

# SIMULATION AND STUDY OF THE nuSTORM (NEUTRINOS FROM STORED MUONS) EXPERIMENT \*

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## Abstract

The nuSTORM facility will create neutrino beams through muon decay in a storage ring, targeting %-level precision in flux determination. With access to two neutrino flavours, it enables precise measurement of  $\nu$ -A cross sections and exhibits sensitivity to Beyond Standard Model (BSM) physics. With muons in the 1–6 GeV/c momentum range, it covers neutrino energy regimes relevant to experiments such as DUNE and T2HK. In addition, nuSTORM serves as a step towards a muon collider, a proof of concept for muon storage rings, and a test for beam monitoring and magnet technologies. The lattice structure consists of a pion transport line and a racetrack storage ring based on a hybrid FFA design, with conventional FODO cells in the production straight combined with FFA cells in the return straight and arcs. Using the nuSIM framework and BDSIM, this study simulates and optimizes the nuSTORM lattice, using beams from existing proton drivers. Using GENIE, neutrino events and their rates at the detector at different energies are also presented. The creation of synthetic neutrino beams through the combination of beams produced using a variety of stored-muon energies, is also discussed. This technique yields neutrino beams with a spread 65% narrower than natural muon decay spectrum which is also discussed.

## INTRODUCTION

The neutrinos from Stored Muon (nuSTORM) facility is a muon storage ring in a racetrack configuration. It has been designed to store muons in the 1–6 GeV range, with a momentum spread of  $\pm 16\%$ . The combination of momentum selection, precise knowledge of muon decay, and beam instrumentation allows for percent-level precision in the flux normalisation. Using these capabilities, many of the questions that are currently open in neutrino physics may be addressed. As larger neutrino experiments such as DUNE and Hyper-Kamiokande prepare to start taking measurements, nuSTORM could help provide insights into neutrino-nucleus cross sections, which are currently poorly understood.

## Motivations

The three broad themes of physics at nuSTORM are:

**Neutrino Nucleus Interactions** The major uncertainties in the constraints in the values of the  $\delta_{cp}$ ,  $\theta_{23}$  and the mass hierarchy are in the flux and the accuracy of the neutrino-nucleus interaction models. On the current  $\delta_{cp}$  measurement at T2K, the neutrino interaction uncertainty

accounts for 3.9% of the the 5% error budget. A study published on the proposed T2K Phase II has shown that reducing systematic uncertainties by a factor of 33% reduces the POT required to reach a  $3\sigma$  measurement on CP violation by 25% (assuming maximal violation). [1] For DUNE, the main systematic uncertainty comes from the  $\sigma(\nu_E)$ . [2] Especially for the measurements of  $\delta_{cp}$ , the lepton flavour universality approximation of the  $\nu_e - A$  to  $\nu_\mu - A$  is not accurate enough, and specific cross section measurements will be required. With a tuneable ring, nuSTORM can effectively target the energy regimes of all of these LBL experiments, effectively aiding cross section analysis.

**Beyond Standard Model Physics** Combining the well constrained flux with high statistics, many exotic and rare scatterings can be studied. These can be used to confirm, complement or even expand our understanding of physics. For example, with access to  $\nu_\mu$  and  $\nu_e$ , the weak coupling mixing angle,  $\sin^2 \theta_W$ , could be extracted at nuSTORM.

nuSTORM can also probe short baseline oscillations, to investigate the LSND and MiniBOONE anomalies. A study of this was conducted in 2014 [3] with a model of an Iron Scintillator detector at a distance of 2km away from the production straight. Using the  $\nu_\mu$  appearance and disappearance mode, nuSTORM will be sensitive to the anomalies of LSND at a  $10\sigma$  level. nuSTORM is also sensitive to other BSM physics processes. The gamut of BSM sensitive physics has been review by Y.F. Perez-Gonzalez in [4].

**Technology Test Bed** nuSTORM will be an invaluable step towards the realisation of a muon collider, as novel techniques will have to be developed and tested. First, it serves as a proof of principle of high flux muon storage. The techniques required for capture and focusing at nuSTORM will be directly transferable to the muon collider. The instrumentation required to constrain the neutrino flux will have a direct analogy in beam monitoring for the muon detector. Hence, a Muon Collider Demonstrator complex has been envisioned, allowing for shared targetry and capture between nuSTORM, a 6D muon cooling test facility and ENUBET. Furthermore, nuSTORM serves as a proof of concept of techniques such as a Fixed Field Alternating Gradient (FFA) focusing.

