Sensitivity reach of scintillation-based detectors for millicharged particles

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In this project we will evaluate the sensitivity for particles with charge much smaller than the electron charge with dedicated scintillator-based detectors at a range of facilities, including the CERN LHC, Fermilab and J-PARC. The data from the milliQan demonstrator will be used to comprehensively evaluate backgrounds for each detector, as well as provide a robust simulation of the response of the detector to low-charge particles.

Over a quarter of the mass-energy of the Universe is widely thought to be some kind of nonluminous "dark" matter (DM), however, all experiments to date have failed to confirm its existence as a particle, much less measure its properties. The possibility that DM is not a single particle, but rather a diverse set of particles with as complex a structure in their sector as normal matter, has grown in prominence in the past decade, beginning with attempts to explain observations in high-energy astrophysics experiments [1, 2]. Many experimental efforts have been launched to look for signs of a dark sector, including searches at high-energy colliders, explorations at low-energy colliders, precision tests, and effects in DM direct detection experiments (for recent reviews see Refs. [3–5]). Most of these experiments target the dark sector via a massive dark photon. However, if the dark photon is massless, the principal physical effect is that new dark sector particles, χ, that couple to the dark photon will have a small effective electric charge [6, 7]. While direct searches robustly constrain the parameter space of millicharged particles, indirect observations can be evaded by adding extra degrees of freedom, which can readily occur in minimally extended dark sector models [7]. In particular, the parameter space $1 < m_\chi < 100$ GeV is largely unexplored by direct searches [8–15].

A range of experiments have been proposed to provide sensitivity to millicharged particles in this well motivated mass range: milliQan [16] at the LHC, FerMINI at Fermilab [17] and SUBMET at J-PARC [18]. The high energy of the LHC beams will allow milliQan to have sensitivity to m_χ up to ~ 45 GeV, while the greater intensities of the beam-dump sources at J-PARC and FerMINI will allow significantly improved sensitivity to m_χ under a few GeV. Recently, a dedicated forward facility at the LHC has also been proposed in a separate Snowmass LOI. A milliQan-like detector in this location, named ForMINI [19], will have significantly improved sensitivity for lower masses because of the increased production at high η values. To fully characterise the reach that will be achieved in the coming years, the sensitivity of neutrino detectors to millicharged particles through electron scattering will be considered as part of a dedicated Snowmass effort.

The design of each scintillator-based experiment is very similar, comprised of large arrays of long scintillator bars arranged into multiple layers. A large path length and sensitive volume of scintillator is required to allow sensitivity to the small energy deposition of a particle with $Q \lesssim 0.1e$. Since millicharged particles would traverse the full length of the detector in $\mathcal{O}(10)$ ns, strict timing requirements allow for a significant reduction in backgrounds by requiring the coincidence of in-time signals in all layers. In addition to time coincidence, subdividing the sensitive volume into multiple layers using scintillator bars allows for background reduction via spatial coincidence through a "pointing" requirement. To allow sensitivity to charges lower than $0.001e$, each scintillator bar must be coupled to a Photomultiplier Tube (PMT) capable of detecting a single scintillation photon. The basic design of the detectors can be seen in Fig. 1.

In addition to the scintillator bars, additional components may be installed to reduce or characterize certain types of backgrounds. These include scintillator panels surrounding the detector, which provide the ability to tag and reject cosmogenic muons, scintillator slabs along the length of the detector, which allow through-going muons to be identified, and lead bricks between layers to prevent low-energy secondary particles from one layer from entering another layer.

Pair production of millicharged particles of a given mass and charge at these facilities is nearly model independent. Every standard model (SM) process that results in dilepton pairs through a virtual photon would, if kinematically allowed, also produce $\chi^+\chi^-$ pairs with a cross section reduced by a factor of $(Q/e)^2$ and by mass-dependent factors that are well understood. Millicharged particles can also be produced through Z boson couplings that depend on their hypercharge [7]. A full consideration of millicharged production mechanisms has been carried out for the LHC, J-PARC and Fermilab.

