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The status of nuSTORM and and its production of non-conventional ν_μ beams*

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Abstract

Neutrino beams produced from the decay of muons in a racetrack-like decay ring (the so called Neutrino Factory) provide a powerful way to study neutrino oscillation physics and, in addition, provide unique beams for neutrino interaction studies. The Neutrinos from STORed Muons (nuSTORM) facility uses a neutrino factory-like design. Due to the particular nature of nuSTORM, it can also provide an intense, very pure, muon neutrino beam from pion decay. This so-called "Neo-conventional" muon neutrino beam from nuSTORM makes nuSTORM a hybrid neutrino factory. In this paper we describe the facility and give a detailed description of the neutrino beam fluxes that are available and the precision to which these fluxes can be determined. We then present sensitivity plots that indicated how well the facility can perform for short-baseline oscillation searches and show its potential for a neutrino interaction physics program. Finally, we comment on the performance potential of the "Neo-conventional" muon neutrino beam optimized for long-baseline neutrino-oscillation physics.

OVERVIEW

The nuSTORM facility is the simplest implementation of the Neutrino Factory concept [1]. Our studies have assumed that 120 GeV/c protons impinge on a conventional solid target to produce pions. The pions are collected with a magnetic horn and quadrupole magnets and they are then transported to, and injected into, a storage ring. The pions that decay in the first straight (production straight) of the ring can yield muons that are captured in the ring. The circulating muons then subsequently decay into electrons and neutrinos. The storage ring design is optimized for 3.8 GeV/c muon central momentum. This momen-

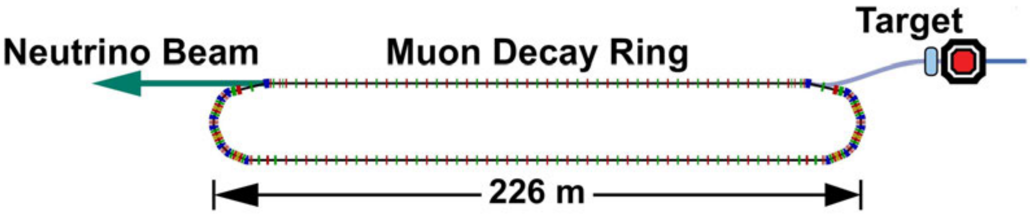

FIG. 1: Schematic of the facility

tum was selected to maximize the physics reach for both short-baseline ν oscillation and ν interaction physics. See Figure 1 for a schematic of the facility. The facility can deliver beams of $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ from the decay of the stored $\mu^\pm$ beam, but since pions are injected into the ring and decay to produce the stored muon beam, $\overset{(-)}{\nu}_\mu$ beams from pion decay are also delivered [2–5]. With these beams, experiments can be carried out that:

- Search for sterile neutrinos with unmatched sensitivity;
- Serve future long- and short-baseline neutrino-oscillation programs by providing measurements of $\overset{(-)}{\nu}_e N$ and $\overset{(-)}{\nu}_\mu N$ scattering cross sections with percent-level precision; and
- Have the potential to study long-baseline ν oscillation physics.

The pion beam (5 ± 1.0 GeV/c) is brought out of the target station and transported to the injection point of the decay ring, which we have called the "Orbit Combination Section" (OCS), where a large dispersion is introduced in order to combine the pion and muon reference orbits. Figure 2 gives a schematic of this concept. In the "production straight section", approximately 50% of the pions decay into muons, a fraction of which are captured within the ring's acceptance. The figure-of-merit for the baseline nuSTORM design is that 8×10^{-3} muons are stored in the ring per proton on target. 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

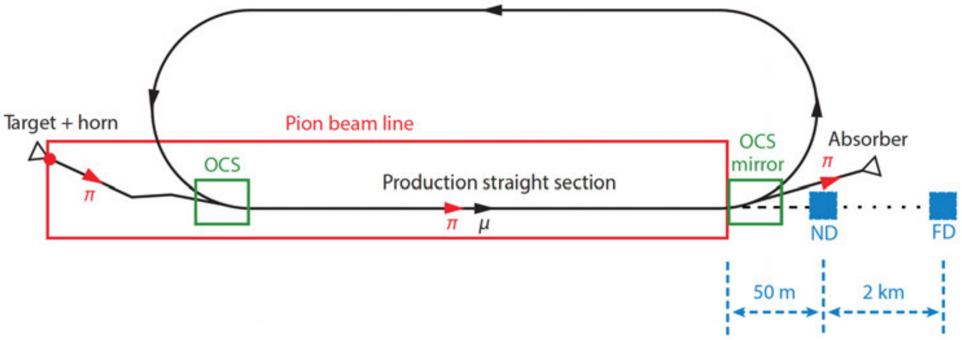

FIG. 2: Schematic of pion injection into the nuSTORM ring.

