# FERMILAB MUON CAMPUS AS A POTENTIAL PROBE TO STUDY NEUTRINO PHYSICS*

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*Abstract*

In the next decade the Fermilab Muon Campus will host two world class experiments dedicated to the search for signals of new physics: The g-2 Experiment will determine with unprecedented precision the anomalous magnetic moment of the muon and the Mu2e experiment will improve by four orders of magnitude the sensitivity on the search for the as-yet unobserved charged lepton flavor violation process of a neutrinoless conversion of a muon to an electron. In this paper, we will discuss a possibility for extending the Muon Campus capabilities for neutrino research. In particular, with the aid of numerical simulations, we estimate the number of produced neutrinos at various locations along the beamlines as well as at the Short-Baseline Near Detector, which sits inline with a straight section of the Delivery Ring. Finally, we discuss items for future study.

## INTRODUCTION

One of the recommendations adopted by the Office of Science from the 2014 HEPAP P5 report is the completion of the g-2 [1] and Mu2e [2] projects in all of the funding scenarios under consideration. Consequently, the construction and operation of a Muon Campus facility to support these experiments is a significant priority at Fermilab for the next decade. The Fermilab Muon Campus consists of a synchrotron – the Delivery Ring (DR) – and the various beamlines necessary to transport beam from the Fermilab Recycler to the DR and from the DR to the g-2 and Mu2e experiments. A layout of the Muon Campus is shown in Fig. 1.


Figure 1: Layout of the Fermilab Muon Campus. Note that AP 10 is the straight section that is well aligned with the SBND detector.

During operation of the DR for the Fermilab g-2 Experiment, a considerable number of muons will be produced through the decay of stored pions. These pion decays also produce a large quantity of neutrinos. While the vast majority of these neutrinos cannot be put to use, it just so happens that one of the DR's straight sections (straight 10) is in good alignment with the Short Baseline Near Detector (SBND) [3], one of the liquid argon time projection chamber (LArTPC) detectors in FNAL's Short-Baseline Neutrino Program [4]. This arrangement is illustrated in Fig. 2. Given the high efficiency of LArTPCs, these neutrinos could be a significant source of data for the SBND.

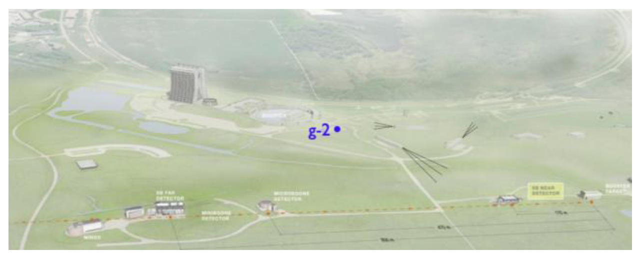


Figure 2: Layout showing the placement of the SBND with respect the Delivery Ring of the Fermilab Muon Campus.

## FERMILAB MUON CAMPUS LINES

Protons with 8 GeV kinetic energy are transported via the M1 beamline to an Inconel target at AP0. Within a 1.33 s cycle length, 16 pulses with $10^{12}$ protons and 120 ns full length arrive at the target. Secondary beam from the target will be collected using a lithium lens, and positively-charged particles with a momentum of 3.1 GeV/c (± 10%) will be selected using a bending magnet. Secondary beam leaving the Target Station will travel through the M2 and M3 lines which are designed to capture as many muons with momentum 3.094 GeV/c from pion decay as possible. The beam will then be injected into the DR. After several revolutions around the DR, essentially all of the pions will have decayed into muons, and the muons will have separated in time from the heavier protons. A kicker will then be used to abort the protons, and the muon beam will be extracted into the new M4 line, and finally into the new M5 beamline which leads to the g-2 storage ring. Note that the M3 line, DR, and M4 line are also designed to be used for 8 GeV proton transport by the Mu2e experiment. However, the two experiments cannot run simultaneously. A detailed performance analysis of the Fermilab g-2 Experiment can be found in **[5]**.

