Neutrinos from stored muons; nuSTORM

Letter of Interest to Snowmass 2021†

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Neutrino Frontier

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Energy Frontier

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Other frontiers:

- ■ Energy Frontier

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[1] nuSTORM collaboration list presented in the appendix.

Neutrinos from stored muons; nuSTORM

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Overview

The ‘Neutrinos from Stored Muons’ facility, nuSTORM, will provide intense beams composed of equal fluxes of electron- and muon-neutrinos for which the energy spectrum is known precisely from the decay of muons confined within a storage ring [1]. It will be possible to store muon beams with central momentum from 1 GeV/c to 6 GeV/c with a momentum acceptance of 16%. The nuSTORM facility will have the capability to:

- Serve a definitive neutrino-nucleus scattering programme with uniquely well-characterised $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ beams;
- Allow searches for light sterile neutrinos with the exquisite sensitivity necessary to go beyond the reach of the FNAL Short Baseline Neutrino programme; and
- Provide the technology test-bed required for the development of muon beams capable of serving as the basis for a multi-TeV lepton-antilepton (muon) collider.

The nuSTORM programme is well aligned with the recent update of the European Strategy for Particle Physics which recommended the study of “*. . . bright muon beams . . .*” and noted that a “*. . . programme of experimentation to determine neutrino cross sections . . . is required*”. We propose the development of nuSTORM as a facility for CERN.

nuSTORM is based on a low-energy muon decay ring (see figure 1). Pions, produced in the bombardment of a target, are captured in a magnetic channel. The magnetic channel is designed to deliver a pion beam with central momentum p_π and momentum spread $\sim \pm 10\%$ p_π to the muon decay ring. The pion beam is injected into the production straight of the decay ring. Roughly half of the pions decay as the beam passes through the production straight. At the end of the straight, the return arc selects a muon beam of central momentum $p_\mu < p_\pi$ and momentum spread $\sim \pm 16\% p_\mu$ that then circulates. Undecayed pions and muons outside the momentum acceptance of the ring are directed to a beam dump. The intense flux of muons emerging from the dump may serve a test facility dedicated to the development of the technologies required to deliver high-brightness muon beams [2]. The CERN layout shown in figure 1 is a development of that proposed for implementation at FNAL [2]. A concept for nuSTORM to be implemented on the ESS campus is also being developed [3].

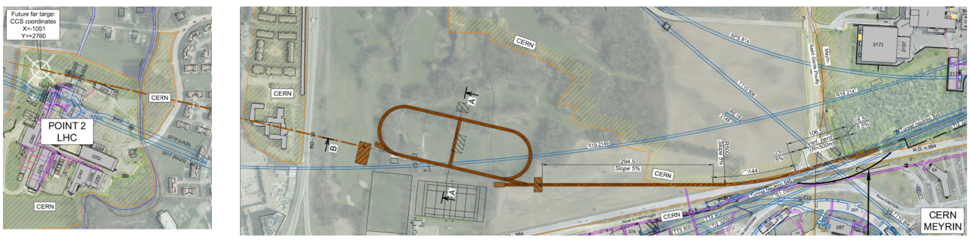

Figure 1: Overview of the proposed implementation of nuSTORM at CERN [1]. The fast-extraction system that will provide protons at 100 GeV to the nuSTORM target will be installed in LSS6 where an existing extraction system serves beam to the West Area. Beam will be transported through an existing transfer tunnel (TT60). Before TT60 enters the Meyrin site, the beam will branch into a new transfer tunnel. The nuSTORM ring will be sited between the West and North areas. The production straight illuminates a near detector hall oriented to allow off-axis operation of neutrino detectors. A suitable location for a far detector has been identified at LHC point 2.

Scientific programme

Neutrino scattering

A systematic programme of precise measurements of neutrino–nucleus scattering is important to advance the understanding of nuclear structure, improve models of νA scattering, and reduce biases and systematic uncertainties in the determination of the neutrino-oscillation parameters [4]. For neutrino energies below approximately $2\,\text{GeV}$, $\overset{(-)}{\nu}_{e,\mu} A$ scattering is dominated by the quasi-elastic (QE) and 1-$\pi(\Delta)$ processes with a smaller, but significant and insufficiently understood, contribution from two-nucleon mechanisms. At higher energies, $E_\nu \gtrsim 2\,\text{GeV}$, poorly-known multi-pion resonance-production as well as shallow-and deep-inelastic scattering processes play an increasingly important role. To complement other experiments, the nuSTORM facility must be capable of delivering neutrino beams that cover this poorly known region with energies that span from the QE-dominated regime to the kinematic regime where deep-inelastic-scattering dominates ($E_\nu \gtrsim 5\,\text{GeV}$).

A detector placed on the axis of the production straight will receive a bright flash of muon neutrinos from pion decay followed by a series of pulses of muon and electron neutrinos from subsequent turns of the muon beam. Appropriate instrumentation in the decay ring and production straight will be capable of determining the integrated neutrino flux from muon decay with a precision of $\lesssim 1\%$. The flavour composition of the neutrino beam from muon decay is known and the neutrino-energy spectrum can be calculated precisely. A high precision detector complex will be required to take full advantage of this beam. The pion and muon momenta (p_π and p_μ) can be optimised to measure $\overset{(-)}{\nu}_\mu A$ and particularly $\overset{(-)}{\nu}_e A$ interactions with percent-level precision over the neutrino-energy range $0.2 \lesssim E_\nu \lesssim 6\,\text{GeV}$.

Searches for physics beyond the Standard Model

Sensitivity to physics beyond the Standard Model (BSM) is provided by unique features of the nuSTORM design: the precisely known flavour composition and neutrino-energy spectrum. This allows exquisitely sensitive searches for short-baseline flavour transitions to be made, covering topics such as light sterile neutrinos, non-standard interactions, and non-unitarity of the neutrino mixing matrix. A detailed sterile neutrino analysis was presented in [5]. The region of parameter space presently preferred at 99% C.L. by the LSND and MiniBooNE experiments can be excluded with a 10σ significance.

In synergy with the goals of the neutrino-scattering programme, new physics searches would also profit from measurements of exclusive final states. This would allow BSM neutrino interactions to be probed by means of precise measurements of neutrino-electron scattering, as well by searching for exotic final states, such as dileptons or single-photon signatures.

nuSTORM as a stepping stone to high-brightness muon beams for particle physics

Muon beams of high brightness have been proposed as the source of neutrinos at a neutrino factory and as the means to deliver multi-TeV lepton-antilepton collisions at a muon collider. In most of these proposals the muon beam is derived from pion decay as is proposed here for nuSTORM. An alternative approach, in which muons are produced with an energy of 22 GeV in the annihilation of 45 GeV positrons with electrons at rest has recently been proposed. nuSTORM will allow many of the challenges associated with the muon storage ring in such facilities to be addressed, including:

- The complete implementation of a muon storage ring of large acceptance including the injection and extraction sections; and
- The design and implementation of instrumentation by which to determine the muon-beam energy and flux to 1% or better. A novel polarimeter system will be required in order to determine the stored-muon energy and the energy spread.

The opportunity nuSTORM provides for the study of ionization cooling is particularly important. The Muon Ionisation Cooling Experiment (MICE) [6] has demonstrated ionization cooling in the 4-dimensional transverse phase space [7]. To prove the feasibility of a muon collider therefore requires a follow-on demonstration of ionization cooling in the full six-dimensional (6D) phase space.

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