hadron absorber, multiple BPMs and toroids to monitor the primary proton beam.

2. Muon monitor data analysis

To understand the NuMI beam's behavior and be able to predict the effect of changes in the key beam parameters, multiple beam scans are carried out. The beam position on target, beam spot size, and focusing horn currents are changed in a controlled fashion. An example of one such scan is shown in Fig. 2. Beam scans indicate how each MM responds to beam position and horn current variations. For this analysis, we rely on the latest beam scans carried out in January, February, and May of 2021 using the new NuMI target capable of handling the 900-kW proton beam.

3. Muon monitor simulation

NuMI beamline simulation is carried out using g4NuMI [3], a Geant4-based [4] beamline simulation tool. As the diagram in Fig. 1a shows, MM1, MM2, and MM3 are located downstream of the NuMI hadron absorber and separated by 12 and 18 m of rock, hence sensitive to muons of different momenta. While the simulation results for MM1 agreed very well with the measurement data, the original g4NuMI simulation required a lot of computing time to produce a large enough sample to reduce the error bars on the muon beam centroid in MM2 and MM3 sufficiently. An

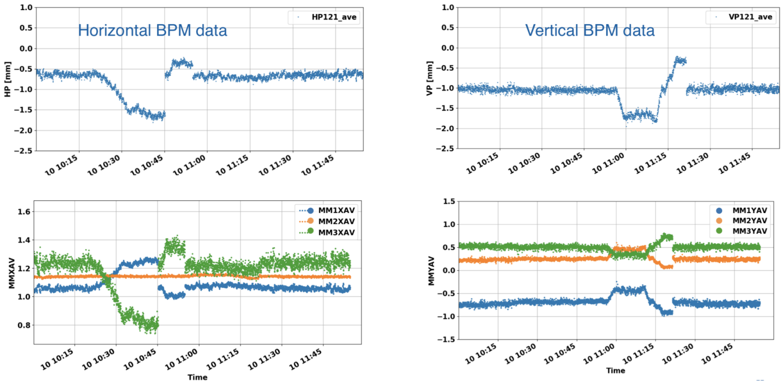


Figure 2: NuMI beam position on target scan data. Left: horizontal scan, right: vertical scan. Top row: beam position on target, bottom row: horizontal and vertical centroids of the muon beam at MM1 (blue), MM2 (orange), and MM3 (green).

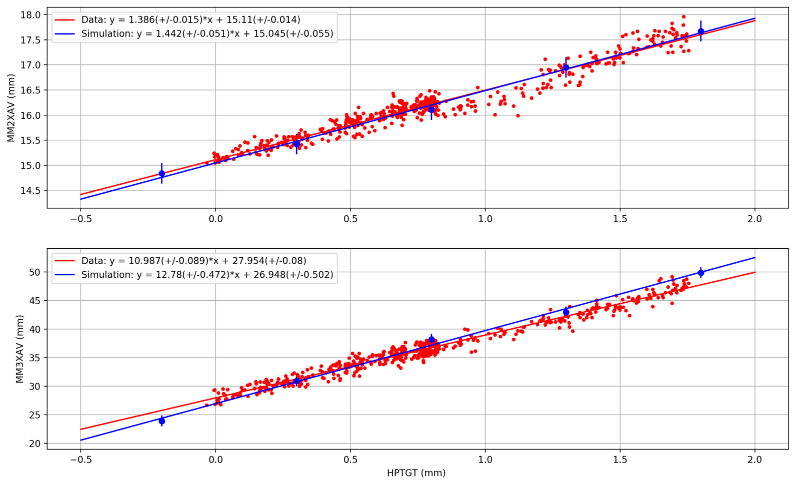
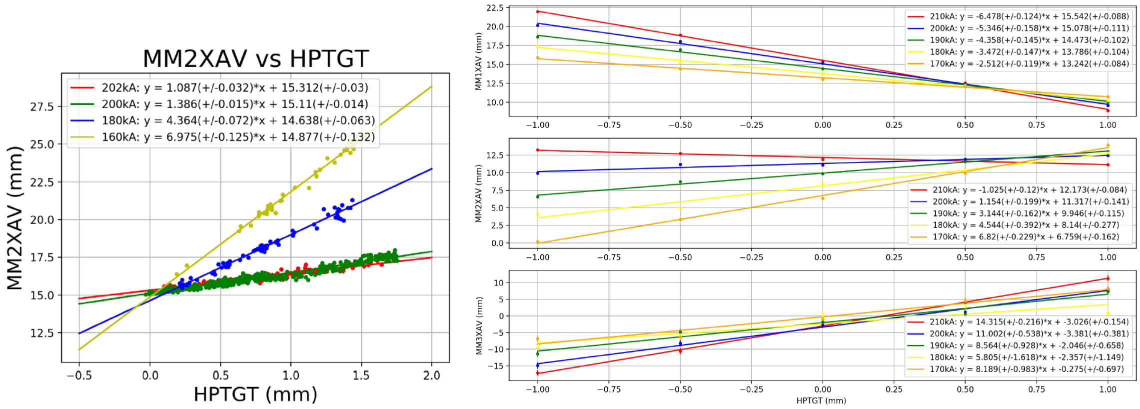


