Snowmass 2021 - Letter of Interest

Accelerator Probes of Millicharged Particles & 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

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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 here[1].

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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 quantization[2] and the related theories[3–5]. It is also considered as a low-energy consequence of well-motivated dark-sector models[6], and neutrinos are also postulated to possess small charges[7;8]. MCP is proposed as a potential dark matter candidate[9–11], and has recently been considered as a solution to the anomaly of 21 cm absorption spectrum reported by the EDGES collaboration[12–17]. 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 photon[6].

MCPs are studied in terrestrial experiments[18–31], 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 probes[29].

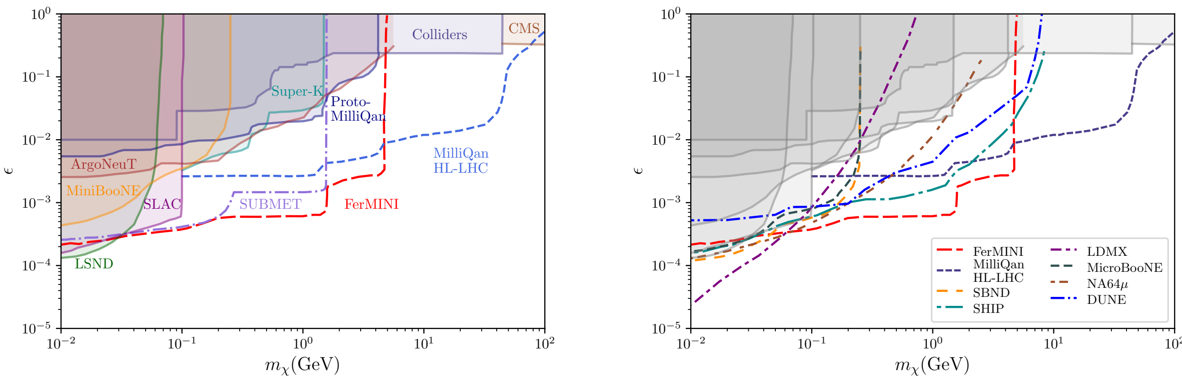
II. Existing bounds and future projections - In the following paragraphs, we roughly classify the accelerator probes of MCPs.

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 LEP[20] 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 MeV[34]. The proposed electron collider, such as Beijing Electron-Positron Collider[35] 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 respectively[36]. 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 recently[36], considering the upcoming neutrino experiments, such as MicroBooNE, the Short-Baseline Neutrino (SBN) Program, the Deep Underground Neutrino Experiment (DUNE) at Fermilab[36]. The sensitivity of the proposed proton fixed-target experiment at CERN, Search for Hidden Particles (SHiP), is also discussed in this paper[36].

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 experiment[19] with the leading sensitivity for $m_{\mathrm{MCP}} < 100$ 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.* LDMX[39] and NA64[40] 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. milliQan[26] and FerMINI[30]. 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 SLAC[19], Colliders[20;25], CMS[32;33], MiniBooNE and LSND[29], ArgoNeuT at Fermilab[38], recent search by milliQan at LHC[34], the diffuse supernova neutrino background search in Super-K[41] are shown. The projections for milliQan HL-LHC[25] (dashed blue) and FerMINI[30] at DUNE (similar sensitivity at NuMI) (dashed red) and SUBMET[42] (dashed purple) are also shown by dashed curves for comparison (see the text for further details).
(b) The projected sensitivities including NA64μ[40] (5×10^{13} muon-on-target) and LDMX[39] (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 in[36], but we show the sensitivity reach based on a more involved and detailed study[37], 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 GeV[34]. The milliQan demonstrator has been invaluable to demonstrate that this type of segmented scintillator detectors can be operated well in LHC experimental conditions.

FerMINI[30] is a proposal to place a milliQan-like detector downstream of a proton fixed-target facility, either at the existing Neutrinos at the Main Injector[43] (NuMI) beamline or the upcoming Long-Baseline Neutrino Facility[44] (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 GeV[42]. Another example of a dedicated detector based on the same principle: MAPP[45] 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 particles[46]. 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 GeV[41] (dedicated analyses based on future experiments, e.g., DUNE, could potentially improve sensitivity).

