Millicharged particles in neutrino experiments

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Introduction: The extensions of the Standard Model (SM) by light weakly charged particles, and their probes at the intensity frontier experiments have become an important direction of modern particle physics [1]. One of the simplest and most natural ways of coupling new particles to the SM is via a “kinetic mixing” or “hypercharge portal” [2, 3], which at low energy may lead to millicharged particles (mCPs), that would seemingly contradict the observed quantization of electric charge in nature [4]. In recent years, a wide class of related models were studied in connection with dark matter [5–7] (see also [8–16]), and mCPs can be viewed as a specific limit of those theories.

It is well appreciated that both proton and electron beam dump experiments provide sensitive probes of vector portal models. In particular, production and scattering of light dark matter [4] has been studied as a function of mediator mass $m_A$, dark sector coupling $\alpha_D$, dark matter mass $m_\chi$, and kinetic mixing parameter $\epsilon_D$. Depending on the relation between these parameters, either the past electron beam dump facilities [12] or the proton fixed target experiments with a primary goal of neutrino physics [10, 13, 19] provide the best sensitivity. However, the simplest limit of $m_A \to 0$, when the parameter space simplifies to the mass effective charge of mCPs, $\{m_\chi, \epsilon_D\}$, was analyzed only in the context of electron beam dump experiments [17, 18]. Clearly, fixed target neutrino experiments, such as the existing data from MiniBooNE [19] and the Liquid Scintillator Neutrino Detector (LSND) [20], and the soon to be released data from MicroBooNE, the ongoing SBN program [21], the Deep Underground Neutrino Experiment (DUNE) [22], and the proposed Search for Hidden Particles (SHiP) [23] serve as a fertile testing ground of MeV–GeV physics due to their inherently high statistics [10, 13, 24, 25]. These experiments all serve as promising avenues to probe the mCP model.

The purpose of this Letter is twofold: First, we demonstrate that existing data from LSND provides leading bounds on mCPs (slightly surpassing existing constraints from SLAC’s mQ experiment [17]) in the low mass regime ($m_\chi \lesssim 35$ MeV). Likewise, newly released data from MiniBooNE [19] can set more stringent bounds on mCPs in the mass range of 100 MeV $< m_\chi \lesssim 180$ MeV. Second, we predict that by optimizing search strategies at ongoing and upcoming experiments (such as MicroBooNE, SBN, DUNE, and SHiP), fixed source neutrino experiments can serve to provide leading bounds for mCP masses over the full range of masses 5 MeV $< m_\chi \lesssim 5$ GeV. The detection signature of mCPs in these experiments is elastic scattering with electrons, and we find that detection prospects are highly sensitive to the threshold imposed on the electron’s recoil energy. Therefore, significant gains in sensitivity to mCPs may be achieved by future experiments by optimizing the detection of low energy electrons.

Our results have direct implications for models with late kinetic coupling of dark matter and baryons [30] that could lead to extra cooling of the baryon fluid and spin temperature at redshifts $z \approx 20$, which in turn may result in a more pronounced 21cm absorption signal. If a fraction of dark matter is in the form of mCPs, this extra cooling mechanism can be naturally realized [31, 32], and fit the unexpected strength of the signal reported by Experiment to Detect the Global Epoch of Reionization Signature (EDGES) [33]. The interpretation of the EDGES result as shedding light on dark matter-baryon interactions necessitates a careful consideration of existing laboratory constraints. In particular, our analysis reveals that sensitivities from LSND, SBN, SHiP, and DUNE can explore previously unprobed regions of parameter space that are favored by the 1%-mCP fractional dark matter hypothesis [29, 32, 34].

