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nuSTORM: neutrino physics on the path to the muon collider

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The nuSTORM facility enables innovative neutrino physics studies through the decay of muons circulating in a storage ring. The well-defined composition and energy spectra of the neutrino beam from the decays of muons, combined with precise muon flux measurements, facilitate a diverse research program probing fundamental neutrino properties. nuSTORM has been optimized to store muons with momentum tunable from 1 to 6 GeV/c, enabling precise measurements of ν_μA and ν_eA scattering over energy ranges relevant for long-baseline experiments. It also allows for highly sensitive searches for exotic processes and studies of short-baseline flavor transitions exceeding the reach of already planned experiments. As a technology testbed for high-brightness muon beams, nuSTORM is on the path towards a multi-TeV muon collider and could be part of a test-facility serving a muon-cooling demonstrator. nuSTORM's status, physics capabilities and potential as a muon collider test-facility will be presented.

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1. Introduction

The Neutrinos from Stored Muons (nuSTORM) facility was designed to provide intense neutrino beams with well-defined energy spectrum and flavour composition. By exploiting the decays of muons circulating in a storage ring and employing adequate beam instrumentation, a beam composed in equal parts of electron and muon neutrinos and with a precisely know flux can be produced. nuSTORM is based on a racetrack-shaped muon ring (as shown in Fig. 1) that can store muon beams with central momenta in the 1–6 GeV/c range, and with a 16% momentum spread.

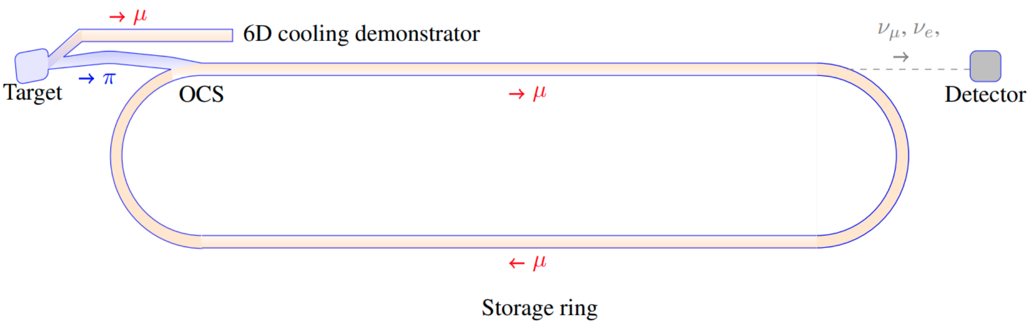

Figure 1: Schematic of the nuSTORM muon and neutrino-beam facility. Protons extracted from the CERN PS or SPS impinge on a static target. Pions are captured using a horn and directed into a transfer line that transports them to the storage ring. Once injected into the ring, the pions travel along the production straight and decay into muons. At the end of the production straight, undecayed pions are dumped, while the muons of specific momenta are accepted into the ring and recirculate. Muons decaying in the production straight generate a neutrino beam that travels towards the detector [1].

Motivation

Through its unique capabilities, the facility is well placed to address questions in neutrino physics while serving as an R&D test bed for a muon collider programme, as follows:

Neutrino-nucleus interactions: The search for CP-invariance violation at present and future long-baseline neutrino experiments, such as Hyper-Kamiokande and DUNE, is based on measuring the ν_e appearance rate in ν_μ beams. The dominant sources of systematic uncertainty in these experiments are the neutrino flux and the neutrino-nucleus interaction cross-section. For example, the lepton flavour universality-based approximation of the $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross-section ratio is not sufficiently accurate over the kinematic regime at DUNE and it is a major source of systematic uncertainty [2]. Having a tunable ring that can accommodate an energy range relevant to long-baseline neutrino experiments, nuSTORM can produce high-statistics cross-section measurements that would reduce the exposure required to reach adequate sensitivity to CP violation.

Beyond Standard Model physics: By combining a precisely characterised neutrino beam with high statistics, nuSTORM could perform studies of rare processes such as coherent meson production, neutrino-electron scattering or neutrino tridents. These processes, while allowed in the Standard Model (SM), may reveal physics beyond SM through precision measurements [1]. Furthermore, nuSTORM can investigate short-baseline neutrino oscillations and the LSND and MiniBooNE anomalies. A study based on a previous iteration of the facility design showed nuSTORM could achieve a 10σ sensitivity to the LSND and MiniBooNE anomalies through exploiting the muon neutrino appearance and muon antineutrino disappearance channels [3].

