Letter of Interest for the Muon Missing Momentum experiment

Nural Akchurin,[1] Christian Herwig,[2] Yonatan Kahn,[3] Gordan Krnjaic,[2]
Cristina Mantilla Suarez,[2] Nhan Tran,[2] and Andrew Whitbeck[1]

[1]*Texas Tech University, Lubbock, TX 79409, USA*
[2]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[3]*University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*

(Dated: September 1, 2020)

New light particles that couple to muons are motivated by the nearly 4σ discrepancy between the measured and predicted magnetic moment of the muon. New light particles are also invoked to mediate interactions between the SM and dark matter, for example in models of thermal freeze out. If such states exist and couple mainly to heavier lepton generations and new weakly interacting matter states, most existing experiments are ill-equipped to constrain such models. The Muon Missing Momentum (M^3) experiment is a muon fixed target experiment that could operate at Fermilab. M^3 will use missing momentum and energy signatures to look for the production of new weakly interacting particles. With a modest integrated luminosity corresponding to 10^{10} muons on target (MoT), the remaining parameter space for which light invisibly decaying particles can resolve the $(g-2)_\mu$ anomaly can be tested. With 10^{13} MoT, M^3 can test much of the parameter space over which sub-GeV dark matter achieves freeze-out via muon-philic forces, including gauged $U(1)_{L_\mu - L_\tau}$ mediators. With modest improvements to existing Fermilab accelerator facilities and by adapting existing detector technology, M^3 can cover vast regions of parameter space that are inaccessible to other accelerator-based experiments. Specifically, M^3 can target generic searches for dark photons, has unique sensitivity to muonphilic mediators, and muonphilic dark matter.

Understanding the particle nature of dark matter (DM) remains one of the top priorities in high energy physics. After decades of experiments searching for relic DM scattering in highly sensitive detectors, decay products of DM, and the production of DM at accelerators, little is know about its particle nature. Recent theoretical work [1, 2] has motivated searches for lighter DM states arising from "hidden sector" models with masses from 1 MeV to 1 GeV. Experimental efforts to target light DM have mainly focused on electron interactions with the dark sector either with e^+e^- colliders, electron fixed-target experiments, or electron recoil measurements [3]. However, well-motivated theoretical models provide hints that SM-DM interactions may be mediated by muon-philic forces such as gauged $U(1)_{L_\mu - L_\tau}$ vector bosons. Furthermore, the nearly 4σ discrepancy between the predicted and measured value of $(g-2)_\mu$ [4, 5] supports the existence of new states that may preferentially couple to higher generations of leptons. A common proposal to explain the measurement of $(g-2)_\mu$ is to predict light, weakly coupled particles [6]. However, recent measurements have ruled out a light ($<$ GeV) dark photon with kinetic mixing $\epsilon \sim 10^{-3}$ and flavor-universal couplings independent of its decays [3]. The only remaining class of light new-physics explanations involves particles that couple predominantly (or exclusively) to muons, thereby evading the searches upon which the dark photon exclusions are based. Thus, a robust test of the new-physics hypothesis requires improved sensitivity to muonic forces.

The Muon Missing Momentum experiment (M^3) [7] is a proposed muon fixed target experiment to search for the existence of invisibly decaying muon-philic particles. The experimental concept builds on other similar missing energy/momentum experiments [8] and *focuses on opportunities with US facilities, namely Fermilab's proton beamlines, which can be put to use immediately with minimal modifications to achieve world-leading sensitivity*. With 10^{10} muons on target (MoT), M^3 can cover all remaining parameter space for which new particles below 1 GeV can resolve the $(g-2)_\mu$ anomaly. M^3 can also generically constrain models of thermal-relic DM over the mass range of 1 MeV to 1 GeV. With 10^{13} MoT, M^3 will have sensitivity that is better than comparable electron-fixed target experiments at high mediator masses [7].

A sketch of the experimental concept of M^3 is shown in Figure 1 (left). A beam of muons will traverse a tracking system before impinging on a target. The low energy, high transverse momentum recoiling muons, indicitive of the production of a massive scalar or vector boson, are then characterized by a second tracking system downstream of the target. Both tracking systems and the target will reside in a magnetic field. The dominant background for M^3 will result from photonuclear reactions and photon conversions via bremsstrahlung off of the incoming beam particles. As compared to similar lepton fixed-target experiments, such as LDMX and NA64, M^3 will employ a thick, $\sim 50\ X_0$, target. Since the rate of bremsstrahlung scales like the mass of the beam particle squared and linearly with the target thickness, photon induced backgrounds in M^3 will occur at 1% the rate of LDMX with comparable kinematic selections. Other key backgrounds for M^3 will include pion contamination from the second beam's production target, photon initiated production of hadrons, and production of pairs of muons. To reduce these backgrounds track multiplicities and track momentum measurements in the downstream tracking system will be utilized. The target will be instrumented, allowing for energy deposited in the target to be an important handle for identifying the production of hadrons. Finally, for events with neutral by-products that escape the target, downstream electromagnetic and hadronic calorimeters will be used to as vetoes.