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## SIMULATION MODEL

For the simulation we use G4Beamline [6], a tracking simulation program that includes key physical processes such as spin tracking and muon decay. The simulation begins right after the pion production target and includes the M2 line, M3 line and the DR. Bending magnets, focusing magnets and beam pipes are simulated. Figure 3 displays the number of pions and muons as the beam travels along the M2, M3 lines and the Delivery ring. It's clear that the number of pions becomes negligible after the first turn suggesting that the majority of neutrinos from pion decays are produced along the first turn. Thus, our study focuses on one turn only and relevant to our previous study [4]. In order to capture and analyze our neutrino distributions we placed virtual detectors at the end of straight 10 (MDRD) and at the approximate location of the SBND, about 270 meters from the end of straight 10. We modeled the SBND detector as a 4m x 4m square with perfect detection efficiency, with its center aligned with the beam centerline. We also added a cap at the end of straight 10 which kills any remaining pion tracks in order to prevent the production of excess neutrinos. The elements of straight 10 are made of a custom material which eliminates any non-neutrino tracks entering it. This saves a lot of computation time on long runs.

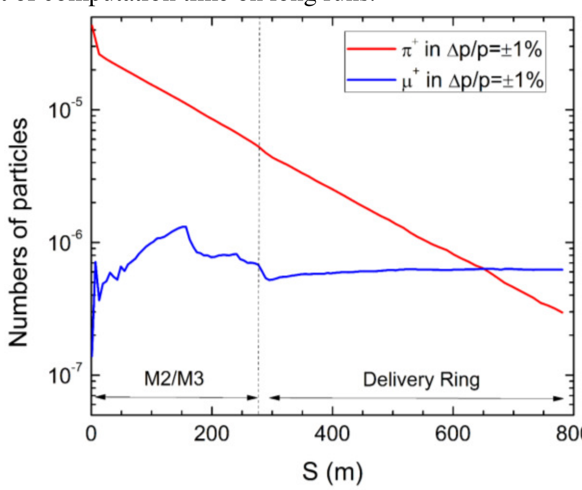


Figure 3: Simulated performance along the M2, M3 and DR beamlines. In the model, only one turn in the DR is assumed. The vertical axis is scaled to the protons on target (POT).

The simulation is split into three parts in order to create checkpoints. The first section runs from the target station to the "CMAG" element (a magnet which kicks the pions into the DR); the second spans the first curved section of the ring; the last section is just the elements of straight 10. These three parts can be run in sequence. The virtual detectors write particle data to ROOT files, which are analyzed by plotting scripts.

## PRELIMINARY RESULTS

Our largest runs started with $10^{11}$ protons on target (POT). Figure 4 displays the simulated neutrino distribution at the end of straight 10. The bulge on the left is likely due to neutrinos produced in the curve before straight 10, virtually none of which go on to hit the SBND. This is clearly illustrated in Fig. 5. We found about 8.1 x $10^{-7}$ nu/POT at the end of straight 10, of which about 2.1 x $10^{-8}$ nu/POT reached the SBND. Figures 6 and 7 display the momentum distributions on straight 10 and SBND, respectively. Clearly, the SBND neutrinos had a very sharp peak in momentum around 1.3 GeV/c and were evenly distributed across the face of the detector. The vast majority of these neutrinos were produced within the confines of the magnet cavities and uniformly throughout straight 10, and thus have a very low angular spread. These peak-momentum neutrinos are concentrated within 3 meters of the beam centerline at the SBND.

Figure 8 and 9 show the transverse phase distributions at the end of straight 10 and the SBND detector. Note that at the SBND detector, the angular spread has been cut from ±100 to ±10 mrad.

Figure 10 plots momentum vs. angle with the centerline for neutrinos at the end of straight 10. This is an overlap of two distributions: the more distinct distribution comes from the neutrinos produced within straight 10, while the background distribution comes from neutrinos produced earlier in the loop.