the muon opening angle ($1/\gamma$) from $\pi \rightarrow \mu$ decay). At the end of the production straight there is a mirror of the OCS which removes the pions that have not decayed, along with muons in the pion momentum band, the forward decays, and transports these particles to a beam absorber. With a beam absorber depth of $\sim$ 3.5 m, all the pions are absorbed, but the muons produce an intense, pulsed low-momentum muon beam (10^{10}/pulse with $100 \leq$ P ≤ 300 MeV/c) exiting the back of the absorber.

The nuSTORM ring (see Figure 3) is a compact racetrack 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 production straight is 185 m long. 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 OCS, which is just a mirror reflection of the injection OCS, is placed at the end of the decay straight. It extracts the residual pions and the muons which are in a 5±0.5 GeV/c momentum band. These extracted muons will enter the absorber along with pions and can be used to produce the intense low-energy muon beam.

FIG. 3: Racetrack ring layout. Pions are injected into the ring at the Orbit Combination Section (OCS). Similarly, extraction of pions and muons at the end of the production straight is done using a mirror image of the OCS.

NEUTRINO FLUXES, EVENT RATES AND SBL OSCILLATION SENSITIVITY

Knowledge of the neutrino flux remains a significant source of systematic error for both neutrino interaction and oscillation experiments. The neutrino beams produced at nuSTORM can be determined with excellent precision with the use of conventional beam diagnostics tools to understand the parent particle distributions, from which the neutrino flux can then be precisely calculated. In order to determine the neutrino beams available at the nuSTORM facility, an ensemble of particles produced in a MARS [6] simulation of the target and horn were tracked using G4Beamline [7] from the downstream face of the horn and then through the transfer line and injection into the decay ring via the OCS. The particles' energy and 4-momenta in the G4Beamline tracking were then used to determine the neutrino flux at an arbitrary distance from the end of the production straight. This methodology was used to both determine the flux from the decay of circulating muons (those that decayed in the production straight) and from pions that decayed in the production straight. The calculation of the flux in this way presents a real-case flux determination based upon a modeled lattice and beam instrumentation. The errors on the binned flux are dependent solely on the knowledge of the particle trajectories and momentum distribution obtained by the beam diagnostics. A combination of instrumentation performance predictions and simulations indicate that the flux error will be below 1%. The simulated flux from the stored muon beam (for an exposure of 10^{21} POT) is given in Figure 4 (left) at the near detector position and at the 2km far detector in Figure 4 (right). The simulated flux from the pion beam is shown at the near detector position in Figure 5 (left) and at the 2km far detector position in Figure 5 (right). As can be seen in the Figure 5, nuSTORM produces an extremely pure ν_μ beam. Based on the flux calculations given above, the total number of neutrino interactions for a 100T detector at the 50m near position (exposure of 10^{21} POT) can be determined and is shown in Table I. With a flux precision of $\leq 1\%$ and with the statistics given in this table, nuSTORM offers unprecedented opportunities for the study of neutrino (both $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$) interaction physics. Table II gives the event rates seen at a 1 kT SuperBIND detector [3] at 2 km from the end of the production straight. Rates assuming no short-baseline oscillation

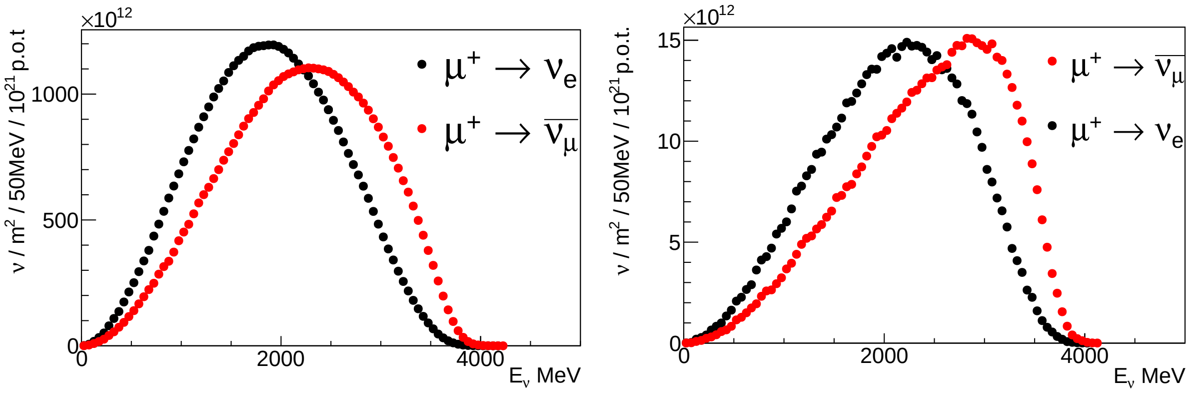

FIG. 4: Neutrino flux from μ decay at the near detector (left) and at the far detector (right)

