nuSTORM: Neutrinos from STORed Muons

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Neutrino beams produced from the decay of muons in a racetrack-like decay ring provide a powerful way to study short-baseline neutrino oscillation and neutrino interaction physics. In this paper, I describe the facility, nuSTORM, and show how the unique neutrino beam at the facility will enable experiments of unprecedented precision to be carried out. I will present sensitivity plots that indicated that this approach can provide 10σ confirmation or rejection of the LSND/MinBooNE results. The unique ν beam available at the nuSTORM facility has the potential to be transformational in our approach to ν interaction physics, offering a "ν light source" to physicists from a number of disciplines.

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1. Introduction

The nuSTORM facility has been designed to deliver beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of a stored $\mu^\pm$ beam with a central momentum of 3.8 GeV/c and a momentum acceptance of 10% [1]. The facility has three primary physics objectives:

- Allow searches for sterile neutrinos of exquisite sensitivity to be carried out; and
- Serve future long- and short-baseline neutrino-oscillation programs by providing definitive measurements of $\overset{(-)}{\nu}_e N$ and $\overset{(-)}{\nu}_\mu N$ scattering cross sections with percent-level precision;
- Constitute the crucial first step in the development of muon accelerators as a powerful new technique for particle physics.

The nuSTORM facility represents the simplest implementation of the Neutrino Factory concept [2]. Protons are used to produce pions off a conventional solid target. These pions are then collected with a magnetic horn and quadrupole magnets and are transported to, and injected into, a decay ring. The pions that decay in the first straight of the ring can yield muons that are captured in the ring. The circulating muons then subsequently decay into electrons and neutrinos. We are using a decay ring design that is optimized for a 3.8 GeV/c muon central momentum. This momentum was selected to maximize the physics reach for both ν oscillation and cross section physics. See Figure 1 for a schematic of the facility. The nuSTORM facility can be considered a "near-term" facility, since if funds were available, it could be built without the development of any new technology.

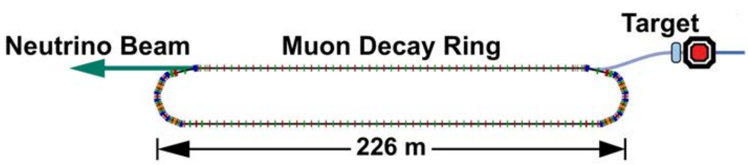

Figure 1: Schematic of the facility

Muon decay yields a neutrino beam of precisely known flavor content and energy. In addition, if the circulating muon flux in the ring is measured accurately (with beam-current transformers, for example), then the neutrino beam flux is also accurately known. Near and far detectors are placed along the line of one of the straight sections of the racetrack decay ring. Purpose-specific near detectors can be located in the near hall ($\simeq$ 20 m from the end of the decay ring straight) and will measure neutrino-nucleon cross sections and can provide the first precision measurements of ν_e and $\bar{\nu}_e$ cross sections. A far detector at $\simeq$ 2000 m would study neutrino oscillation physics and would be capable of performing searches in both appearance and disappearance channels. The experiment will take advantage of the "golden channel" of oscillation appearance $\nu_e \to \nu_\mu$ (μ^+ stored in the ring), where the resulting final state has a muon of the wrong-sign from interactions of the $\bar{\nu}_\mu$ in the beam. This detector would need to be magnetized for the wrong-sign muon appearance channel, as is the case for the current baseline Neutrino Factory detector [3]. A number of possibilities for

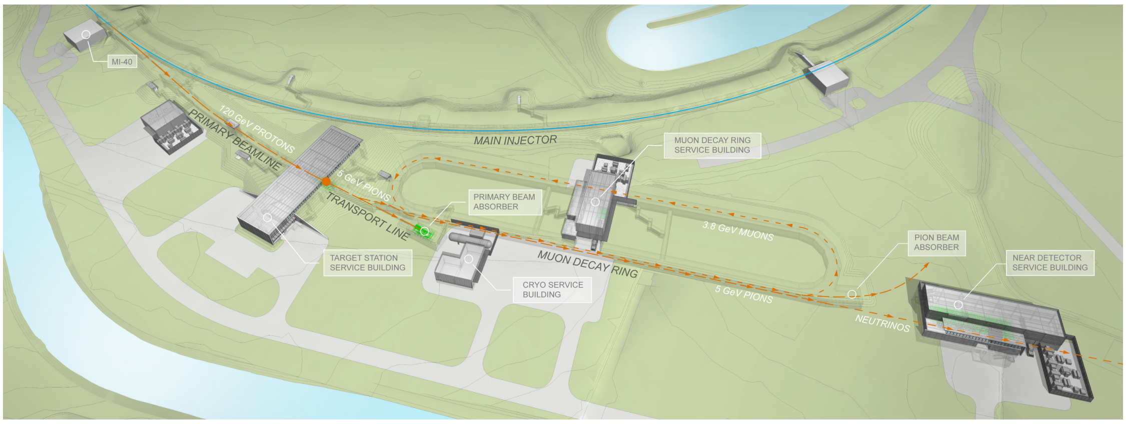

Figure 2: nuSTORM facility components.

