

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

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Abstract

The NuMI muon monitors (MMs) are a very important diagnostic tool for monitoring the stability of the neutrino beam used by the NOvA experiment at Fermilab. The goal of our study is to maintain the quality of the MM signal and to establish the correlations between the neutrino and muon beam profile. This study could also inform the LBNF decision on the beam diagnostic tools. We report on the progress of beam scan data analysis (beam position, spot size, and magnetic horn current scan) and comparison with the simulation outcomes.

NuMI BEAM AT FERMILAB

NOvA uses Fermilab's NuMI neutrino beam [1]. The beam is created by 120 GeV protons from the Main Injector striking a 1.2-m-long graphite and beryllium 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 muons and muon neutrinos. This muon neutrino beam is delivered to neutrino experiments such as NOvA. The layout of the beamline is shown schematically in Fig. 1.

MUON MONITORS

Three muon monitors (MM1, MM2, MM3) are located downstream of the hadron absorber and separated by 12 and 18 m of rock, hence sensitive to muons of different momenta. Each muon monitor consists of a 9×9 array of ionization

chambers, see Fig. 2. Each ionization chamber consists of two parallel plate electrodes separated by a 3-mm gap. The chambers are filled with He gas. A typical muon signal on MM1 is shown in Fig. 3.

BEAM SCANS: DATA AND SIMULATION

To understand the behavior of the NuMI beam and be able to predict the effect of the 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. The results of such scans (beam horizontal and vertical position scan, horn current scan) are shown in Figs. 4, 5. The two left plots in Fig. 5 show the change in the horizontal position of the proton beam on target (top) and the change in the position of the horizontal centroid of the beam on the three muon monitors (bottom). Similarly, the two right plots show the change in the vertical position of the proton beam on target and the change of the vertical centroid of the beam on the muon monitors.

Beam scans demonstrate that each MM responds to beam position and horn current variation. Consolidated diagnostic plots similar to the beam scan plots will be eventually incorporated in the NOvA shifter routine to monitor the MM data.

The results of the simulations using the g4numi software package and reproducing the beam position and horn current scans are shown to be consistent with the data. One example of such an analysis is illustrated in Fig. 6. As can be seen from the graph, the centroids of the muon beam on MM1 and MM3 have the opposite slopes as a function of the beam

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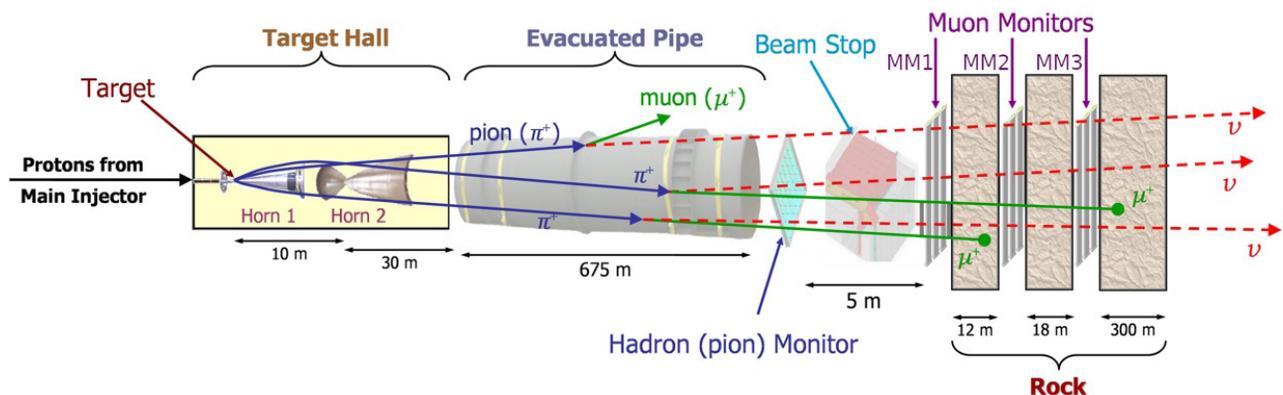


Figure 1: Schematics of the NuMI beamline.

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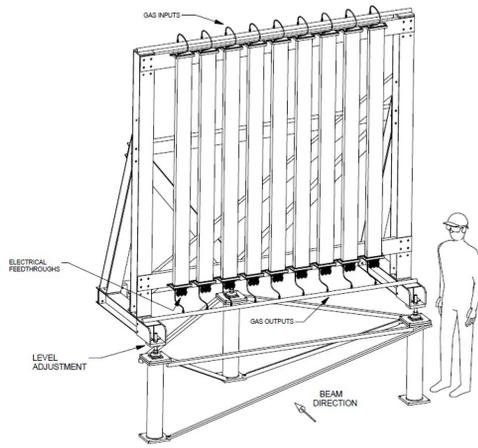


Figure 2: NuMI beamline muon monitor schematics.

