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nuSTORM: Neutrinos from Stored Muons[*]

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Abstract

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 talk, I will 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 10 σ confirmation or rejection of the LSND/MinBooNE results and can be used to perform neutrino interaction measurements of unprecedented precision. The unique ν beam available at the nuSTORM facility has the potential to be transformational in our approach to ? interaction physics, offering a "ν light source to physicists from a number of disciplines. Finally, the nuSTORM facility can also provide intense short-pulsed beams of low energy muons suitable for future 6D muon ionization cooling experiments. This can be done simultaneously while carrying out the neutrino program.

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 is unique in that it will:

- 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.

nuSTORM represents the simplest implementation of the Neutrino Factory concept [2]. In our case, 120 GeV/c protons are used to produce pions off a conventional solid target. The pions are collected with a magnetic horn and quadrupole magnets and are then transported to, and injected into, a storage ring. The pions that decay in the first straight of the ring can yield a muons that are captured in the ring. The circulating muons then subsequently decay into electrons and neutrinos. We are using a storage ring design that is optimized for 3.8 GeV/c muon momentum. This momentum was selected to maximize the physics reach for both ν oscillation and the cross section physics. See Fig. 1 for a schematic of the facility.

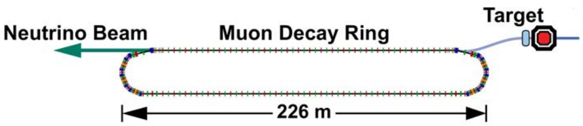

Figure 1: Schematic of the facility

Muon decay yields a neutrino beam of precisely known flavor content and energy. For example for positive muons: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. 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. The near detector can be placed as close as 20 meters from the end of the straight. A near detector for disappearance measurements will be identical to the far detector, but only about one tenth the fiducial mass. Additional purpose-specific near detectors can also be located in the near hall 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 $\nu_e \to \nu_\mu$, where the resulting final state has a muon of the wrong-sign from interactions of the $\bar{\nu}_\mu$ in the beam. In the case of μ^+ stored in the ring, this would mean the observation of an event with a μ^-. 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 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. For the purposes of the nuSTORM oscillation physics, a detector inspired by MINOS, but with thinner plates and much larger excitation current (larger B field) is assumed.

NUSTORM FACILITY OVERVIEW

The nuSTORM facilities are anticipated to consist of six (6) functional areas consisting of the Primary Beamline, Target Station, Transport Line, Muon Decay Ring, Near and Far Detector Halls [4].

The facilities will be located in an area south of the existing Main Injector accelerator and west of Kautz Road on the Fermilab site. In general terms, a proton beam will be

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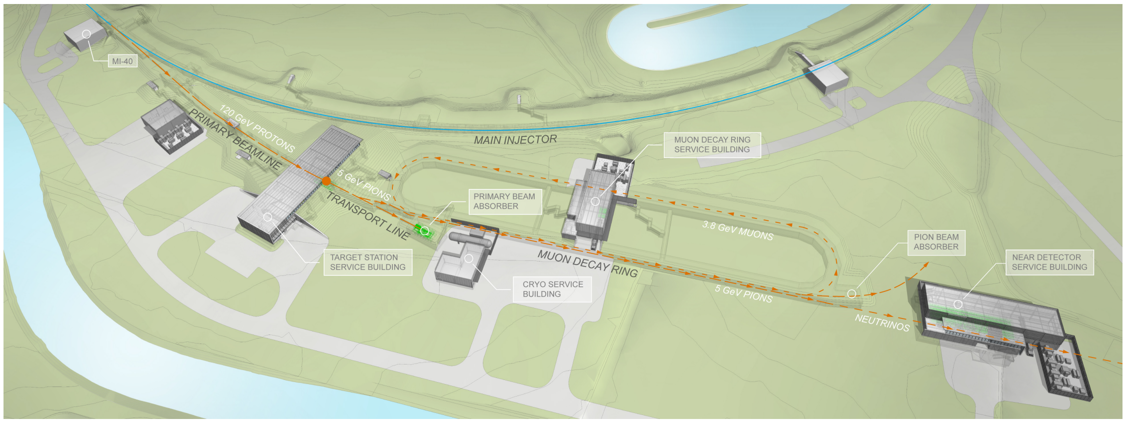

Figure 2: nuSTORM facility components.

extracted from the existing Main Injector at the 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). Fig. 2 shows the nuSTORM facility components as they will be sited near the Fermilab Main Injector. nuSTORM will follow wherever possible (primary proton beam line, target, horn, etc.) NuMI [6] 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 (see [5]). 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: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ or $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$. For the implementation which is described here, we chose a 3.8 GeV/c storage 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.

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 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 the 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. Fig. 3 shows the pion transport line and the beginning of the decay ring FODO straight section. 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 (small divergence relative to the muon opening angle $(1/\gamma)$ from $\pi \rightarrow \mu$ 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 $\beta_{\max} \sim 30.2$ m, and $\beta_{\min} \sim 23.3$ m for the 3.8 GeV/c muons, which for the 5.0 GeV/c pions, implies ~ 38.5 m and ~ 31.6 m pion's $\beta_{\max}$ and $\beta_{\min}$, respectively.