Muon Collider test bed: As nuSTORM will provide the world's highest power stored muon beam, it is uniquely well placed to serve as a R&D platform for muon accelerator technologies essential for the realisation of a Muon Collider [4, 5]. The design of the storage ring arcs and return straight is based on Fixed Field Alternating gradient (FFA) magnets. Hence nuSTORM can be used to develop and test the FFA magnet technology, which has applications for muon fast acceleration and is an attractive option for the muon collider accelerating complex. Muon-beam monitoring instrumentation can be also be developed at nuSTORM. Finally, as both nuSTORM and the Muon Collider employ the same pion production mechanism, nuSTORM could share a target system with a muon ionisation cooling facility designed to demonstrate the reduction of the muon beam six-dimensional phase space [6].

2. Facility Design

The following sections give a brief description of the latest nuSTORM facility design developments, with a focus on simulation-driven studies of its subsystems.

2.1 Target and Horn

The current design of the pion production and capture system assumes a CERN siting for the facility, with a protons extracted from the CERN Proton Synchrotron or Super Proton Synchrotron. The proton beam (26 GeV or 100 GeV) is focused and impinges on an inconel target housed inside a focusing horn. FLUKA [7] simulations of the current target and horn design [8] were carried out to characterise the horn pion capture efficiency [9]. Ongoing studies are aimed at improving the production and capture yield of low-energy pions ($p_\pi \leq 2$ GeV/c). While initial work has shown that running a higher current through the horn can improve the pion capture efficiency, current work investigates different horn geometries and the option of using a second horn.

2.2 Pion transport line

The pions collected by the horn are directed into a short transfer line with a large momentum acceptance of $\sim \pm 10\%$. This section of the lattice transports the pions to the ring and its design has been validated in tracking studies using the Beam Delivery Simulation software (BDSIM) [10, 11]. Current studies are focused on improving the beam matching flexibility of the lattice in order to accommodate a wider range of beam optical functions for the pion beam collected by the horn.

2.3 Storage Ring

The nuSTORM ring, shown in Fig. 2, is a compact racetrack-shaped storage ring ~ 616 m in circumference composed of large aperture magnets. It has been designed to store muon beams with momentum in the 1–6 GeV/c range, with a momentum acceptance of $\sim \pm 16\%$ and dynamical acceptance of 1 mm rad. The arcs and the return straight are based on FFA magnets to achieve a large dynamic acceptance, while a conventional focusing-defocusing optics is employed in the production straight to maximise the muon production efficiency. A model of the production straight has been implemented in BDSIM and it is used for tracking-based muon production studies (section 3), and current BDSIM development work is aimed at modelling FFA magnets. Upon completion, this will enable tracking-based neutrino-production studies utilising a full ring model.

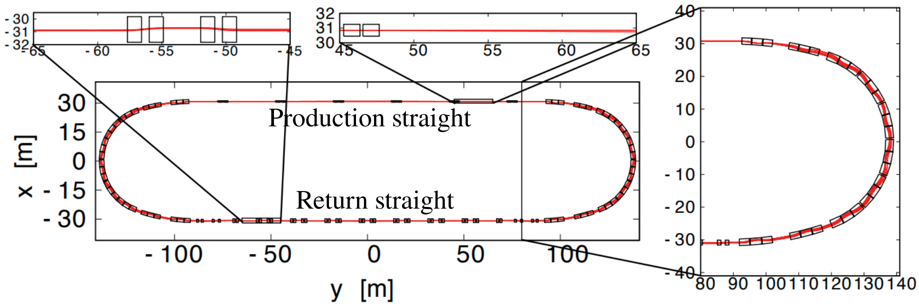

Figure 2: Schematic of the nuSTORM storage ring lattice.

3. Muon Production

To study muon production, FLUKA-generated pions were tracked from the horn to the end of the production straight using BDSIM. In its baseline design, the ring is tuned to accept muons with a central momentum $p_\mu = 0.76 p_\pi$. This specific setup was optimised to store 3.8 GeV/c muons from 5 GeV/c pions, and it was chosen to avoid an overlap between the target muon momentum window and the momenta of the undecayed pions.

Simulations of pion beams (10^5 events) with mean momenta as low as 1.32 GeV/c revealed a decrease in the muon production efficiency with decreasing p_π. A dip occurs at the center of the p_μ spectrum and the effect accentuates with decreasing momentum. This effect can be observed in the top panels of Fig. 3, which show the p_μ distribution produced from 5 GeV/c (left) and 1.32 GeV/c (right) pions. The effect translates into a lower number of muons accepted into the ring, shown in orange, and can be explained by the kinematics of pion decay: the muons in the central region of the momentum spectrum are the ones that decay perpendicularly to the direction of motion in the pion rest frame; at lower beam energies, the lower Lorentz boost leads to larger muon angles ($p_\perp / p_z$) which translates to an increase in muon losses in the apertures of the production straight magnets.