the far detector exist. However, a magnetized iron detector similar to that used in MINOS is seen to be the most straight forward and cost effective approach.

2. nuSTORM facility overview

The components of nuSTORM consist of six major elements: the Primary proton beam line, Target station, Pion transport line, Muon decay ring, Near and Far detector halls [4].

These areas will be located south of the existing Main Injector accelerator and west of Kautz Road on the Fermilab site. In general terms, a proton beam will be extracted from the Main Injector at the existing MI-40 absorber, directed east towards a new below grade target station, pion transport line and muon decay ring. The neutrino beam will be directed towards a Near Detector Hall located 20 m East of the muon decay ring and towards the Far Detector located approximately 1900 m away in the existing D0 Assembly Building (DAB). Figure 2 shows the nuSTORM facility components as they will be sited near the Fermilab Main Injector. The nuSTORM facility will follow, wherever possible (primary proton beam line, target, horn, etc.), NuMI [5] designs. Our plan is to extract one "booster batch" at 120 GeV from the Main Injector ($\simeq 8 \times 10^{12}$ protons) and place this beam on a carbon target. Forward pions are focused by a horn into a capture and transport channel. Pions are then "stochastically" injected into the decay ring (see [6]). Pion decays within the first straight of the decay ring can yield a muon that is stored in the ring. Muon decay within the straight sections will produce ν beams of known flux and flavor via: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ or $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$. For the implementation which is described here, we chose a 3.8 GeV/c decay ring to obtain the desired spectrum of $\simeq 2$ GeV neutrinos. This means that we capture pions at a momentum of approximately 5 GeV/c.

3. Facility details

As mentioned above, the primary proton beam line and target station (and its components, i.e., target and horn) for nuSTORM follow the NuMI designs. From the downstream end of the horn, however, the nuSTORM beam system is no longer similar to a conventional neutrino beam. From the downstream end of the horn, we continue the pion transport with several radiation-hard (MgO insulated) quadrupoles. Although conventional from a magnetic field point of view, the first two to four quads need special and careful treatment in their design in order to maximize their lifetime in this high-radiation environment. The pion beam is brought out of the Target Station and transported to the injection point of the decay ring, which we have called the "Beam Combination Section" or BCS. The decay ring straight-section FODO cells were designed to have betatron functions β_x, β_y (the Twiss parameters) optimized for beam acceptance and neutrino beam production such that the divergence is small relative to the muon opening angle ($1/\gamma$) from $\pi \to \mu$ decay). Large betatron functions increase the beam size leading to aperture losses, while smaller betatron functions increase the divergence of the muon beam. Balancing these criteria, we have chosen FODO cells with $\beta_{\text{max}} \sim 30.2$ m, and $\beta_{\text{min}} \sim 23.3$ m for the 3.8 GeV/c muons, which for the 5.0 GeV/c pions, implies ~ 38.5 m and ~ 31.6 m for the pion's β_{max} and β_{min}, respectively.

A large dispersion, D_x, is required at the injection point, in order to achieve π and μ beam separation. The BCS readily reaches this goal. A schematic drawing of the injection scenario is shown in Figure 3. The pure sector dipole for muons in the BCS has an exit angle for pions that

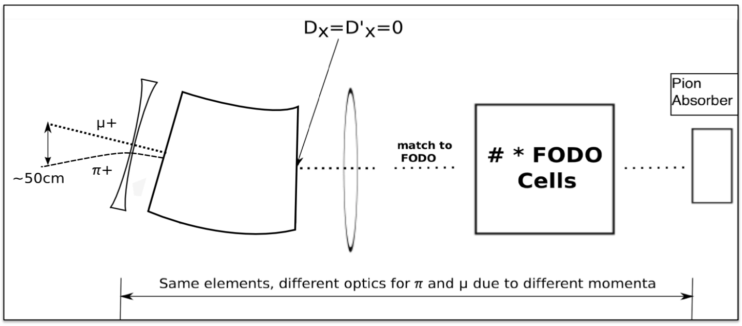

Figure 3: Schematic drawing of the injection scenario.