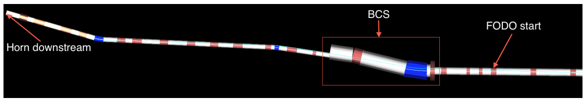

Figure 3: The G4beamline drawing from horn downstream to the FODO cells. Red: quadrupole, Blue: dipole, White: drift.

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 Fig. 4. The pure sector dipole for muons in the BCS has an exit angle for pions that 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

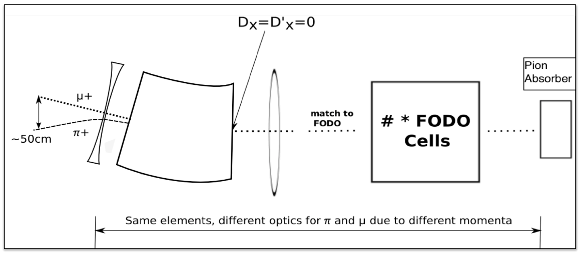

Figure 4: The schematic drawing of the injection scenario.

non-perpendicular to the edges. The BCS will be followed by a short matching section to the decay FODO cells (see Fig. 3). The performance of the injection scenario can be gauged by determining the number of muons at the end of the decay straight using G4beamline. We were able to obtain 0.012 muons per POT (see Fig. 5). These muons have a wide momentum range (beyond that which the ring can accept, 3.8 GeV/c ± 10%) and thus will only be partly accepted by the ring. The green region in Fig. 5 shows the 3.8±10% GeV/c acceptance of the ring, and the red region shows the high momentum muons which will be extracted by the BCS. Within the acceptance of the decay ring, we obtain approximately 0.008 muons per POT.

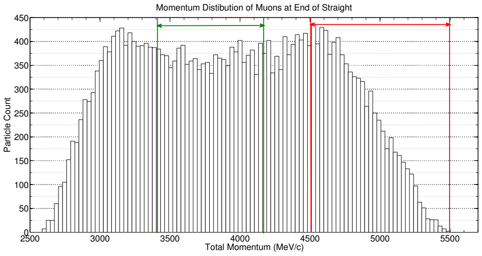

Figure 5: The muon momentum distribution at the end of decay straight.

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 Fig. 6 and the current ring design parameters are given in Table 1.

Figure 6: Racetrack 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.

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]. A contour plot showing the sensitivity of the ν_μ appearance experiment to sterile neutrinos utilizing a boosted-decision-tree (BDT) multivariate analysis appears in Fig. 7 for the exposure given above.

Table 1: Decay ring specifications

Parameter	Specification	Unit
Central momentum P_μ	3.8	GeV/c
Momentum acceptance	± 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	

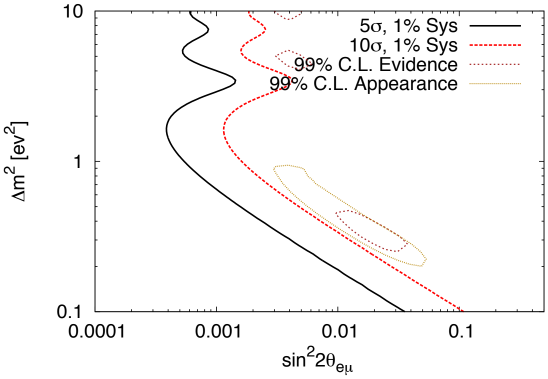

Figure 7: 5 and 10 σ contours for the BDT analysis. The 99% confidence level contours from a global fit to all experiments showing evidence for unknown signals (appear + reactor + Gallium) and the contours derived from the accumulated data from all applicable neutrino appearance experiments [8] are also shown.

REFERENCES

[1] D. Adey *et al.*,, nuSTORM Proposal, arXiv:13.

[2] S. Geer, "Neutrino beams from muon storage rings: Characteristics and physics potential", Phys.Rev., **D57**, 6989-6997, (1998).

[3] S. Choubey *et al.*,"Interim Design Report for the International Design Study for a Neutrino Factory", arXiv:1112.2853 (2011).

[4] T. Lackowski *et al.*, "nuSTORM Project Definition Report", arXiv:1309.1389.

[5] A. Liu *et al.*, "nuSTORM Pion Beamline Design Update," TUPBA18, these proceedings.

[6] A. G. Abramov *et al.*,"Beam optics and target conceptual designs for the NuMI project," Nucl. Instrum. Meth. A **485**, 209 (2002).

[7] K. N. Abazajian *et al.*,"Light Sterile Neutrinos: A White Paper," arXiv:1204.5379 [hep-ph].

[8] J. Kopp *et al.*, "Sterile Neutrino Oscillations: The Global Picture," JHEP **1305**, 050 (2013).