Figure 3: Horizontal muon beam centroid position at MM2 and MM3 as a function of the horizontal position of the proton beam on target: measurement data (red dots and fitted line) and simulation (blue line).

improved simulation was developed that forced each pion produced in the target to decay into multiple muons. The technique was thoroughly validated by comparing the outcomes of the multiple decay approach (up to 75x decays per pion) with the reference simulation and was found in agreement with the latter. This allowed us to use the multiple decay simulation and produce 50 times more hits in muon monitors routinely. The result of the comparison between the simulation and measurement is shown in Fig. 3.

3.1 Magnetic horn current scan

In addition to varying the position of the beam centroid, beam scans involve repeating such measurements at different focusing horn currents. For example, Fig. 4a shows the results of the magnetic horn current scan performed on February 22, 2021 (horn current set to 160, 180, 200, and 202 kA). Figure 4b shows the corresponding simulation results. The offsets of the lines in these two graphs should not be compared directly because the simulation is carried out under ideal conditions while in the actual beamline the individual components are aligned relative to each other and alignment errors need to be accounted for. What matters are the slopes of the lines characterizing muon beam horizontal position dependence on the proton beam horizontal position as a function of horn current. For example, as seen in Fig. 4, at 180 kA the slope of the line is 4.363±0.072 as measured and 4.544±0.392 based on the simulation. The full comparison is shown in Fig. 5.



(a) **(b)**

Figure 4: (a) Horizontal muon beam centroid position at MM2 as a function of the horizontal position of the proton beam on target: measurement data at the magnetic horn currents of 160, 180, 200, and 202 kA. (b) Horizontal muon beam centroid position at MM1, MM2, and MM3 as a function of the horizontal position of the proton beam on target: simulation at the magnetic horn currents of 170, 180, 190, 200, and 210 kA.

Horn current scans indicate a substantial (≈10 kA) offset between the simulation and measurement similar to the observation made by the MINOS group. This issue is currently under study.

4. Machine Learning algorithms based on muon monitor data

In addition to analyzing MM data and simulation results, we built a machine learning model (ML) that predicts/reconstructs primary beam parameters and the magnetic horn current by using muon monitor data. The model is trained using randomly selected past data samples. ML predictions can be used to monitor beamline issues in the future. The plan is to implement the ML model predictions for daily NuMI beamline data monitoring and catching common failure modes.

References

[1] NOvA Experiment, `https://novaexperiment.fnal.gov/`.

[2] P. Adamson *et al.*, "The NuMI neutrino beam," Nucl. Instr. Meth. Phys. Res. A **806** (2016) 279, `http://www.sciencedirect.com/science/article/pii/S016890021501027X`.

[3] G4NuMI documentation, `http://www.hep.utexas.edu/~zarko/geant4/`, see also `https://indico.fnal.gov/event/48024/`.

[4] S. Agostinelli *et al.* [GEANT4 Collaboration], "Geant4—a simulation toolkit," NIM A **506** (2003) 250.

