

Snowmass 2021 - Letter of Interest

Accelerator Probes of Millicharged Particles and Dark Matter

RF Topical Groups:

- (RF6) Dark Sector Studies at High Intensities

EF Topical Groups:

- (EF9) BSM: More General Explorations
- (EF10) BSM: Dark Matter at Colliders

NF Topical Groups:

- (NF3) BSM
- (NF5) Neutrino Properties

CF Topical Groups:

- (CF1) Dark Matter: Particle Like
- (CF3) Dark Matter: Cosmic Probes
- (CF7) Cosmic Probes of Fundamental Physics

TF Topical Groups:

- (TF7) Collider Phenomenology
- (TF8) BSM Model Building
- (TF9) Astro-Particle Physics & Cosmology

AF Topical Groups:

- (AF5) Accelerators for PBC & Rare Processes

UF Topical Groups:

- (UF3) Underground Detectors

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Abstract:

In this letter, we introduce the studies of the millicharged particle (MCP). We then describe and classify the studies of millicharged particles in accelerator-based experiments.

This document is expanded based on a document with the same title, submitted to the CERN-based “PBC Meets Theory – Selected Topics” organizational efforts, prepared by Yu-Dai Tsai and Saeid Foroughi-Abari. A live-update version of this LOI can be found here¹.

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I. Introduction

The study of the millicharged particle (MCP) is linked to several fundamental mysteries in particle physics. First, it is connected to the test of the empirical electric charge quantization² and the related theories³⁻⁵. It is also considered as a low-energy consequence of well-motivated dark-sector models⁶, and neutrinos are also postulated to possess small charges^{7,8}. MCP is proposed as a potential dark matter candidate⁹⁻¹¹, and has recently been considered as a solution to the anomaly of 21 cm absorption spectrum reported by the EDGES collaboration¹²⁻¹⁷. We consider MCP, labeled χ , with electric charge Q_χ and define $\epsilon \equiv Q_\chi/e$. This can arise if χ directly has a small charge under standard model $U(1)$ hypercharge, or if χ is coupled to a massless kinetic mixing dark photon⁶.

MCPs are studied in terrestrial experiments¹⁸⁻³¹, and their signatures as dark matter is also studied in astrophysical/cosmological observations. Our focus here is to briefly describe and classify the accelerator-based probes. The MCPs are usually produced when the beam collides with another beam or impacts a target. They can be produced either directly, or through secondary mesons decay. The experimental signature can be roughly classified as tracking (dE/dx signature), hard scattering (to detect the electron recoil), or missing momentum/energy. The electron-scattering signatures have been one of the main focus to study MCPs. When studying such signatures, since there is a $1/E$ enhancement in the scattering cross-section (E here is the electron-recoil energy), experiments with sensitivity to low-energy recoil or scintillation signatures are often preferred as MCP probes²⁹.

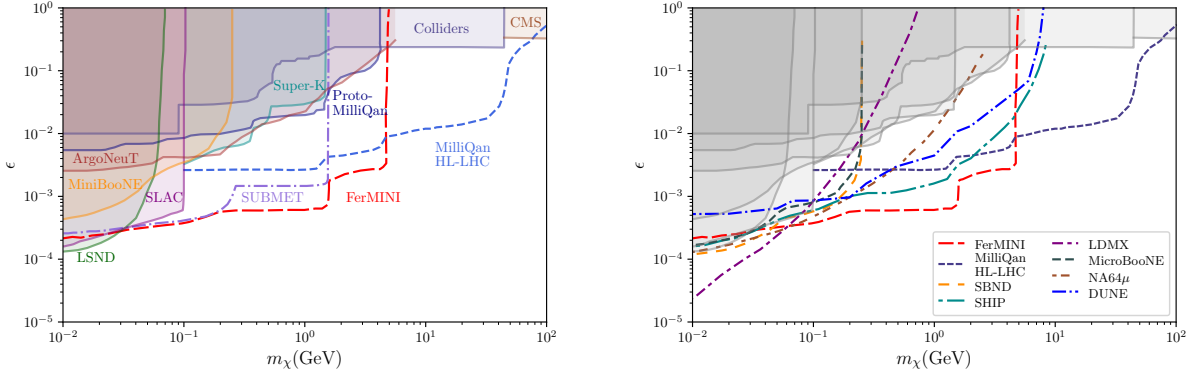
II. Existing bounds and future projections - In the following paragraphs, we roughly classify the accelerator probes of MCPs.

Colliders - Searches for MCP at Large Hadron Collider (LHC) and Tevatron have delivered strong constraints in the mass region above 100 MeV. These consist of bounds from trident process searches, the invisible width of the Z boson as well as direct searches for particles with fractional charges at LEP²⁰ and low ionizing particles at CMS^{32,33}, with focus on $\pm 2e/3$ and $\pm e/3$. In addition, new sensitivity is achieved recently by milliQan (a prototype scintillator-based detector) for masses larger than a few hundred MeV³⁴. The proposed electron collider, such as Beijing Electron-Positron Collider³⁵ could also improve the sensitivity to MCPs.