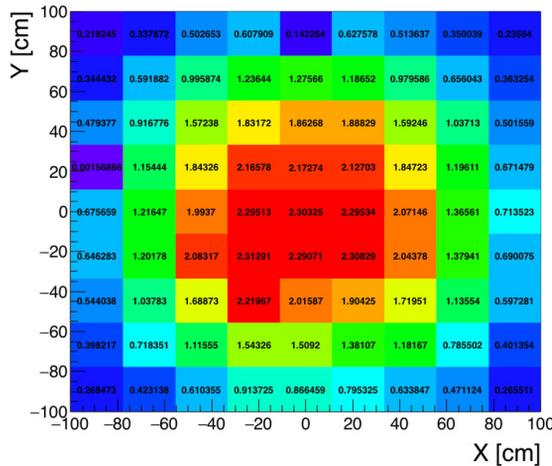


Figure 3: 81 pixels of signal readout on MM1.

position on the target. The change in slope is consistent with the measured data as the muon beam is underfocused at MM1 and overfocused at MM2.

Analysis of the individual pixels, for example, the central row or column of the muon monitor, as shown in Fig. 7, provides further insight into the distribution of the muon momentum and flux. Figure 8 illustrates how the peak of the muon distribution changes as a function of the horizontal position within the detector: both the height of the peak and its location are affected.

The patterns outlined above could be analyzed using machine learning techniques and be used to predict potential beam issues.

MACHINE LEARNING APPLICATIONS TO MONITOR THE BEAM

We are working on applying machine learning algorithms to understand the neutrino beam variations with the help of the muon monitor data and simulation studies.

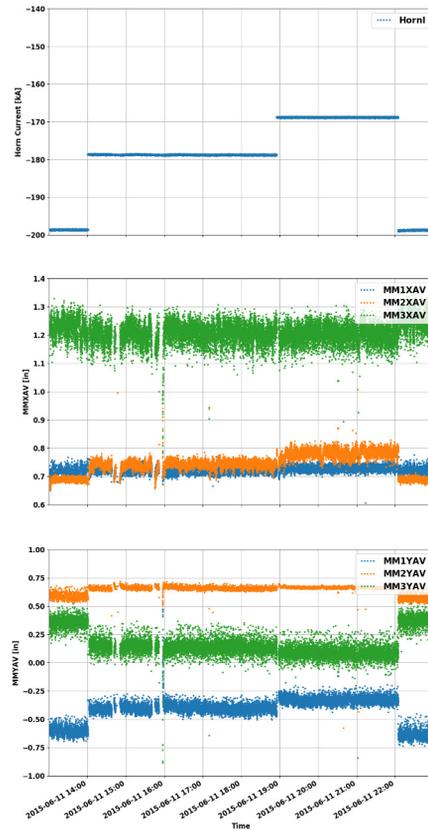


Figure 4: NuMI horn current scan data. Top plot: horn current, center and bottom plots: horizontal and vertical centroids of the muon beam on MM1 (blue), MM2 (orange), and MM3 (green).

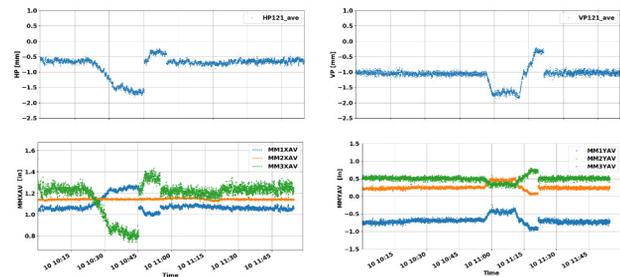


Figure 5: NuMI beam position on target scan data. Left plots: horizontal scan, right plots: vertical scan. Top row: beam position on the target, bottom row: horizontal and vertical centroids of the muon beam on MM1 (blue), MM2 (orange), and MM3 (green).

One example would be the muon beam centroid prediction. The muon beam centroids in each MM have been modeled as a function of the incident beam profile measurements and horn current data:

$$\begin{pmatrix} x_{\text{beam}}^{\text{pred}} \\ y_{\text{beam}}^{\text{pred}} \end{pmatrix} = f(x_{\text{beam}}, y_{\text{beam}}, \sigma_x, \sigma_y, \text{Intensity}_{\text{beam}}, I_{\text{horn}}),$$

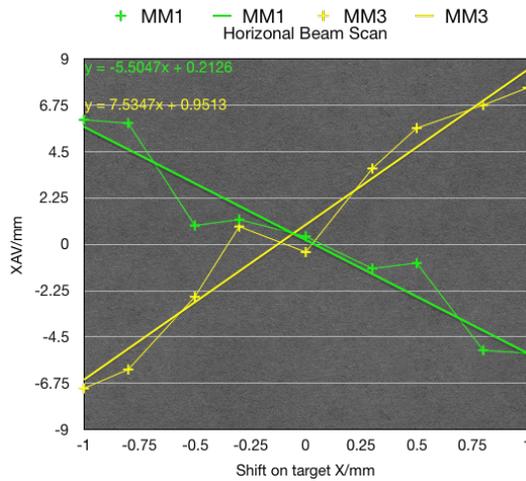


Figure 6: g4numi simulation results: beam centroids on the corresponding muon monitor vs NuMI beam position on target. The horizontal axis corresponds to the top left plot in Fig. 5, the vertical axis – to the bottom left plot in Fig. 5. “XAV” is the horizontal position of the beam centroid in mm.