References:

[1] Snowmass Letter of Intent: Accelerator Probes of Millicharged Particles & Dark Matter. 2020. https://www.overleaf.com/read/gjxmbfppgsrr.

[2] Paul A. M. Dirac. Quantized Singularities in the Electromagnetic Field. *Proc. Roy. Soc. Lond.*, A133:60–72, 1931. [,278(1931)].

[3] Jogesh C. Pati and Abdus Salam. Unified Lepton-Hadron Symmetry and a Gauge Theory of the Basic Interactions. *Phys. Rev.*, D8:1240–1251, 1973.

[4] Howard Georgi. The State of the Art—Gauge Theories. *AIP Conf. Proc.*, 23:575–582, 1975.

[5] Gary Shiu, Pablo Soler, and Fang Ye. Milli-Charged Dark Matter in Quantum Gravity and String Theory. *Phys. Rev. Lett.*, 110(24):241304, 2013.

[6] Bob Holdom. Two U(1)'s and Epsilon Charge Shifts. *Phys. Lett.*, 166B:196–198, 1986.

[7] P. Vogel and J. Engel. Neutrino Electromagnetic Form-Factors. *Phys. Rev. D*, 39:3378, 1989.

[8] Carlo Giunti and Alexander Studenikin. Neutrino electromagnetic interactions: a window to new physics. *Rev. Mod. Phys.*, 87:531, 2015.

[9] David E. Brahm and Lawrence J. Hall. U(1)-prime DARK MATTER. *Phys. Rev.*, D41:1067, 1990.

[10] Jonathan L. Feng, Manoj Kaplinghat, Huitzu Tu, and Hai-Bo Yu. Hidden Charged Dark Matter. *JCAP*, 07:004, 2009.

[11] James M. Cline, Zuowei Liu, and Wei Xue. Millicharged Atomic Dark Matter. *Phys. Rev. D*, 85:101302, 2012.

[12] Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen, and Nivedita Mahesh. An absorption profile centred at 78 megahertz in the sky-averaged spectrum. *Nature*, 555(7694):67–70, 2018.

[13] Rennan Barkana. Possible interaction between baryons and dark-matter particles revealed by the first stars. *Nature*, 555(7694):71–74, 2018.

[14] Julian B. Muñoz and Abraham Loeb. A small amount of mini-charged dark matter could cool the baryons in the early Universe. *Nature*, 557(7707):684, 2018.

[15] Asher Berlin, Dan Hooper, Gordan Krnjaic, and Samuel D. McDermott. Severely Constraining Dark Matter Interpretations of the 21-cm Anomaly. 2018.

[16] Tracy R. Slatyer and Chih-Liang Wu. Early-Universe constraints on dark matter-baryon scattering and their implications for a global 21 cm signal. *Phys. Rev.*, D98(2):023013, 2018.

[17] Hongwan Liu, Nadav Joseph Outmezguine, Diego Redigolo, and Tomer Volansky. Reviving Millicharged Dark Matter for 21-cm Cosmology. *Phys. Rev.*, D100(12):123011, 2019.

[18] M. I. Dobroliubov and A. Yu. Ignatiev. MILLICHARGED PARTICLES. *Phys. Rev. Lett.*, 65:679–682, 1990.

[19] A. A. Prinz et al. Search for millicharged particles at SLAC. *Phys. Rev. Lett.*, 81:1175–1178, 1998.

[20] Sacha Davidson, Steen Hannestad, and Georg Raffelt. Updated bounds on millicharged particles. *JHEP*, 05:003, 2000.

[21] E. Golowich and R. W. Robinett. Limits on Millicharged Matter From Beam Dump Experiments. *Phys. Rev.*, D35:391, 1987.

[22] K. S. Babu, Thomas M. Gould, and I. Z. Rothstein. Closing the windows on MeV Tau neutrinos. *Phys. Lett.*, B321:140–144, 1994.

[23] S. N. Gninenko, N. V. Krasnikov, and A. Rubbia. Search for millicharged particles in reactor neutrino experiments: A Probe of the PVLAS anomaly. *Phys. Rev.*, D75:075014, 2007.