Proton fixed-target and neutrino experiments - In the fixed-target neutrino experiments category, the Liquid Scintillator Neutrino Detector (LSND) and MiniBooNE experiments are found to provide new constraints in MCP mass windows, 5 – 35 MeV and 100 – 180 MeV respectively³⁶. Using existing data in Fermilab’s MuMI beam, ArgoNeUT, a small liquid Argon neutrino detector, has further constrained new regions of the MCP parameter space by searching for two hit aligned with the distant target^{37,38}. Sensitivity projections for MCPs over a range of masses 5 MeV to 5 GeV has been analyzed recently³⁶, considering the upcoming neutrino experiments, such as MicroBooNE, the Short-Baseline Neutrino (SBN) Program, the Deep Underground Neutrino Experiment (DUNE) at Fermilab³⁶. The sensitivity of the proposed proton fixed-target experiment at CERN, Search for Hidden Particles (SHiP), is also discussed in this paper³⁶.

Lepton fixed-target experiments - In the low-mass region, the most sensitive constraints on MCPs were placed by electron fixed-target experiments, *e.g.* SLAC mQ experiment¹⁹ with the leading sensitivity for $m_{\text{MCP}} < 100$ MeV. Despite the mass reach limit due to the beam energy, further sensitivity enhancement to MCP coupling can be reached by future lepton beam-dump facilities using missing energy and momentum techniques, *e.g.* LDMX³⁹ and NA64⁴⁰ with 10^{16} electron-on-target and 5×10^{13} muon-on-target, respectively.

MilliQan/FerMINI: dedicated detectors - Dedicated MCP detectors were proposed at the LHC, proton fixed-target, and neutrino experiments, *e.g.* milliQan²⁶ and FerMINI³⁰. The detectors consist of 3-4 layers of scintillator arrays, where MCPs traversing the scintillators produce a few photo-electrons in each



(a) Existing bounds and MCP dedicated experiments

(b) Comparison of future projections

Figure 1: **(a)** Exclusions from previous accelerator searches include SLAC¹⁹, Colliders^{20;25}, CMS^{32;33}, MiniBooNE and LSND²⁹, ArgoNeuT at Fermilab³⁸, recent search by milliQan at LHC³⁴, the diffuse supernova neutrino background search in Super-K⁴¹ are shown. The projections for milliQan HL-LHC²⁵ (dashed blue) and FerMINI³⁰ at DUNE (similar sensitivity at NuMI) (dashed red) and SUBMET⁴² (dashed purple) are also shown by dashed curves for comparison (see the text for further details).

(b) The projected sensitivities including NA64 μ ⁴⁰ (5×10^{13} muon-on-target) and LDMX³⁹ (10^{16} electron-on-target) are shown by dashed curves in comparison to the existing bounds excluded by different sources (shaded in gray). The reaches of neutrino experiments such as MicroBooNE, SBND, SHIP is taken from . A DUNE analysis was first conducted in³⁶, but we show the sensitivity reach based on a more involved and detailed study³⁷, taking into account realistic background assumptions and using the double-hit technique discussed in the text.

layer. The idea is to use multiple-coincidence scintillation as an experimental signature within a short time window, to suppress backgrounds mainly from dark currents in the PMTs and coincidence with radioactive decays in the cavern. The milliQan detector is proposed to be placed in the transverse region with respect to the LHC beamline. Recently, a new sensitivity has been achieved by the first results of milliQan demonstrator (placed in the same traverse location) for masses larger than 700 MeV and reaching up to almost 5 GeV³⁴. The milliQan demonstrator has been invaluable to demonstrate that this type of segmented scintillator detectors can be operated well in LHC experimental conditions.

FerMINI³⁰ is a proposal to place a milliQan-like detector downstream of a proton fixed-target facility, either at the existing Neutrinos at the Main Injector⁴³ (NuMI) beamline or the upcoming Long-Baseline Neutrino Facility⁴⁴ (LBNF) beamlines. The FerMINI proposal consists of a milliQan-type detector. It could provide sensitivity to ϵ below 10^{-3} and up to about $m_\chi \sim 5$ GeV, taking advantage of the higher flux of MCP produced in the collision of the high-luminosity proton beams on a fixed target at the neutrino facilities. The SUBMET detector is proposed at the J-PARC proton fixed-target facility, having a similar sensitivity as FerMINI for masses below 1 GeV⁴². Another example of a dedicated detector based on the same principle: MAPP⁴⁵ is planned to be part of the MoEDAL experiment upgrade program, foreseen to operate during RUN-3 at the LHC, and will also search for fractionally charged particles⁴⁶. Recently, a new setup has been proposed, to place a milliQan-like detector at the LHC forward region to study MCP^{47;48}.

Cosmic-ray accelerator - Another interesting probe of the milli-charged particles is through the production of MCPs from cosmic ray hitting the atmosphere. Using large underground neutrino detectors such as Super-K, a recent study has set new limits on MCPs for the mass range 0.1 GeV to 1.5 GeV⁴¹ (dedicated analyses based on future experiments, e.g., DUNE, could potentially improve sensitivity).

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