One explored mitigating solution consisted in tuning the ring to accept muons from either the forward or backward regions of the p_μ spectrum, which are populated with lower transverse momentum muons. The impact on the yield of muons accepted into the ring was studied through simulations in which the pion momentum was tuned such that the forward or backward muon momentum peaks were centered at the momentum of interest (1 GeV/c). The corresponding momentum distributions are shown in the bottom two panels of Fig. 3. Improvements in the number of accepted muons of ~ 2 and ~ 6 were observed when the target momentum was situated at the backward and forward peaks of the momentum distribution, respectively.

4. Simulated Neutrino Fluxes

The muon decay in the storage range was simulated using the nuSTORM SIMulator (nuSIM) software, a bespoke Python-based framework. nuSIM was developed for fast neutrino beam production simulations, to enable preliminary physics studies. The code uses an input pion beam

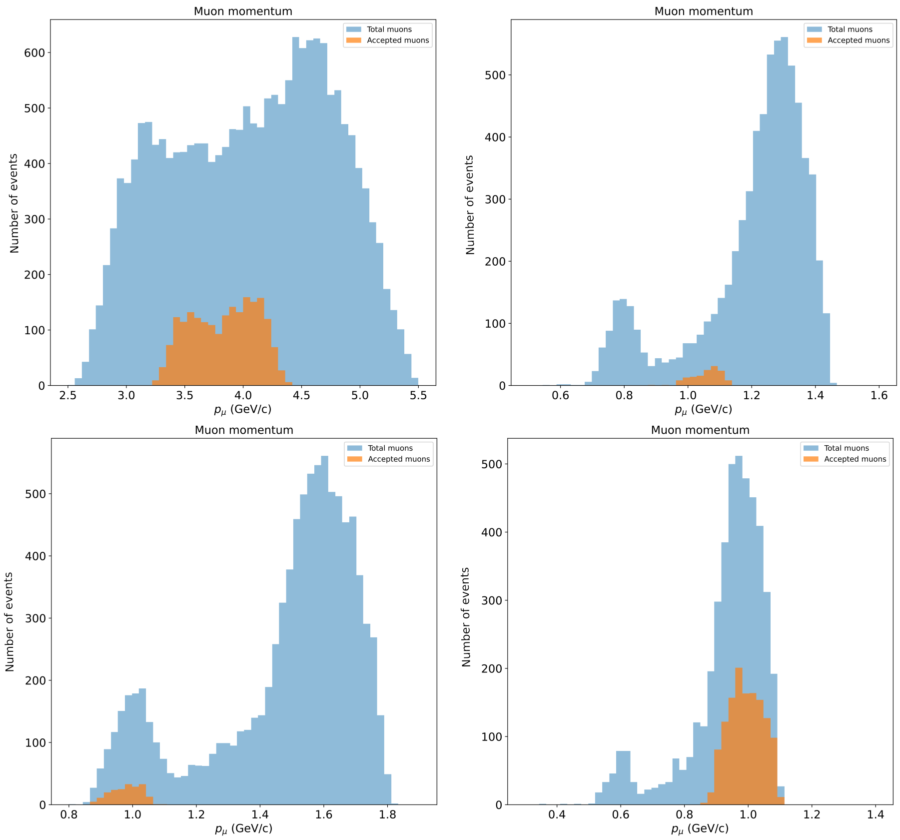

Figure 3: Muon momentum distribution at the end of the production straight. All produced muons are shown in blue, while muons that would be accepted into the ring are shown in orange. The muons produced from pion beams with four different mean momenta are shown: (top left) p_π = 5 GeV/c, (top right) p_π = 1.32 GeV/c, (bottom left) p_π = 1.65 GeV/c and (bottom right) p_π = 1 GeV/c.

distribution and performs detailed simulations of the pion and muon decays. Preliminary nuSIM-generated fluxes of muon and electron neutrinos from muons at four different momenta are shown in Fig. 4. The fluxes are estimated at the upstream face of a detector placed 50 m downstream of the ring, and using the baseline ring configuration.

4.1 Synthetic Neutrino Beams

nuSTORM can create synthetic neutrino beams in similar fashion to the nuPRISM technique which will be employed in DUNE and Hyper-K [**?**]. However, instead of combining different neutrino flux spectra recorded at various off-axis angles, at nuSTORM on-axis fluxes produced from different muon beam energies can be linearly combined to create bespoke synthetic fluxes. Fig. 5 shows synthetic ν_e and ν_μ fluxes created by combining the four fluxes shown in Fig. 4, which highlights nuSTORM's unique capability to produce synthetic electron neutrino beams. A more detailed description of the procedure can be found in [13].