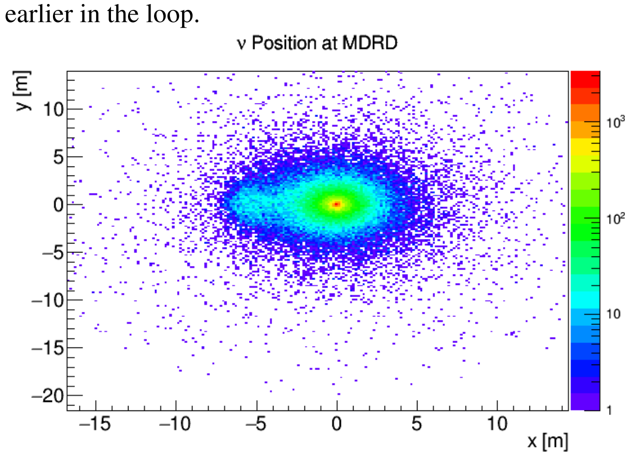


Figure 4: Simulated neutrino distribution at the end of straight 10. The distribution is not symmetric.

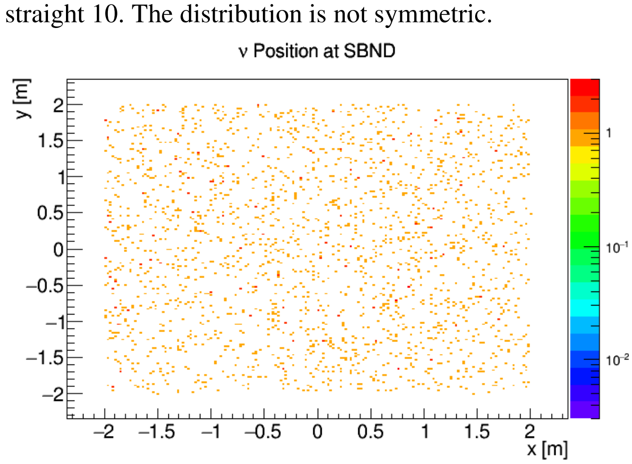


Figure 5: Simulated neutrino distribution at the SBND. Note the uniformity of the distribution over the face of the detector.

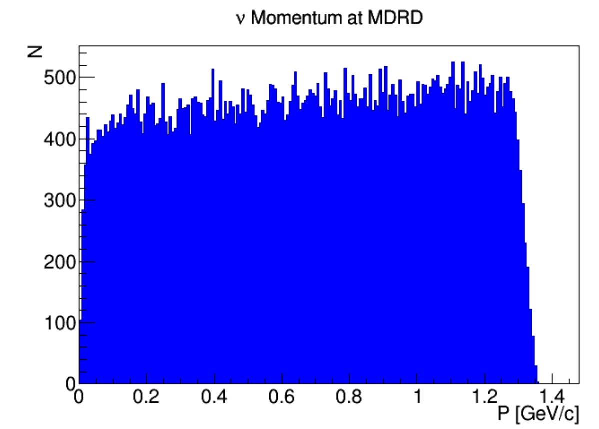


Figure 6: Momentum distribution of simulated neutrinos at the end of straight 10. This uniformity is due to the large size of the virtual detector.

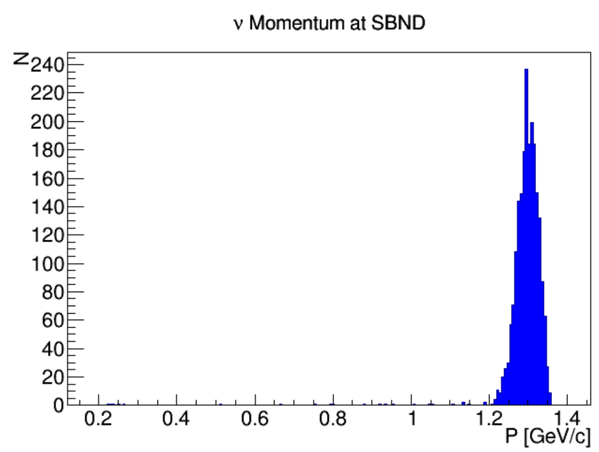


Figure 7: Momentum distribution of simulated neutrinos at the SBND. Note the sharp peak at 1.3 GeV/c.