## DESIGN AND SIMULATIONS

### Lattice Studies

As shown in Fig. 1, nuSTORM is a racetrack-shaped muon storage ring measuring approximately 616 meters in circumference. In its current "forward" configuration, the detector is placed at the end of the initial straight. When pions are

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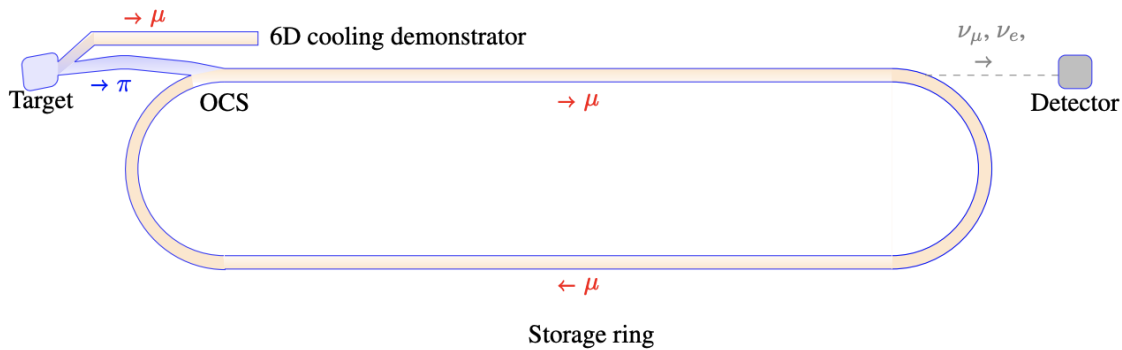


Figure 1: Schematic of nuSTORM: The pions are injected into the production straight - where they will decay into muons. The detector sees an initial flash of muon neutrinos from pion decay, followed by muon and electron neutrinos from muon decay.

injected into the ring, the detector will first see a flash of muon neutrinos, arising from pion decay, followed by pulses of muon and electron neutrinos, arising from subsequent muon decay in the production straight.

The entire lattice can be tuned to accept different pion and muon momenta, hence allowing for the study of different energy regimes. This effectively spans the entire range of the accelerator neutrino experiments currently being proposed. The entire lattice can be divided into the initial (production) straight, the arcs and the return straight. The production straight is equipped with large-aperture room temperature quadrupoles, whilst the return straight incorporates combined-function room-temperature magnets. To keep the arc length as short as possible and maximize the number of useful muon decays, strong bending magnets are employed in the arcs. These magnets are superconducting combined-function magnets capable of producing magnetic fields up to about 2.6 T. Finally, the Orbit Combination Section (OCS) and a mirror OCS are present at the pion injection and dumping points, to allow for stochastic injection of pions into the ring.

### nuSIM

First, the muon decay in the storage ring was simulated using nuSTORM Simulator (nuSIM). This code was developed so that the physics studies could be conducted in parallel to the lattice design. This code uses a pion flux generated from a horn design in FLUKA. nuSIM is a Python-based simulation framework that accelerates simulations through a parameterization approach with detailed physics simulations of particle decay. This method has allowed for a reduction in computing time and has enabled preliminary physics studies to be conducted. Concurrently, more detailed and time-intensive accelerator simulations that include the full beam optics design are being developed in the Geant4-based Beam Delivery Simulation (BDSIM) software.

### Neutrino Nucleus Interactions

Initial studies on what events at nuSTORM could look like have also been initiated. These have been carried out

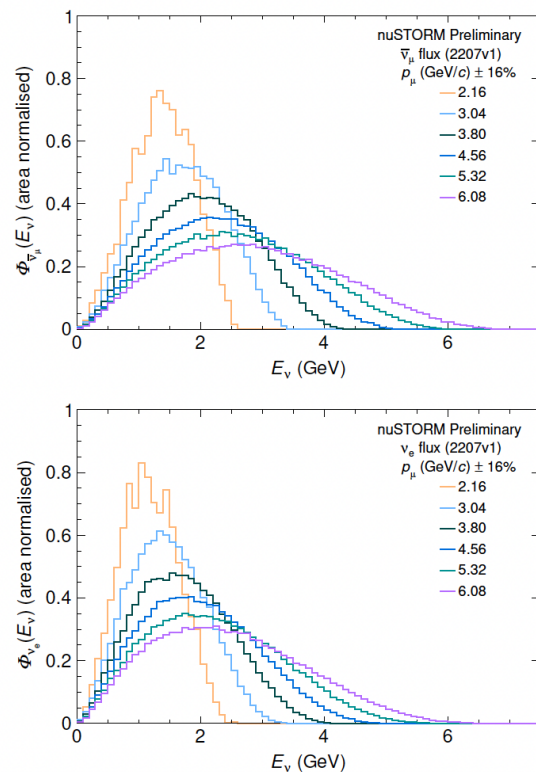


Figure 2: The nuSTORM spectra at different muon momenta.

using the GENIE MC generator - an extremely powerful tool to simulate neutrino-nucleus interactions. Studies of these datasets provide insight into parameters and observables such as outgoing lepton kinematics in charged current interactions, and hadronic final states. Such studies will be an invaluable first step to inform detector design. In this case, the interactions of the neutrino flux have been modelled using liquid Argon as the active medium. In Fig.3, an event energy spectrum CC events of  $\nu_e$  ( $2 \times 10^{19}$  POT) has been presented.