Production and detection: Fixed target neutrino experiments rely on the production of neutrinos from weak decays of charged pions. In generating an appro-
where, of electron scattering as a detection signal is related to the low-$Q^2$ sensitivity of the scattering cross section. Explicitly, in the limit of small electron mass, we have
\[ \frac{d\sigma_{ex}}{dQ^2} = 2\pi\alpha^2e^2 \times \left( \frac{2(s-m_e^2)^2 - 2sQ^2 + Q^4}{(s-m_e^2)^2Q^4} \right). \] (2)

Upon integrating over momentum transfers, we see that the total cross section will be dominated by the small-$Q^2$ contribution to the integral. In this limit, we have $d\sigma_{ex}/dQ^2 \approx 4\pi\alpha^2e^2/Q^4$, and so we can see immediately that $\sigma_{ex} \approx 4\pi\alpha^2e^2/Q_{min}^4$. We may relate $Q_{min}$ in the lab frame to the recoil energy of the electron via $Q^2 = 2m_e(E_e - m_e)$ [35]. An experiment’s recoil energy threshold, $E_e^{(min)}$, then sets the scale of the detection cross section as
\[ \sigma_{ex} = 2.6 \times 10^{-25} \text{cm}^2 \times e^2 \times \frac{1 \text{ MeV}}{E_e^{(min)} - m_e}. \] (3)

Consequently, sensitivity to mCPs can be greatly enhanced by accurately measuring low electron energy recoils (an important feature for search strategies at future experiments).

**Results:** We now discuss the details of the modelling and analysis used to create Fig. 1. The various curves are obtained by performing a sensitivity analysis [36]: given a number of predicted background events $b$ and data $n$, the number of signal events $s_{up}$ consistent with the observation and backgrounds at $(1 - \alpha)$ credibility level is found by solving the equation $\alpha = \Gamma(1 + n, b + s_{up})/\Gamma(1 + n, b)$ where $\Gamma(x,y)$ is the upper incomplete gamma function [37]. Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ and calculate the corresponding bounds implied by $s_{up}$ on our mCP model according to the formula
\[ s_{up} = \sum_{\text{Energies}} \epsilon^4 \times N_{\chi}(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{ex}(E_i; m_{\chi}) \times \mathcal{E}. \] (4)

Here, $\epsilon$ is the mCP electric charge (in units of $e$), $N_{\chi}(E_i)$ represents the number of mCPs with energy $E_i$ arriving at the detector, $\sigma_{ex}(E_i)$ is the detection cross section consistent with the angular and recoil cuts in the experiment, $N_e$ is the total number of electrons inside the active volume of the detector, $\mathcal{E}$ is an overall electron detection efficiency. Finally, “Area” in (4) stands for the active volume divided by the average length ($l$) traversed by particles inside the detector. The total exposure is contained in $N_{\chi}(E_i)$. For most of the mCP parameter space under consideration, electromagnetic decays of mesons provide the dominant flux contribution, whereas Drell-Yan production (DYP) dominates for the large mCP masses that are only accessible at DUNE and SHiP.

To estimate how many mCPs of energy $E_i$ arrive at the detector, we model the angular and energy distributions of the mesons using one of several empirical formulas to be discussed below. Given a meson produced at a certain angle and energy, we numerically sample its branching fraction.
ratio to mCPs over all possible angles and energy in the lab frame, and determine the fraction of its branching ratio to mCPs in which one of such particles has energy $E_i$ and is pointed towards the detector. Repeating this procedure over all production energies and angles of the meson yields the contribution to $N_\chi(E_i)$. For DYP of mCPs from a quark and anti-quark pair, we integrate over the full production phase-space using MSTW parton distribution functions [13], and using Heaviside functions, we select the proportion of events containing an mCP pointed towards the detector, with energy $E_i$.

Having given a general overview of how our sensitivities are obtained, we now focus the discussion on the details of each experiment. In Table I we show for each experiment: the lifetime rates for $\pi^\pm$ and $\eta$ mesons, the geometric acceptance $A_{geo}(m_\chi)$ [14], the cuts that we have imposed, and the expected number of background events. Using Eq. [4] this is sufficient information to approximately reproduce our results.