is non-perpendicular to the edge, and the pure defocusing quadrupole in the BCS for muons is a combined-function dipole for the pions, with both entrance and exit angles non-perpendicular to the edges. The BCS will be followed by a short matching section to the decay FODO cells. The performance of the injection scenario can be gauged by determining the number of muons at the end of the decay straight using a G4beamline simulation. In this simulation, we were able to obtain 0.012 muons per POT (see Figure 4). These muons have a wide momentum range which is beyond that which the ring can accept (3.8 GeV/c $\pm$ 10%) and thus will only be partly accepted by the ring. The green region in Figure 4 shows the 3.8$\pm$10% GeV/c acceptance of the ring, and the red region shows the high momentum muons which will be extracted by the mirror BCS at the end of the injection straight (see below). Within the acceptance of the decay ring, we obtain approximately 0.008 muons per POT.

3.1 Decay ring

We propose a compact racetrack ring design (480 m in circumference) based on large aperture, separate function magnets (dipoles and quadrupoles). The ring is configured with FODO cells combined with DBA (Double Bend Achromat) optics. The ring layout, including pion injection/extraction points, is illustrated in Figure 5 and the current ring design parameters are given in

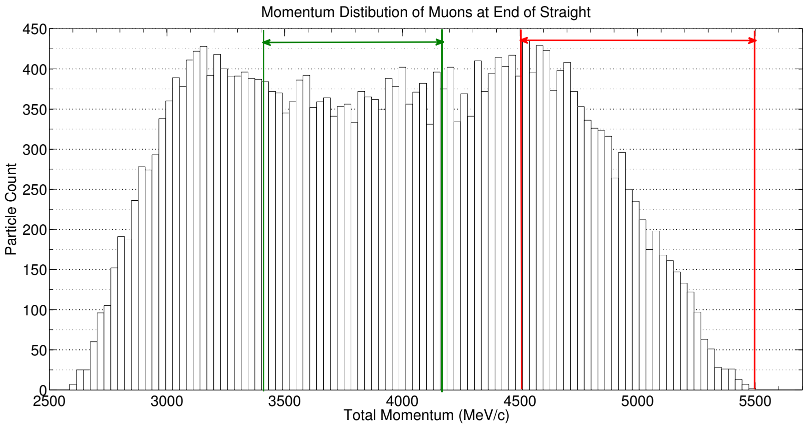

Figure 4: The muon momentum distribution at the end of decay straight.

Table 1. With the 185 m length for the injection straight, $\sim 48\%$ of the pions decay before reaching the arc. Since the arcs are set for the central muon momentum of 3.8 GeV/c, the pions remaining at the end of the straight will not be transported by the arc, making it necessary to guide the remaining pion beam into an appropriate absorber. Another BCS, which is just a mirror reflection of the injection BCS, is placed at the end of the decay straight. It extracts the residual pions and muons which are in the 5 ± 0.5 GeV/c momentum range. These extracted muons will enter the absorber along with pions in this same momentum band and can be used to produce an intense low-energy muon beam.

Figure 5: Decay ring layout. Pions are injected into the ring at the Beam Combination Section (BCS). Similarly, extraction of pions and muons at the end of the production straight is done using a mirror image of the BCS.

4. Performance

With an exposure of 10^{21} 120 GeV protons on target, we obtain approximately 1.9 $\times 10^{18}$ useful μ decays. The appearance of ν_μ, via the channel $\nu_e \rightarrow \nu_\mu$, gives nuSTORM broad sensitivity to sterile neutrinos and directly tests the LSND/MiniBooNE anomaly [7].

4.1 Far Detector

We have chosen an iron and scintillator sampling calorimeter (Super B Iron Neutrino Detector, SuperBIND) which is similar in concept to the MINOS detector [8]. It has a cross section of 6 m in order to maximize the ratio of the fiducial mass to total mass. The magnetic field will be toroidal as in MINOS and SuperBIND will also use extruded scintillator for the readout planes. However, SuperBIND will use superconducting transmission lines to carry the excitation current and thus

Table 1: Decay ring specifications

Parameter	Specification	Unit
Central momentum P_μ	3.8	GeV/c
Momentum acceptance	$\pm$ 10%	
Circumference	480	m
Straight length	185	m
Arc length	50	m
Arc cell	DBA	
Ring Tunes (ν_x, ν_y)	9.72, 7.87	
Number of dipoles	16	
Number of quadrupoles	128	
Number of sextupoles	12	

will allow for a much larger B field in the steel ($\approxeq$ 2T over most of the steel plate). Fig. 6 gives an overall schematic of the detector.