[24] R. Agnese et al. First Direct Limits on Lightly Ionizing Particles with Electric Charge Less Than $e/6$. *Phys. Rev. Lett.*, 114(11):111302, 2015.

[25] Andrew Haas, Christopher S. Hill, Eder Izaguirre, and Itay Yavin. Looking for milli-charged particles with a new experiment at the LHC. *Phys. Lett.*, B746:117–120, 2015.

[26] Austin Ball et al. A Letter of Intent to Install a milli-charged Particle Detector at LHC P5. 2016.

[27] Ping-Kai Hu, Alexander Kusenko, and Volodymyr Takhistov. Dark Cosmic Rays. *Phys. Lett. B*, 768:18–22, 2017.

[28] S. I. Alvis et al. First Limit on the Direct Detection of Lightly Ionizing Particles for Electric Charge as Low as e/1000 with the Majorana Demonstrator. *Phys. Rev. Lett.*, 120(21):211804, 2018.

[29] Gabriel Magill, Ryan Plestid, Maxim Pospelov, and Yu-Dai Tsai. Millicharged particles in neutrino experiments. *Phys. Rev. Lett.*, 122(7):071801, 2019.

[30] Kevin J. Kelly and Yu-Dai Tsai. Proton fixed-target scintillation experiment to search for millicharged dark matter. *Phys. Rev.*, D100(1):015043, 2019.

[31] C. A. Argüelles et al. White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter). 2019.

[32] Serguei Chatrchyan et al. Search for Fractionally Charged Particles in pp Collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev.*, D87(9):092008, 2013.

[33] Joerg Jaeckel, Martin Jankowiak, and Michael Spannowsky. LHC probes the hidden sector. *Phys. Dark Univ.*, 2:111–117, 2013.

[34] A. Ball et al. Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. D*, 102(3):032002, 2020.

[35] Zuowei Liu and Yu Zhang. Probing millicharge at BESIII. 2018.

[36] Gabriel Magill, Ryan Plestid, Maxim Pospelov, and Yu-Dai Tsai. Dipole Portal to Heavy Neutral Leptons. *Phys. Rev.*, D98(11):115015, 2018.

[37] Roni Harnik, Zhen Liu, and Ornella Palamara. Millicharged Particles in Liquid Argon Neutrino Experiments. *JHEP*, 07:170, 2019.

[38] R. Acciarri et al. Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab. *Phys. Rev. Lett.*, 124(13):131801, 2020.

[39] Asher Berlin, Nikita Blinov, Gordan Krnjaic, Philip Schuster, and Natalia Toro. Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX. 2018.

[40] S. N. Gninenko, D. V. Kirpichnikov, and N. V. Krasnikov. Probing millicharged particles with NA64 experiment at CERN. 2018.

[41] Ryan Plestid, Volodymyr Takhistov, Yu-Dai Tsai, Torsten Bringmann, Alexander Kusenko, and Maxim Pospelov. New Constraints on Millicharged Particles from Cosmic-ray Production. 2 2020.

[42] Suyong Choi et al. Letter of Intent: Search for sub-millicharged particles at J-PARC. 7 2020.

[43] P. Adamson et al. The NuMI Neutrino Beam. *Nucl. Instrum. Meth.*, A806:279–306, 2016.

[44] R. Acciarri et al. Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). 2015.

[45] Mariana Frank, Marc de Montigny, Pierre-Philippe A. Ouimet, James Pinfold, Ameir Shaa, and Michael Staelens. Searching for Heavy Neutrinos with the MoEDAL-MAPP Detector at the LHC. *Phys. Lett. B*, 802:135204, 2020.

[46] Michael Staelens. MoEDAL - Expanding the LHC's Discovery Frontier. *PoS*, LHCP2019:031, 2019.

[47] Felix Kling and Jonathan L. Feng. *Forward Physics Facility*, August 2020.

[48] Yu-Dai Tsai. Looking Forward for Millicharged Particles at the LHC. 2020. https://indico.fnal.gov/event/43963/contributions/191745/attachments/131726/163538/Forward_MCP_Tsai_v1.pdf.