At LSND, the $\pi^\pm$ spectrum is modelled using a Burman-Smith distribution [15, 16] assuming 2 years of operation on a water target and 3 years of operation on a tungsten target. Our LSND analysis is based on [13], which featured $1.7 \times 10^{23}$ protons on target (POT), a beam energy of 0.798 GeV, and a single electron background of approximately 300 events with energies ranging between 18 MeV and 52 MeV. We estimate the $N_\chi$/Area in Eq. [4] to be $2.5 \times 10^{26} \text{e}^-/\text{cm}^2$.

The resultant meson spectrum from Fermilab’s Booster Neutrino Beam (BNB) is relevant for MiniBooNE, MicroBooNE, and SBND. The BNB delivers 8.9 GeV protons on target and so can produce substantial numbers of both $\pi^\pm$ and $\eta$ mesons. The former’s angular and energy spectra are modelled by the Sanford-Wang distribution [16, 17], and $\eta$ mesons by the Feynman Scaling hypothesis [17]. These distributions are common across all three of the aforementioned experiments. We have compared our geometric acceptances with those generated using [16] and reasonable (to within an $O(1)$ factor) agreement.

At MiniBooNE we perform two distinct analyses: First we consider the recently updated neutrino oscillation search [19]. We combine data from both neutrino and anti-neutrino runs and consider a sample of $2.41 \times 10^{21}$ POT for which we take the single electron background to be $2.0 \times 10^3$ events and the measured rate to be $2.4 \times 10^3$. Next, motivated by a dedicated dark matter search with $1.86 \times 10^{20}$ protons on target [48], we consider an anticipated parallel analysis [10] involving electron-recoil data. Backgrounds were suppressed by operating the beamline in an “off-target” mode, (i.e. not collimating charged pions), and these can be further suppressed (to zero) by imposing a cut of $\cos \theta > 0.99$ on the recoil angle [38]. In both cases we estimate an electron number density of $3.2 \times 10^{26} \text{e}^-/\text{cm}^2$. The sensitivity curve quoted in Fig. [1] assumes that the upcoming analysis reports no signal consistent with mCPs.

At MicroBooNE, the meson rates assume $1.32 \times 10^{21}$ POT and we estimate that the detector has an electron density of $3.9 \times 10^{26} \text{e}^-/\text{cm}^2$. The chosen recoil cuts are based on the lowest reaches achievable given the wire spacing in MicroBooNE’s liquid argon detector [41]. The wire spacing is 3 mm and the ionization stopping power is approximately 2.5 MeV/cm, so electrons with energy larger than 0.8 MeV produce tracks long enough to be reconstructed. Based on this and the requirement for ionization signals that don’t shower, we limit ourselves to recoil cuts between 0.8 MeV and 40 MeV. The treatment of SBND is broadly similar to MicroBooNE, but we assume $6.6 \times 10^{20}$ POT, which corresponds to half the run time of MicroBooNE.

At SHiP our results assume $2 \times 10^{20}$ POT and a near detector 50 m from the beam stop with an electron density of $2.7 \times 10^{26} \text{e}^-/\text{cm}^2$. The large beam energies of 400 GeV allow us to include $J/\psi$ and $\Upsilon$, in addition to $\pi^0$ and $\eta$. We do not include mesons such as $\rho$, $\omega$ and $\phi$, because they do not serve to significantly alter the sensitivity offered by $J/\psi$ (although their inclusion would only serve to increase sensitivity at SHiP for $m_\chi \lesssim 400$ MeV). At the energies of SHiP, production of $\pi^0$ and $\eta$ can be described by the BMPT distribution [16, 19]. These distributions are slightly different depending on the mass of the meson with the $\eta$ having a spectrum that is more forward pointed. We have compared our geometric acceptances to those obtained using [16] and found reason-