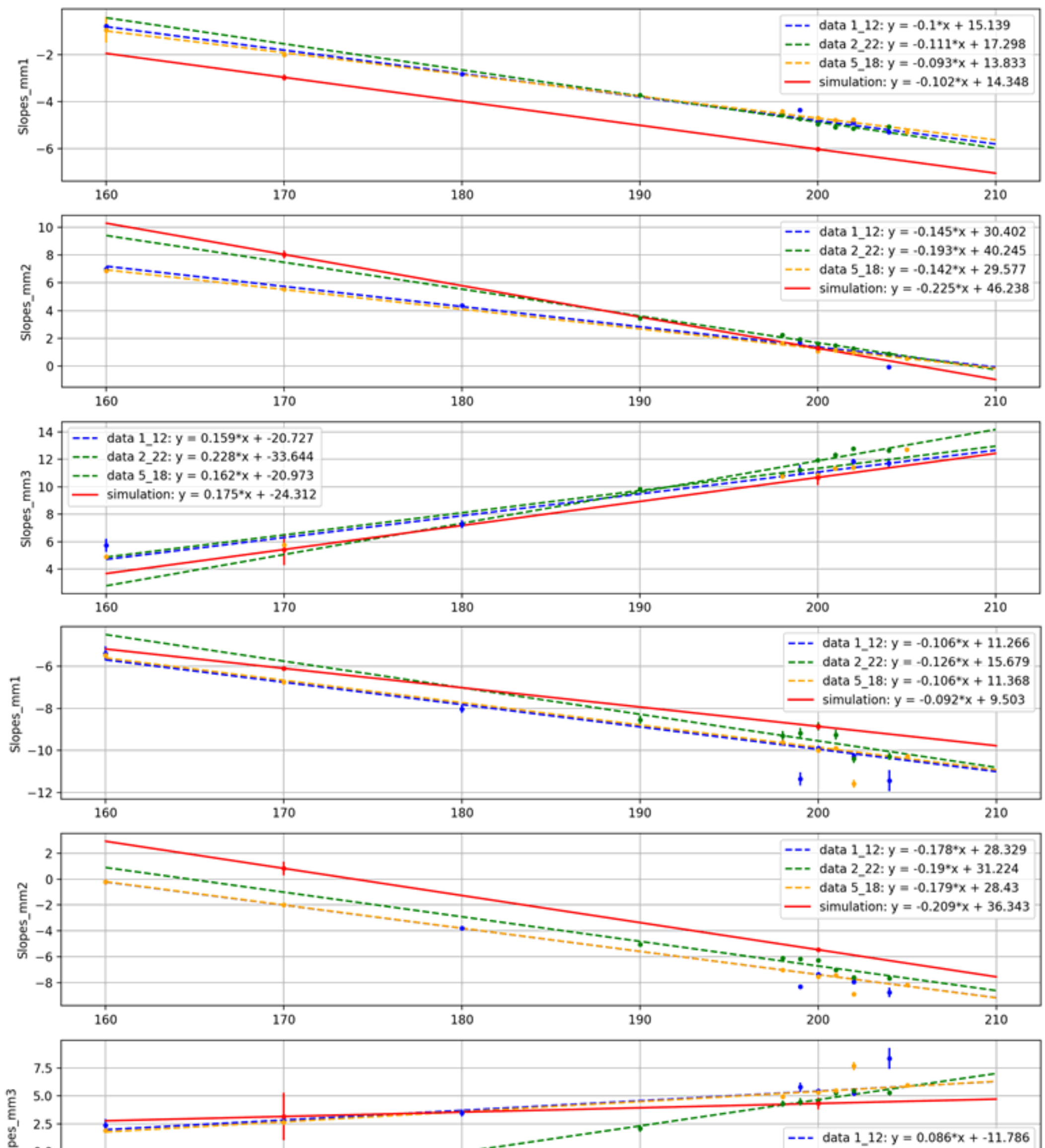


Figure 5: Slope of the line characterizing muon beam horizontal (vertical) position dependence on the proton beam horizontal (vertical) position as a function of horn current. Solid red line: simulation result, blue dashed line: Jan 12, 2021 horn current scan, green dashed line: Feb 22, 2021 horn current scan, yellow dashed line: May 18, 2021 horn current scan.