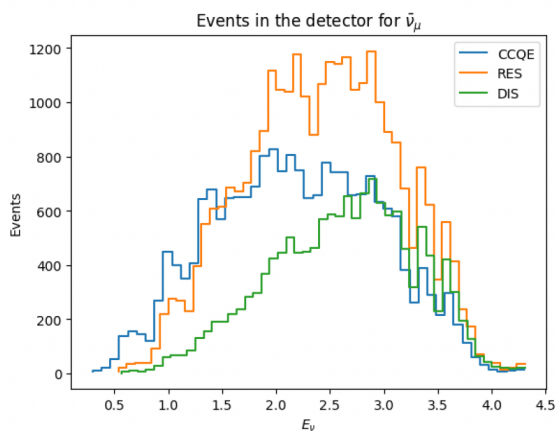


Figure 3: The event spectrum generated from electron neutrinos at nuSTORM at 5 GeV/c pion momentum.

### Synthetic Neutrino Beams

A powerful tool which will be employed in both DUNE and Hyper-K is the nuPRISM concept, in which the neutrino energy spectrum is selected using a detector which can be moved perpendicular to the beam axis. As one moves to larger angles, this results in a narrower and lower peak in the neutrino flux. Furthermore, using many off axis angles, one can make linear combinations of these to create bespoke "synthetic" neutrino fluxes. For example, they can be combined to form a (quasi) mono energetic neutrino beam with a Gaussian distribution in energy with a specified width and mean. nuPRISM can also be used to construct the spectrum of the far detector using the linear combinations of the off axis near detector spectra, and to further constrain the error on the flux measurements. In the case of T2K, a study has been done about the feasibility of completely replacing the ND280 with a moveable water cherenkov detector for estimation of the far flux. [5]

The nuSTORM can also be used to create synthetic neutrino beams, with the added advantage that the detector always remains on axis. Instead, nuSTORM leverages the fact that at different momentum settings, the flux of neutrinos varies, with narrower peaks at lower energies, and broader peaks at higher energies. A treatment similar to that at nuPRISM is as follows.

The neutrino spectra at different muon momenta is shown in Fig. 2. These spectra can be weighted like to yield a synthetic flux:

$$\Phi_{LC}(E_\nu) = \sum_i^{N_\mu} c_i \phi_i(E_\nu) \quad (1)$$

where  $\phi_i(E_\nu)$  is the energy spectrum of the neutrino beam and  $c_i$  are their respective weights. These are summed over  $N_\mu$ , the number of different muon momenta.

The coefficients  $c_i$  are minimised with respect to the target function using the figure of merit (FOM):

$$FOM = \sum_{E_\nu} \frac{(f(E_\nu) - \Phi_{LC}(E_\nu))^2}{A + Bf(E_\nu)^2}, \quad (2)$$

where  $f(E_\nu)$  is the target function, and  $A$  and  $B$  are different parameters that can be tuned to weight different parts of the curve on the fit. This can be a normal distribution for neutrino-nucleus interaction studies, or can also be modelled after any arbitrary spectrum.

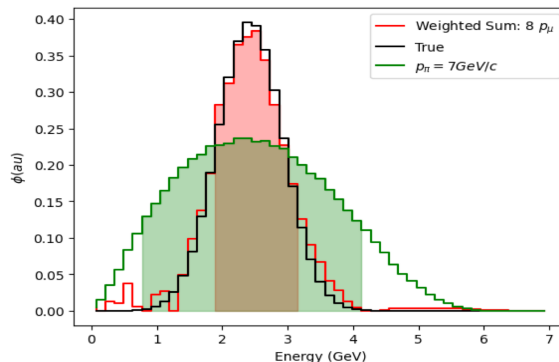


Figure 4: Synthetic Neutrinos at nuSTORM. A 2.5 GeV synthetic beam has been created, with a much narrower spectrum spectrum than one generated from the muons generated from 7 GeV pions.

For the studies at nuSTORM, the target spectrum was chosen to be a Gaussian beam, in an effort to create a synthetic monochromatic neutrino beam, as shown in Fig. 4. In this study, a beam with a mean of 2.5 GeV and a standard deviation of 0.5 GeV has been created. This spectrum is comparable to the neutrino spectrum generated from an injected pion momentum of 7 GeV. However, the optimization allows for a 63.5% reduction in the FWHM of the beam. These results underscore the potential for enhanced precision for experiments at nuSTORM, facilitating a deeper understanding of neutrino properties and interactions.

## CONCLUSION

The design and initial studies of nuSTORM has been discussed. Using neutrinos from muon decay, nuSTORM will create neutrino beams for which the flux can be determined with %level precision. The design has been discussed along with initial simulations of the neutrino flux at different configurations of muon energies. This flux can be used to probe the gamut of cross section models from quasi-elastic to deep inelastic scattering. Finally a method of creating synthetic neutrino beams allowing for 65% narrower neutrino beams has been demonstrated.

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