<table>
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<th>Bkg</th>
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<td>0.05</td>
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TABLE I. Summary of the lifetime meson rates ($N$), mCP detector acceptances ($A_{geo}$), electron recoil energy cuts, and backgrounds at each of the experiments considered in this paper. In all experiments a cut of $\cos \theta > 0$ is imposed in our analysis (*except for at MiniBooNE’s dark matter run where a cut of $\cos \theta > 0.99$ effectively reduces backgrounds to zero [38]). For the SHiP and DUNE experiments, we also include $J/\psi$ and $\Upsilon$ mesons as well as Drell-Yan production which are discussed in the text. We use an efficiency of $E=0.2$ for Cherenkov detectors, $E=0.5$ for nuclear emulsion detectors, and $E=0.8$ for liquid argon time projection chambers. The data at LSND and MiniBooNE is taken from [39] and [19] respectively. Projections at MiniBooNE* [40], MicroBooNE [41], SBND [21], DUNE [22] and SHiP [42] are based on expected detector performance.
able agreement, with our acceptances being smaller by a factor of four. For production of $J/\psi$, we assume that their energy production spectra are described by the distributions in [50]. These distributions rely on production being highly peaked in the forward direction and parameterized as $d\sigma/dx_F \sim (1-|x_F|)^{1.5}$, where $x_F = 2p_T/\sqrt{s}$ is the meson’s longitudinal component in the COM frame of the collision. We account for geometric losses by using an empirical formulae for the $p_T$ distribution provided in [51]. We assume that the production spectrum of $\Upsilon$ mesons are similarly given, and normalize their total cross section to the data in [52]. Using this, we have reproduced the Pb rates in Table 3 of [53] for $J/\Psi$, and for $\Upsilon$ we reproduced the Pt rates in Table 1 of [54]. As for our results in Fig. 1, we estimate $N_{J/\psi} = 2.1 \times 10^{15}$ with an acceptance of $A_{geo}(100 \text{ MeV}) = 8 \times 10^{-2}$, and $N_{\Upsilon} = 1.2 \times 10^{11}$ with $A_{geo}(100 \text{ MeV}) = 7.2 \times 10^{-2}$. For large mCP masses, DYP becomes the main production mechanism. We calibrate our DYP calculations by reproducing the dimuon invariant mass spectrum in Fig. 11 of [55] from the FNAL-772 experiment [56].

At DUNE, our treatment of meson production is very similar to the treatment at SHiP. We model pseudoscalar meson production using the BMPT distribution, as before, but use a beam energy of 80 GeV [22] and account for differences in the target material. We also include $J/\psi$ and $\Upsilon$ mesons and treat them as described above. Our detector treatment and electron recoil cuts are motivated by the capability of MicroBooNE’s liquid argon time projection chamber (LAr-TPC) detector, and in particular its ability to measure low energy electron recoils. We assume $3 \times 10^{22} \text{ POT}$ and a 30 tonne liquid argon detector which corresponds to $5.4 \times 10^{25} \text{ e}^{-2}/\text{cm}^2$. We estimate $N_{J/\psi} = 3 \times 10^{16}$ with an acceptance of $A_{geo}(100 \text{ MeV}) = 2.4 \times 10^{-3}$ and $N_{\Upsilon} = 5.1 \times 10^{10}$ with $A_{geo}(100 \text{ MeV}) = 3.7 \times 10^{-3}$. Lastly, it is important to point out that our results do not include multiple scattering effects through dirt. Low velocity mCPs with a moderate charge (i.e. $\epsilon \gtrsim 0.03$) might get impeded by their long transit through dirt. This is relevant for DYP at DUNE and could weaken our sensitivity for $m_\chi \gtrsim 2 \text{ GeV}$. Larger $\epsilon$ may also lead to a double scattering of mCPs inside the detectors, which could be used as an additional tool of discriminating their signature against the neutrino background.

We now discuss our modelling of the single electron backgrounds appearing in Table I. We consider two classes of backgrounds: those coming from each experiments flux of neutrinos [i.e. $\nu_e \rightarrow \nu_e$ and $\nu_x \rightarrow e^+ e^-$], and those coming from external sources such as cosmics, mis-identified particles, or dirt related events.