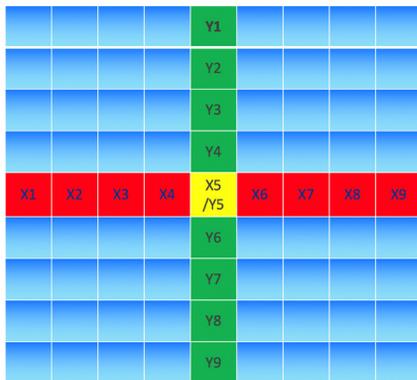


Figure 7: MM pixels selected for a more in-depth study. Horizontal row (red) and vertical column (green) through the center of the detector, pixels are numbered X1–X9 from left to right, Y1–Y9 from top to bottom (beam direction is into the page).

where $x_{\text{beam}}, y_{\text{beam}}$ are the muon beam centroid coordinates, σ_x, σ_y are the beam sizes, beam intensity is the number protons on target per spill, and I_{horn} is the horn current.

The underlying machine learning algorithm used in the study is a linear regression model. It is trained using randomly selected past data samples. Predictions follow trend of MM measurements, with $\leq 5\%$ difference as can be seen in Figs. 9, 10.

REFERENCES

[1] P. Adamson *et al.*, “The NuMI neutrino beam”, *Nucl. Instr. Meth. Phys. Res. A*, vol. 806, p. 279, 2016. <http://www.sciencedirect.com/science/article/pii/S016890021501027X>.

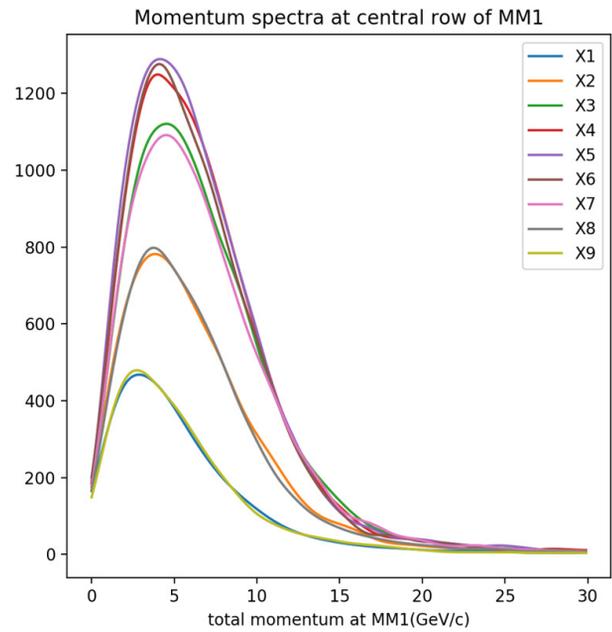


Figure 8: Muon momentum distributions per pixel in the horizontal row X1–X9 as shown in Fig. 7.

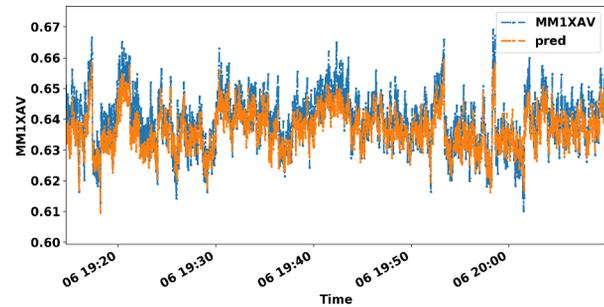


Figure 9: MM1 muon beam centroid horizontal position prediction (orange) vs. measurement (blue).

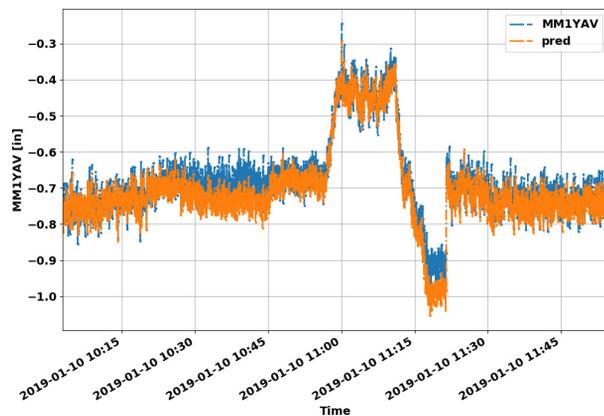


Figure 10: MM1 muon beam centroid vertical position prediction (orange) vs. measurement (blue).