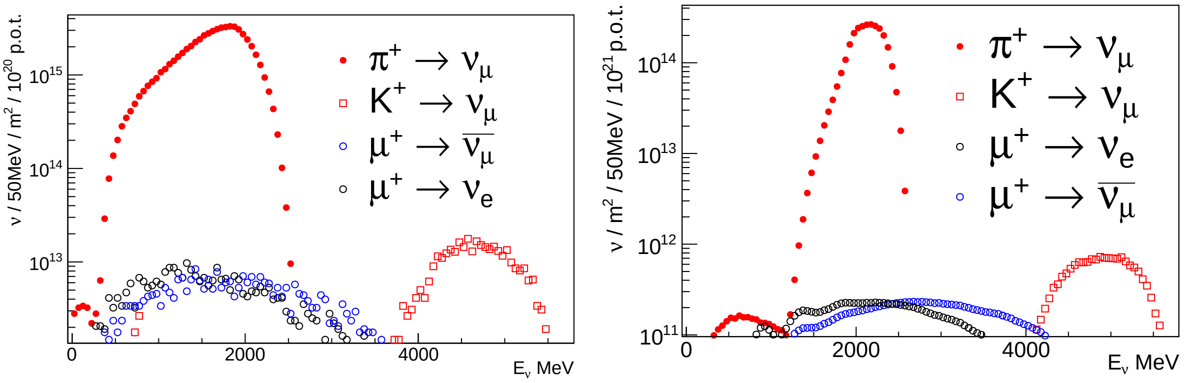

FIG. 5: Neutrino flux from π decay at the near detector (left) and at the far detector (right)

TABLE I: Event rates at 50 m from the end of the decay straight per 100 T for 10^{21} POT.

μ^+ stored		μ^- stored	
Channel	**k**Events	Channel	**k**Events
ν_eCC	5,188	$\bar{\nu}_e$CC	2,519
$\bar{\nu}_\mu$CC	3,030	ν_μCC	6,060
ν_eNC	1,817	$\bar{\nu}_e$NC	1,002
$\bar{\nu}_\mu$NC	1,174	ν_μNC	2,074

π^+ injected		π^- injected	
Channel	**k**Events	Channel	**k**Events
ν_μCC	41,053	$\bar{\nu}_\mu$CC	19,939
ν_μNC	14,384	$\bar{\nu}_\mu$CC	6,986

TABLE II: Event rates at 2 km per 1.3 kT for 10^{21} POT for the no oscillation scenario and one with 1 sterile neutrino.

μ^+ Stored		
Channel	No Oscillation	Oscillation
$\nu_e \to \nu_\mu$	0	288
$\nu_e \to \nu_e$	188,292	176,174
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	99,893	94,776
$\bar{\nu}_\mu \to \bar{\nu}_e$	0	133

π^+ Injected		
Channel	No Oscillation	Oscillation
$\nu_\mu \to \nu_\mu$	915,337	854,052
$\nu_\mu \to \nu_e$	0	1,587

and an oscillation scenario following a 3+1 scenario (3 standard neutrinos and 1 sterile neutrino) are given. The nuSTORM facility also provides the opportunity to perform searches for sterile neutrinos with unmatched sensitivity and breadth. In Figure 6 we show the exclusion plot for ν_μ appearance that is obtainable using a $\bar{\nu}_e$ beam from μ^+ decay normalized to 10^{21} POT and using the SuperBIND detector.