We treat neutrino induced backgrounds in detail for each experiment by summing over the neutrino fluxes provided by each collaboration and accounting for the detection efficiencies $E$. Furthermore, a large background reduction is obtained by imposing the electron recoil cuts $E_{\text{recoil}}^{(\text{max})}$ shown in Table I. These do not significantly affect the signal (which is dominated by low electron recoils), but significantly reduce charged and neutral current backgrounds [57, 58].

We model the external sources of backgrounds by multiplying the neutrino induced backgrounds by an overall multiplicative factor. LAr-TPC detectors can use timing and directionality information as vetoes to reduce additional sources of backgrounds; this is not possible in a nuclear emulsion chamber. Therefore, we multiply our neutrino induced backgrounds by a factor of 10 for LAr-TPC detectors (MiniBooNE, SBND, and DUNE) and a factor of 25 for nuclear emulsion detectors (SHiP); this increase in the backgrounds decreases our sensitivity to $\epsilon$ by $20-30\%$. Although our naive procedure likely overestimates the backgrounds, we emphasize that our results in Fig. 1 can be easily revised for different background assumptions according to [37].

**Outlook:** We have shown that millicharged particles can be effectively probed at fixed target neutrino experiments due to large number of mesons produced with electromagnetic decay pathways. This includes using existing data from both LSND and MicroBooNE that are able to provide the leading sensitivity to mCPs for certain sub-GeV masses. Beyond serving as a probe of fundamental physics questions such as charge quantization, this newfound sensitivity has implications for models of physics beyond the Standard Model. In particular it further restricts the parameter space of cosmological models where a fraction of mCP dark matter results in extra cooling of baryons that modifies 21cm physics at high redshifts.

Equally important are our projected sensitivities at MicroBooNE, SBND, DUNE and SHiP. The successful deployment of these experiments as probes of mCPs will rely heavily on their respective collaboration’s search strategy. In particular by working to increase the sensitivity to low energy electron recoils the predicted signal rate can be enhanced, with a scaling proportional to $1/(E_e - m_e)$. MicroBooNE in particular has shown preliminary work that suggests good sensitivity to electron recoils with kinetic energies as low as 300 keV is possible [41]. If this can be achieved, it is conceivable that the combined sensitivity of LSND, SBND, MicroBooNE, and SHiP could provide the leading sensitivity to mCPs in the full range of $5 \text{ MeV} \lesssim m_\chi \lesssim 5 \text{ GeV}$.

Finally, we close by noting that besides the discussed current and future neutrino experiments, further progress may come from new experimental concepts. Significant progress may come from coupling large underground neutrino detectors with purposely installed new accelerators [59]. Millicharged particles may also be searched by experiments in disappearance channels [60, 62], where $e^+ e^- \rightarrow \gamma + \tilde{\chi}$ and $Z + e^- \rightarrow Z + e^- + \chi + \tilde{\chi}$ production leads to anomalous missing momentum/energy from the $\chi$-pair that pass through a detector without
depositing energy. Because of the advantageous scaling with \( \epsilon \) (second, rather than the fourth power), there are clear prospects on improving bounds on mCPs above the 100 MeV energy range.

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[35] Note that for nucleon scattering, the cross section \( \sigma \propto 1/Q^2 \) is suppressed by \( 1/m_g \) rather than \( 1/m_c \).
[37] Given Eq. (41) and \( \alpha = \Gamma(1 + n, b + s_{up})/\Gamma(1 + n, b) \), any of our limits on \( \epsilon \) can be rescaled for different choices of backgrounds. This is important for our projected sensitivities since detailed modelling of backgrounds will likely differ from what is assumed here.
[38] R. Dharmapalan et al. (MiniBooNE), (2012), arXiv:1211.2258 [hep-ex]
[40] We anticipate the release of electron recoil data from MiniBooNE’s dark matter run. Our modelling of backgrounds is motivated by their nucleon scattering data [48].
[44] Defined as the ratio between the number of mCPs that reach the detector and the total number produced.