The Fermilab proton beam can be used to produce a muon beam with energy in the 10-30 GeV range. Such a beam will allow for a compact detector design. Since the beam energy only affects the production cross section logarithmically [7], there is little to be gained from higher beam energies. The fixed target beamlines at the Fermilab accelerator complex extract protons from the main injector roughly once per minute over a 4.2 second spill. Two beam lines have

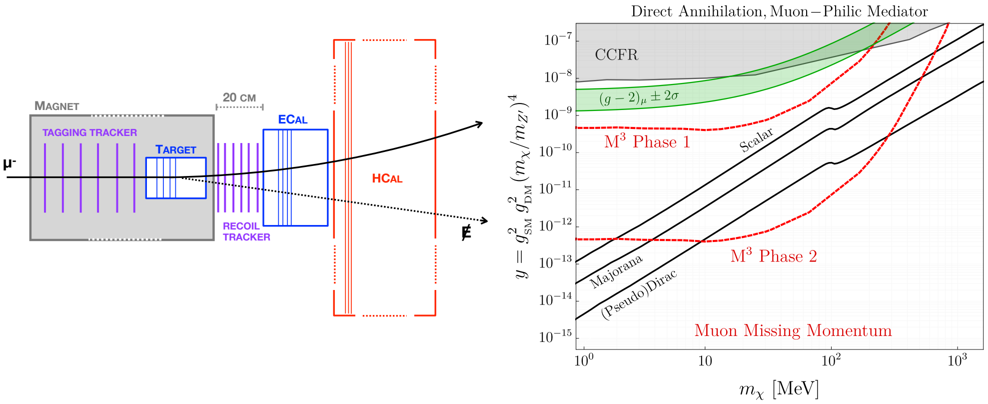

FIG. 1. Left: Schematic of M^3 with a depiction of a typical signal event. Right: Parameter space for thermal-relic DM which is charged under $U(1)_{L_\mu - L_\tau}$. Black lines show the lower bounds for which various models could explain at least part of the thermal relic density of dark matter. Regions of parameter space that could explain $(g-2)_\mu$ are represented by a green band. M^3 sensitivity is shown in red, for Phase 1 (2) datasets with 10^{10} (10^{13}) MoT.

been considered for M^3: MTest and the NM4 beamline. These beam lines are be able to produce as many as 10^5 and 10^7 muons per spill, respectively, with a repetition rate of 53 MHz. The MTest scenario would enable 10^{10} MoT over several months of operation. The NM4 scenario could achieve 10^{13} MoT over a two year period. While MTest is currently capable of producing a muon beam, the NM4 beamline would need modification to enable the production of muons. At the higher rates expected while operating at the NM4 beamline M^3 would need a dedicated trigger system to reduce the event rate to 100 kHz.

With this setup, M^3 seeks to target four areas of well-motivated physics:

- testing the remainder of the $(g-2)_\mu$ parameter space by covering invisible signatures and directly probing new physics that couples to muons;
- searching for muon-philic dark matter through missing momentum signatures;
- providing complementary sensitivity for higher-mass dark matter benchmark scenarios;
- searching for extended hidden sector physics utilizing visible and invisible signatures.

Assuming the various detectors can veto SM backgrounds at sufficient rates to produce near-zero background expectation in a 10^{13} MoT dataset, Figure 1 (right) shows the projected sensitivity of M^3 to a vector-type muon-philic particle, assuming 100% branching fraction to invisible particles. Even with the more conservative integrated luminosities expected (labeled as Phase 1), M^3 can decisively test whether light new particles can explain the $(g-2)_\mu$ anomaly. The black lines in Figure 1 (right) represent lower bounds on the dimensionless coupling y consistent with thermal DM scenarios.

M^3 is a missing momentum experiment utilizing Fermilab proton beam to enable a muon fixed-target configuration. With modest improvements to existing Fermilab accelerator facilities and by adapting existing detector technology, M^3 can cover vast regions of parameter space that are inaccessible to other accelerator-based experiments. Specifically, M^3 can target generic searches for dark photons, has unique sensitivity to muonphilic mediators, and muonphilic dark matter.

---

[1] Rouven Essig et al. Working Group Report: New Light Weakly Coupled Particles. In *Community Summer Study 2013: Snowmass on the Mississippi*, 10 2013.

[2] Jim Alexander et al. Dark Sectors 2016 Workshop: Community Report. 8 2016.

[3] Marco Battaglieri et al. US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report. In *U.S. Cosmic Visions: New Ideas in Dark Matter*, 7 2017.

[4] G. W. Bennett, B. Bousquet, H. N. Brown, G. Bunce, R. M. Carey, P. Cushman, G. T. Danby, P. T. Debevec, M. Deile, H. Deng, and et al. Final report of the e821 muon anomalous magnetic moment measurement at bnl. *Physical Review D*, 73(7), Apr 2006.

[5] T. Aoyama et al. The anomalous magnetic moment of the muon in the Standard Model. 6 2020.

[6] Maxim Pospelov. Secluded U(1) below the weak scale. *Phys. Rev. D*, 80:095002, 2009.

[7] Yonatan Kahn, Gordan Krnjaic, Nhan Tran, and Andrew Whitbeck. M^3: a new muon missing momentum experiment to probe $(g-2)$ and dark matter at Fermilab. *JHEP*, 09:153, 2018.

[8] Torsten Åkesson et al. Light Dark Matter eXperiment (LDMX). 8 2018.