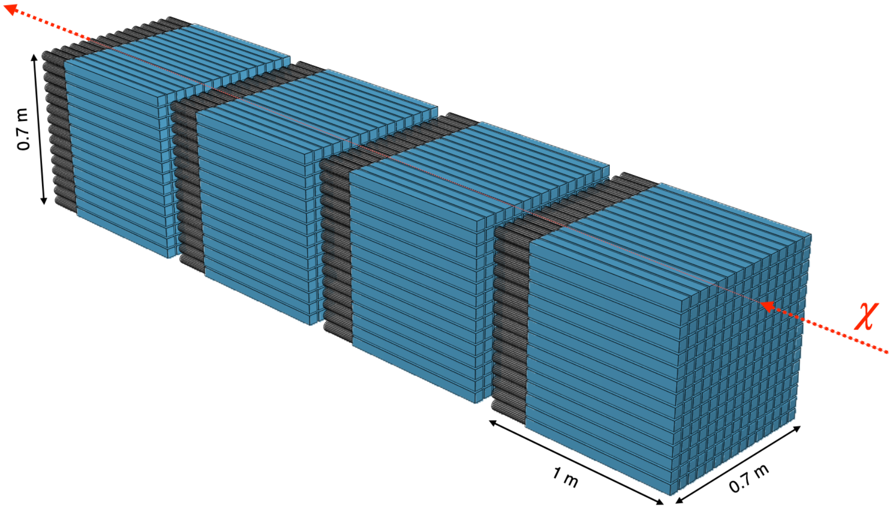

FIG. 1. Scintillator based detector for millicharged particles. This design, taken from the SUBMET proposal [18], is representative of the design used for milliQan, SUBMET and FerMINI. The scintillator bars (blue) are connected to PMTs which readout the scintillation photons.

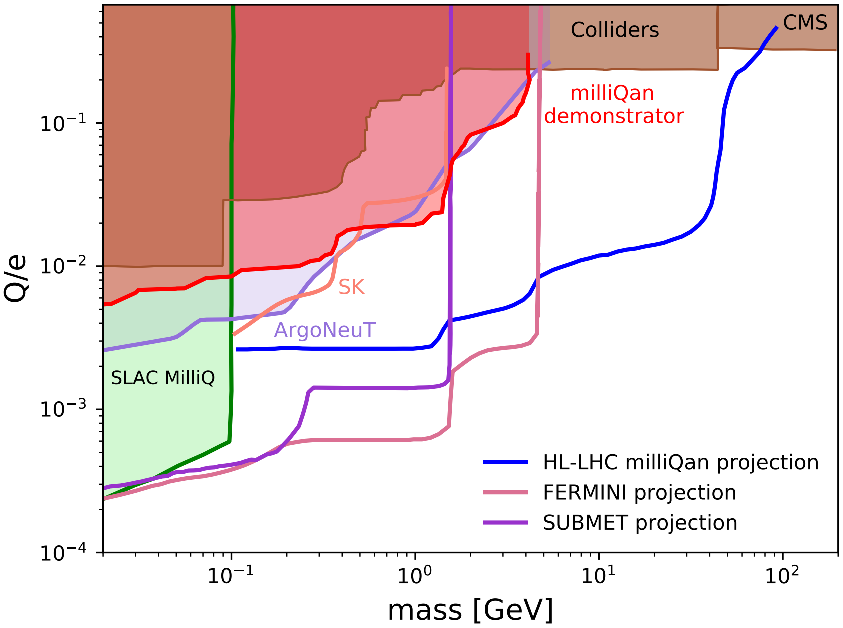

FIG. 2. The exclusion limits projected to be achieved by milliQan [16], FerMINI [17] and SUBMET [18] are compared to current bounds. Note that the signal production for the HL-LHC milliQan projection does not include non-prompt resonances.

The expected reach of these detectors is shown in Fig. 2. Whereas the simulation of the production and propagation of millicharged particles is considered thoroughly, the background rates and performance of each detector rely on broad assumptions. At the LHC a prototype scintillator-based detector, the milliQan demonstrator, has been installed to prove the feasibility of the detector design and characterise the dominant backgrounds. The demonstrator successfully collected around 3800h and 37.5 fb^{-1} of proton-proton collisions. This dataset allowed a recently published search that provides competitive constraints on the existence of millicharged particles (shown in Fig. 2) [20].

The aim of the effort described in this LOI is to comprehensively evaluate millicharged particle detector performance at future facilities using simulation that has been fully calibrated with the data collected by the milliQan demonstrator. The goals for each milliQan-like detector study are as follows:

- Fully evaluate backgrounds, including shower particles from cosmogenic muons, shown to be a dominant background in Ref. [20], and overlapping signals from PMT dark rate.
- Robustly evaluate the signal acceptance for each mass and charge using a full GEANT4 simulation that has been calibrated using data collected by the demonstrator.
- Make recommendations for the design of each detector based on the experience from the demonstrator, including the number of layers of scintillator bars, the length of the scintillator bars, PMT species, and the use of additional scintillator components to tag and reject backgrounds. Opportunities for further development, including improved detector technologies, such as solid state scintillators, will also be considered.
- Using comprehensive simulation of all modes of production of millicharged particles at each facility, make projections of the sensitivity for each detector given the background rate and signal acceptance derived above. This will significantly improve the accuracy of the projections in Fig. 2.

In summary, the projections derived as part of this project will allow a robust comparison of the reach of scintillator-based millicharged particle detectors at any facility with fully calibrated simulation as well as a robust estimation of the dominant backgrounds.

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