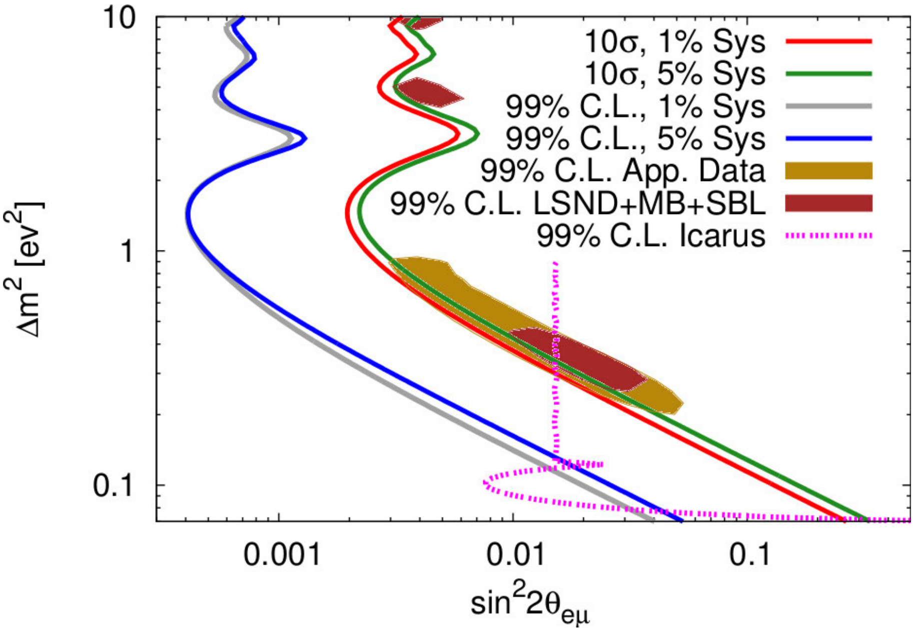

FIG. 6: The sensitivity of a ν_μ appearance experiment to a short baseline oscillation due to a sterile neutrino at nuSTORM assuming a 3+1 model. Both the 10σ significance and 99% confidence level contours are shown for two different scenarios for the systematic uncertainties; one in which the total systematic uncertainty is 1% of the beam normalization and a second when the systematic uncertainty is a factor of 5 times larger. The 99% contours generated from the fit to the MiniBooNE and LSND data is shown with the brown dotted line (Evid. Data), while the fit to all available appearance data is shown with the black dotted line (App. Data). The 99% exclusion contour from Icarus is also shown.

OPTIMIZATION OF THE NUSTORM PION BEAM LINE FOR LONG-BASELINE OSCILLATION PHYSICS

If the decay ring of nuSTORM is tilted, beams could be used for a long-baseline neutrino oscillation experiment. We have investigated this option, but have determined that the flux available from pion decay in the production (injection) straight is too small to be useful. We then considered a configuration that was optimized for the production of a $\overset{(-)}{\nu}_\mu$ beam from pion decay. We removed the capability for a stored muon beam, considering only a pion injection line (from the target to the end of the production straight). This concept of producing neutrinos from an instrumented pion beam line, nuPIL, is shown in Figure 7. In this configuration, the injection OSC, the arcs and the return straight are removed (no ring) and the lattice design is only optimized to transport pions in a momentum of band of 5 ± 1 GeV/c. Since the straight is no longer required to transport both pions and muons (with a lower momentum), the compromises needed to do so are no longer incorporated and pion transport is more efficient. In this case, a simplified mirror OSC is used to extract the remaining pions (and some muons as described above) to a beam absorber. This pion injection beam line would, of course, need to be tilted at an appropriate angle. Figure 8 (left) shows the ν_μ flux/yr obtained at 1300 km for this configuration. This is for 1.47×10^{21} POT. Also shown is the flux that would be obtained for nuSTORM and, for reference, the current optimized flux for DUNE [8]. This configuration shows that nuPIL produces $\simeq$ 40X the flux of nuSTORM. The flux does fall short of what is obtained at DUNE, but the beam systematics will be greatly reduced since effects due to uncertainties in secondary particle production, proton-beam targeting stability, target degradation/stability and horn stability can be removed by in situ measurement of the pion flux (via beam line instrumentation) in the production straight. In addition, the wrong-flavor neutrinos ($\bar{\nu}_\mu$ in the ν_μ beam and vice versa) and the high-energy component of the $\overset{(-)}{\nu}_\mu$ beam are essentially entirely suppressed in this neutrino beam line design. In order to increase the flux, we are investigating a lattice design utilizing Fixed-Field Alternating Gradient (FFAG) optics with a much larger pion momentum acceptance than the FODO design. See Figure 8 (right).

