Potential storage ring and Muon Campus experiments
Letter of Interest for Snowmass 2021

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The Muon $g-2$ and Mu2e experiments are currently collecting data and being constructed at the Muon Campus respectively. The Fermilab Muon Campus provides world class experiment and accelerator infrastructure that can support next generation intensity frontier research. The Proton Improvement Plan-II (PIP-II) upgrades to the Fermilab accelerator complex will allow for megawatt level proton beams that can enable particle physics experiments that produce very large data sets. The existing infrastructure and PIP-II upgrades represent a substantial investment, and it is worthwhile to explore ideas for developing new experiments at the Muon Campus that have a small incremental cost on top of the existing infrastructure investments. It will benefit the particle physics and accelerator communities if existing Fermilab infrastructure is used to support a diversified short-, medium-, and long-term intensity frontier program that studies Standard Model (SM) physics and searches for physics beyond the SM. A workshop on potential storage ring and Muon Campus experiments that considers both muon and non-muon based measurements would help support the Snowmass exercise.

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The transport, reassembly, and refurbishment of the Muon $g-2$ Storage Ring, along with the construction of the associated cryogenic and other support systems, represent a substantial investment. The Muon $g-2$ Project cost was $46M [1]. When you include off project costs, e.g. the salaries of most collaborators, then the total construction cost of the experiment is on the order of three times the project cost. When everything is included, e.g. the operations, then the total Muon $g-2$ Experiment [2] cost will be on the order of two times the total construction cost. Furthermore, the Fermilab Muon Campus [3, 4] accelerator complex represents an even more substantial investment, which includes contributions from the Muon $g-2$ and Mu2e projects, where the estimated Mu2e Project cost is $271M [5]. The Muon Campus was born out of upgrades and modifications to existing Fermilab accelerator infrastructure, including the construction of new buildings and beamlines, to support the Muon $g-2$ and Mu2e experiments. Fermilab is also beginning to implement the Proton Improvement Plan-II (PIP-II) [6, 7], which will provide important upgrades to the Fermilab accelerator infrastructure that are estimated to cost around $600M [6]. The planned increase in proton beam power will help make future Muon Campus experiments more scientifically competitive or practical to implement within Fermilab's resource and schedule constraints.

There are two Muon g–2 Storage Ring based measurements that could be completed on a short to medium time scale after finishing the current Muon g–2 Experiment. The BNL Muon g–2 Experiment [8] measured a muon anomaly value more than 3 standard deviations from the Standard Model (SM) prediction, and the Fermilab Muon $g-2$ Experiment has the goal of measuring the muon anomaly approximately 4 times more precisely than the BNL experiment [2]. The current Fermilab experiment is only approved for positive muon operations, as higher beam intensities are achievable in the Muon Campus when using positive instead of negative muons. A Muon $g-2$ measurement using existing equipment and negative muons is interesting [9], as the measurement can be used as a test of charge, parity, and time reversal (CPT) and Lorentz invariance by comparing it to the positive muon measurements.

The Muon $g-2$ Experiment will also measure an upper limit on the muon electric dipole moment (EDM) [10]. The muon EDM predicted by the SM is too small to be detected with current experimental techniques, and so the detection of a muon EDM would imply physics beyond the SM. There are several potential avenues for producing an improved muon EDM measurement by modifying the existing experiment. The Muon $g-2$ straw tracker detectors are used for measuring the muon EDM. A dedicated EDM measurement could be done by increasing the number of straw tracker detectors, using improved tracker technology, or improving the measurement of the magnetic field components within the storage region of the ring (e.g. a radial magnetic field component mimics the effects of a muon EDM).

A variety of intensity frontier experiments could potentially fit within a medium- to long-term Muon Campus program. The Muon $g-2$ Storage Ring could also be used for non-muon anomaly and EDM measurements. For instance, it might be possible to use the storage ring for measuring radiative muon decays [11–13], which could provide a test of the $V-A$ weak interaction. Another possibility is to consider pion injection into the storage ring, as this could be used in the determination of the pion decay constant [14, 15], as well as measuring the difference between the positive and negative pion lifetimes that would provide a test of CPT invariance. A modern version of the proposed NuMass Experiment (BNL E952) [16] could also use pion injection into the storage ring to look for the effects of a sterile neutrino in the shape of the tail from the resulting decay muon momentum distribution. Polarized proton injection into the storage ring could potentially be used for an inexpensive proton EDM measurement. The size of the proton EDM predicted by the SM is below current experimental sensitivities, and so a nonzero measurement would imply physics beyond the SM.

The Muon Campus also provides many interesting avenues of future research that would not involve repurposing the Muon g–2 Storage Ring. The following are just three of the possibilities. The proposed REDTOP Experiment [17, 18] would be an eta and eta-prime factory that could be used to study CPT dependent symmetries, as well as looking for evidence of new particles, e.g. dark photons, leptoquarks, axion-like particles, etc. The Mu2e Experiment is currently under construction and is searching for charged lepton flavor violation by looking for neutrinoless muon-to-electron conversion in the field of a nucleus. The SM predicts muon-to-electron conversion at such a suppressed rate as to be unobservable with current experimental techniques, and so the observation of muon-to-electron conversion would imply physics beyond the SM. A potential next generation Mu2e experiment (Mu2e-II) [19, 20] is being studied, which will take advantage of continuing detector improvements and accelerator upgrades at Fermilab. There is also ongoing work to develop a potential proton EDM measurement that would not make use of the Muon $g-2$ Storage Ring. The Proton Storage Ring EDM Experiment (srEDM) [21–23] would use a hybrid proton storage ring (electric bending and magnetic focusing) and the frozen spin method.

A workshop on potential storage ring and Muon Campus experiments held during the spring of 2021 would help support the Snowmass planning exercise. The types of experiments being considered in such a workshop would naturally fit into the intensity frontier part of particle physics research. Very large amounts of data will be produced, and these experiments can benefit from recent advances in machine learning, big data analysis techniques, and data processing using GPUs. The discussion will be multidisciplinary by its very nature, as it will require input from particle physics experimentalists and theorists, as well as scientific computing and accelerator scientists.

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