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Studies of a Muon Collider and nuSTORM at CERN

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1 Introduction

The 2020 Update of the European Strategy for Particle Physics in June of this year [1] recommended that muon beam R&D should be considered a high-priority future initiative due to the excellent potential for physics studies at a muon collider, and that a programme of experimentation to determine neutrino cross sections is required. We propose measurements of neutrino cross sections at nuSTORM as a stepping stone to construction of a muon collider.

The UK has a world-leading programme in muon beam physics studies. The UK hosted the international Muon Ionization Cooling Experiment (MICE) [2] to demonstrate muon cooling; constructed the Electron Model for Many Applications (EMMA) to demonstrate fast acceleration suitable for muons [3]; and made a number of studies to develop high power targetry suitable for a multi-MW beam comprising very short proton bunches. The UK also has played a leading role in design studies such as the Neutrino Factory International Design Study. Currently, ISIS is designing a fixed field alternating gradient (FFA) proton accelerator as part of its upgrade strategy, which also has applications for muon beam physics [4]. The UK has played a leading role in the physics and accelerator design of the muon g-2 exoeriment at Fermilab.

The UK has leadership in the nuSTORM facility design, which would enable definitive neutrino cross section measurements. The UK delivered an FFA-based design for the nuSTORM storage ring and led the nuSTORM design as part of the Physics Beyond Collider programme [5].

2 The Muon Collider

Circular muon colliders have the potential to reach centre-of-mass energies of tens of TeV with high luminosity. Muons are point-like particles, so the entire beam energy is available to produce short-distance reactions, which allows direct searches for new particles over a wide range of unexplored masses. A muon collider also allows accurate tests of the Standard Model to be performed at extremely high energy, offering great opportunities to detect new physics indirectly and to confirm and to characterise direct discoveries. Furthermore, by exploiting the copious rate for vector boson fusion and vector boson scattering processes, the muon collider provides the opportunity to probe the finest details of the electroweak symmetry breaking mechanism.

A baseline muon collider scheme was developed in the US and demonstrated a practical end-to-end facility design. The baseline scheme takes pions from short multi-MW proton bunches incident on a target. The pions decay to muons, which are captured by a sequence of RF cavities and solenoids. The muon beam emittance is reduced in a series of cooling lattices. The muons are then accelerated rapidly in a series of Rapid Cycling Synchrotrons or a single FFA before colliding. Unlike other energy frontier facilities, the footprint of the muon collider is small enough to fit on the site of existing facilities such as the CERN complex.

3 nuSTORM

The nuSTORM facility has three main aims:

- Serve a definitive neutrino-nucleus scattering programme to measure neutrino cross sections with uniquely well-characterised ν_e and ν_μ beams;
- Allow searches for light sterile neutrinos and other Beyond Standard Model processes with the exquisite sensitivity necessary to go beyond the reach of the FNAL Short Baseline Neutrino programme and the near detector systems of next generation long-baseline experiments; and

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- 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.

nuSTORM is based on a multi-GeV muon decay ring. Pions, produced by 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 $\pm 10\%$ p_π to the muon decay ring. The pion beam is injected into the production straight of the decay ring. A significant fraction 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 $\pm 16\%$ p_μ that then circulates. The facility is planned to operate with central momentum p_μ between 1 and 6 GeV/c. Undecayed pions and muons outside the momentum acceptance of the ring are extracted. The intense flux of muons may be used in a test facility dedicated to the development of the technologies required to deliver high-brightness muon beams, such as those in a muon collider.

The technologies that will be developed in the nuSTORM and muon collider study have application elsewhere in the UK science, innovation, and impact programmes. For example, the use of FFA systems have been proposed for the MW upgrade of ISIS, for use in the gantry that delivers the beam in particle-beam therapy systems, and for the rapid acceleration of beams in laser-hybrid systems for biomedical application. High power targetry is required for the ISIS upgrade and the long baseline neutrino programme.

4 Plans

Following the Strategy Update, the European Large National Laboratories Directors Group (LDG) has initiated an international muon collider collaboration, which covers the physics, detector and collider facility [6]. The study aims to validate the feasibility of existing muon collider concepts and to develop the critical technologies to a level of maturity that, supported by a validation of the physics reach, allows commitment to construction.

The UK has the leading expertise in Europe and the world on muon beam physics thanks to significant past investment. Strategic investment in muon beam physics now would maintain and enhance this leadership. In particular, development of a demonstrator facility design would produce significant return on investment in the medium term. In order to support this aim, we propose development of:

- the physics case for the muon collider and nuSTORM facilities;
- the nuSTORM facility design;
- detailed analysis of technical risks inherent in the muon collider accelerator facility and mitigation strategies [7] [8];
- a case for using nuSTORM as a demonstrator for the Muon Collider; and
- the muon collider design.

The international Muon Collider collaboration study will be split in two phases, the exploratory phase, which will last about two years, and the definition phase. In the exploratory phase, the collaboration will define goals for the muon collider performance for the physics, detector and accelerator facility and develop a prioritised list of key challenges that have to be addressed in the definition phase. nuSTORM as a demonstrator facility will also be considered in the exploratory phase. The physics reach and its dependence on luminosity and detector performances will be studied. In the definition phase, the work programmes developed in the exploratory phase will be implemented.

Prioritisation of muon beam R&D would maintain and enhance the UK's leadership position in this technology. A failure to prioritise would negate many years of investment in this area. We therefore propose to bring forward a Statement of Interest in the development of a UK activity in the forefront of the emerging international muon collider and nuSTORM activities.

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