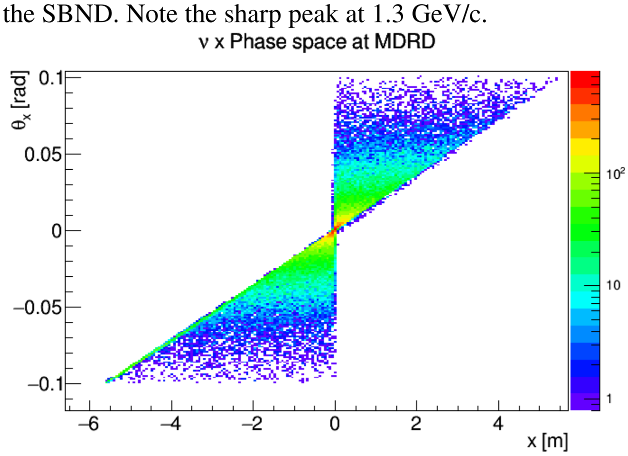


Figure 8: x-phase space for simulated neutrinos at the end of straight 10.

## FUTURE WORK

A couple of changes could be made to increase the fidelity of the simulation. One would be to give the materials composing the magnet elements more realistic properties to see if they have any effect on neutrino production. Another would be to use the actual location and orientation of the SBND relative to the DR. This would be more enlightening than the optimal settings that the optical settings we used. Finally runs with higher statistics are planned using the high performance computing at NERSC [7].

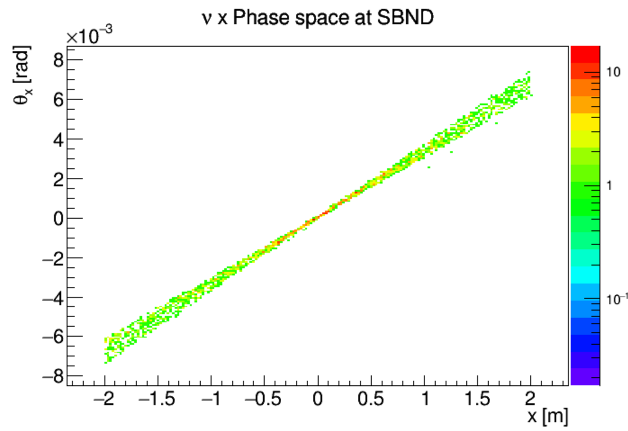


Figure 9: x-phase space for simulated neutrinos at the SBND.

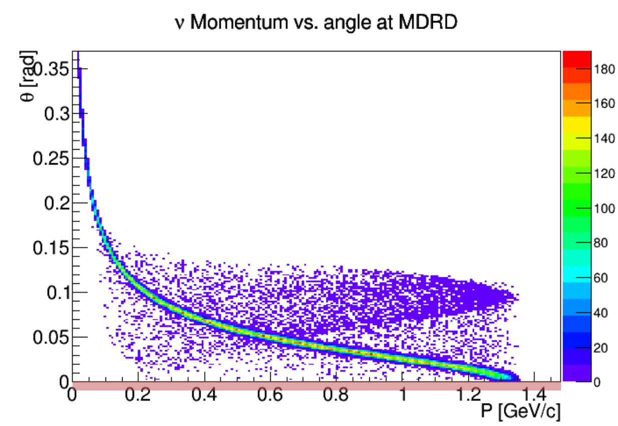


Figure 10: Neutrino momentum vs. angle with centreline at the end of straight 10. The neutrinos we see at the SBND come from within the highlighted area in the bottom of the figure.

## ACKNOWLEDGMENT

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