5. Conclusion

The nuSTORM facility is uniquely positioned to serve a rich neutrino physics program and contribute to the muon collider technology development. The latest facility design advancements

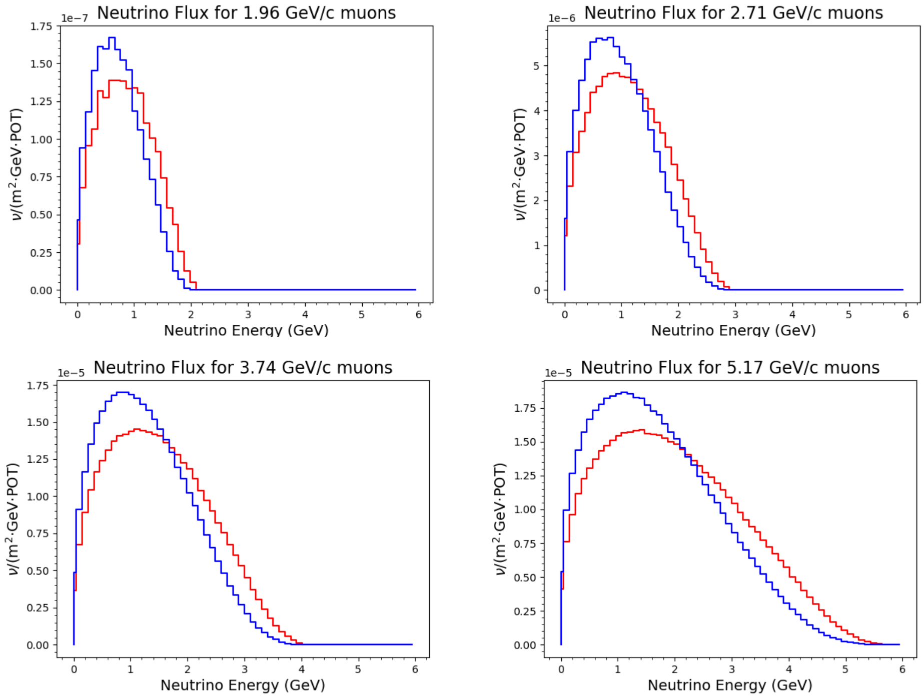

Figure 4: nuSTORM (blue) electron and (red) muon neutrino flux spectra produced from muons at four different momenta: (top left) p_μ = 1.96 GeV/c, (top right) p_μ = 2.71 GeV/c, (bottom left) p_μ = 3.74 GeV/c and (bottom right) p_μ = 5.17 GeV/c.

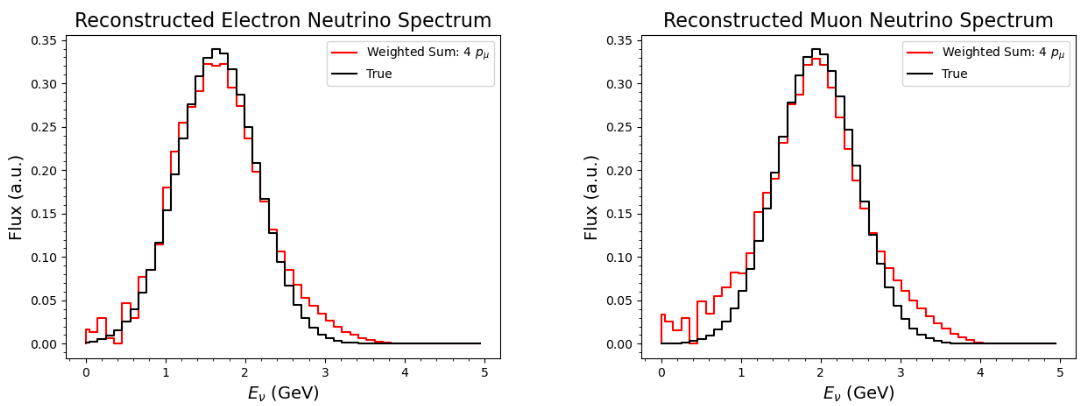

Figure 5: Simulated synthetic (left) electron and (right) muon neutrino flux spectra at nuSTORM. The black line indicates the target Gaussian distribution, while the red line shows the obtained flux.

have been presented, including improvements in pion production, capture, and transport, as well as an optimization study aimed at improving the yield of stored low-energy muons. Furthermore, preliminary simulations of the nuSTORM neutrino fluxes have been shown. Finally, nuSTORM's capability to generate synthetic neutrino beams, by linearly combining fluxes from different muon energies, has been highlighted. This technique strengthens nuSTORM's potential for reducing systematic uncertainties in neutrino-nucleus interaction cross section measurements and investigating physics beyond the Standard Model.

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