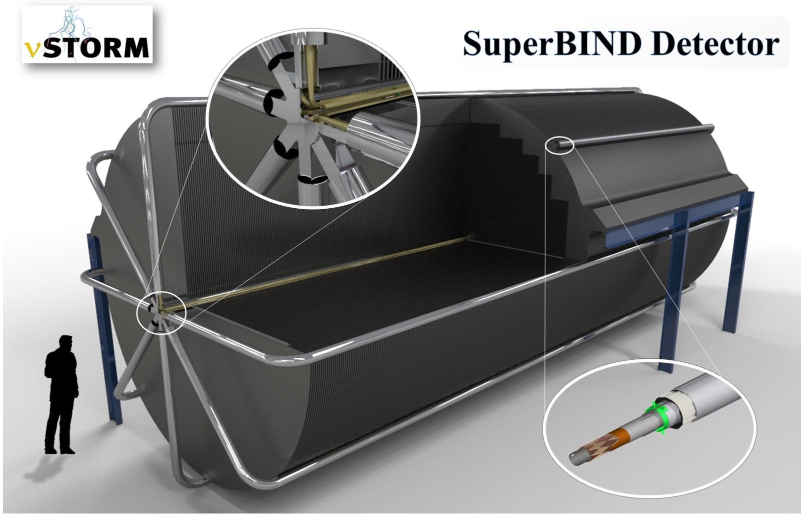

Figure 6: Far Detector concept

4.2 Results

A detailed detector simulation and reconstruction program has been developed to determine the detector response for the far detector in the short baseline experiment. Event reconstruction uses multiple passes of a Kalman-filter algorithm to identify muon trajectories within events and to determine the momentum and charge of an identified track. Multiple tracks are identified within the simulation, and all identified tracks are fit to determine the length of the tracks. The longest track is chosen as the prospective muon track for the event and all other tracks are assumed to be the result of pion production or electron showers.

Following the reconstruction, the events are analyzed to select events with well reconstructed muon tracks, and remove tracks that are mis-identified from pions or electron showers. A contour

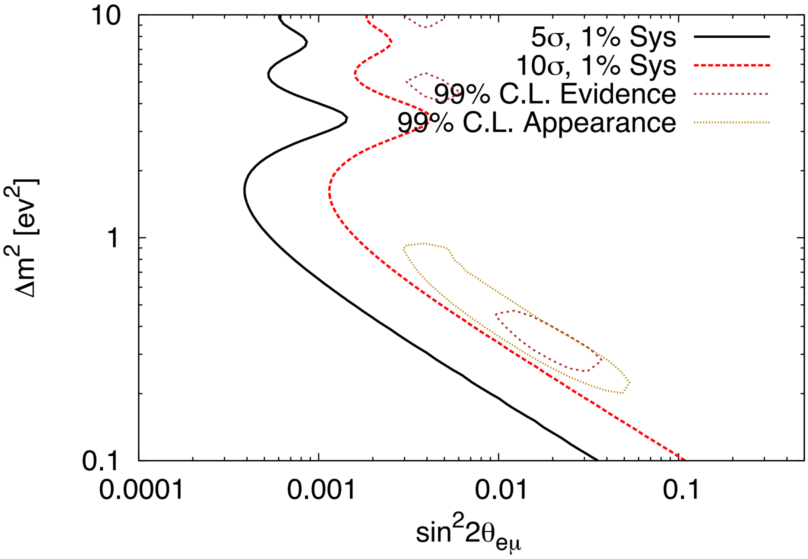

Figure 7: The 5 and 10 σ contours for the BDT analysis. Also shown are the global fit contours from [9] for Evidence (appearance + reactor +Gallium results) and Appearance (neutrino appearance experiments only).

plot showing the sensitivity of the ν_μ appearance experiment to sterile neutrinos, utilizing a boosted-decision-tree (BDT) multi-variate analysis, appears in Figure 7 for the exposure given above. The 99% confidence level contours from a global fit to all experiments showing evidence for unknown signals (appear + reactor + Gallium) and the contours derived from the accumulated data from all applicable neutrino appearance experiments [9] are also shown.

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