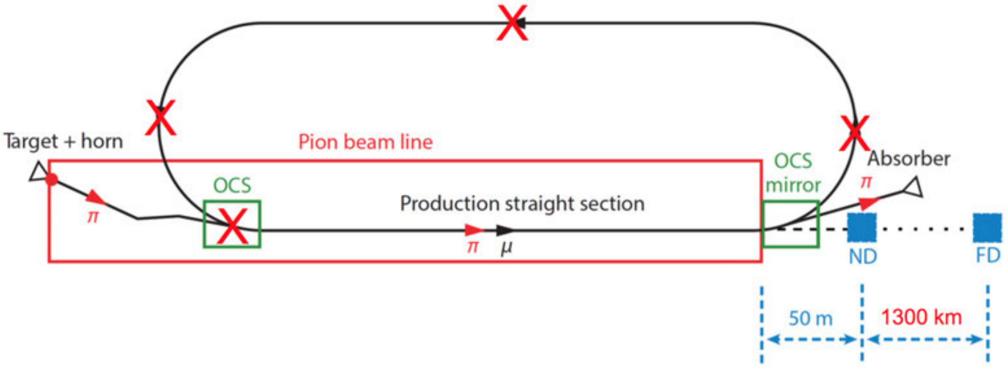

FIG. 7: Schematic of the pion injection line. The red Xs indicate the components removed from the nuSTORM configuration.

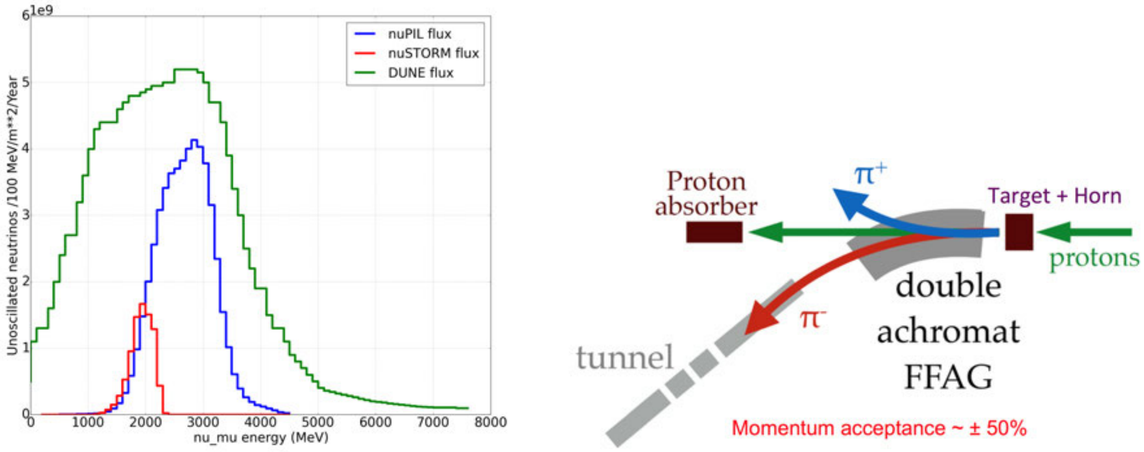

FIG. 8: Left: The neutrino flux (ν_μ from pion decay at a distance of 1300 km for nuSTORM and nuPIL. The baseline flux for DUNE is shown for comparison. Right: A schematic of the concept to extend the nuPIL FODO design to a FFAG lattice.

CONCLUSIONS

In this article we have summarized the status and capabilities of the nuSTORM facility. We have also shown how one component of the facility (the pion injection line) could be re-optimized solely for the production of $\overset{(-)}{\nu}_\mu$ from $\pi^\pm$ decay, producing a neutrino beam with very small flux uncertainties.

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[1] S. Geer, Phys. Rev. **D57**, 6989 (1998), [Erratum: Phys. Rev.D59,039903(1999)], hep-ph/9712290.

[2] D. Adey, R. Bayes, A. Bross, and P. Snopok, Ann. Rev. Nucl. Part. Sci. **65**, 145 (2015).

[3] D. Adey et al. (nuSTORM) (2013), 1308.6822.

[4] A. Liu, D. Neuffer, and A. Bross, Nucl. Instrum. Meth. **A801**, 44 (2015).

[5] A. Liu, A. Bross, and D. Neuffer, Nucl. Instrum. Meth. **A794**, 200 (2015).

[6] N. V. Mokhov, K. K. Gudima, C. C. James, M. A. Kostin, S. G. Mashnik, E. Ng, J. F. Ostiguy, I. L. Rakhno, A. J. Sierk, and S. I. Striganov, Radiat. Prot. Dosim. **116**, 99 (2005),

nucl-th/0404084.

[7] K. B. Beard, T. J. Roberts, and P. Degtiarenko, Conf. Proc. **C0806233**, MOPD017 (2008).

[8] C. Adams et al. (LBNE) (2013), 1307.7335, URL `http://www.osti.gov/scitech/biblio/1128102`.